A primer on LIGO and Virgo gravitational wave detection

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LECTURE 3

LSC LIGO Scientific Collaboration

Advanced Virgo

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Towards a global network: KAGRA and LIGO-India

LIGO and Virgo upgrades: A+ and AdV+

Third generation: Einstein Telescope and Cosmic Explorer

Gravitational wave detection in space: LISA

Summary and outlook

Advanced Virgo

Brief summary: scientific impact of GW science

Multi-messenger astronomy started: a broad community is relying of detection of gravitational waves
Scientific program is limited by the sensitivity of LVC instruments over the entire frequency range

Fundamental physics

Access to dynamic strong field regime, new tests of General Relativity
Black hole science: inspiral, merger, ringdown, quasi-normal modes, echo's
Lorentz-invariance, equivalence principle, polarization, parity violation, axions

Astrophysics

First observation for binary neutron star merger, relation to sGRB
Evidence for a kilonova, explanation for creation of elements heavier than iron

Astronomy

Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies

Cosmology

Binary neutron stars can be used as standard “sirens”
Dark Matter and Dark Energy

Nuclear physics

Tidal interactions between neutron stars get imprinted on gravitational waves
Access to equation of state

Nobel Prize in Physics 2017

https://www.nobelprize.org/nobel_prizes/physics/laureates/2017/press.html

KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Press Release: The Nobel Prize in Physics 2017

3 October 2017

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics 2017 with one half to

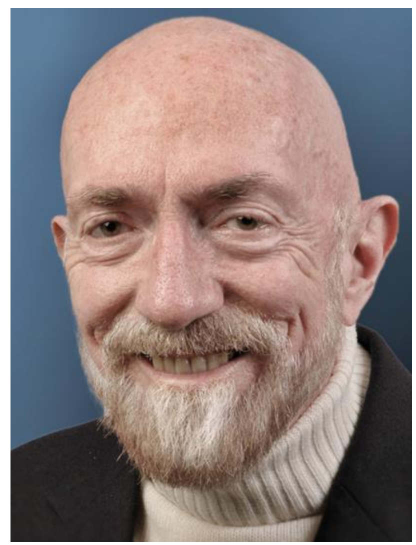
Rainer Weiss
LIGO/VIRGO Collaboration

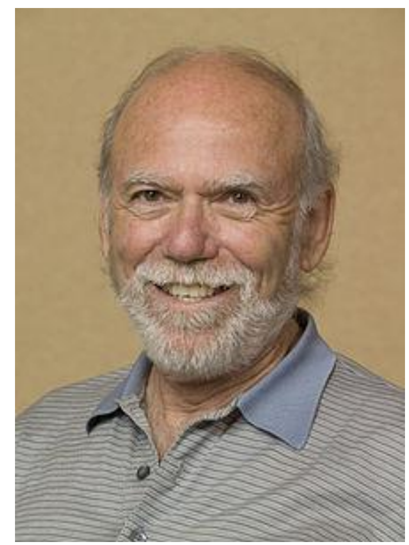
and the other half jointly to

Barry C. Barish
LIGO/VIRGO Collaboration

and

Kip S. Thorne
LIGO/VIRGO Collaboration



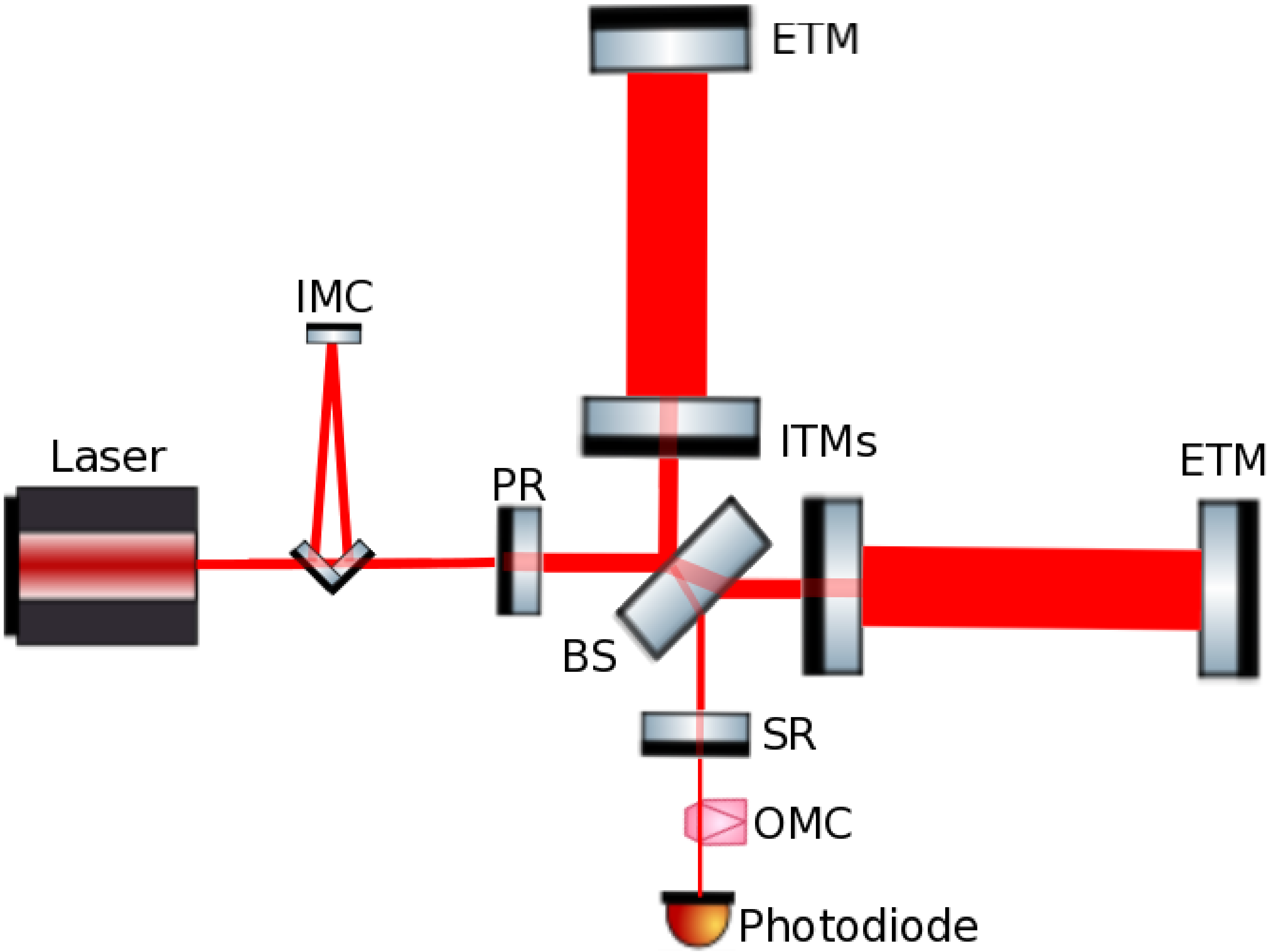


Special thanks to Virgo’s founding fathers

Alain Brillet and Adalberto Giazotto

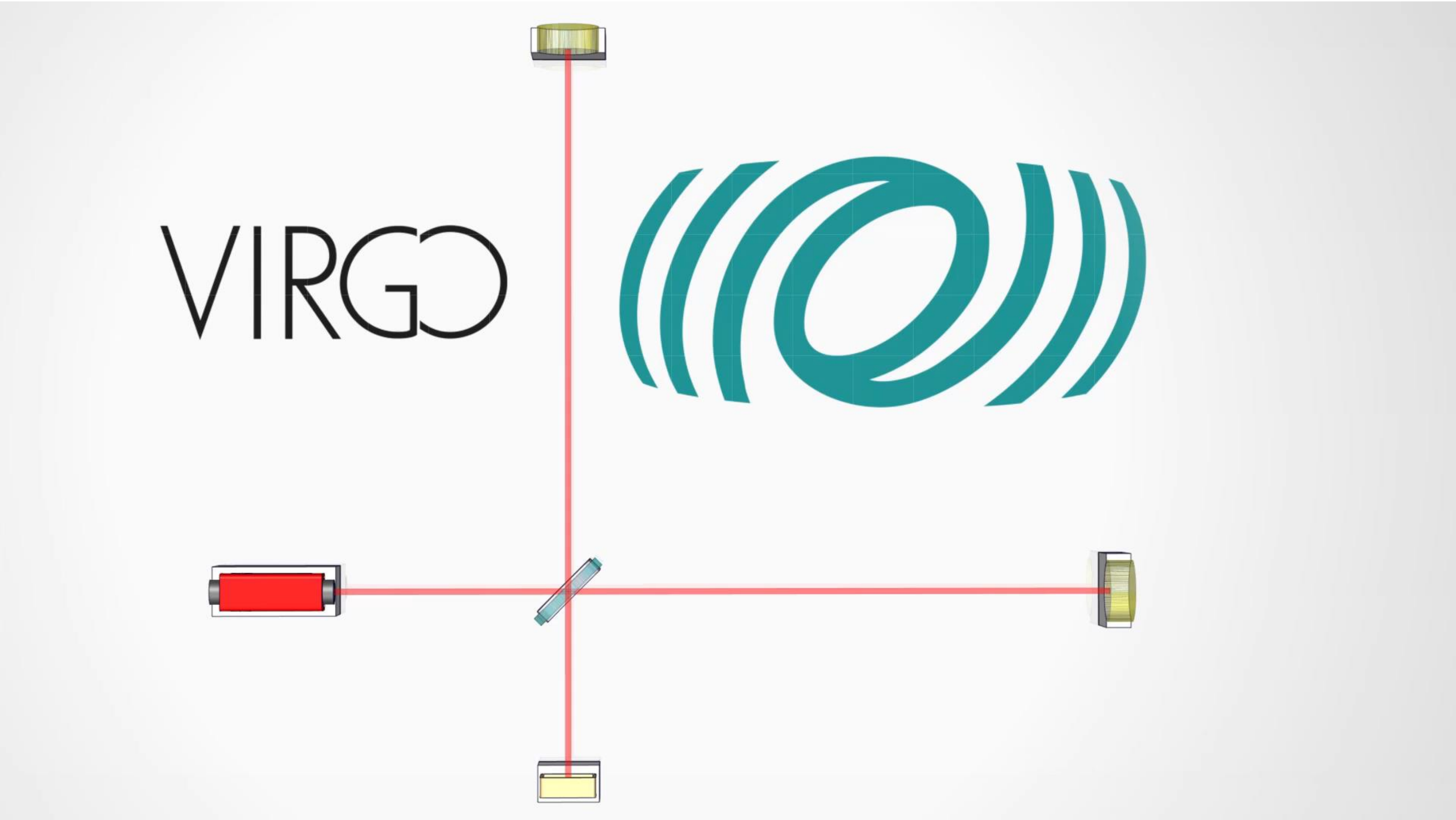
Dual recycled Fabry-Perot interferometer

LIGO and Virgo will use dual recycled Fabry-Perot interferometers including input mode cleaner and output mode cleaner



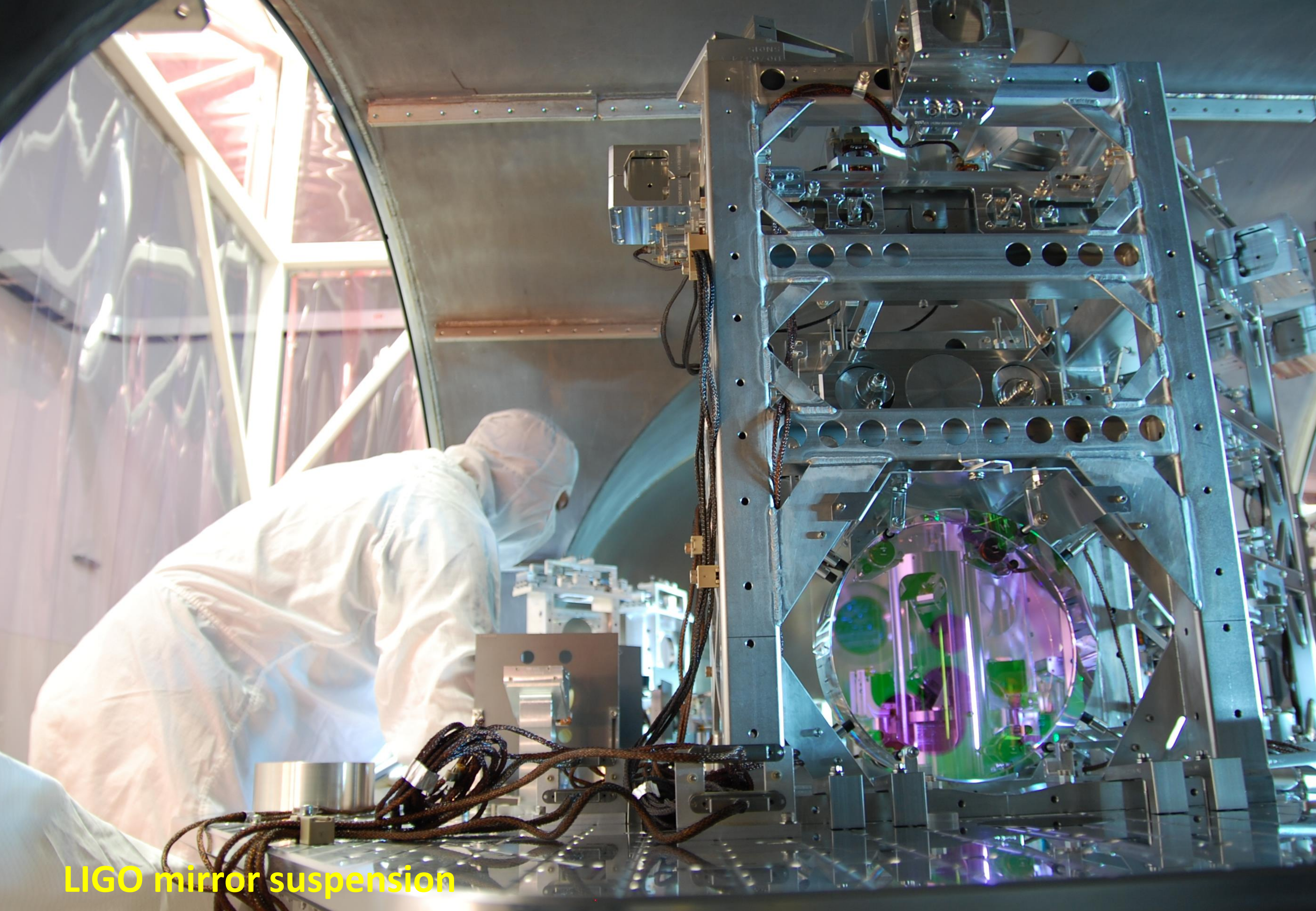
Detecting gravitational waves with an interferometer

During our detection of GW150914 the mirrors moved by about 10^{-18} m




LIGO Livingston, Louisiana

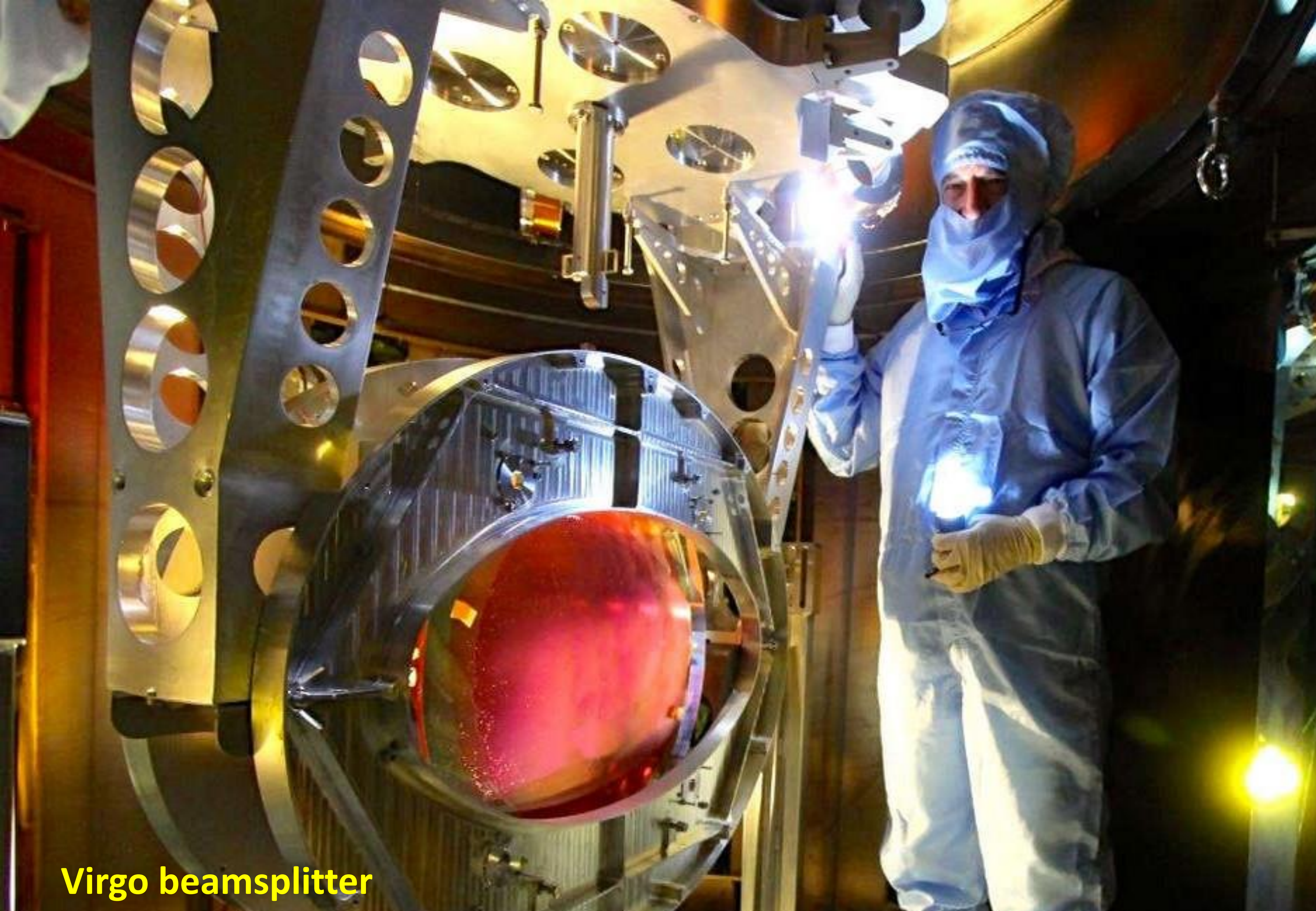

LIGO mirror



LIGO mirror suspension


Virgo interferometer


Virgo interferometer



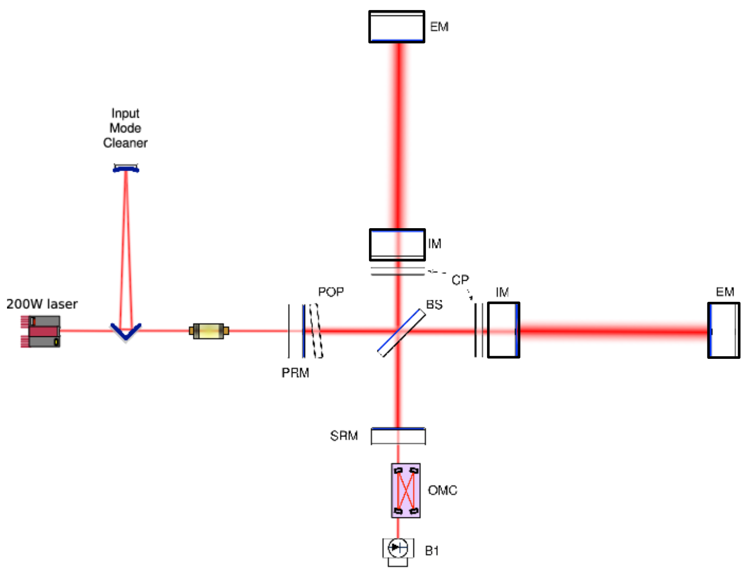
Virgo beamsplitter

Input mode cleaner cavity

Di-hedron: two-mirror system

Input mode cleaner

- 144 m long triangular ring cavity
- Finesse about 1100
- Di-hedron cavity mirror pair
- Filter unwanted modes
- First step in Virgo's frequency stabilization
- Designed by Nikhef
- Fabricated in collaboration with Optronica

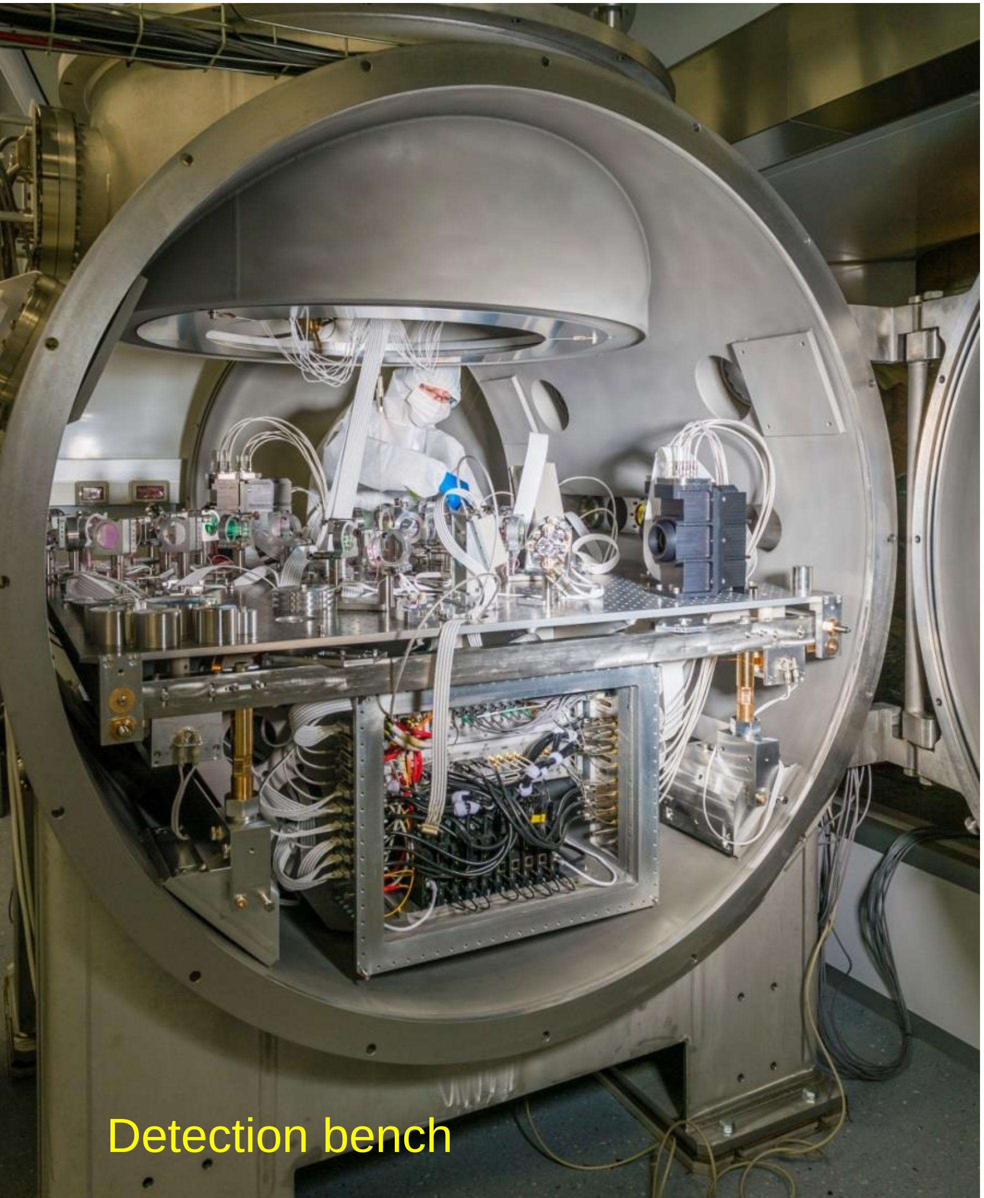


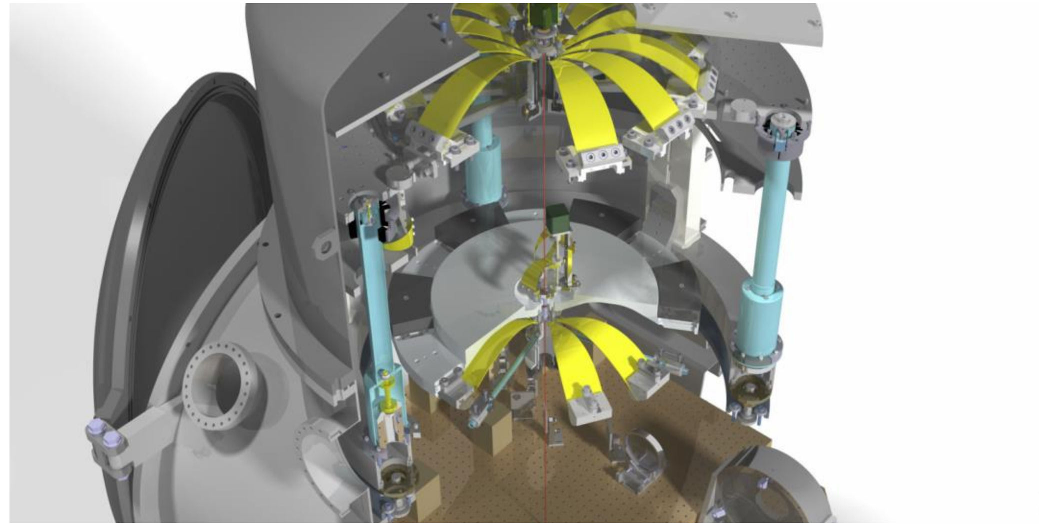
End mirror system of the input mode cleaner

End mirror including recoil mass and marionette. Installed and commissioned for Advanced Virgo

Vibration isolation systems

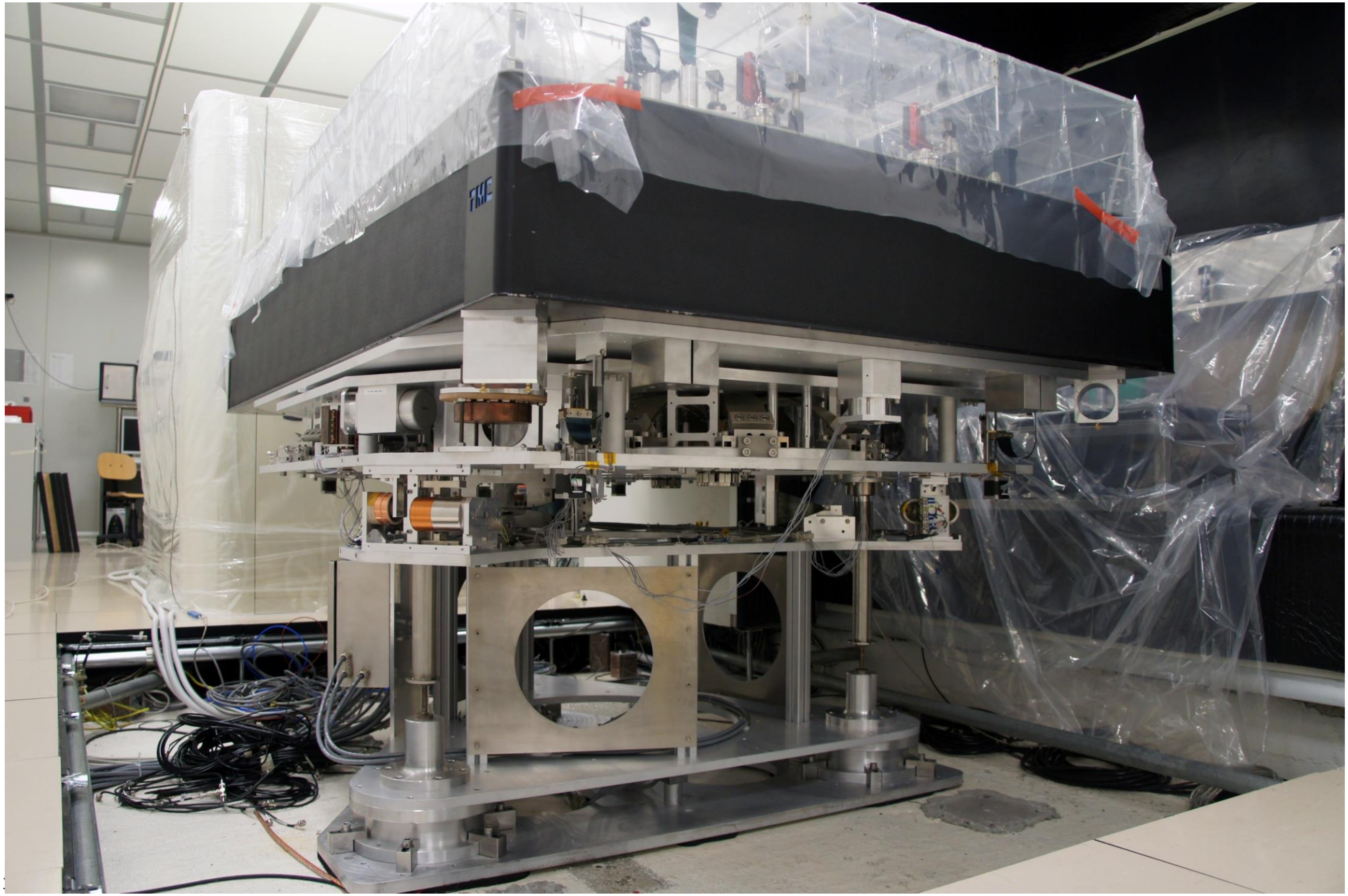
Optical systems for linear alignment, vibration isolation, IMC and phase camera’s, etc.





External injection bench suspended

EIB is last laser bench before laser enters the vacuum. EIB-SAS provides vibration attenuation by about a factor 1000 in 6 DOFs



Phase camera

Spatial amplitude and phase distribution at high speed for carrier and side bands. Unique tool to identify distortions of circulating beams

Diagnostic tool for Virgo commissioning

- Mode purity of circulating light
- Clipping of HG08 mode? Stray light?

