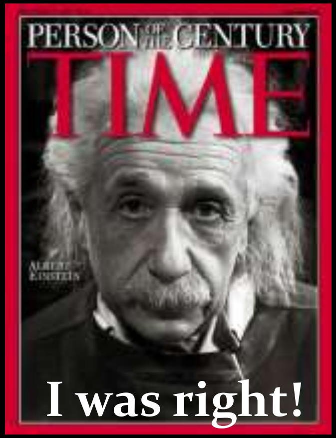
EGO EUROPEAN GRAVITATIONAL OBSERVATORY

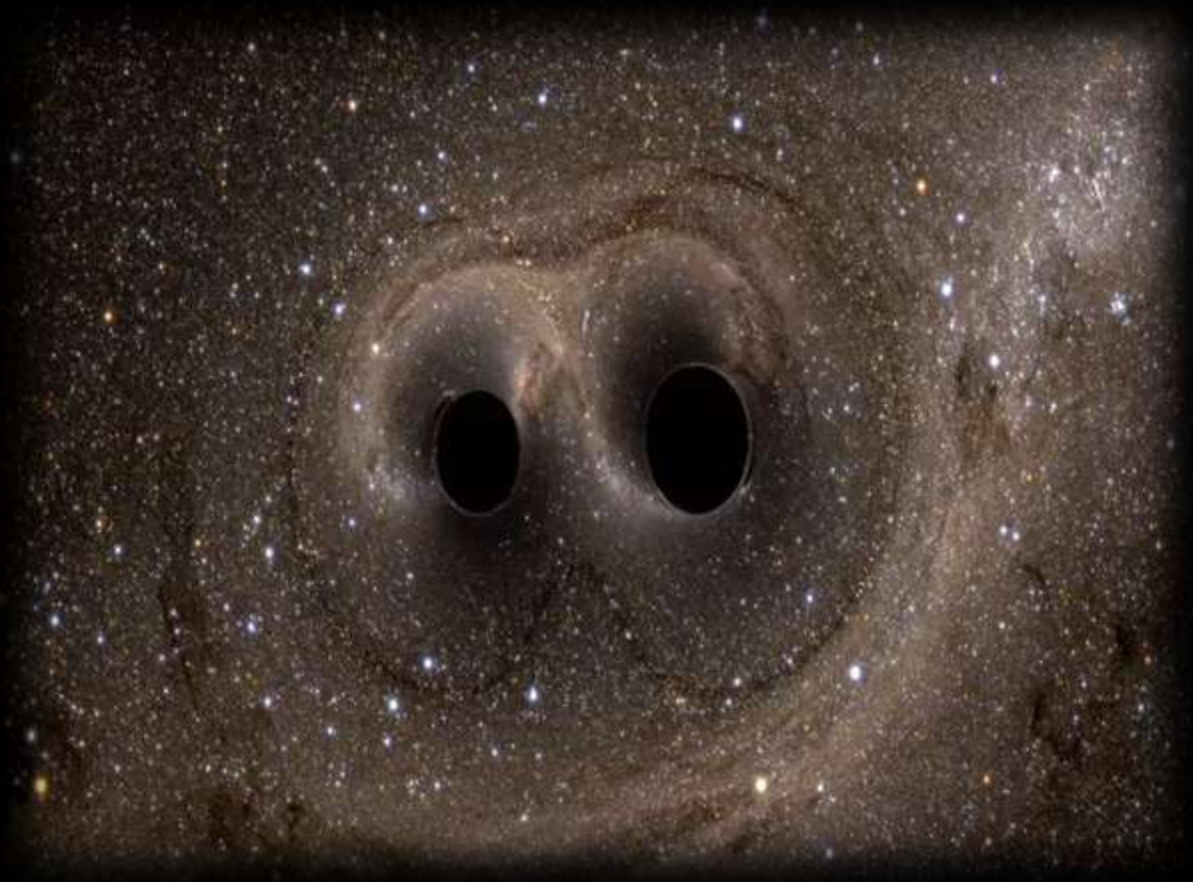
The art and science of Gravitational waves

Frontiers Summer School
12 July 2020

Σ. Κατσανεβας , DIrector
European Gravitational Observatory

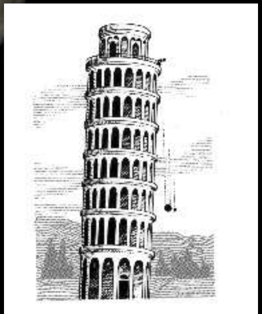
September 14th 2015: first Gravitational Waves detection!

