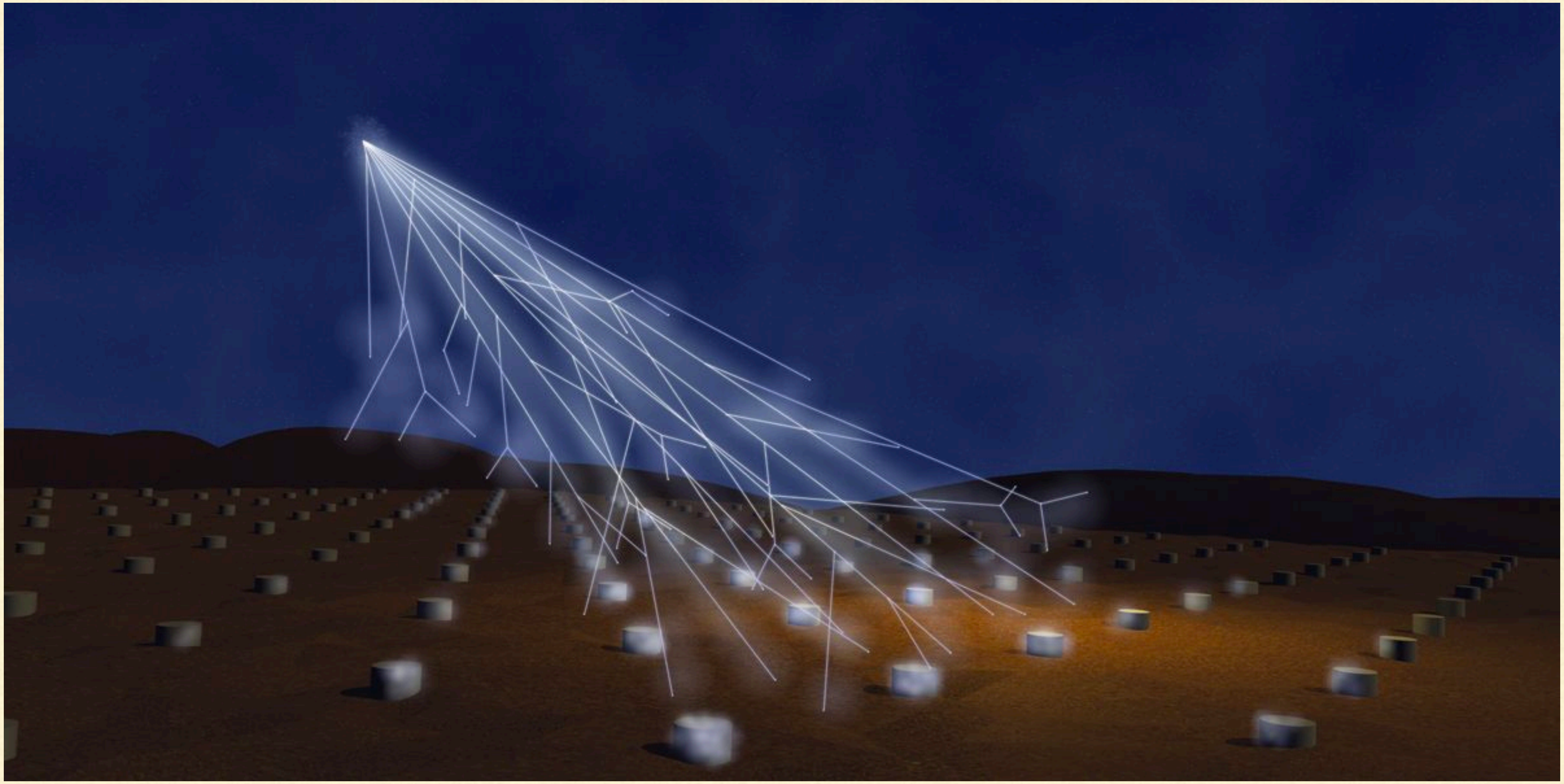
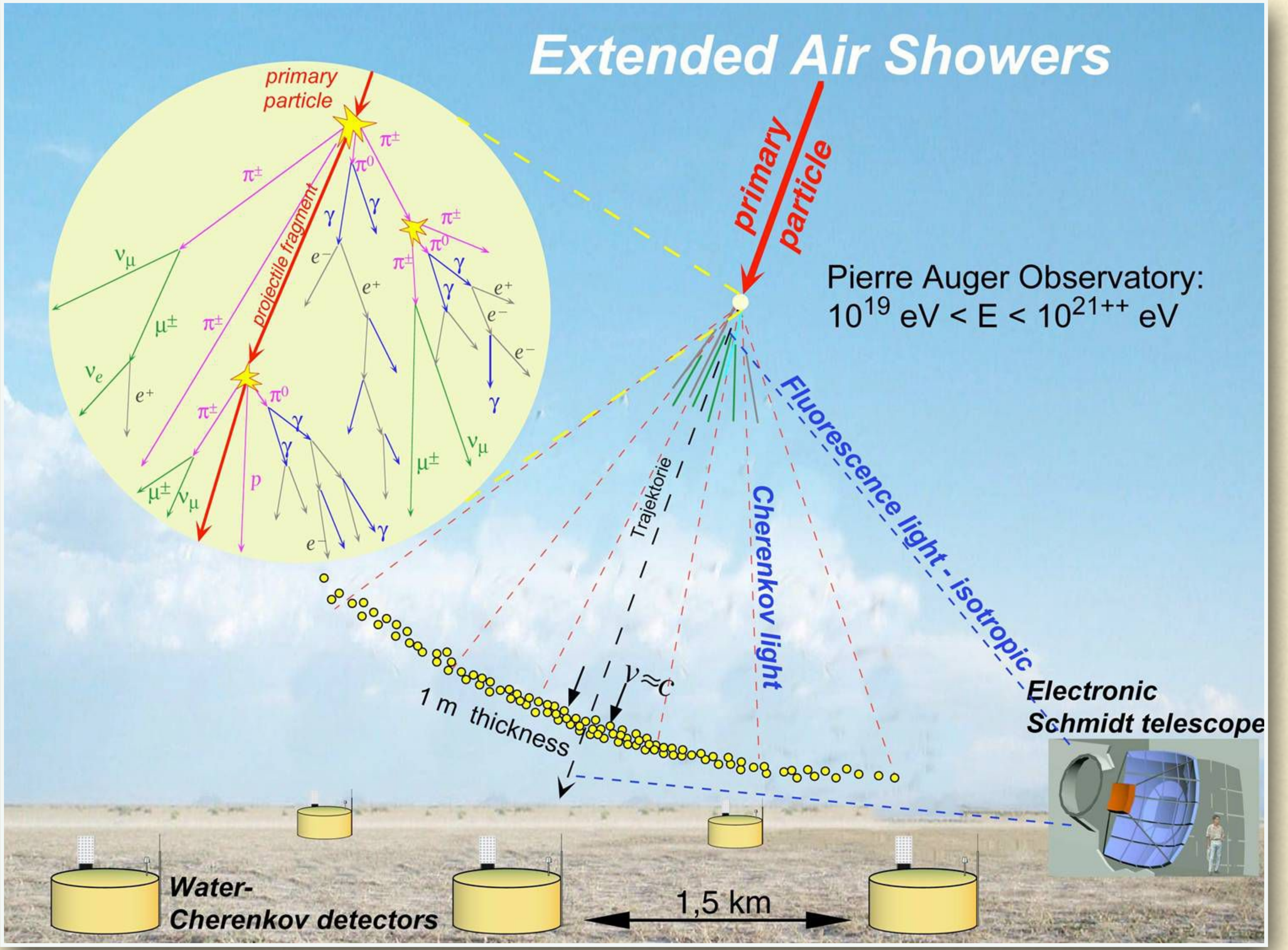


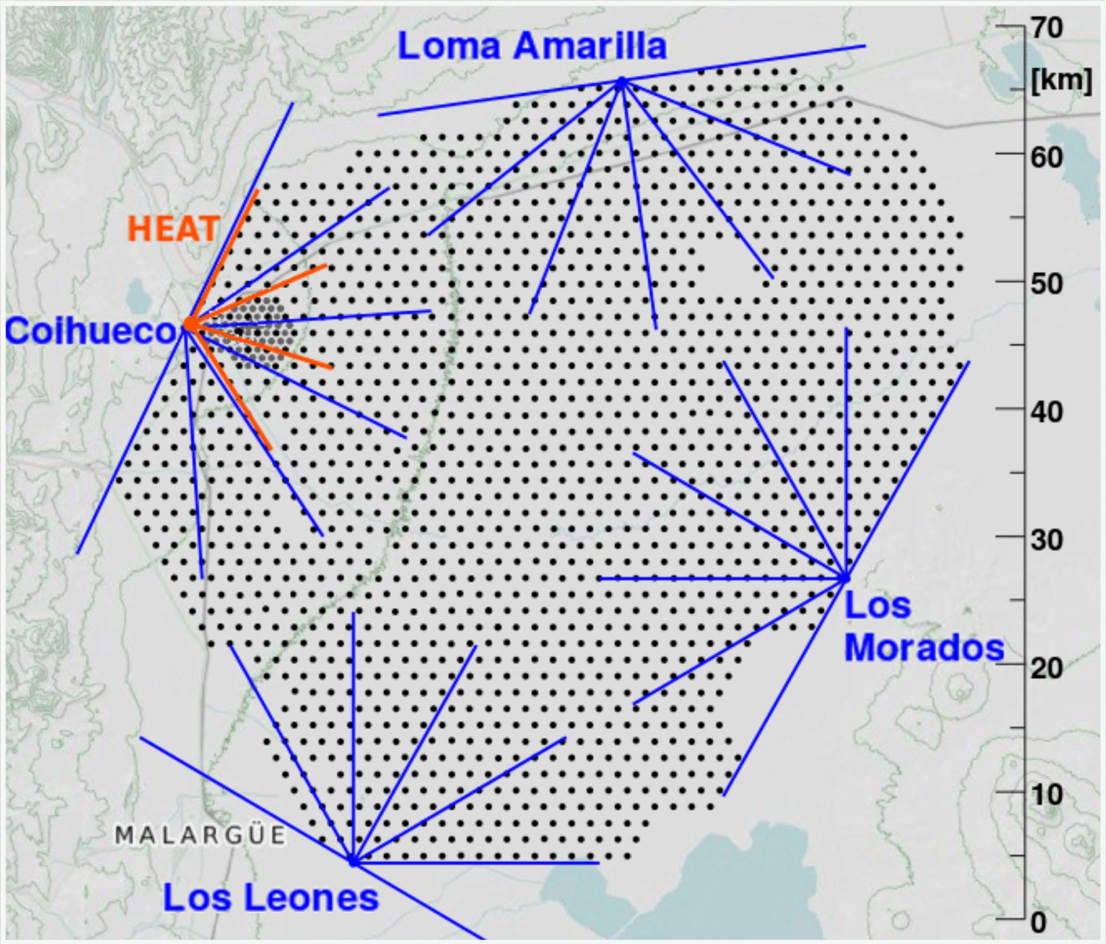
INTRODUCCIÓN A LA ASTROFÍSICA RELATIVISTA

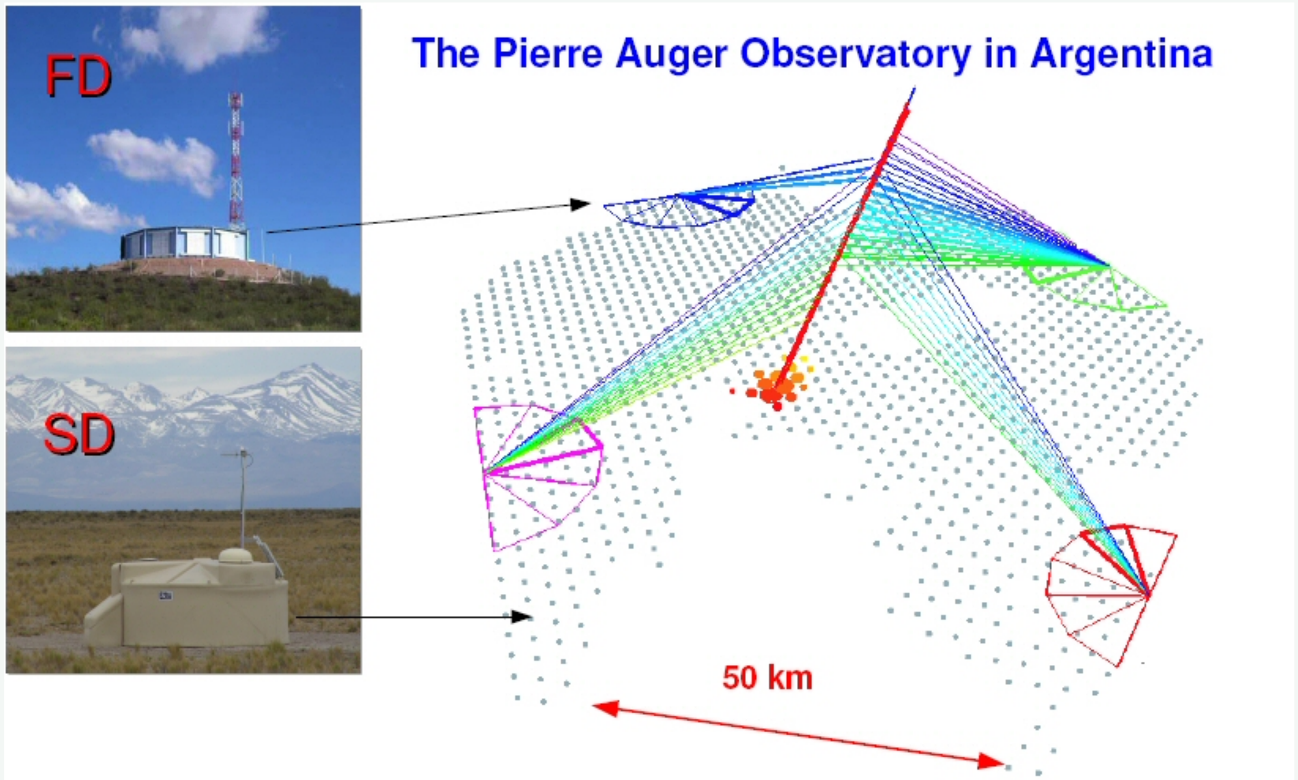
Gustavo E. Romero
Cursada 2020, FCAyG/UNLP

Detección de rayos cósmicos: el observatorio Pierre Auger

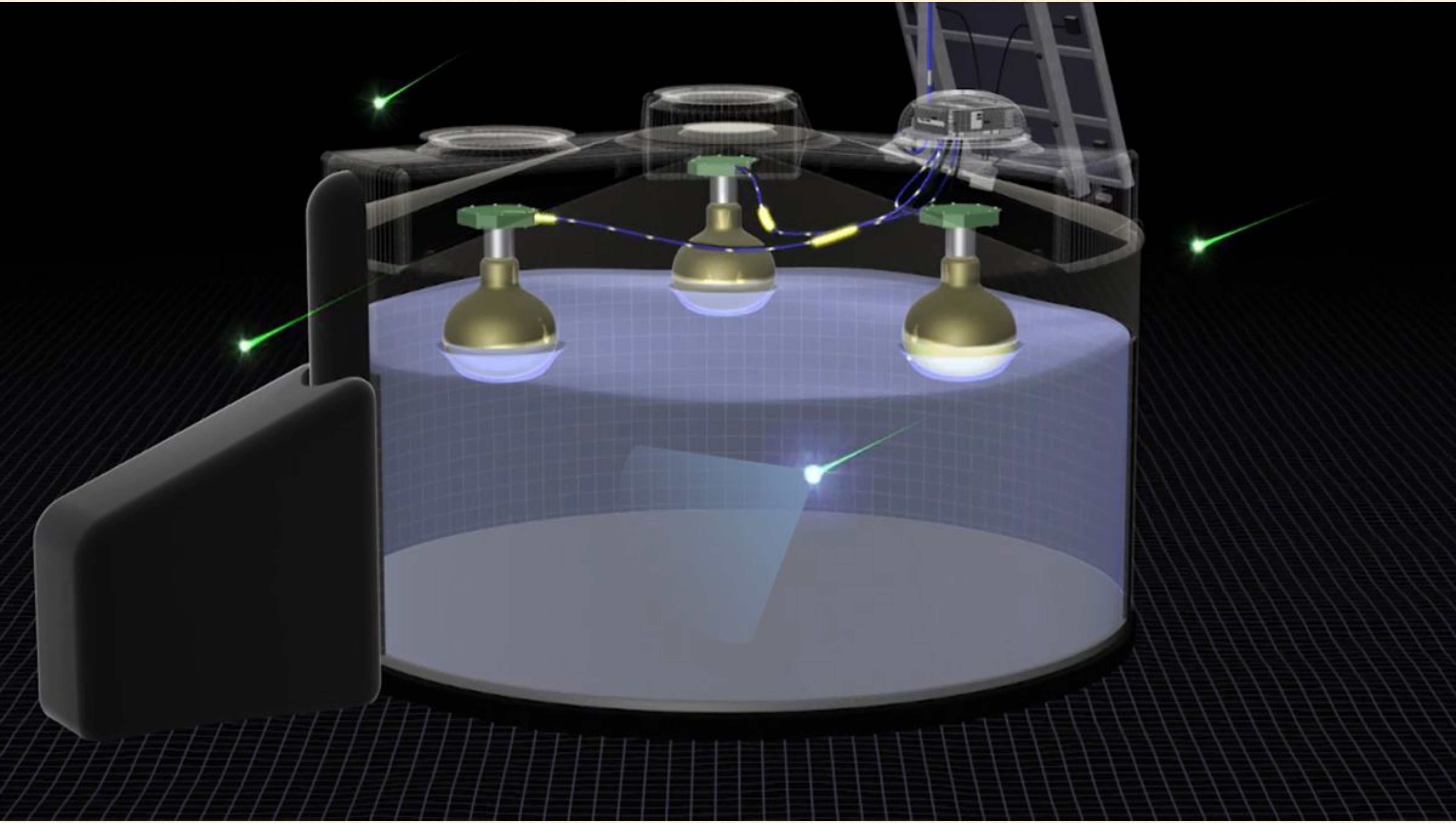


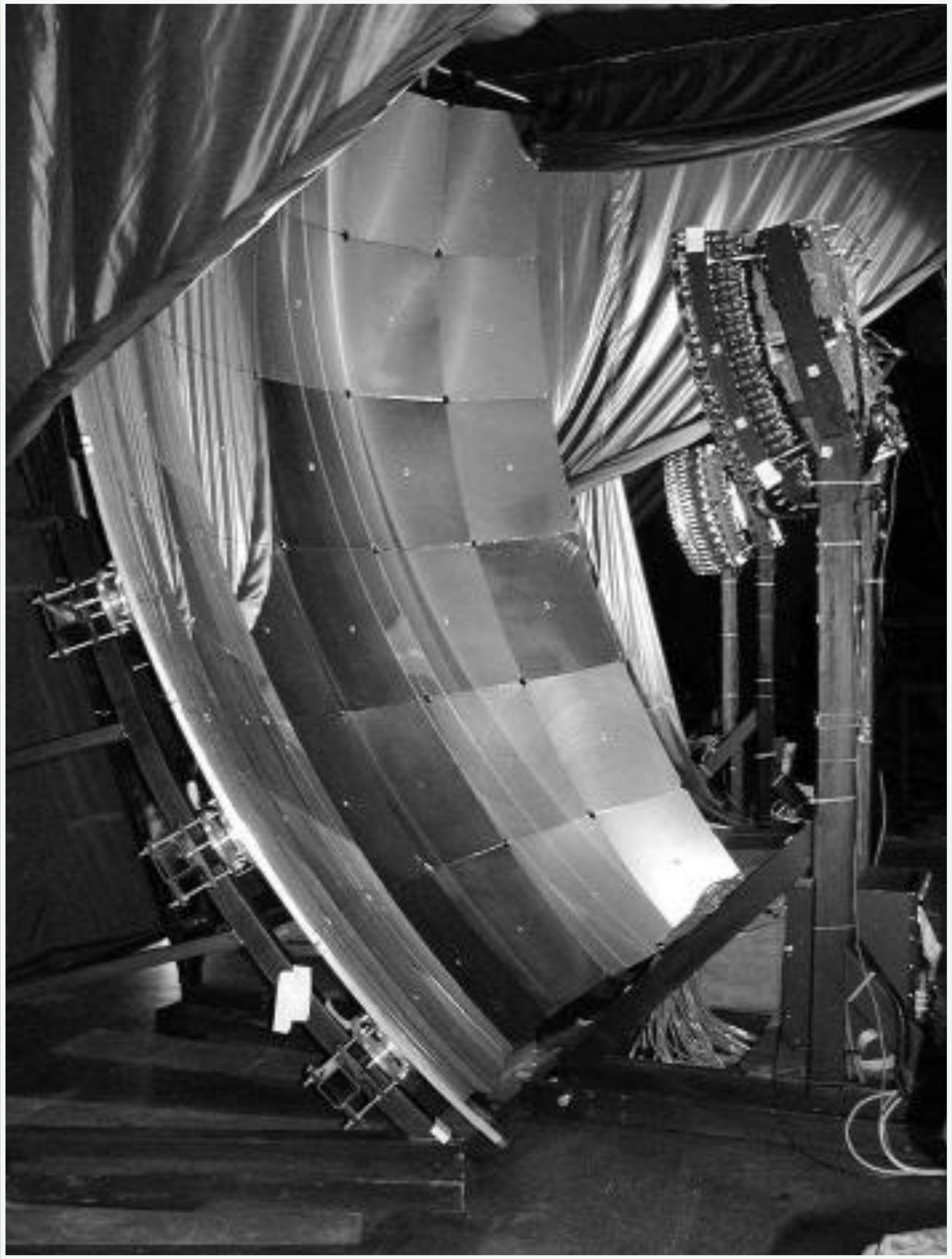
Un observatorio "híbrido"