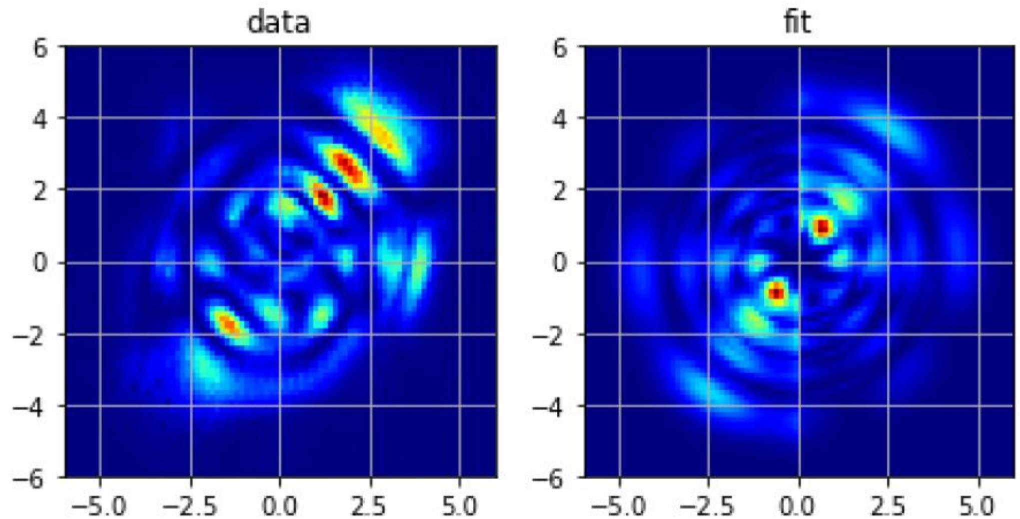
Crucial sensor for TCS

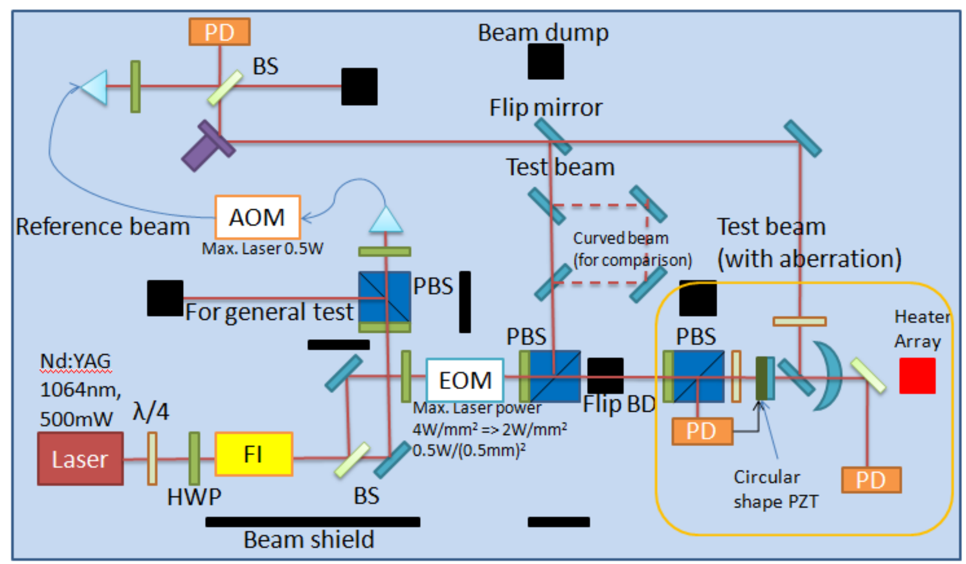
Increasingly important at higher powers (3G)

Interest from LIGO (UBirmingham)

Applications:

See http://www.liquidinstruments.com/

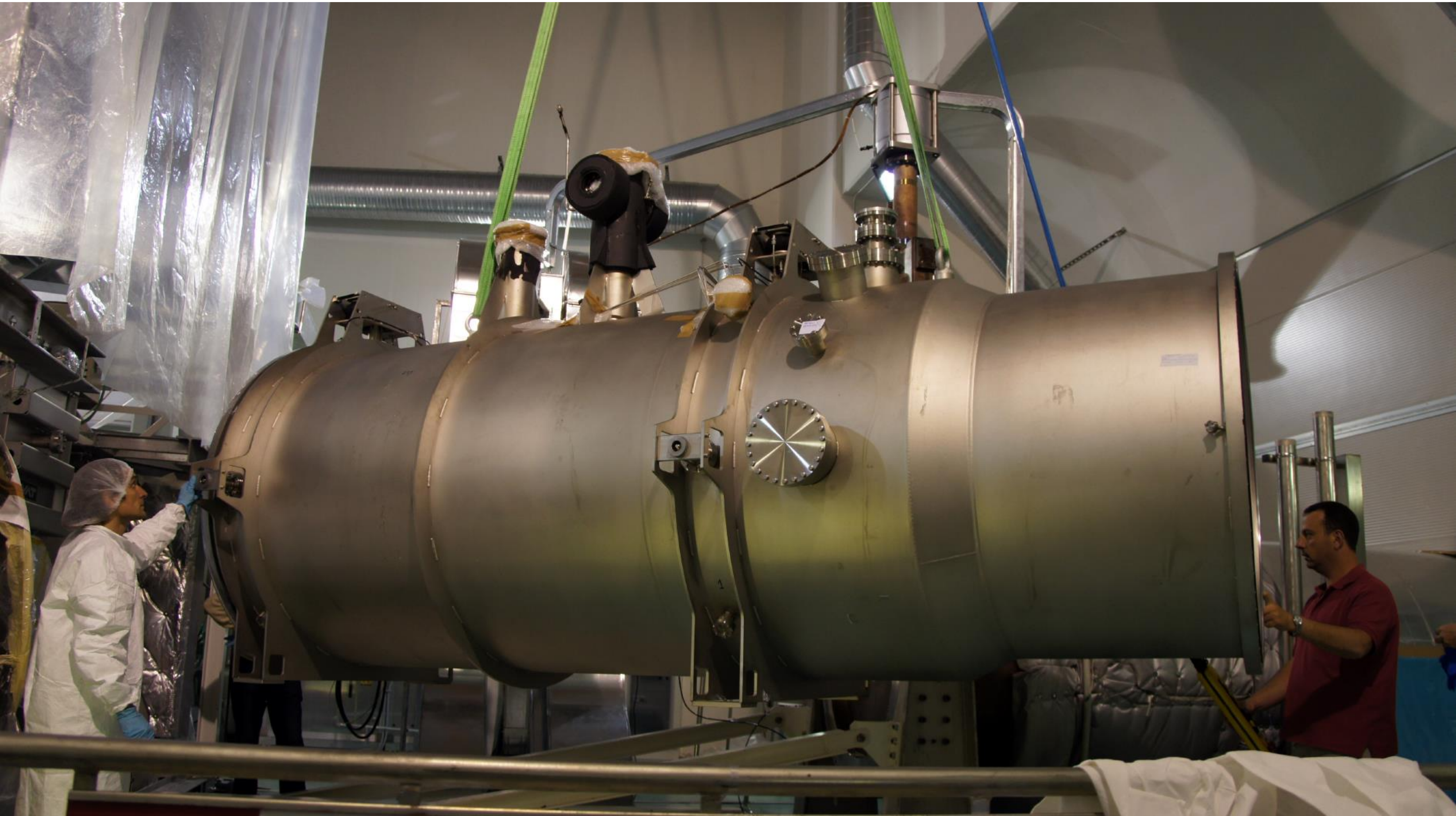




Virgo vacuum system

Cryolinks to achieve UHV in the ITF arms of Advanced Virgo

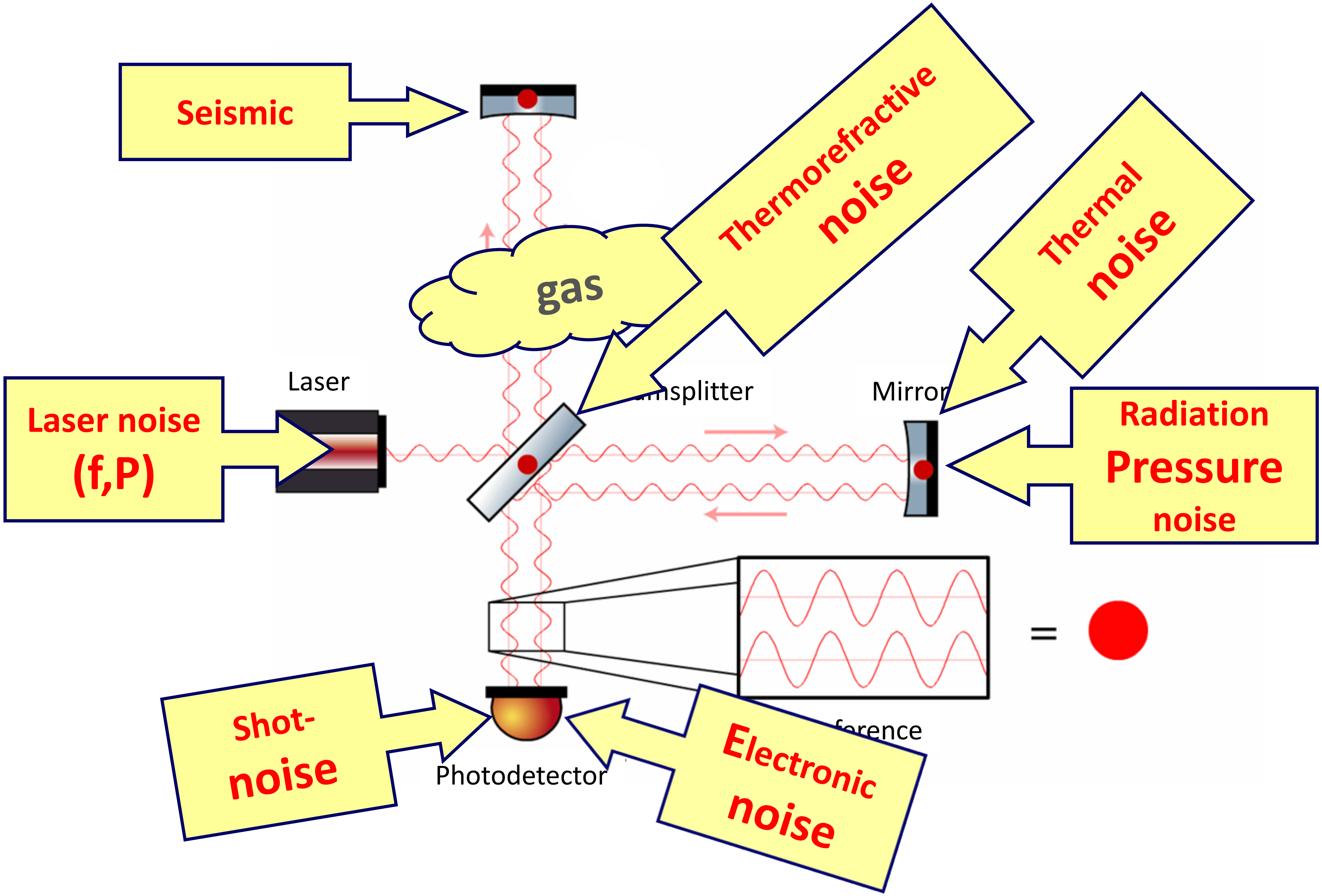
Four cryogenic links installed and commissioned. Advanced Virgo requires an ultra-high vacuum with pressures below 10^{-9} mbar



Interferometer: noise sources

Interferometer: noise sources

Fundamental and technical noise sources limit the sensitivity of our instruments



Laser interferometer detectors

Fundamental limits: shot noise

A light beam consists of a stream of photons: a beam with power *P* has a photon flux (photons/sec)

$$\bar{N} = \frac{P}{h\nu}$$

We know that

- nothing guarantees that *N* photons will arrive every second; some seconds there will arrive more, and in other seconds fewer photons will arrive at the photodiode;
- experiments show that the behavior is regulated by a Poisson statistics;
- then, if we expect *N* independent events on average, the standard deviation is $\sigma = \sqrt{N}$
- then, the higher the power, the lower the relative fluctuation

In frequency domain the photon counting error appears as white noise with rms value

$$\Delta P_{shot} = \sqrt{2h\nu P \Delta f}$$

The corresponding minimum GW signal observable over 1 Hz bandwidth is (close to the dark fringe)

$$h_{min}^{GW} = \frac{\lambda}{4\pi L_e}\sqrt{\frac{2h\nu}{P_{in}}} = 1 \cdot 10^{-24}$$

ν = *300* THz
P_{in} = *3.9* kW
L_e = 840 km

Laser interferometer detectors

Fundamental limits: radiation pressure

Photons carry momentum and exert a mechanical pressure on the mirrors (static and dynamic)

$$F_{static} = 2\bar{N}\frac{h\nu}{c}$$

$$F_{noise} = 2\frac{h\nu}{c}\sqrt{\bar{N}} = 2\frac{h\nu}{c}\sqrt{\frac{P}{h\nu}} = 2\sqrt{\frac{Ph}{\lambda c}}$$

$$x_{noise} = \frac{2}{m\omega^2}\sqrt{\frac{Ph}{\lambda c}}$$

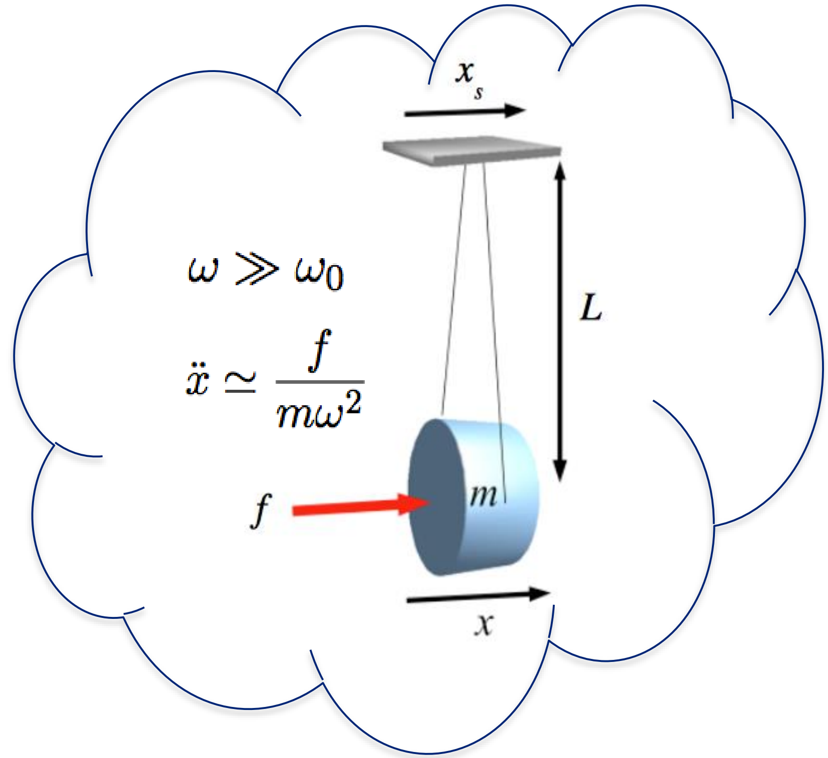
for a simple **Michelson** interferometer

$$h_{GW}^{rp} = \frac{2x_n}{L}$$

for a **FP Michelson** interferometer

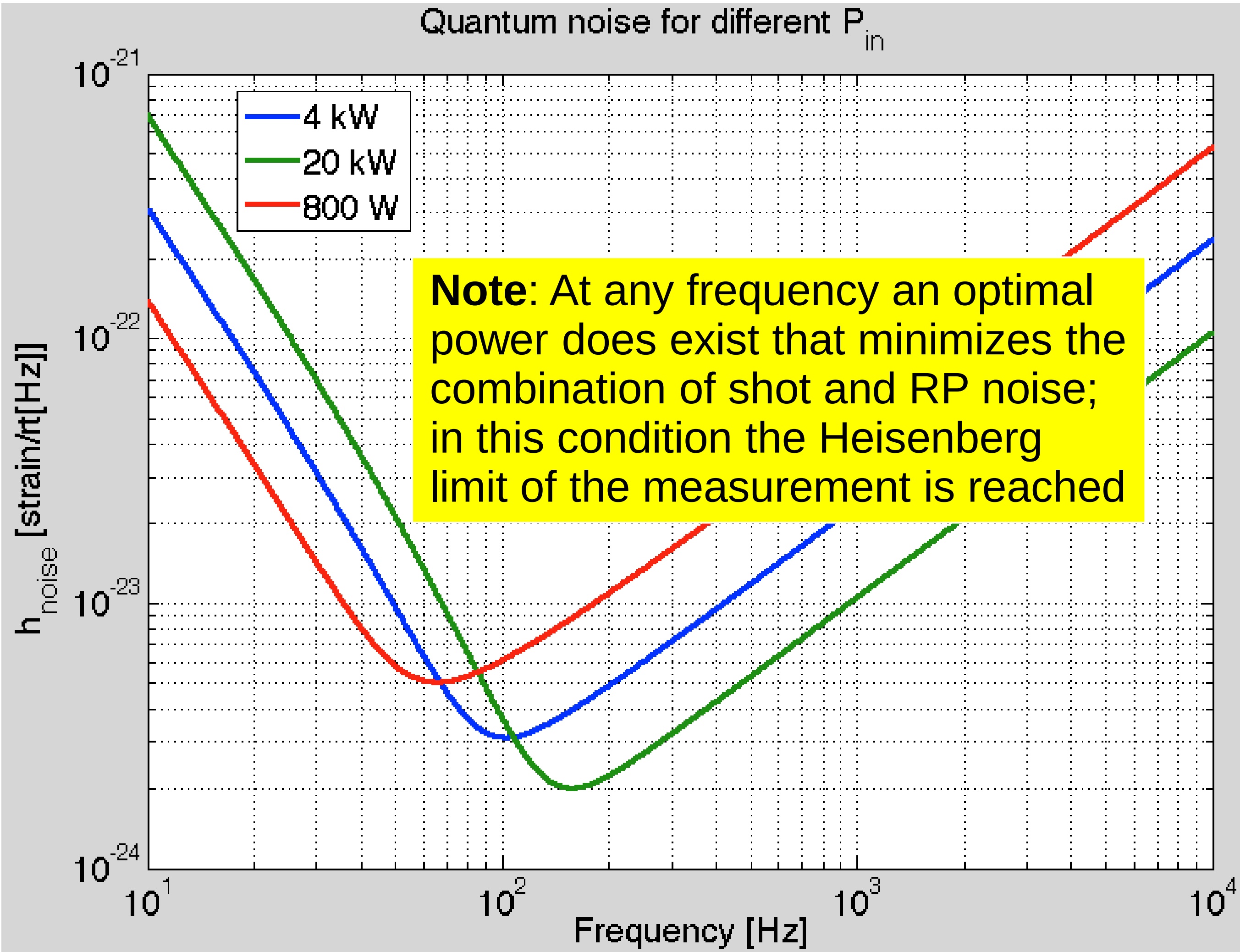
$$h_{GW}^{rp} = 2\cdot\sqrt{2}\cdot\frac{2F}{\pi}\frac{x_n}{L} = \frac{8F}{\pi L m\omega^2}\sqrt{\frac{2P_{in}h}{\lambda c}}$$

Reminder



Laser interferometer detectors

Fundamental limits: radiation pressure

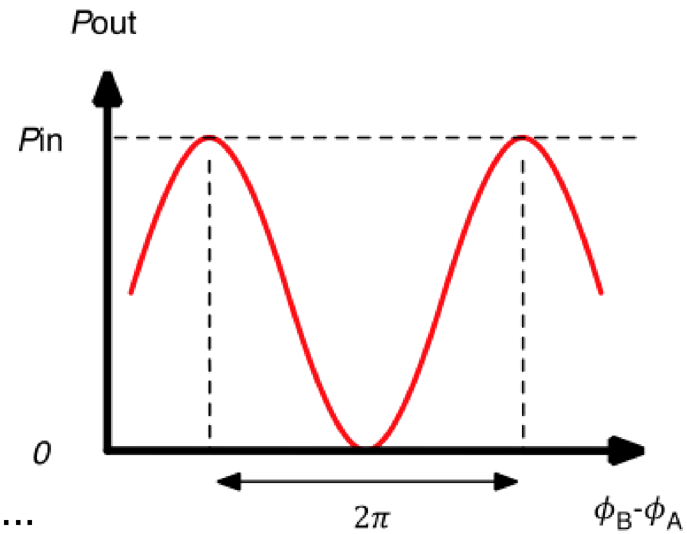


Laser interferometer detectors

Working point (why the dark fringe?)

$$P_{out} = \frac{P_{in}}{2}\left[1 - \cos\left(\phi_0 + \frac{4\pi L_e}{\lambda}h\right)\right]$$

$$\Delta P_{out} = \frac{2\pi L_e}{\lambda} P_{in} \sin\phi_0 h$$



The max response to *h* is at π/2 but laser power fluctuations...
Even if the lasers used in GW detectors are the best ever made (dP/P < 10^{-8} at f > 10 Hz)

$$\Delta P_{out} = \frac{\Delta P_{in}}{2}(1 - \cos\phi_0) \Longrightarrow h_{min} = 10^{-8}\frac{\lambda}{4\pi L_e} = 8 \cdot 10^{-22}$$

not good enough !!

… better with a little offset from the dark fringe

$$\Delta P_{out} \simeq \frac{2\pi L_e}{\lambda} P_{in} \phi_0 h$$

$$h_{min} = 10^{-8}\phi_0 \frac{\lambda}{4\pi L_e} = 8 \cdot 10^{-26}$$

Laser interferometer detectors

Seismic noise

Earth crust moves relentlessly in a wide frequency range from nHz to hundreds of Hz:

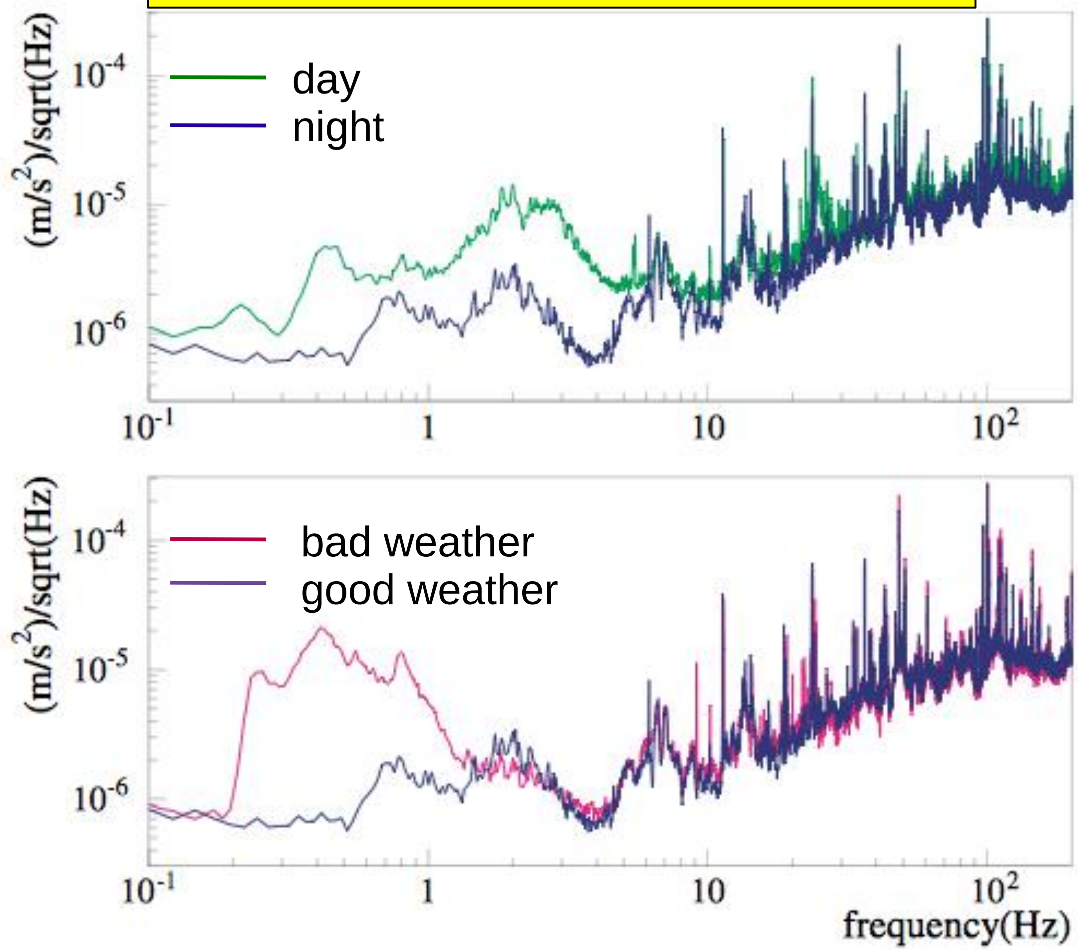
- Tectonic movements
- Lunar tides (few μHz)
- Microseismic peak from ocean waves (0.1-0.3 Hz)
- Anthropogenic and wind induced noise (f>1 Hz)

Amplitude exceeds by several orders of magnitude the test mass background motion aimed for GW detection (<10^{-18}m)

At the Virgo site:

at f > 10 Hz $$x_s \simeq \frac{10^{-7}}{f^2}\left[\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\right]$$

Typical ground motion spectra at the Virgo site



Laser interferometer detectors

Simple pendulum transfer function

Reminder

at low frequencies ($\omega \ll \omega_0$)

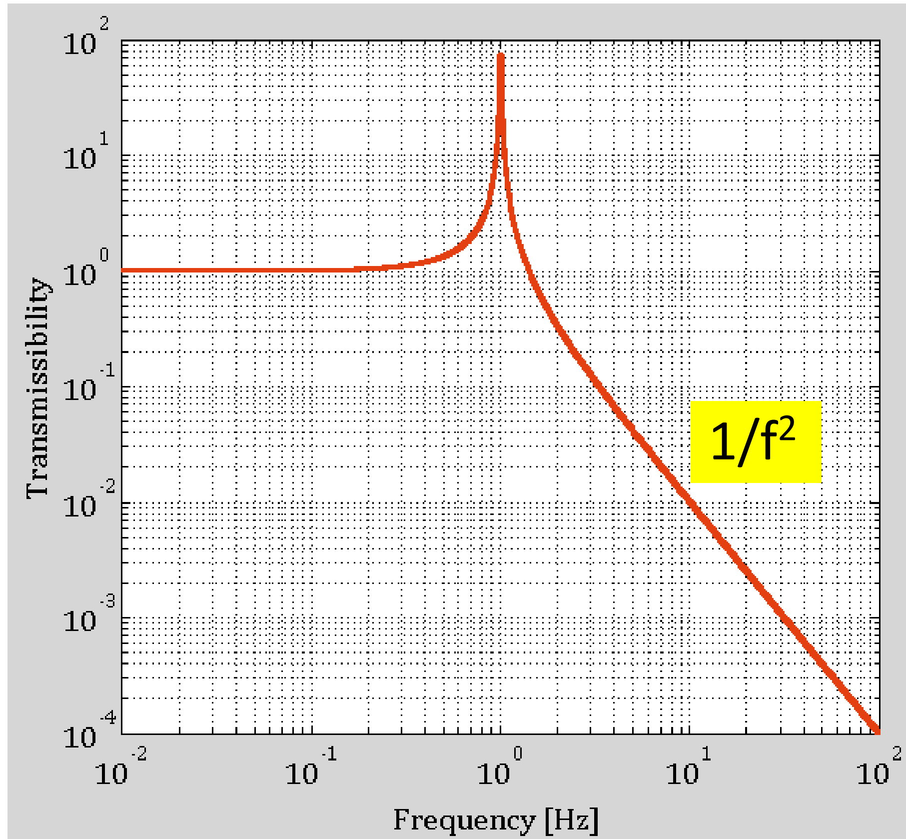
$$X \simeq X_s + F/m{\omega_0}^2$$

at the natural frequency ($\omega = \omega_0$)

$$X \simeq Q(X_s + F/m{\omega_0}^2)$$

while at high frequency ($\omega \gg \omega_0$)

$$X \simeq \frac{{\omega_0}^2}{\omega^2} X_s + F/m\omega^2$$



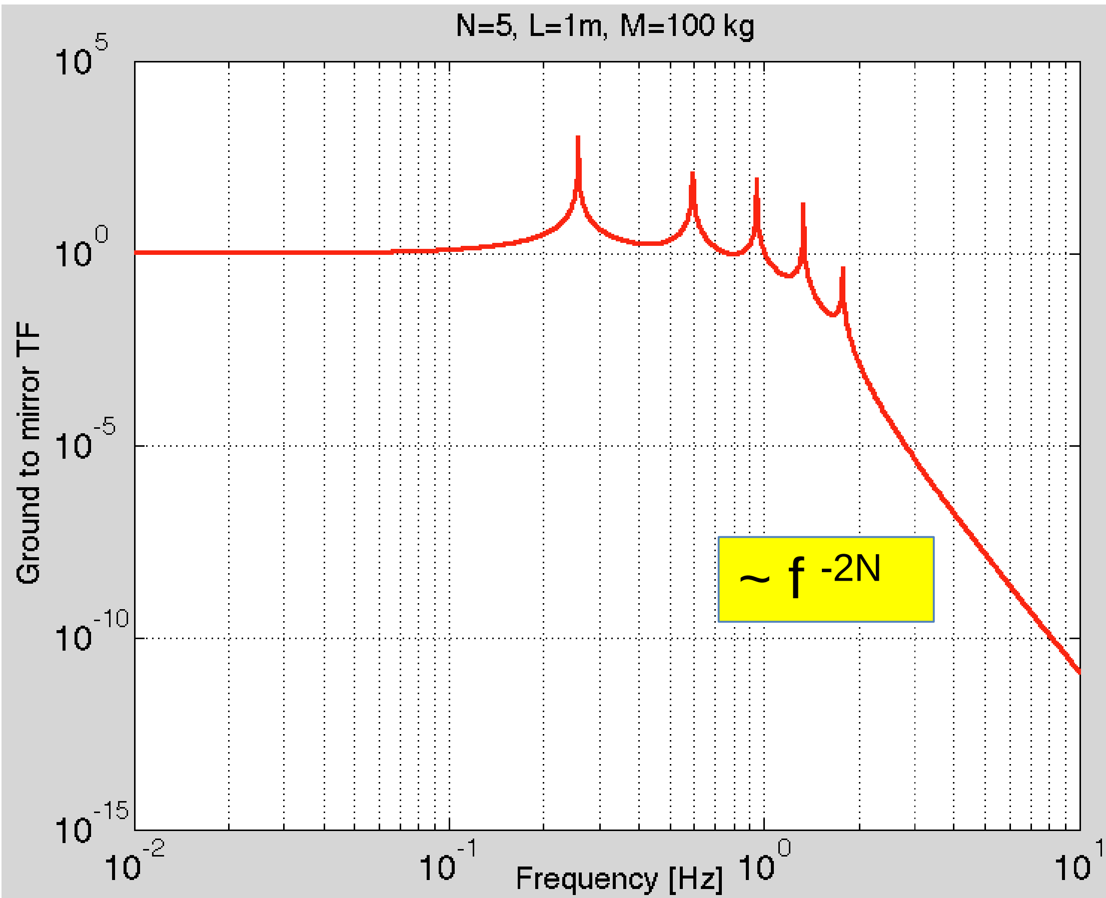
The suspension also provides attenuation of ground vibrations, ... but far from the 10^8-10^{10} seismic attenuation required in the GW detection band (10 Hz - 3 kHz)

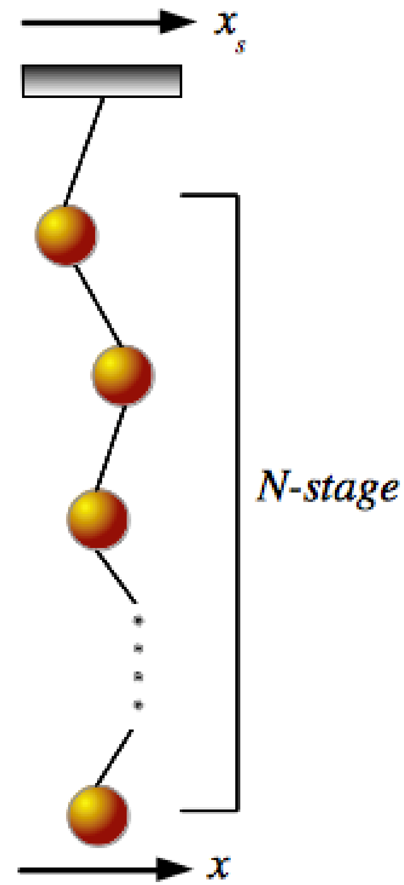
Laser interferometer detectors

Solution: cascading mechanical filters (*seismic filters*) with uncoupled natural frequencies sufficiently lower than 10 Hz

The Lagrangian of a chain of simple pendulums is:

