Title: Einstein Telescope: A look at the dawn of the Universe

Speakers: Fernando Ferroni

Collection/Series: Colloquium

Subject: Particle Physics

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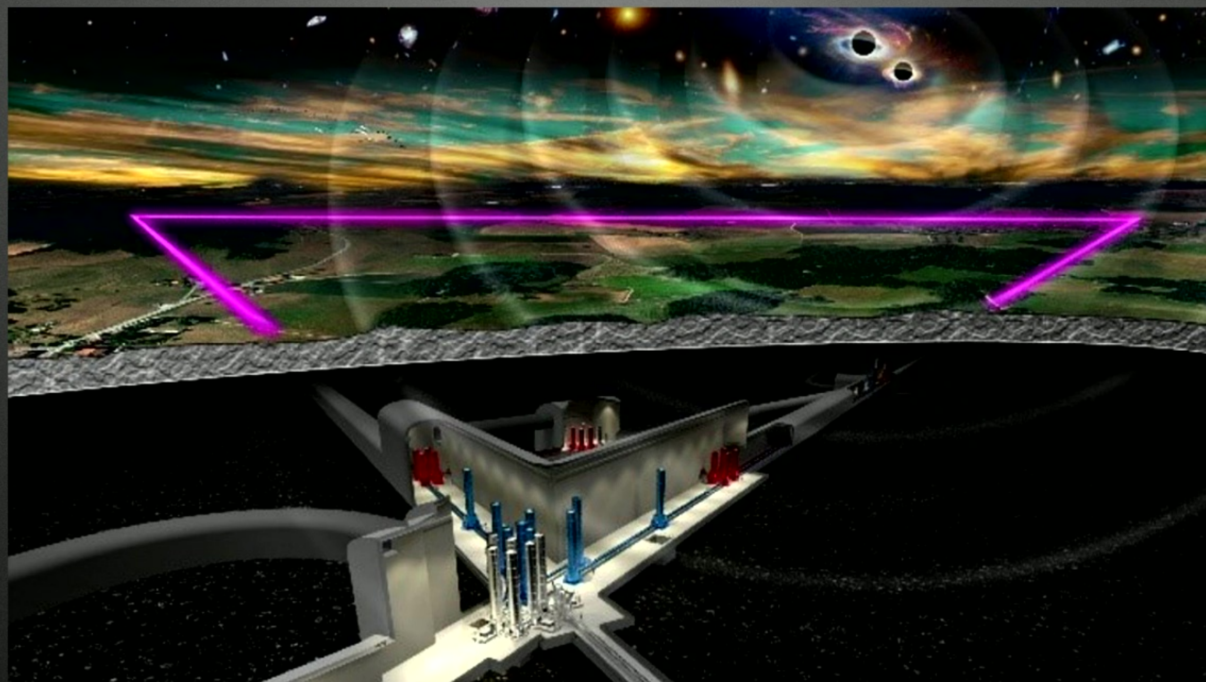
Abstract:

Gravitational waves were detected in 2015 after 100 years of their prediction. Coalescence of black holes and neutron stars have been studied giving birth to a new way of studying our Universe. The coincidence of the gravitational signal with a gamma ray burst has been identified as the beginning of multi-messenger astronomy. In order to move from the limited statistics, allowed by the actually running interferometers (LIGO and VIRGO), to a huge sample a new generation of detectors has to be designed , built and operated. Einstein Telescope is the project for a third generation detector, supported by a large European collaboration. It is going to be formed by a combination of a Low Frequency Cryogenic interferometer and an High Frequency high laser power interferometer both located underground in order to minimise the noise. Laser technology, seismic noise attenuation, quantim squeezing are a few of the keys to success. The experiment is going to produce results in several field of research like astronomy, astrophysics, nuclear physics, cosmology. It is going to be in competition and cooperation with the US project Cosmic Explorer.

Einstein Telescope
A look at the dawn of the Universe



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GRAN SASSO SCIENCE INSTITUTE

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Fernando Ferroni
Gran Sasso Science Institute & INFN

INFN

Einstein announces GW !

688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

154 Gesamtsitzung vom 14. Februar 1918. — Mitteilung vom 31. Januar

Über Gravitationswellen.

Von A. Einstein.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

All the attempt of disavowing the claim failed miserably !

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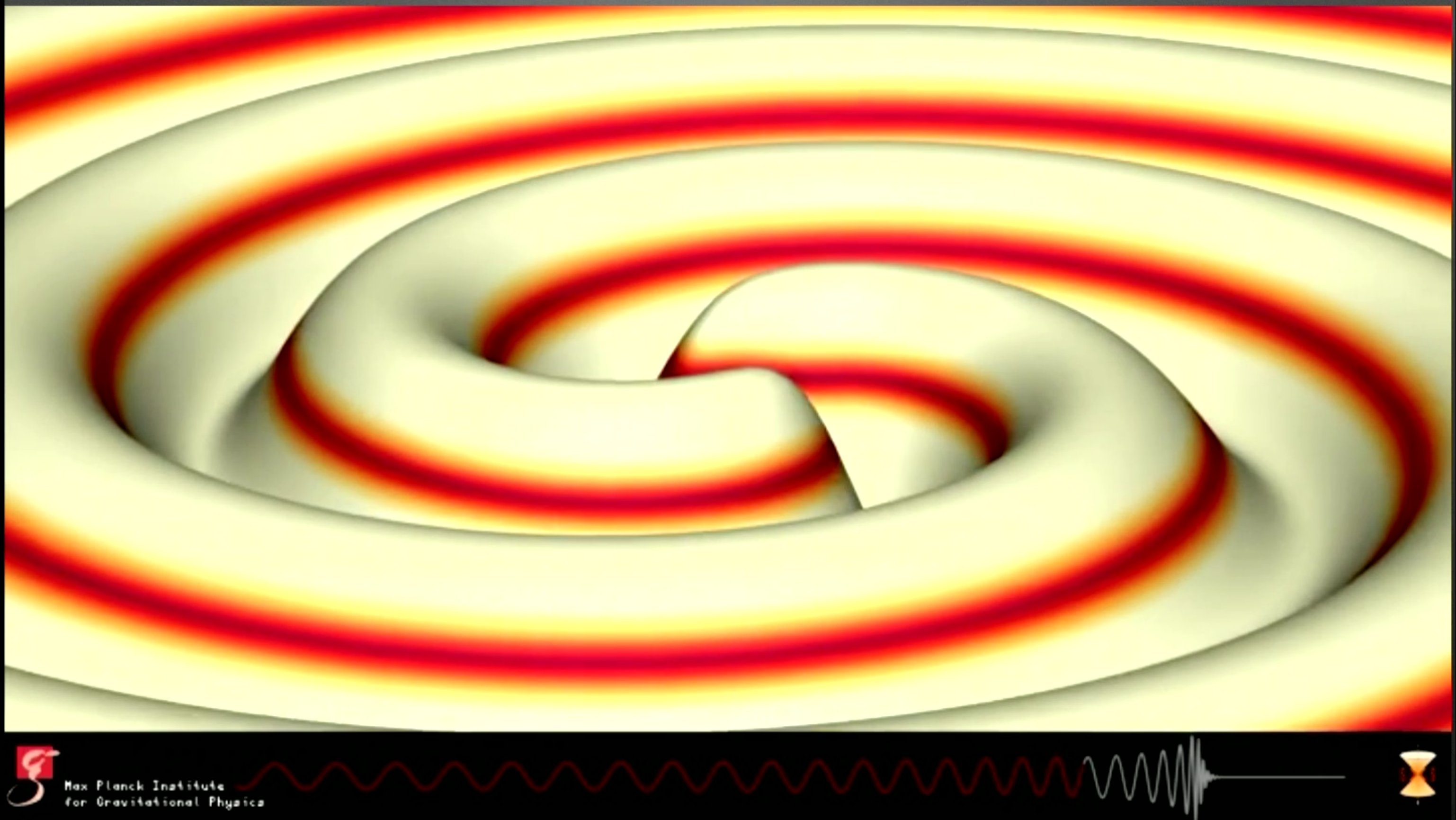
An example of a Gravitational Wave



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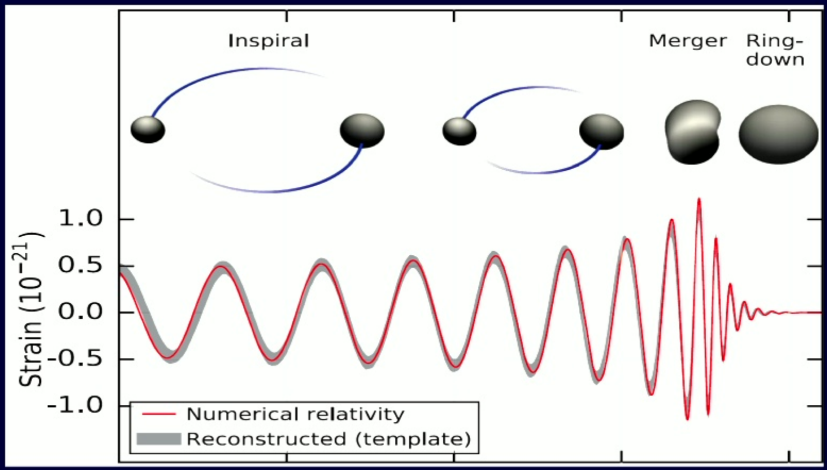
Courtesy of H. Lueck (ET Collaboration)

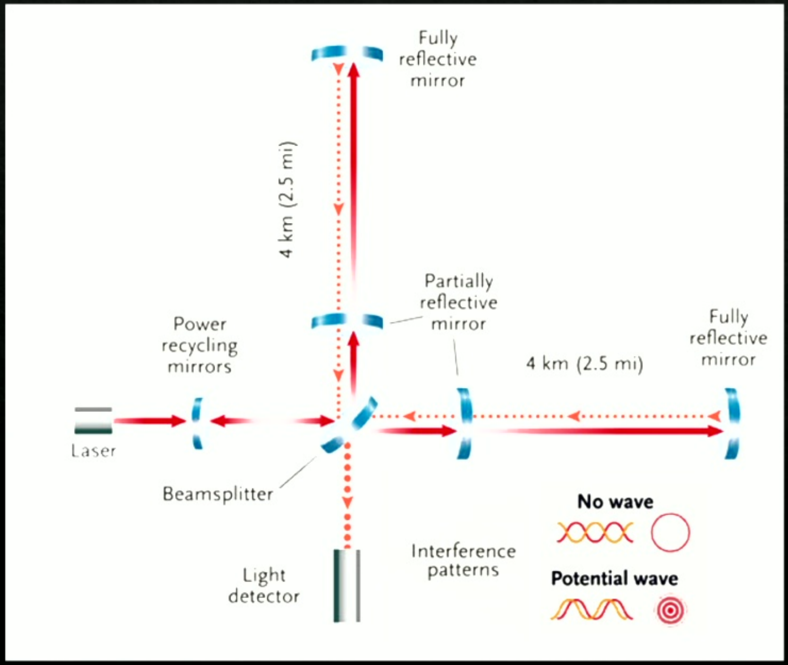
As observed in 2015

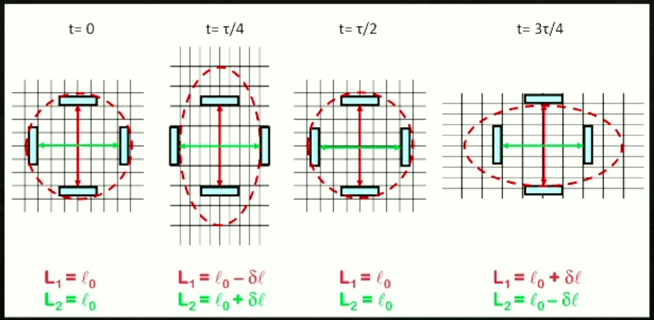
GW150914



Phys. Rev. Lett. 116, 061102

Very simple in principle





Gravitational waves change the distance between suspended test masses, which leaves an imprint on the phase of the laser beam.

