H2020 MSCA RISE 2020
GA 101003460

Gravitational-waves detectors: from *Advanced* detectors to 3rd generation

Matteo Barsuglia

barsu@apc.in2p3.fr

CNRS - Laboratoire Astroparticule et Cosmologie

26/2/2024

Introduction

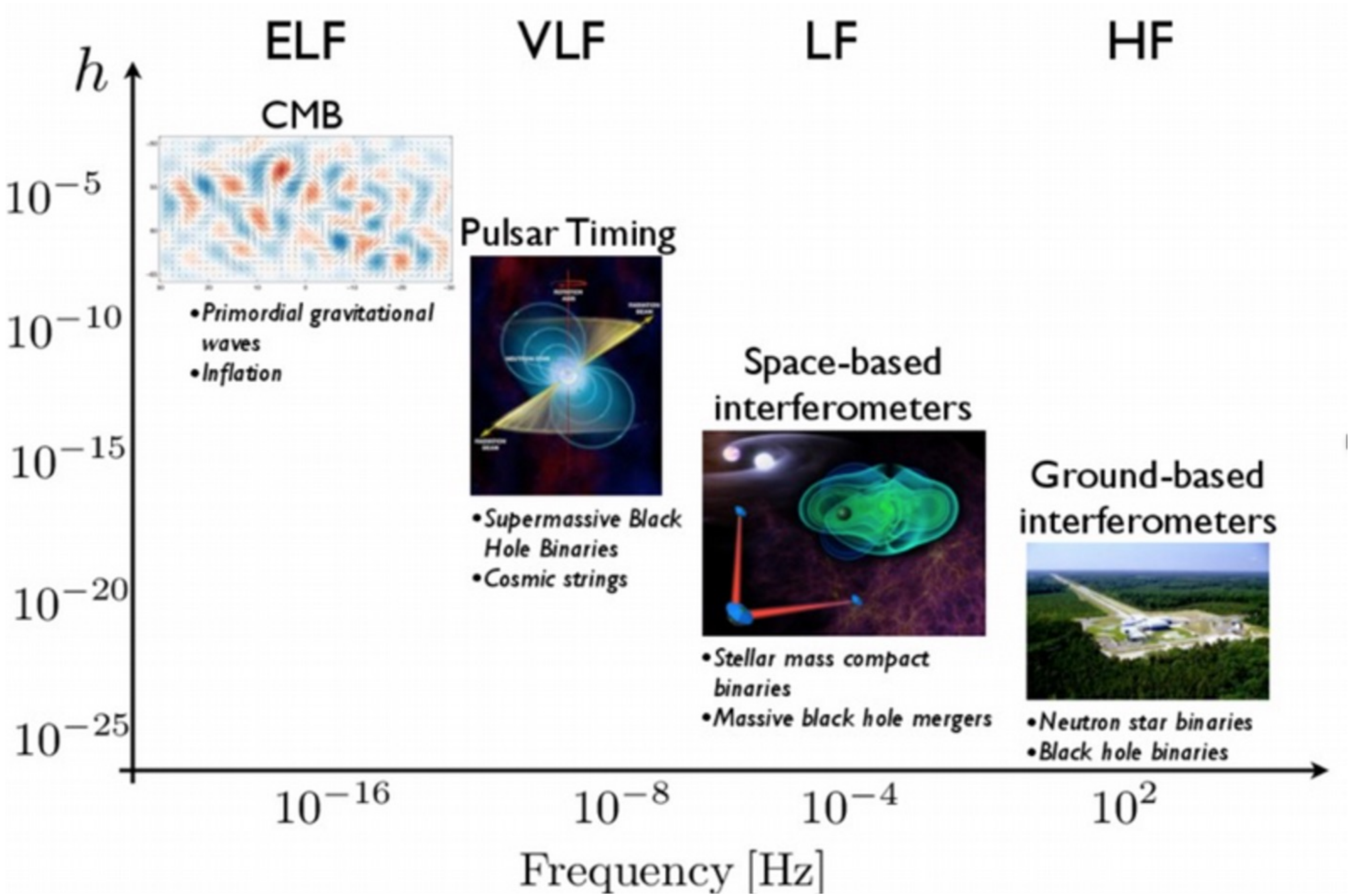
Gravitational-waves (GW) in GR

- Consequence of general relativity
- Oscillatory small perturbation of the metric
- Speed of light
- 2 transverse polarizations
- Produced by acceleration of the mass quadrupole moment

$$h_{ij}(t) = \frac{2}{r}\frac{G}{c^4}\ddot{Q}_{ij}(t - r/c) \qquad \mathcal{L} = \epsilon \frac{c^5}{G}\left(\frac{R_S}{R}\right)^2 \left(\frac{v}{c}\right)^6$$

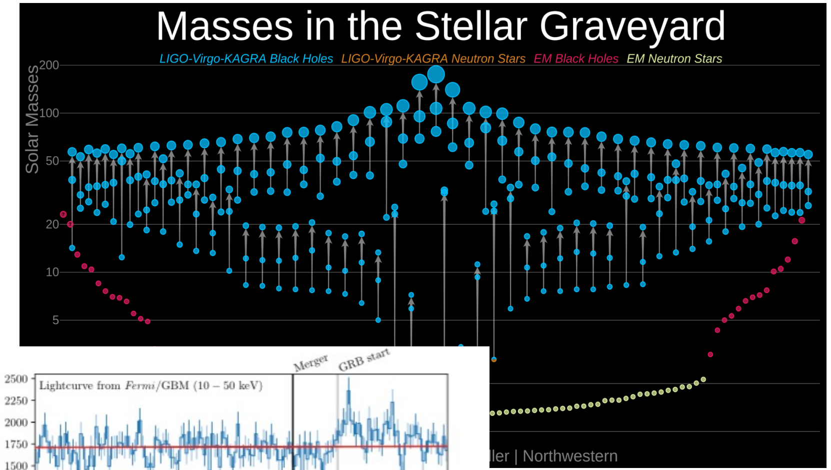
h ~ 10^{-21}

Detectors and projects

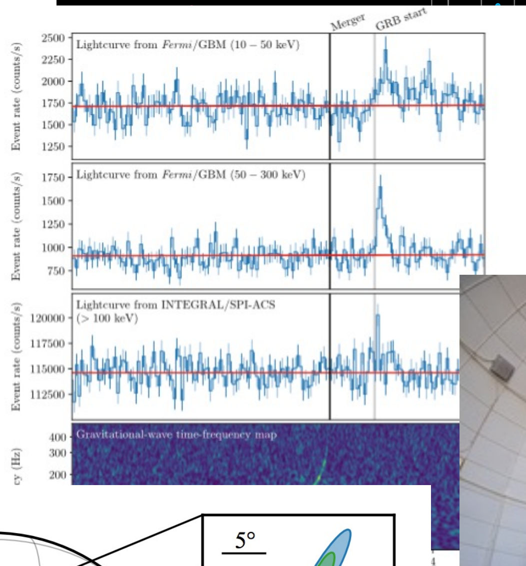


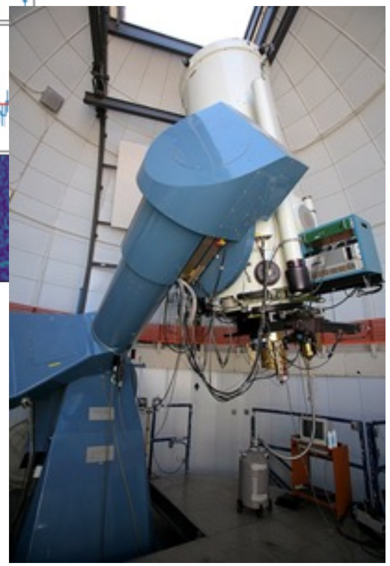
Why GW with (ground-based) detectors science?

New objects, new populations

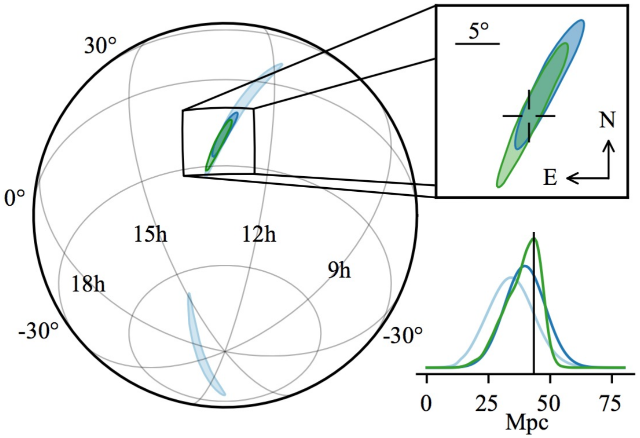


Same objects observed in a new way



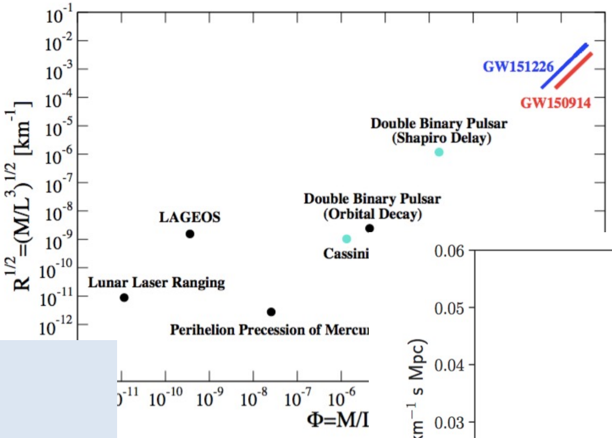


Alerts for electromagnetic observatories

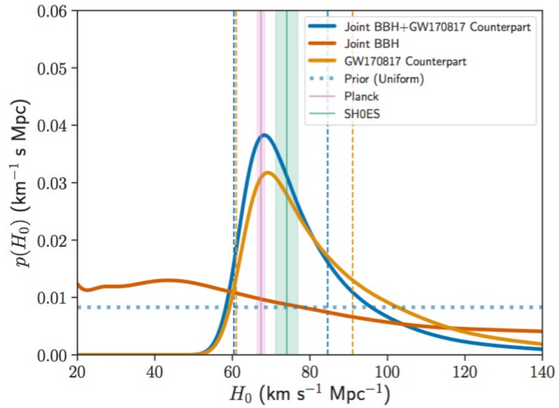


Why GW with (ground-based) detectors science?

