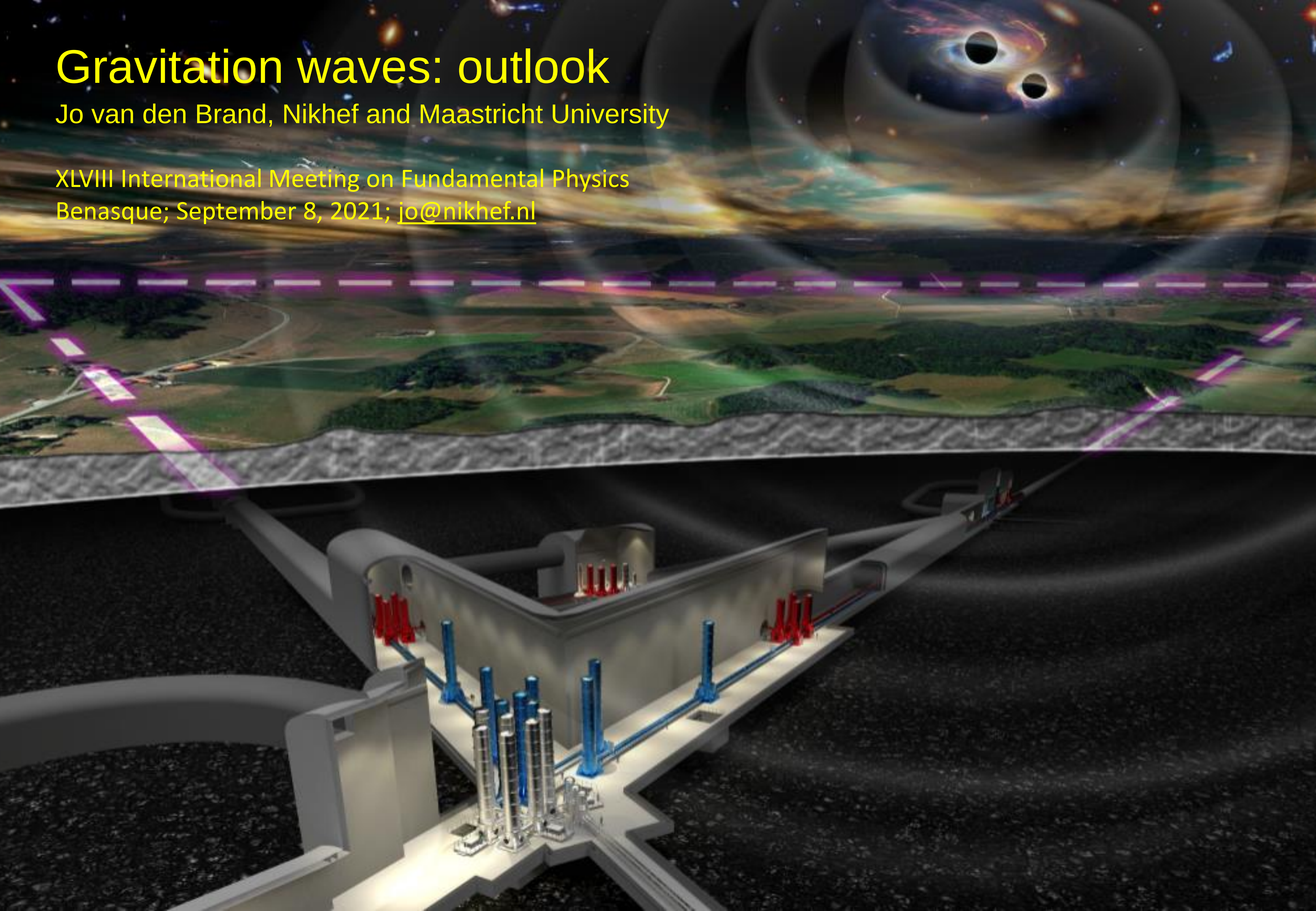
Gravitation waves: outlook

Jo van den Brand, Nikhef and Maastricht University

XLVIII International Meeting on Fundamental Physics
Benasque; September 8, 2021; jo@nikhef.nl



Scientific impact of gravitational wave 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

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

Joining O3 is another important step for Virgo

Gravitational-Wave Transient Catalog, GWTC - 2

Compact binary coalescences observed by LIGO &Virgo during the first half of the third observing run

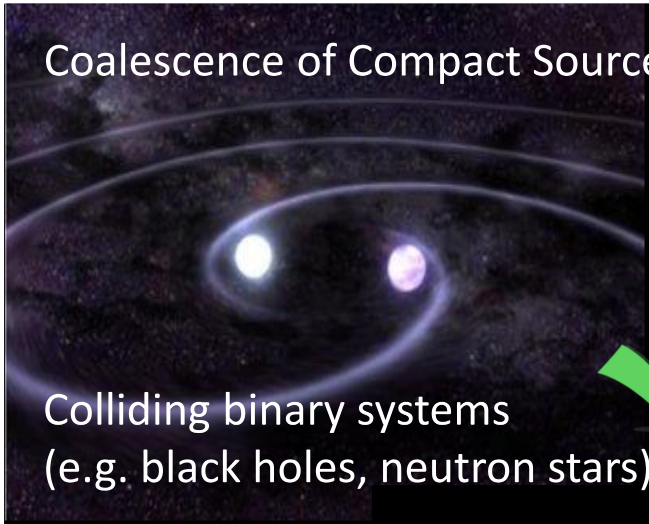
See Abbott et al. Phys. Rev. X 11, 021053 (2021)

Zoheyr Doctor / University of Oregon / LIGO-Virgo Collaboration

Status of gravitational-wave detections

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

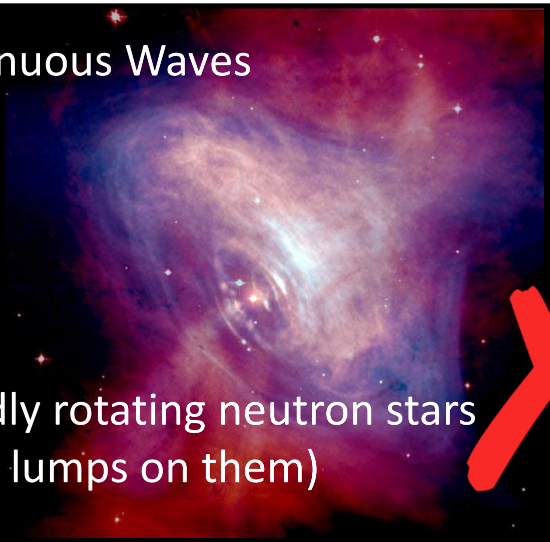
Coalescence of Compact Sources



✓

Colliding binary systems
(e.g. black holes, neutron stars)

Continuous Waves



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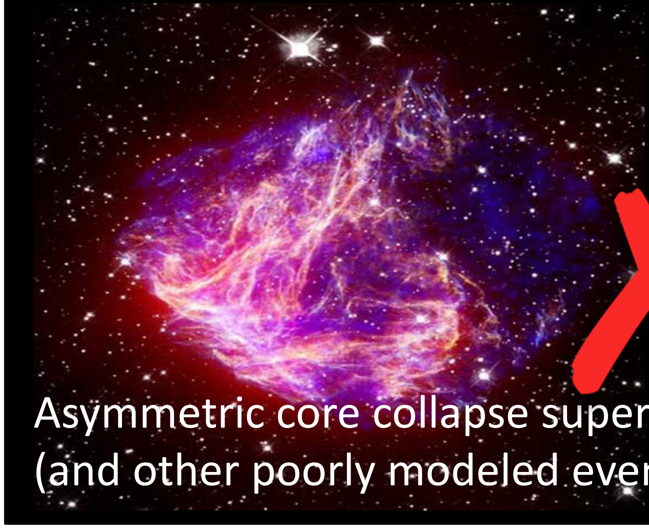
Rapidly rotating neutron stars
(with lumps on them)

Burst



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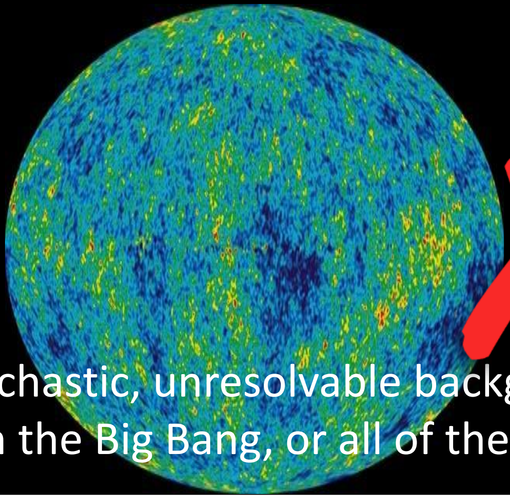
Asymmetric core collapse supernovae
(and other poorly modeled events)

Stochastic



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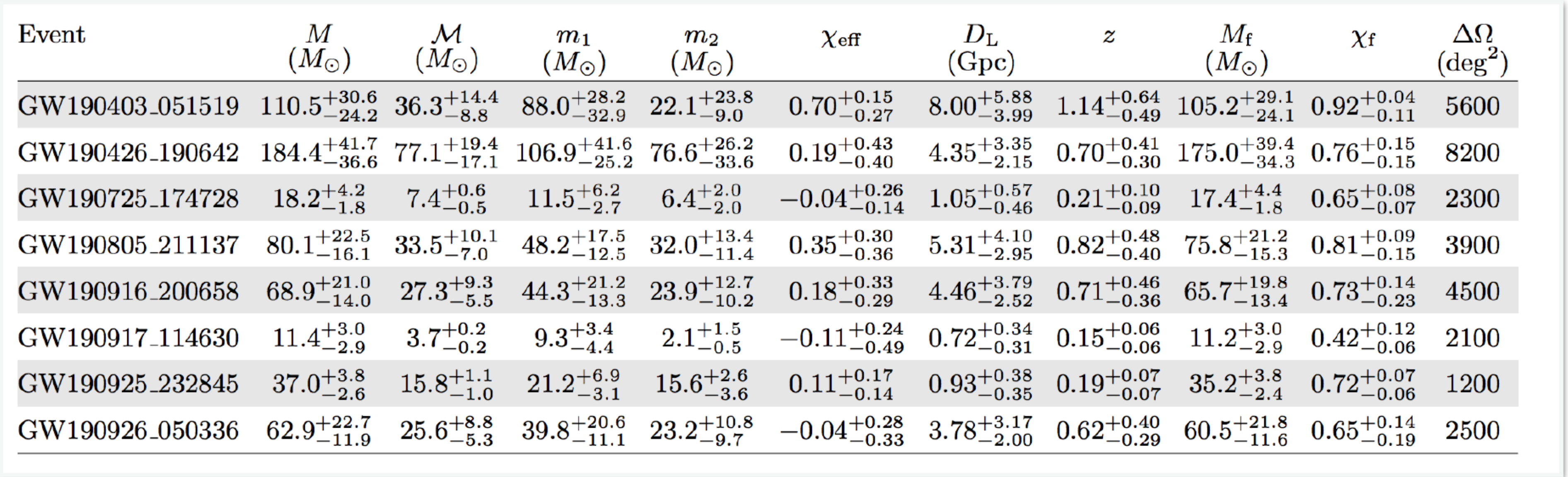
A stochastic, unresolvable background
(from the Big Bang, or all of the above)

GWTC-2.1

Deep extended catalog of compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run; see https://arxiv.org/abs/2108.01045

8 new events that were not in GWTC-2 with probability of astrophysical origin > 0.5

1201 candidates that pass a false alarm rate threshold of 2 per day

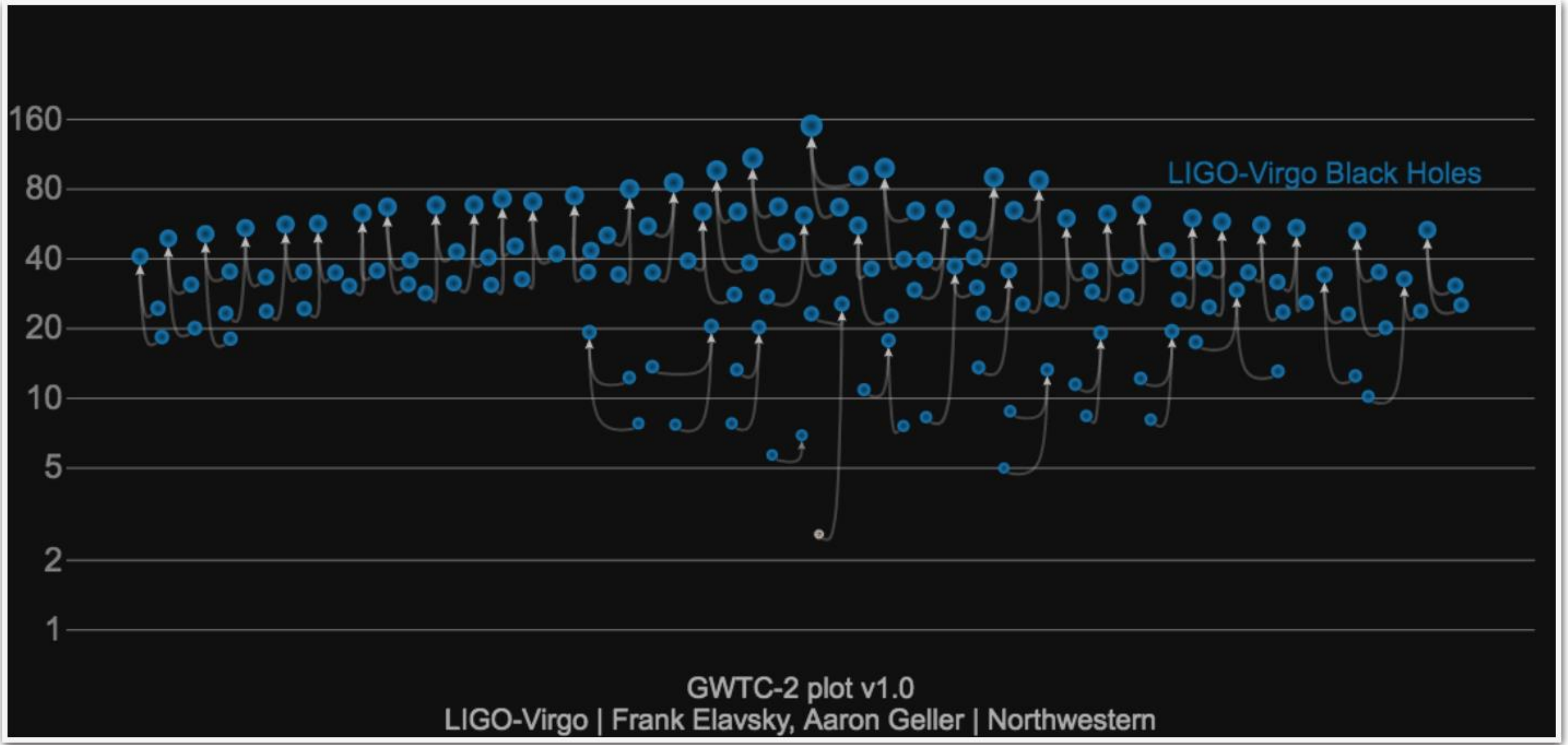


Event	M $(M_\odot)$	$\mathcal{M}$ $(M_\odot)$	m_1 $(M_\odot)$	m_2 $(M_\odot)$	χ_eff	D_L (Gpc)	z	M_f $(M_\odot)$	χ_f	$\Delta\Omega$ (deg^2)
GW190403_051519	$110.5^{+30.6}_{-24.2}$	$36.3^{+14.4}_{-8.8}$	$88.0^{+28.2}_{-32.9}$	$22.1^{+23.8}_{-9.0}$	$0.70^{+0.15}_{-0.27}$	$8.00^{+5.88}_{-3.99}$	$1.14^{+0.64}_{-0.49}$	$105.2^{+29.1}_{-24.1}$	$0.92^{+0.04}_{-0.11}$	5600
GW190426_190642	$184.4^{+41.7}_{-36.6}$	$77.1^{+19.4}_{-17.1}$	$106.9^{+41.6}_{-25.2}$	$76.6^{+26.2}_{-33.6}$	$0.19^{+0.43}_{-0.40}$	$4.35^{+3.35}_{-2.15}$	$0.70^{+0.41}_{-0.30}$	$175.0^{+39.4}_{-34.3}$	$0.76^{+0.15}_{-0.15}$	8200
GW190725_174728	$18.2^{+4.2}_{-1.8}$	$7.4^{+0.6}_{-0.5}$	$11.5^{+6.2}_{-2.7}$	$6.4^{+2.0}_{-2.0}$	$-0.04^{+0.26}_{-0.14}$	$1.05^{+0.57}_{-0.46}$	$0.21^{+0.10}_{-0.09}$	$17.4^{+4.4}_{-1.8}$	$0.65^{+0.08}_{-0.07}$	2300
GW190805_211137	$80.1^{+22.5}_{-16.1}$	$33.5^{+10.1}_{-7.0}$	$48.2^{+17.5}_{-12.5}$	$32.0^{+13.4}_{-11.4}$	$0.35^{+0.30}_{-0.36}$	$5.31^{+4.10}_{-2.95}$	$0.82^{+0.48}_{-0.40}$	$75.8^{+21.2}_{-15.3}$	$0.81^{+0.09}_{-0.15}$	3900
GW190916_200658	$68.9^{+21.0}_{-14.0}$	$27.3^{+9.3}_{-5.5}$	$44.3^{+21.2}_{-13.3}$	$23.9^{+12.7}_{-10.2}$	$0.18^{+0.33}_{-0.29}$	$4.46^{+3.79}_{-2.52}$	$0.71^{+0.46}_{-0.36}$	$65.7^{+19.8}_{-13.4}$	$0.73^{+0.14}_{-0.23}$	4500
GW190917_114630	$11.4^{+3.0}_{-2.9}$	$3.7^{+0.2}_{-0.2}$	$9.3^{+3.4}_{-4.4}$	$2.1^{+1.5}_{-0.5}$	$-0.11^{+0.24}_{-0.49}$	$0.72^{+0.34}_{-0.31}$	$0.15^{+0.06}_{-0.06}$	$11.2^{+3.0}_{-2.9}$	$0.42^{+0.12}_{-0.06}$	2100
GW190925_232845	$37.0^{+3.8}_{-2.6}$	$15.8^{+1.1}_{-1.0}$	$21.2^{+6.9}_{-3.1}$	$15.6^{+2.6}_{-3.6}$	$0.11^{+0.17}_{-0.14}$	$0.93^{+0.38}_{-0.35}$	$0.19^{+0.07}_{-0.07}$	$35.2^{+3.8}_{-2.4}$	$0.72^{+0.07}_{-0.06}$	1200
GW190926_050336	$62.9^{+22.7}_{-11.9}$	$25.6^{+8.8}_{-5.3}$	$39.8^{+20.6}_{-11.1}$	$23.2^{+10.8}_{-9.7}$	$-0.04^{+0.28}_{-0.33}$	$3.78^{+3.17}_{-2.00}$	$0.62^{+0.40}_{-0.29}$	$60.5^{+21.8}_{-11.6}$	$0.65^{+0.14}_{-0.19}$	2500

LIGO EGO European Gravitational Observatory LSC LIGO Scientific Collaboration VIRGO

Binary black hole population inference from GWTC-2

Combine many observations to infer underlying properties. More sensitive than single-event inference. See Abbott et al. ApJ Lett. 913, L7 (2021)