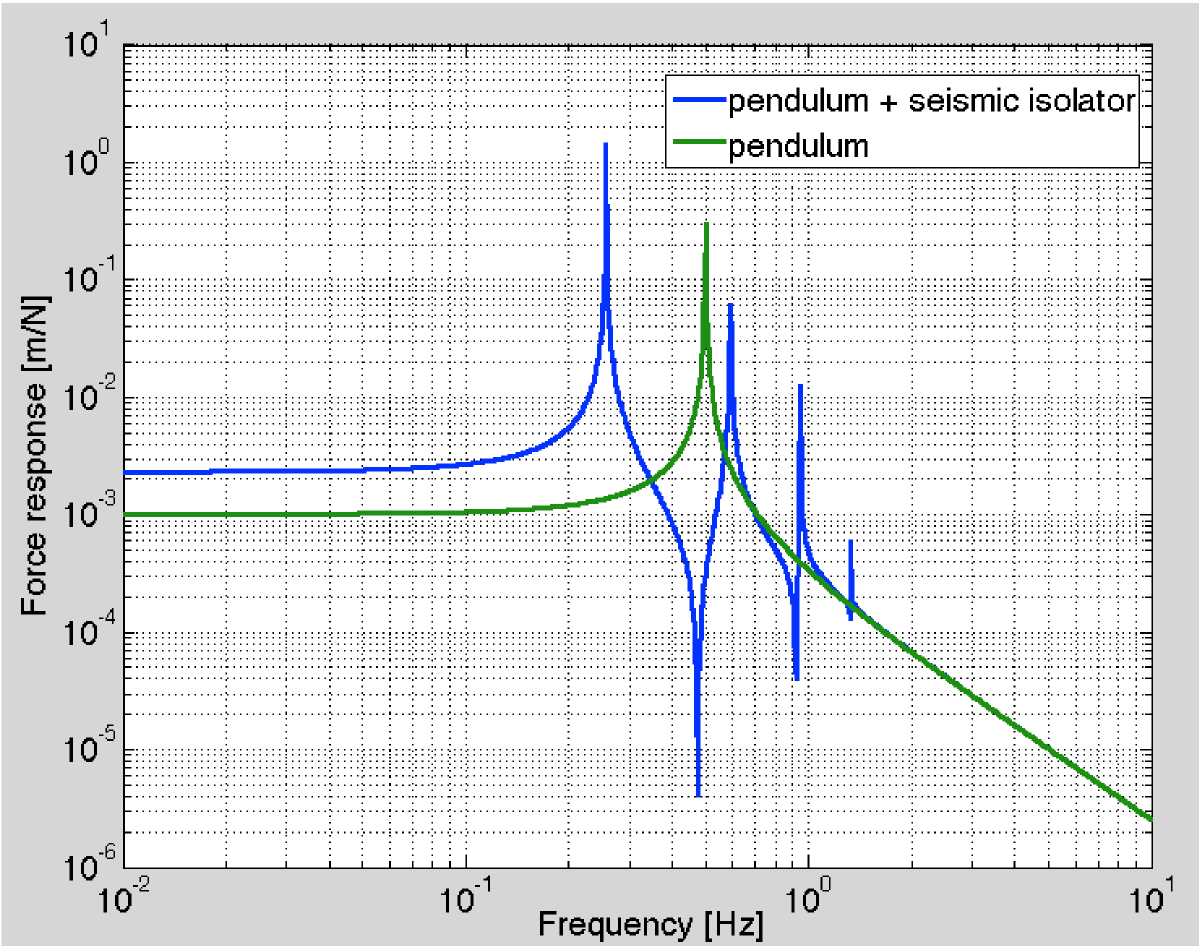
$$\mathcal{L} = T - V = \frac{1}{2}\sum_{i=1}^{N} m_i \dot{x}_i{}^2 - \frac{1}{2} g \sum_{i=1}^{N} \frac{\sum_{j=i}^{N} m_j}{L_i} (x_i - x_{i-1})^2$$

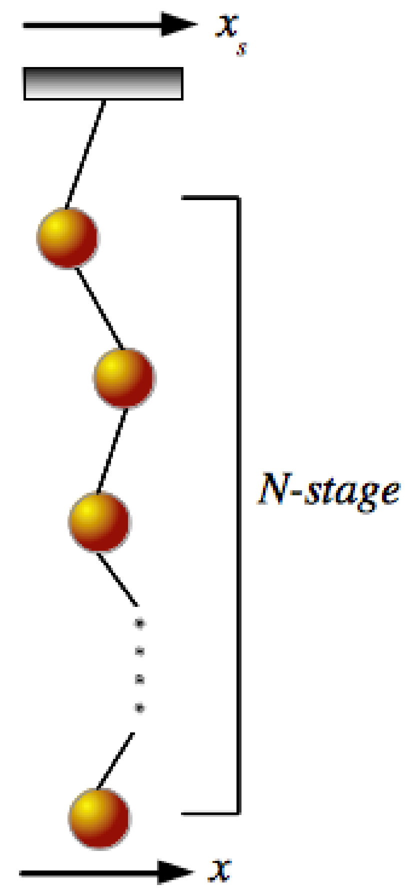




Laser interferometer detectors

Applying a force to the test-mass





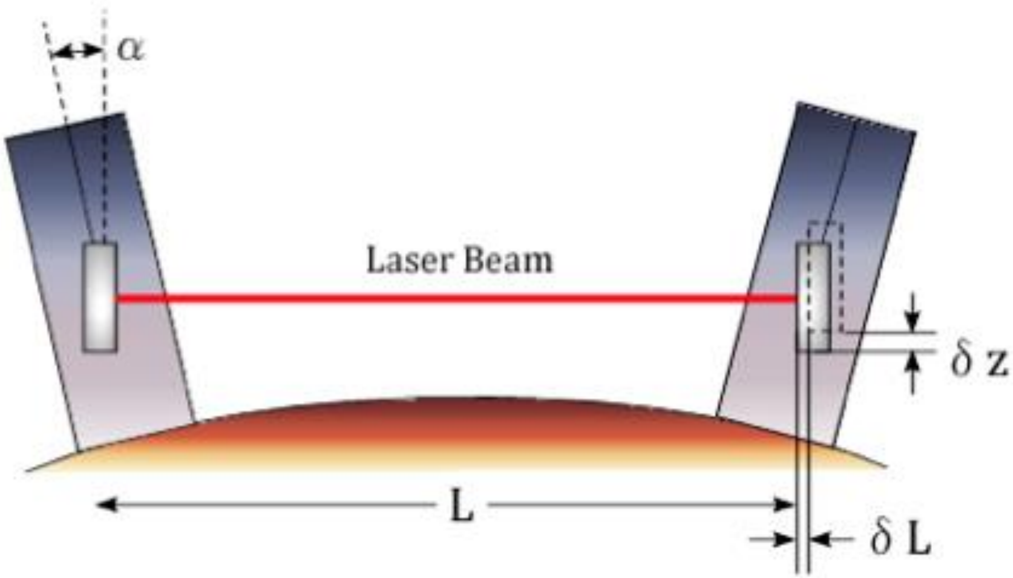
Above the seismic isolator cut-off the mirror responds as a single simple pendulum

Laser interferometer detectors

… but life is hard …

Horizontal seismic filtering is not sufficient because:

1. Non-parallelism of verticality between objects a few km apart channels vertical seismic noise along the GW sensing axis ($2*10^{-4}$ coupling over 3 km)

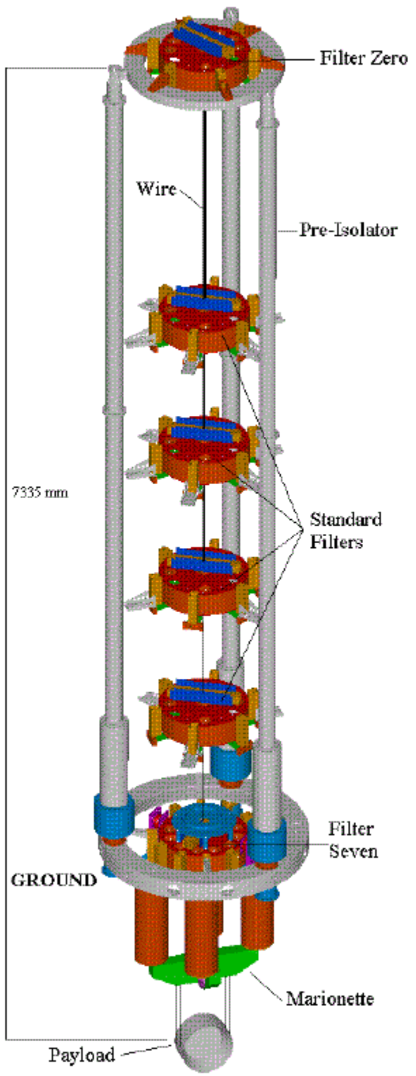


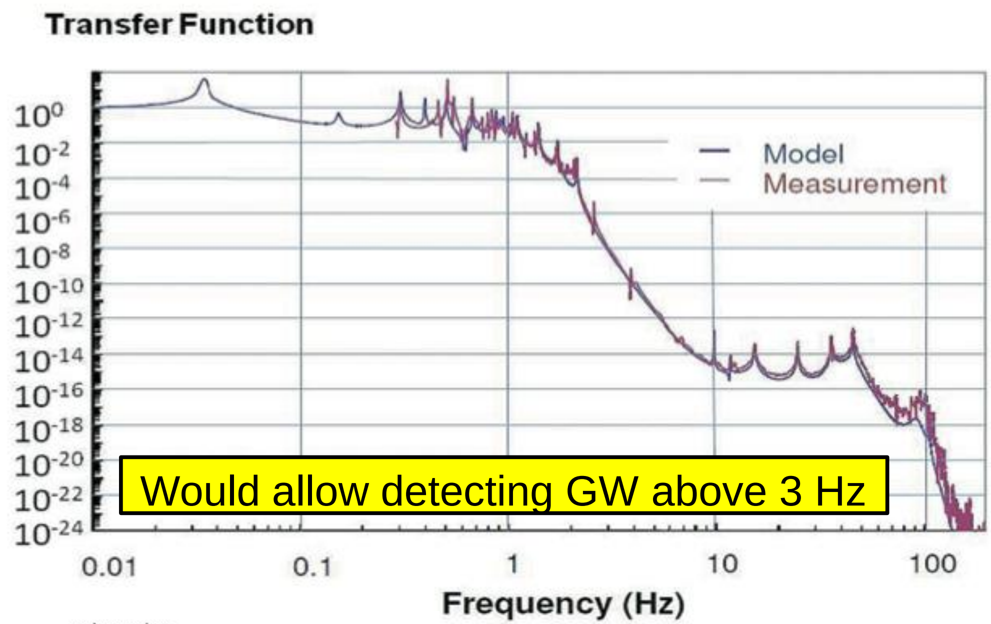
2. Imperfections in the mechanical assembly may cause even larger couplings (up to 1%)

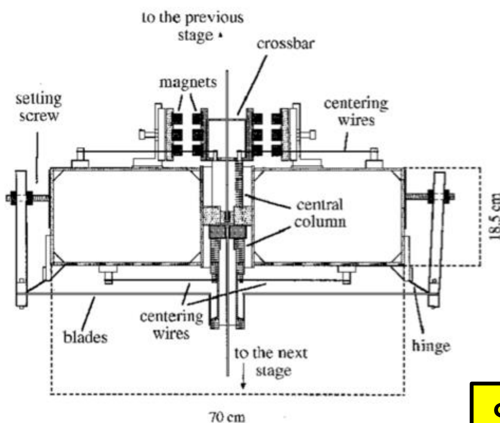
Vertical seismic isolation is necessary !!

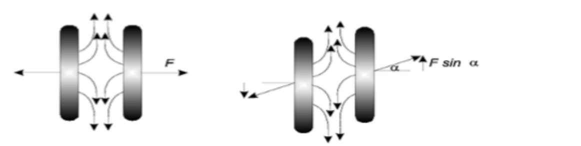
Laser interferometer detectors

The Virgo superattenuator









working principle of the magnetic anti-spring system. When the magnets are displaced in the vertical direction (right side) a vertical component of the repulsive force appears.

SA Magnetic anti-spring vertical filters

Tilt meters are important for seismic vibration isolation

Sensor used at CERN could help gravitational-wave hunters

A new seismic device developed by CERN and JINR is now being tested at the Advanced Virgo detector

30 AUGUST, 2019 | By Ana Lopes (/authors/ana-lopes)

(//cds.cern.ch/images/CERN-HOMEWEB-PHO-2019-104-1)

Aerial view of the Advanced Virgo detector, where a precision laser interferometer used at CERN was installed and is being tested (Image: Virgo collaboration)

Collaboration between CERN and the Joint Institute for Nuclear Research (JINR) in Dubna, Russia made a precision laser inclinometer that can potentially serve as early warning systems for earthquakes and can be used to monitor other seismic vibrations. Researchers are now testing one device at the Advanced Virgo detector. If all goes to plan, this device could help gravitational-wave hunters minimise the noise that seismic events cause on the waves' signal.

The precision laser inclinometer (PLI) measures by pointing laser light at a liquid and seeing how it is reflected. Compared to weight–spring seismometers, the PLI can detect angular motion in addition to translational motion and it can pick up low-frequency motion with a very high precision. Sensitivity is equivalent to measuring a vertical displacement of 24 picometres over a distance of 1 meter.

Principal investigator Beniamino Di Girolamo, CERN
Co-principal investigator Julian Budagov, JINR

Laser interferometer detectors

Brownian motion

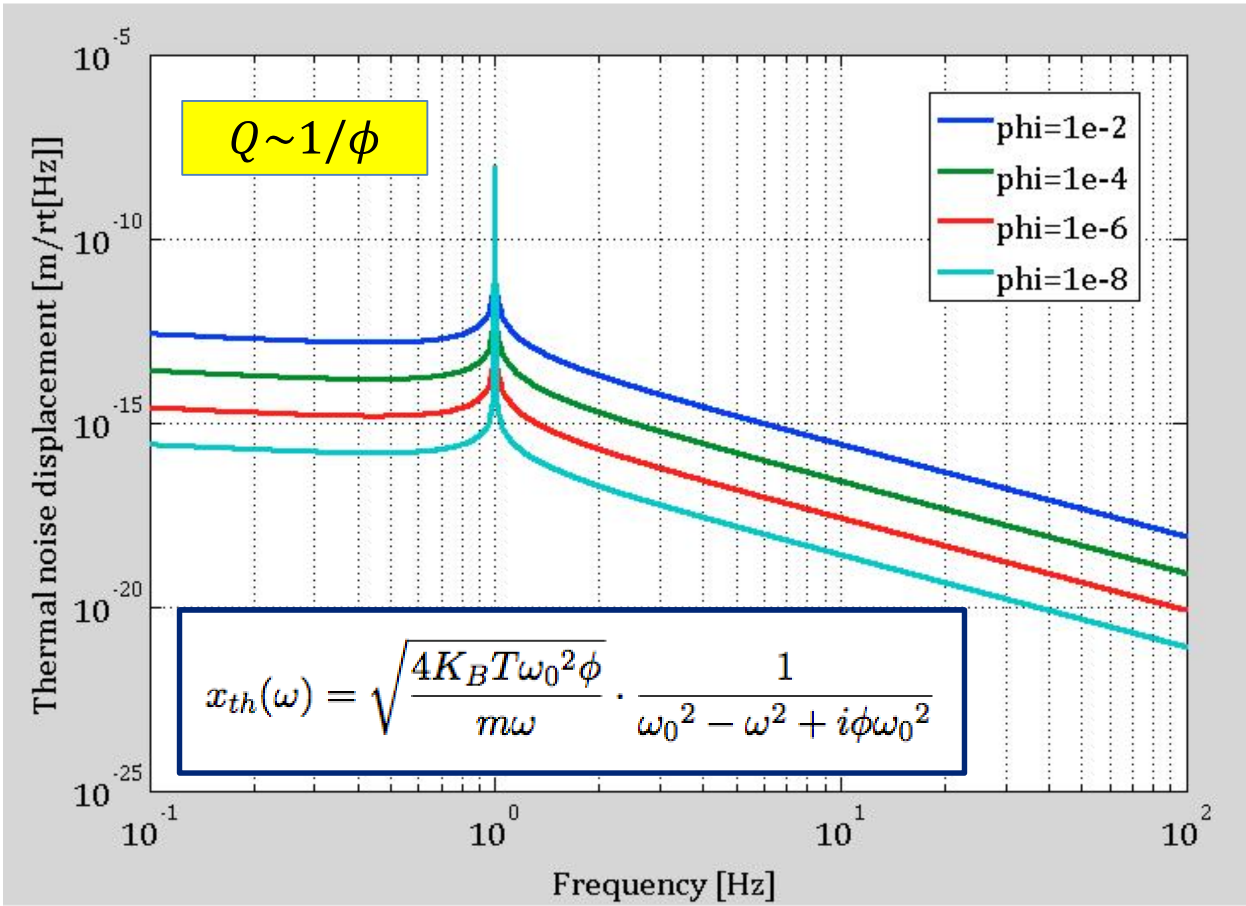
- Internal friction in the material of the suspension wires causes the mirrors to move

- The effect dominates over filtered seismic at f > 3 Hz

Two possible choices for the wire material:

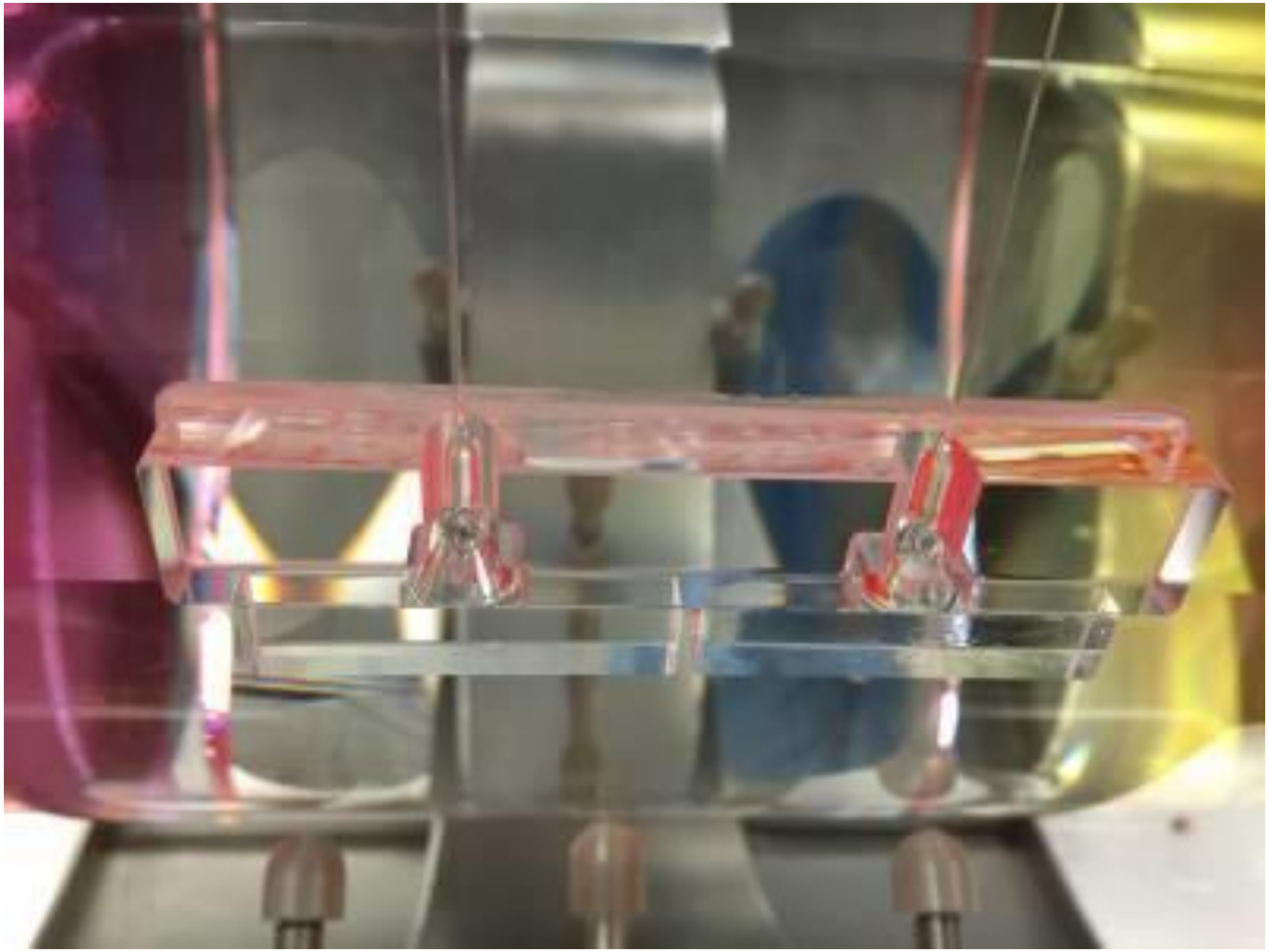
- ❑ a 'perfect' crystal

- ❑ a 'perfect' glass



Thermal noise

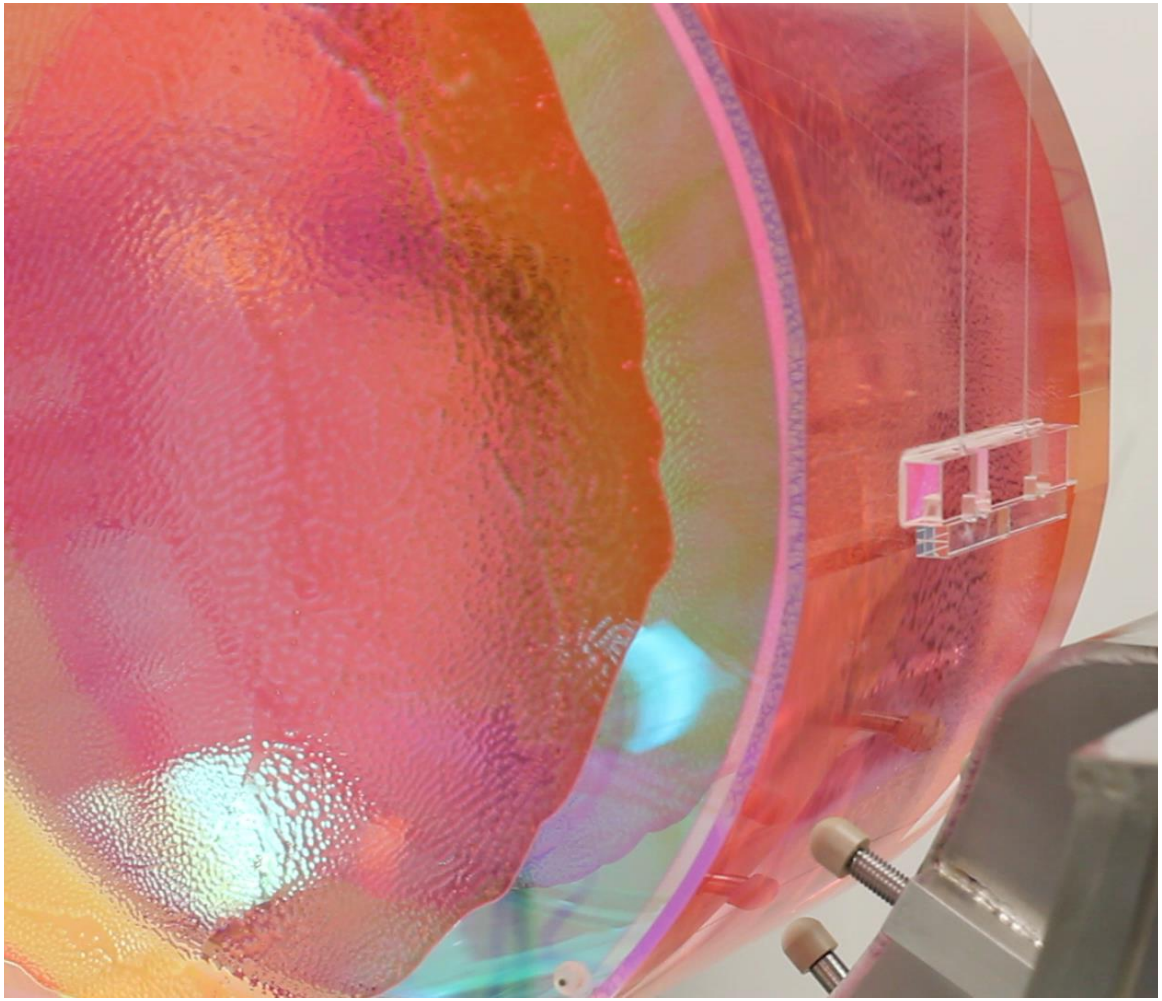
Monolithic suspensions. High Q-values, but now sensitive to parametric instabilities

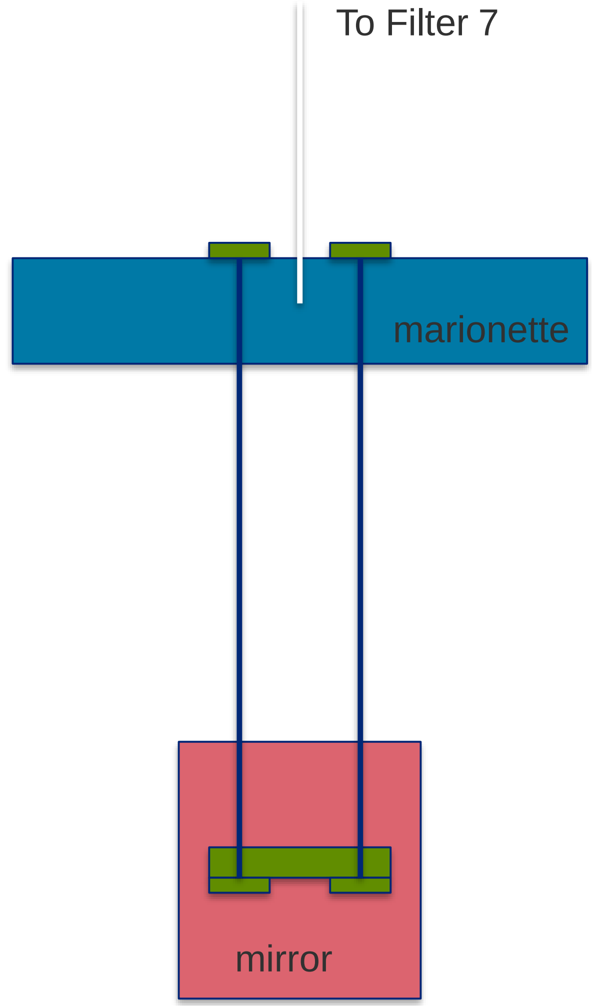


Monolithic suspended mirrors

Test masses in Advanced Virgo are suspended with thin silica fibers: 0.4 mm diameter and 0.7 m long

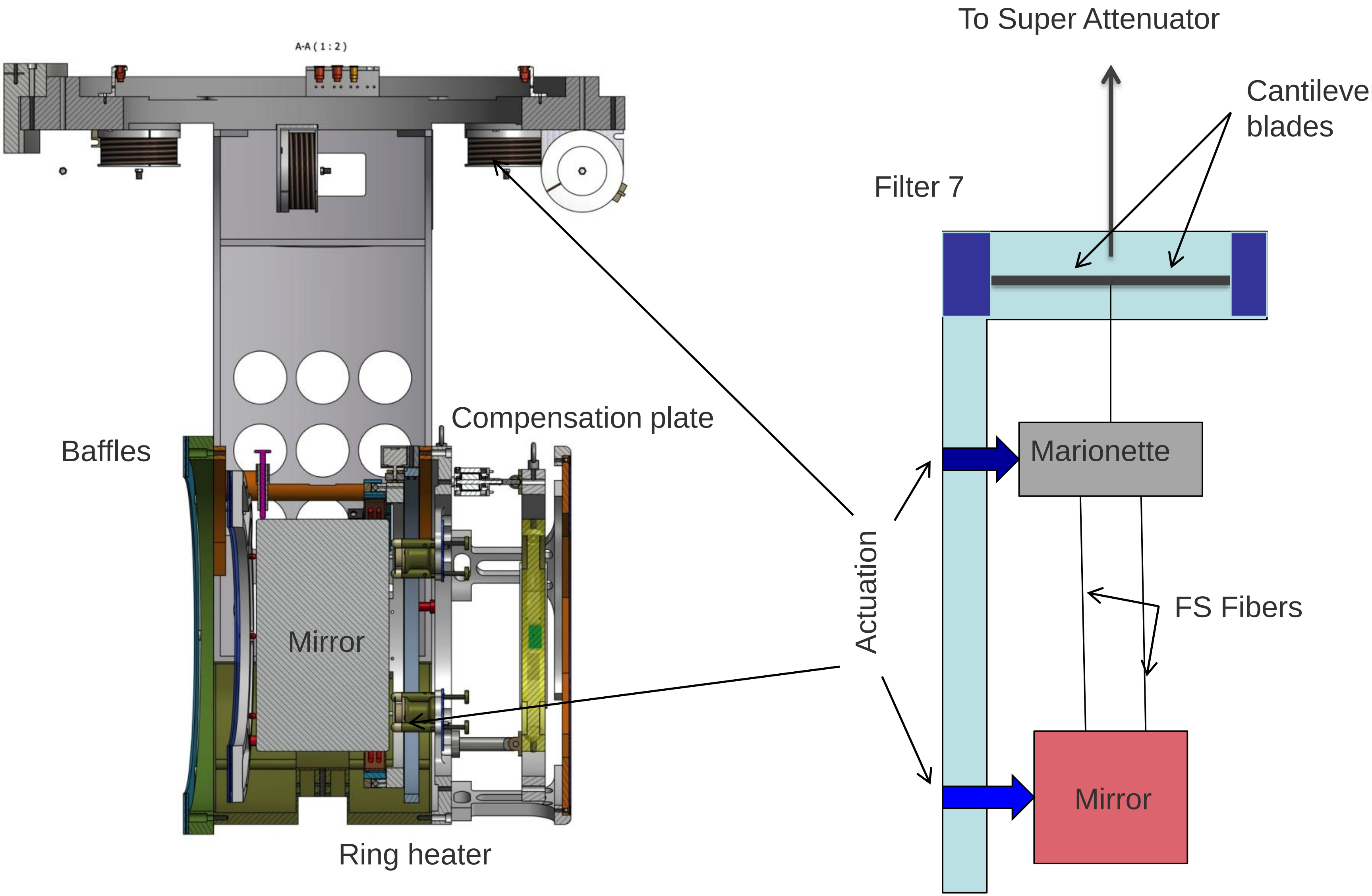
Note: the colored foil is a protective coating





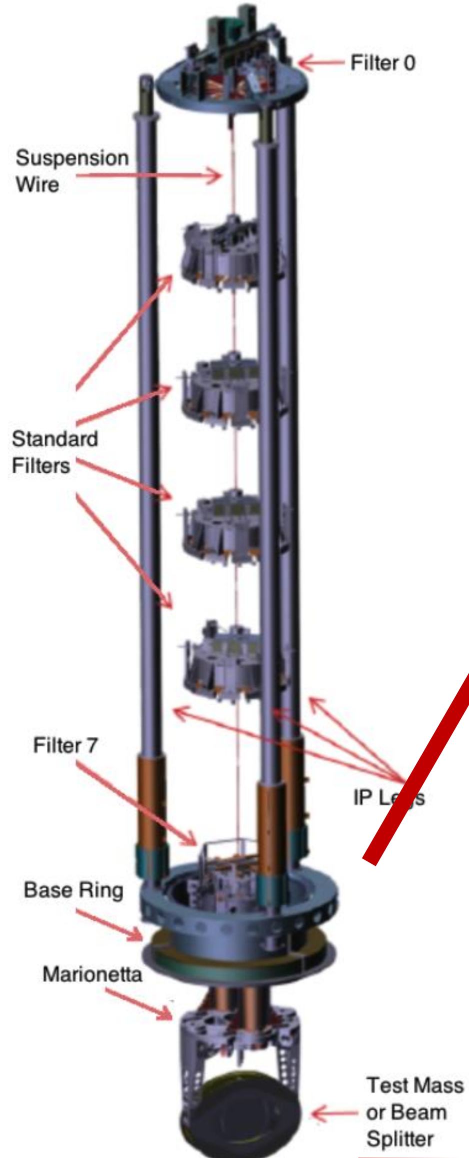
Actuation on suspended mirrors

Advanced Virgo employs magnetic actuation to control the mirror. In addition a thermal compensation system is used



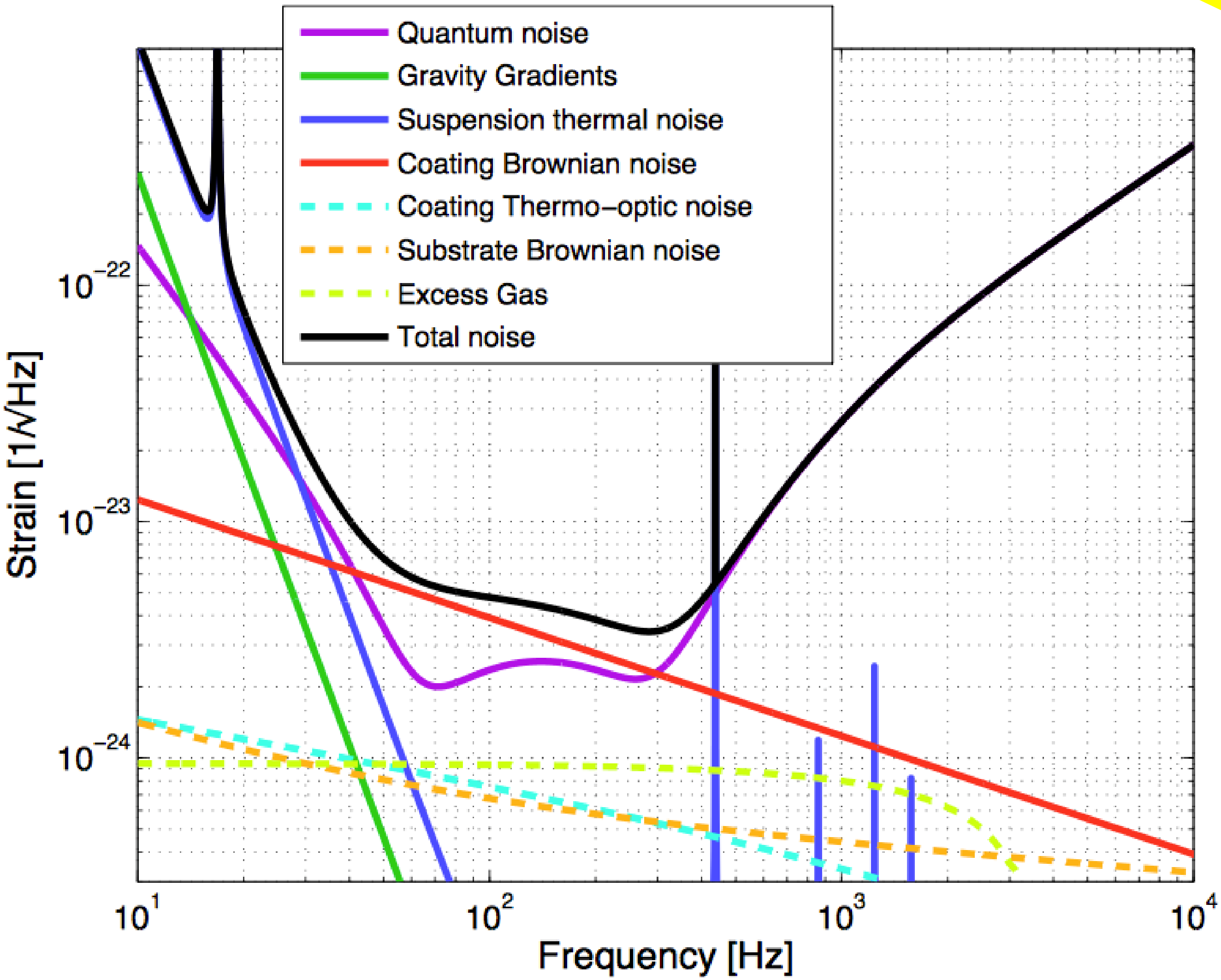
Virgo’s test masses

8 m



Laser interferometer detectors

Advanced Virgo sensitivity curve



… now working hard to reach it ….