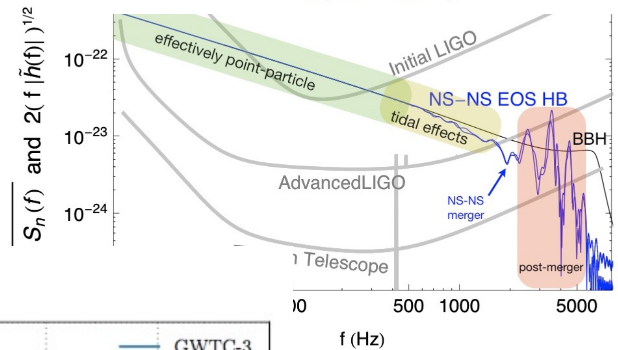
New tests of gravity



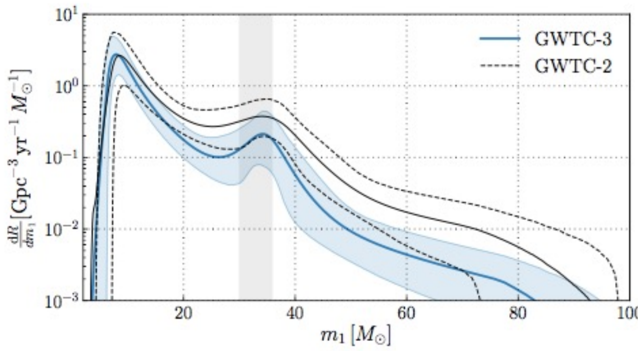
New cosmological measurements



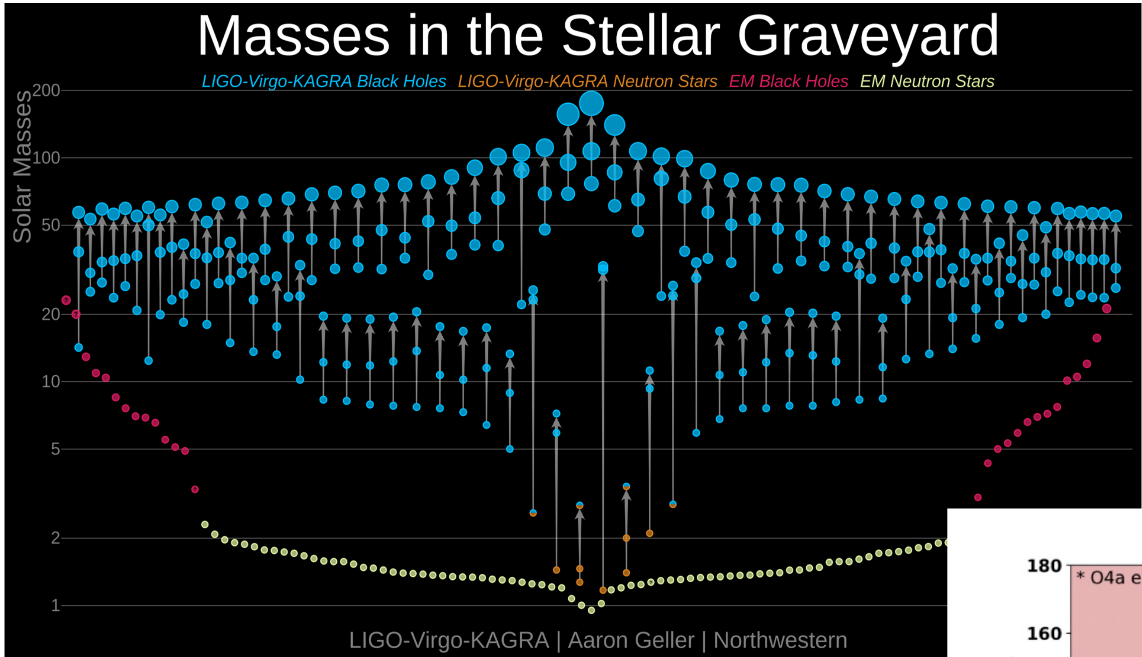
Study of extreme states of matter

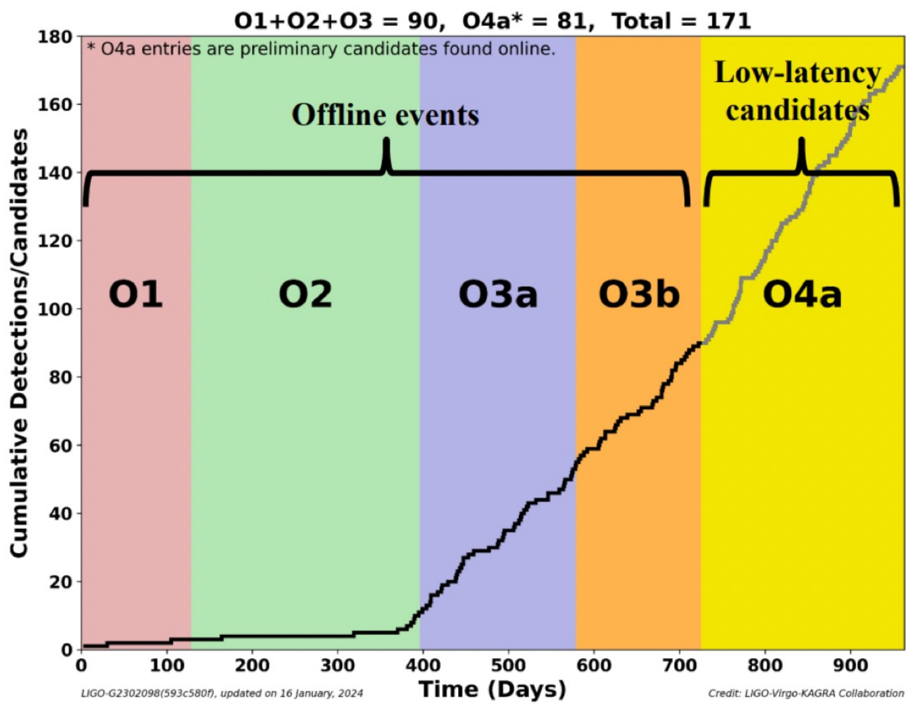


Populations of compact objects



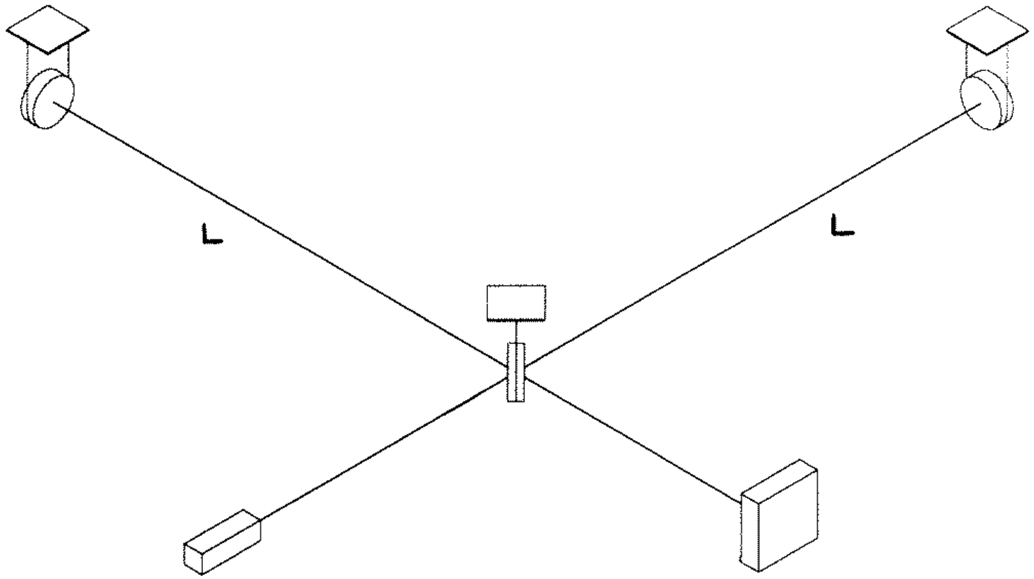
Detections so far by LIGO-Virgo-KAGRA





GW detectors

Interferometers

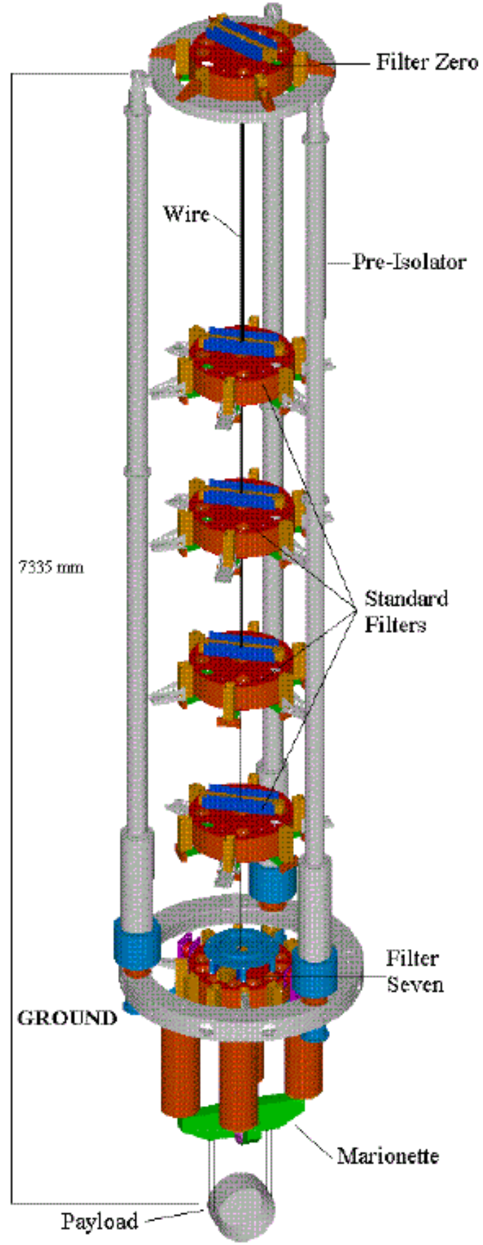


Sensitivity needed h ~ 10^{-21} @ ~ 100 Hz (~10^{-18} m for 3 km arms)