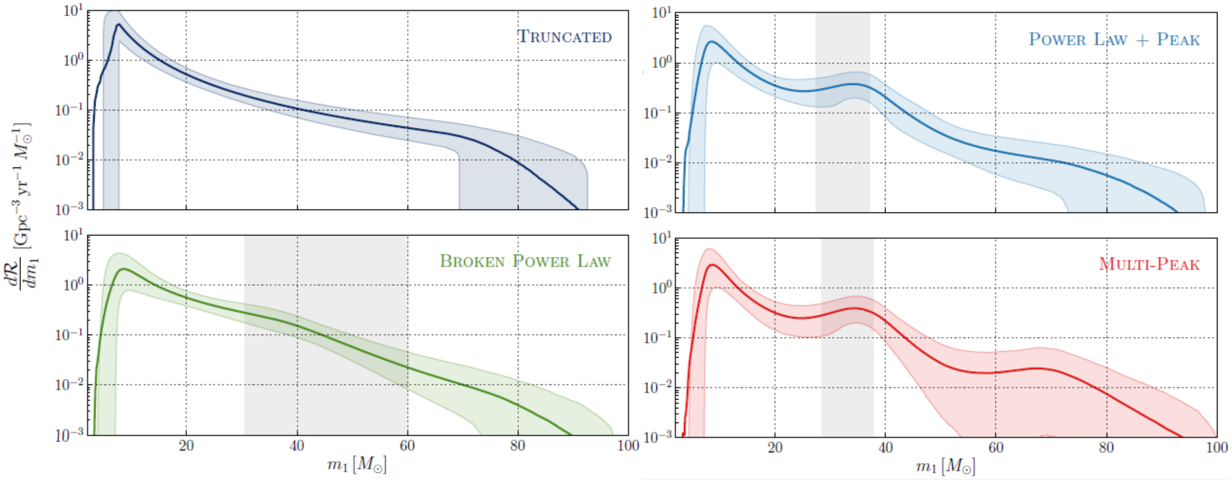
GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Binary black hole population inference from GWTC-2

Combine many observations to infer underlying properties. More sensitive than single-event inference. See Abbott et al. ApJ Lett. 913, L7 (2021)

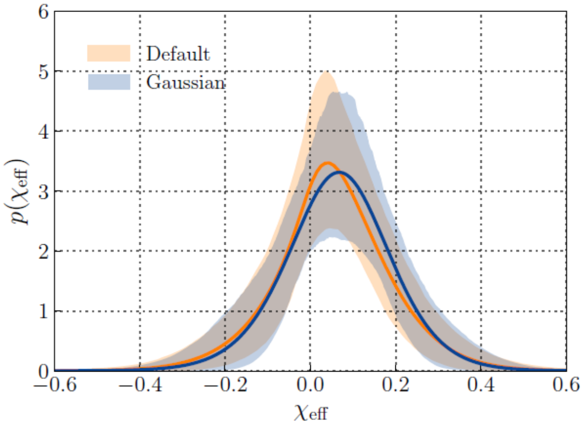
Mass distribution

- Used 47 BBH events
- FAR < 1 per yr
- Truncated model is not a good fit to the data
- Evidence of a feature around 35 - 40 M⨀



Spin distribution

- Some BBH systems have spins misaligned with orbital angular momentum



Evidence for deviations from general relativity

Learning about gravity with LIGO and Virgo
See Abbott et al. Phys. Rev D. 103, 122002 (2021)

Observations

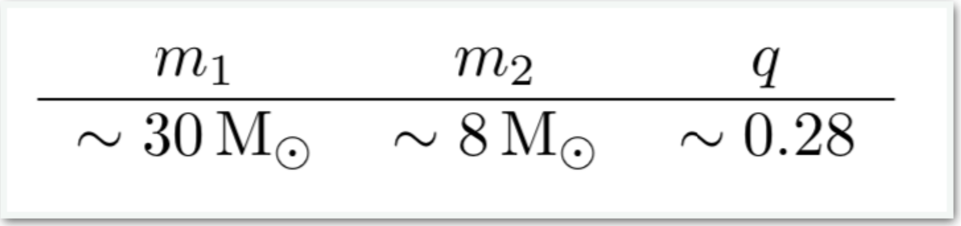
- Residuals from best-fit waveforms consistent with noise ✓
- Consistency of parameters inferred from inspiral and merger-ringdown phases ✓
- No evidence for deviations from the PN coefficients predicted by GR ✓
- Consistency with no dispersion of GWs and massless graviton ✓
- BH spin-induced quadrupole moments are consistent with their Kerr values ✓
- Ringdown frequencies and damping times consistent with GR ✓
- No detection of echoes ✓
- No evidence for pure scalar or pure vector polarizations ✓

- New bound on mass of graviton: $\boxed{m_g \leq 1.76 \times 10^{-23} \mathrm{eV}/\mathrm{c}^2}$

Exceptional detections

GW190412: an unequal mass binary black hole merger

First clear evidence for unequal mass components and a clear measurement of higher-order multipoles
See Abbott et al. Phys. Rev. D 102, 043015 (2020)



m_1	m_2	q
$\sim 30\,\mathrm{M}_\odot$	$\sim 8\,\mathrm{M}_\odot$	~ 0.28

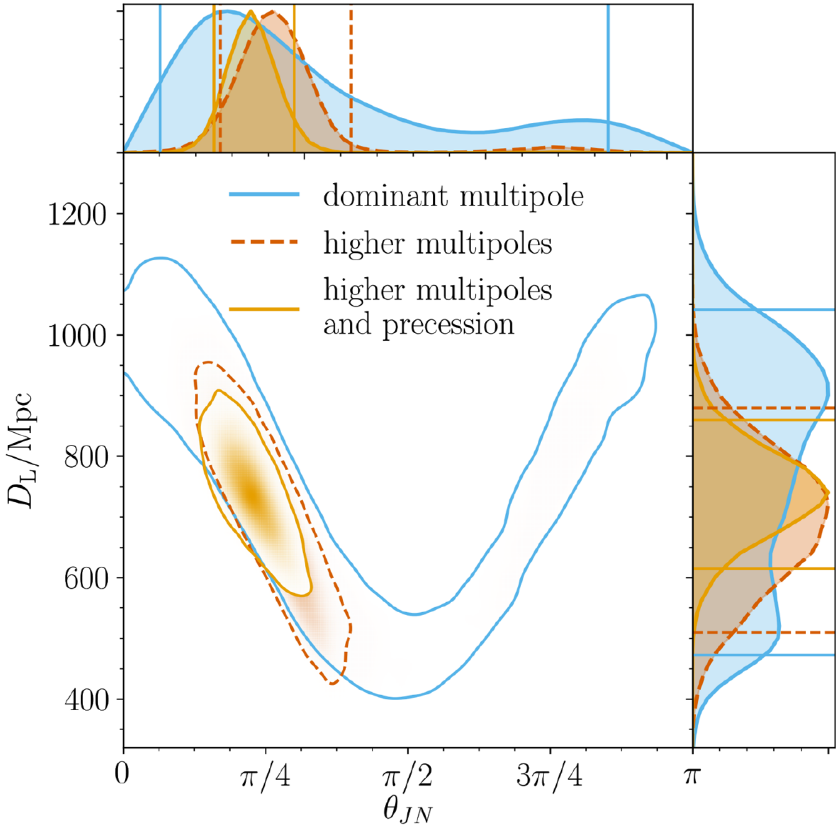
Still consistent with BBH population inferred from O1/O2

Gravitational radiation beyond the leading quadrupolar order in the observed signal

$$h_+ - ih_\times = \sum_{\ell\geq 2}\sum_{-\ell\leq m\leq\ell} \frac{h_{\ell m}(t,\boldsymbol{\lambda})}{D_\mathrm{L}}\,{}_{-2}Y_{\ell m}(\theta,\phi)$$

More massive black hole rotated with a dimensionless spin magnitude between 0.22 and 0.60 (90% probability)

Posterior is constrained by including HOMs and precession



GW190814: a 23 $M_\odot$ BH merges with a 2.6 $M_\odot$ compact object

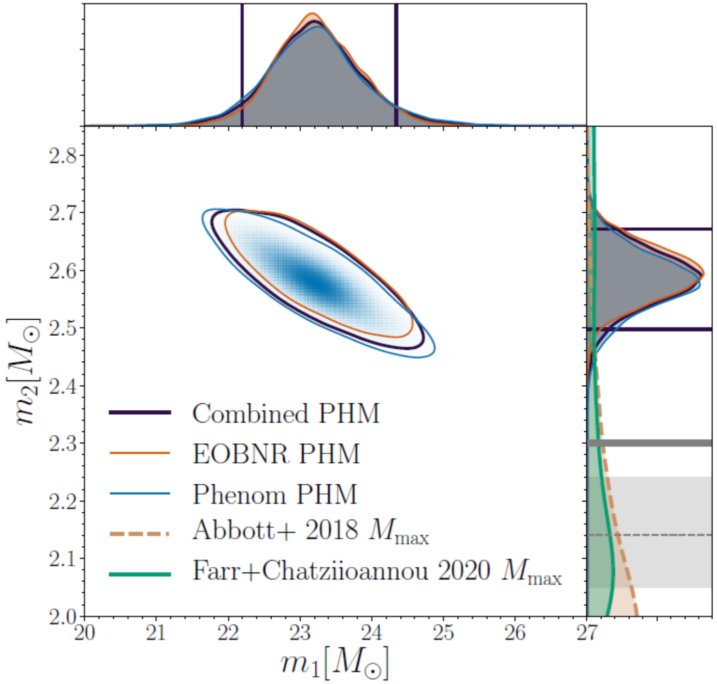
Either the heaviest neutron star or lightest black hole ever observed (ever = not only via GW)
Can we distinguish neutron stars and black holes based on mass?

Press Release on June 24, 2020

Remarks:

- Signal first identified by LIGO-Livingston (L1) and Virgo; classified as mass gap and later NSBH
- Subsequent 3-interferometer analysis yields SNR = 25
- Most unequal mass ratio yet observed of 9:1
- Strongest evidence for multipole emission observed so far, and in agreement with General Relativity
- Spin of primary black hole well constrained to ≤ 0.07
- Clear evidence for inclination
- Challenge for formation models
- Sky map had a 90% credible region of 18.5 deg^2
- Luminosity distance of 241^{+41}_{-45} Mpc

Posteriors of component masses



GW190425: LIGO-Virgo detect a second binary neutron star merger

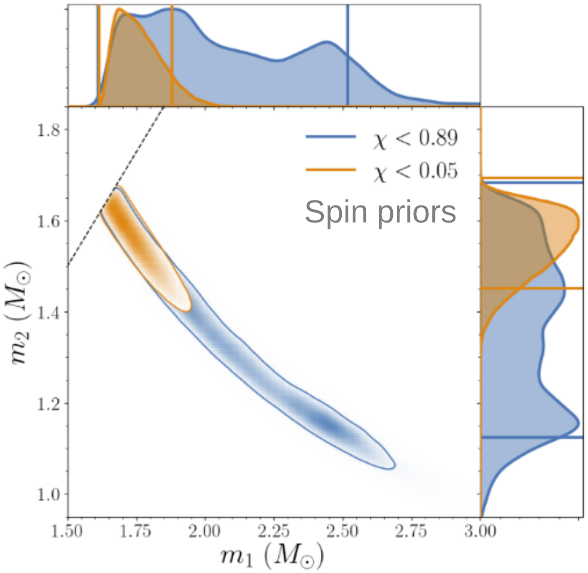
Confirmation of our BNS merger detection in 2017 (most likely). Cannot rule out BBH or NSBH

First released event of O3 run: Press Release on January 6, 2020 at IAU meeting in Hawaii

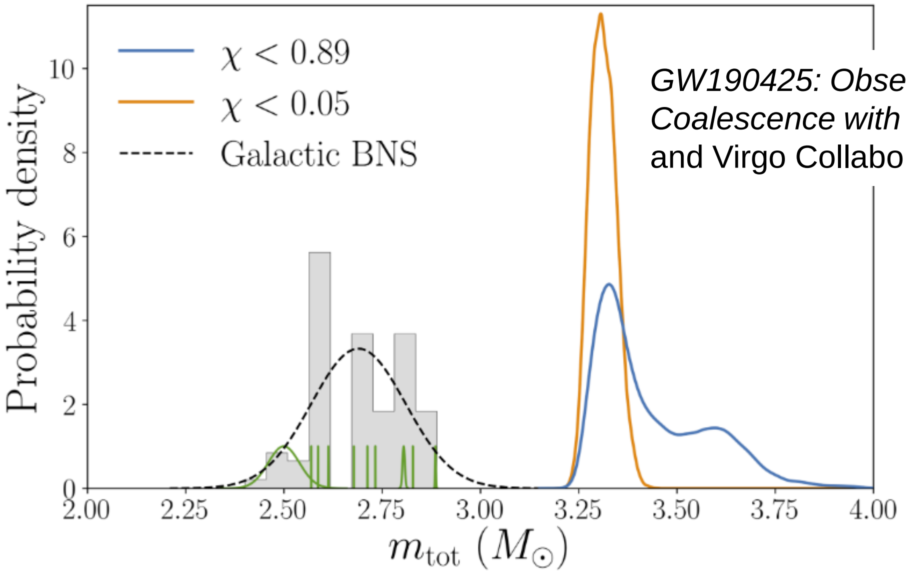
Remarks:

- 2-interferometer observation with SNR = 12.9 (FAR > 1 in 69,000 yr): LIGO-Livingston (L1) and Virgo
- Total mass of about 3.4 $M_\odot$ is larger than in any known system
- Evidence for a new population?
- Initial sky map had a 90% credible region of 10,200 deg^2 at luminosity distance of 159^{+69}_{-72} Mpc

Posteriors of component masses



Total system masses under different spin priors

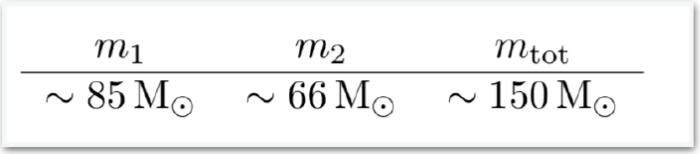


GW190425: Observation of a Compact Binary Coalescence with Total Mass ~ 3.4 M, LIGO and Virgo Collaborations, ApJL, 892:L3, 2020

GW190521: discovery of an intermediate mass black hole

Binary black hole merger at 5.3 Gpc
See Abbott et al. Phys. Rev. Lett. 125, 101102 (2020) and Abbott et al. ApJ Lett. 900, L13 (2020)

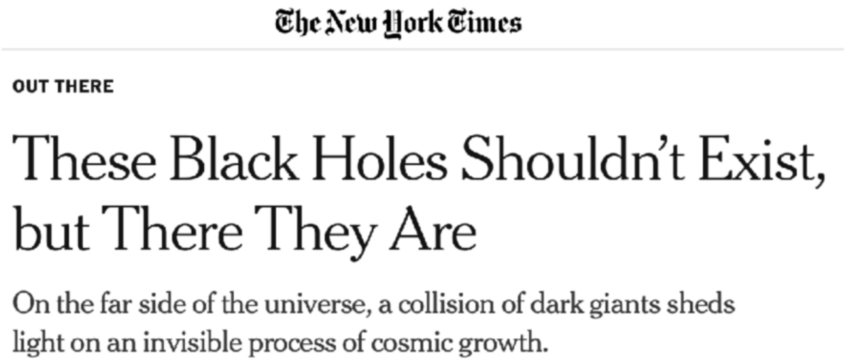
A massive binary black hole merger encroaching on the pair-instability mass gap



m_1	m_2	$m_{\rm tot}$
$\sim 85\,{\rm M}_\odot$	$\sim 66\,{\rm M}_\odot$	$\sim 150\,{\rm M}_\odot$

Remarks:

- GW190521: Triple LIGO-Virgo open public alert of a BBH candidate at 3931±953 Mpc and 765 deg^2
- Most massive GW binary observed to-date
- First clear detection of “intermediate mass” black hole
- Primary sits squarely in expected mass gap between 50 and 120 solar mass
- Also challenging for standard formation scenarios!

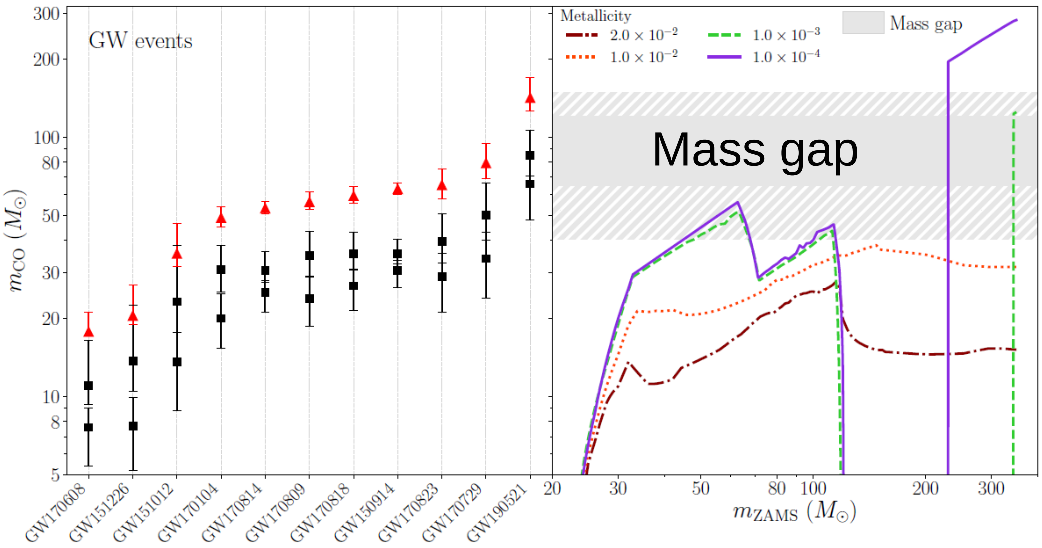


The New York Times

OUT THERE

These Black Holes Shouldn’t Exist, but There They Are

On the far side of the universe, a collision of dark giants sheds light on an invisible process of cosmic growth.

