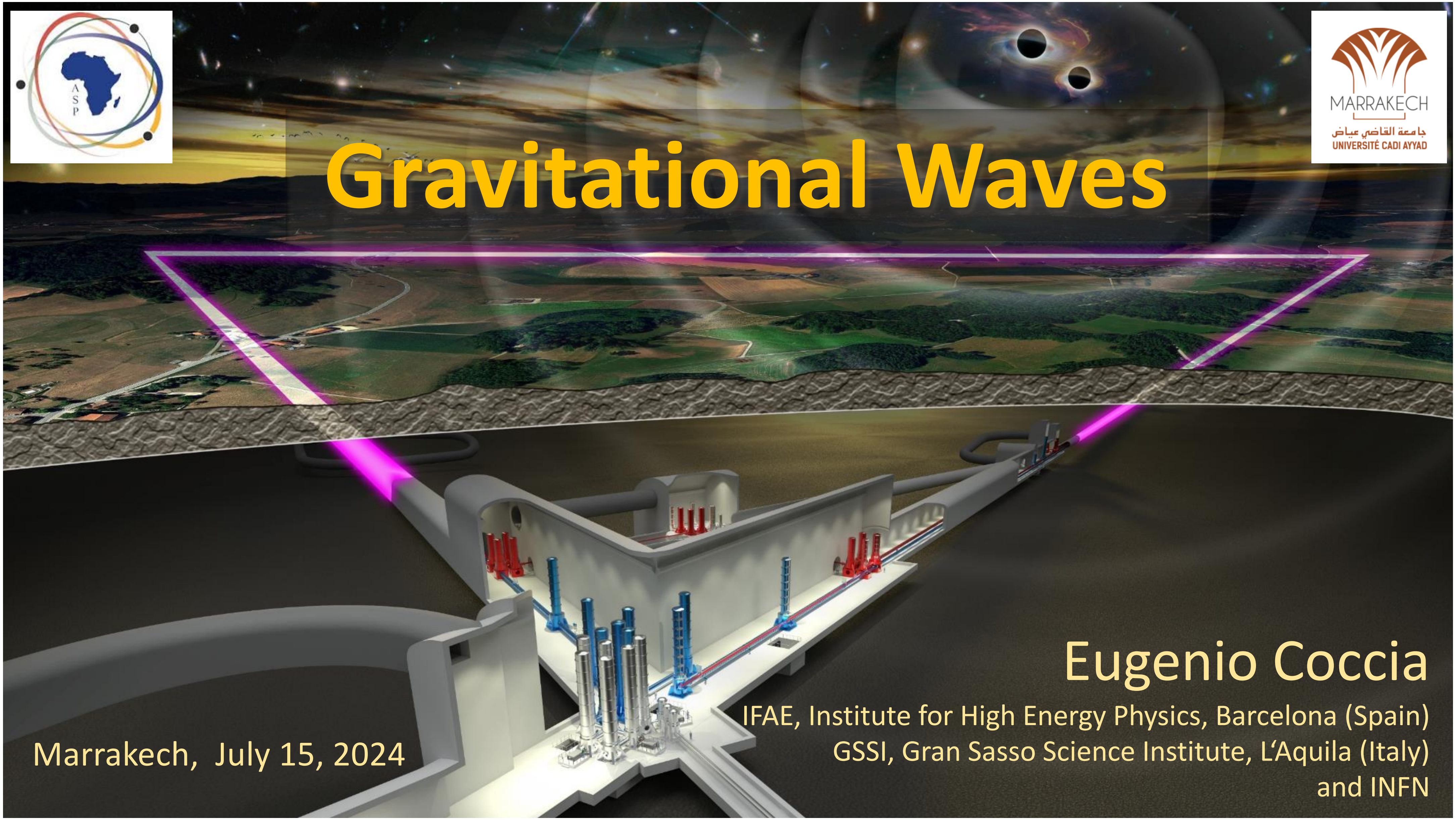
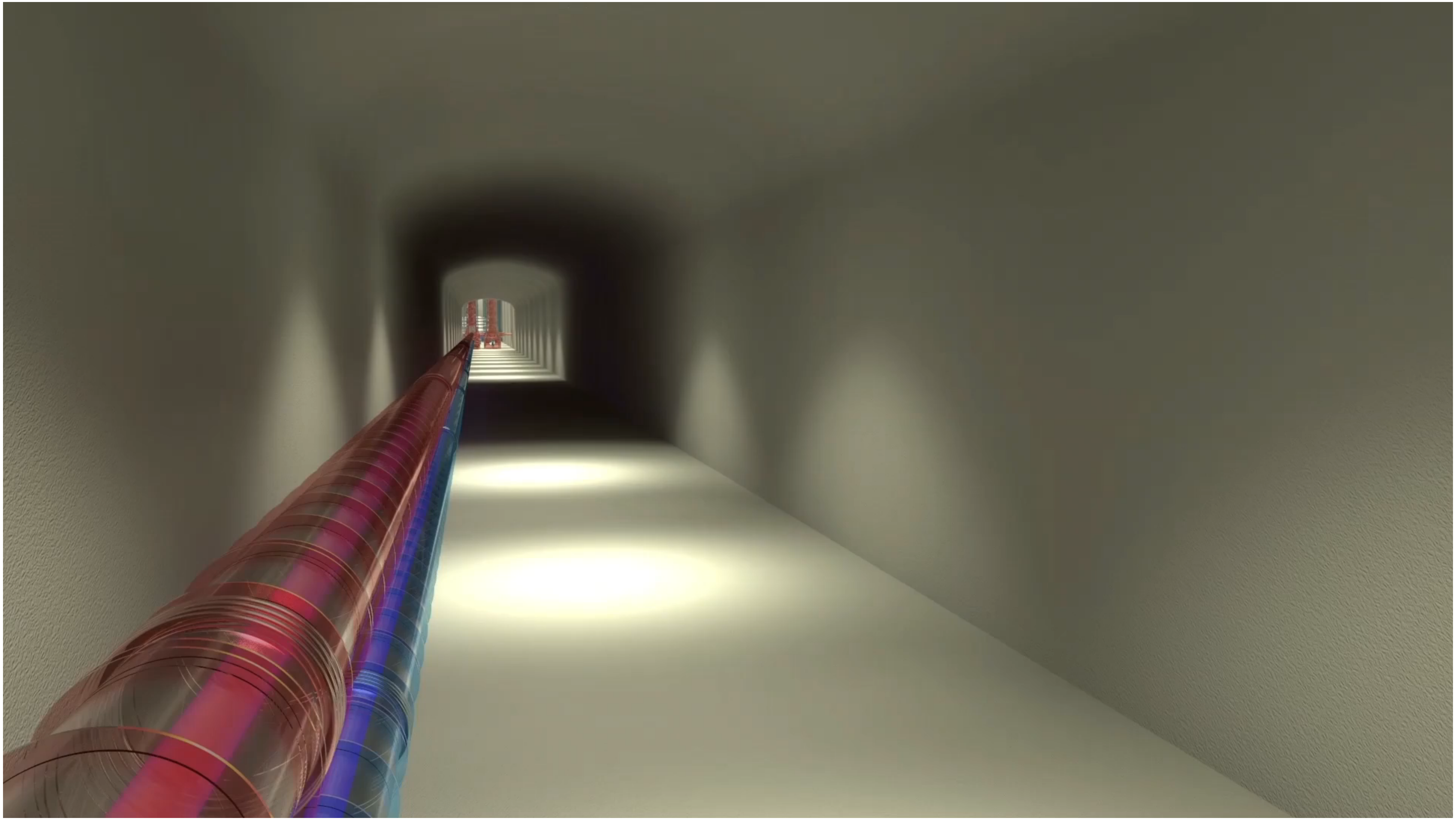
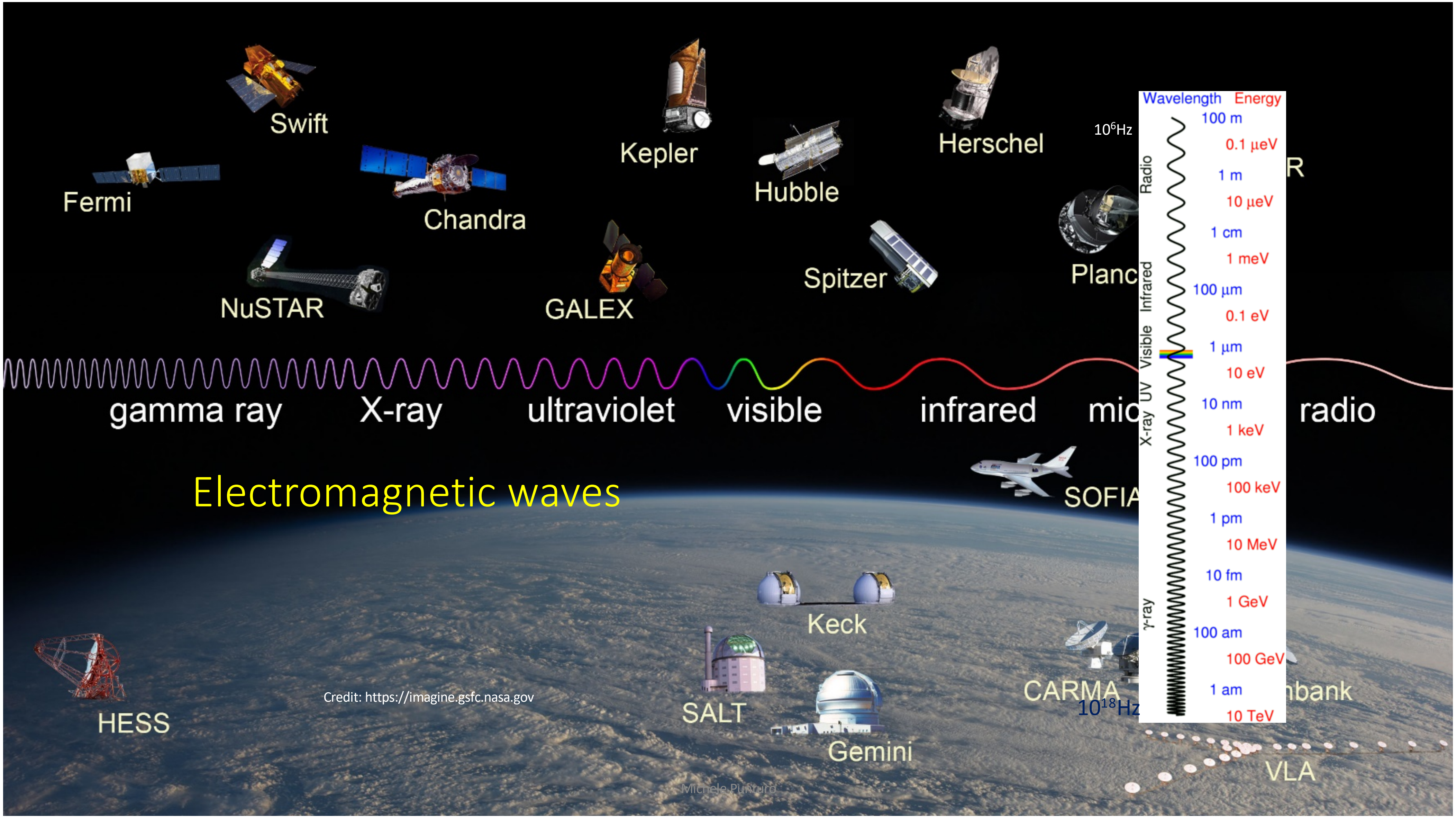


Gravitational Waves

Eugenio Coccia
IFAE, Institute for High Energy Physics, Barcelona (Spain)
GSSI, Gran Sasso Science Institute, L'Aquila (Italy)
and INFN

Marrakech, July 15, 2024



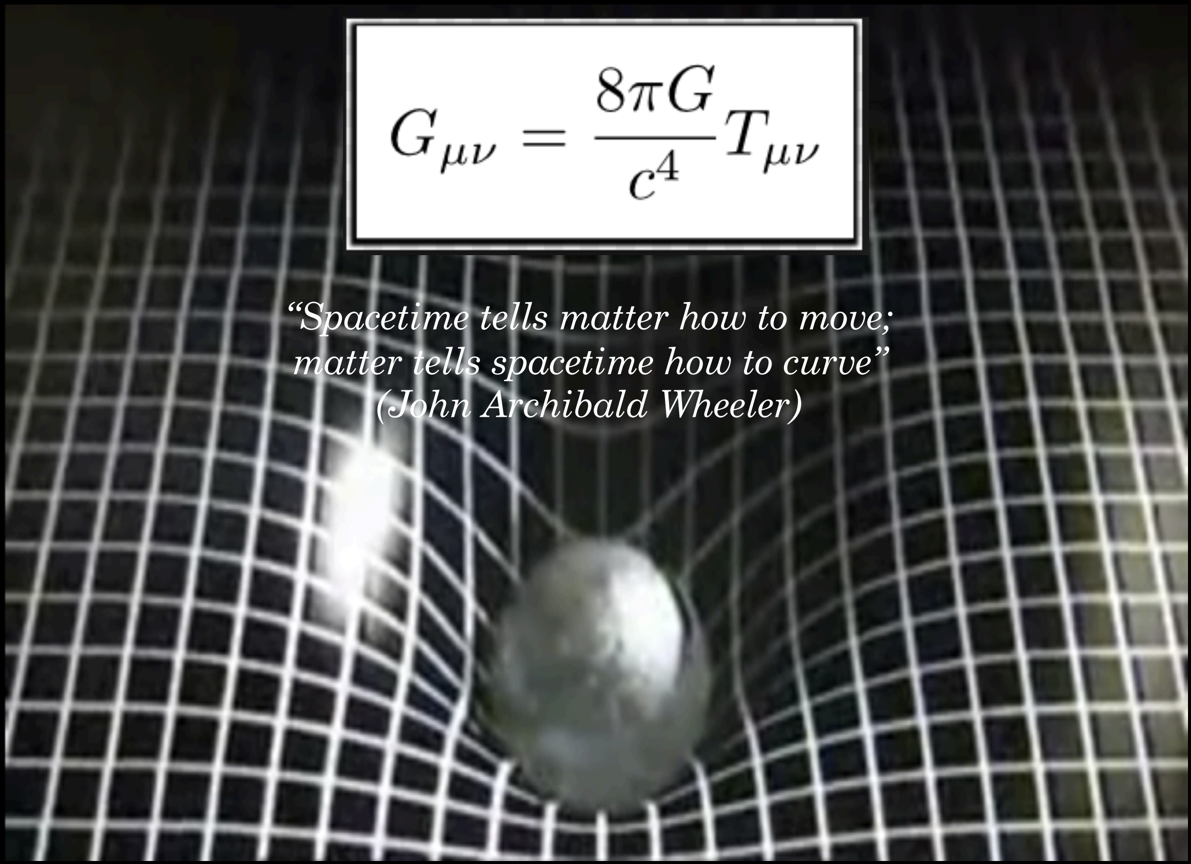


Swift
Fermi
Chandra
Kepler
Hubble
Herschel
NuSTAR
GALEX
Spitzer
Planc
R
10^6Hz
Wavelength Energy
100 m
0.1 μeV
1 m
10 μeV
1 cm
1 meV
100 μm
0.1 eV
1 μm
10 eV
10 nm
1 keV
100 pm
100 keV
1 pm
10 MeV
10 fm
1 GeV
100 am
100 GeV
1 am
10 TeV
Radio
Infrared
Visible
UV
X-ray
γ-ray
gamma ray
X-ray
ultraviolet
visible
infrared
mic
radio
Electromagnetic waves
SOFIA
Keck
SALT
Gemini
HESS
CARMA
10^18Hz
bank
VLA
Credit: https://imagine.gsfc.nasa.gov
Michele Punturo

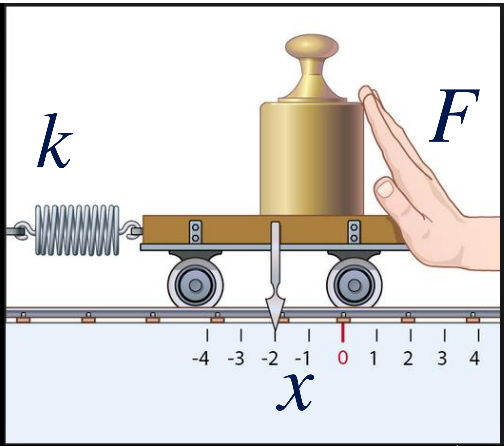
Einstein’s Theory of Gravitation

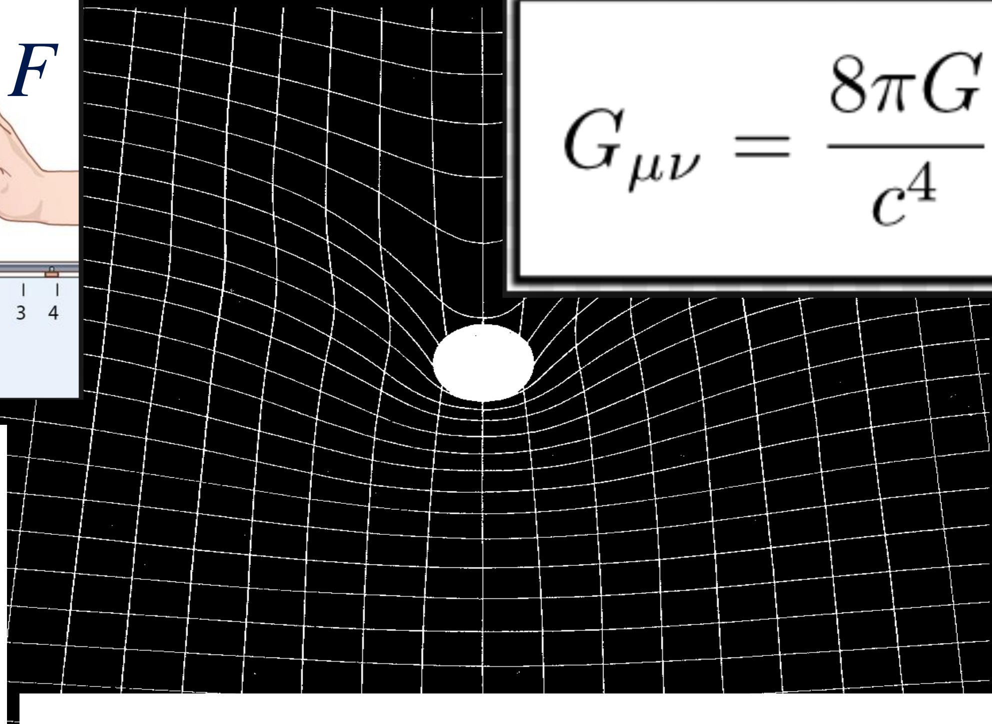
Gravity is a manifestation of spacetime curvature induced by mass-energy

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$



“Spacetime tells matter how to move;
matter tells spacetime how to curve”
(John Archibald Wheeler)





$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$F = -kx$$

$$F \Leftrightarrow T_{\mu\nu}$$

$$x \Leftrightarrow G_{\mu\nu}$$

$$k \Leftrightarrow \frac{c^4}{8\pi G}$$

$$c = 299\ 792\ 458\ \ m/s = 3\times10^{8}\ \ m/s$$

$$G = 0{,}000\ 000\ 000\ 066\ 7\ \frac{m^3}{kg\ s^2} = 6{,}67\times10^{-11}\ \frac{m^3}{kg\ s^2}$$

$$k \approx 10^{45}\ \frac{kg}{s^2} \qquad STIFF!$$

Über Gravitationswellen.

Von A. Einstein.

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 las betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

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

setzen zu können, wählen wir, wie es in der speziellen Relativitätstheorie üblich ist, die Zeitvariable x_4 rein imaginär, indem wir

$$x_4 = it$$

setzen, wobei t die »Lichtzeit« bedeutet. In (1) ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$ ist. Die $\gamma_{\mu\nu}$ sind gegen 1 kleine Größen, welche die Abweichung des Kontinuums vom feldfreien darstellen; sie bilden einen Tensor vom zweiten Range gegenüber Lorentz-Transformationen.

§ 1. Lösung der Näherungsgleichungen des Gravitationsfeldes durch retardierte Potentiale.

Wir gehen aus von den für ein beliebiges Koordinatensystem gültigen[2] Feldgleichungen

$$-\sum_{\alpha} \frac{\partial}{\partial x_\alpha} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} + \sum_{\alpha} \frac{\partial}{\partial x_\nu} \begin{Bmatrix} \mu\alpha \\ \alpha \end{Bmatrix} + \sum_{\alpha\beta} \begin{Bmatrix} \mu\alpha \\ \beta \end{Bmatrix} \begin{Bmatrix} \nu\beta \\ \alpha \end{Bmatrix} - \sum_{\alpha\beta} \begin{Bmatrix} \mu\nu \\ \alpha \end{Bmatrix} \begin{Bmatrix} \alpha\beta \\ \beta \end{Bmatrix} = -\varkappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right). \qquad (2)$$

[1] Diese Sitzungsber. 1916, S. 688 ff.

[2] Von der Einführung des »λ-Gliedes« (vgl. diese Sitzungsber. 1917, S. 142) ist dabei Abstand genommen.

La prima pagina di un lavoro di Albert Einstein del 1918 in cui per la prima volta vengono dedotte le equazioni della propagazione ondosa del campo gravitazionale.

1916

Weak field approximation

$$g_{\mu\nu} = \overset{o}{g}_{\mu\nu} + h_{\mu\nu}$$

$$|h_{\mu\nu}| << 1$$

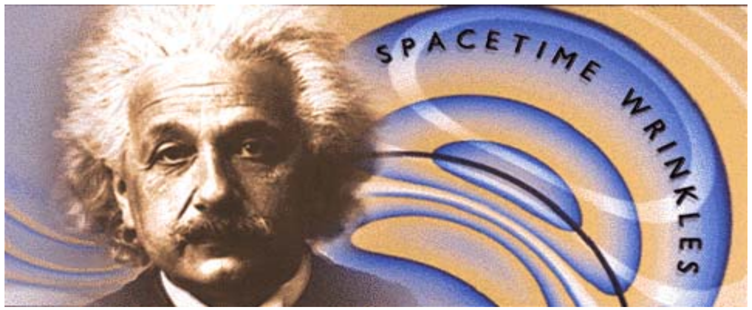
The Einstein equation in vacuum becomes

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

Having solutions

$$h_{\mu\nu}(t - x/c)$$

Spacetime perturbations, propagating in vacuum like waves, at the speed of light : gravitational waves



Gravitational waves are strain in space propagating with the speed of light

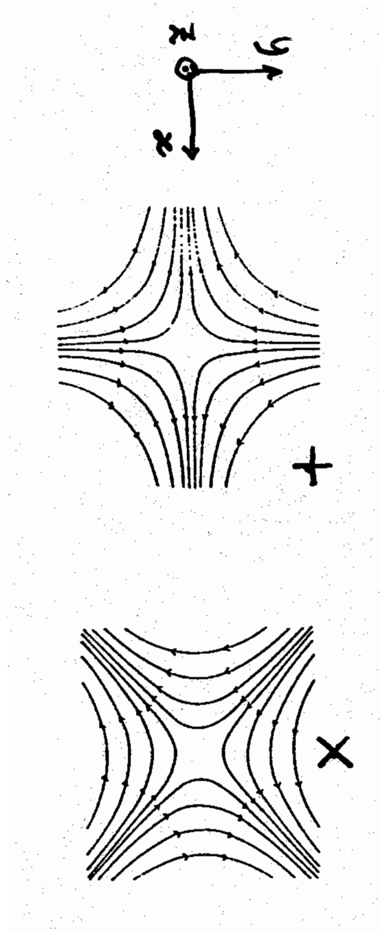
Main features

- 2 transversal polarization states
- Associated with massless, spin 2 particles (gravitons)
- Emitted by time-varying quadrupole mass moment
  no dipole radiation because of conservation laws

$$-\frac{dE}{dt} = \cancel{\frac{2G}{3c^3}\left(\dot{d}\right)^2} + \frac{G}{45c^5}\left(\dddot{Q}\right)^2 + \dots$$

$$\dot{d} = \sum_i m_i \dot{x}_i \Rightarrow \ddot{d} \equiv 0 \qquad Q_{ij} = \int \rho x_i x_j d^3x$$

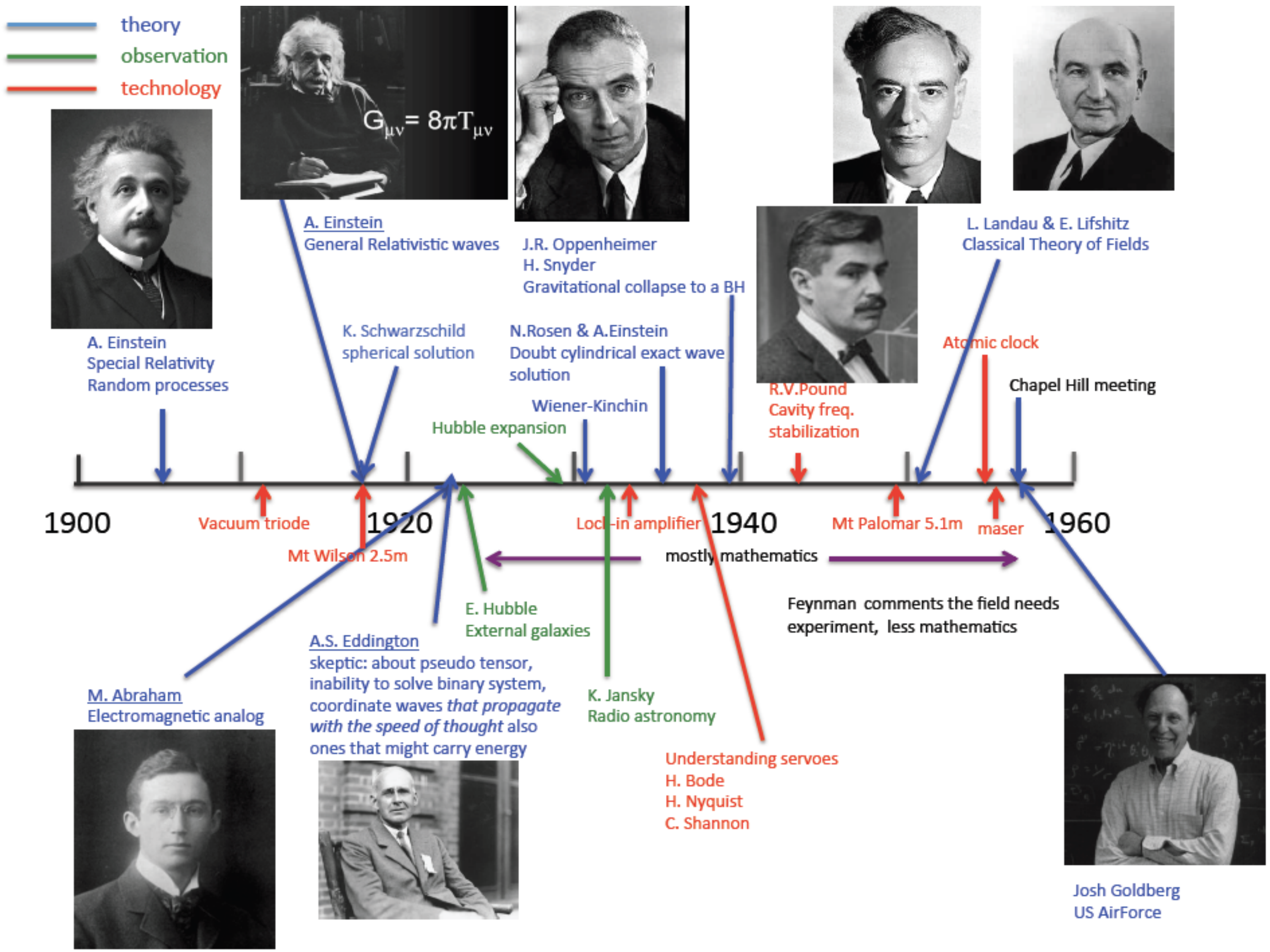
$$h_{ij}(t) = \frac{2G}{rc^4}\ddot{Q}_{ij}(t - r/c)$$



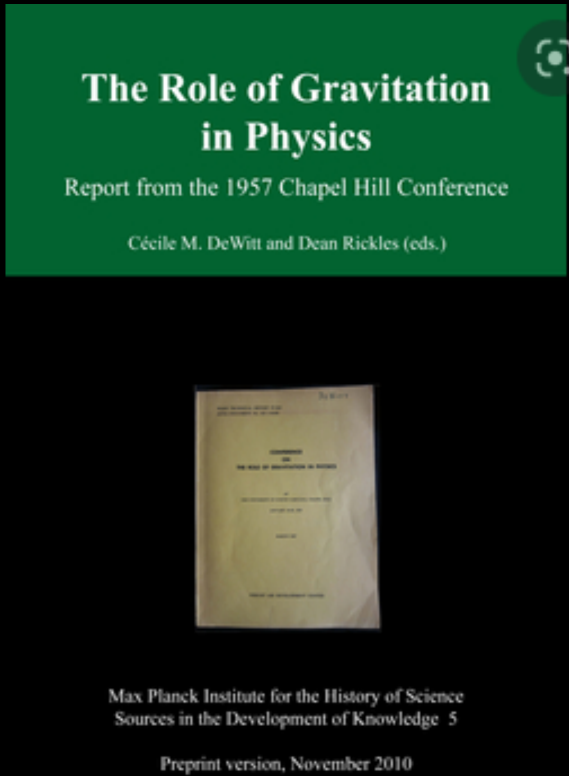
$$A = \frac{\varkappa}{24\pi} \sum_{\alpha\beta} \left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3} \right)^2. \quad (21)$$

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.

"…..in any case one can think of A will have a practically vanishing value."

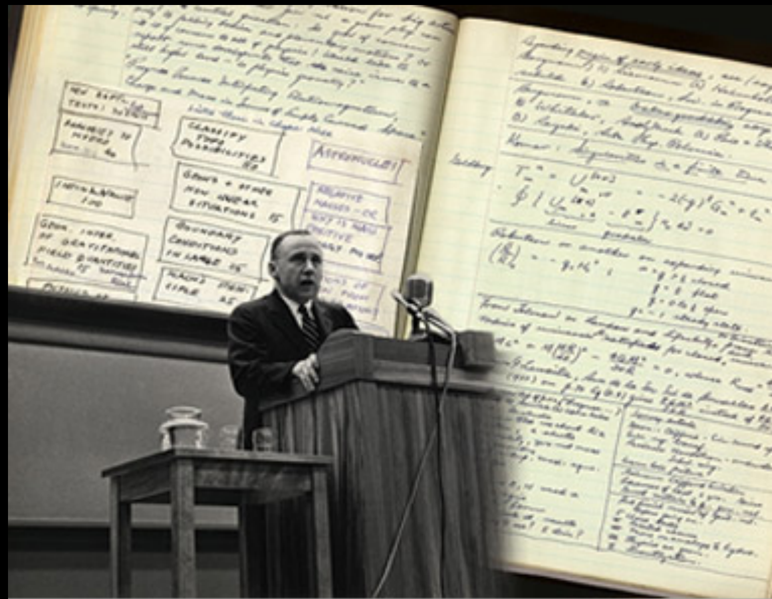


theory
observation
technology
A. Einstein
Special Relativity
Random processes
$G_{\mu\nu} = 8\pi T_{\mu\nu}$
A. Einstein
General Relativistic waves
K. Schwarzschild
spherical solution
J.R. Oppenheimer
H. Snyder
Gravitational collapse to a BH
N.Rosen & A.Einstein
Doubt cylindrical exact wave
solution
Wiener-Kinchin
Hubble expansion
R.V.Pound
Cavity freq.
stabilization
L. Landau & E. Lifshitz
Classical Theory of Fields
Atomic clock
Chapel Hill meeting
1900
Vacuum triode
1920
Mt Wilson 2.5m
Lock-in amplifier
1940
Mt Palomar 5.1m
maser
1960
mostly mathematics
Feynman comments the field needs
experiment, less mathematics
E. Hubble
External galaxies
A.S. Eddington
skeptic: about pseudo tensor,
inability to solve binary system,
coordinate waves *that propagate*
with the speed of thought also
ones that might carry energy
M. Abraham
Electromagnetic analog
K. Jansky
Radio astronomy
Understanding servoes
H. Bode
H. Nyquist
C. Shannon
Josh Goldberg
US AirForce



Bergmann
Bondi
deWitt
Dicke
Feinman
Misner
Pirani
Wheeler

1957



Chapter 14
Measurement of Classical Gravitation Fields

Felix Pirani

Because of the principle of equivalence, one cannot ascribe a direct physical interpretation to the gravitational field insofar as it is characterized by Christoffel symbols $\Gamma^{\mu}_{\nu\rho}$. One can, however, give an invariant interpretation to the variations of the gravitational field. These variations are described by the Riemann tensor; therefore, measurements of the relative acceleration of neighboring free particles, which yield information about the variation of the field, will also yield information about the Riemann tensor.

Now the relative motion of free particles is given by the equation of geodesic deviation

$$\frac{\partial^2 \eta^\mu}{\partial \tau^2} + R^{\mu}_{\nu\rho\sigma} v^\nu \eta^\rho v^\sigma = 0 \quad (\mu,\nu,\rho,\sigma = 1,2,3,4) \tag{14.1}$$

Here η^μ is the infinitesimal orthogonal displacement from the (geodesic) worldline ζ of a free particle to that of a neighboring similar particle. v^ν 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 (14.1) becomes

$$\frac{\partial^2 \eta^a}{\partial \tau^2} + R^{a}_{0b0} \eta^b = 0 \quad (a,b = 1,2,3,) \tag{14.2}$$

Here η^a are the physical components of the infinitesimal displacement and R^a_{0b0} 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.

Now the Newtonian equation corresponding to (14.2) is

$$\frac{\partial^2 \eta^a}{\partial \tau^2} + \frac{\partial^2 v}{\partial x^a \partial x^b} \eta^b = 0 \tag{14.3}$$

It is interesting that the empty-space field equations in the Newtonian and general relativity theories take the same form when one recognizes the correspondence $R^a_{0b0} \sim \frac{\partial^2 v}{\partial x^a \partial x^b}$ between equations (14.2) and (14.3), for the respective empty-space equations may be written $R^a_{0a0} = 0$ and $\frac{\partial^2 v}{\partial x^a \partial x^b} = 0$. (Details of this work are in the course of publication in *Acta Physica Polonica.*)

BONDI: Can one construct in this way an absorber for gravitational energy by inserting a $\frac{d\eta}{d\tau}$ term, to learn what part of the Riemann tensor would be the energy producing one, because it is that part that we want to isolate to study gravitational waves?

PIRANI: I have not put in an absorption term, but I have put in a "spring." You can invent a system with such a term quite easily.

LICHNEROWICZ: Is it possible to study stability problems for η?

PIRANI: It is the same as the stability problem in classical mechanics, but I haven't tried to see for which kind of Riemann tensor it would blow up.

- **No laboratory equivalent of Hertz experiments for production of GWs**

Luminosity due to a mass M and size R oscillating at frequency $\omega \sim v/R$:

$$L = \frac{2G}{5c^5}\left\langle \dddot{Q}^2 \right\rangle \approx \frac{GM^2v^6}{R^2c^5} \qquad Q \approx MR^2 \sin\omega t$$

M=1000 tons, steel rotor, f = 4 Hz ⟹ $L = 10^{-30}$ W
Einstein: " .. *a pratically vanishing value…*"

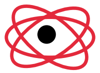
Collapse to neutron star 1.4 M_o ⟹ $L = 10^{52}$ W

$h \sim W^{1/2}d^{-1}$; source in the Galaxy ***$h \sim 10^{-18}$***, in VIRGO cluster ***$h \sim 10^{-21}$***
Fairbank: "*...a challenge for contemporary experimental physics..*"

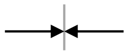
How Small 10^{-18} meter is?