Challenges:

- Seismic noise ~ 10^{-6} m
- Wavelength of the light ~ 10^{-6} m
- Brownian motion of the atoms of the mirrors
- Other environmental and technical noises

Suspensions



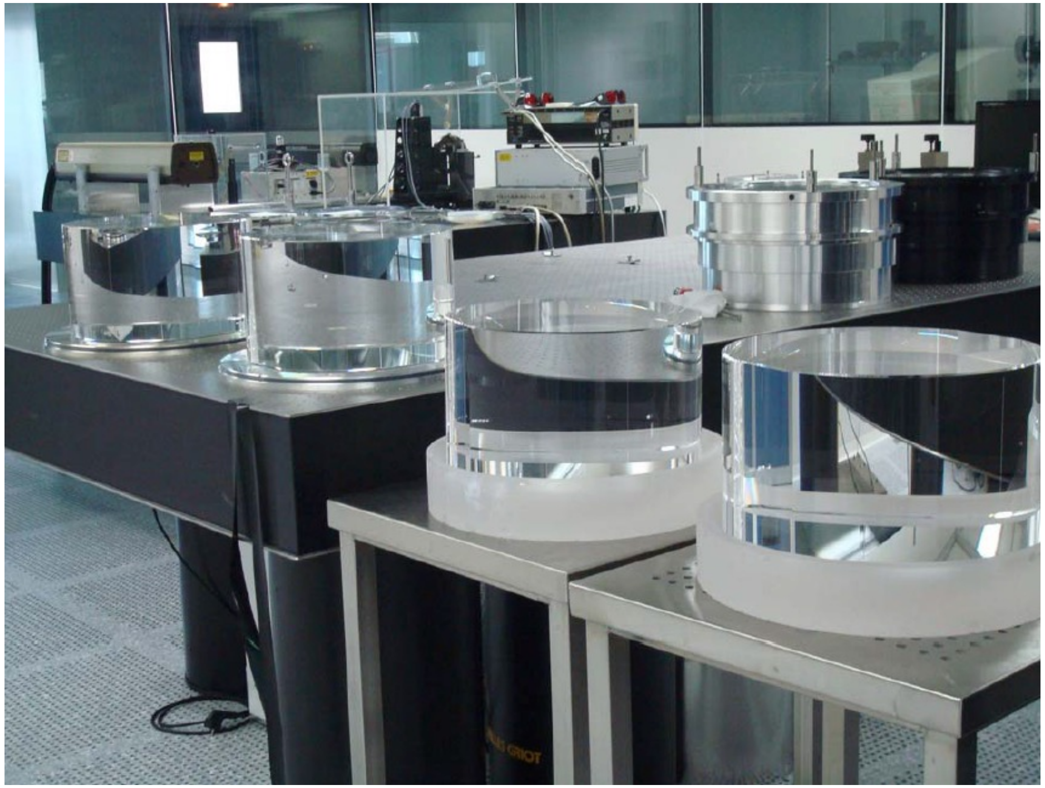
Credit: Virgo

applied optics

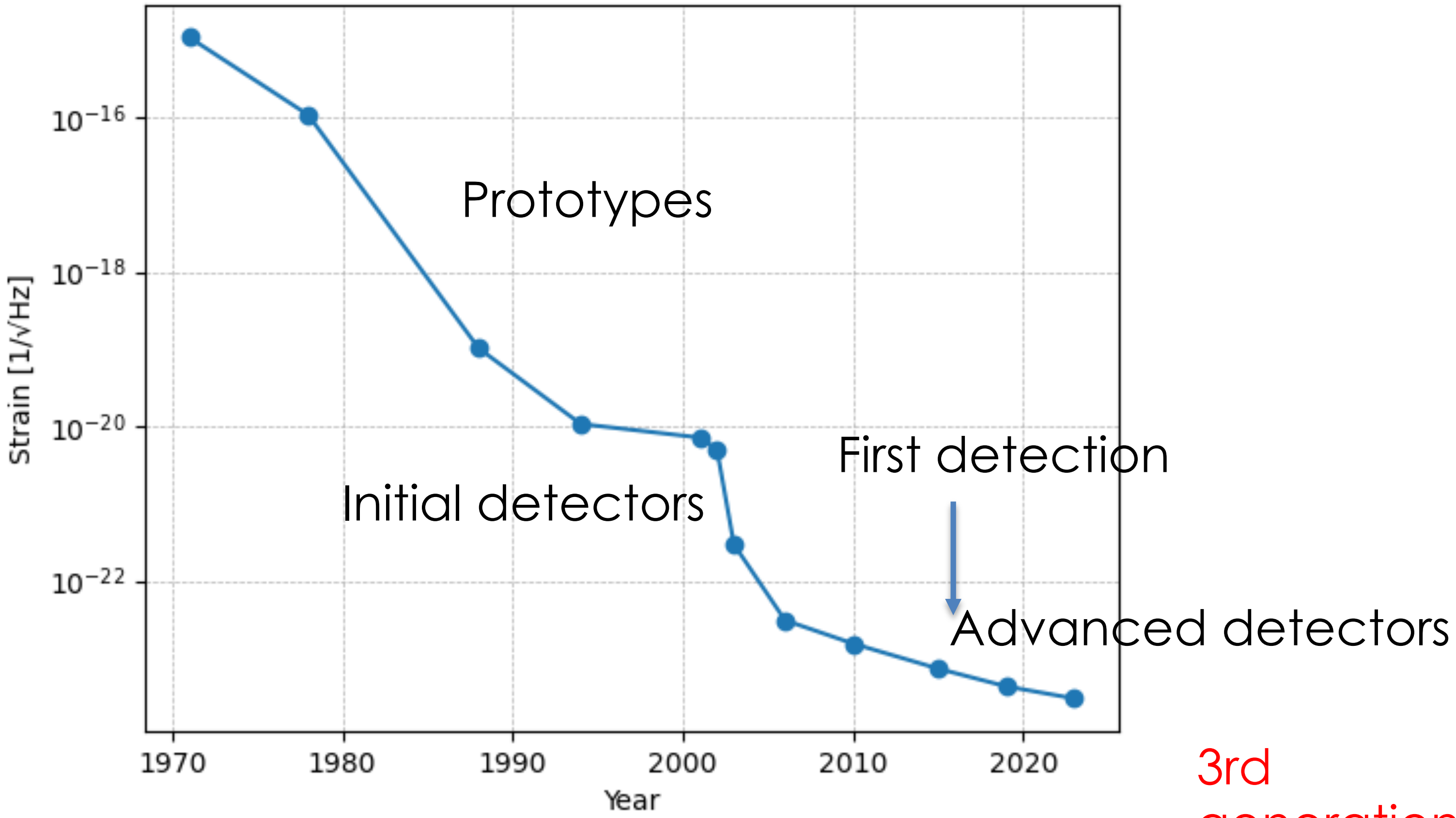
Mirrors used in the LIGO interferometers for first detection of gravitational waves

L. Pinard,[1,*] C. Michel,[1] B. Sassolas,[1] L. Balzarini,[1,2] J. Degallaix,[1] V. Dolique,[1] R. Flaminio,[3] D. Forest,[1] M. Granata,[1] B. Lagrange,[1] N. Straniero,[1] J. Teillon,[1] and G. Cagnoli[1,2]

[1]Laboratoire des Matériaux Avancés—CNRS/IN2P3, F-69622 Villeurbanne, France
[2]Université Claude Bernard Lyon 1, F-69622 Villeurbanne, France
[3]National Astronomical Observatory of Japan, 181-8588 Tokyo, Japan
*Corresponding author: l.pinard@lma.in2p3.fr