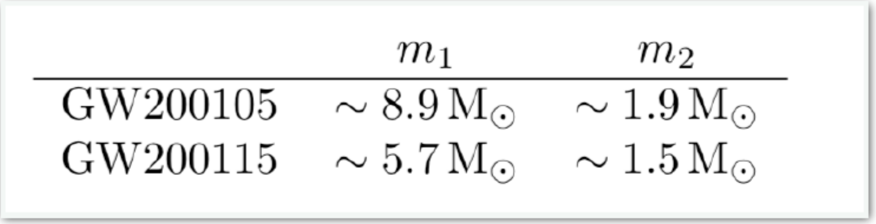


GW200105 & GW200115: two neutron star-black hole coalescences

First detections of neutron star-black hole systems: a new type of astrophysical system
See Abbott et al. ApJ Lett. 915, L5 (2021)

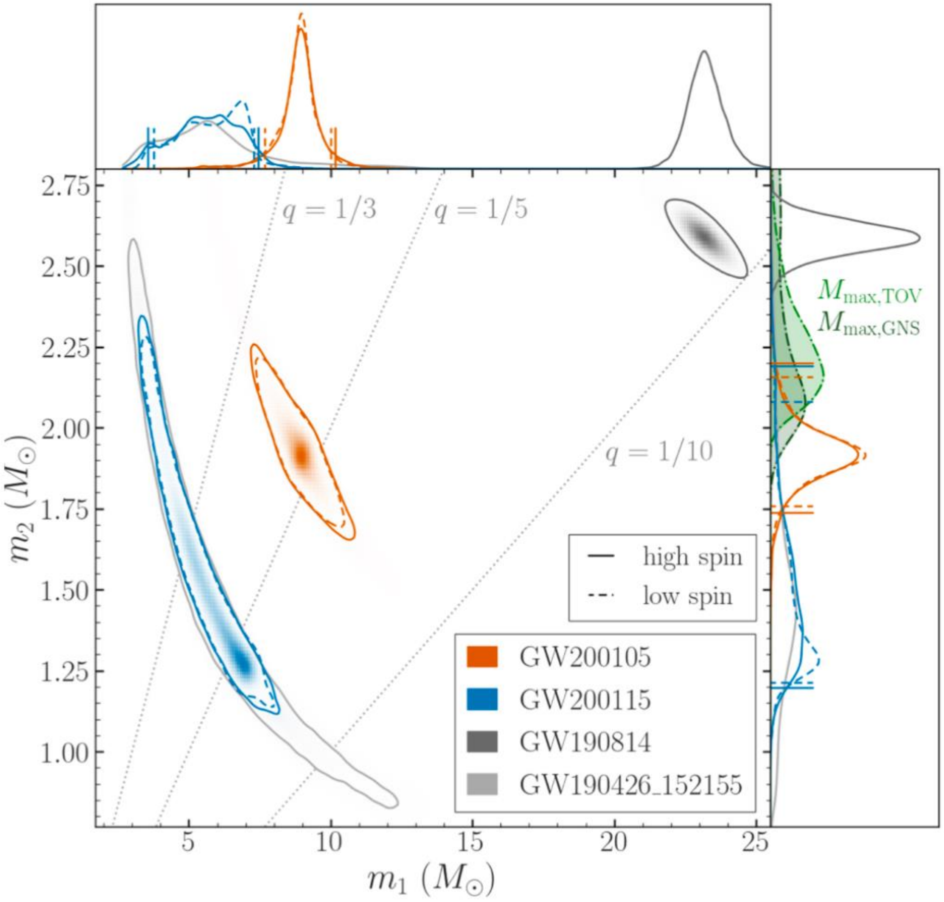
Remarks:

- No EM counterpart observed (as expected)
- GW200115: preference for spin to be anti-aligned with orbital angular momentum



	m_1	m_2
GW200105	$\sim 8.9\,\mathrm{M}_\odot$	$\sim 1.9\,\mathrm{M}_\odot$
GW200115	$\sim 5.7\,\mathrm{M}_\odot$	$\sim 1.5\,\mathrm{M}_\odot$

- Luminosity distances 280 and 300 Mpc



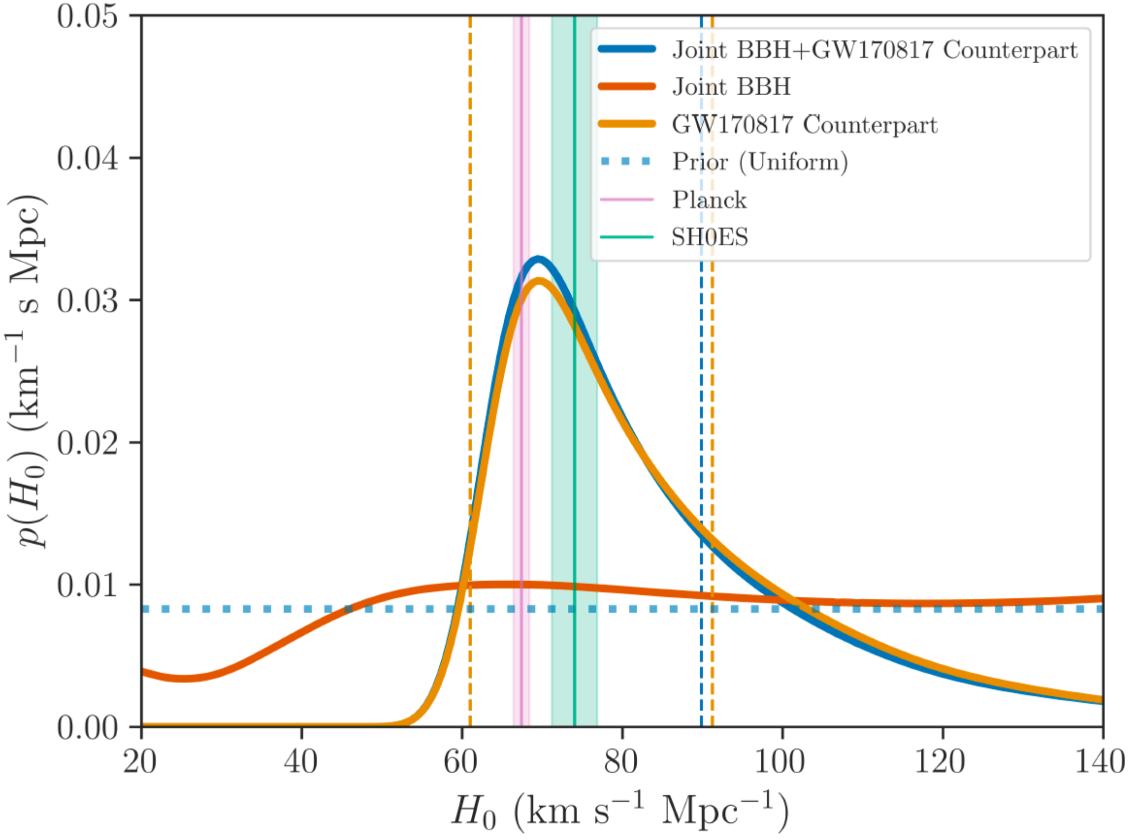
Update: improved LVK Hubble constant measurement

Gravitational-wave measurement of the Hubble constant following the second observing run of Advanced LIGO and Virgo
See Abbott et al. ApJ 909, 218 (2021)

Analysis uses 11 confident detections from GWTC-1 (BBHs and GW170817)

$$H_0 = 69^{+16}_{-8}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

Uncertainty reduced by 4%!



Release of Open Public Alerts

LIGO and Virgo Collaborations release Open Public Alerts, with low latency, for all interesting signal triggers, and follow-up information sufficient for non-GW observers to find hosts. We also release data and data analysis software

For a quick overview of all our new papers
See our Science Summaries available in multiple languages:
https://www.ligo.org/science/outreach.php

You can also find tutorials, GW data analysis software and other tools
at our Gravitational Wave Open Science Center:
https://www.gw-openscience.org/about/

If you'd like to receive alerts about new GW detections
Check out our LIGO/Virgo Public Alerts User Guide:
https://emfollow.docs.ligo.org/userguide/

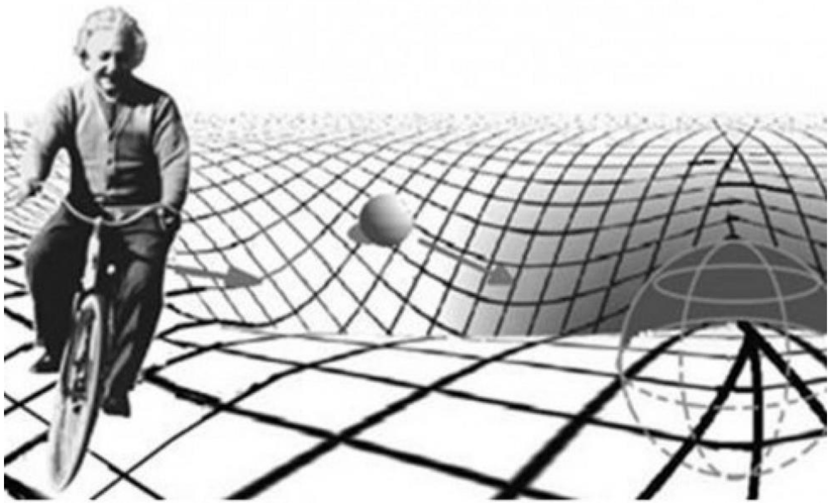
Outlook

Einstein predicts existence of gravitational waves

Einstein publishes his discovery in Sitzungberichte Preussische Akademie der Wissenschaften, 22 June 1916 and on 14 February 1918

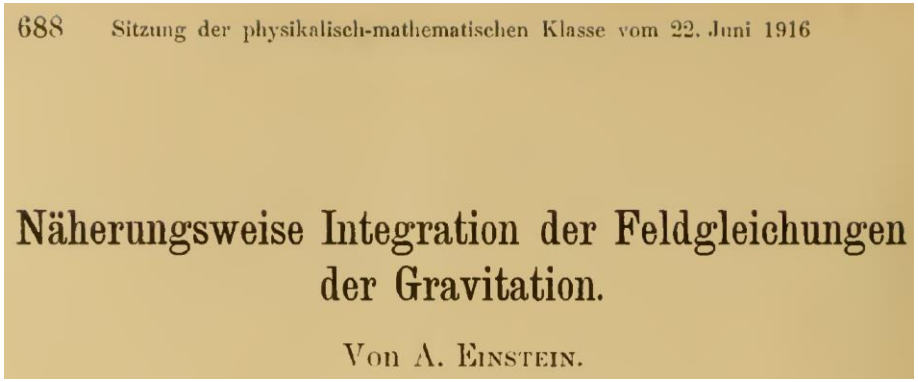
Einstein's Gravity

- Space and time are physical entities
- Gravity as a geometry



Predictions

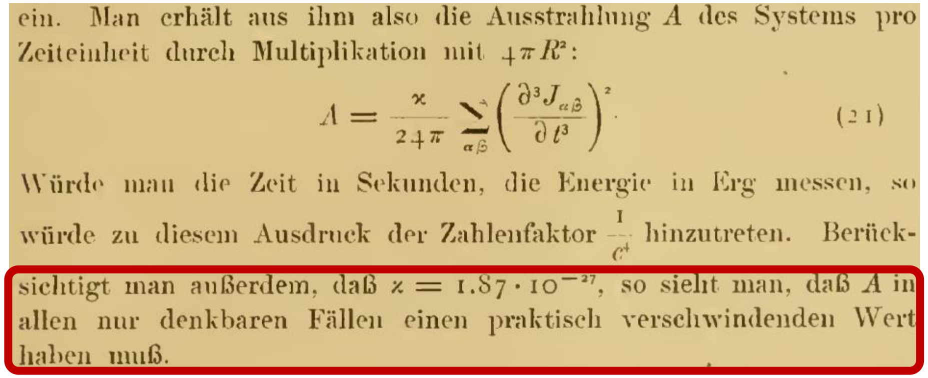
- Gravitation is curvature of spacetime
- Light bends around the Sun
- Expansion of the Universe
- Black holes, wormholes, structure formation, …
- Gravitational waves: curvature perturbations in the spacetime metric



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

Näherungsweise Integration der Feldgleichungen der Gravitation.

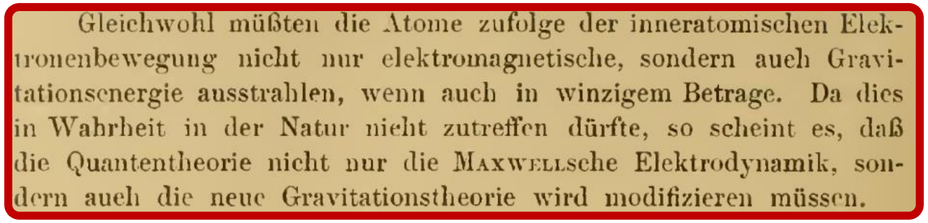
Von A. Einstein.



ein. Man erhält aus ihm also die Ausstrahlung A des Systems pro Zeiteinheit durch Multiplikation mit $4\pi R^2$:

$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right)^2 . \qquad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

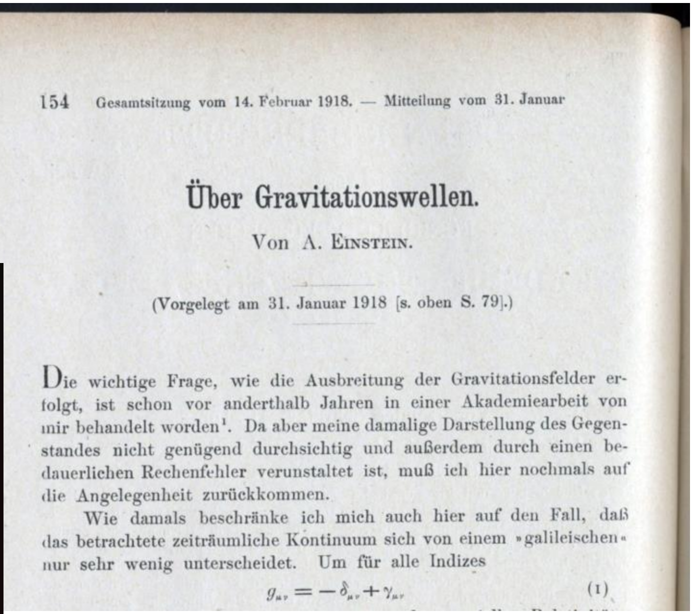


Gleichwohl müßten die Atome zufolge der inneratomischen Elektronenbewegung nicht nur elektromagnetische, sondern auch Gravitationsenergie ausstrahlen, wenn auch in winzigem Betrage. Da dies in Wahrheit in der Natur nicht zutreffen dürfte, so scheint es, daß die Quantentheorie nicht nur die Maxwellsche Elektrodynamik, sondern auch die neue Gravitationstheorie wird modifizieren müssen.

Gravitational waves

Einstein publishes his discovery in Sitzungberichte Preussische Akademie der Wissenschaften, 22 June 1916 and on 14 February 1918

Curvature perturbations in the spacetime metric that propagate with the speed of light



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

Über Gravitationswellen.

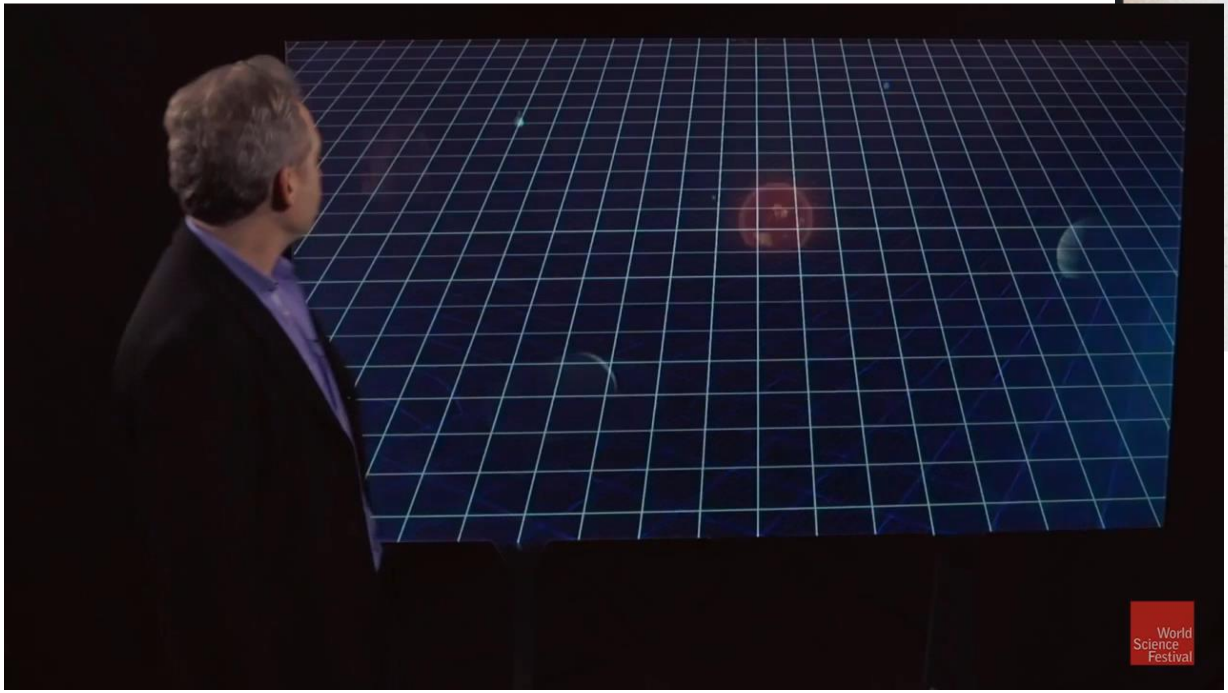
Von A. Einstein.

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

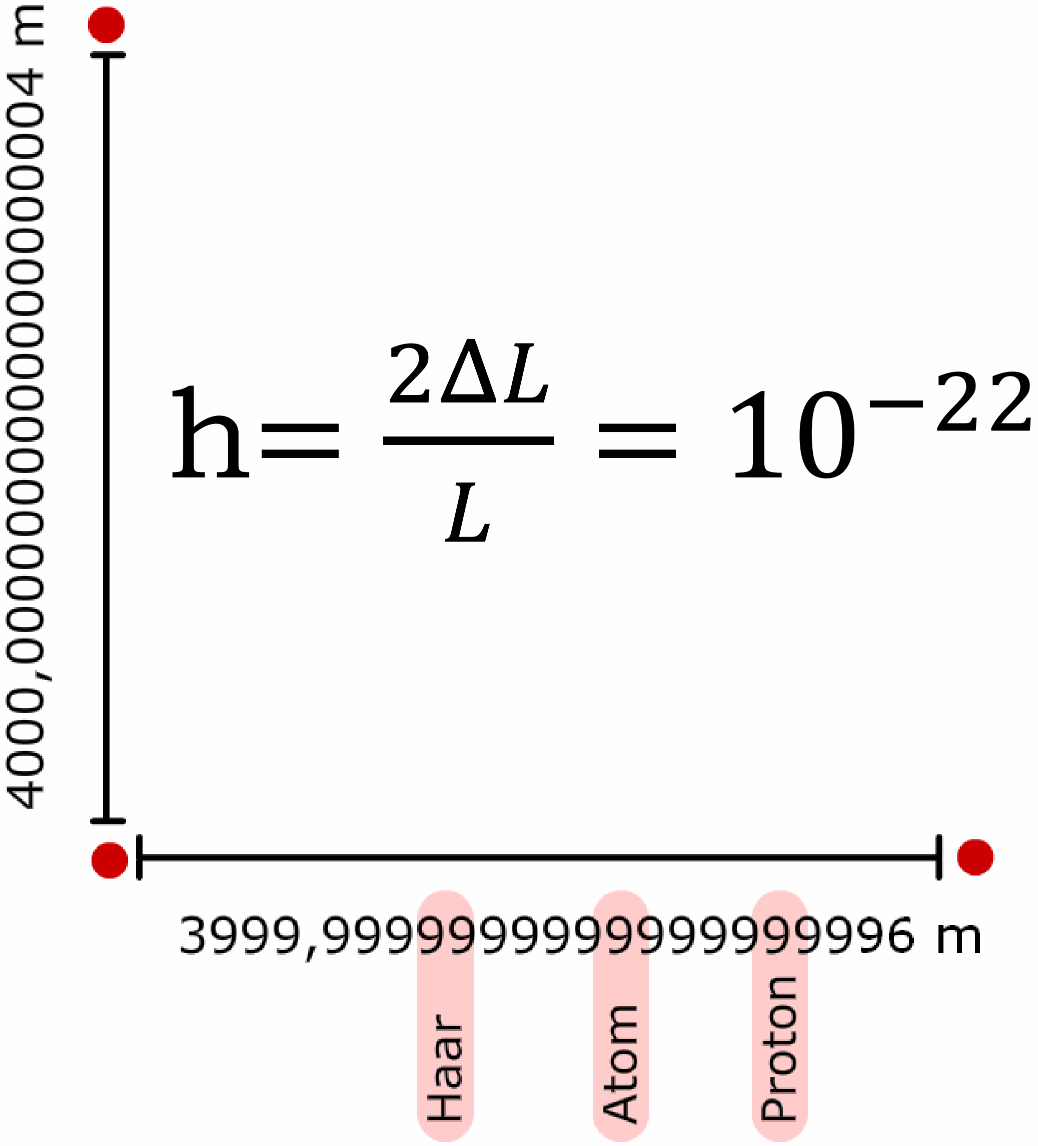
Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden[1]. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$