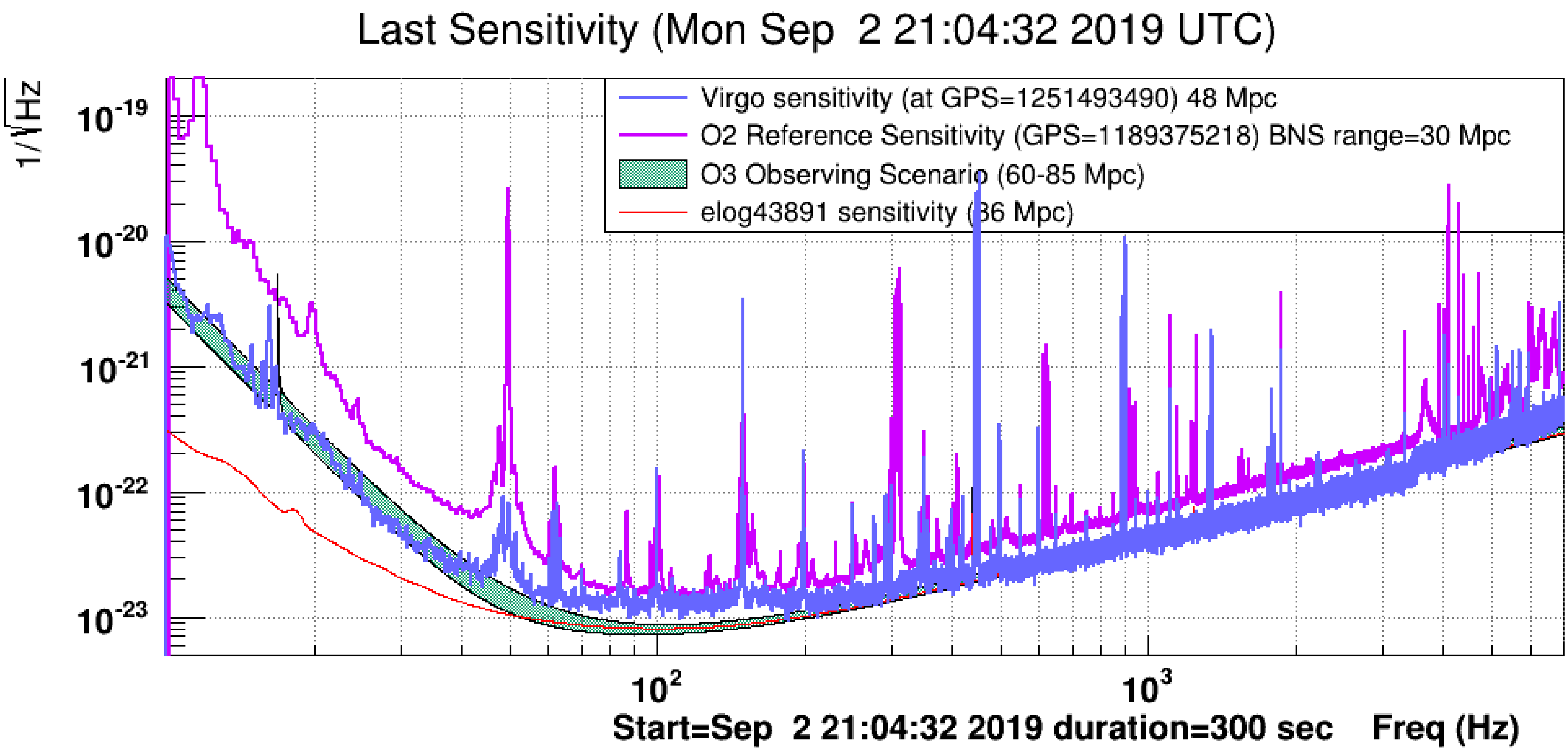
Science run O3 is underway

April 1, 2019: LIGO and Virgo started Observation run O3

Joining O3 is another big step for Virgo

Virgo sensitivity: best value about 50 Mpc

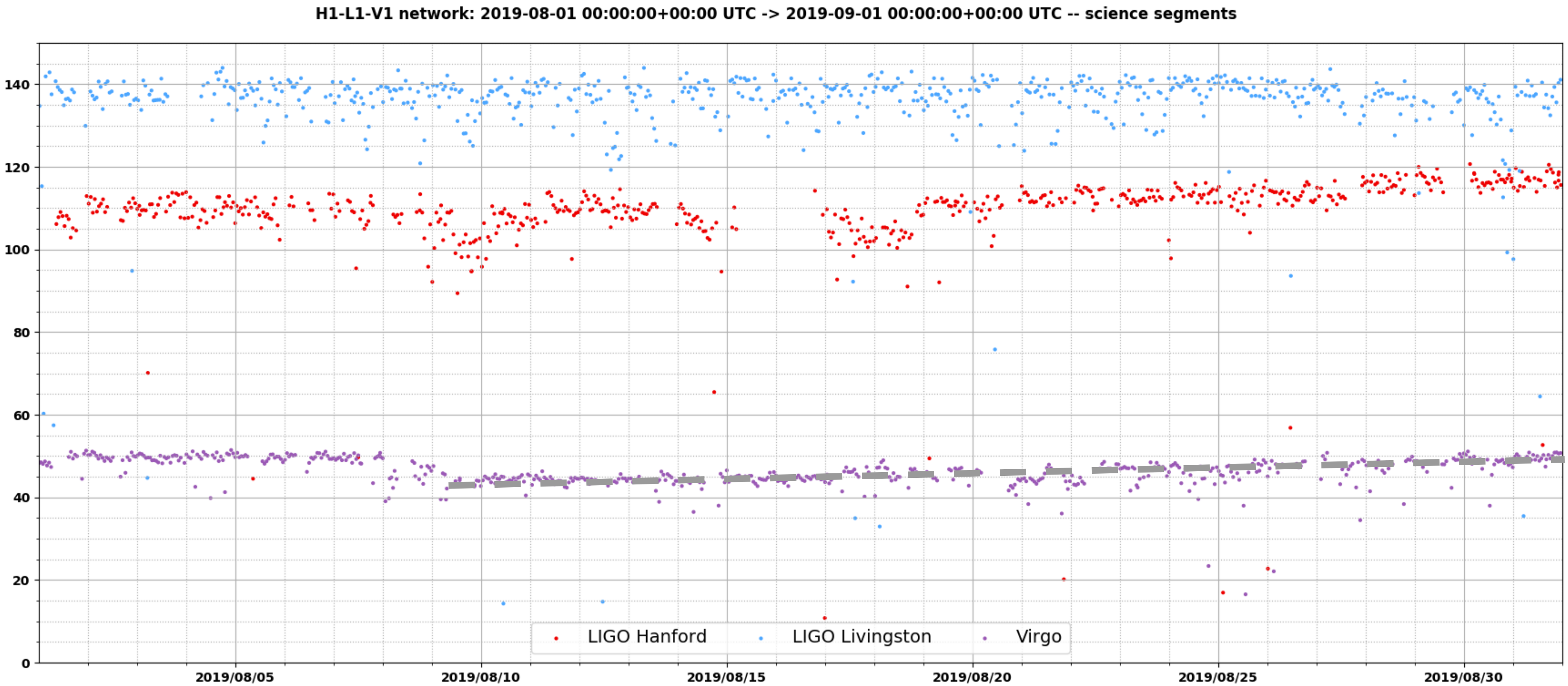
Significant improvement with respect to the best sensitivity obtained in O2. However, we see a flat noise contribution at mid-frequencies, significant noise around 50 Hz. Virgo uses 18 W of power



O3 Summary: H, L, V sensitivity

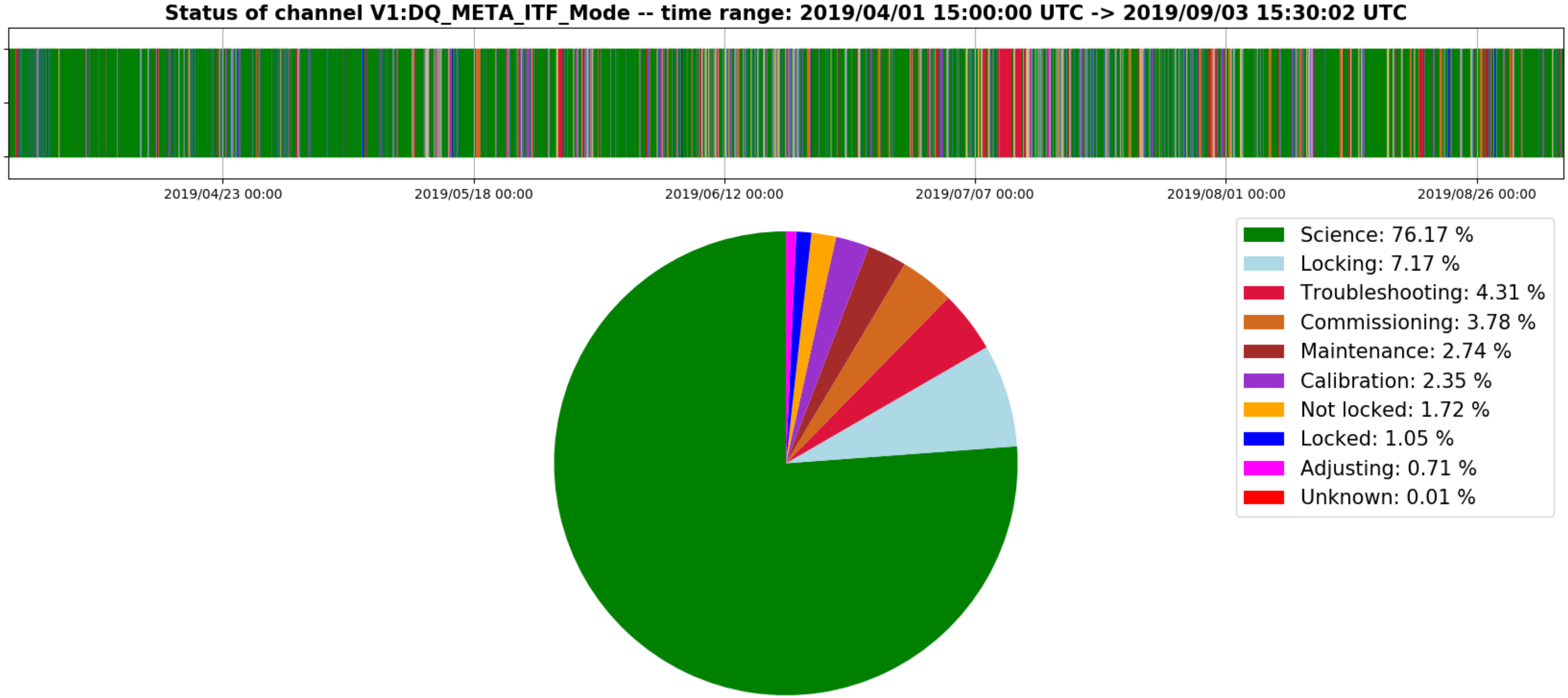
Virgo’s BNS range is now on the rise

August 2019



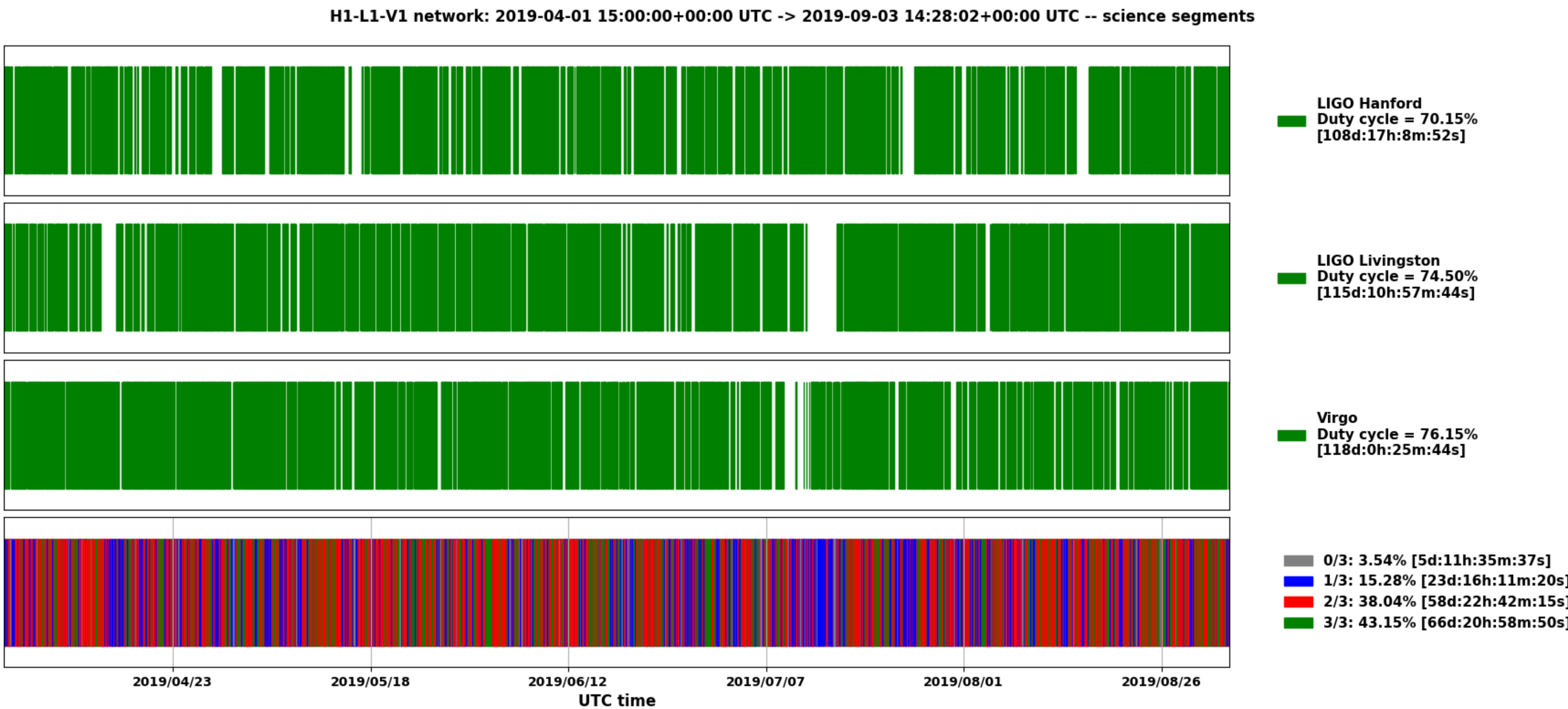
O3 Summary: efficiency

Science mode (green) for 76%. Significant time is now devoted to commissioning (orange). These activities are still ongoing with the focus on stability. Maintenance (brown) and calibration (purple) are other significant activities



O3 Summary: network performance

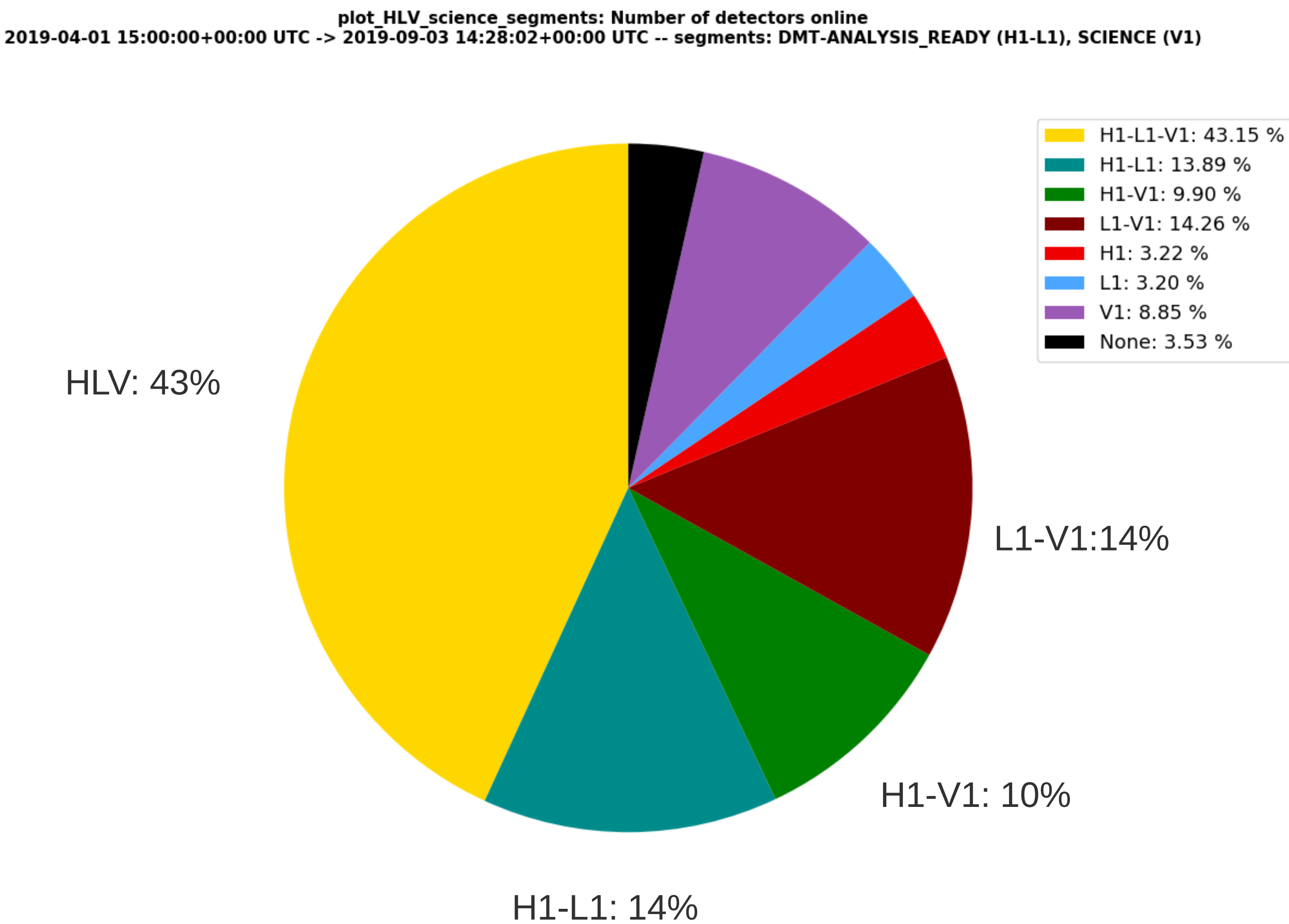
Triple event efficiency about 43% and double events about 38%



Advanced Virgo

O3 Summary: number of detectors online

H1-L1 double efficiency 57%, H1-L1-V1 double+triple efficiency 82%



https://gracedb.ligo.org/latest/

Already 33 (= 41 - 8) public alerts in the 3rd science run: more candidates than O1 and O2 combined

Latest — as of 10 October 2019 17:29:34 UTC

Test and MDC events and superevents are not included in the search results by default; see the query help for information on how to search for events and superevents in those categories.

Query:

Search for: Superevent

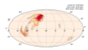
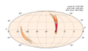
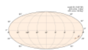
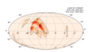
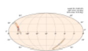
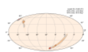
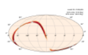
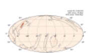
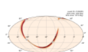
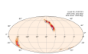
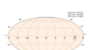
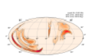
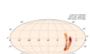
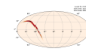
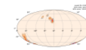
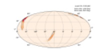
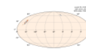
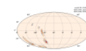
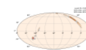
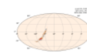
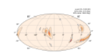
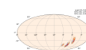
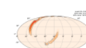
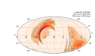
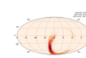
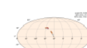
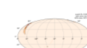
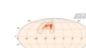
Search

UTC

UID	Labels	t_start	t_0	t_end	FAR (Hz)	Created
S190930t	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253889264.685342	1253889265.685342	1253889266.685342	1.543e-08	2019-09-30 14:34:30 UTC
S190930s	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253885758.235347	1253885759.246810	1253885760.253734	3.008e-09	2019-09-30 13:36:04 UTC
S190928c	ADVNO EM_Selected SKYMAP_READY DQOK GCN_PRELIM_SENT	1253671923.328316	1253671923.364500	1253671923.400684	6.729e-09	2019-09-28 02:14:18 UTC
S190924h	PE_READY ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253326743.785645	1253326744.846654	1253326745.876674	8.928e-19	2019-09-24 02:19:25 UTC
S190923y	ADVOK EM_Selected SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1253278576.645077	1253278577.645508	1253278578.654868	4.783e-08	2019-09-23 12:56:22 UTC
S190915ak	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252627039.685111	1252627040.690891	1252627041.730049	9.735e-10	2019-09-15 23:57:25 UTC
S190910h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252139415.544299	1252139416.544448	1252139417.544448	3.584e-08	2019-09-10 08:30:21 UTC
S190910d	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1252113996.241211	1252113997.242676	1252113998.264918	3.717e-09	2019-09-10 01:26:35 UTC
S190901ap	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251415878.837767	1251415879.837767	1251415880.838844	7.027e-09	2019-09-01 23:31:24 UTC
S190829u	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251147973.281494	1251147974.283940	1251147975.283940	5.151e-09	2019-08-29 21:06:19 UTC
S190828l	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251010526.884921	1251010527.886557	1251010528.913573	4.629e-11	2019-08-28 06:55:26 UTC
S190828j	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1251009262.739486	1251009263.756472	1251009264.796332	8.474e-22	2019-08-28 06:34:21 UTC
S190822c	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1250472616.589125	1250472617.589203	1250472618.589203	6.145e-18	2019-08-22 01:30:23 UTC
S190816i	PE_READY ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249995888.757789	1249995889.757789	1249995890.757789	1.436e-08	2019-08-16 13:05:12 UTC
S190814bv	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249852255.996787	1249852257.012957	1249852258.021731	2.033e-33	2019-08-14 21:11:18 UTC
S190808ae	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1249338098.496141	1249338099.496141	1249338100.496141	3.366e-08	2019-08-08 22:21:45 UTC
S190728q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248331527.497344	1248331528.546797	1248331529.706055	2.527e-23	2019-07-28 06:45:27 UTC
S190727h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1248242630.976288	1248242631.985887	1248242633.180176	1.378e-10	2019-07-27 06:03:51 UTC
S190720a	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1247616533.703127	1247616534.704102	1247616535.860840	3.801e-09	2019-07-20 00:08:53 UTC
S190718y	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1247495729.067865	1247495730.067865	1247495731.067865	3.648e-08	2019-07-18 14:35:34 UTC
S190707q	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246527223.118398	1246527224.181226	1246527225.284180	5.265e-12	2019-07-07 09:33:44 UTC
S190706ai	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246487218.321541	1246487219.344727	1246487220.585938	1.901e-09	2019-07-06 22:26:57 UTC
S190701ah	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1246048403.576563	1246048404.577637	1246048405.814941	1.916e-08	2019-07-01 20:33:24 UTC
S190630ag	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1245955942.175325	1245955943.179550	1245955944.183184	1.435e-13	2019-06-30 18:52:28 UTC
S190602aq	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1243533584.081266	1243533585.089355	1243533586.346191	1.901e-09	2019-06-02 17:59:51 UTC
S190524q	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242708743.678669	1242708744.678669	1242708746.133301	6.971e-09	2019-05-24 04:52:30 UTC
S190521r	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242459856.453418	1242459857.460739	1242459858.642090	3.168e-10	2019-05-21 07:44:22 UTC
S190521g	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242442966.447266	1242442967.606934	1242442968.888184	3.801e-09	2019-05-21 03:02:49 UTC
S190519bj	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242315361.378873	1242315362.655762	1242315363.676270	5.702e-09	2019-05-19 15:36:04 UTC
S190518bb	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242242376.474609	1242242377.474609	1242242380.922655	1.004e-08	2019-05-18 19:19:39 UTC
S190517h	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1242107478.819517	1242107479.994141	1242107480.994141	2.373e-09	2019-05-17 05:51:23 UTC
S190513bm	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241816085.736106	1241816086.869141	1241816087.869141	3.734e-13	2019-05-13 20:54:48 UTC
S190512at	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241719651.411441	1241719652.416286	1241719653.518066	1.901e-09	2019-05-12 18:07:42 UTC
S190510g	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1241492396.291636	1241492397.291636	1241492398.293185	8.834e-09	2019-05-10 03:00:03 UTC
S190503bf	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240944861.288574	1240944862.412598	1240944863.422852	1.636e-09	2019-05-03 18:54:26 UTC
S190426c	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1240327332.331668	1240327333.348145	1240327334.353516	1.947e-08	2019-04-26 15:22:15 UTC
S190425z	ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1240215502.011549	1240215503.011549	1240215504.018242	4.538e-13	2019-04-25 08:18:26 UTC
S190421ar	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239917953.250977	1239917954.409180	1239917955.409180	1.489e-08	2019-04-21 21:39:16 UTC
S190412m	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1239082261.146717	1239082262.222168	1239082263.229492	1.683e-27	2019-04-12 05:31:03 UTC
S190408an	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1238782699.268296	1238782700.287958	1238782701.359863	2.811e-18	2019-04-08 18:18:27 UTC
S190405ar	ADVNO SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK	1238515307.863646	1238515308.863646	1238515309.863646	2.141e-04	2019-04-05 16:01:56 UTC

https://gracedb.ligo.org/superevents/public/O3/

Already 41 public alerts in the 3rd science run: more candidate events than O1 and O2 combined

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190822c	BNS (>99%)	Aug. 22, 2019 01:29:59 UTC	GCN Circulars Notices | VOE		1 per 5.1566e+09 years	RETRACTED
S190816i	NSBH (83%), Terrestrial (17%)	Aug. 16, 2019 13:04:31 UTC	GCN Circulars Notices | VOE		1 per 2.2067 years	RETRACTED
S190814bv	NSBH (>99%)	Aug. 14, 2019 21:10:39 UTC	GCN Circulars Notices | VOE		1 per 1.559e+25 years	
S190808ae	Terrestrial (57%), BNS (43%)	Aug. 8, 2019 22:21:21 UTC	GCN Circulars Notices | VOE		1.0622 per year	RETRACTED
S190728q	BBH (95%), MassGap (5%)	July 28, 2019 06:45:10 UTC	GCN Circulars Notices | VOE		1 per 1.2541e+15 years	
S190727h	BBH (92%), Terrestrial (5%), MassGap (3%)	July 27, 2019 06:03:33 UTC	GCN Circulars Notices | VOE		1 per 229.92 years	
S190720a	BBH (99%), Terrestrial (1%)	July 20, 2019 00:08:36 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190718y	Terrestrial (98%), BNS (2%)	July 18, 2019 14:35:12 UTC	GCN Circulars Notices | VOE		1.1514 per year	
S190707q	BBH (>99%)	July 7, 2019 09:33:26 UTC	GCN Circulars Notices | VOE		1 per 6018.9 years	
S190706ai	BBH (99%), Terrestrial (1%)	July 6, 2019 22:26:41 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190701ah	BBH (93%), Terrestrial (7%)	July 1, 2019 20:33:06 UTC	GCN Circulars Notices | VOE		1 per 1.6543 years	
S190630ag	BBH (94%), MassGap (5%)	June 30, 2019 18:52:05 UTC	GCN Circulars Notices | VOE		1 per 2.2077e+05 years	
S190602aq	BBH (99%)	June 2, 2019 17:59:27 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190524q	Terrestrial (71%), BNS (29%)	May 24, 2019 04:52:06 UTC	GCN Circulars Notices | VOE		1 per 4.5458 years	RETRACTED
S190521r	BBH (>99%)	May 21, 2019 07:43:59 UTC	GCN Circulars Notices | VOE		1 per 100.04 years	
S190521g	BBH (97%), Terrestrial (3%)	May 21, 2019 03:02:29 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190519bj	BBH (96%), Terrestrial (4%)	May 19, 2019 15:35:44 UTC	GCN Circulars Notices | VOE		1 per 5.5578 years	
S190518bb	BNS (75%), Terrestrial (25%)	May 18, 2019 19:19:19 UTC	GCN Circulars Notices | VOE		1 per 3.1557 years	RETRACTED
S190517h	BBH (98%), MassGap (2%)	May 17, 2019 05:51:01 UTC	GCN Circulars Notices | VOE		1 per 13.354 years	
S190513bm	BBH (94%), MassGap (5%)	May 13, 2019 20:54:28 UTC	GCN Circulars Notices | VOE		1 per 84864 years	
S190512at	BBH (99%), Terrestrial (1%)	May 12, 2019 18:07:14 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190510g	Terrestrial (58%), BNS (42%)	May 10, 2019 02:59:39 UTC	GCN Circulars Notices | VOE		1 per 3.5872 years	
S190503bf	BBH (96%), MassGap (3%)	May 3, 2019 18:54:04 UTC	GCN Circulars Notices | VOE		1 per 19.368 years	
S190426c	BNS (49%), MassGap (24%), Terrestrial (14%), NSBH (13%)	April 26, 2019 15:21:55 UTC	GCN Circulars Notices | VOE		1 per 1.6276 years	
S190425z	BNS (>99%)	April 25, 2019 08:18:05 UTC	GCN Circulars Notices | VOE		1 per 69834 years	
S190421ar	BBH (97%), Terrestrial (3%)	April 21, 2019 21:38:56 UTC	GCN Circulars Notices | VOE		1 per 2.1285 years	
S190412m	BBH (>99%)	April 12, 2019 05:30:44 UTC	GCN Circulars Notices | VOE		1 per 1.883e+19 years	
S190408an	BBH (>99%)	April 8, 2019 18:18:02 UTC	GCN Circulars Notices | VOE		1 per 1.1273e+10 years	
S190405ar	Terrestrial (>99%)	April 5, 2019 16:01:30 UTC	GCN Circulars Notices | VOE		6756.4 per year	IMPORTANT: this trigger (S190405ar) is not considered to be astrophysical in o issued but the event ID was truncated to S190405a due to a bug. RETRACTED

https://gracedb.ligo.org/superevents/public/O3/

Black holes are now seen at distances up to 3.9 - 6.7 Gpc (redshift 0.9 - 1.6)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments

