Exploring the Universe with gravitationa radiation: where we come from and where we're going

V. Fafone
Dipartimento di Fisica - Università di Roma Tor Vergata and INFN

INSPYRE 2023

REVOLUTION IN SCIENCE.

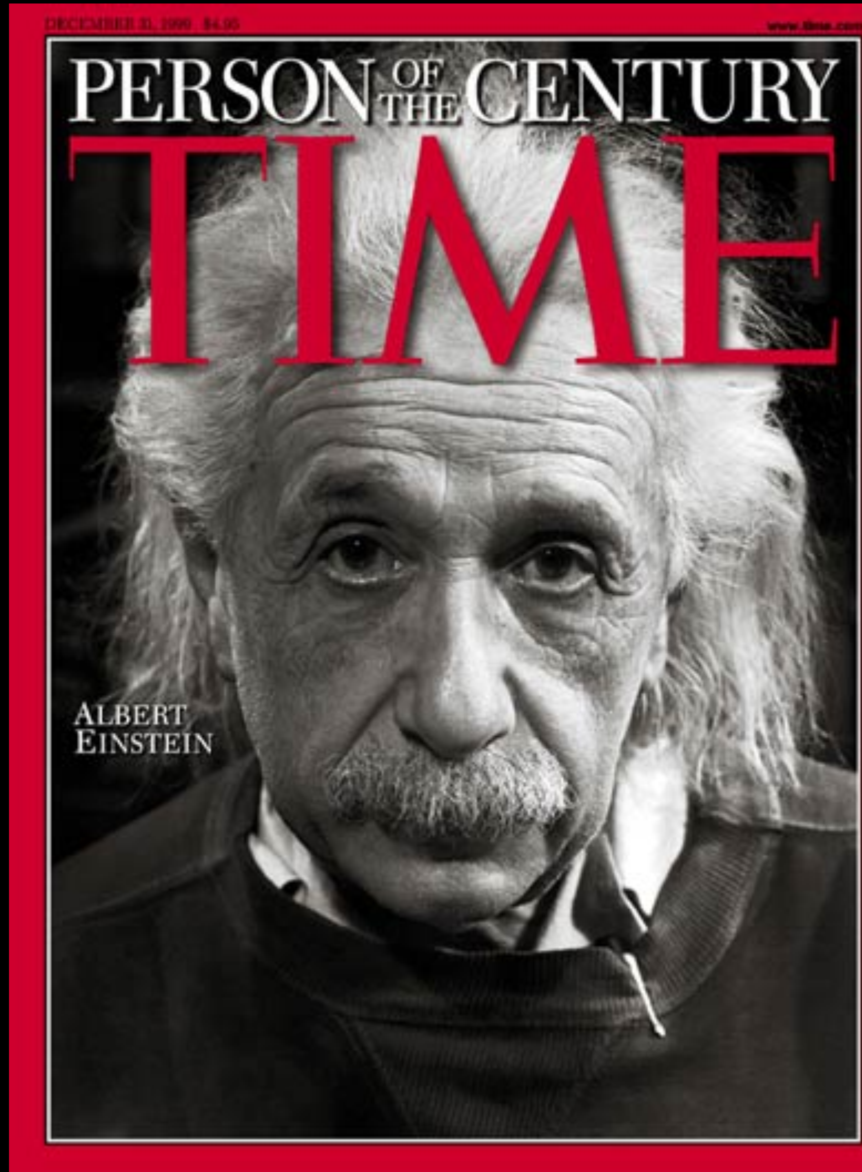
NEW THEORY OF THE UNIVERSE.

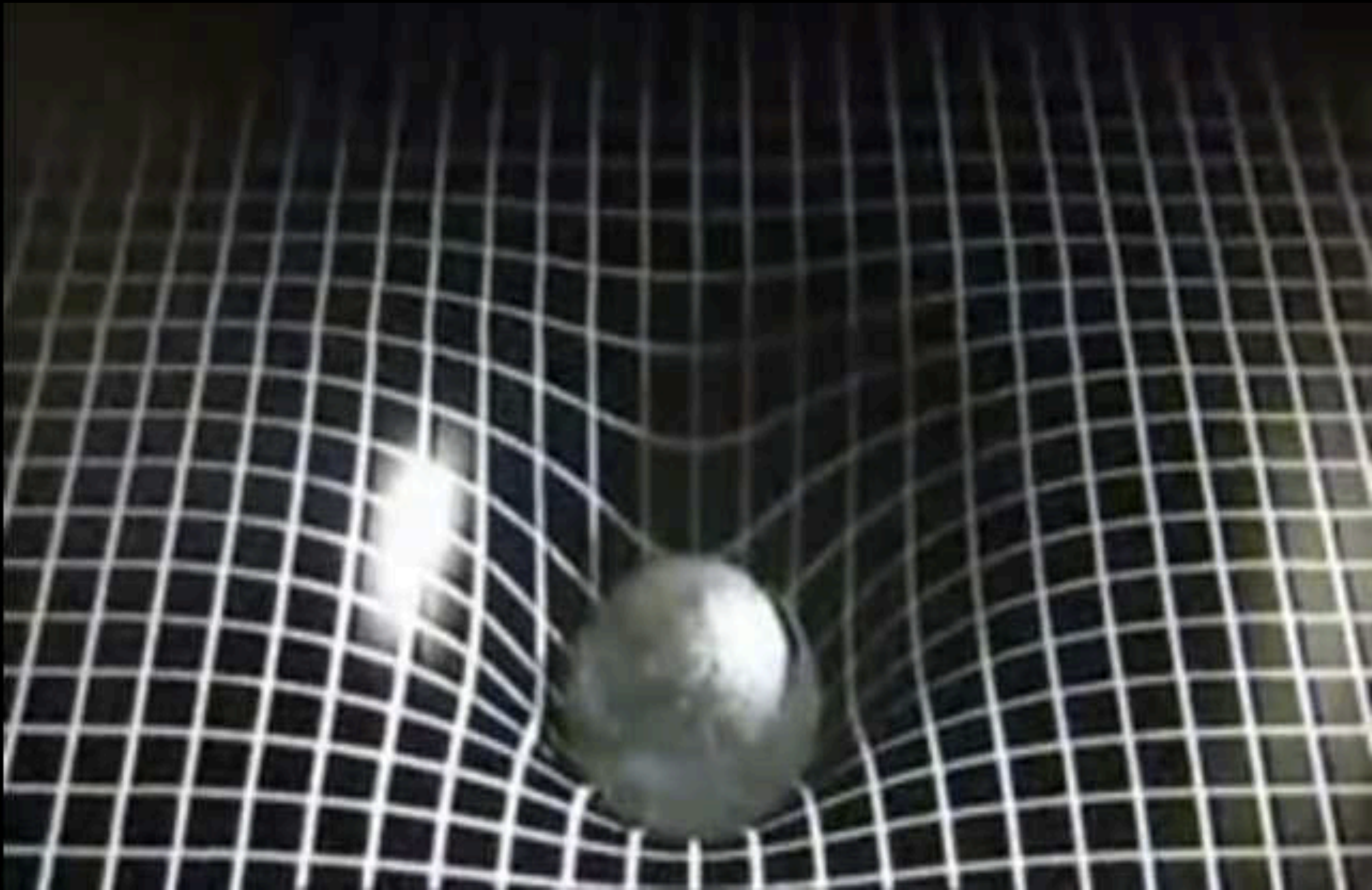
NEWTONIAN IDEAS OVERTHROWN.

Yesterday afternoon in the rooms of the Royal Society, at a joint session of the Royal and Astronomical Societies, the results obtained by British observers of the total solar eclipse of May 29 were discussed.

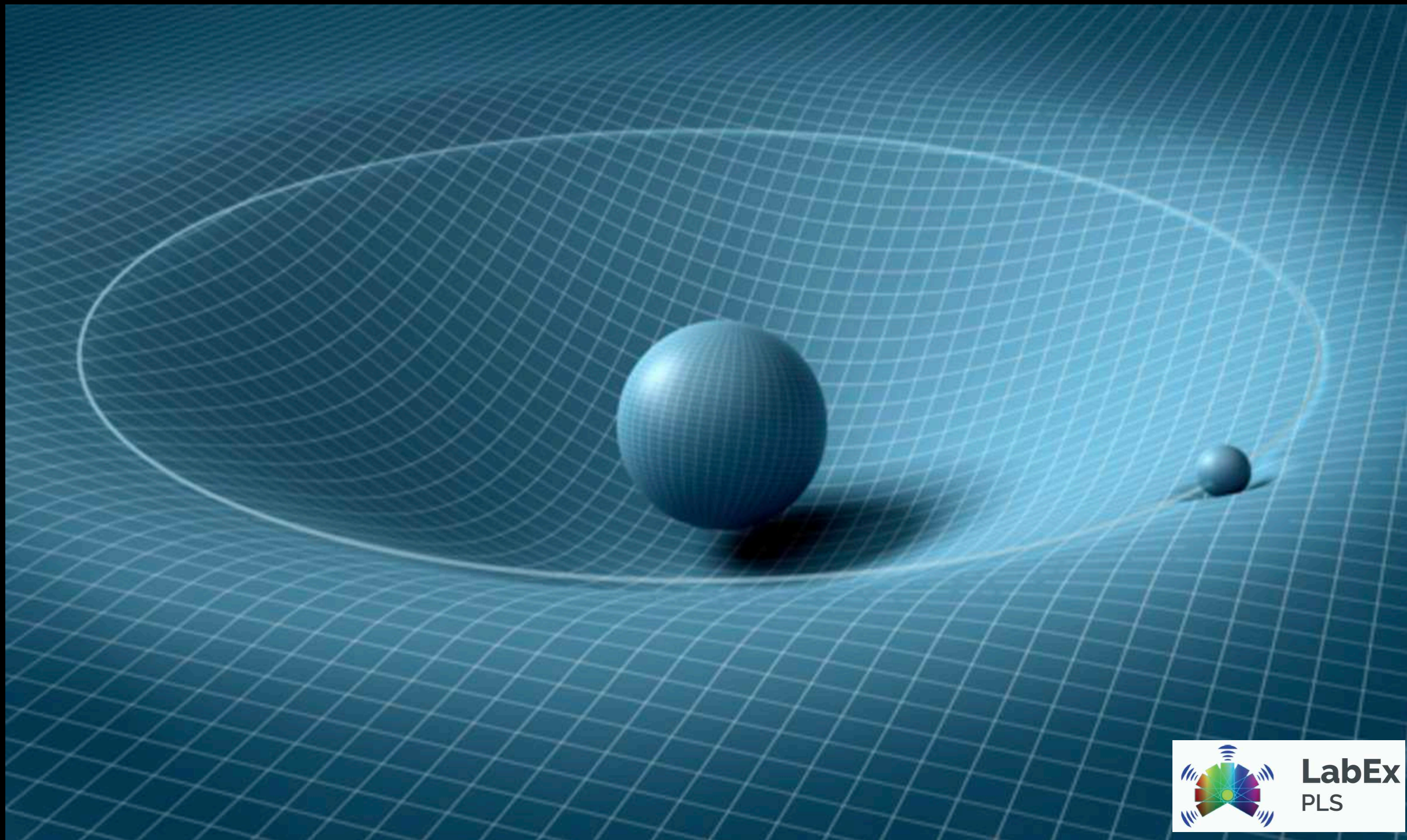
The greatest possible interest had been aroused in scientific circles by the hope that rival theories of a fundamental physical problem would be put to the test, and there was a very large attendance of astronomers and physicists. It was generally accepted that the observations were decisive in the verifying of the prediction of the famous physicist, Einstein, stated by the President of the Royal Society as being the most remarkable scientific event since the discovery of the predicted existence of the planet Neptune. But there was differ-

London Times, 6 Novembre 1919





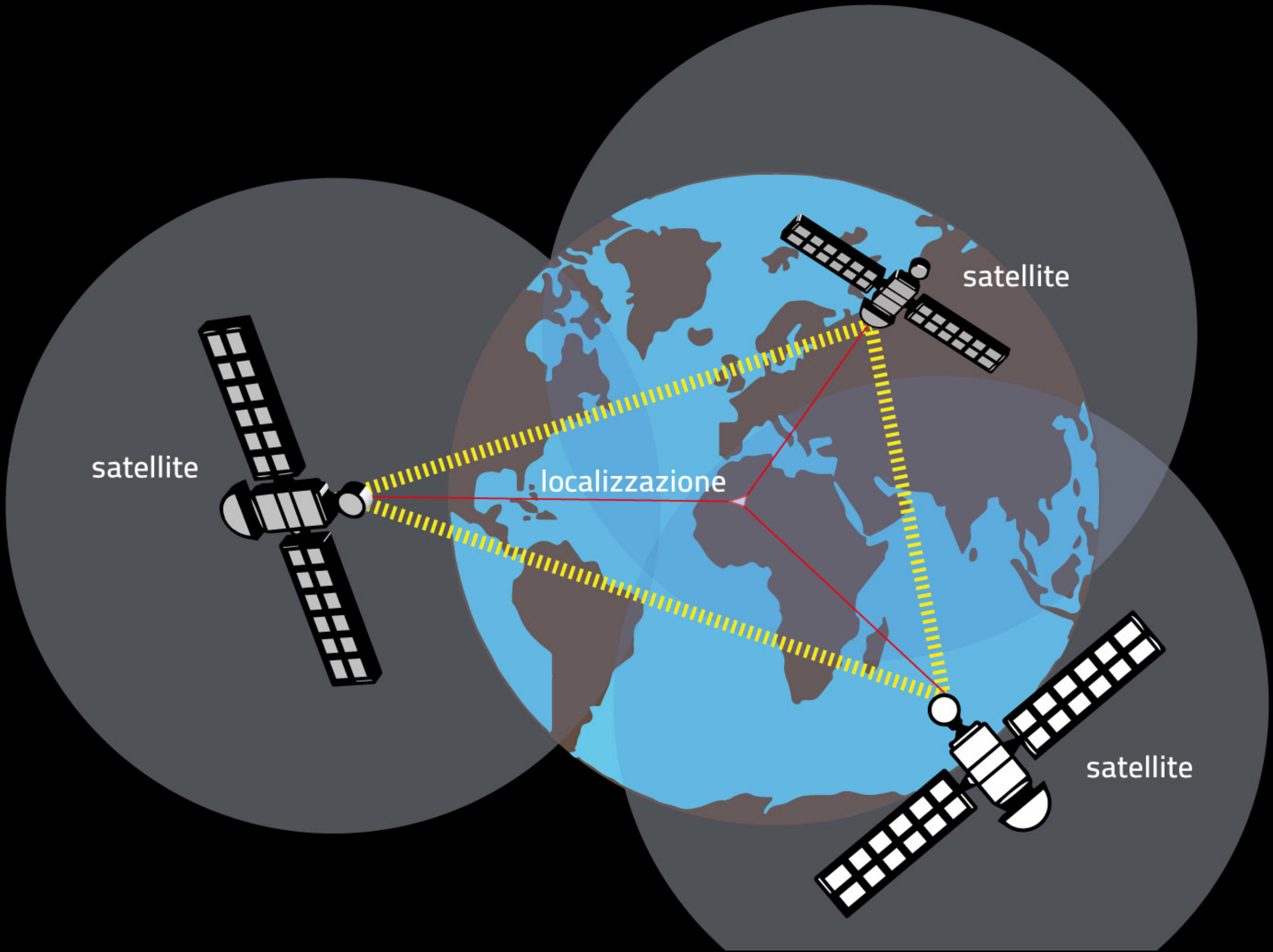
“Spacetime tells matter how to move; matter tells spacetime how to bend
(John Archibald Wheeler)