One meter

÷10,000  Human hair ~ 10^{-4} m (0.1 mm)

÷1,000,000  Atomic diameter 10^{-10} m

÷100,000  Nuclear diameter 10^{-15} m

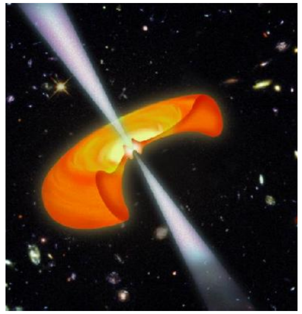
÷1,000  GW detector 10^{-18} m

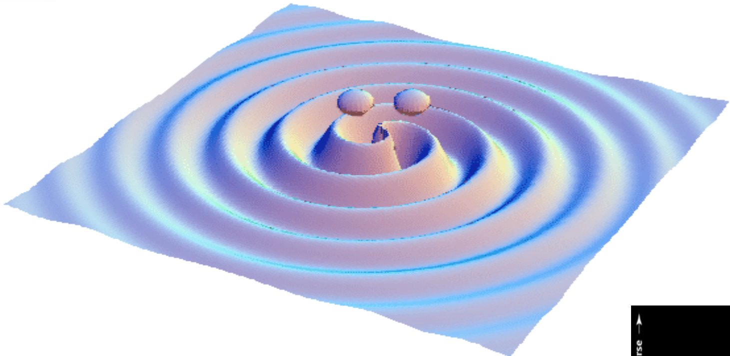
GW OBJECTIVES

FIRST DETECTION
test Einstein prediction

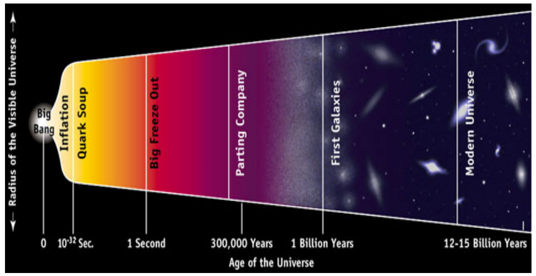
$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}$$

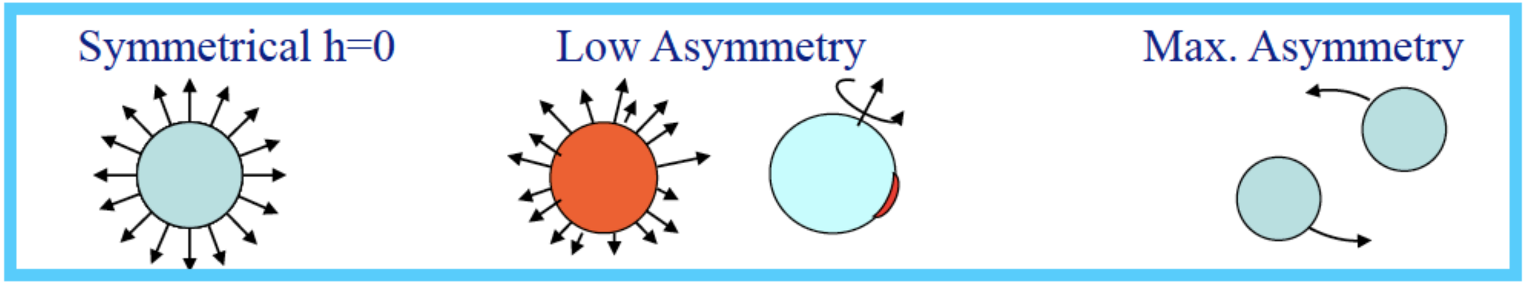
ASTRONOMY & ASTROPHYSICS
look beyond the visible,
understand Black Holes,
Neutron Stars and supernovae
understand GRB





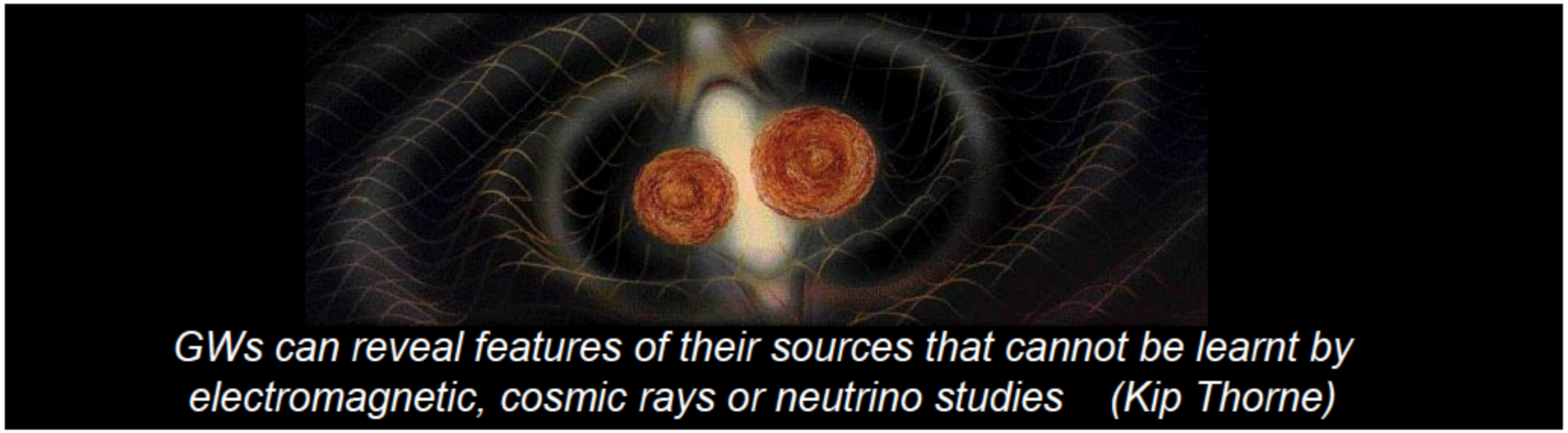
COSMOLOGY
the Planck time:
look as back in time as theorist can conceive

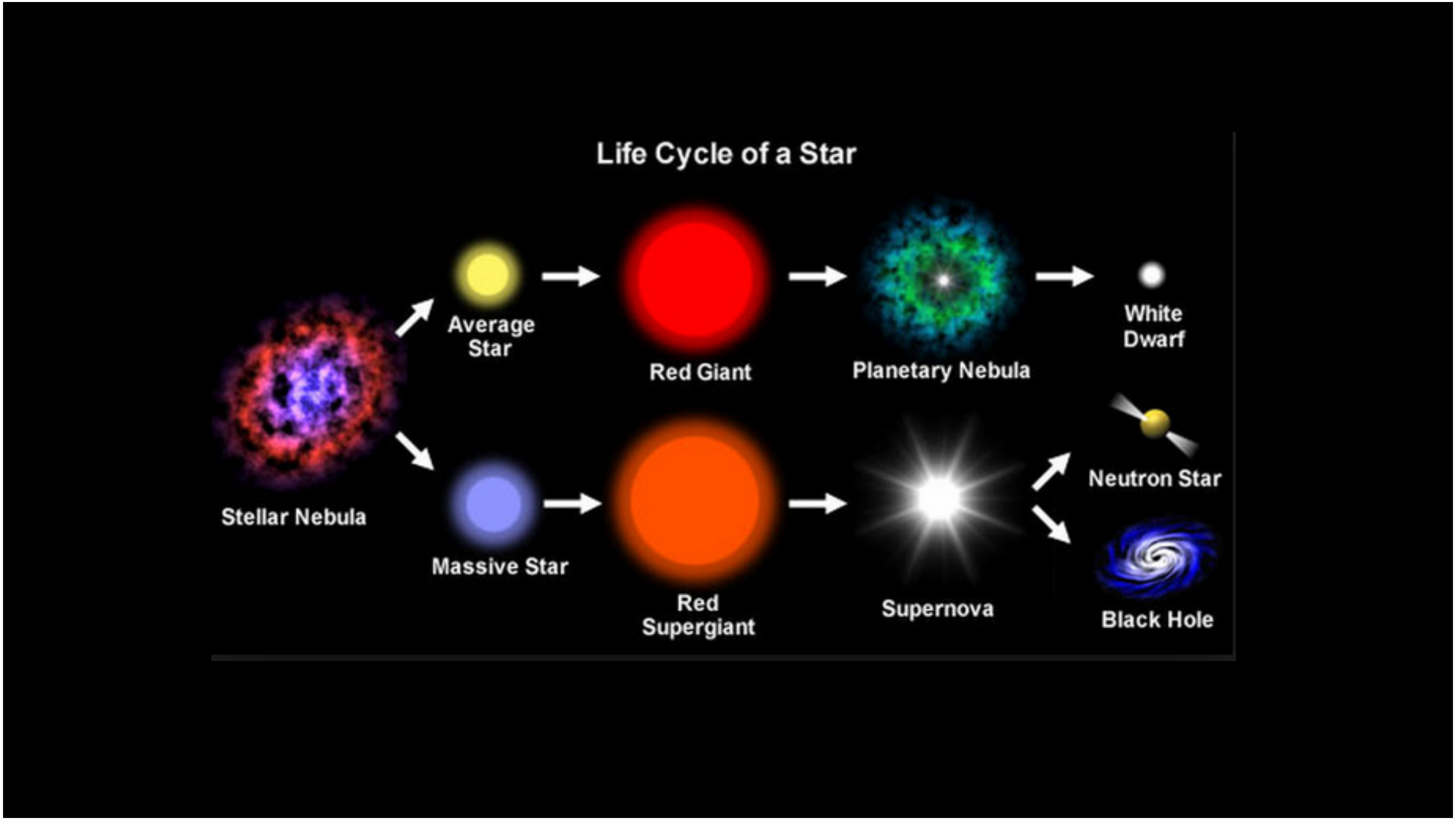


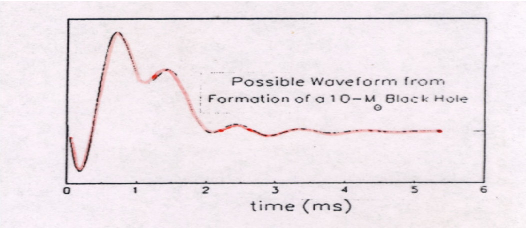


Observing gravitational radiation gives unique information complementary to those derived by em observations

- em radiation is the result of an incoherent combination of the radiation emitted by electrons, atoms and molecules ←→ gravitational radiation is the result of a coherent mass acceleration.
- em radiation interacts strongly with matter, and is absorbed significantly while travelling toward the detector ←→ gravitational radiation propagates "freely" and can bring us info from the innermost region of a star

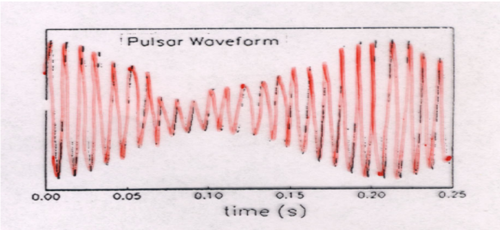



Life Cycle of a Star
Average Star
Red Giant
Planetary Nebula
White Dwarf
Stellar Nebula
Massive Star
Red Supergiant
Supernova
Neutron Star
Black Hole



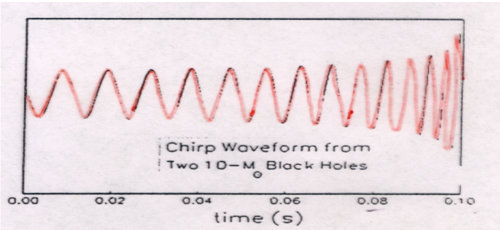
SUPERNOVAE.
If the collapse core is non-symmetrical, the event can give off considerable radiation in a millisecond timescale.

Information
Inner detailed dynamics of supernova
See NS and BH being formed
Nuclear physics at high density



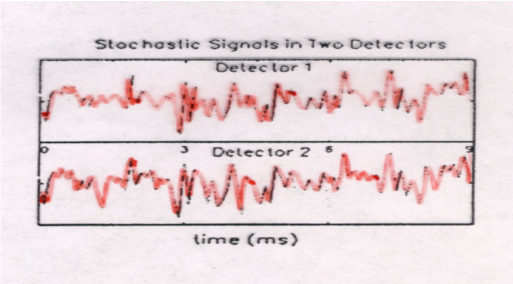
SPINNING NEUTRON STARS.
Pulsars are rapidly spinning neutron stars. If they have an irregular shape, they give off a signal at constant frequency (prec./Dpl.)

Information
Neutron star locations near the Earth
Neutron star Physics
Pulsar evolution



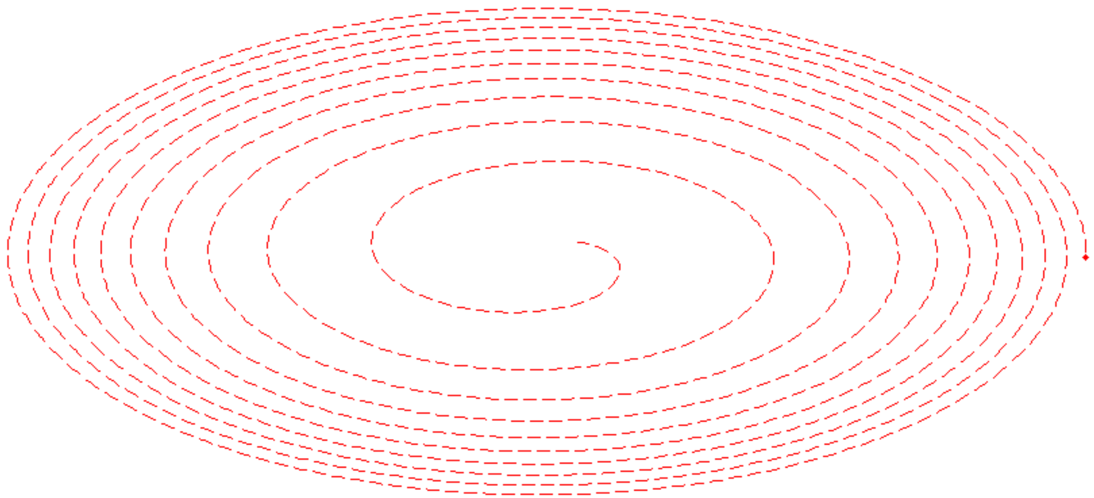
COALESCING BINARIES.
Two compact objects (NS or BH) spiraling together from a binary orbit give a chirp signal, whose shape identifies the masses and the distance

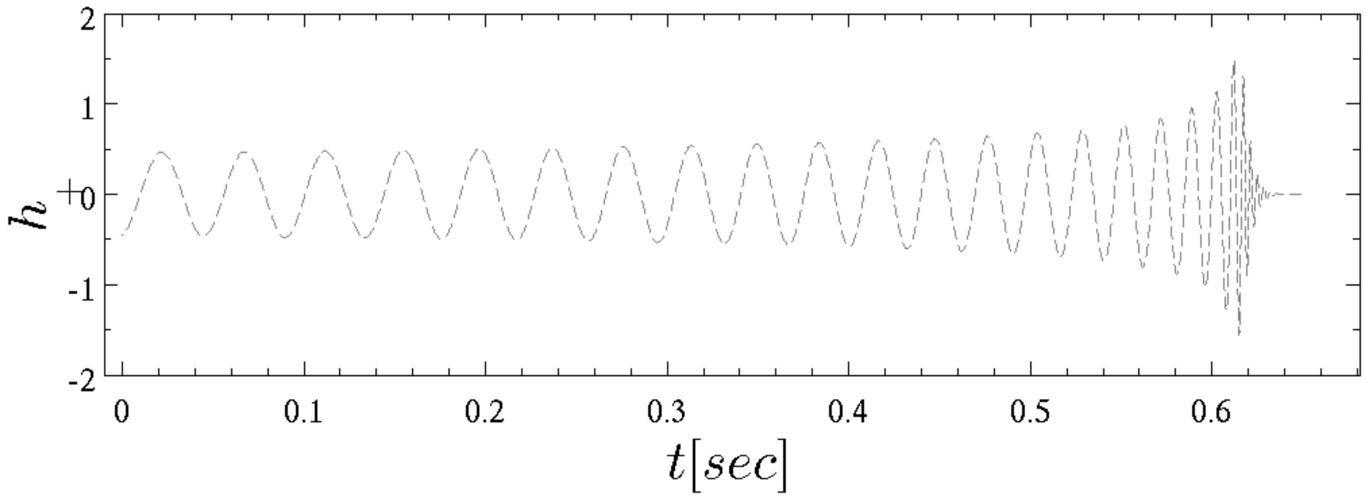
Information
Masses of the objects
BH identification
Distance to the system
Hubble constant
Test of strong-field general relativity



STOCHASTIC BACKGROUND.
Random background, relic of the early universe and depending on unknown particle physics. It will look like noise in any one detector, but two detectors will be correlated.

Information
Confirmation of Big Bang, and inflation
Unique probe to the Planck epoch
Existence of cosmic strings

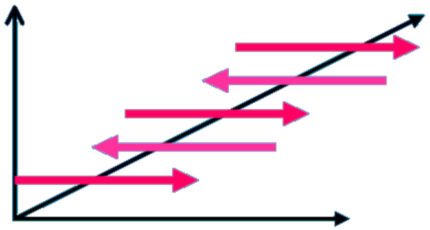



2
1
0
-1
-2
0
0.1
0.2
0.3
0.4
0.5
0.6
$t[sec]$
h_+

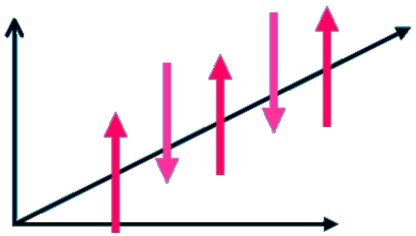
Gravitational Waves

Comparison with electromagnetic waves

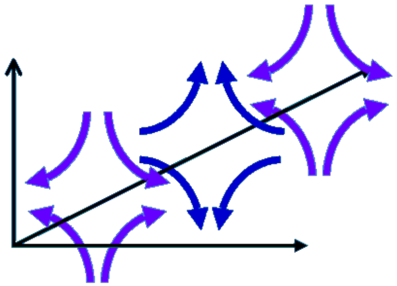
Horizontal polarization



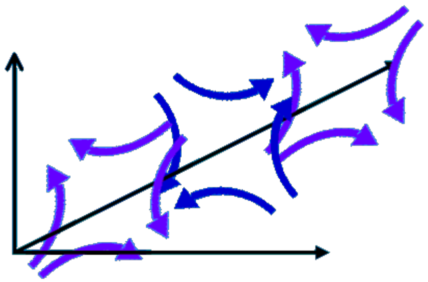
Vertical polarization



Plus polarization

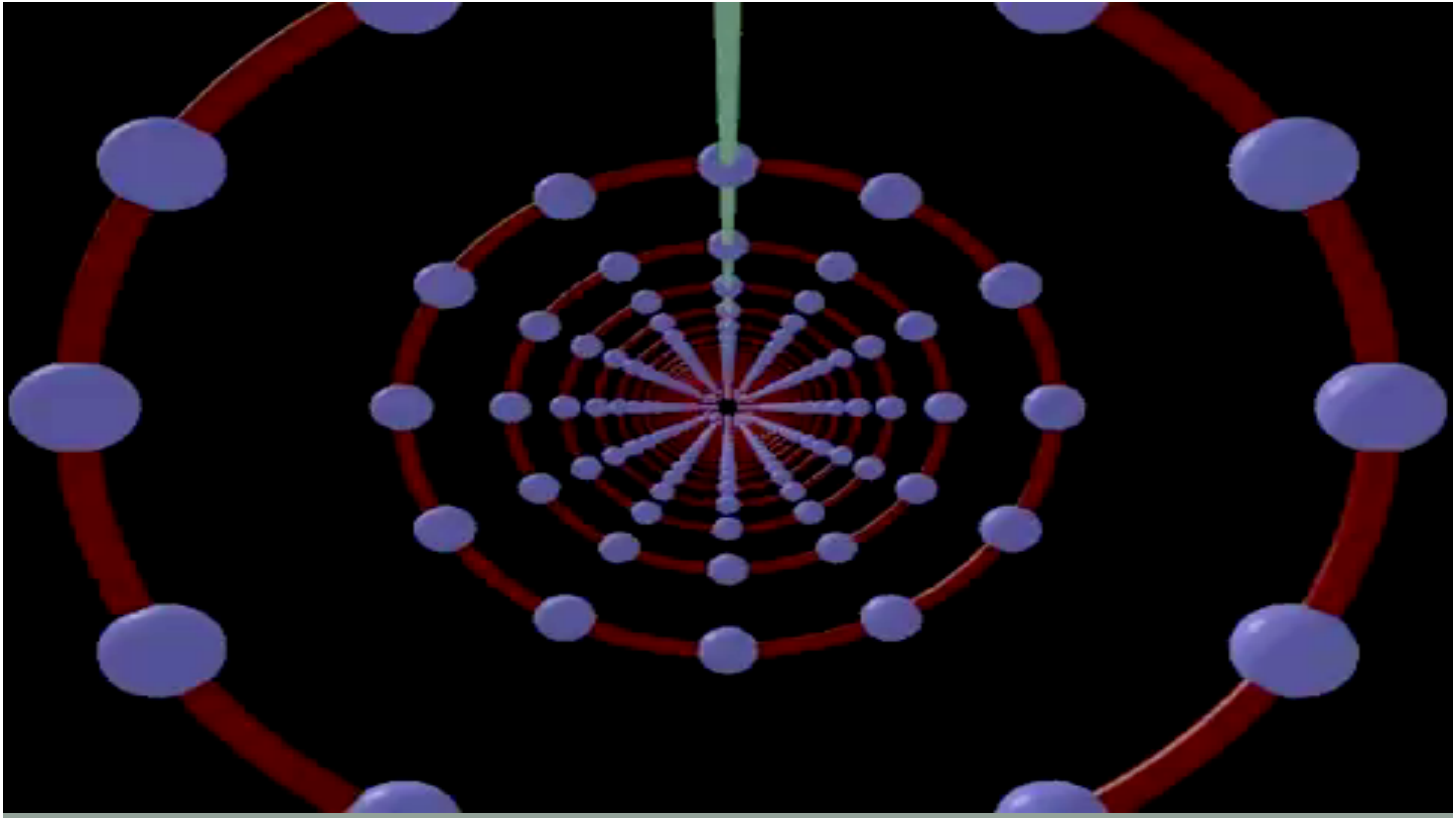


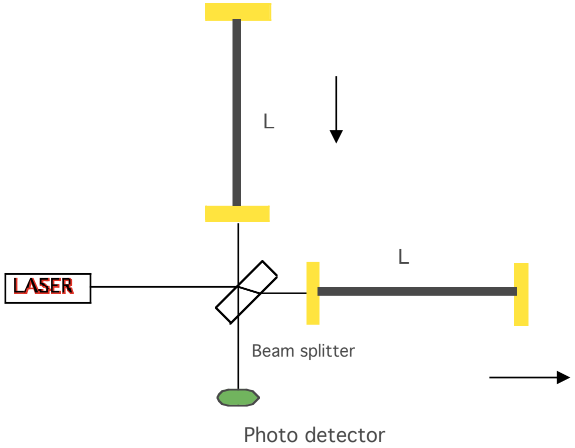
Cross polarization



The so-called "electromagnetic theory of light" has not helped us hitherto . . it seems to me that it is rather a backward step . . . the one thing about it that seems intelligible to me, I do not think is admissible . . That there should be an electric displacement perpendicular to the line of propagation'

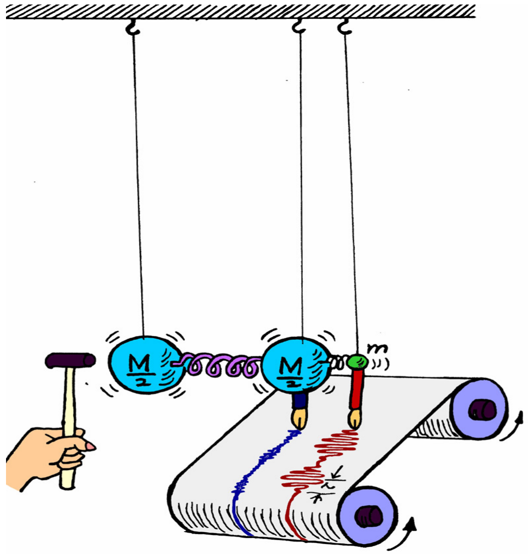
Lord Kelvin



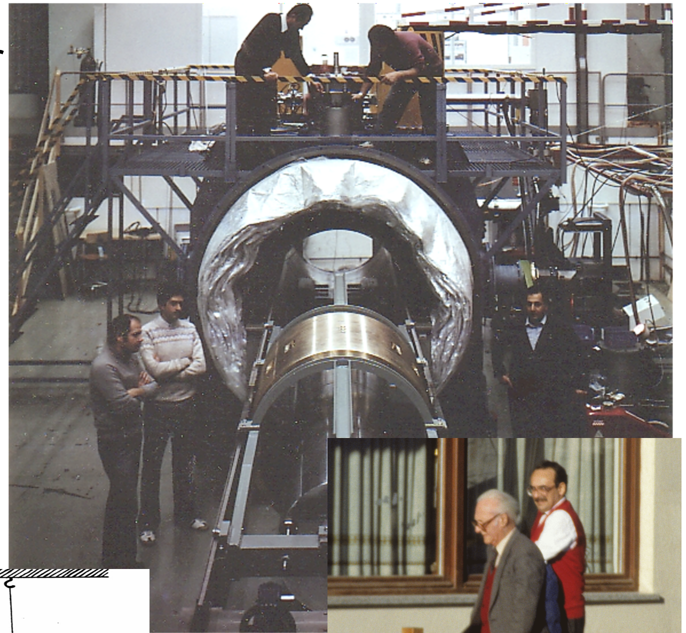


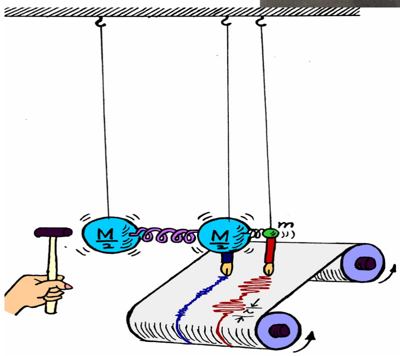
$$h = \frac{\Delta L}{L}$$

$$\ddot{x}(t) + \tau^{-1}\dot{x}(t) + \omega_0^2 x(t) = \frac{1}{2}\ddot{h}(t)$$

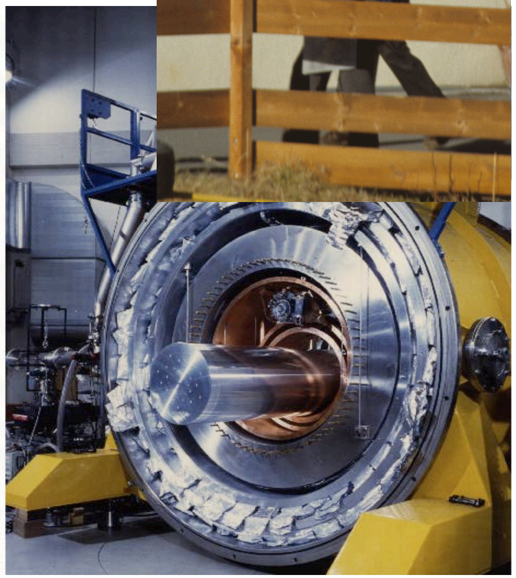


Explorer
CERN





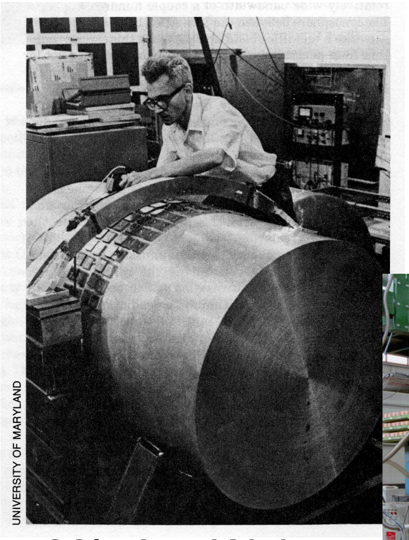
Nautilus, LNF



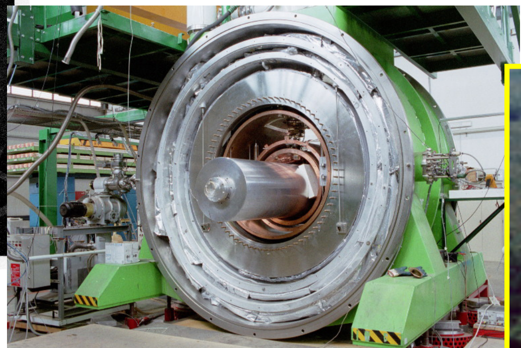
Auriga, LNL

Some perspective: 50 years of attempts at detection:

Since the pioneering work of Joseph Weber in the ‘60, the search for Gravitational Waves has never stopped, with an increasing effort of manpower and ingenuity:



60’: Joe Weber pioneering work



90’: Cryogenic Bars

2000’ - : Large Interferometers

1997: GWIC was formed

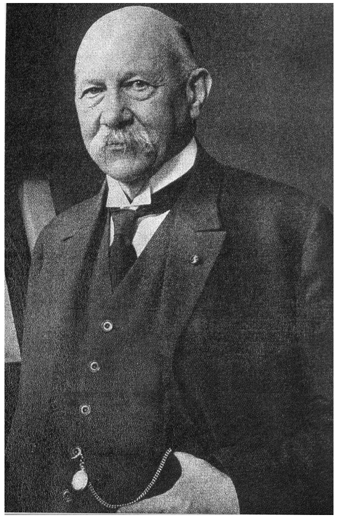
Experimental gravitational physicists are heirs to several great traditions:

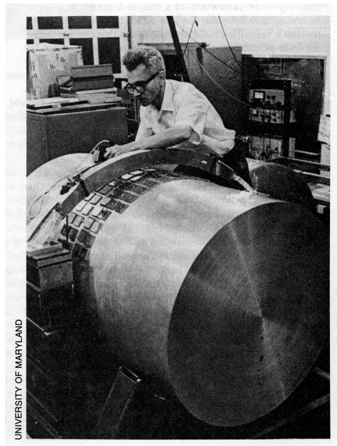
- High precision mechanical experiments (Cavendish, Eotvos, Dicke..)
  detection of weak forces applied on mechanical test bodies

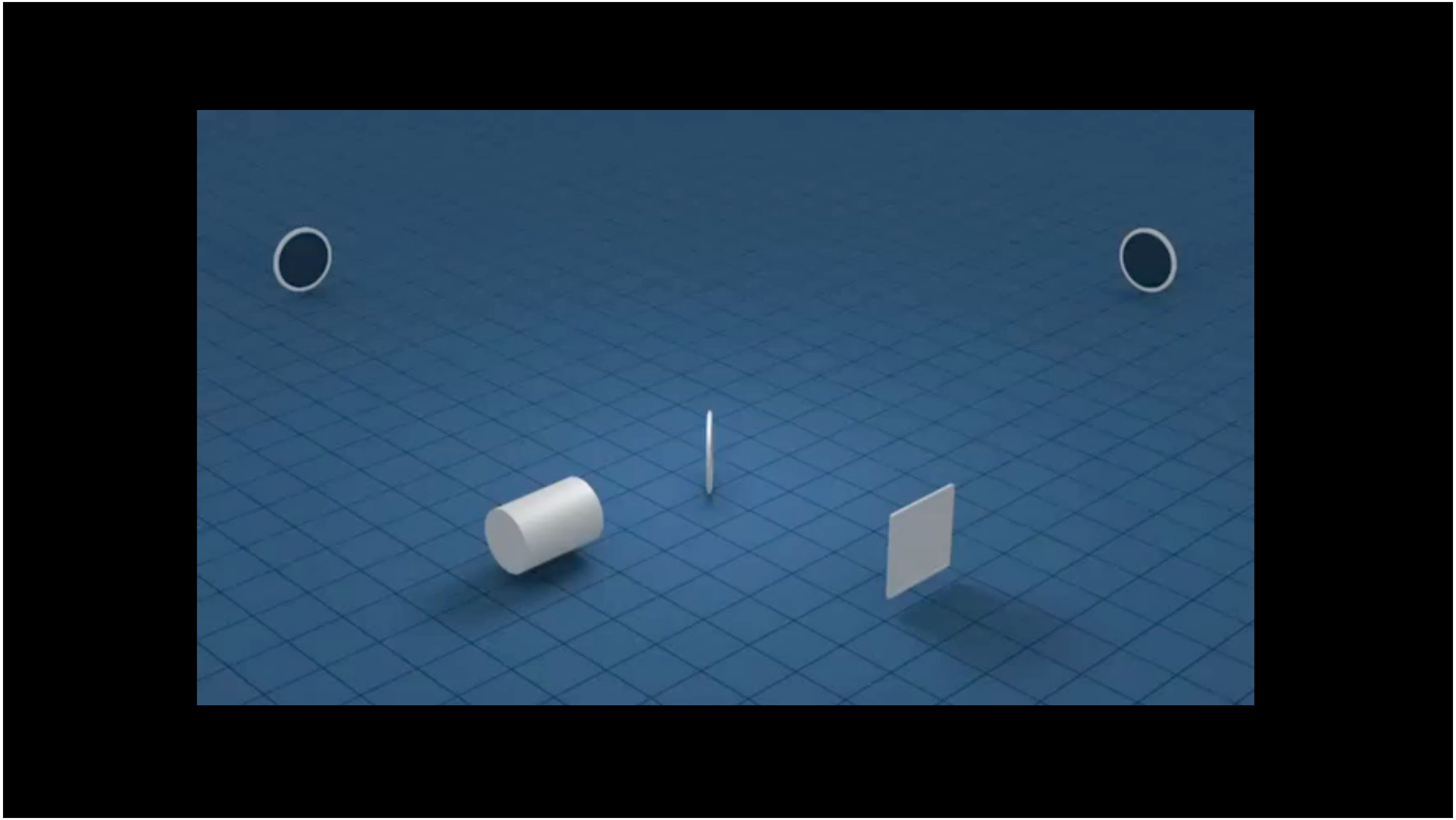
- High precision optical measurements (Michelson, laser developers…)

- Operation of ultraprecise e-m measurement systems (microwave pioneers of World War II)

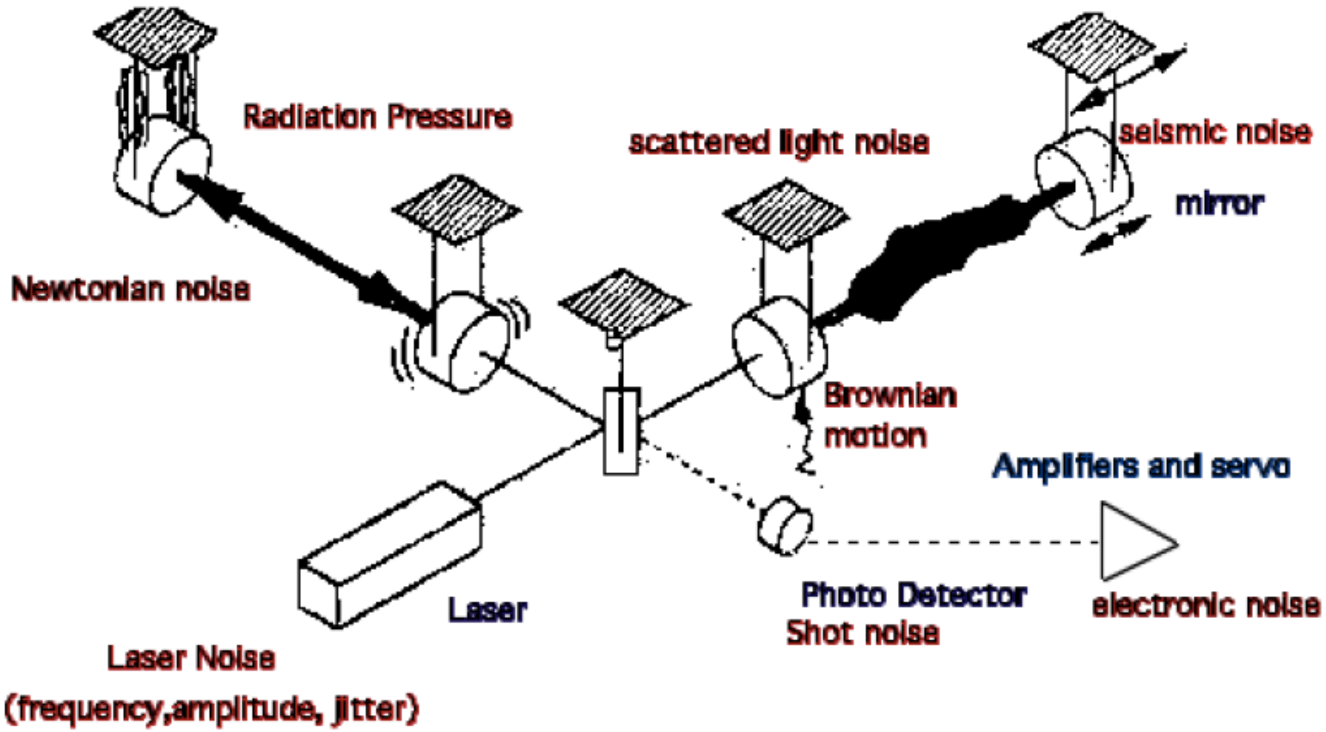
- Low temperature physics (K. Onnes)
  superfluids and superconductors technology