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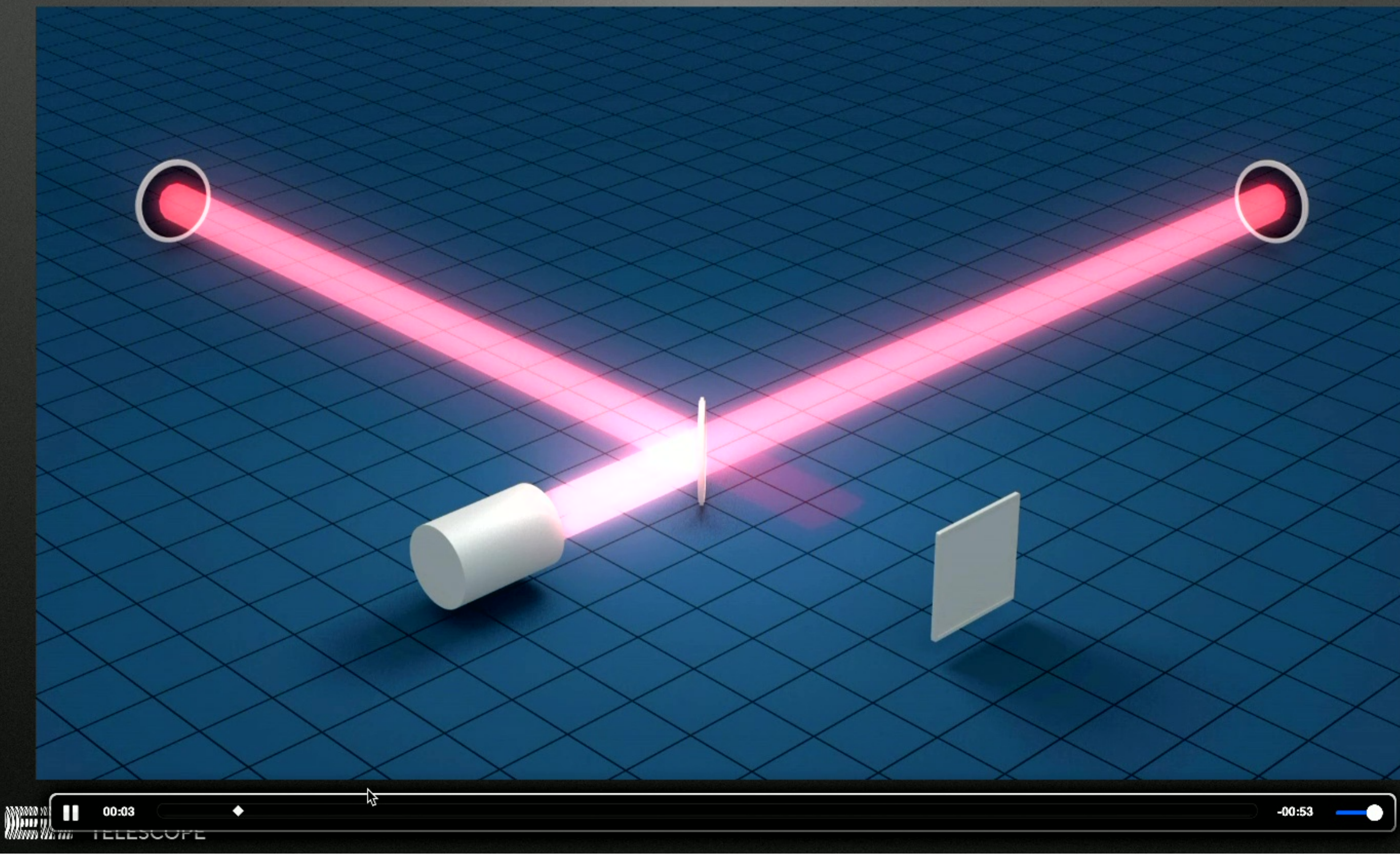
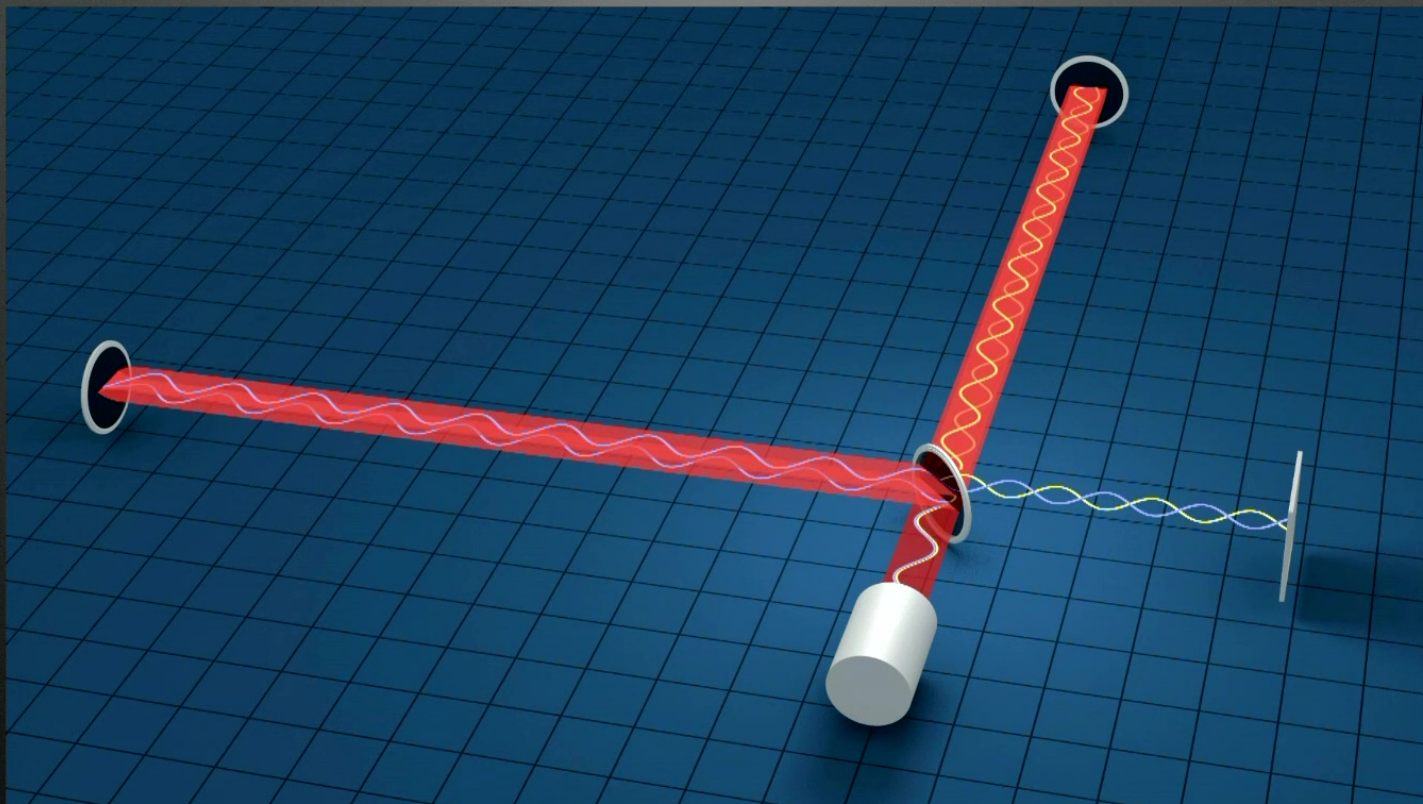
As simple as such



As simple as such



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VIRGO at Cascina (Pisa)

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The difficulty
(sensitivity at first detection)

$$\delta L / L \simeq 10^{-21}$$

Try this ….the distance Earth-Sun is $150 \times 10^{9} m$
$\delta L \simeq (150 \times 10^{9} m) \times 10^{-21} = 1.5 \times 10^{-10} m$

The radius of a typical atom is $10^{-10} m$

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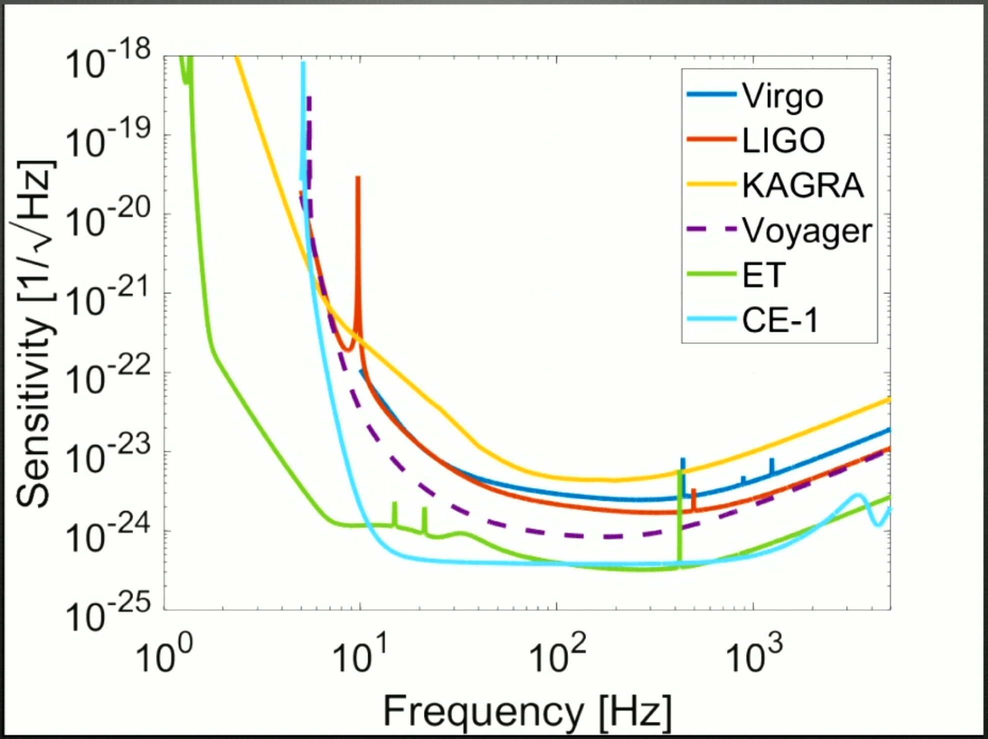
Sensitivity Models