RETRACTED
Terrestial noise

NSBH (99%)

RETRACTED

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190728q	BBH (95%), MassGap (5%)	July 28, 2019 06:45:10 UTC	GCN Circulars Notices | VOE		1 per 1.2541e+15 years	
S190727h	BBH (92%), Terrestrial (5%), MassGap (3%)	July 27, 2019 06:03:33 UTC	GCN Circulars Notices | VOE		1 per 229.92 years	
S190720a	BBH (99%), Terrestrial (1%)	July 20, 2019 00:08:36 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190718y	Terrestrial (98%), BNS (2%)	July 18, 2019 14:35:12 UTC	GCN Circulars Notices | VOE		1.1514 per year	
S190707q	BBH (>99%)	July 7, 2019 09:33:26 UTC	GCN Circulars Notices | VOE		1 per 6018.9 years	

BBH (99%) at 0.9 < z < 1.6

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190701ah	BBH (93%), Terrestrial (7%)	July 1, 2019 20:33:06 UTC	GCN Circulars Notices | VOE		1 per 1.6543 years	
S190630ag	BBH (94%), MassGap (5%)	June 30, 2019 18:52:05 UTC	GCN Circulars Notices | VOE		1 per 2.2077e+05 years	
S190602aq	BBH (99%)	June 2, 2019 17:59:27 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	

RETRACTED

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190521r	BBH (>99%)	May 21, 2019 07:43:59 UTC	GCN Circulars Notices | VOE		1 per 100.04 years	
S190521g	BBH (97%), Terrestrial (3%)	May 21, 2019 03:02:29 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190519bj	BBH (96%), Terrestrial (4%)	May 19, 2019 15:35:44 UTC	GCN Circulars Notices | VOE		1 per 5.5578 years	

RETRACTED

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190517h	BBH (98%), MassGap (2%)	May 17, 2019 05:51:01 UTC	GCN Circulars Notices | VOE		1 per 13.354 years	
S190513bm	BBH (94%), MassGap (5%)	May 13, 2019 20:54:28 UTC	GCN Circulars Notices | VOE		1 per 84864 years	
S190512at	BBH (99%), Terrestrial (1%)	May 12, 2019 18:07:14 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	

BNS (42%) TERRESTIAL (58%)

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190503bf	BBH (96%), MassGap (3%)	May 3, 2019 18:54:04 UTC	GCN Circulars Notices | VOE		1 per 19.368 years	

BNS (49%) NSBH (13%) M GAP (24%)

BNS (99%)

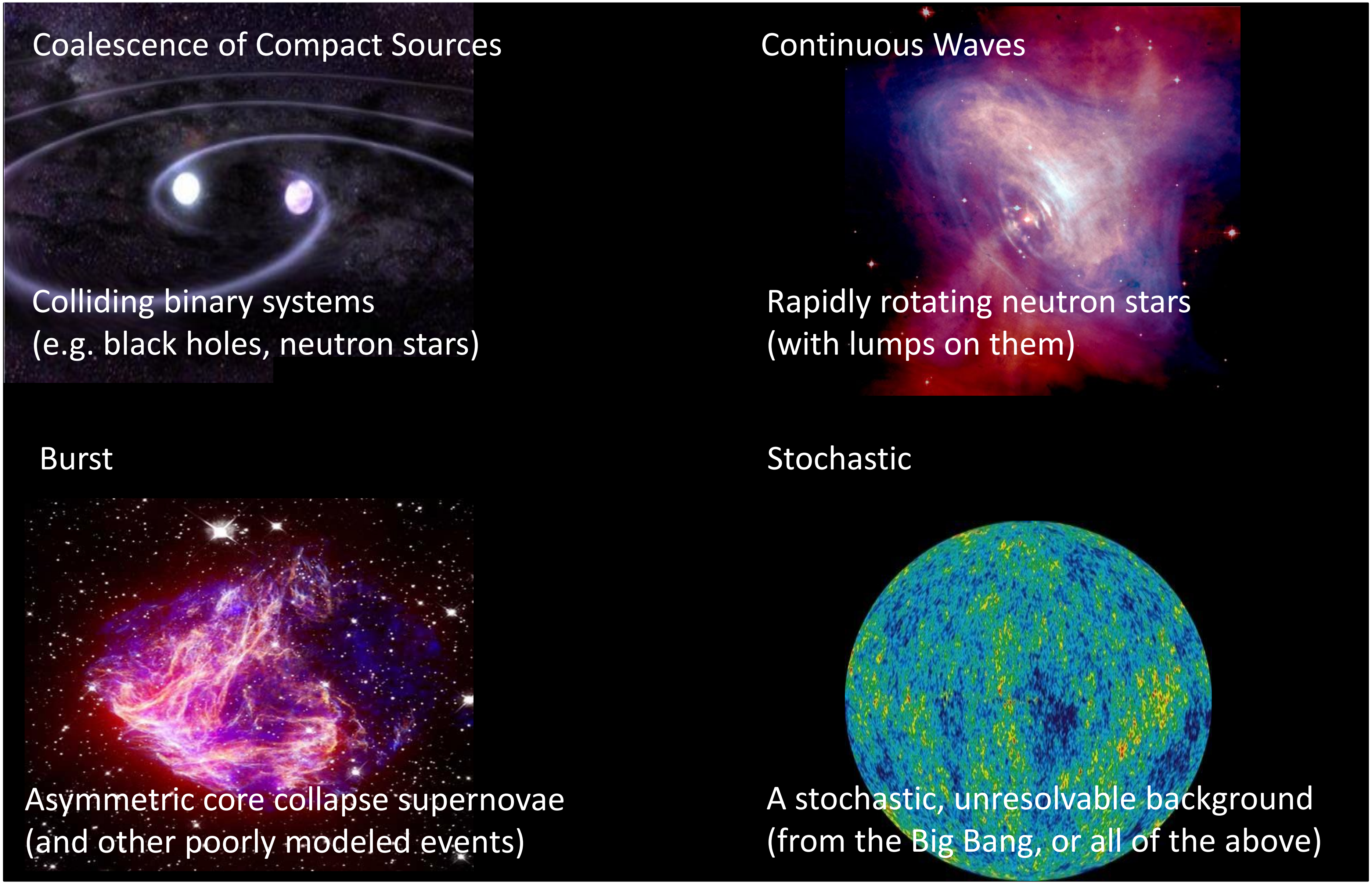
Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190421ar	BBH (97%), Terrestrial (3%)	April 21, 2019 21:38:56 UTC	GCN Circulars Notices | VOE		1 per 2.1285 years	
S190412m	BBH (>99%)	April 12, 2019 05:30:44 UTC	GCN Circulars Notices | VOE		1 per 1.883e+19 years	
S190408an	BBH (>99%)	April 8, 2019 18:18:02 UTC	GCN Circulars Notices | VOE		1 per 1.1273e+10 years	

RETRACTED

(S190405ar) is not considered to be astrophysical in o
as truncated to S190405a due to a bug. RETRACTED

LIGO-Virgo analyses for sources of gravitational waves

Sources can be transient or of continuous nature, and can be modeled or unmodeled



Continuous Waves

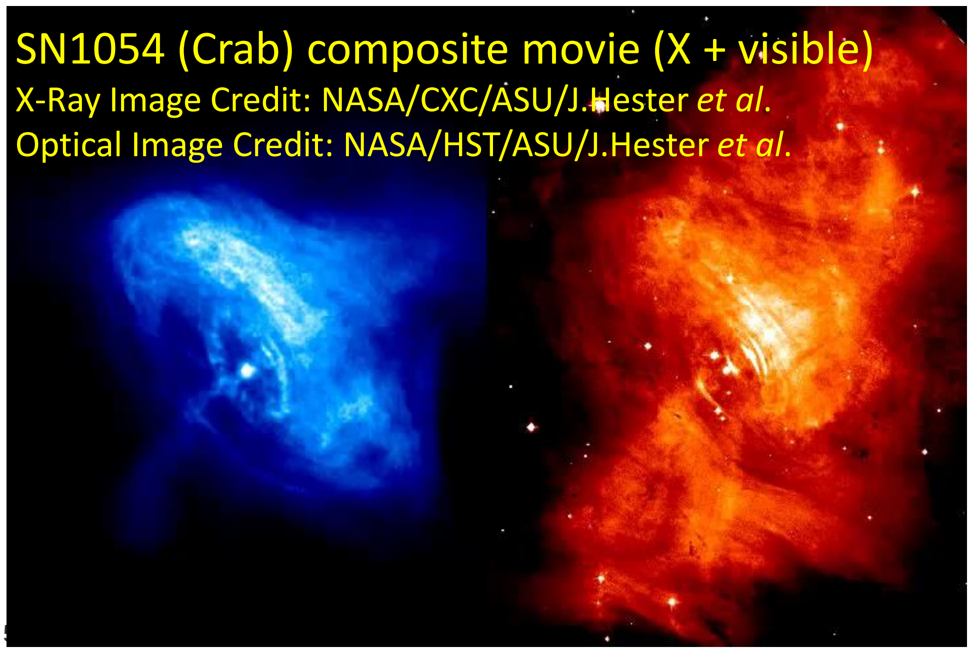
Astrophysics

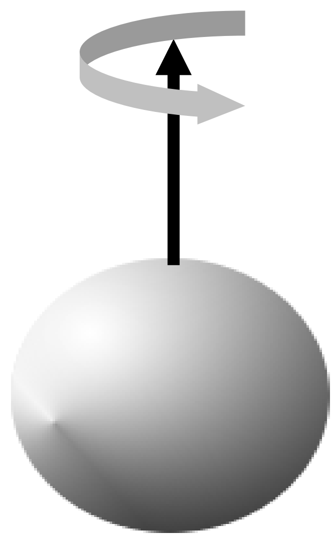
More than 2500 observed NSs (mostly pulsars) and O(10^8 –10^9) expected to exist in our galaxy
Sources must have some degree of non-axisymmetry originating from

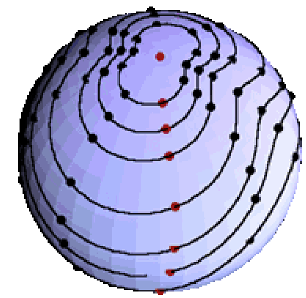
- deformation due to elastic stresses or magnetic field not aligned to the rotation axis ($f_{GW} = 2f_r$)
- free precession around rotation axis ($f_{GW} \sim f_{rot} + f_{prec}$; $f_{GW} \sim 2f_{rot} + 2f_{prec}$)
- excitation of long-lasting oscillations (e.g. *r*-modes; $f_{GW} \sim 4f_r/3$)
- deformation due to matter accretion (e.g. LMXB; $f_{GW} \sim 2f_r$)

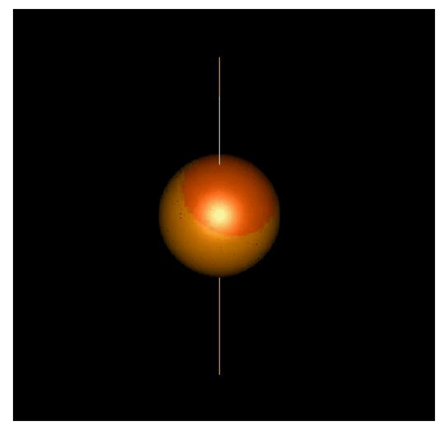
Source characteristics

Emission of quasi-monochromatic waves with a slowly decreasing intrinsic frequency
Constant amplitude, but weak, and persistent over years of data taking









Continuous Waves analysis

Types of Continuous Waves searches

- Targeted searches: observed NSs with known source parameters as sky location, frequency & frequency derivatives (e.g. the Crab and Vela pulsars)
- Narrowband searches: observed NSs with uncertainties in rotational parameters. A small mismatch between the GW frequency (spindown) and the rotational star frequency (spindown) inferred from EM observations needs to be taken into account
- Directed searches: sky location is known while frequency and frequency derivatives are unknown (e.g. Cassiopeia A, SN1987A, Scorpius X-1, galactic center, globular clusters)
- All-sky searches: unknown pulsars => computing challenge (Einstein@Home – Cloud – Grid)

Papers

- First search for gravitational waves from known pulsars (LVC, ApJ 839, 12, 2017)
  - Analyzed 200 known pulsars (119 out of 200 are in binary systems)
  - Spindown limit beaten for 8 pulsars, including both Crab & Vela: For the Crab and Vela pulsars less than 2x10-3 and 10-2 of the spindown luminosity is being lost via GWs, respectively
- Narrowband search: LVC, PRD 96, 122006 (2017)
- Directed searches from Scorpius-X1 (LVC 2017: PRD 95, 122003; ApJ 847, 47, PRL 118, 121102)
- All-sky searches up to high frequencies (LVC, PRD 97, 102003, 2018)
- All-sky searches at low frequencies LVC, PRD 96, 122004, 2018)
- Search for non-tensorial polarizations (LVC, PRL 120, 031104, 2018)

Still to come: O2 results from targeted, narrowband, directed and all-sky searches

- See https://galaxy.ligo.caltech.edu/svn/cw/public/index.html

Stochastic GW Background

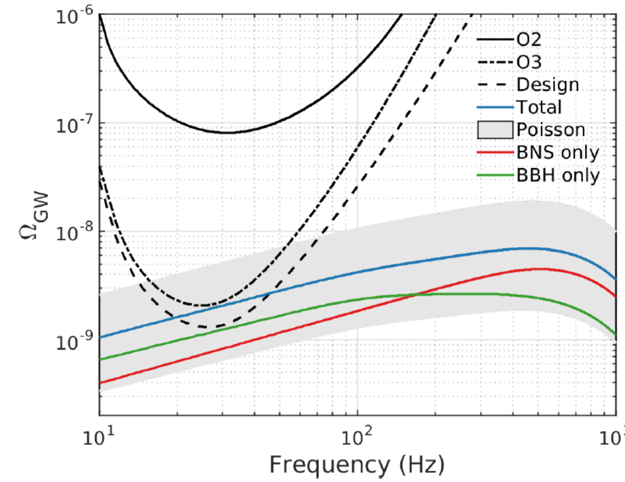
A stochastic background of gravitational waves has resulted from the superposition of a large number of independent unresolved sources from different stages in the evolution of the Universe

Astrophysical SGWB

All the sources since the beginning of stellar activity
Dominated by compact binary coalescences: BBHs, BNSs, BH-NSs

LIGO and Virgo have already published 10 BBHs and 1 BNS
Events are individual sources at z~0.07-0.2 for BBHs, 0.01 for BNS

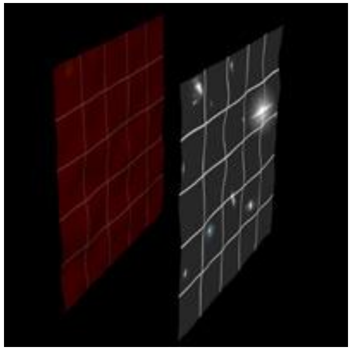
Many individual sources at larger distances that contribute to SGWB
This could be the next milestone for LIGO/Virgo

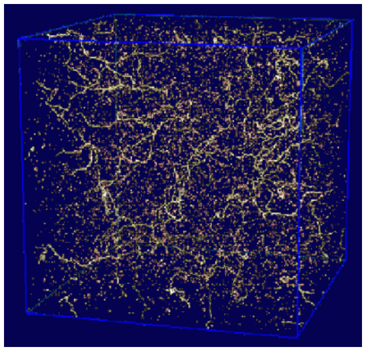


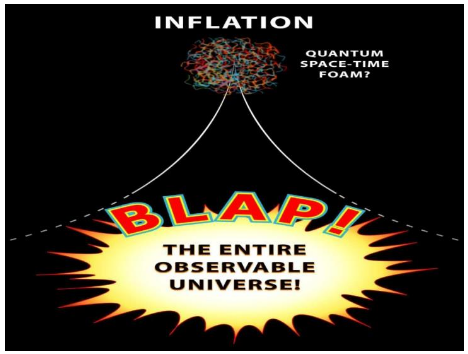
Abbott et al. PRL120.091101, 2017

Cosmological SGWB

Signatures of the early Universe
Inflation, cosmic strings, no phase transition in LIGO/Virgo







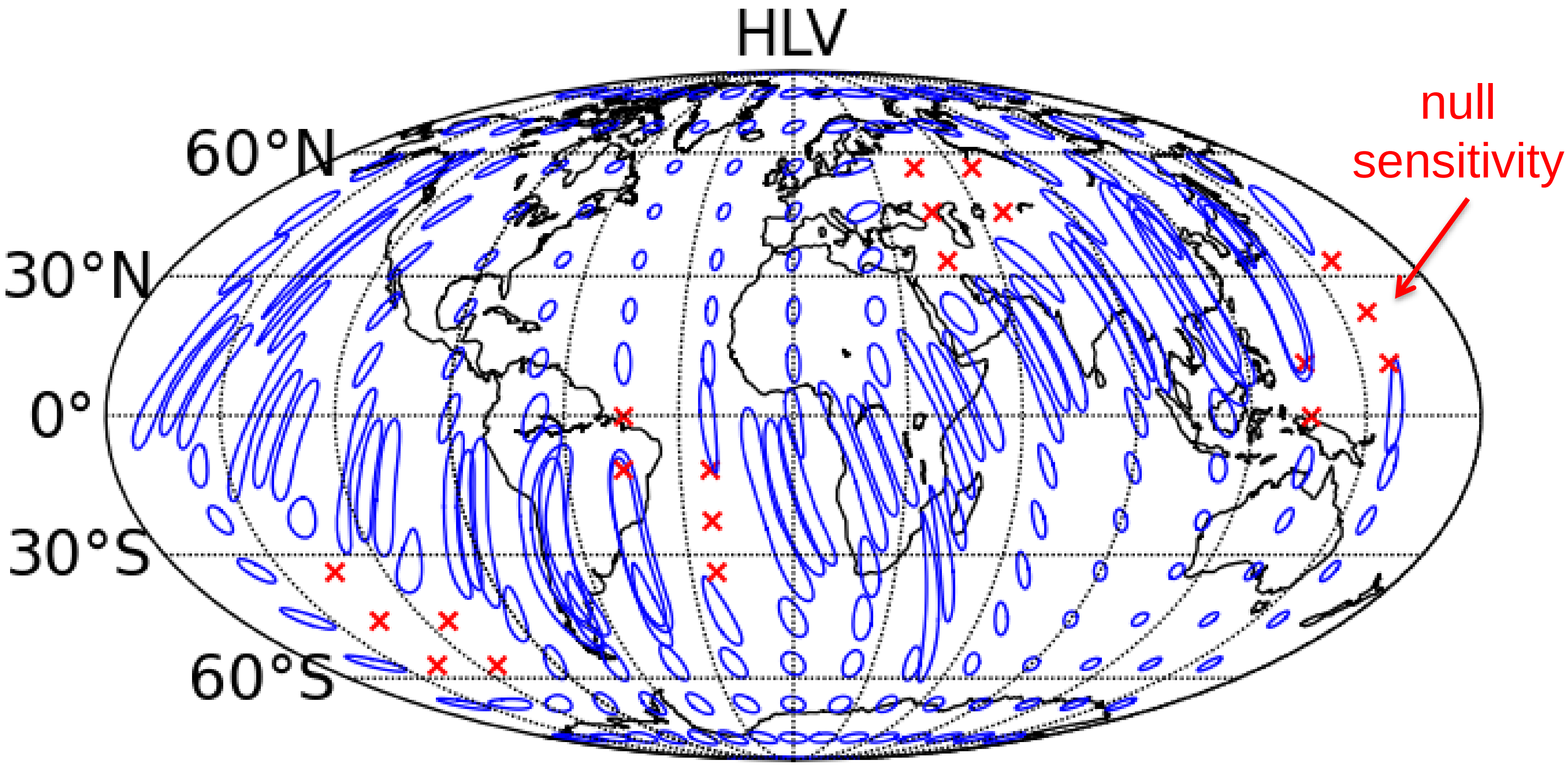
Towards a global network

Global GW Detector Network

- Current state-of-the-art: Second-generation ("advanced") laser interferometers

Sky localization c. 2016 – 17 (LIGO + Virgo)

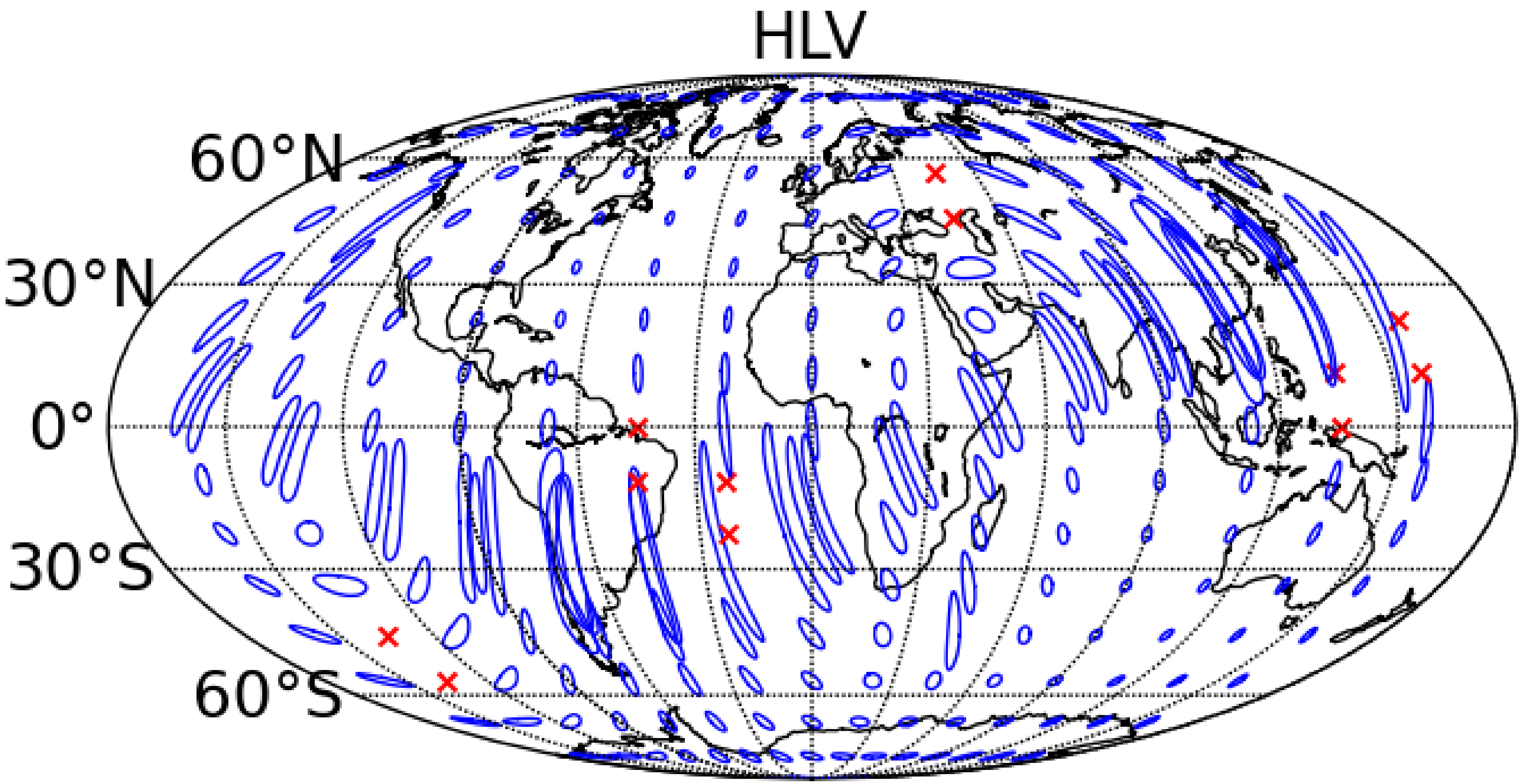
Schematic 90% error box areas for NS-NS binaries
Abbott et al., Living Rev. Relativity 19 (2016), 1



Sky localization c. 2019+ (design sensitivity)

Schematic 90% error box areas for NS-NS binaries

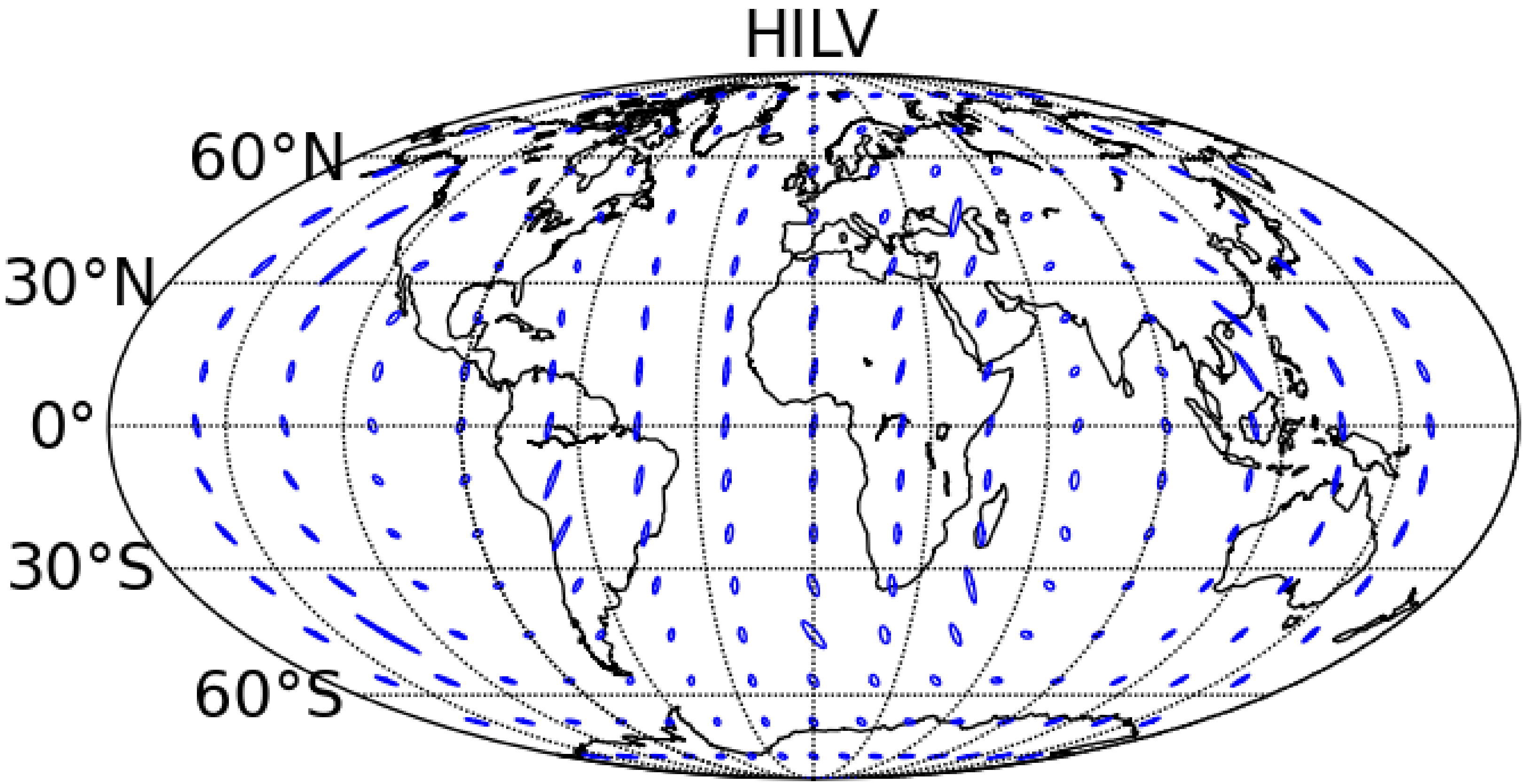
Abbott et al., Living Rev. Relativity 19 (2016), 1



Sky localization c. 2023+ (+ LIGO – India/KAGRA)

A global GW detector network is needed for MMA

Abbott et al., Living Rev. Relativity 19 (2016), 1



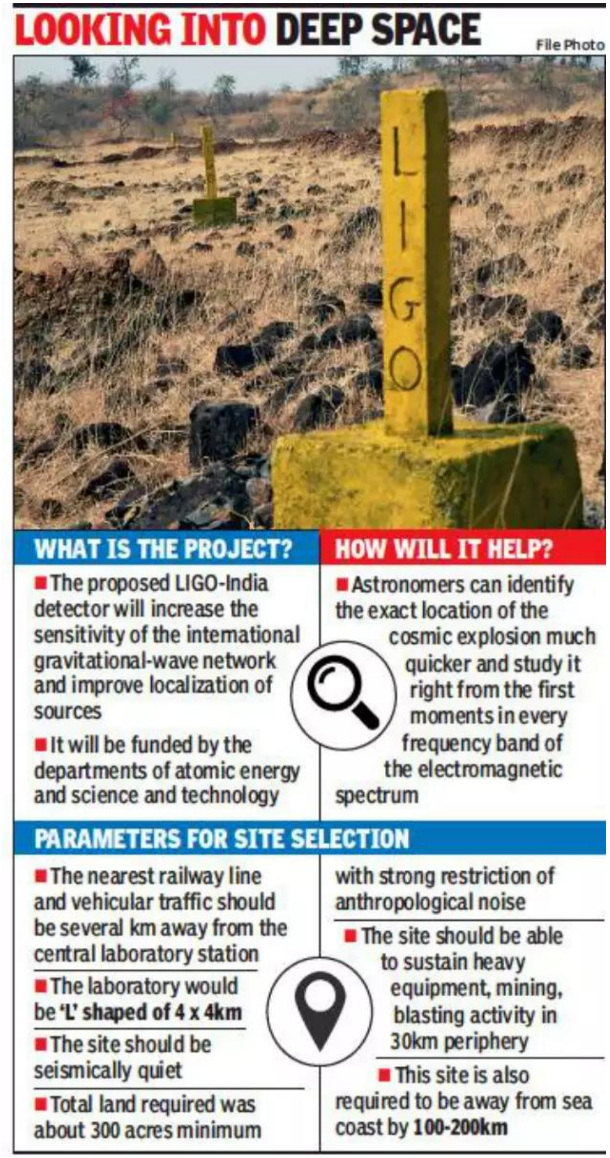
KAGRA inauguration

Signing of the MOA with LIGO and VIRGO
Toyama, October 4, 2019


KAGRA
TOSHIBA
KEK
ICRR

LIGO-India: construction has started (online 2024?)