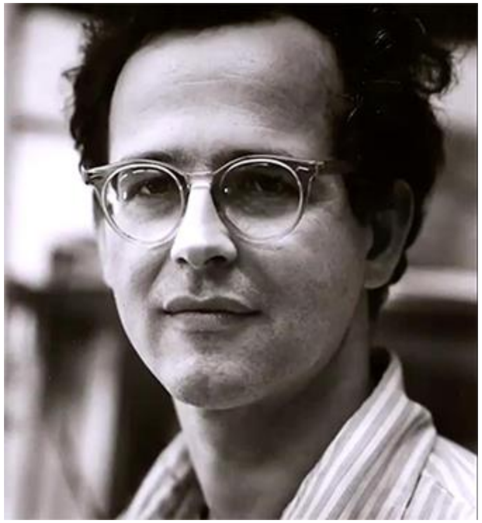
Gravitational waves can be measured with an ITF



$$h = \frac{2\Delta L}{L} = 10^{-22}$$

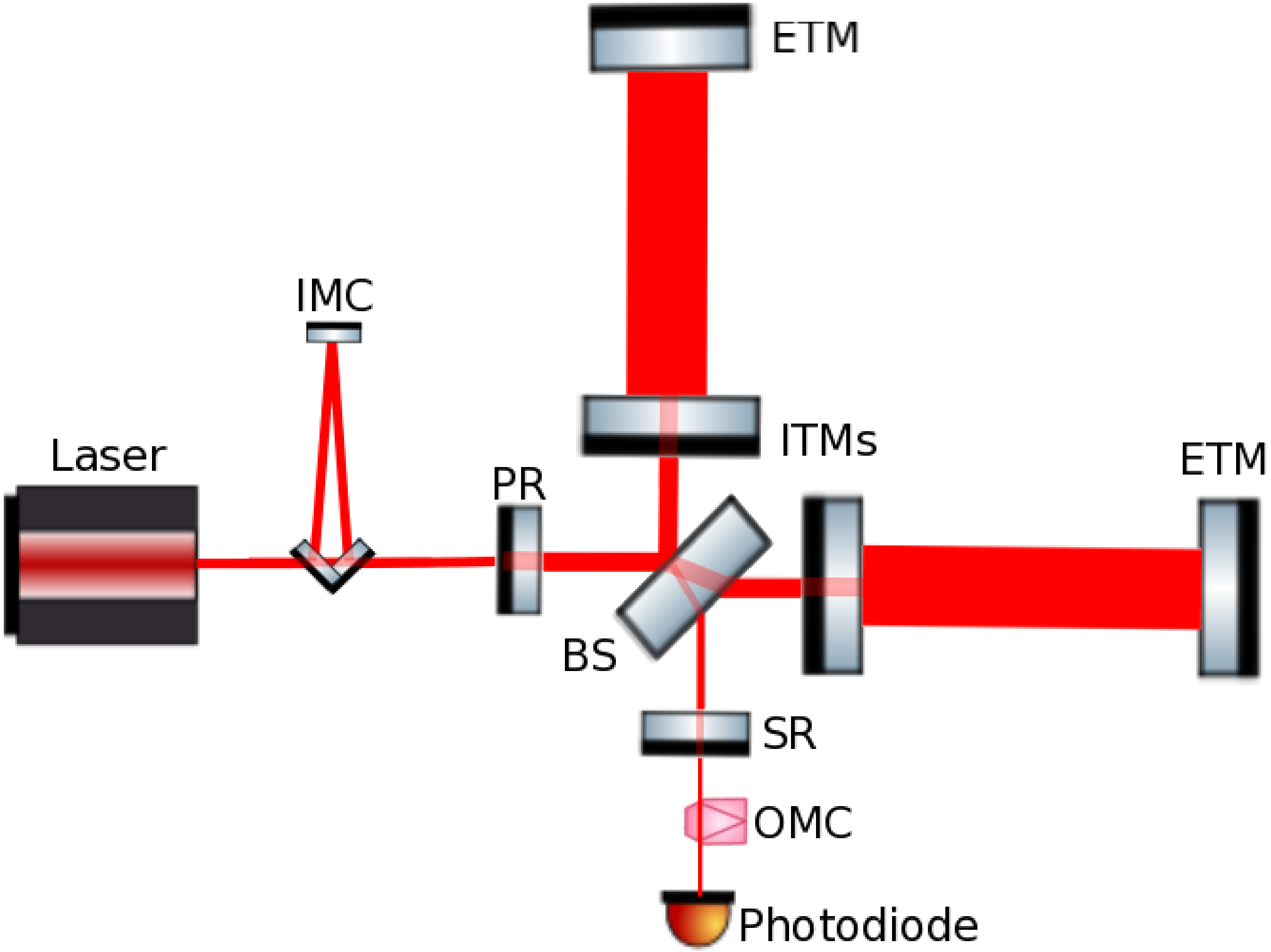
In 1964, Rai Weiss was at MIT as a professor, and assigned to teach general relativity.

He asked, What’s really measurable in general relativity? He found the answer in Pirani’s papers presented at Chapel Hill in 1957



Dual recycled Fabry-Perot interferometer

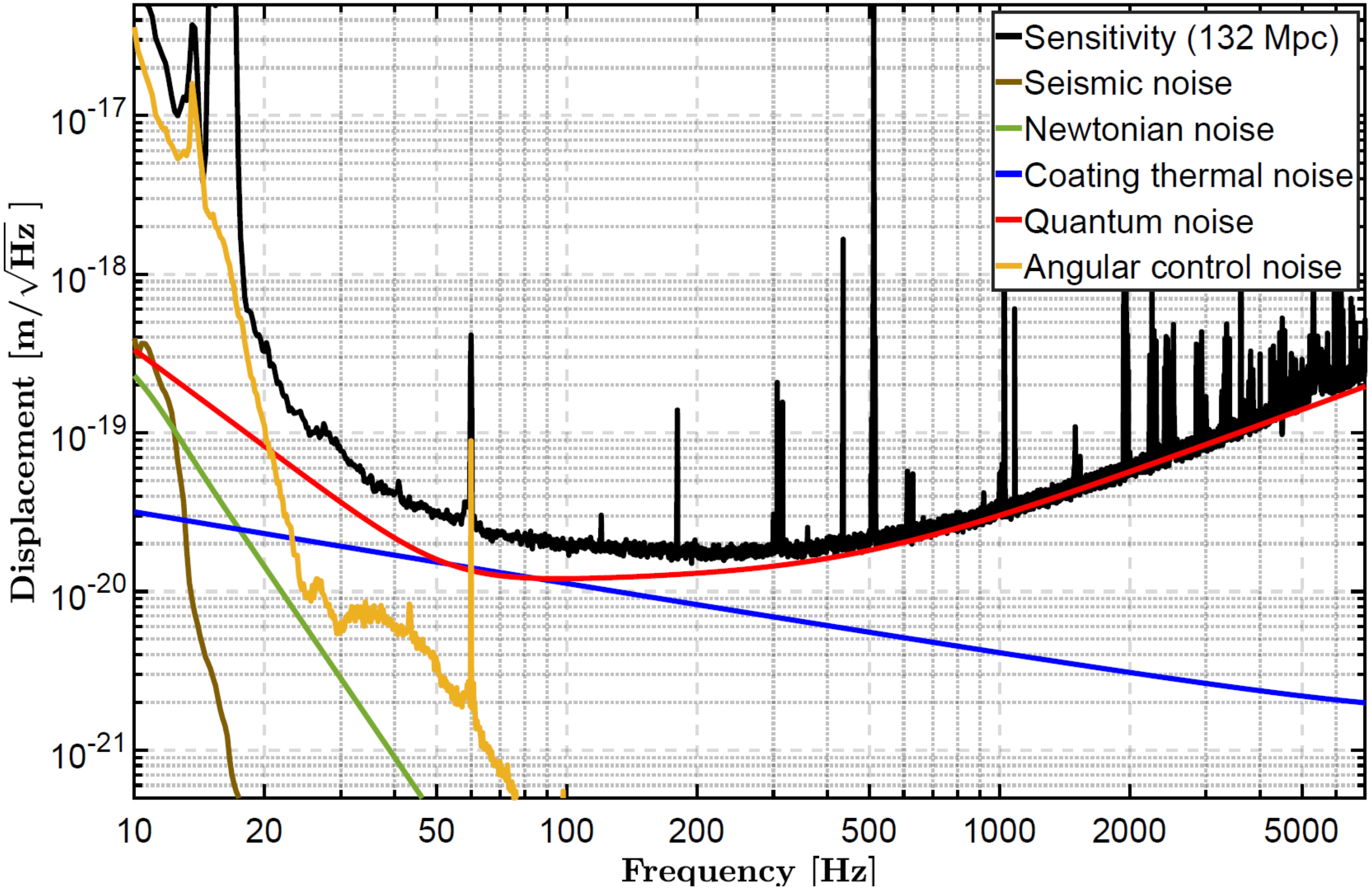
LIGO and Virgo will use dual recycled Fabry-Perot interferometers including input mode cleaner and output mode cleaner



Sensitivity curve of LIGO Livingston on April 2019

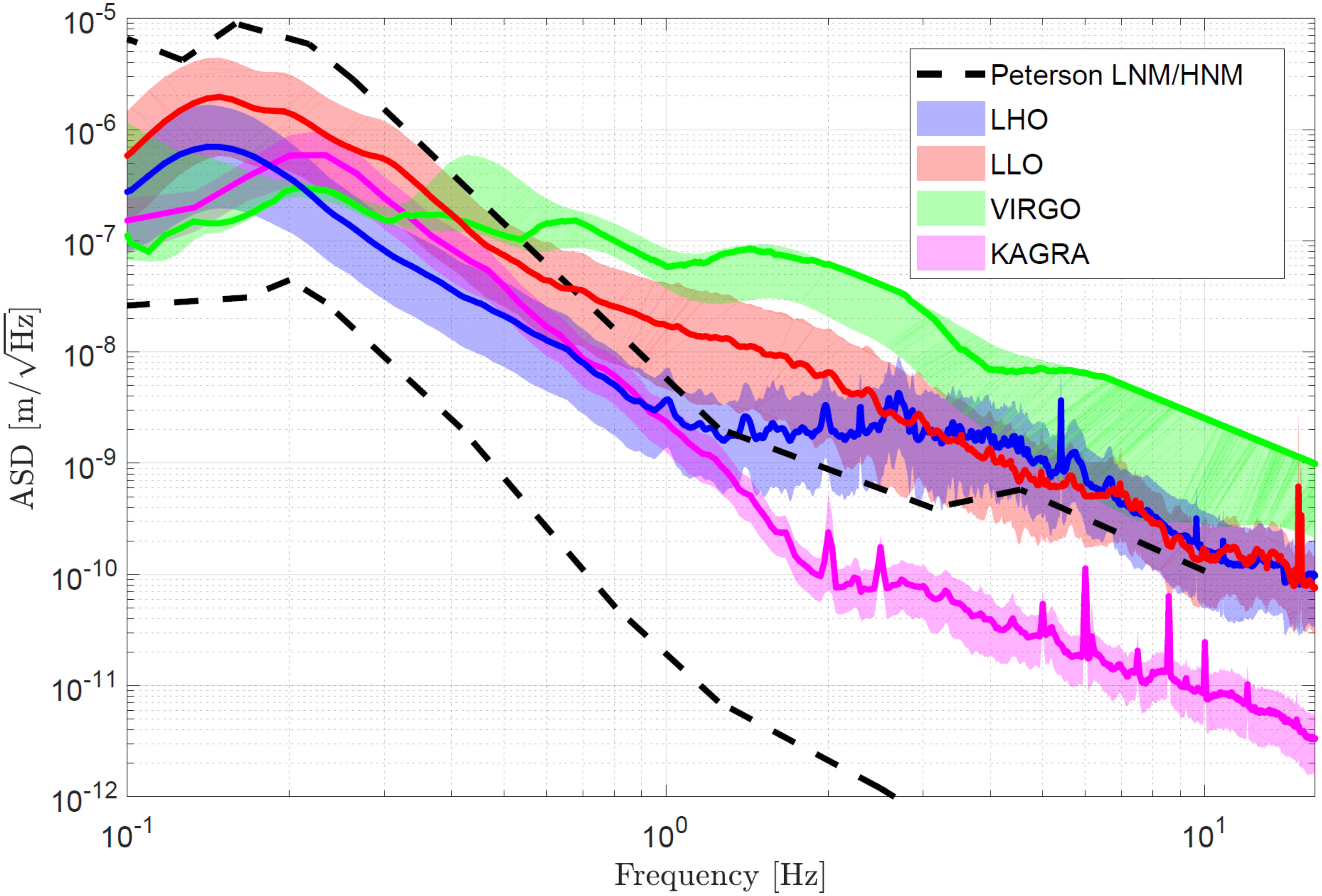
Most important fundamental and technical noise sources are shown

The range is the distance to which a binary neutron star system could be detected (averaged over all sky orientations)



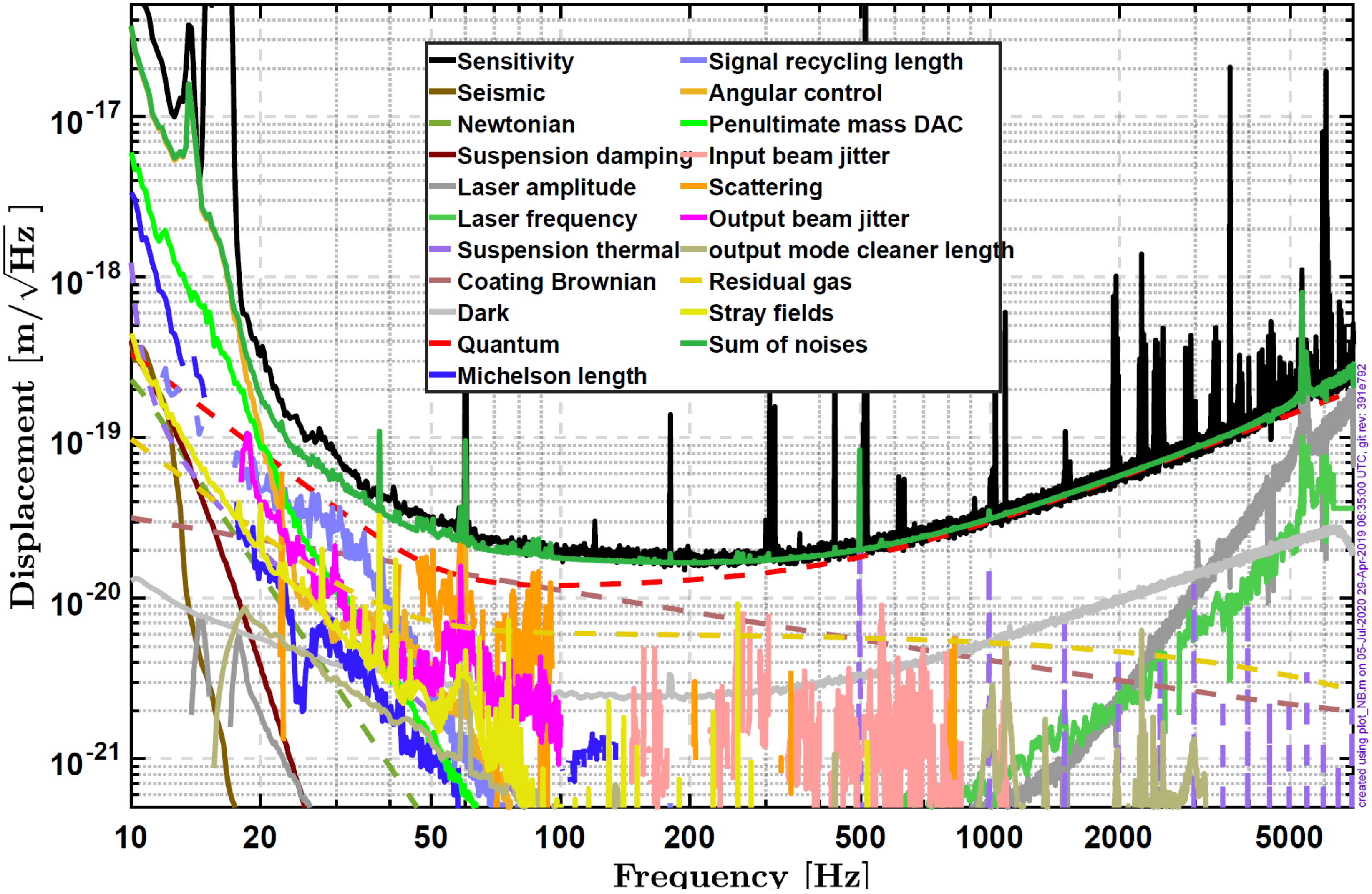
Seismic noise at the various detector sites

Amplitude spectral density of seismic noise in the horizontal direction at each of the LIGO, VIRGO and KAGRA sites. The solid curves represent the mode, while the shaded bands show the10th to 90th percentiles. The dashed curves represent Peterson’s low and high noise models



Noise budget of Advanced LIGO

Solid curves show measured noise projections and dashed curves are models. The incoherent sum of all known noise sources matches the measured noise curve



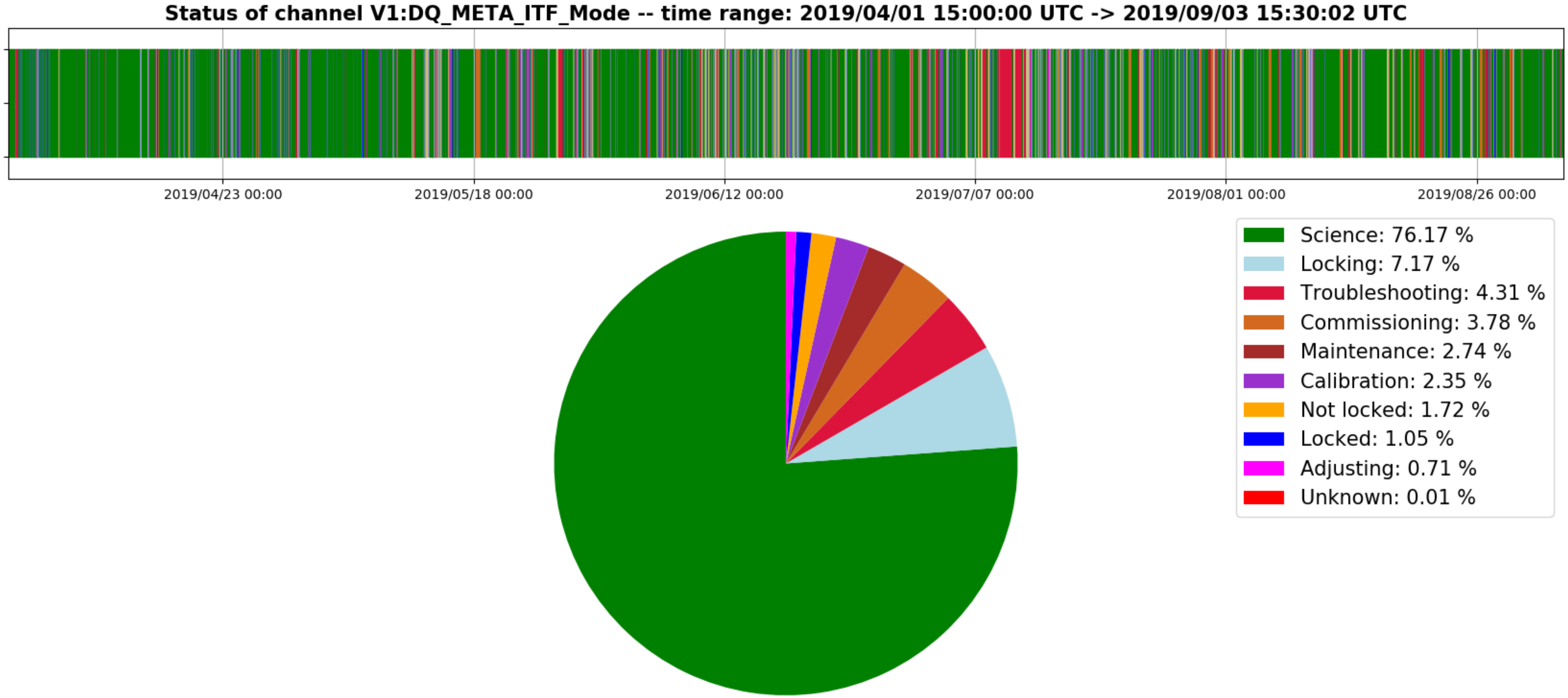
Virgo interferometer

Virgo interferometer

O3a 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

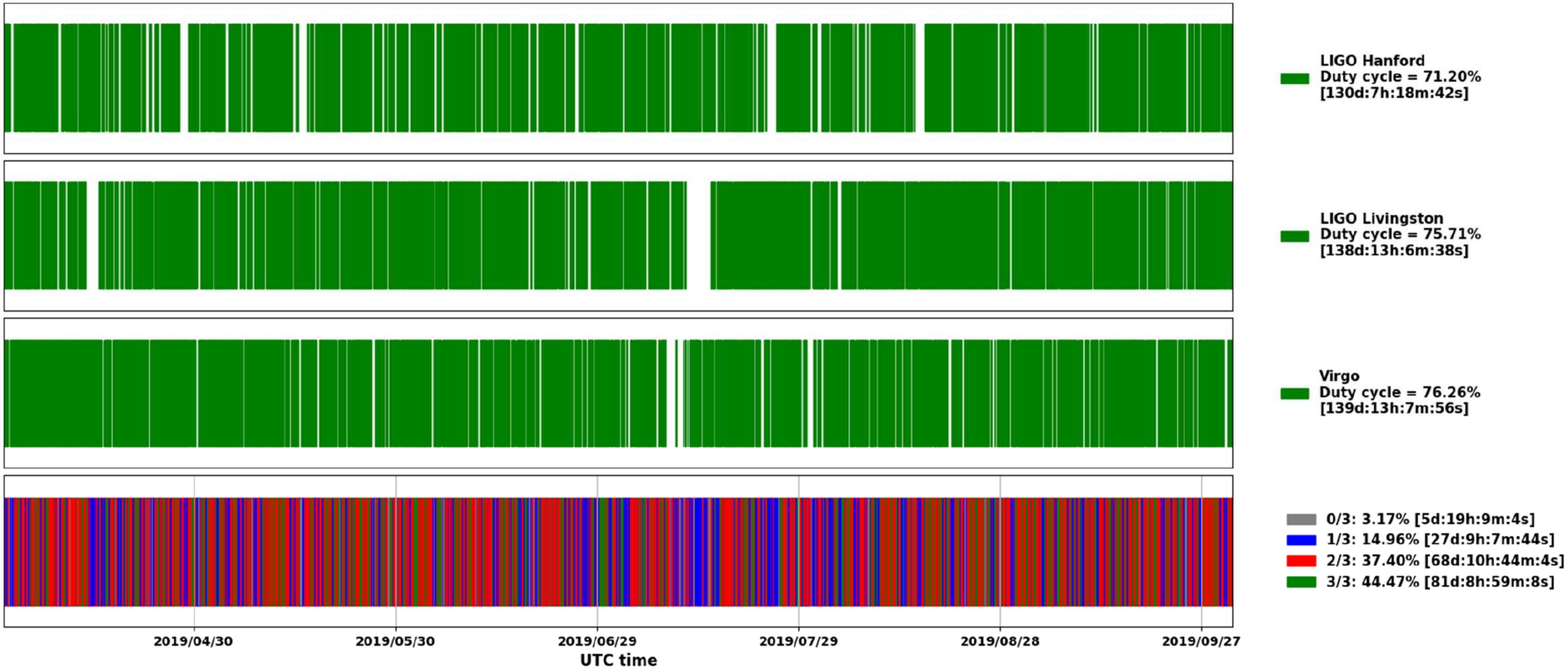
Efficiency higher than 83% without considering calibration, maintenance and commissioning