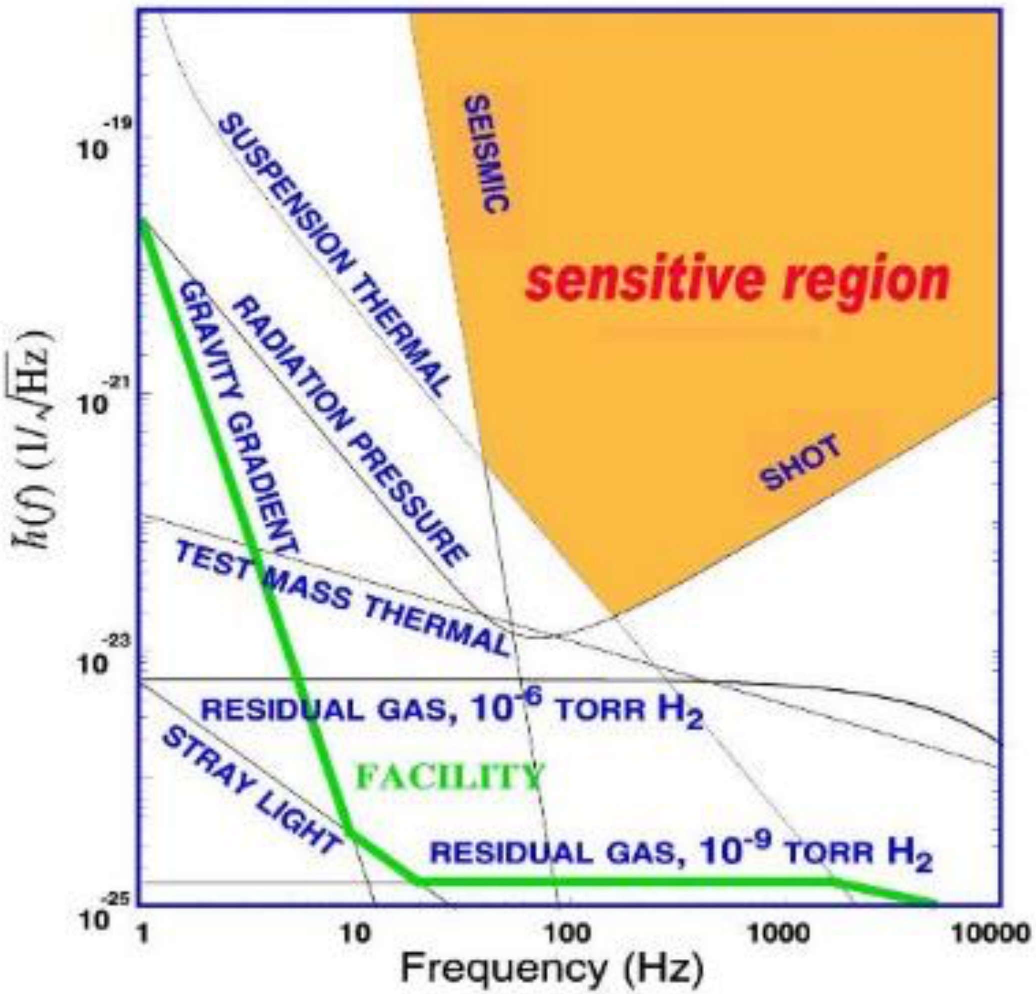




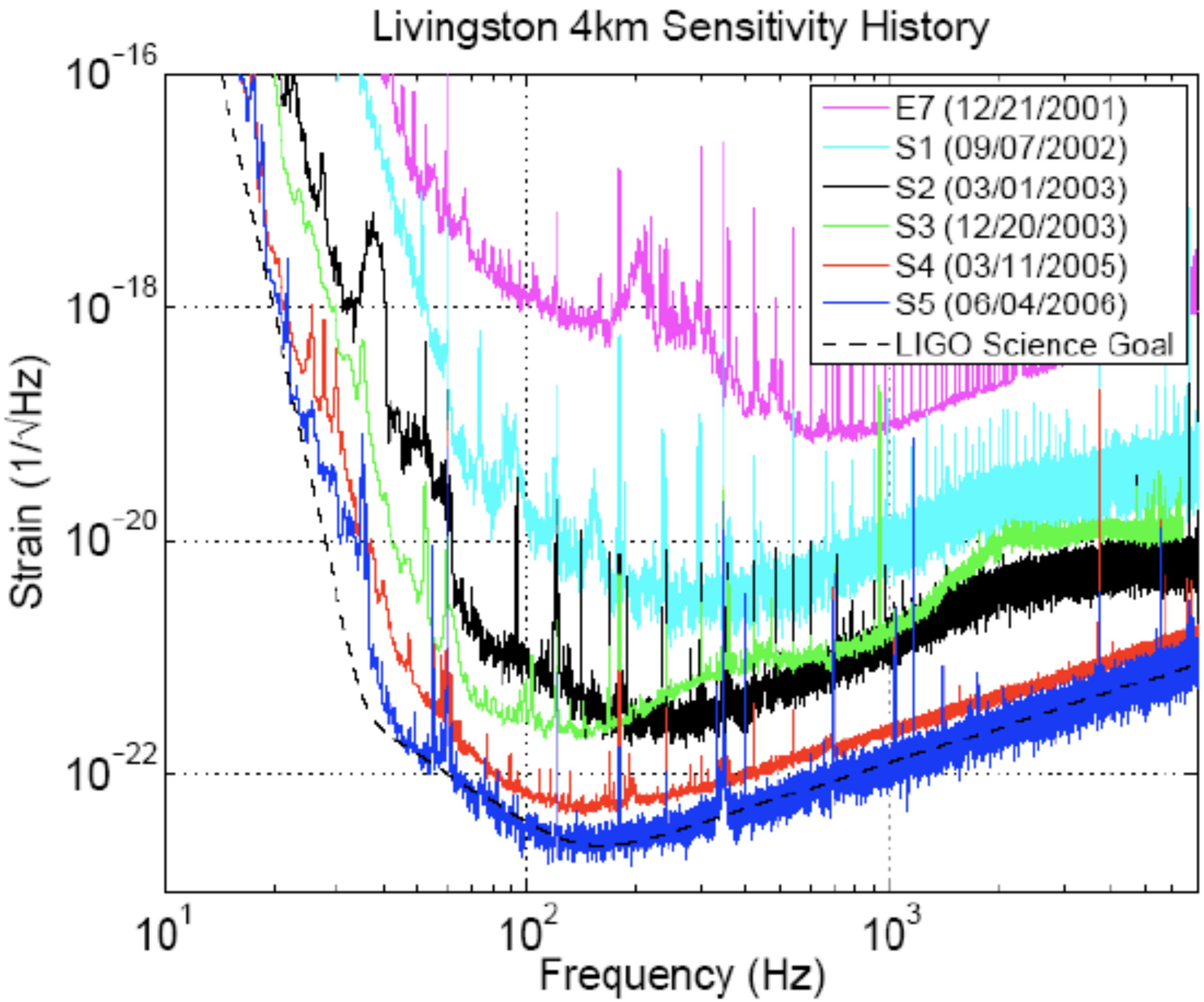


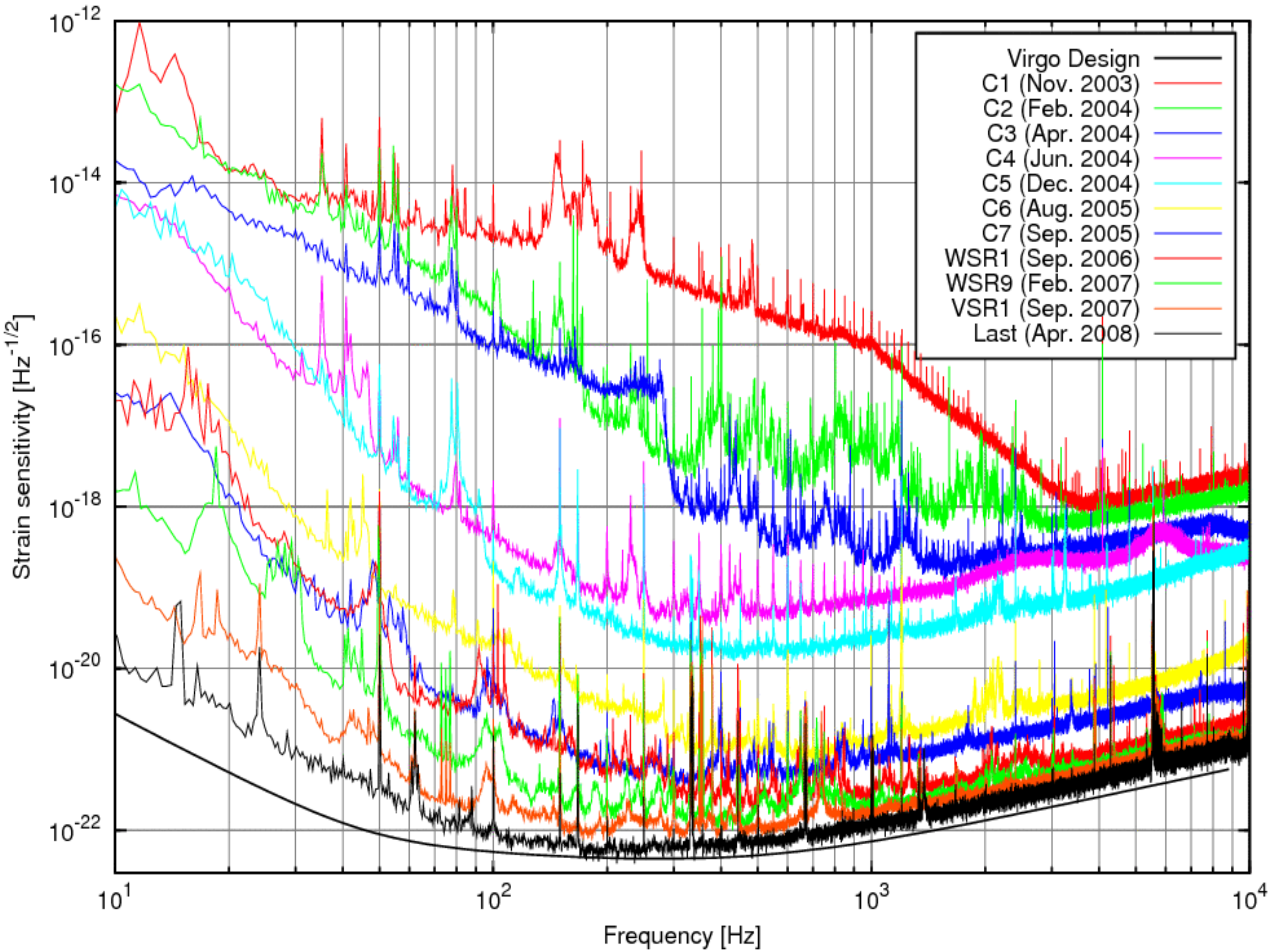
Main noise sources in interferometric GW detectors



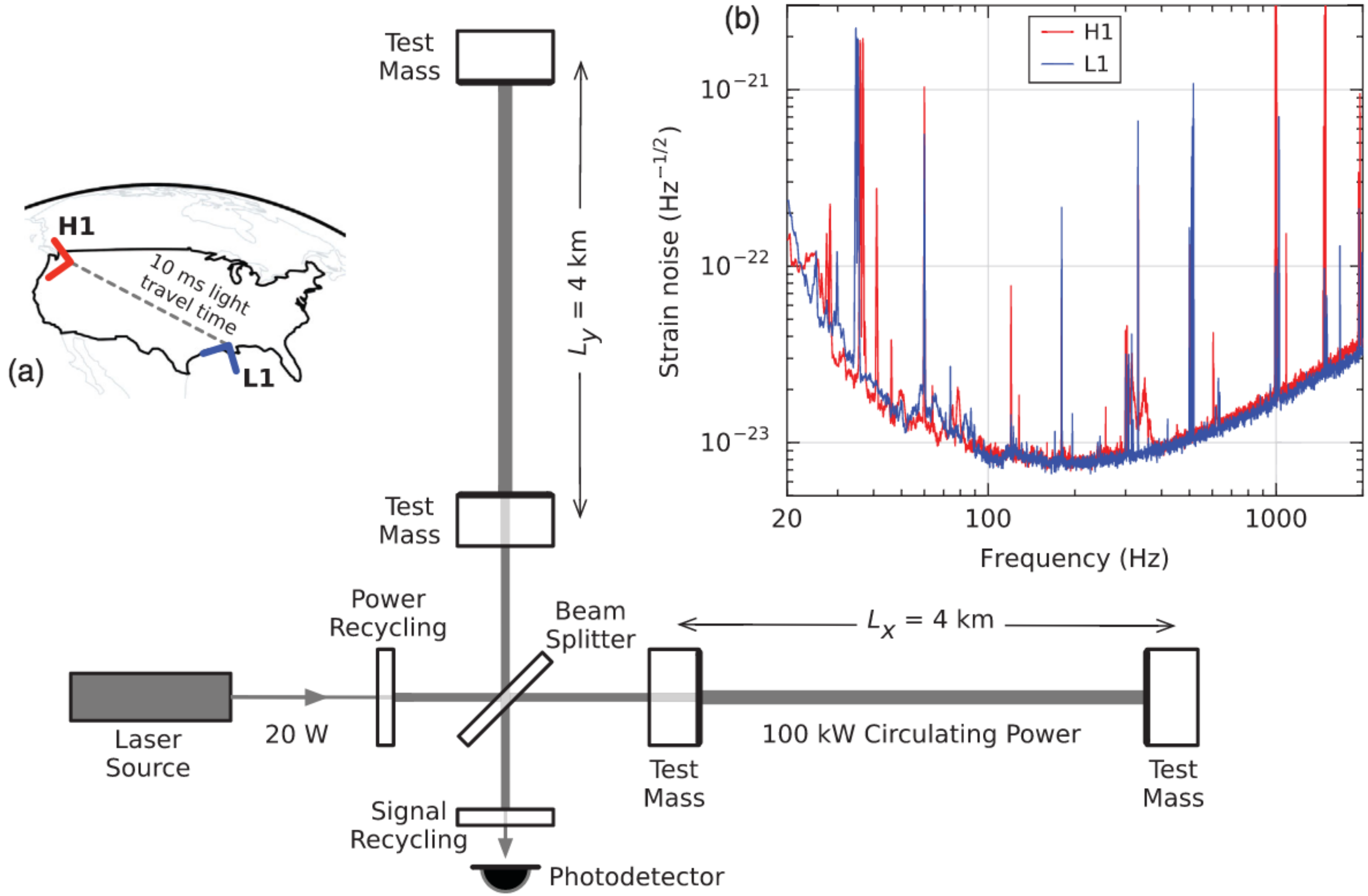


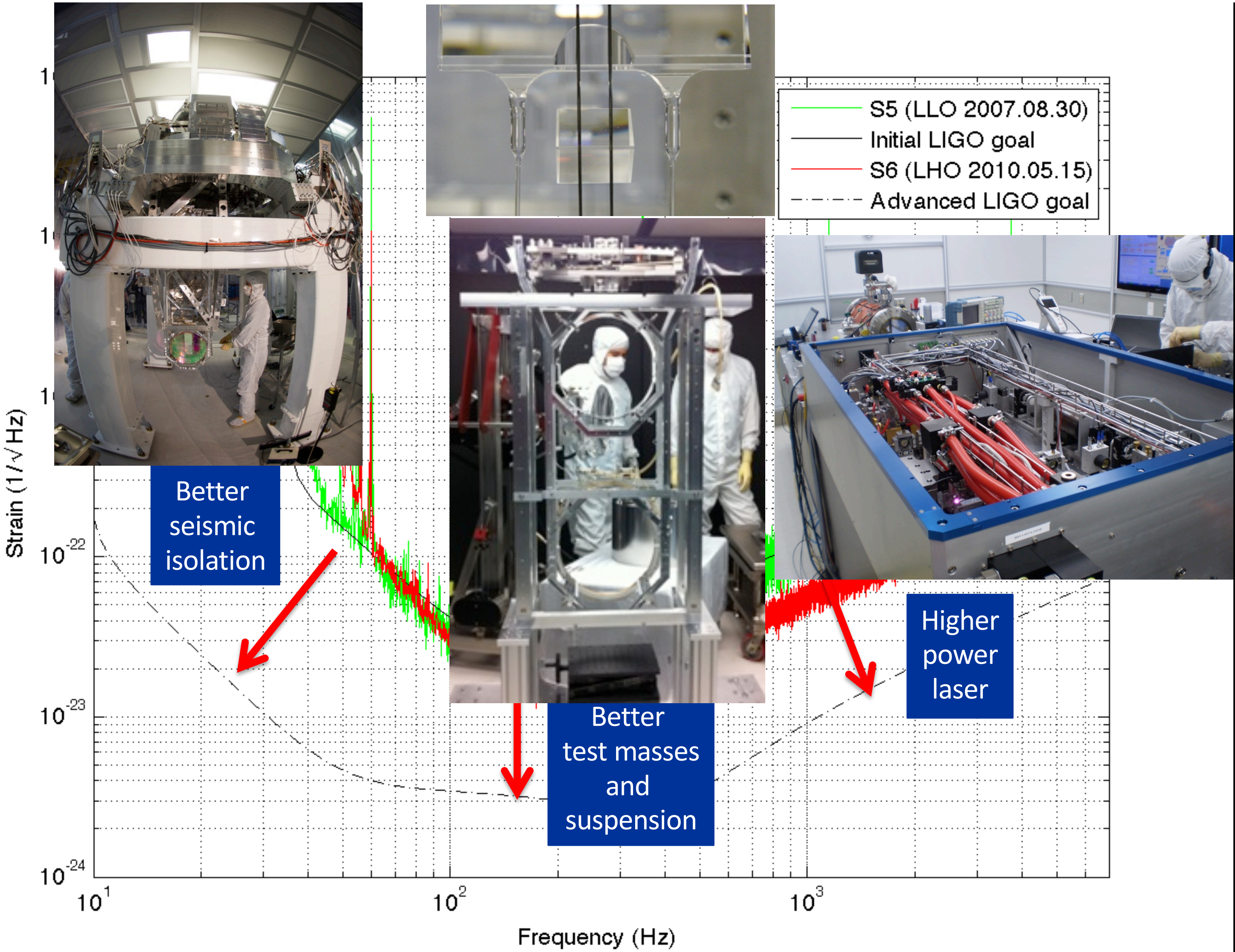
sensitive region
SEISMIC
SUSPENSION THERMAL
RADIATION PRESSURE
GRAVITY GRADIENT
SHOT
TEST MASS THERMAL
RESIDUAL GAS, 10^{-6} TORR H_2
FACILITY
STRAY LIGHT
RESIDUAL GAS, 10^{-9} TORR H_2
$h(f)$ $(1/\sqrt{Hz})$
10^{-19}
10^{-21}
10^{-23}
10^{-25}
1
10
100
1000
10000
Frequency (Hz)


Livingston 4km Sensitivity History
E7 (12/21/2001)
S1 (09/07/2002)
S2 (03/01/2003)
S3 (12/20/2003)
S4 (03/11/2005)
S5 (06/04/2006)
LIGO Science Goal
Strain (1/√Hz)
Frequency (Hz)
10^-16
10^-18
10^-20
10^-22
10^1
10^2
10^3



Virgo Design
C1 (Nov. 2003)
C2 (Feb. 2004)
C3 (Apr. 2004)
C4 (Jun. 2004)
C5 (Dec. 2004)
C6 (Aug. 2005)
C7 (Sep. 2005)
WSR1 (Sep. 2006)
WSR9 (Feb. 2007)
VSR1 (Sep. 2007)
Last (Apr. 2008)
Strain sensitivity [Hz^-1/2]
Frequency [Hz]

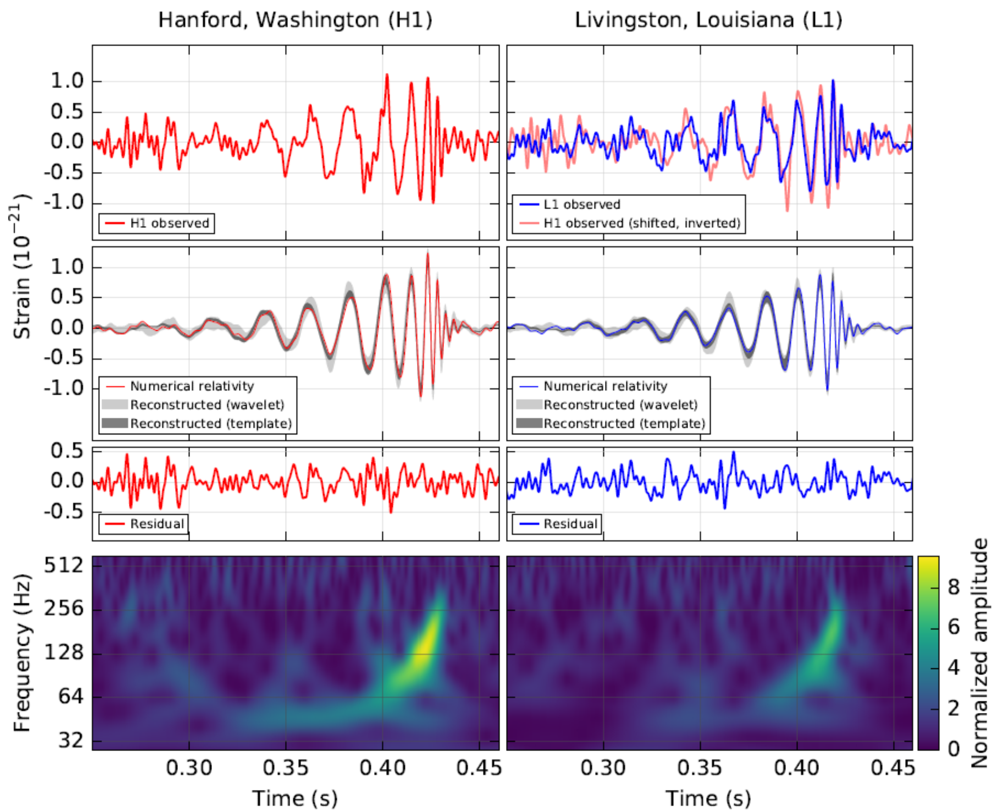

(a)
H1
L1
10 ms light travel time
(b)
H1
L1
Strain noise (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector


S5 (LLO 2007.08.30)
Initial LIGO goal
S6 (LHO 2010.05.15)
Advanced LIGO goal
Better seismic isolation
Better test masses and suspension
Higher power laser
Strain (1/√Hz)
Frequency (Hz)
10^-22
10^-23
10^-24
10^1
10^2
10^3

GW150914: the signal

- Top row left – Hanford
- Top row right – Livingston
- Time difference ~ 6.9 ms with Livingston first
- Second row – calculated GW strain using Numerical Relativity Waveforms for quoted parameters compared to reconstructed waveforms (Shaded)
- Third Row –residuals
- Bottom row – time frequency plot showing frequency increases with time (chirp)

September 14th, 2015 at 09:50:45 UTC

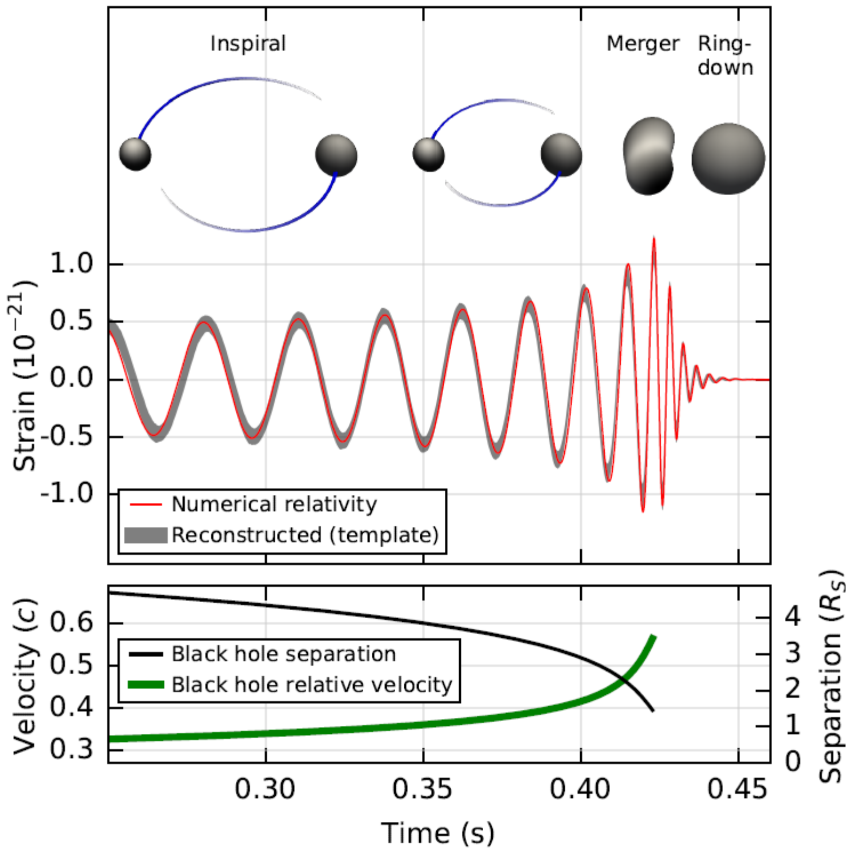


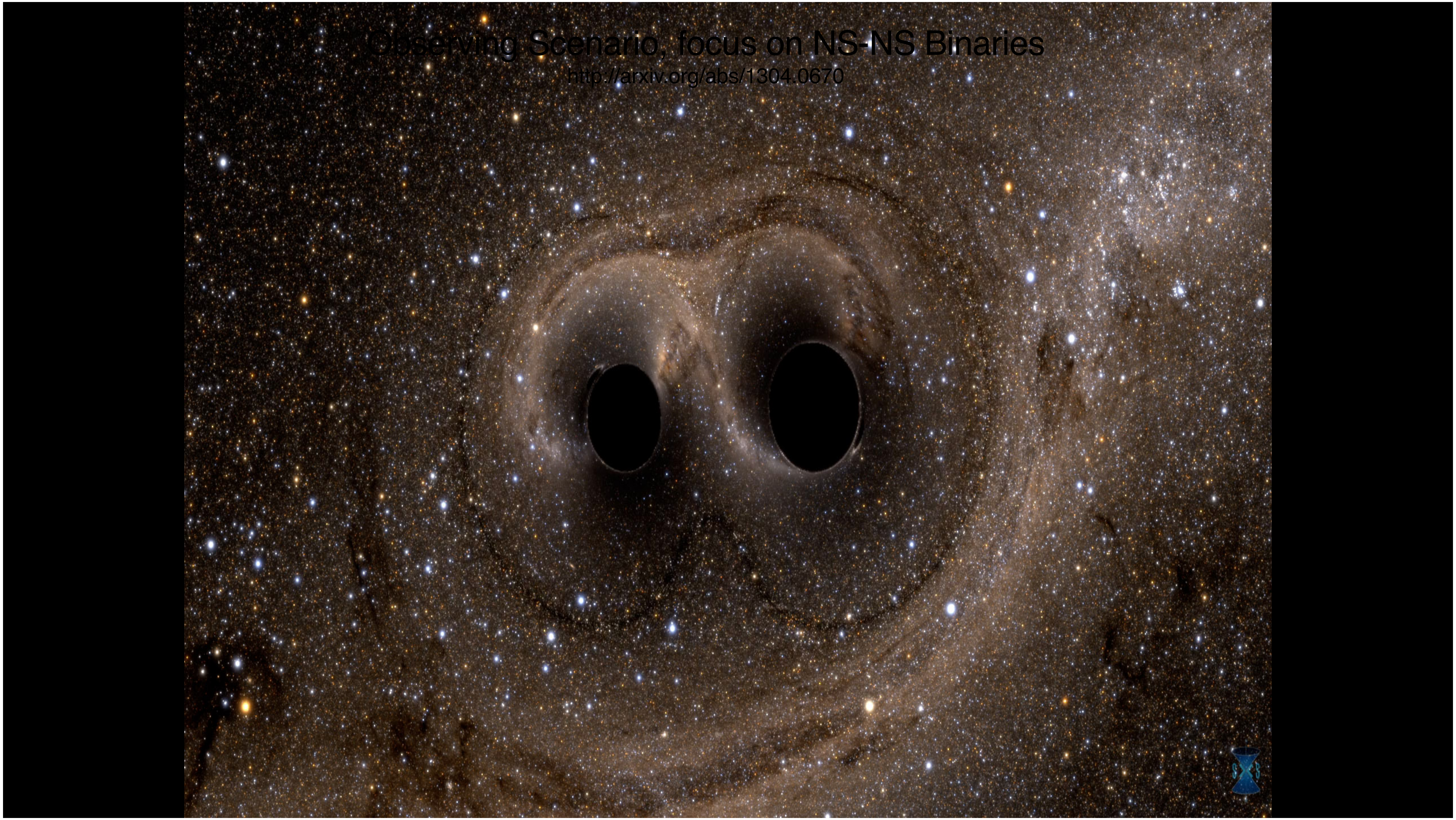
GW150914: Estimated Strain Amplitude

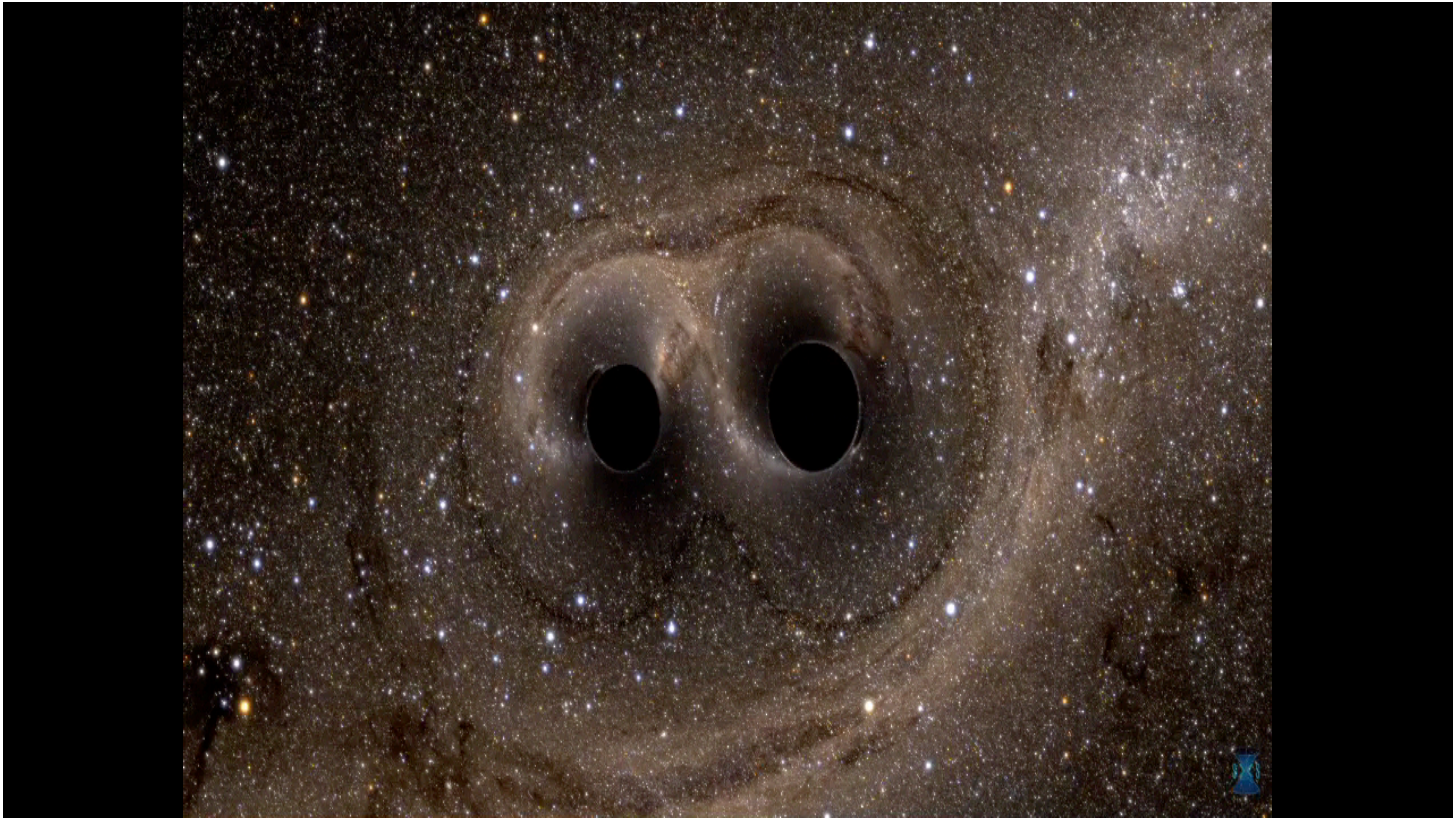
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \frac{c^3}{G}\left[\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right]^{3/5}$$

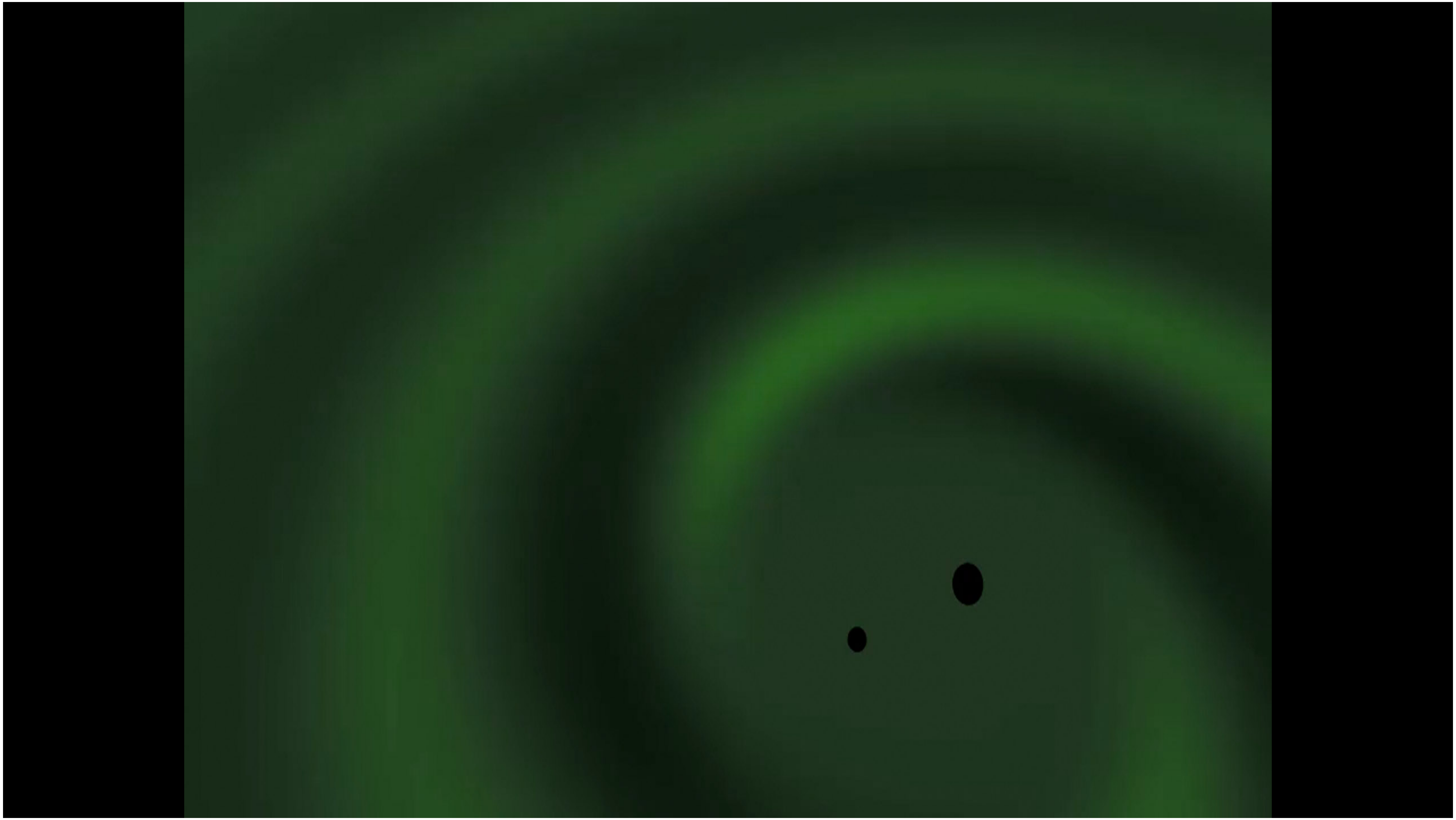
- Numerical relativity models of black hole horizons during coalescence
- Effective black hole separation in units of Schwarzschild radius ($R_s=2GM_{tot}/c^2=210$km); and effective relative velocities given by post-Newtonian parameter $v/c = (GM_{tot}\pi f_{GW}/c^3)^{1/3}$

