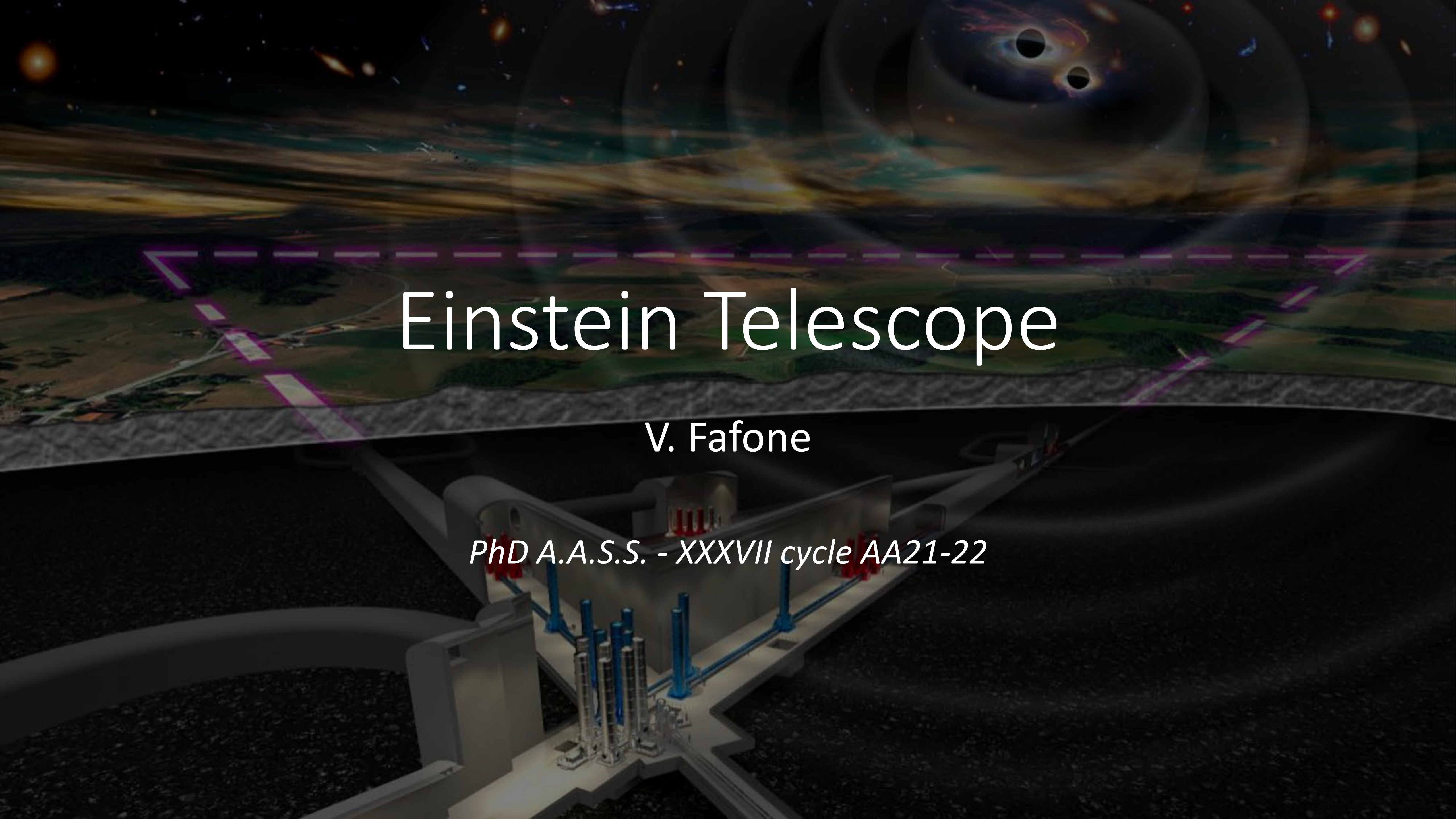
Einstein Telescope

V. Fafone

PhD A.A.S.S. - XXXVII cycle AA21-22



GWs in a nutshell

1) Start from the Einstein equations

Gravitational waves are dynamic fluctuations in the fabric of space-time

3) Linearize metric in weak field approximation

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \qquad |h_{\mu\nu}| << 1$$

Minkowsky flat space

Small perturbation (i.e. the GWs)

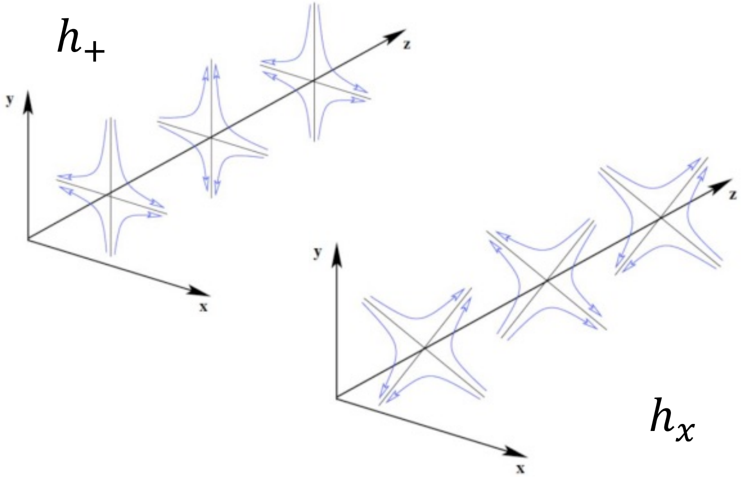
4) Choose a gauge (Lorenz) and put yourself far from the source

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0$$

Solutions are transverse plane waves, that **in GR** move at the speed of light and have two polarization states, just like EM waves.

$$h_{\mu\nu} = h_+(t - z/c) + h_x(t - z/c)$$

GWs in a nutshell



In GR, GWs are described by a rank 2 tensor, thus the two polarization states are rotated by 45° wrt each other.

In the vicinity of the source, the GW tensor $h_{\mu\nu}$ can be written as a multipole expansion of the matter energy-momentum tensor:

- mass conservation → no monopole radiation;
- momentum conservation → **no dipole emission**;
- The first nonzero contribution is the **quadrupole** term

Dipole mass moment ~ sum($m_i x_i$) ➔ d($m_i x_i$)/dt ~ p ➔ $d^2(m_i x_i)/dt^2$ ~ dp/dt =0

GWs are emitted by time-varying quadrupole mass moment

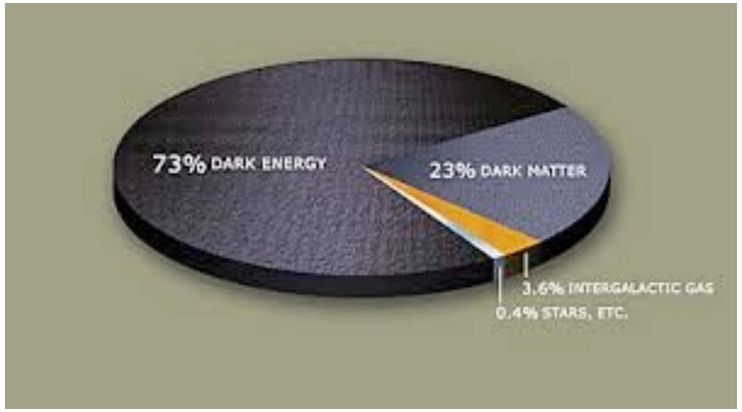
$$\boxed{h_{\mu\nu}(t) = \frac{2G}{rc^4}\ddot{Q}_{\mu\nu}(t - \frac{r}{c})}$$

$$Q_{\mu\nu} = \int \rho(x_\mu x_\nu - \frac{1}{3}r^2\delta_{\mu\nu})d^3x$$

A different window on the universe

E.M. radiation	Gravitational radiation
Primary emitters: charged elementary particles, mainly electrons	Emitted by cumulative mass and momentum of entire systems
Typically emitted in small regions, with short wavelengths (because of overall charge neutrality)	Long wavelengths
Conveys direct information about the physical conditions of small portions of the astronomical sources	Conveys direct information about large-scale regions
Couples strongly to charges → easy to detect but also easily scattered or absorbed by material between us and the source	**Couples extremely weakly to matter → very hard to detect but also able to travel to us substantially unaffected by intervening matter, even from the earliest moments of the Big Bang**

Given that 96% of the mass-energy of the universe carries no charge, GWs provide us with our first opportunity to observe directly a major part of the universe. It might turn out to be as complex and interesting as the charged minor component, the part that we call “normal” matter.



Can we generate GWs?

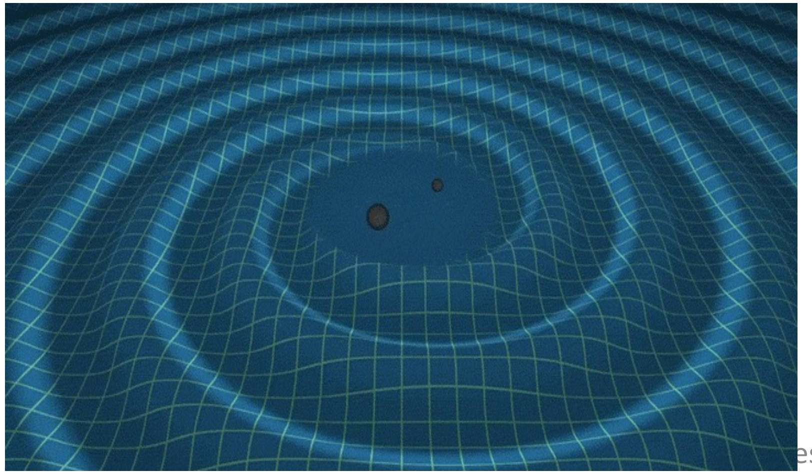
Power emitted by a mass M and size R oscillating at frequency $\omega \sim v/R$:

$$P = \frac{G}{5c^5}\langle \dddot{Q}^{\mu\nu}\dddot{Q}_{\mu\nu}\rangle \approx \frac{GM^2v^6}{R^2c^5} \qquad Q \approx MR^2 \sin \omega t$$

M=1000 tons, steel rotor, f = 4 Hz ➔ **P = 10^{-30} W;** Einstein: “ .. *a practically vanishing value*…”

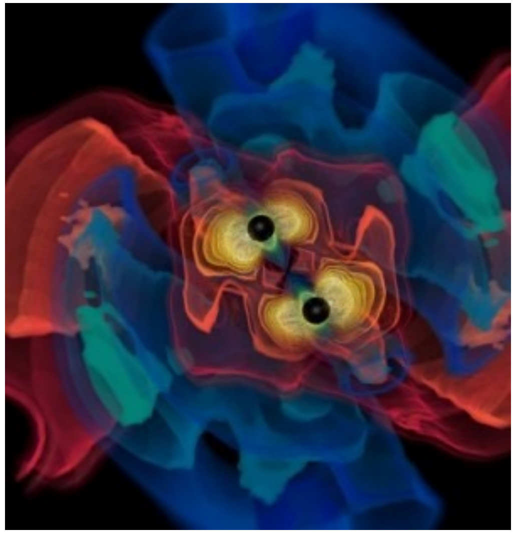
No Hertz experiment for GWs!

Efficient sources of GW must have a **large mass** and be **asymmetric**, **compact** and **fast: strong field, highly relativistic systems!**



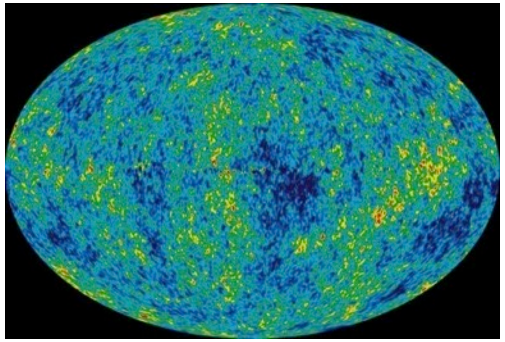
This means mostly binary systems made of Black Holes and Neutron Stars

GW sources



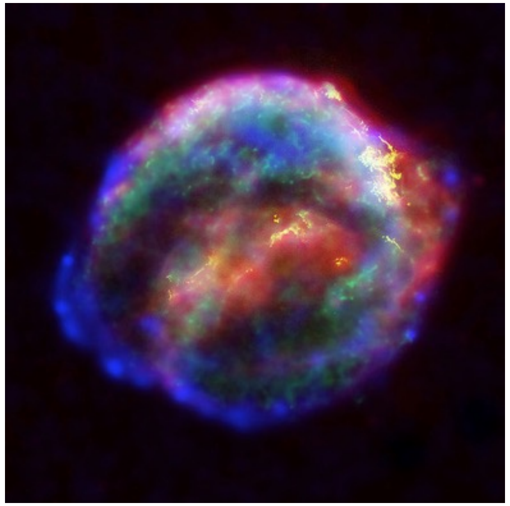
AEI, CCT, LSU

Compact binary systems (NSNS, NSBH, BHBH)



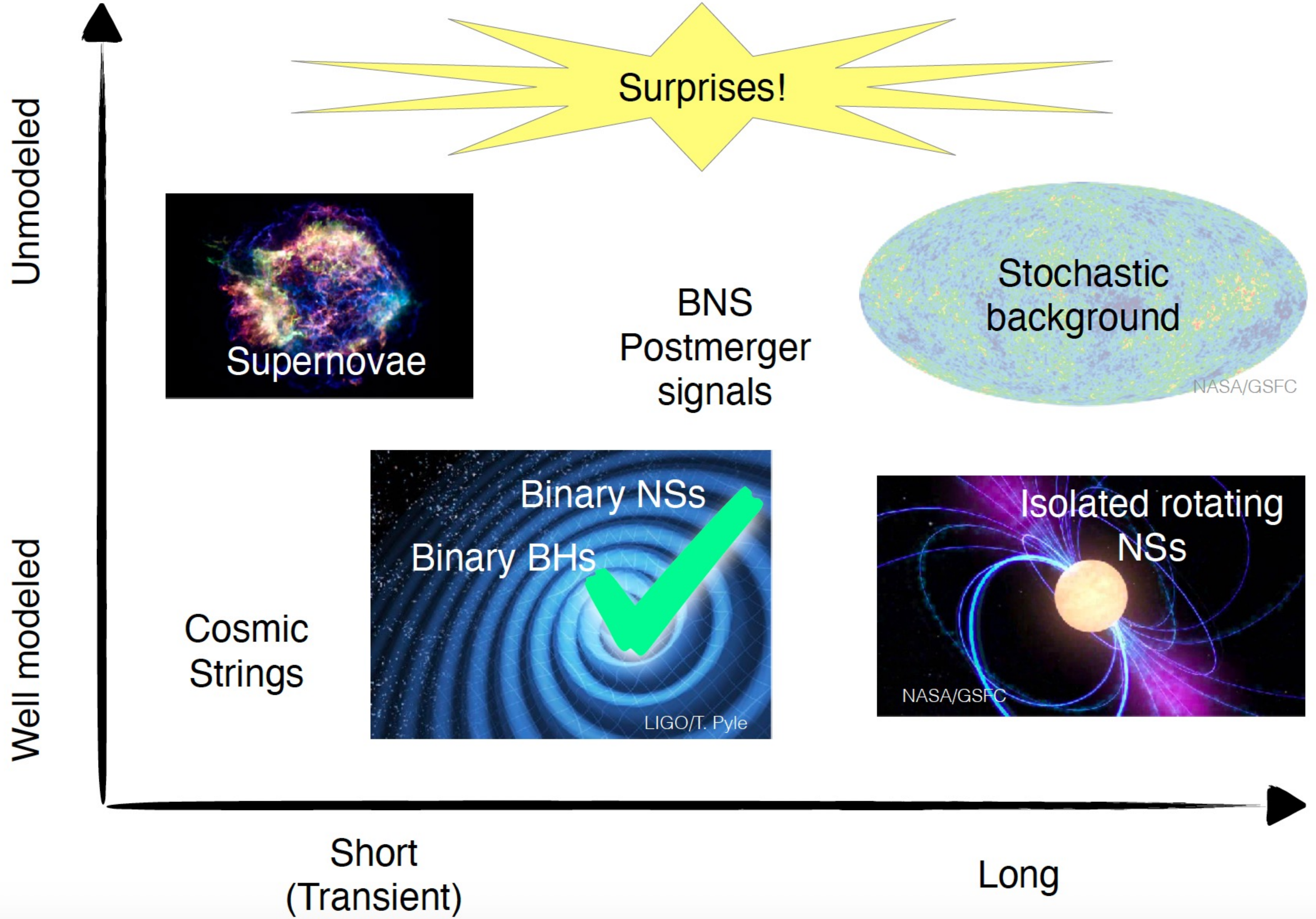
NASA/WMAP Science Team

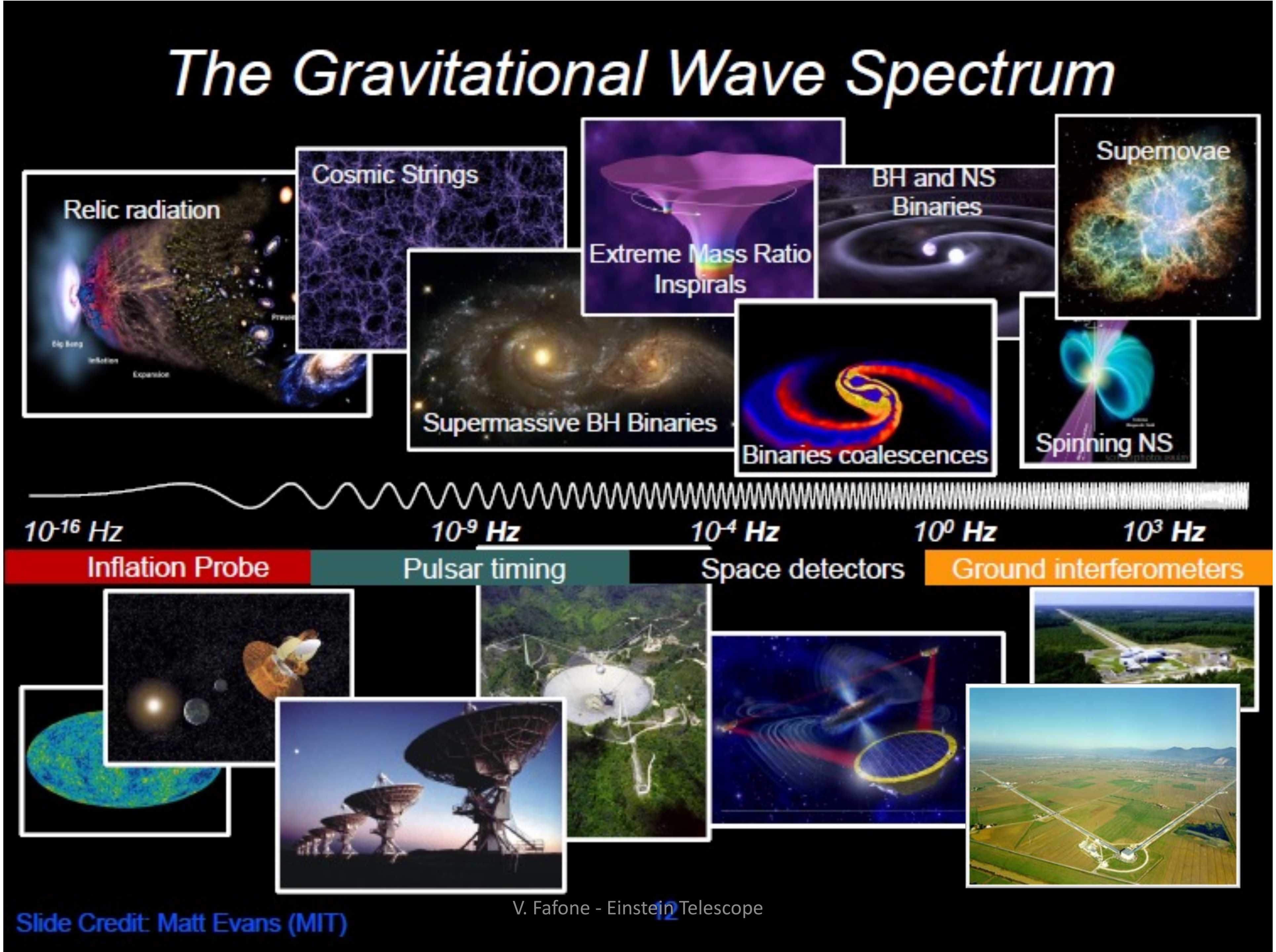
Stochastic background of cosmological origin (inflation)



Core Collapse Supernovae

Spinning neutron stars (Pulsars)


Surprises!
Unmodeled
Well modeled
Supernovae
BNS
Postmerger
signals
Stochastic
background
NASA/GSFC
Binary NSs
Binary BHs
LIGO/T. Pyle
Cosmic
Strings
Isolated rotating
NSs
NASA/GSFC
Short
(Transient)
Long


The Gravitational Wave Spectrum
Relic radiation
Cosmic Strings
Extreme Mass Ratio Inspirals
BH and NS Binaries
Supernovae
Supermassive BH Binaries
Binaries coalescences
Spinning NS
10^{-16} Hz
10^{-9} Hz
10^{-4} Hz
10^{0} Hz
10^{3} Hz
Inflation Probe
Pulsar timing
Space detectors
Ground interferometers
Slide Credit: Matt Evans (MIT)
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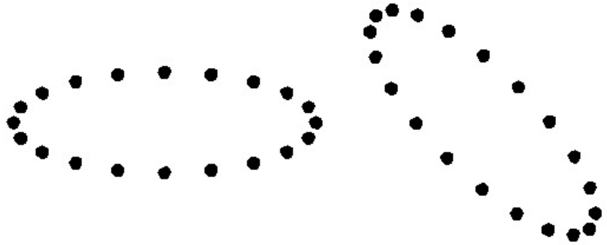
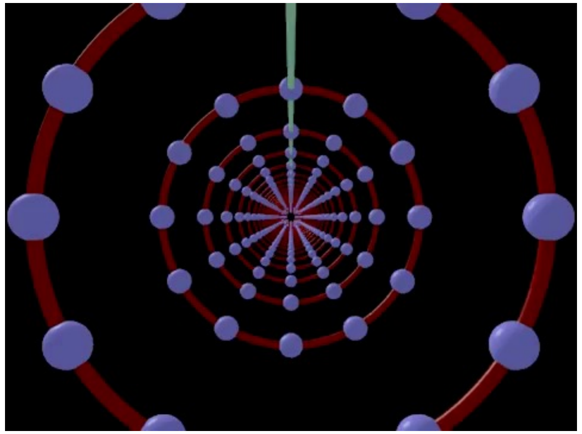
Can we detect GWs?

The gravitational wave produces a time dependent strain of space. The deformation of a ring of test particles due to a gravitational wave propagating in the direction normal to the plane of the ring has the pattern shown below:

+ polarization



× polarization



$$\delta\xi^i = \frac{1}{2} h^i_k \xi^k$$

In any realistic case, wave is so weak that the changes $\delta\xi^i$ are very small compared to the original distance ξ^i.
Some order of magnitude:
Typically, *h* is O(10^{-19}-10^{-22}); ξ is O(10^3 m) → δξ is **O(10^{-16}-10^{-19}) m** (a proton is O(10^{-15}) m)

Troublesome history

Einstein predicted GWs in 1916 … but then doubted their existence for the rest of his life.

The controversy lasted four decades, until the Chapel Hill Conference in **1957.**

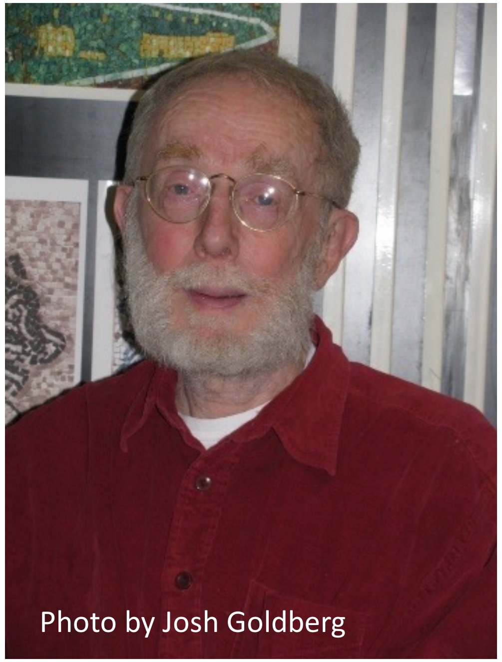


Photo by Josh Goldberg

Felix Pirani solved the problem of the reality of gravitational waves, showing that gravitational waves must have physical reality, as they carry energy, and you could invent a (thought) experiment that could detect them.

line ζ of a free particle to that of a neighboring similar particle. v^μ is the 4-velocity of the first particle, and τ the proper time along ζ. If now one introduces an orthonormal frame on ζ, v^μ being the timelike vector of the frame, and assumes that the frame is parallelly propagated along ζ (which insures that an observer using this frame will see things in as Newtonian a way as possible) then the equation of geodesic deviation (1) becomes

$$\frac{d^2\eta^a}{d\tau^2} + R^a{}_{obo}\,\eta^b = 0 \qquad (a,b = 1,2,3) \qquad (2)$$

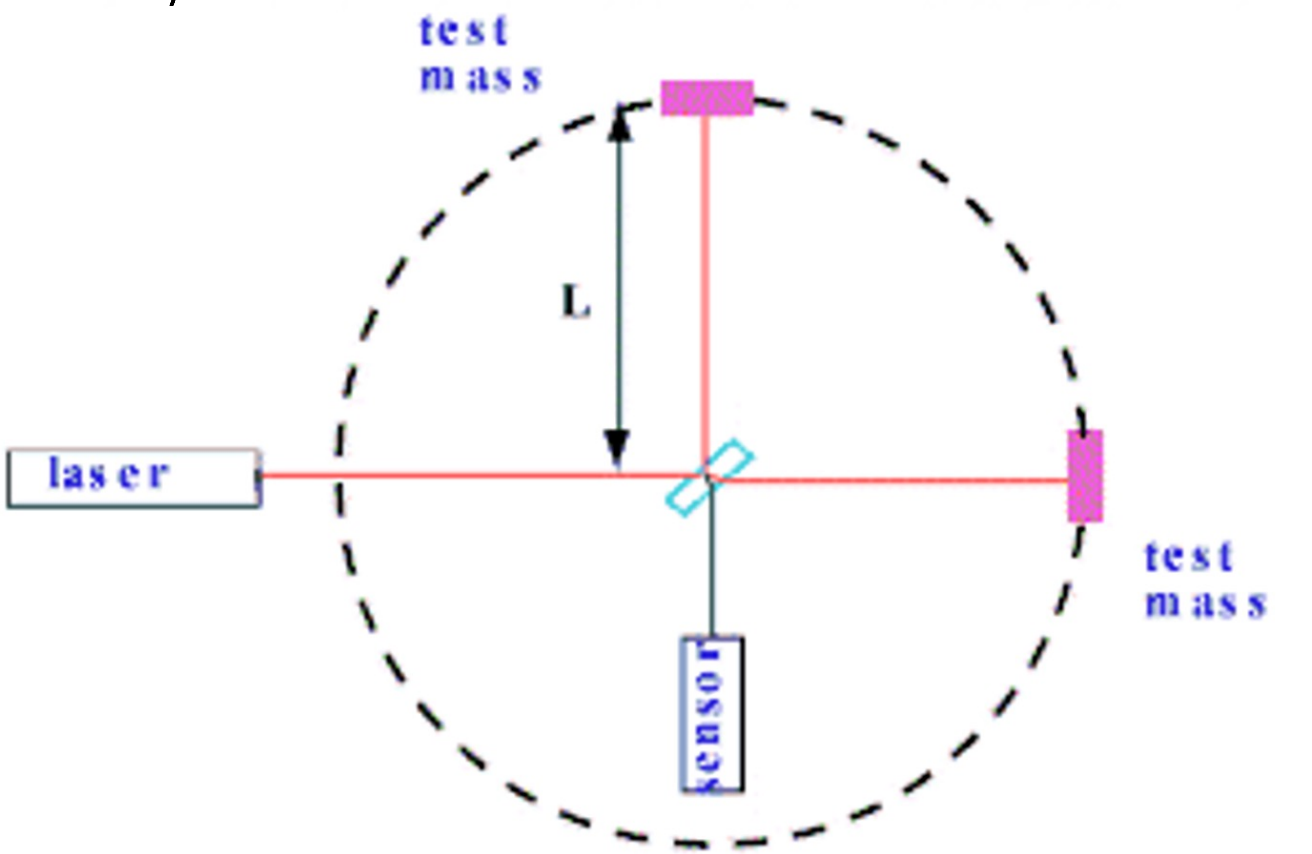
Here η^a are the physical components of the infinitesimal displacement and $R^a{}_{obo}$ some of the physical components of the Riemann tensor, referred to the orthonormal frame.

By measurements of the relative accelerations of several different pairs of particles, one may obtain full details about the Riemann tensor. One can thus very easily imagine an experiment for measuring the physical components of the Riemann tensor.