Interferometer progress in the last 40 years

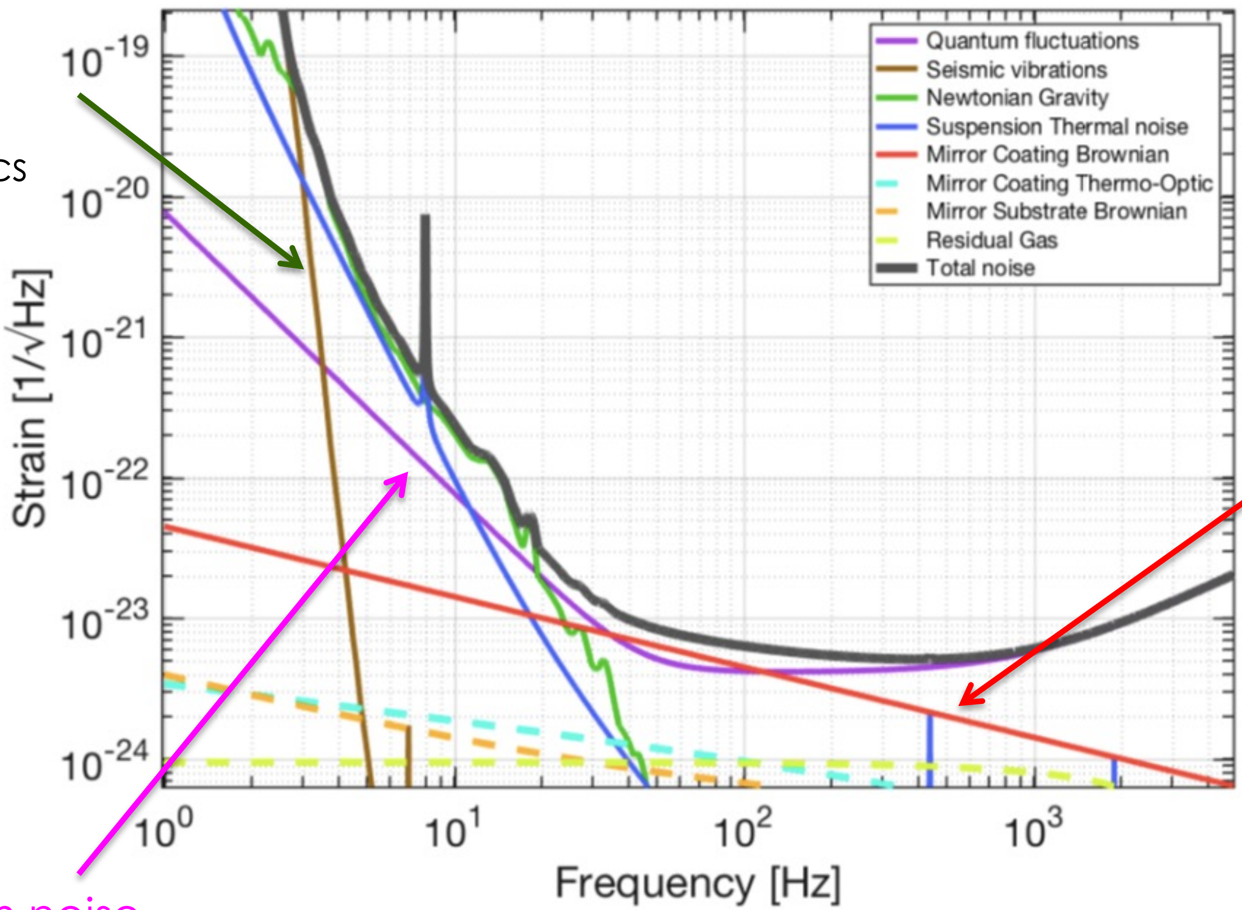


3rd
generation
detectors

Figure modified by E.Capocasa from R.Adhikari, Gravitational Radiation Detection with Laser Interferometry, arXiv:1305.5188, 2013

Advanced Virgo sensitivity curve

Seismic and gravity gradient noise
Geophysics



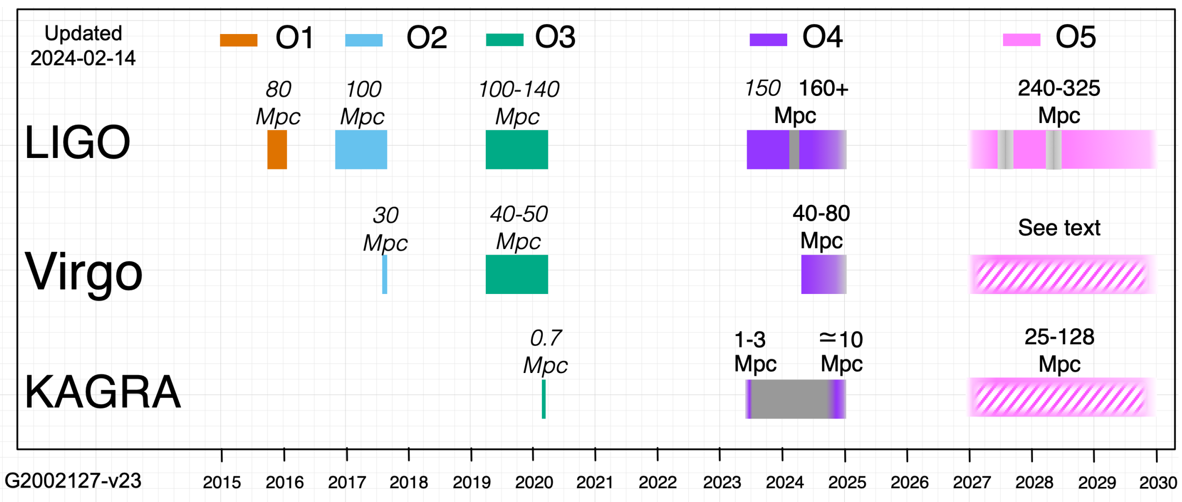
Thermal noise
Thermodynamics

Quantum noise
Quantum mechanics

Ground based GW detectors:
the big picture

Current infrastructures

New infrastructures



- A#
- Virgo_nEXT

Decade 2030

- Cosmic Explorer
- EinsteinTelescope

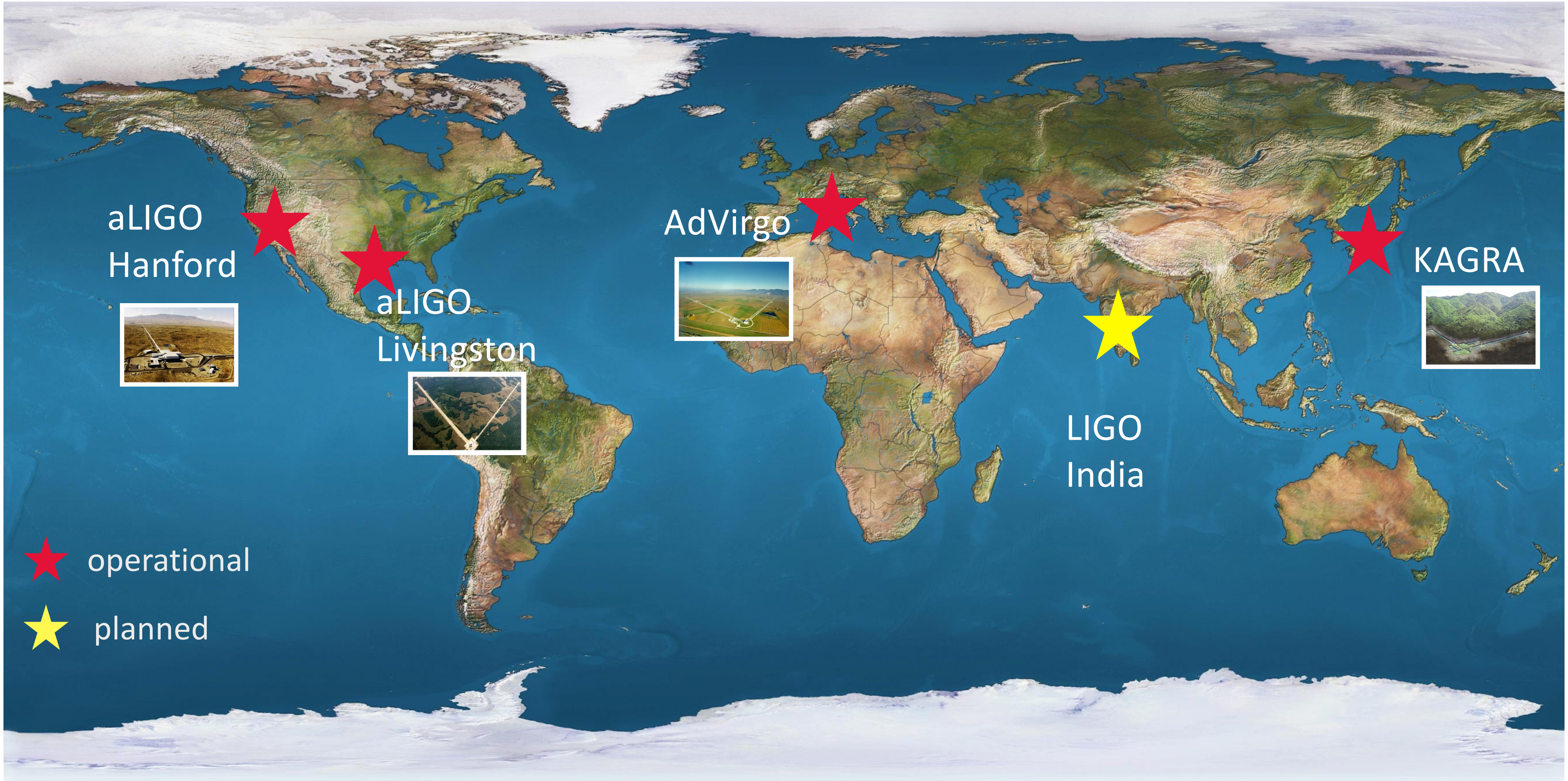
First detection

90 sources

Now

First mulit-messenger source

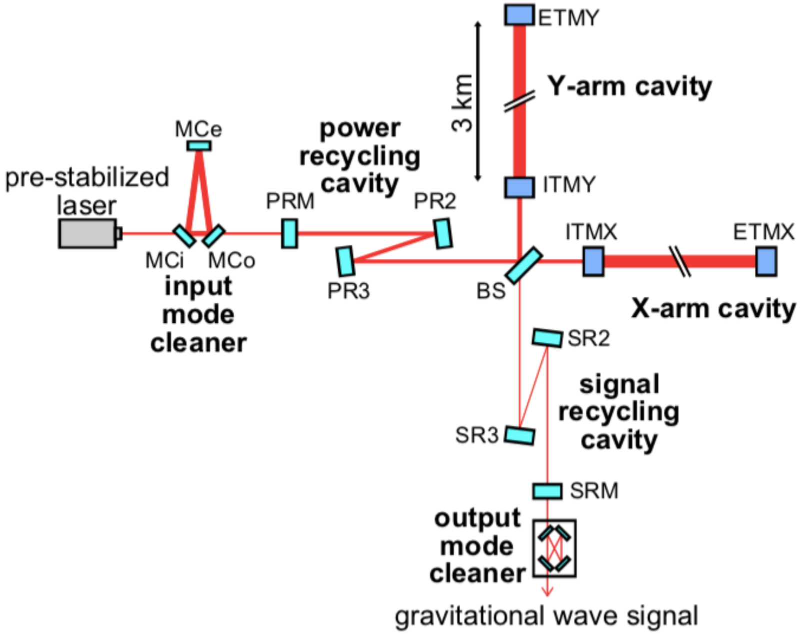
Intro: Gravitational-wave observatory network