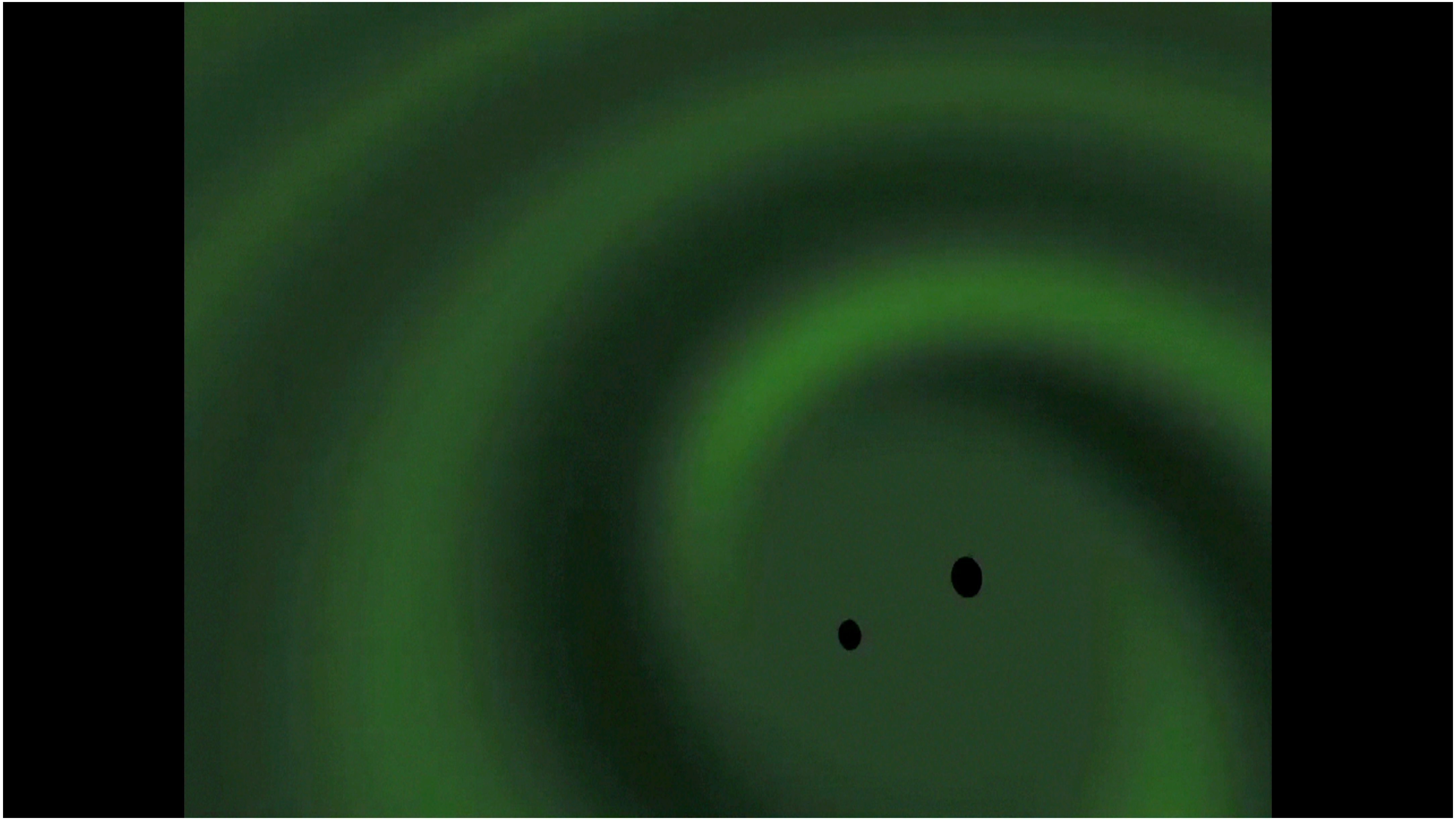
Binary Black Hole System
- M1 = 36 +5/-4 M_{sol}
- M2 = 29 +/- 4 M_{sol}
- Final Mass = 62 +/- 4 M_{sol}
- distance=410 +160/-180 MPc (redshift z = 0.09)




Observing Scenario, focus on NS-NS Binaries
http://arxiv.org/abs/1304.0670





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12 FEBRUARY 2016
Published by
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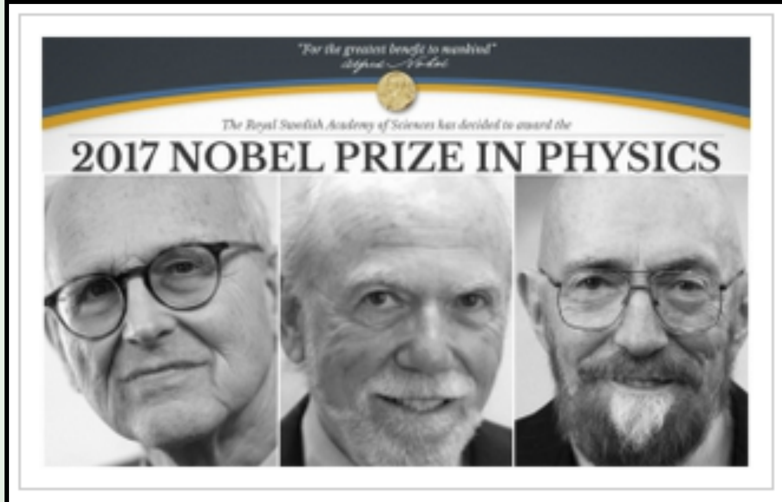
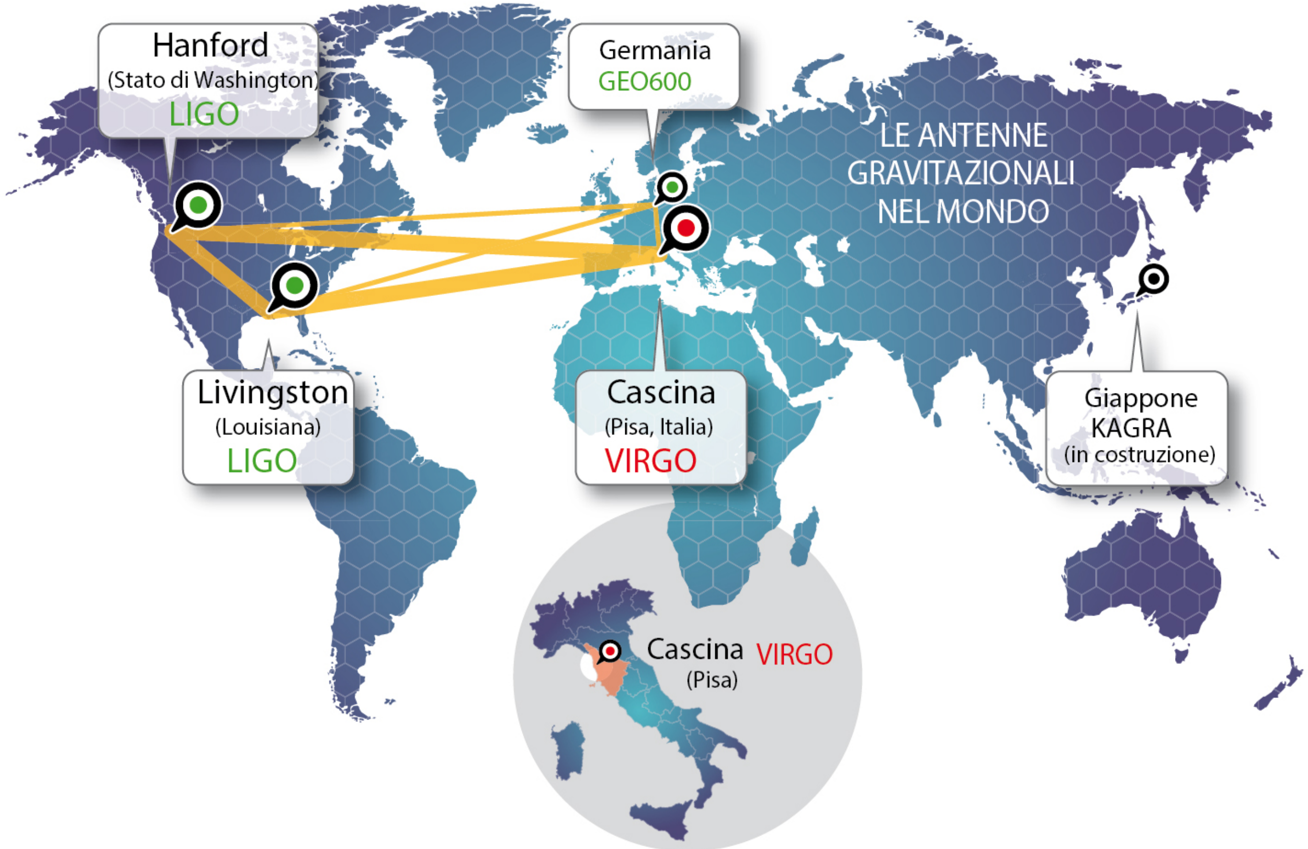
APS physics
Volume 116, Number 6

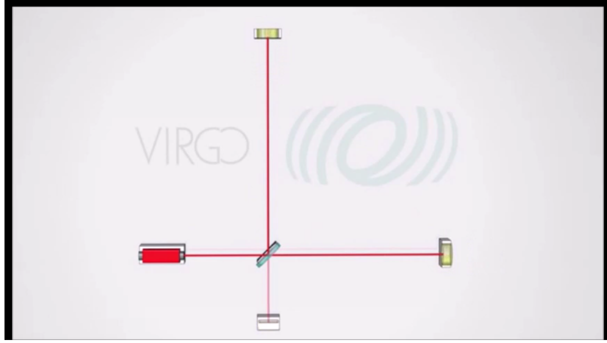

2017 NOBEL PRIZE IN PHYSICS

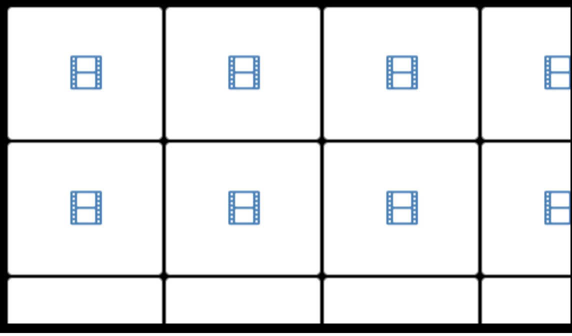
Break ?

Global Network of Detectors



Current GW detectors





Bounding graviton mass

- If gravitation is propagated by a massive field, then the velocity of GWs (gravitons) will depend upon their frequency as

$$\frac{v_g}{c} = 1 - \left(\frac{c}{f\lambda_g}\right)^2$$

$\lambda_g = h/m_g c$ is the graviton Compton wavelenght.

- In the case of inspiralling compact binaries, GWs emitted at low frequency early in the inspiral will travel slightly slower than those emitted at high frequency later, resulting in an offset in the relative arrival times at a detector → the phase evolution of the observed inspiral gravitational waveform is modified.
- Matched filtering of the waveforms can bound such frequency-dependent variations in propagation speed →bound the graviton mass

Compton Wave-length of the Graviton

C. M. Will, Phys. Rev. D 57, 2061 (1998).

- We assume a modified dispersion relation for gravitational waves

$$(v_g/c)^2 = 1 - \{\hbar c/(\lambda_g E)\}^2$$

- In the massive graviton theory an extra phase term is added to the CBC evolution (formally a 1PN order term)

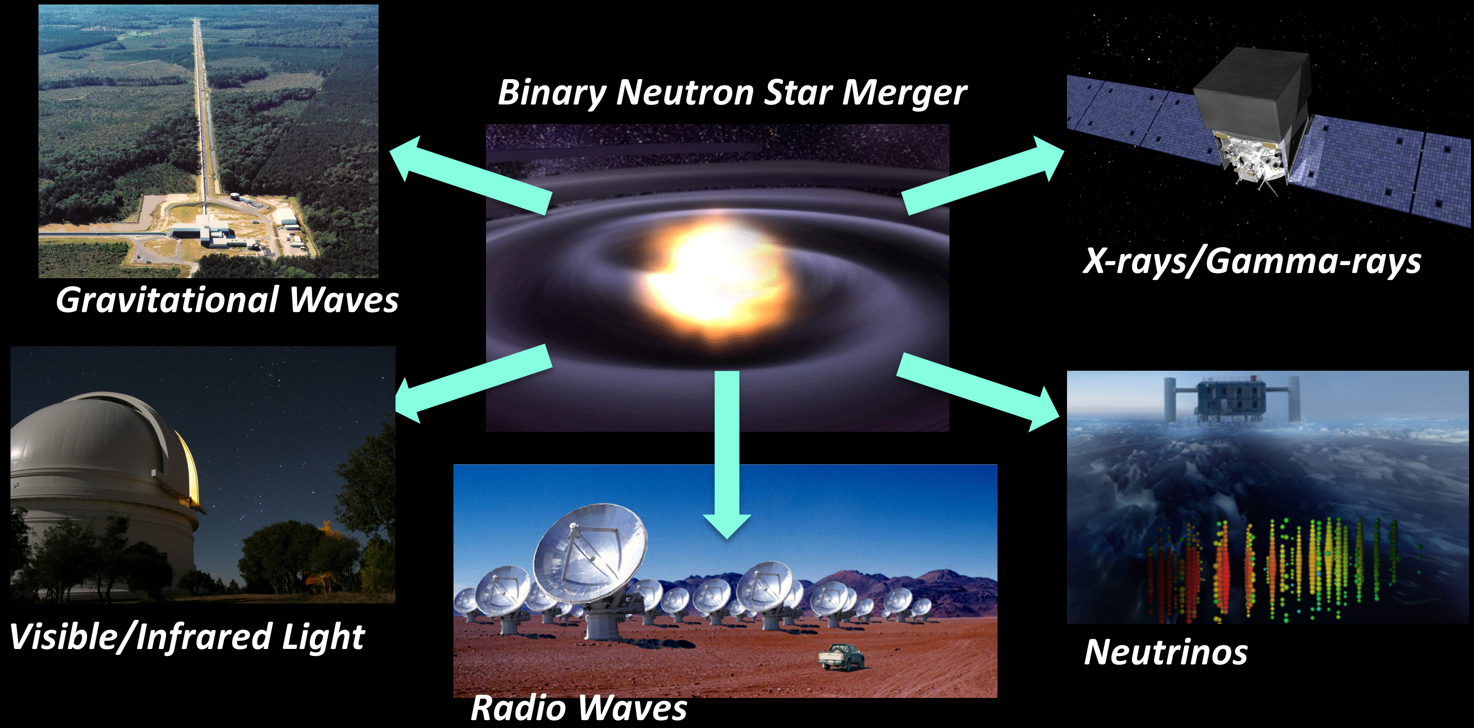
$$\phi_{MG}(f) = -(\pi D c)/[\lambda_g^{\ 2}(1+z) f]$$

- Our constrain on the 1PN terms permit to derive a down limit for the Compton wavelength of the graviton

$$\lambda_g = 2\pi \hbar/(m_g c) > 10^{13}\ \text{km}$$

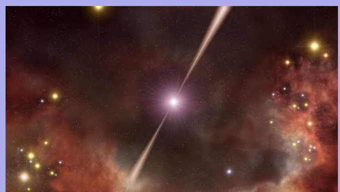
- It corresponds to a limit $m_g < 1.2 \times 10^{-22}$ eV/c^2.
  - limit better than that set by Solar System observations
  - thousand time better of the binary pulsar bounds
  - worse than bounds from dynamics of galaxy clusters and weak lensing observations (model- dependent bounds)

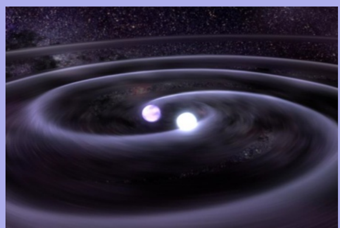
Multi-Messenger Astronomy:
Gravitational Wave + Photons + Neutrinos



A goal of **LIGO** and **Virgo** interferometers is the **first direct detection** of gravitational waves from **ENERGETIC ASTROPHYSICAL** events:

- **Mergers** of **NeutronStars** and/or **BlackHoles** ⇨ **SHORT GRB** ⇨ **Kilonovas**
- **Core Collapse** of **Massive Stars** ⇨ **Supernovae** ⇨ **LONG GRB**
- **Cosmic String Cusps** ⇨ **EM burst**

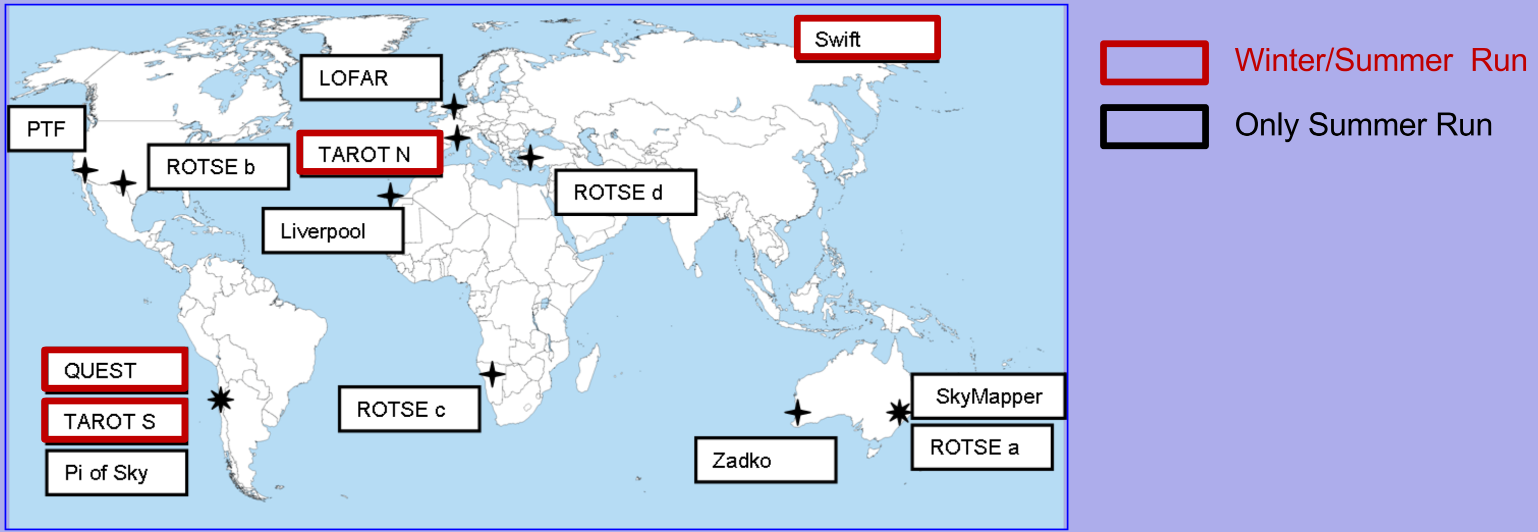




Main motivations for joint GW/EM observations:

- Increase the GW detection confidence;
- Get a precise (arcsecond) localization, identify host galaxy;
- Provide insight into the progenitor physics;
- In the long term start a joint GW/EM cosmology.

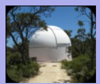
Ground-based and space EM facilities observing the sky at Optical, X-ray and Radio wavelengths involved in the follow-up program



Optical Telescopes

TAROT SOUTH/NORTH
1.86° X 1.86° FOV

Zadko
25 X 25 arcmin FOV



ROTSE
1.85 ° X 1.85° FOV

QUEST
9.4 square degree FOV

SkyMapper
5.6 square degree FOV

Pi of the Sky
20° X 20° FOV

Palomar Transient Factory
7.8 square degree FOV

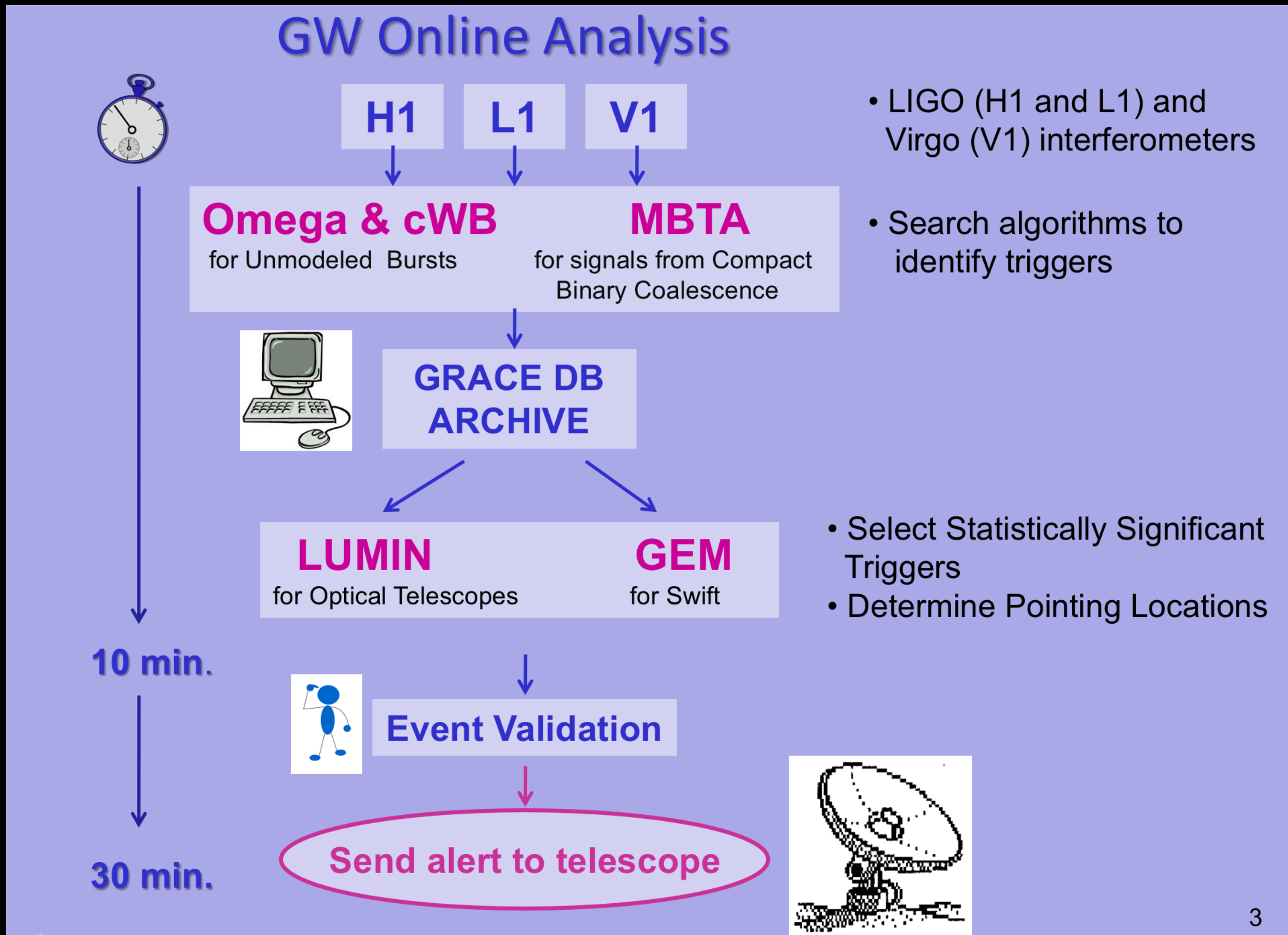
Liverpool telescope
4.6 X 4.6 arcmin FOV

X-ray and UV/Optical Telescope

Swift Satellite
0.4° X 0.4° FOV

Radio Interferometer

LOFAR
10 – 250 MHz


GW Online Analysis
H1
L1
V1
Omega & cWB
for Unmodeled Bursts
MBTA
for signals from Compact Binary Coalescence
GRACE DB ARCHIVE
LUMIN
for Optical Telescopes
GEM
for Swift
Event Validation
Send alert to telescope
10 min.
30 min.
• LIGO (H1 and L1) and Virgo (V1) interferometers
• Search algorithms to identify triggers
• Select Statistically Significant Triggers
• Determine Pointing Locations
3

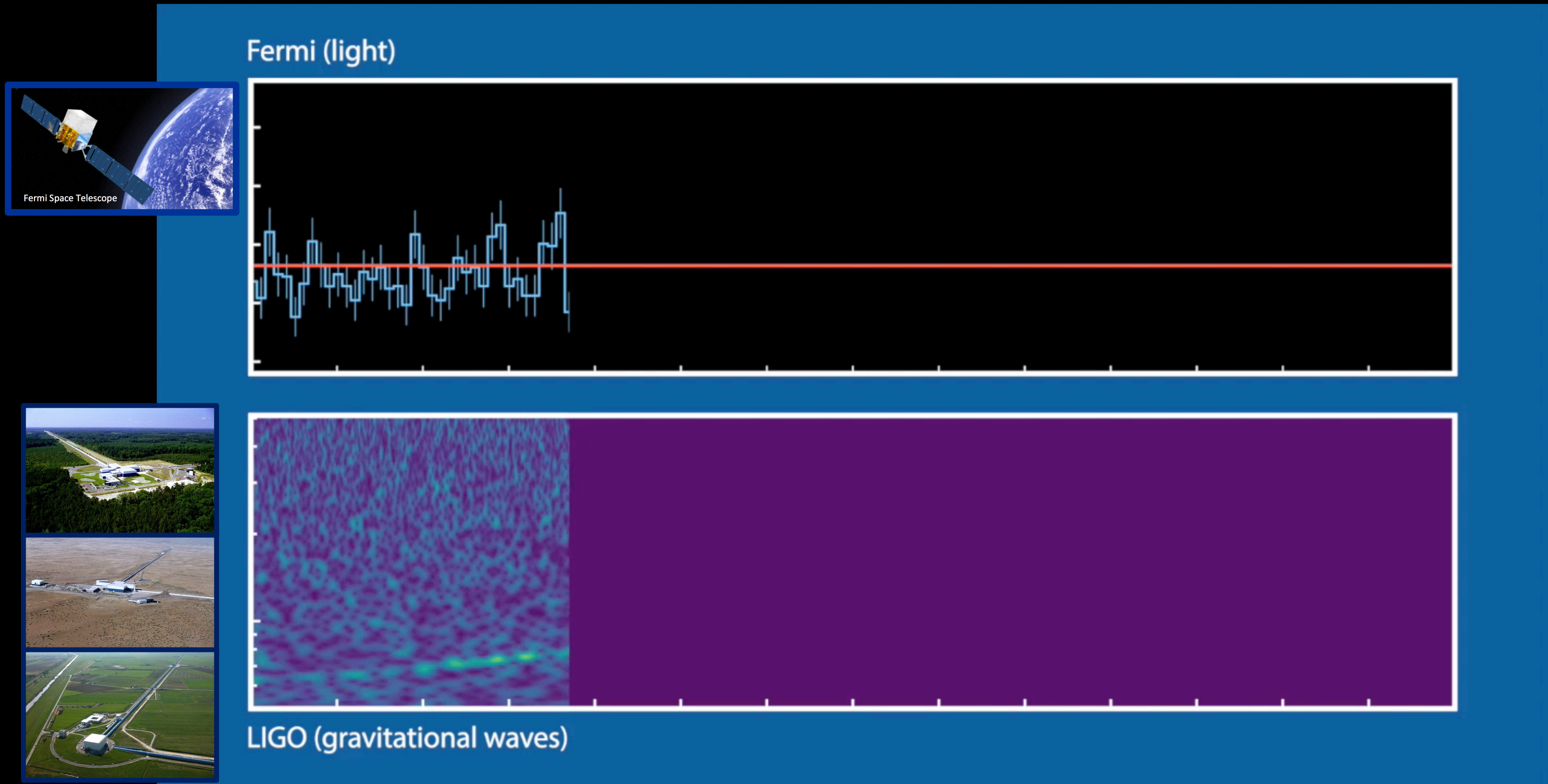
17 August 2017

Scientists to discuss new developments in gravitational-wave astronomy

Scientists representing LIGO, Virgo, and some 70 observatories will reveal new details and discoveries made in the ongoing search for gravitational waves.

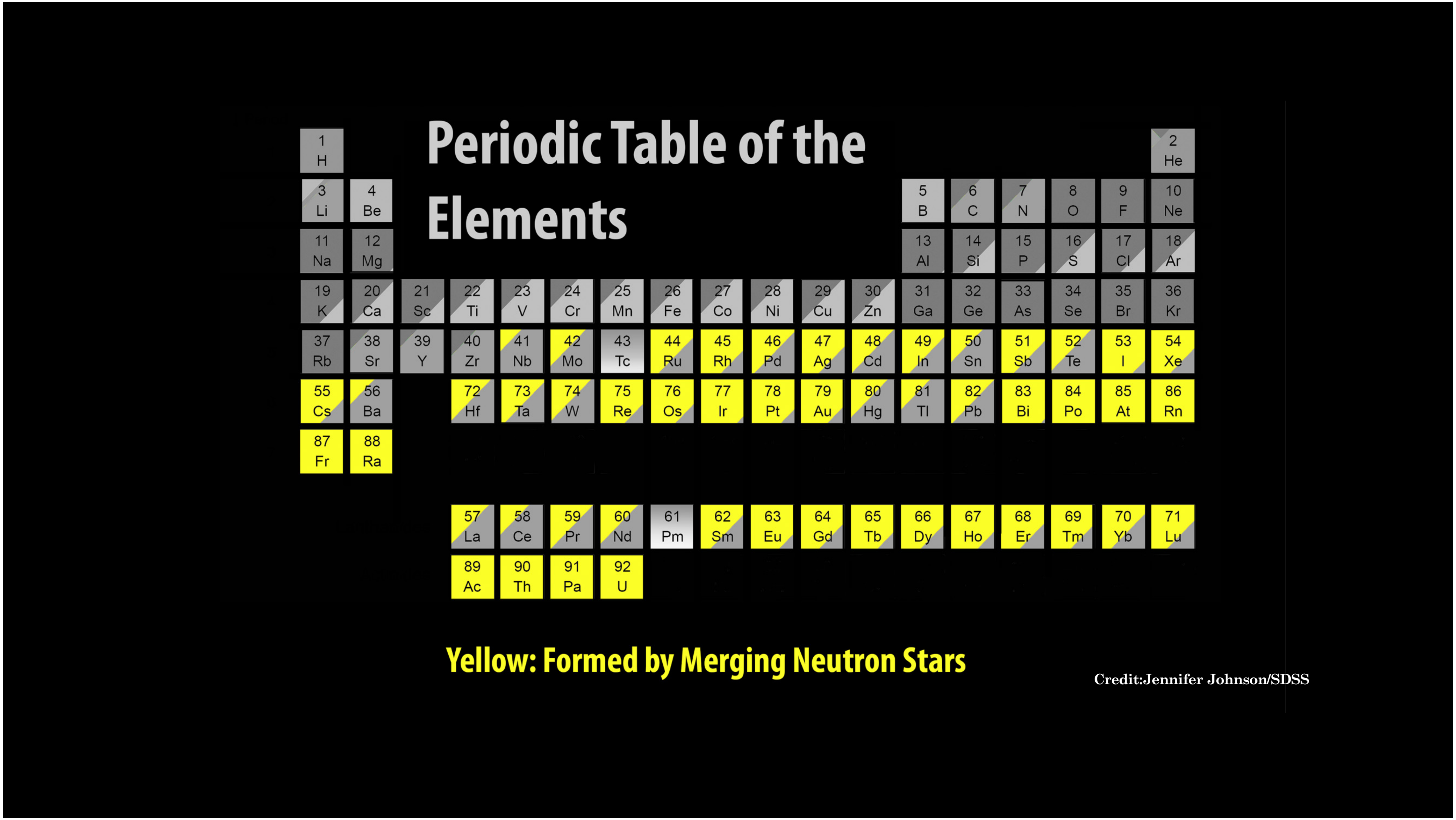
WHAT: Journalists are invited to join the National Science Foundation as it brings together scientists from the LIGO and Virgo collaborations, as well as representatives for some 70 observatories, on Monday, October 16, at 10:00 a.m. EDT at the National Press Club in Washington, D.C.

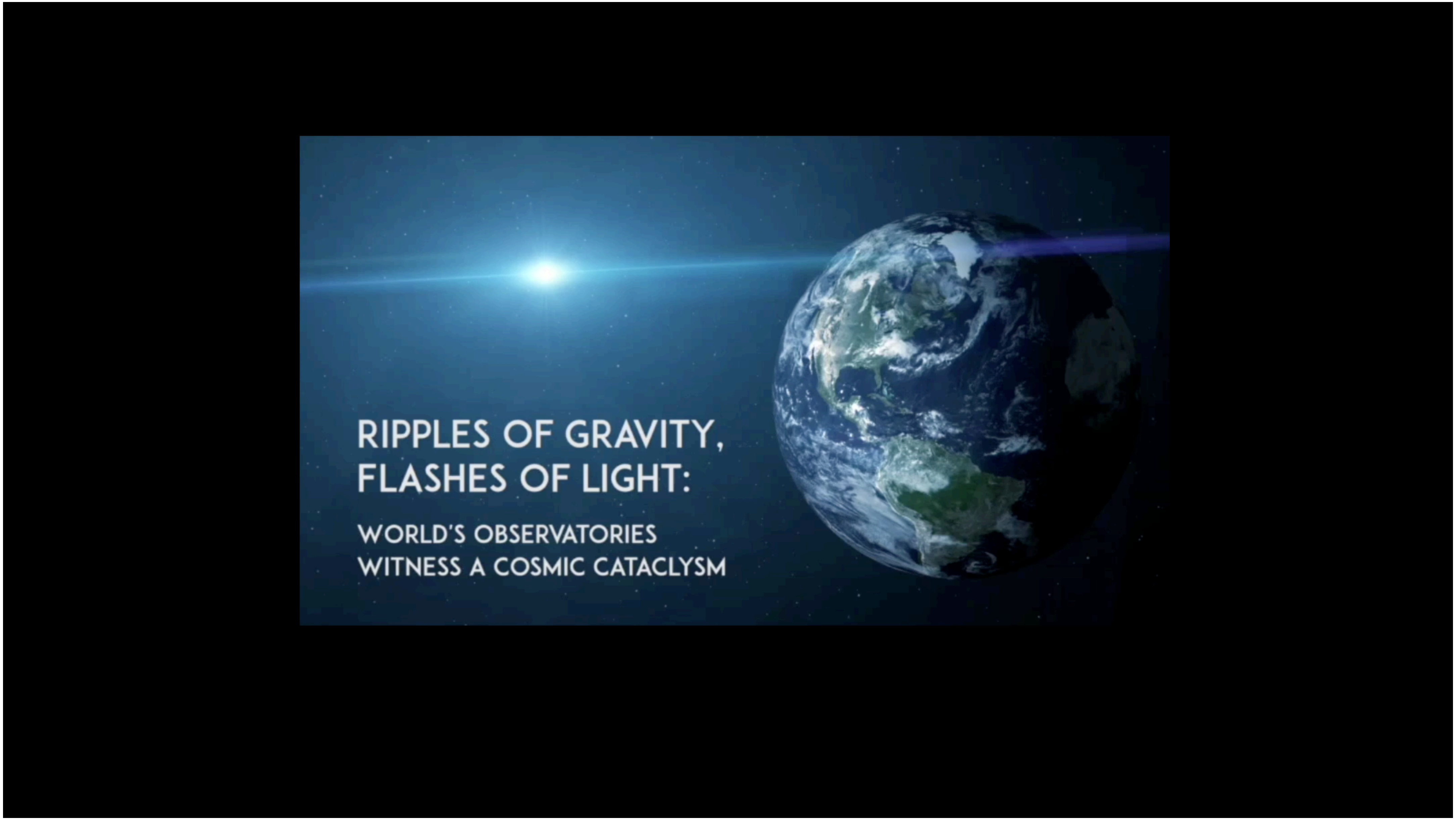
The gathering will begin with an overview of new findings from LIGO, Virgo, and partners that span the globe, followed by details from telescopes that work with the LIGO and Virgo Collaboration to study extreme events in the cosmos.