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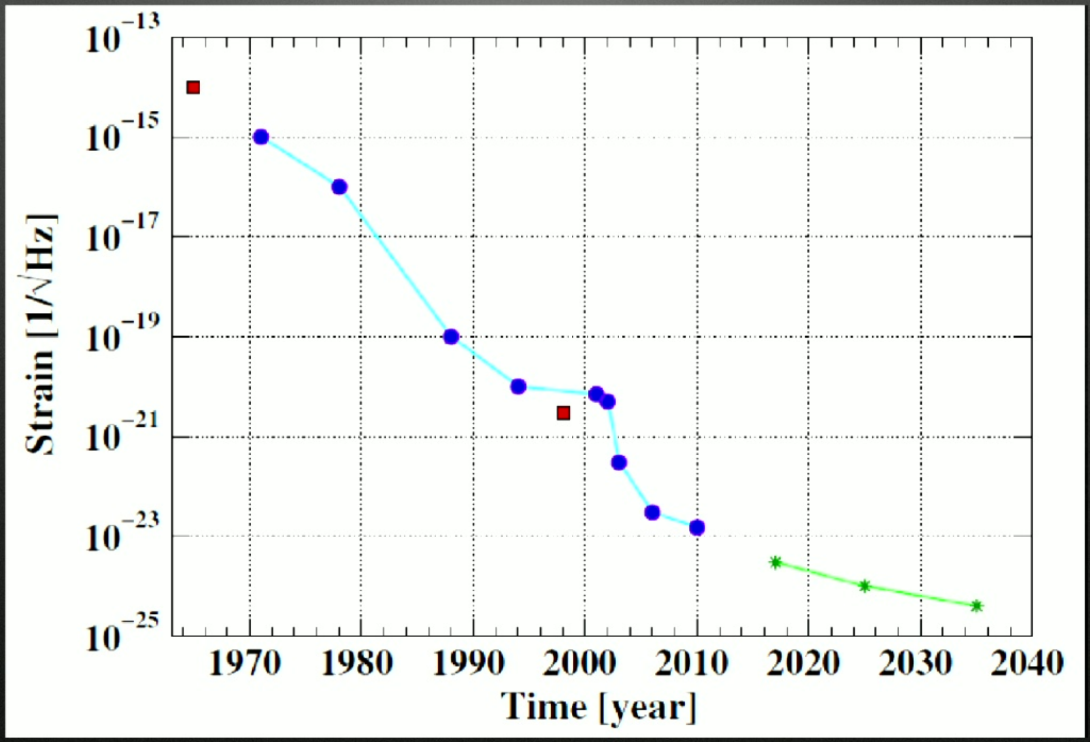
An amazing story of progresses



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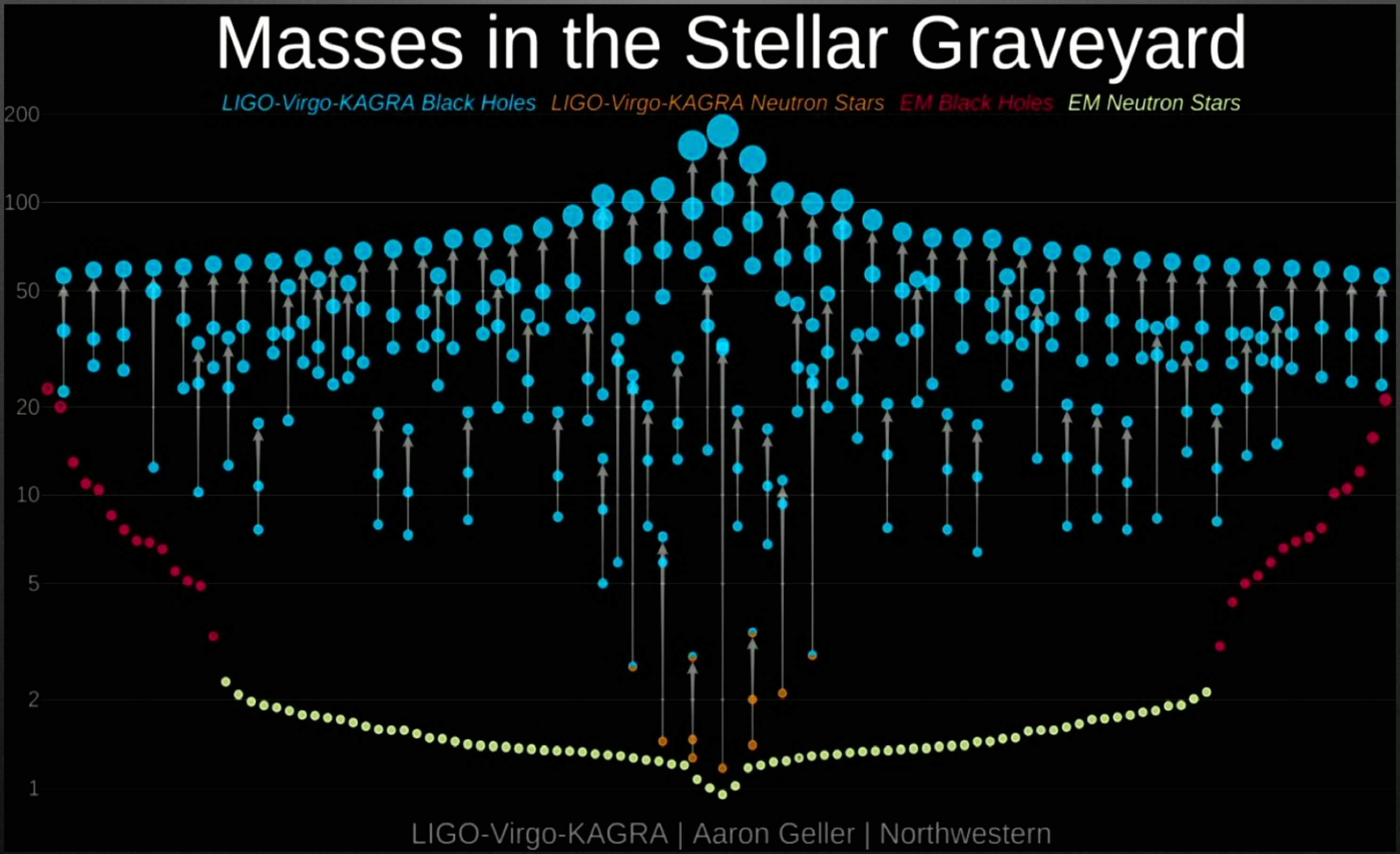
Mergers



LIGO-VIRGO so far..........

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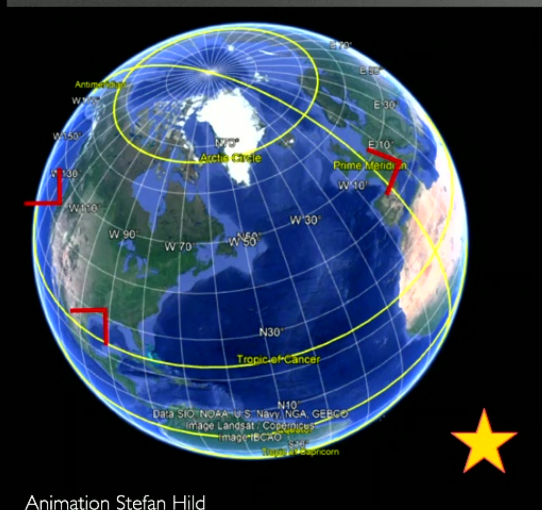
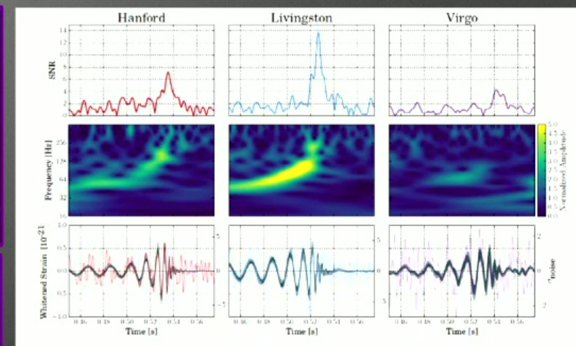
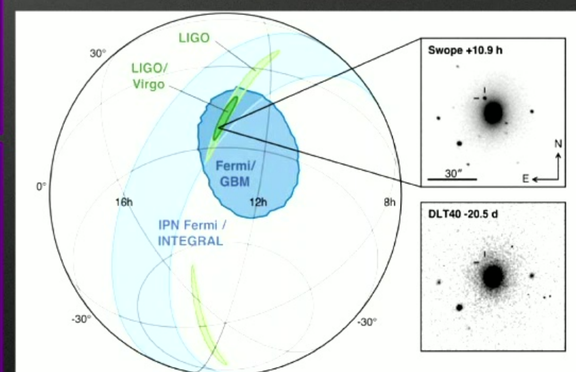
NS-NS merger : GW170817







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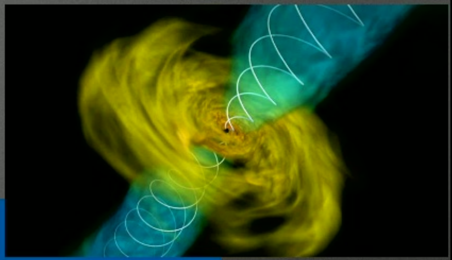
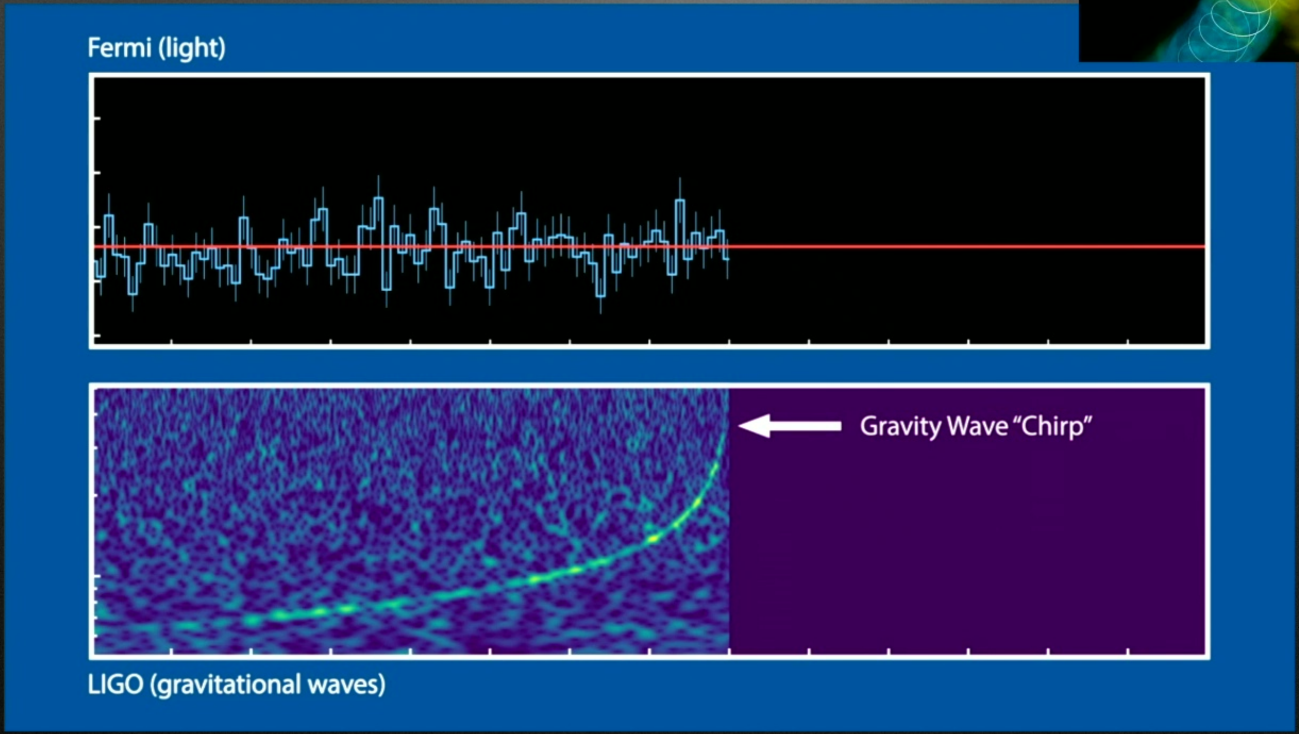
Multimessenger astronomy is born