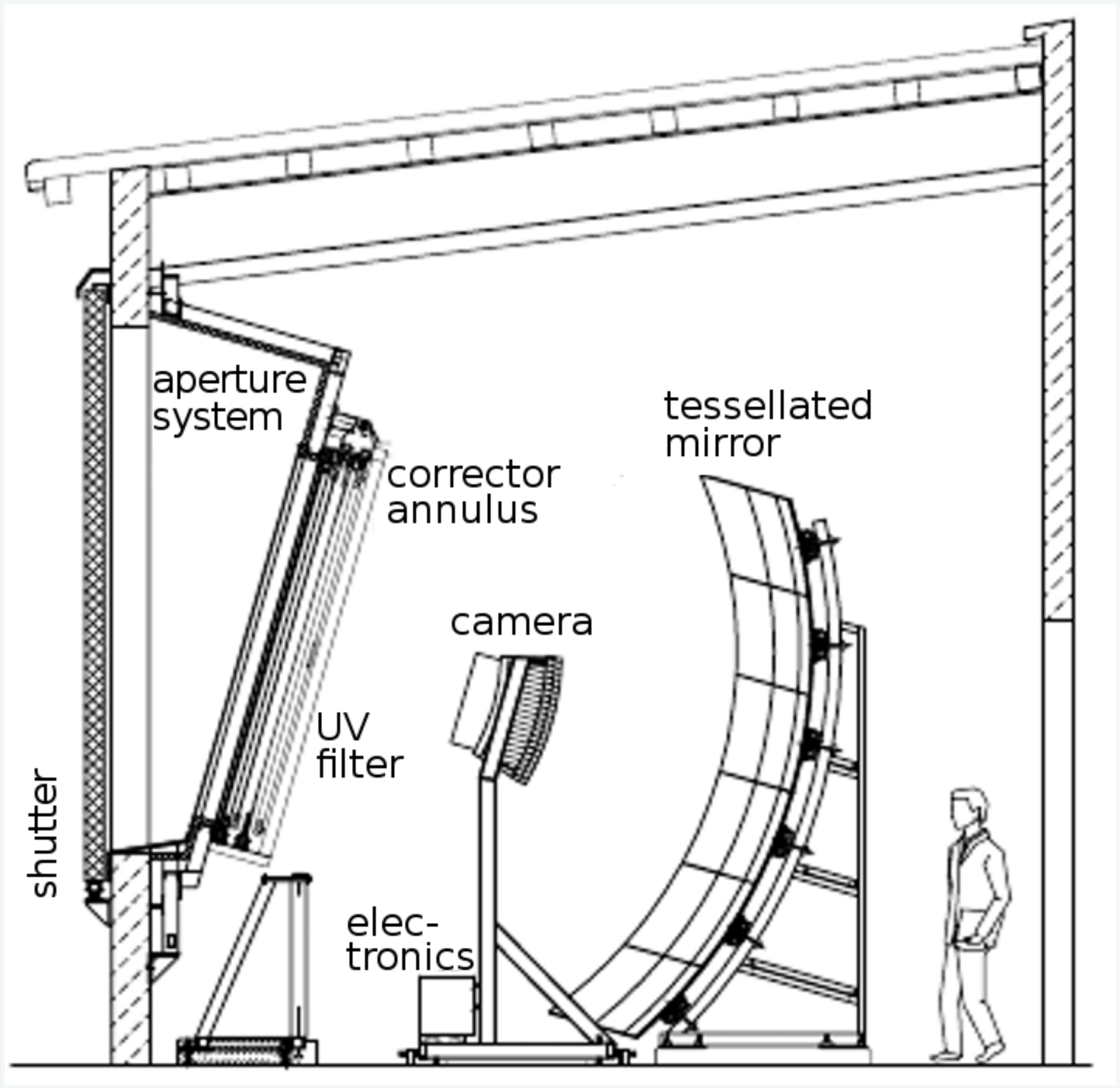




A very high-energy cosmic ray (~10^{19} eV) simultaneously detected by the Fluorescence Detector (FD) and the Surface Detector (SD) – 21st May 2007







aperture
system
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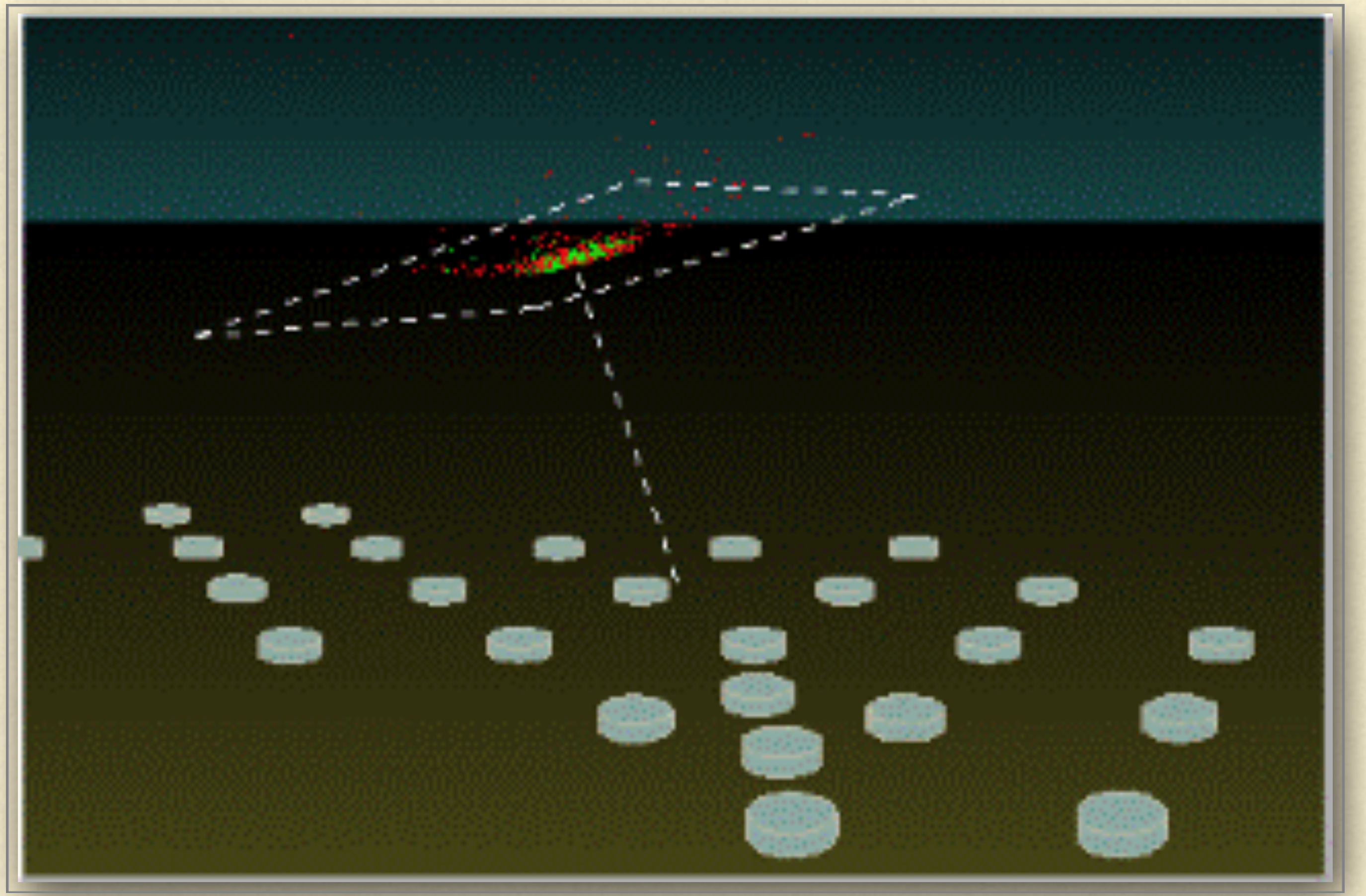
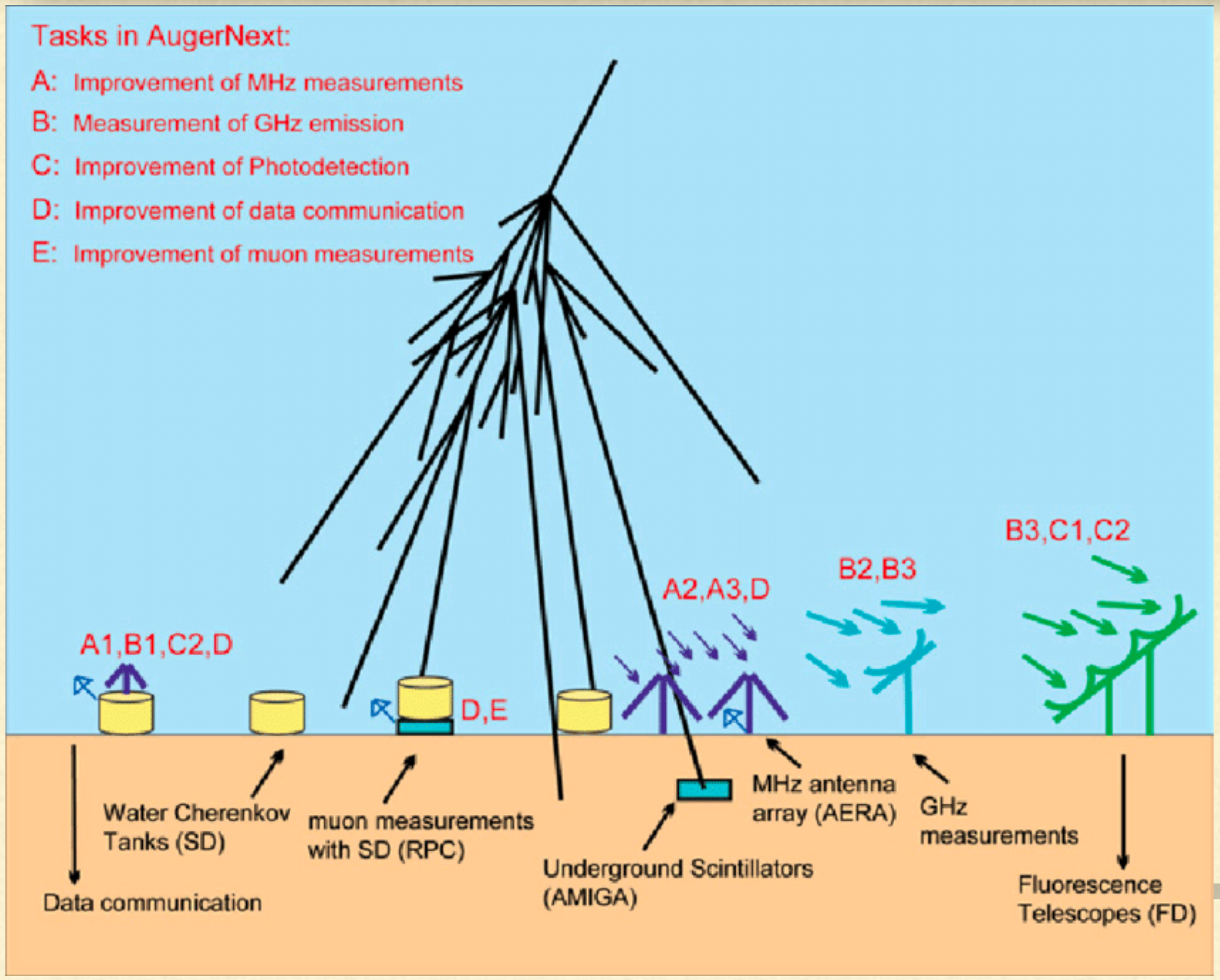
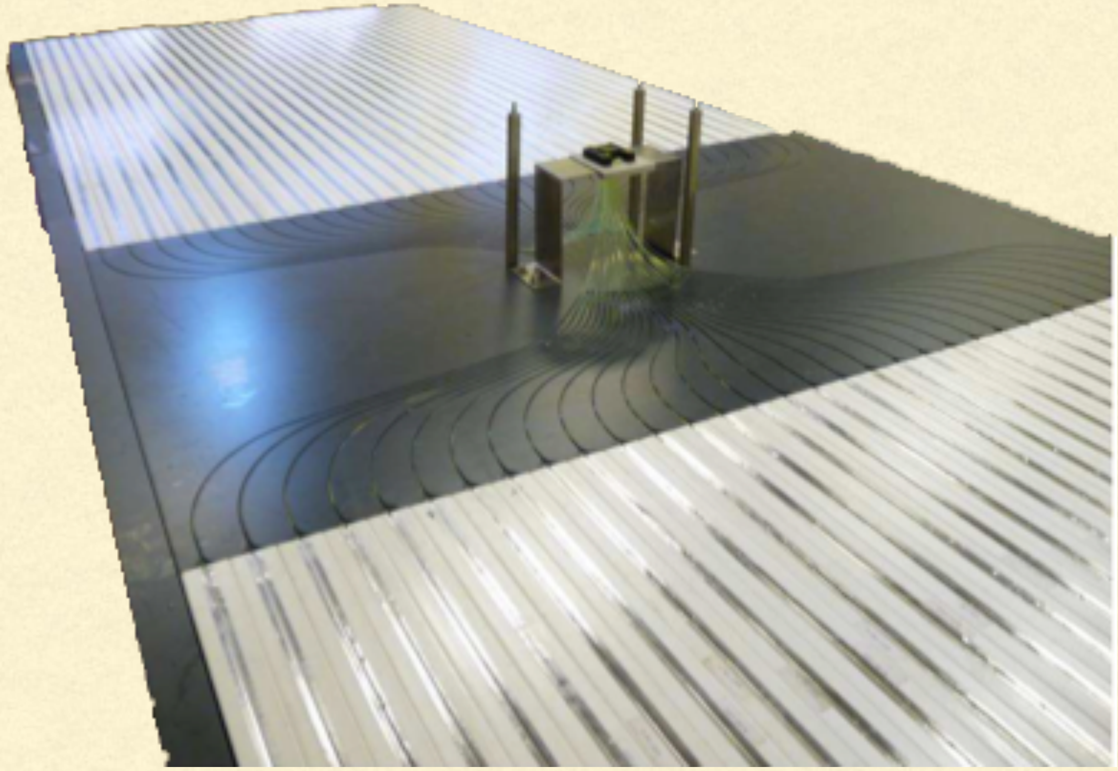
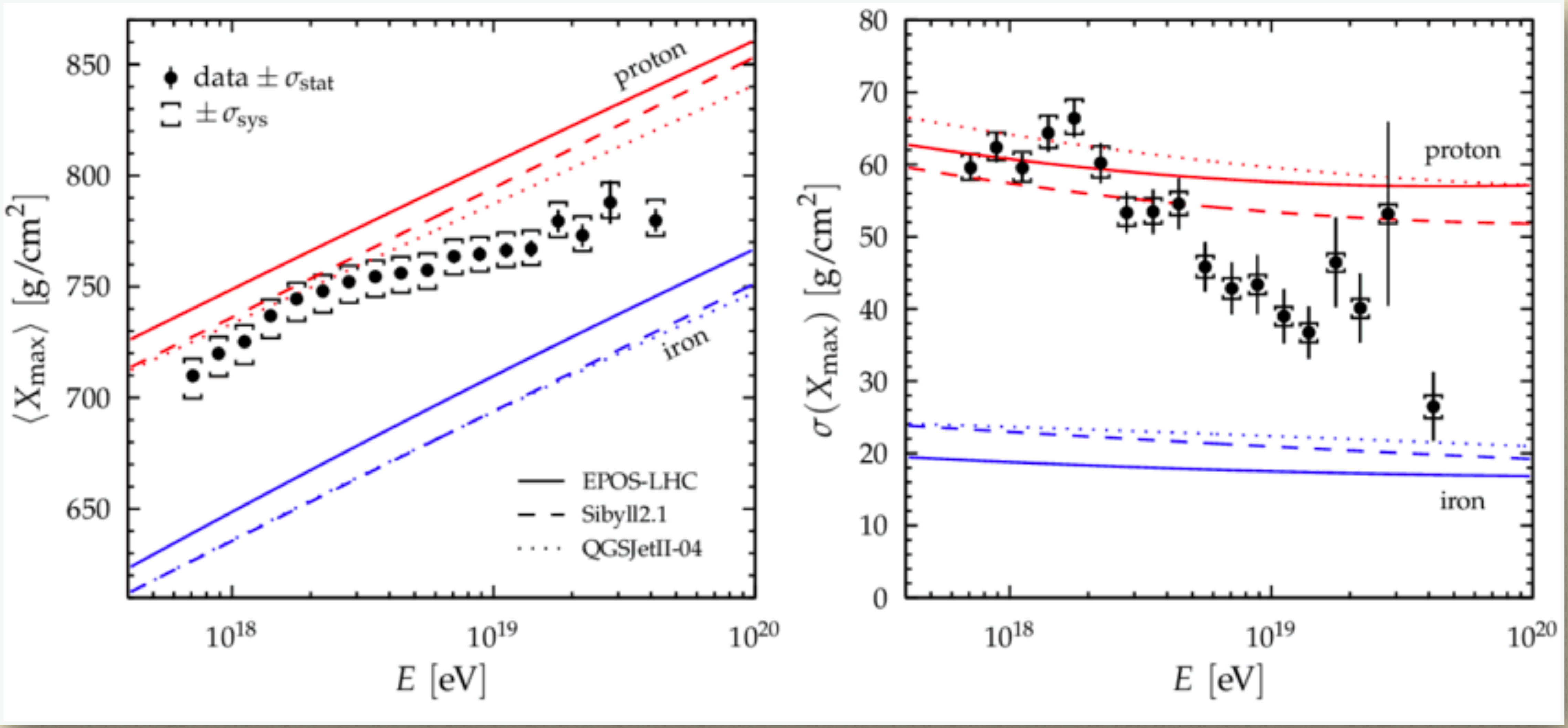




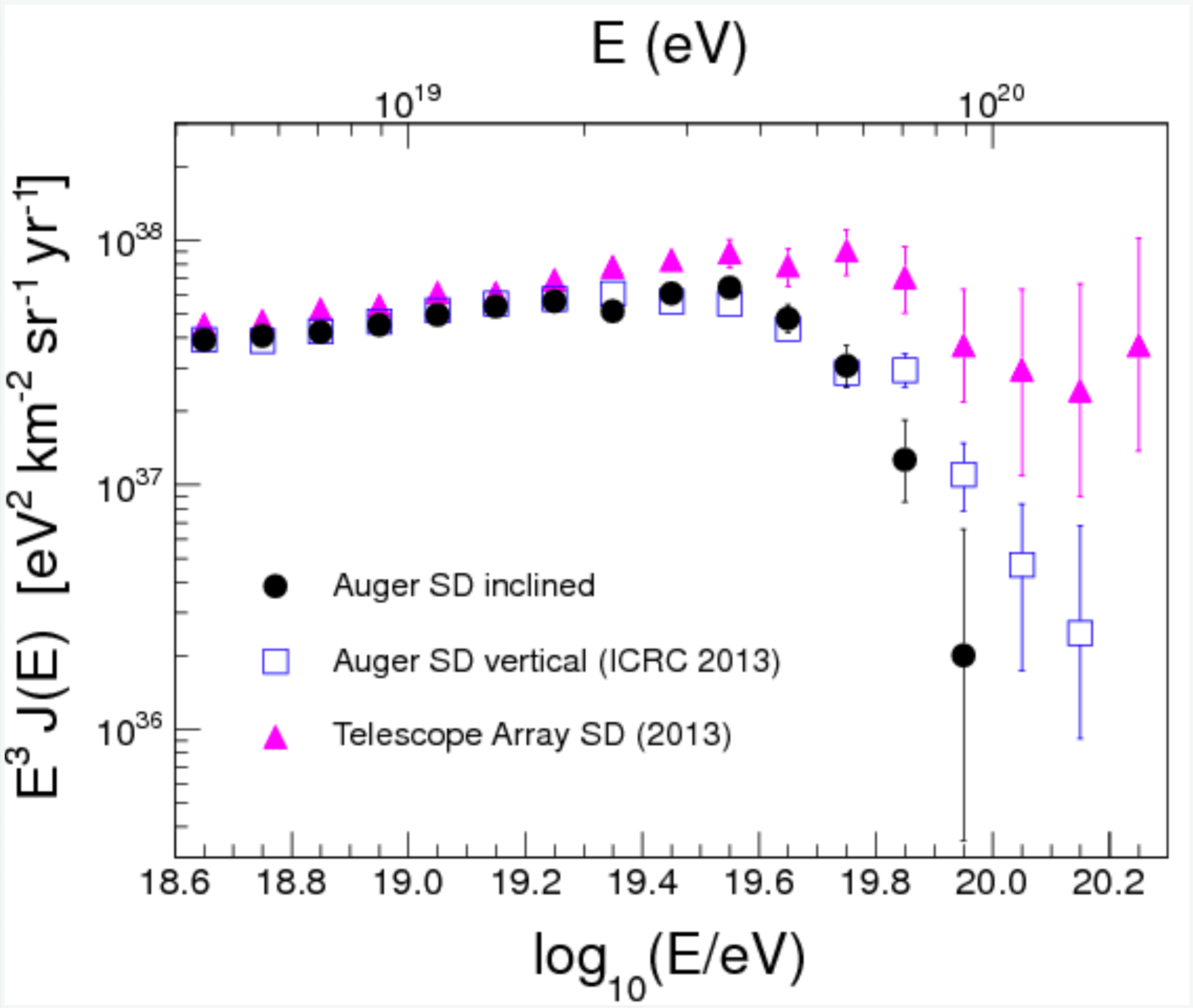


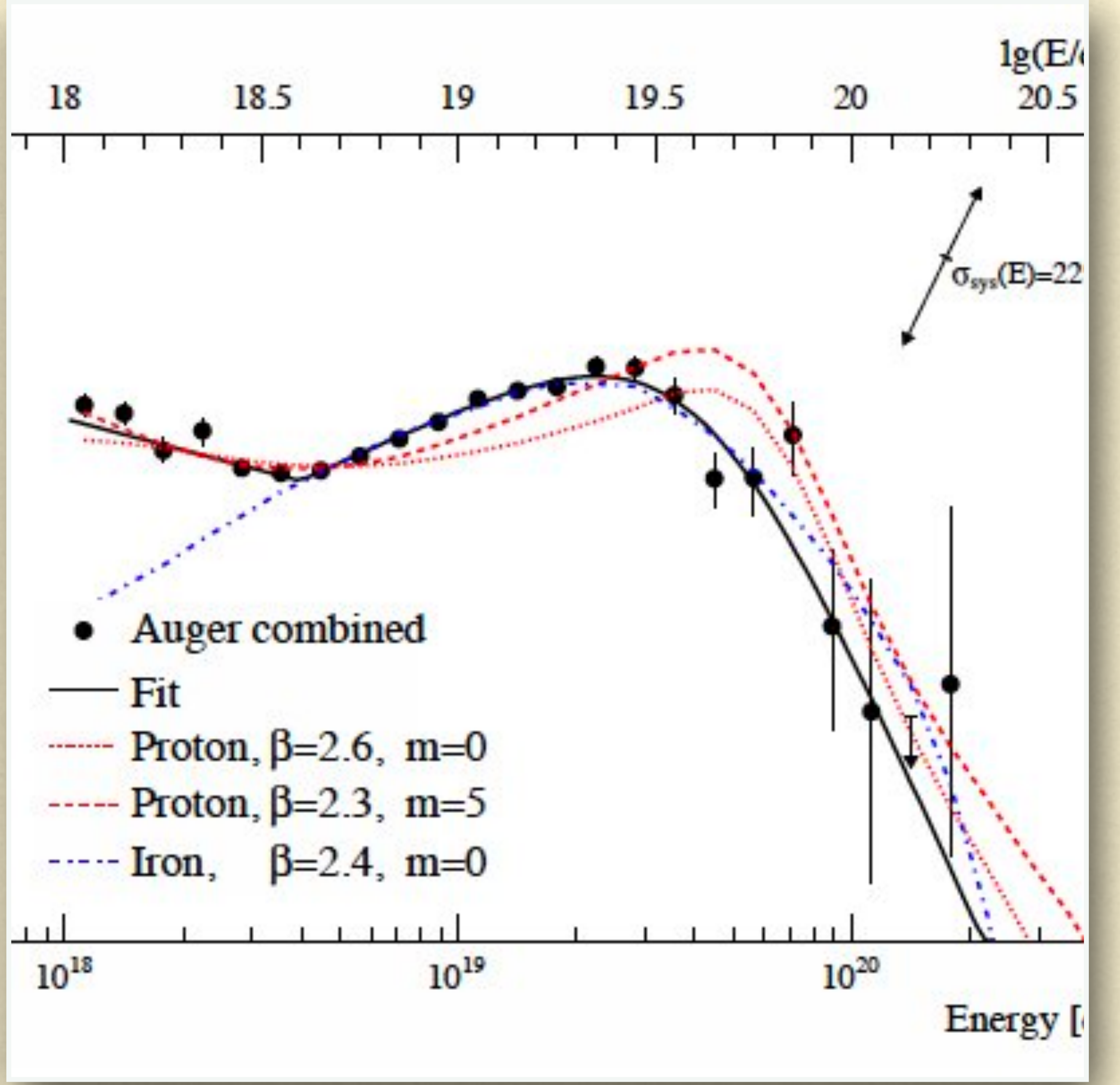
Detectores de muones subterráneos: AMIGA