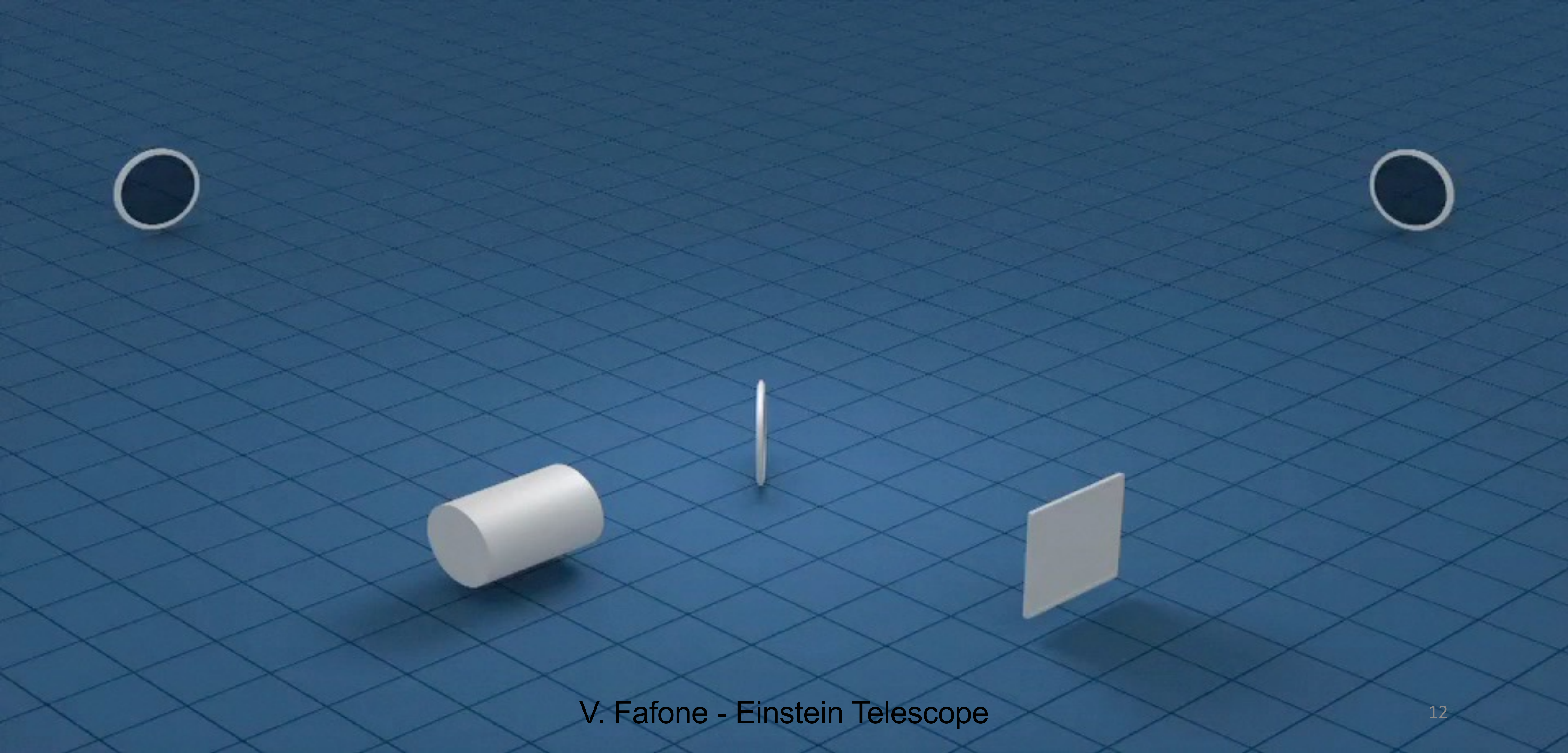
Interferometers as GW detectors

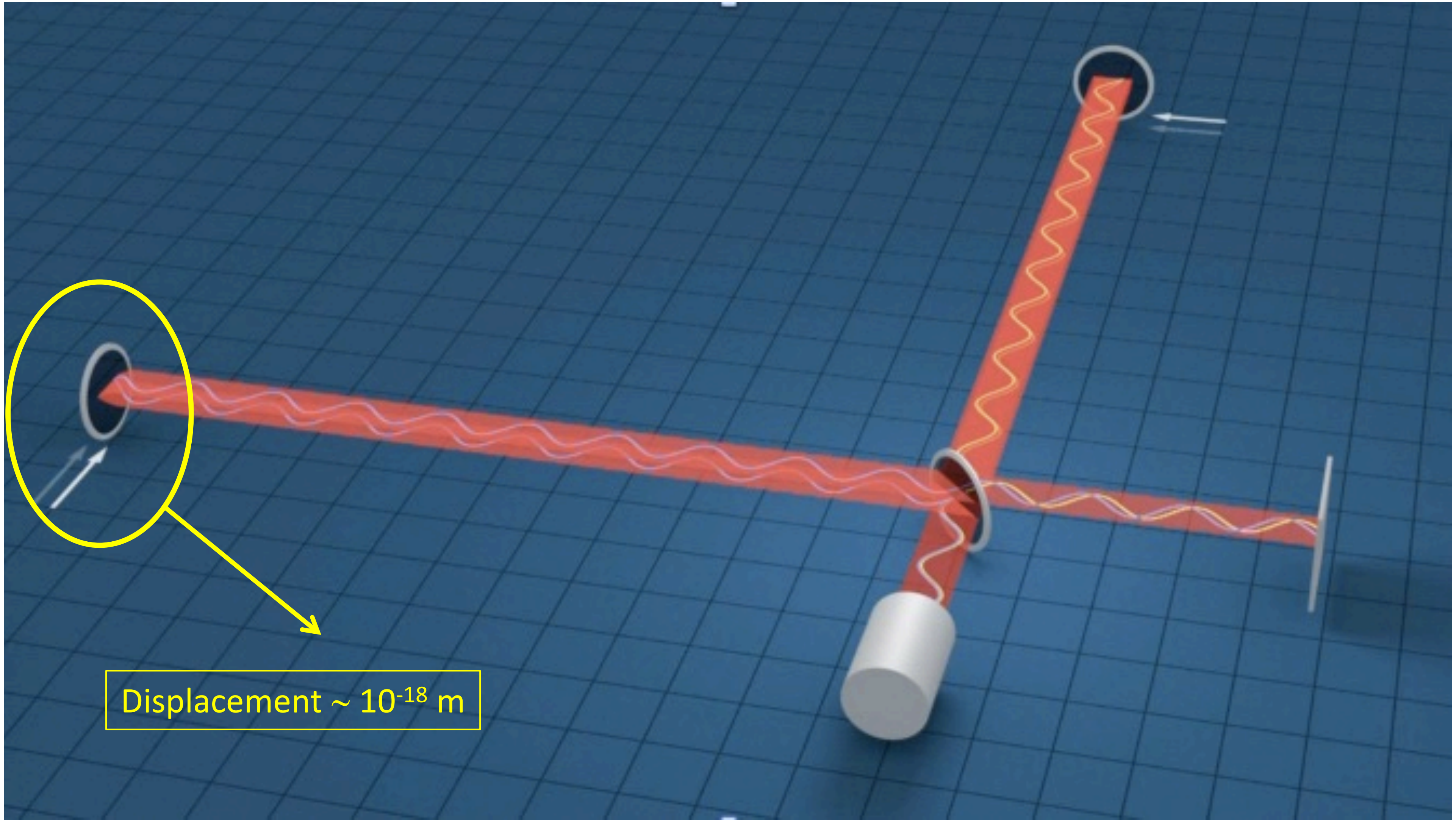
In Pirani's papers: "It is assumed that an observer, by the use of light signals or otherwise, determine the coordinates of a neighboring particle in his local Cartesian coordinate system"

Interferometers can make the job!



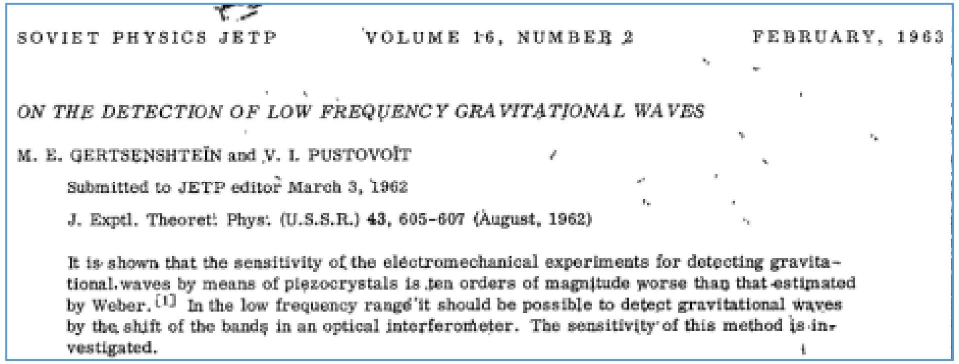
Interferometri per misurare le onde gravitazionali




Displacement ~ 10^{-18} m

Interferometers as GW detectors

- First proposed by Gertsenshtein and Pustovoit - Sov . Phys. JETP 878 16, 433 (**1962**) 879
- First built by Forward at Hughes Research Laboratories - G . E. Moss, L. R. Miller, and R. L. Forward, Appl. Opt. 880 10, 2495 (**1971**)
- First study of the noise and performance of such detectors - R. Weiss, *Electromagnetically coupled broadband gravitational antenna*, Tech. Rep. (MIT, **1972**) Quarterly report of the Research Laboratory for Electronics. https://dcc.ligo.org/LIGO P720002/public


SOVIET PHYSICS JETP VOLUME 16, NUMBER 2 FEBRUARY, 1963

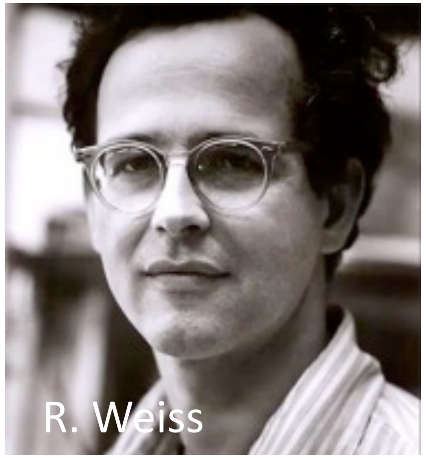
ON THE DETECTION OF LOW FREQUENCY GRAVITATIONAL WAVES

M. E. GERTSENSHTEIN and V. I. PUSTOVOIT

Submitted to JETP editor March 3, 1962

J. Exptl. Theoret. Phys. (U.S.S.R.) 43, 605-607 (August, 1962)

It is shown that the sensitivity of the electromechanical experiments for detecting gravitational waves by means of piezocrystals is ten orders of magnitude worse than that estimated by Weber.[1] In the low frequency range it should be possible to detect gravitational waves by the shift of the bands in an optical interferometer. The sensitivity of this method is investigated.



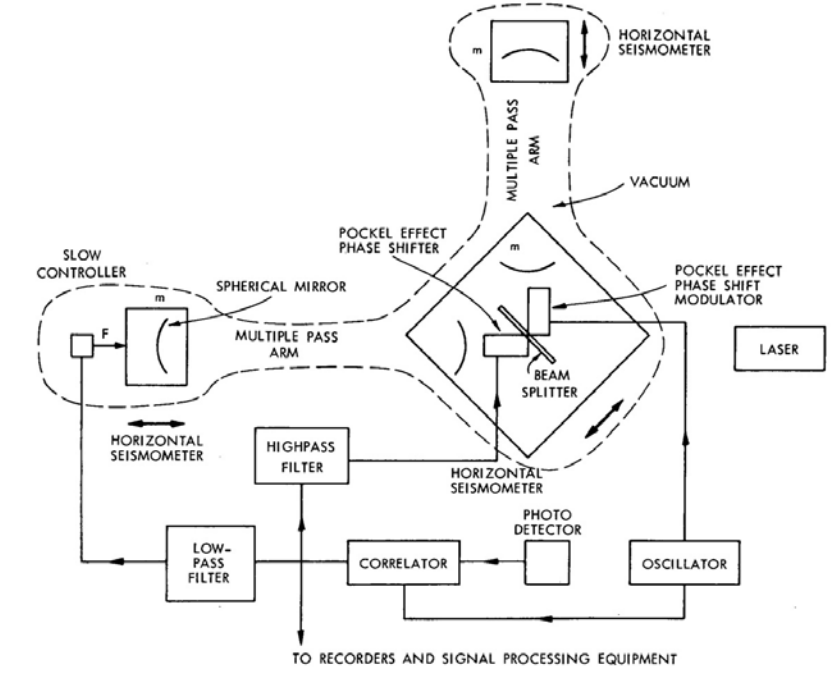
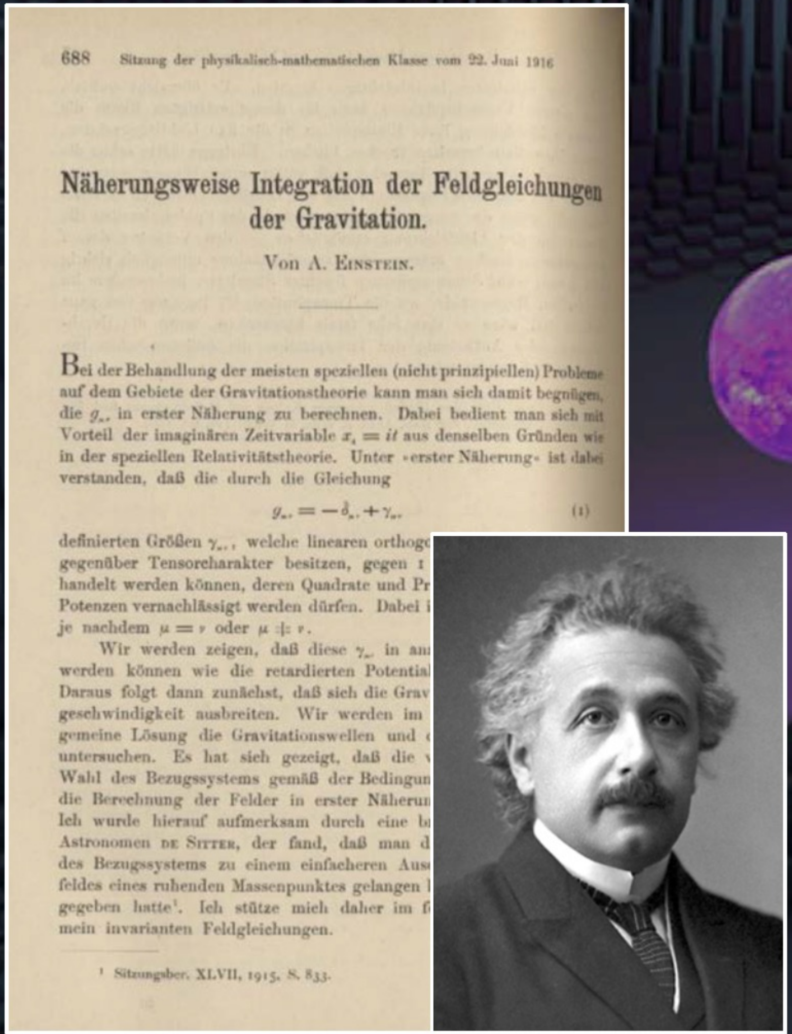


Fig. V-20. Proposed antenna.

We have come a long way ….



Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

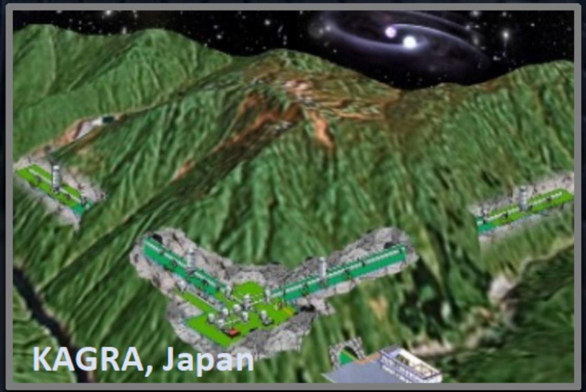
Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

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

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogo
gegenüber Tensorcharakter besitzen, gegen 1
handelt werden können, deren Quadrate und Pr
Potenzen vernachlässigt werden dürfen. Dabei i
je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

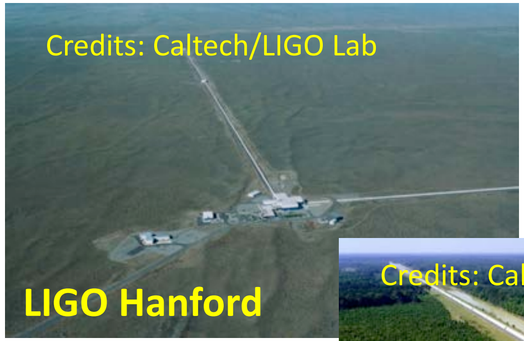
Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in an
werden können wie die retardierten Potential
Daraus folgt dann zunächst, daß sich die Grav
geschwindigkeit ausbreiten. Wir werden im
gemeine Lösung die Gravitationswellen und
untersuchen. Es hat sich gezeigt, daß die
Wahl des Bezugssystems gemäß der Bedingun
die Berechnung der Felder in erster Näherun
Ich wurde hierauf aufmerksam durch eine b
Astronomen de Sitter, der fand, daß man d
des Bezugssystems zu einem einfacheren Aus
feldes eines ruhenden Massenpunktes gelangen
gegeben hatte[1]. Ich stütze mich daher im f
mein invarianten Feldgleichungen.

[1] Sitzungsber. XLVII, 1915, S. 833.



The GW detectors network

- Why a network
  - Coincidence detection
  - Sky localization

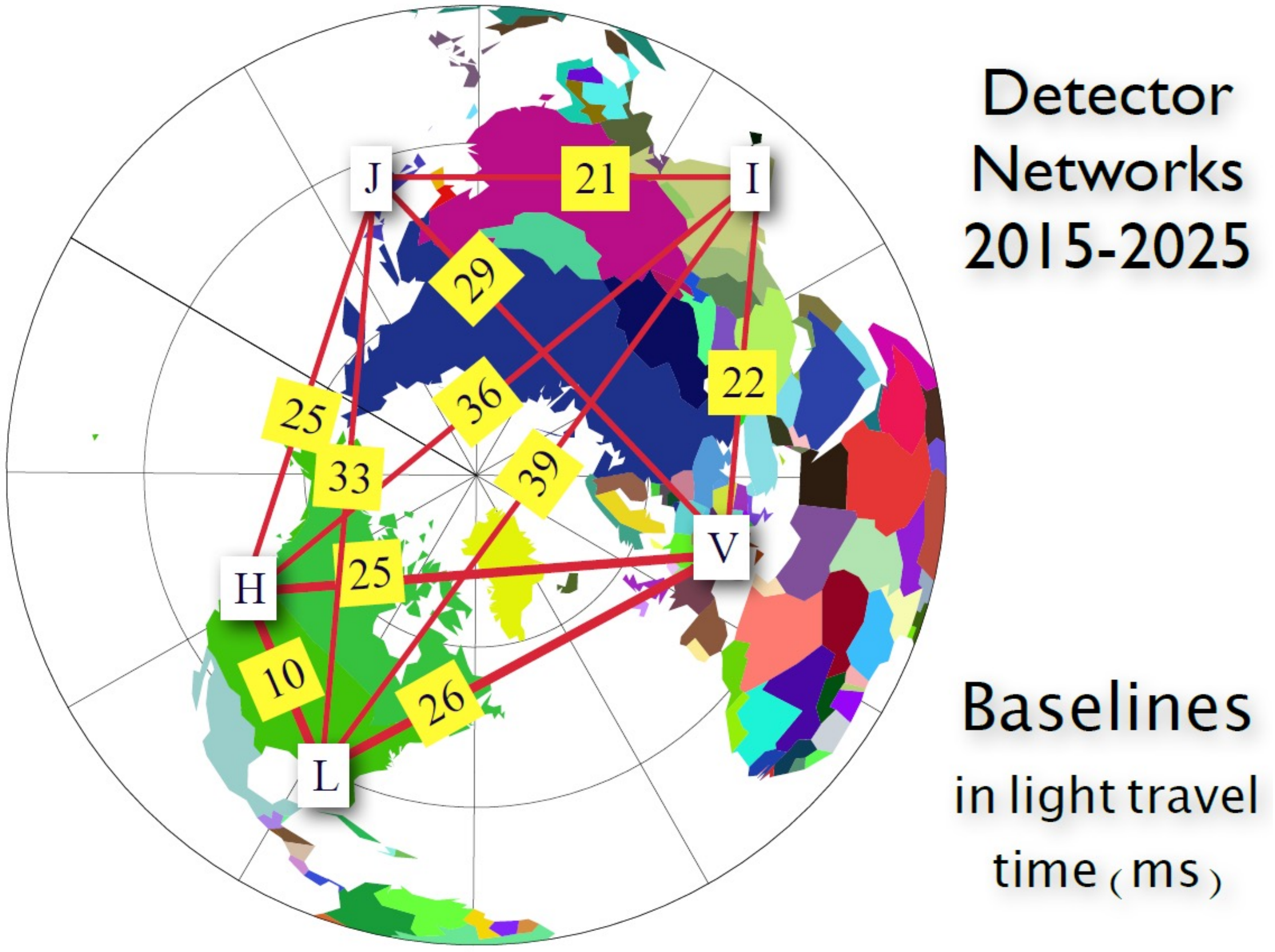


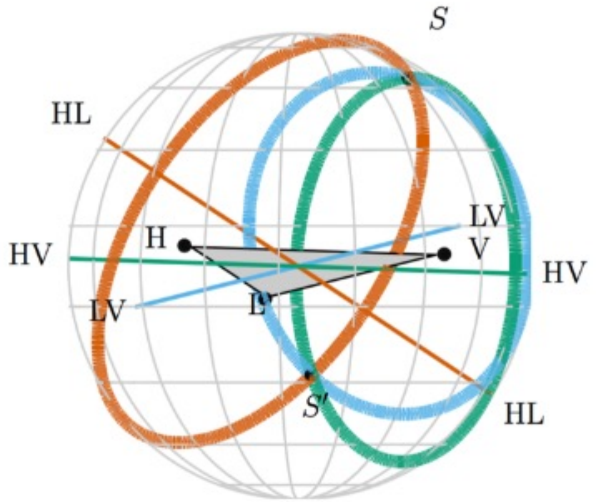
- “Twin” detectors
- 4 km arms

- Cryogenic & underground
- 3 km arms

- High-tech facility
- 0.6 km arms

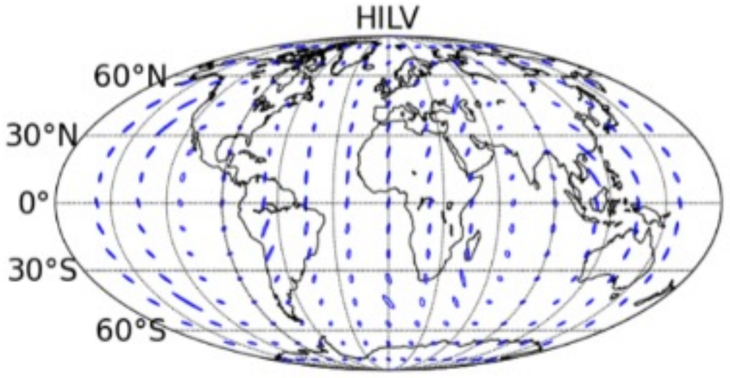
Sky localization



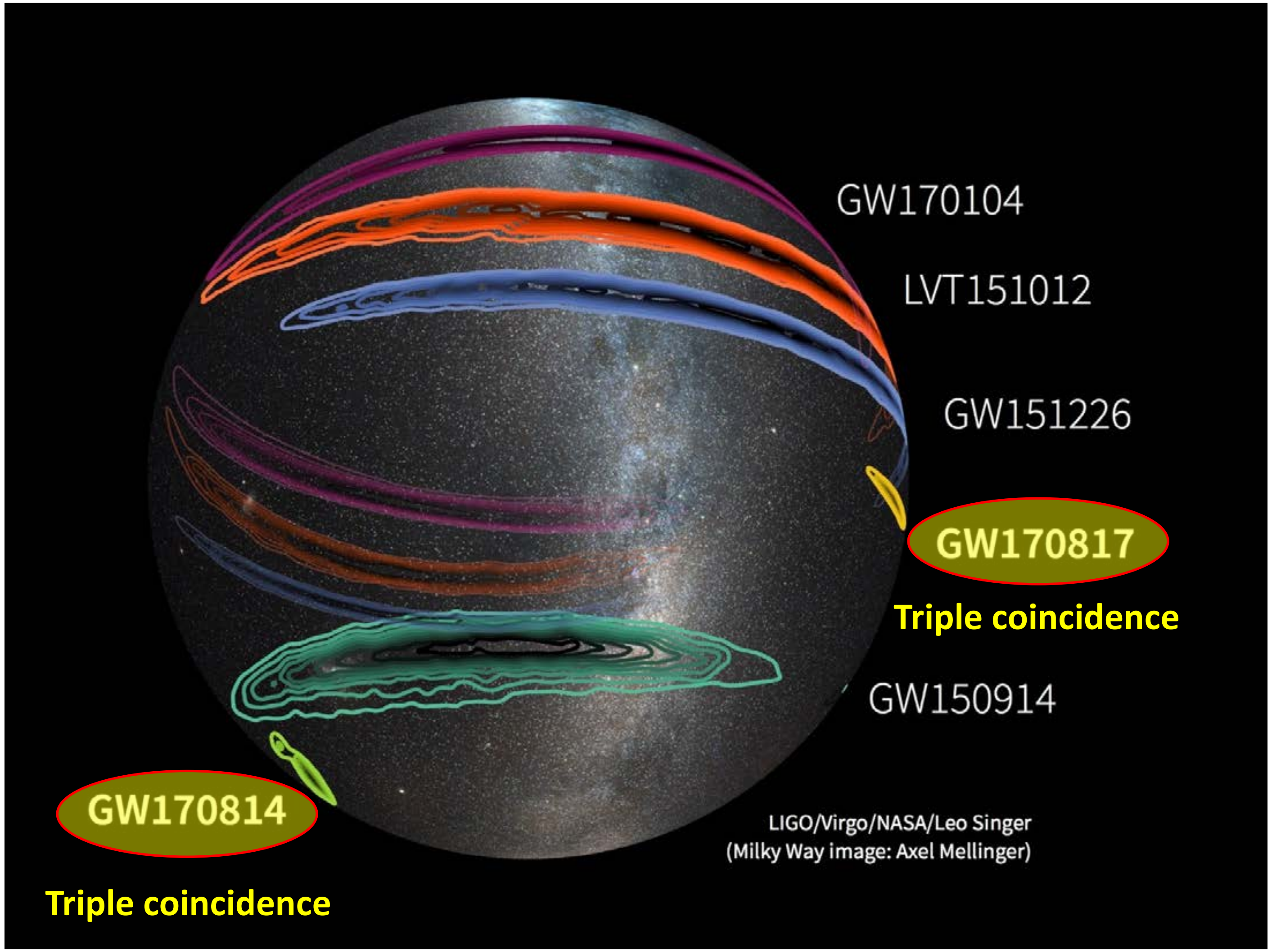


Sky location reconstructed through the time of arrival of GW radiation at the different detector sites, as well as the relative amplitude and phase of the GWs in different detectors.

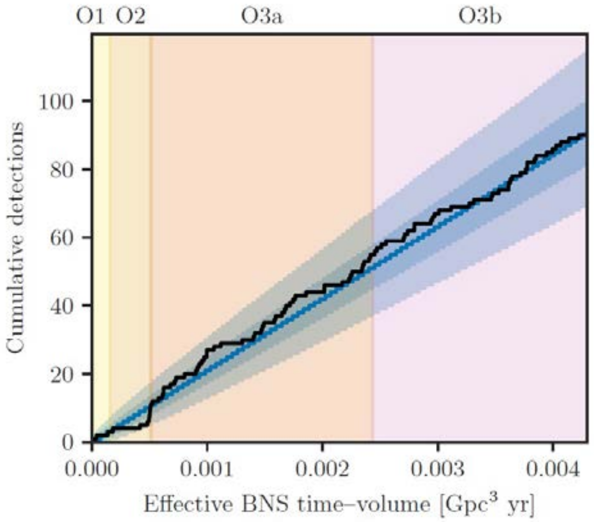
Two interferometers can only determine an **annulus** in the sky.