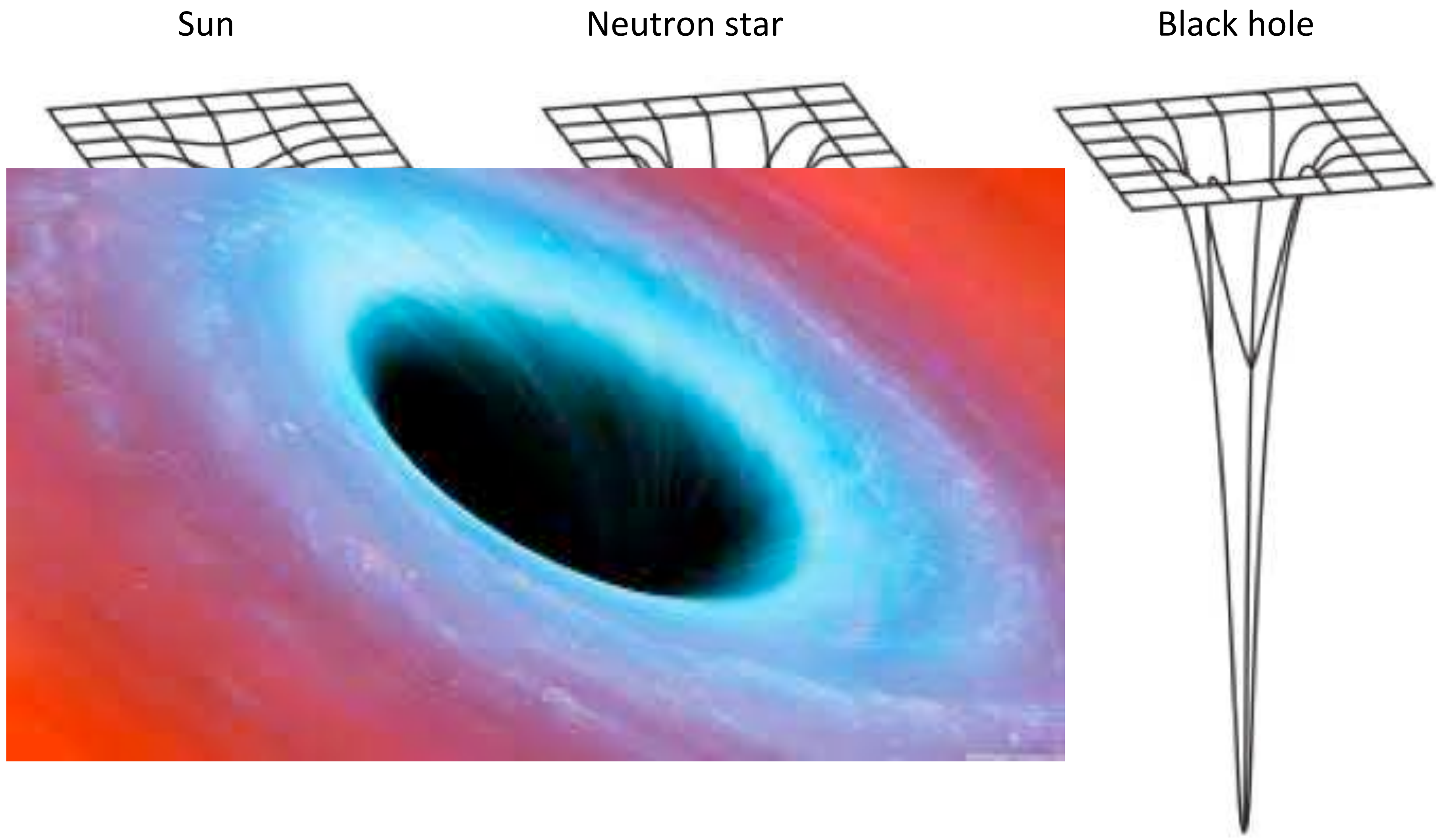


Time in General Relativity

Time flows more slowly as the gravitational field increases

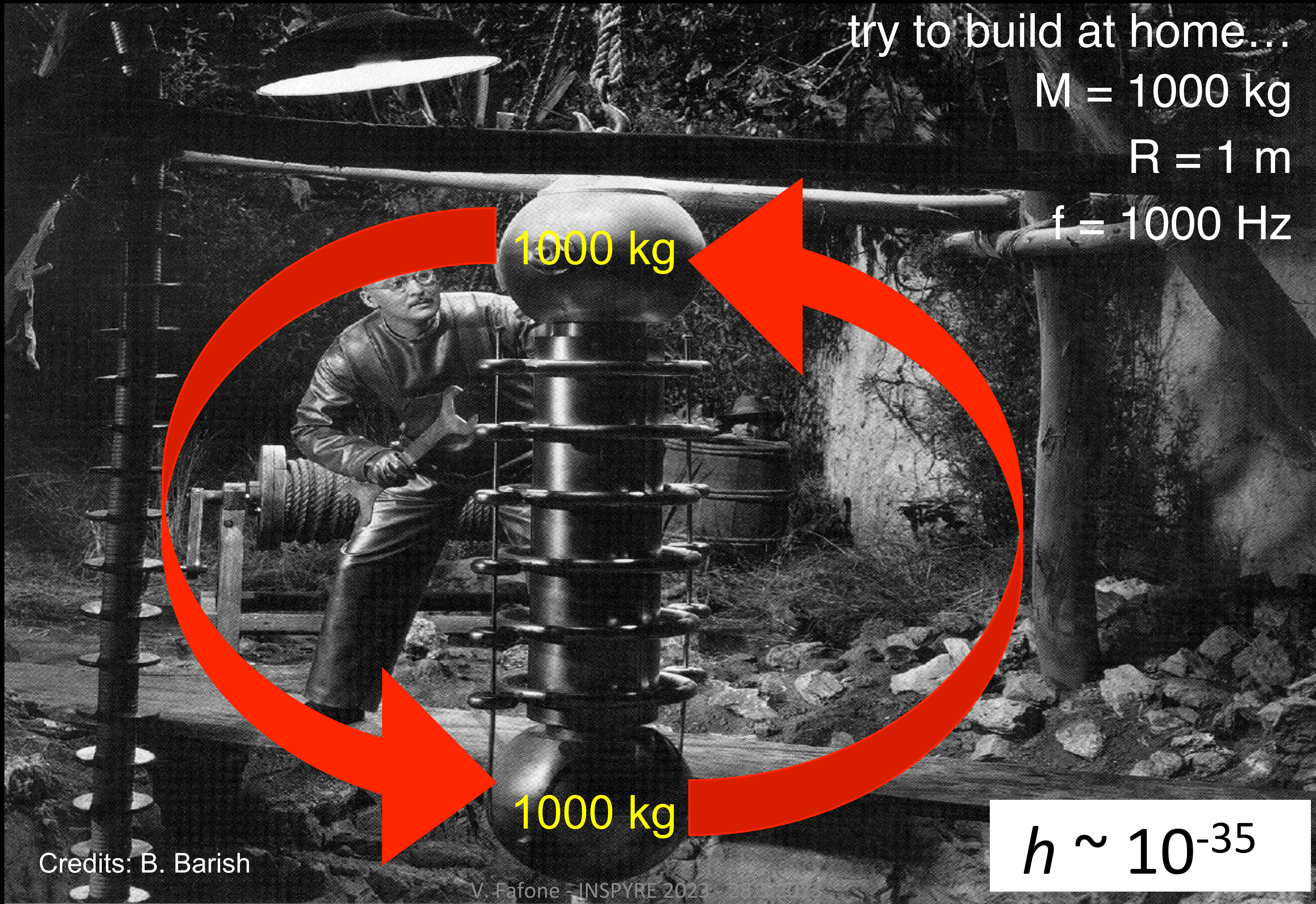
General Relativity in our pocket: the GPS




Sun
Neutron star
Black hole

Ripples in spacetime moving at the speed of light

How can we generate a gravitational wave?



How to generate a detectable gravitational wave?

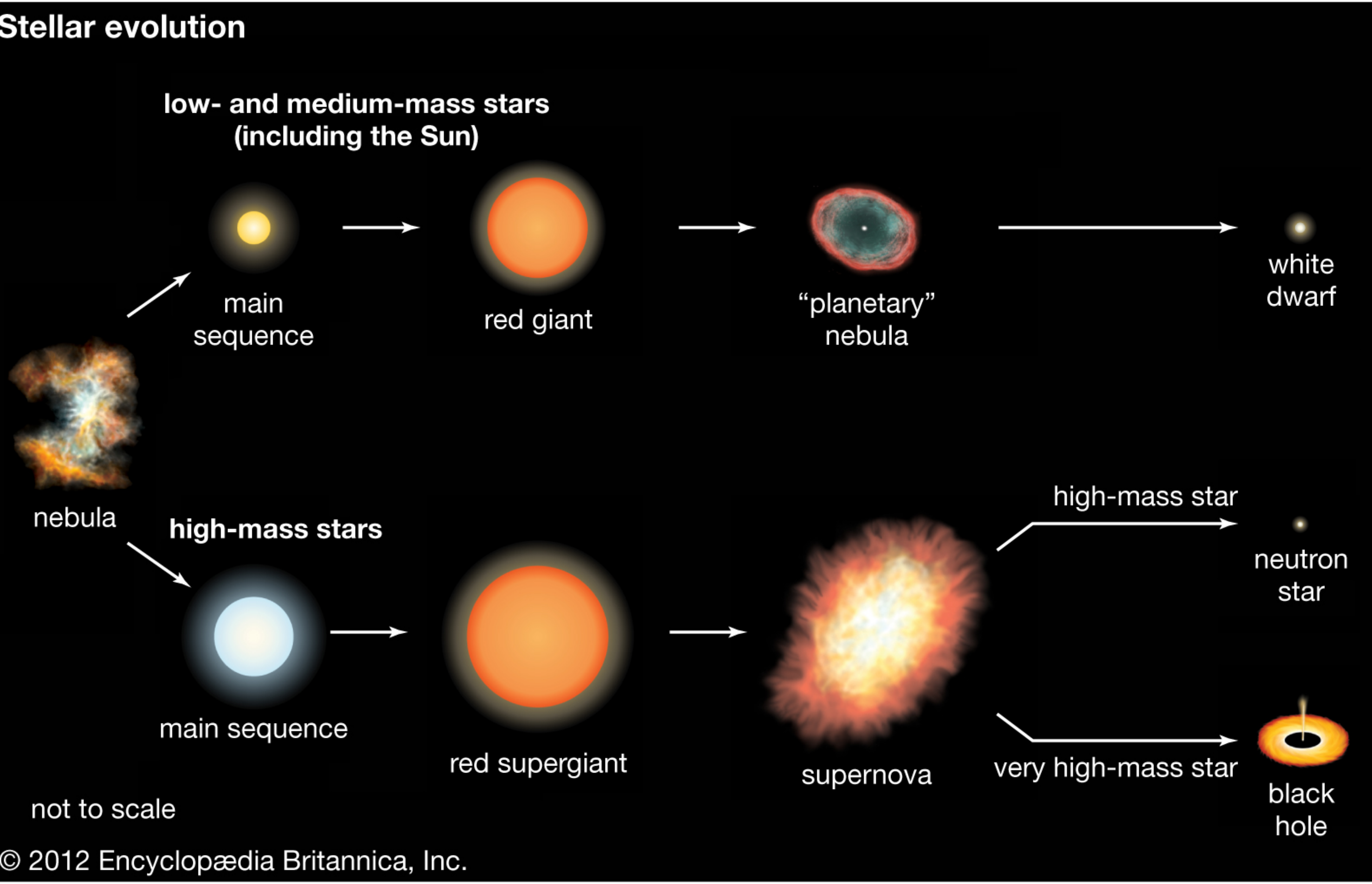
Binary system with 2 neutron stars (1.4 solar mass each)

R = 20 km

f = 400 Hz

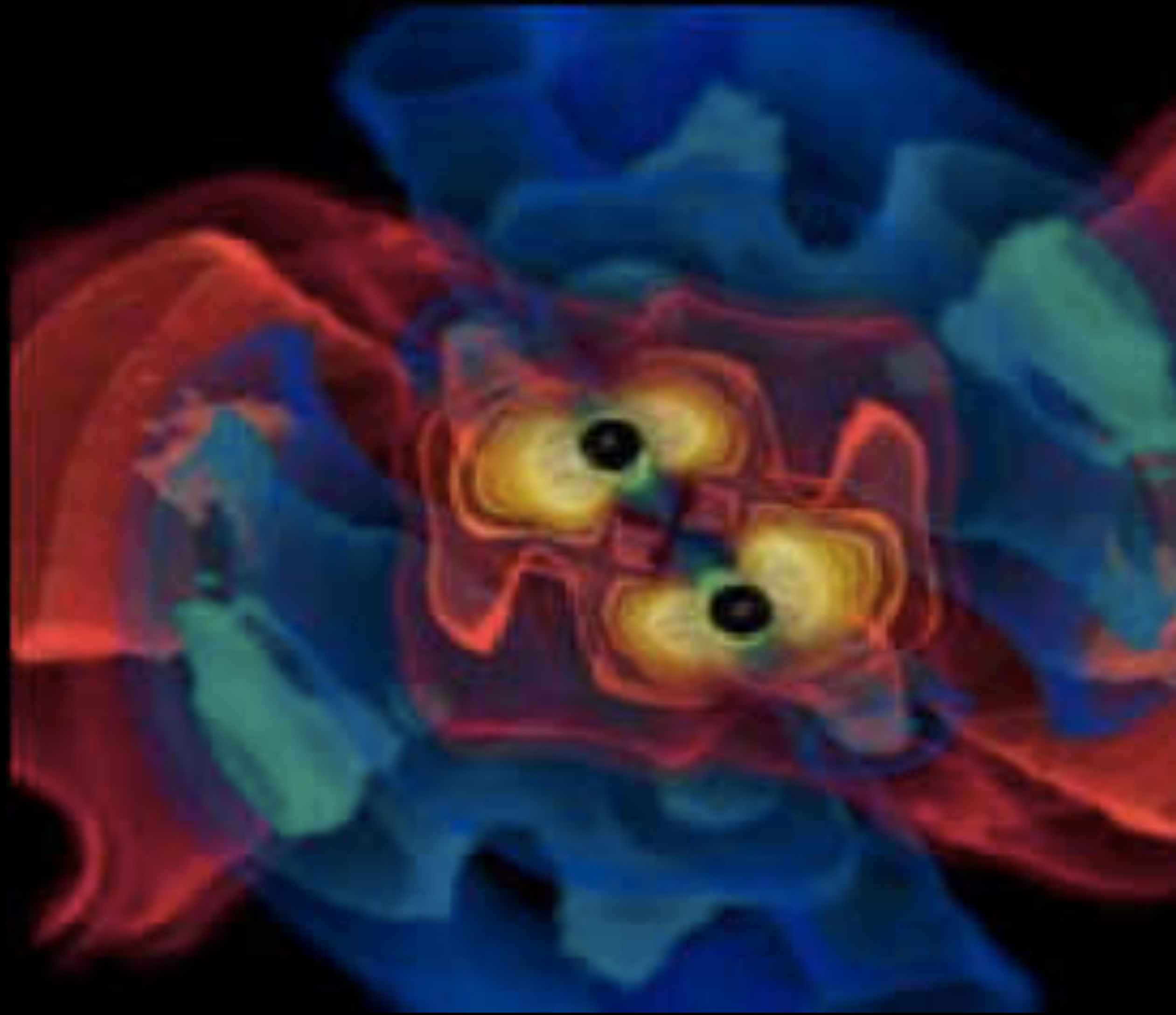
r = 5 10^{23} m (15Mpc i.e. about 50 million light years)

$h \sim 10^{-21}$


Stellar evolution
low- and medium-mass stars
(including the Sun)
main sequence
red giant
“planetary” nebula
white dwarf
nebula
high-mass stars
main sequence
red supergiant
supernova
high-mass star
neutron star
very high-mass star
black hole
not to scale

GW sources

Binary systems (made of BHs, NSs, or both)