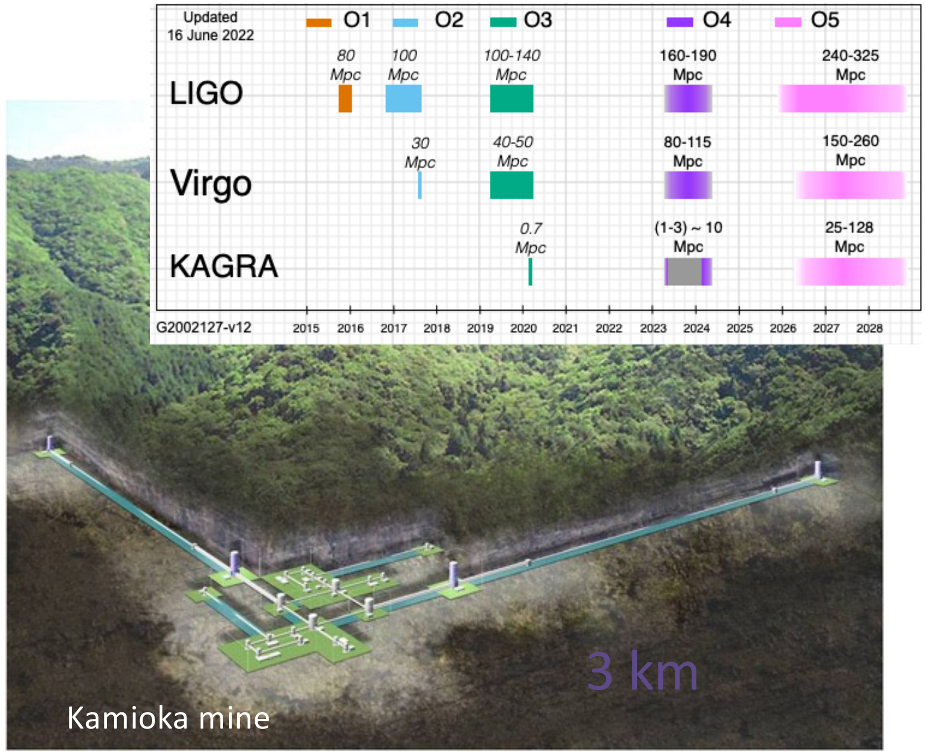


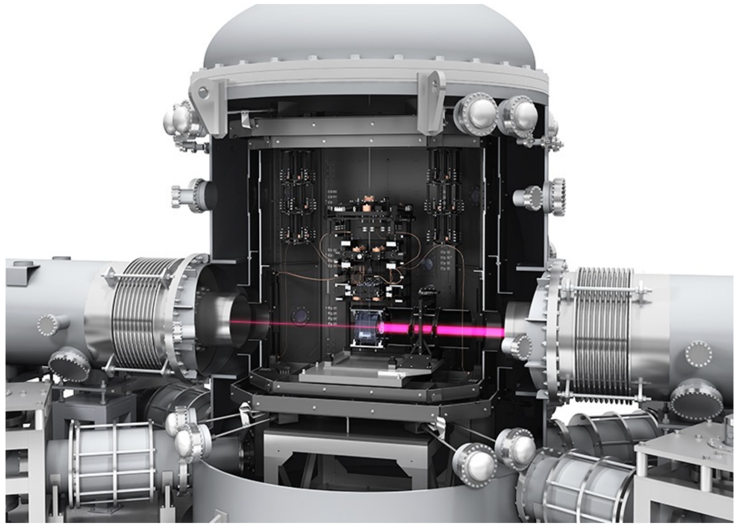
KAGRA

Japanese "2.5" Generation detector

- Undeground
- Cryogenic







The period 2030-2040
New Virgo/LIGO upgrades under study
A# and Virgo_nEXT

- Reach the limit of the infrastructures with 2G detectors
- Continue the science program

- Ultimate goal ~ x2 with respect to AdVanced Virgo+ and Advanced LIGO+

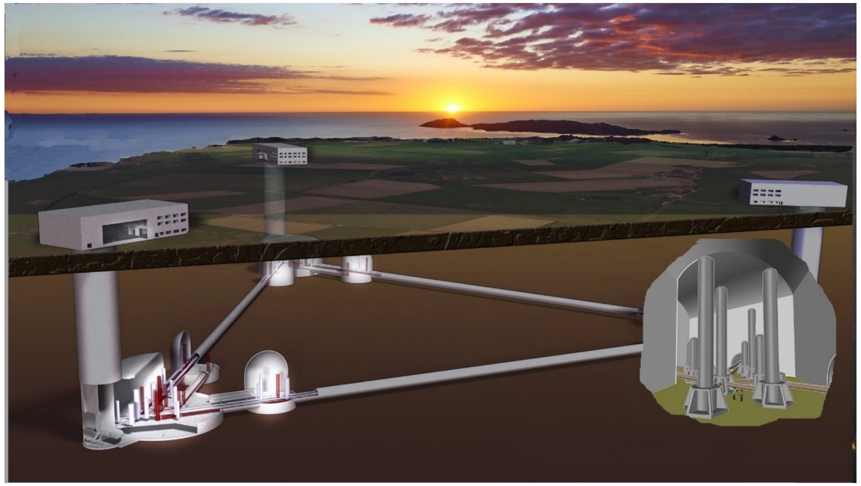
- Testbench for 3G detectors technologies

- Technologies

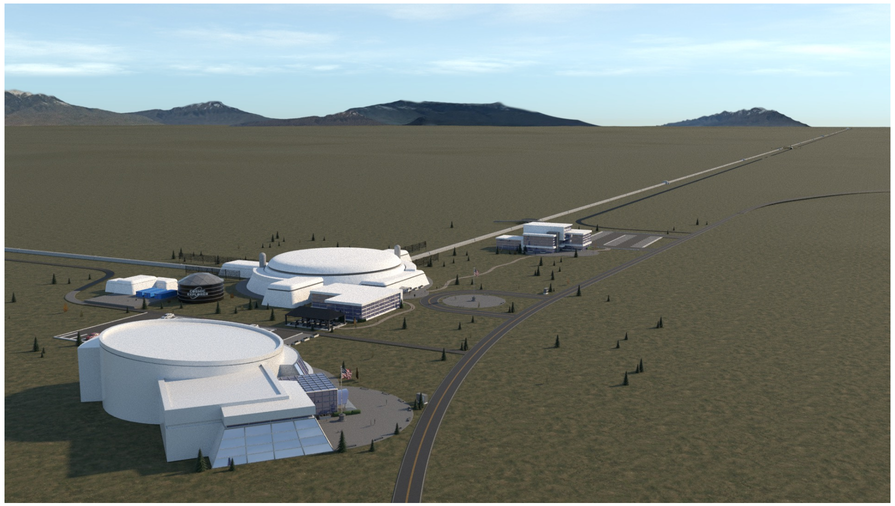
  - Better coatings
  - Higher laser powers
  - Higher squeezing level
  - Reduce technical noises at low frequency
  - Reduce Newtonian noise

Einstein Telescope (ET) and Cosmic Explorer (CE) projects

- EU
- Triangular shape (3 detectors)
- 10 km
- Underground
- Xilophone (hot and cold)