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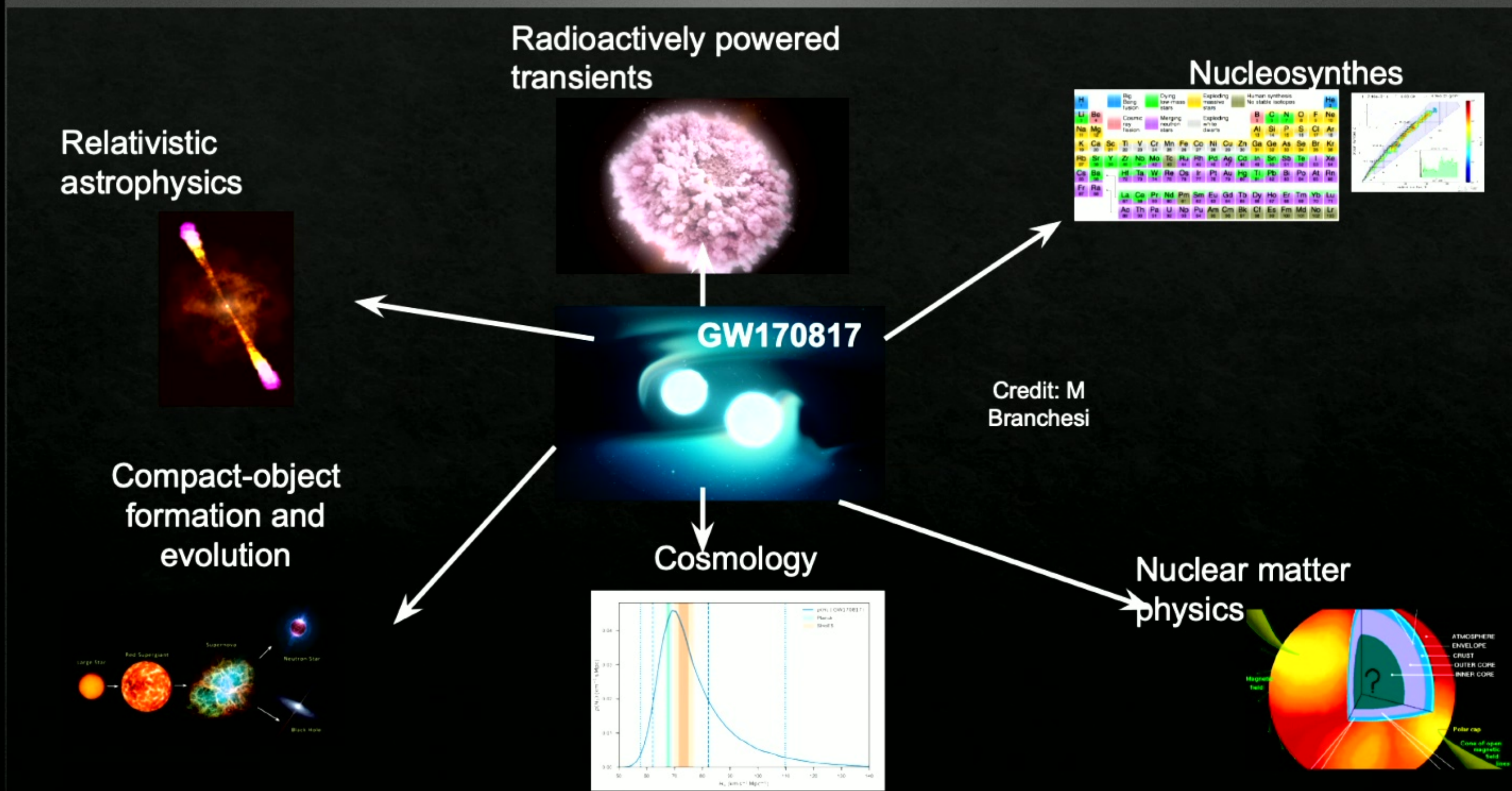
Science of Neutron Stars



A new field of research has been opened by LIGO,VIRGO

- Next: statistics, statistics, statistics
- Next: sensitivity, sensitivity, sensitivity

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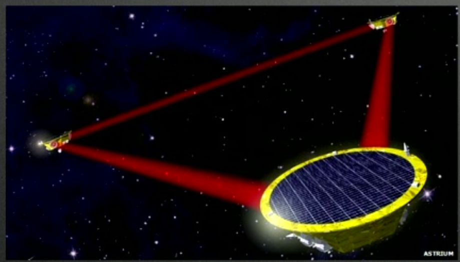
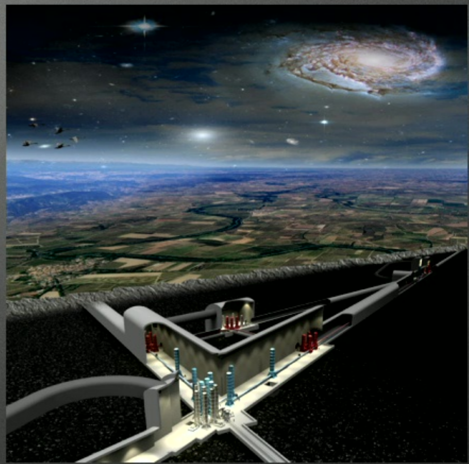
Next steps

Long baselines

Maximize your response to GWs





Operate at different frequency

Sensitivity with Frequency has to do with the arm length

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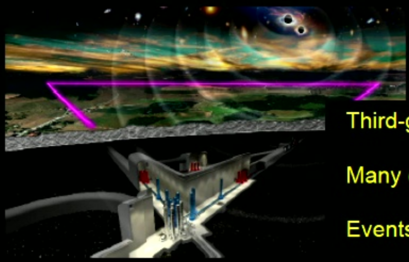
A travel back in time

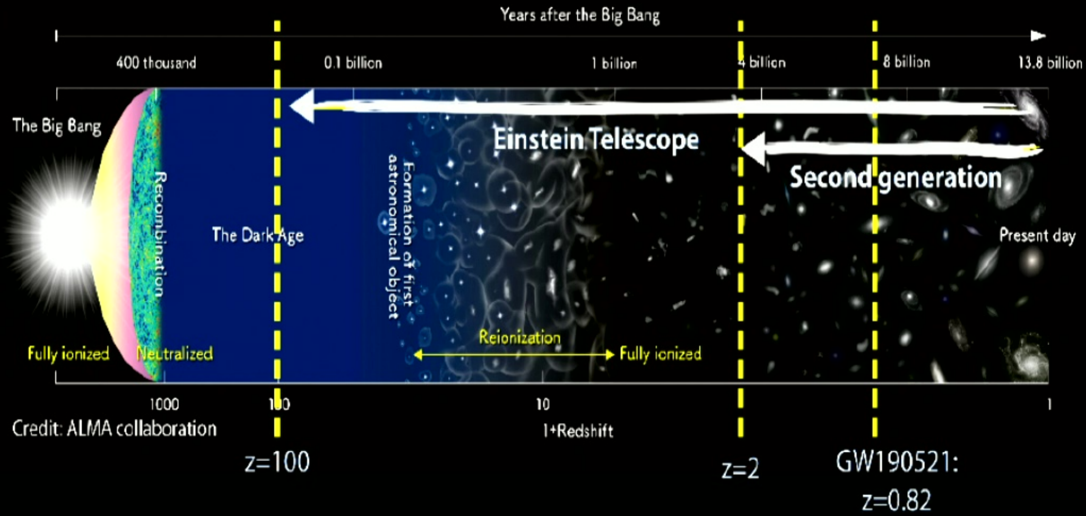


Third-generation instruments will observe hundreds of thousands of black hole mergers per year

Many events will have signals with an SNR up to 1,000 allowing precision black hole science

Events are distributed through the entire Universe allowing cosmography

Detection horizon for black-hole binaries



Credit: ALMA collaboration

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- As long as possible (given the many constrains)
- Go to as low frequency as possible
- A strain significantly better that 10^{-24} at medium frequency

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Playing with length

Noise	Scaling	Remarks
Coating Brownian	$1/L^{3/2}$	Fixed cavity geometry
Substrate Thermo-Refractive	$1/L^2$	Fixed cavity geometry
Suspension Thermal	$1/L, 1$	Horizontal, vertical noise
Seismic	$1/L, 1$	Horizontal, vertical noise
Newtonian	$1/L$	
Residual Gas Scattering	$1/L^{3/4}$	Fixed cavity geometry
Residual Gas Damping	$1/L$	
*Quantum Shot Noise	$1/L^{1/2}$	Fixed bandwidth
*Quantum Radiation pressure	$1/L^{3/2}$	Fixed bandwidth

Europe is the wrong place for having a long instrument on surface (villages, highways, train tracks, land use permissions…)

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3G concept: extend the band

WIDEN THE BAND: XYLOPHONE

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- Improving al low and high frequency with a single detector is very challenging
  - HF requires more laser power
  - LF requires cold mirrors
- Idea: split the detection band over 3 “specialized” instruments

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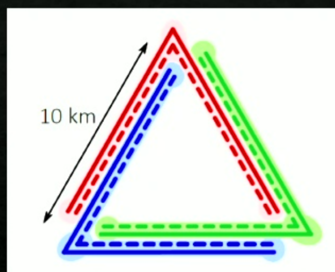
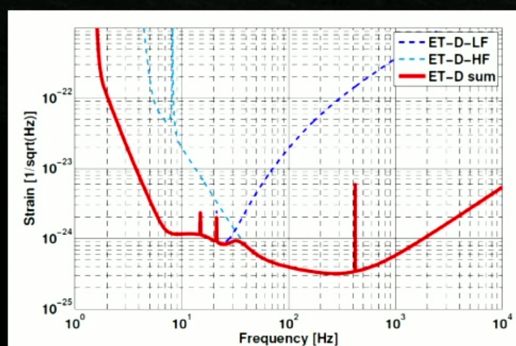
Einstein Telescope as Xylophone

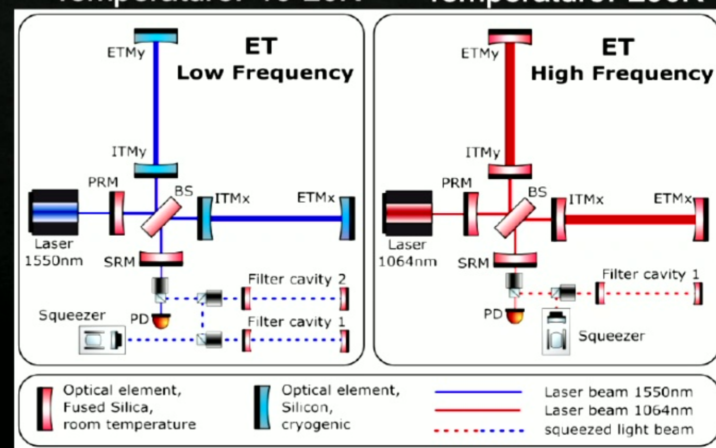


Each vertex is the center of a pair of interferometers, i.e., 6 interferometers in total.