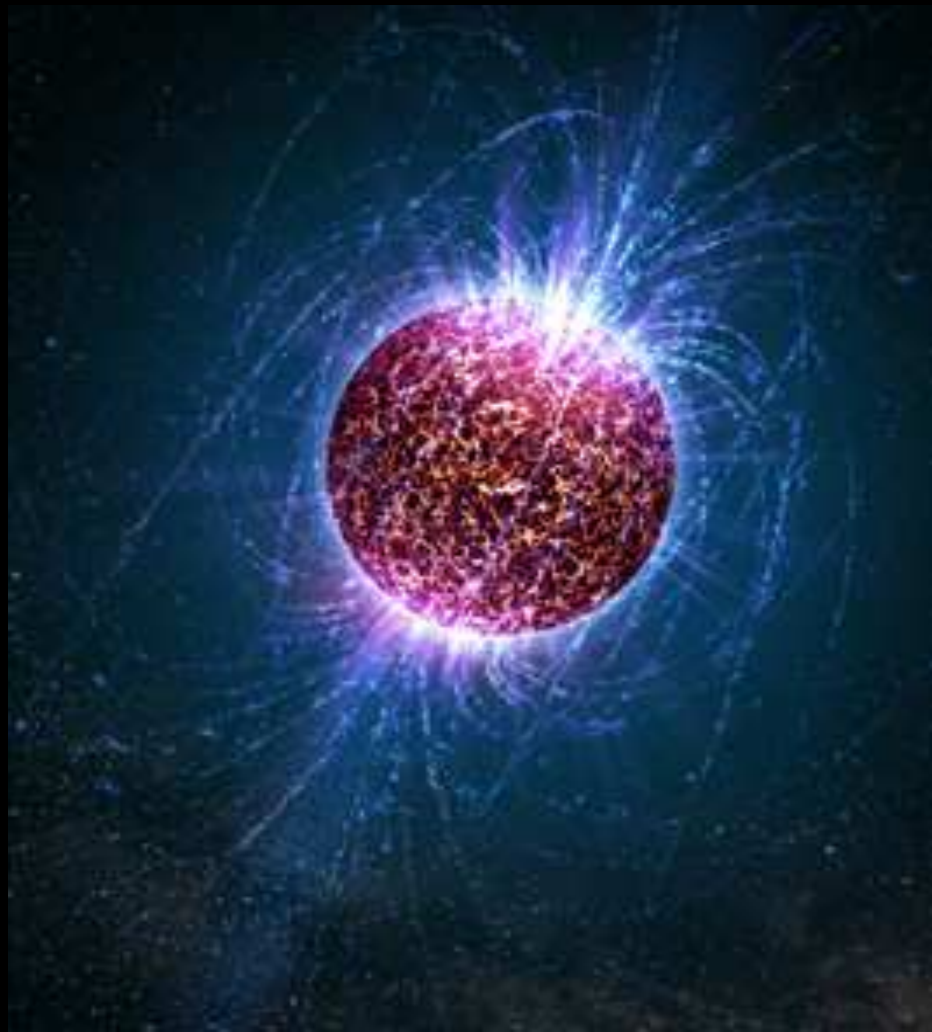


GW sources

upernova explosion

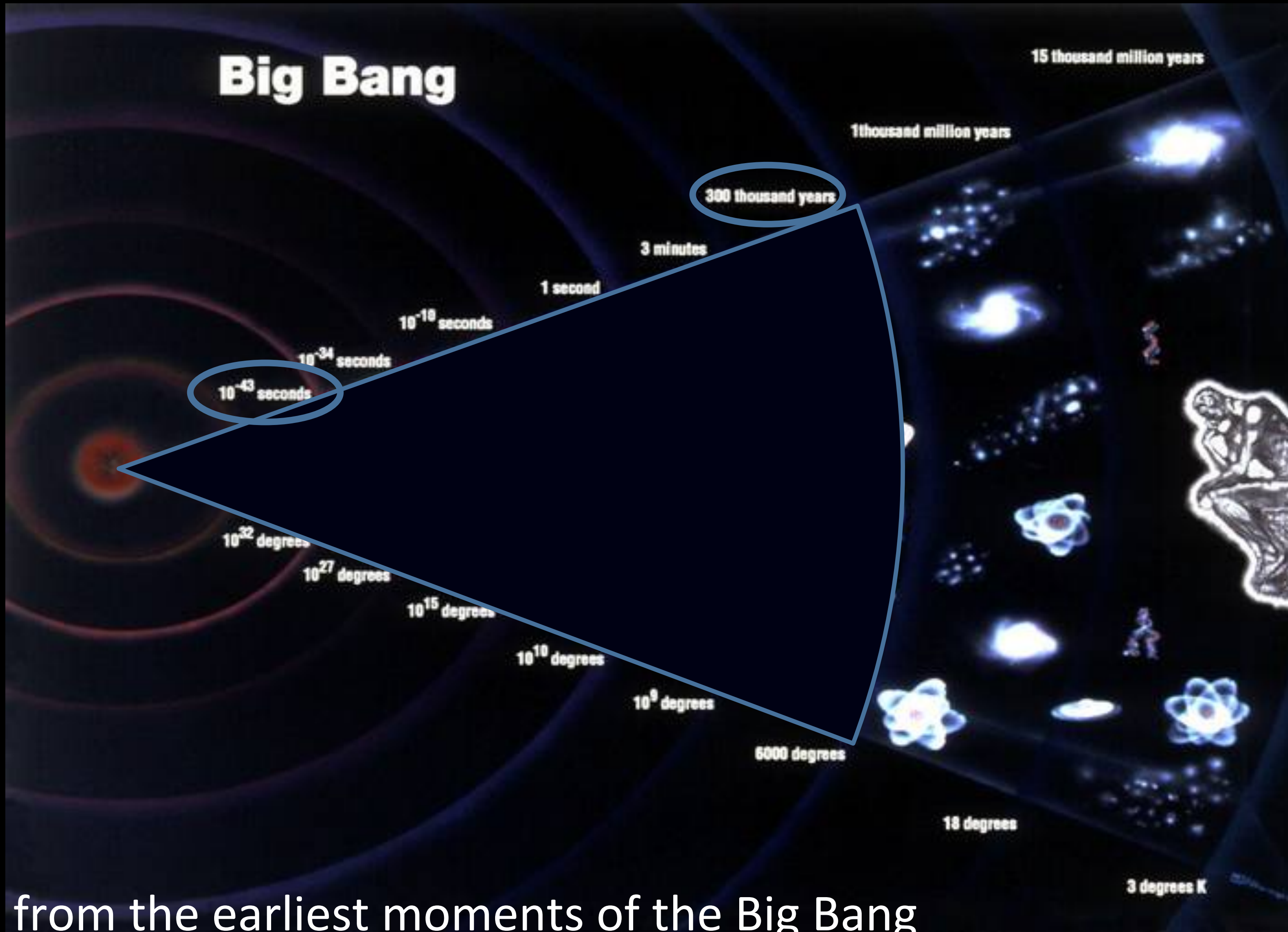
GW sources

Rotating neutron stars



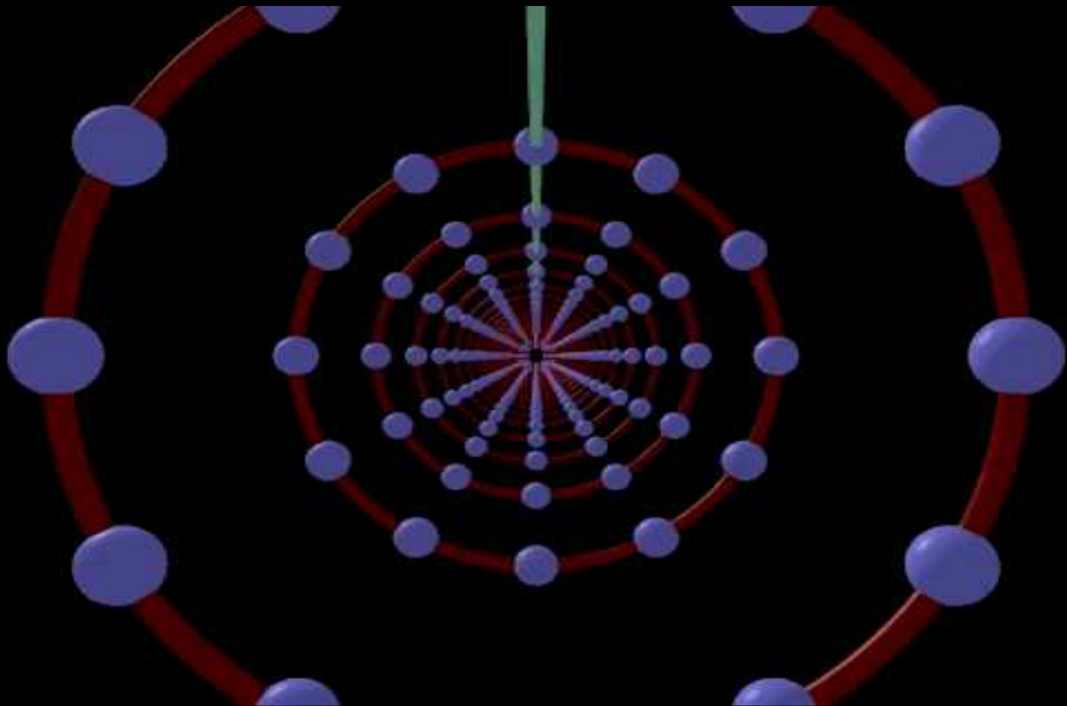
GW sources

Stochastic background of GWs (the gravitational equivalent of the cosmic microwave background)



Only GWs can escape from the earliest moments of the Big Bang

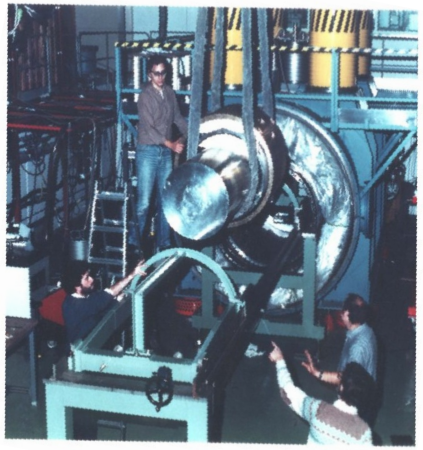
How can we measure a GW?



GWs in oblivion for about 40 years…

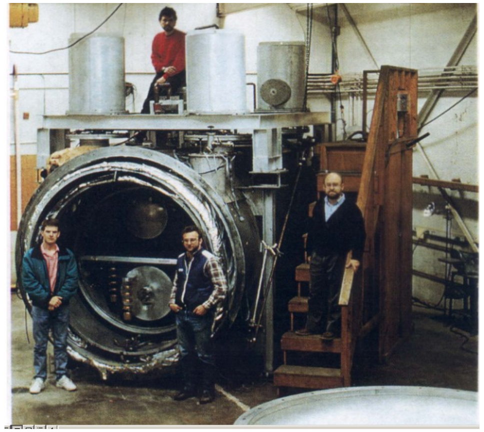
- …about till beginning of sixties

The network of bar detectors



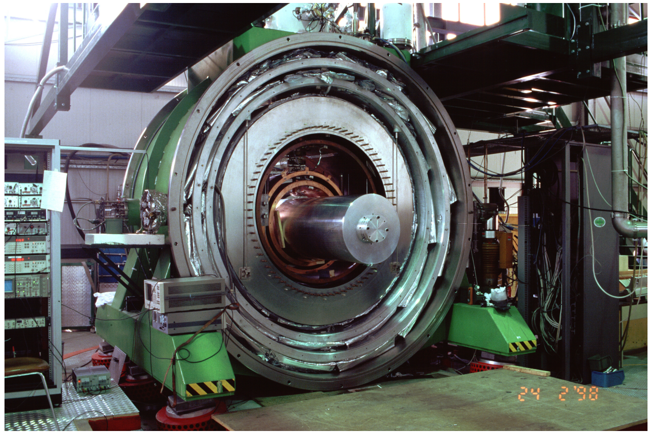
EXPLORER
CERN

ALLEGRO
Louisiana

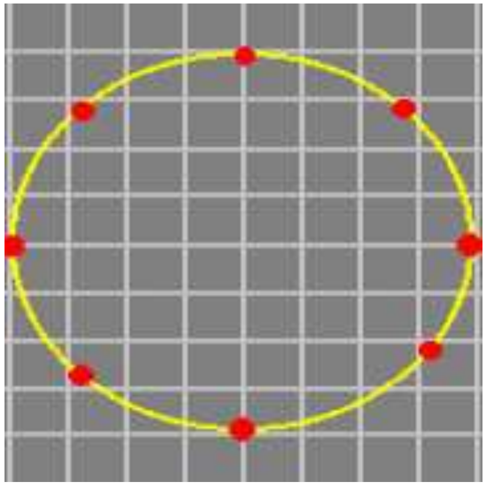


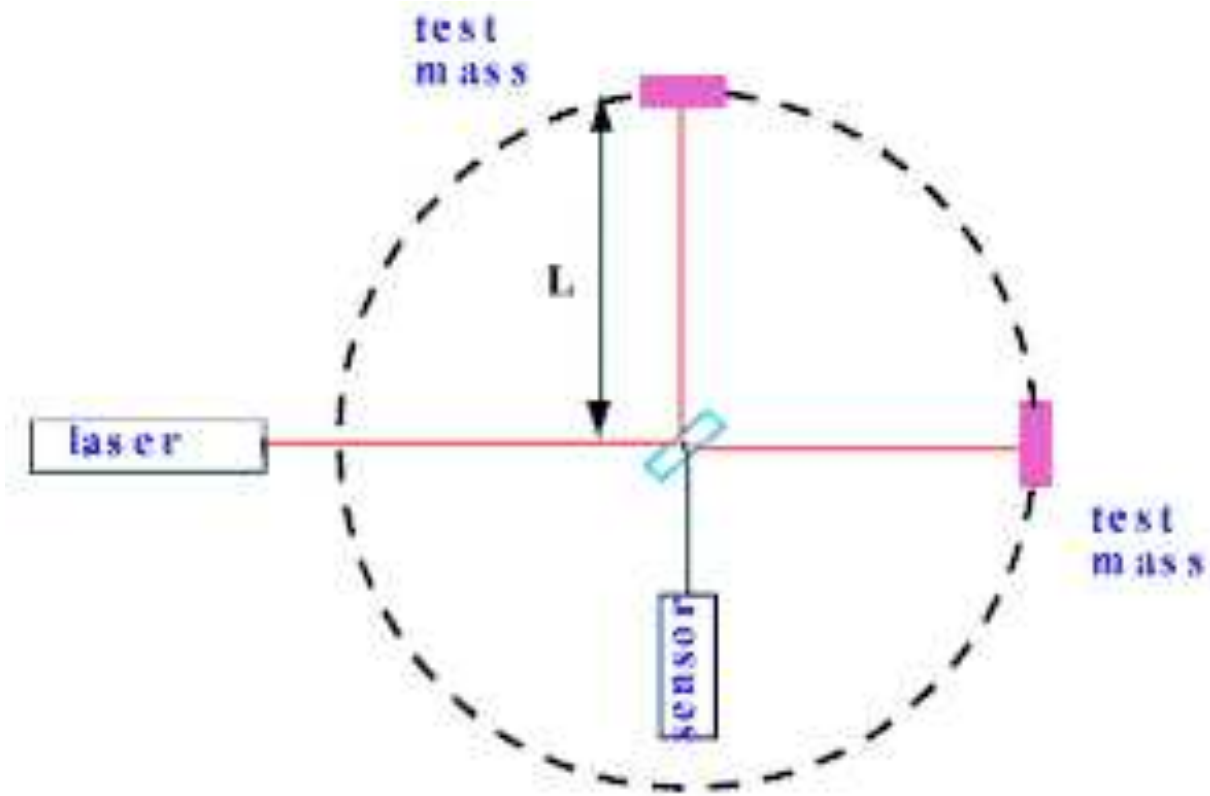
AURIGA
INFN National Labs in Legnaro

NAUTILUS
CERN → INFN National Labs in Frasc



Detecting GWs with light





The first proposals

Proposal to the National Science Foundation

A
LASER INTERFEROMETER
GRAVITATIONAL-WAVE
OBSERVATORY
(LIGO)