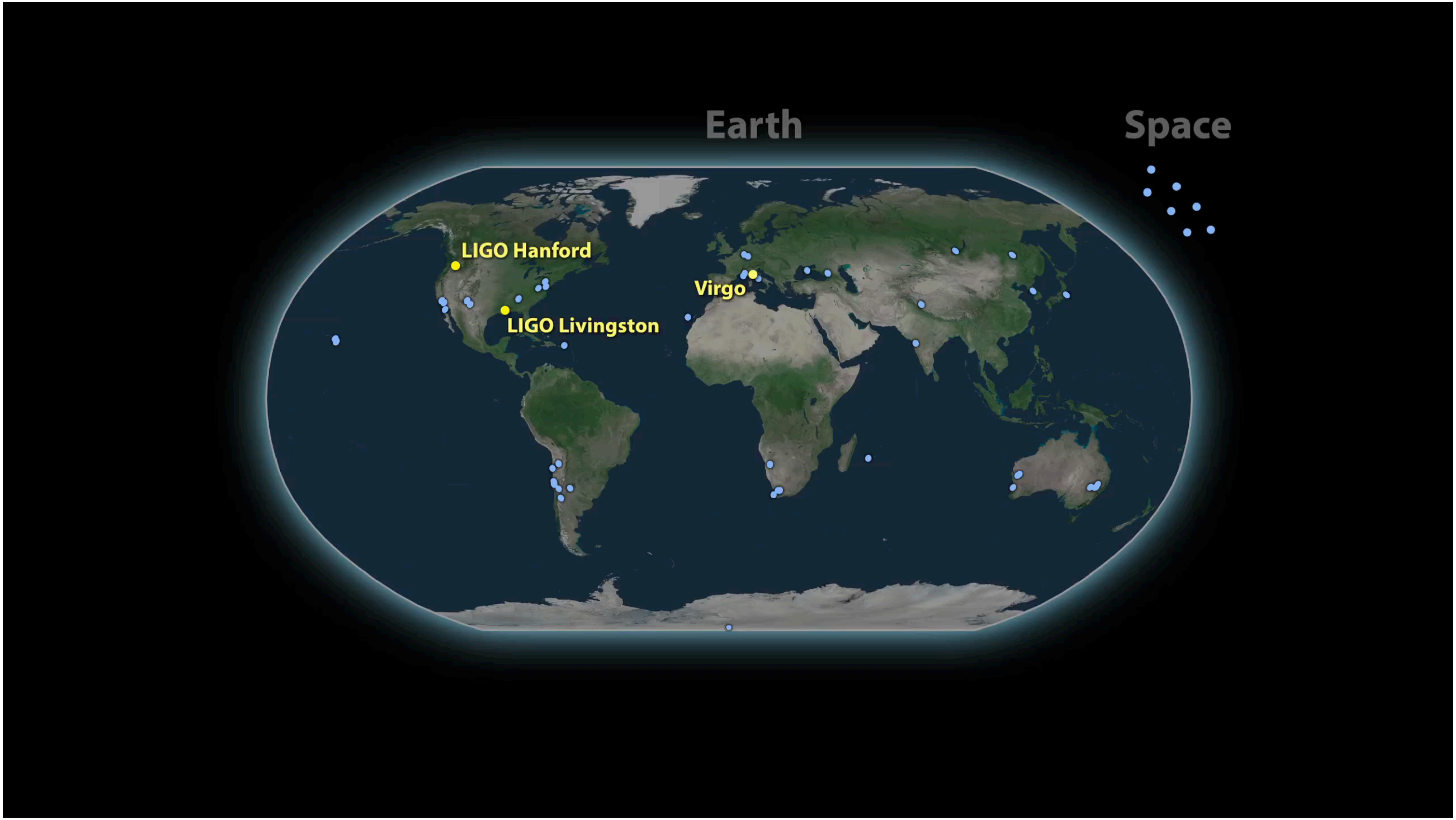


Credit: NASA's Goddard Space Flight Center/CI Lab

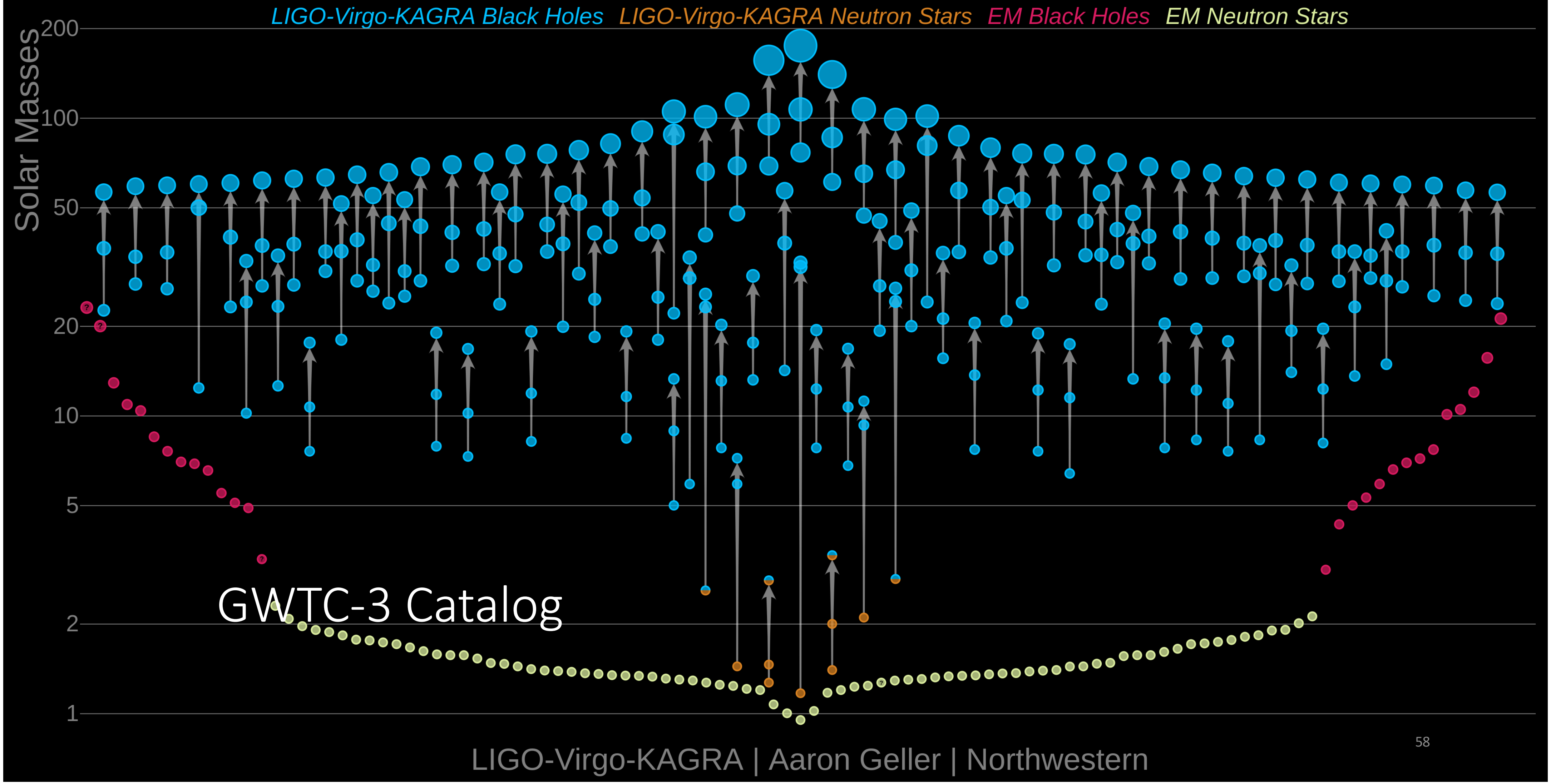
Credit:N. Risinger (skysurvey.org), LIGO-Virgo, Digitized Sky Survey 2, ESO.


Periodic Table of the Elements
1 H
2 He
3 Li 4 Be
5 B 6 C 7 N 8 O 9 F 10 Ne
11 Na 12 Mg
13 Al 14 Si 15 P 16 S 17 Cl 18 Ar
19 K 20 Ca 21 Sc 22 Ti 23 V 24 Cr 25 Mn 26 Fe 27 Co 28 Ni 29 Cu 30 Zn 31 Ga 32 Ge 33 As 34 Se 35 Br 36 Kr
37 Rb 38 Sr 39 Y 40 Zr 41 Nb 42 Mo 43 Tc 44 Ru 45 Rh 46 Pd 47 Ag 48 Cd 49 In 50 Sn 51 Sb 52 Te 53 I 54 Xe
55 Cs 56 Ba 72 Hf 73 Ta 74 W 75 Re 76 Os 77 Ir 78 Pt 79 Au 80 Hg 81 Tl 82 Pb 83 Bi 84 Po 85 At 86 Rn
87 Fr 88 Ra
57 La 58 Ce 59 Pr 60 Nd 61 Pm 62 Sm 63 Eu 64 Gd 65 Tb 66 Dy 67 Ho 68 Er 69 Tm 70 Yb 71 Lu
89 Ac 90 Th 91 Pa 92 U
Yellow: Formed by Merging Neutron Stars
Credit:Jennifer Johnson/SDSS


RIPPLES OF GRAVITY,
FLASHES OF LIGHT:
WORLD'S OBSERVATORIES
WITNESS A COSMIC CATACLYSM


Earth
Space
LIGO Hanford
LIGO Livingston
Virgo

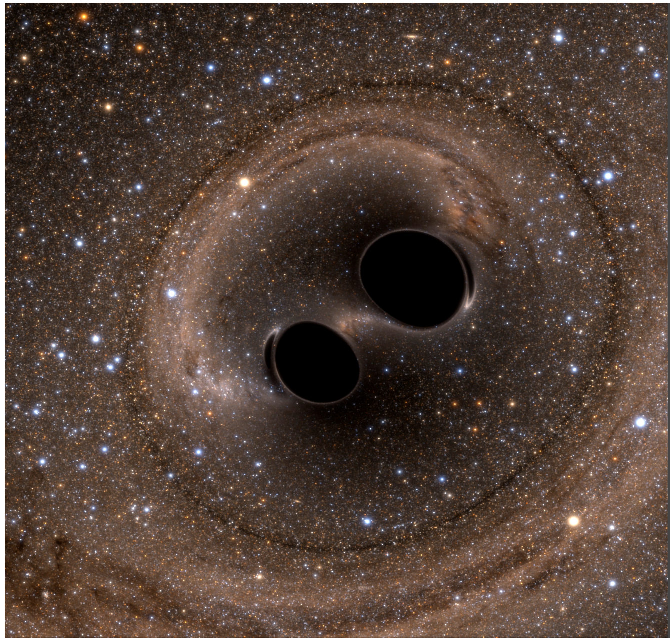
Masses in the Stellar Graveyard



FIND OUT MORE:

Visit our websites:

www.ligo.org, www.virgo-gw.eu, gwcenter.icrr.u-tokyo.ac.jp/en/



Monumental successes of the Advanced detectors

- First detection of GWs from a BBH system (GW150914)
  - Physics of BHs
- First detection of GWs from a BNS system (GW170817)
  - Birth of the multimessenger astronomy with GWs
  - Costraining EOS of NS
- Localisation capabilities of a GW source
- Measurement of the GW propagation speed
- Test of GR
- Alternative measurement of H_0
- GW polarisations
- Intermediate mass black hole (GW190521)

Many remarkable results in astrophysics and in fundamental physics have already been obtained thanks to these first detections. To mention only a few highlights:

- the observation of the BNS coalescence GW170817 solved the long-standing problem of the origin of (at least some) short gamma ray bursts;

- the observations of the associated kilonova revealed that BNS mergers are a major formation site of the heaviest elements through r-process nucleosynthesis;

- the observation of tens of BBH coalescences has revealed a previously unknown population of stellar-mass BHs, much heavier than those detected through the observation of X-ray binaries, and has shown that BBH exist, and coalesce within a Hubble time at a detectable rate.

Concerning fundamental physics, cosmology and General Relativity (GR):

- the observation of the GWs and the gamma-ray burst from the BNS GW170817 proved that the speed of GWs is the same as the speed of light to about a part in 10^{15} ;

- the GW signal, together with the electromagnetic determination of the redshift of the source, provided the first measurement of the Hubble constant with GWs;

- the tail of the waveform of the first observed event, GW150914, showed oscillations consistent with the prediction from General Relativity for the quasi-normal modes of the final BH;

- several possible deviations from GR (graviton mass, post-Newtonian coefficients, modified dispersion relations, etc.) could be tested and bounded.

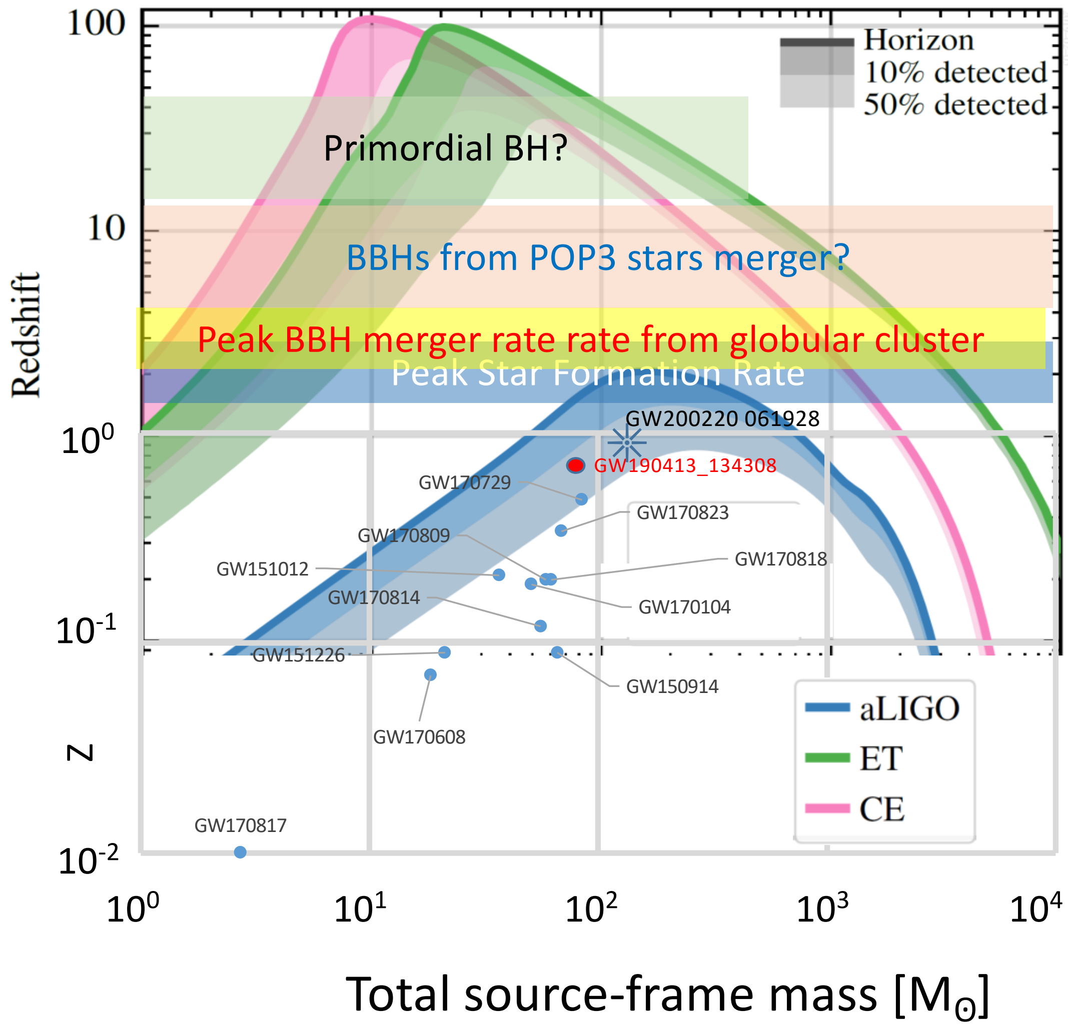
The present second-generation detectors such as Advanced LIGO, Advanced Virgo, and KAGRA (LVK) have the potential to push their sensitivity further, but the possible enhancements are limited by the current available infrastructure.

For this reason, since more than ten years, the GW community is preparing a third–generation of ground–based detectors: Einstein Telescope (ET) in Europe and Cosmic Explorer (CE) in the US.

These instruments will be hosted in completely new facilities and feature major technological advancements as compared to the current second–generation detectors, resulting in a predicted gain in terms of sensitivity as large as one order of magnitude compared to LVK in a wide frequency range, as well as an extended bandwidth, especially towards frequencies below 10 Hz.

- aLIGO and AdV achieved awesome results with a sensitivity poorer than the nominal one
- When they will reach or over-perform their nominal (updated) sensitivity, can we exploit all the potential of GW observations?

- 2nd generation GW detectors will explore the local Universe, even in their post-O5 configuration, initiating precision GW astronomy, but to have cosmological investigations a factor of 10 improvement in terms detection distance is needed

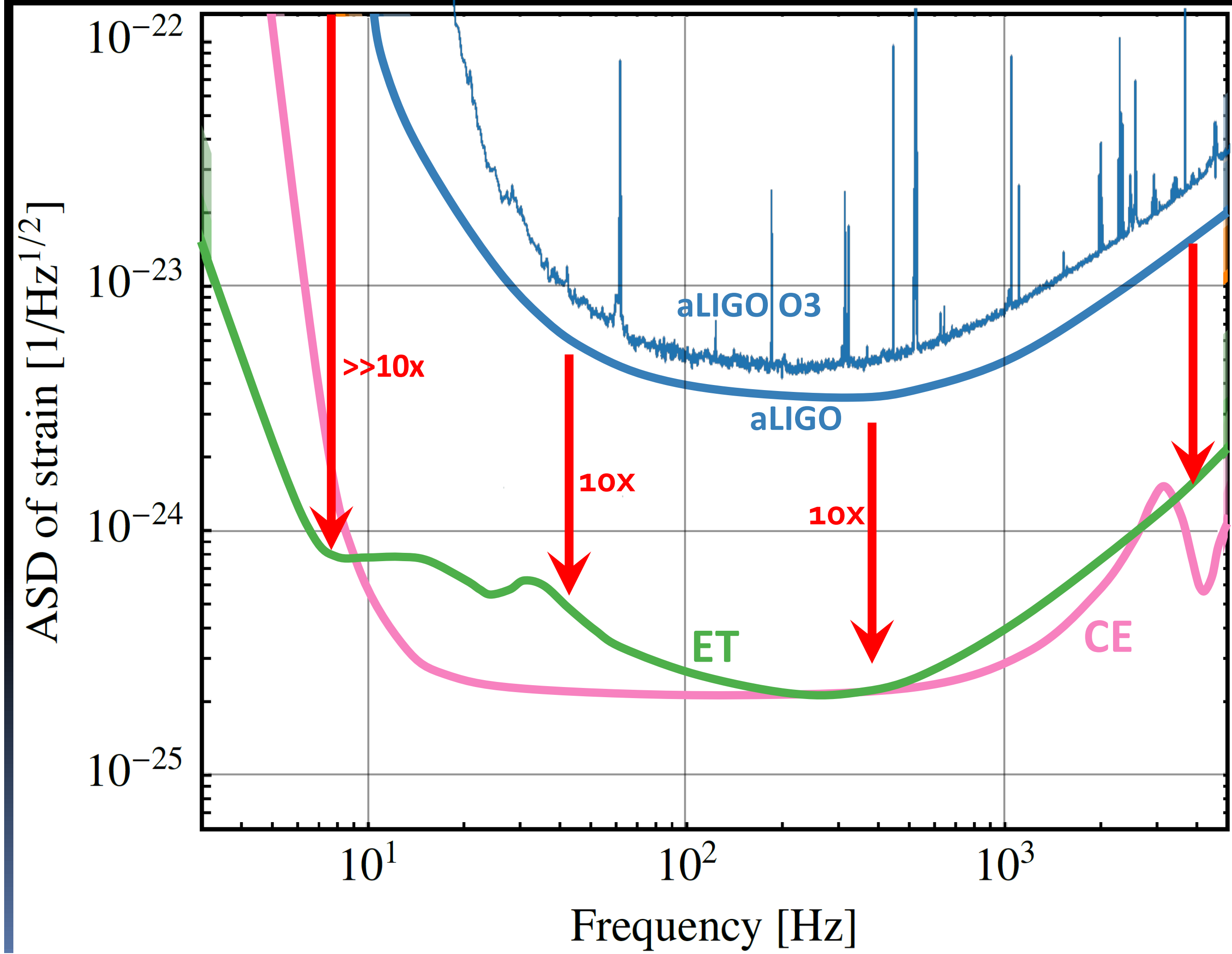


3G ground-based detectors will be required to access the high redshift Universe

2nd → 3rd Generation

EINSTEIN TELESCOPE

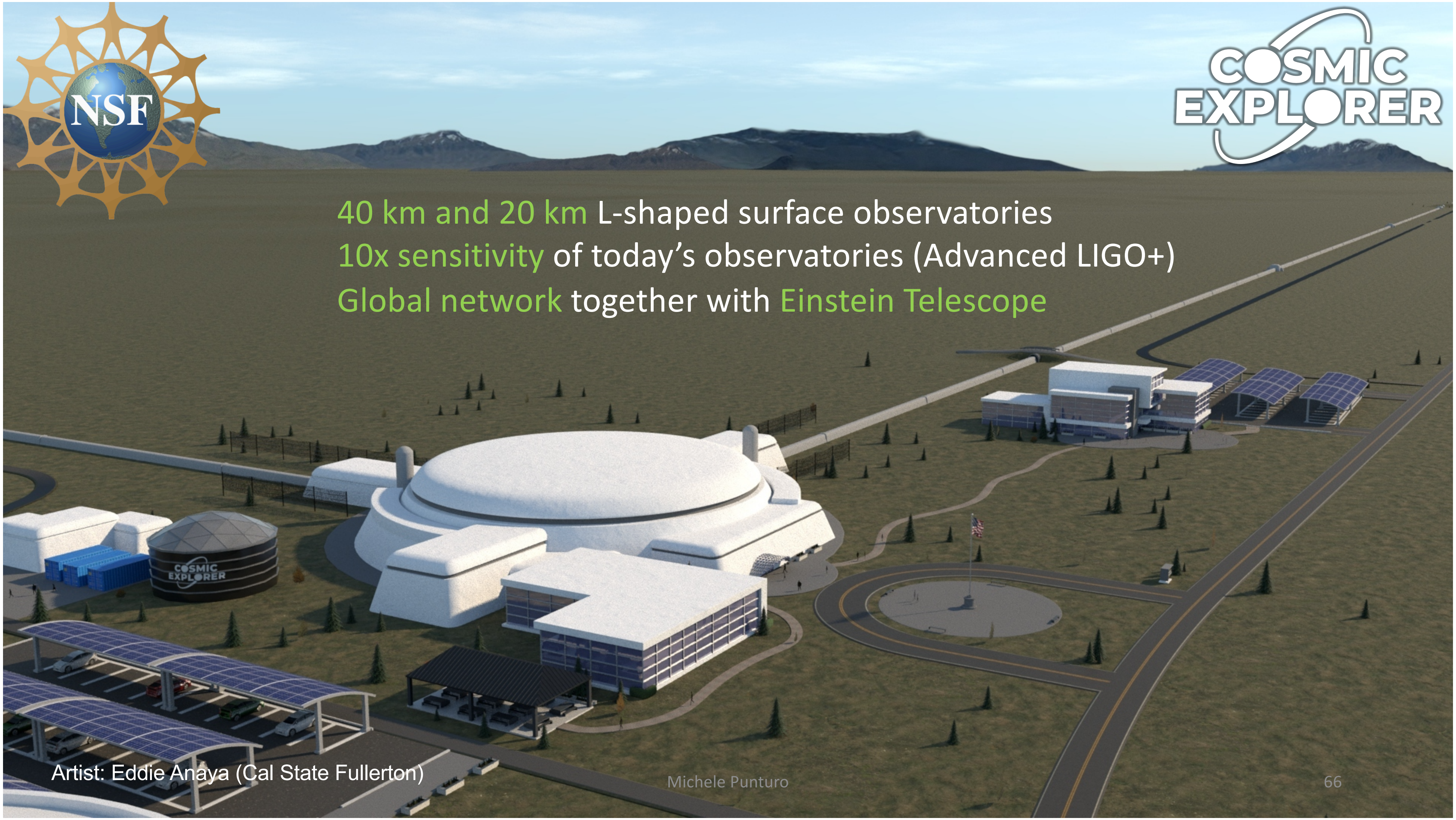
PHYS. REV. D 102, 062003 (2020)



40 km and 20 km L-shaped surface observatories

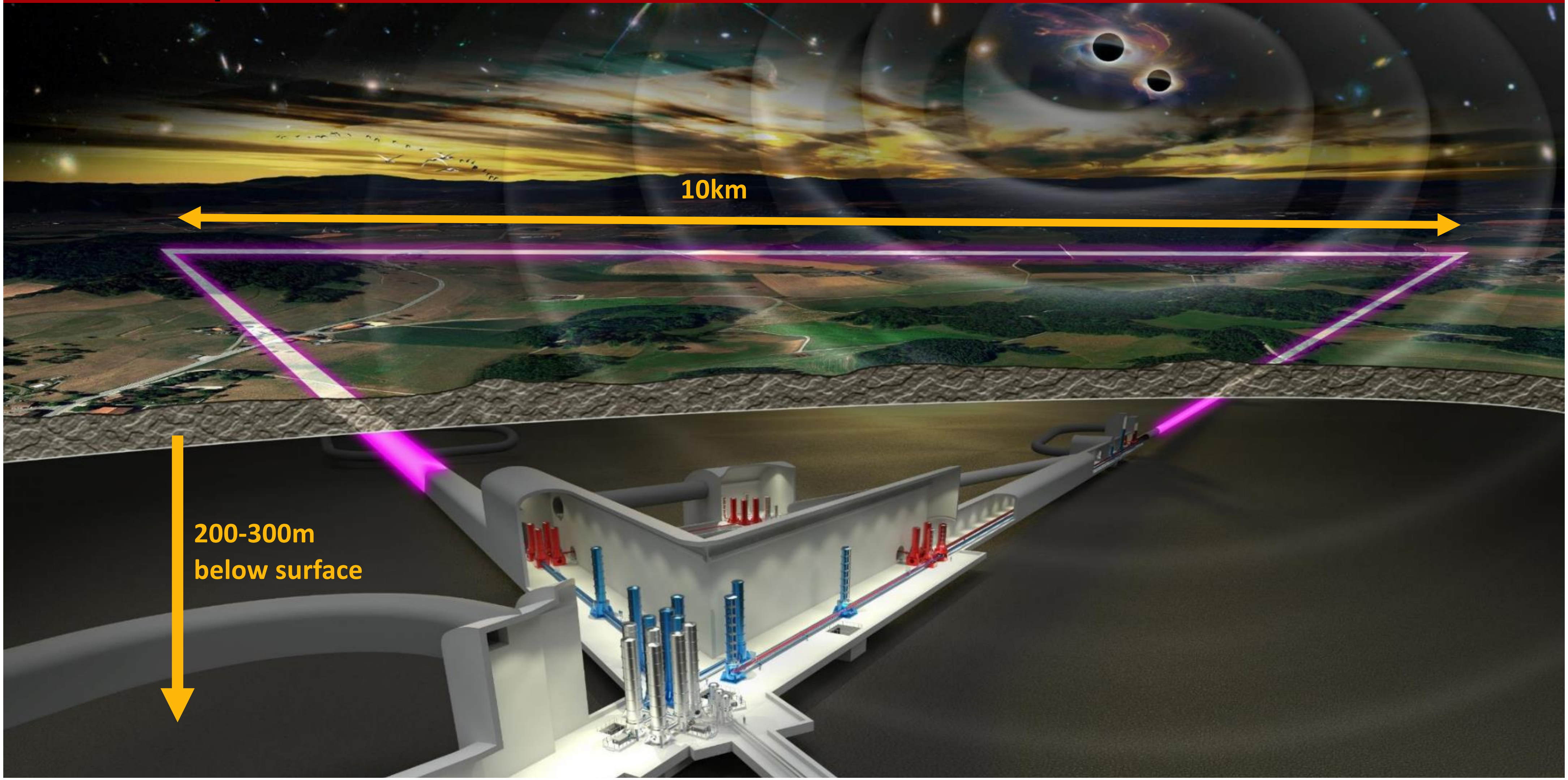
10x sensitivity of today's observatories (Advanced LIGO+)

Global network together with Einstein Telescope



Artist: Eddie Anaya (Cal State Fullerton)

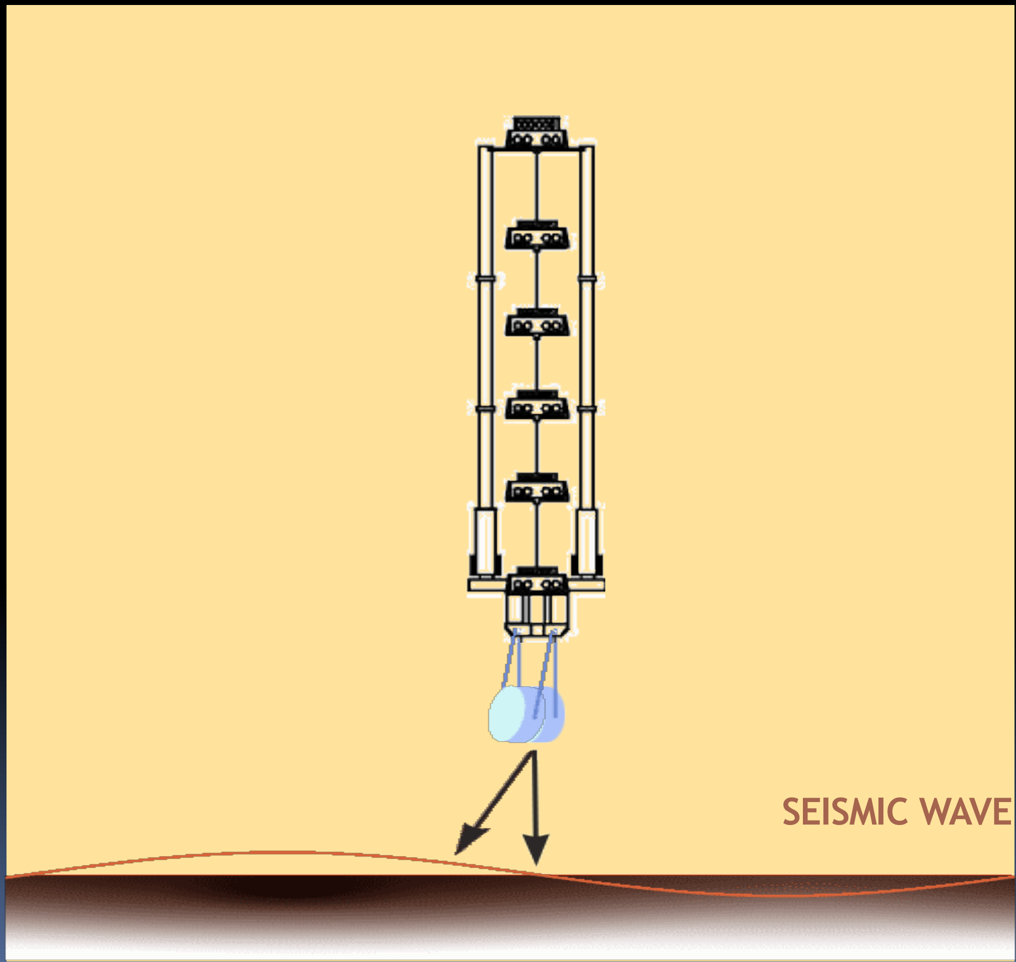
ET: The European 3G GW observatory



Newtonian Noise

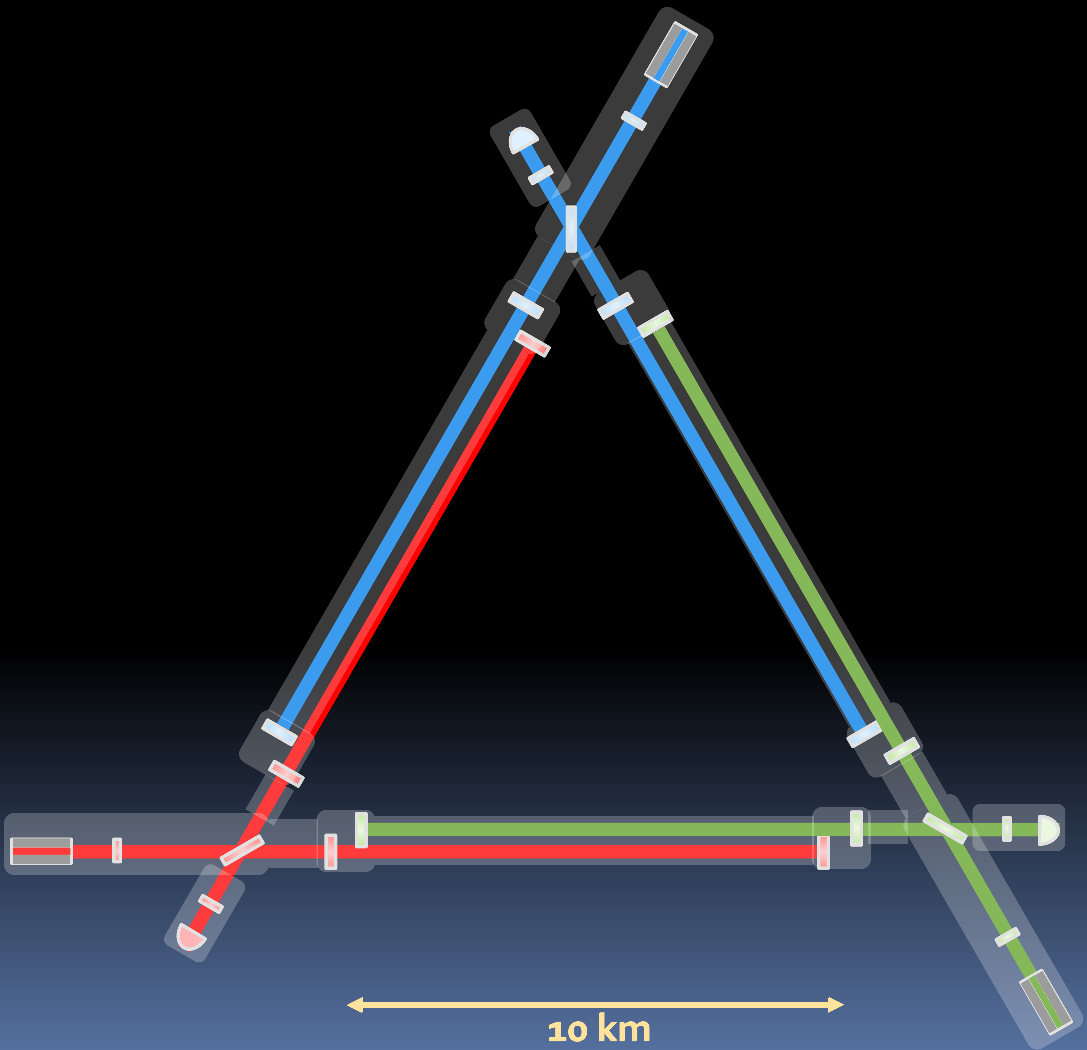
- Suspension chains can filter seismic noise well enough
- Newtonian Noise circumvents this isolation chain

→ EINSTEIN TELESCOPE to be built underground



Credit M.Lorenzini

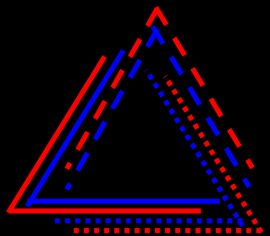
ET: Shape and size



Trying to optimise tunnel usage →
3 detectors in triangular configuration:

- Sensitive for both polarisations (+ & x)
- Null Stream:
  h(t) + h(t) + h(t) = 0
  allows to distinguish GW signals from noise and to do excellent noise characterisation of the individual detectors