The 4 km interferometer will be sited at Hingoli in Maharashtra, about 450 km from Pune



LOOKING INTO DEEP SPACE

File Photo

WHAT IS THE PROJECT?

- The proposed LIGO-India detector will increase the sensitivity of the international gravitational-wave network and improve localization of sources
- It will be funded by the departments of atomic energy and science and technology

HOW WILL IT HELP?

- Astronomers can identify the exact location of the cosmic explosion much quicker and study it right from the first moments in every frequency band of the electromagnetic spectrum

PARAMETERS FOR SITE SELECTION

- The nearest railway line and vehicular traffic should be several km away from the central laboratory station
- The laboratory would be **'L' shaped of 4 x 4km**
- The site should be seismically quiet
- Total land required was about 300 acres minimum with strong restriction of anthropological noise
- The site should be able to sustain heavy equipment, mining, blasting activity in 30km periphery
- This site is also required to be away from sea coast by **100-200km**

What’s next?

AdV+ and A+ as the next steps forward in sensitivity

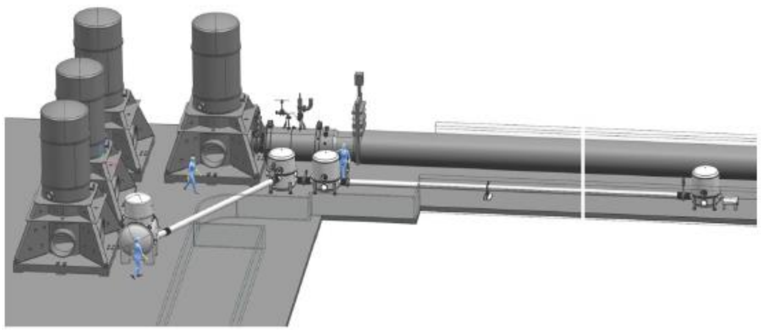
AdV+ is the European plan to maximize Virgo’s sensitivity within the constrains of the EGO site. It will be carried out in parallel with the LIGO A+ upgrade

AdV+ features

- Maximize science
- Secure Virgo’s scientific relevance
- Safeguard investments by scientists and funding agencies
- Implement new innovative technologies
- De-risk technologies needed for third generation observatories
- Attract new groups wanting to enter the field

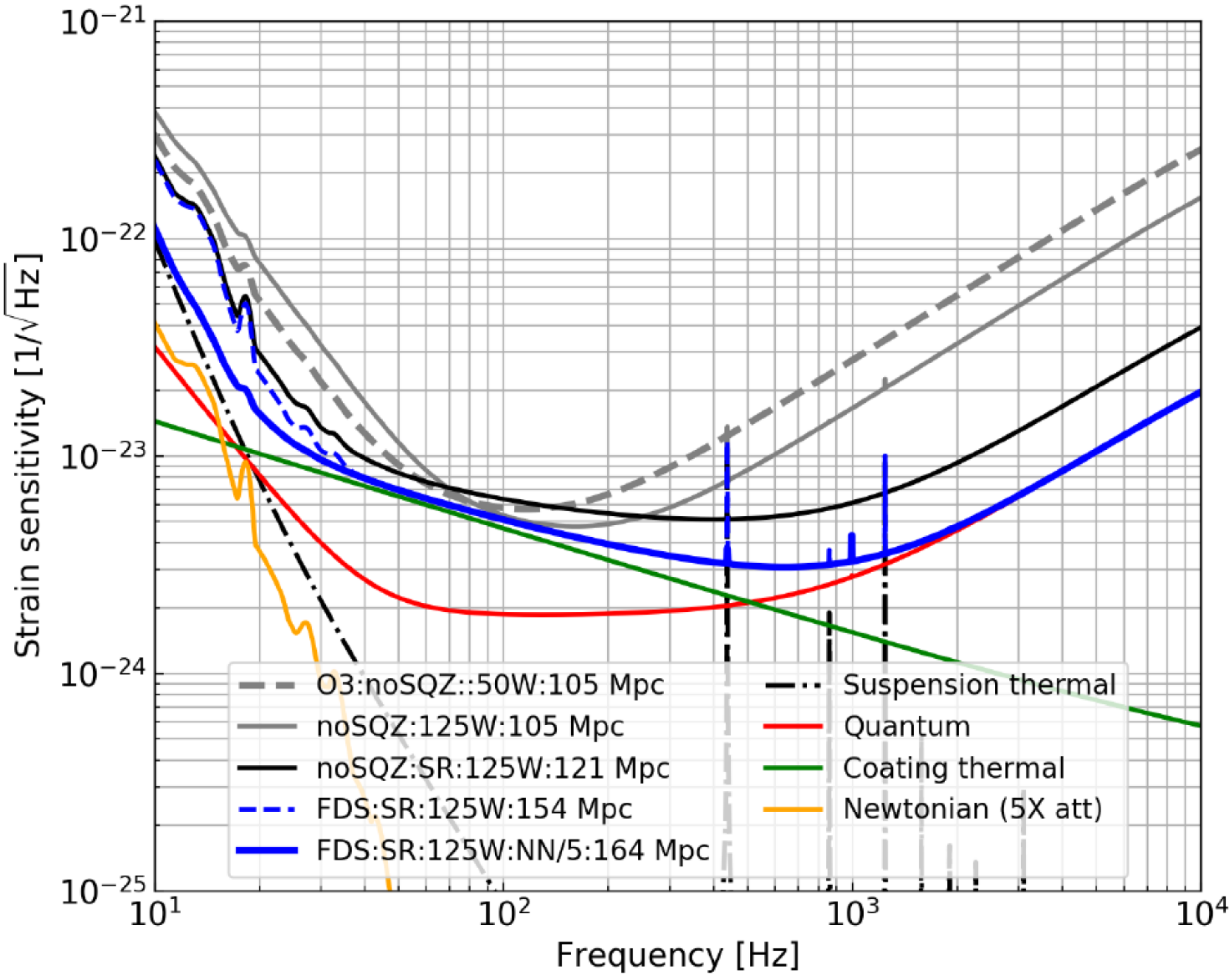
Upgrade activities

- Tuned signal recycling and HPL: 120 Mpc
- Frequency dependent squeezing: 150 Mpc
- Newtonian noise cancellation: 160 Mpc
- Larger mirrors (105 kg): 200-230 Mpc
- Improved coatings: 260-300 Mpc



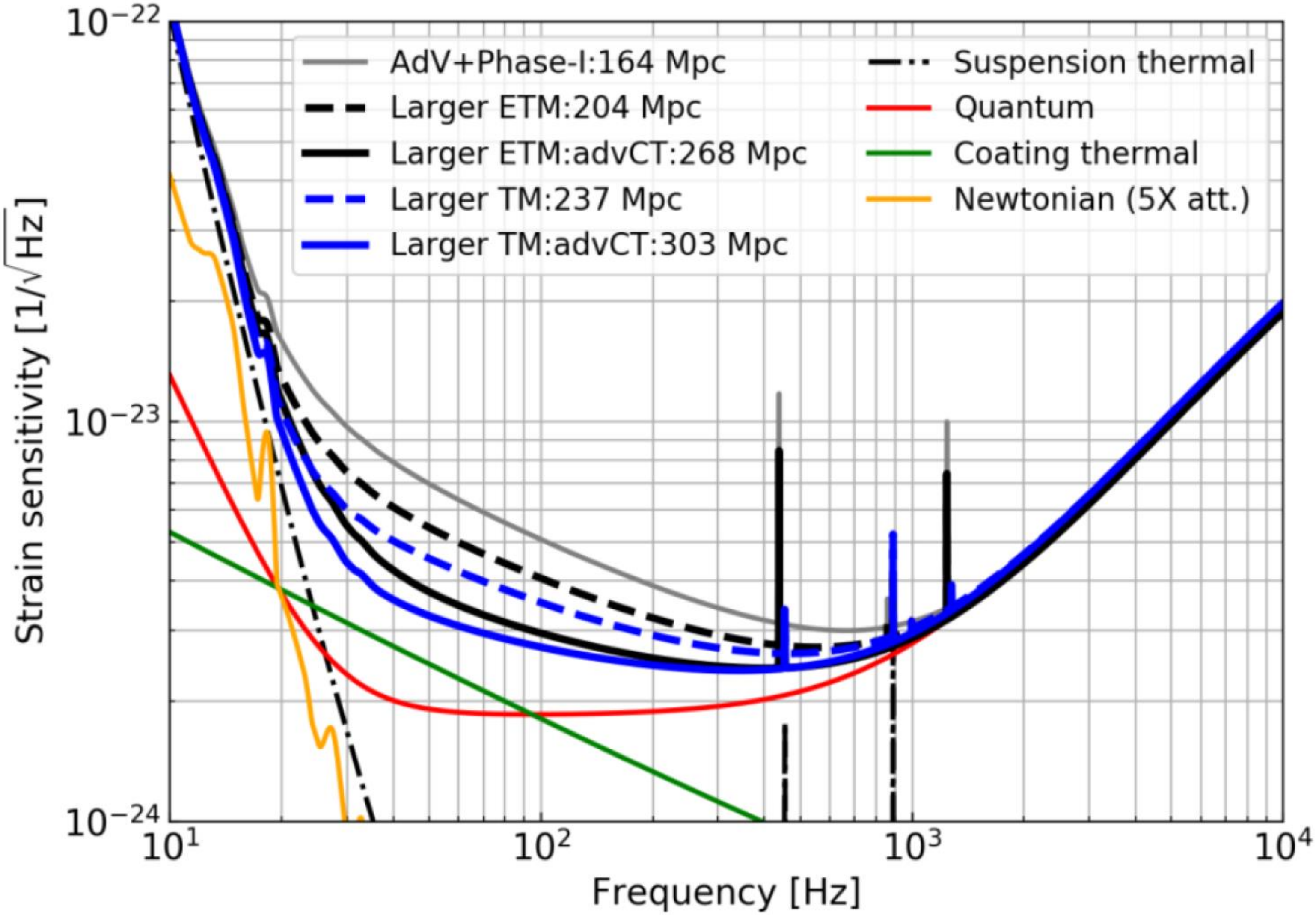
AdV+ Phase 1: reaching the thermal noise wall

Increase laser power, implement signal recycling, frequency dependent squeezing and Newtonian noise suppression



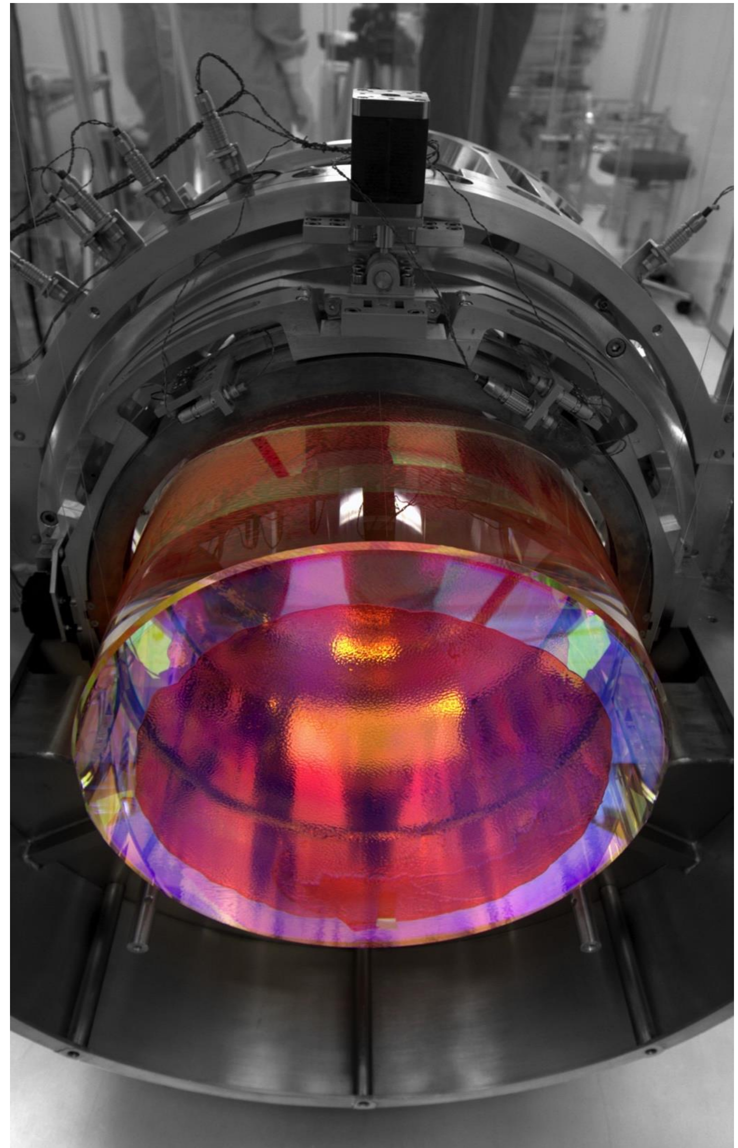
AdV+ Phase 2: pushing the thermal noise wall down

Implement larger ETMs and employ better coatings
Part of Phase 2 deserves a timely start to avoid significant delay



AdV+ upgrade and extreme mirror technology

Laboratoire des Matériaux Avancés LMA at Lyon produced the coatings used on the main mirrors of the two working gravitational wave detectors: Advanced LIGO and Virgo. These coatings feature low losses, low absorption, and low scattering properties



Features

- Flatness < 0.5 nm rms over central 160 mm of mirrors by using ion beam polishing (robotic silica deposition was investigated)
- Ti:Ta_2O_5 and SiO_2 stacks with optical absorption about 0.3 ppm

Expand LMA capabilities for next generation

LMA is the only coating group known to be capable of scaling up

Lasers, quantum optics. Also controls: ML and deep learning

Ultra-stable laser systems. Not only 1 um, but also 1.55 and 2 um under investigation

Virgo squeezer from AEI

Squeezing results

Target of the squeezing project has been reached: Virgo is ready to take advantage of the injection of squeezed light in AdV during O3

Squeezing results

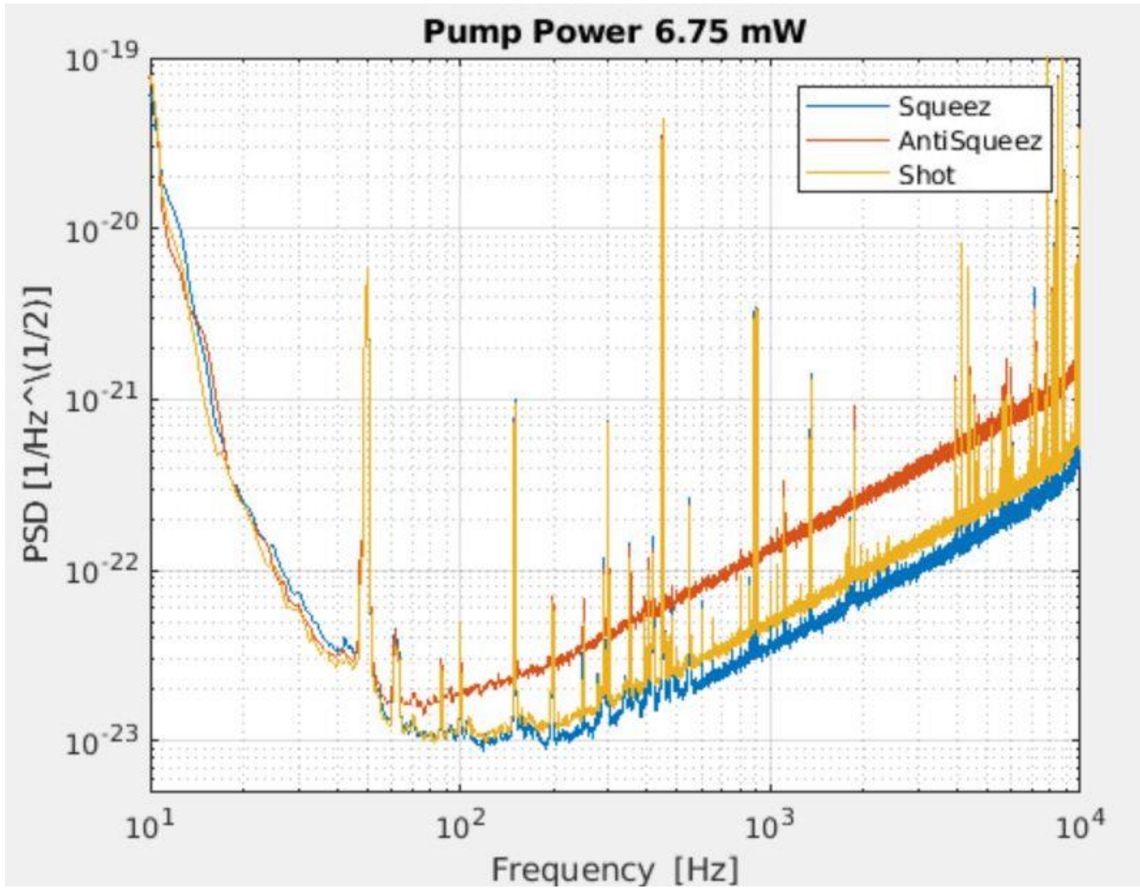
Best present value of the high frequency sensitivity gain is about 3 dB

Maximum increase of the BNS range is achieved when the HF gain is kept to about 2.5-2.7 dB (injecting less squeezing)

Limits

Currently optical losses about 43%

Losses will decrease by about 10% due to newly installed high-QE PDs



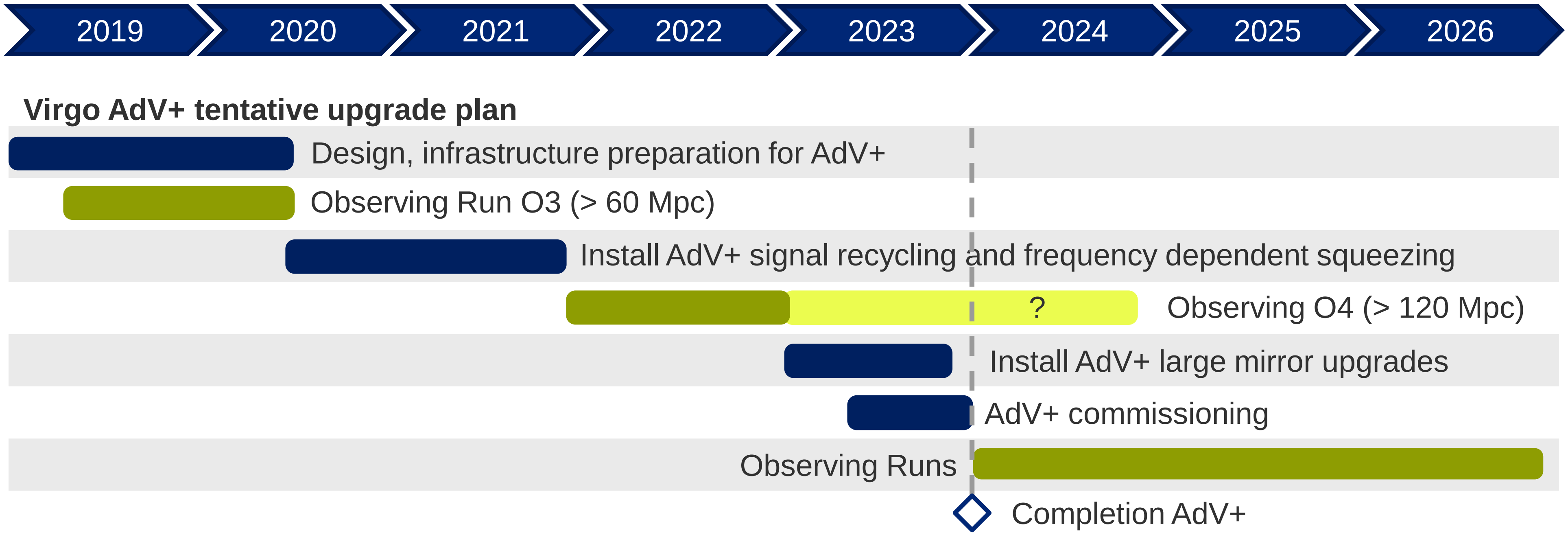
Newtonian noise subtraction

Test sensor array installed at WE and measurements were carried out

Off-line data analysis in progress
Tune seismic noise model by using the data

Scheduling of science runs, AdV+ installation and commissioning

Five year plan for observational runs, commissioning and upgrades



Commissioning break in October 2019

Duration of O3: until the end of April 2020 (duration of O4 has not been decided)

Break between O3 and O4 probably around 18 months (allow installation and commissioning)

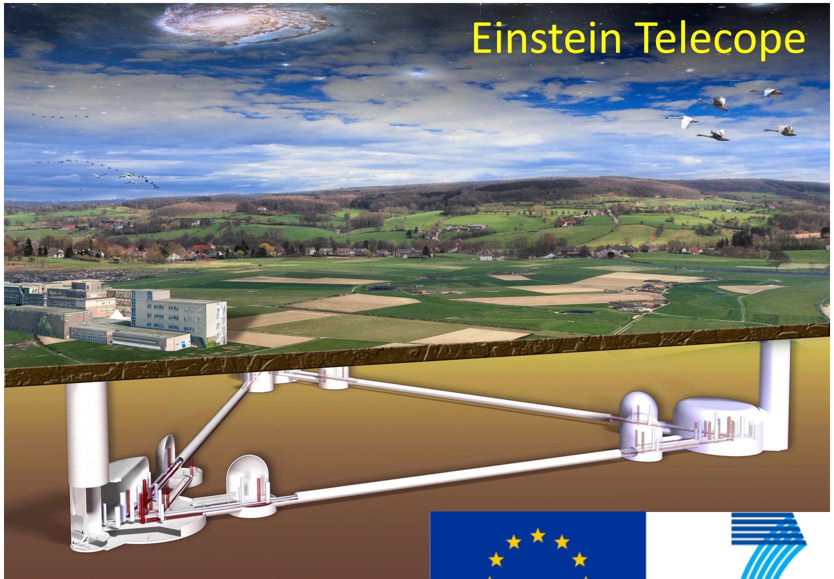
AdV+ to be carried out in parallel with LIGO's A+ upgrade

AdV+ is part of a strategy to go from 2nd generation to Einstein Telescope

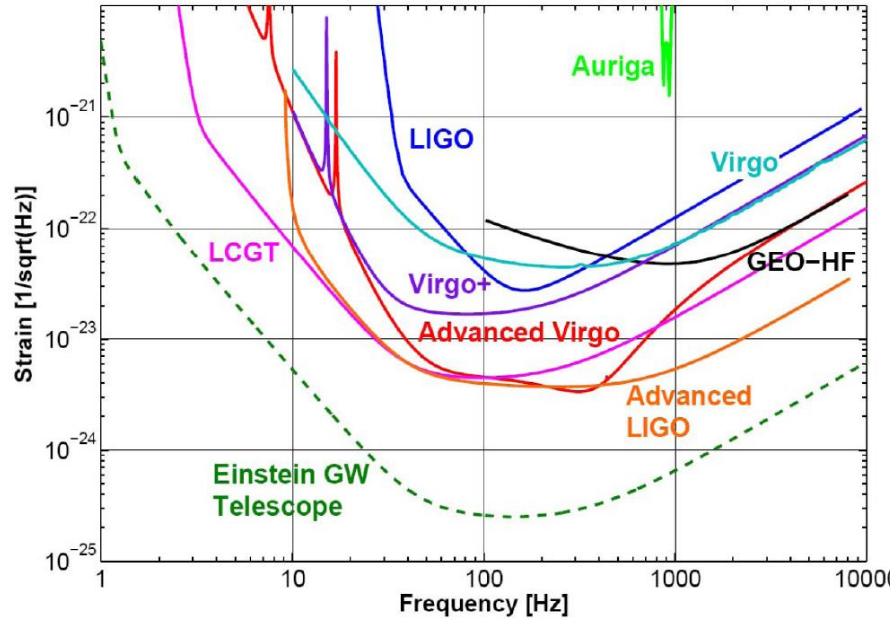
Third generation GW detectors

Einstein Telescope and Cosmic Explorer

Realizing the next gravitational wave observatories is a coordinated effort with US to create a worldwide 3G network

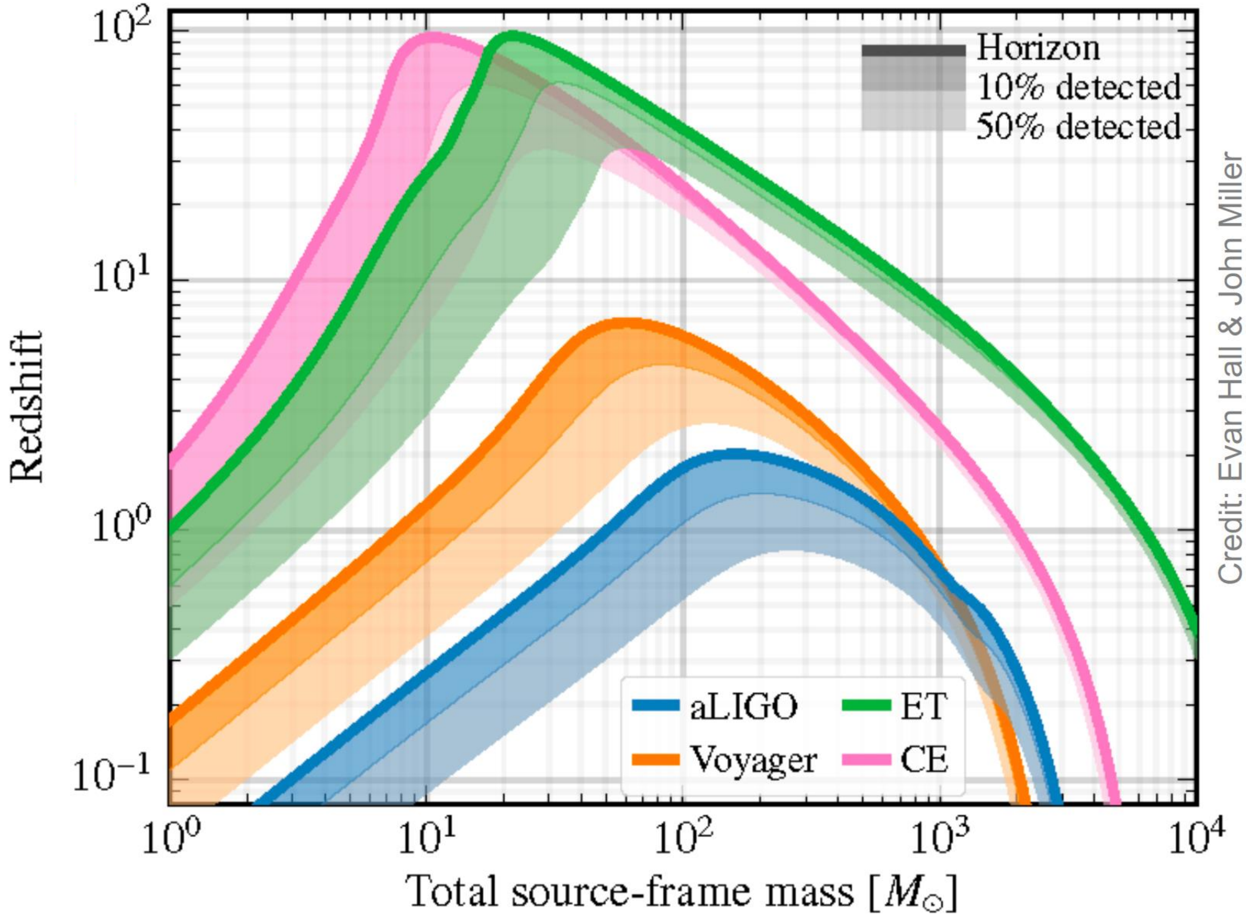


SEVENTH FRAMEWORK PROGRAMME



Einstein Telescope and Cosmic Explorer

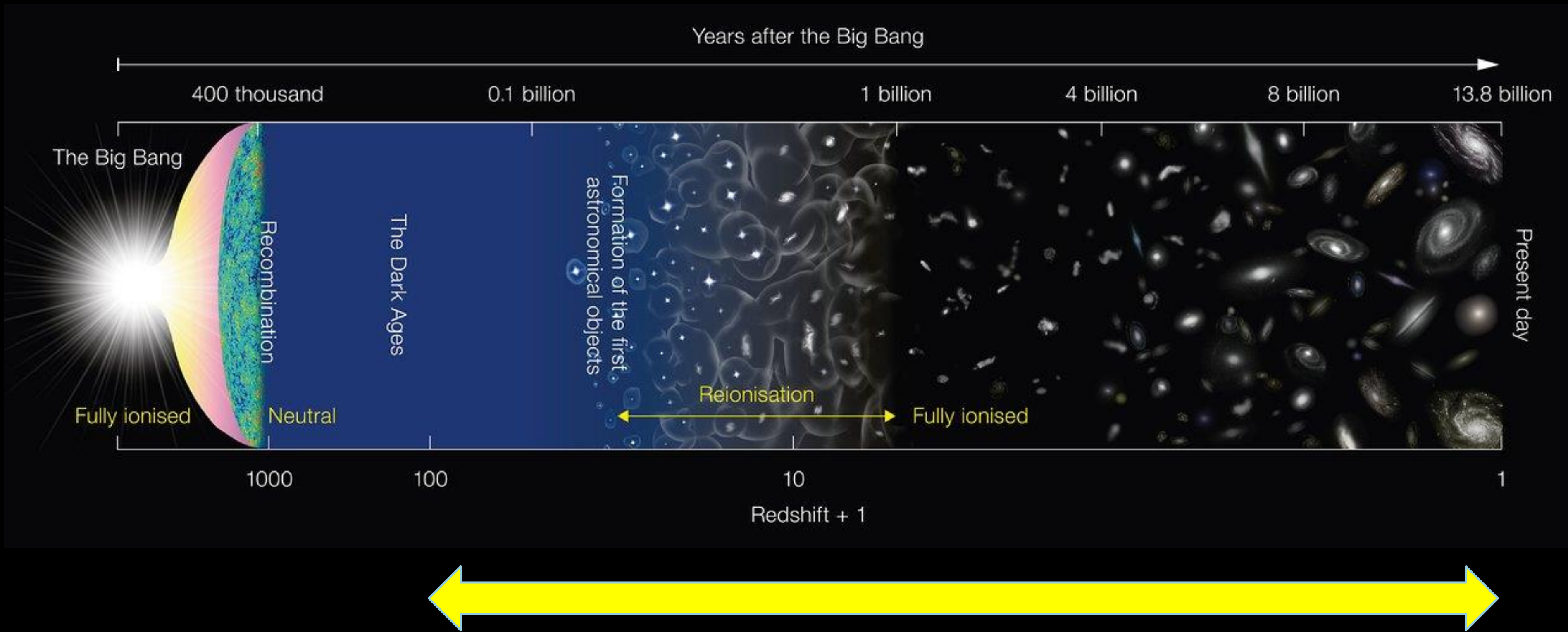
Einstein Telescope will feature excellent low-frequency sensitivity and have great discovery potential



For science case, see https://www.dropbox.com/s/gihpzcue4qd92dt/science-case.pdf?dl=0

Einstein Telescope

Einstein Telescope can observe BBH mergers to red shifts of about 100. This allows a new approach to cosmography. Study primordial black holes, BH from population III stars (first metal producers), *etc*.



Einstein Telescope has direct access to signals from black hole mergers in this range

Einstein Telescope

Einstein Telescope can observe BBH mergers to a redshift more than 20. This allows a new approach to cosmography. Study primordial black holes, BH from population III stars (first metal producers), *etc*.