Power: 18kW
Temperature: 10-20K

Power: 3MW
Temperature: 290K



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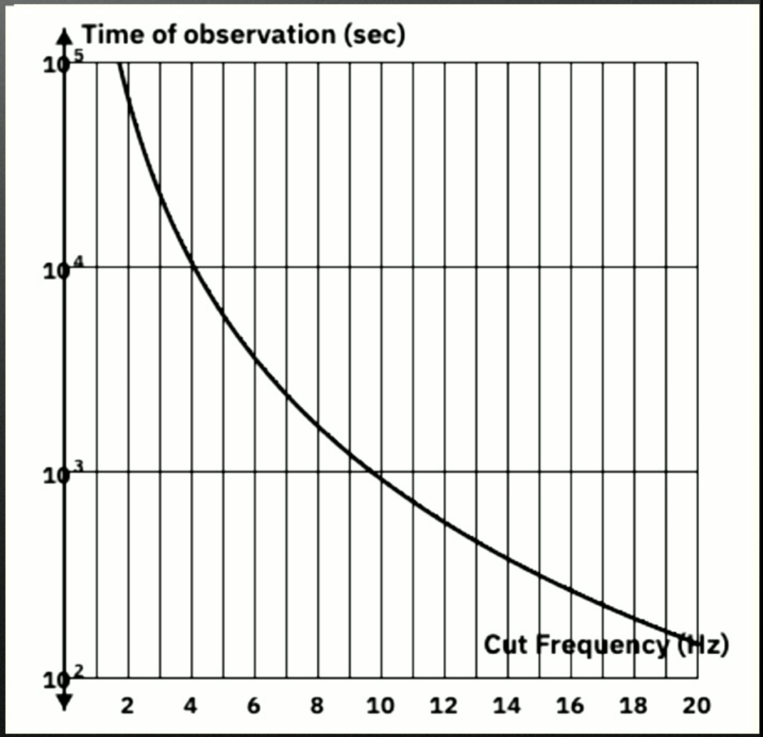
The relation Time-Frequency

$$\tau_c \sim 2(f_0/100Hz)^{(-8/3)} \text{ s}$$

For a BNS coalescence
1.4 solar masses each



Time for alerting the optical telescope

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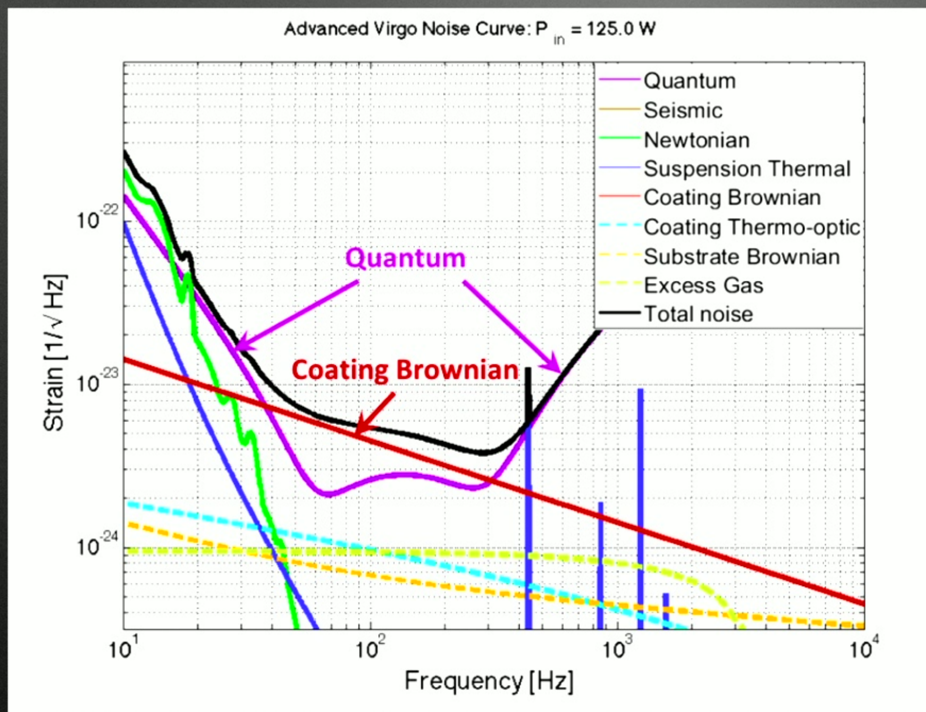
Noise, noise, more noise ! Principles



Controls
Seismic
Thermal
Quantum
Newtonian

Quantum noise is the sum of radiation pressure and shot noise….(with a different frequency spectrum)

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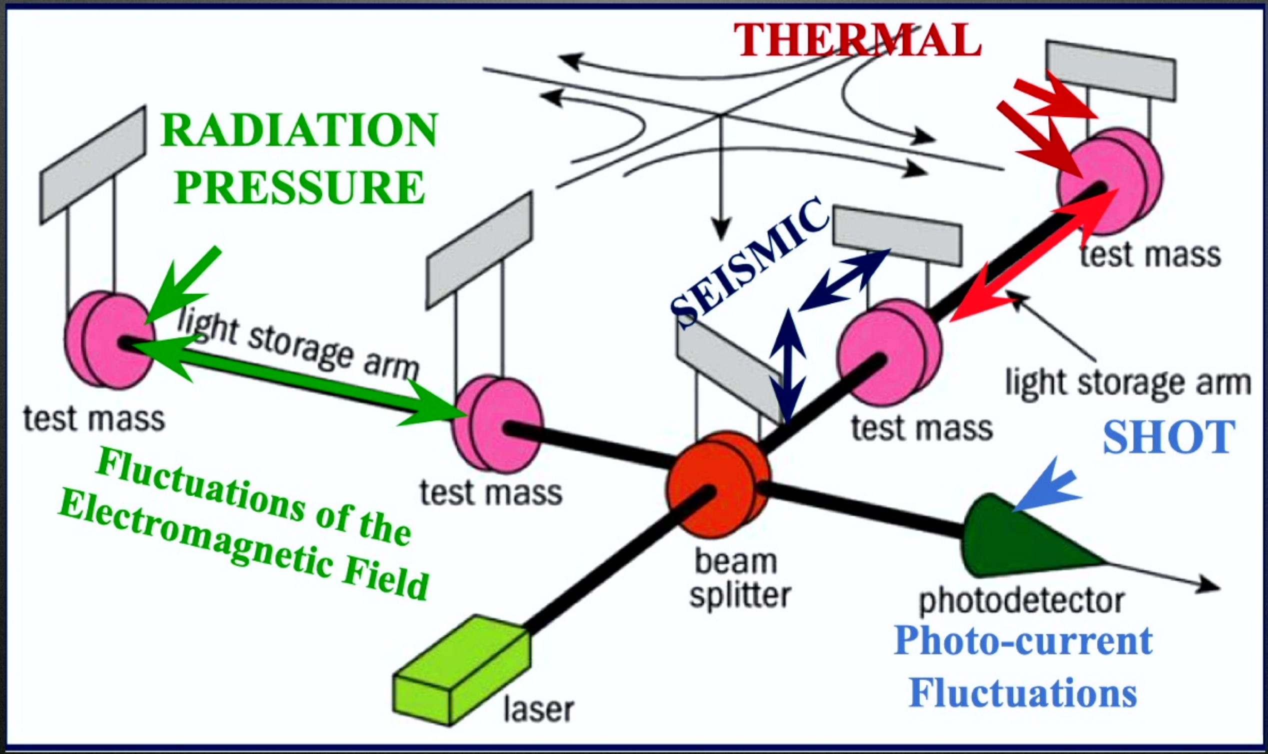
Where the Noise appears



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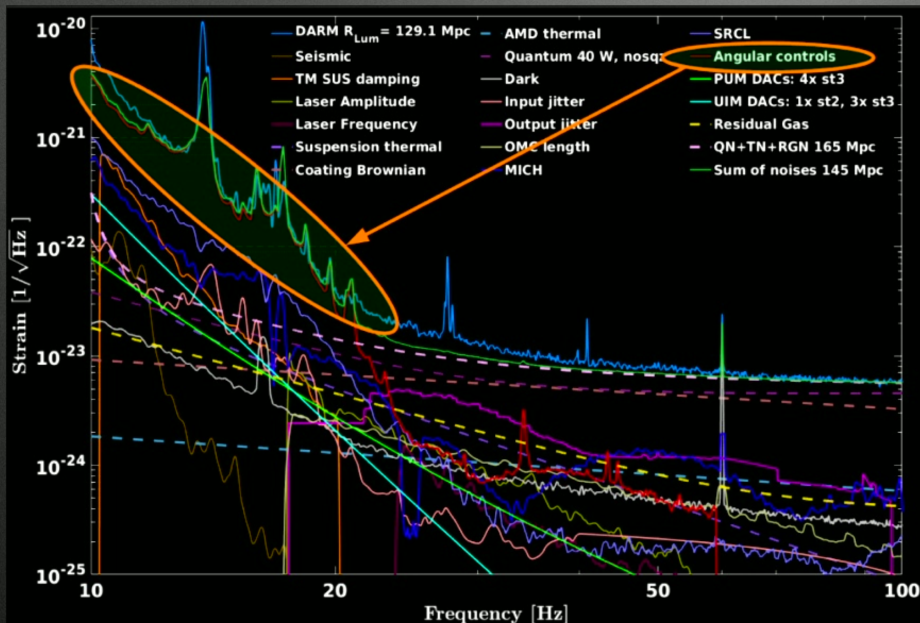
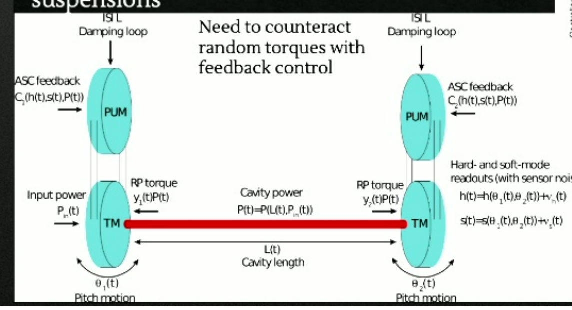
Noise from Detector Control



ET Strategy:
Low Power , High Mass

Torques continuously act on test masses:
Radiation pressure, noise from suspensions



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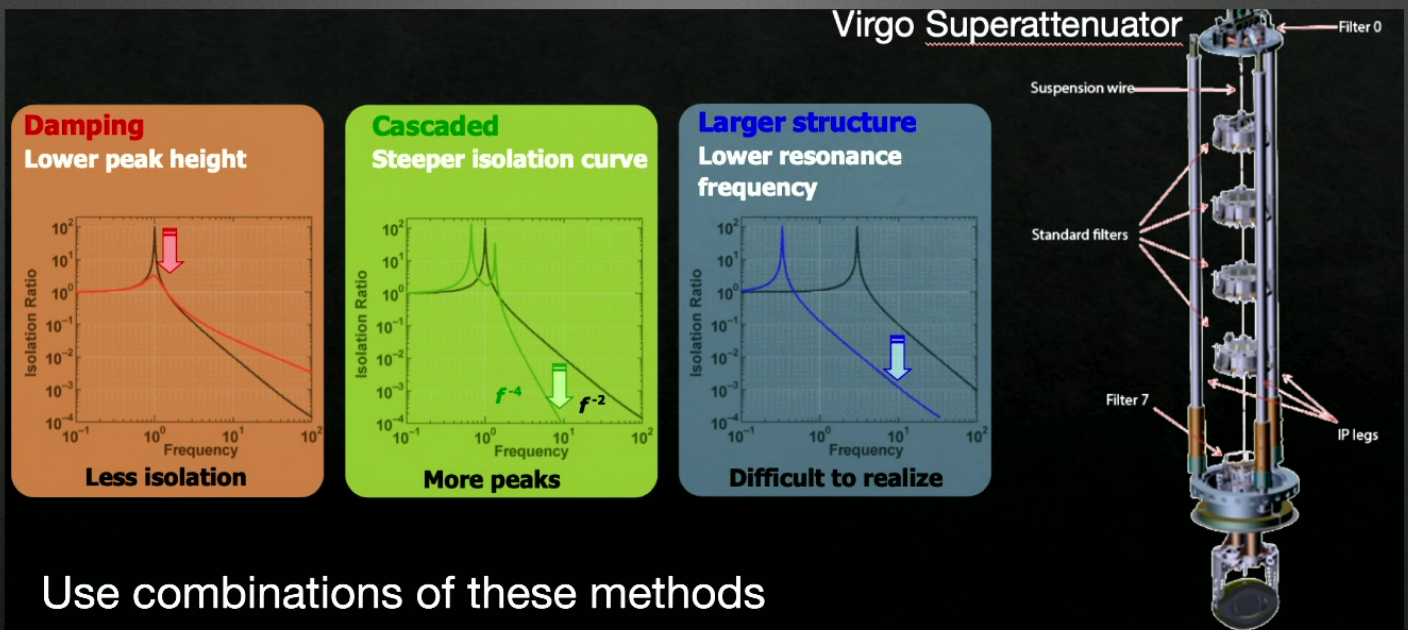
Principles of Seismic Isolation