LIGO-M890001-00-M

VOLUME 1:
LIGO Science and Concepts

December 1989

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LIGO PROJECT

12 Maggio 1987
INFN PI/AE 87/1

Proposta di

Antenna interferometrica a grande base per la ricerca di Onde Gravitazionali

Laboratori INFN Pisa e Universita' di Pisa:

Carlo BRADASCHIA
Raffaele DEL FABBRO
Angela DI VIRGILIO
Adalberto GIAZOTTO
Hans KAUTZKY
Vinicio MONTELATICI
Diego PASSUELLO

Universita' di Napoli

Fabrizio BARONE
Riccardo BRUZZESE
Antonello CUTOLO
Luciano DI FIORE (INFN)
Massimo LANDINI
Maurizio LONGO
Leopoldo MILANO
Salvatore SOLIMENO

CNR Frascati

Franco BORDONI
Franco FULIGNI
Valerio IAFOLLA

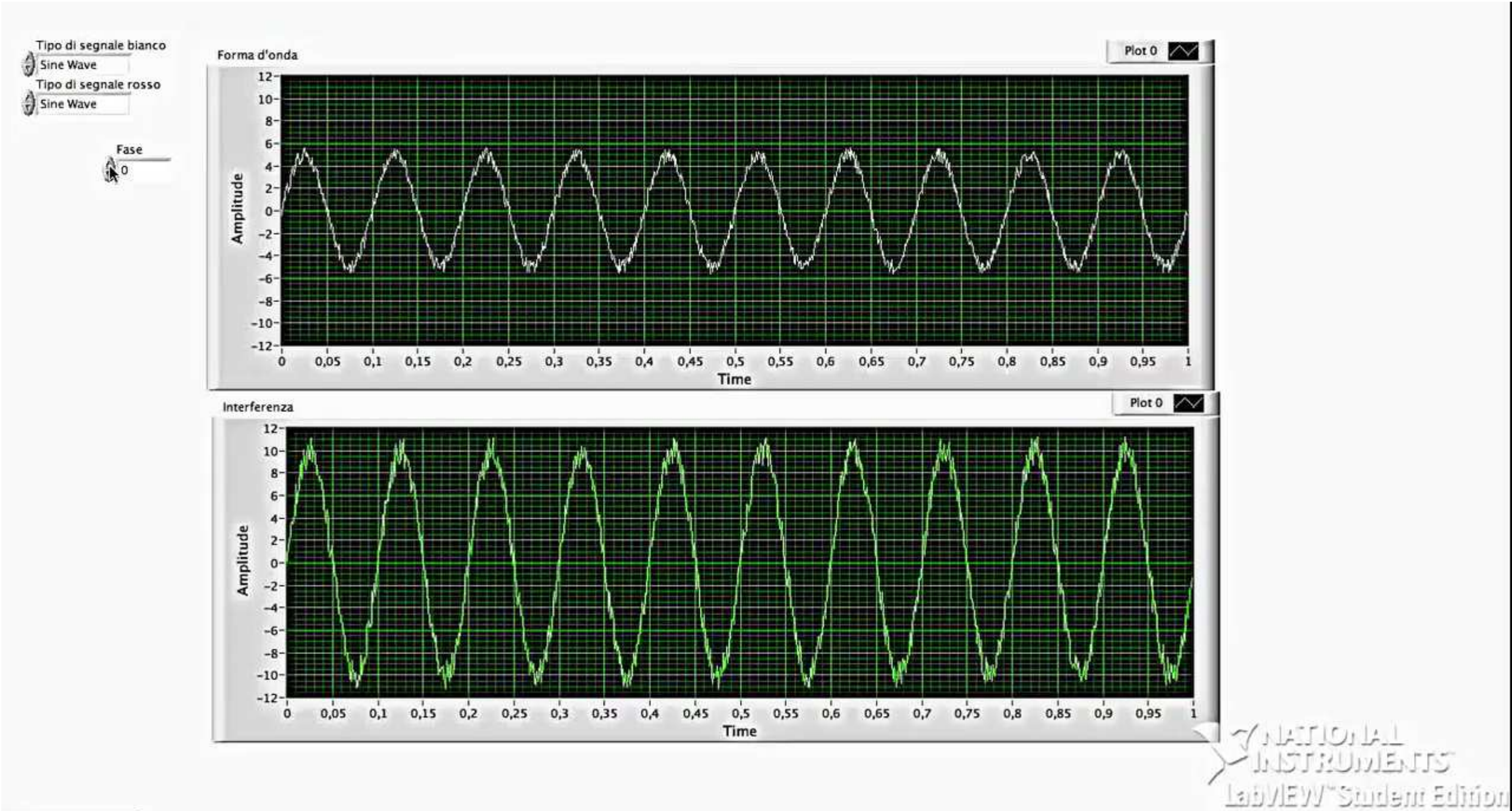
Universita' di Salerno

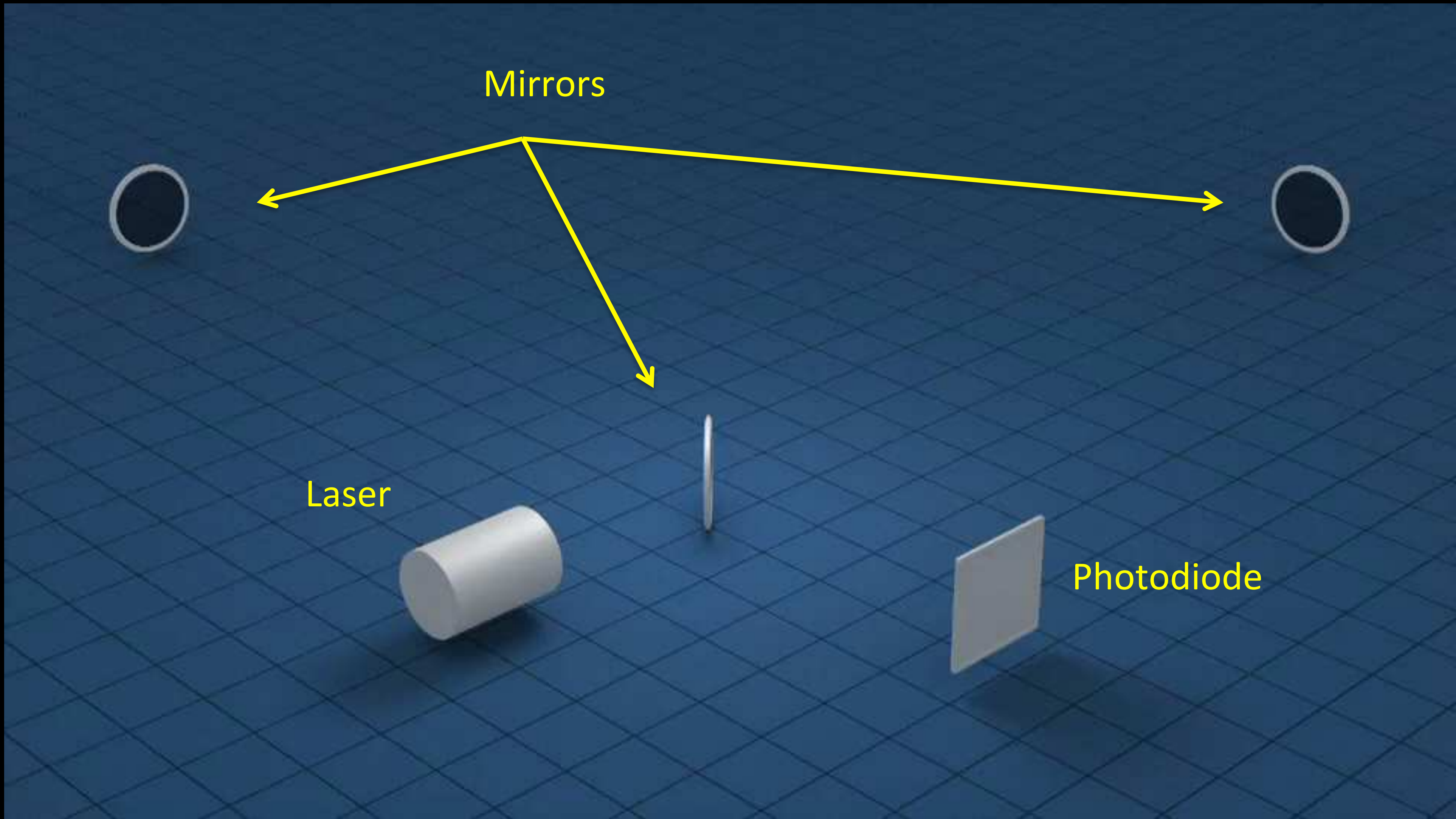
Innocenzo PINTO

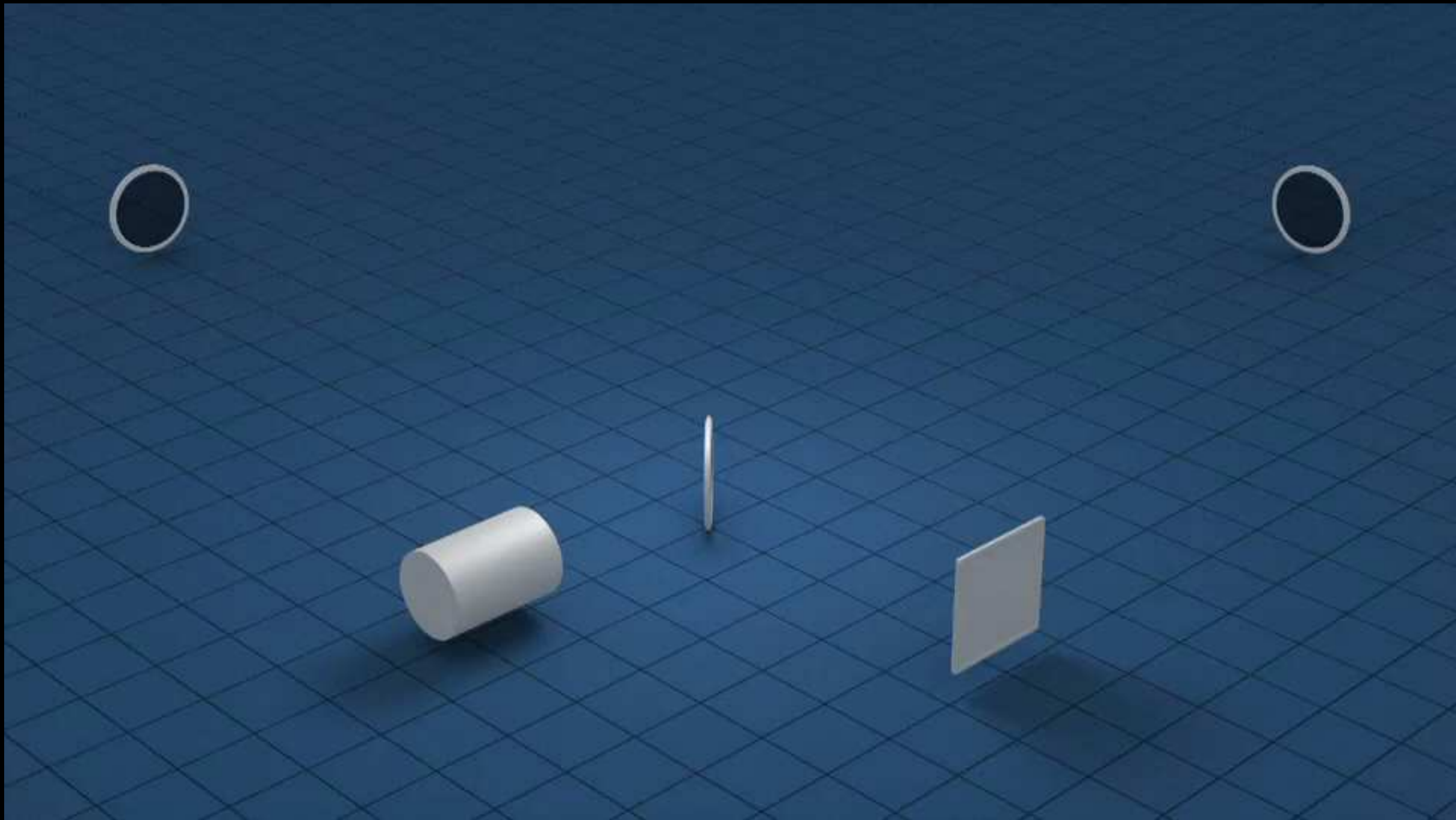
Gravitation et cosmologie Relativiste (Orsay-Paris)
CNRS-Univ. Pierre et Marie Curie

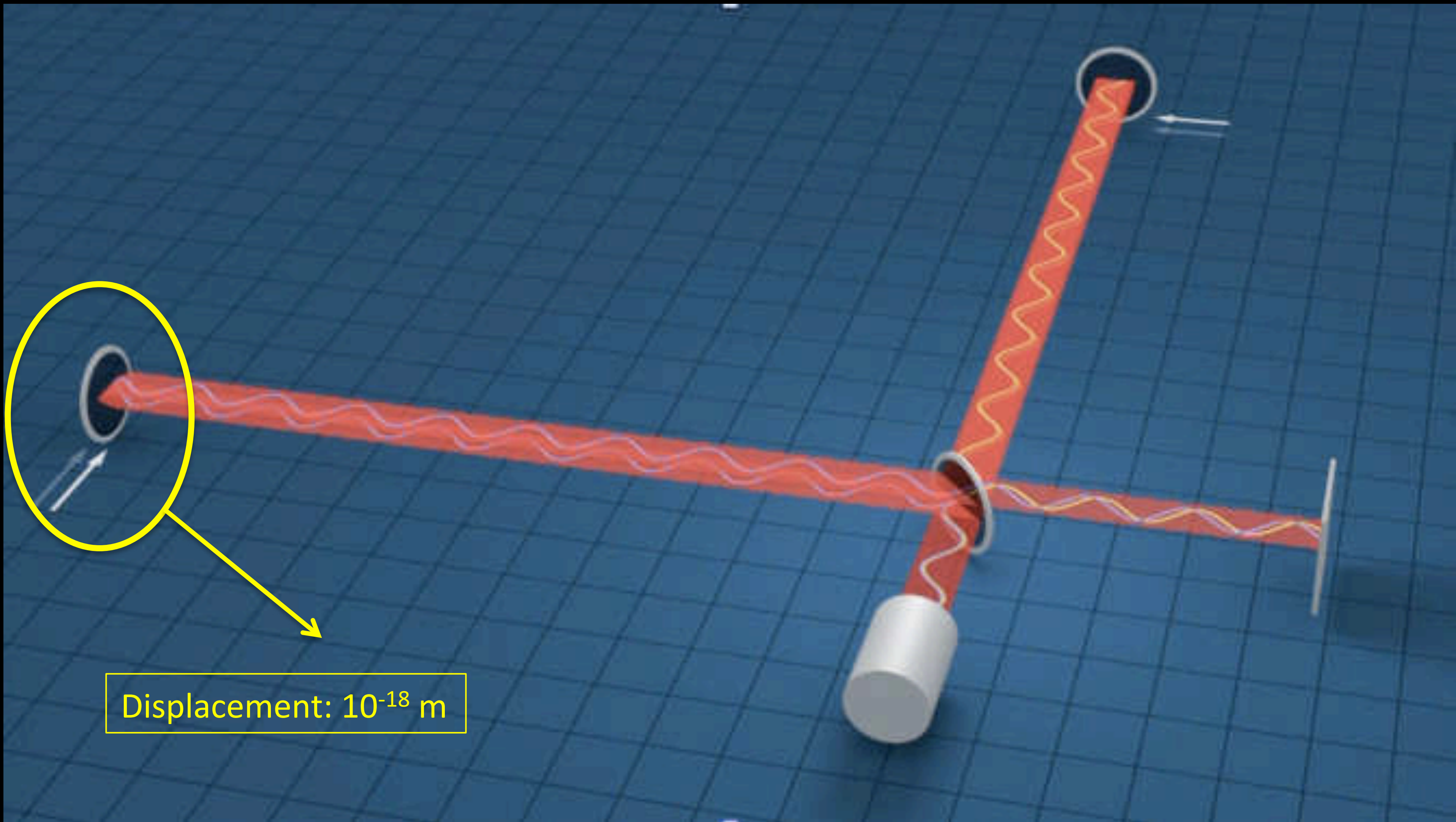
J.L. BOULANGER
Alain BRILLET
Oliver CREGUT
C. Nary MAN
Alain MARRAUD
David SHOEMAKER
Philippe TOURRENC
Jean-Yves VINET