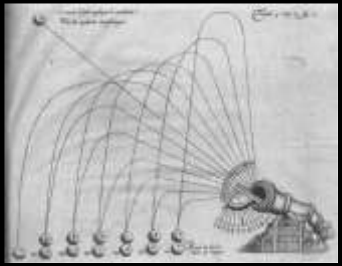




Gravitational Waves Elements of Theory

Galileo and Newton
1623-1687





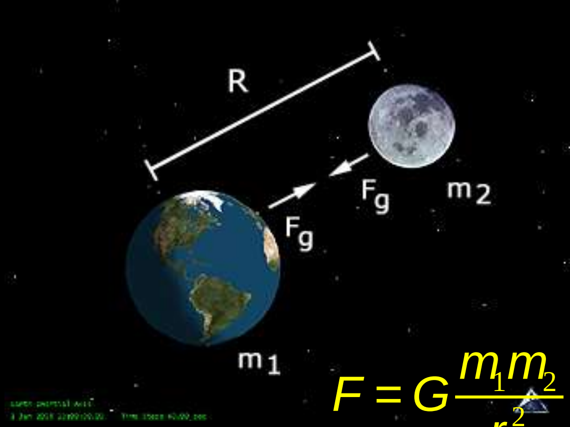
Galileo. The lunar spots are not "marbled texture" but real shadows produced by sunlight. Therefore the moon is of the same substance as the earth. Unification of the two regions (sub and sur-lunary)

From a "Rythmic" Universe to a universe of trajectories

Newton and the universal law of gravity

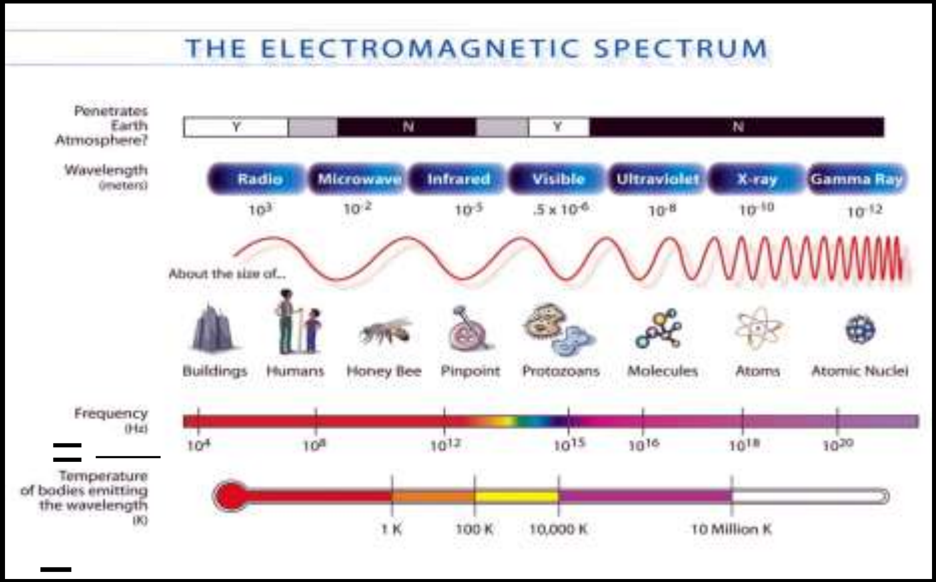
Space and Time as an absolute framework.

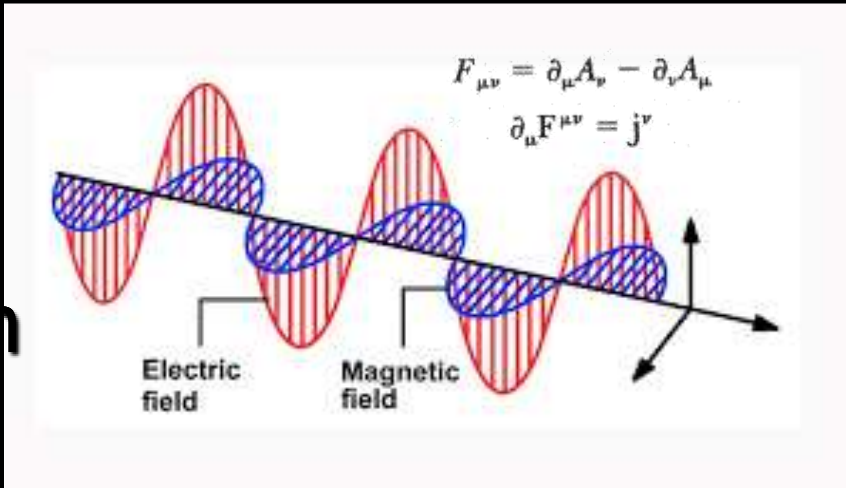
"It is inconceivable that inanimate brute matter should without the mediation of something else which is not material, operate upon and affect other matter without mutual contact"; Hypotheses non-fingo.