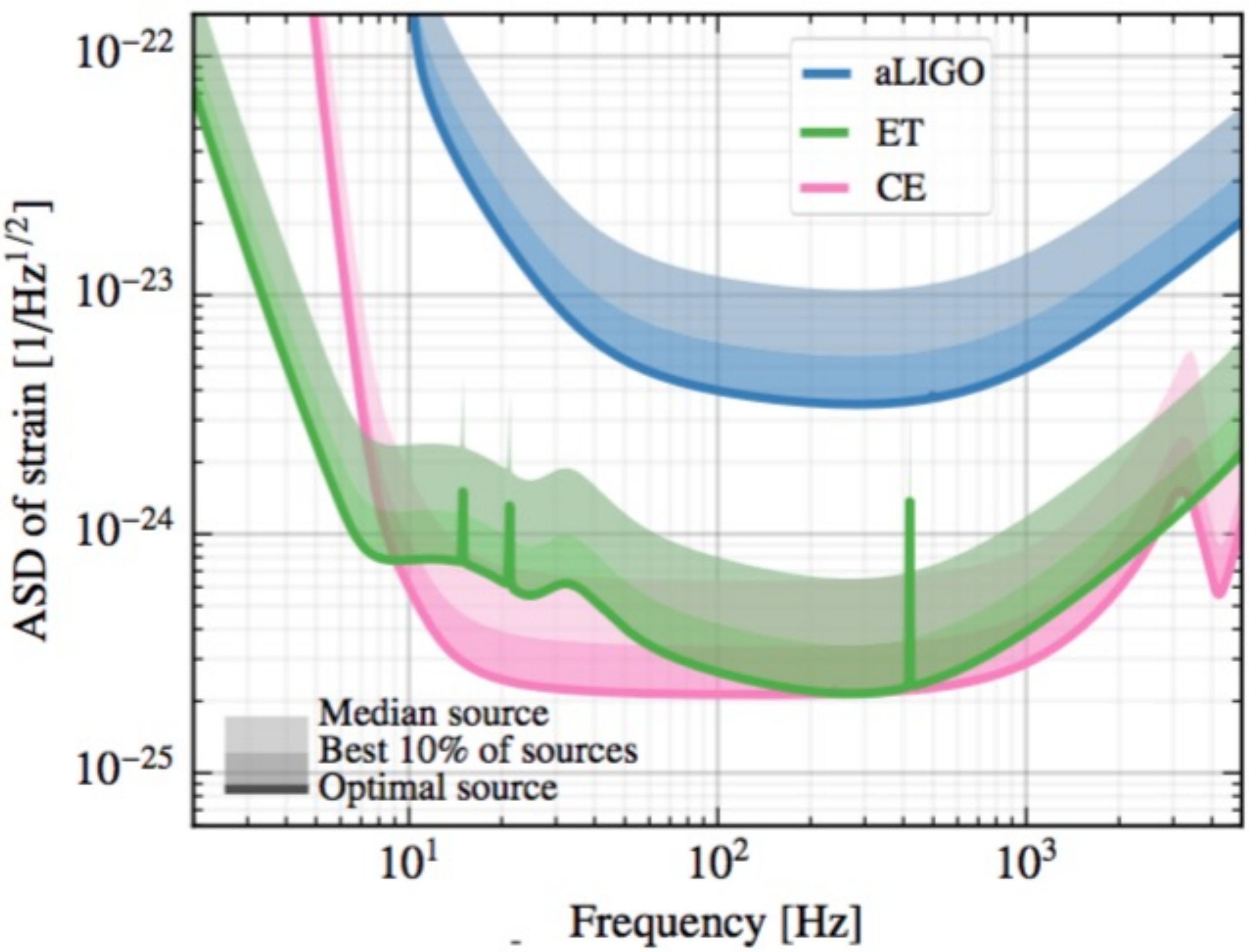


- US
- 1-2 L-shaped
- 20-40 km
- Surface
- Room temperature (initially)



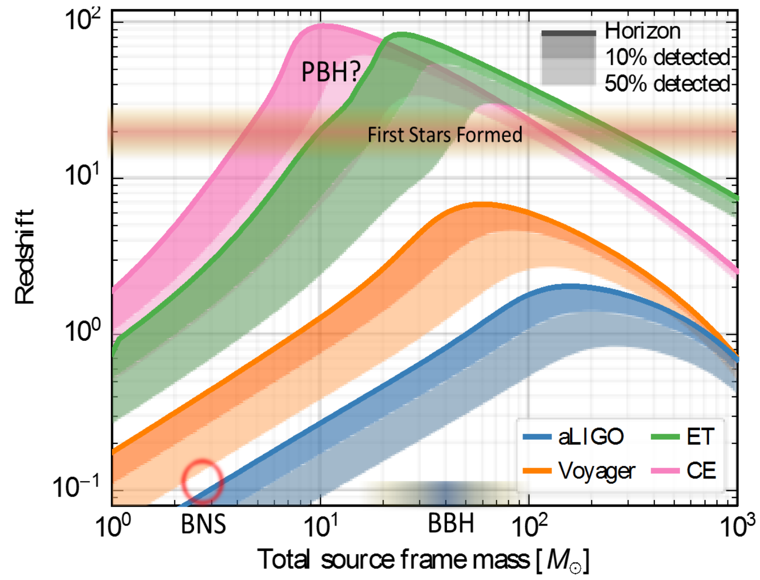
Credit: Eddie Anaya, California State University Fullerton

Gain one order of magnitude in sensitivity and enlarge the bandwidth



ET science

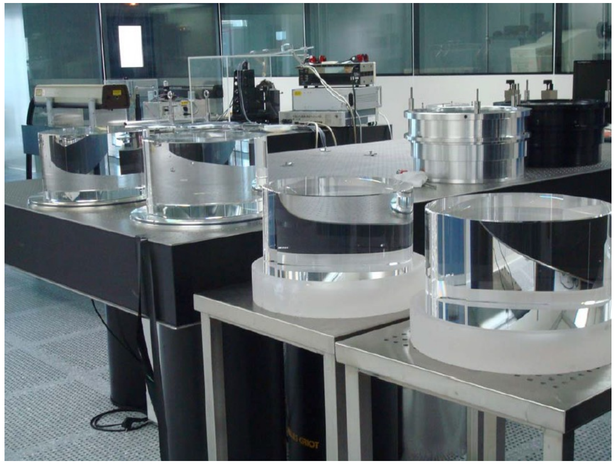
- Black-holes evolution
  - Black-hole mergers in the entire Universe and before the first galaxies
  - Intermediate-mass black-holes
- Nature of gravitation
  - Nature of black-holes
  - Process in the primordial Universe
  - Signs of quantum gravity (i.e. échos)
- Cosmology Nature of dark eneregy
  - An alternative cosmology
  - Test of modified gravity theories with new observables
- Nature of matter at the smaller scales
  - Study of nuclear matter
- Physics of Supernovae
- Multi-messenger astrophysics



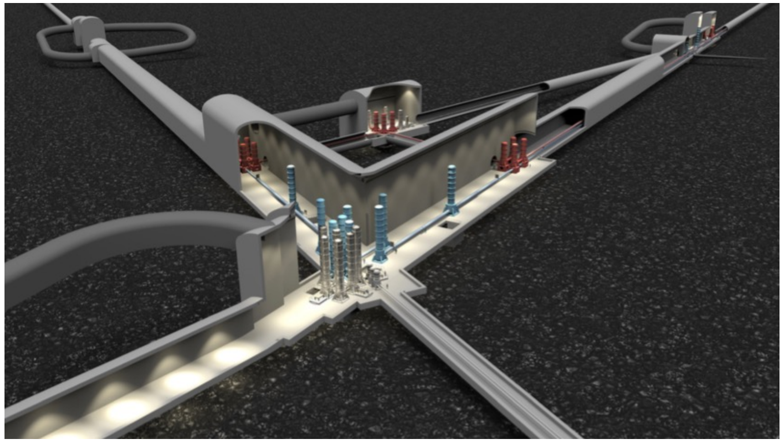
https://arxiv.org/pdf/1912.02622
ET science case

The ET technologies and challenges

- Extrapolation of current or planned technologies for Virgo and LIGO
  - Squeezing (non classical states of light)
  - High-power lasers
  - Large mirrors
  - New mirror's coatings
  - Thermal compensation techniques
  - Seismic suspension systems



- Technologies not tested in Virgo and LIGO
  - Cryogenics (also in KAGRA)
  - New cryogenic materials
  - New laser wavelengths



GW detectors and PROBES

GW EU-Usa-Japan collaborations

- Strong pressure on the Virgo scientists working on the instrument to start the O4 data taking (March 2024)

- Among the main collaborations with USA and Japan:
  - Squeezing/quantum technologies
  - calibration
  - Suspensions, cryogenics (cryogenic payload), sensors, squeezing

GW EU-Usa-Japan collaborations

PHYSICAL REVIEW D **106,** 102003 (2022)

Demonstration of length control for a filter cavity with coherent control sidebands

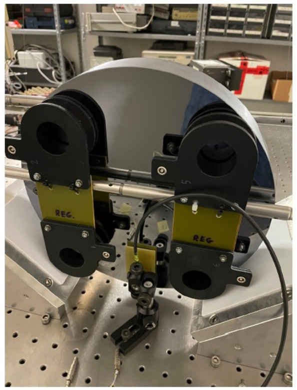
Naoki Aritomi,[1,2,*] Yuhang Zhao,[3] Eleonora Capocasa,[4] Matteo Leonardi,[1] Marc Eisenmann,[1] Michael Page,[1] Yuefan Guo,[5] Eleonora Polini,[6] Akihiro Tomura,[7] Koji Arai,[8] Yoichi Aso,[1] Martin van Beuzekom,[5] Yao-Chin Huang,[9] Ray-Kuang Lee,[9] Harald Lück,[10] Osamu Miyakawa,[11] Pierre Prat,[4] Ayaka Shoda,[1] Matteo Tacca,[5] Ryutaro Takahashi,[1] Henning Vahlbruch,[10] Marco Vardaro,[5] Chien-Ming Wu,[9] Matteo Barsuglia,[4] and Raffaele Flaminio[6]

[1]*National Astronomical Observatory of Japan (NAOJ), Mitaka City, Tokyo 181-8588, Japan*
[2]*LIGO Hanford Observatory, Richland, Washington 99352, USA*
[3]*Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Kashiwa City, Chiba 277-8582, Japan*
[4]*Université de Paris, CNRS, Astroparticule et Cosmologie, F-75013 Paris, France*
[5]*Nikhef, Science Park 105, 1098 XG Amsterdam, Netherlands*
[6]*Laboratoire d'Annecy de Physique des Particules (LAPP),Université Savoie Mont Blanc, CNRS/IN2P3, F-74941 Annecy, France*
[7]*The University of Electro-Communications, Chofu City, Tokyo 182-8585, Japan*
[8]*LIGO Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
[9]*National Tsing Hua University, Hsinchu City 30013, Taiwan*
[10]*Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-30167 Hannover, Ger*
[11]*Institute for Cosmic Ray Research (ICRR), KAGRA Observatory, The University of Tokyo, Hida City, Gifu 506-1205, Japan*