Detecting GWs with light

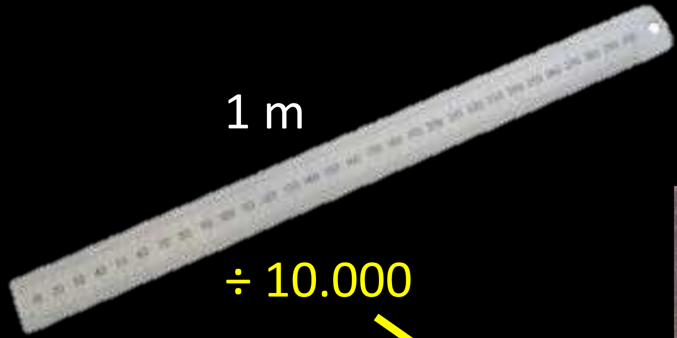



Mirrors
Laser
Photodiode



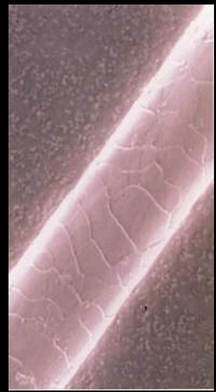

Displacement: 10-18 m

1 m



÷ 10.000

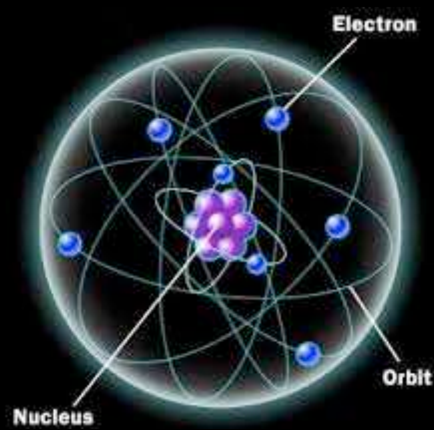
10^{-4} m



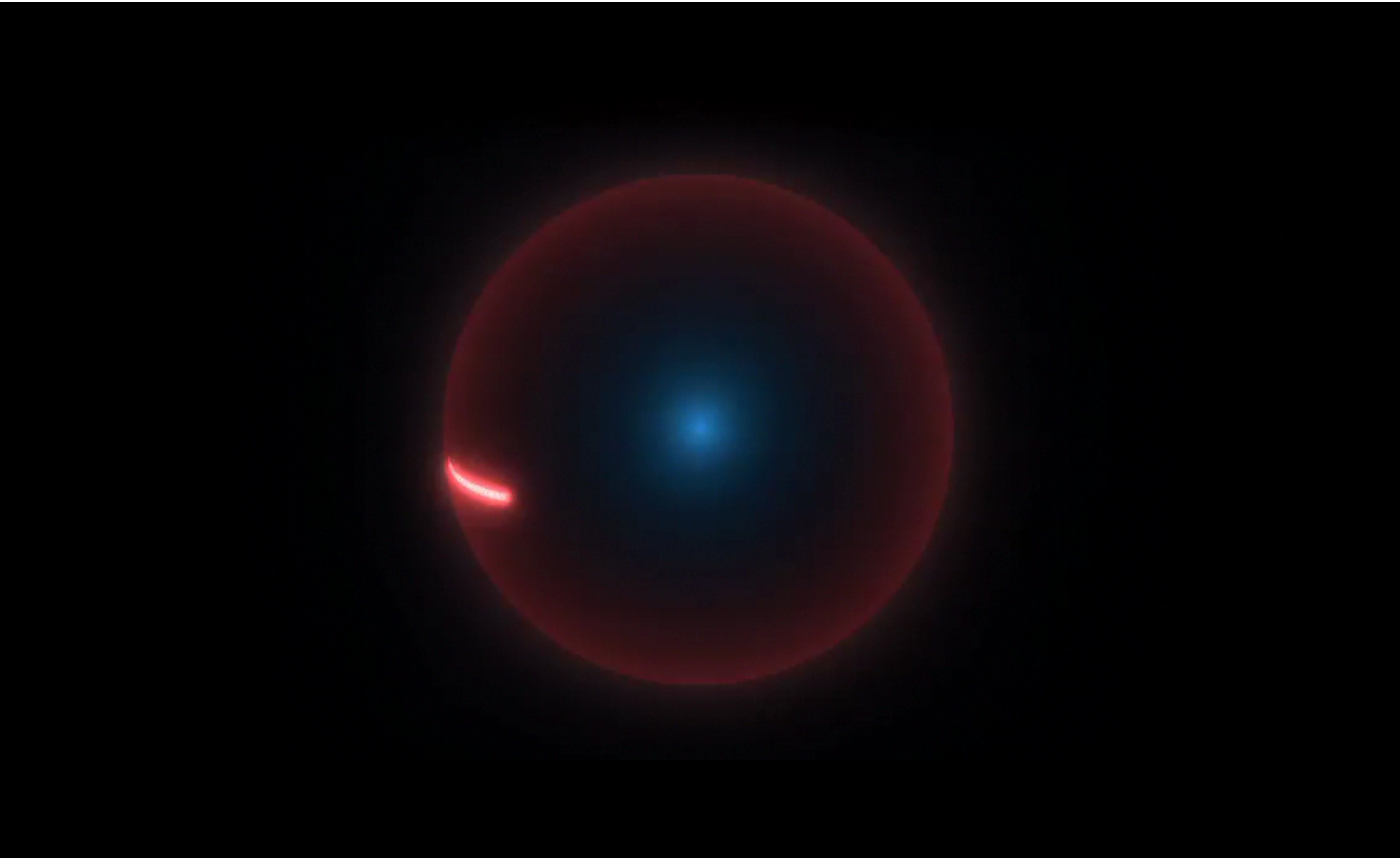
÷ 100

10^{-6} m

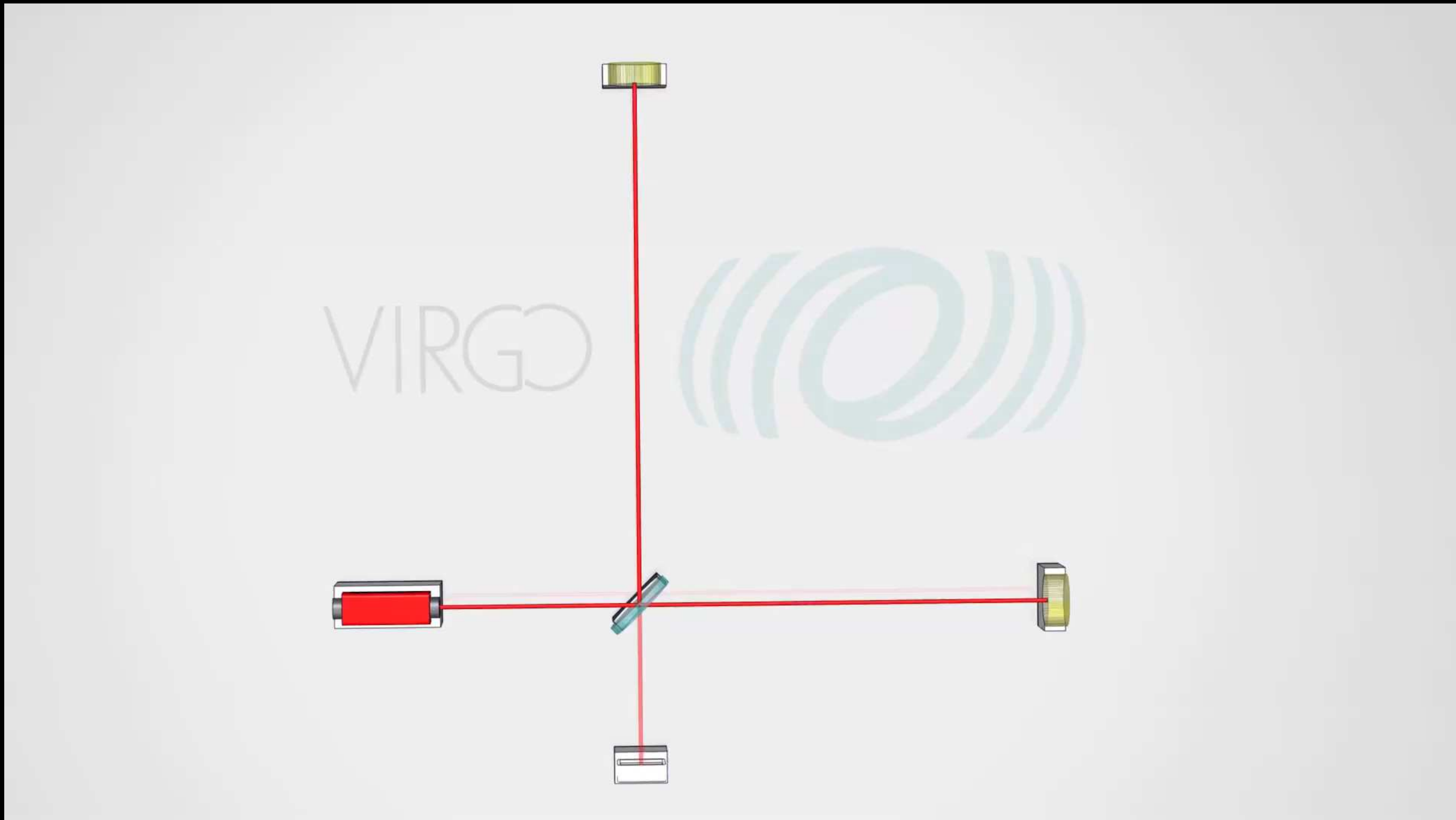
÷ 10.000



10^{-10} m

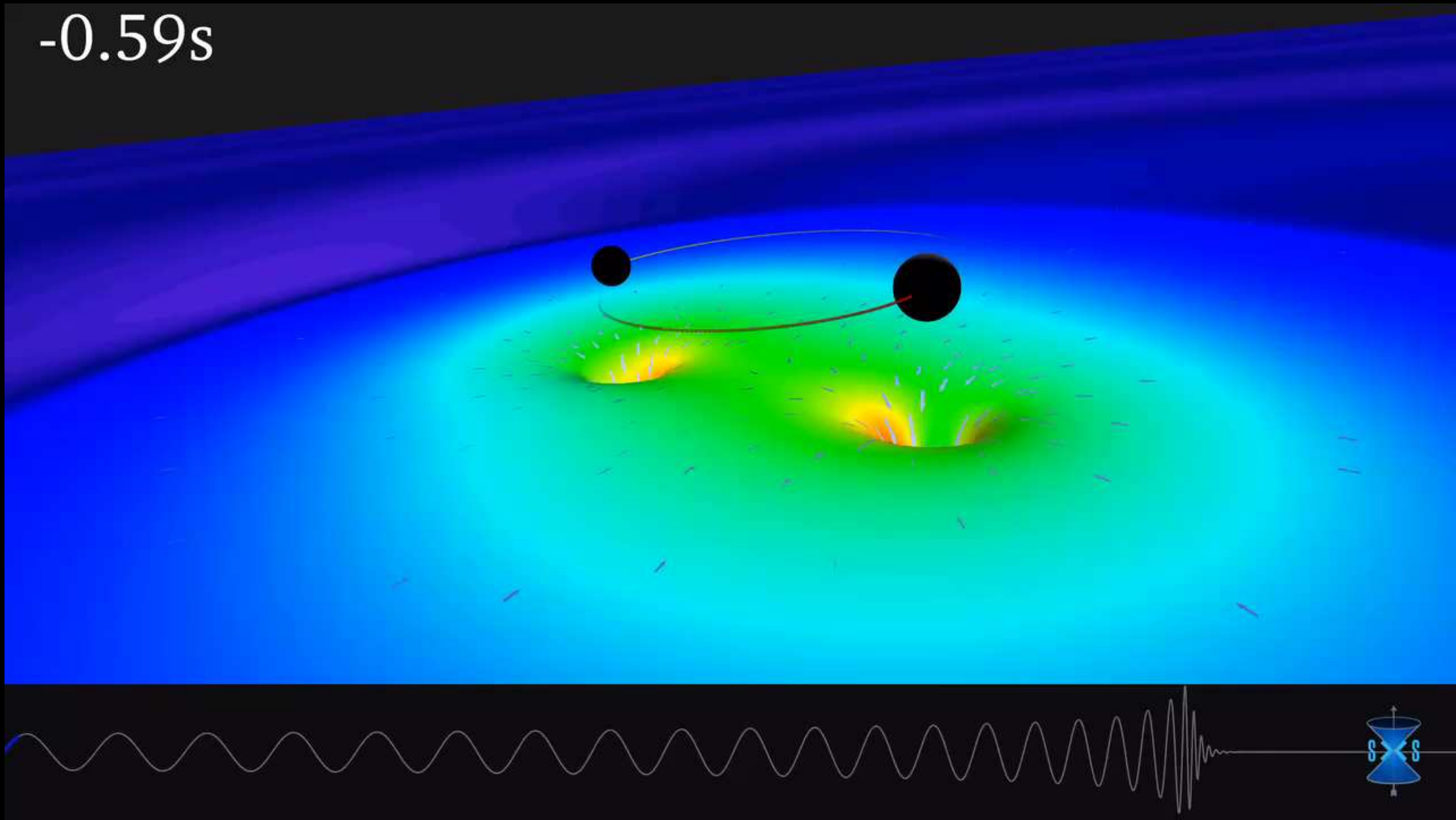


How to build a GW interferometer




Hanford
(Stato di Washington)
LIGO
Germania
GEO600
LE ANTENNE GRAVITAZIONALI NEL MONDO
Livingston
(Louisiana)
LIGO
Cascina
(Pisa, Italia)
VIRGO
Giappone
KAGRA
LIGO India
Fufuture project
Cascina VIRGO
(Pisa)

14 September 2015 11:50:45 CET


-0.59s

- Initial masses of the two BHs: 36 M_{sol} and 29 M_{sol}
- Final mass = 62 M_{sol}

- 3 solar masses have been converted in gravitational energy

$E = mc^2$

50 x light emitted by all the stars in the Universe in a few tenths of seconds

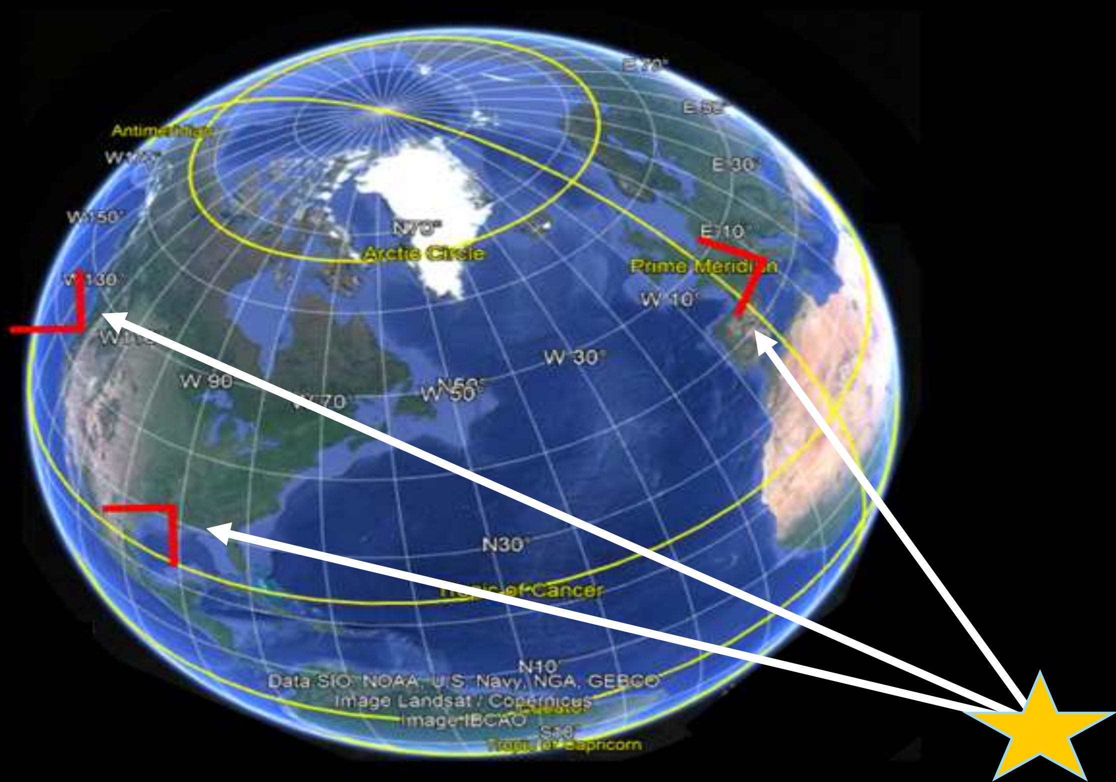
- Distance = 1,3 billions light years
- 10^{-18} meters measured by the interferometer