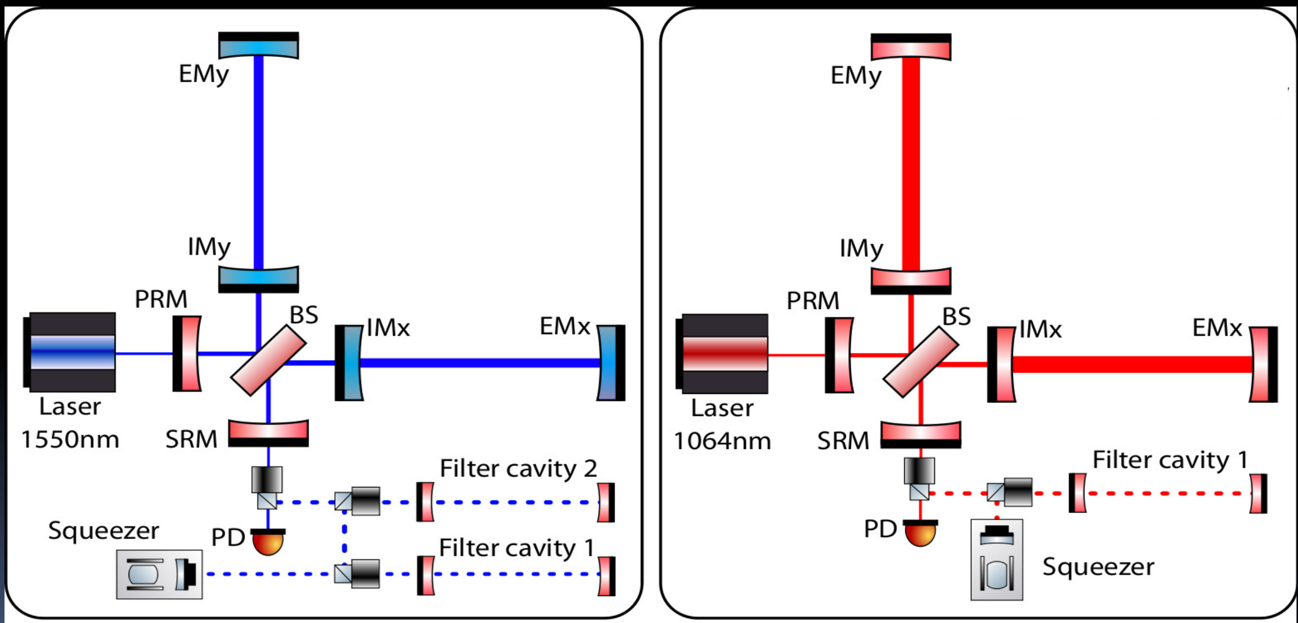
ET - Xylophone Concept



each detector = two interferometers

ET - LF
low-power, cryogenic
low-frequency detector

ET – HF
high-power, room-temperature
high-frequency detector



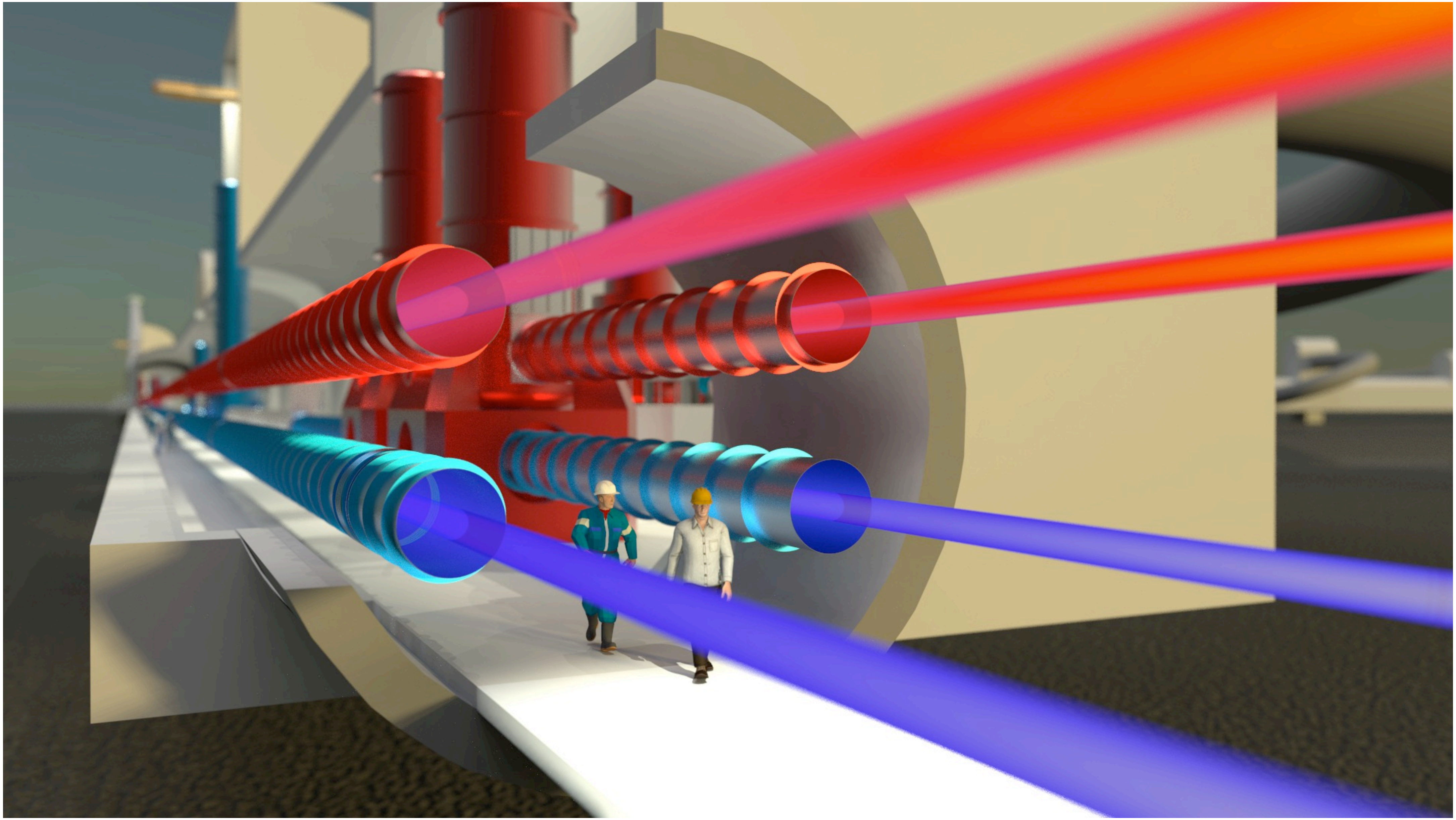
Optical element, Fused Silica, room temperature
Optical element, Silicon, cryogenic
Laser beam 1550nm
Laser beam 1064nm
squeezed light beam

ET-HF: 300 K

- 1064 nm Laser (500W)
- High circulating light power, 3MW
- Thermal compensation
- Large test masses (SiO2, 200kg)
- New coatings
- Frequency dependent squeezing

ET-LF: 10 – 20 K

- Cryogenics
- Long Seismic suspensions (17m towers)
- Silicon (Sapphire) test masses
- Large test masses (200kg, 45cm diam.)
- New coatings
- New laser wavelength (1550nm)
- + low power
- Frequency-dependent squeezing



ET enabling Technologies

- The multi-interferometer approach needs two parallel technology developments:

ET-LF:

- Underground
- Cryogenics
- Silicon (Sapphire) test masses
- Large test masses
- New coatings
- New laser wavelength
- Seismic suspensions
- Frequency dependent squeezing

ET-HF:

- High power laser
- Large test masses
- New coatings
- Thermal compensation
- Frequency dependent squeezing

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,m/f^2$	$5 \cdot 10^{-10}\,m/f^2$
Gravity gradient subtraction	none	factor of a few

Challenging engineering

New technology in cryo-cooling

New technology in optics

New laser technology

High precision mechanics and low noise controls

High quality opto-electronics and new controls

Evolved laser technology

Evolved technology in optics

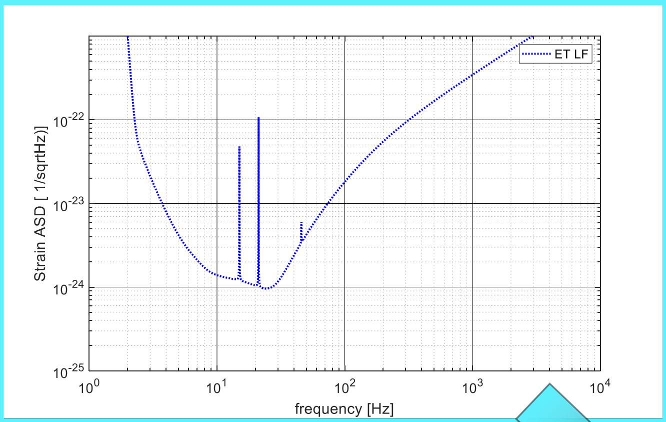
Highly innovative adaptive optics

High quality opto-electronics and new controls

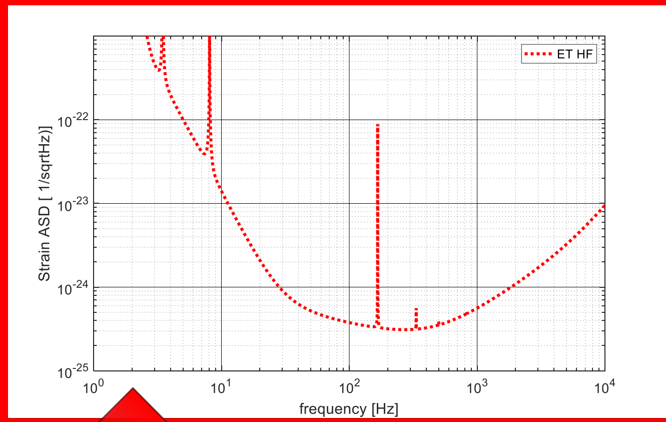
EINSTEIN TELESCOPE

ET Xylophone Sensitivity (CDS)

update being prepared / published

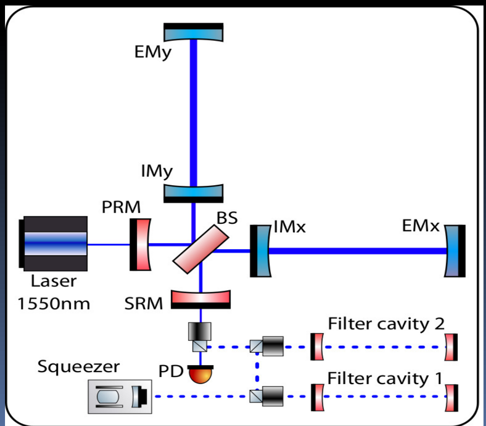


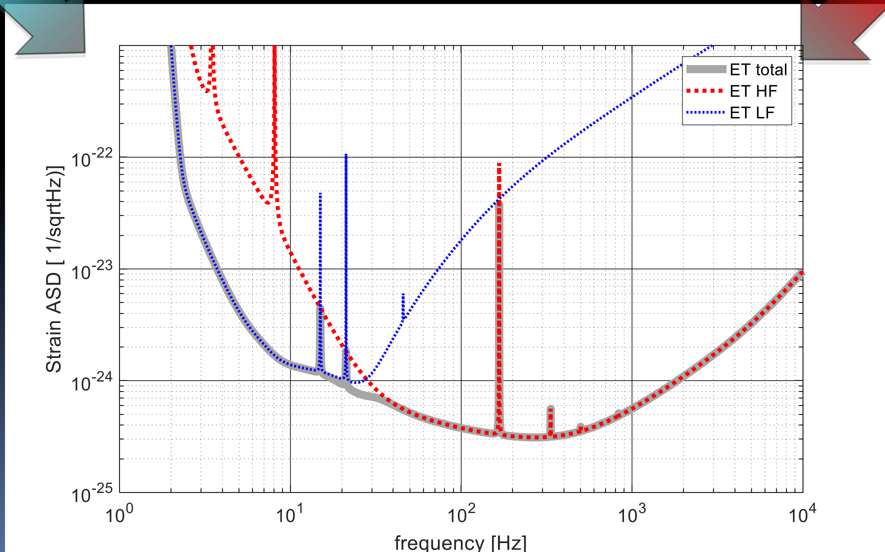
Noise traces shown here correspond to a single interferometer with an intersection angle of 90° (“L” shape).

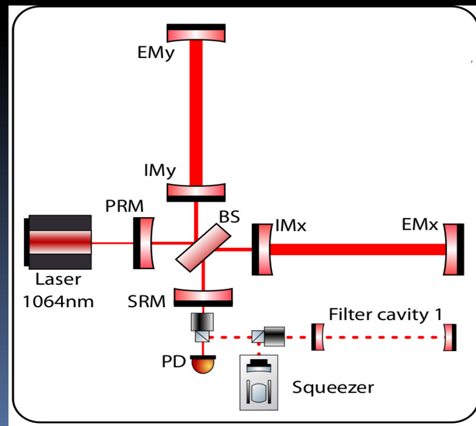


ET-LF

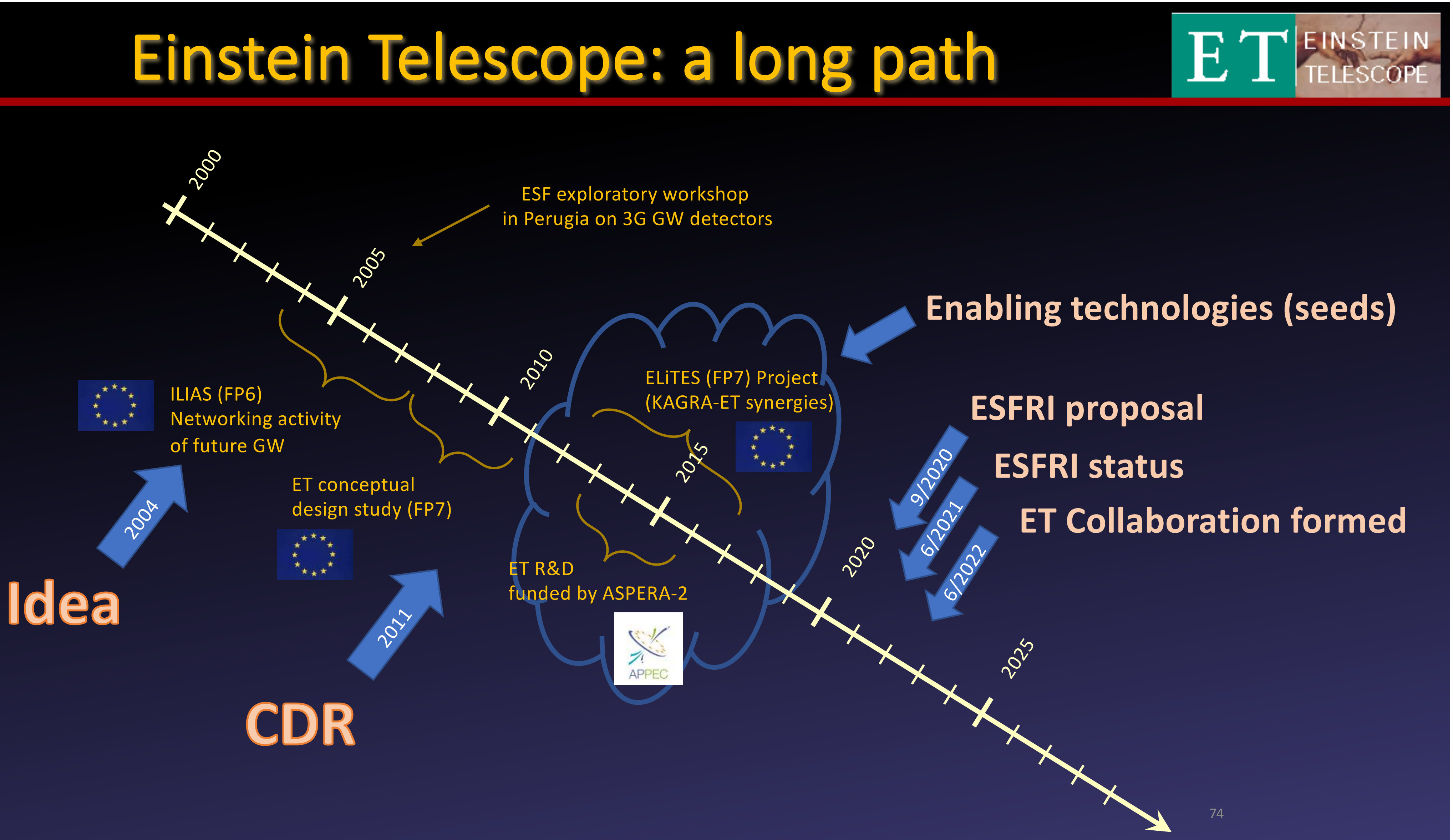
ET-HF







Einstein Telescope: a long path

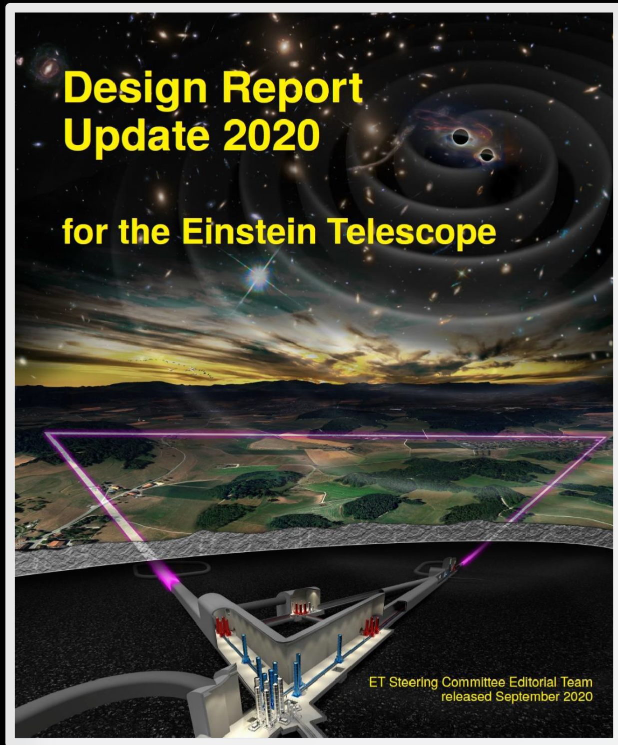


Einstein Telescope Conceptual Design Reports

https://tds.virgo-gw.eu/?call_file=ET-0106C-10.pdf

https://apps.et-gw.eu/tds/?content=3&r=17245

ESFRI



- In 2020 governments of 5 EU countries (Italy [lead], the Netherlands, Belgium, Spain and Poland) submitted the **ET application to ESFRI** (European Strategy Forum on Research Infrastructure).
- **July 2021: ET obtained ESFRI status**
- **Now in „Preparatory Phase“**

Detection distance for BBHs

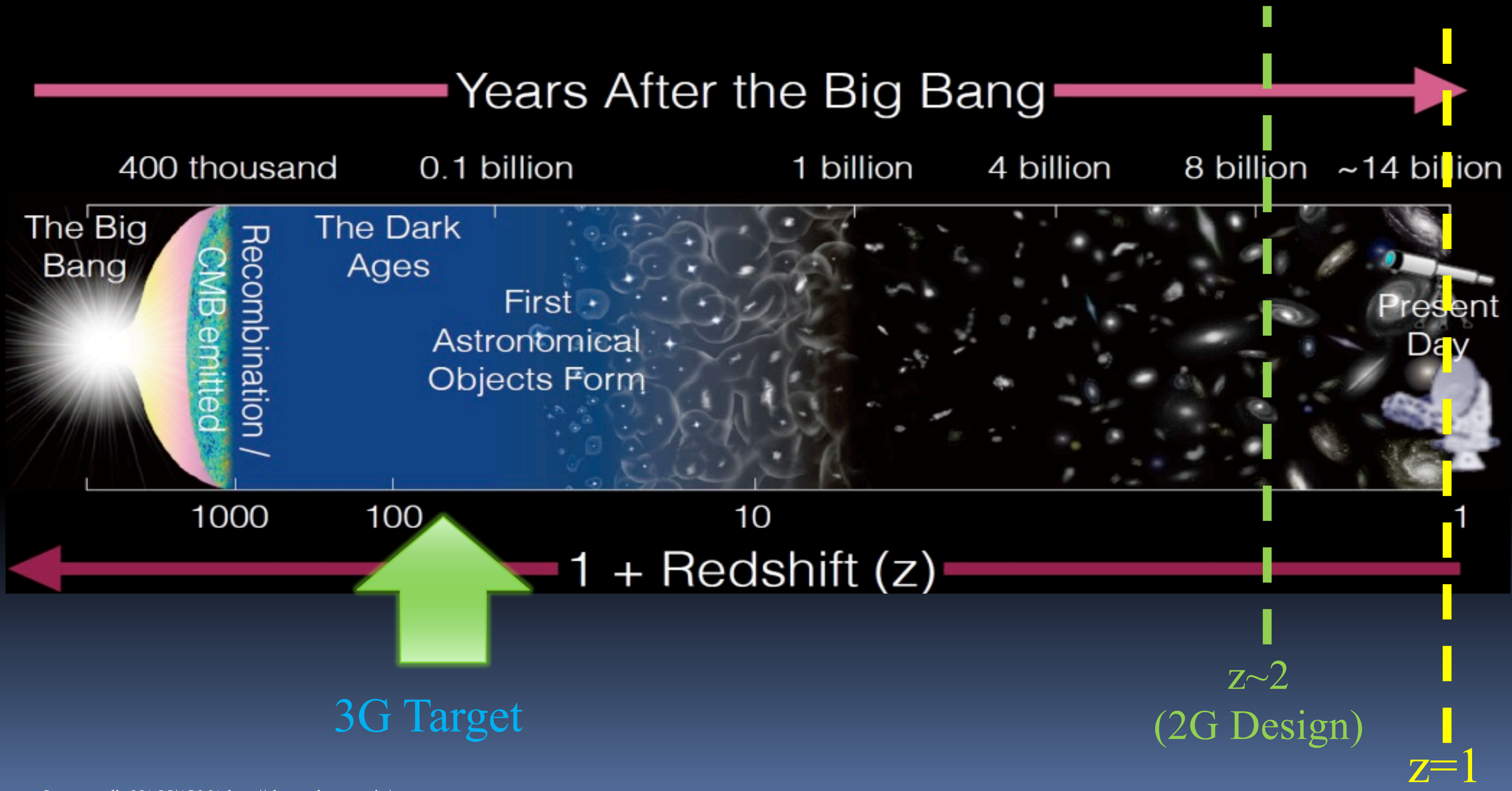
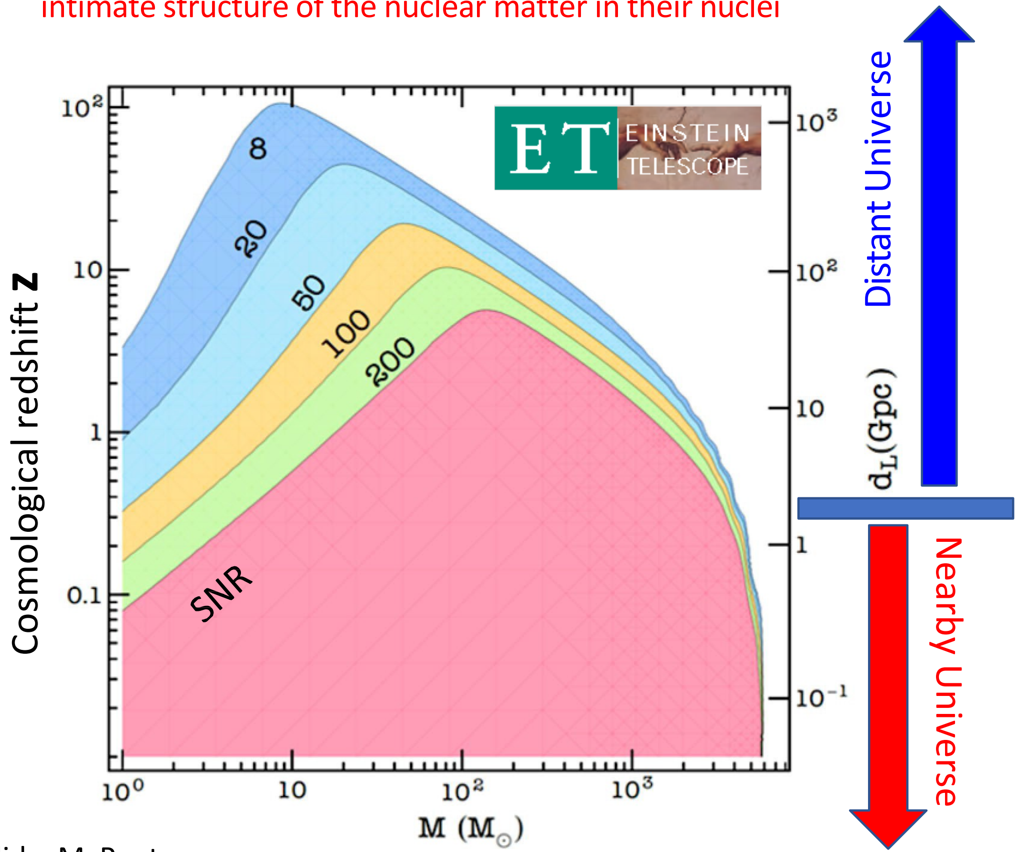


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

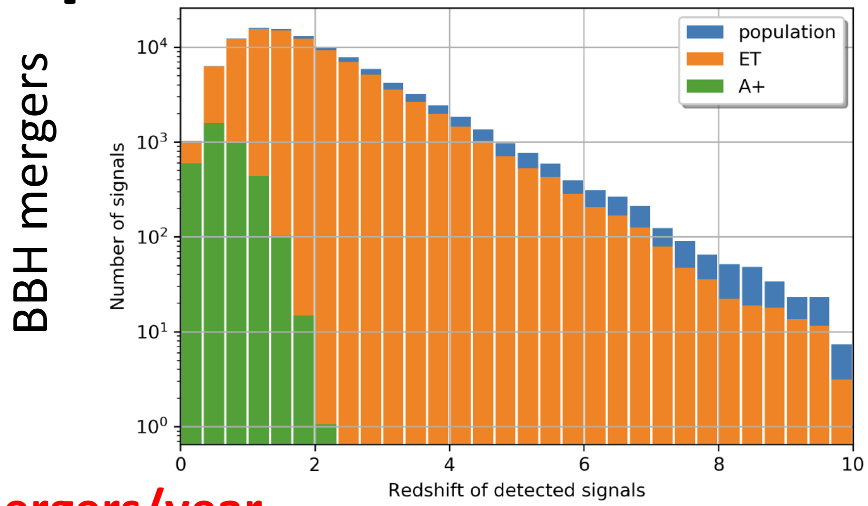
ET Science in a (tiny) nutshell

- ET will explore almost the entire Universe listening the gravitational waves emitted by black hole, back to the dark ages after the Big Bang
- ET will detect, with high SNR, hundreds of thousands coalescences of binary systems of Neutron Stars per year, revealing the most intimate structure of the nuclear matter in their nuclei

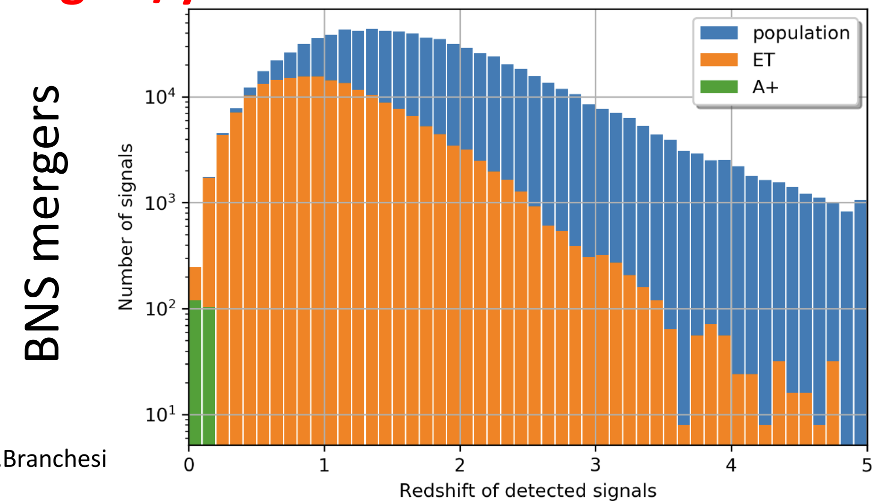


Slide: M. Punturo

Compact Object Binary Populations



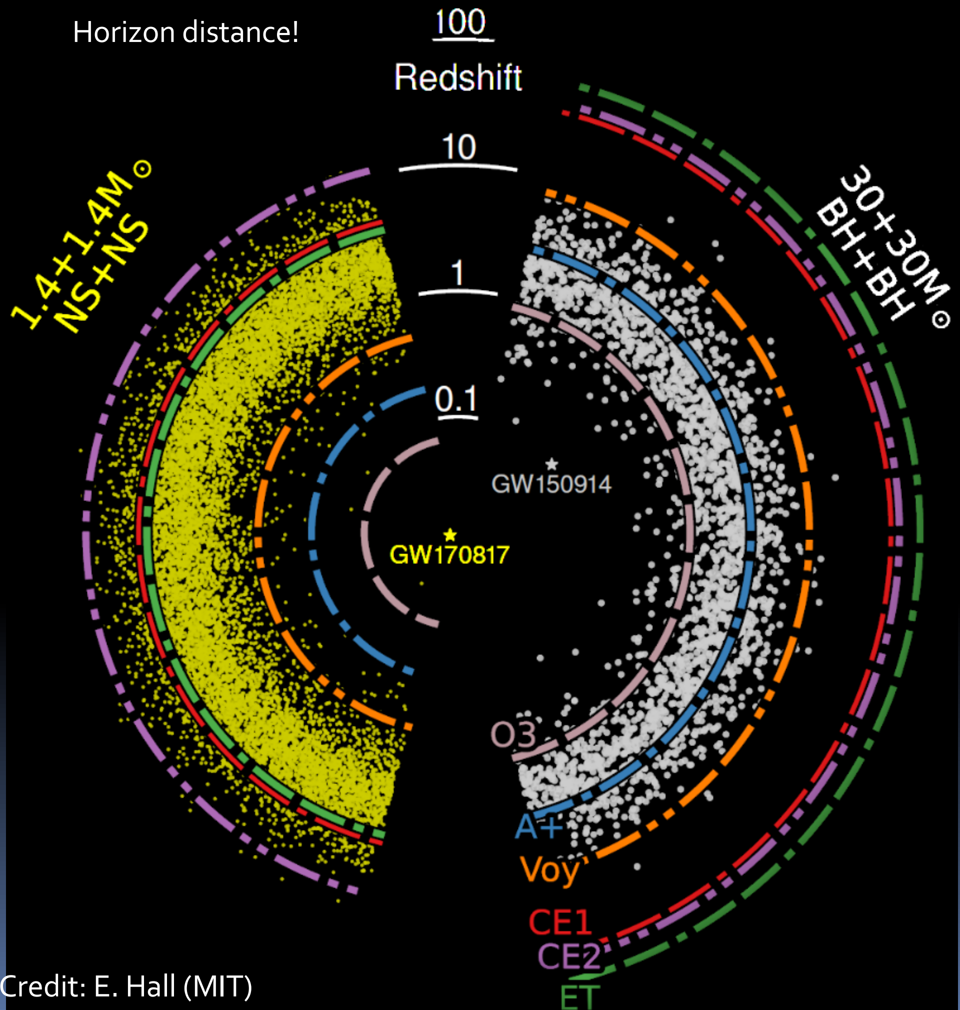
O(10^5) mergers/year



Credit: M.Branchesi

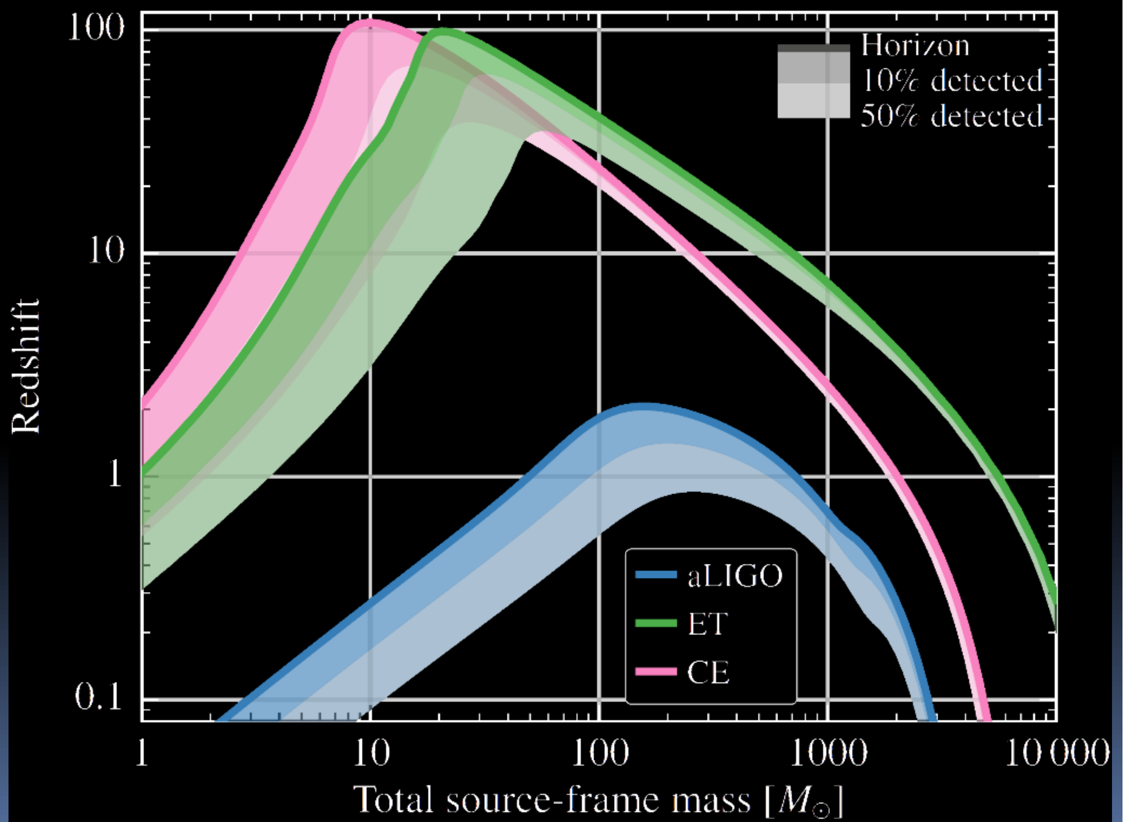
Hearing the „whole universe“…

EINSTEIN TELESCOPE



Credit: E. Hall (MIT)

CBC Sources throughout the universe



ET science case

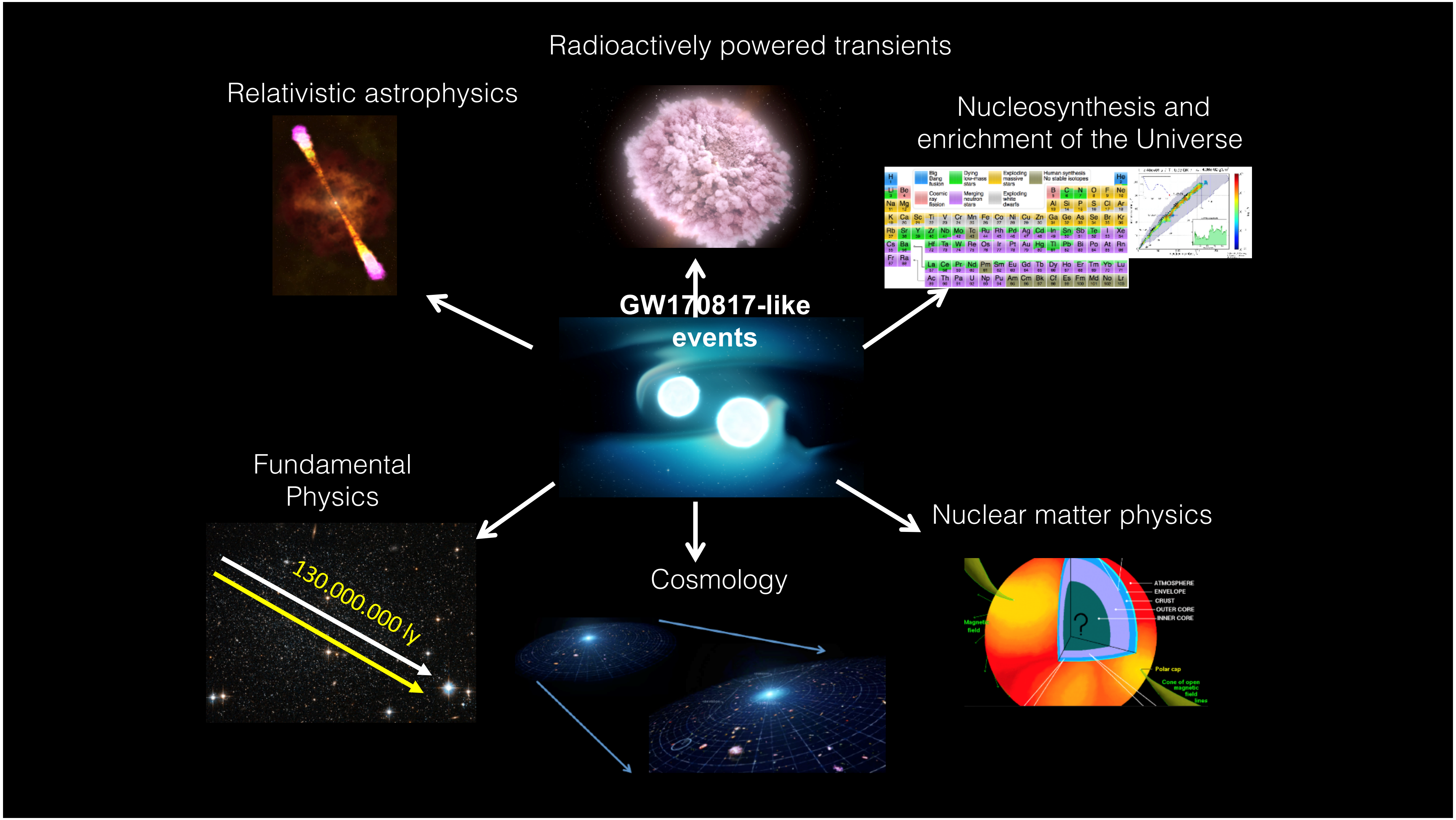
ASTROPHYSICS

- **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 …**
  - joint GW/EM observa… …B, kilonova,...)
  - multiband GW detectio… (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