Status of channel V1:DQ_META_ITF_Mode -- time range: 2019/04/01 15:00:00 UTC -> 2019/09/03 15:30:02 UTC

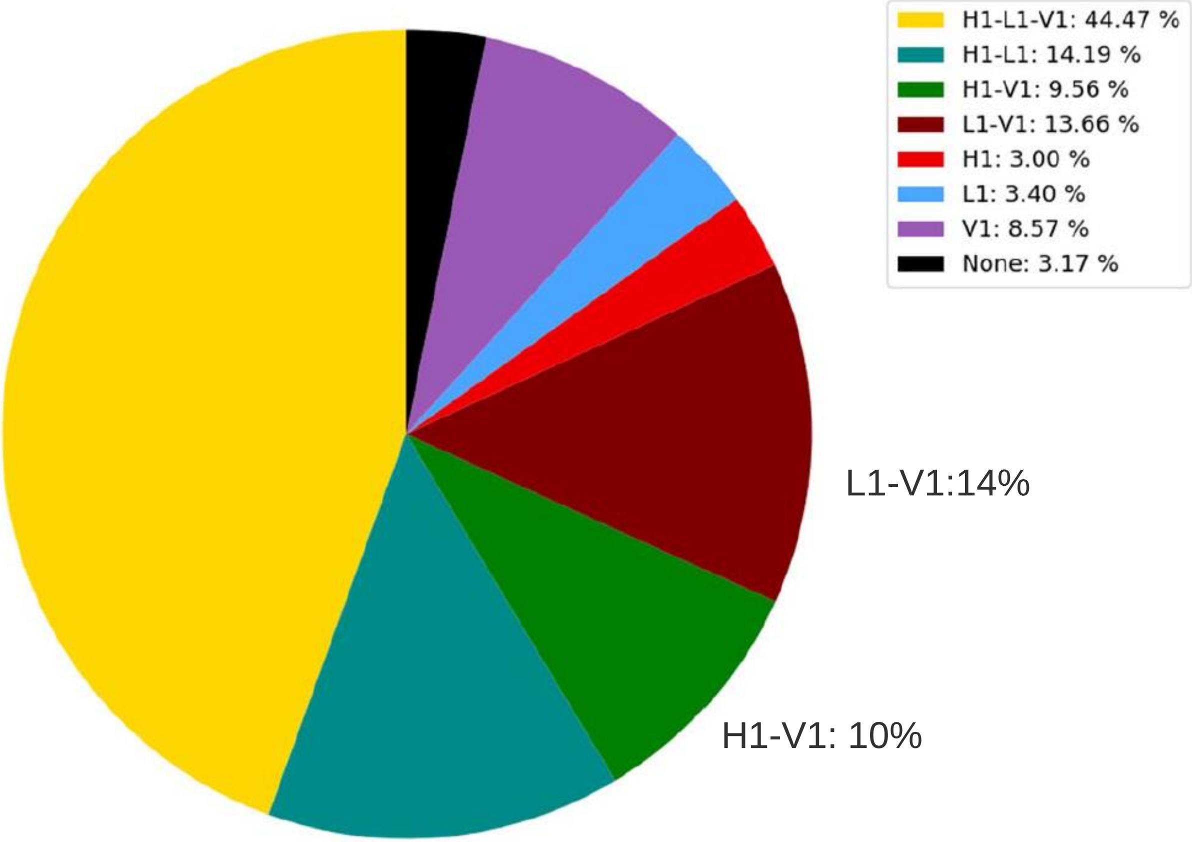
O3a Summary: network performance

Triple event efficiency about 44.5% double events about 37.4%, single 15.0% and no detector 3.2%



O3a Summary: number of detectors online

At least 2 detectors online for 82% of the time



HLV: 44%

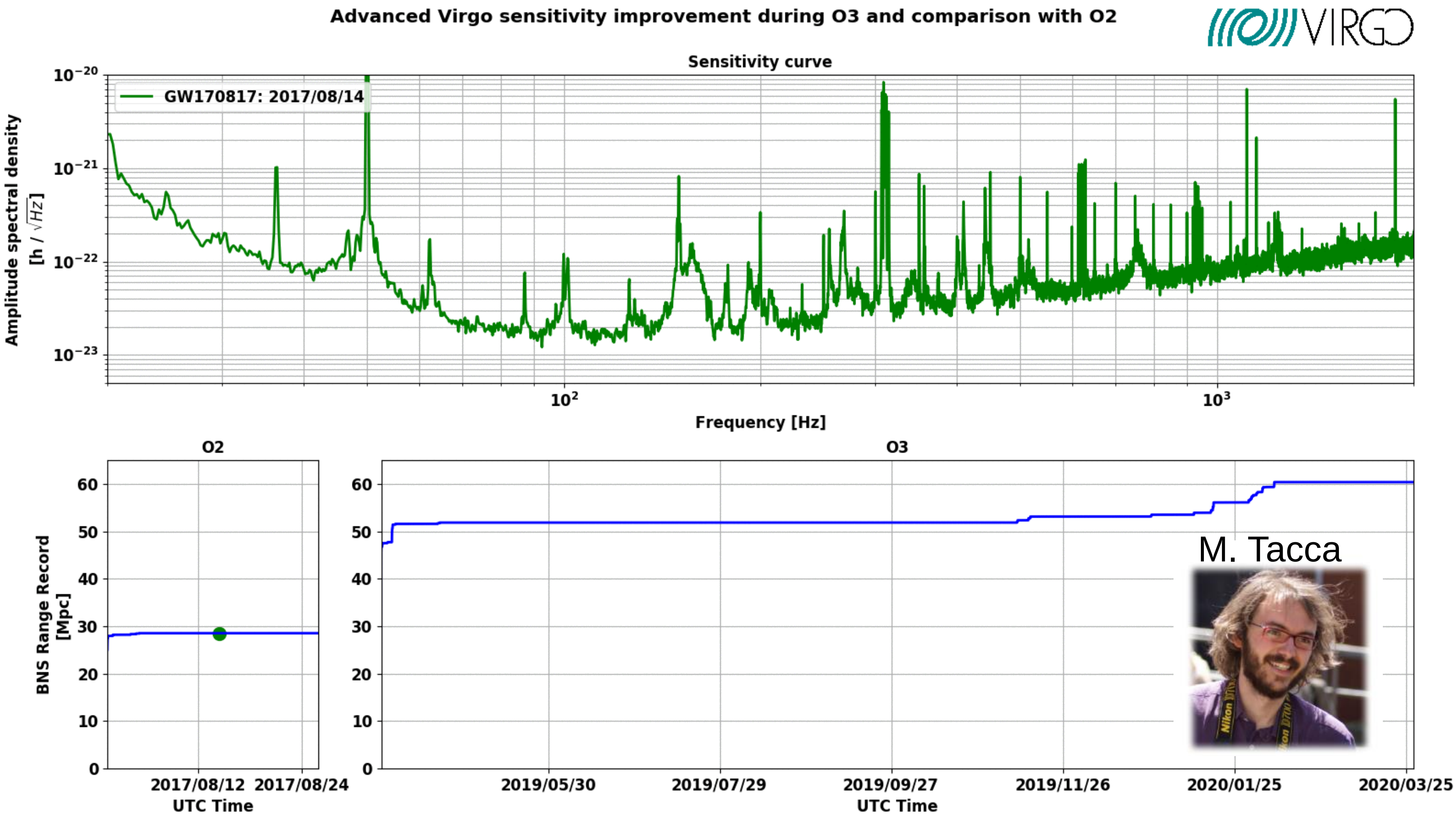
L1-V1:14%

H1-V1: 10%

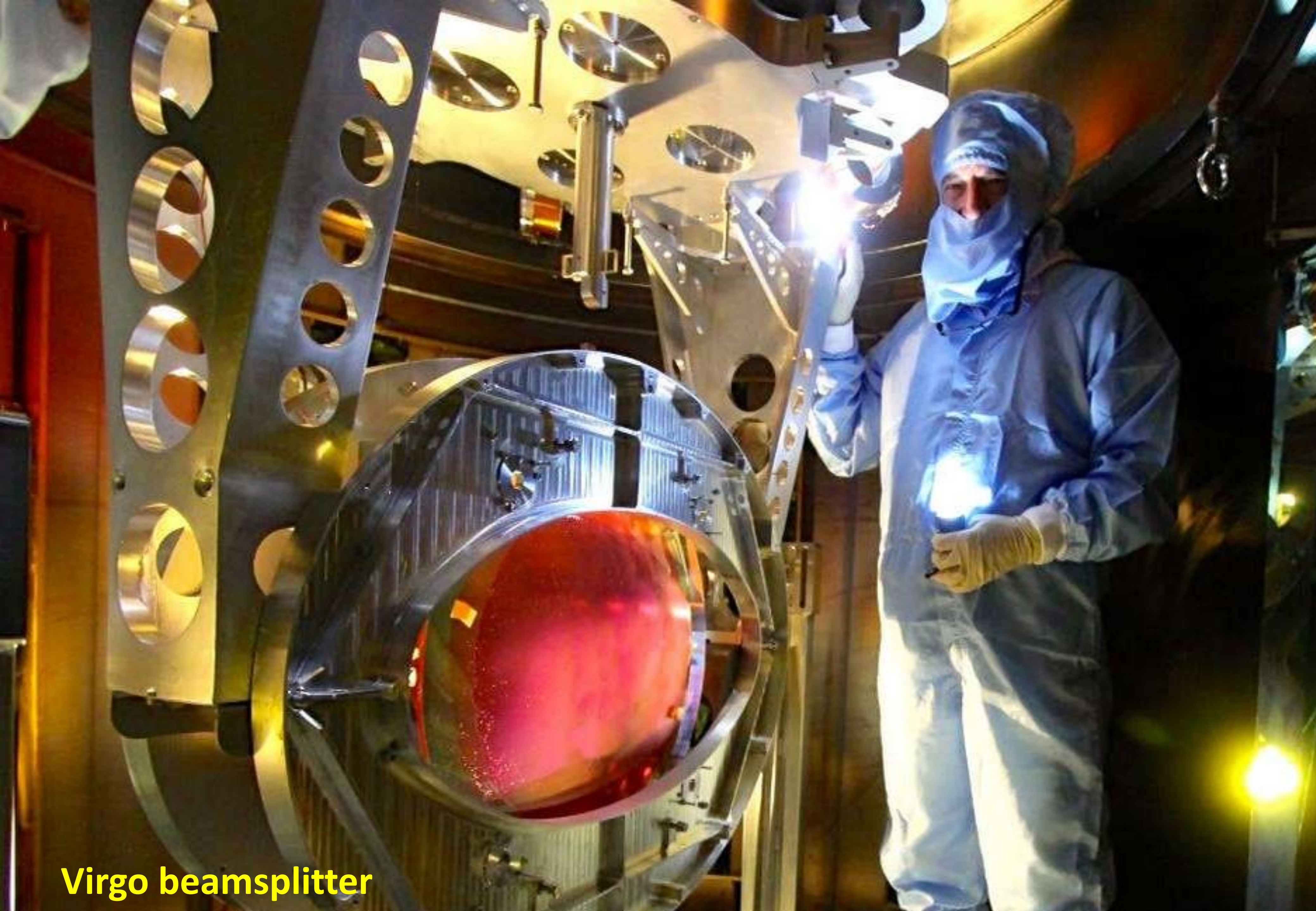
H1-L1: 14%

Delivering on a promise

AdV sensitivity improvement during O3 and comparison with O2



M. Tacca

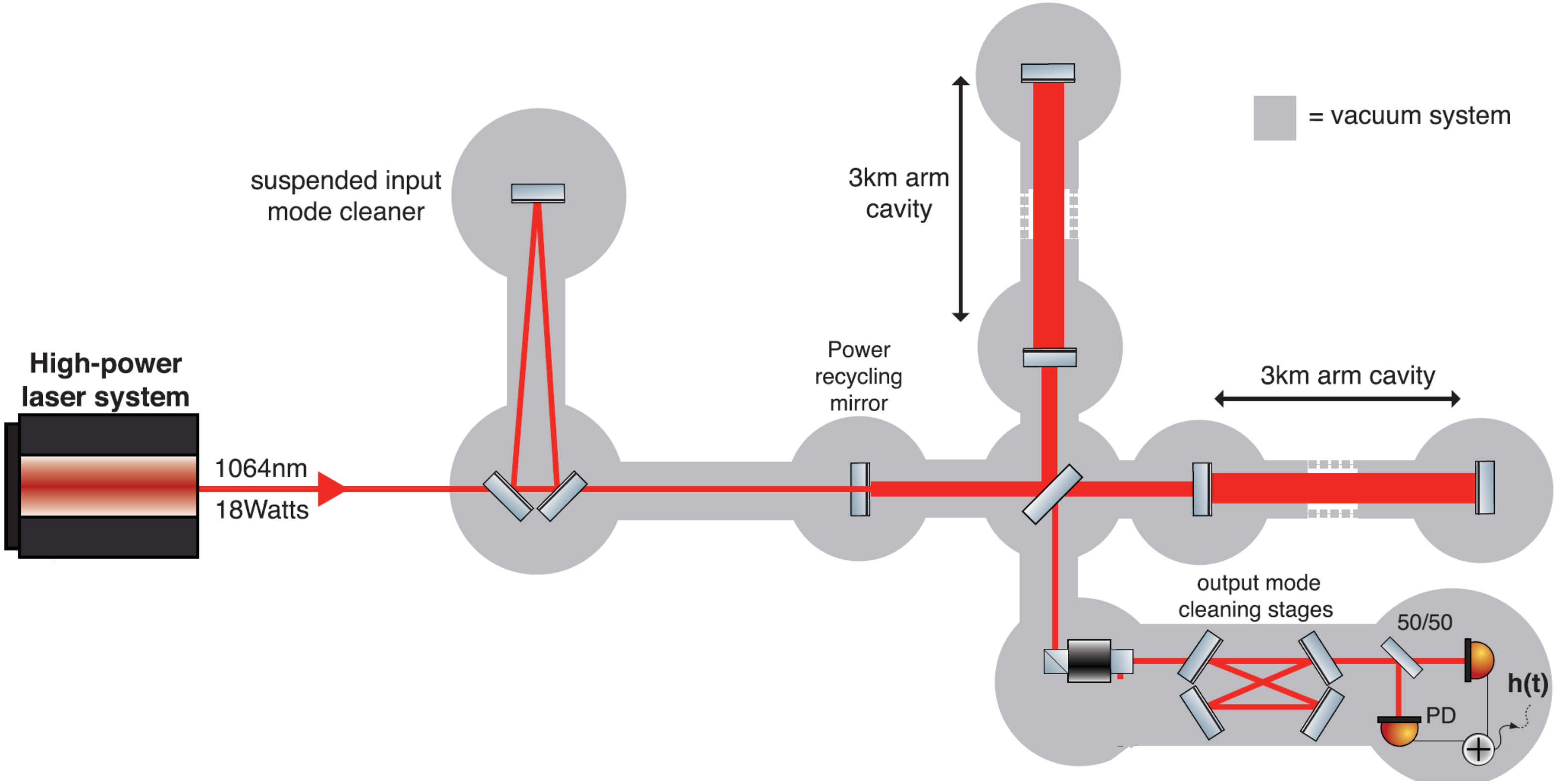


Virgo beamsplitter

LIGO mirror

Advanced Virgo: optical configuration

In O3a Virgo injected 18 W of power. In O3b Virgo injected 26 W of power in the interferometer.
Signal recycling will be implemented after O3

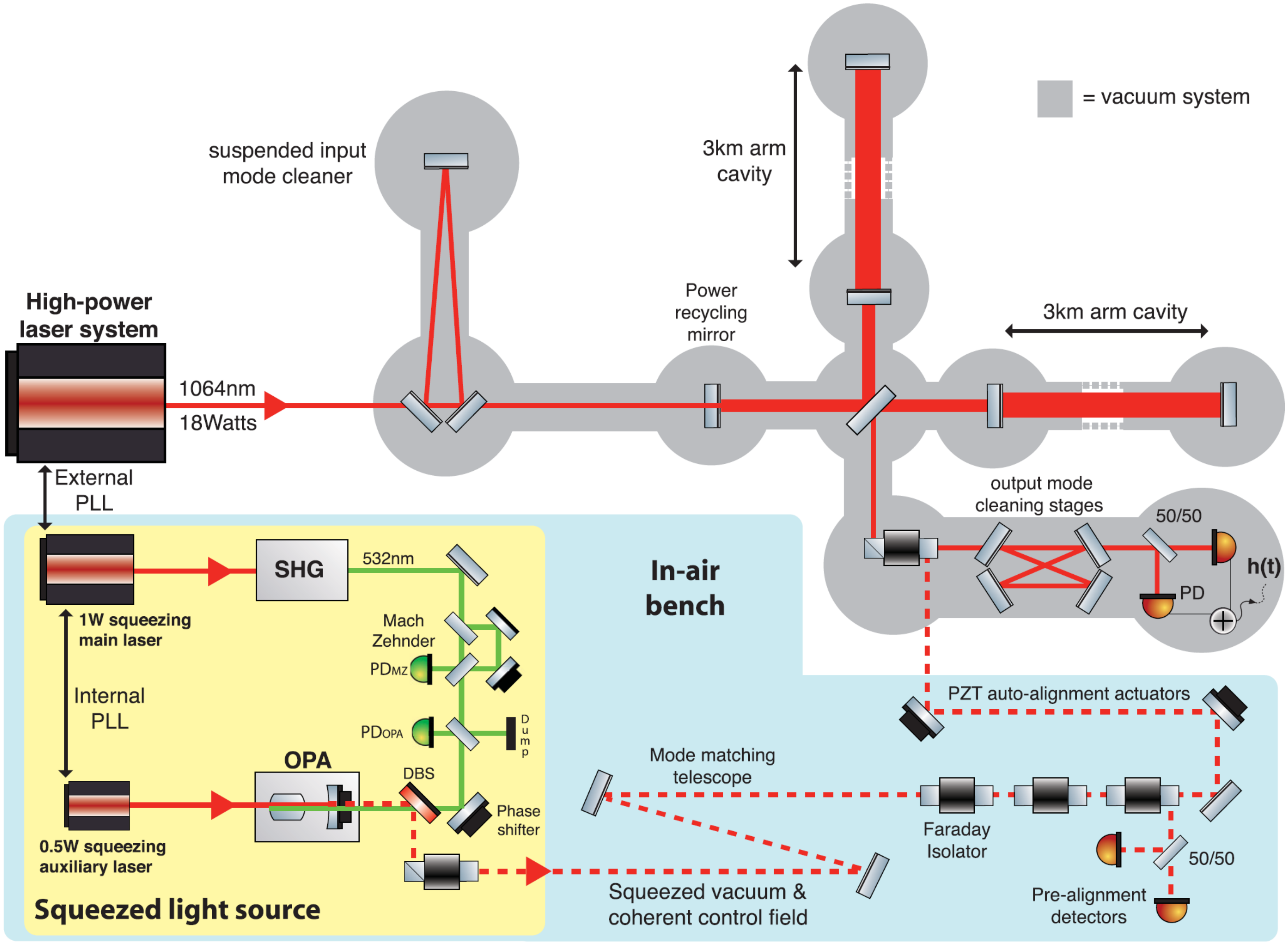


High frequency sensitivity is limited by shot noise

Detailed understanding in full quantum-mechanical treatment of system and detector