2017 Nobel Prize

Also GWs coming form two neutron stars have been measured

August 17, 2017

GW170817: the localization

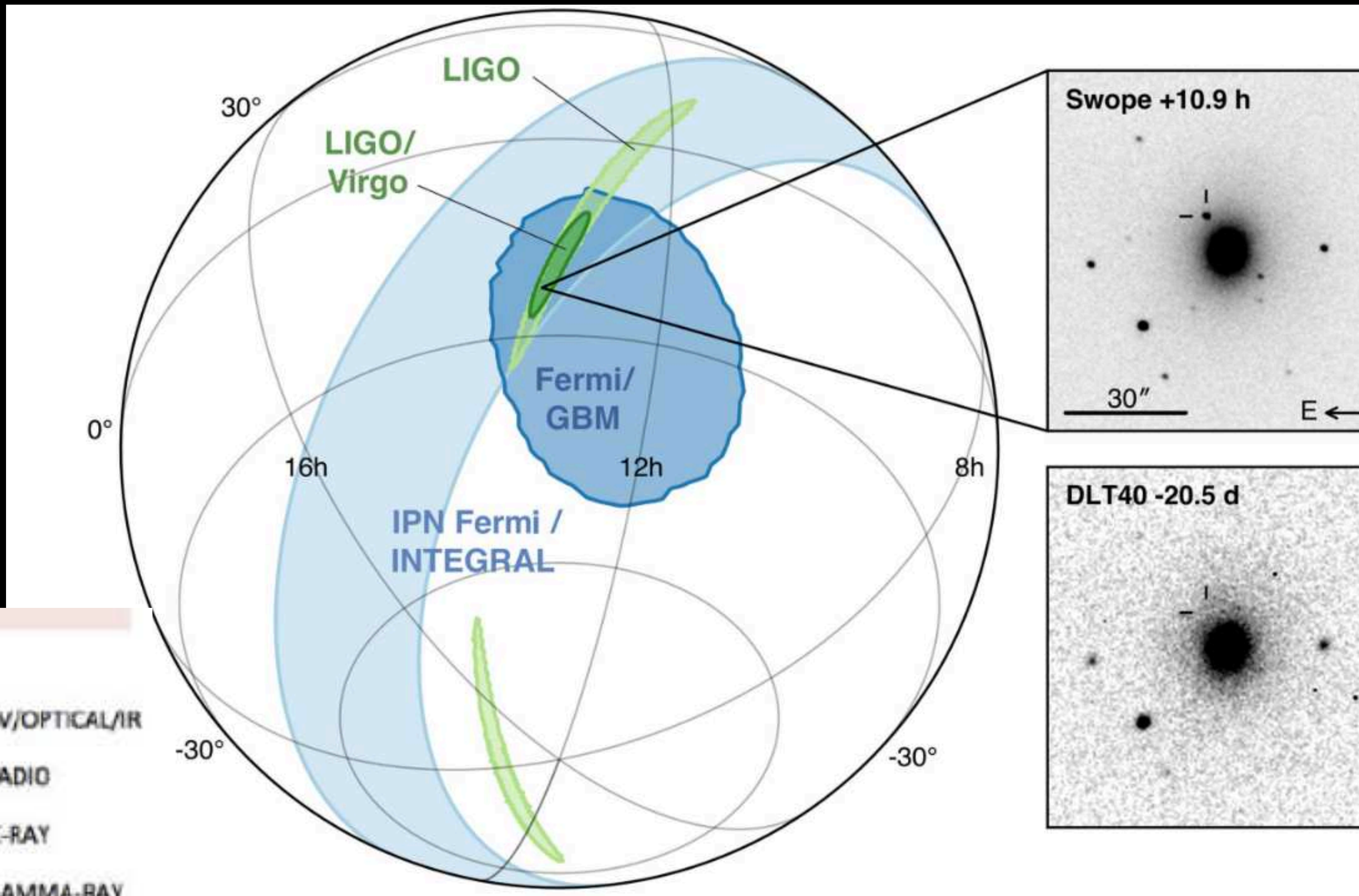


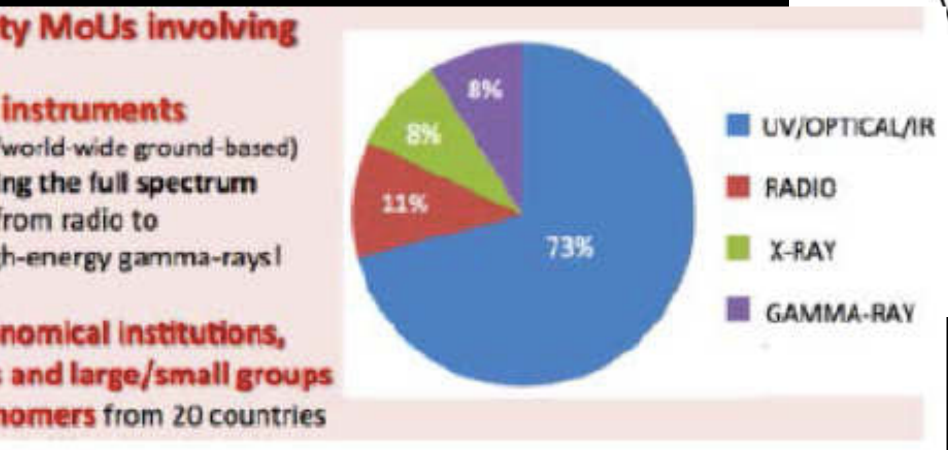
The international network

/ observatories
observatories

About 70 ground and space telescopes followed up this event

La localization of the source



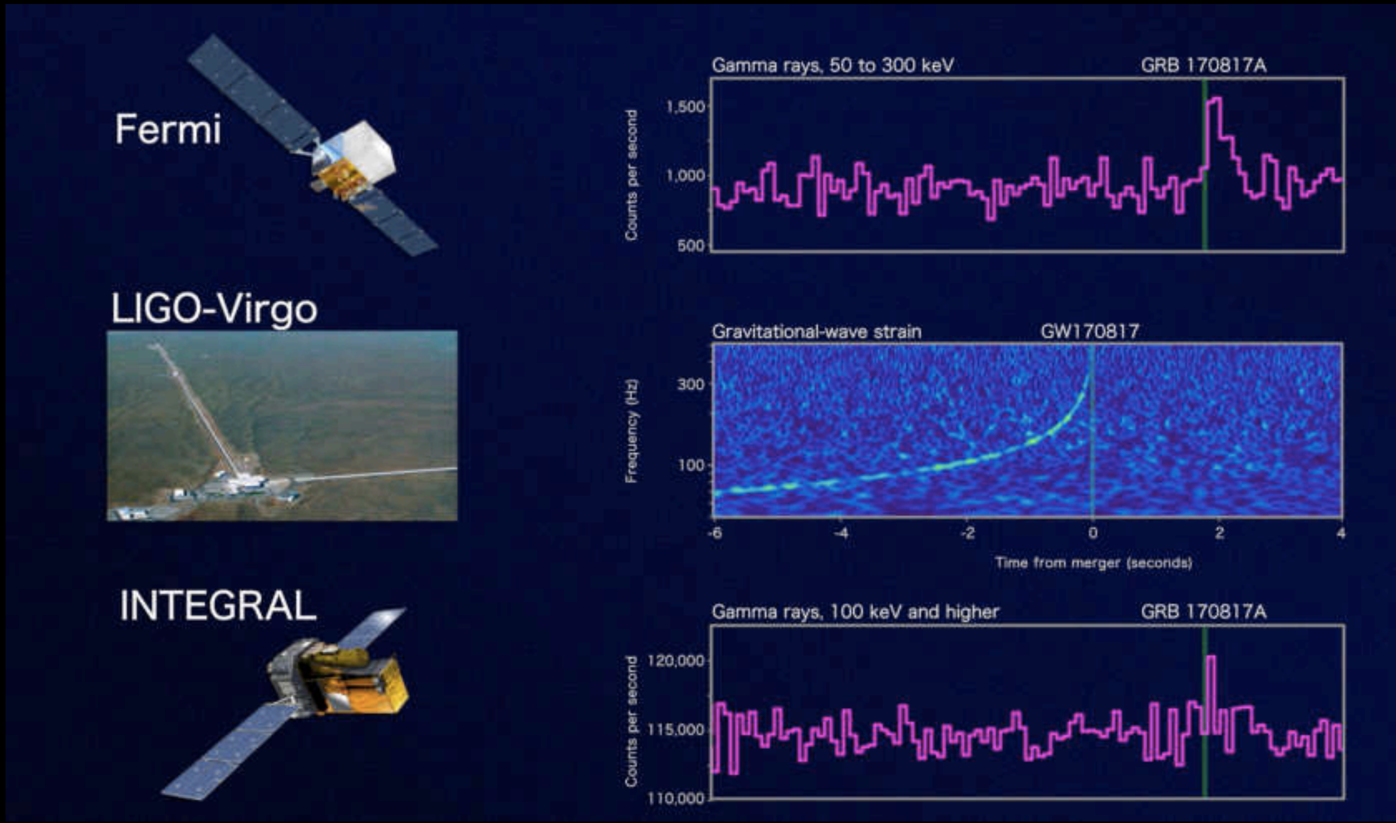


The birth of multimessenger astronomy

What we learnt:

(i) GWs came first and after 1,7 seconds a gamma ray burst was observed

→ binary neautron star mergers are the progenitors of short gamma ray bursts



The birth of multimessenger astronomy

What we learnt:

(ii) From the followingUV, visible and IR emission

→ we understood where heavy elements are made

inary neutron star mergers as factories of heavy elements in the Universe

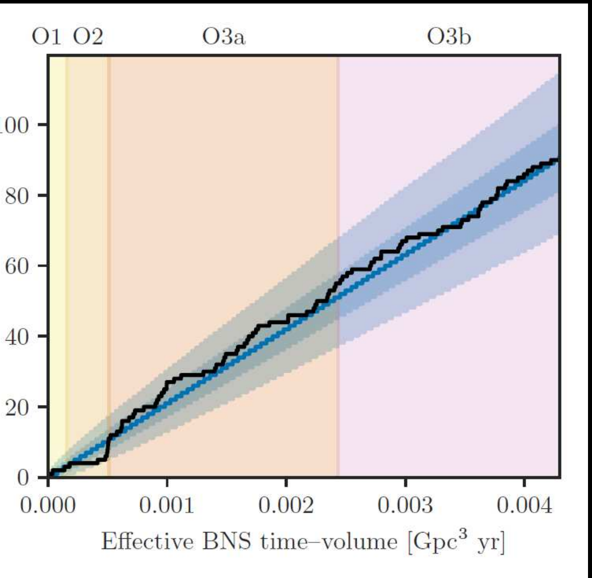
Iridium
Z= 77, A= 192

Platinum
Z= 78, A= 195

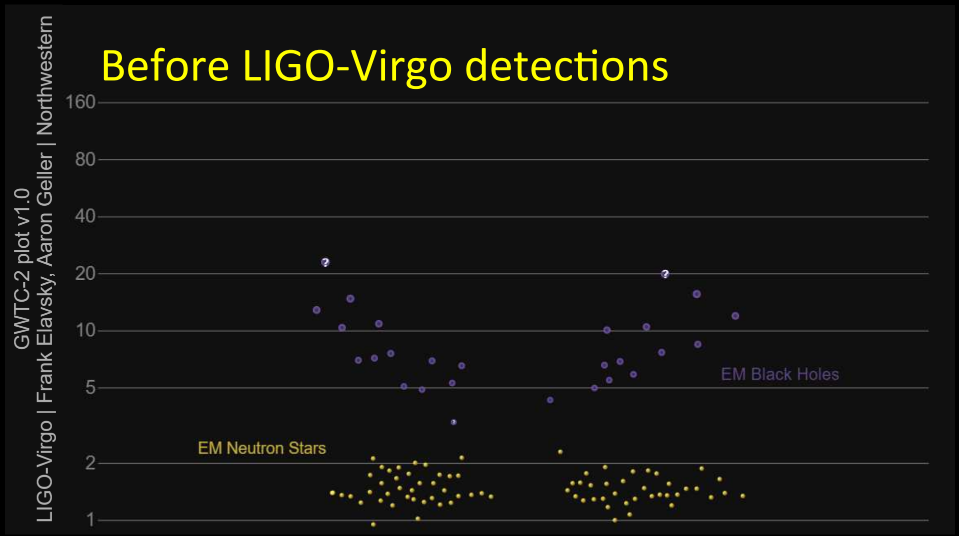
Gold
Z= 79, A= 197

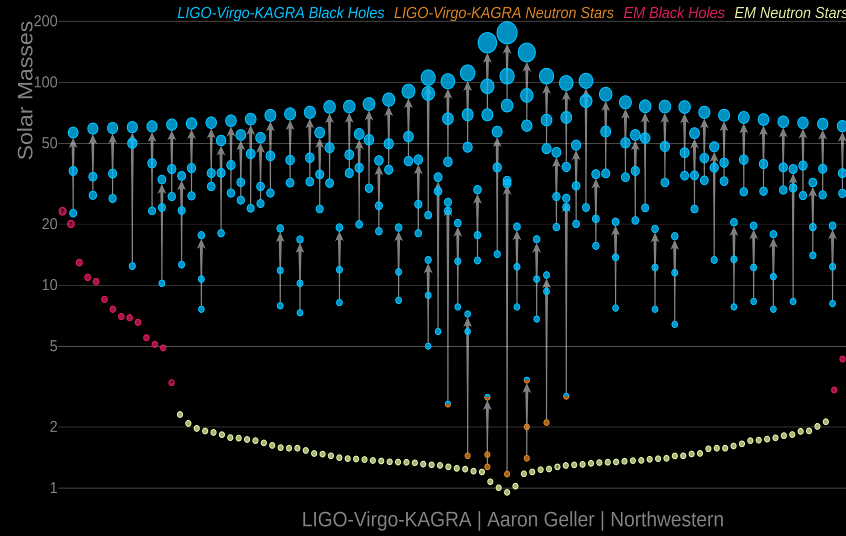
Lead
Z= 82, A= 207

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;
- We are now completing the upgrade/commissioning phase toward O4, planned to start in May 2023