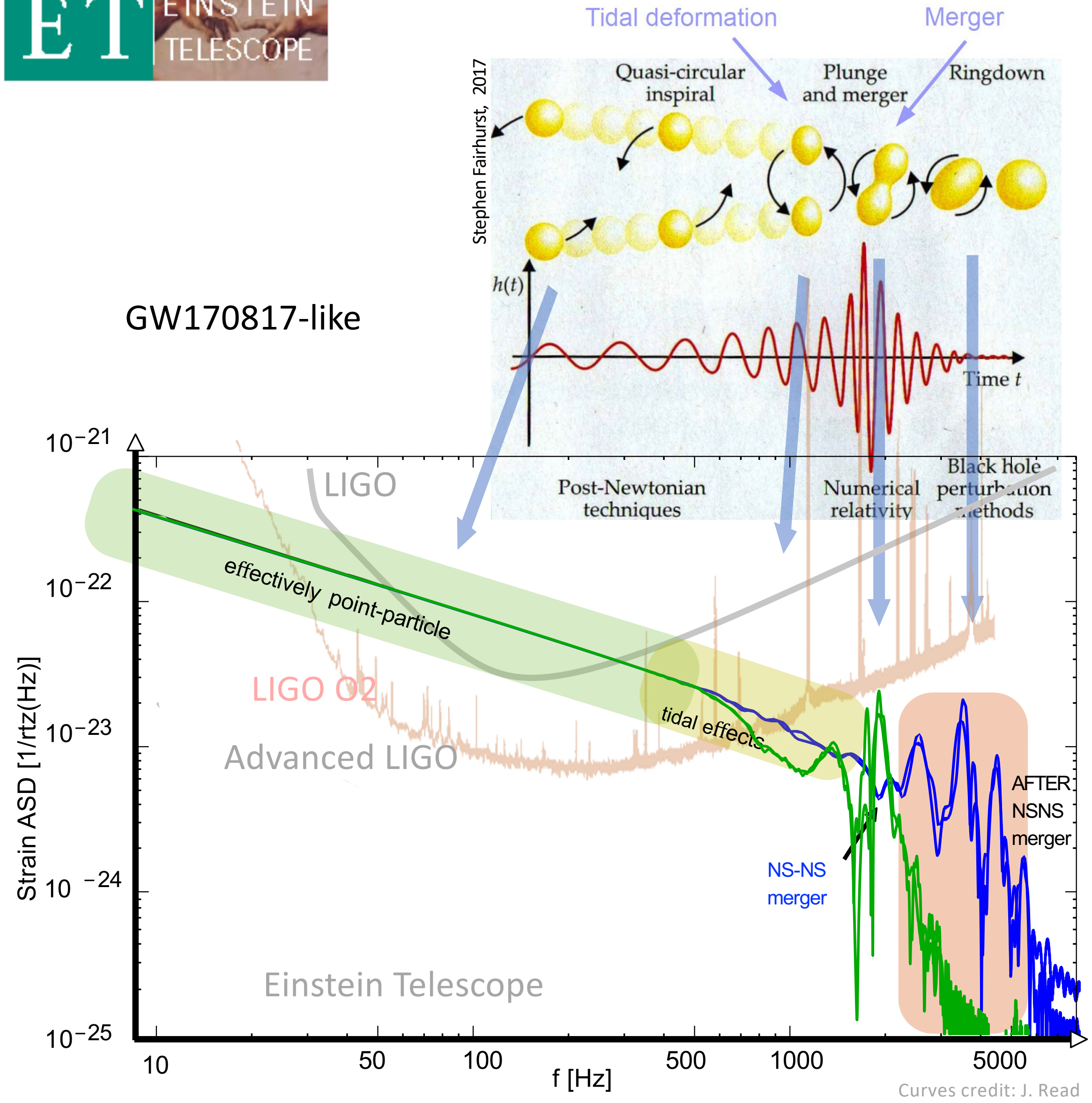
- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of Ge… …lativity**
  - po… …xpansion
  - …d regime
- **…ark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

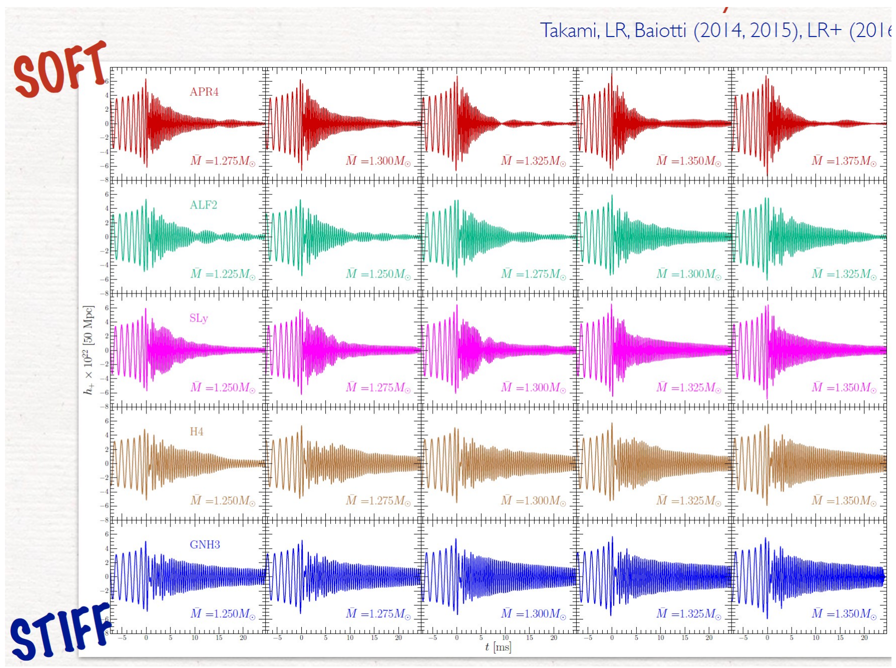
Expect the unexpected!


Radioactively powered transients
Relativistic astrophysics
Nucleosynthesis and enrichment of the Universe
GW170817-like events
Fundamental Physics
130.000.000 ly
Cosmology
Nuclear matter physics
ATMOSPHERE
ENVELOPE
CRUST
OUTER CORE
INNER CORE
?
Polar cap
Cone of open magnetic field lines

Probing the Structure of a Neutron Star

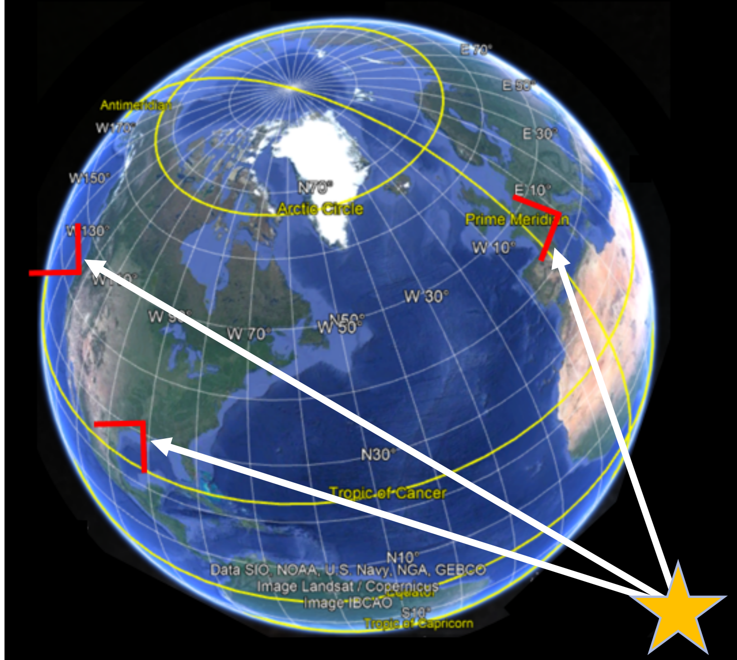
GW170817-like



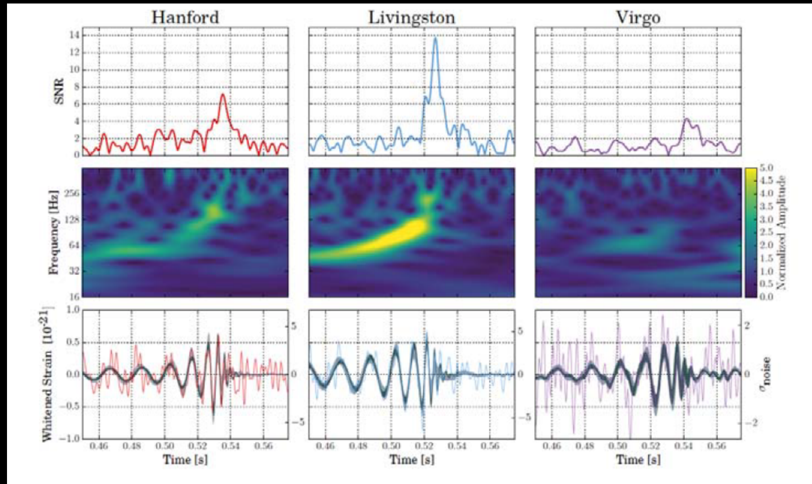


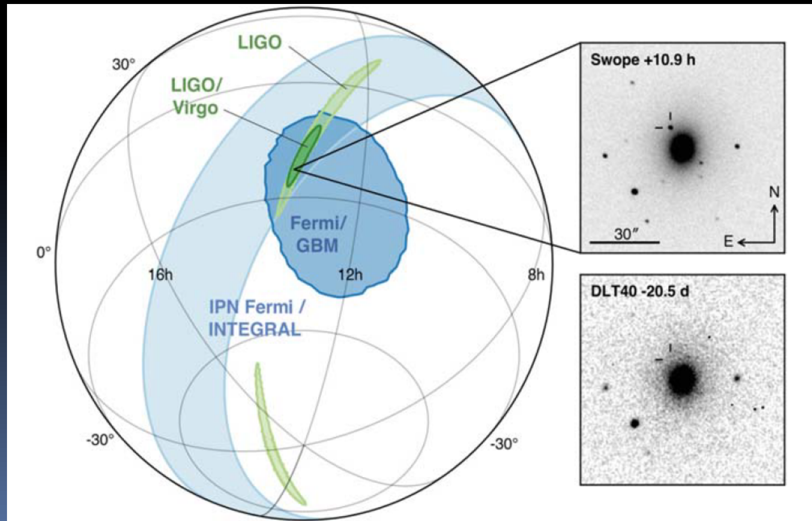
Slide: M.Punturo, modified

Localisation by Trilateration (LVK)

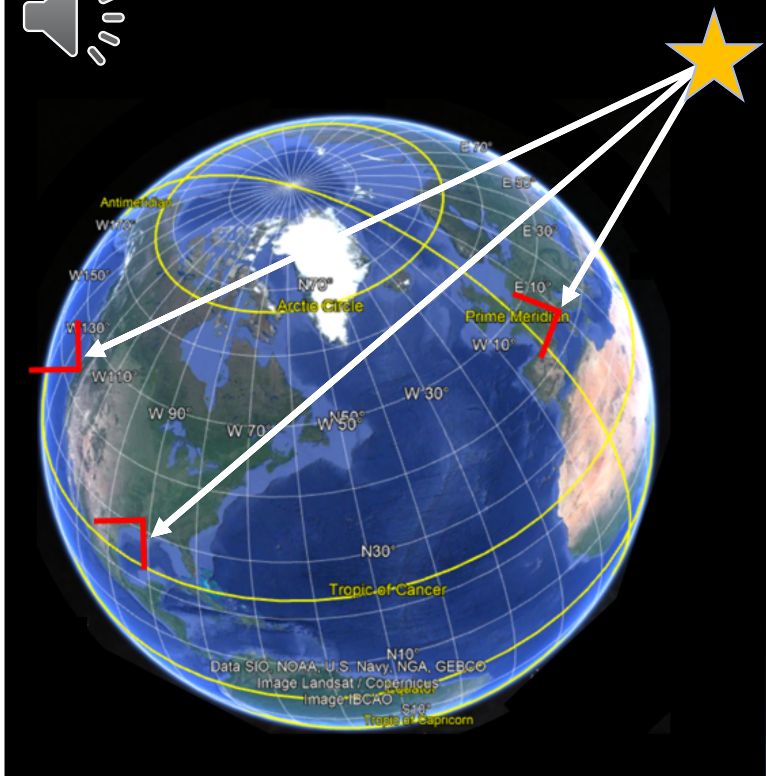


Animation Stefan Hild

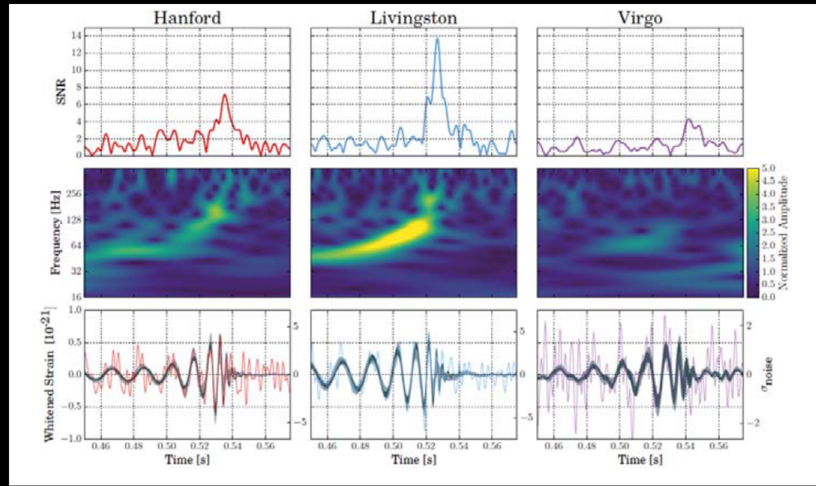


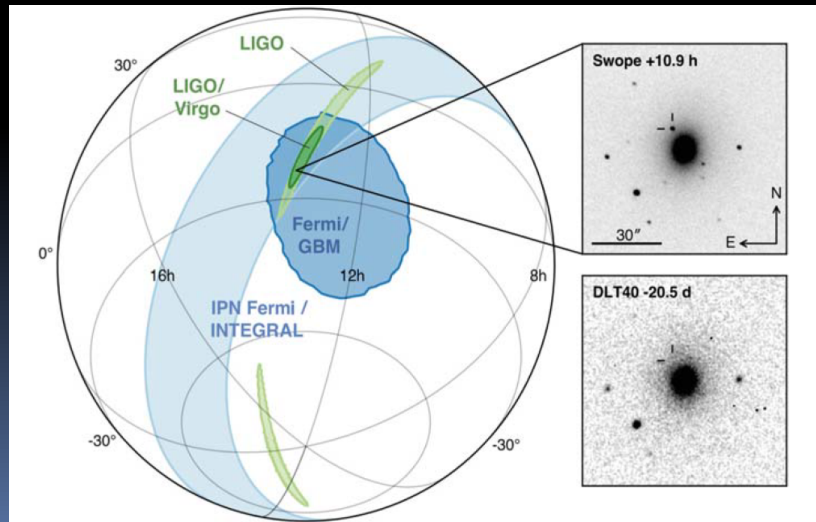


Localisation by Trilateration



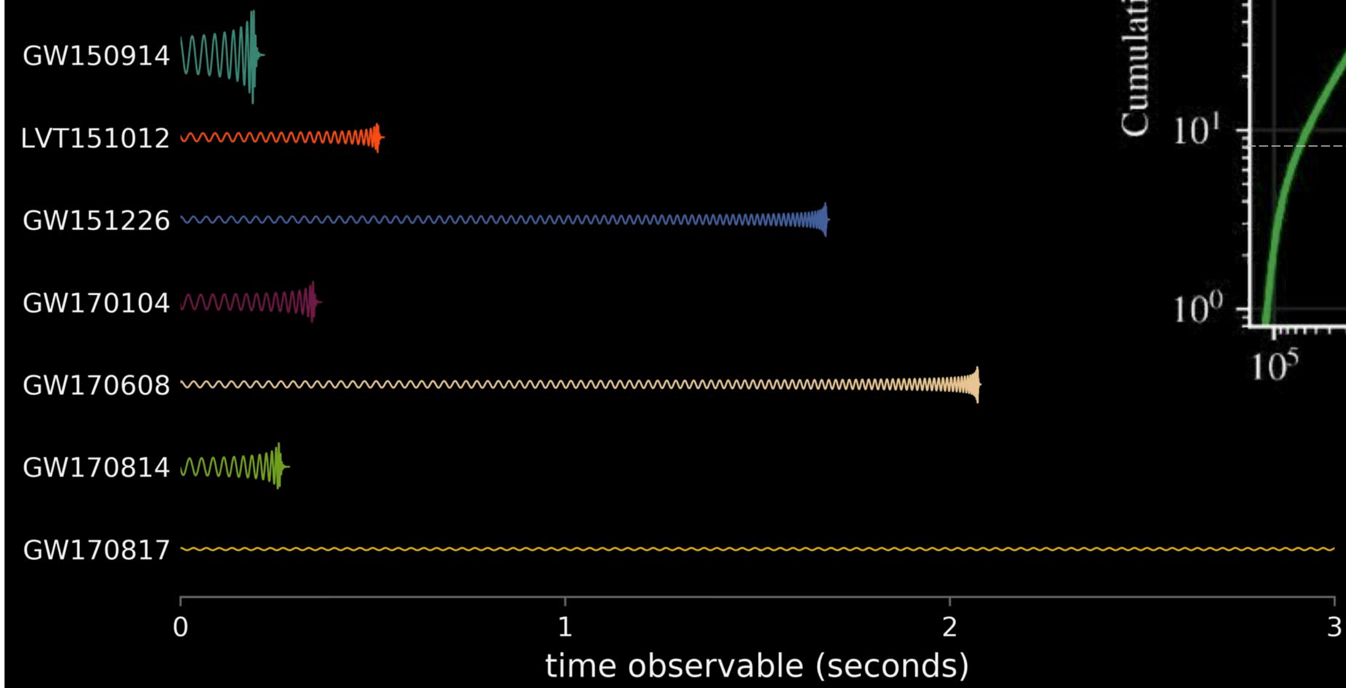
Animation Stefan Hild

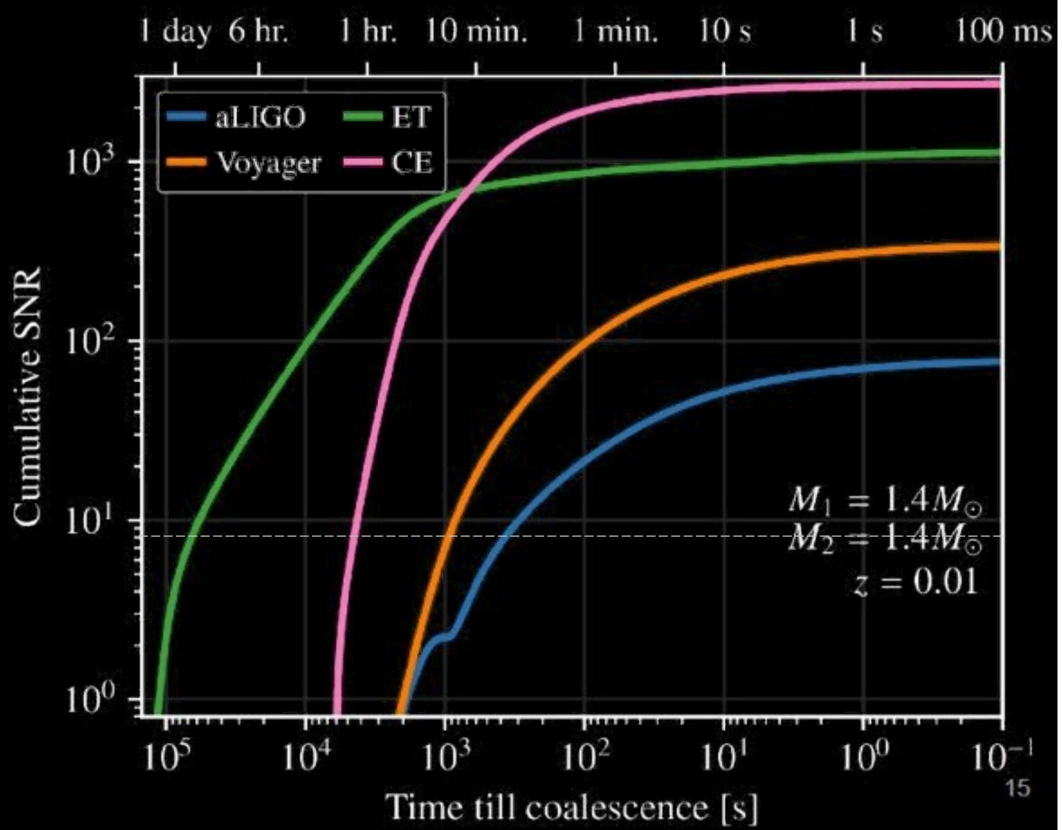




Low frequency: Multi-messenger astronomy

- If we were able to accumulate enough SNR before the merging phase, we could trigger e.m. observations before the emission of photons
- Keyword: low frequency sensitivity

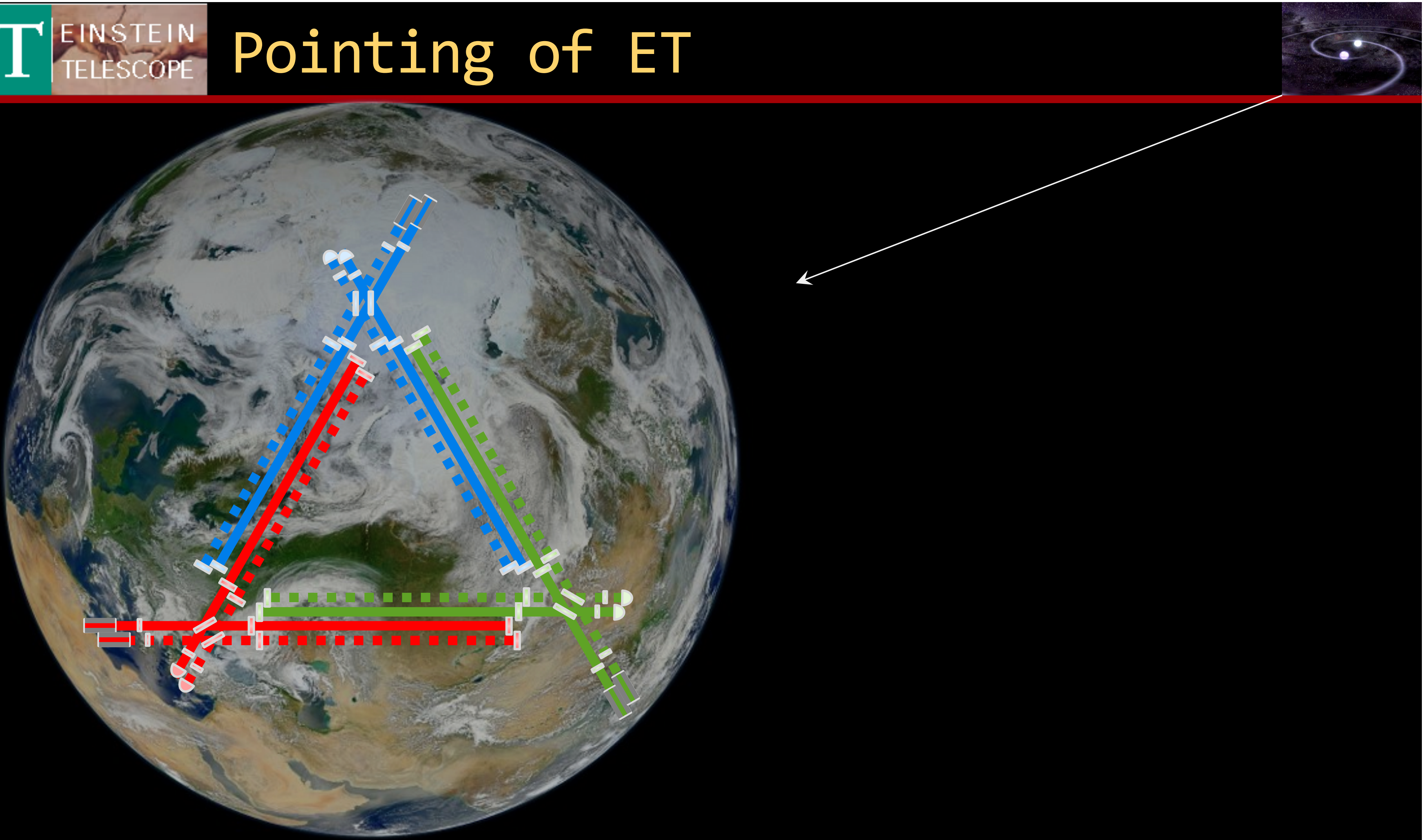




Slide: M.Punturo, modified

ET EINSTEIN TELESCOPE

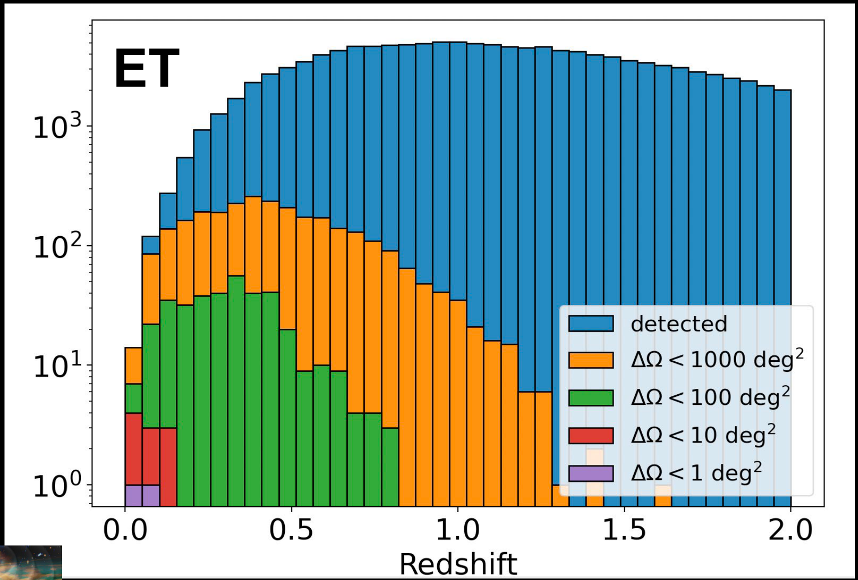
Pointing of ET

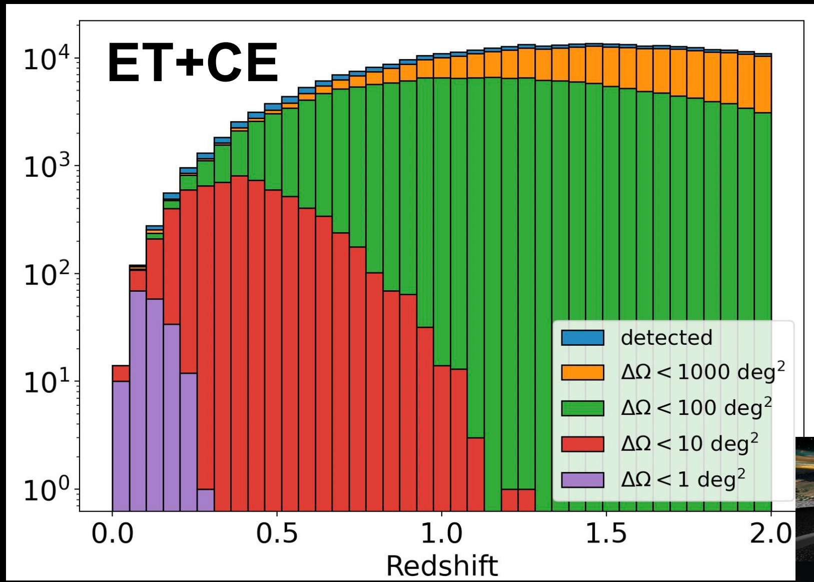


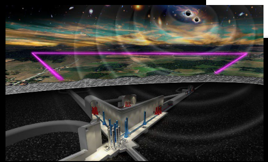
ET Localisation Capabilities

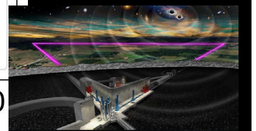
GW170817 was @ z= 0.01 and
pointing uncertainty was ~30 deg^2

credits: M.Branchesi









The ET low frequency sensitivity makes it possibile to localize BNS!

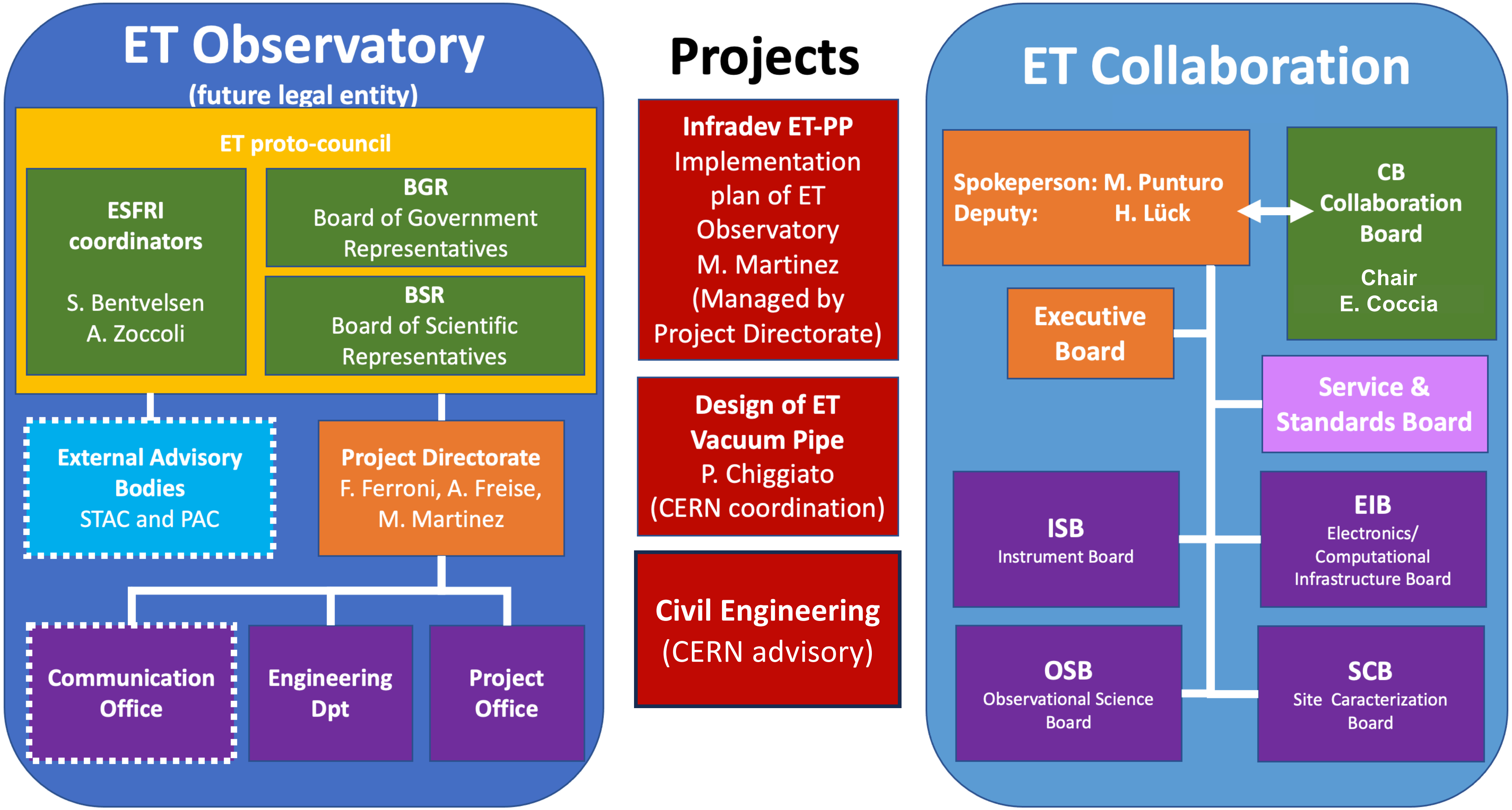
O(100) detection per year with
sky-localization (90% c.r.)<100 deg^2 (early warning alerts!)

O(1000) detection per year with
sky-localization (90% c.r.)<10 deg^2

Einstein Telescope in the ESFRI Roadmap

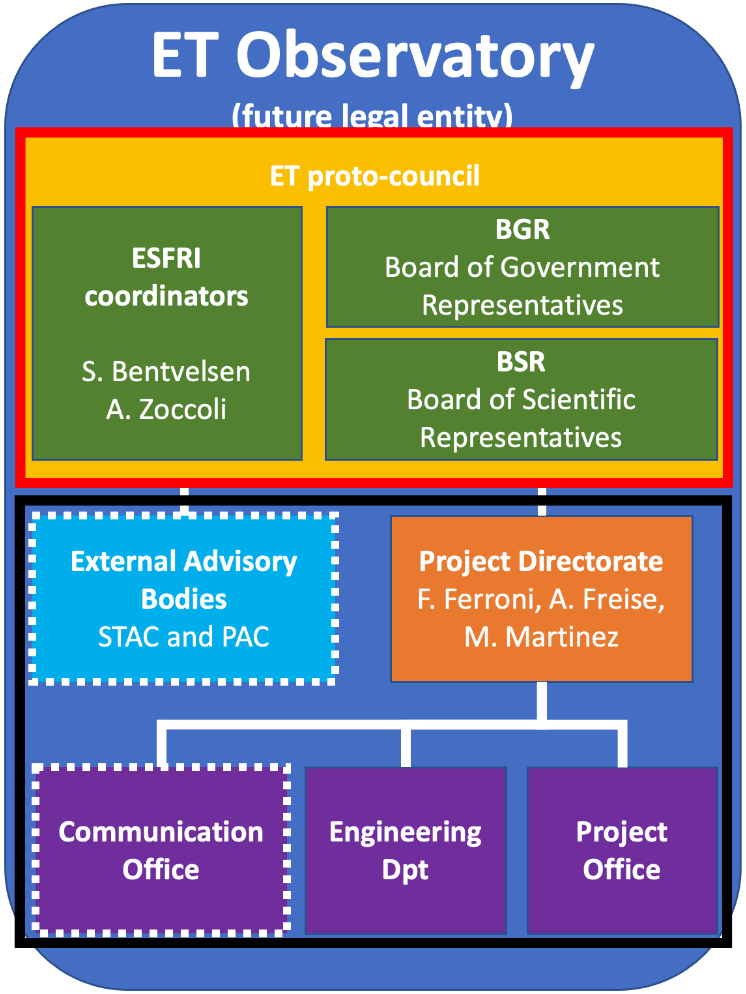
- ET entered in the 2021 ESFRI roadmap update
- The ET proposal has been presented by the following countries: Italy, the Netherlands, Belgium, Spain and Poland
- The ET consortium is leaded by INFN and Nikhef
- The ET (current) governance has been consequently structured

ET Current Organization



Simplified rapresentation by P.Verdier

ET Current Organization

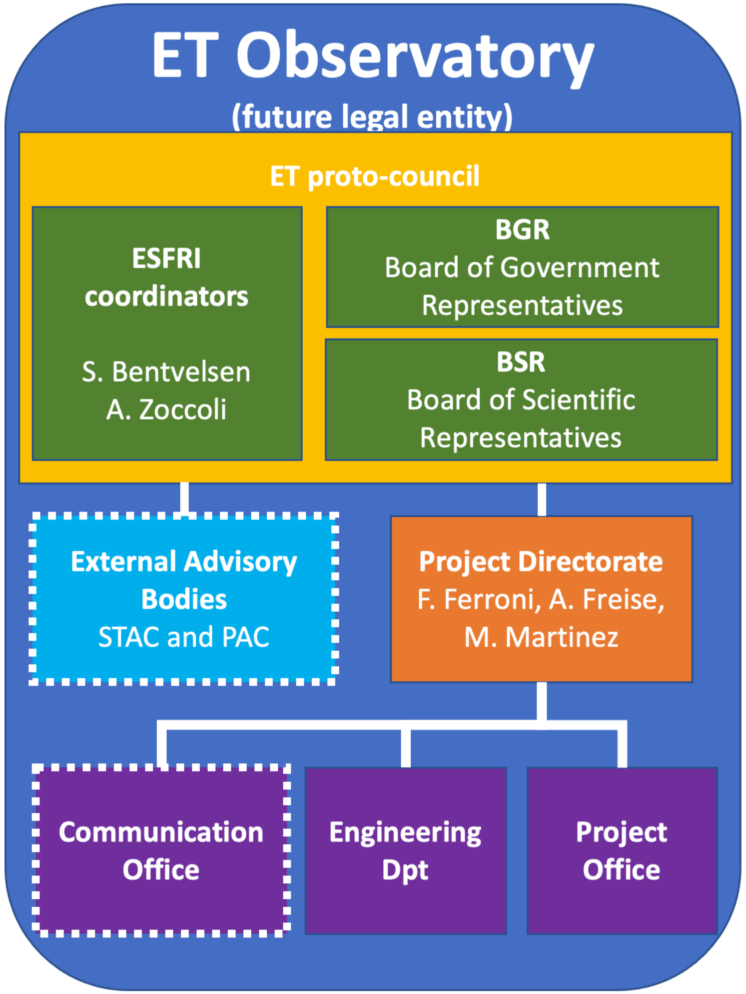


Temporary groups, working towards becoming the ET governing body, such as a Council. **Our most important link to governments and funding agencies** (Austria, Belgium, France, Italy, Netherlands, Poland, Spain, UK are members with Germany as observer).