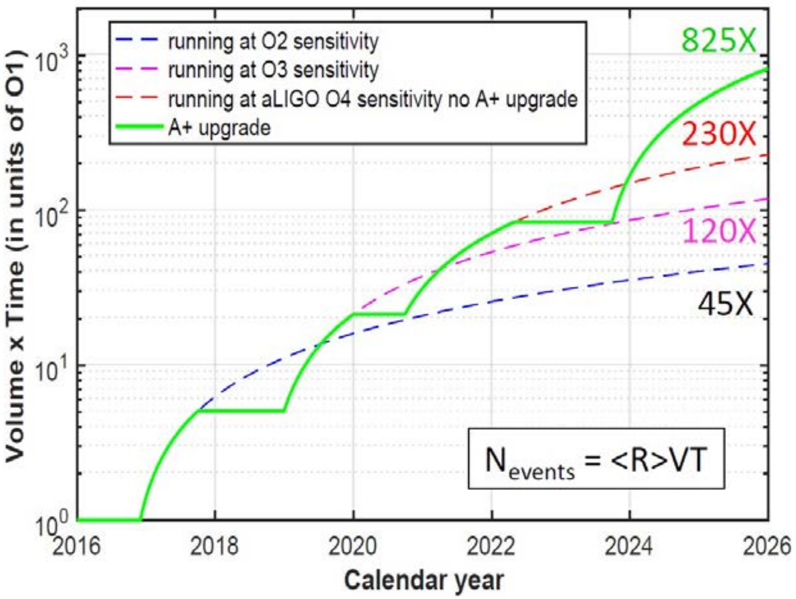
Sky localization



The Observing Runs

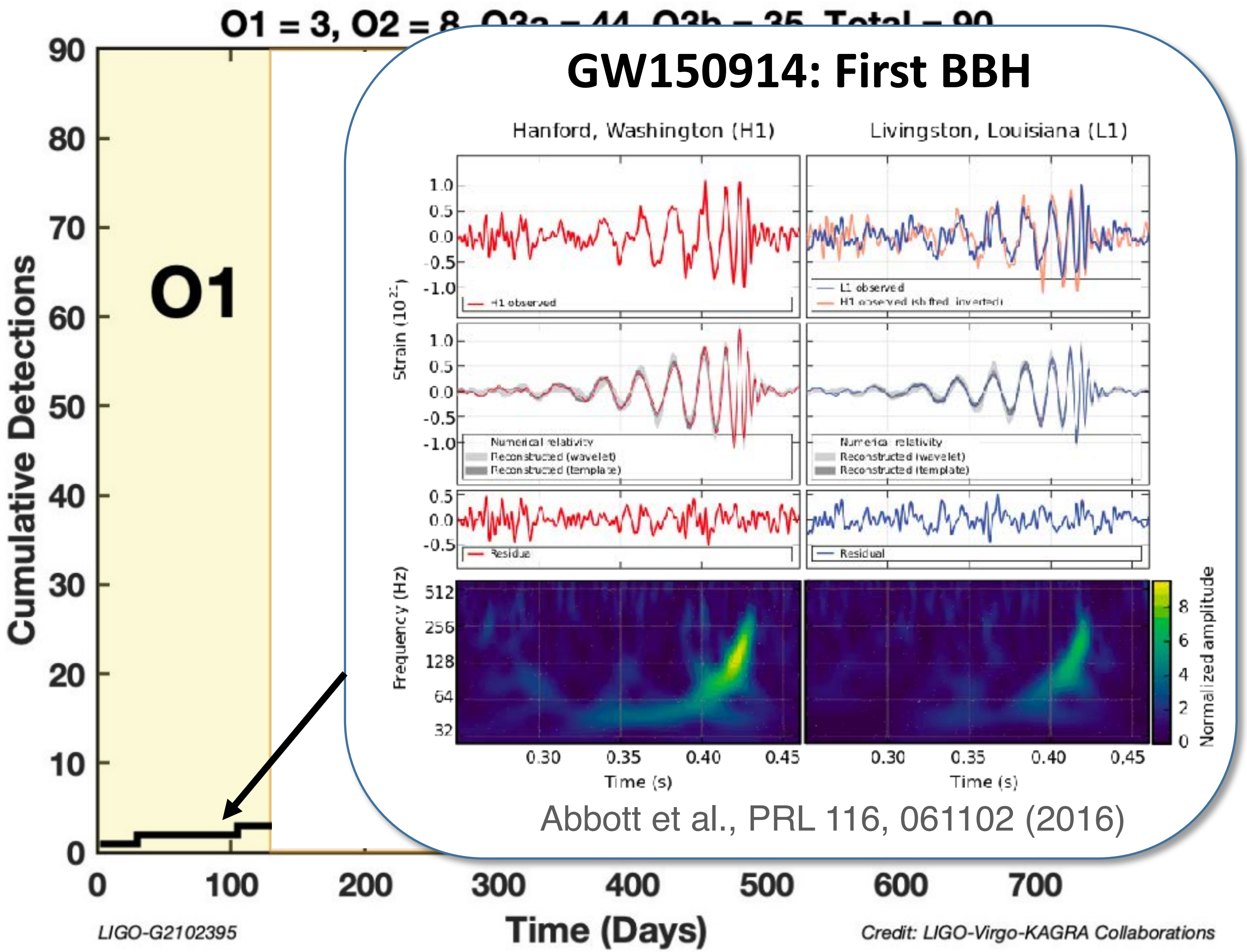


- Three observing runs performed so far:
  - O1: September 12th 2015 to January 12th 2016;
  - O2: November 30th 2016 to August 25th 2017;
  - O3: April 1st 2019 to March 27th 2020.
- Each observing run has been followed/proceeded by an upgrade and commissioning phase;
- Events scale as expected according to sensitivity improvement



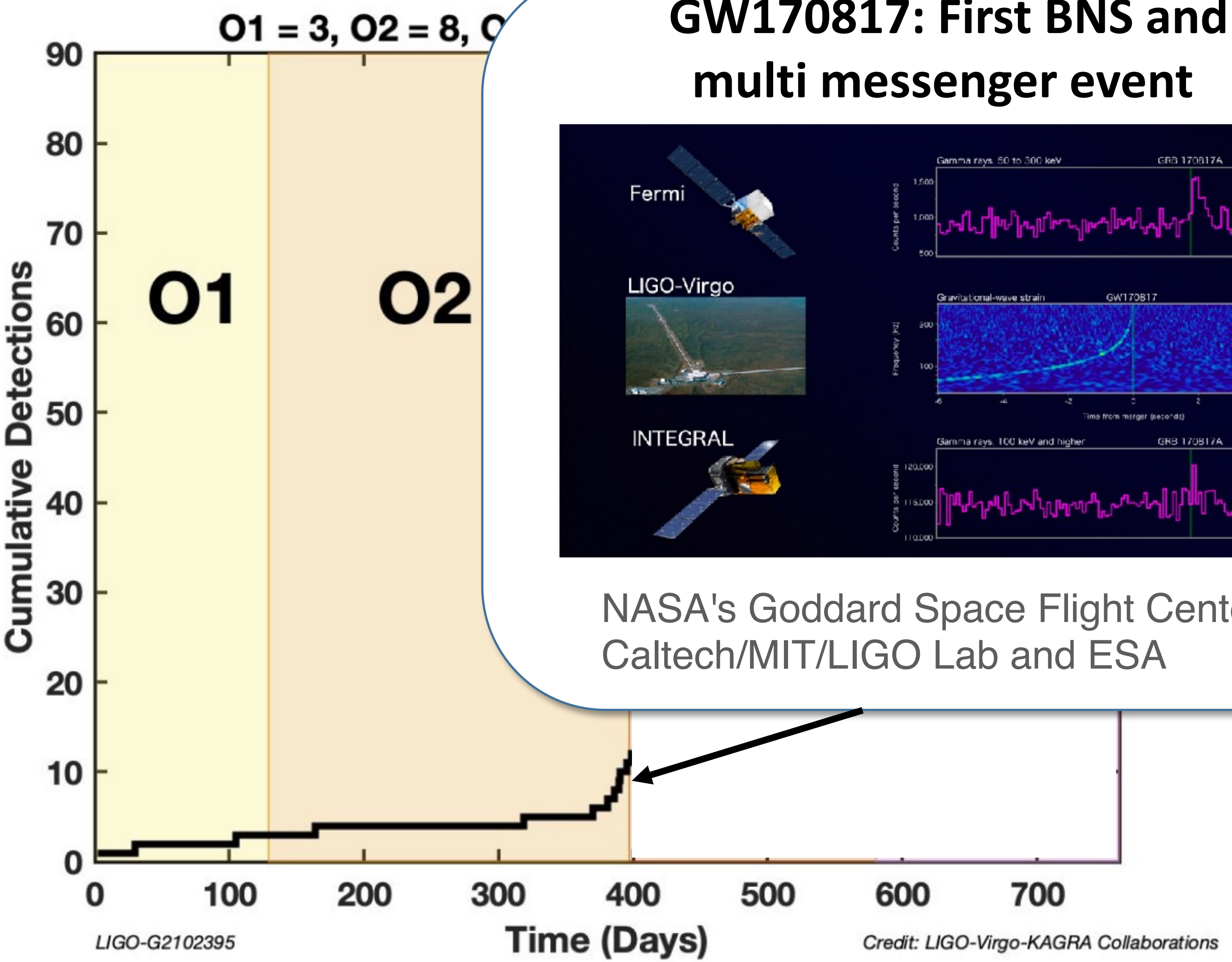
• <R>	average astrophysical rate	
• V	volume of the universe probed → (Range)³	
• T	coincident observing time	

- O1:
  - LH (BNS range ~80 Mpc*)



* Estimated ranges from LVK Observing Scenario: Living Reviews in Relativity 23, 3 (2020)

- O1:
  - LH (BNS range ~80 Mpc*)
- O2:
  - LH (BNS range ~100 Mpc), V (BNS range ~30 Mpc)

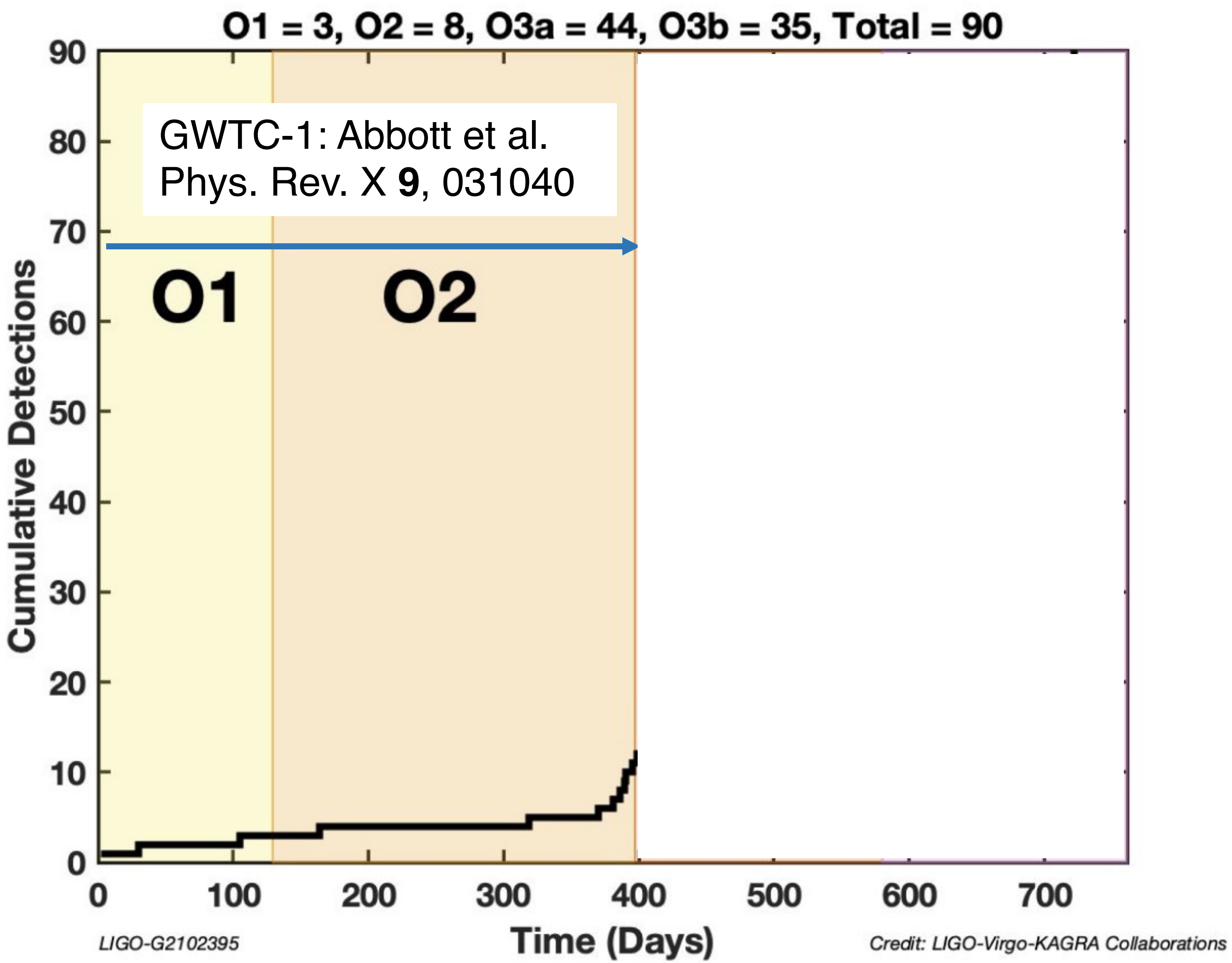


GW170817: First BNS and multi messenger event

NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab and ESA

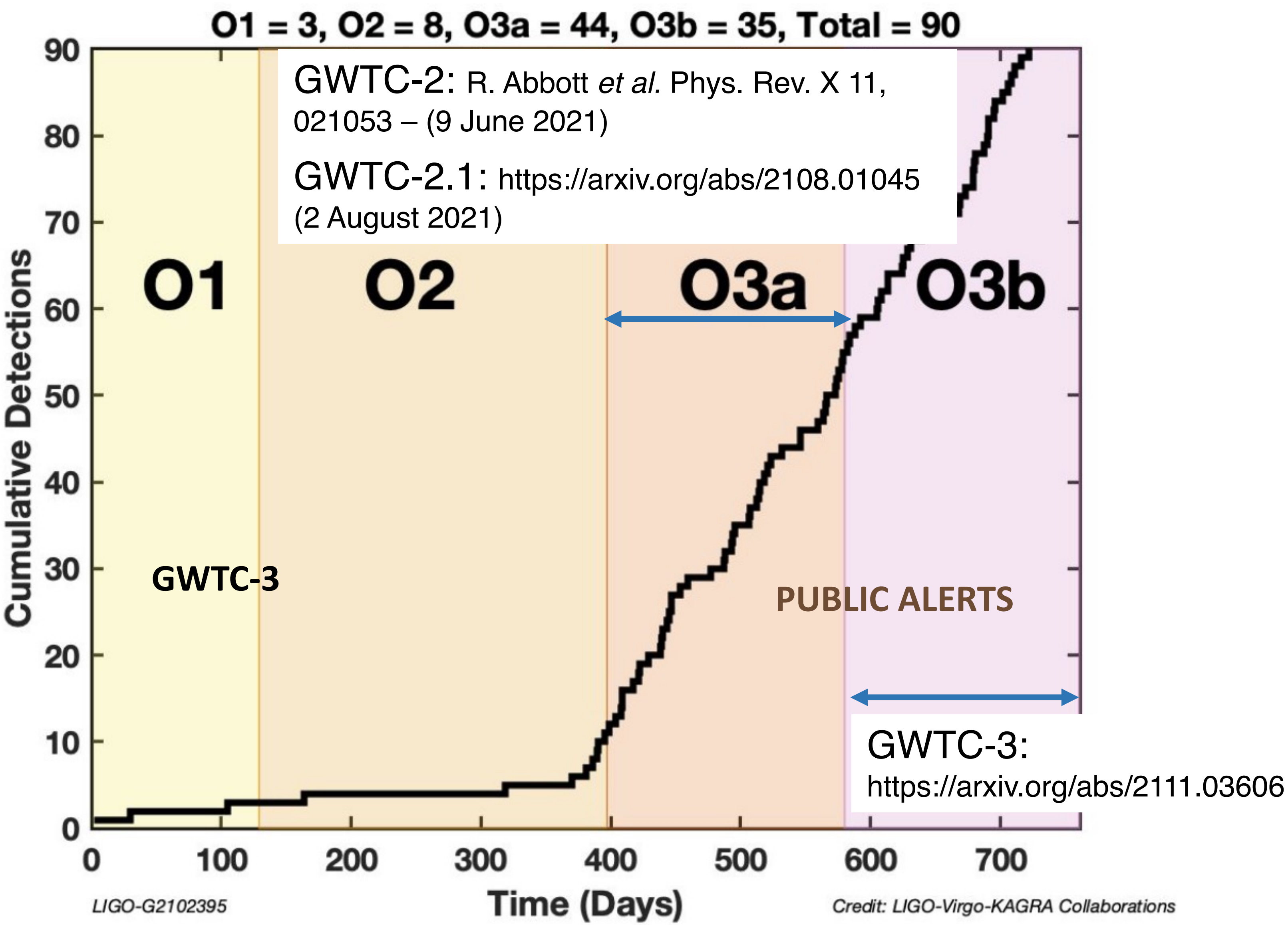
* Estimated ranges from LVK Observing Scenario: Living Reviews in Relativity 23, 3 (2020)

- O1:
    - LH (BNS range ~80 Mpc*)
- O2:
    - LH (BNS range ~100 Mpc), V (BNS range ~30 Mpc)



* Estimated ranges from LVK Observing Scenario: Living Reviews in Relativity 23, 3 (2020)

- O1:
  - LH (BNS range ~80 Mpc*)
- O2:
  - LH (BNS range ~100 Mpc), V (BNS range ~30 Mpc)
- O3:
  - O3a: Apr 2019 - September 2019
    - LH (BNS range ~130 Mpc), V (BNS range ~50 Mpc)
  - O3b: November 2019 - March 2020
    - Addition of KAGRA



* Estimated ranges from LVK Observing Scenario: Living Reviews in Relativity 23, 3 (2020)

O3 Open Public Alerts

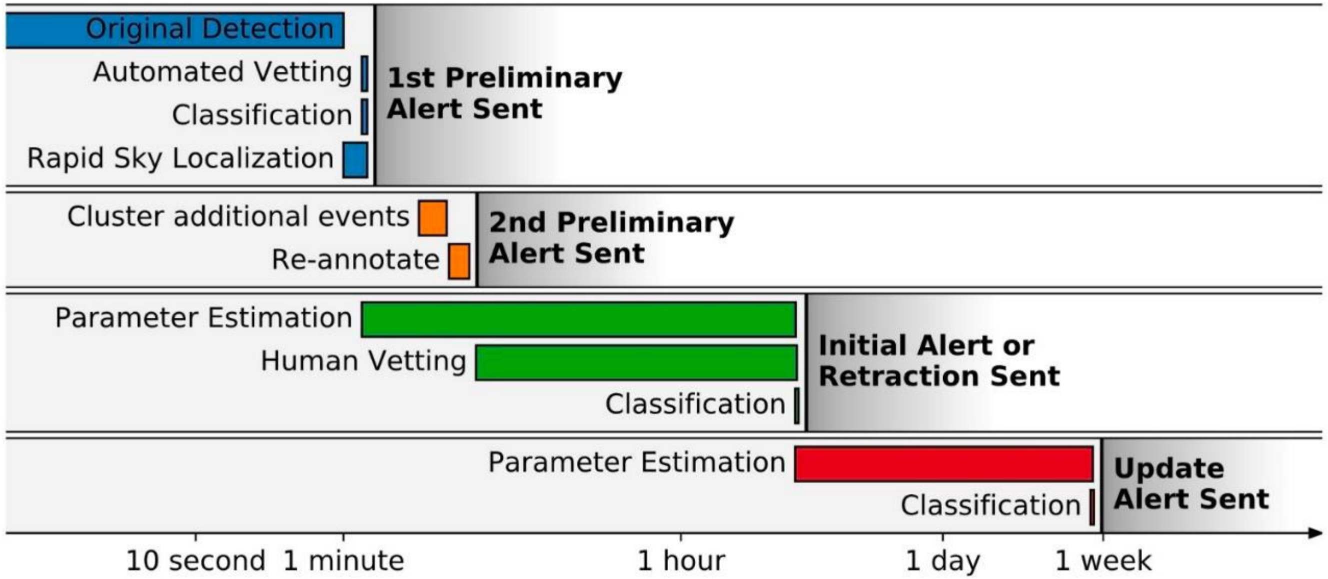
LIGO-Virgo data are jointly analyzed in real-time

- Modelled (compact binary coalescences) and unmodelled searches («bursts»)
- ➢ Detect and localize potential transient GW signals

When a significant-enough candidate is found

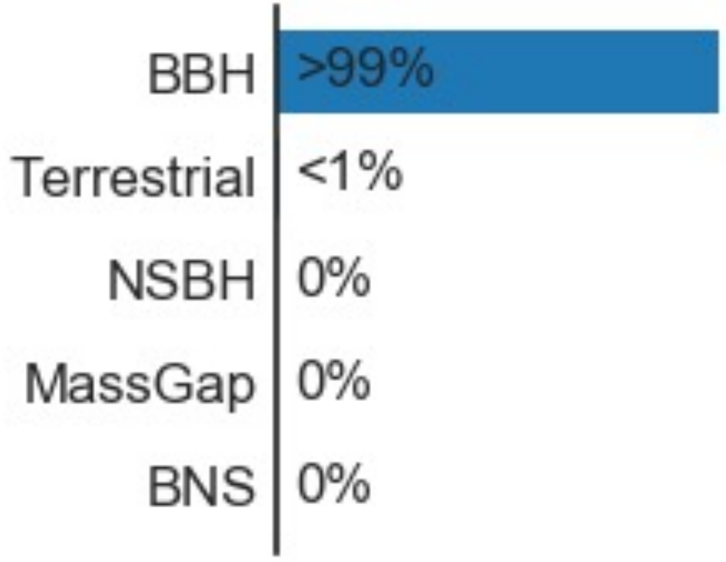
- False-alarm rate lower than 1 / O(few months)
- ➢ Alert sent to astronomers in order to search for counterparts through NASA's Gamma-ray Coordinates Network (GCN)

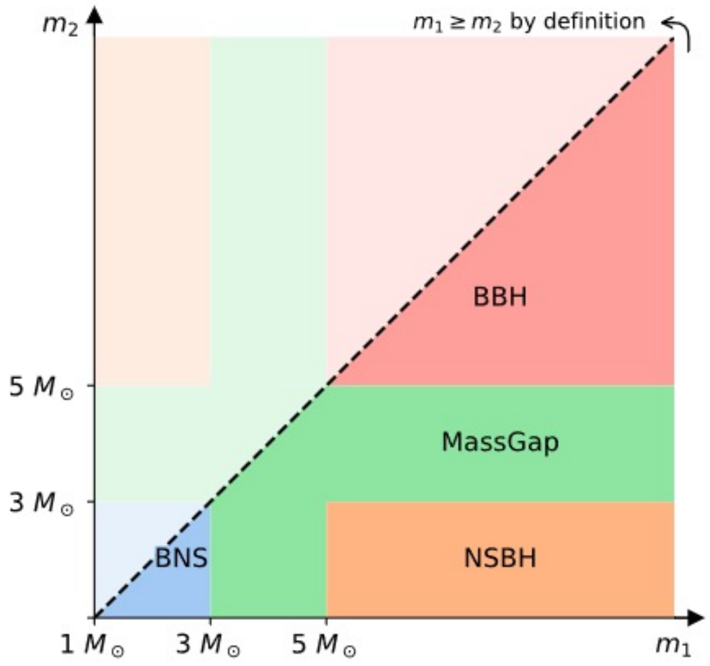
- Expert vetting
- ➢ Public alerts can be retracted



O3 Open Public Alerts

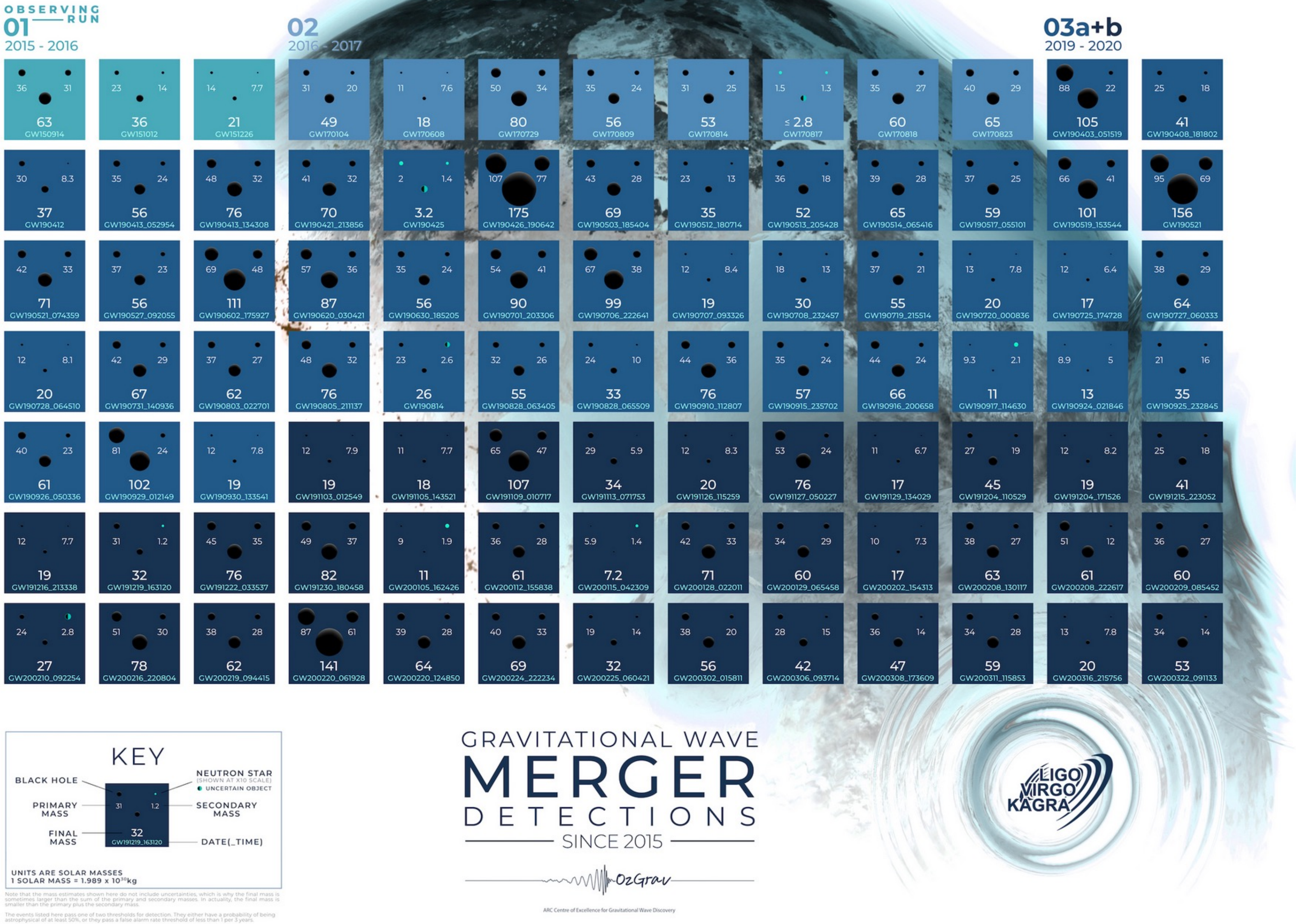
- **Localization:** 3D map for follow-up
- **Classification:** probability that the source belongs to five categories



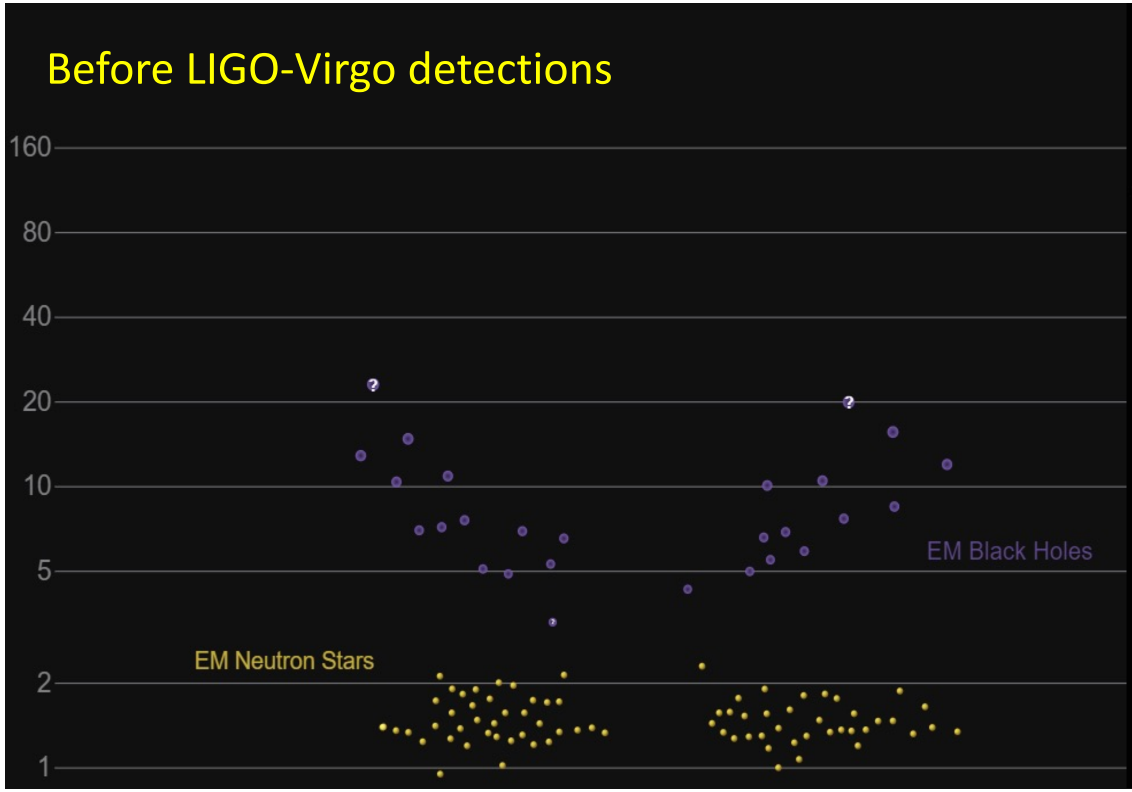


Gravitational Waves Open Science Center

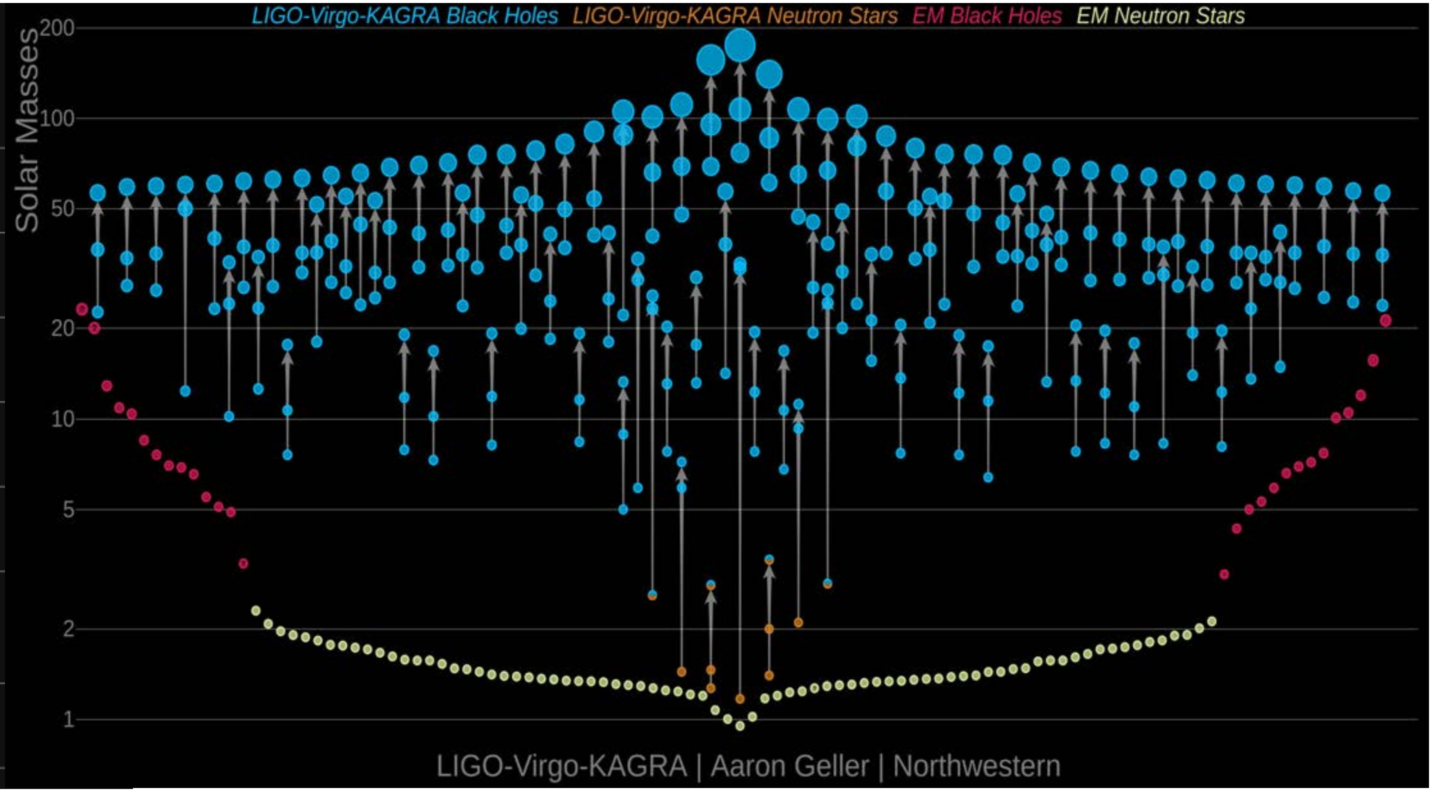
- All O3 (along with O1 and O2) data available online @ https://www.gw-openscience.org/
- 1-hour time-series data around each published event (prior to full data release)
- Also contains:
  - Pointers to analysis software tools;
  - Materials from Open Data Workshops;
  - Online tutorials.