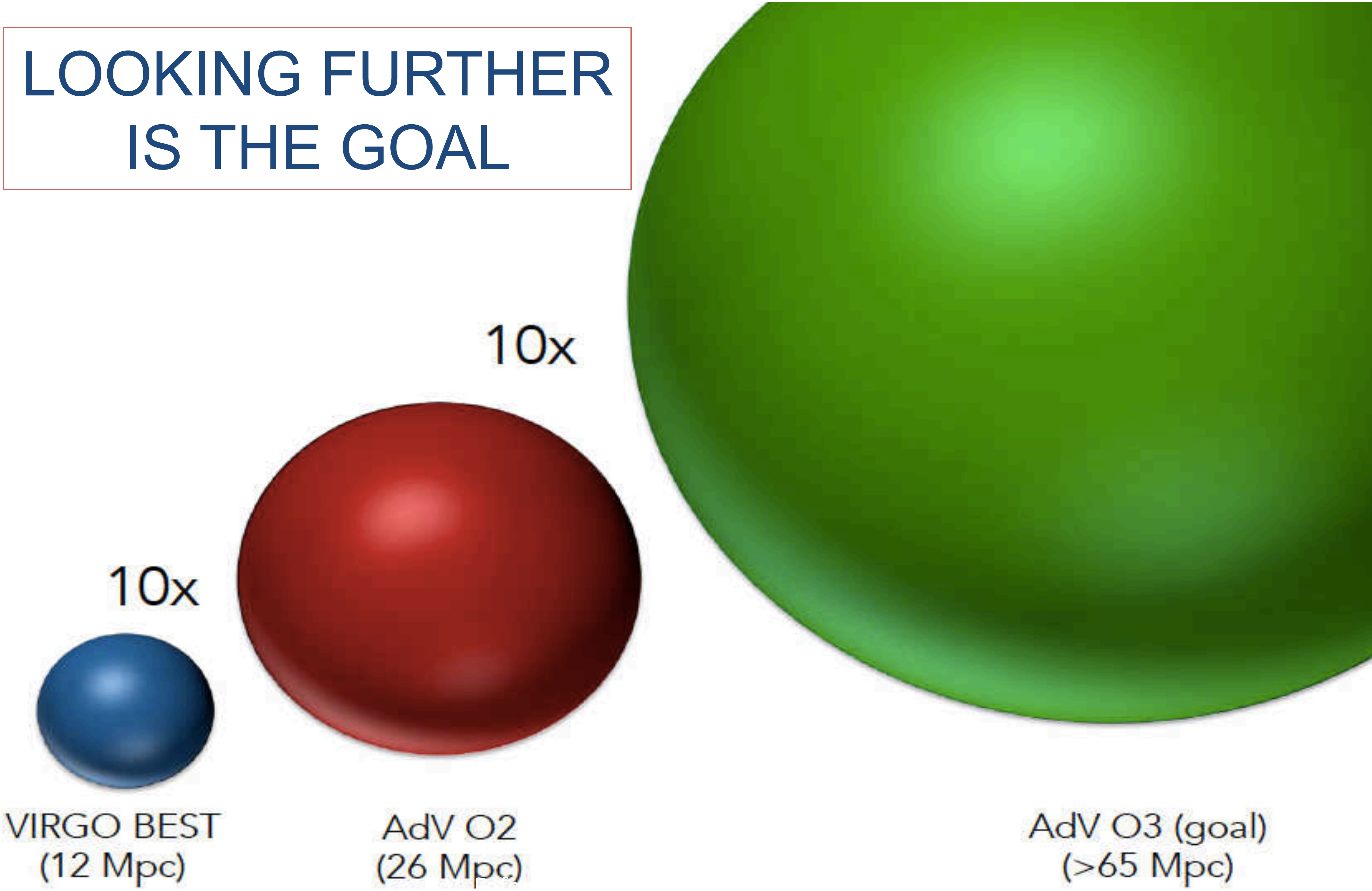




Monumental successes of the Advanced detectors

- First detection of GWs from a BBH system (GW1509
    - Physics of BHs
- First detection of GWs from a BNS system (GW1708
    - Birth of the multimessenger astronomy with GW
    - 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)

LOOKING FURTHER IS THE GOAL



Detection distance of GWD

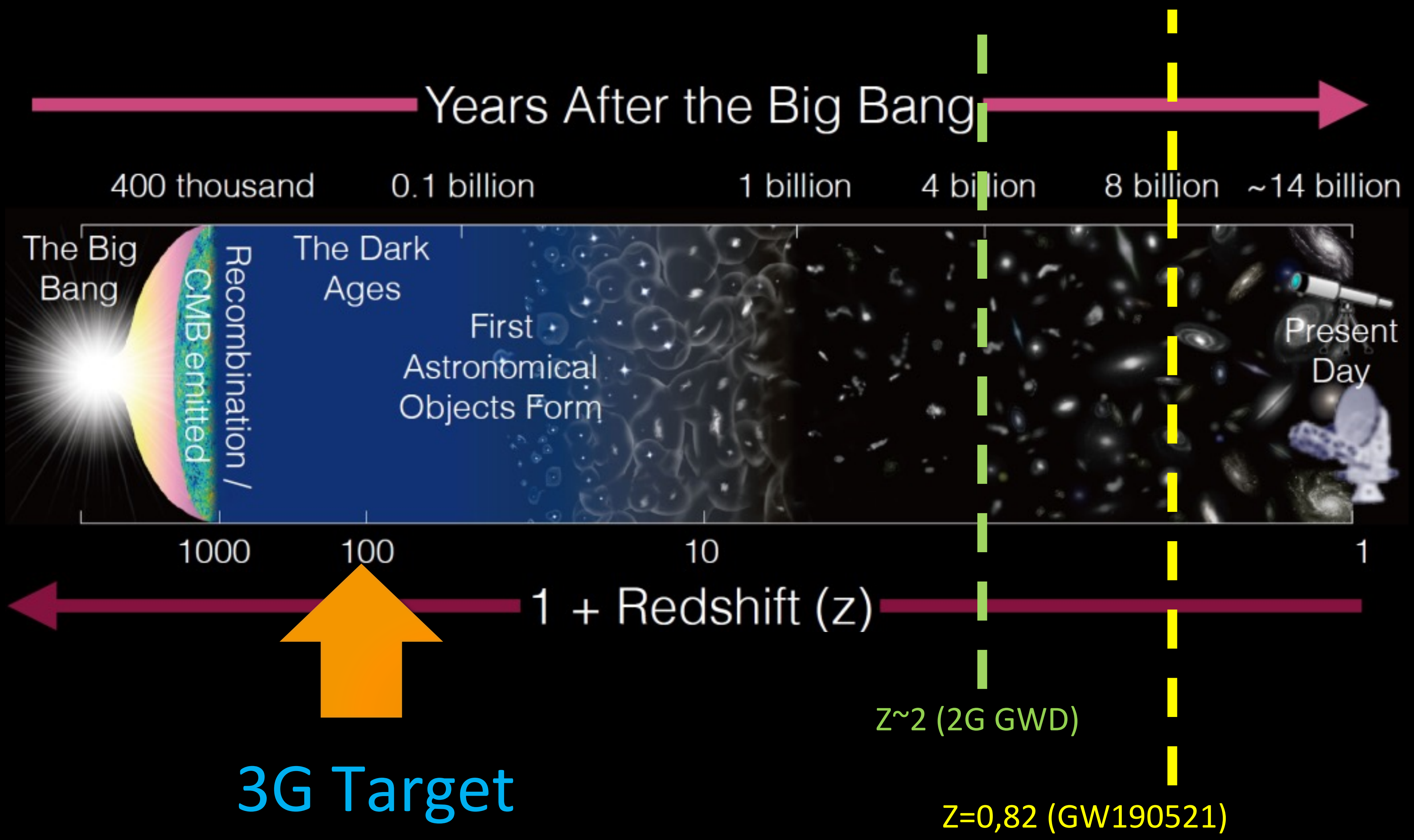
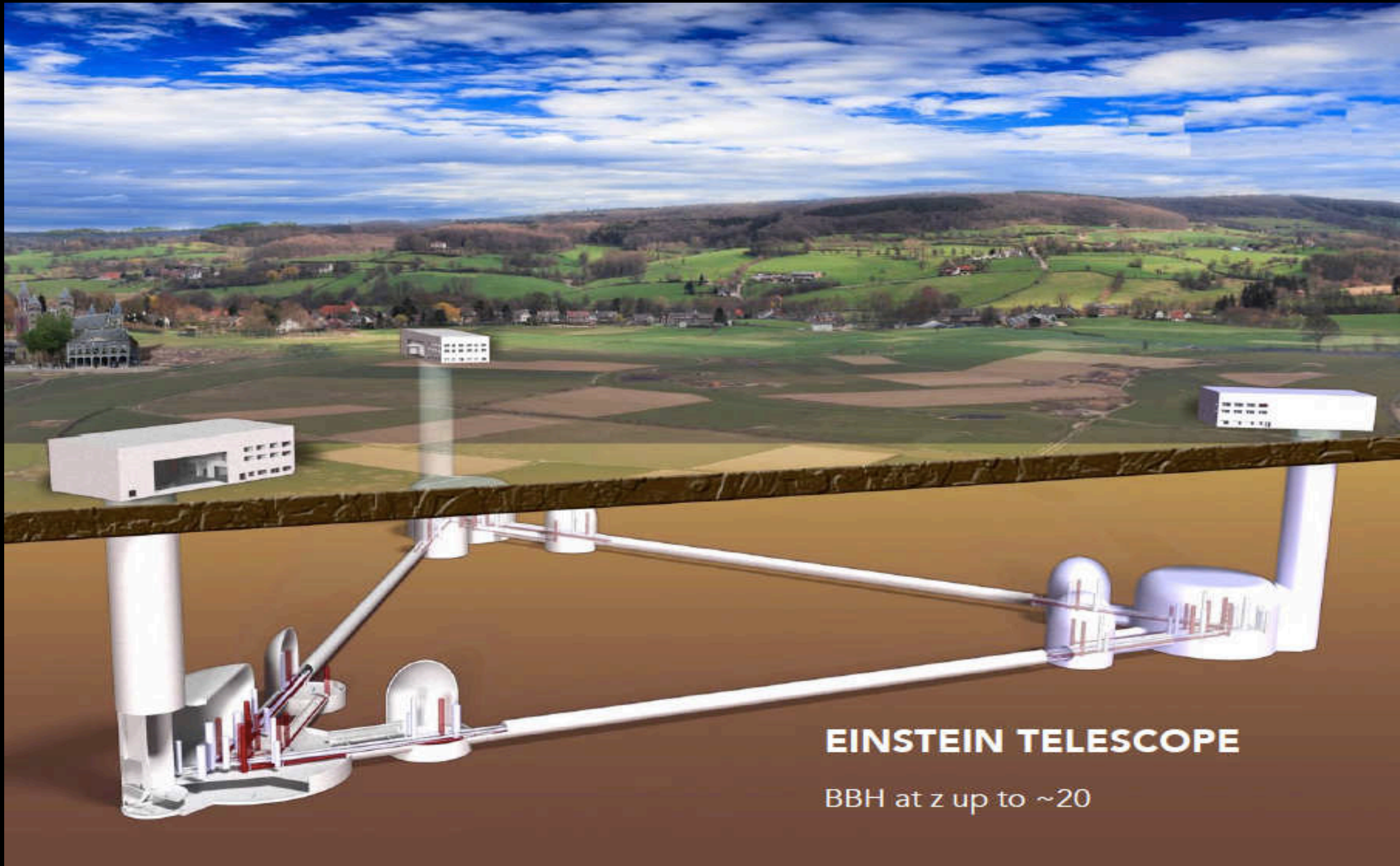
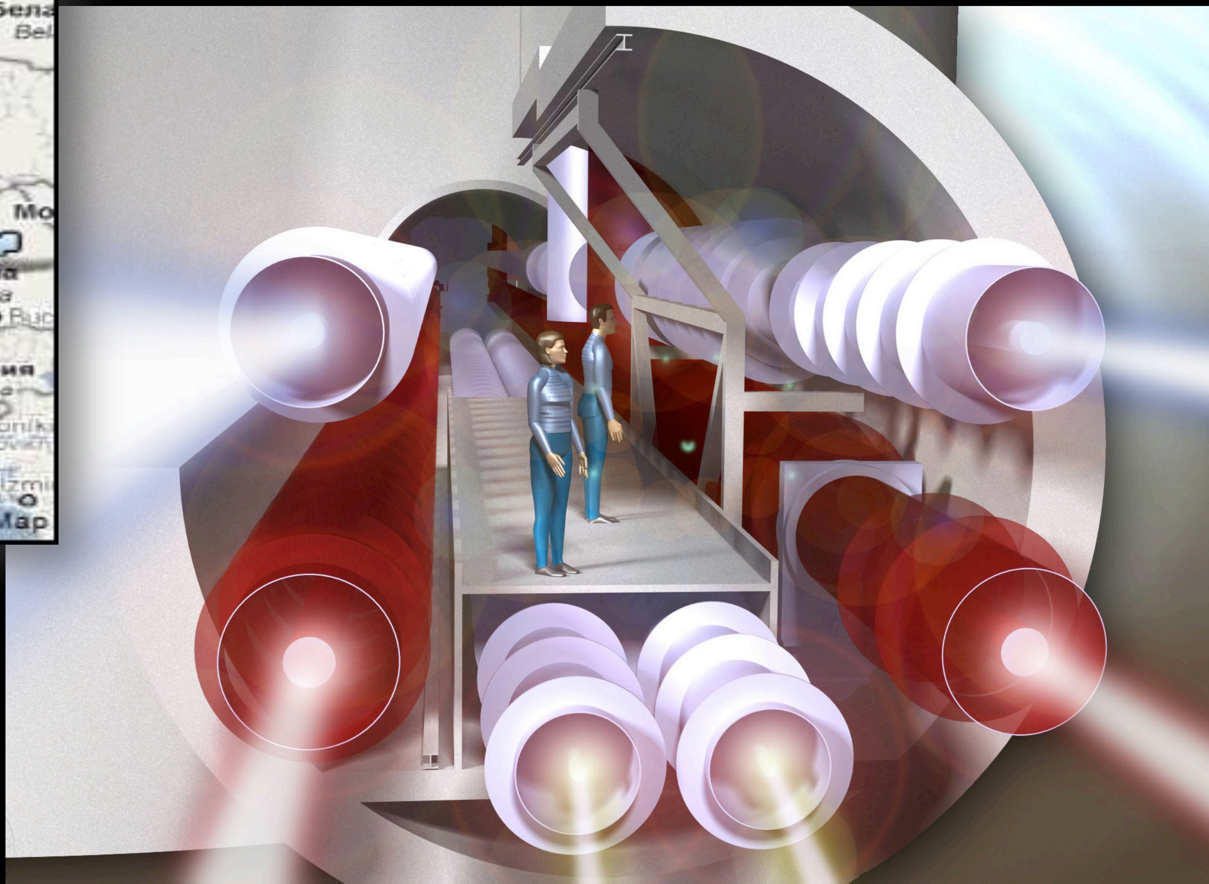


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

The further future in Europe: Einstein Telescope (ET)



The further future in Europe: Einstein Telescope (ET)



ET site(s)

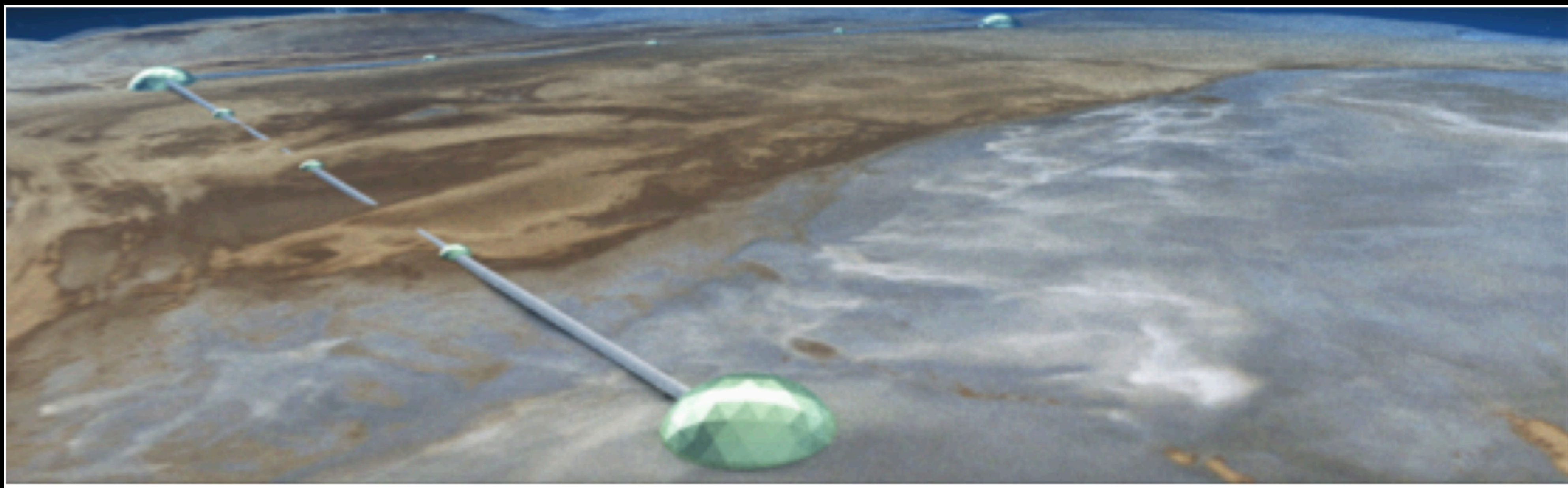
Currently there are two sites, in Europe, candidate to host ET:
- The Sardinia site, close to the Sos Enattos mine
- The EU Regio Rhine-Meusse site, close to the NL-B-D border