An small but active organisation with the formal responsibility to realise of ET. **A future legal entity for ET would be based on this structure.**

Credits: A. Freise

ET Current Organization



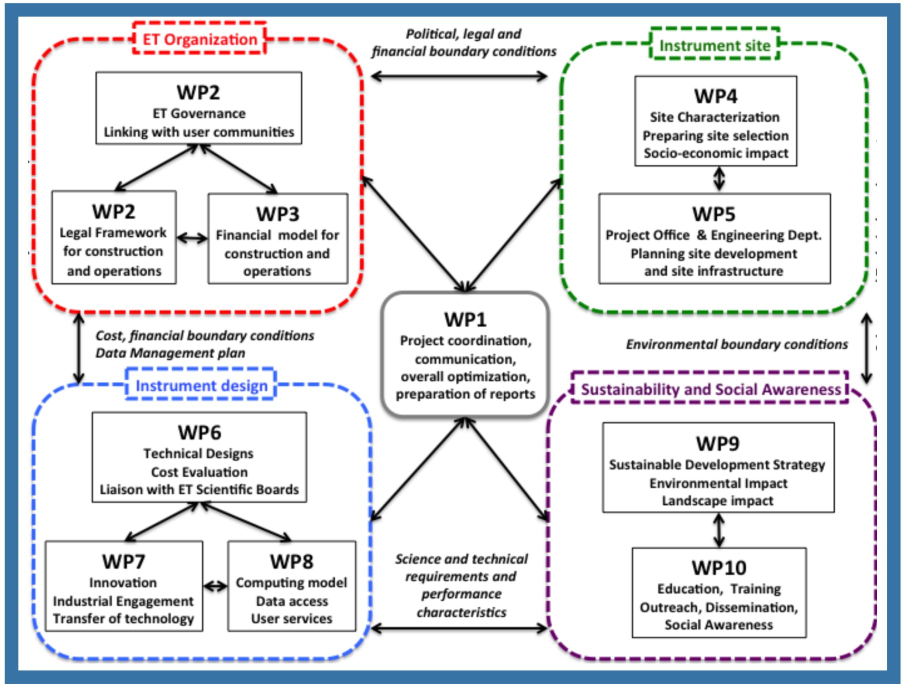
Simplified rapresentation by P.Verdier

Projects

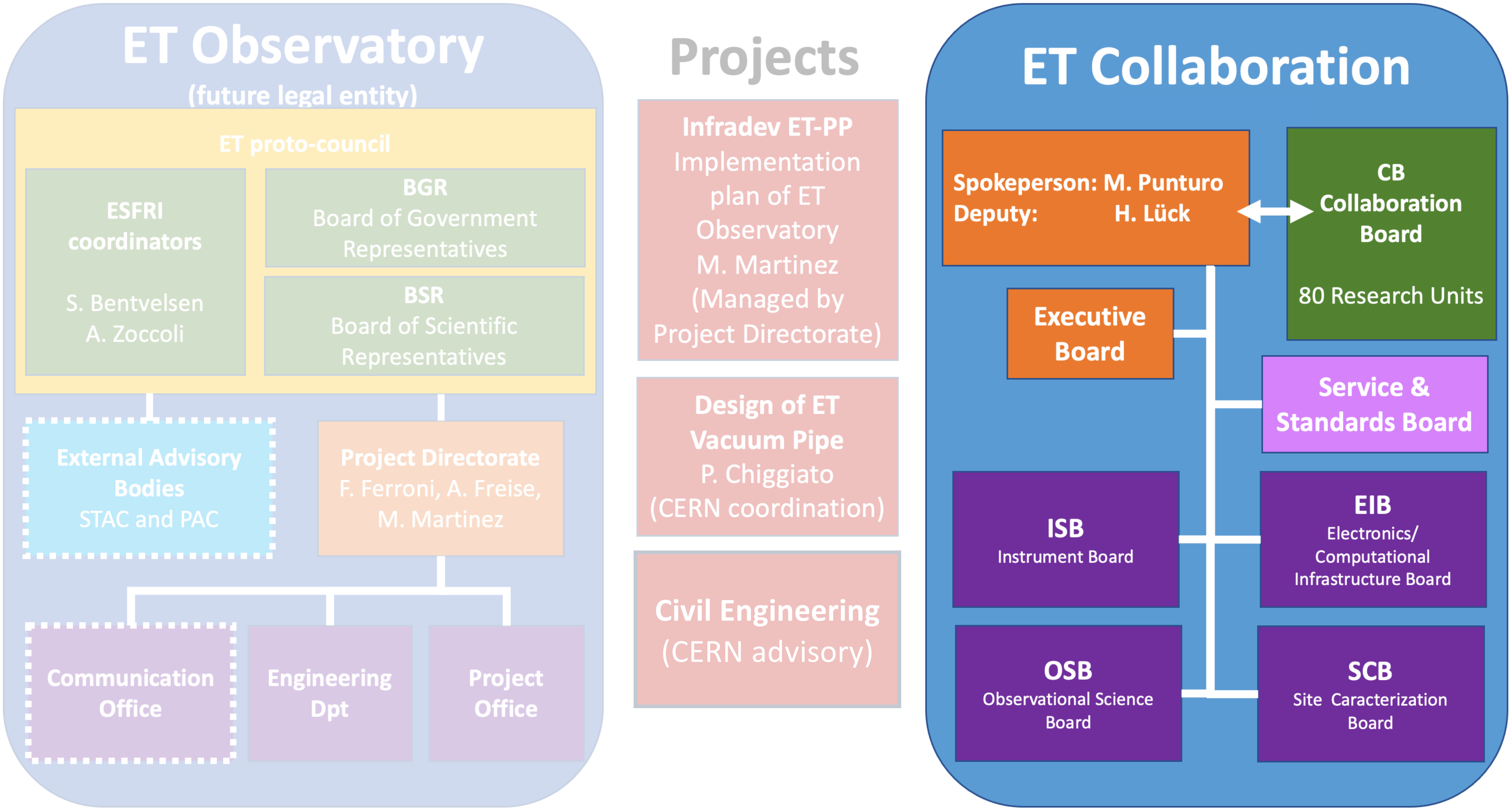
Infradev ET-PP
Implementation plan of ET Observatory
M. Martinez
(Managed by Project Directorate)

Design of ET Vacuum Pipe
P. Chiggiato
(CERN coordination)

Civil Engineering
(CERN advisory)



ET Current Organization



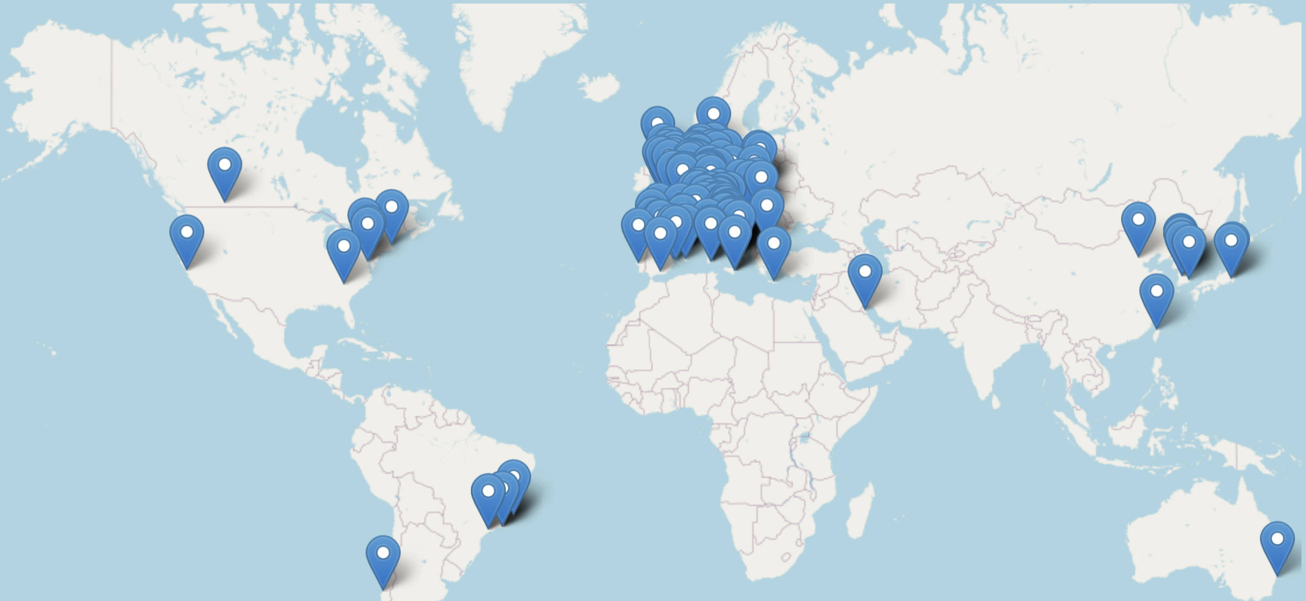
Simplified rapresentation by P.Verdier

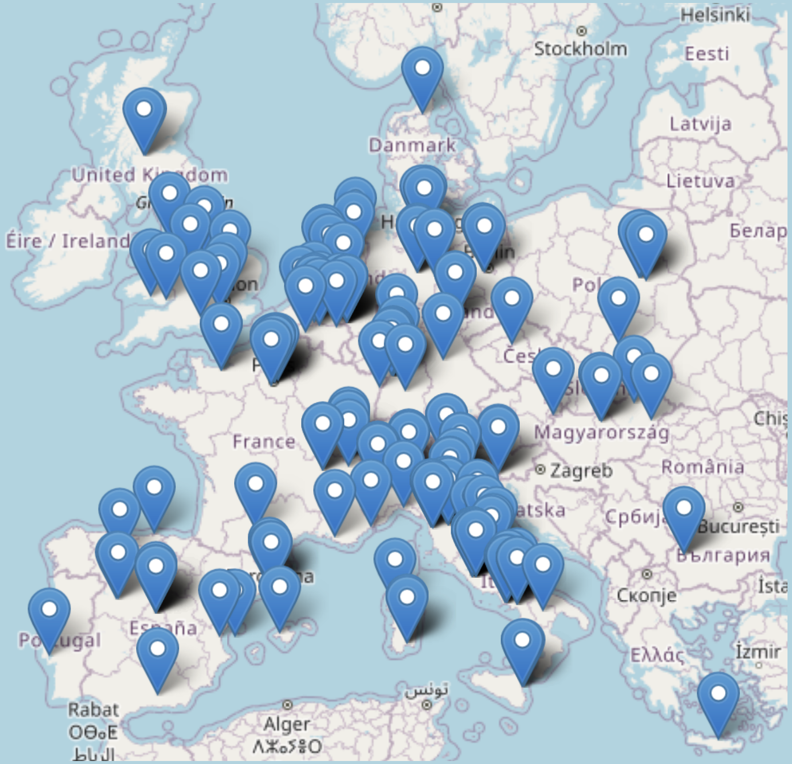
The Einstein Telescope Collaboration

- **85 Research Units (+1 request pending)**
- **1568 members (24/11/2023 15:29)**
- **Total: 226 Institutions**

in 25 Countries

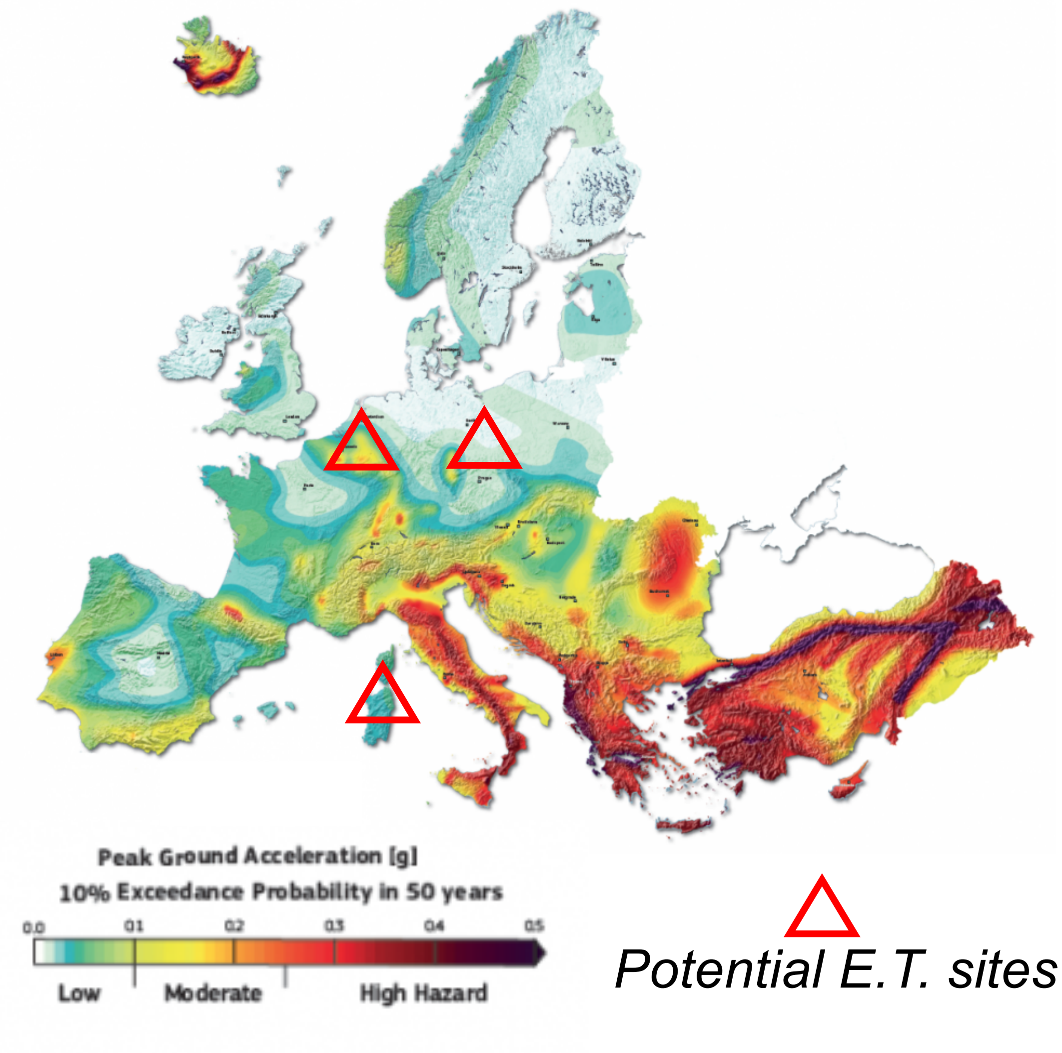
- **ET member database**





ET Member's affiliation map

ET site candidates



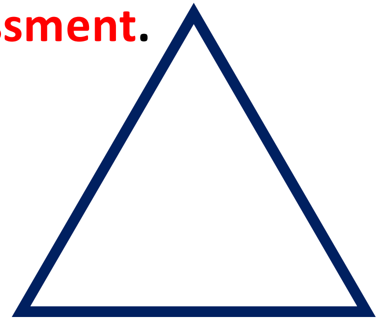
ET design: Δ or (two) L

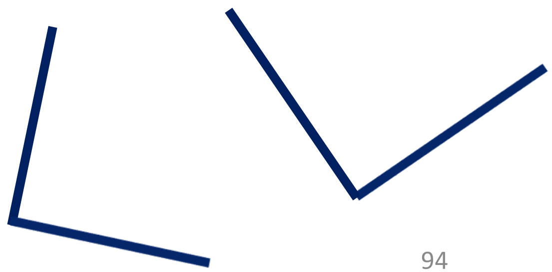
In the last couple of years, the collaboration started the evaluation of the best configuration for ET, considering the alternative of two L configuration (as LIGO, Cosmic Explorer) to maximize the science return and reduce risks.

Since 2011 (CDS, triangle configuration) the situation drastically changed:

- ❑ First detections, GTWC-3 catalog → BH population → new SF and evolution models;
- ❑ Science case developed;
- ❑ Know-how with advanced (L) detectors;
- ❑ International scenario (+ Cosmic Explorer in US);
- ❑ Two candidate sites strongly supported (and a potential third site…).

The collaboration is analyzing both configurations: **optimizing science return**, **differential risk assessment**.

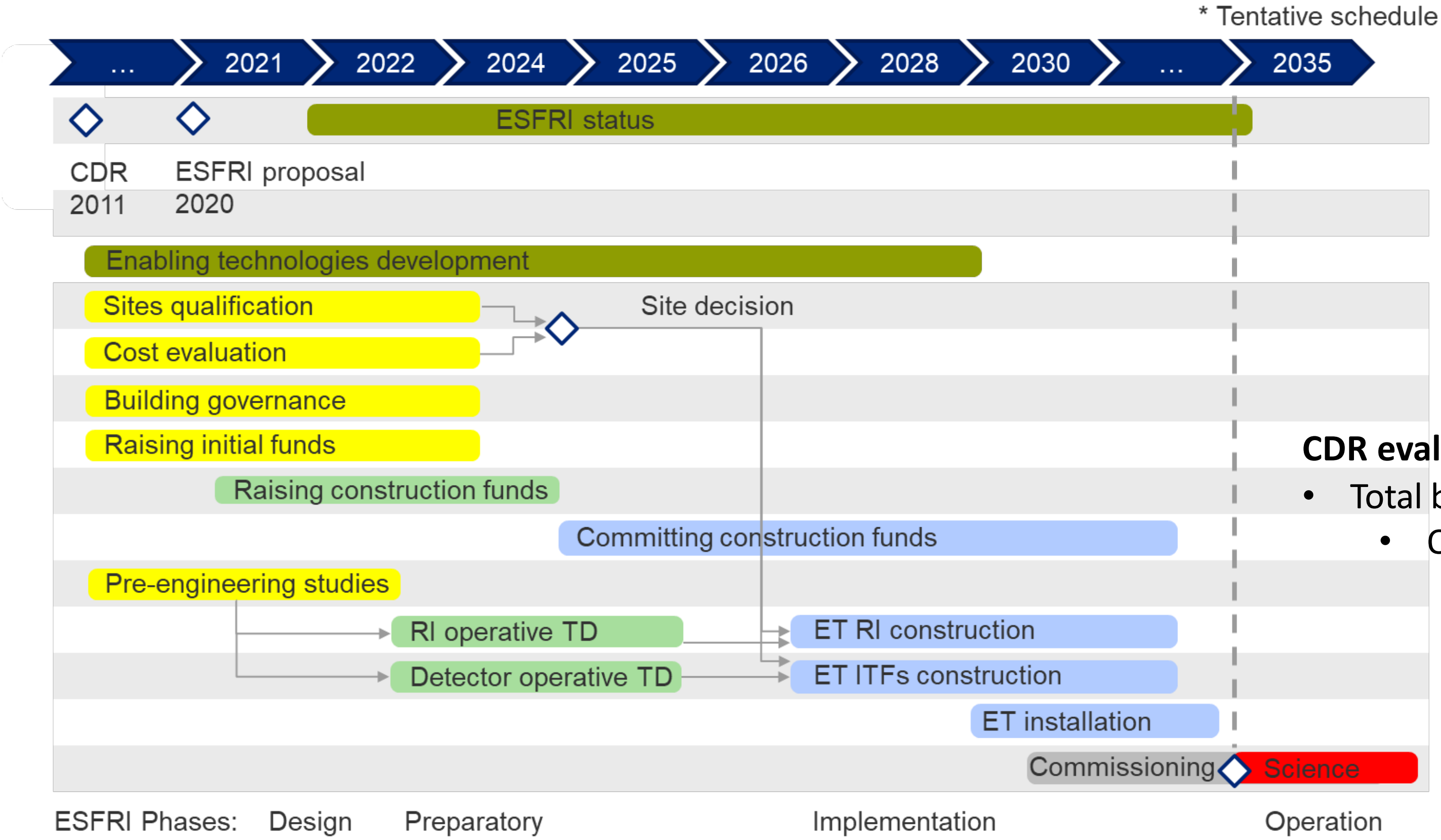




ET timeline as presented to ESFRI

Timelines have to be discussed among:

- Scientists
- Agencies
- Governments



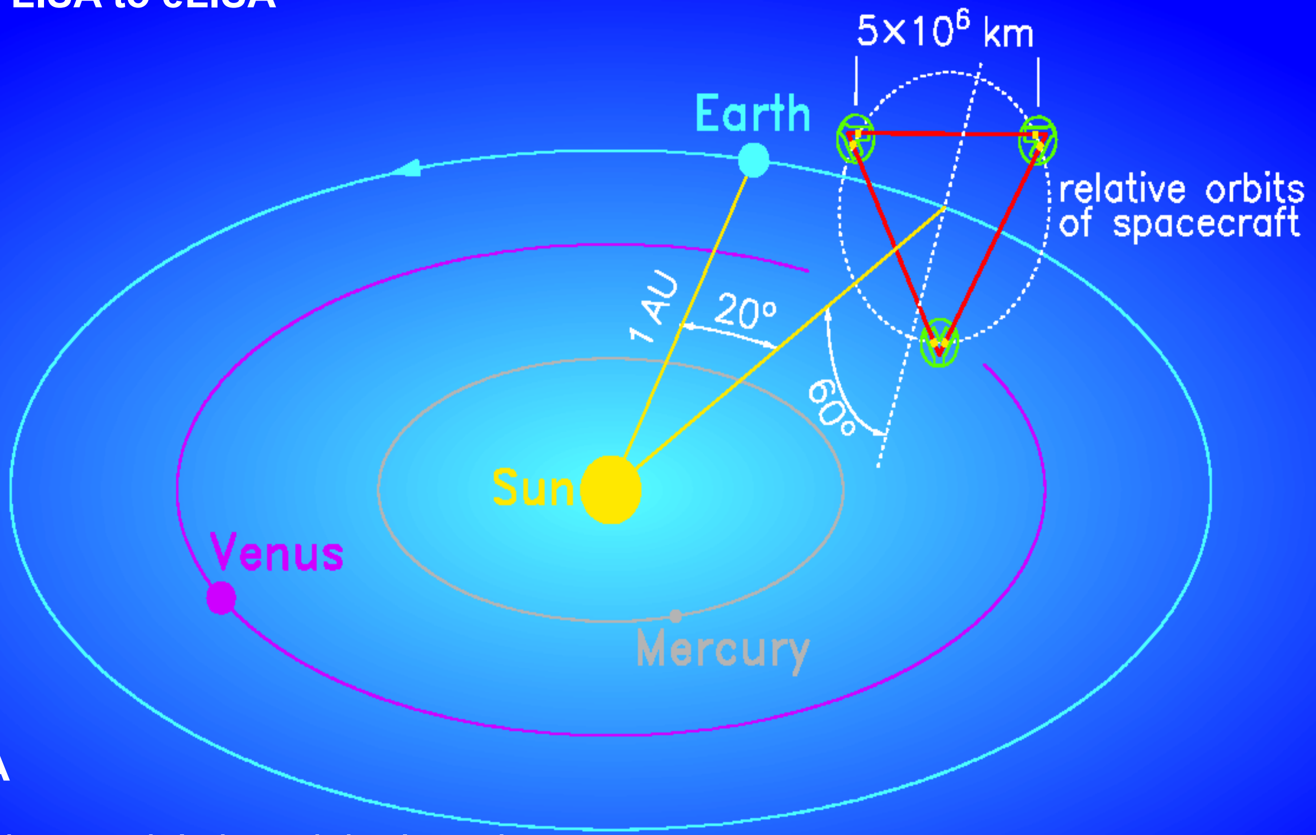
CDR evaluations:

- Total budget ~ 2G€
  - Observatory budget ~ 1.7G€
    - Infrastructure Budget:
      - Civil infrastructure: ~930M€
      - Vacuum system: ~570M€

Some Einstein Telescope Links

- https://arxiv.org/abs/2303.15923 (CoBA)
- https://iopscience.iop.org/article/10.1088/1475-7516/2020/03/050 (ET Science case 2020)
- https://apps.et-gw.eu/tds/?call_file=ET-0028A-20_EinsteinTelescopeScienceCaseDe.pdf (Design Study Update 2020, short version)
- https://arxiv.org/abs/2207.02771 (detection capabilities of third-generation gravitational-wave detectors)
- https://apps.et-gw.eu/tds/?call_file=ET-0007B-20_ETDesignReportUpdate2020.pdf (Design Study Update 2020, long version)
- https://www.et-gw.eu/index.php/relevant-et-documents

From LISA to eLISA



eLISA

- Savings mainly in weight, launch cost.
- Two active arms, not three;
- Smaller arms (1Gm, not 5Gm);
- Re-use LISA Pathfinder hardware;

2034?

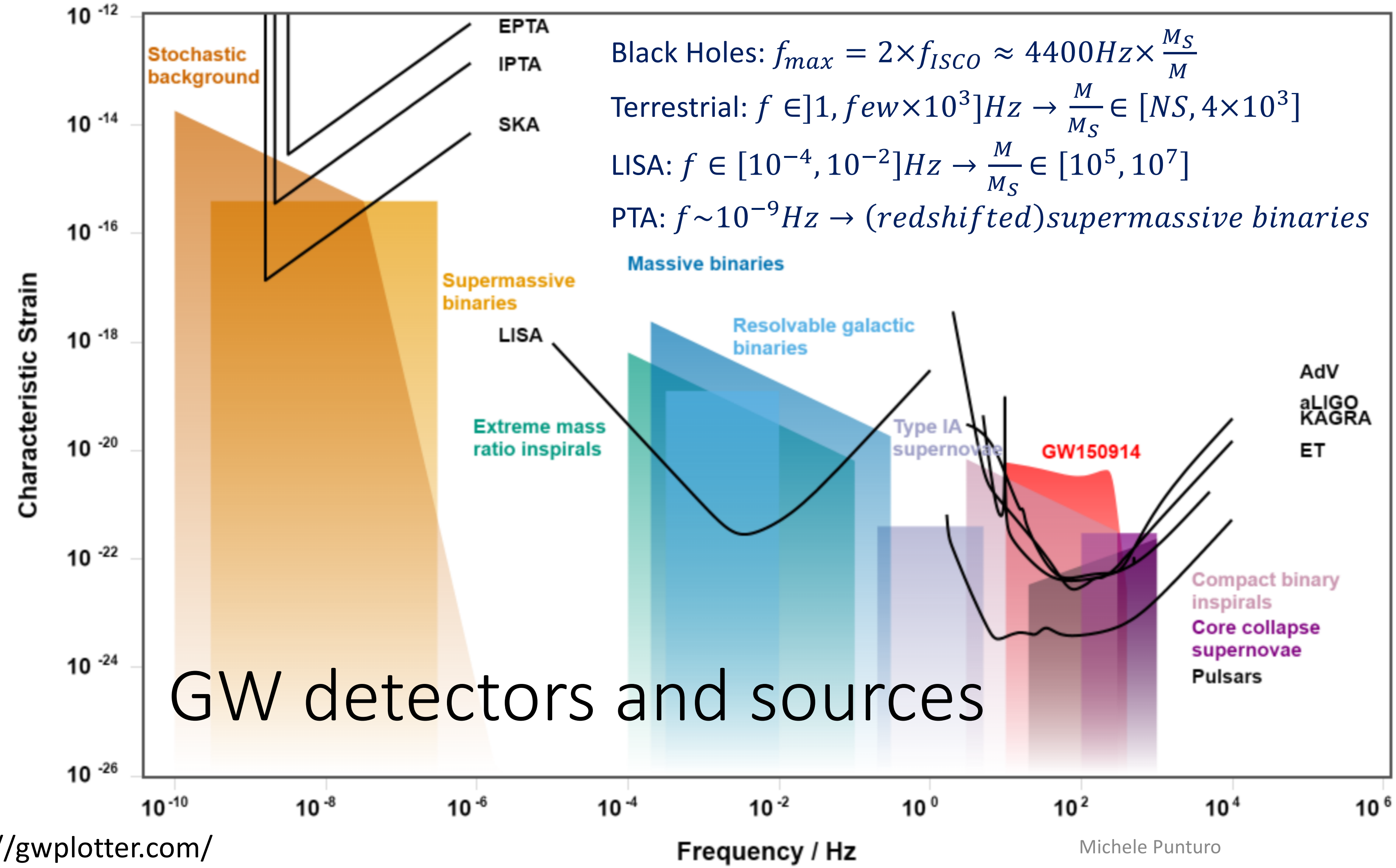
GW detectors and sources

Black Holes: $f_{max} = 2\times f_{ISCO} \approx 4400Hz\times \frac{M_S}{M}$

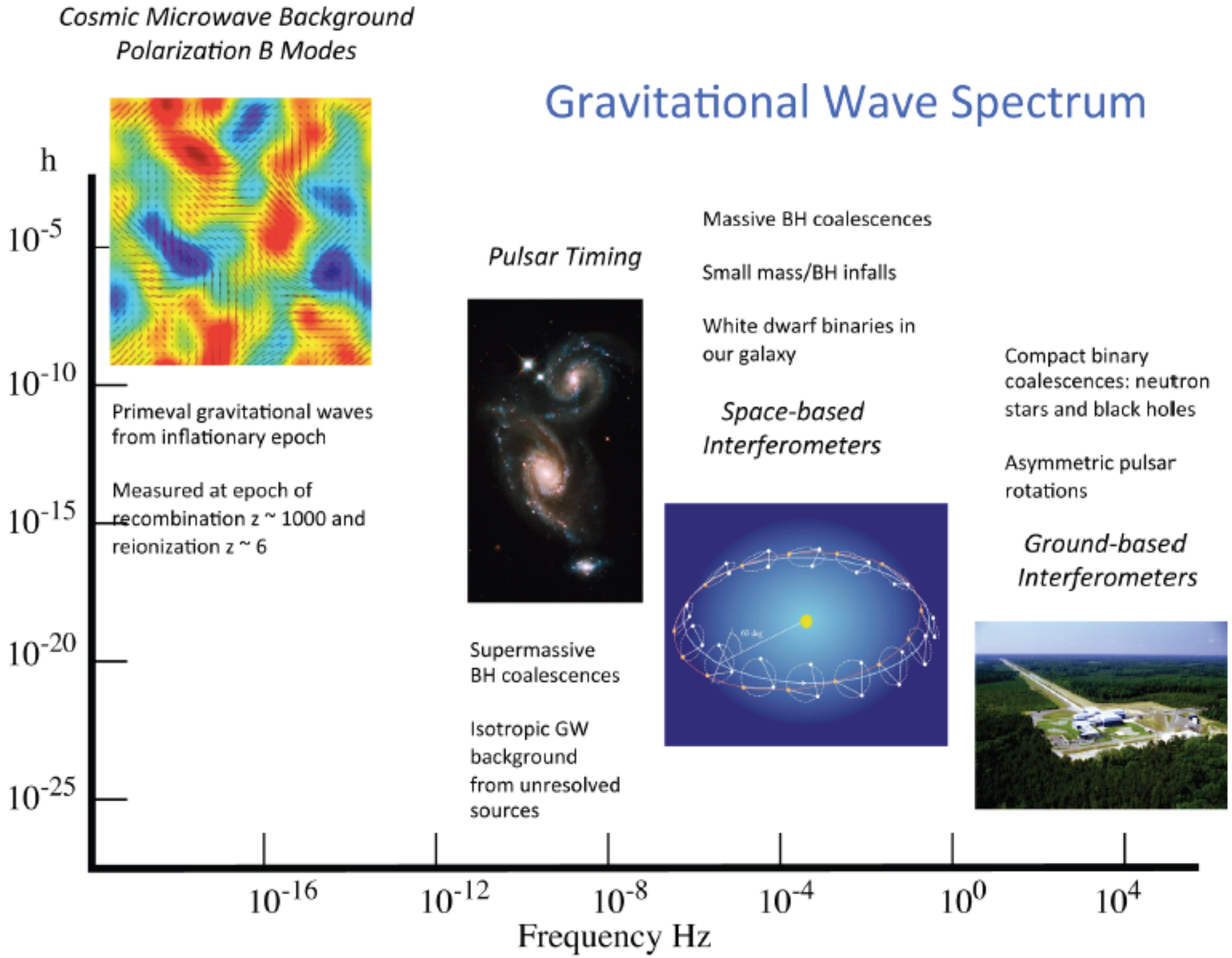
Terrestrial: $f \in]1, few\times10^3]Hz \rightarrow \frac{M}{M_S} \in [NS, 4\times10^3]$

LISA: $f \in [10^{-4}, 10^{-2}]Hz \rightarrow \frac{M}{M_S} \in [10^5, 10^7]$

PTA: $f \sim 10^{-9}Hz \rightarrow (redshifted)supermassive\ binaries$



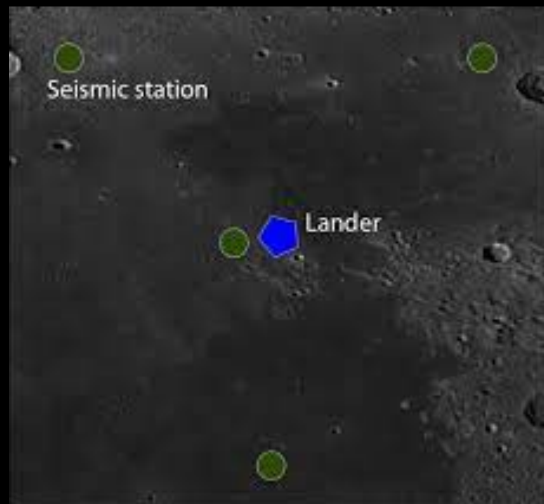
http://gwplotter.com/



Gravitational Wave Spectrum
Cosmic Microwave Background Polarization B Modes
h
10-5
10-10
10-15
10-20
10-25
Primeval gravitational waves from inflationary epoch
Measured at epoch of recombination z ~ 1000 and reionization z ~ 6
Pulsar Timing
Supermassive BH coalescences
Isotropic GW background from unresolved sources
Massive BH coalescences
Small mass/BH infalls
White dwarf binaries in our galaxy
Space-based Interferometers
Compact binary coalescences: neutron stars and black holes
Asymmetric pulsar rotations
Ground-based Interferometers
10-16
10-12
10-8
10-4
100
104
Frequency Hz

Lunar Gravitational-wave Antenna

The Astrophysical Journal,910:1(22pp), 2021 March 20



Every newly opened astronomical window has found unexpected results

Window	Opened	1st Surprise	Year
Optical	1609 Galilei	Jupiter's moons	1610
Cosmic Rays	1912	Muon	1930s
Radio	1930s	Giant Radio Galaxies CMB Pulsars	1950s 1964 1967
X - ray	1948	Sco X-1 X-ray binaries	1962 1969 Uhuru
g - ray	1961	GRBs	Late 1960s+ Vela
GW	2015	Massive BH-BH mergers	2016


Thank you for your attention