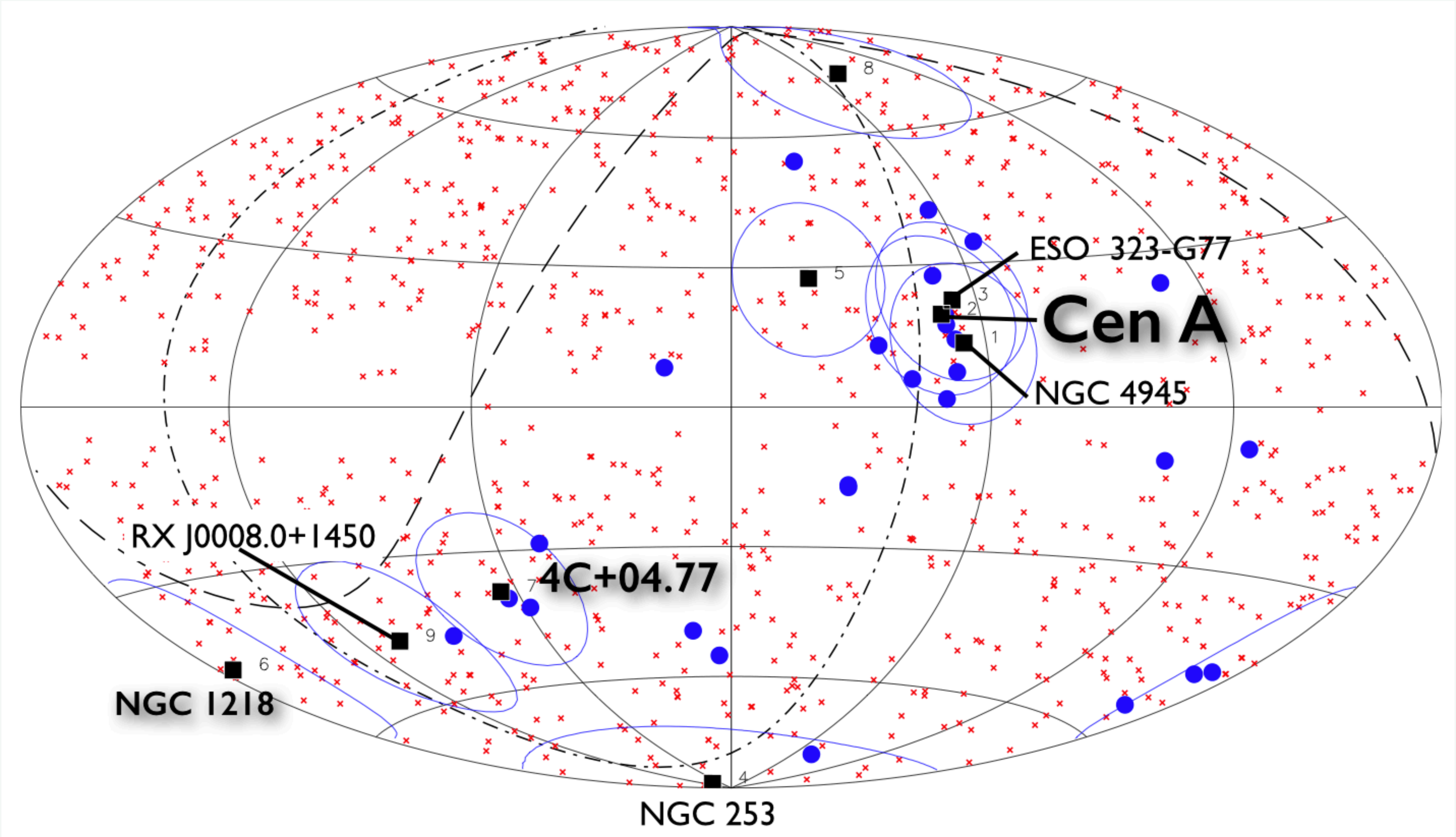
Auger: resultados



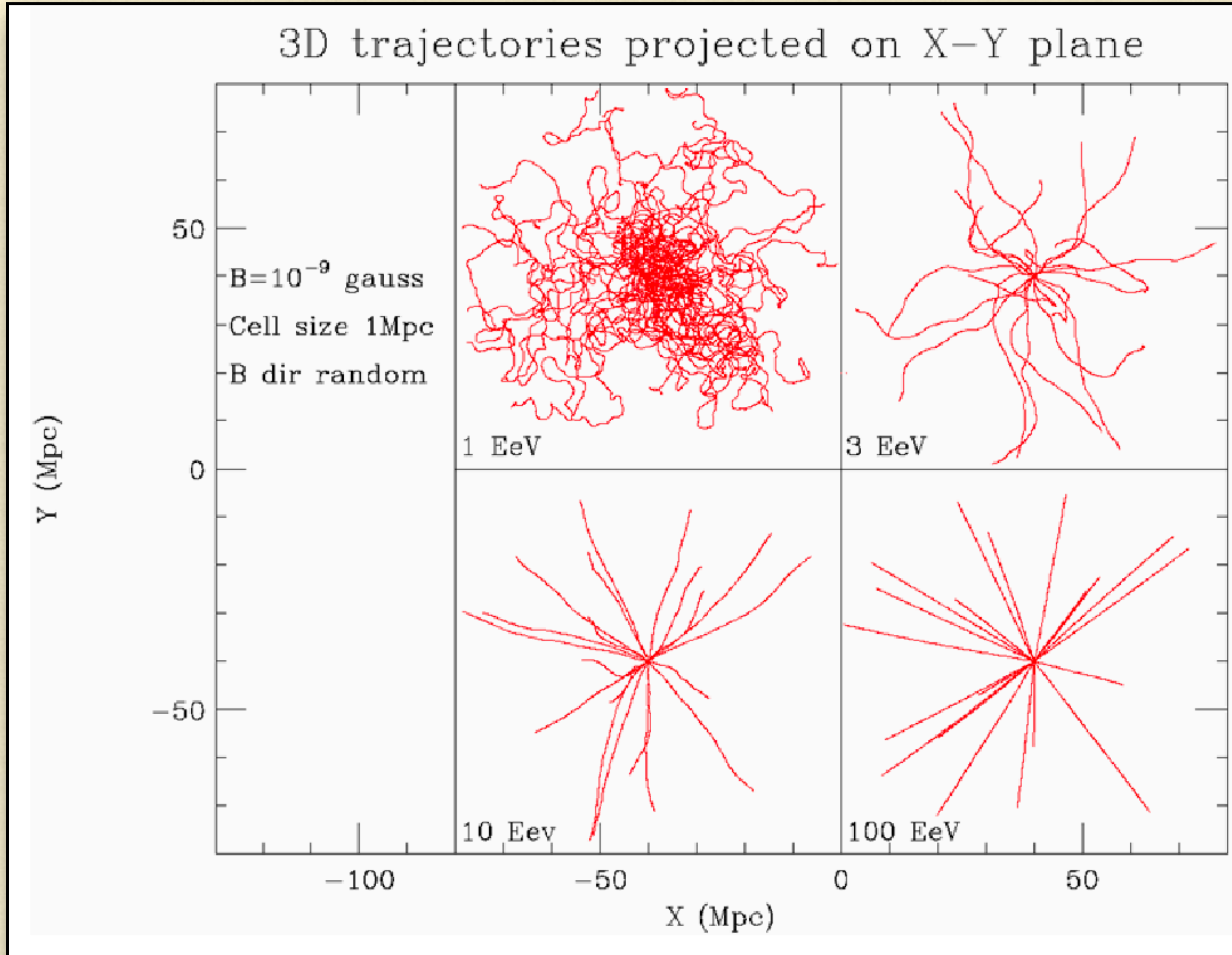
Auger: resultados

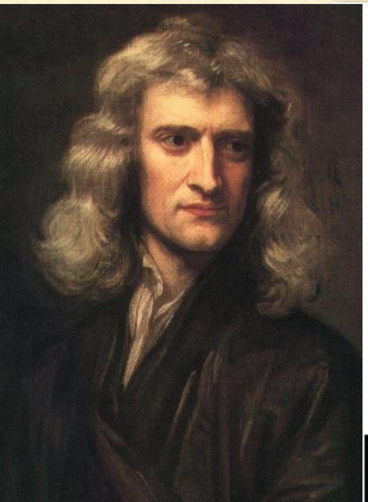






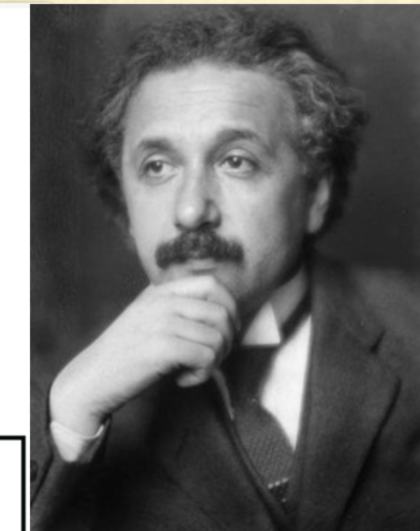
8
5
ESO 323-G77
3
2
Cen A
1
NGC 4945
RX J0008.0+1450
4C+04.77
7
9
6
NGC 1218
4
NGC 253

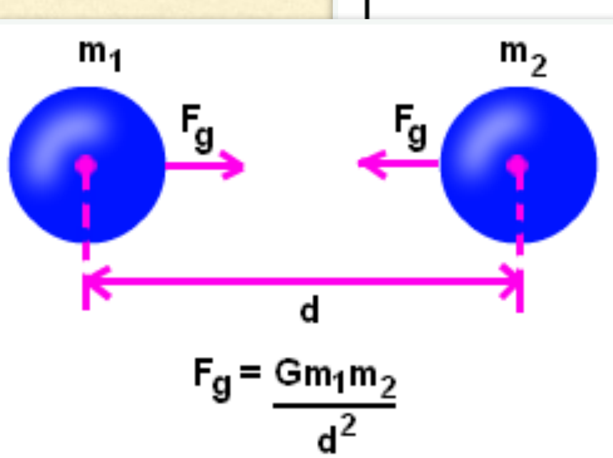

3D trajectories projected on X−Y plane
B=10^−9 gauss
Cell size 1Mpc
B dir random
1 EeV
3 EeV
10 Eev
100 EeV
50
0
−50
−100
−50
0
50
Y (Mpc)
X (Mpc)

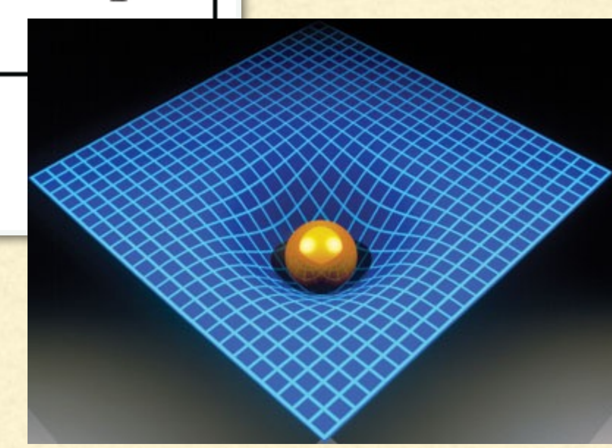


Newtonian vs General Relativistic gravity

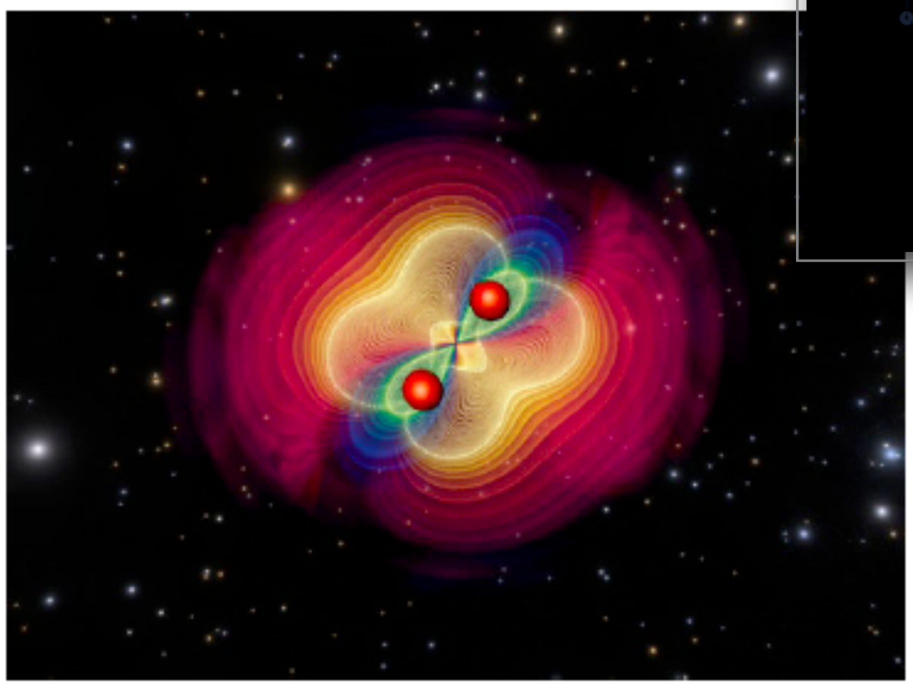
Newtonian field equations	GR field equations
$\nabla^2\Phi = 4\,\pi G\rho$	$G^{ab} = \frac{8\pi G}{c^4} T^{ab}$
Source: mass density Gravitational field: scalar Φ	Source: energy-momentum tensor (includes mass densities/currents) Gravitational field: metric tensor g_{ab}

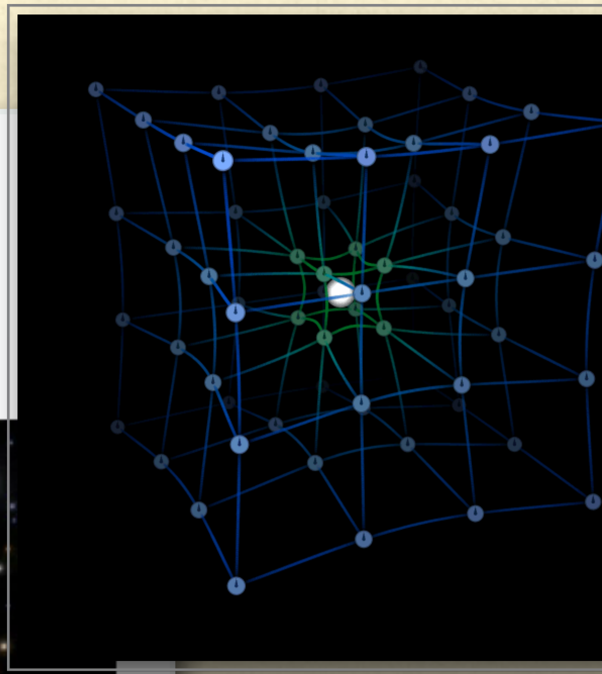




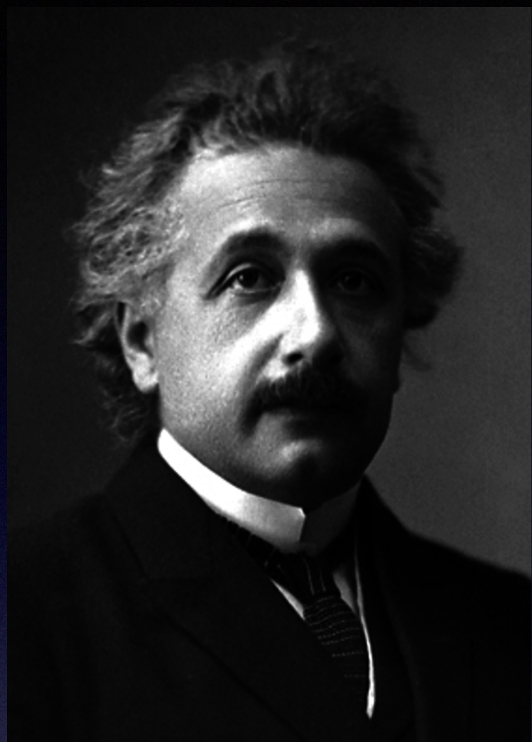


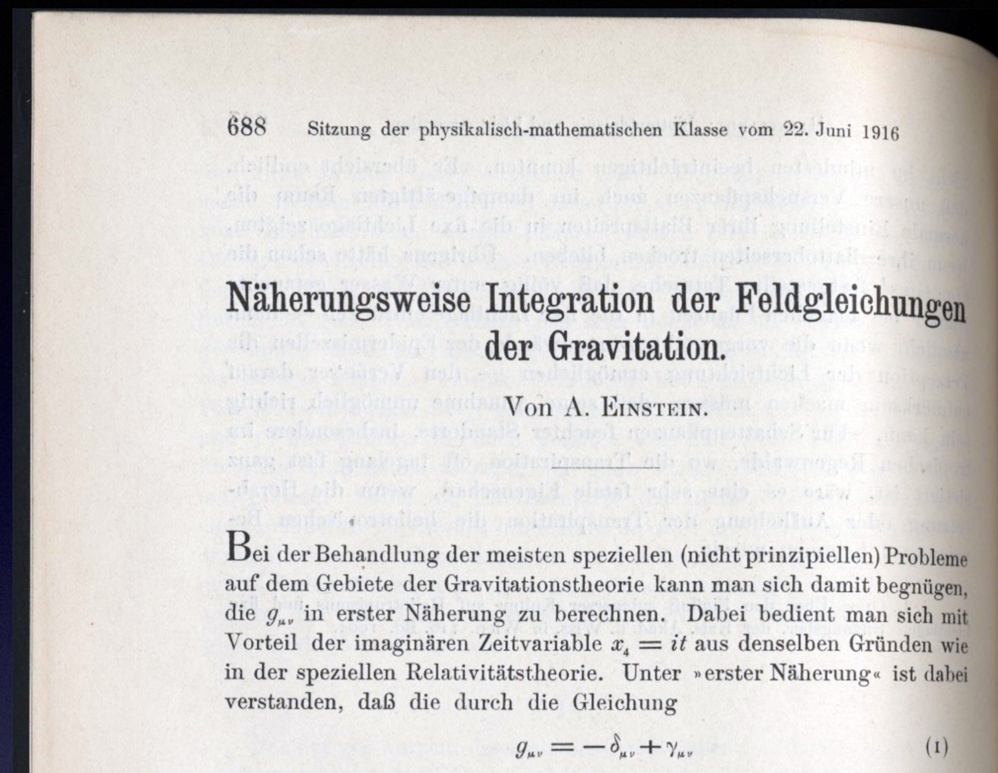
- Electromagnetism: accelerating charges produce EM radiation.





- Gravitation: accelerating masses produce gravitational radiation.
(another hint: gravity has finite speed.)





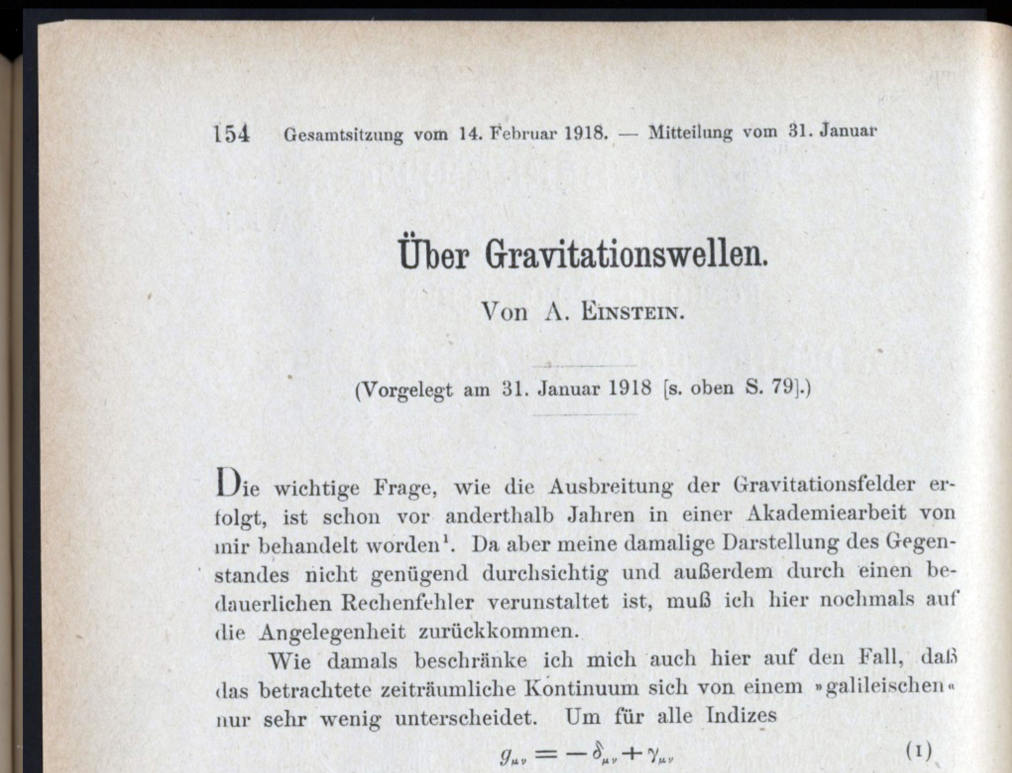
688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

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

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



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

Über Gravitationswellen.

Von A. Einstein.

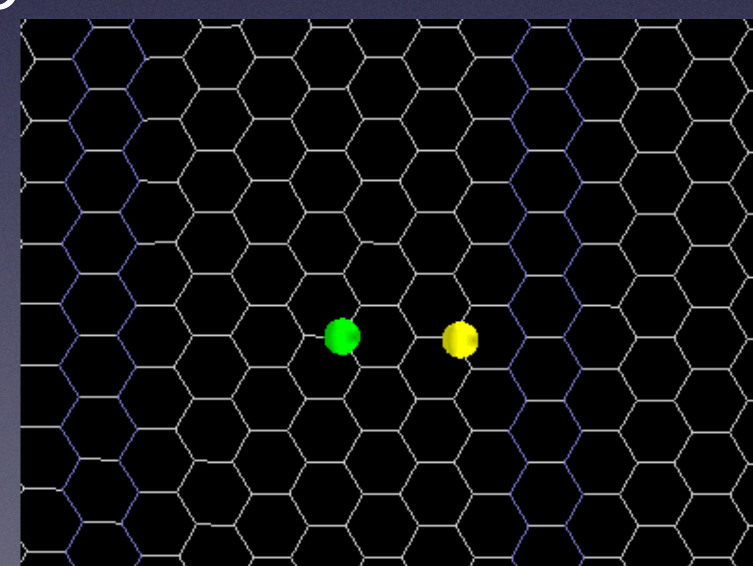
(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

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

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

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

Two seminal papers 1916 1918



GWs in linear gravity

- We consider weak gravitational fields:

$$g_{\mu\nu} \approx \eta_{\mu\nu} + h_{\mu\nu} + \mathcal{O}(h^2_{\mu\nu})$$

↑ flat Minkowski metric

- The GR field equations in vacuum reduce to the standard wave equation:

$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2\right) h^{\mu\nu} = \Box h^{\mu\nu} = 0$$

- Comment: GR gravity like electromagnetism has a "gauge" freedom associated with the choice of coordinate system. The above equation applies in the so-called "transverse-traceless (TT)" gauge where

$$h_{0\mu} = 0, \qquad h^{\mu}_{\mu} = 0$$

Wave solutions

- Solving the previous wave equation in weak gravity is easy. The solutions represent "plane waves":

$$h_{\mu\nu} = A_{\mu\nu} e^{ik_a x^a}$$

wave-vector

- Basic properties: $A_{\mu\nu} k^\mu = 0,\qquad k_a k^a = 0$

transverse waves

null vector = propagation along light rays

- Amplitude: $A^{\mu\nu} = h_+ e_+^{\mu\nu} + h_\mathrm{x} e_\mathrm{x}^{\mu\nu}$

two polarizations

$$\epsilon_+^{\mu\nu} \equiv \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \qquad \epsilon_\times^{\mu\nu} \equiv \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

GWs: more properties

- EM waves: at lowest order the radiation can be emitted by a dipole source (l=1). Monopolar radiation is forbidden as a result of charge conservation.

- GWs: the lowest allowed multipole is the quadrupole (l=2). The monopole is forbidden as a result of mass conservation. Similarly, dipole radiation is absent as a result of momentum conservation.

- GWs represents propagating “ripples in spacetime” or, more accurately, a propagating curvature perturbation. The perturbed curvature (Riemann tensor) is given by (in the TT gauge):

$$R^{\mathrm{TT}}_{j0k0} = -\frac{1}{2}\,\partial_t^2 h^{\mathrm{TT}}_{jk}\,, \qquad j,k = 1,2,3$$

Basic estimates

- Another estimate for the GW amplitude can be derived from the flux formula

$$F_{\rm GW} = \frac{L_{\rm GW}}{4\pi r^2} = \frac{c^3}{16\pi G}|\partial_t h|^2$$

- We obtain:

$$h \approx 10^{-22}\left(\frac{E_{\rm GW}}{10^{-4}\,M_\odot}\right)^{1/2}\left(\frac{1\,{\rm kHz}}{f_{\rm GW}}\right)\left(\frac{\tau}{1\,{\rm ms}}\right)^{-1/2}\left(\frac{15\,{\rm Mpc}}{r}\right)$$

for example, this formula could describe the GW strain from a supernova explosion at the Virgo cluster during which the energy $E_{\rm GW}$ is released in GWs at a frequency of 1 kHz, and with signal duration of the order of 1 ms.

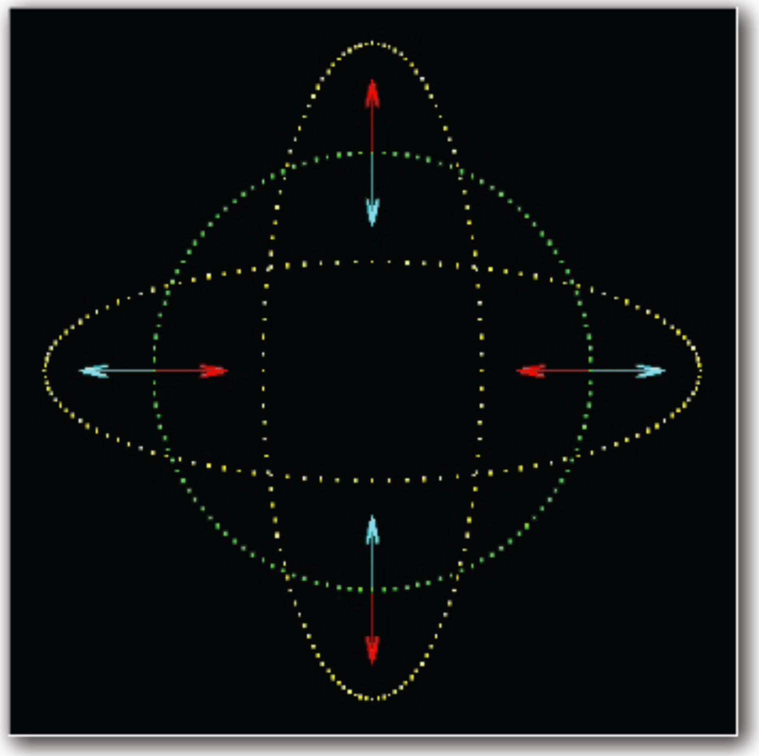
- This is why GWs are hard to detect: for a GW detector with arm length of $l = 4\,{\rm km}$ we are looking for changes in the arm-length of the order of

$$\Delta l = hl = 4\times 10^{-17}\,{\rm cm} \quad !!$$

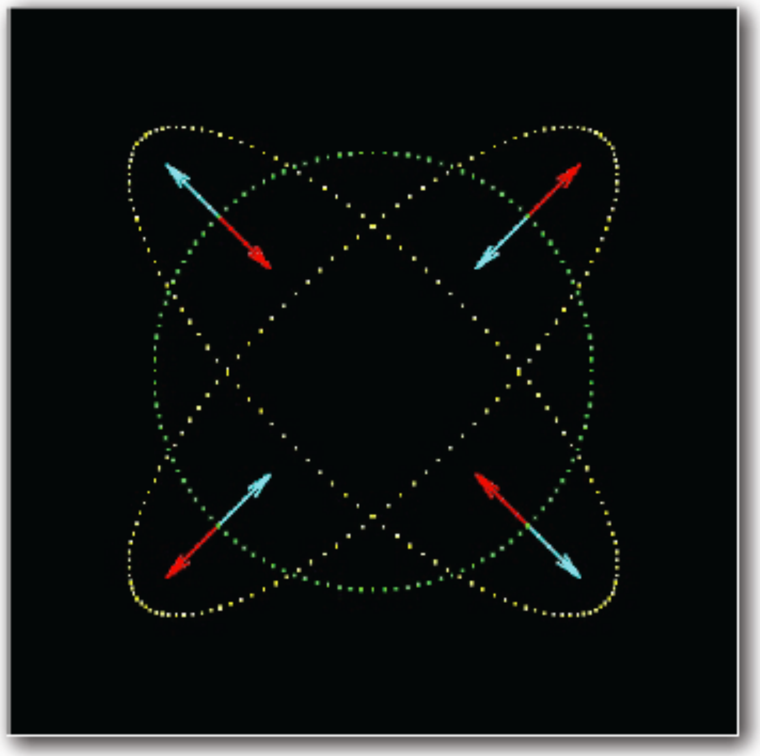
$r_{\rm proton} \sim 0.87\times 10^{-17}$ cm