Use combinations of these methods

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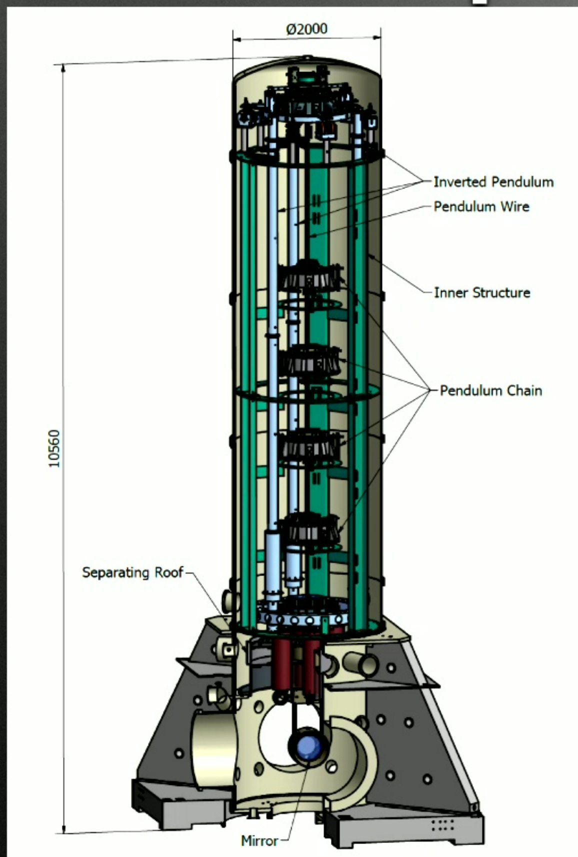
Mechanical Noise: Super attenuators



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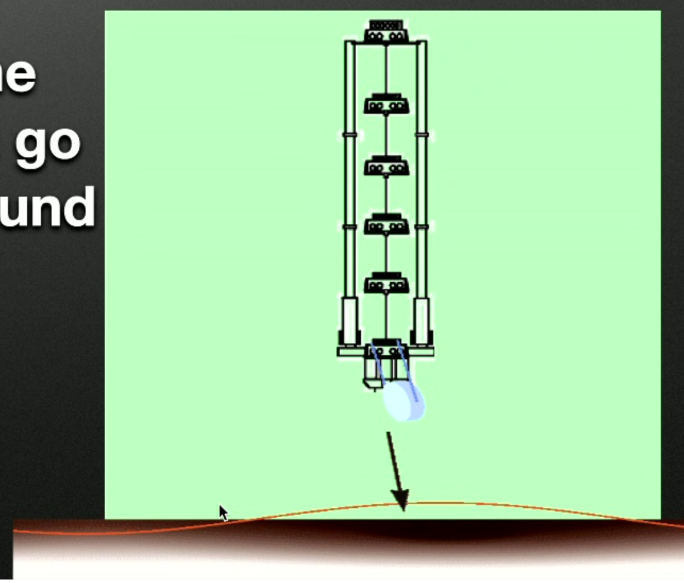
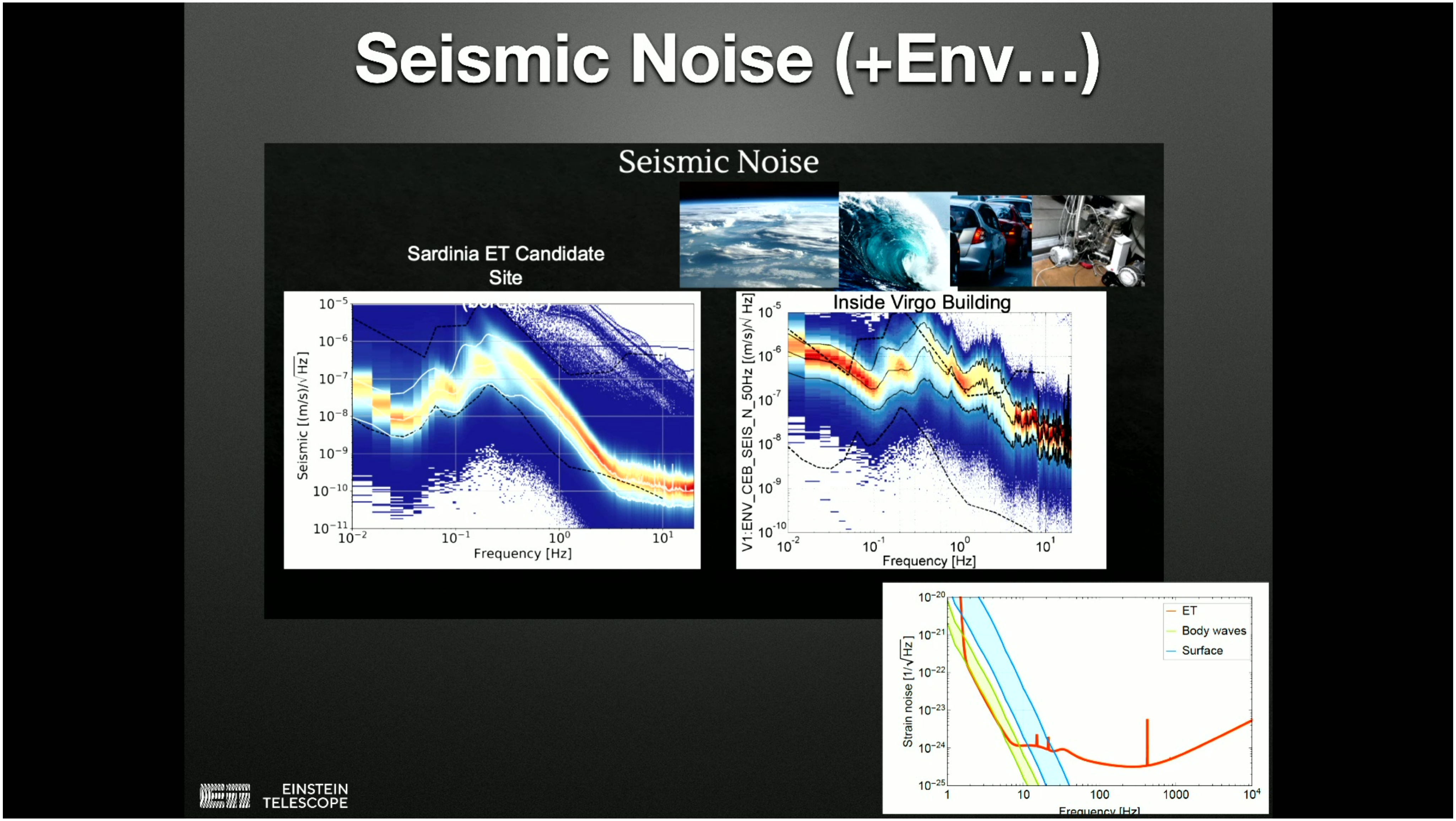
- Multiple pendulum (idea from A. Giazotto)

- Very good at High Frequency
- Very ineffective at Low Frequency

Extreme solution: go underground




Seismic Noise (+Env...)
Seismic Noise
Sardinia ET Candidate Site
Seismic [(m/s)/√Hz]
Frequency [Hz]
Inside Virgo Building
V1:ENV_CEB_SEIS_N_50Hz [(m/s)/√Hz]
Frequency [Hz]
Strain noise [1/√Hz]
ET
Body waves
Surface
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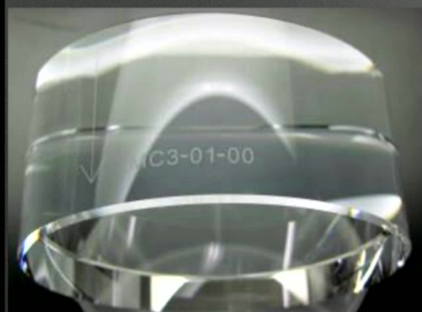
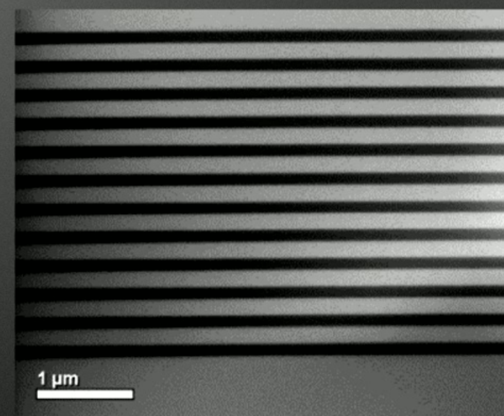
Thermal Noise : basics



Substrate thermal noise
- ***Thermo-elastic noise***
- Brownian noise

Coating thermal noise
- ***Brownian noise***
- Thermo-refractive noise
- Thermo-elastic noise
- Photothermal noise

Suspension thermal noise
- Brownian noise
- ***Thermo-elastic noise***



Mirrors are coated: need (100-ϵ)% reflectivity

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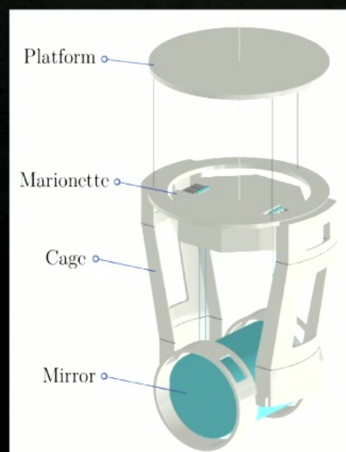
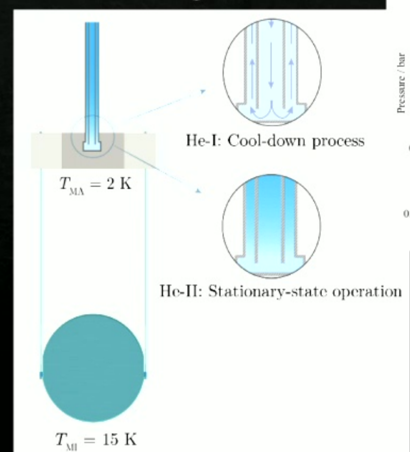
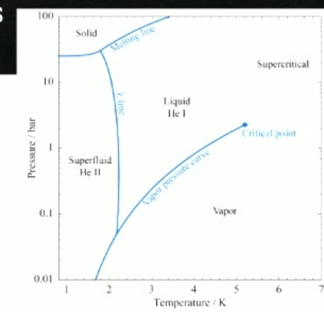
Cryogenic system: a challenge

Cooling the ET-LF test masses is one of the biggest technological challenges of ET.