Einstein Telescope

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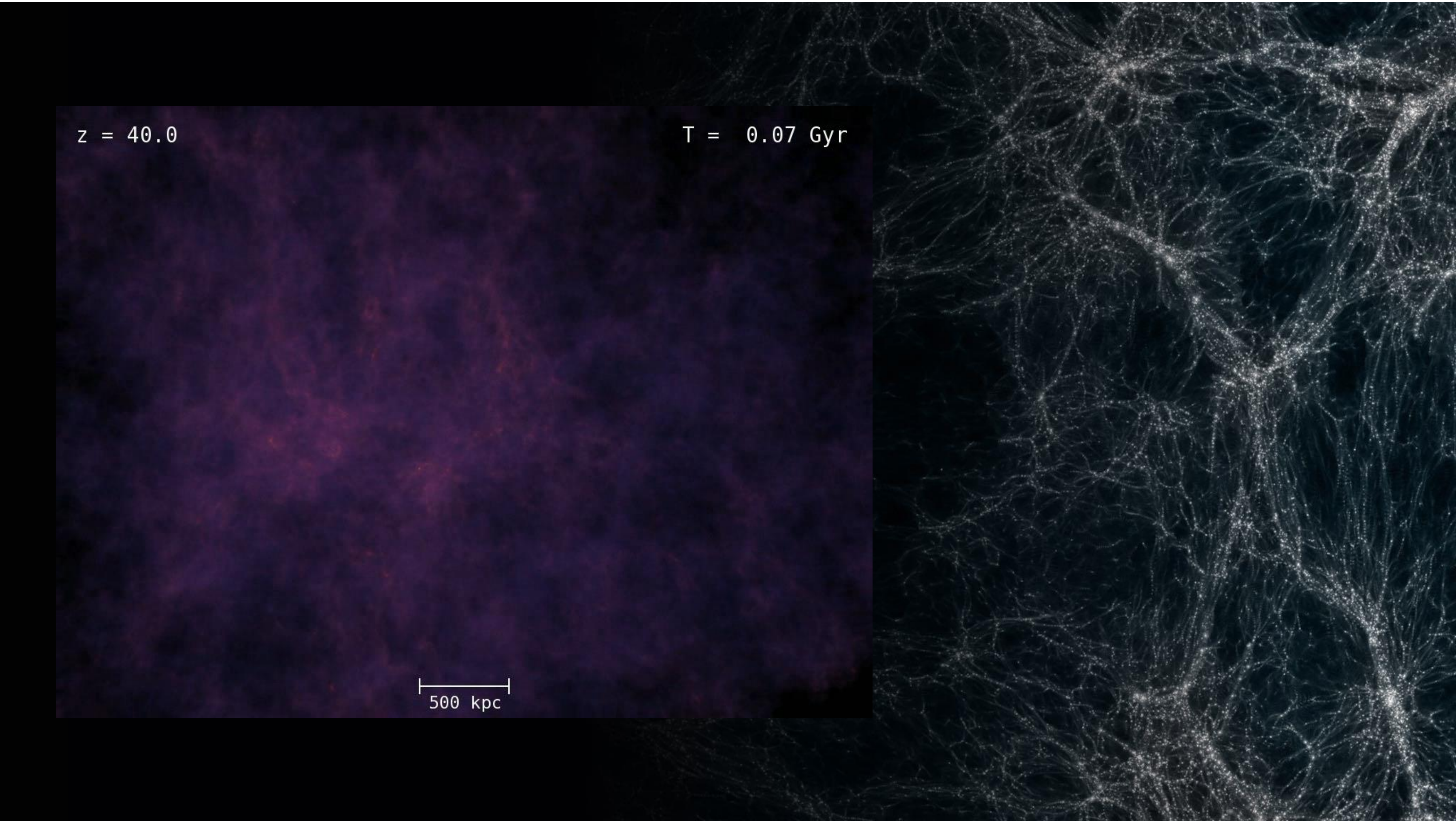
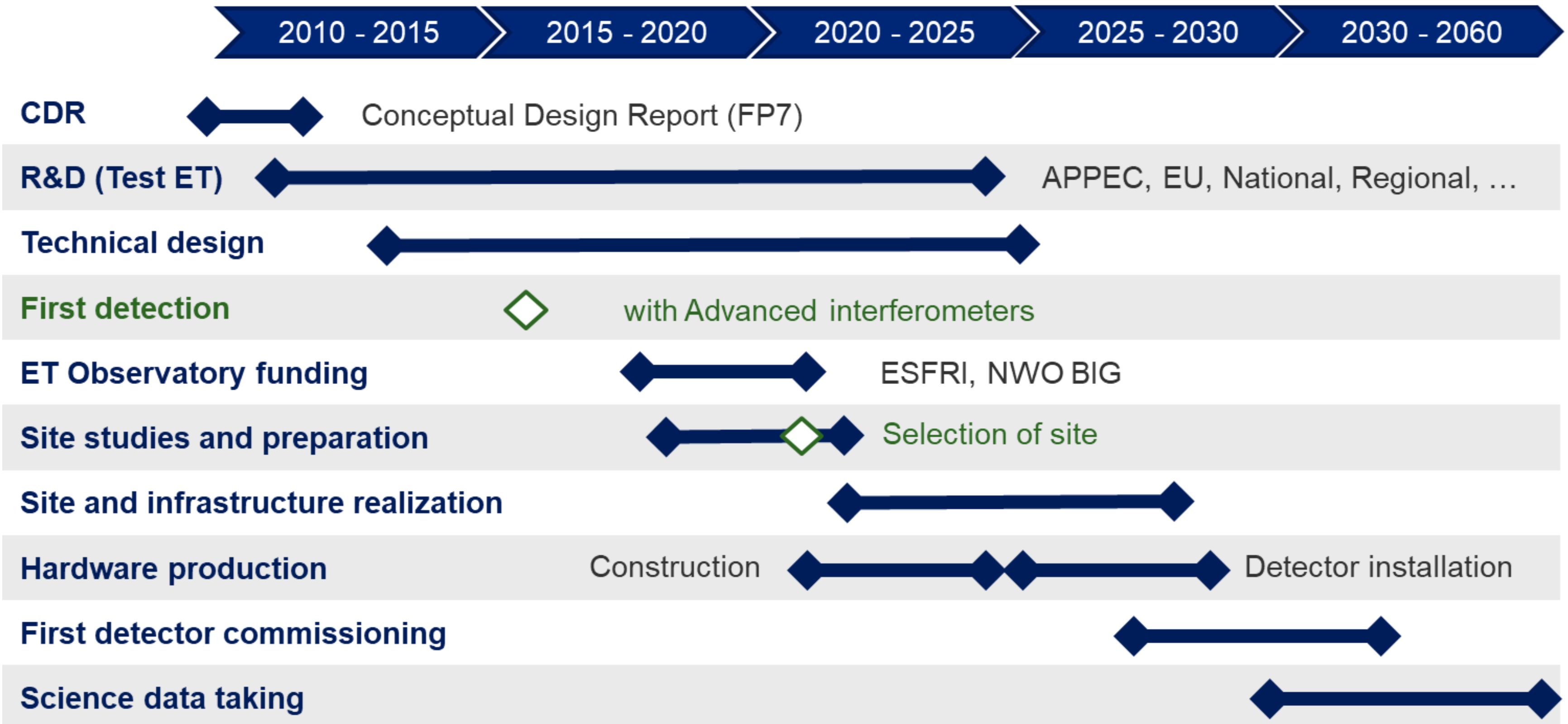
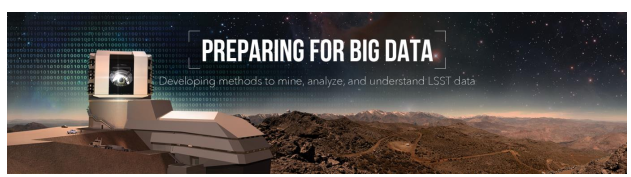


Einstein Telescope: an infrastructure for 50 to 100 years

ET will study events from the entire Universe. Gravitational waves will become a common tool just like conventional astronomy has been for the last four centuries





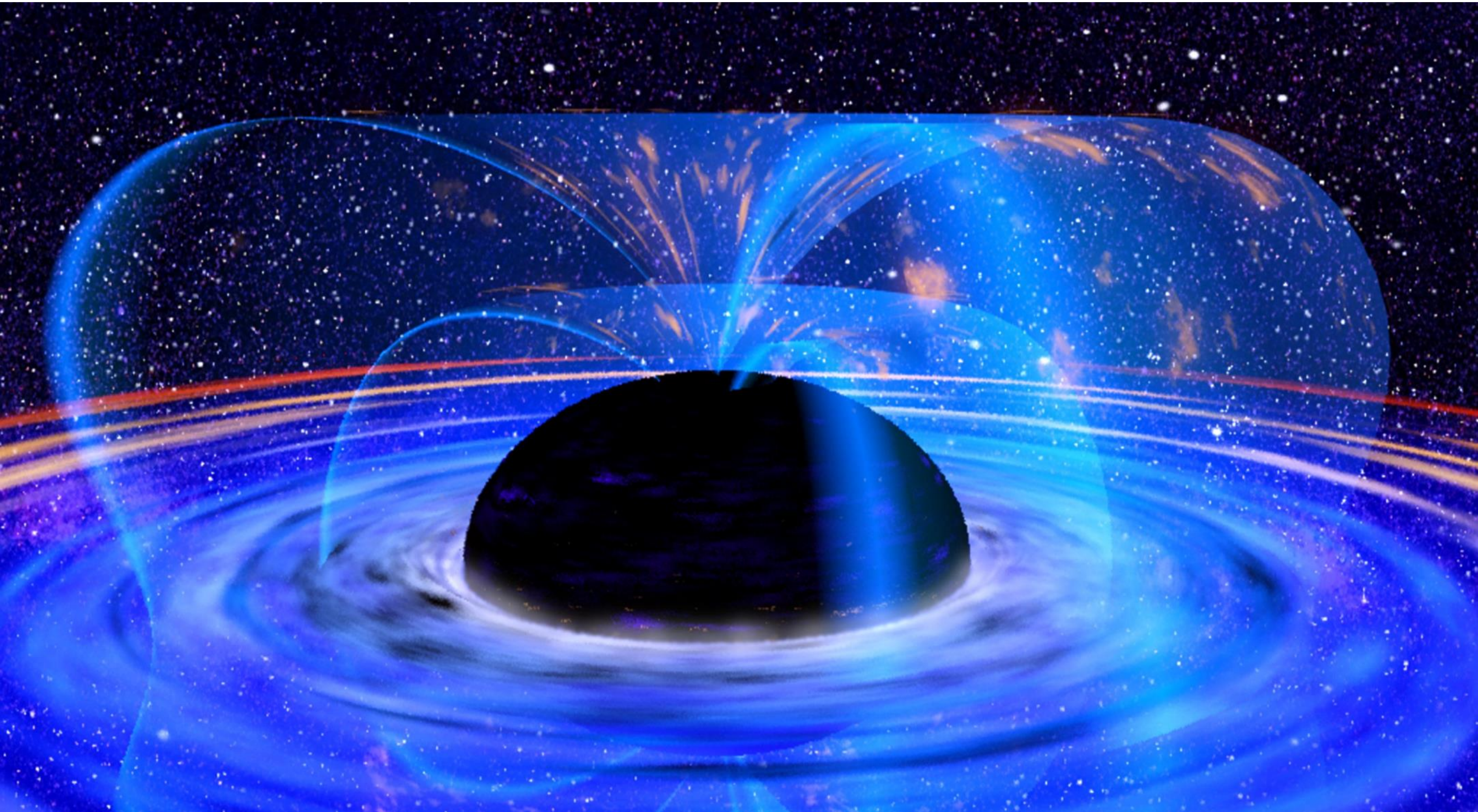
Einstein Telescope: cosmography

What is this mysterious dark energy that is tearing the Universe apart?
Use BNS and BBH as standard “candles” (so-called “sirens”)

Einstein Telescope: fundamental physics

What happened at the edge of a black hole?

Is Einstein’s theory correct in conditions of extreme gravitation? Of does new physics await?



Observe intermediate-mass black holes

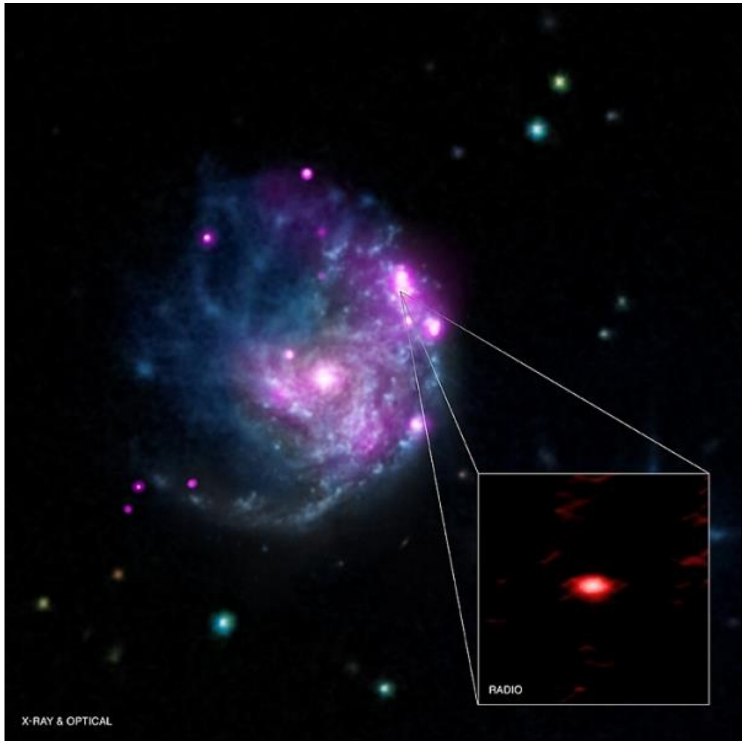
Globular clusters may host intermediate-mass black holes (IMBHs) with masses in the range 100 to 1000 solar masses

IMBH will be the most massive object in the cluster and will readily sink to the center

Binary with a compact-object companion will form. The binary will then harden through three-body interactions

Binary will eventually merge via an intermediate-mass-ratio inspiral (IMRI)

The number of detectable mergers depends on the unknown distribution of IMBH masses and their typical companions. Detect 300 events per year out to z = 1:5 for 100M (redshifted) primaries and 10M secondaries

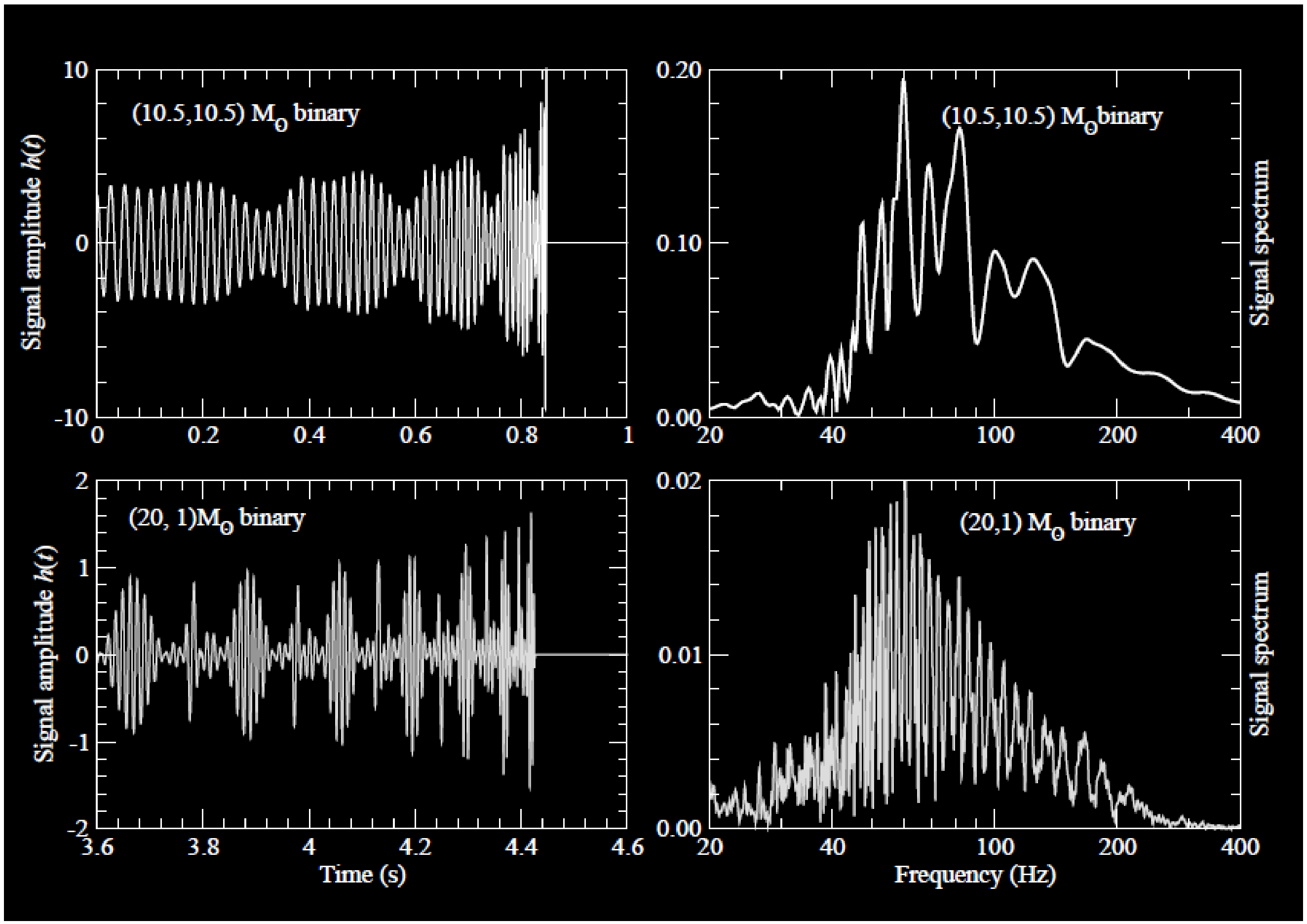


NGC 2276-3c: NASA's Chandra Finds Intriguing Member of Black Hole Family Tree
http://chandra.harvard.edu/photo/2015/ngc2276/

Provide early warning alerts hours in advance

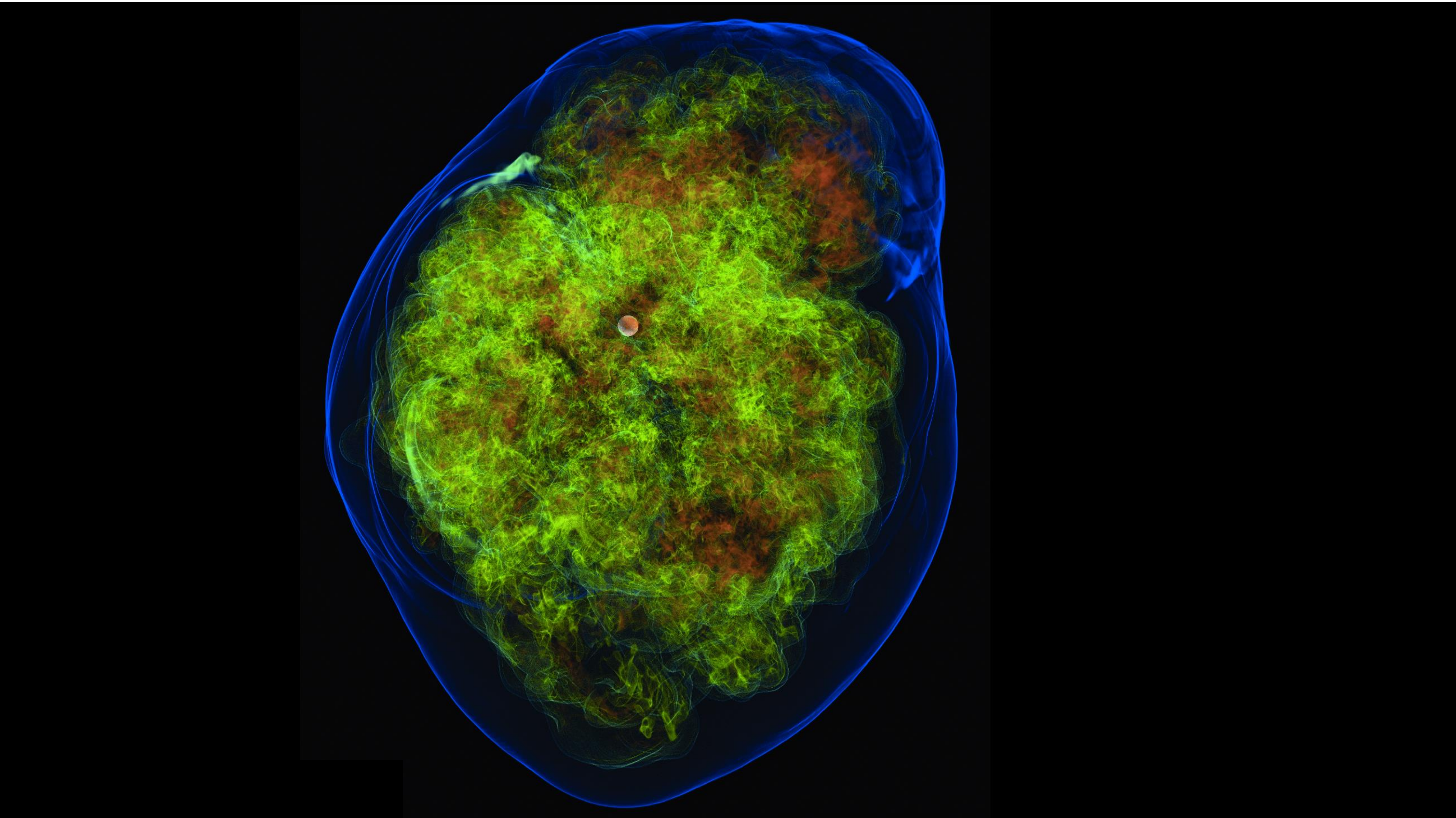
A BNS system will stay in ET's sensitivity band for nearly 20 hours starting from 2 Hz, and a little less than 2 hours starting from 5 Hz. For the same lower frequency limits the duration of a BBH signal from a pair of 10 M BHs is 45 minutes and 4 minutes

It is of great importance to study spin-precession effects. Modulations encode the parameters of sources such as their masses, spins, and inclination of the orbit



Physics of supernovae

Study progenitor mass, proto neutron star (NS) core oscillations, core rotation rate, mass accretion rate from shock, geometry of core collapse, effects of NS Equation of State, fate of collapse: NS or BH



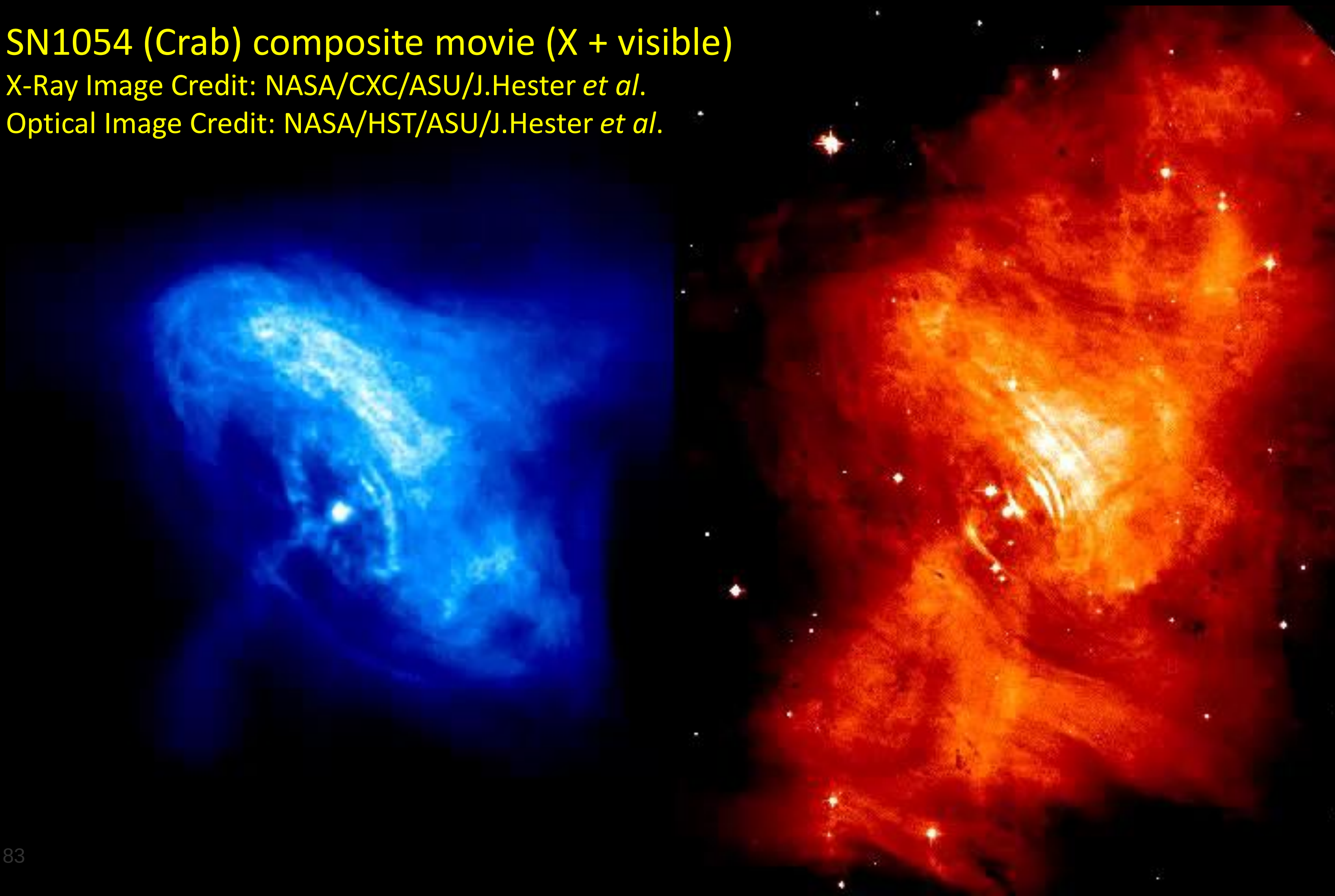
Physics of neutron stars

Deformation due to elastic stresses or magnetic field not aligned to the rotation axis, free precession around rotation axis, excitation of long-lasting oscillations (e.g. *r*-modes), deformation due to matter accretion (e.g. LMXB)

SN1054 (Crab) composite movie (X + visible)

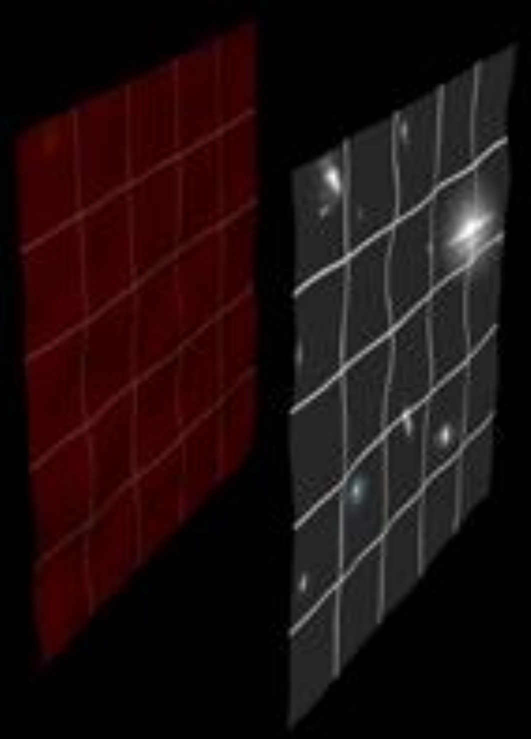
X-Ray Image Credit: NASA/CXC/ASU/J.Hester *et al.*

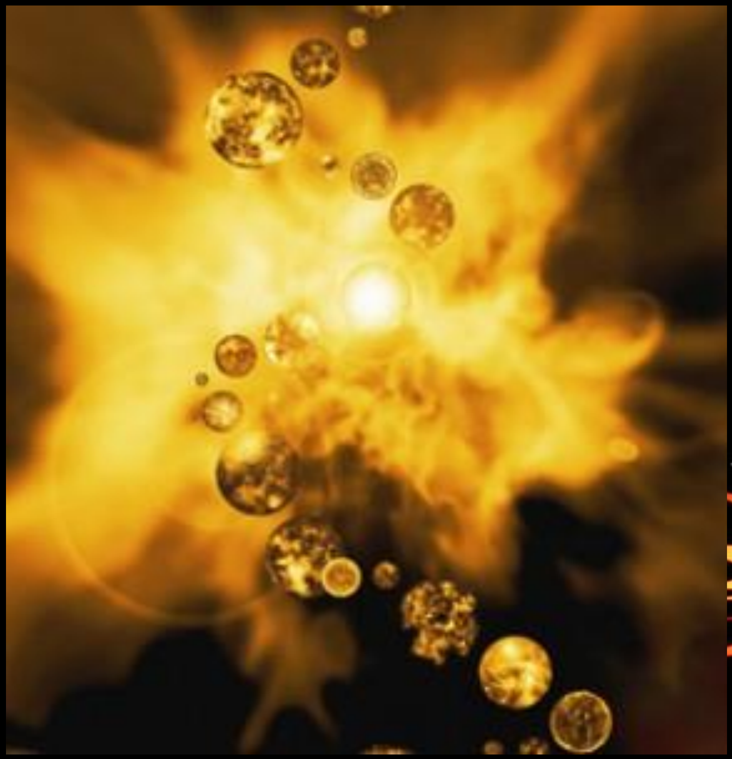
Optical Image Credit: NASA/HST/ASU/J.Hester *et al.*

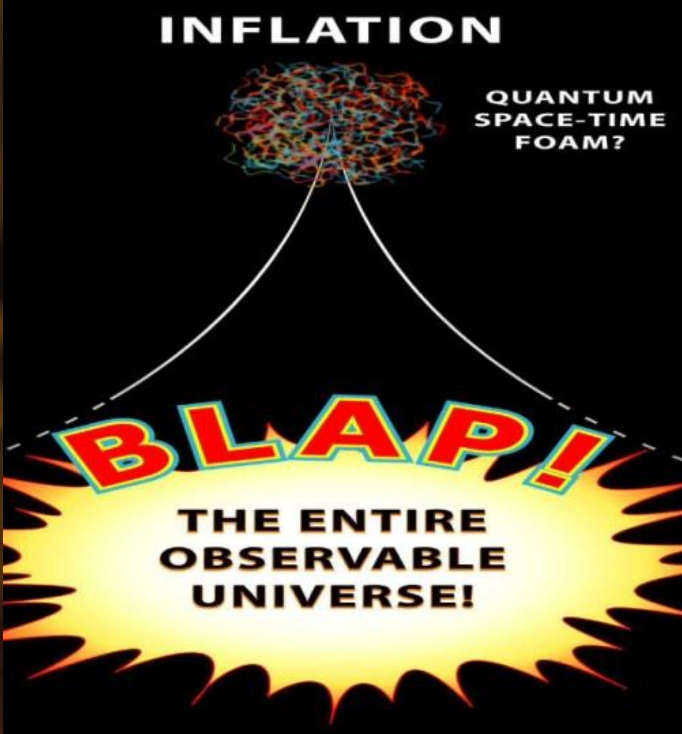


Physics from the early Universe

A stochastic background of gravitational waves may be observed from the earliest stages of the Universe