Advanced Virgo: optical configuration

Virgo injects 26 W of power in the interferometer. Signal recycling will be implemented after O3



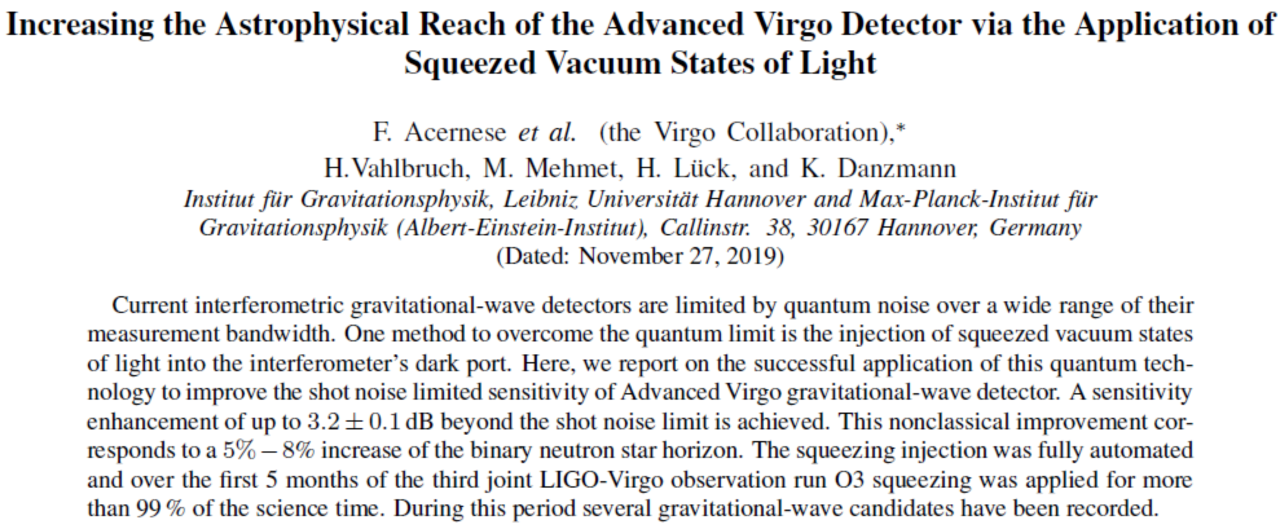
Quantum enhanced Advanced Virgo gravitational-wave detector

Application of squeezed vacuum states of light


Virgo squeezer from AEI

Virgo’s squeezing paper

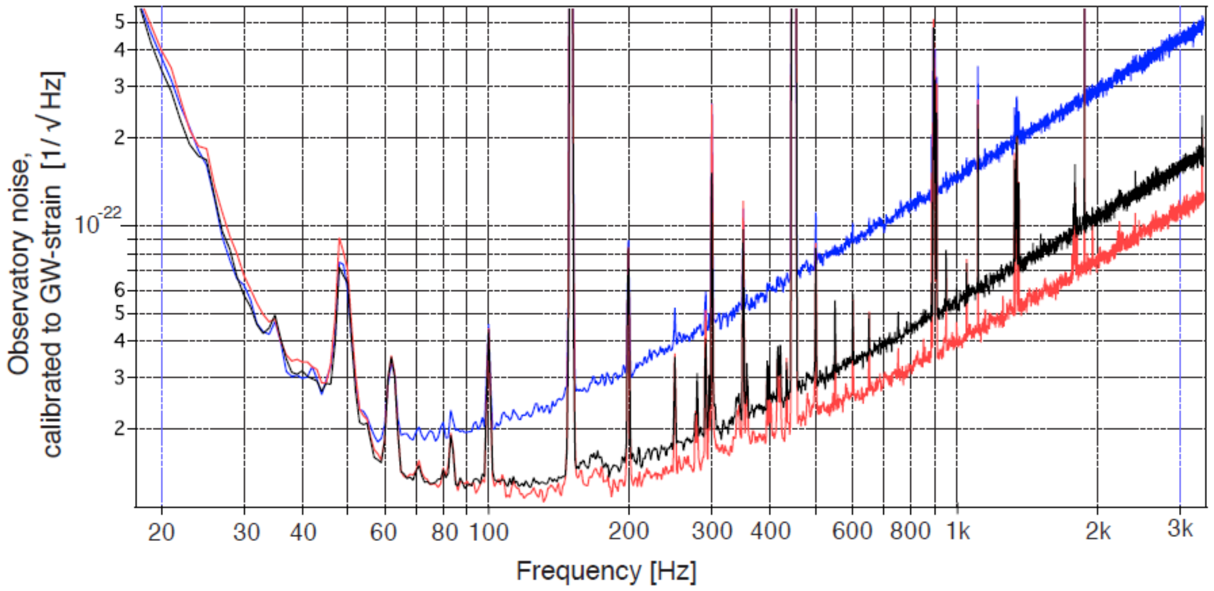
Beautiful work! Publication appeared in PRL on December 5, 2019

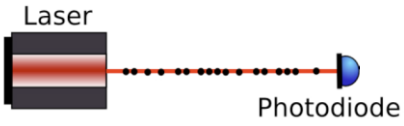


Increasing the Astrophysical Reach of the Advanced Virgo Detector via the Application of Squeezed Vacuum States of Light

F. Acernese *et al.* (the Virgo Collaboration),*
H. Vahlbruch, M. Mehmet, H. Lück, and K. Danzmann
Institut für Gravitationsphysik, Leibniz Universität Hannover and Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Callinstr. 38, 30167 Hannover, Germany
(Dated: November 27, 2019)

Current interferometric gravitational-wave detectors are limited by quantum noise over a wide range of their measurement bandwidth. One method to overcome the quantum limit is the injection of squeezed vacuum states of light into the interferometer’s dark port. Here, we report on the successful application of this quantum technology to improve the shot noise limited sensitivity of Advanced Virgo gravitational-wave detector. A sensitivity enhancement of up to 3.2 ± 0.1 dB beyond the shot noise limit is achieved. This nonclassical improvement corresponds to a $5\% - 8\%$ increase of the binary neutron star horizon. The squeezing injection was fully automated and over the first 5 months of the third joint LIGO-Virgo observation run O3 squeezing was applied for more than 99 % of the science time. During this period several gravitational-wave candidates have been recorded.





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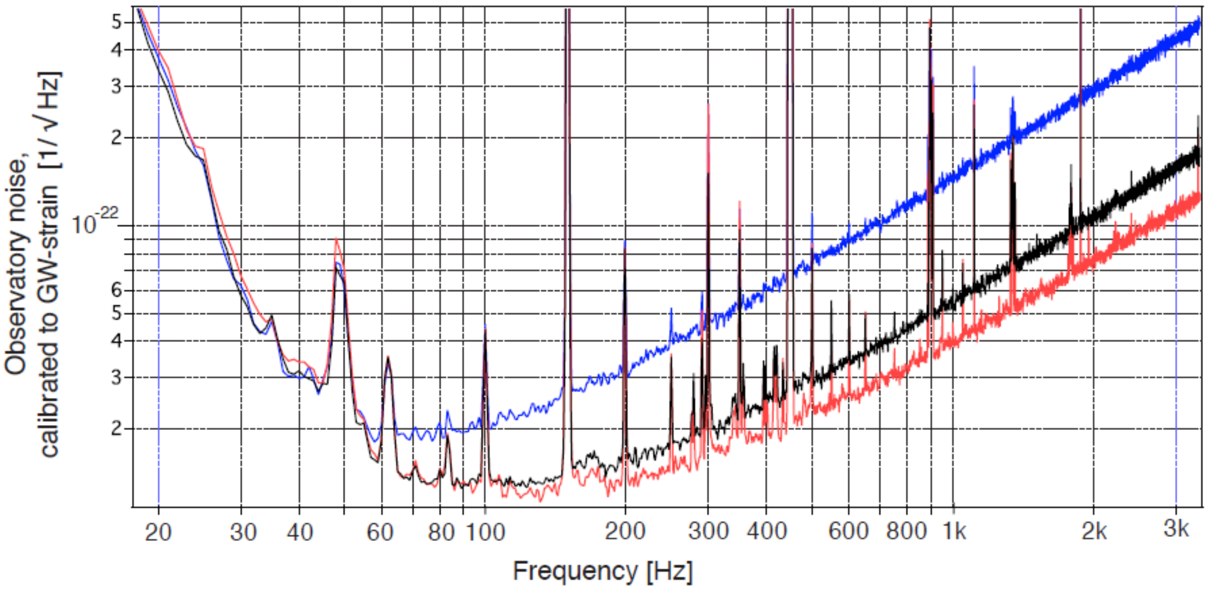
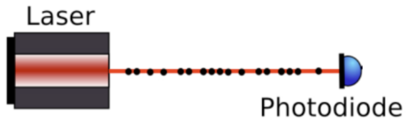
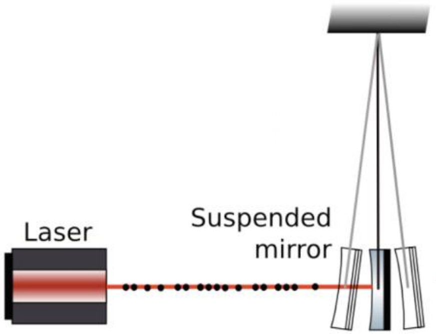






The path forward …

AdV+ as the next step forward in Virgo sensitivity

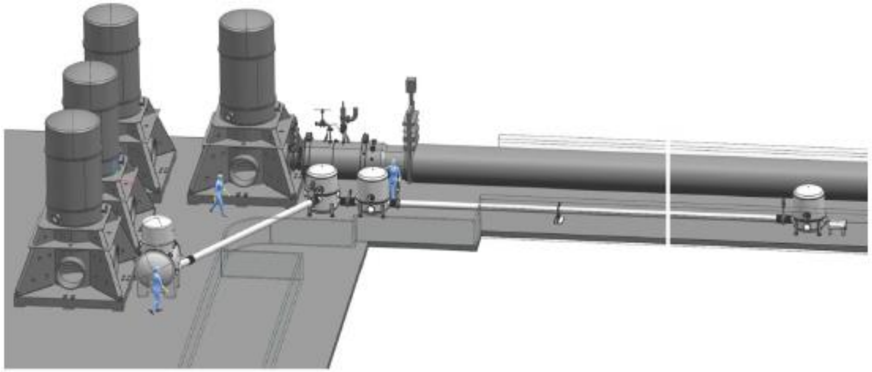
AdV+ will maximize Virgo's sensitivity within the constrains of the EGO site. It has the potential to increase Virgo's detection rate by up to an order of magnitude

AdV+ features

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

Upgrade activities: we now need to discuss Phase 2

- 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



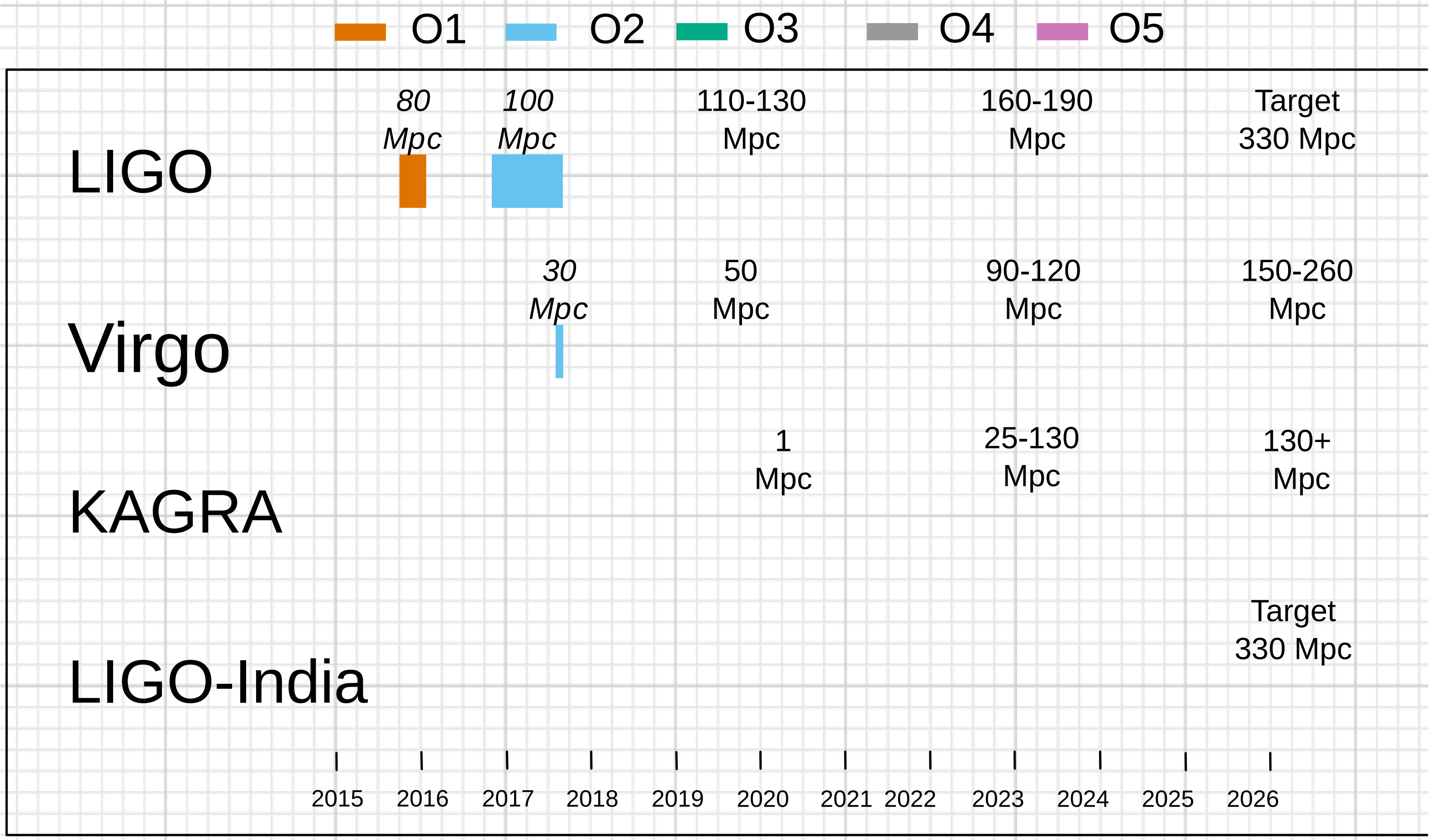
Phase 2 timeline

- Stringent time constrains due to international context: LIGO, Indigo, KAGRA

Timeline for future science runs

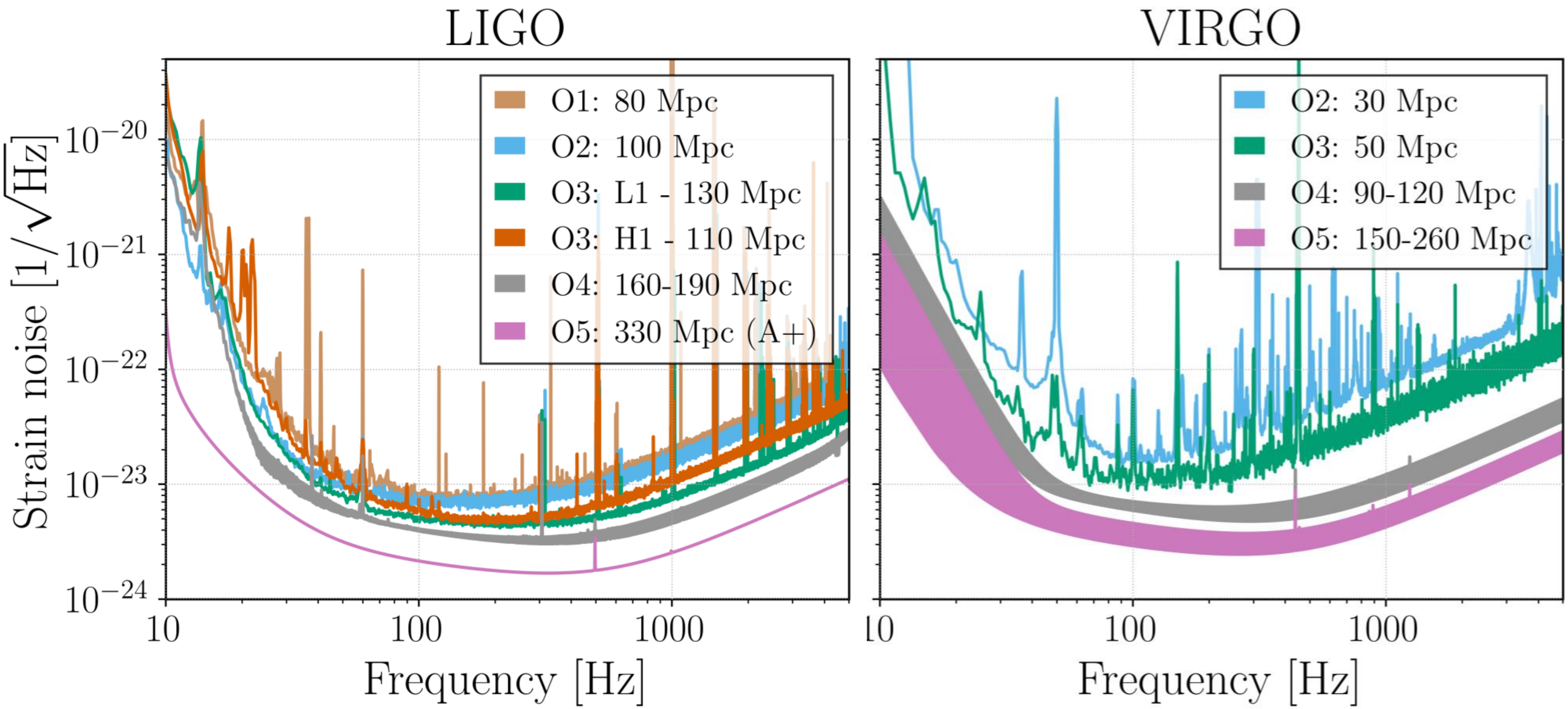
AdV+ and A+ will be carried out in two steps
This allows installation and commissioning in between O4 and O4

O4 is scheduled to start in second-half of 2022



Sensitivity targets for A+ and AdV+

Detector noise expressed as equivalent GW strain



AdV+ phase 1

Signal recycling will be implemented after O3, higher laser power, and improved squeezing