GWs: polarization

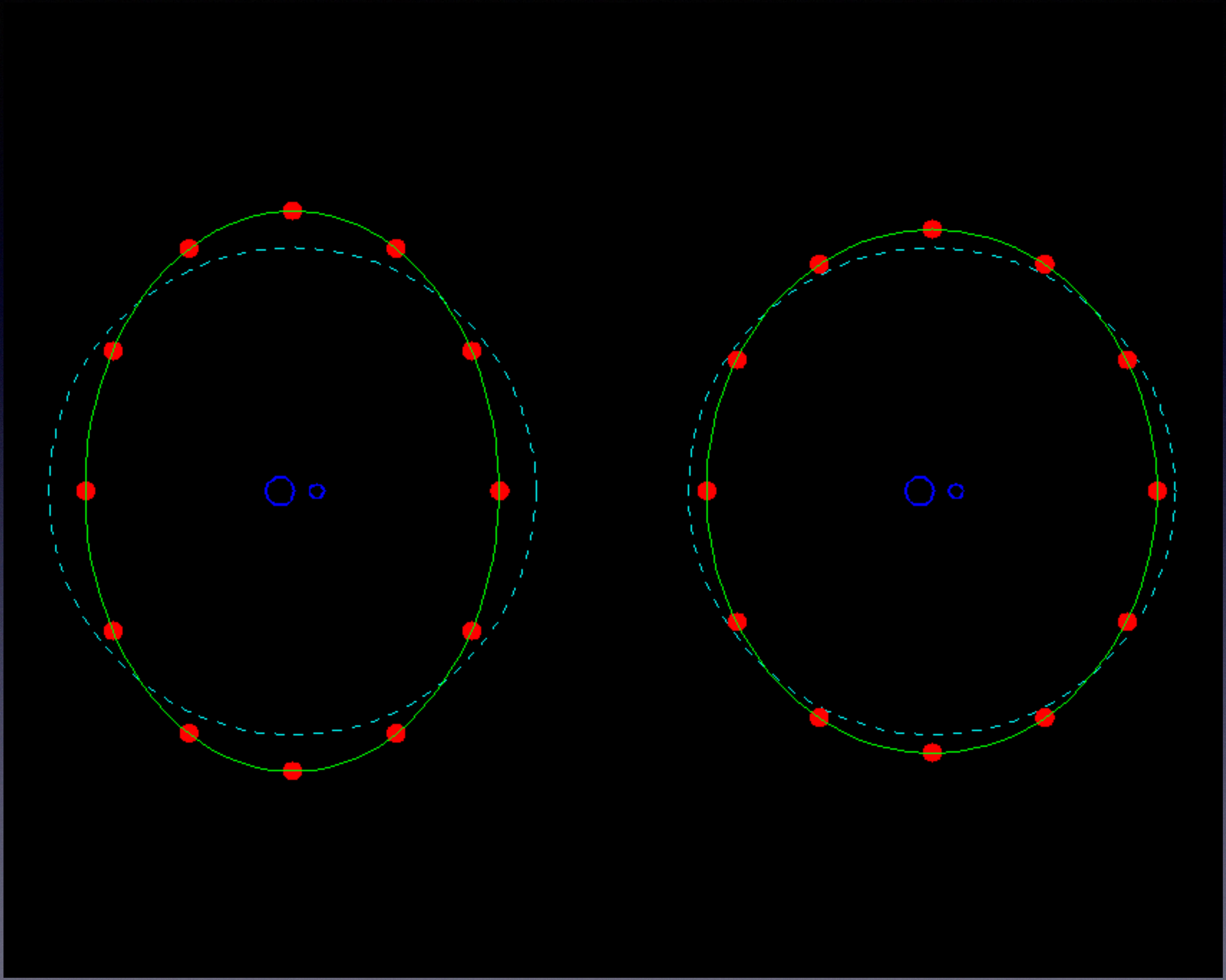
- GWs come in two polarizations:

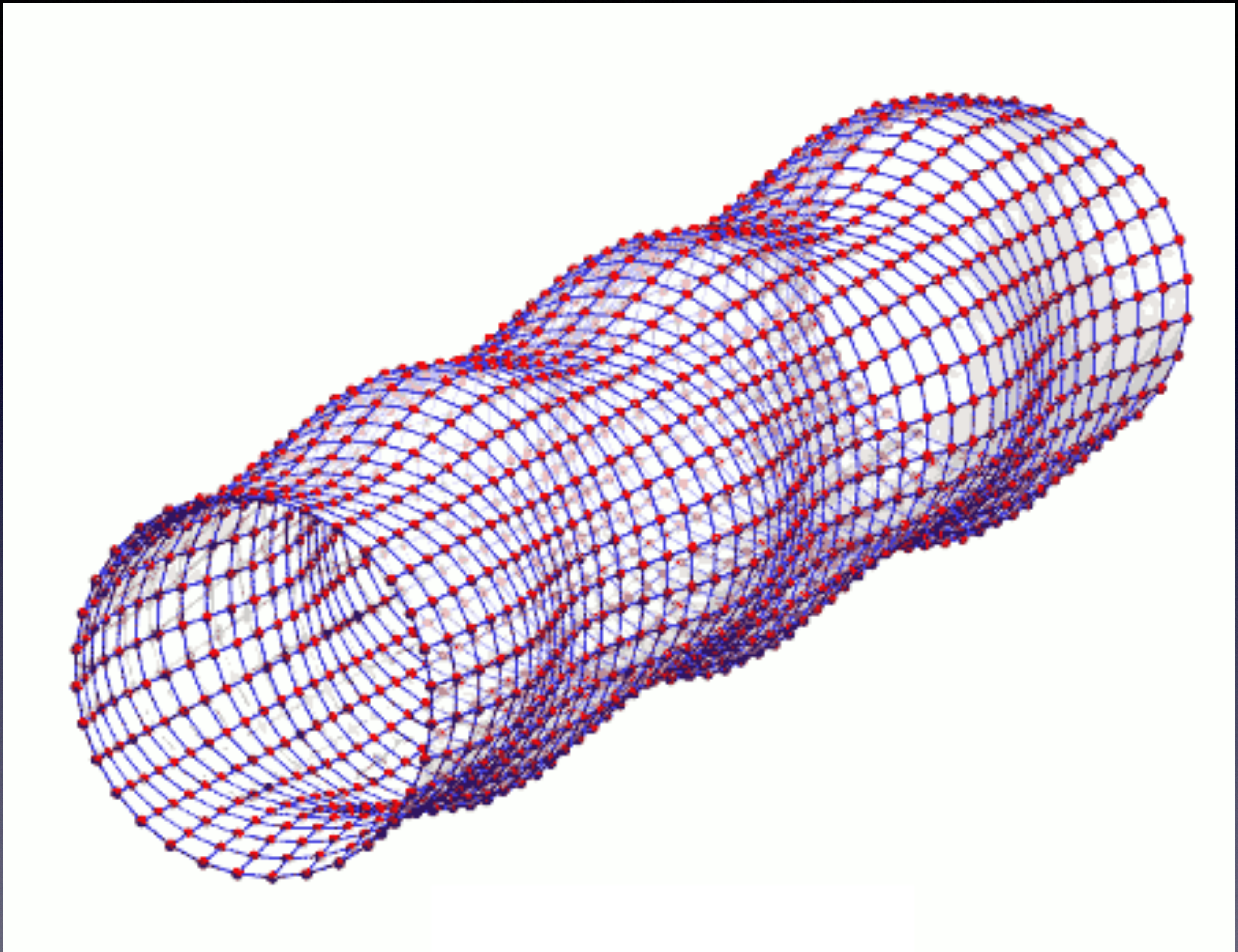


“+” polarization



“x” polarization

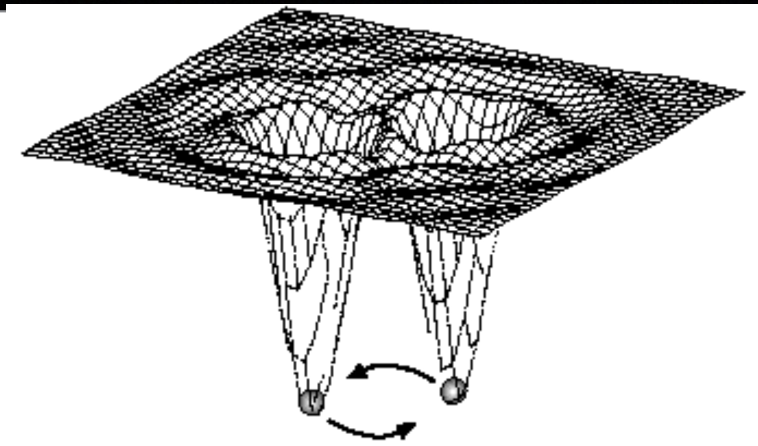




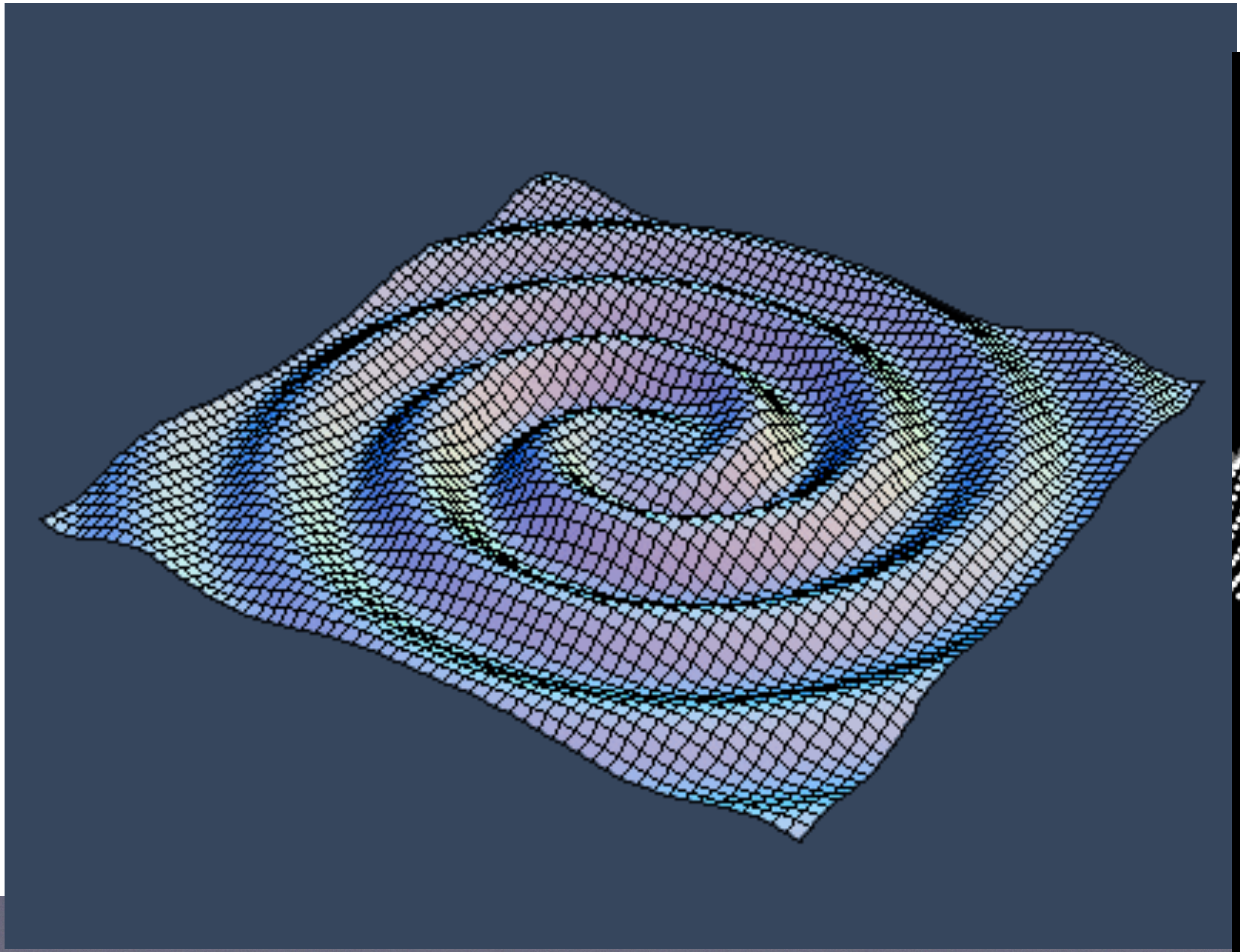
+ waves

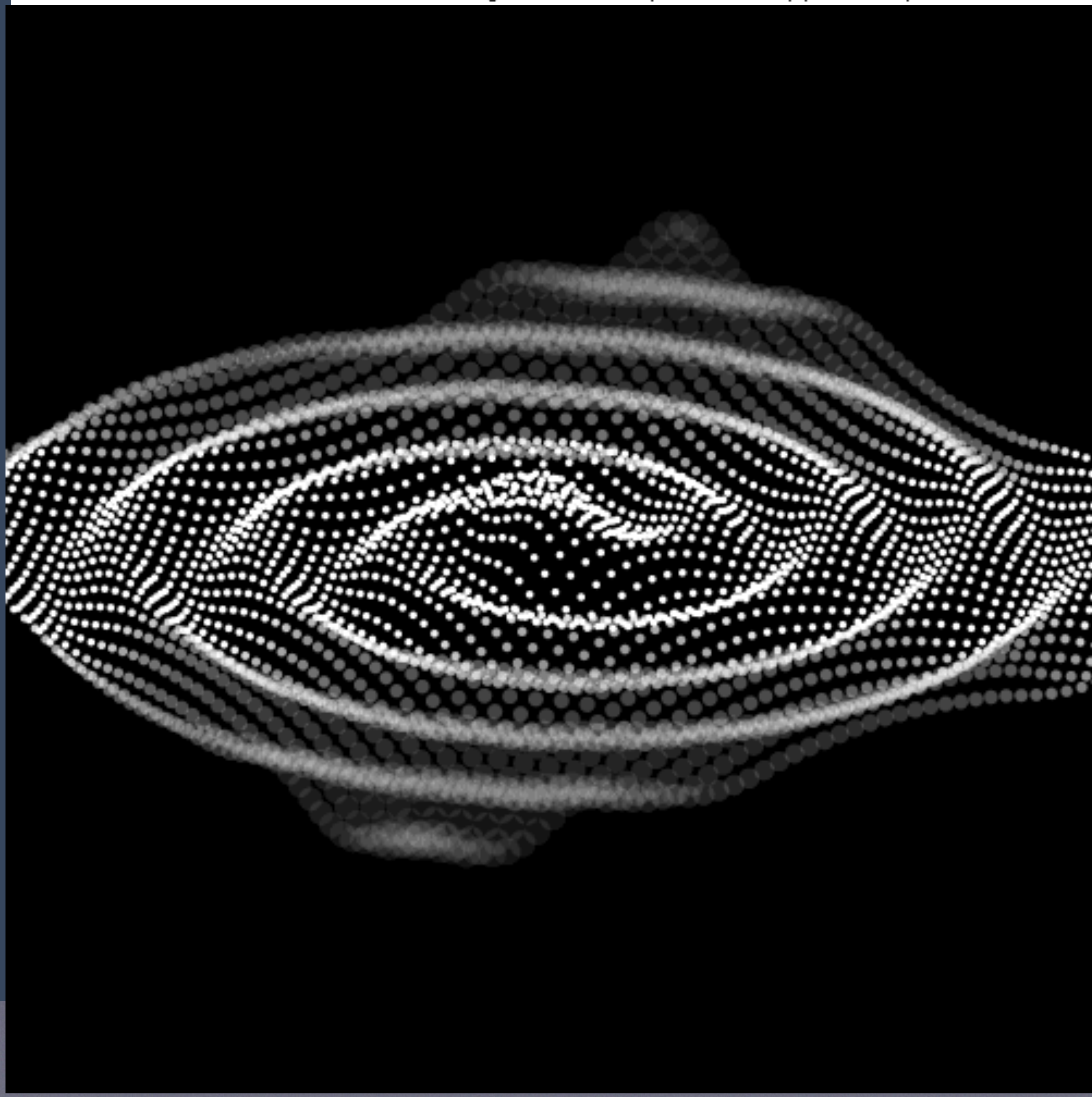
GWs and curvature

- As we mentioned, GWs represent a fluctuating curvature field.



A binary system of compact massive objects rapidly orbiting each other produces ripples in spacetime.





GWs vs EM waves

- Similarities:

✓ Propagation with the speed of light.

✓ Amplitude decreases as ~ 1/r.

✓ Frequency redshift (Doppler, gravitational, cosmological).

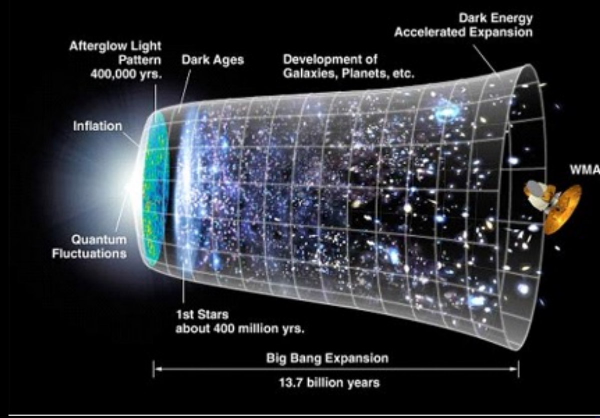
- Differences:

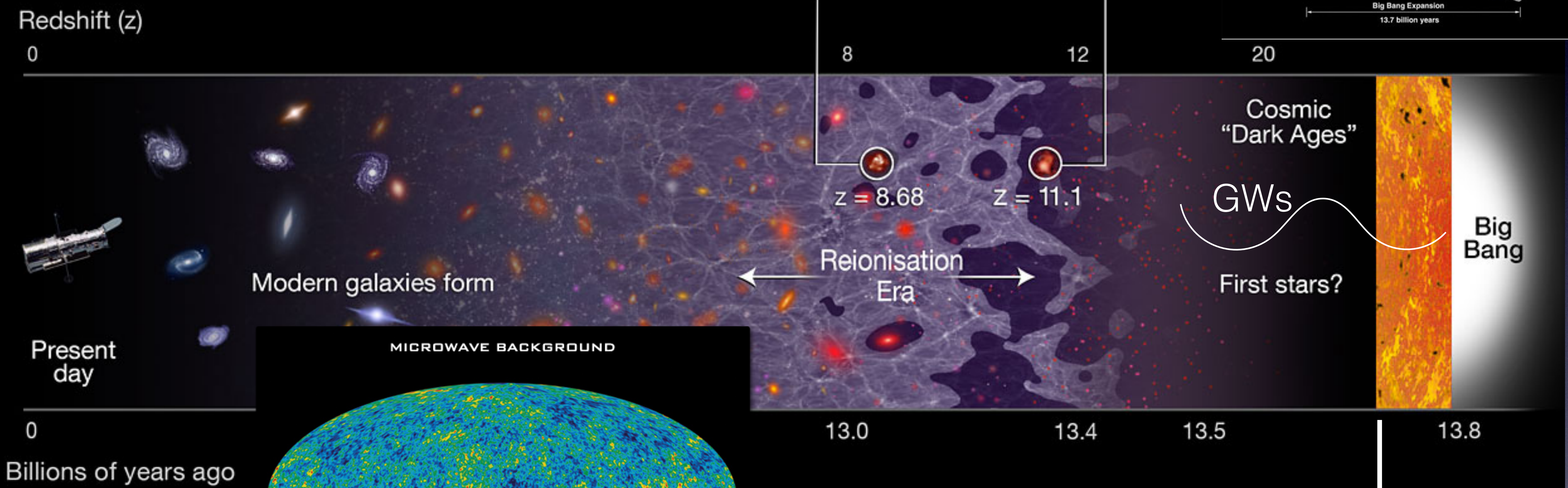
✓ GWs propagate through matter with little interaction. Hard to detect, but they carry uncontaminated information about their sources.

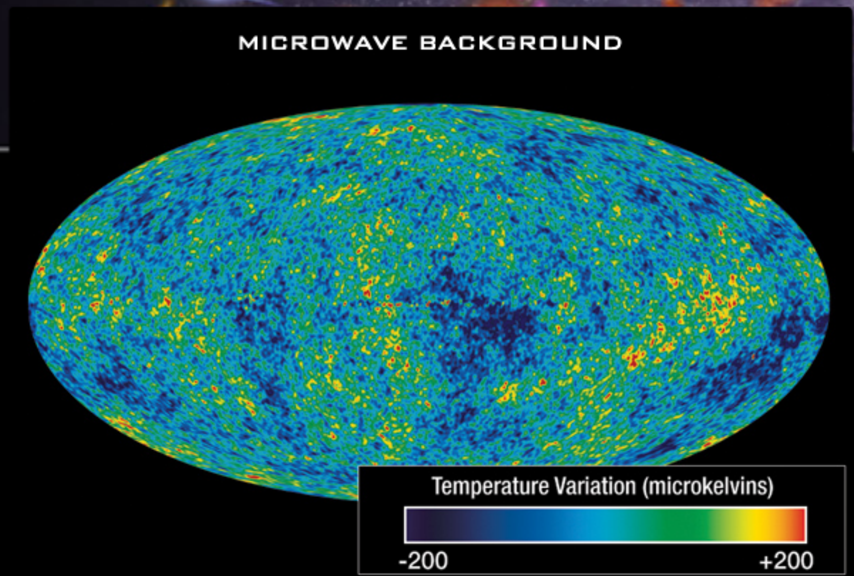
✓ Strong GWs are generated by bulk (coherent) motion. They require strong gravity/high velocities (compact objects like black holes and neutron star).

✓ EM waves originate from small-scale, incoherent motion of charged particles. They are subject to “environmental” contamination (interstellar absorption etc.).

GW can propagate from the inflationary period, if it existed, to the present, contrary to EM waves





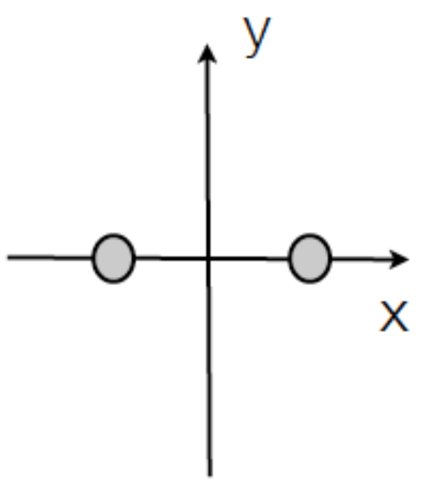


B-modes in the polarization.
E.g. QUBIC instrument

Effect on test particles

- We consider a pair of test particles on the cartesian axis Ox at distances $\pm x_0$ from the origin and we assume a GW traveling in the z-direction.

- Their distance will be given by the relation:



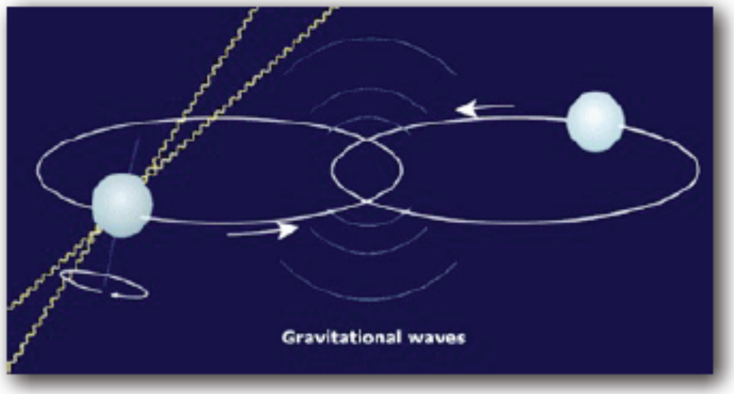
$$dl^2 = g_{\mu\nu} dx^\mu dx^\nu = ... = -g_{11} dx^2 =$$

$$= (1 - h_{11})(2x_0)^2 = [1 - h_+ \cos(\omega t)] \, (2x_0)^2$$

$$dl \approx \left[1 - \frac{1}{2} h_+ \cos(\omega t)\right] (2x_0)$$

PSR 1913+16: a Nobel-prize GW source

- The now famous Hulse & Taylor binary neutron star system provided the first astrophysical evidence of the existence of GWs !