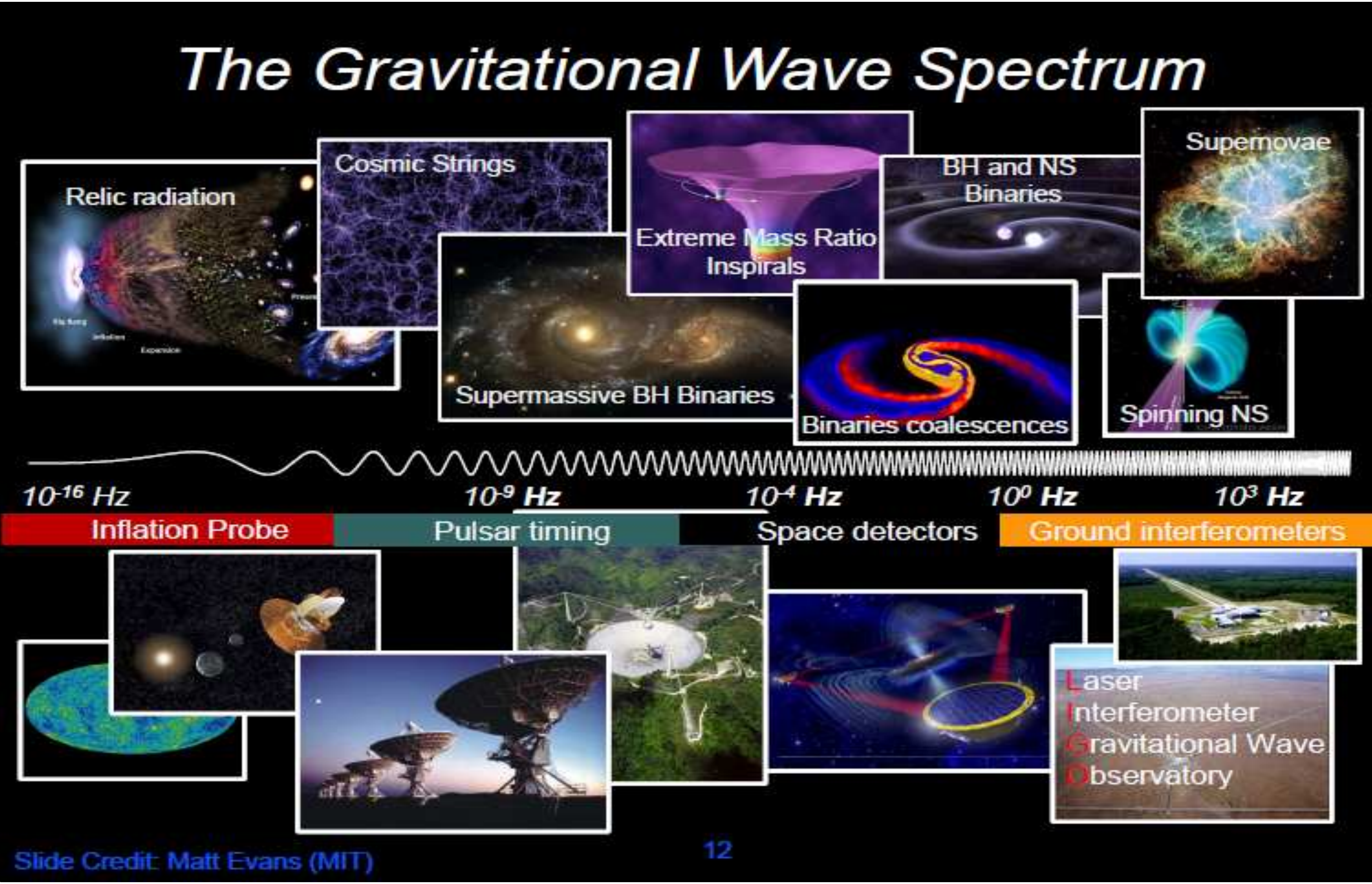
A third option in Saxony (Germany) is under discussion

es are investigated through
- seismic noise measurements on surface, in boreholes and in mine (Sardinia)
- Magnetic and ambient noises measurements
- Geophysical and geotechnical characterizations

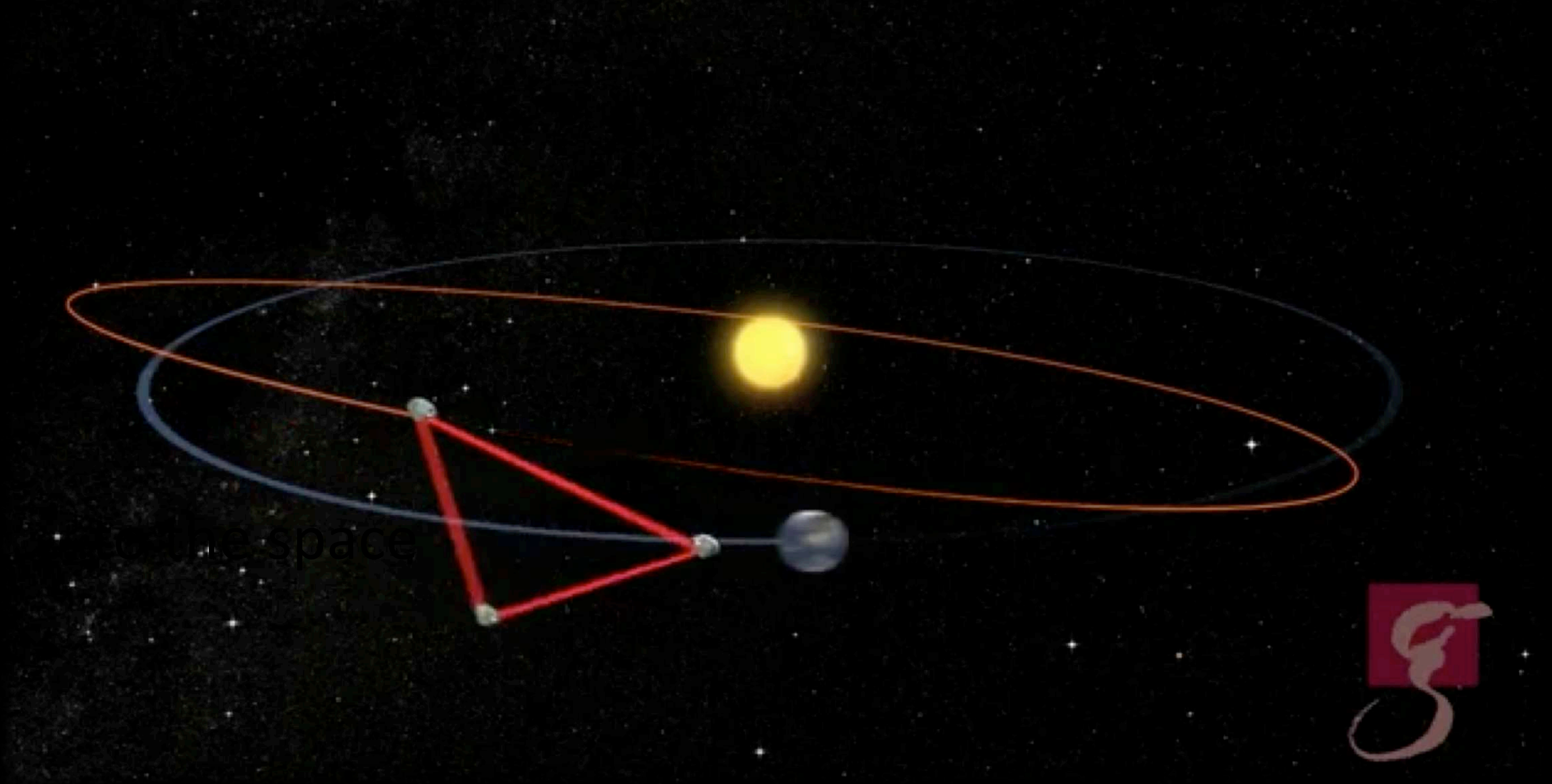
rge funds needed to elaborate and propose the ndidature of the sites

The further future in the US: Cosmic Explorer




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
100 Hz
103 Hz
Inflation Probe
Pulsar timing
Space detectors
Ground interferometers
Laser
Interferometer
Gravitational Wave
Observatory
Slide Credit: Matt Evans (MIT)
12

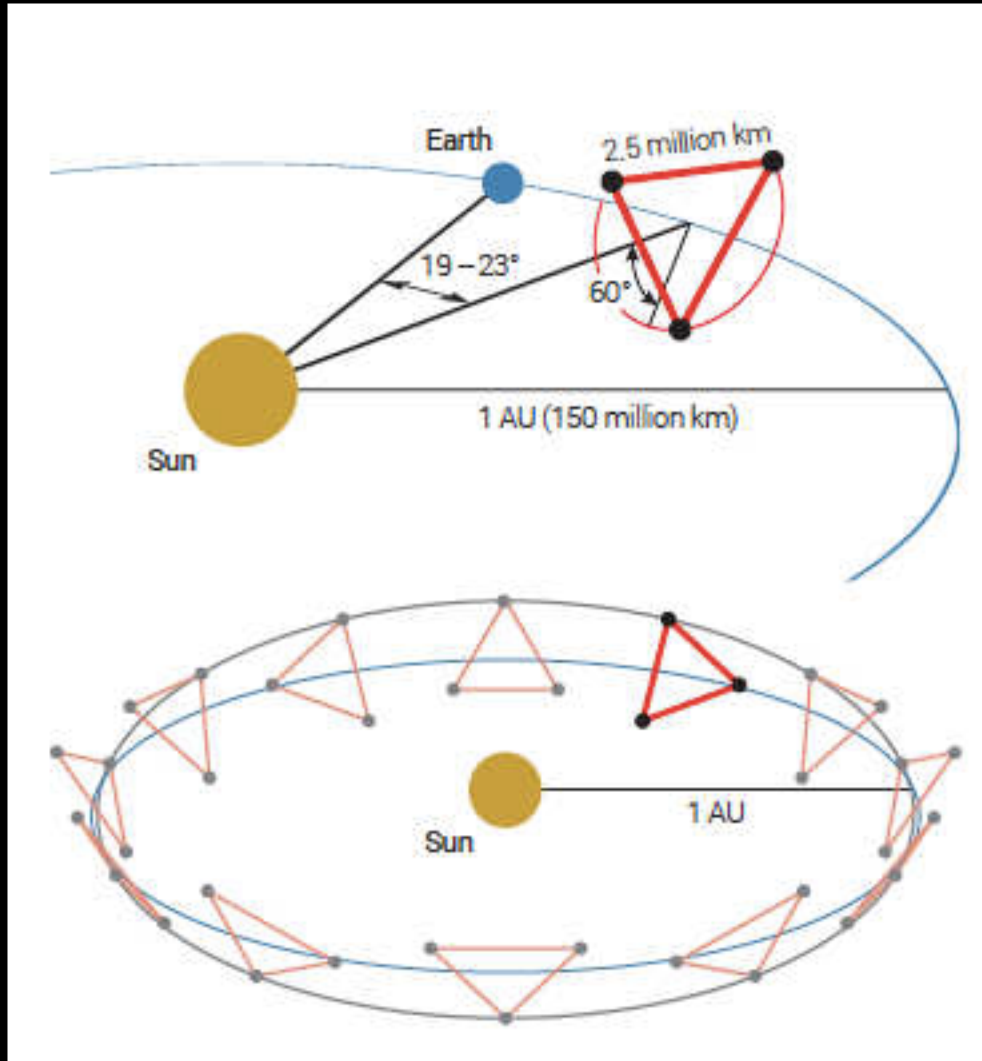
Space detectors: eLISA



LISA concept

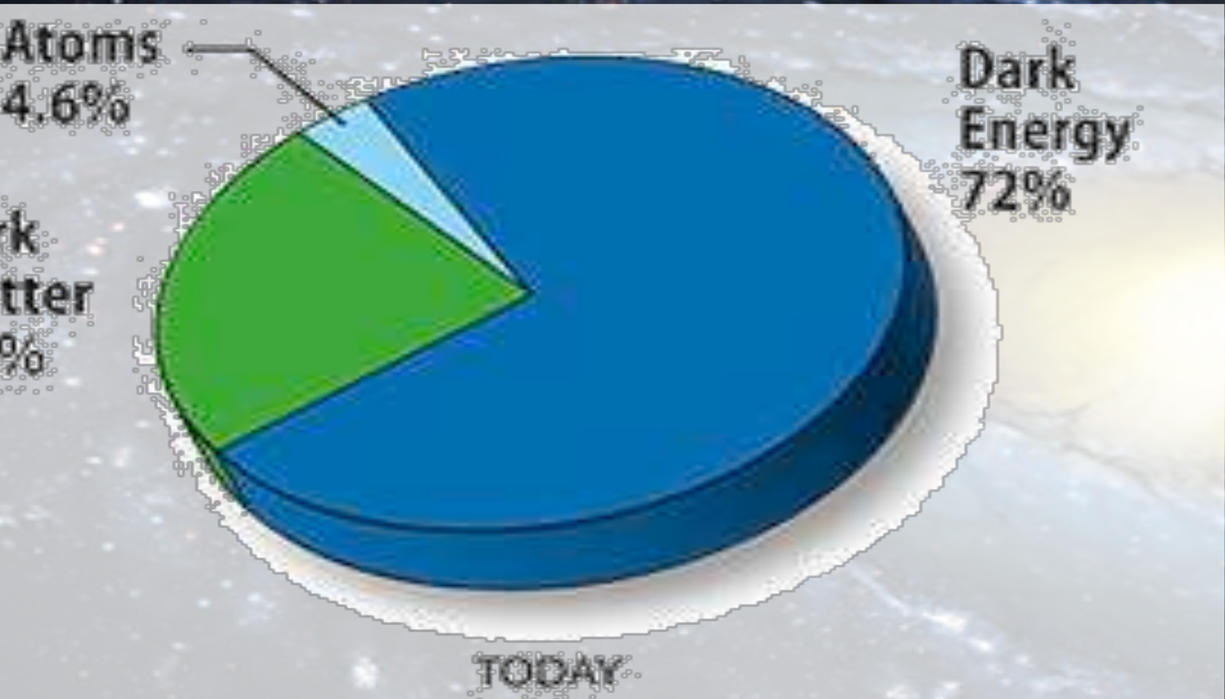
The plane of the constellation is inclined by 60° on the ecliptics

Heliocentric orbit, 1 AU radius, following the Earth by 20°



Multimessenger Science

urrent (lack of) understanding of the Universe



- To re-compose a photograph of the Universe we need to observe it with several "eyes
- E.M. astronomy
- Neutrino astronomy
- Gravitational wave astronom

Multi-messenger and multi-wavelenght observation!


Thank you for your attention