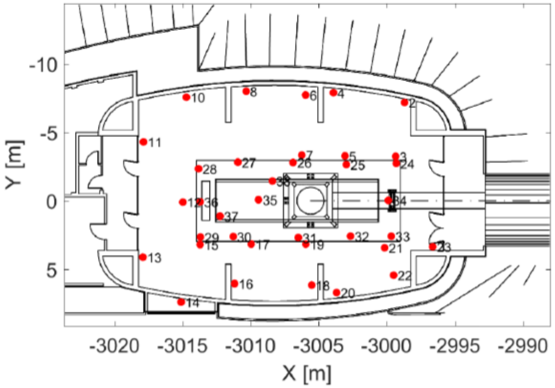
Frequency dependent squeezing

Filter cavity construction progressing at Nikhef; Coordinator: Alessandro Bertolini

Newtonian noise cancellation

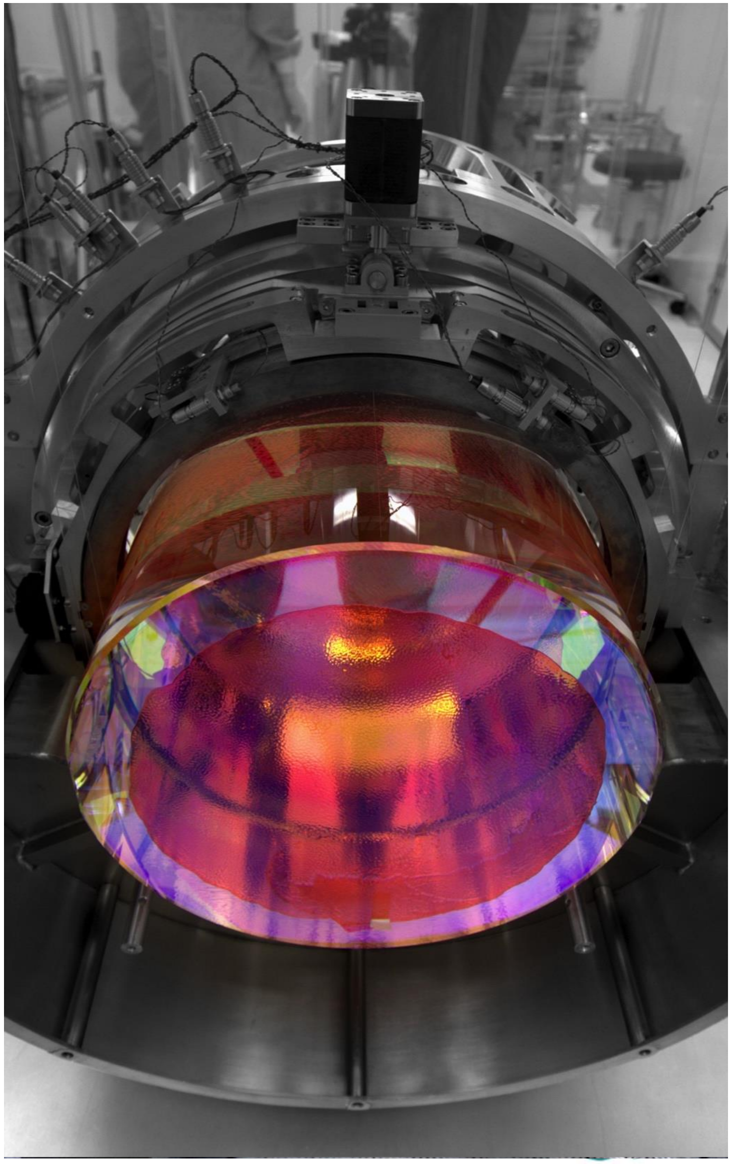
Smart sensor network (140 sensors) to monitor displacement field

Subtraction algorithms are under development



AdV+ phase 2 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

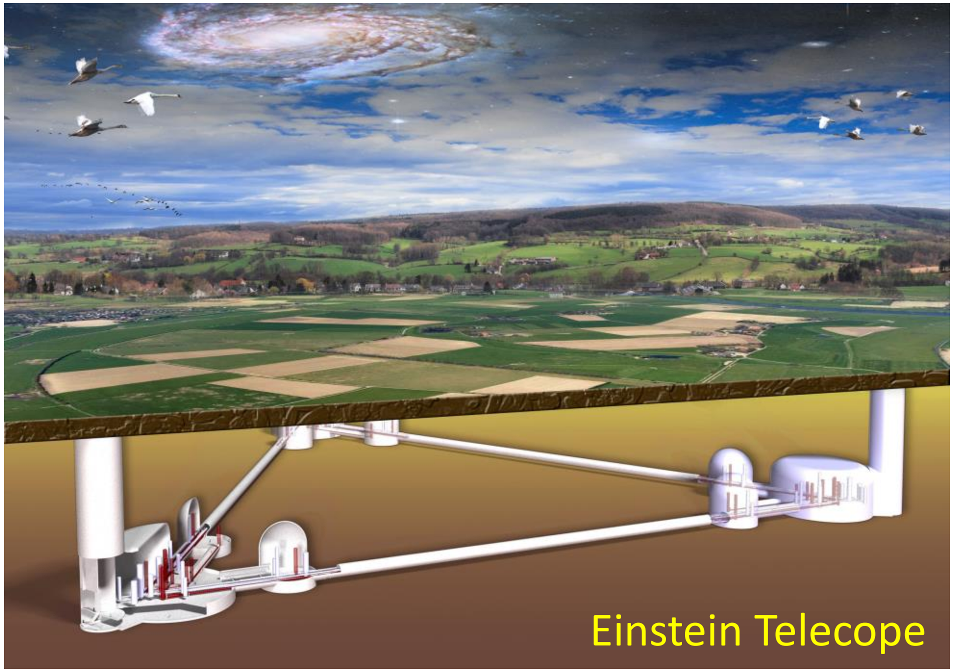
Expand LMA capabilities for next generation

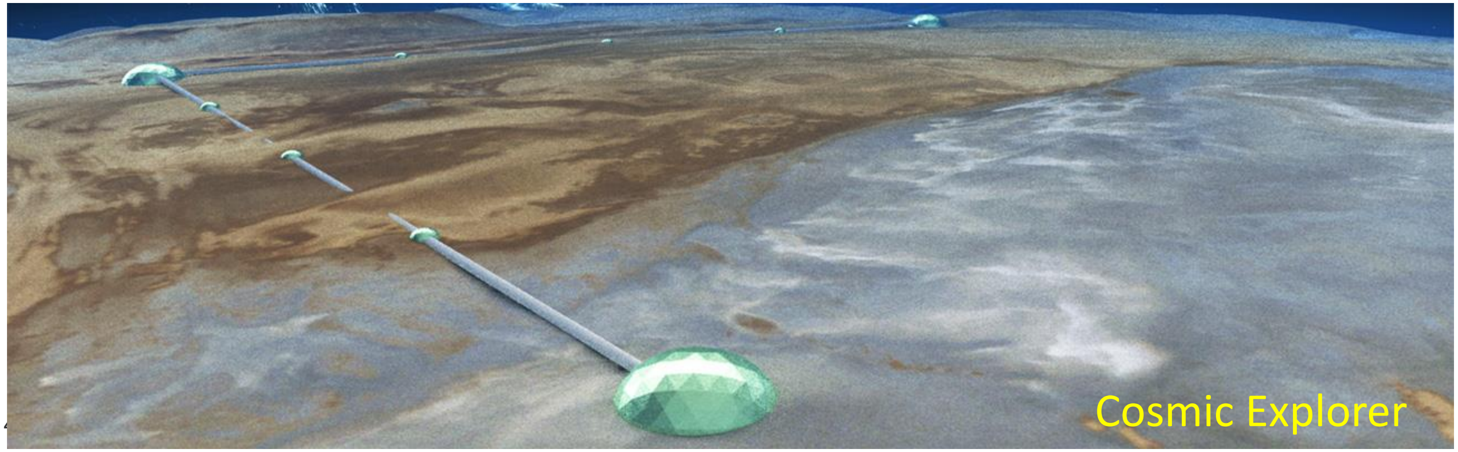
LMA is the only coating group known to be capable of scaling up

Third-generation gravitational wave detectors

Third-generation gravitational wave detectors

Einstein Telescope was placed on Europe’s ESFRI Roadmap on June 30, 2021
Cosmic Explorer submitted a conceptual design study to NSF in the USA





Einstein Telescope

The Einstein Telescope Consortium is composed of the institutions that signed the Consortium Agreement submitted to ESFRI (European Strategy Forum on Research Infrastructures)

ET Consortium Agreement

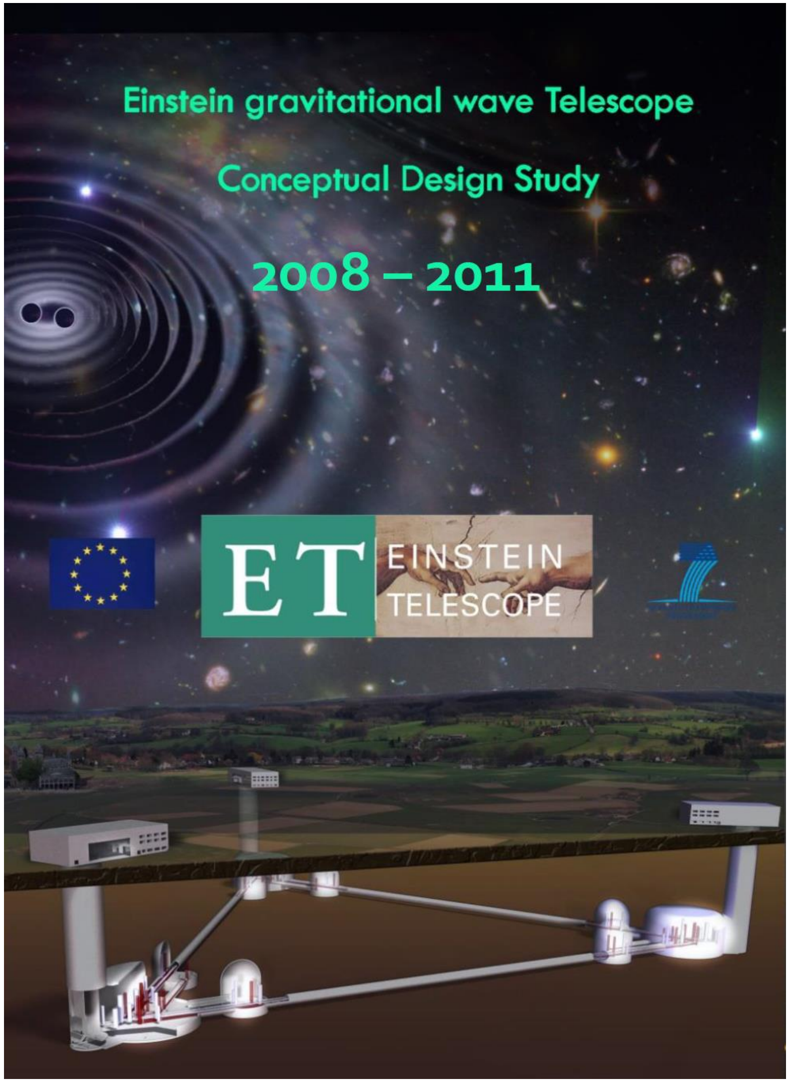
Light agreement at this level
Signed by 41 institutions
Coordinated by INFN and Nikhef

Milestones

ESFRI hearing: April 14, 2021
ESFRI approval: June 30, 2021
https://www.esfri.eu/latest-esfri-news/n

Einstein Telescope Design Studies

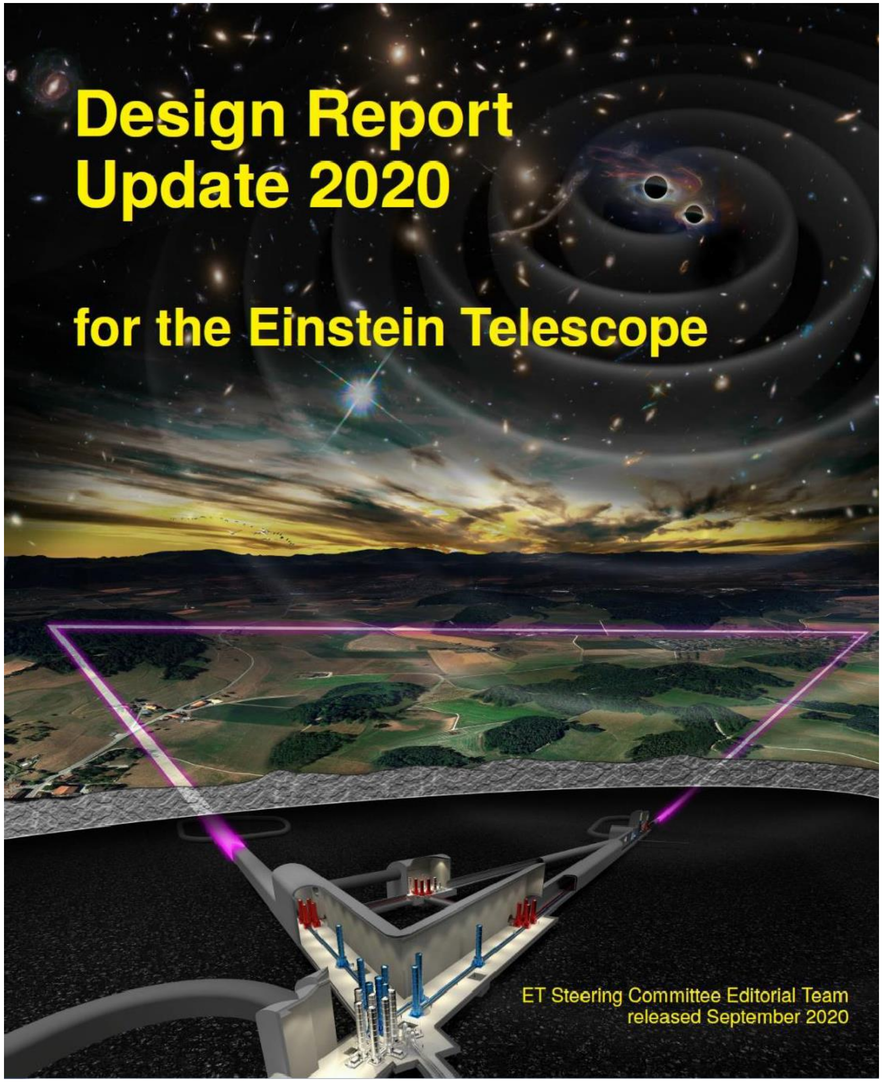
Conceptual Design Study: https://tds.virgo-gw.eu/?call_file=ET-0106C-10.pdf
Design Report Update: https://apps.et-gw.eu/tds/?content=3&r=17245


Einstein gravitational wave Telescope

Conceptual Design Study

2008 – 2011

ET EINSTEIN TELESCOPE


Design Report
Update 2020

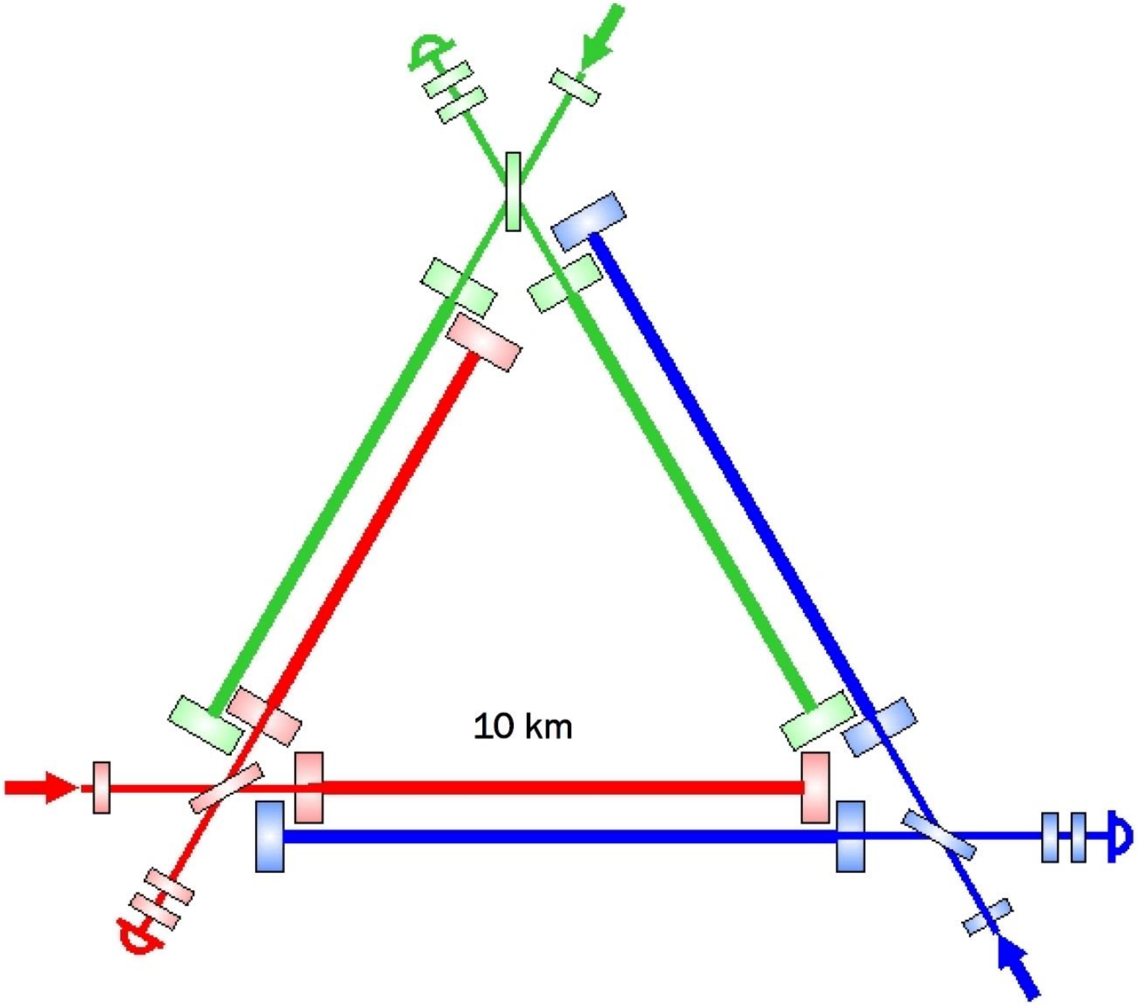
for the Einstein Telescope

ET Steering Committee Editorial Team
released September 2020

Triangular configuration

Three detectors with arm length of 10 km

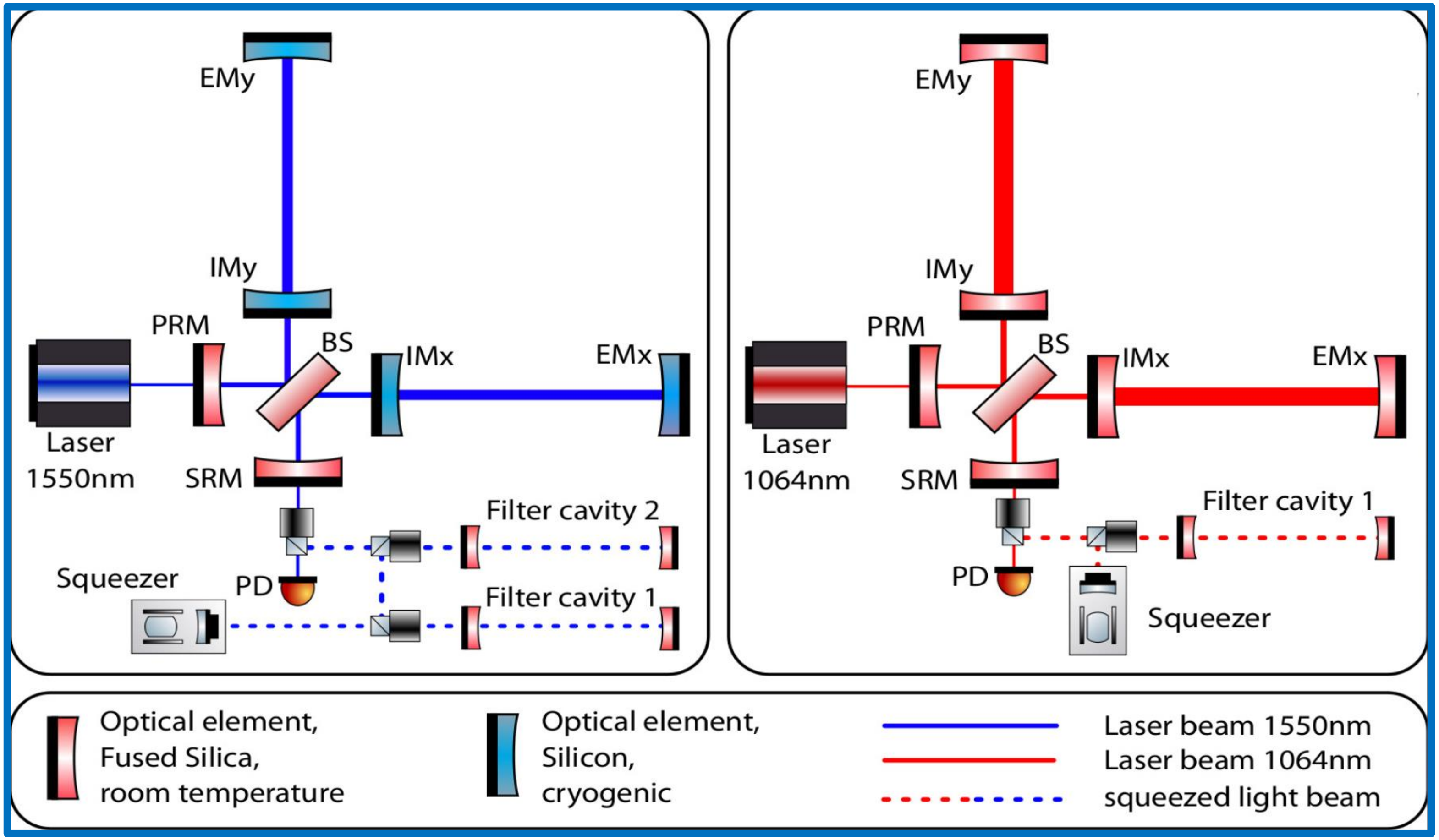
Detectors will be sited a few hundred meters underground in hard-rock