https://www.ligo.org/detections/O3bcatalog/files/gwmerger-poster-white-md.jpg



Before LIGO-Virgo detections
160
80
40
20
10
5
2
1
EM Black Holes
EM Neutron Stars



LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

Some highlights on what we have learned

Astrophysics

- GW170817 solved the long-standing problem of the origin of (at least some) short GRB
- NS-NS mergers are a site for the formation of some of the heaviest elements through r-process nucleosynthesis
- BH-BH binaries exist and merge within the age of the Universe
- discovered a new population of stellar-mass BHs, much heavier than those detected through X-ray binaries

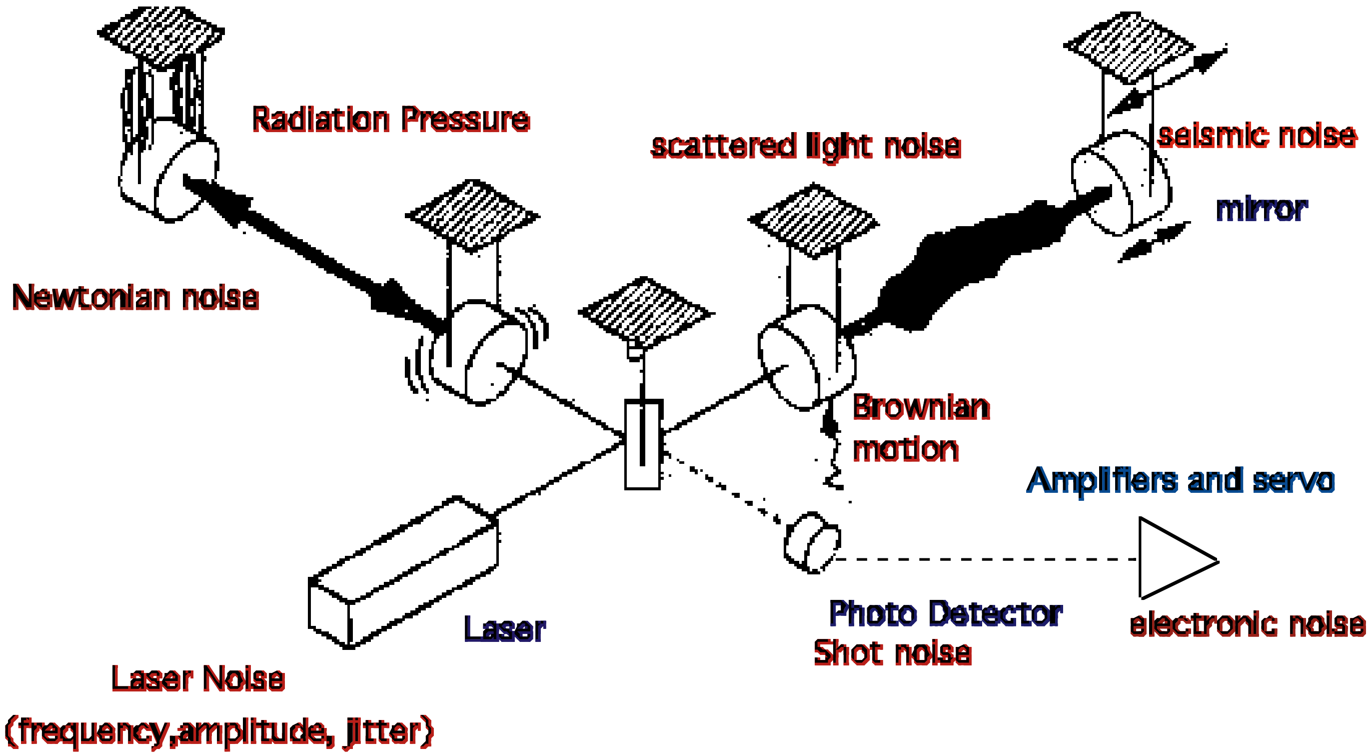
Some highlights on what we have learned

Cosmology/fundamental physics

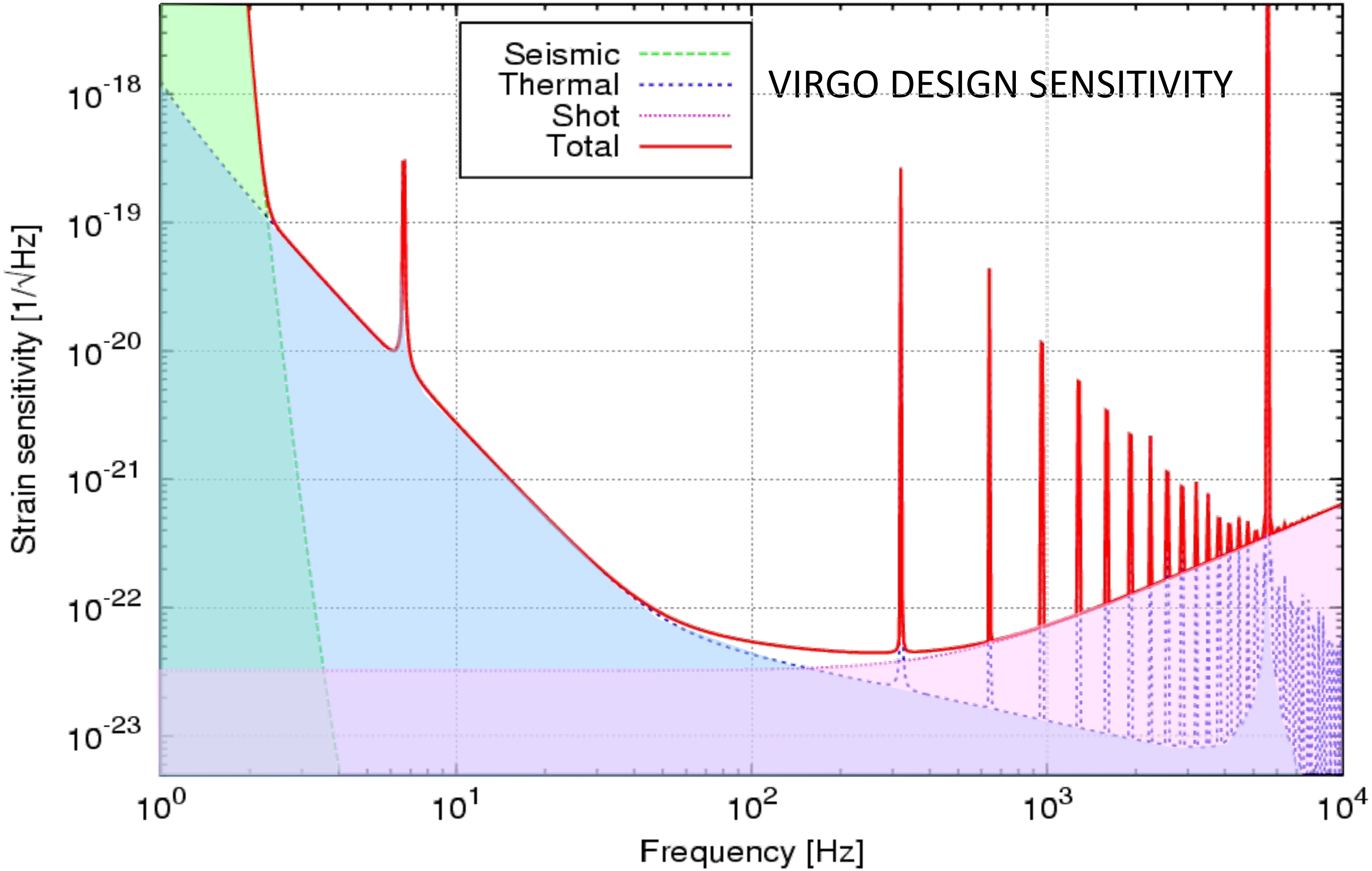
- speed of GWs equal to speed of light (1:10^{15})
- first measurement of the Hubble constant with GWs
- the tail of the waveform of GW150914 consistent with the prediction from General Relativity for the quasi-normal modes of the final BH
- deviations from GR (graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.) could be tested and bounded

What made this results possible?

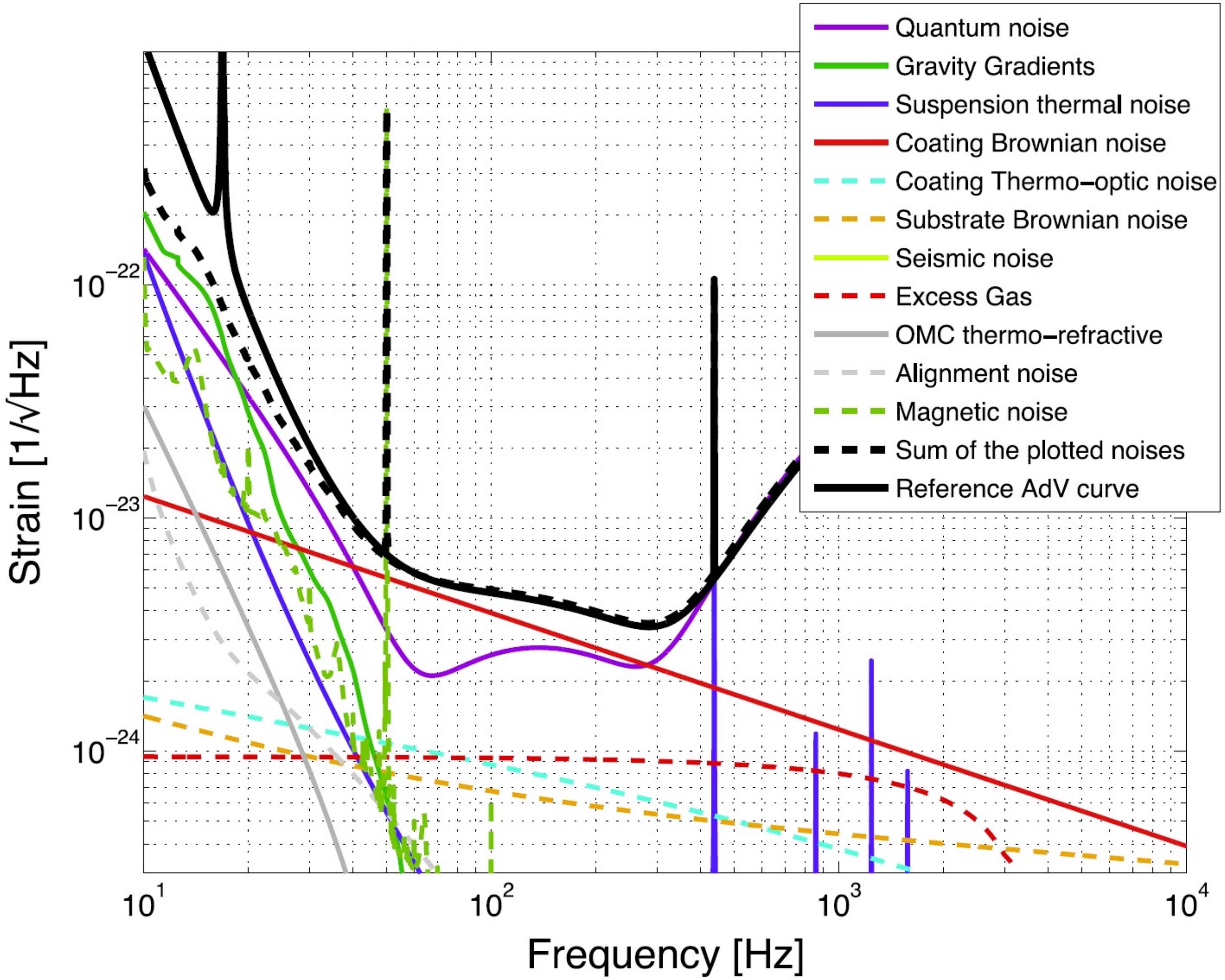
- Fundamental and technical noise sources limit the sensitivity of our instruments



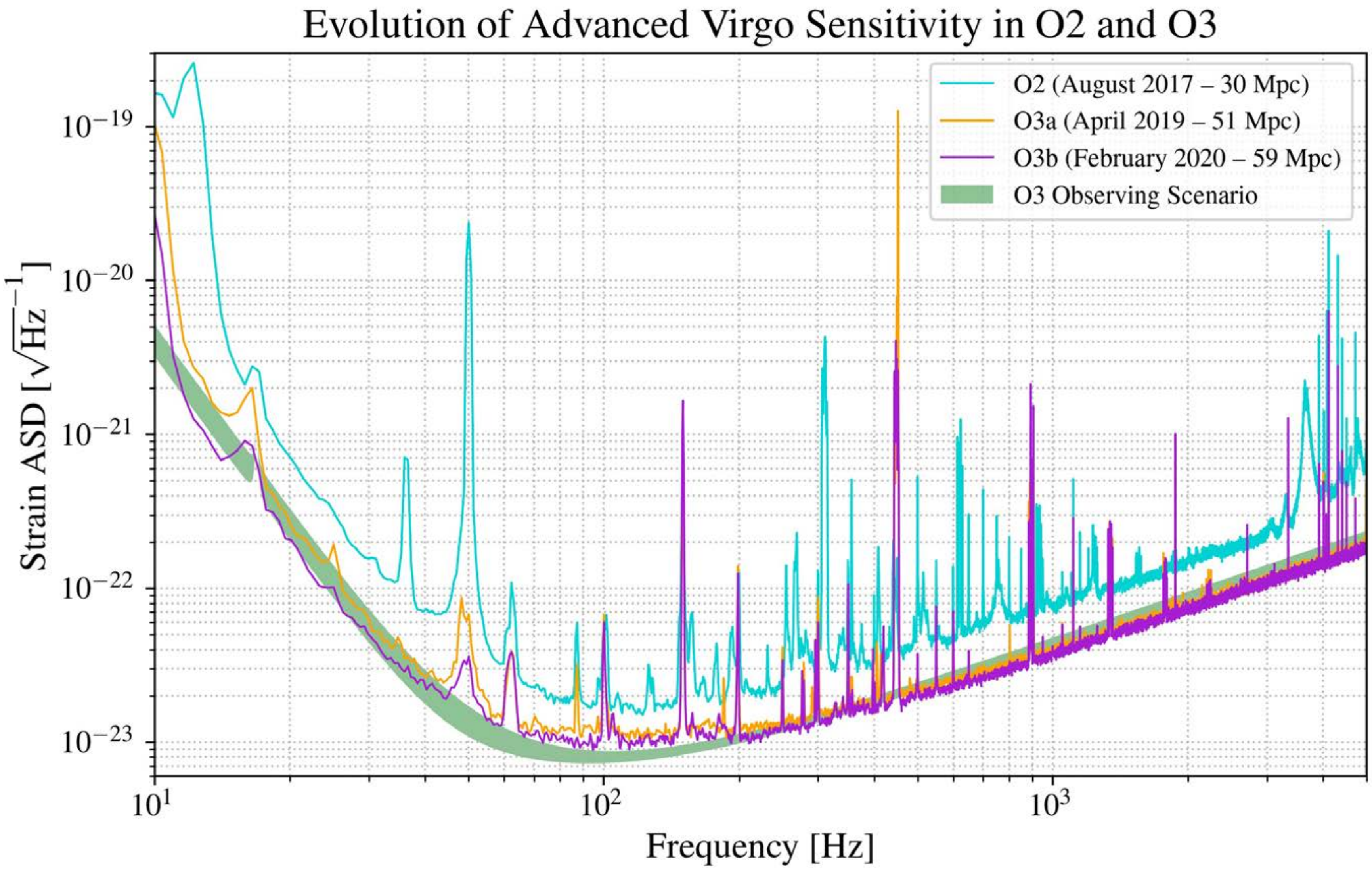
What made this results possible?



Virgo sensitivity: noise budget

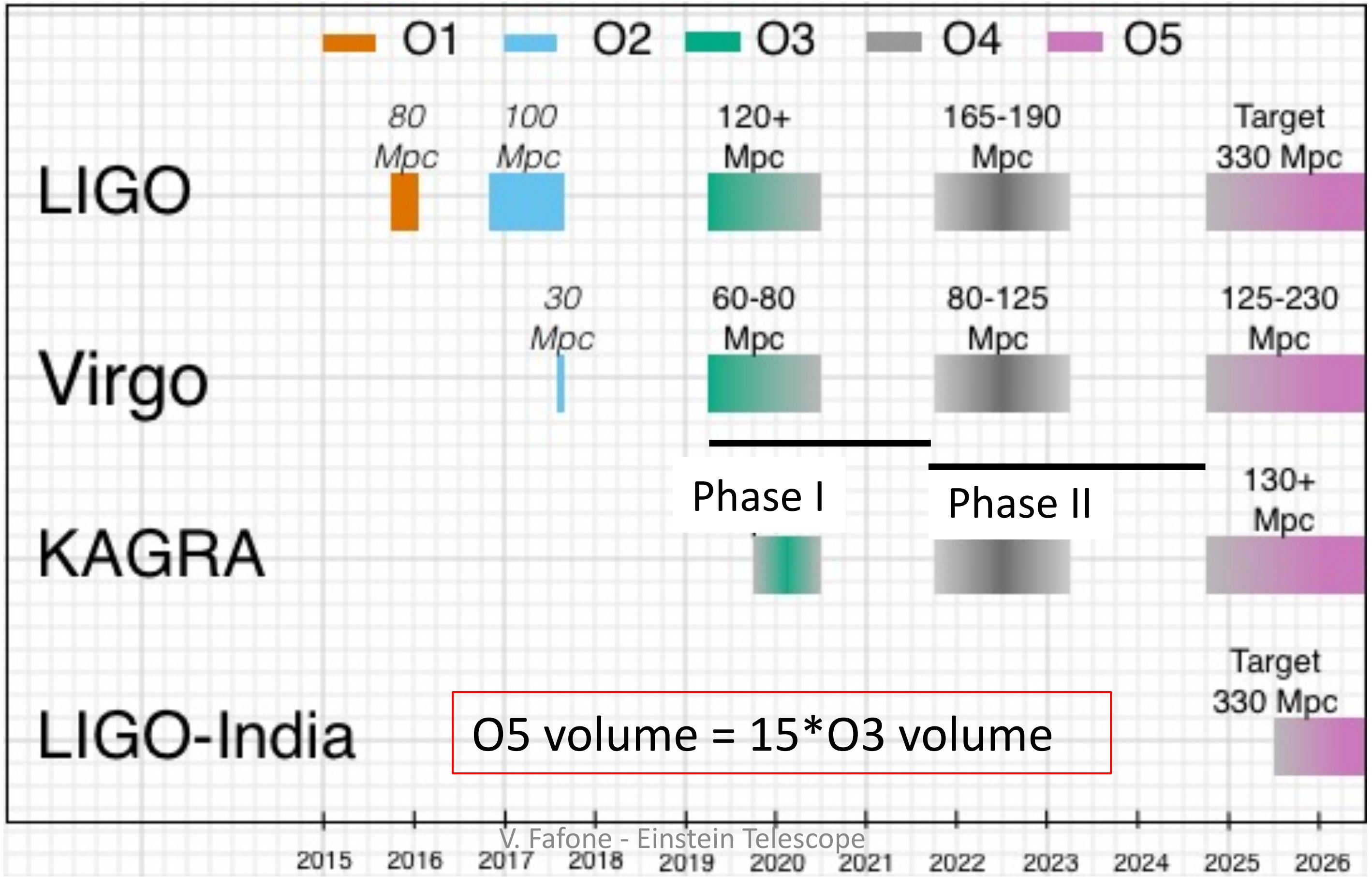


Virgo sensitivity: O2 vs O3



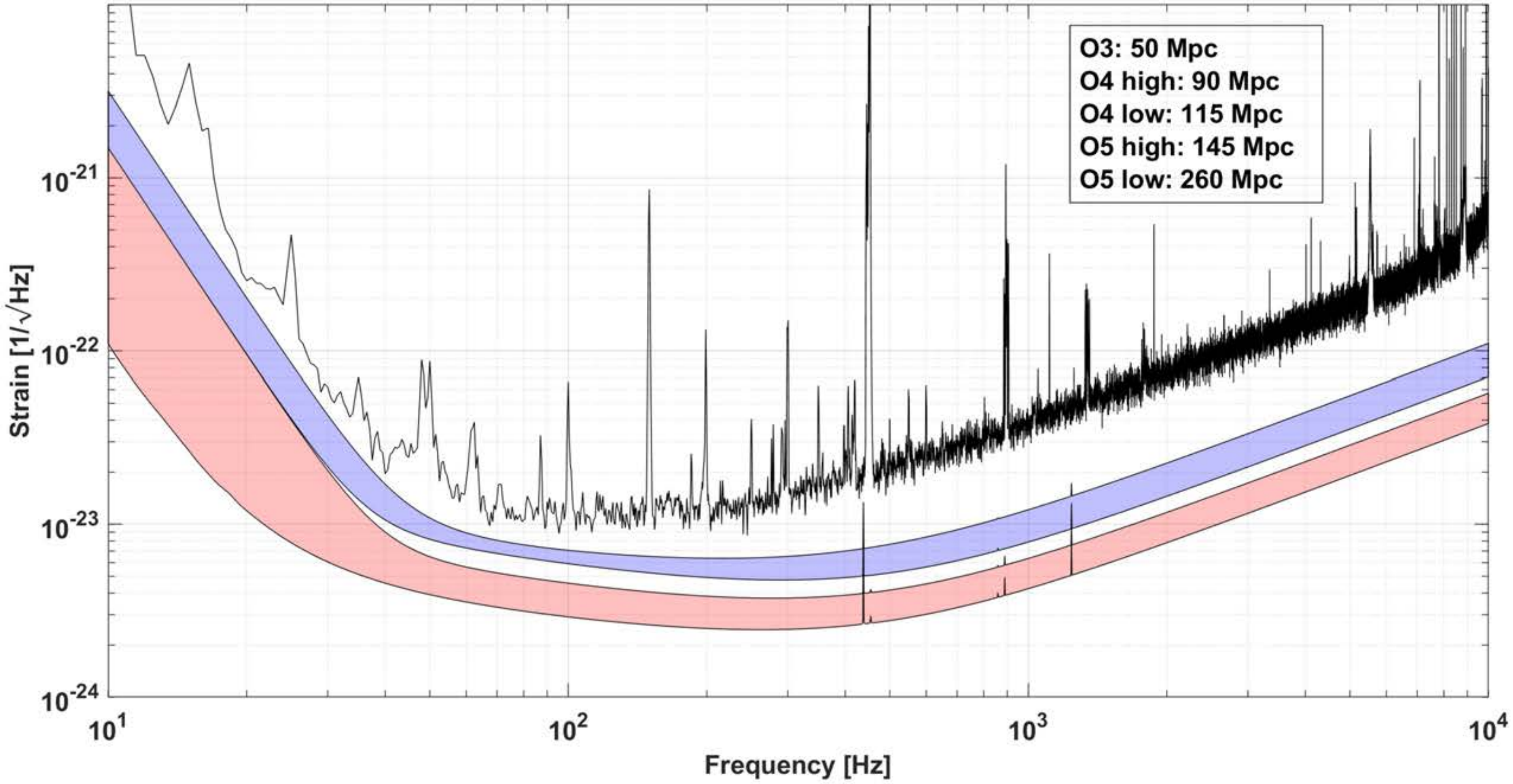
The path towards O4 and O5

- Shutdown period between O3 and O4 to upgrade the current detectors → Advanced+ detectors
- Four detectors online in O4: 2 LIGOs, Virgo and KAGRA

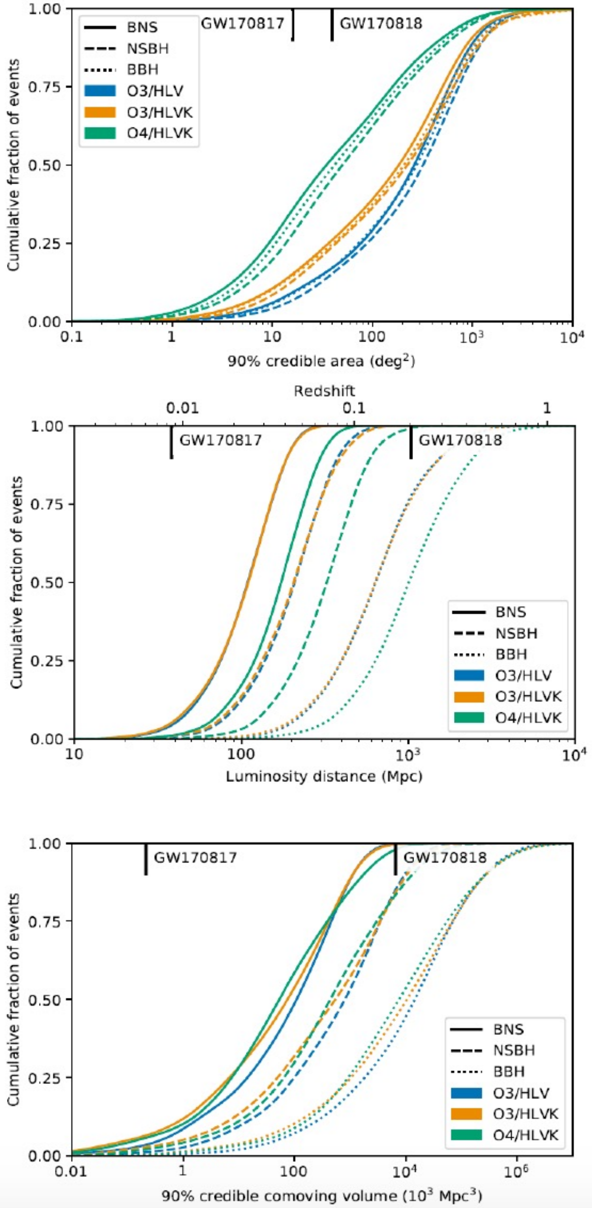


AdV+: sensitivity goal

- **Phase I:** reduce quantum noise, hit against thermal noise
- **Phase II:** push down the thermal noise wall



Perspectives



		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
$1.4M_\odot + 1.4M_\odot$	AdV	-	30	50	90 – 120	150 – 260
	KAGRA	-	-	8 – 25	25 – 130	130+
BBH Range (Mpc)	aLIGO	740	910	990 – 1200	1400 – 1600	2500
$30M_\odot + 30M_\odot$	AdV	-	270	500	860 – 1100	1300 – 2100
	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc)	aLIGO	140	180	190 – 240	300 – 330	590
$1.4M_\odot + 10M_\odot$	AdV	-	50	90	170 – 220	270 – 480
	KAGRA	-	-	15 – 45	45 – 290	290+
Burst Range (Mpc)	aLIGO	50	60	80 – 90	110 – 120	210
$[E_{GW} = 10^{-2} M_\odot c^2]$	AdV	-	25	35	65 – 80	100 – 155
	KAGRA	-	-	5 – 25	25 – 95	95+
Burst Range (kpc)	aLIGO	15	20	25 – 30	35 – 40	70
$[E_{GW} = 10^{-9} M_\odot c^2]$	AdV	-	10	10	20 – 25	35 – 50
	KAGRA	-	-	0 – 10	10 – 30	30+

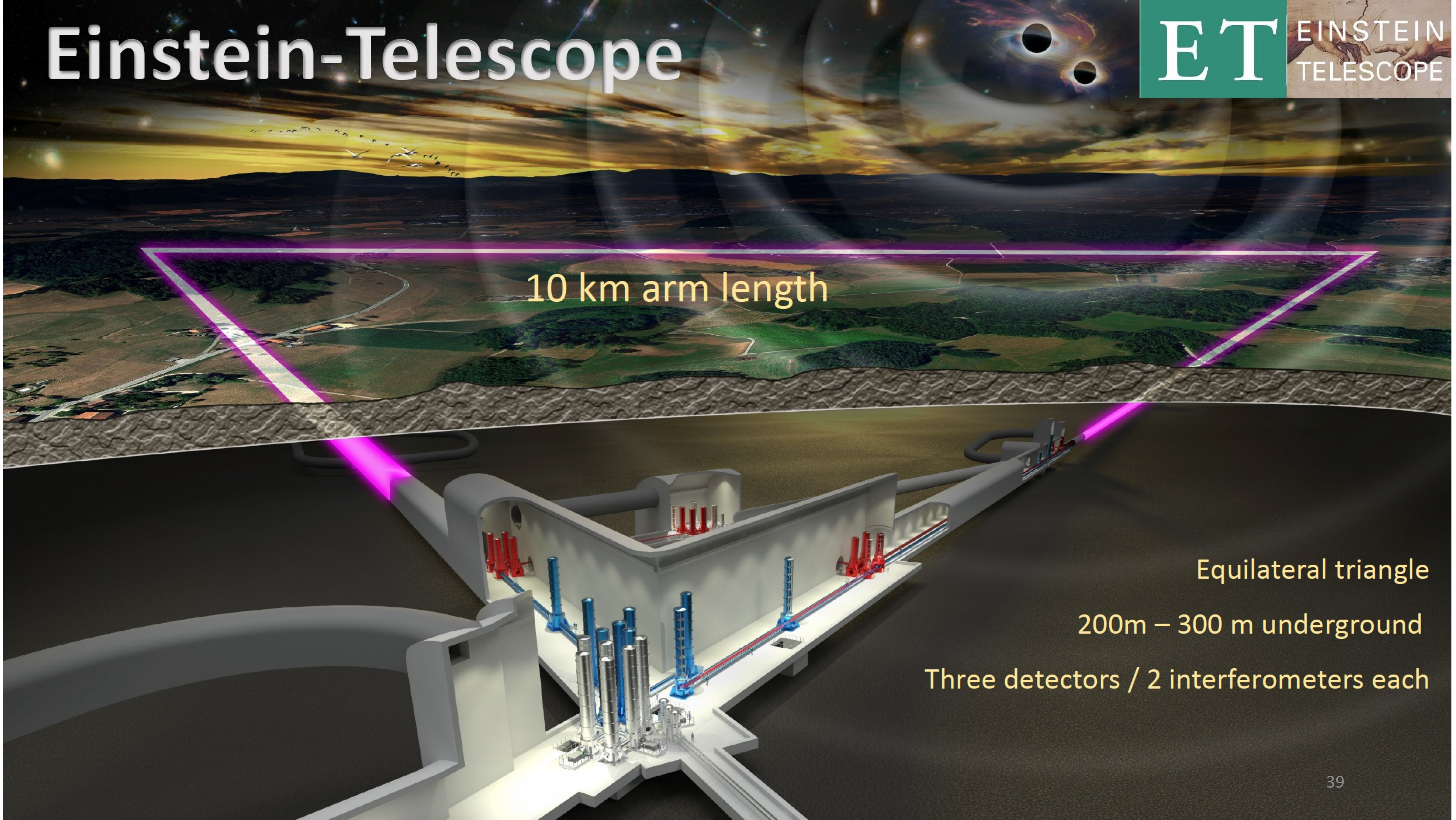
SNR = 8 su ciascun rivelatore

What's Next?