Conductive tube for initial He-I cool down, and stationary heat-transport with He-II is under investigation.





Far from having a solution

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Quantum Noise

- Shot noise: Poisson photon statistics (mitigate increasing laser power)
- Pressure Radiation noise : amplitude fluctuations cause damaging effects inversely proportional to frequency (suspensions reacts with more sensitivity to low frequency)

The two effects cannot be optimised in a single interferometer

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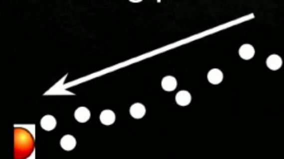
Heisenberg……

Fundamental measurement in ET: Counting photons



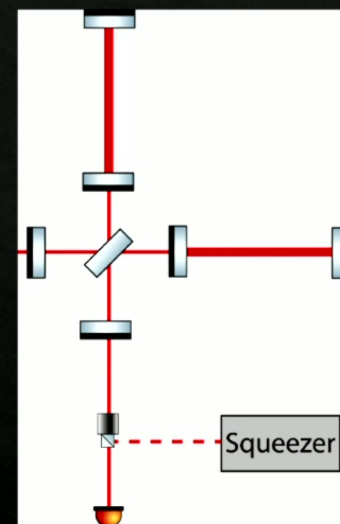
Heisenberg uncertainty principle

$$\Delta p \, \Delta x \geq \frac{\hbar}{2}$$

What are the position and momentum variables in the case of light?

Multiple answers, but for GW detectors, the conjugate variables are the quadratures of the EM field:

$$E(t) = E_1(t)\cos(\omega_0 t) + E_2(t)\sin(\omega_0 t)$$



Caves: manipulate quantum state at the dark port.

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The trick....

If we write the Electro-magnetic field in terms of quadrature operators:

$$\hat{E}_x = E_0 \sin(kz)\left(\hat{X}_1 \cos\omega t + \hat{X}_2 \sin\omega t\right)$$

Amplitude quadrature uncertainty ➡ $\Delta\hat{X}_1$ **Radiation Pressure Noise**

Phase quadrature uncertainty ➡ $\Delta\hat{X}_2$ **Shot Noise**

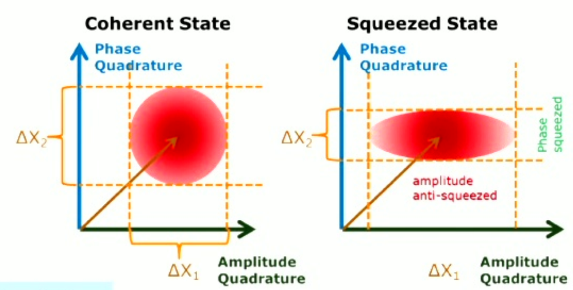
RPN and SN are related to the uncertainties of EM-field quadratures

It follows that SN and RPN are linked by the **Heisenberg Uncertainty Principle** $\left\langle(\Delta\hat{X}_1)^2\right\rangle\left\langle(\Delta\hat{X}_2)^2\right\rangle \geq \frac{1}{16}$

MINIMUM UNCERTAINTY STATE $\left\langle(\Delta\hat{X}_1)^2\right\rangle\left\langle(\Delta\hat{X}_2)^2\right\rangle = \frac{1}{16}$

COHERENT STATE $\left\langle(\Delta\hat{X}_1)^2\right\rangle = \left\langle(\Delta\hat{X}_2)^2\right\rangle$

SQUEEZED STATE $\left\langle(\Delta\hat{X}_1)^2\right\rangle < \left\langle(\Delta\hat{X}_2)^2\right\rangle$ $\left\langle(\Delta\hat{X}_1)^2\right\rangle > \left\langle(\Delta\hat{X}_2)^2\right\rangle$



SQL can be seen as a manifestation of the Heisenberg Uncertainty Principle

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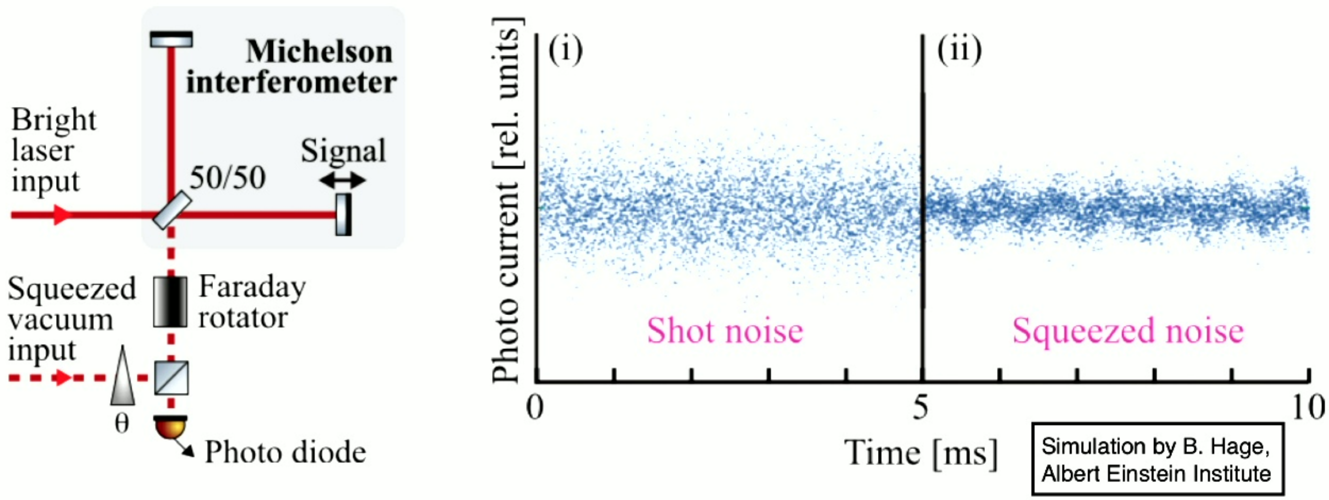
In theory....



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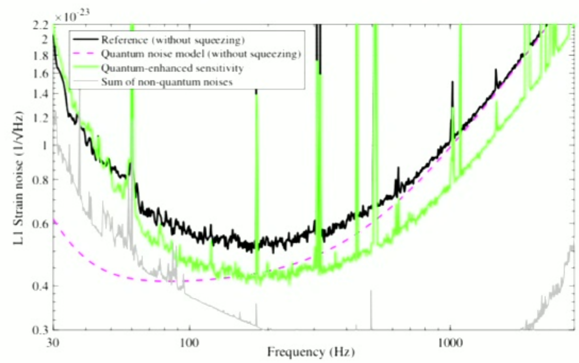
In practice (not a final result !)

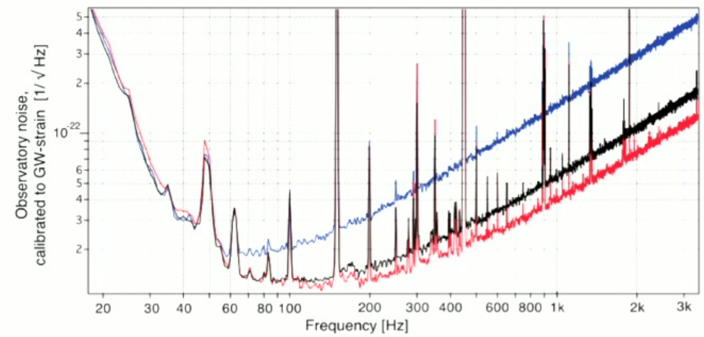


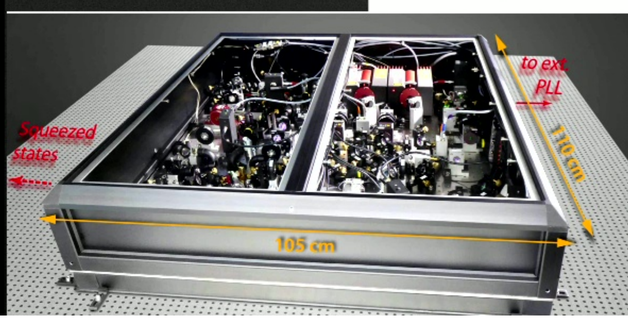
Advanced LIGO

- Best measured ~3 dB
- BNS Range improvement: 14%
- Detection rate improvement: 50%

Advanced Virgo

- Best measured ~3dB
- BNS Range improvement: 5%-8%
- Detection rate improvement: 16-26%





The story is much longer and more complex

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A billion (perhaps 3) Euro question

A Δ or 2L ?

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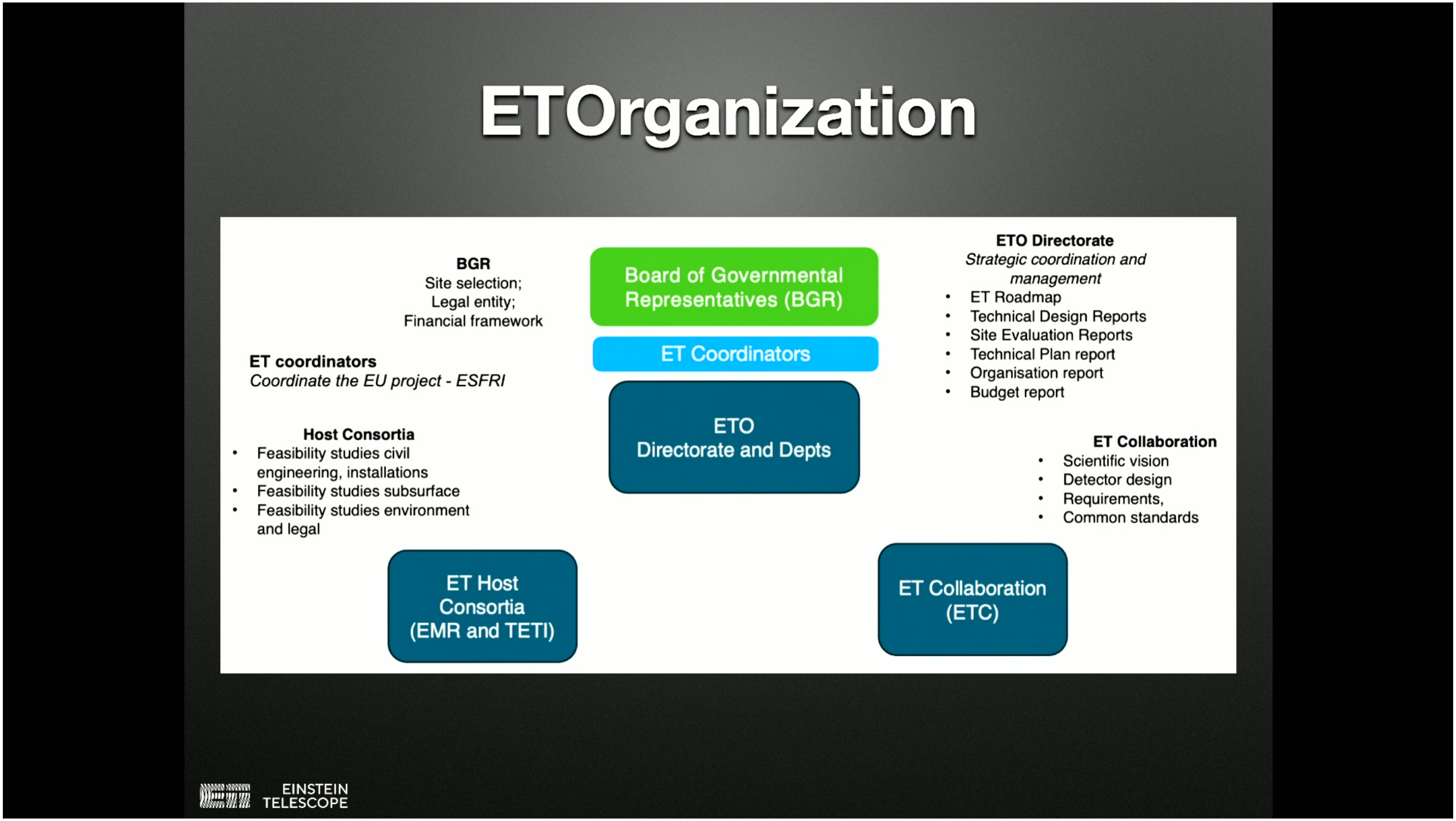
ETOrganization
BGR
Site selection;
Legal entity;
Financial framework
Board of Governmental Representatives (BGR)
ETO Directorate
Strategic coordination and management
• ET Roadmap
• Technical Design Reports
• Site Evaluation Reports
• Technical Plan report
• Organisation report
• Budget report
ET Coordinators
ET coordinators
Coordinate the EU project - ESFRI
ETO
Directorate and Depts
Host Consortia
• Feasibility studies civil engineering, installations
• Feasibility studies subsurface
• Feasibility studies environment and legal
ET Collaboration
• Scientific vision
• Detector design
• Requirements,
• Common standards
ET Host Consortia (EMR and TETI)
ET Collaboration (ETC)
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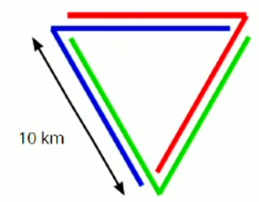
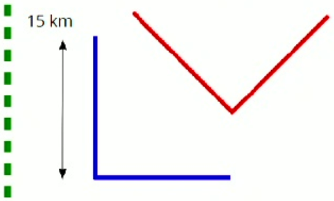
A scientific/political/technical/financial question