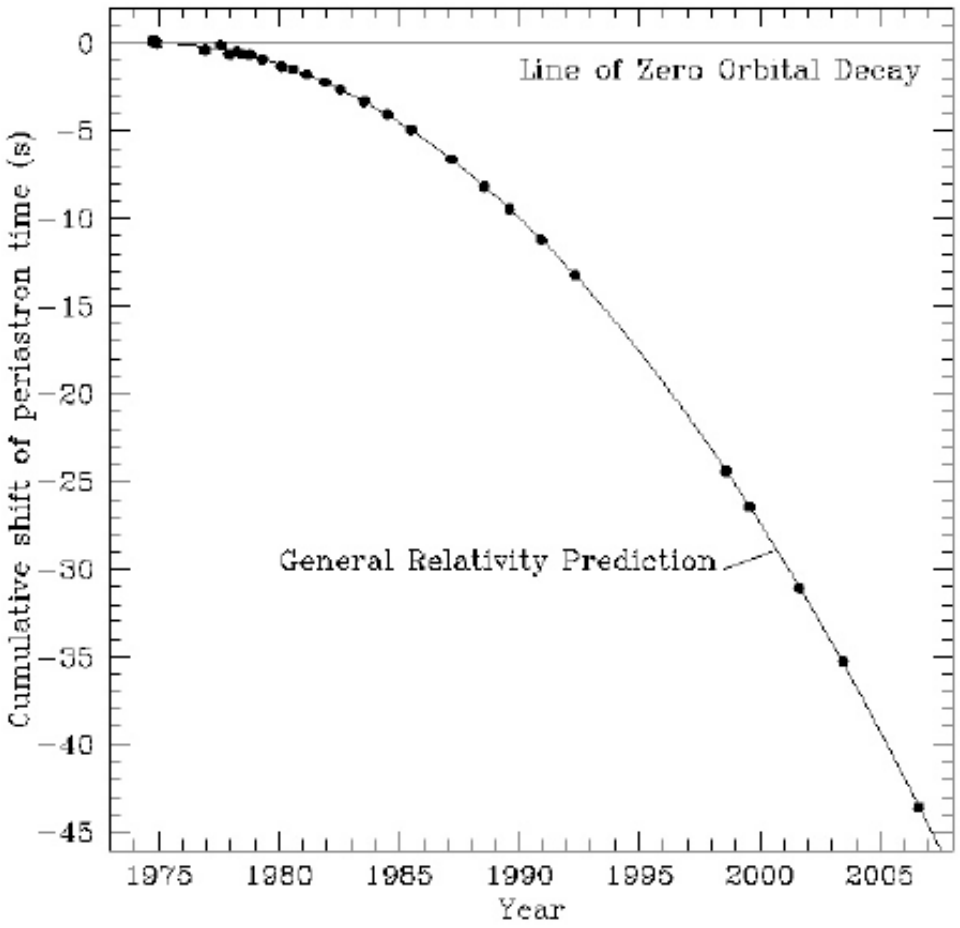
- The system's parameters: $r = 5\,\mathrm{Kpc}, \quad M_1 \approx M_2 \approx 1.4\,M_\odot, \quad T = 7\,\mathrm{h}\ 45\,\mathrm{min}$

- Using the previous equations we can predict:

$$\dot{T} = -2.4 \times 10^{-12}\,\mathrm{sec/sec}, \qquad f_{\mathrm{GW}} = 7 \times 10^{-5}\,\mathrm{Hz}, \qquad h \sim 10^{-23}, \quad \tau \approx 3.5 \times 10^{8}\,\mathrm{yr}$$

Theory vs observations

- How can the orbital parameters be measured with such high precision?
- One of the neutron stars is a pulsar, emitting extremely stable periodic radio pulses. The emission is modulated by the orbital motion.
- Since the discovery of the H-T system in 1974 more such binaries were found by astronomers.



A toy model GW detector

- Consider a GW propagating along the z-axis (with a "+" polarization and frequency ω), impinging on an idealized detector consisting of two masses joined by a spring (of length L) along the x-axis

- The resulting motion is that of a forced oscillator (with friction τ, natural frequency ω_0):

$$\ddot{\xi} + \dot{\xi}/\tau + \omega_0^2 \xi = -\frac{1}{2}\omega^2 L h_+ e^{i\omega t}$$

- The solution is:

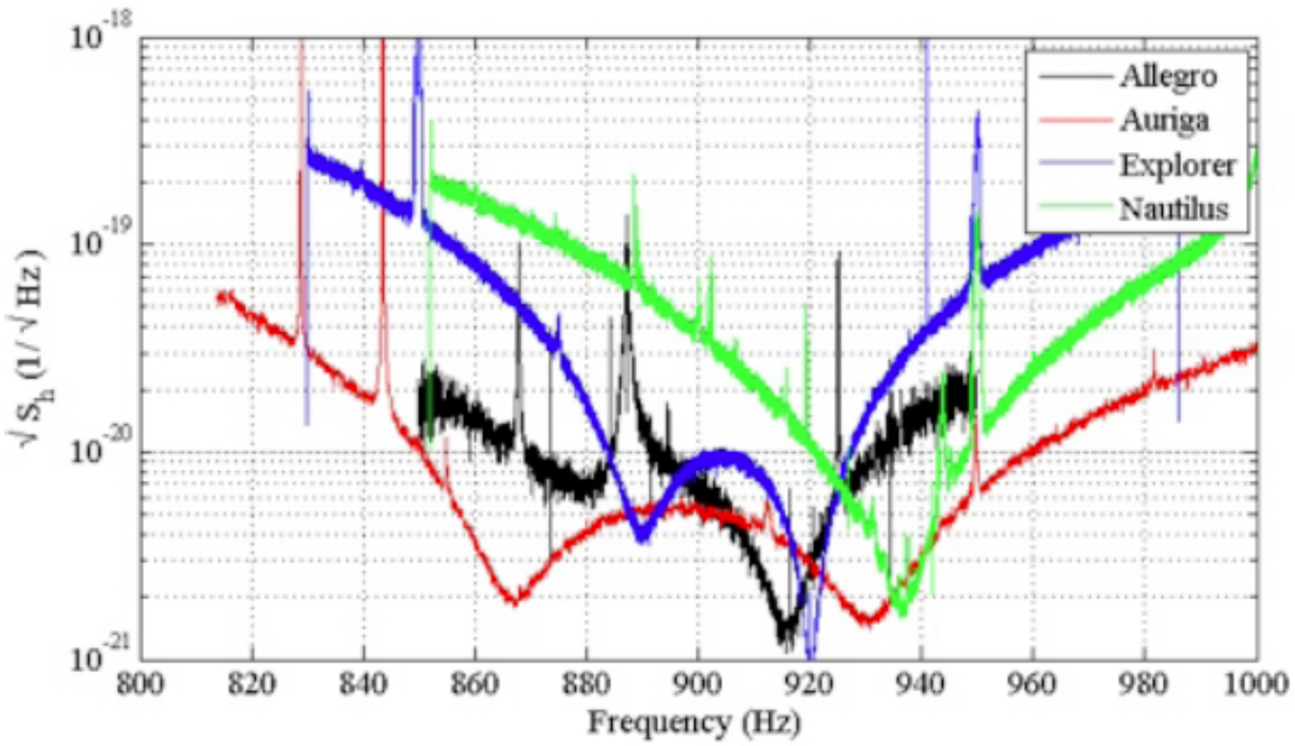
$$\xi = \frac{\omega^2 L h_+}{2(\omega_0^2 - \omega^2 + i\omega/\tau)} e^{i\omega t}$$

- The maximum amplitude is achieved at $\omega \approx \omega_0$ and has a size: $\xi_{\max} = \frac{1}{2}\omega_0 \tau L h_+$

- The detector can be optimized by increasing $\omega_0 \tau L$.

Bar detectors

- Bar detectors are narrow bandwidth instruments (like the previous toy-model)



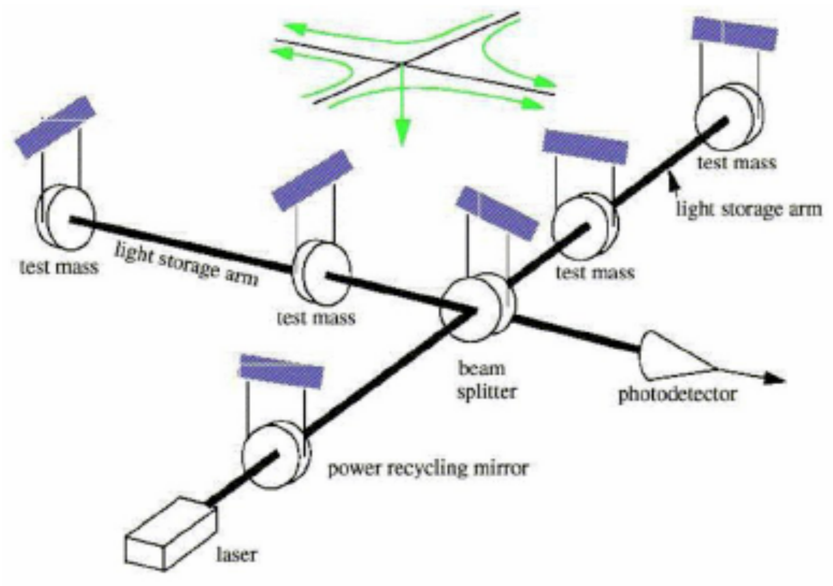
Sensitivity curves of various bar detectors

Joseph Weber

Detectors: laser interferometry

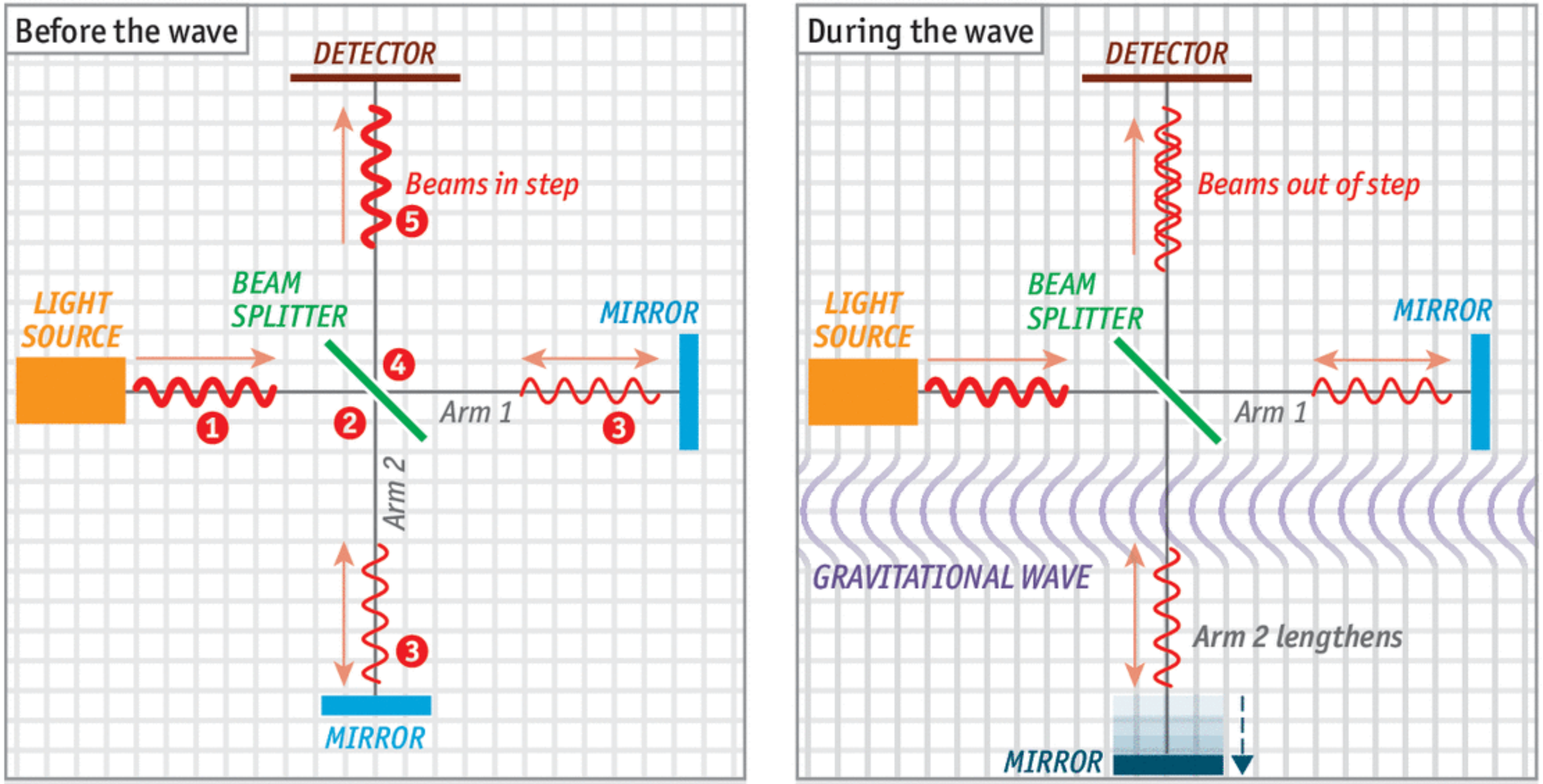
- A laser interferometer is an alternative choice for GW detection, offering a combination of very high sensitivities over a broad frequency band.

- Suspended mirrors play the role of “test-particles”, placed in perpendicular directions. The light is reflected on the mirrors and returns back to the beam splitter and then to a photodetector where the fringe pattern is monitored.



Catching a wave

How a laser-interferometer observatory works



The light source sends out a beam 1 that is divided by a beam splitter 2. The half-beams produced follow paths of identical length 3, reflecting off mirrors to recombine 4, then travel in step to the detector 5.

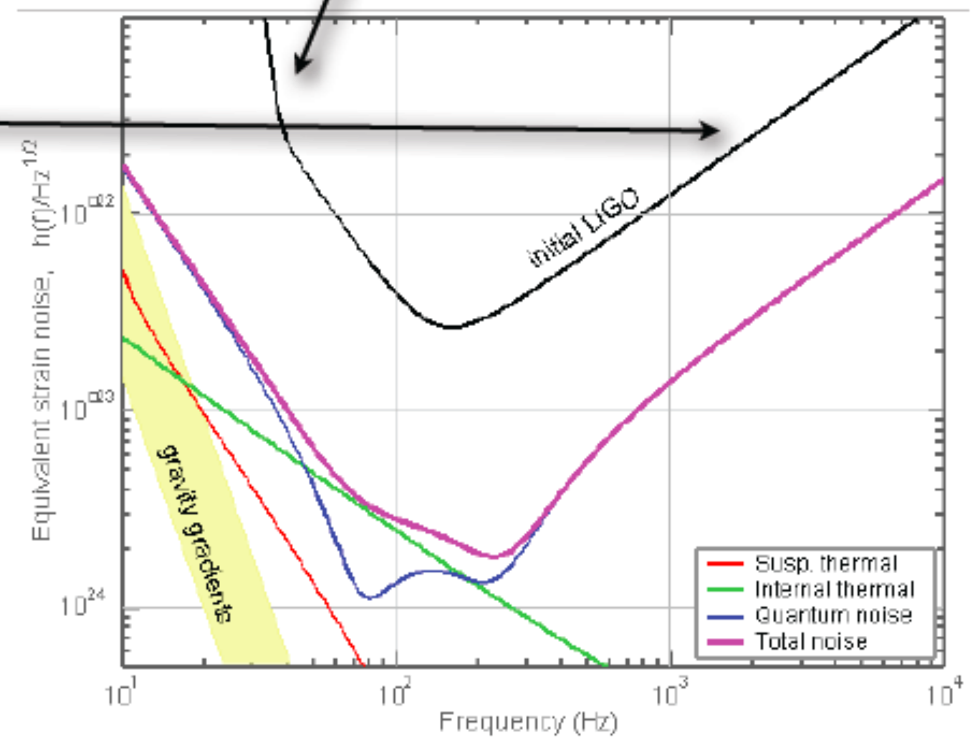
When a *gravitational wave* arrives, it disturbs space-time, lengthening (in this example) the light's path along **arm 2**; when the beams recombine and arrive at the detector, they are no longer in step.

Source: *The Economist*

Noise in interferometric detectors

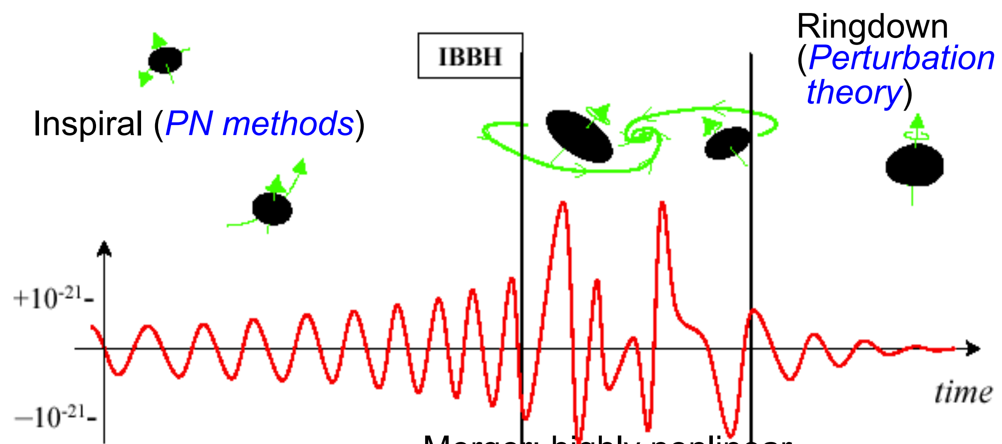
- Seismic noise (low frequencies). At frequencies below 60 Hz, the noise in the interferometers is dominated by seismic noise. The vibrations of the ground couple to the mirrors via the wire suspensions which support them. This effect is strongly suppressed by properly designed suspension systems. Still, seismic noise is very difficult to eliminate at frequencies below 5-10 Hz.

- Photon shot noise (high frequencies). The precision of the measurements is restricted by fluctuations in the fringe pattern due to fluctuations in the number of detected photons. The number of detected photons is proportional to the intensity of the laser beam. Statistical fluctuations in the number of detected photons imply an uncertainty in the measurement of the arm length.

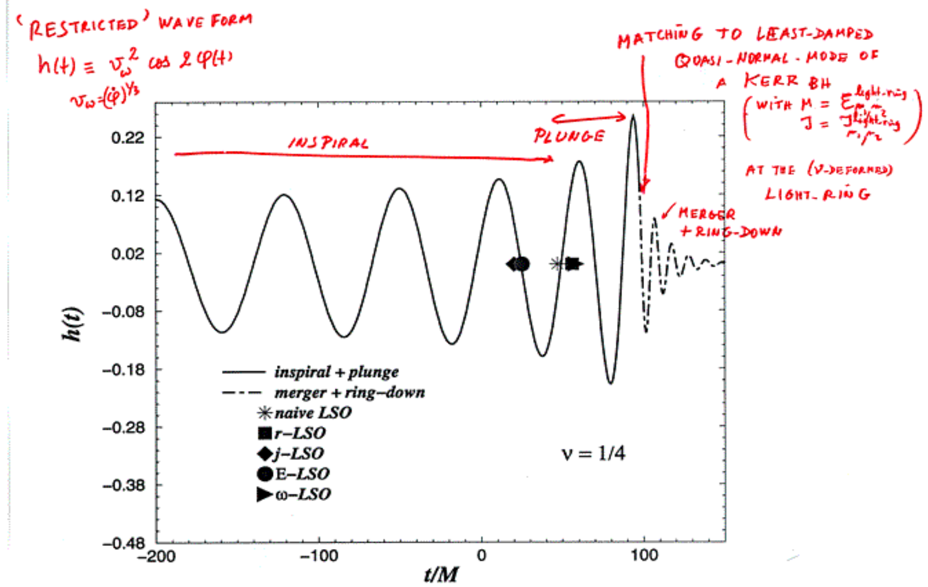


Templates for GWs from BBH coalescence

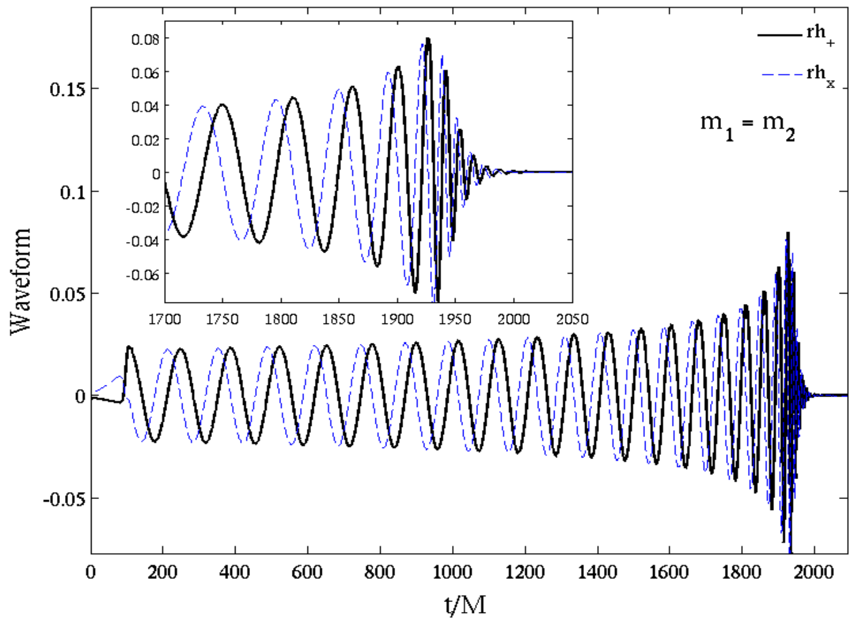
(Brady, Craighton, Thorne 1998)



(Buonanno & Damour 2000)



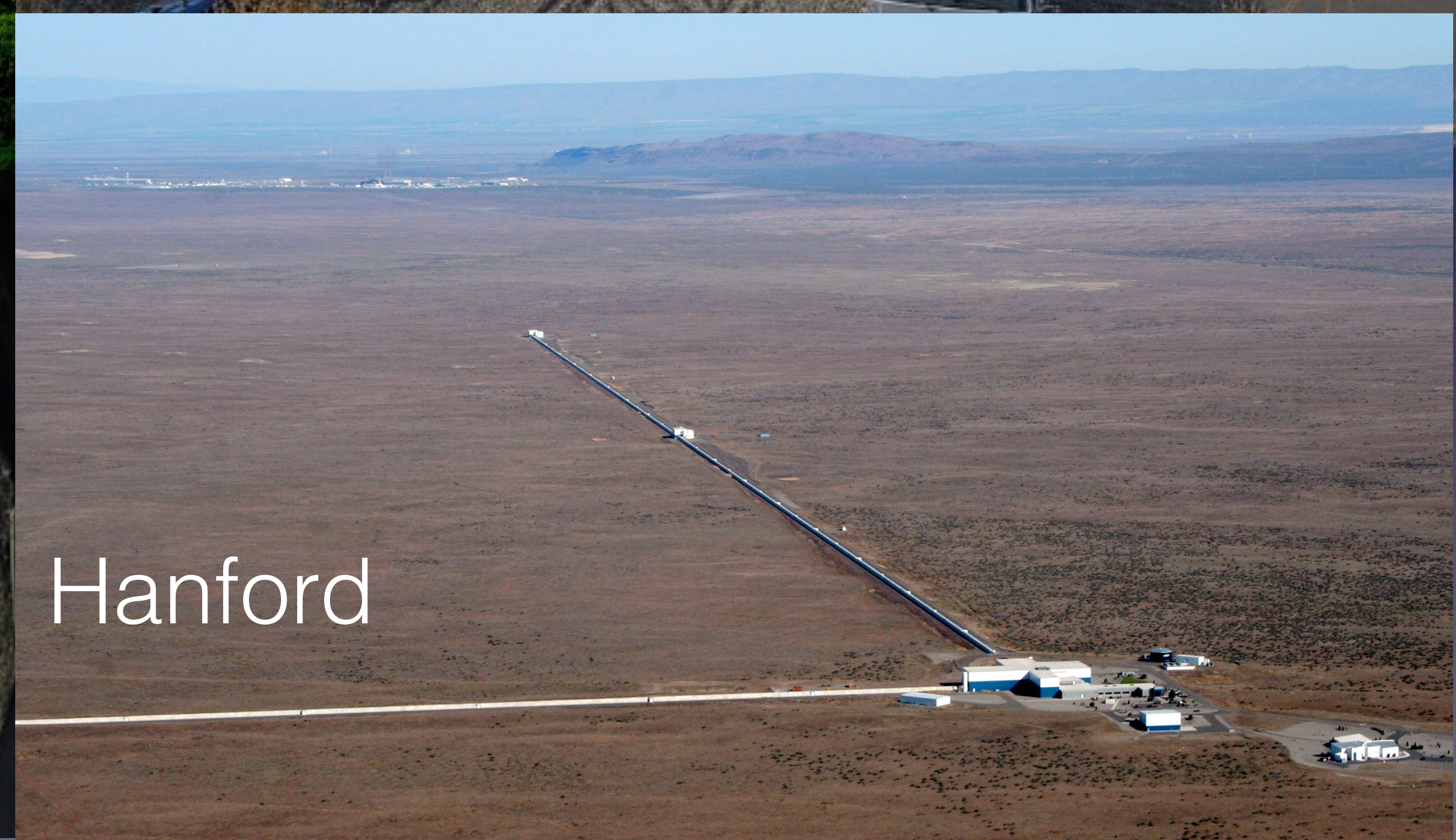
Numerical Relativity, the 2005 breakthrough:
Pretorius, Campanelli et al., Baker et al. …