- The detection of GW has been a huge scientific achievement, result of a century of efforts, but actually it is the beginning of a new era in the observation of the Universe
- 2nd generation GW detectors will explore local Universe, initiating the precision GW astronomy, but to have cosmological investigations a factor of 10 improvement is needed

→ need to develop a third generation of GW detectors

Einstein-Telescope



Equilateral triangle

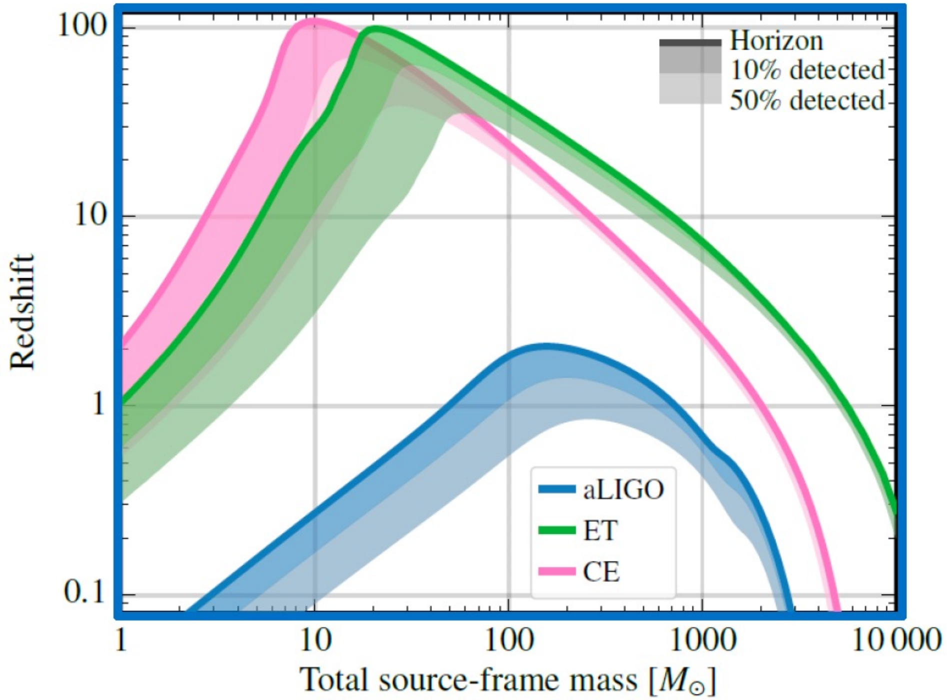
200m – 300 m underground

Three detectors / 2 interferometers each

Science potentials for 3G detectors

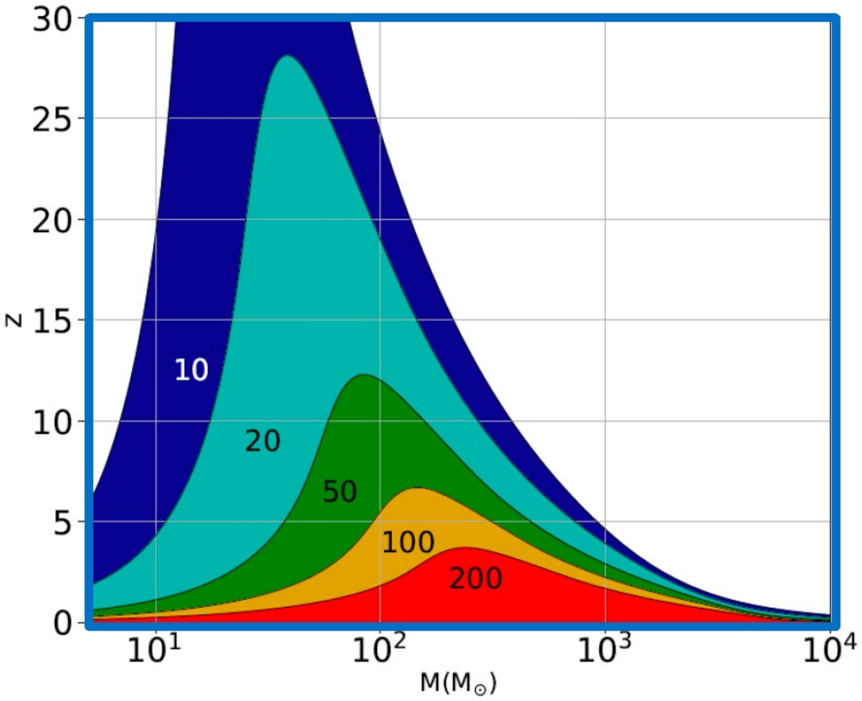
Sensitivity improvement by at least an order of magnitude compared to 2G design sensitivities

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

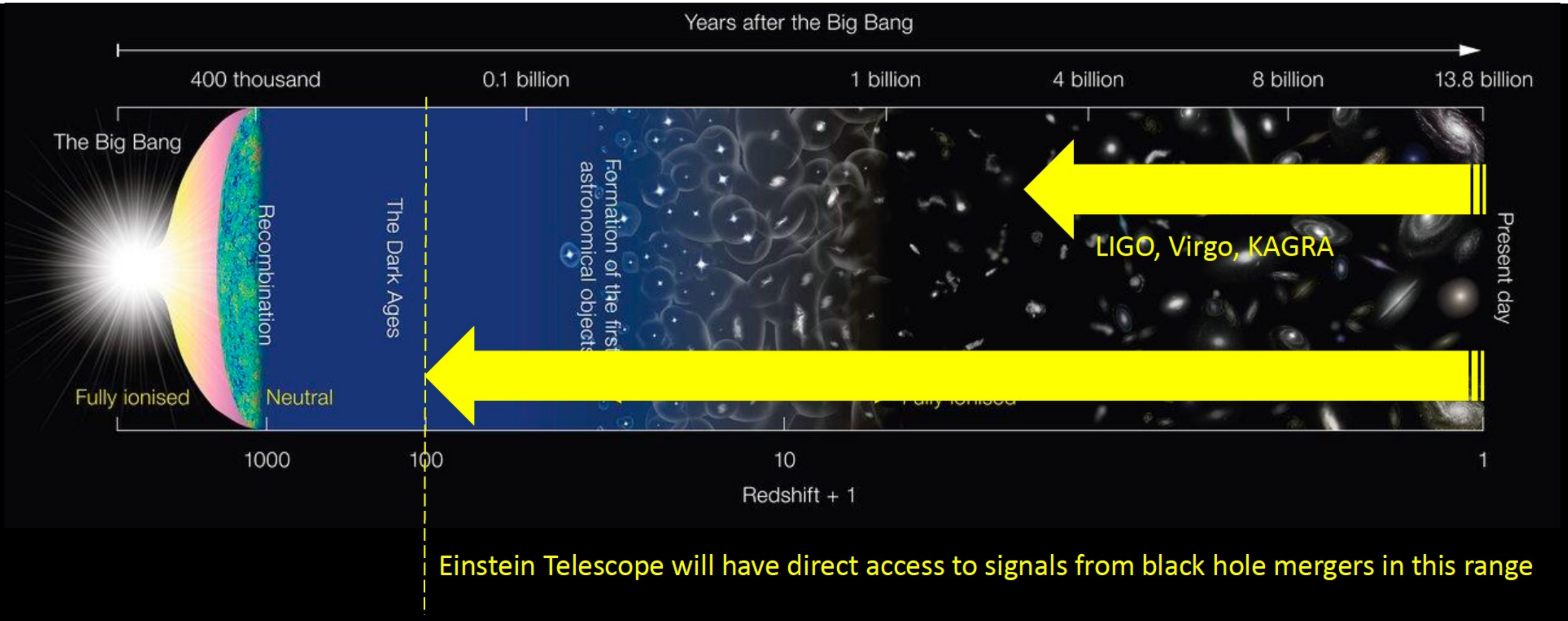
Curves of constant SNR in the (total mass, redshift) plane, for a network of one ET and two CE detectors.



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*.



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

BNS to $z \approx 2$: 10^5 BNS/yr (15-50/yr with counterpart)

Einstein Telescope's science in a nutshell

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

ASTROPHYSICS

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

FUNDAMENTAL PHYSICS AND COSMOLOGY

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

ET in the global network

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

Science questions to be addressed by GWs

- Fundamental questions in Gravity:
  - New/further tests of GR
  - Exploration of possible alternative theories of Gravity
  - How to disprove that Nature black holes are black holes in GR (e.g. non tensorial radiation, quasi normal modes inconsistency, absence of horizon, echoes, tidal deformability, spin-induced multipoles)

Fundamental interactions, Dark matter, dark energy

- Fundamental questions in particle physics
  - Axions and ultralight particle through the evaluation of the consequences of new interactions, their impact on two bodies mechanics, in population and characterisics of BHs, NSs

Inflation, additional interactions, dark matter

- Probing the EOS of neutron stars

Nuclear physics, quark-gluon plasma, Neutrino Physics

- Exotic objects and phenomena (cosmic strings, exotic compact objects: boson stars, strange stars/gravastars, …)
- Cosmology and Cosmography with GWs

Cosmology

- Accurate Modelling of GW waveforms
- GW models in alternative theory of gravitation

Cosmology

- The population of compact objects discovered by GWs is the same measured by EM? Selection effects on BHs and NSs?
- What is the explosion mechanism in Supernovae?

Nuclear physics, Neutrino Physics

- What is the history of SuperMassive black holes?
- GW Stochastic Background? Probing the big bang?

Cosmology, inflation

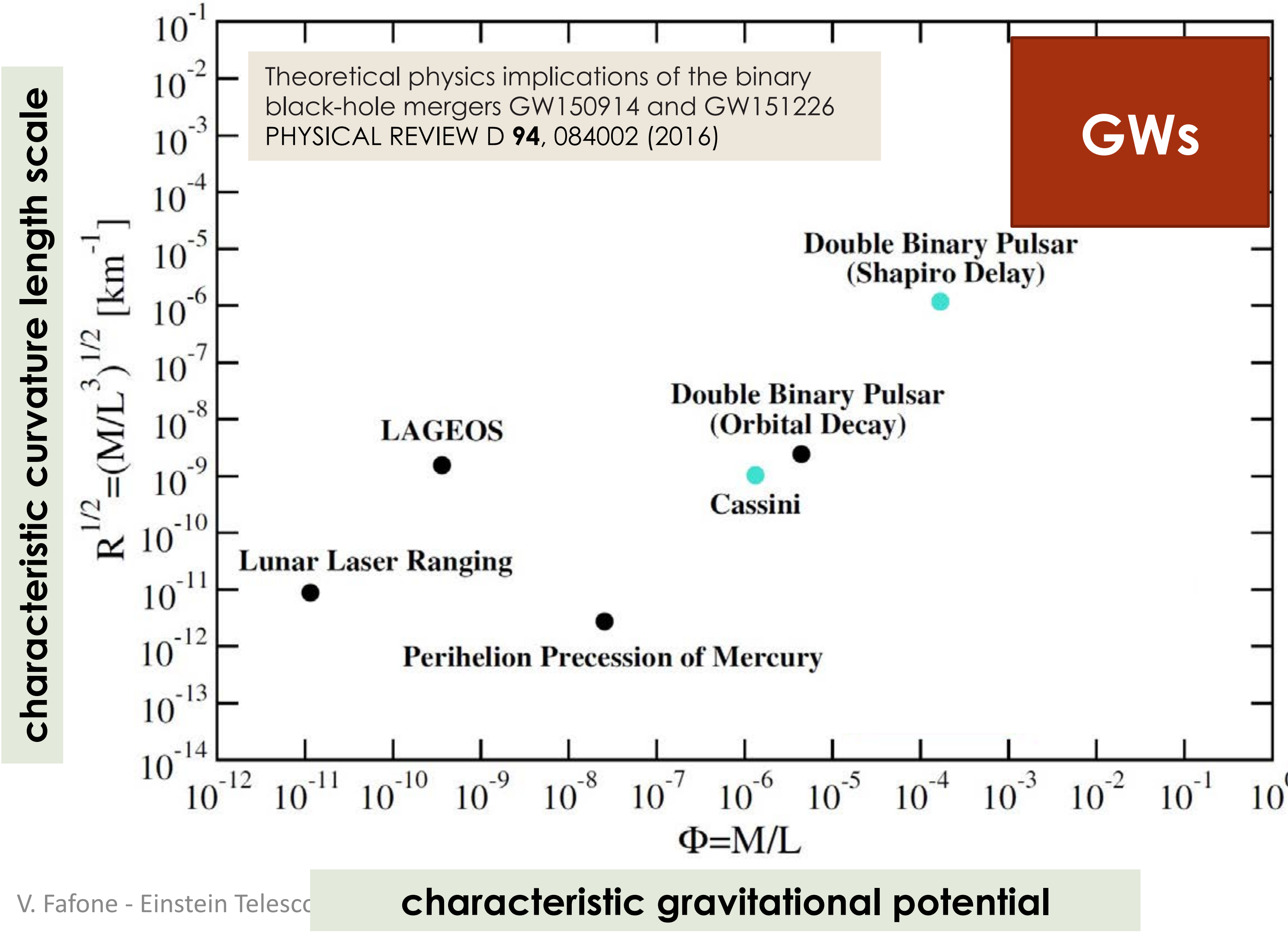
- Multimessenger Astronomy in 3G?

Astroparticle, GRB, Neutrino Physics

Highlights in some fundamental questions: #1

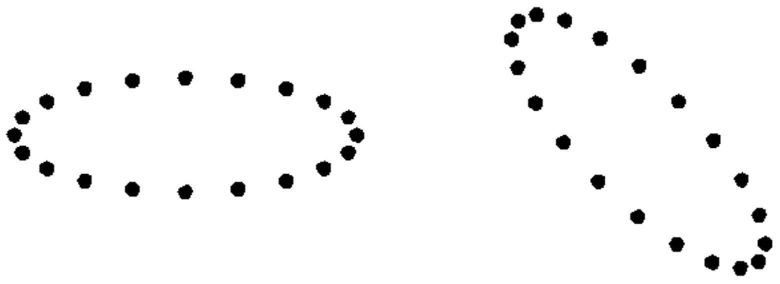
- Is Einstein's General Relativity THE theory of gravitation?
  - Test of GR
  - Polarisations of GWs
  - Black Hole Quasi-Normal modes
  - Test of wave propagation
    - Massive Gravity

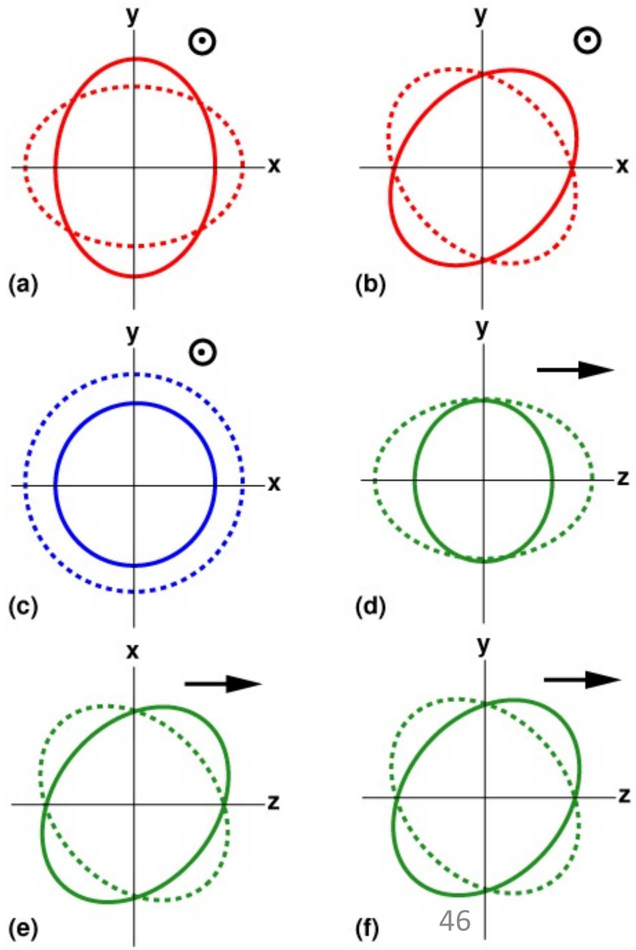
NB: the following slides are extracted from the GWIC-3G and ET science case documents



Alternative theories of Gravity: polarisations

- GR predicts a tensorial nature of GW with two polarisations
  - Alternative theories of gravity could predict extra polarisations of GW (up to 6)



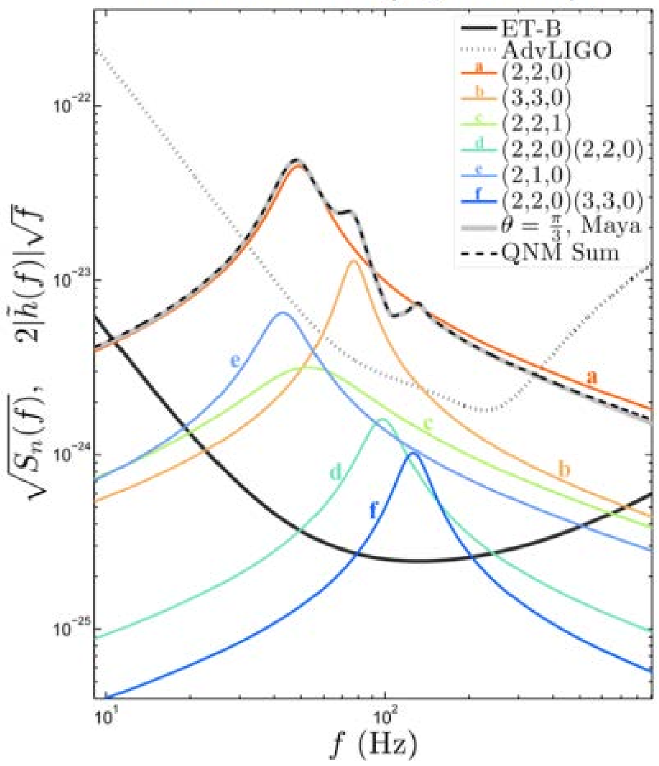


- 2G detectors are attempting to verify the GW tensorial nature:
  - \+ and x polarisations can be resolved by 2 interferometers at 45° (C)
  - A null stream can be realised (B): $h_{null} = h_1 - h_2$
- ET, thanks to its multi-detector design, is capable to resolve the two polarisations of the GW

QuasiNormal modes of a BH

- In GR, no-hair theorem predicts that BHs are described only by their mass and spin (and charge)
  - However, when a BH is perturbed, it reacts (in GR) in a very specific manner, relaxing to its stationary configuration by oscillating in a superpositions of quasi-normal modes, which are damped by the emission of GWs.
  - A BH, a pure space-time configuration, reacts like an elastic body → Testing the “elasticity” of the space-time fabric
  - Exotic compact bodies (boson stars, stars made of dark matter particles...) could have a different QN emission and have echoes

350 Msun binary @ 100 Mpc



ET will resolve QN emission by BH

Test of wave propagation

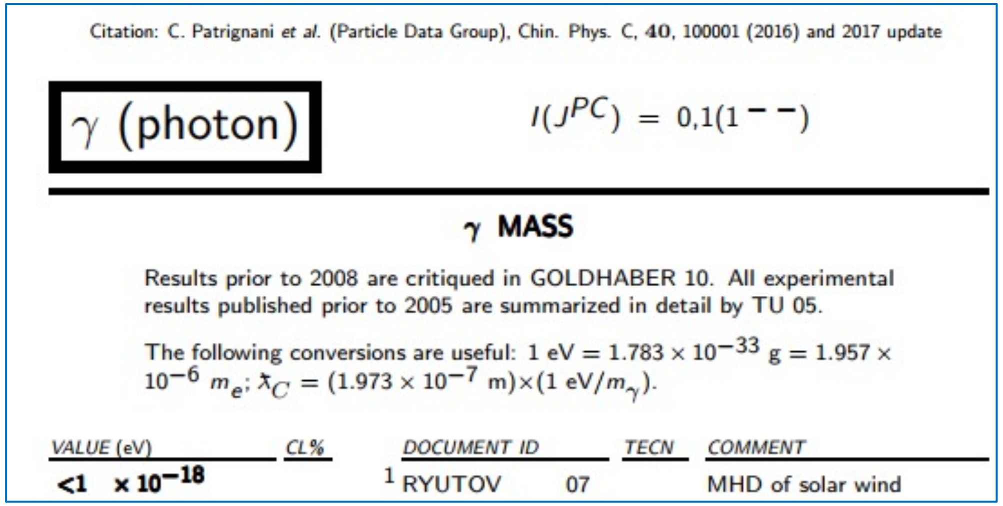
$$E^2 = p^2c^2 + Ap^\alpha c^\alpha$$

$$E^2 = p^2c^2 + m_g^2c^4 \qquad \lambda_g = h/(m_g c)$$

- Modified theories of gravity predict dispersion
  - Dispersion modifies the phase and frequency of the detected GW signal
  - 2G detectors already imposed a severe limit on:

$$m_g < 1.8\ 10^{-23}\ \mathrm{eV}/c^2$$

  - ET and the 3G network, observing GW sources at $z \sim 20$ will improve the limit by about 2 orders of magnitude



Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016) and 2017 update

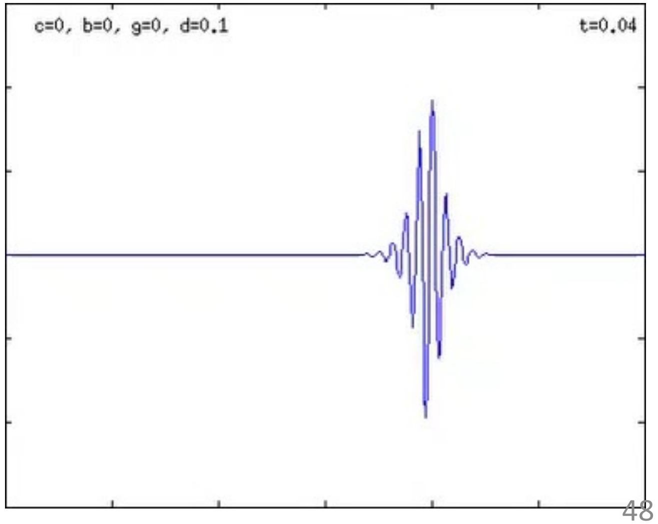
γ (photon) $\qquad I(J^{PC}) = 0,1(1^{--})$

γ MASS

Results prior to 2008 are critiqued in GOLDHABER 10. All experimental results published prior to 2005 are summarized in detail by TU 05.

The following conversions are useful: 1 eV = 1.783×10^{-33} g = $1.957 \times 10^{-6}\ m_e$; $ƛ_C = (1.973 \times 10^{-7}\ \mathrm{m}) \times (1\ \mathrm{eV}/m_\gamma)$.

VALUE (eV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
<1 × 10⁻¹⁸		[1] RYUTOV	07		MHD of solar wind

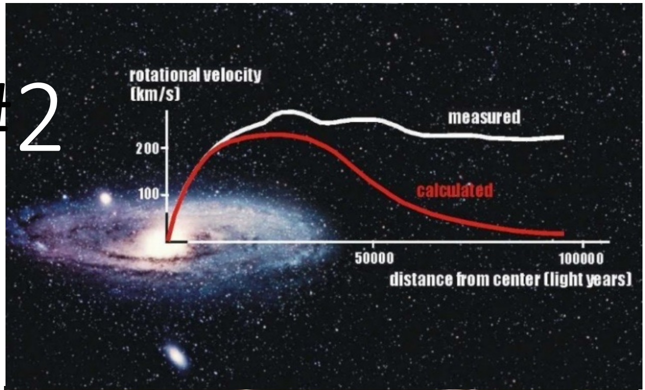


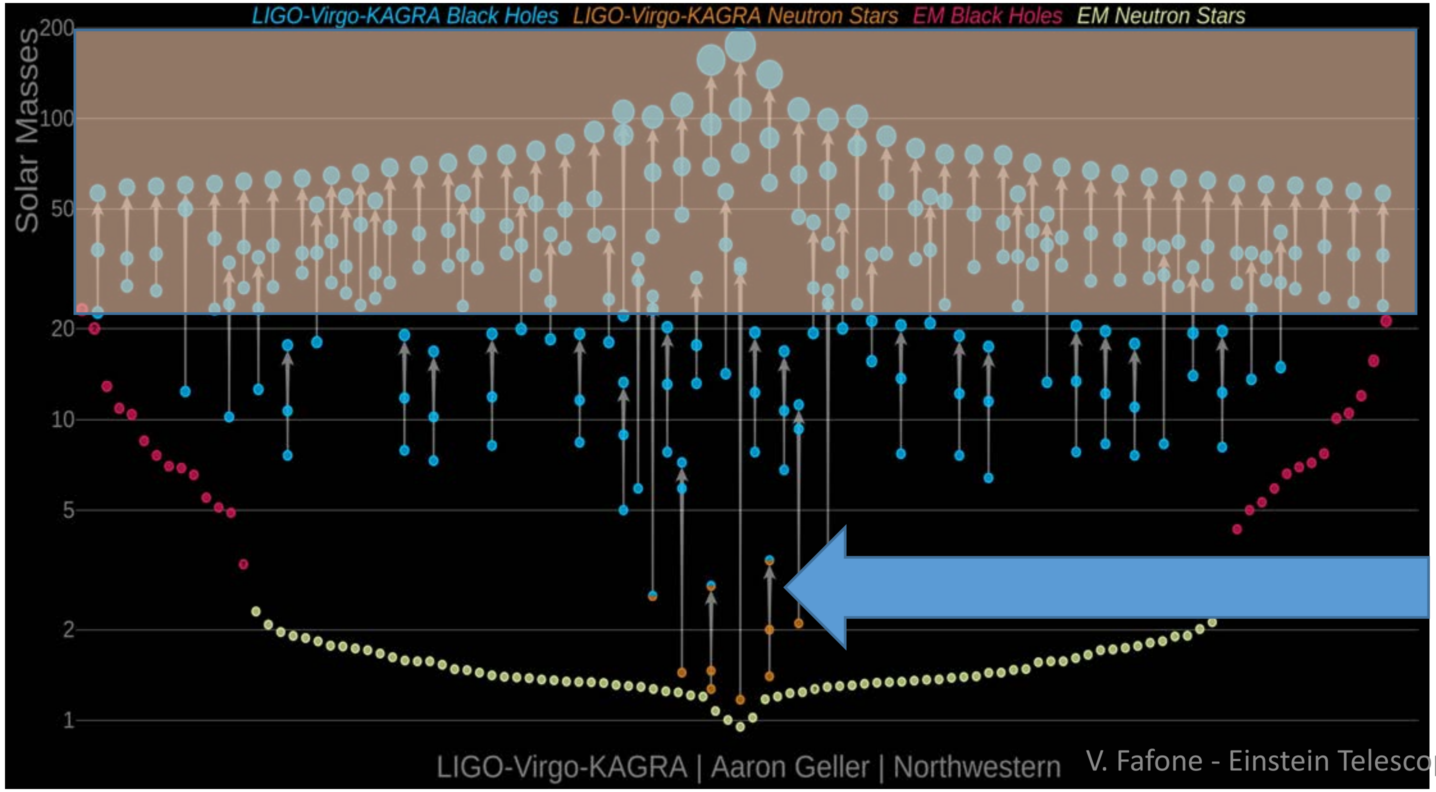
Highlights in some fundamental questions: #2

- What is the nature of Dark Matter?