Xylophone detector design

Einstein Telescope splits the detection band over two instruments: an interferometer optimized for measuring low-frequency gravitational waves and an optimized high-frequency interferometer

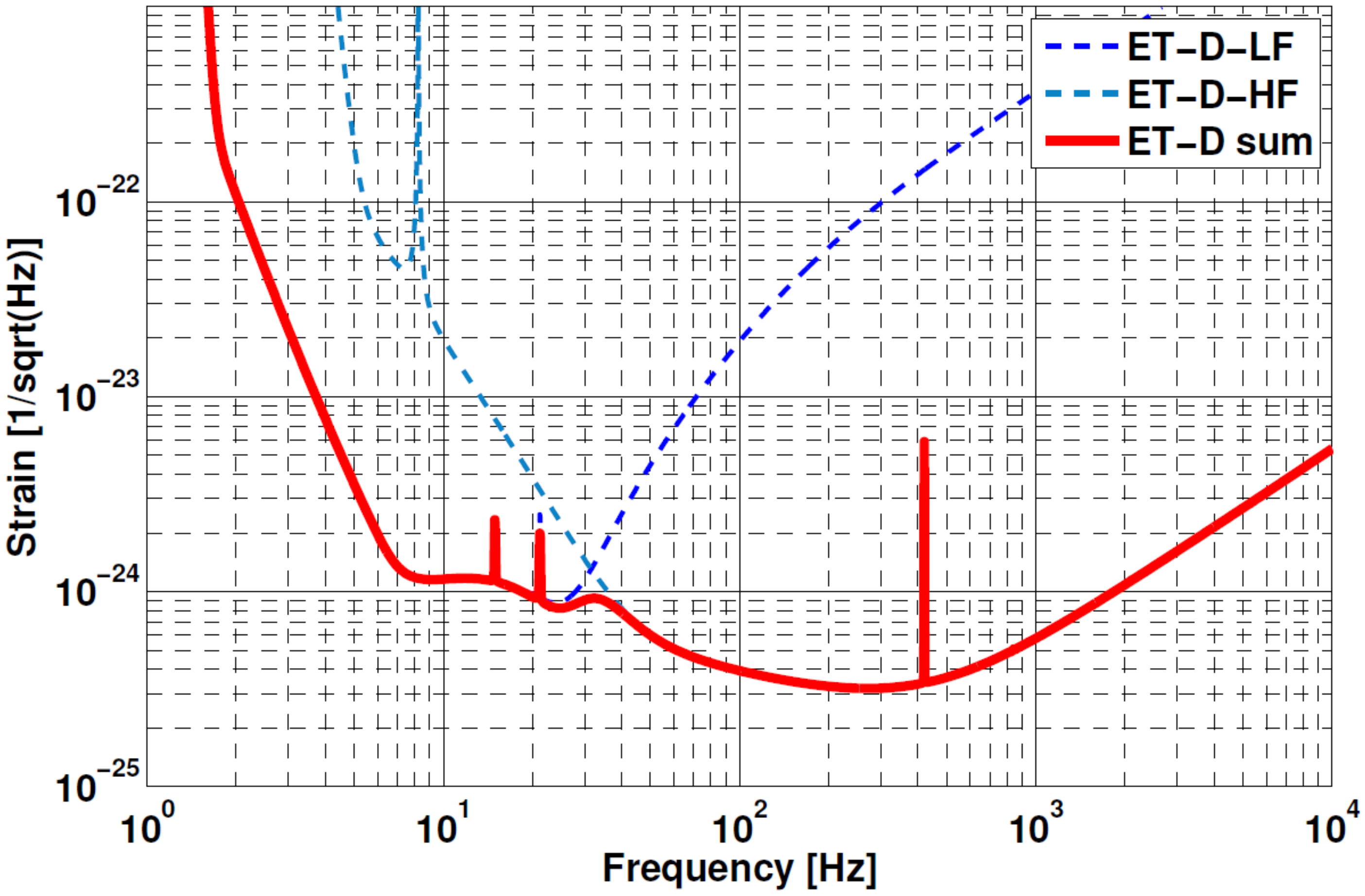
ET-LF: large cryogenic (10 - 20 K) silicon test masses, seismic suspensions, new wavelength, FDS, ..
ET-HF: high power laser, high circulating light power, thermal compensation, large test masses, FDS, ..



Einstein Telescope xylophone sensitivity

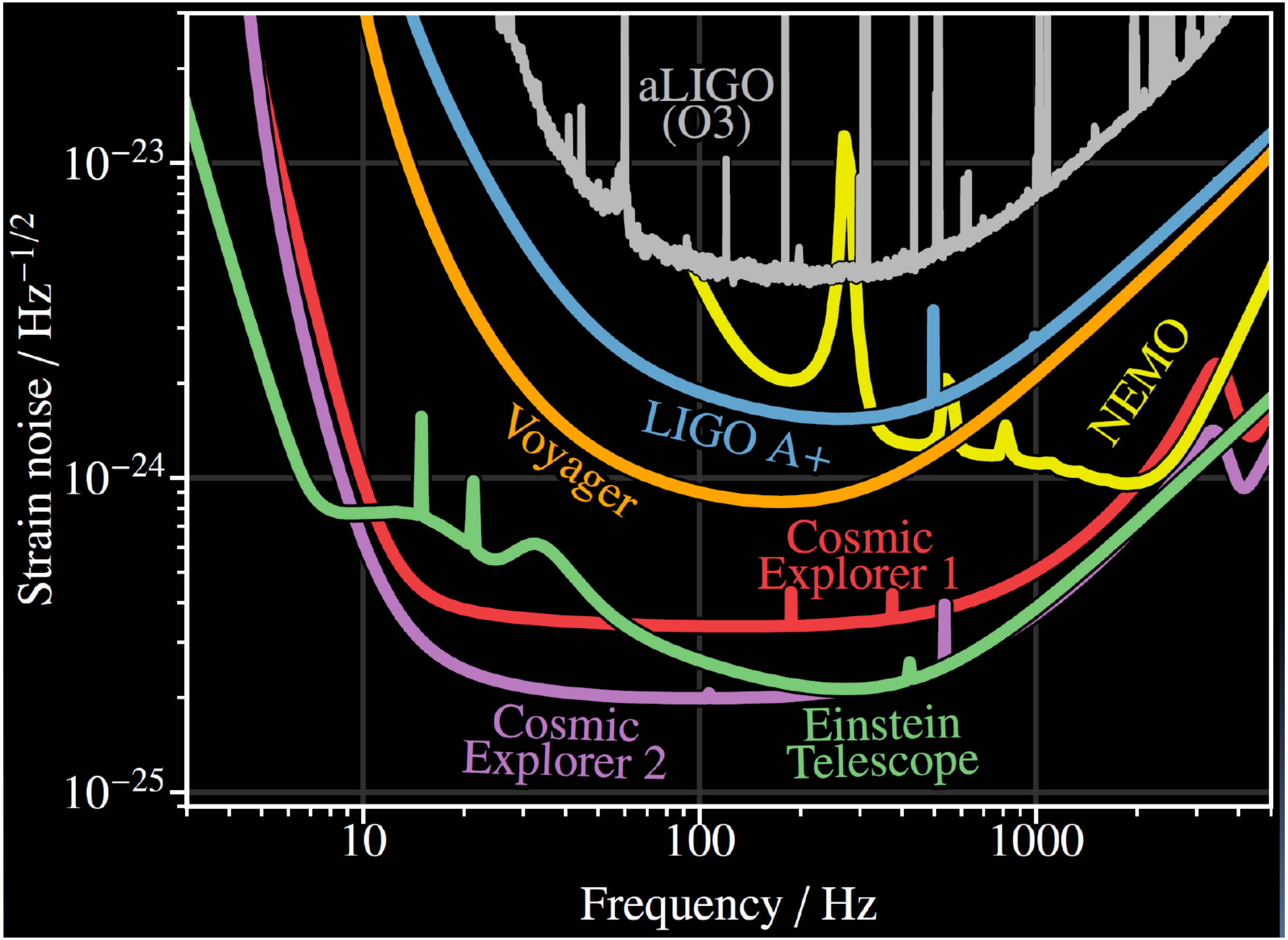
Three detectors with arm length of 10 km

Each detector consists of a low-frequency and a high-frequency interferometer
All six interferometers will be sited in hard-rock up to a few hundred meters underground



Sensitivities in the 3G era

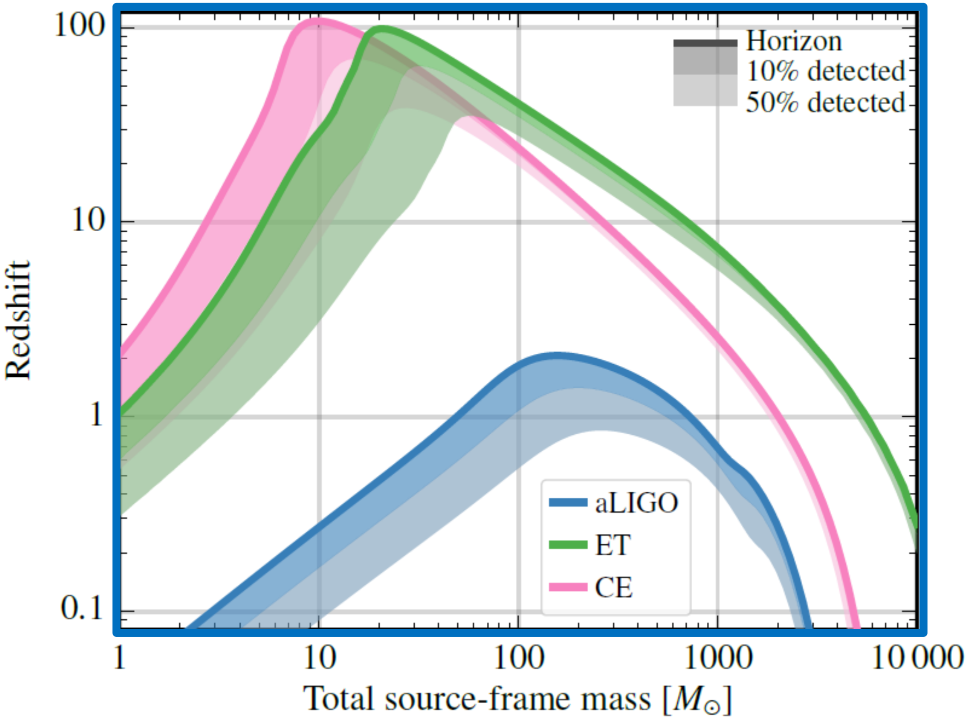
Sensitivity improvement by at least an order of magnitude compared to 2G design sensitivities



Science potential of 3G detectors

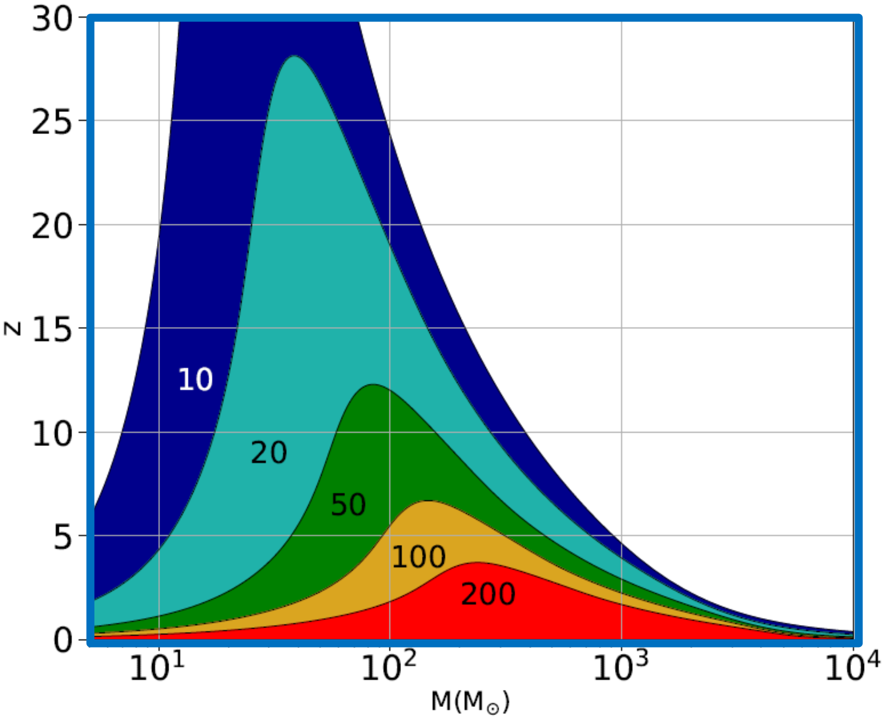
Sensitivity improvement by at least an order of magnitude compared to 2G design sensitivities

Astrophysical reach for equal-mass, non-spinning binaries for Advanced LIGO, Einstein Telescope and Cosmic Explorer



Credit: M. Maggiore *et al*., Science case for the Einstein Telescope, https://arxiv.org/abs/1912.02622

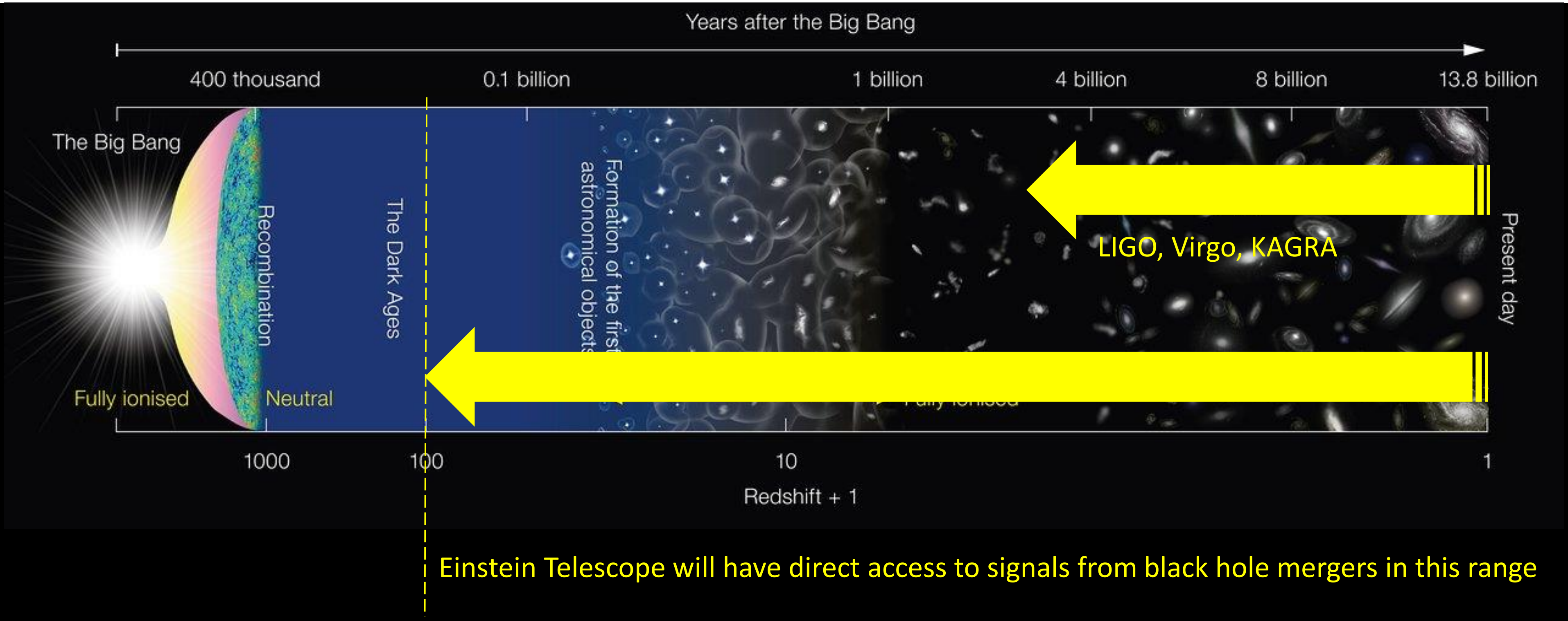
Curves of constant SNR in the (total mass, redshift) plane, for a network of one ET and two CE detectors



Credit: M. Colpi and A. Mangiagli

Detection horizon for black hole binaries

Einstein Telescope can observe BBH mergers to redshifts 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 will have direct access to signals from black hole mergers in this range

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

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 object**s
  - 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

Multi-messenger observatories

Einstein Telescope will operate in synergy with a new generation of innovative observatories

Einstein Telescope observatory

Summary

Einstein Telescope has a high discovery potential, remarkably precise measurement capabilities and highest scientific yield. It is timely and important for Europe

- Unique approach to directly study the early Universe in gravitational waves
- Precision studies of compact objects: black holes and neutron stars
- Invaluable data for fundamental physics, astronomy, astrophysics, nuclear physics and cosmology

Interest in gravitational-wave science and in Einstein Telescope is growing in Europe

- GW science appears prominently on APPEC, Astronet as well as on various national roadmaps
- ET's scientific and technological output will boost knowledge and innovations in many sectors

Governance, management, budget and risk

- Recent actions to professionalize governance and to map the evolution toward the Project phase
- Initial budget estimates were made with professional input
  - About 85% of the budget is in underground construction and vacuum system: relatively low to modest risk
  - These underground construction and vacuum-related engineering activities have well established management practices
  - Detector instrumentation (15% of the budget) is in the hands of physicists and engineers that created LIGO and Virgo

Europe intends to play a leading role in future of gravitational wave research

- ET promises to strengthen this position a most advanced 3G GW observation project
- ET needs a pan-European effort and coordination and by inclusion in the ESFRI Roadmap can promote gathering European countries around this unique project