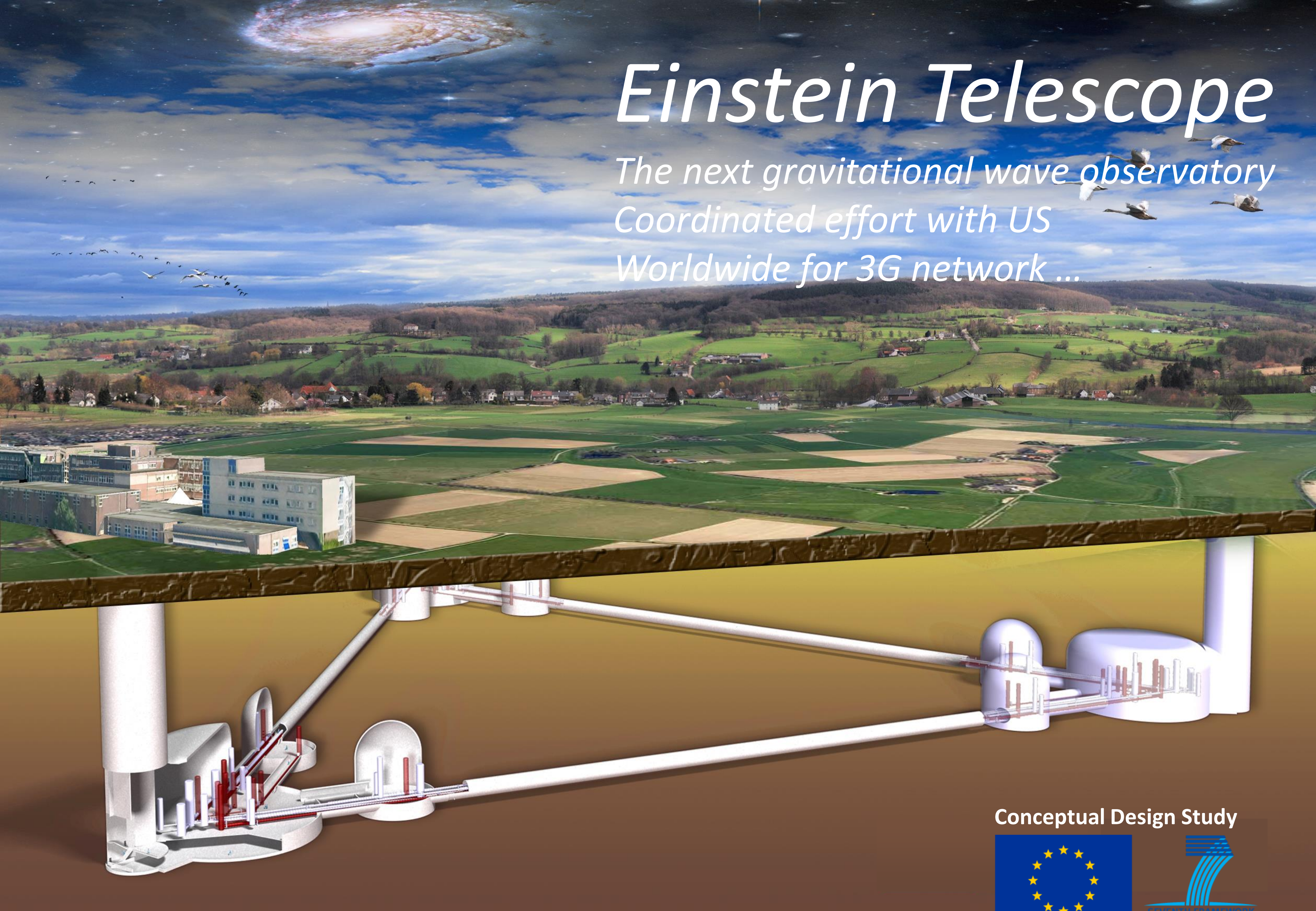


Observe the entire sky with high pointing precision

We want to constantly observe the entire sky and this requires multiple 3G observatories

It would be optimal to have a network of 3G detectors spread over the globe

- Correlate high statistics GW data with other (e.g. EM) observations (SKA-II, LSST, Theseus, …)


Einstein Telescope
The next gravitational wave observatory
Coordinated effort with US
Worldwide for 3G network …
Conceptual Design Study

Einstein Telescope and CERN

Interesting would be a CERN role in our quest for Einstein Telescope. There is strong scientific overlap, and it would be wise to take advantage of existing expertise and resources

Science

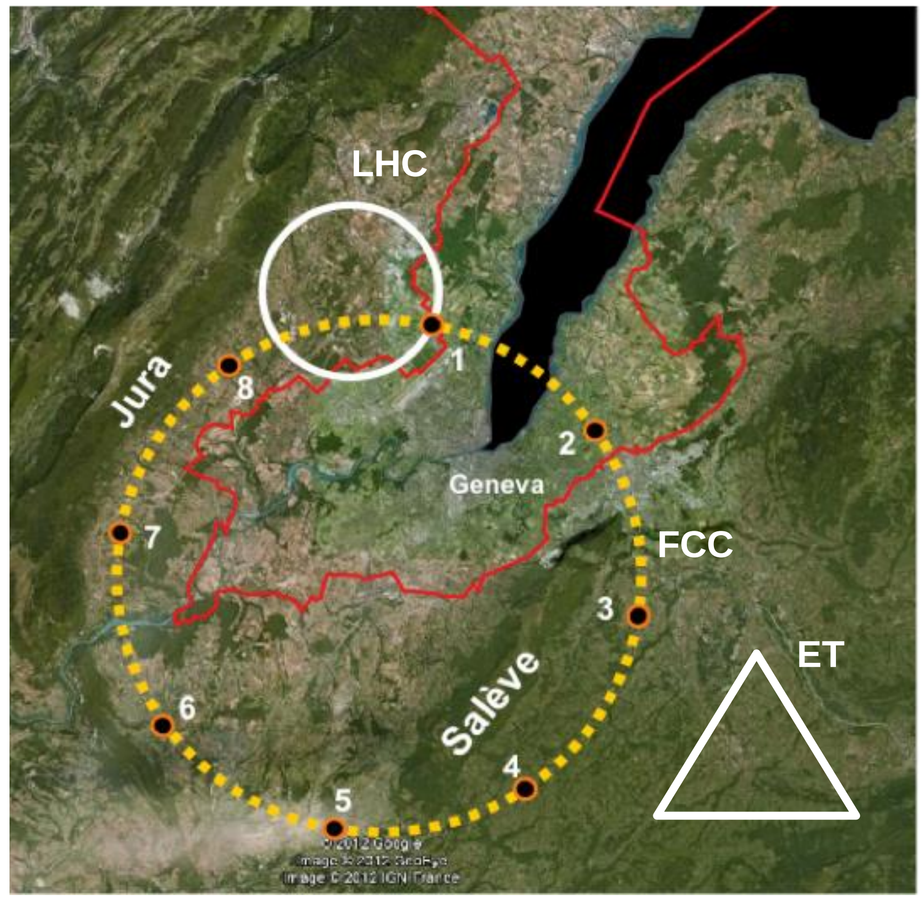
- Gravity is a fundamental interaction with most important open scientific issues
- GWs are the dynamical part of gravity
- Strong scientific interest from HEP
- GW scientists have been involved in the EU HEP Strategy discussion

Governance

- Financial and project management
- Excellent, robust and proven organization

Technical

- Vacuum infrastructure, underground construction
- Cryogenics, controls

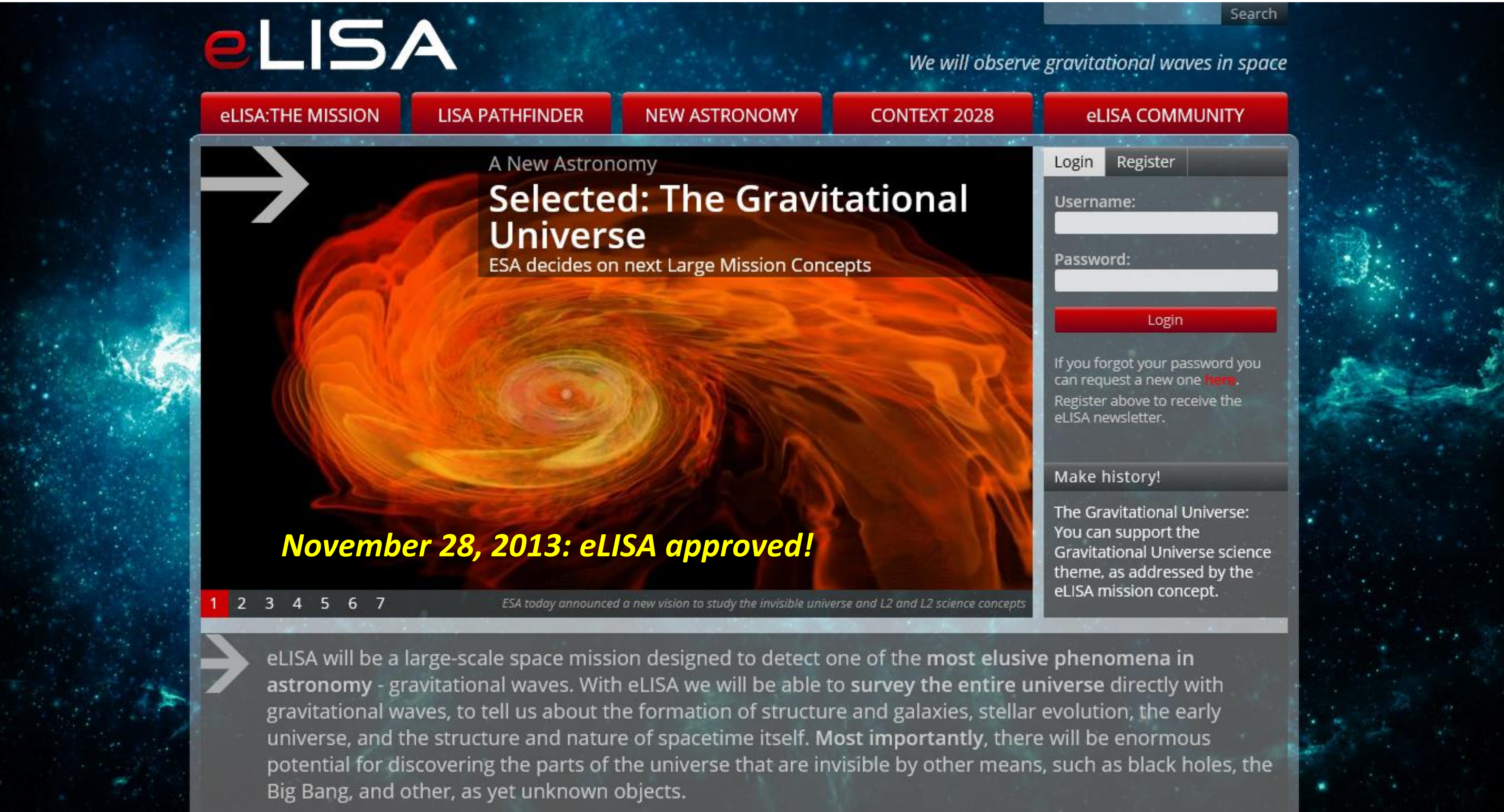


Gravitational wave detection in space

Laser Interferometer Space Antenna will search for gravitational waves from 0.1 to 100 mHz
Three satellites at millions kilometer distance!

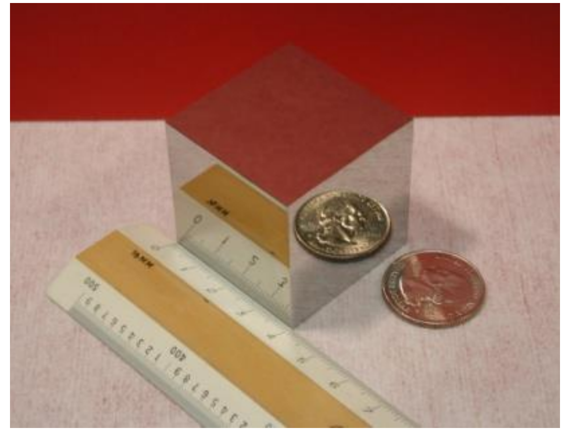
LISA

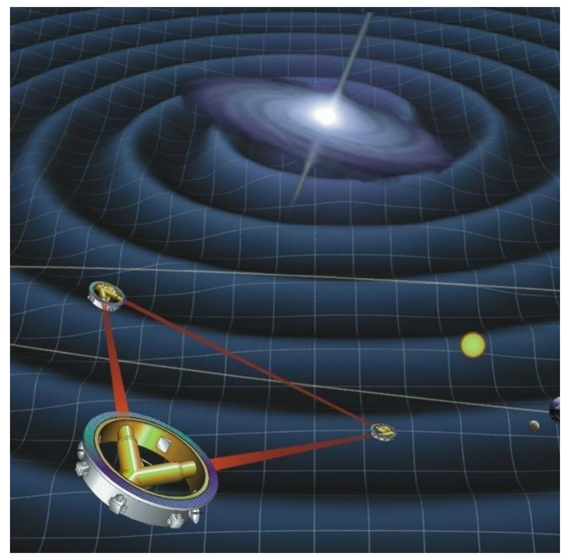
Laser Interferometer Space Antenna will search for gravitational waves from 0.1 to 100 mHz
Three satellites at millions kilometer distance!

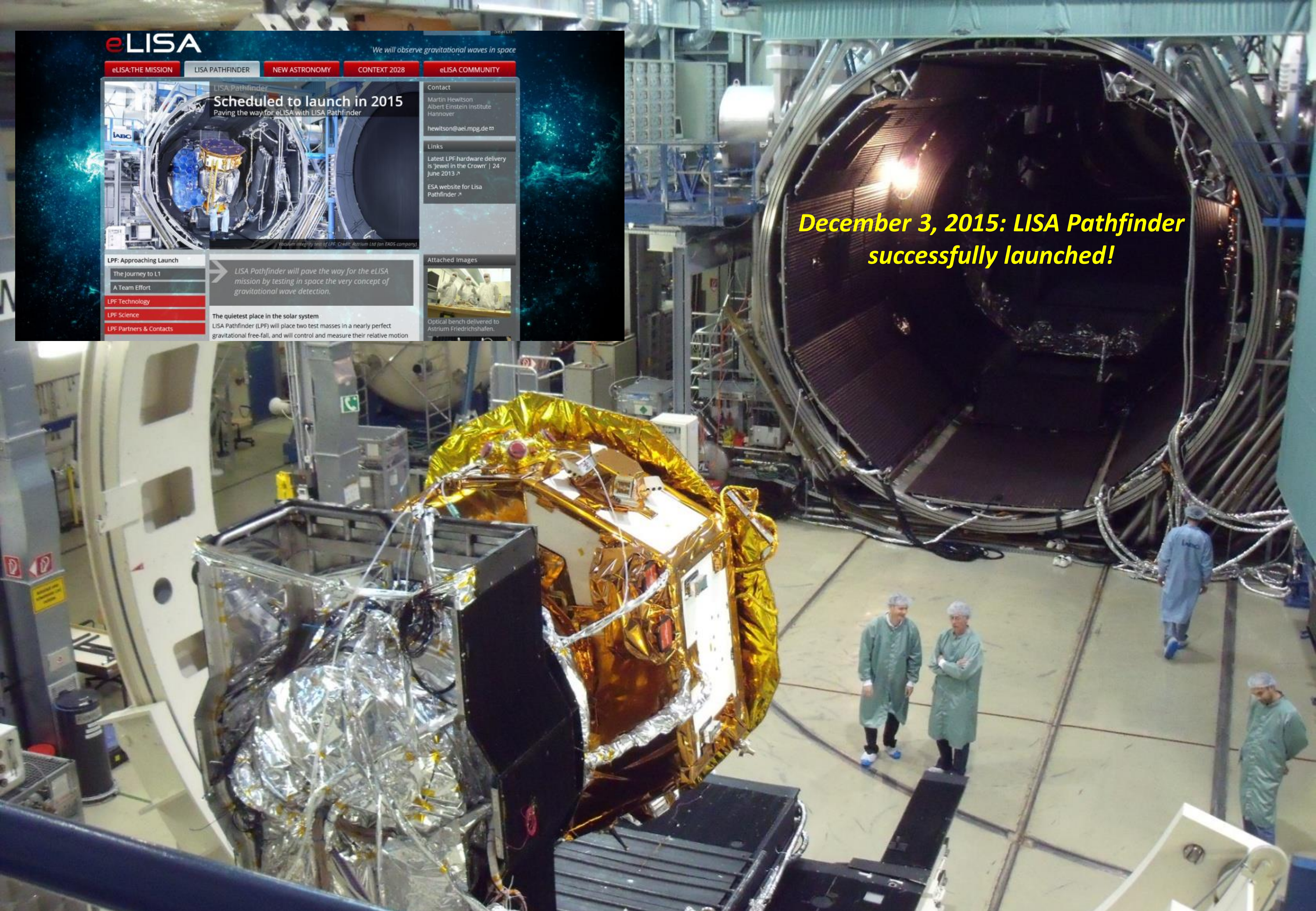


LISA

The Laser Interferometer Space Antenna (LISA) will be the first space-based gravitational wave observatory. Selected to be ESA's third large-class mission, it will address the science theme of the Gravitational Universe. LISA will consist of three spacecraft separated by 2.5 million km in a triangular formation, following Earth in its orbit around the Sun. Launch is expected in 2034







eLISA
We will observe gravitational waves in space
eLISA:THE MISSION
LISA PATHFINDER
NEW ASTRONOMY
CONTEXT 2028
eLISA COMMUNITY
LISA Pathfinder
Scheduled to launch in 2015
Paving the way for eLISA with LISA Pathfinder
Contact
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Albert Einstein Institute
Hannover
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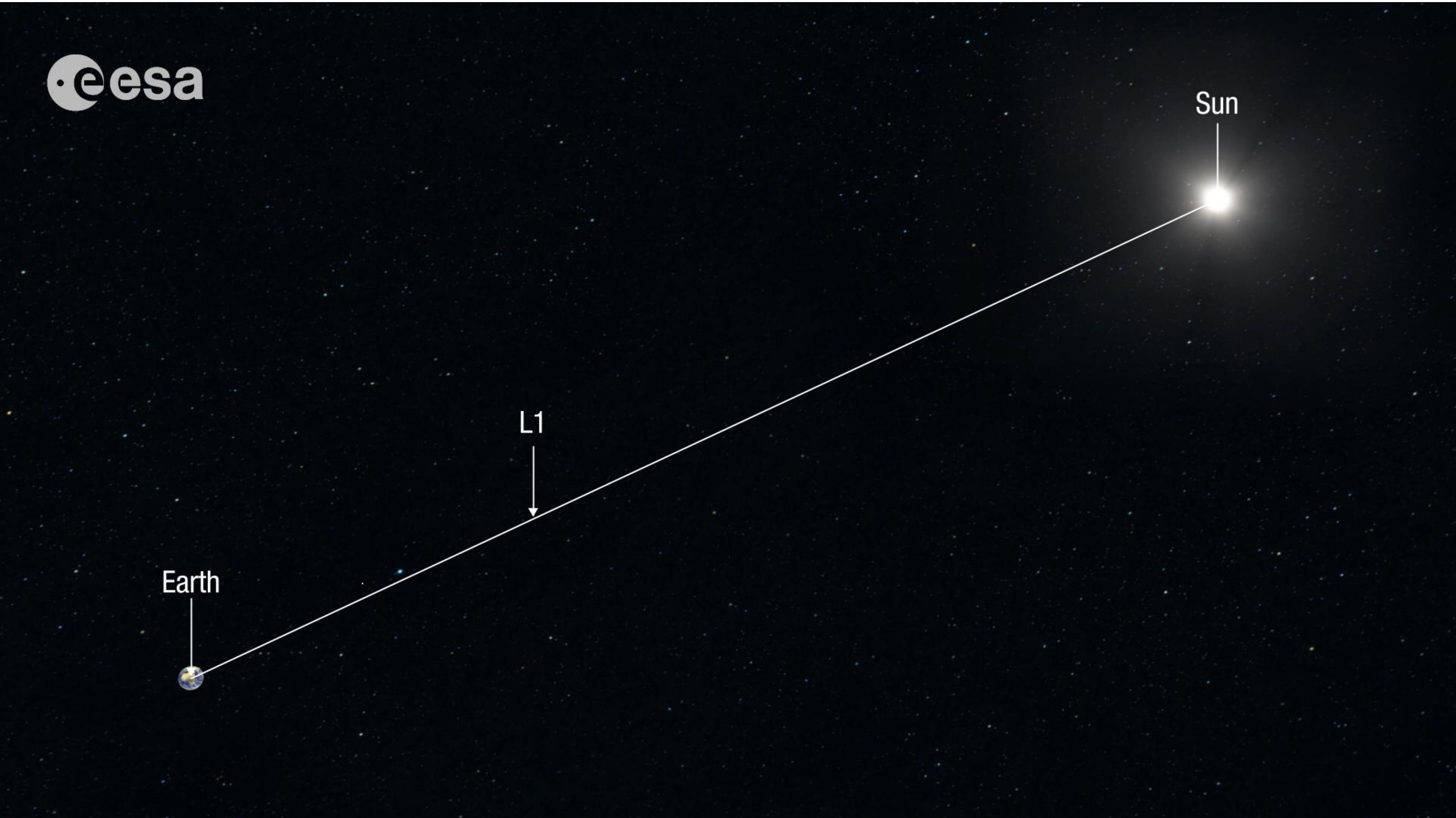
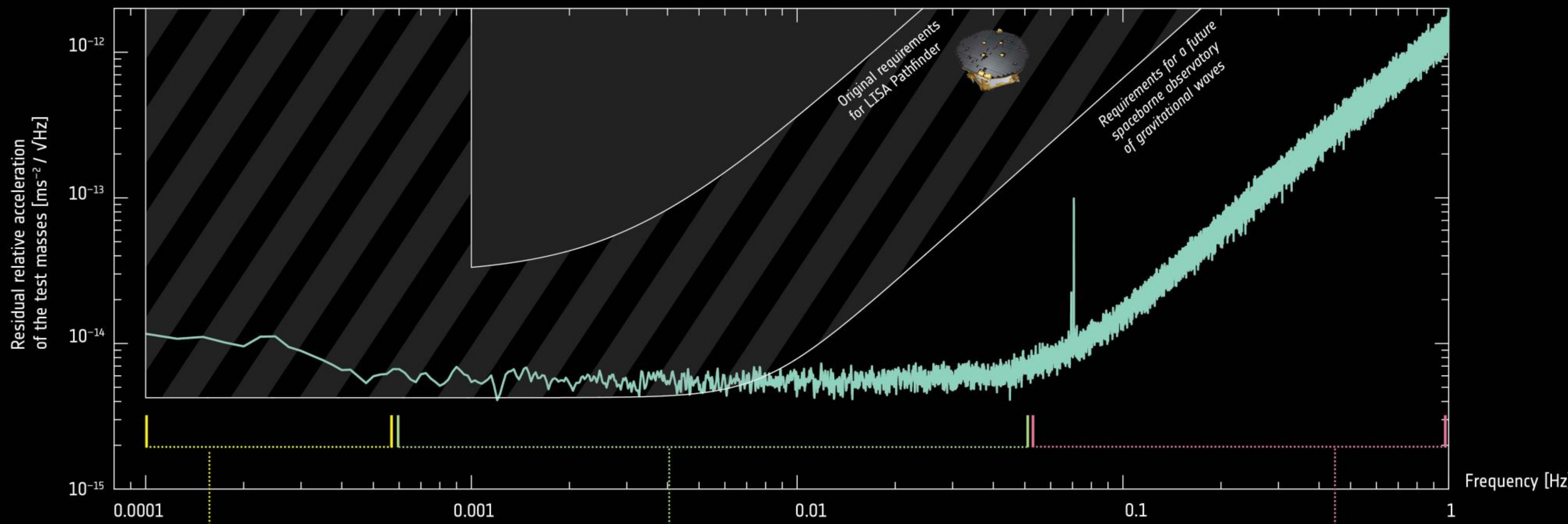
Links
Latest LPF hardware delivery is 'Jewel in the Crown' | 24 June 2013
ESA website for Lisa Pathfinder
LPF: Approaching Launch
The Journey to L1
A Team Effort
LPF Technology
LPF Science
LPF Partners & Contacts
LISA Pathfinder will pave the way for the eLISA mission by testing in space the very concept of gravitational wave detection.
The quietest place in the solar system
LISA Pathfinder (LPF) will place two test masses in a nearly perfect gravitational free-fall, and will control and measure their relative motion
Attached Images
Optical bench delivered to Astrium Friedrichshafen.
December 3, 2015: LISA Pathfinder successfully launched!

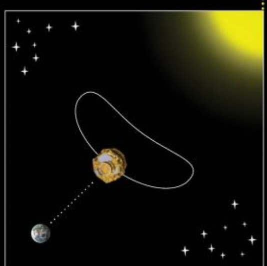
Lisa Pathfinder

"Technology demonstrator" for eLISA. Successfully launched on December 3, 2015



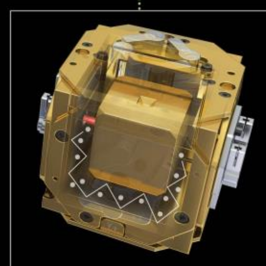
➜ LISA PATHFINDER EXCEEDS EXPECTATIONS





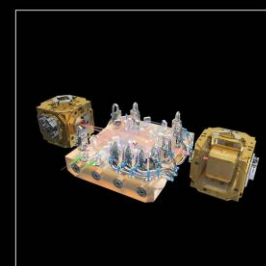
Centrifugal force

The rotation of the spacecraft required to keep the solar array pointed at the Sun and the antenna pointed towards Earth, coupled with the noise of the startrackers produces a noisy centrifugal force on the test masses. This noise term has been subtracted, and the source of the residual noise after subtraction is still being investigated.



Gas damping

Inside their housings, the test masses collide with some of the few gas molecules still present. This noise term becomes smaller with time, as more gas molecules are vented to space.



Sensing noise

The sensing noise of the optical metrology system used to monitor the position and orientation of the test masses, at a level of 35 fm / √Hz, has already surpassed the level of precision required by a future gravitational-wave observatory by a factor of more than 100.

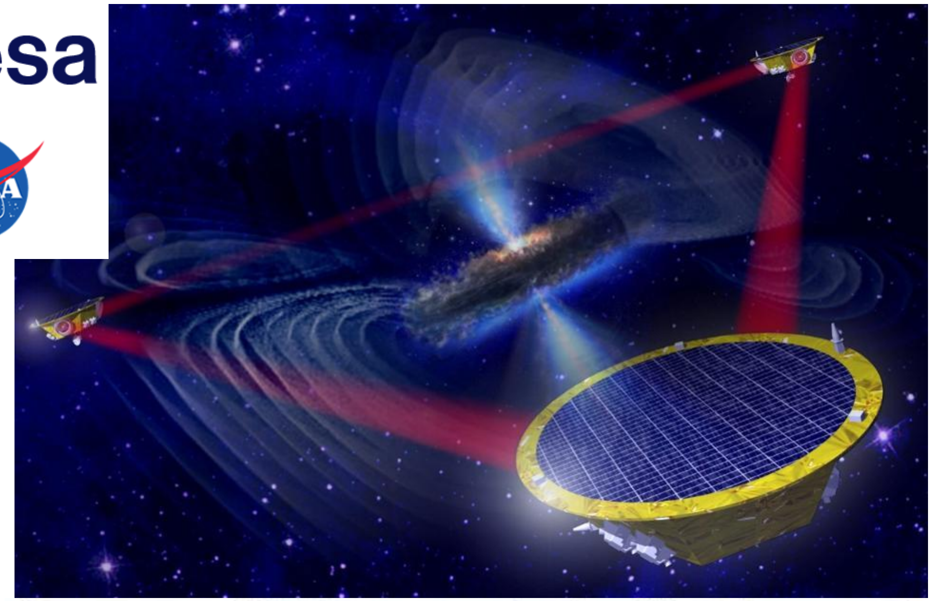
Spacecraft: ESA/ATG medialab; data: ESA/LISA Pathfinder Collaboration

Bright future for gravitational wave research

LIGO and Virgo are operational. KAGRA in Japan joins this year, LIGO-India under construction. ESA launches LISA in 2034. Einstein Telescope and CE CDRs financed. Strong support by APPEC

Gravitational wave research

- LIGO and Virgo operational
- KAGRA to join this year
- LIGO-India under construction (2025)
- ESA selects LISA, NASA rejoins
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation



Einstein Telescope and Cosmic Explorer

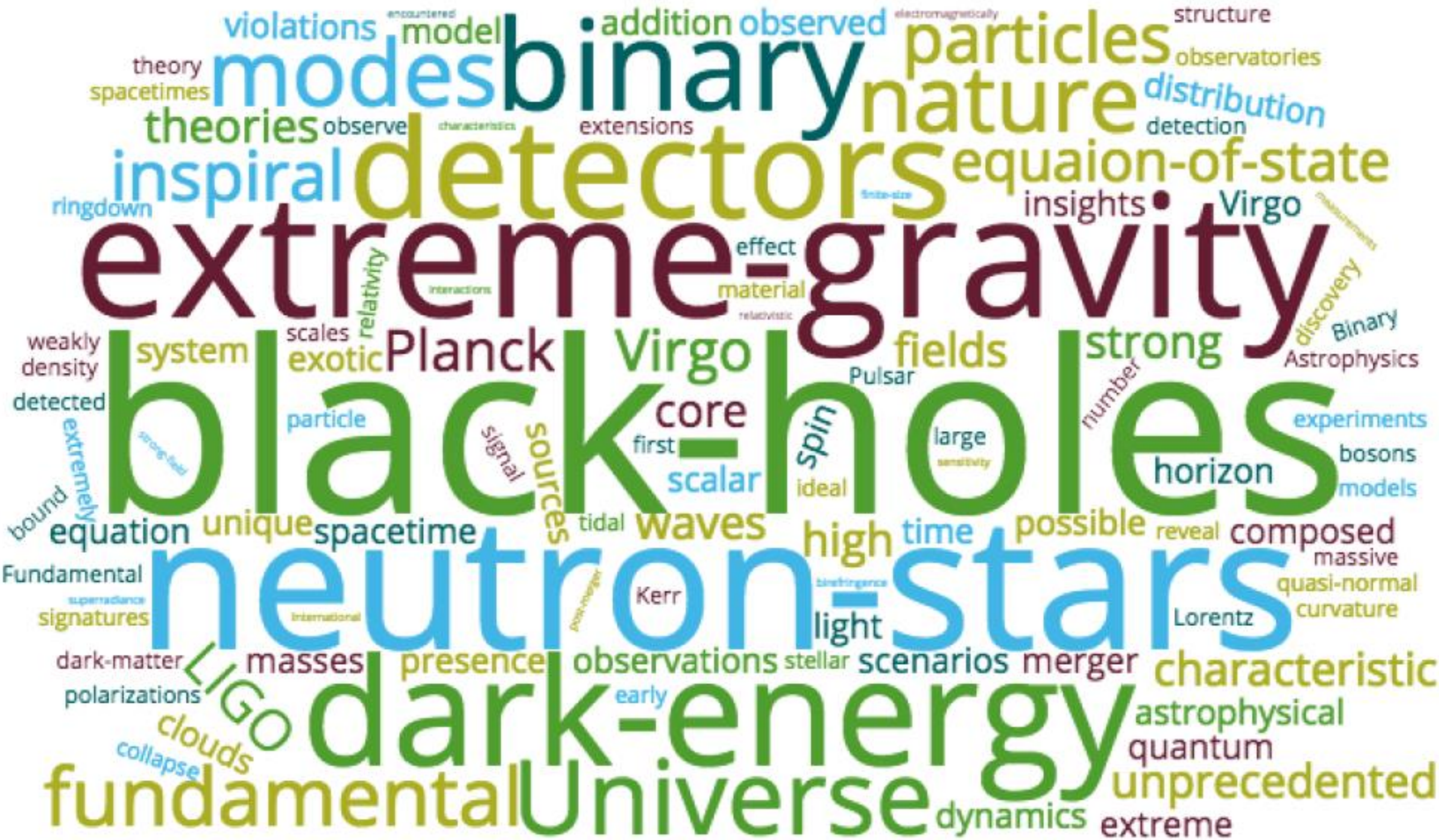
- CDR ET financed by EU in FP7, CE by NSF
- APPEC gives GW a prominent place in the new Roadmap and especially the realization of ET

Next steps for 3G

- Organize the community and prepare a credible plan for EU funding agencies
- ESFRI Roadmap (2020)
- Support 3G: http://www.et-gw.eu/index.php/letter-of-intent

Thank you for your attention!

Questions?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ringdown
insights
Virgo
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Binary
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Fundamental
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quantum
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Universe
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dynamics
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