- The ET ESFRI proposal was based on the triangle geometry. This is one of two well known geometries for GW detectors. The other one being the combination of two L-shaped detectors in separate sites.
- Since then **the community has split**: the Italian agencies strongly prefers the option of 2Ls, whereas the EMR agencies work towards a triangle.
- This means **significant more work** (comparing two designs, costs etc) and also requires a procedure to decide on the geometry, not just the site.
- From the ETO Directors mandate: "The **final report** as delivered by the Directors should include a comparison of two scenarios, namely the baseline consisting of one **triangle versus an alternative option based on two L-shaped infrastructures**, in scientific potential, risk analysis and costs."



Baseline (like LISA)



Alternative (like LIGO)

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Science outcome

- All the triangular and 2L geometries that we have investigated can be the baseline for a superb next-generation detector, that will allow us to improve the number of detections by orders of magnitudes compared to LIGO and Virgo.

- The 2L-15km (45 deg) configuration in general offers better scientific return with respect to the 10 km triangle, improving on most figures of merits and scientific cases, by factors typically of order 2-3 on the errors of the relevant parameters.

- The 2L-15km (45 deg) configuration and the 15 km triangle have very similar performances on all parameters [...], except for luminosity distance, where the 2L-15km-45 (deg) configuration is better by a factor ~ 3 in the number events with accurately measured distance.

- The differences between the two geometries become smaller when considered in a network with a US based observatory, Cosmic Explorer.

- A single L-shaped detector is not a viable alternative, regardless of the arm length. If a single-site solution should be preferred for ET, the detector must necessarily have the triangular geometry.

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Nowadays

- Two countries provide money for the excavations
- Community has grown
- US is engaging in Cosmic Explorer (we won't be alone)

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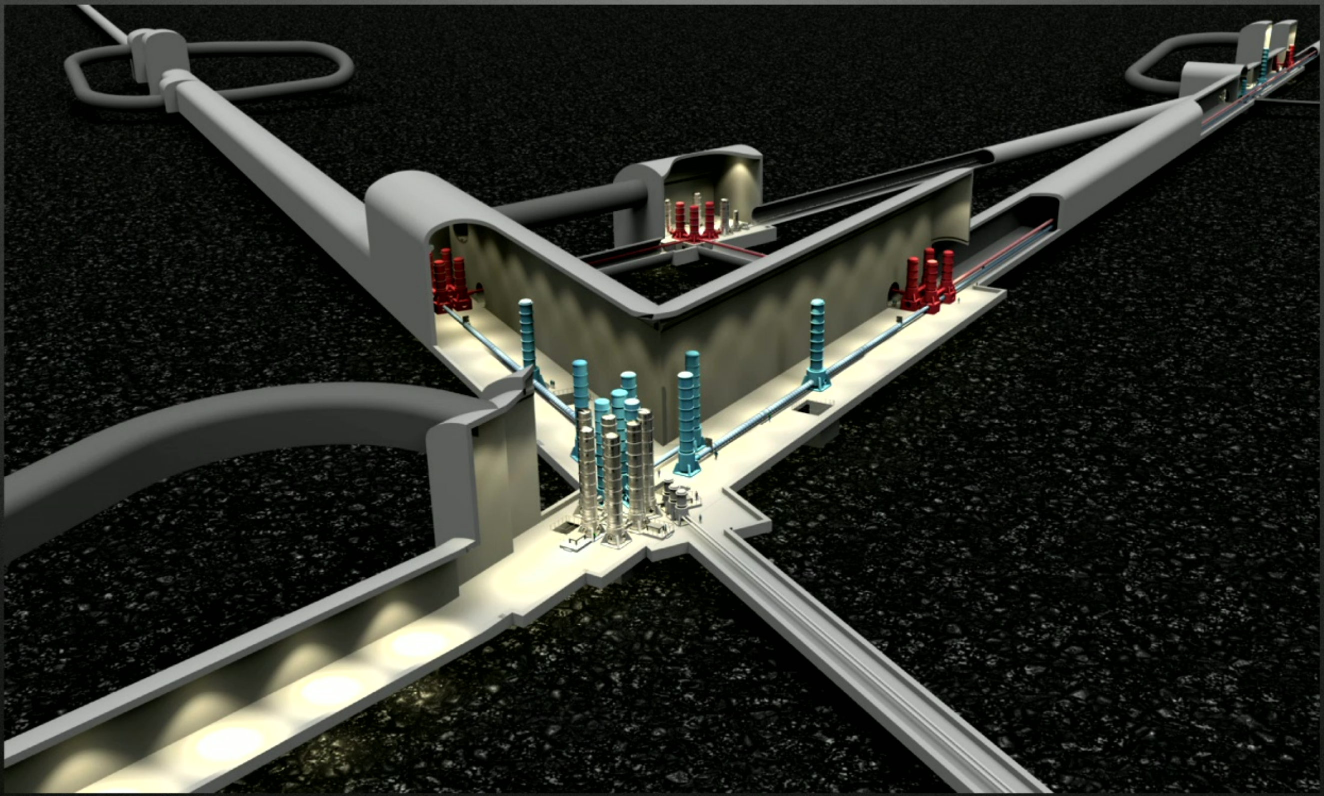
Arms and towers



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A lot of Science

Einstein Telescope's science in a nutshell

ET will serve a vast scientific community: fundamental physics, astronomy, astrophysics, particle physics, nuclear physics and cosmology

ASTROPHYSICS

- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

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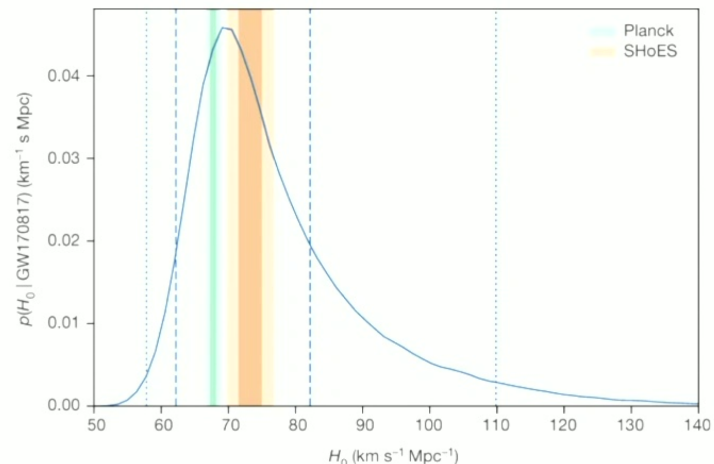
A great physics case amongst many others

Nature

volume 551, pages 85–88 (2017)

Here we report a measurement of the Hubble constant that combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using the electromagnetic data.

Figure 1: GW170817 measurement of H_0.



These events are pretty rare.
Learning how to do from BBH.

One event !!!!

$$H_0 = 70.0^{+12.0}_{-8.0} \mathrm{km\ s^{-1} Mpc^{-1}}$$

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By far not final....just to get an idea

Activity	Cost [M€]	Start	End	Note
Infrastructure costs	932			
Excavation	781			Excavation of the underground tunnels with TBMs and of the caverns. Cost based on the evaluation by two independent external companies.
Direction of the civil works	9			Evaluation based on the 1% of the underground and surface infrastructures realisation cost.
Civil works on the surface	98			Realisation of the technical and civil infrastructures on the surface. Cost evaluation based on the Conceptual Design study.
Services underground (ventilation ...)	44			Technical infrastructures serving the underground facilities and apparatuses.
Detector costs	804			
Vacuum system	566			Vacuum plant, pumps and pipes.
Optics and Laser	125			Main mirrors, auxiliary optics and lasers.
Suspension system	48			Filtering and suspension systems.
Cryogenics	45			Cryogenic plants.
ET installation	20			Contracts and activities for the installation of the ET components.
Total	1736			

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ET Collaboration to-date

Site choices

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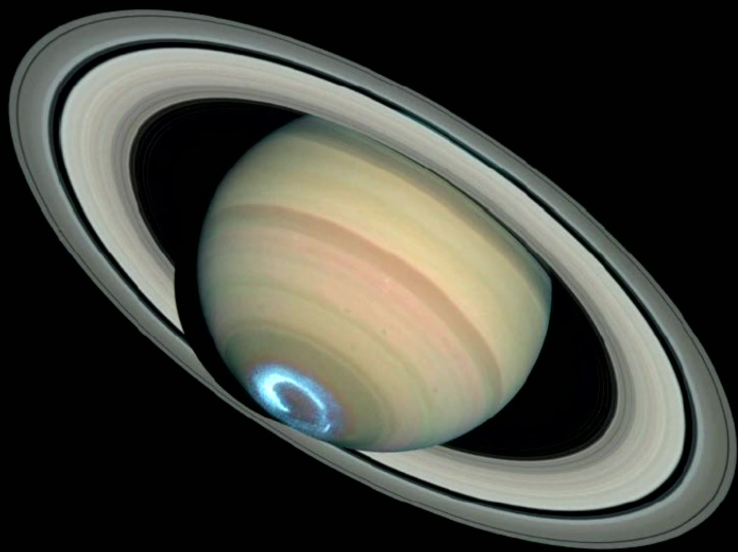
Matter of technology

WE HAVE THE RIGHT INSTRUMENT.
NOW WE NEED TO MAKE IT BETTER AND BETTER AND BETTER…

Galileo, 1610

Galileo, 1616



HST, 400 yrs later

G Losurdo - INFN Pisa

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ET Collaboration to-date

Site choices

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