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \Rightarrow G_{\mu\nu} = \frac{8\pi G}{c^4}\left(T_{\mu\nu} + T^{DM}_{\mu\nu}\right)$$

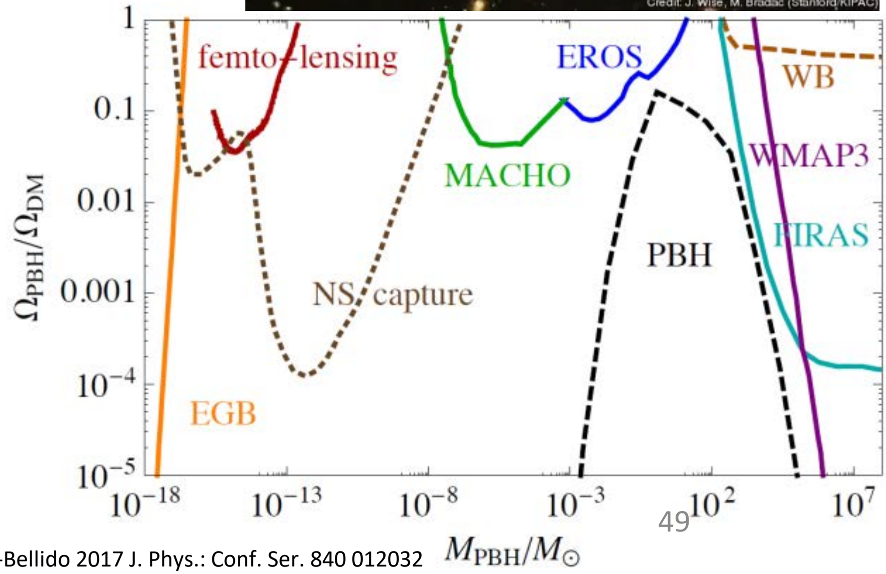
$T^{WIMP}_{\mu\nu}$ $T^{axion}_{\mu\nu}$ $T^{BH}_{\mu\nu}$





New family of BH?

BHs or a Hypermassive NSs in the mass gap?

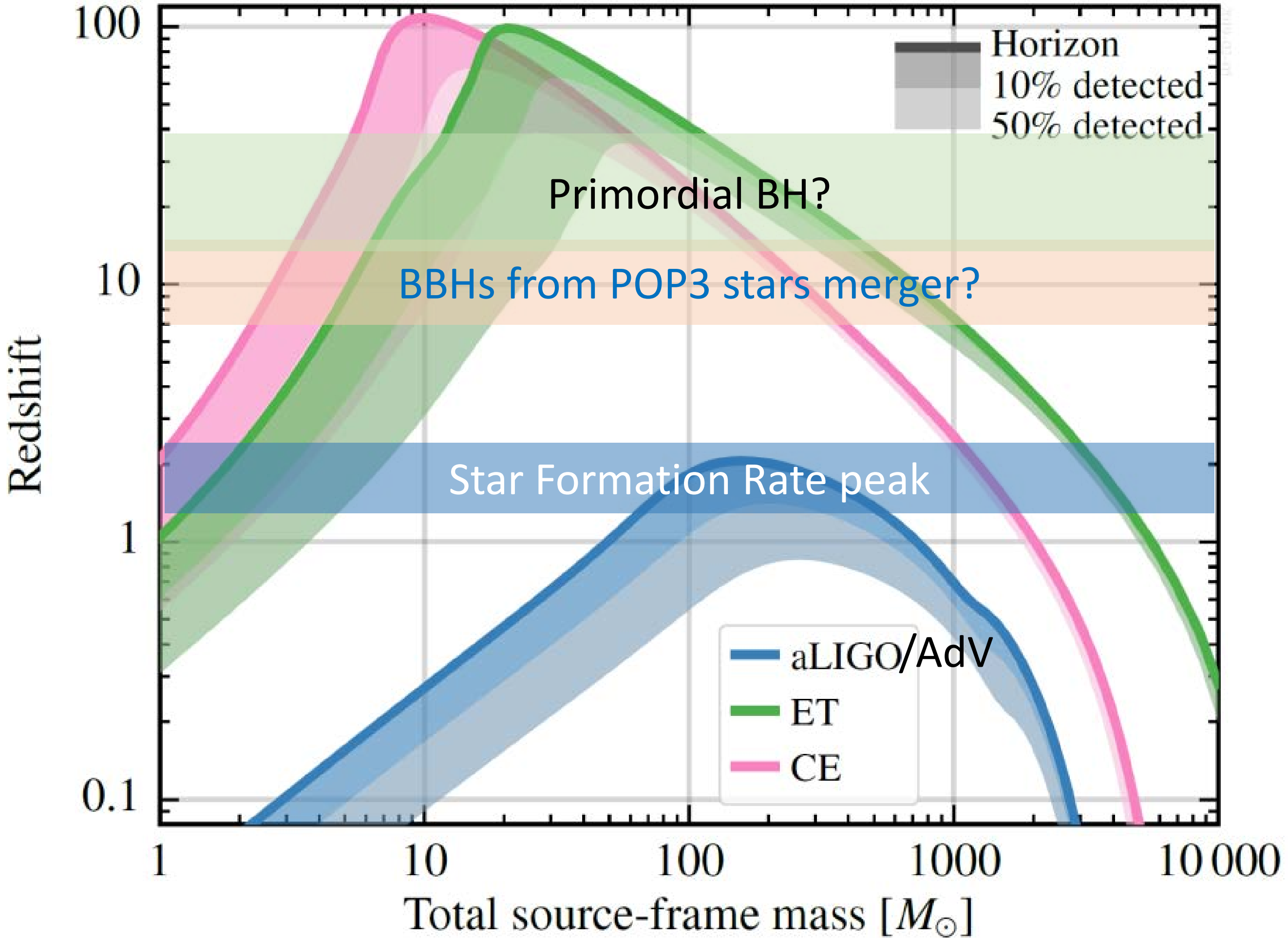


Juan García-Bellido 2017 J. Phys.: Conf. Ser. 840 012032

Primordial BHs in ET

- ET will detect BH well beyond the SFR peak $z{\sim}2$
  - comparing the redshift dependence of the BH-BH merger rate with the cosmic star formation rate it will be possible to disentangle the contribution of BHs of stellar origin from that of possible BHs of primordial origin (whose merger rate is not expected to be correlated with the star formation density)

- The huge number of detections in ET will allow to perform cross-correlations between the detected GW events and large-scale structures, providing another clue to the origin of the observed BHs.
- Primordial BHs of mass around a solar mass could have formed at the QCD quark-hadron transition via gravitational collapse of large curvature fluctuations generated during the last stages of inflation.
  - This could explain not only the present abundance of dark matter but also the baryon asymmetry of the universe.

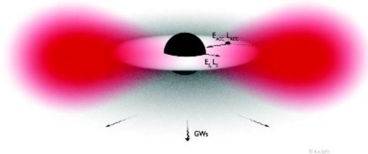


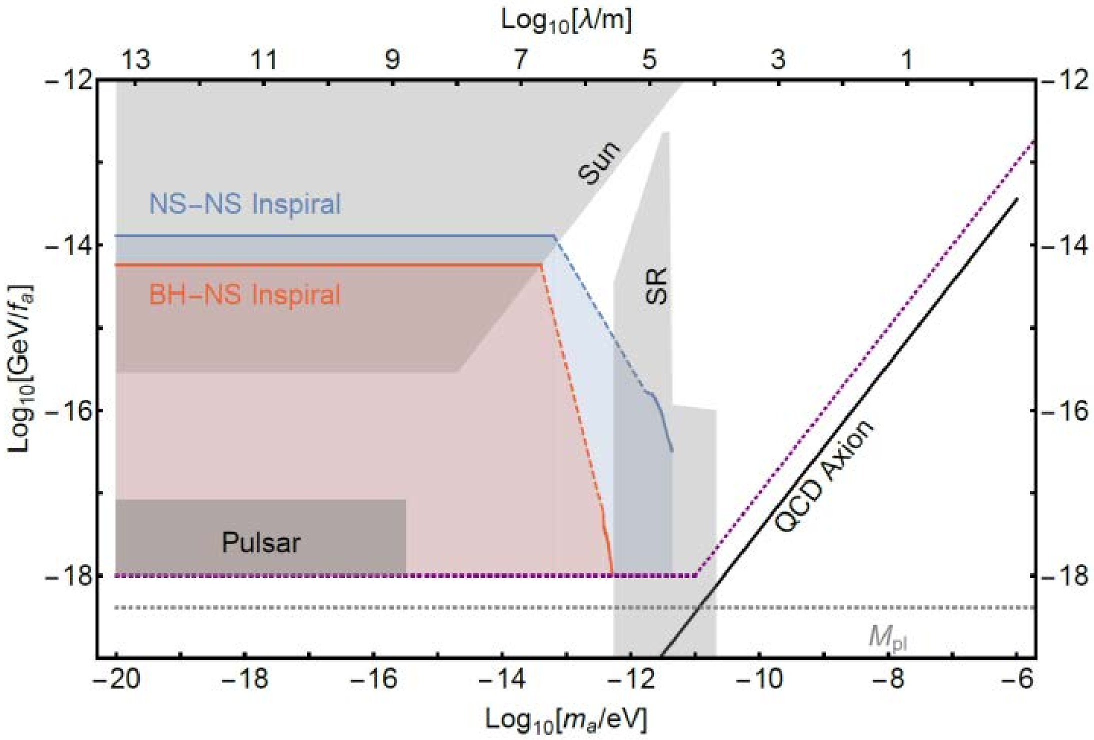
V. Fafo

Investigating axion-like particle with GWs

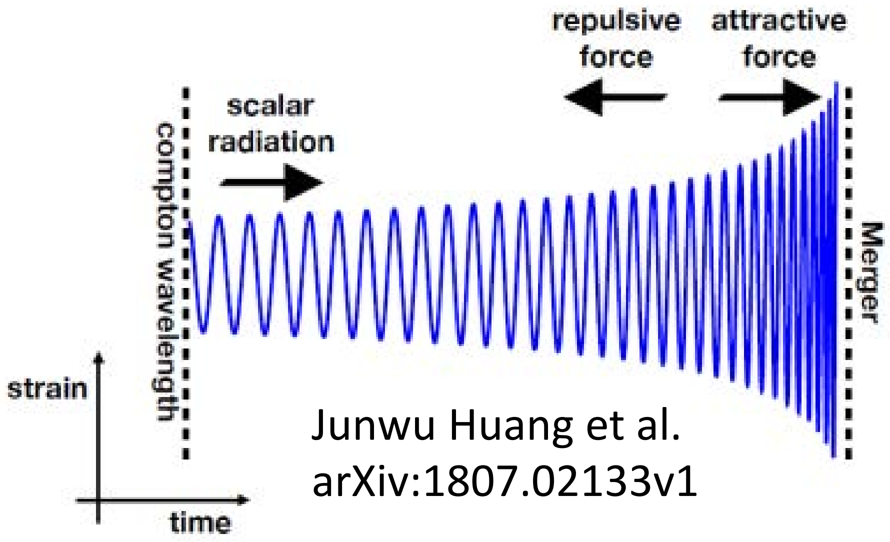
- Axions or, in general, light scalar fields are a possible extension of the Particle standard model and they could be a component of the dark matter or dark energy
  - Axions could provide an inflation mechanism
- What GW could tell about Axions?

BH super-radiance





BNS coalescence



Junwu Huang et al.
arXiv:1807.02133v1

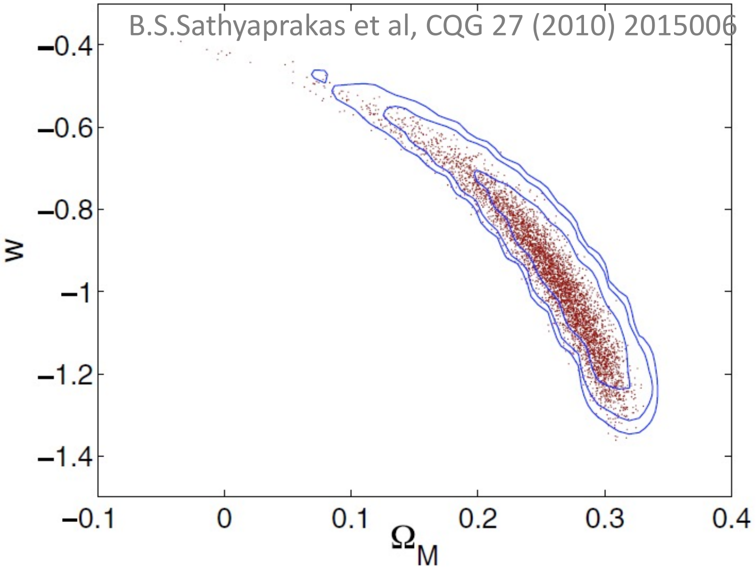
Highlights in some fundamental questions: #3

- What is the nature of the Dark Energy?
- ET will detect O(10^5-10^6) BNS and BBH coalescences per year
- Let suppose that only O(10^2-10^3) will have an em counterpart
- It is possible to combine the two messenger to fit the cosmological model of the Universe
  - ET will define the luminosity distance dL of the source
  - The em counterpart will give the red shift z

$$d_L(z) = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_M (1+z')^3 + \Omega_\Lambda (1+z')^{3(1+w)}}}$$

Ω_M Dark matter density

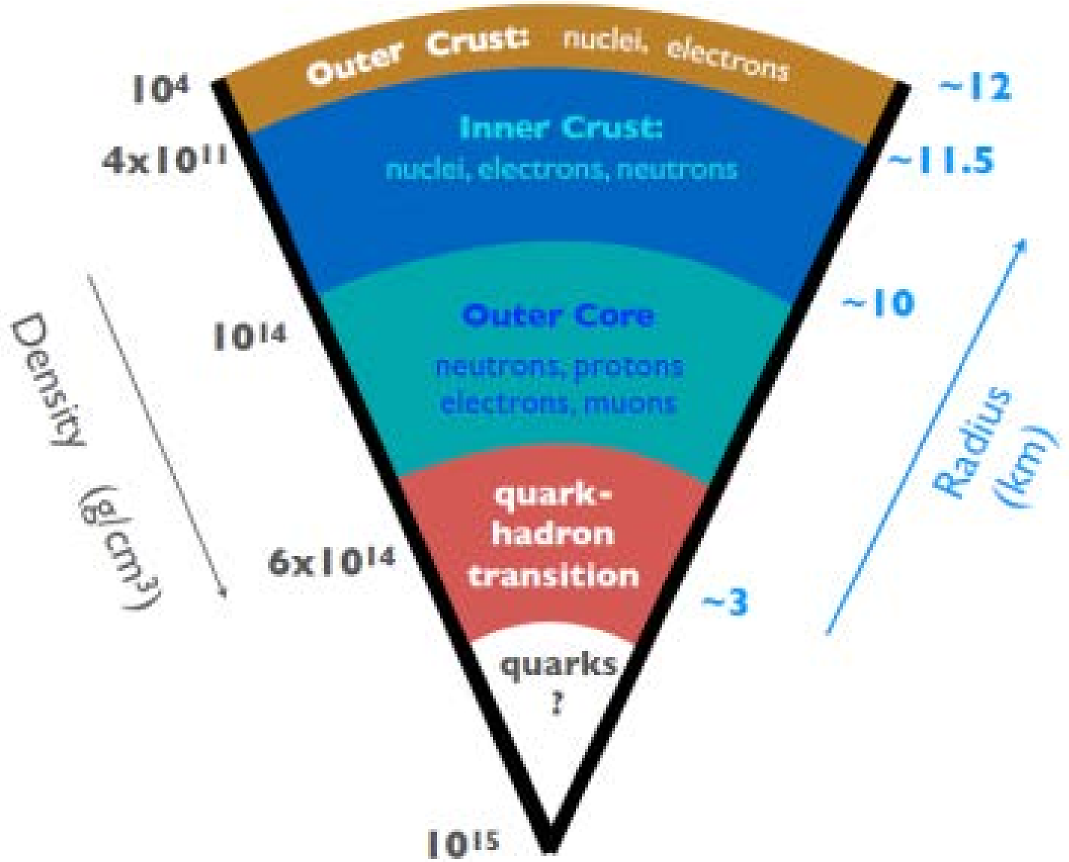
$$\Omega_\Lambda = \frac{\rho_{DE}}{\rho_C} \quad \frac{\text{Dark Energy density}}{\text{Closure density}}$$

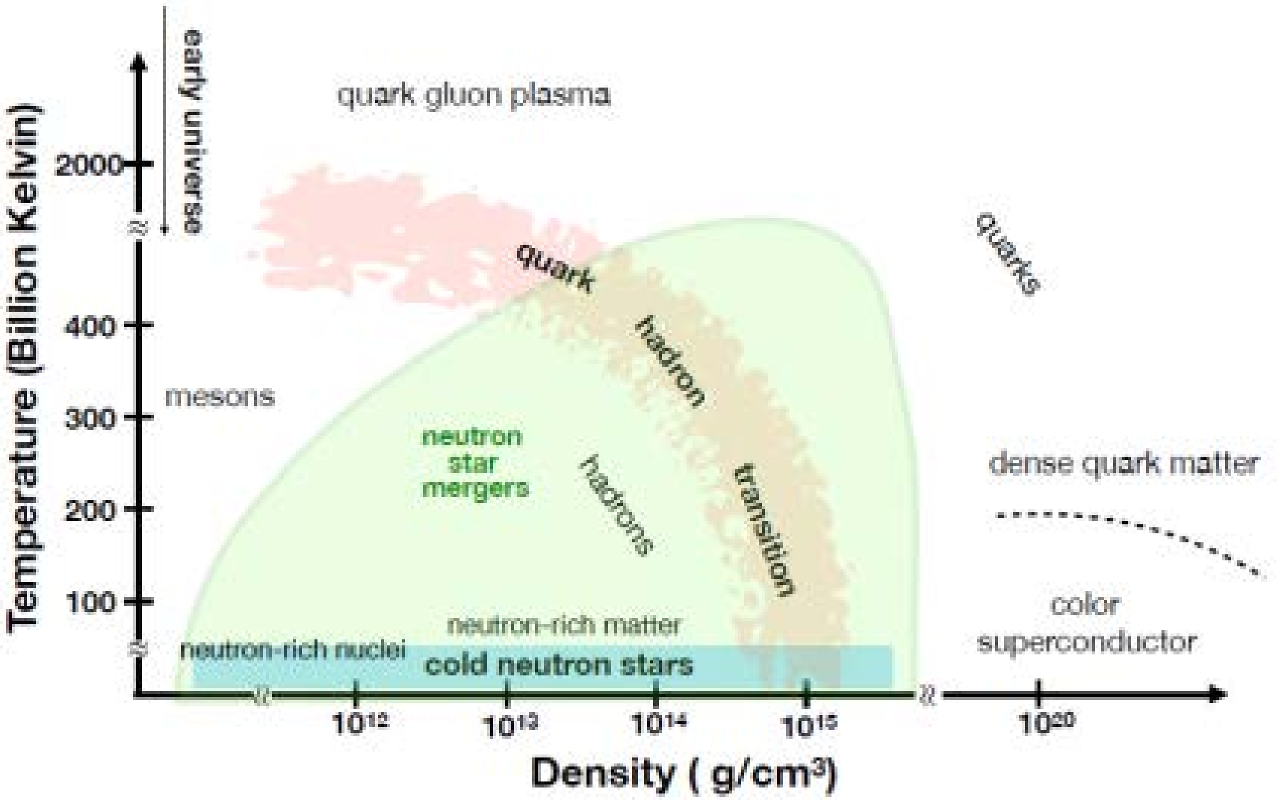


First “attempt” with the measurement of H0 made with GW170817

Highlights in some fundamental questions: #4

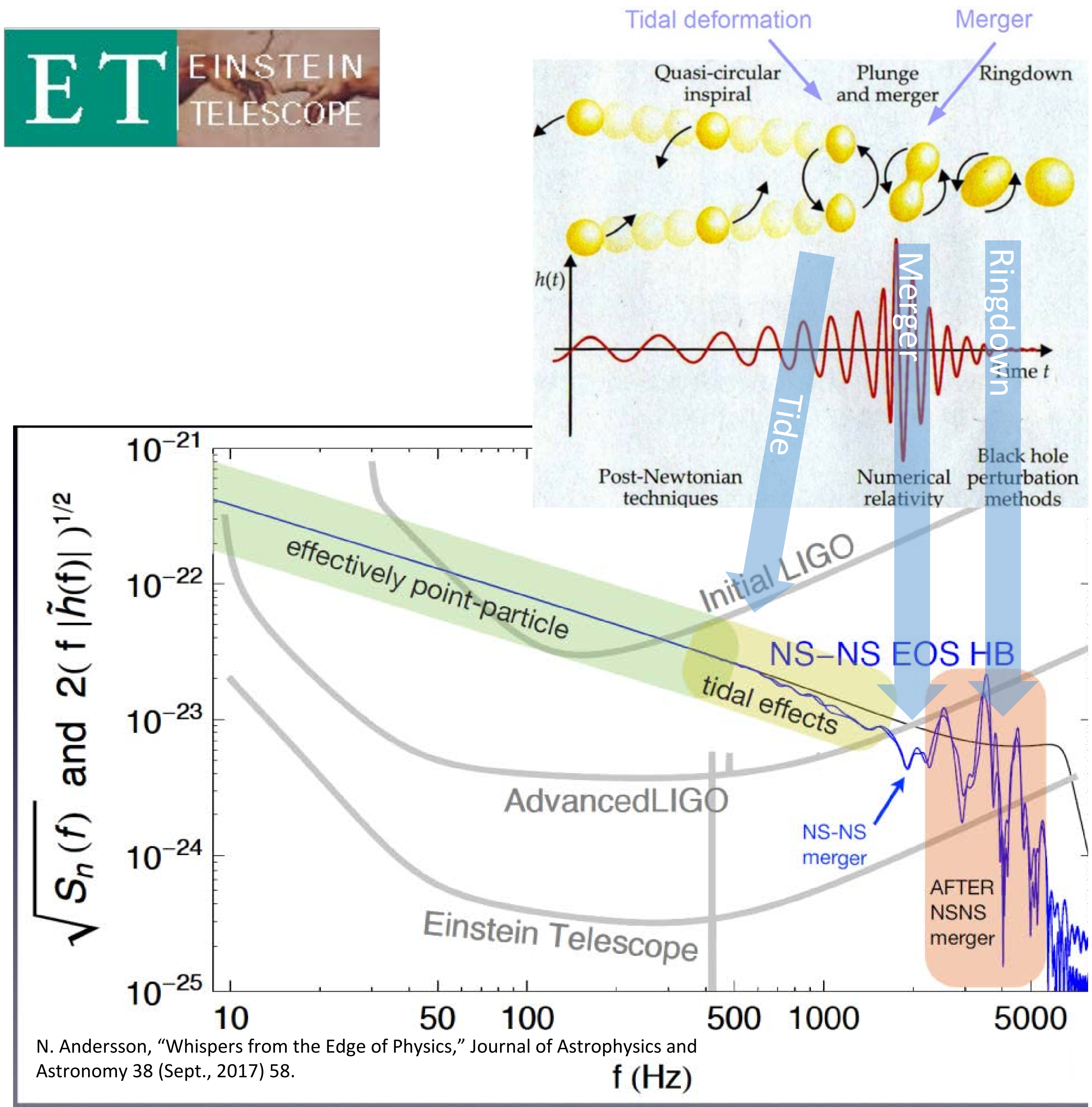
- What are the fundamental properties of sub-atomic matter in critical density conditions?
  - Neutron Star Equation of state



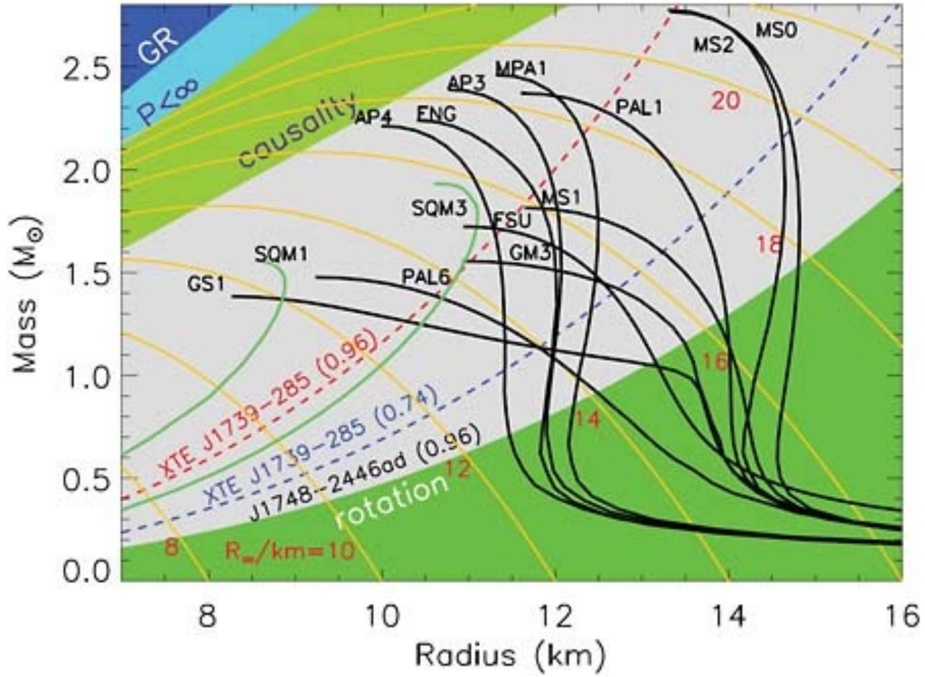


Structure of a Neutron Star

- Measuring the tidal deformation through the dephasing in the GW signal is possible to constrain the EOS of the NS
  - Advanced+ detector could arrive to an accuracy less than 1km
  - To go below 100m we need 3G detectors

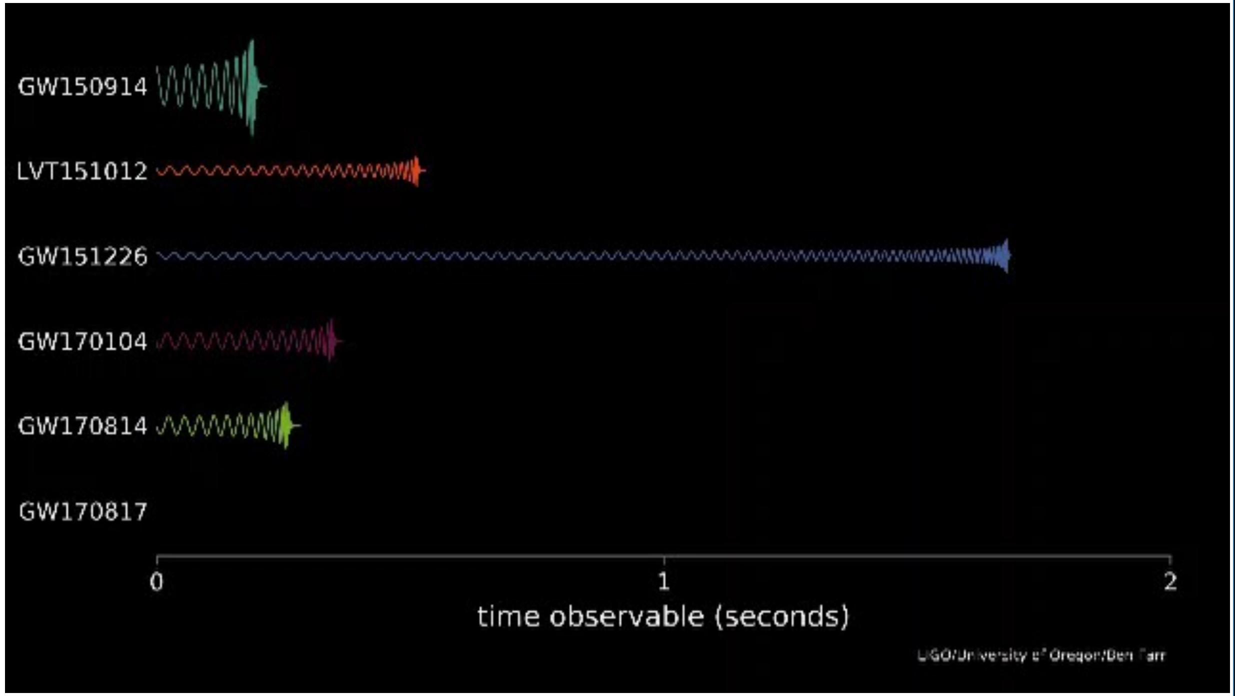


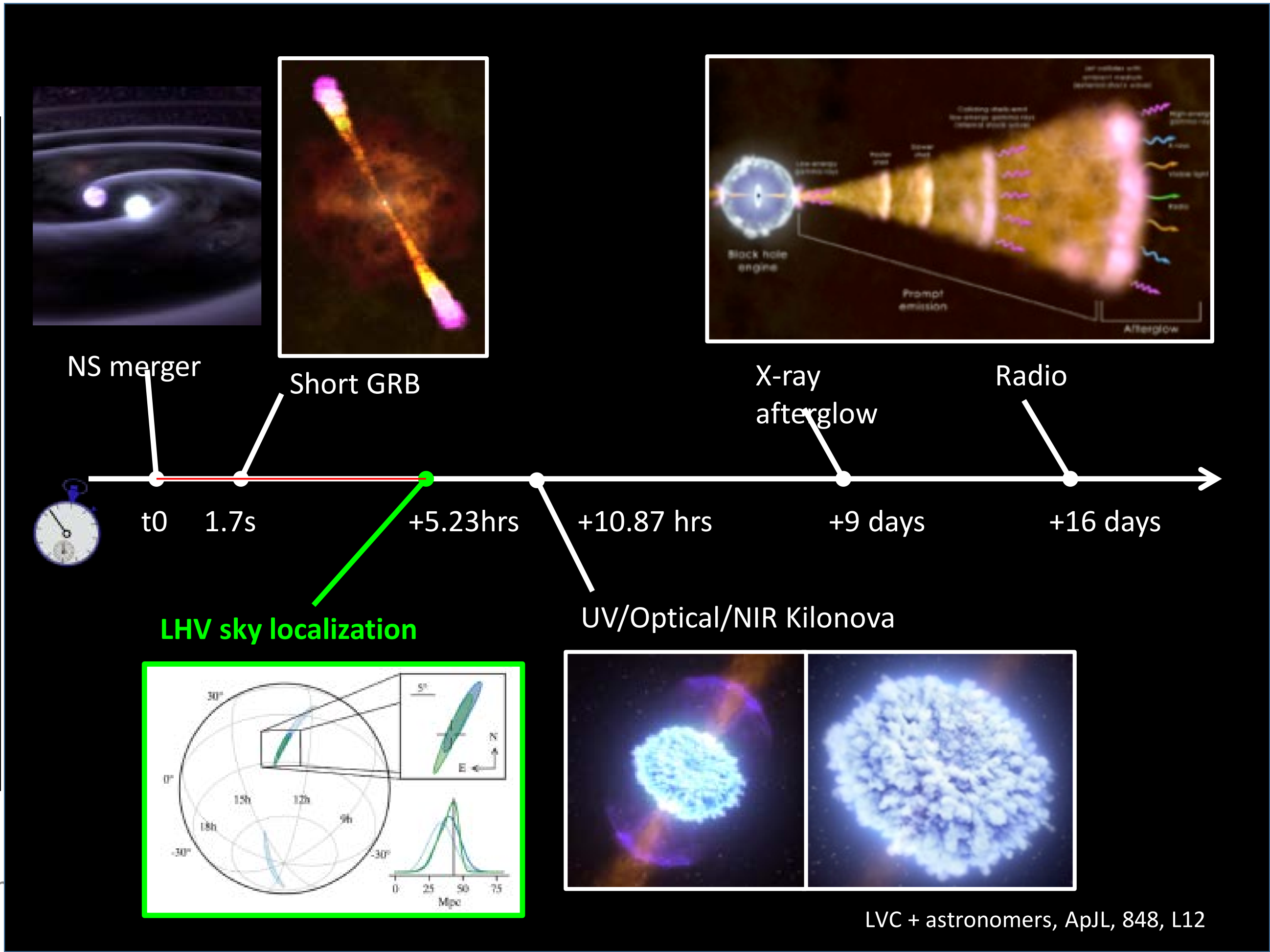
N. Andersson, "Whispers from the Edge of Physics," Journal of Astrophysics and Astronomy 38 (Sept., 2017) 58.