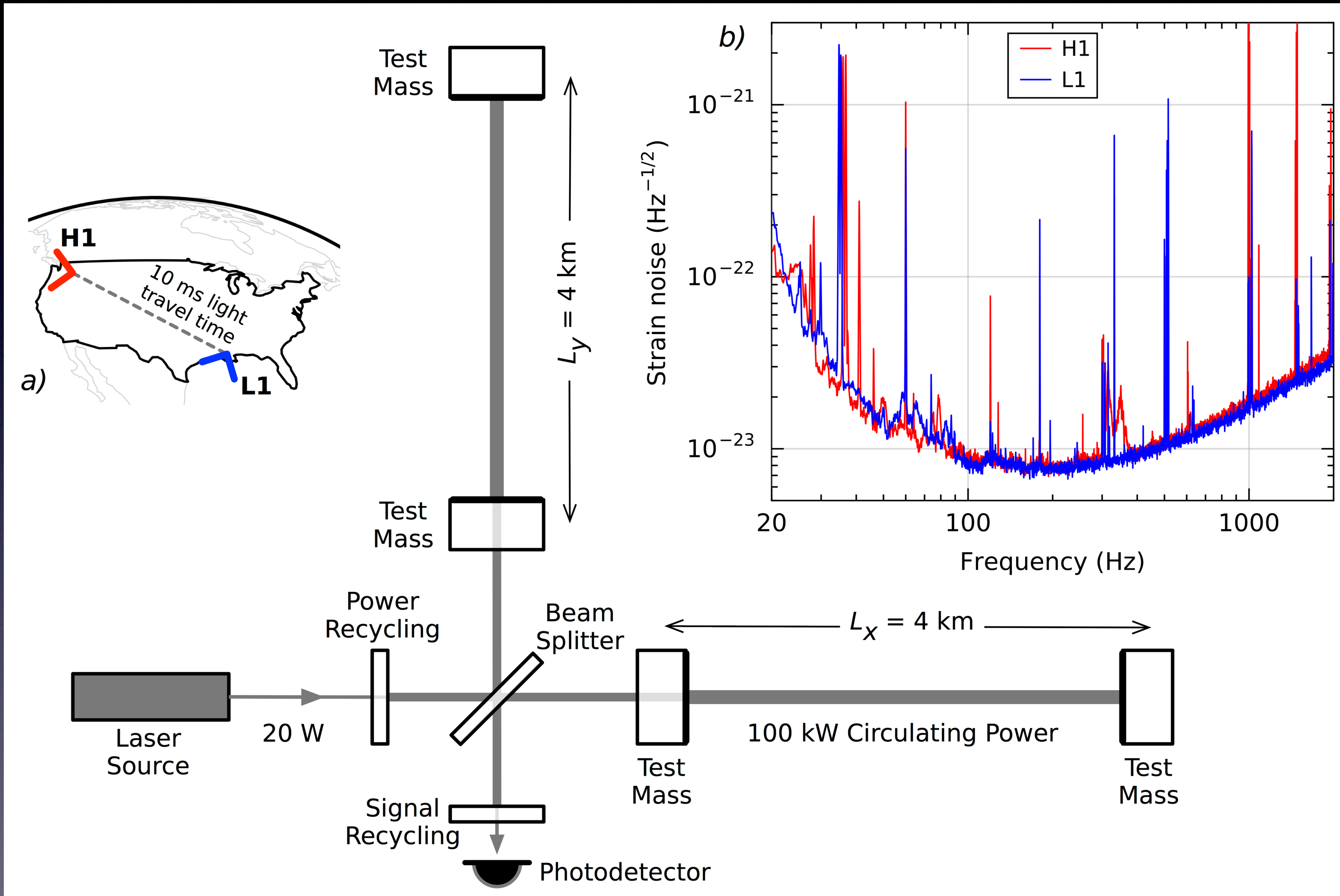


Detectors: the present (I)

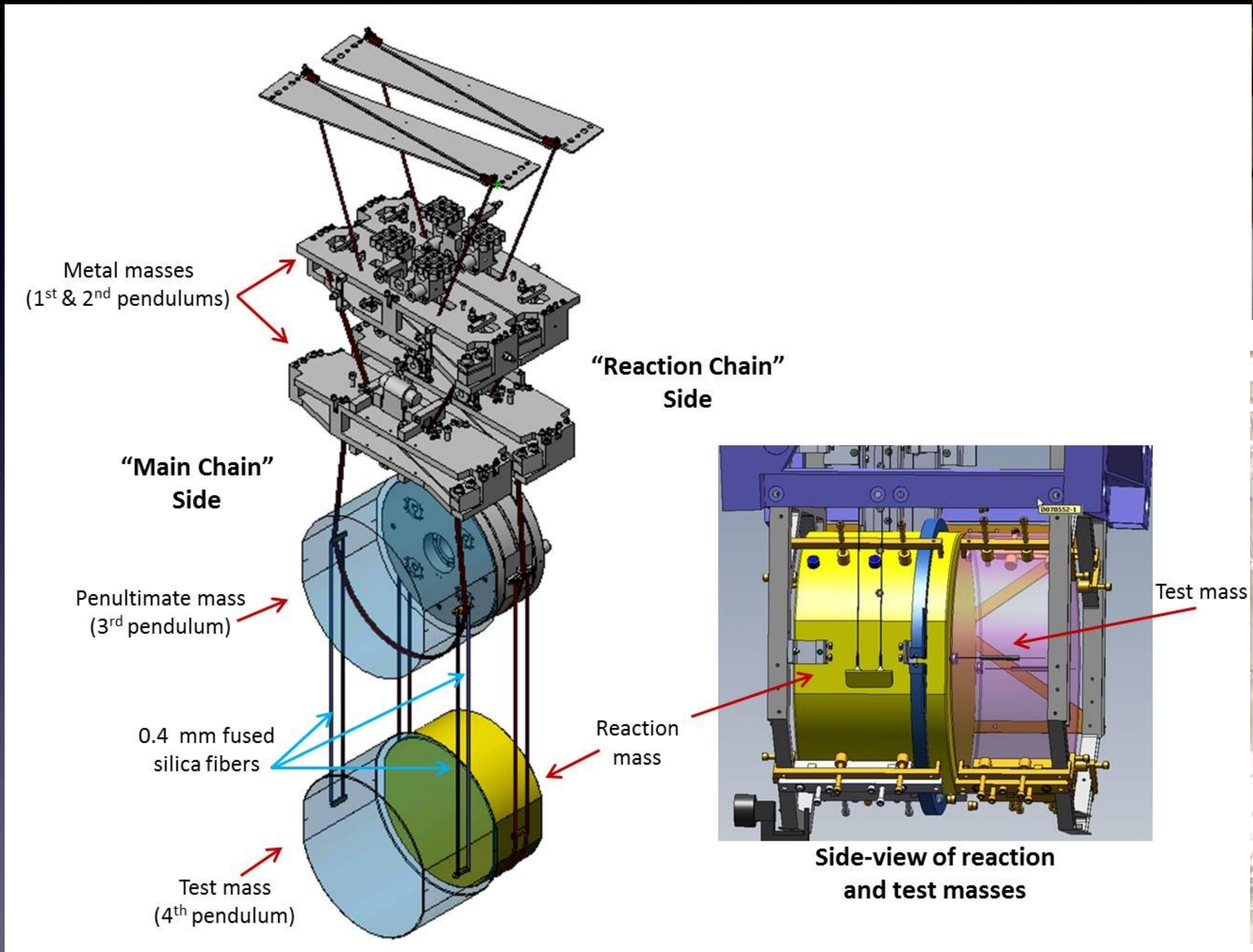
The twin LIGO detectors (L = 4 km) at Livingston Louisiana and Hanford Washington (US).


Livingston


Hanford



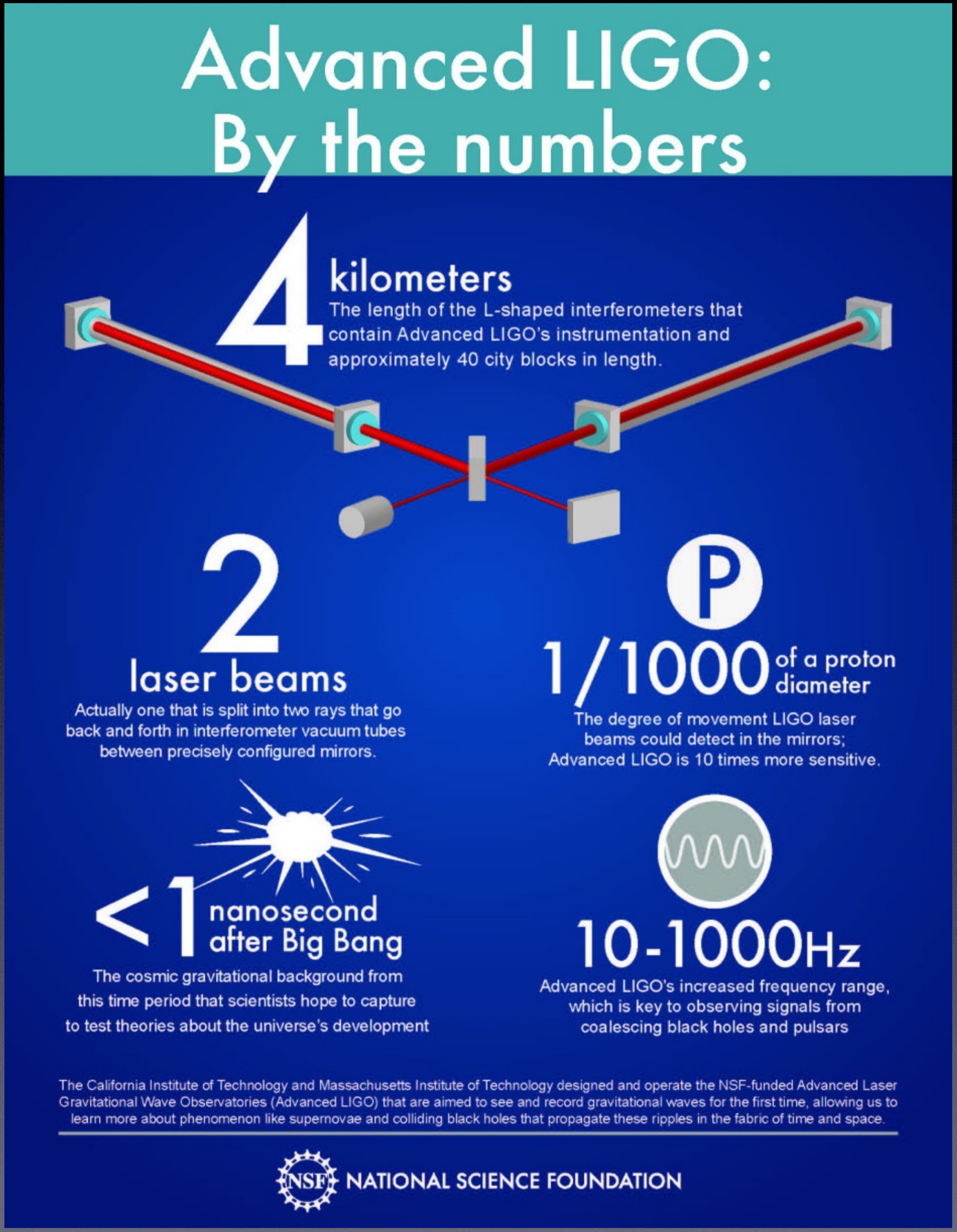
H1
10 ms light travel time
L1
a)
Test Mass
Test Mass
L_y = 4 km
b)
H1
L1
Strain noise (Hz$^{-1/2}$)
10^{-21}
10^{-22}
10^{-23}
20
100
1000
Frequency (Hz)
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector


Metal masses
(1st & 2nd pendulums)
"Reaction Chain" Side
"Main Chain" Side
Penultimate mass
(3rd pendulum)
0.4 mm fused
silica fibers
Reaction
mass
Test mass
(4th pendulum)
Test mass
Side-view of reaction
and test masses

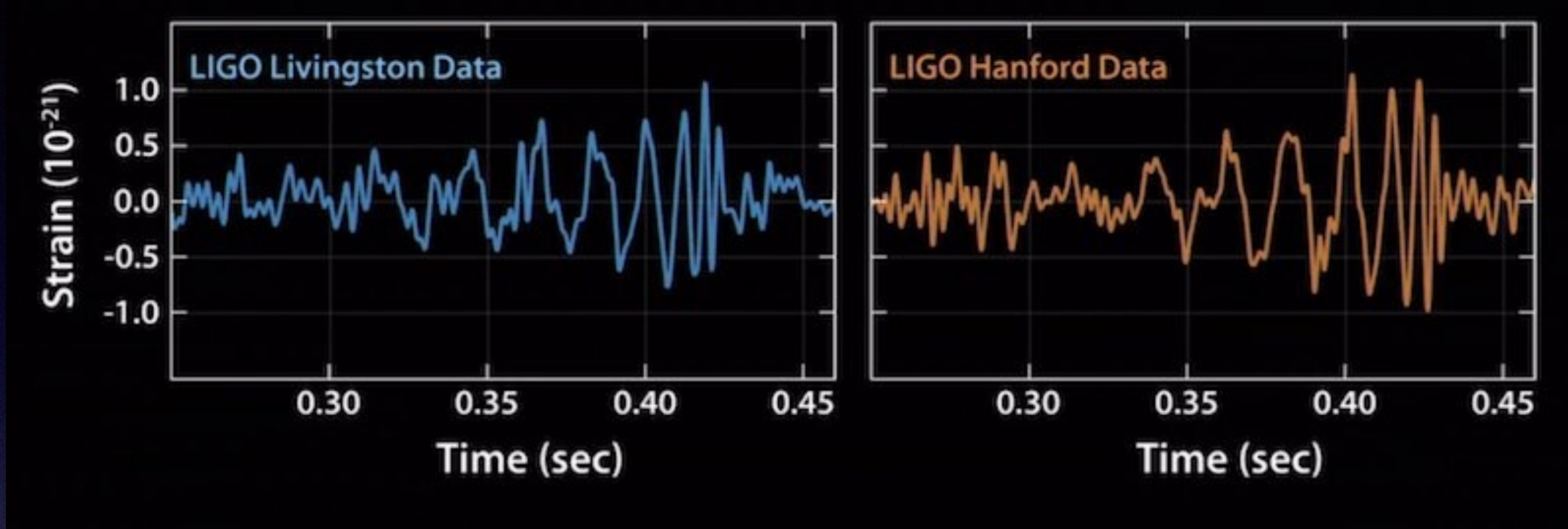

2010/5/11 10:51

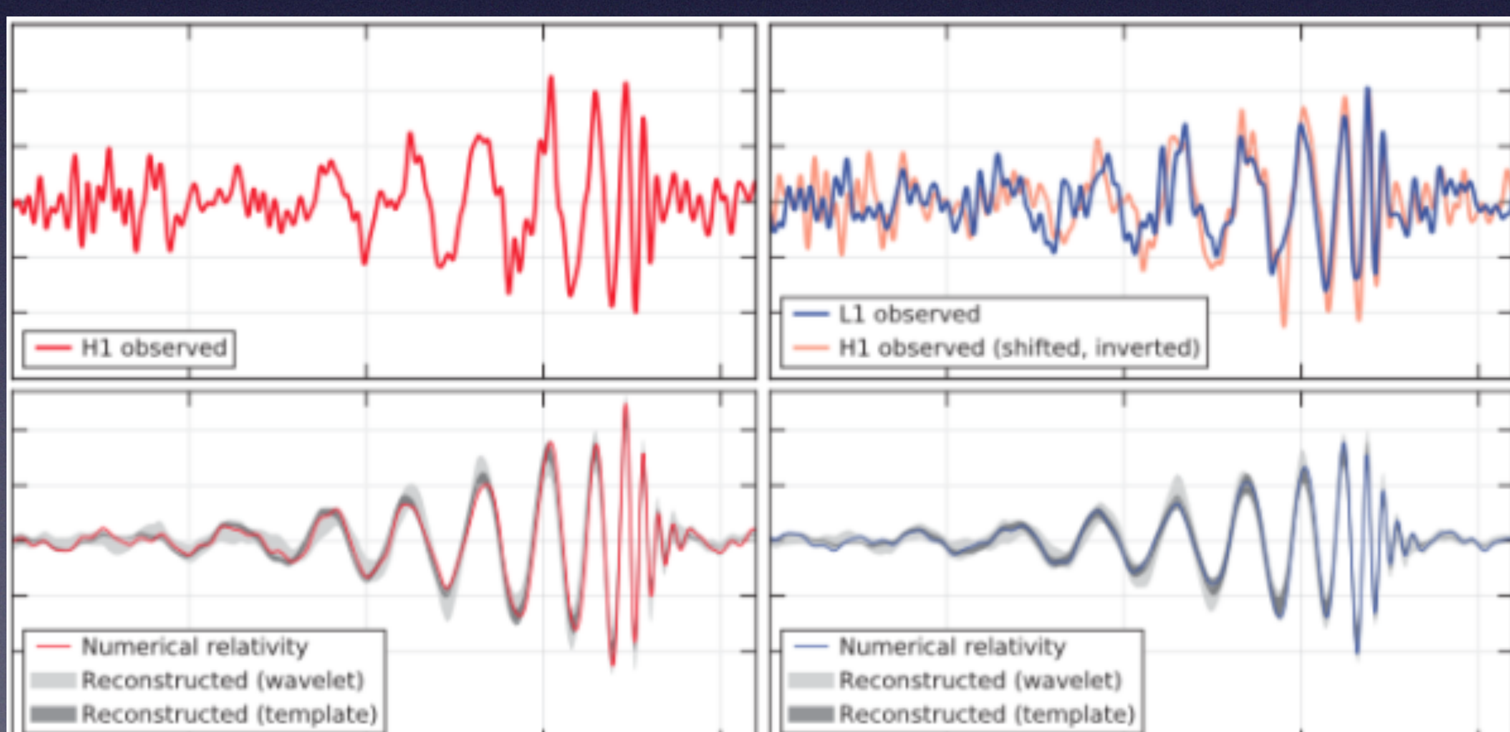
LIGO's interferometer is classified as a **Dual Recycled, Fabry-Perot Michelson Interferometer.**

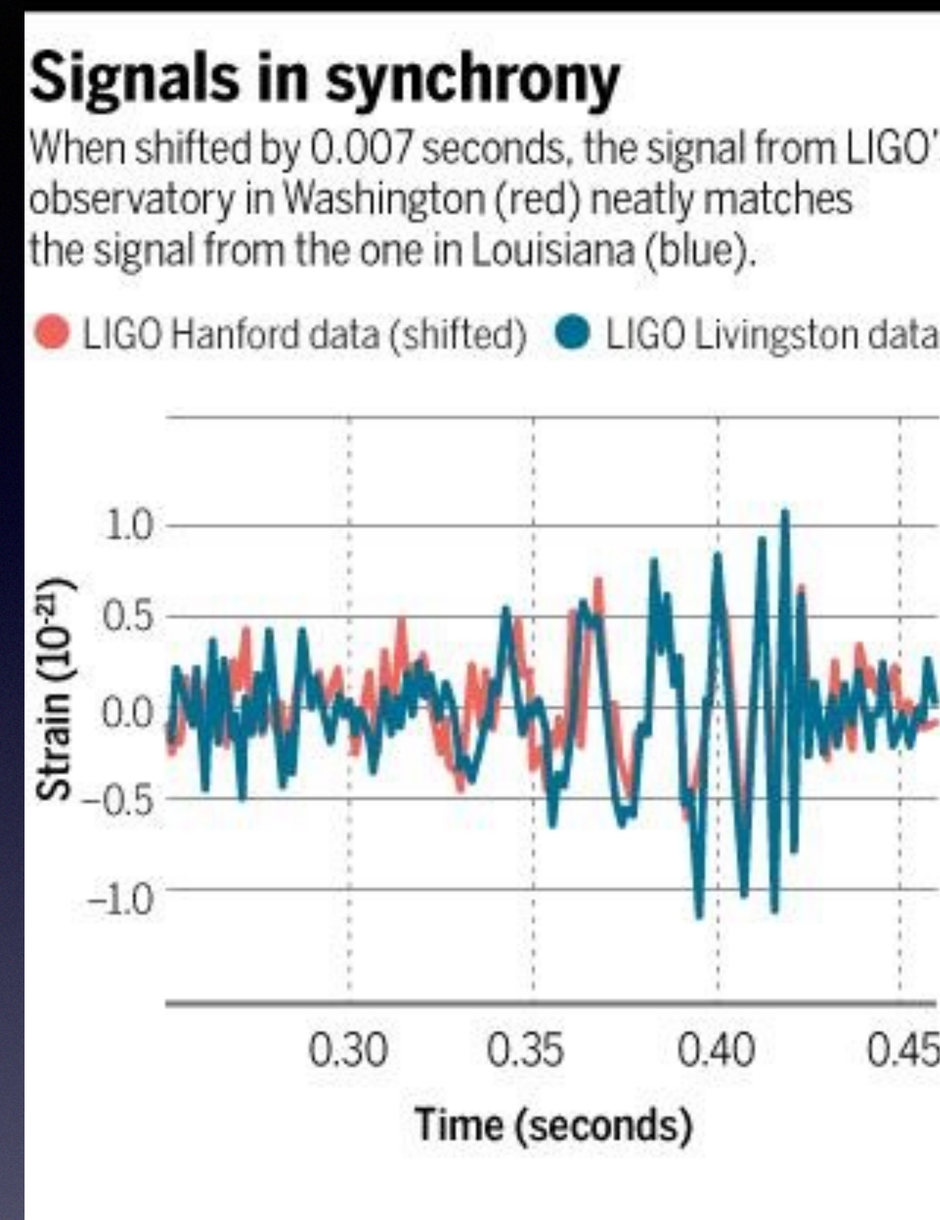
aLIGO started operations in 2015



Gravitational waves detected by LIGO!



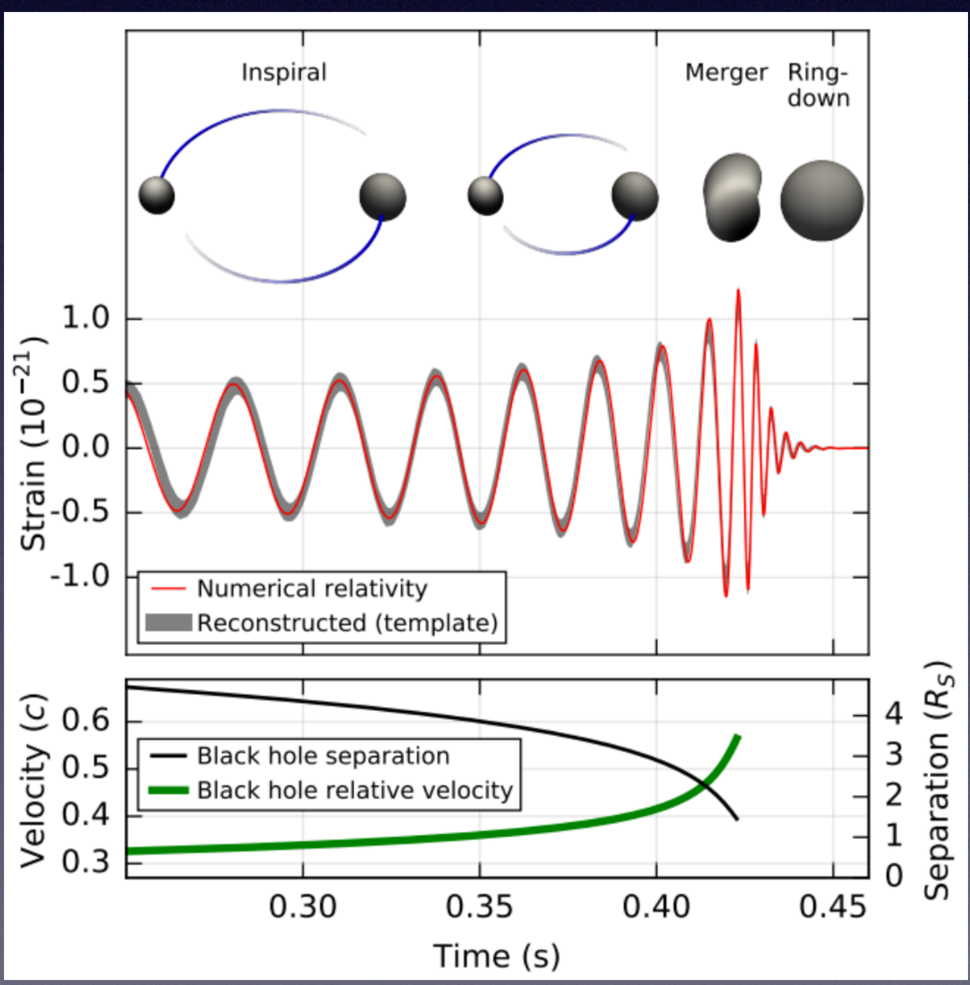


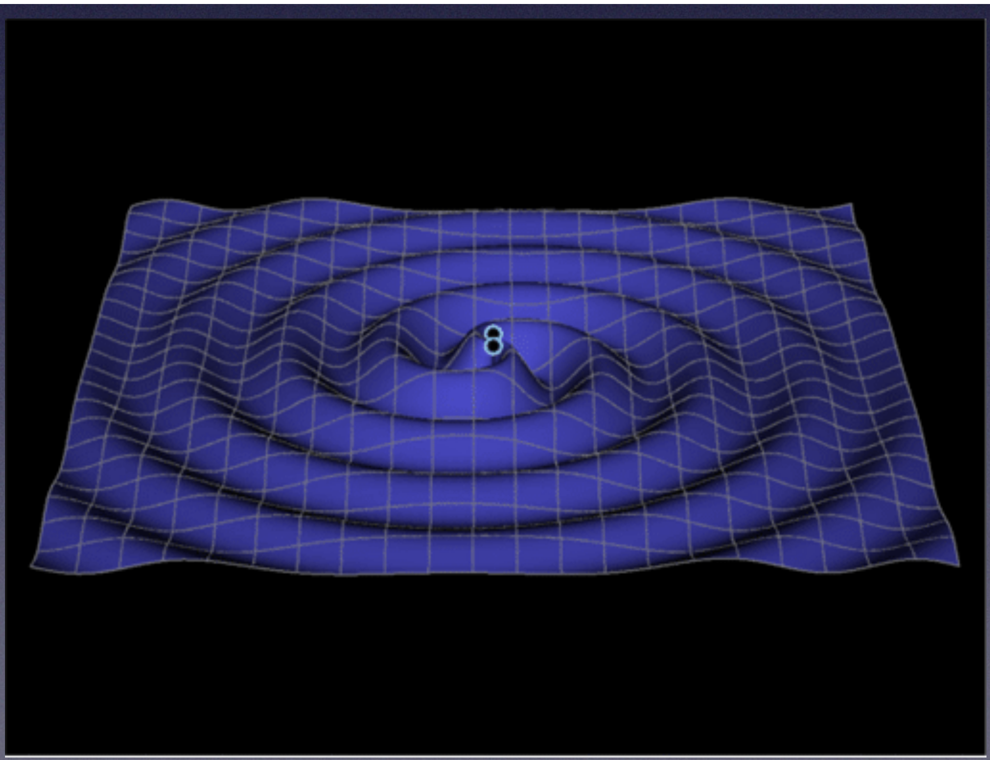


September 14th, 2015, 09:50:45 UTC.