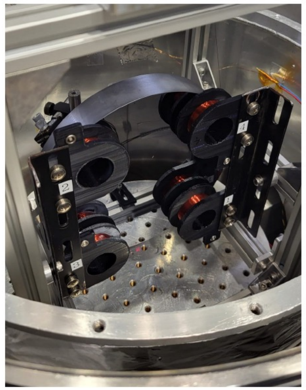
Squeezing

Cryogenic payload control

- Preliminary tests of the suspension ant actuators were performed in Perugia
- In 2023 we moved most of the system to ICRR
- In the first phase we worked on the control in air
- Finally we moved the suspension into the vacuum chamber of the cryostat



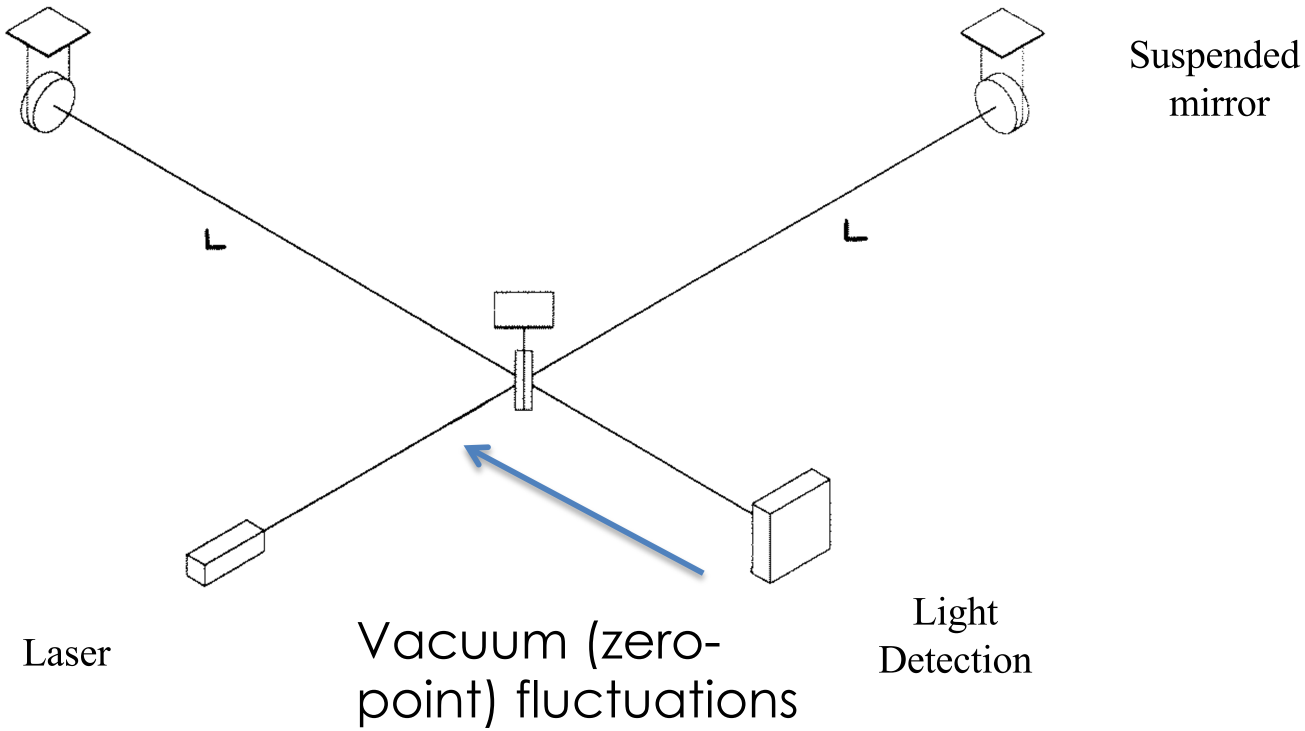
Suspended substrate in Perugia

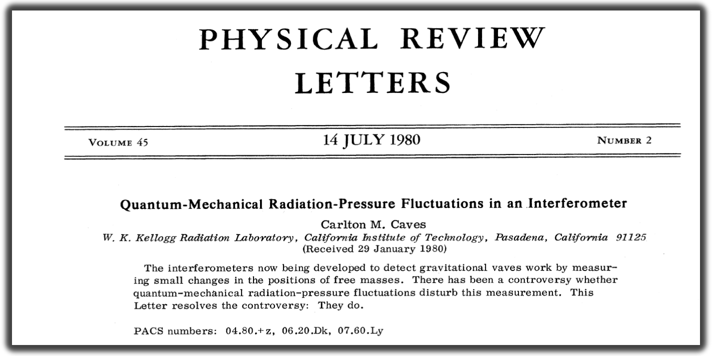


Suspended substrate at ICRR

Credit H.Vocca

Which is the fundamental limitation of this measurement ?





PHYSICAL REVIEW LETTERS

VOLUME 45 | 14 JULY 1980 | NUMBER 2

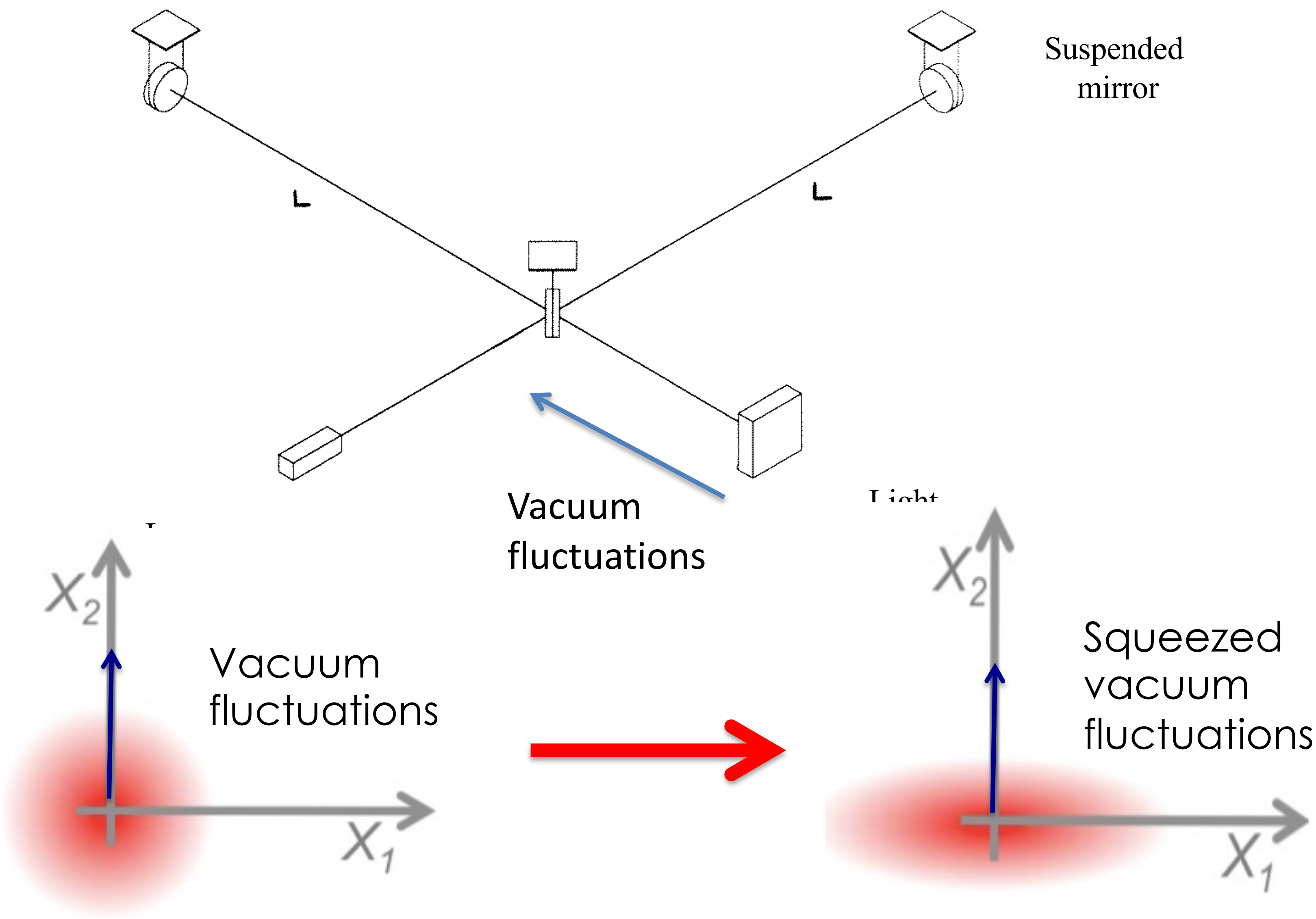
Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