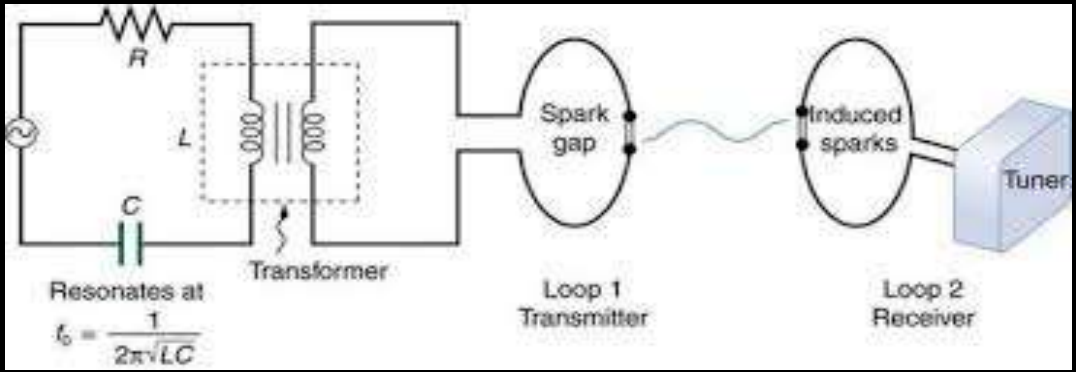


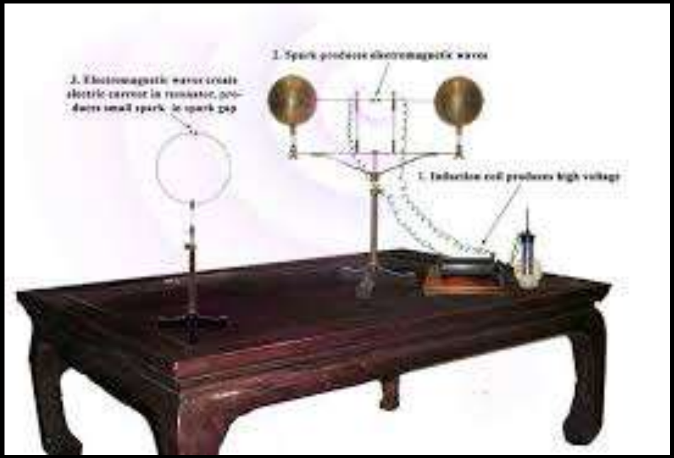
$$F = G\frac{m_1 m_2}{r^2}$$

Maxwell and Hertz (Faraday aussi)
Electromagnetic waves
1861-1868



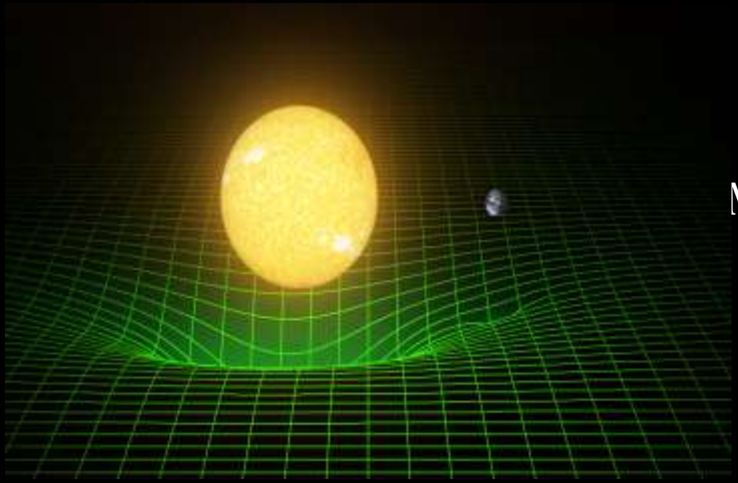






Einstein's Theory of Gravity 1915

For Newton Space and Time are absolute frameworks



For Einstein Space-Time is a deformable medium

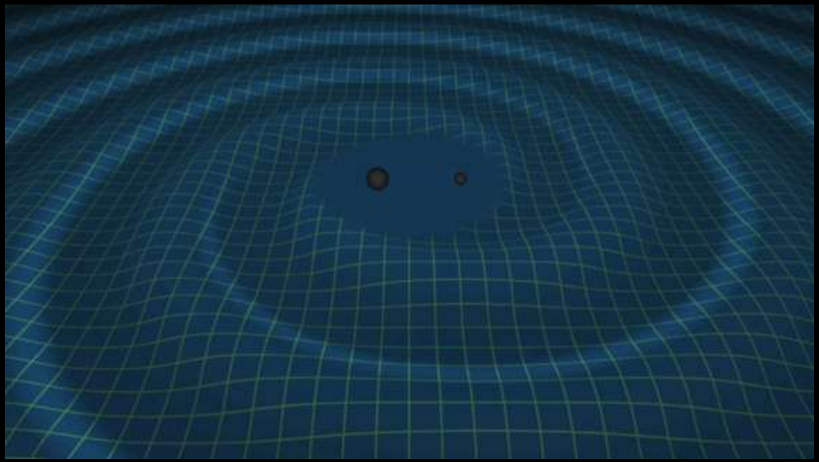
Mass and Energy deform space-time around them and inversely they follow the deformed paths inside it