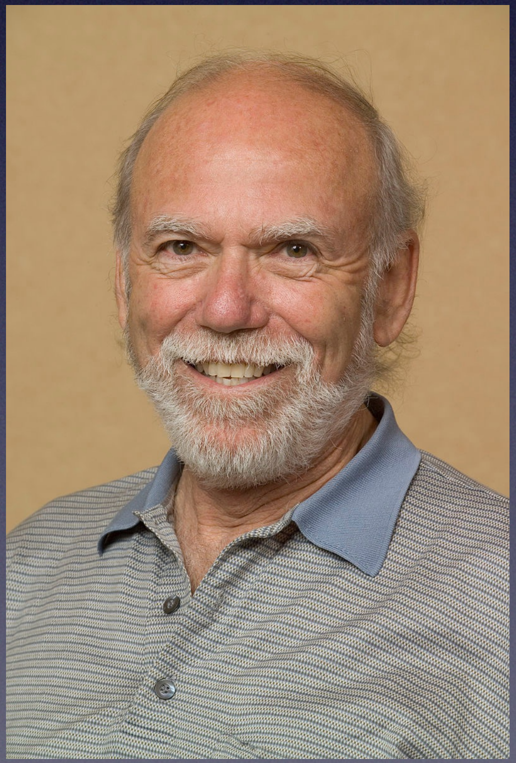
Range: from 35 to 250 Hz

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$





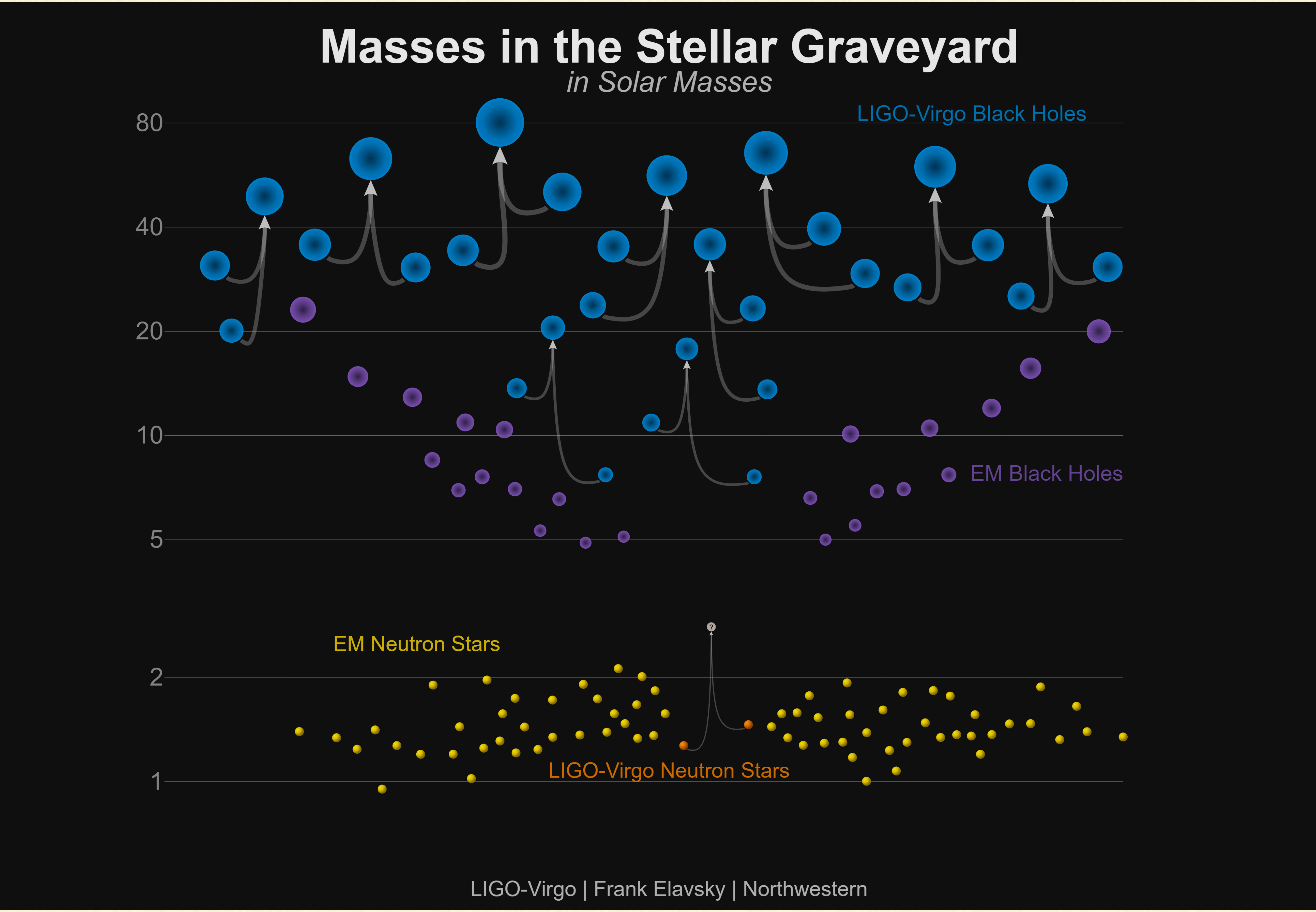
In 2017, Reiner Weiss, Barry Barish, and Kip Thorne received the Nobel Prize in Physics "for decisive contributions to the LIGO detector and the observation of gravitational waves." Weiss was awarded one-half of the total prize money, with Barish and Thorne each received a one-quarter prize.



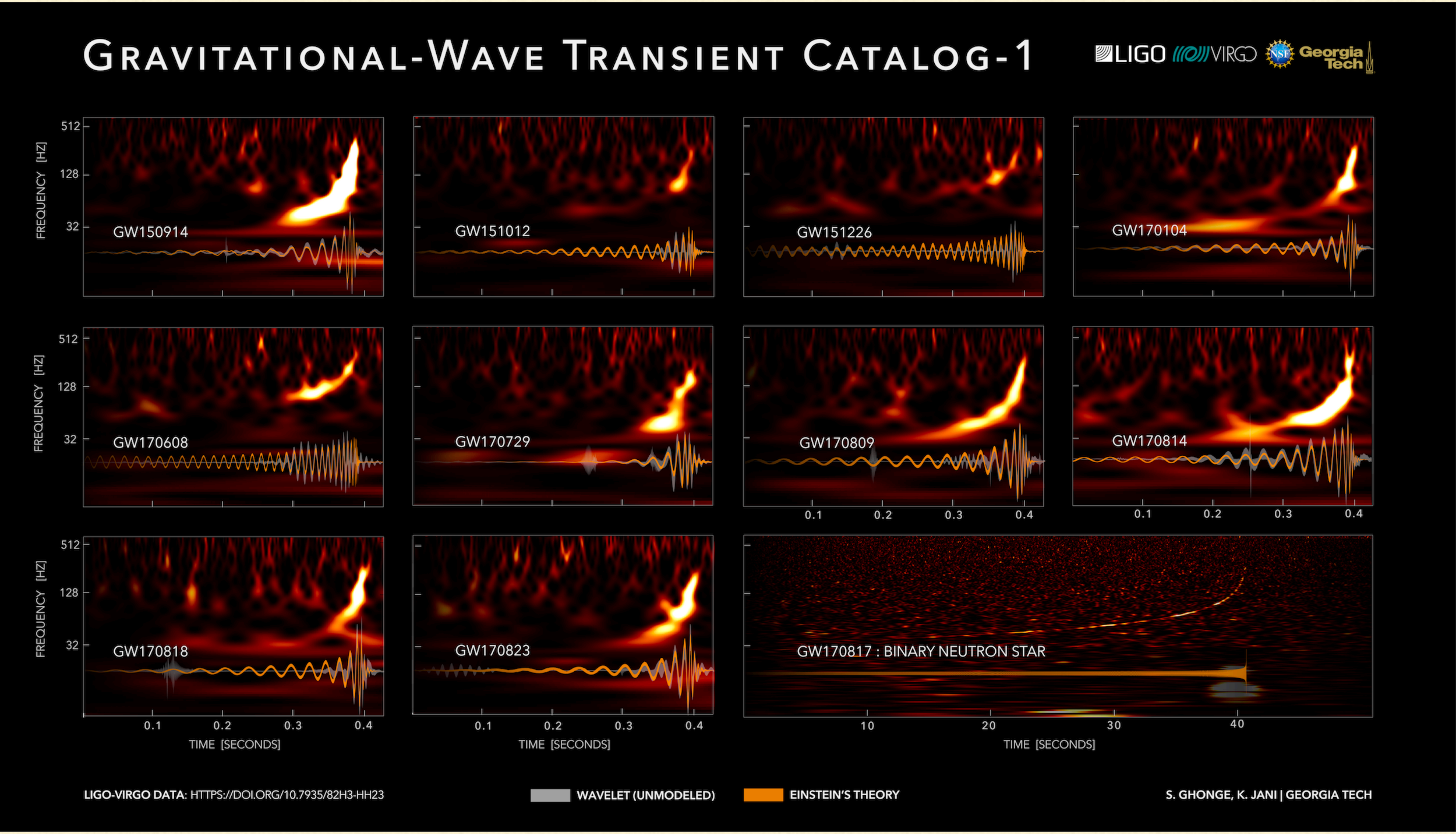
List of gravitational wave events

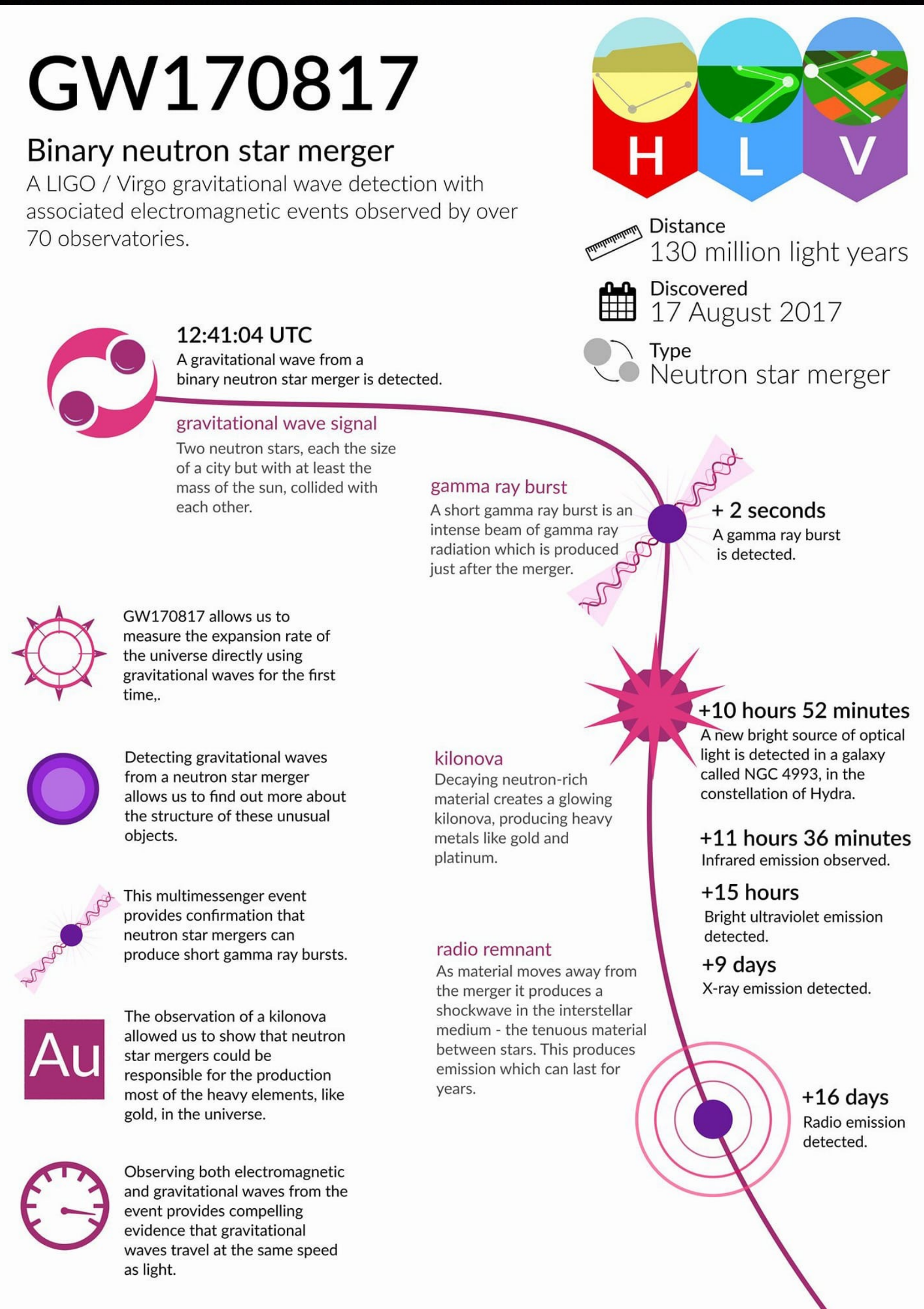
List of binary merger events

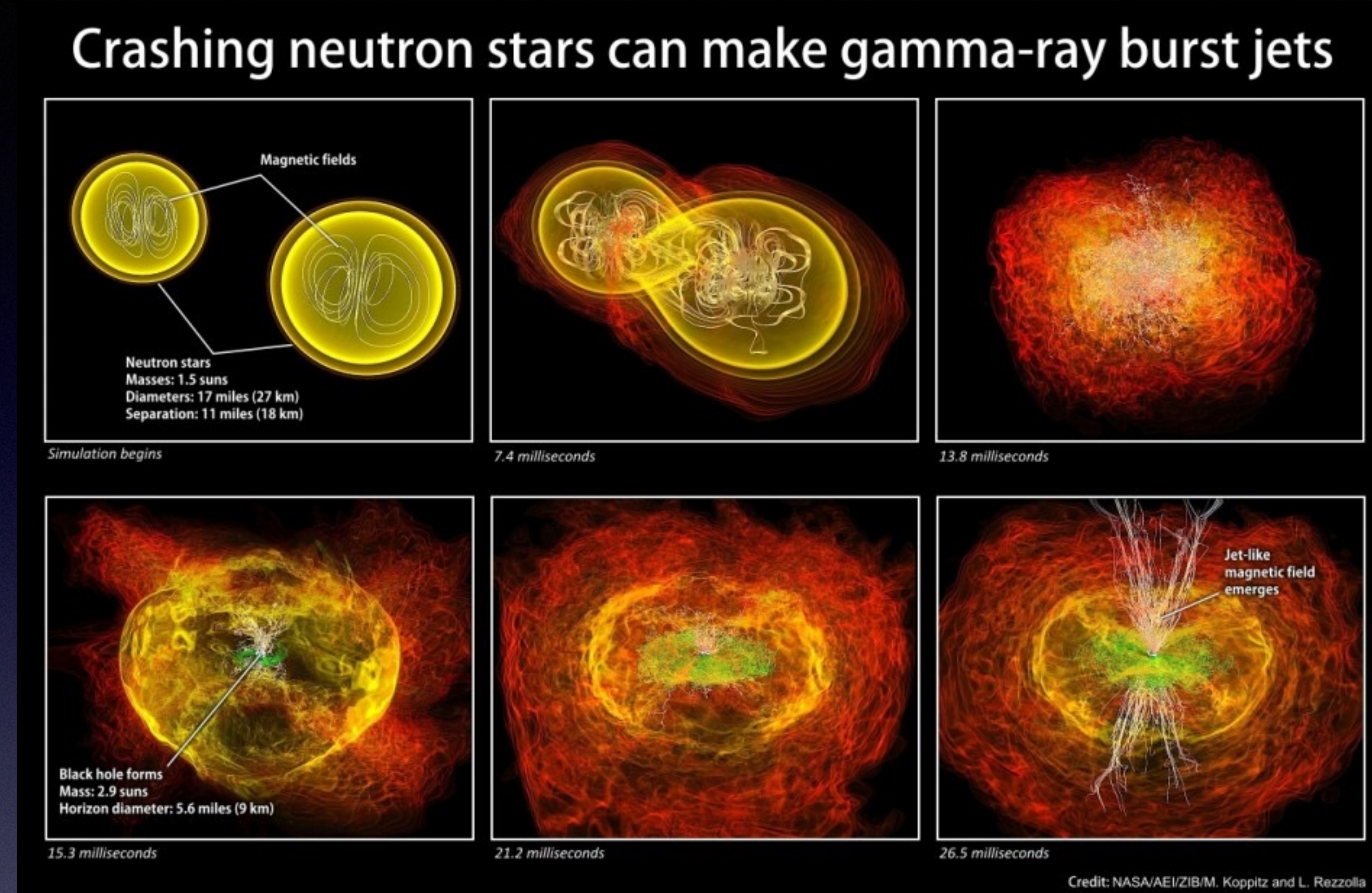
GW event	Detection time (UTC)	Date published	Location area[n 1] (deg^2)	Luminosity distance (Mpc)[n 2]	Energy radiated ($c^2 M_\odot$)[n 3]	Primary		Secondary		Remnant		
						Type	Mass ($M_\odot$)	Type	Mass ($M_\odot$)	Type	Mass ($M_\odot$)	Spin[n 4]
GW150914	2015-09-14 09:50:45	2016-02-11	600; mostly to the south	440^{+160}_{-180}	$3.0^{+0.5}_{-0.5}$	BH[n 5]	$35.4^{+5.0}_{-3.4}$	BH[n 6]	$29.8^{+3.3}_{-4.3}$	BH	$62.2^{+3.7}_{-3.4}$	$0.68^{+0.05}_{-0.06}$
LVT151012	2015-10-12 09:54:43	2016-06-15	1600	1000^{+500}_{-500}	$1.5^{+0.3}_{-0.4}$	BH	23^{+18}_{-6}	BH	13^{+4}_{-5}	BH	35^{+14}_{-4}	$0.66^{+0.09}_{-0.10}$
GW151226	2015-12-26 03:38:53	2016-06-15	850	440^{+180}_{-190}	$1.0^{+0.1}_{-0.2}$	BH	$14.2^{+8.3}_{-3.7}$	BH	$7.5^{+2.3}_{-2.3}$	BH	$20.8^{+6.1}_{-1.7}$	$0.74^{+0.06}_{-0.06}$
GW170104	2017-01-04 10:11:58	2017-06-01	1200	880^{+450}_{-390}	$2.0^{+0.6}_{-0.7}$	BH	$31.2^{+8.4}_{-6.0}$	BH	$19.4^{+5.3}_{-5.9}$	BH	$48.7^{+5.7}_{-4.6}$	$0.64^{+0.09}_{-0.20}$
GW170608	2017-06-08 02:01:16	2017-11-16	520; northern hemisphere	340^{+140}_{-140}	$0.85^{+0.07}_{-0.17}$	BH	12^{+7}_{-2}	BH	7^{+2}_{-2}	BH	19^{+5}_{-1}	$0.69^{+0.04}_{-0.05}$
GW170814	2017-08-14 10:30:43	2017-09-27	60; towards Eridanus	540^{+130}_{-210}	$2.7^{+0.4}_{-0.3}$	BH	$30.5^{+5.7}_{-3.0}$	BH	$25.3^{+2.8}_{-4.2}$	BH	$53.2^{+3.2}_{-2.5}$	$0.70^{+0.07}_{-0.05}$
GW170817	2017-08-17 12:41:04	2017-10-16	28; NGC 4993	40^{+8}_{-14}	> 0.025	NS	1.36 - 1.60[n 7]	NS	1.17 - 1.36[n 8]	NS or BH[n 9]	$< 2.74^{+0.04}_{-0.01}$ [n 10]	



Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
EM Black Holes
EM Neutron Stars
LIGO-Virgo Neutron Stars
?
LIGO-Virgo | Frank Elavsky | Northwestern


GRAVITATIONAL-WAVE TRANSIENT CATALOG-1
LIGO
VIRGO
NSF
Georgia Tech
FREQUENCY [HZ]
512
128
32
GW150914
GW151012
GW151226
GW170104
GW170608
GW170729
GW170809
GW170814
GW170818
GW170823
GW170817 : BINARY NEUTRON STAR
0.1
0.2
0.3
0.4
10
20
30
40
TIME [SECONDS]
LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23
WAVELET (UNMODELED)
EINSTEIN'S THEORY
S. GHONGE, K. JANI | GEORGIA TECH

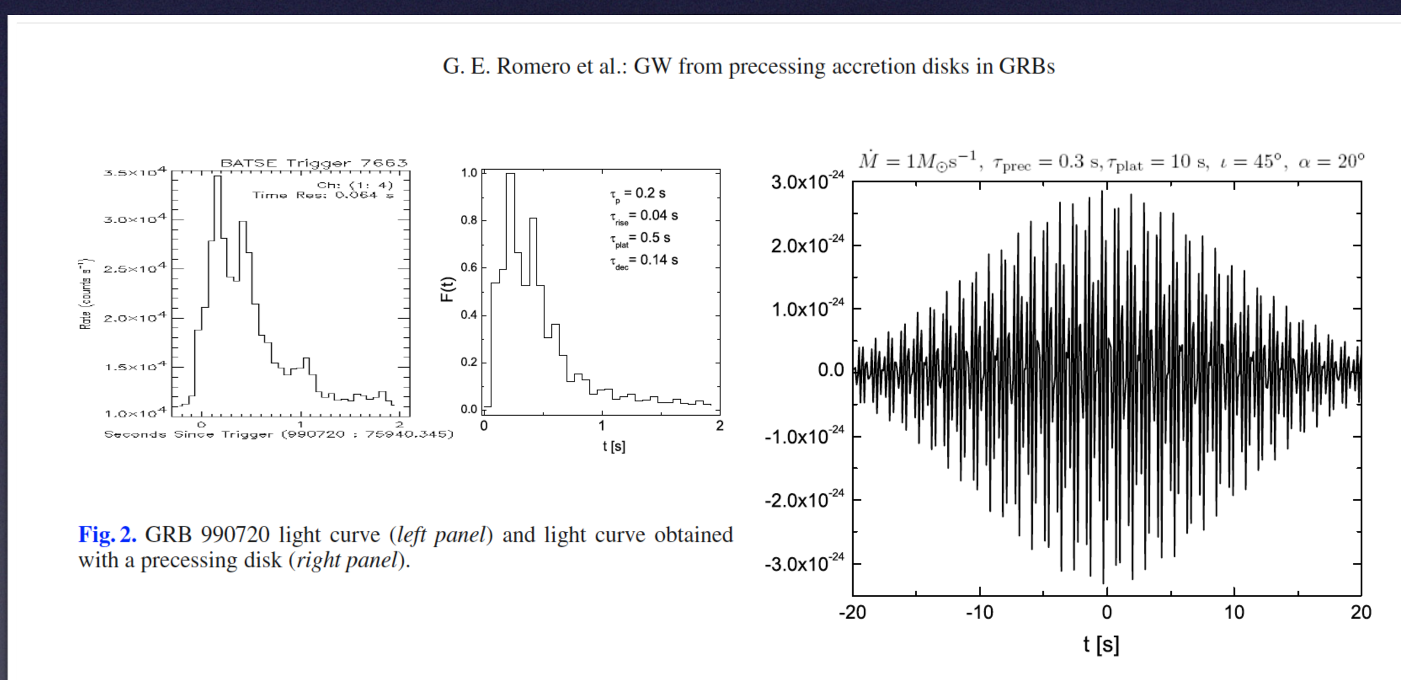




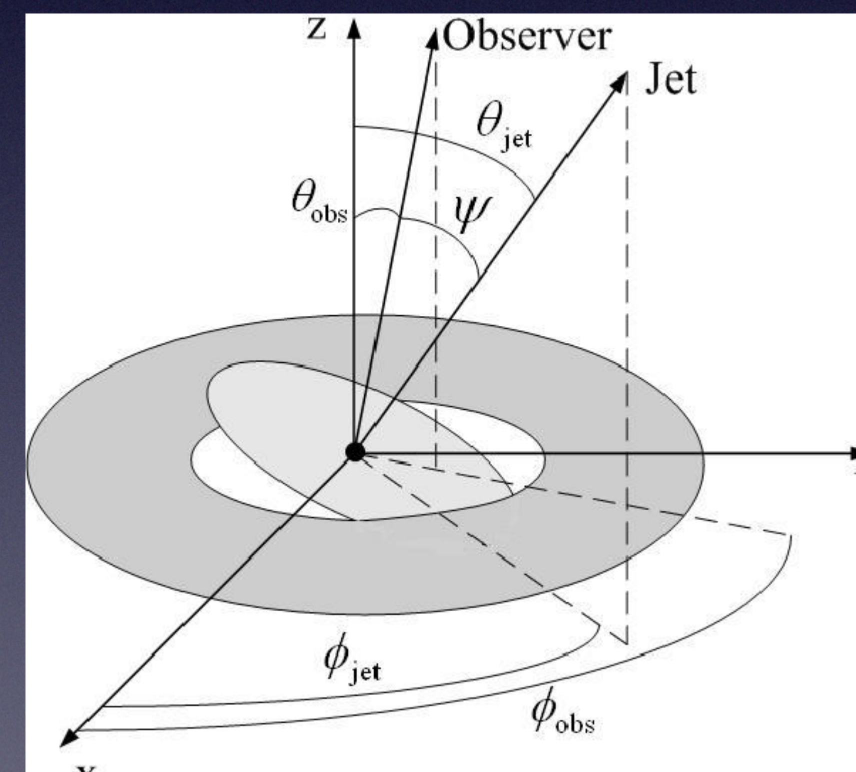
The most intensively observed astronomical event in history: more than 5000 scientist involved.