Multi-messenger astronomy

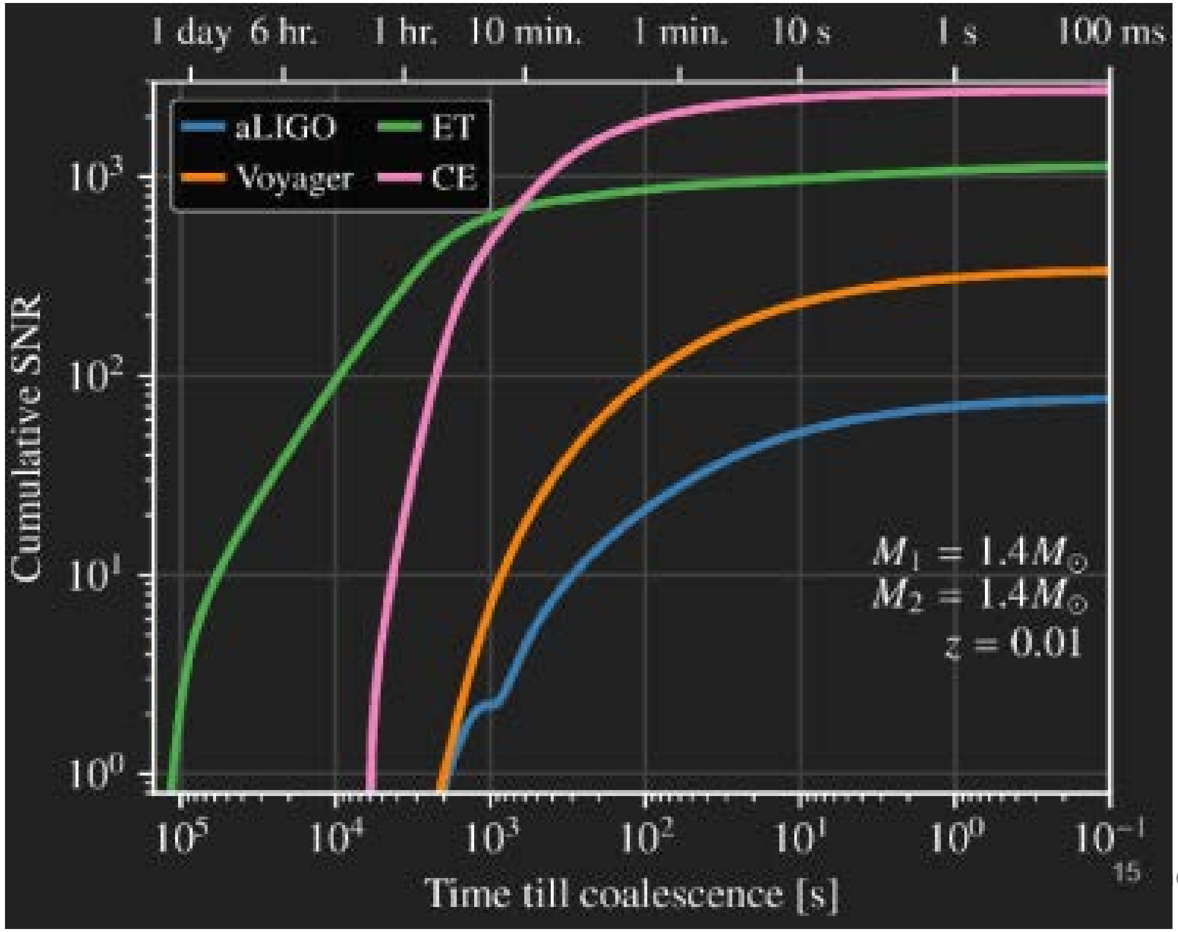
- GW are the only messenger that transport information before the event is occurred
- In GW170817 we had a large delay between the event and the alert, but in O3 the alert are automatically sent in few minutes AFTER the merging

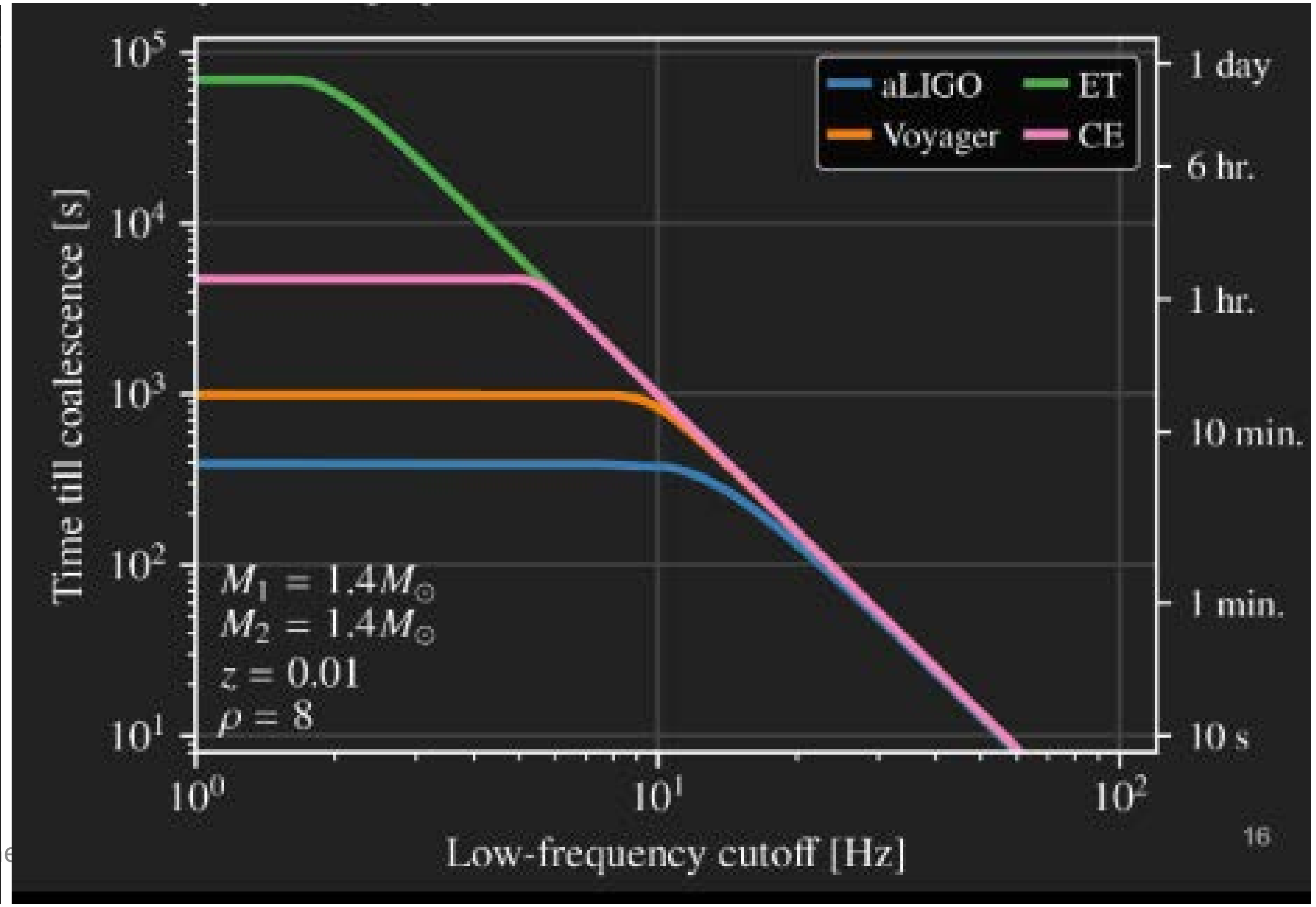




Low frequency: Multi-messenger astronomy

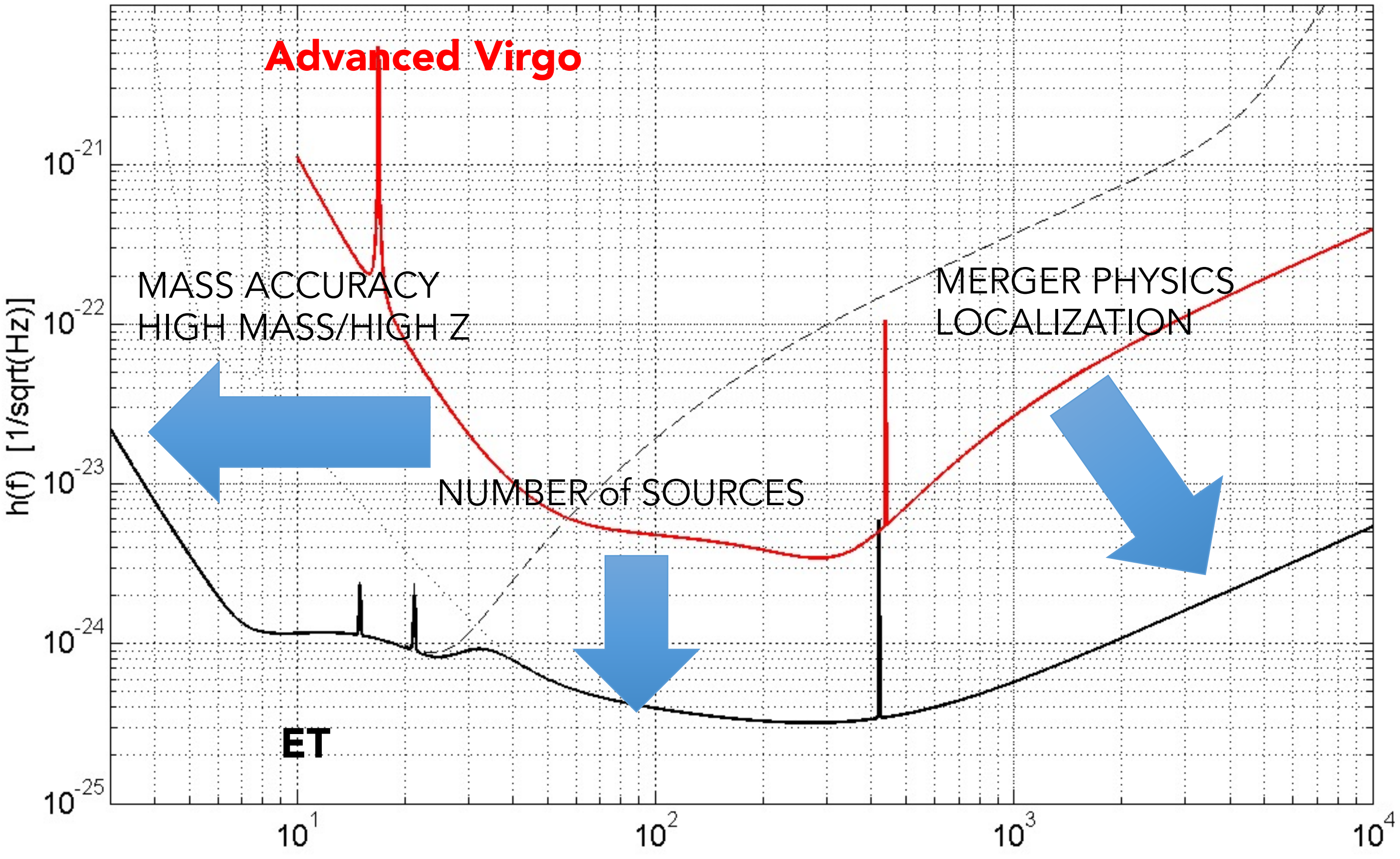
- If we are able cumulate enough SNR before the merging phase, we can trigger e.m. observations before the emission of photons
- Keyword: low frequency sensitivity→ET





From 2G to 3G

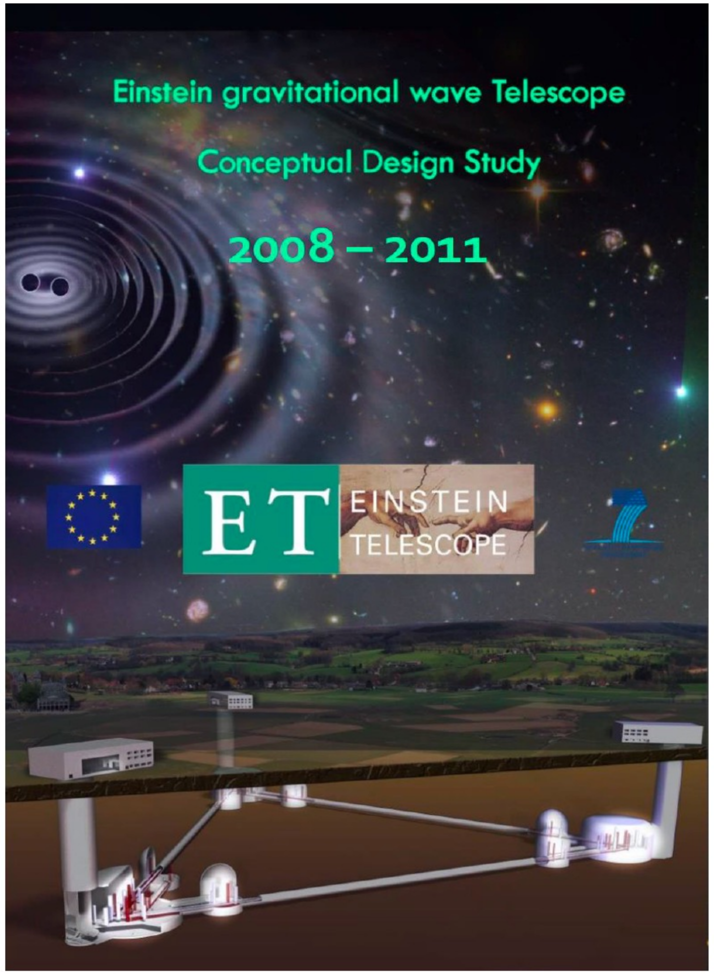
- To achieve the expected targets of physics, ET must gain about an order of magnitude of frequency wrt the 2G detectors

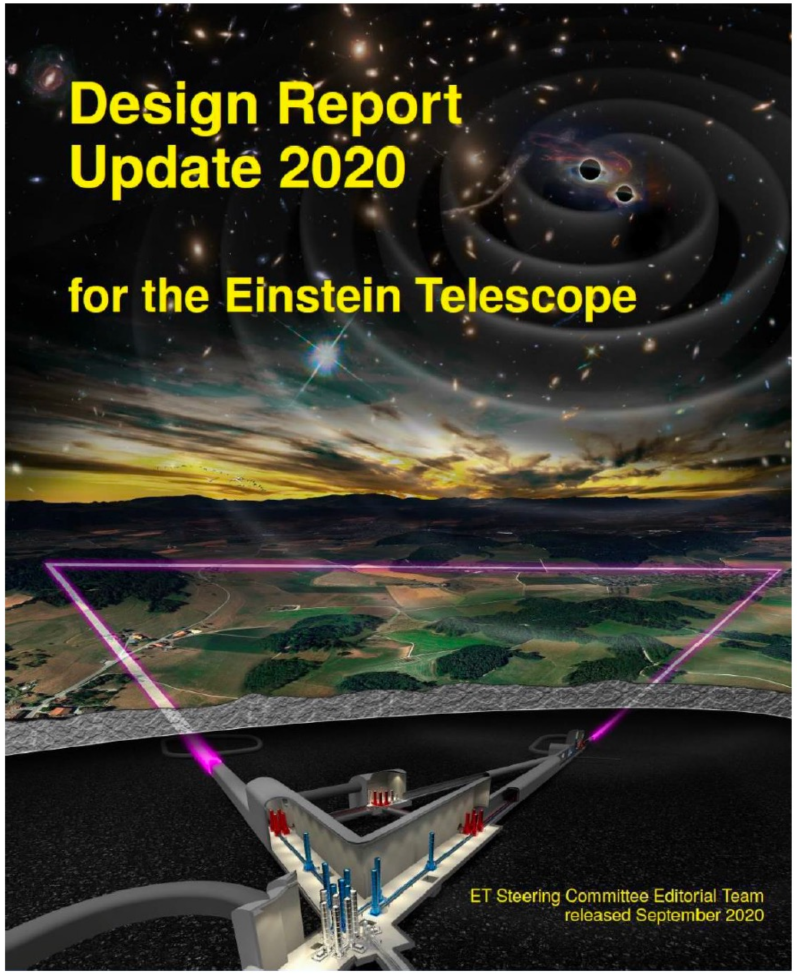


- This is obtaining mixing up 3 ingredients:
  - Infrastructure
  - Detector design
  - Technology

Einstein Telescope Design Studies

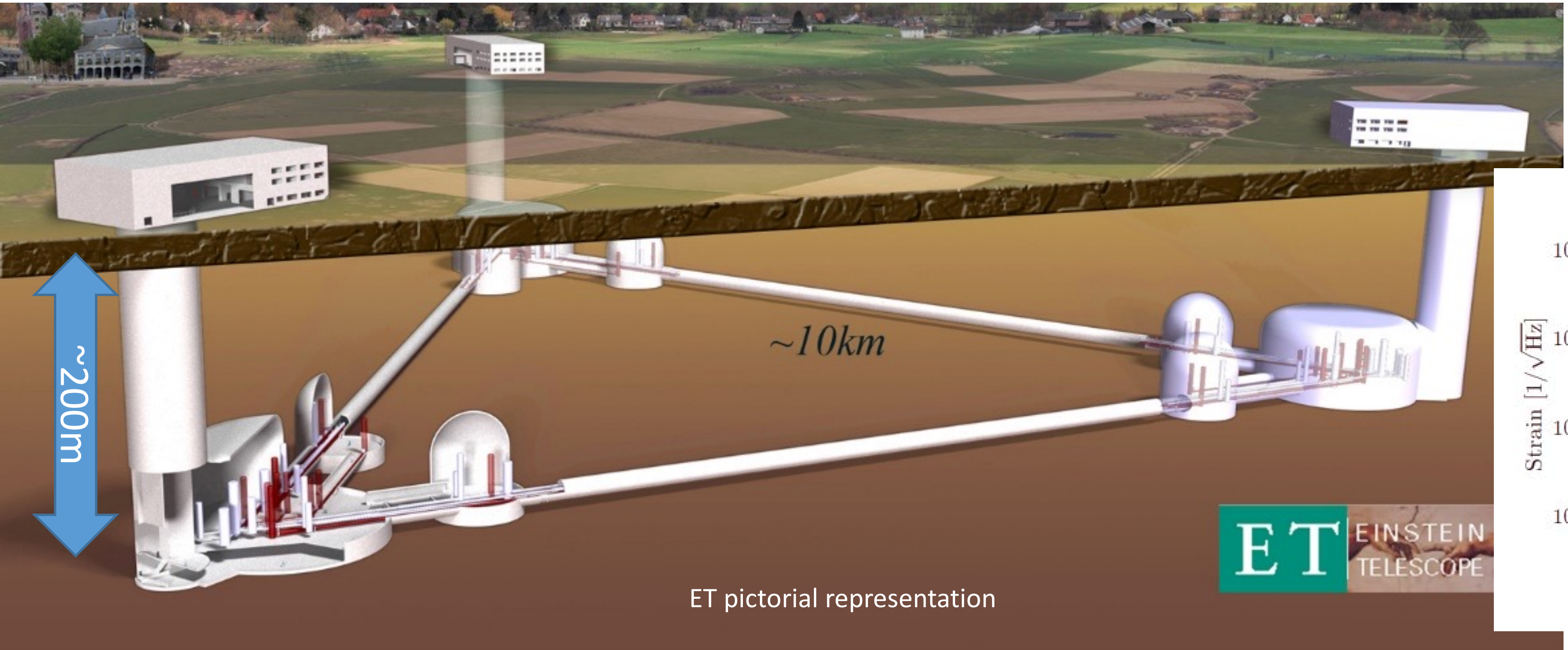
- Conceptual Design Study: https://tds.virgo-gw.eu/?call_file=ET-0106C-10.pdf
- Design Report Update: https://apps.et-gw.eu/tds/?content=3&r=17245



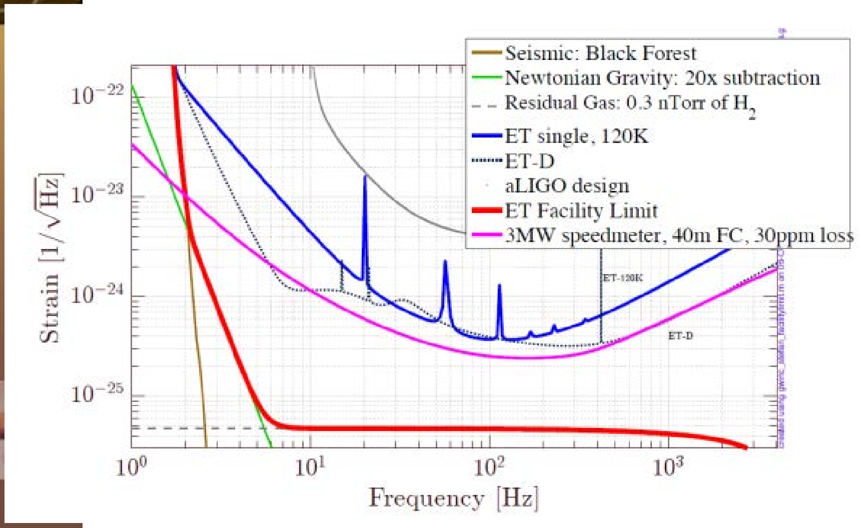


The ET underground infrastructure

- GW detectors sensitivity scales linearly with the length of the arms:
  - From 3km of AdV to 10km of ET
- To reduce the impact of the environmental disturbances (seismic, acustic, electromagnetic) the ET infrastructure is located underground

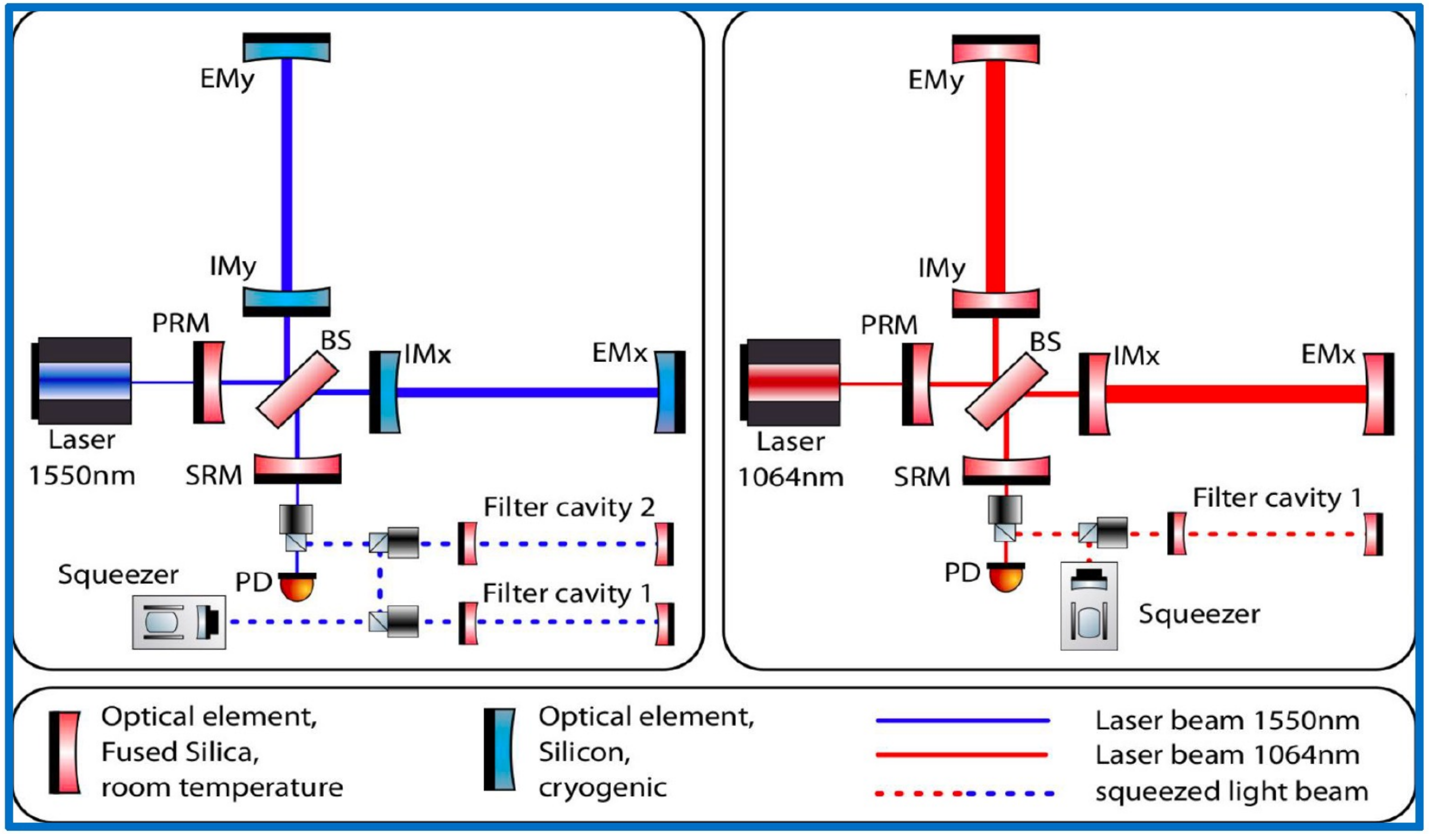


ET pictorial representation



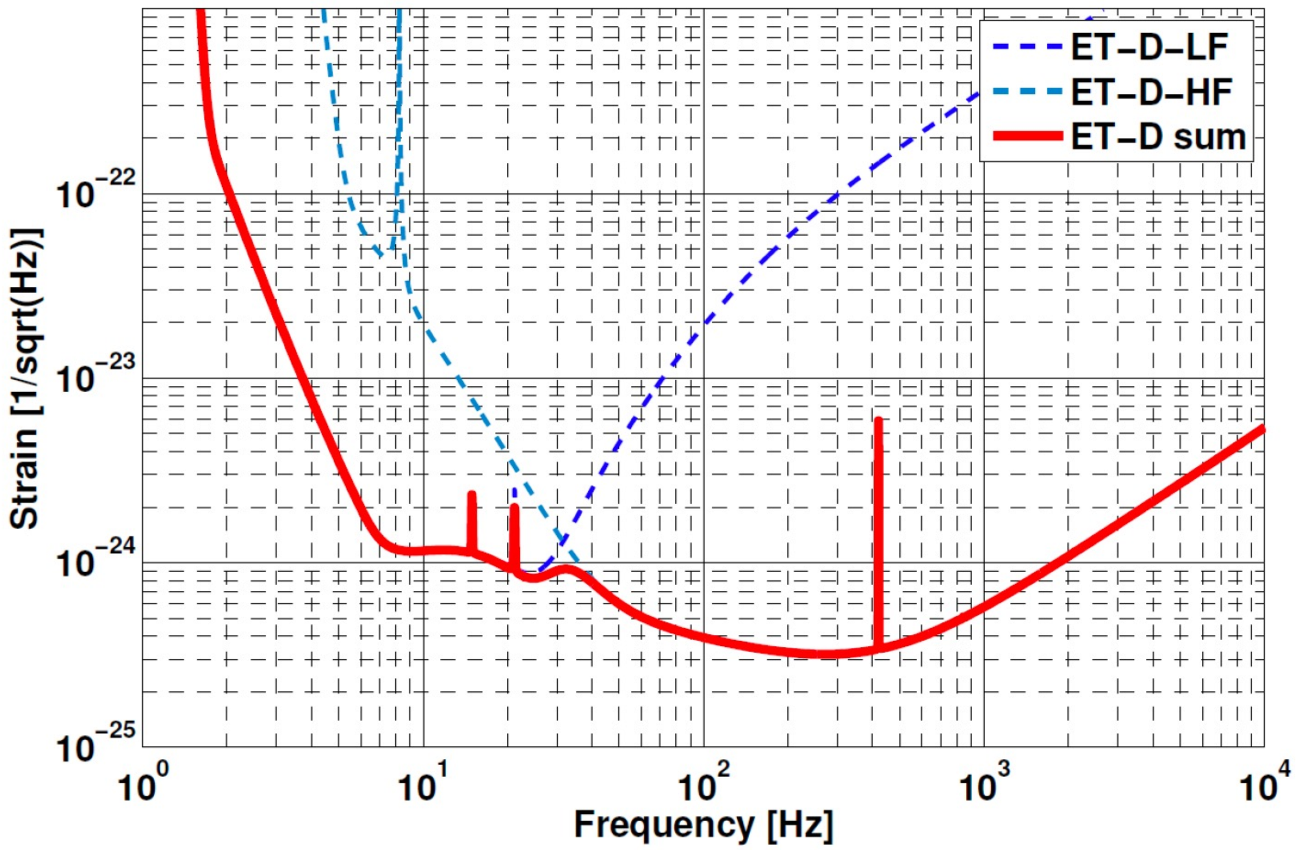
Xylophone detector design

- 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, ..