PACS numbers: 04.80.+z, 06.20.Dk, 07.60.Ly

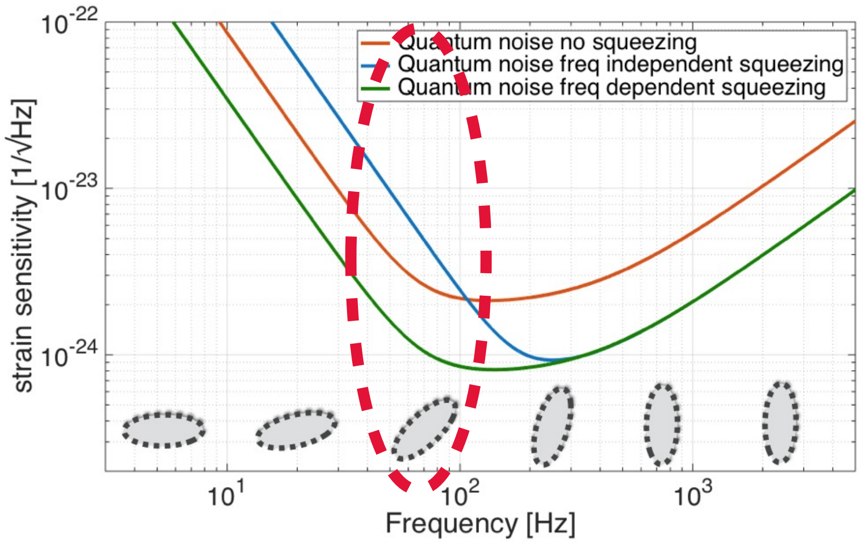
Squeezing

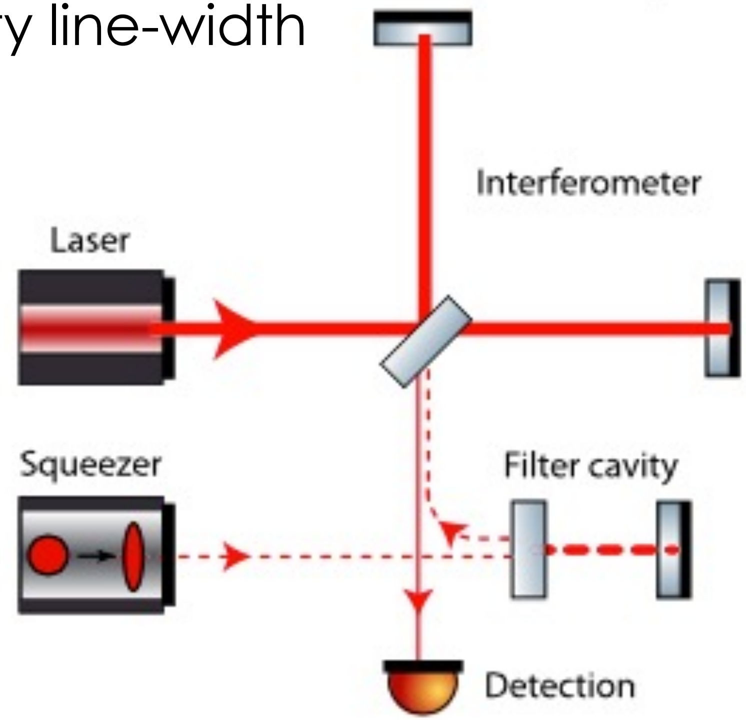


Suspended mirror
L
L
Vacuum fluctuations
X_2
X_1
Vacuum fluctuations
X_2
X_1
Squeezed vacuum fluctuations

Frequency dependent squeezing via filter cavity

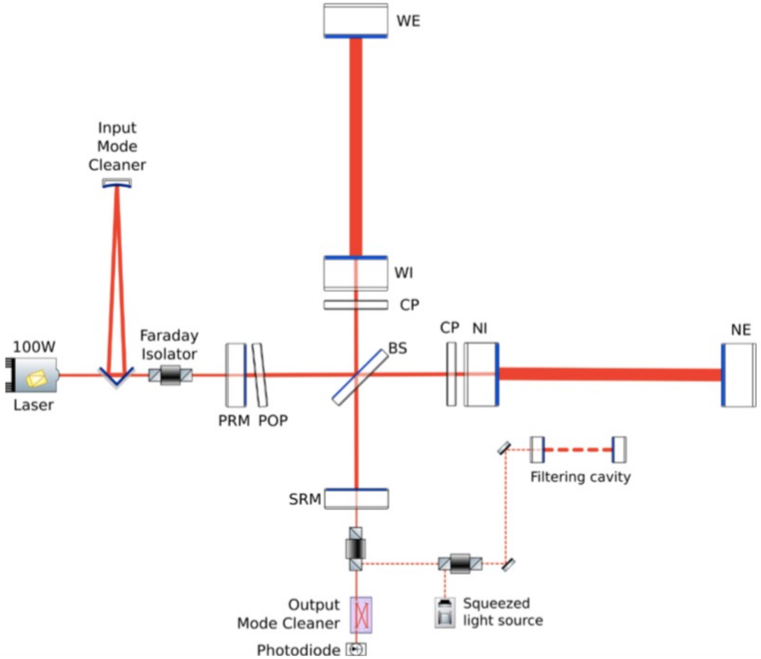
- Reflect frequency independent squeezing off a detuned Fabry-Perot cavity
- Rotation frequency depends on cavity line-width

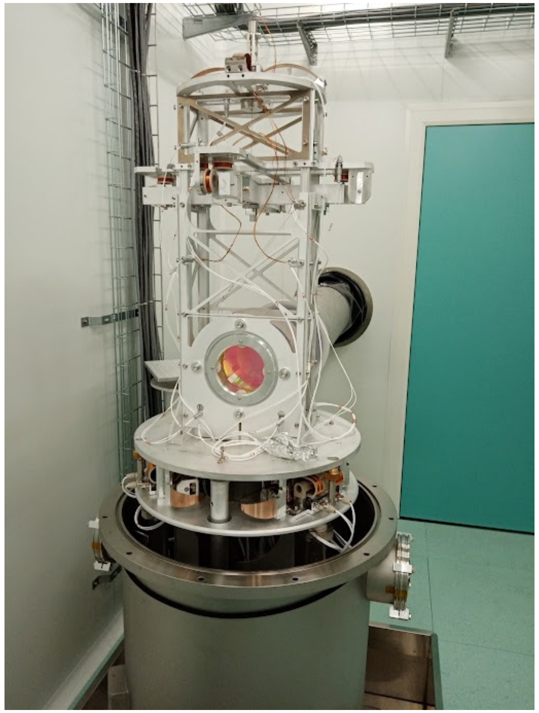


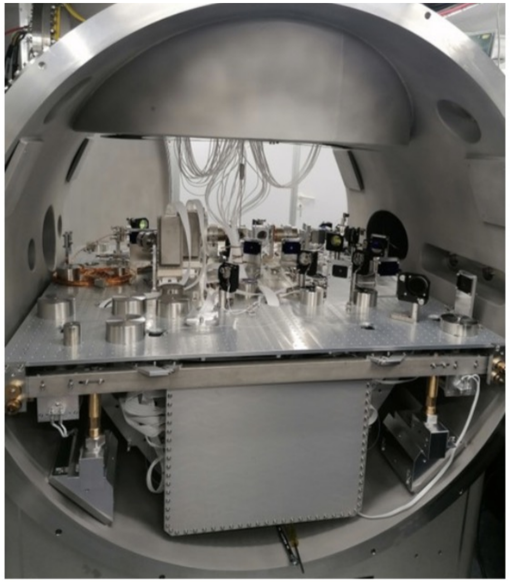


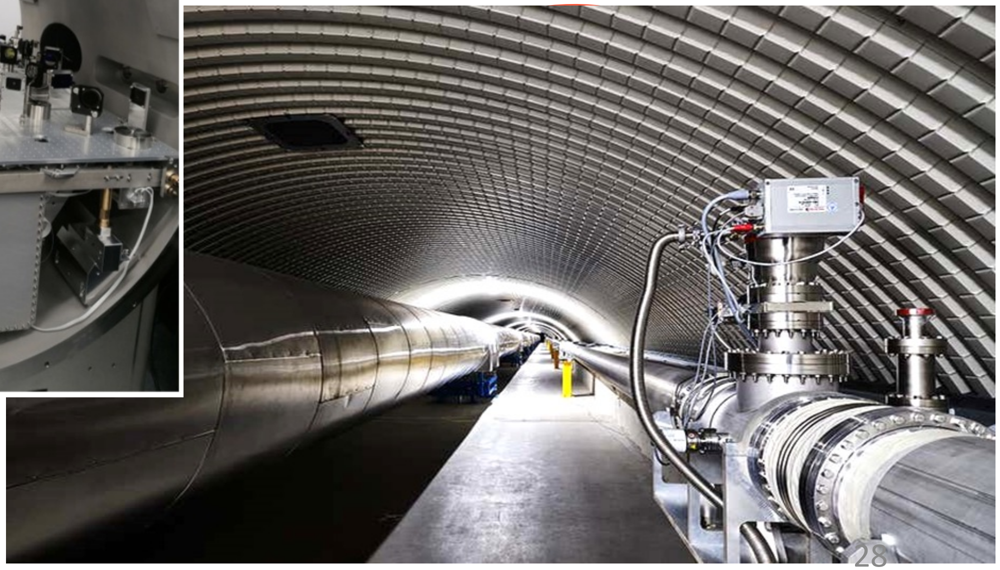
- Optimal rotation frequency around 25 Hz for Advirgo

Filter cavity recently implemented in Virgo









Conclusions

- LIGO-Virgo-KAGRA O4b data taking will start soon for Virgo, lot of science expected (see Barbara Patricelli talk)
- Next upgrades A# and Virgo_nEXT (2030-2040) at study, as bridge with 3rd detectors (Einstein Telescope, Cosmic explorer)
- 3rd generation detector program (> 2035) start to be solid
- Huge collaboration program EU-Japan-US about detector physics in view of 3rd generation
- Central role of PROBES for exchange of scientists and students