Next steps

- To detect long gamma-ray bursts
- To detect supernovae in other galaxies
- To detect GW from close binaries (not mergers)
- To detect supermassive black hole binaries

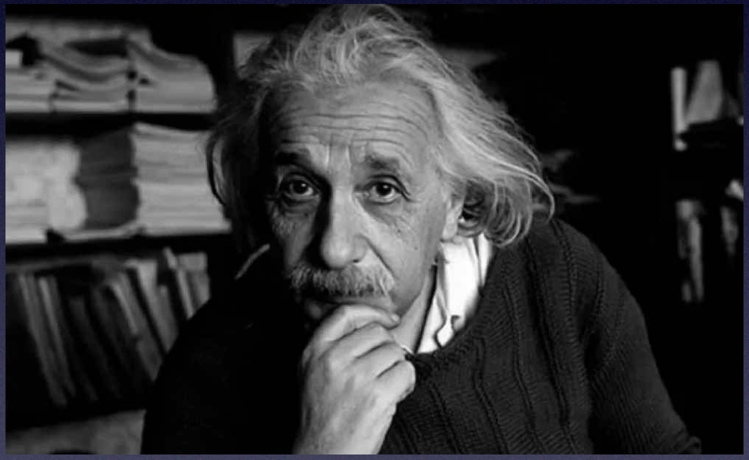


Romero et al.: A&A 2010



Implications of the detections:

- Gravitational waves exist and travel at the speed of light
- Black holes exist. Pop III black holes?
- Gravitational waves transport energy —> spacetime has energy in absence of matter/radiation
- Spacetime has a dimensionality of n=4 or higher.
- Short GRBs are mergers of neutron stars
- Heavy elements are synthesized in kilo-novas
- Constraints on modified theories of gravity
- Constraints on the EoS of NS
- Independent measure of the Hubble constant (no standard candles)



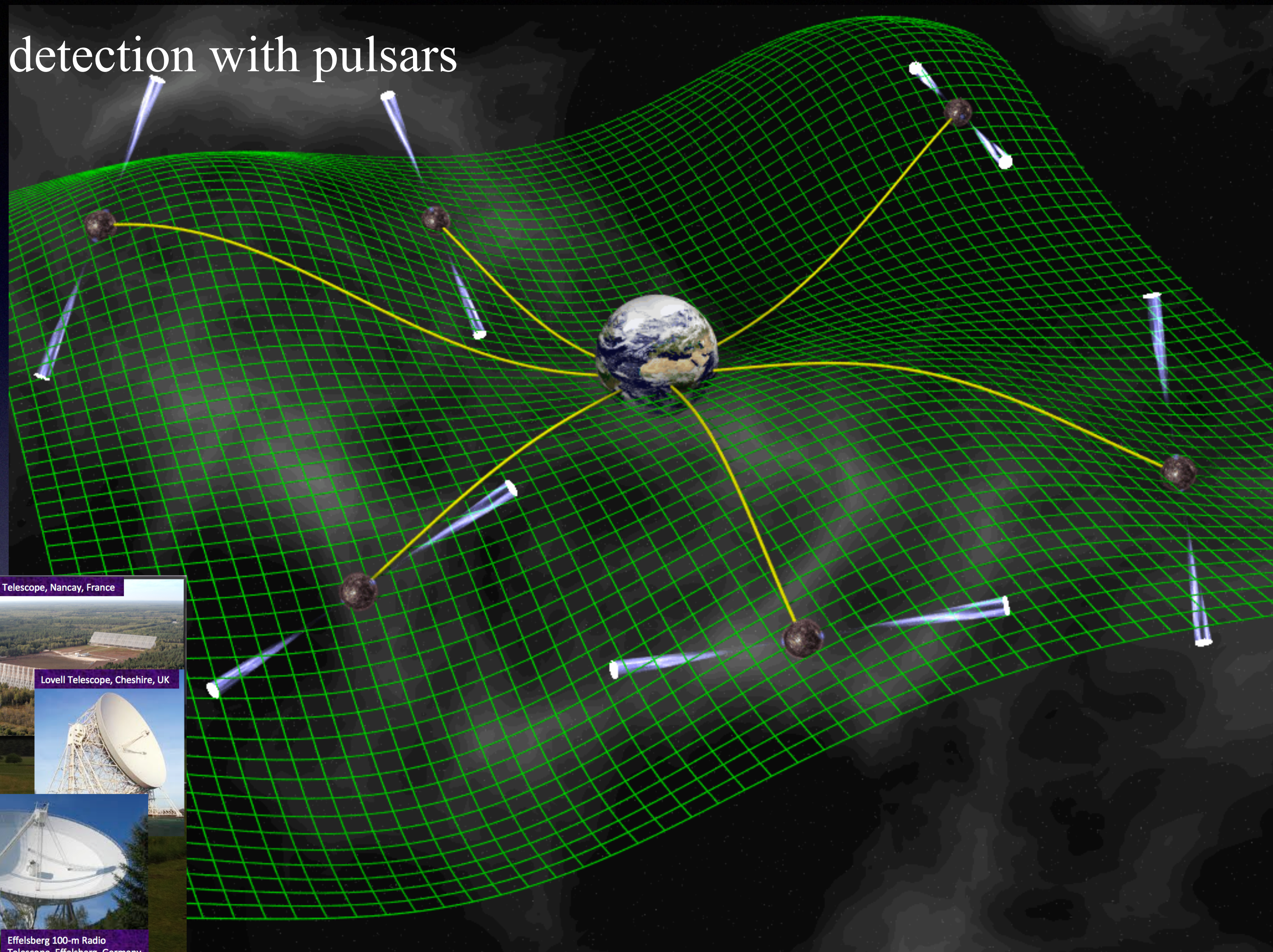
Gravitational wave astronomy is born!

Gravitational wave detection with pulsars

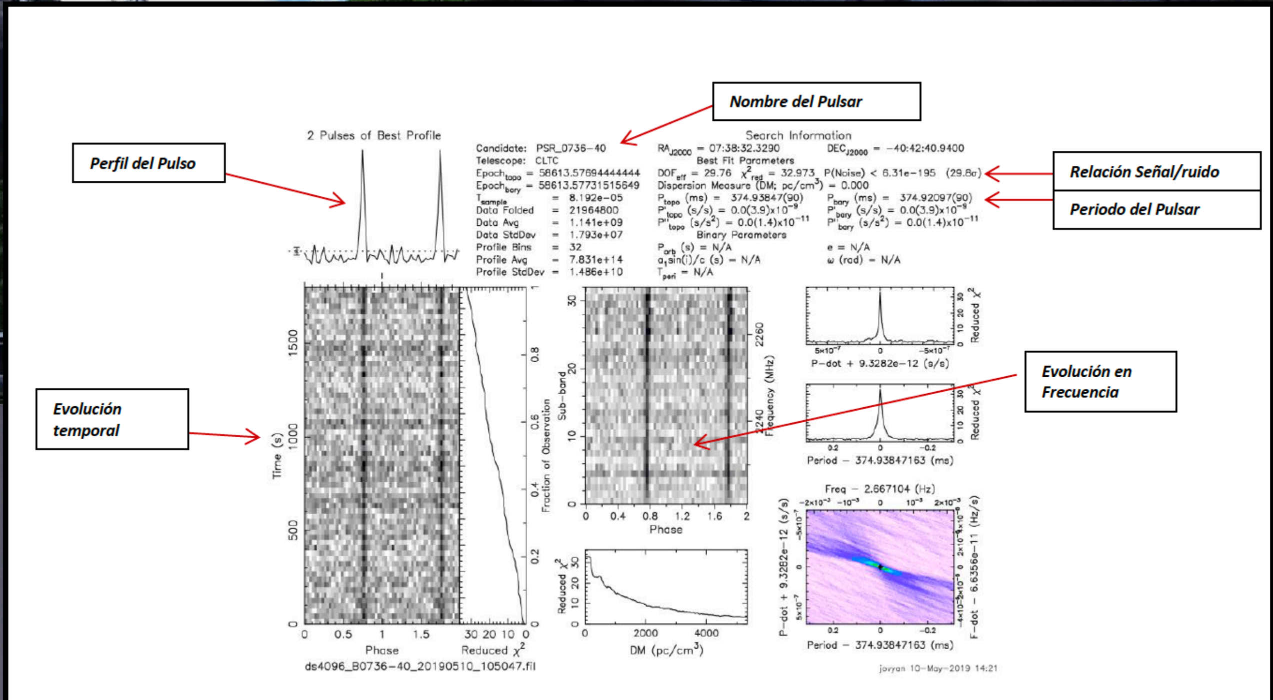
EPTA/LEAP
IPTA

International Pulsar Timing Array

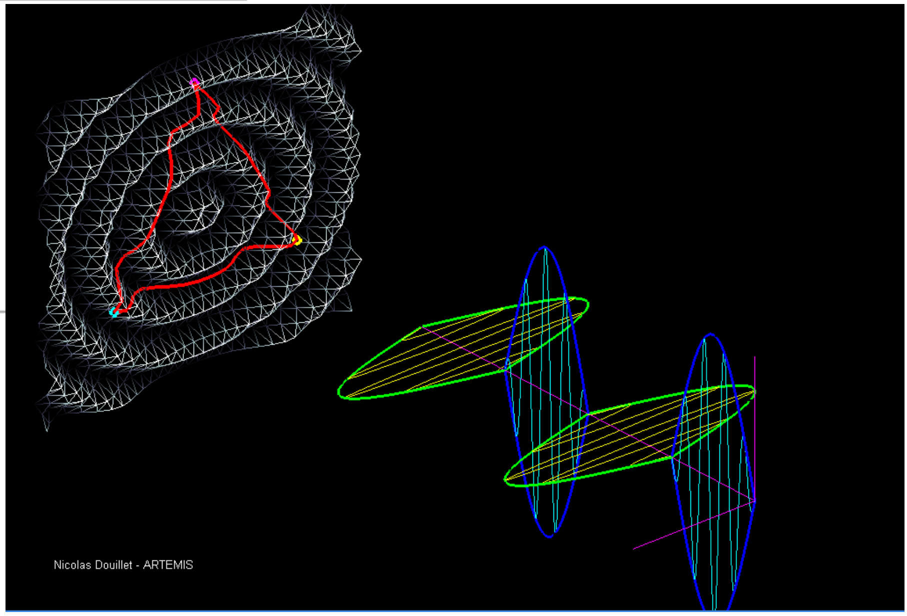
Nanograv



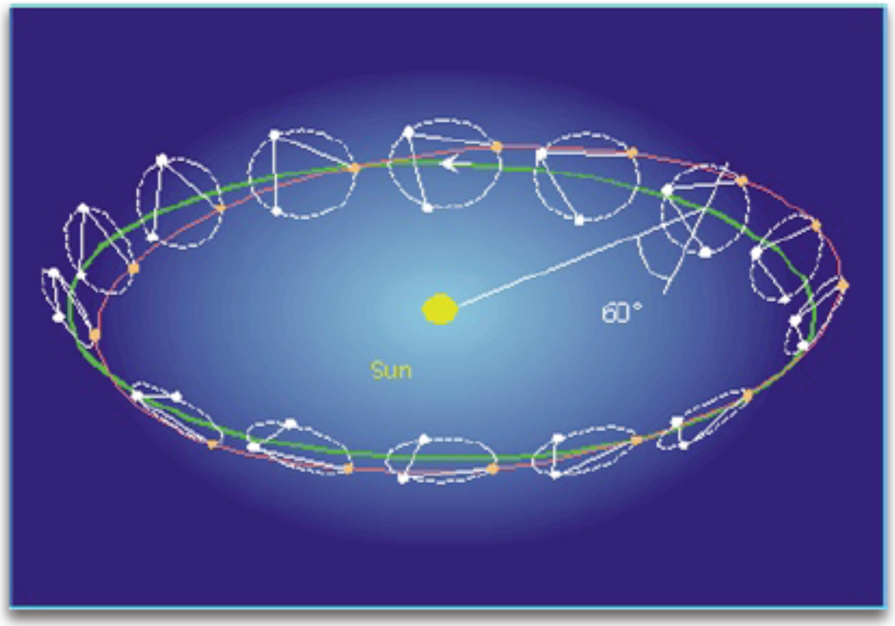
Búsqueda de ondas gravitacionales con púlsares desde el IAR

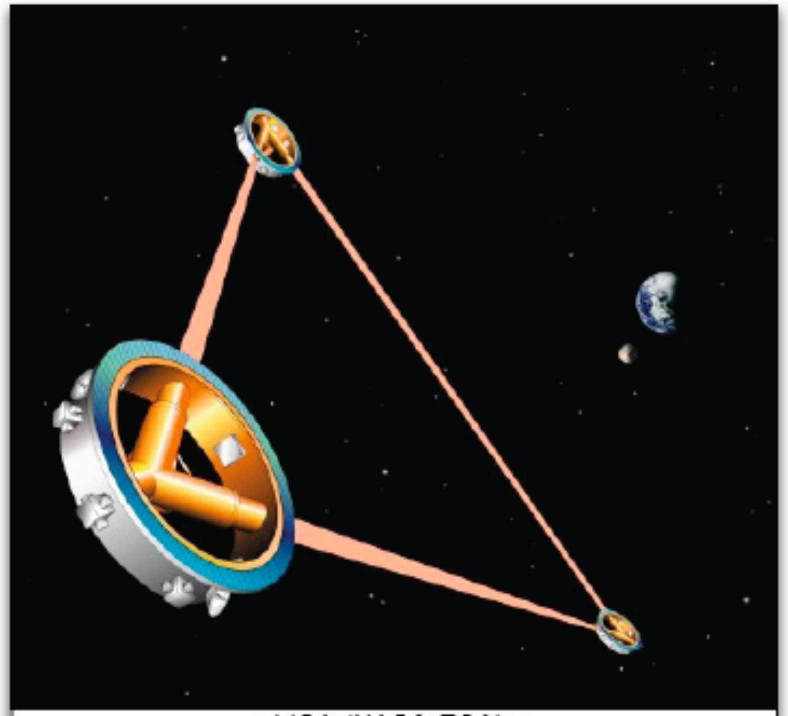


Going to space: the LISA detector

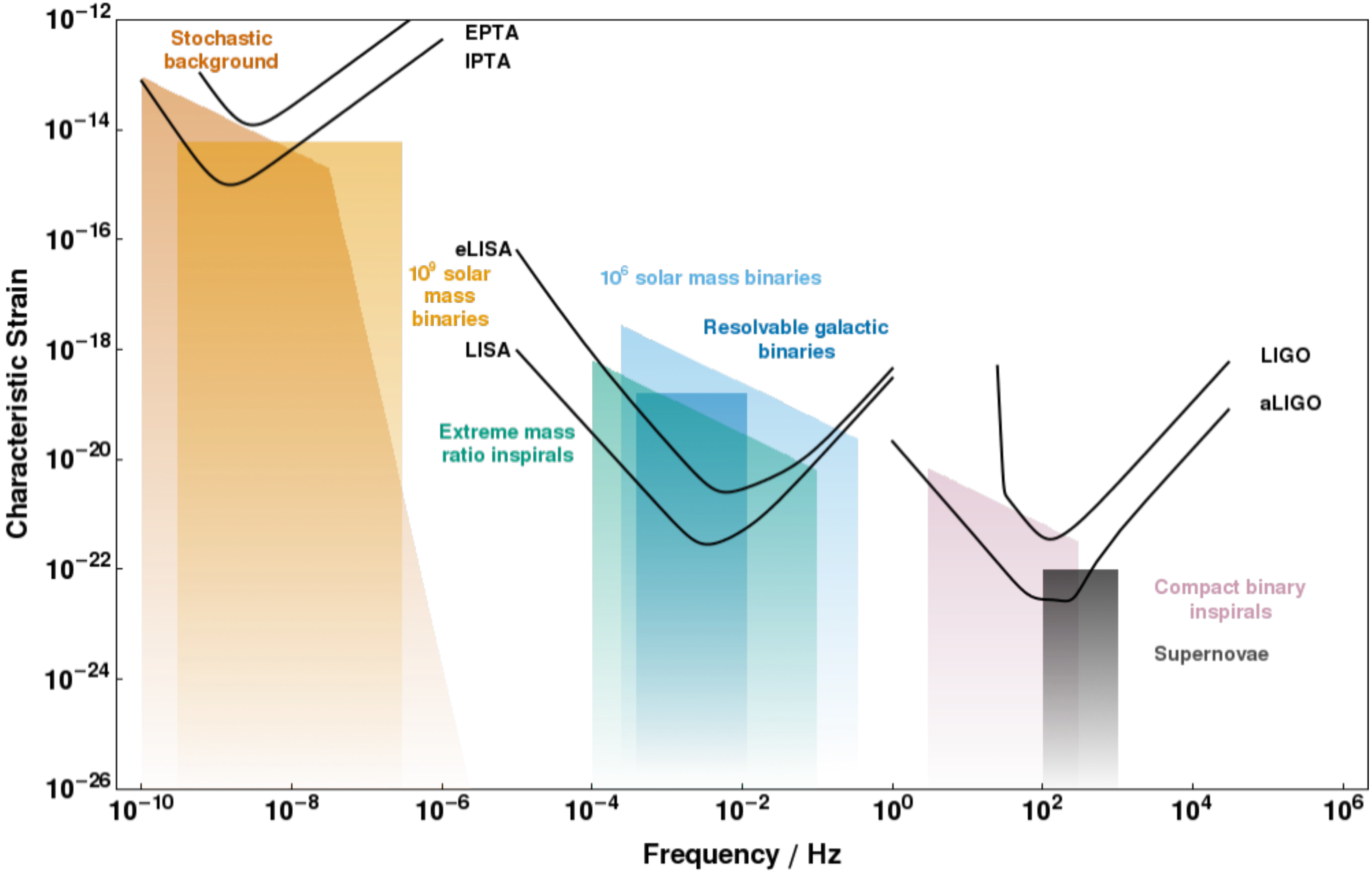


- Space-based detectors: “noise-free” environment, abundance of space!
- Long-arm baseline, low frequency sensitivity
- LISA: Up until recently a joint NASA/ESA mission, now an ESA mission only.




LISA (NASA-ESA)

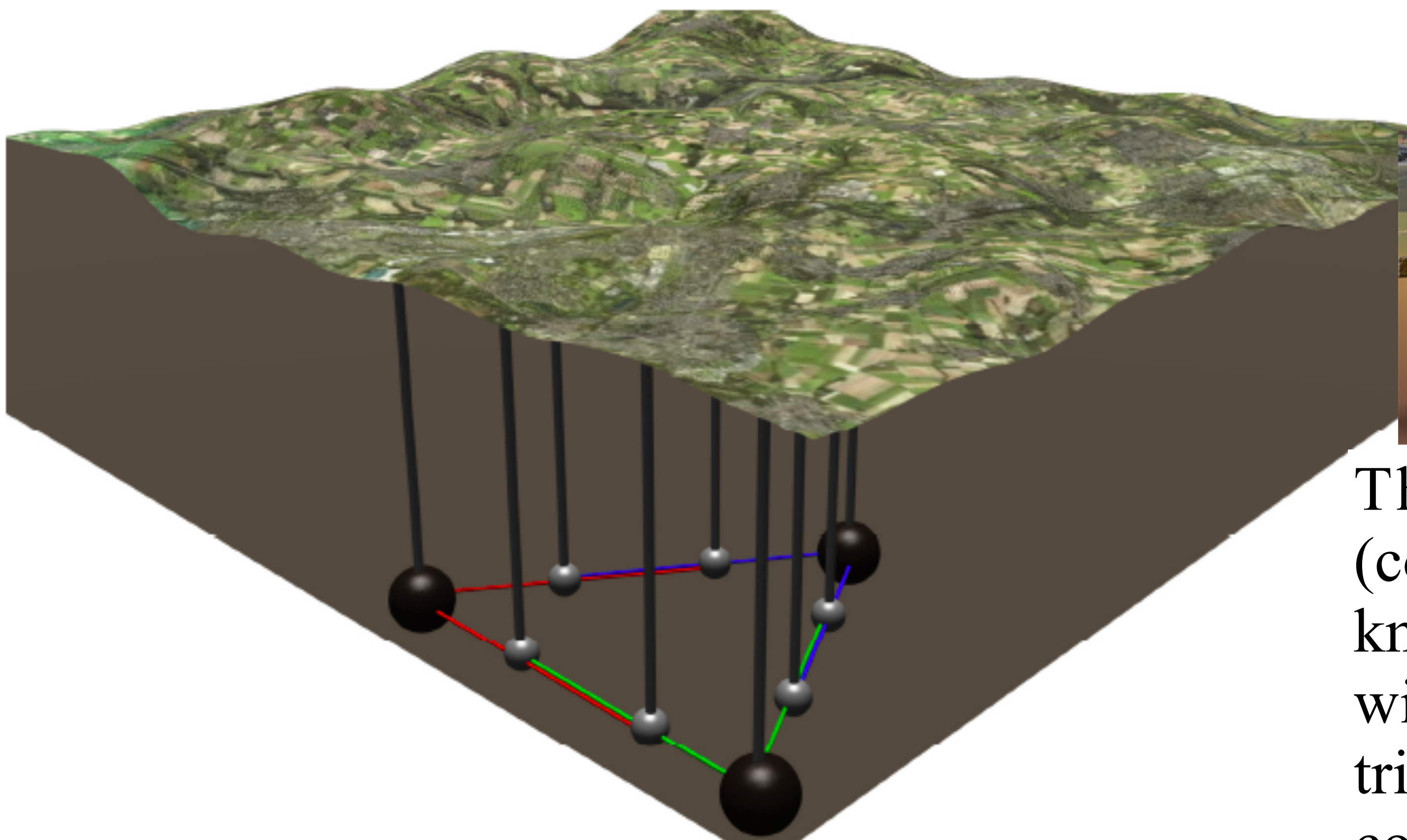
To be launched around 2034

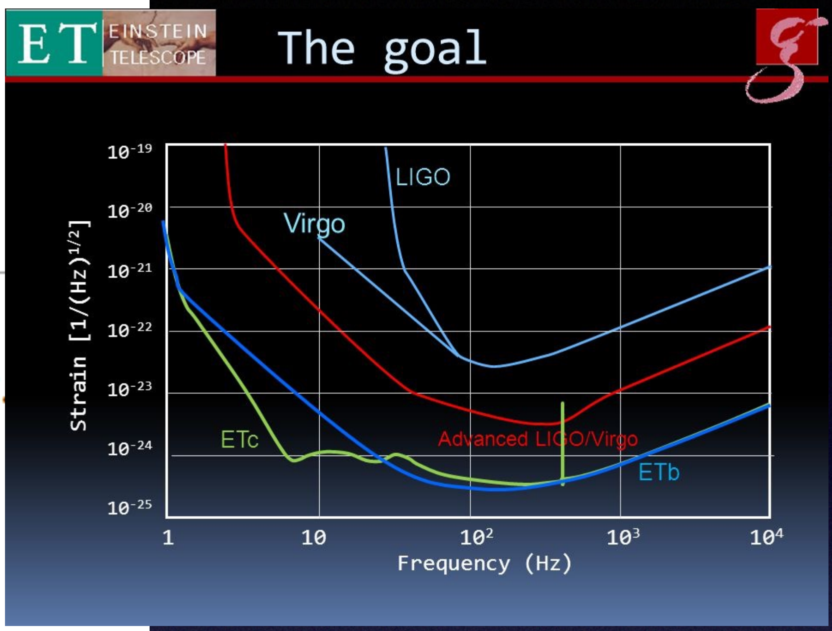


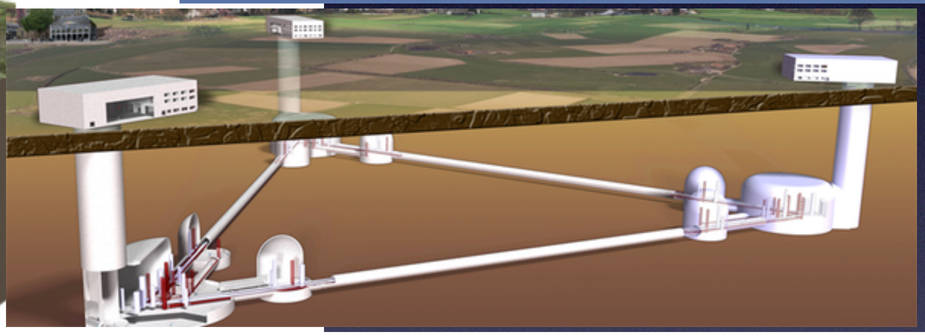
Stochastic background
EPTA
IPTA
eLISA
LISA
10^9 solar mass binaries
10^6 solar mass binaries
Resolvable galactic binaries
Extreme mass ratio inspirals
LIGO
aLIGO
Compact binary inspirals
Supernovae
Characteristic Strain
Frequency / Hz
10^{-12}
10^{-14}
10^{-16}
10^{-18}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}

Going underground: the ET

- The Einstein Telescope will be the next generation underground detector.







The arms will be 10 km long (compared to 4 km for LIGO, and 3 km for Virgo), and like LISA, there will be three arms in an equilateral triangle, with two detectors in each corner.