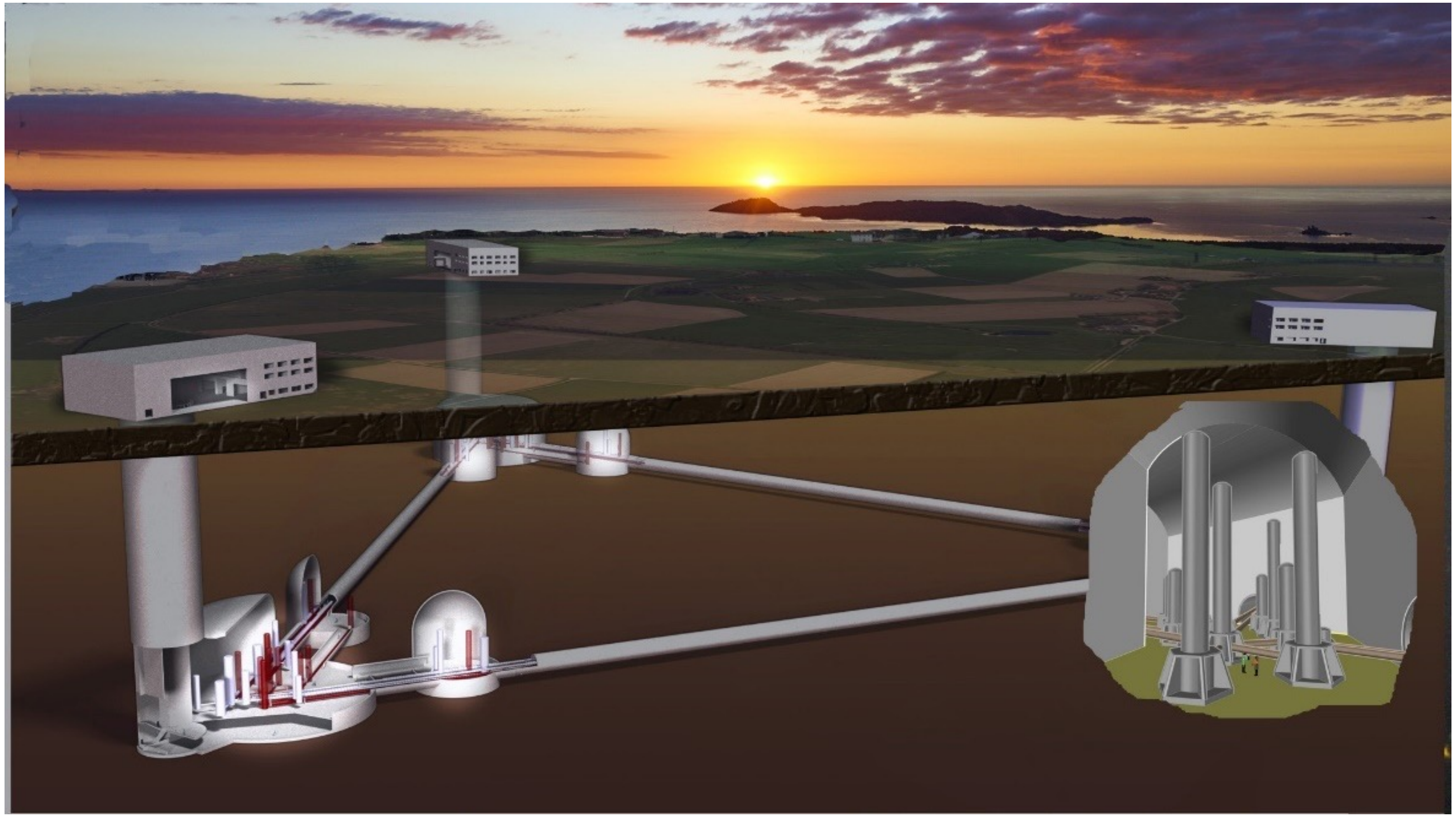
Einstein Telescope xylophone sensitivity

- 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



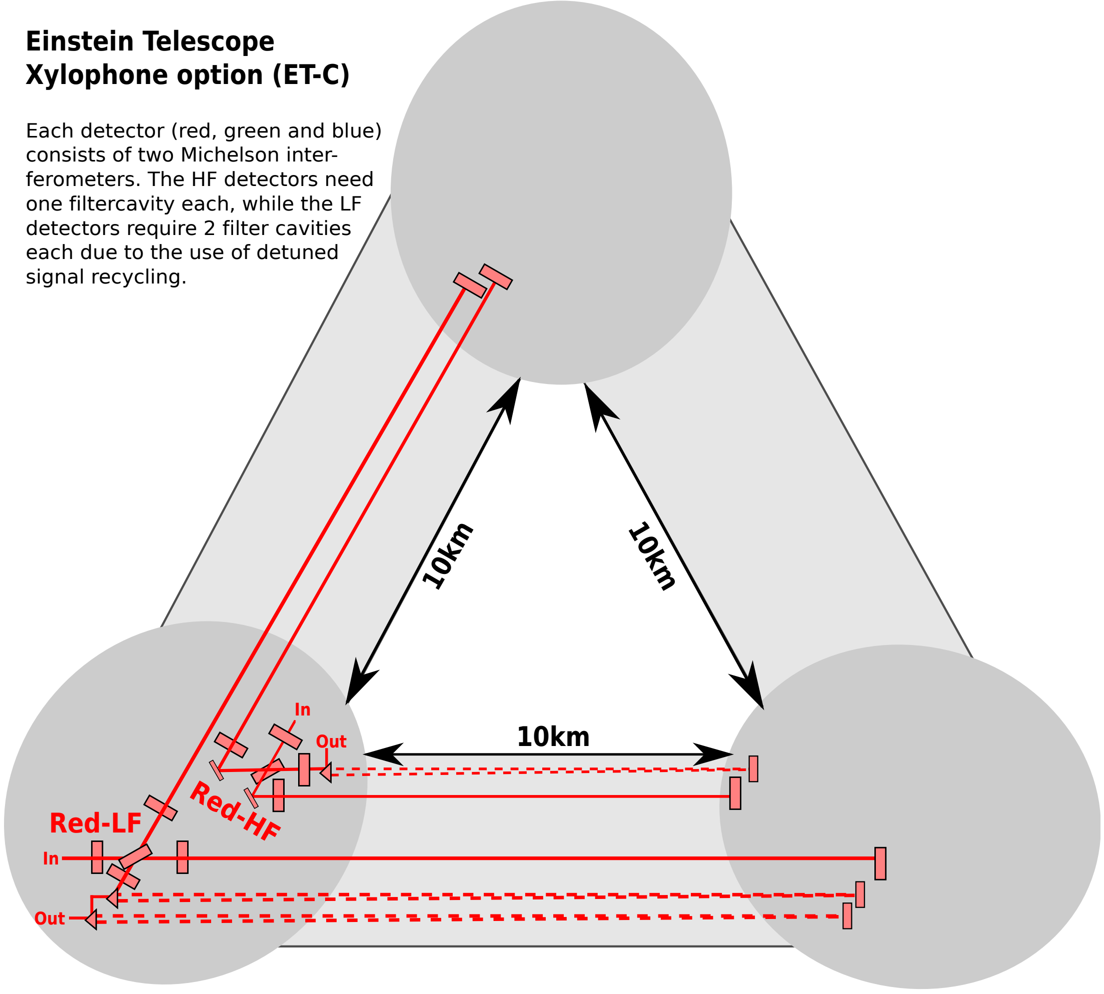
Detector Design

- The second ingredient to gain sensitivity and science potential in ET wrt 2G detectors is the detector design:
- ET is an Observatory
  - The Observatory is composed by 3 detectors
    - Each detector is composed by two interferometers



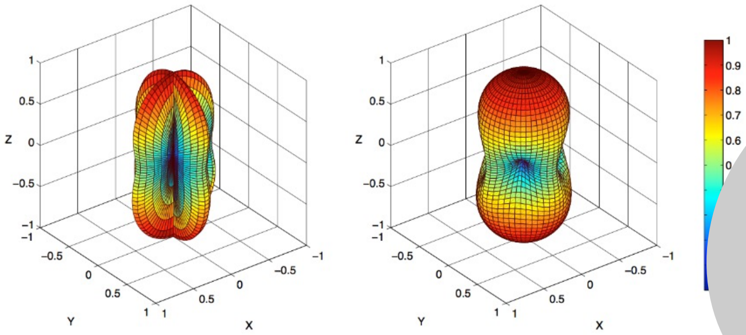
STAND-ALONE OBSERVATORY

- Start with a single (xylophone) detector



STAND-ALONE OBSERVATORY

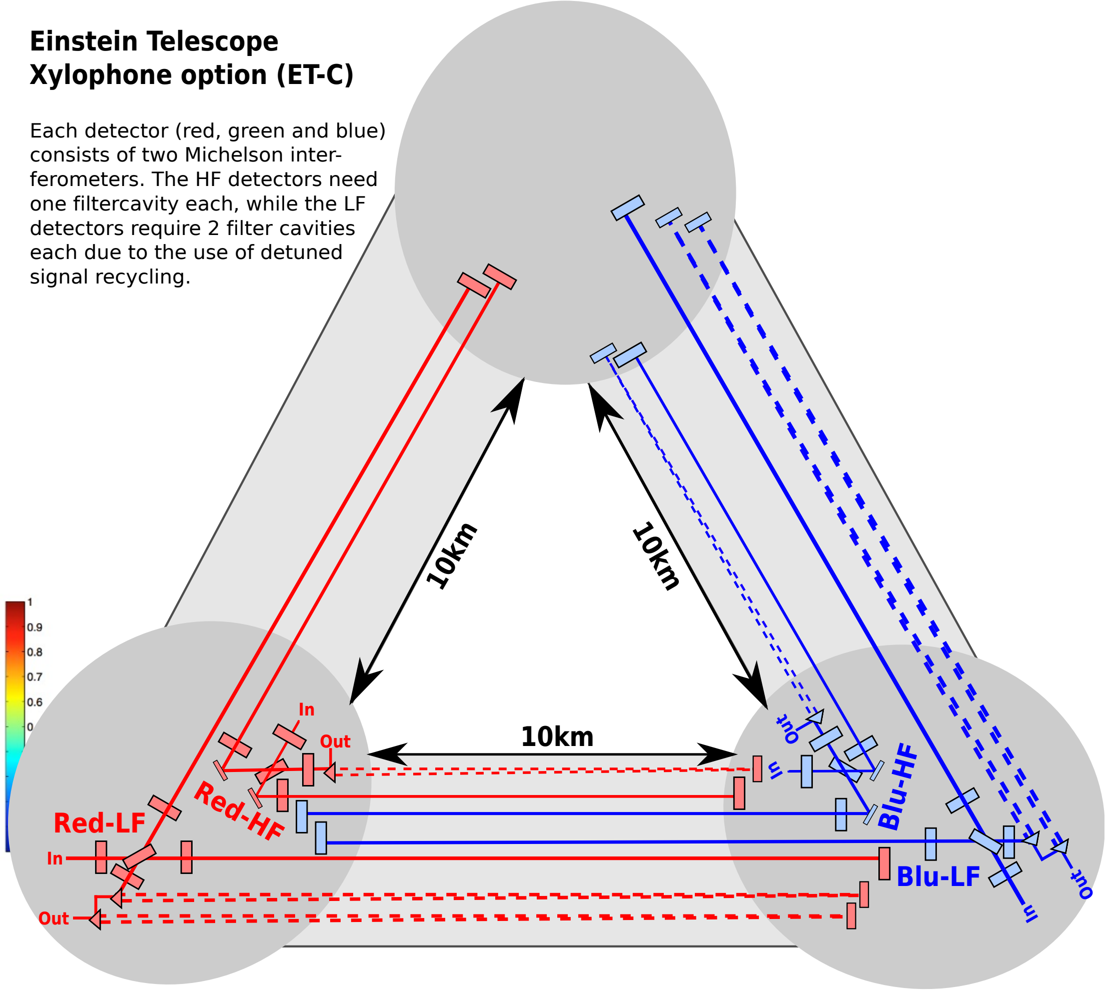
- Start with a single (xylophone) detector
- Add a second one to fully resolve polarizations



Antenna pattern for a polarized GW: simple "L" (left) vs Triangle (right)

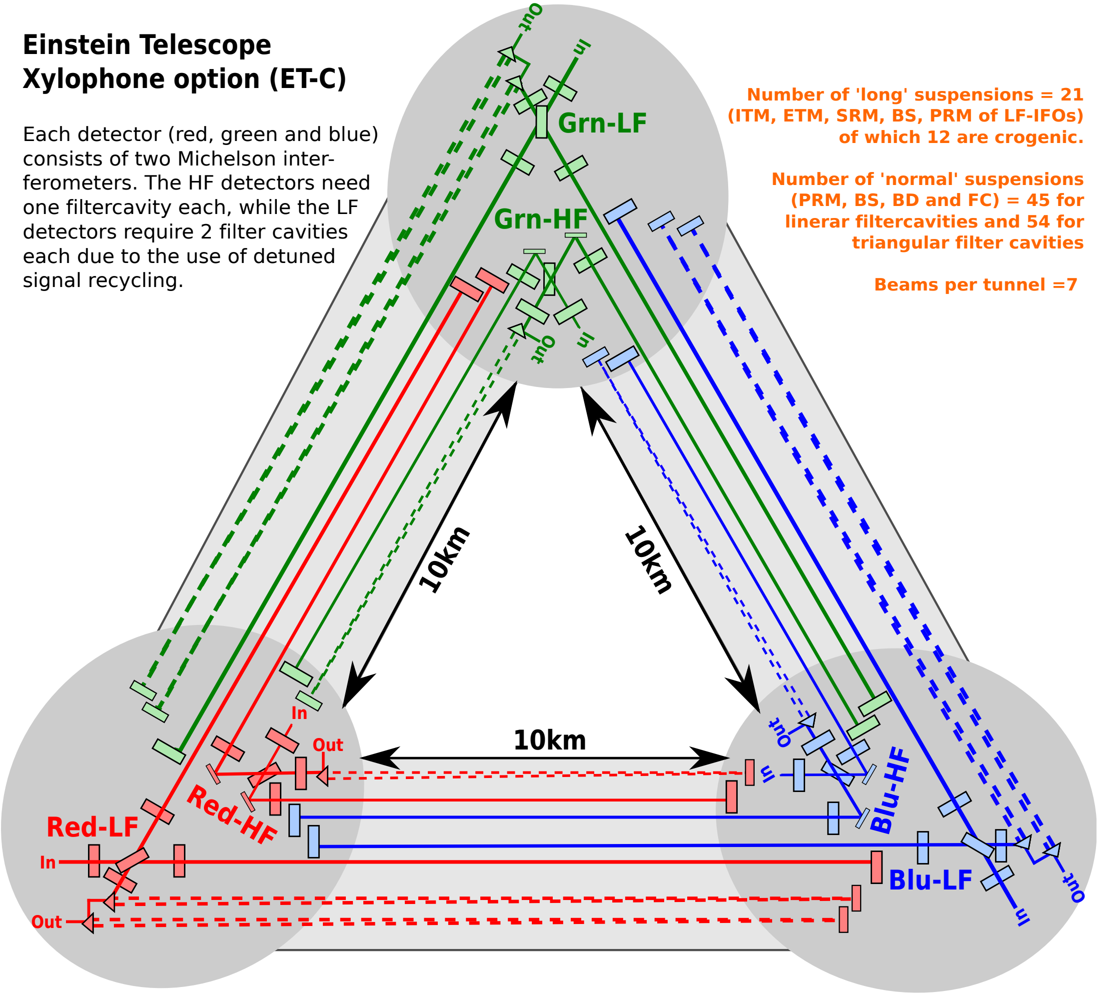
Einstein Telescope Xylophone option (ET-C)

Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.



STAND-ALONE OBSERVATORY

- Start with a single (xylophone) detector
- Add a 2nd one to fully resolve polarization
- Add a 3rd one for redundancy

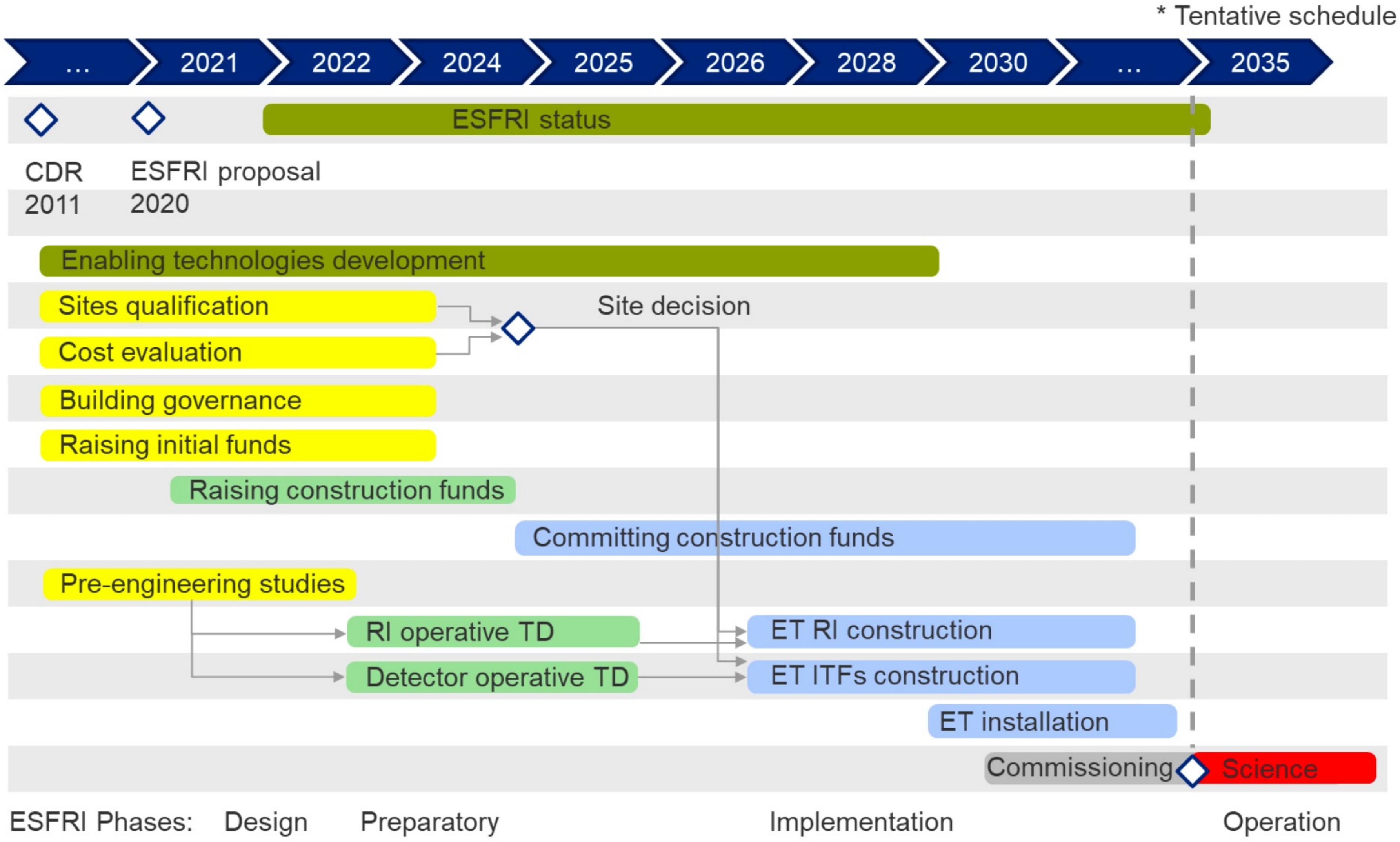


Examples for 3G challenges

- the identification of a facility site with low seismic and acoustic noise, and other suitable environmental properties
- development of mitigation techniques for gravity gradient noise
- development of low-noise, efficient cryogenic mirror suspension
- the production of large, high-quality test mass substrates, both silica and silicon or sapphire
- the polishing and coating of large test mass substrates to very low spatial roughness at larger spatial scales
- the development of suitable mirror coatings
- the development of multi-stage suspensions supporting test masses of several 100 kg
- the development of lower cost vacuum technology for ultra-high vacuum in vacuum chambers and the beam pipes
- …

Project timeline

- Approved by ESFRI for the 2021 Roadmap



Site decision timeline and procedure

- Activities are well underway. Decision and site selection procedure determined at government level

- Site qualification activities in progress

- Currently there are two sites, in Europe, candidate to host ET:
  - The Sardinia site, close to the SosEnattosmine
  - The EU RegioRhine-Meussesite, close to the NL-B-D border
  - A third option in Saxony (Germany) is under discussion

Value creation for society

- ET stimulates national and regional innovation power, activity, employment and attractivity for top scientists

Socio-economic studies

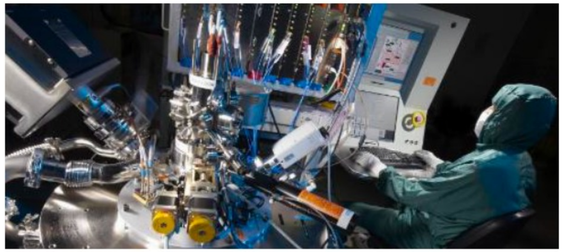
employment: 34,000 man-years during construction; 1,500 jobs structurally

each euro invested provides a total of 3.6 euros in the economy

Measuring and attenuating vibrations: nano-technology, medical, defense

Optics: coatings, special materials, laser technology, semiconductor technology

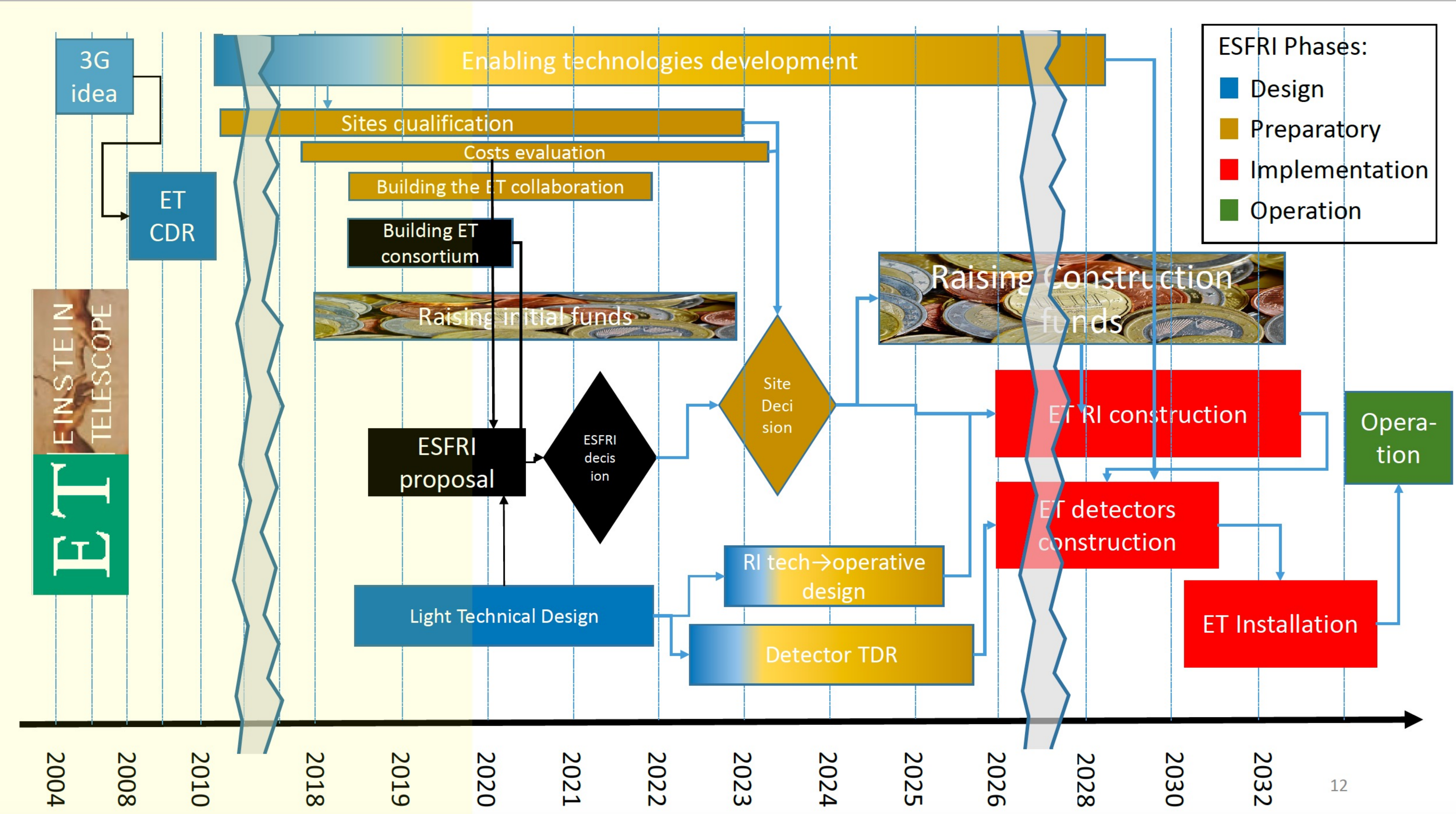
Cryogenic systems: ET's low frequency interferometer will feature cooled silicon optics



Vacuum technology: ET will feature one of the biggest vacuum systems worldwide

ET UHV system:
- beam tubes: 120,000 m^3
- pressure < 10^{-10} hPa
- hydrocarbons < 10^{-14} hPa
- area: 420,000 m^2

LHC at CERN:
- beam tubes: 2,000 m^3
- pressure < 10^{-10} hPa
- insulating vac.: 15,000 m^3
- pressure < 10^{-6} hPa


ESFRI Phases:
Design
Preparatory
Implementation
Operation
3G idea
ET CDR
EINSTEIN TELESCOPE
ET
Enabling technologies development
Sites qualification
Costs evaluation
Building the ET collaboration
Building ET consortium
Raising initial funds
ESFRI proposal
ESFRI decision
Site Decision
Raising Construction funds
ET RI construction
ET detectors construction
RI tech→operative design
Light Technical Design
Detector TDR
ET Installation
Opera-tion
2004
2008
2010
2018
2019
2020
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2026
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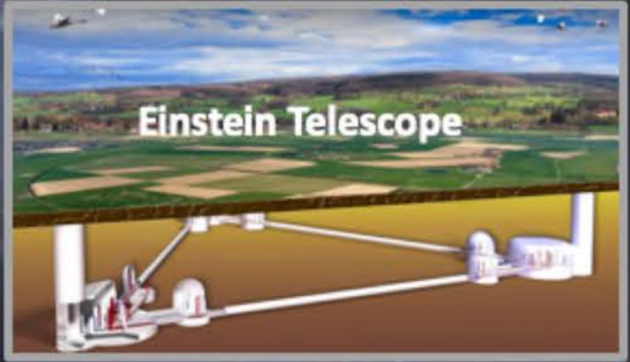
2032

Actually, really exciting times ahead on all gravitational wave fronts!



+ LIGO India **+ Pulsar Timing Array** **+ many other future projects**