Waves can be produced by violent phenomena

Spacetime Mass-Energy

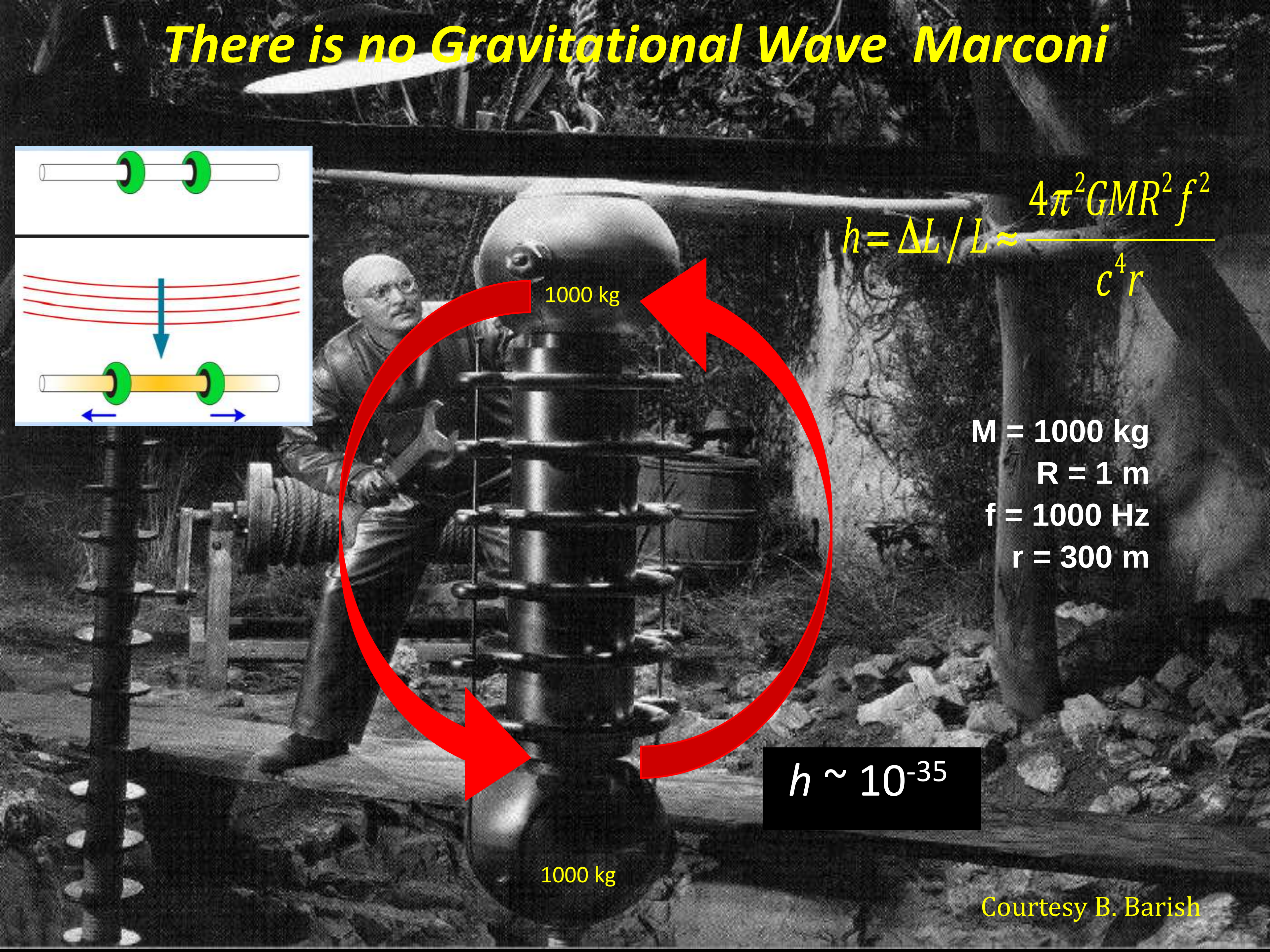
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$\sim 10^{-43}$



Papers predicting gravitational waves 1916-1918

There is no Gravitational Wave Marconi



$$h = \Delta L / L \approx \frac{4\pi^2 G M R^2 f^2}{c^4 r}$$

M = 1000 kg
R = 1 m
f = 1000 Hz
r = 300 m

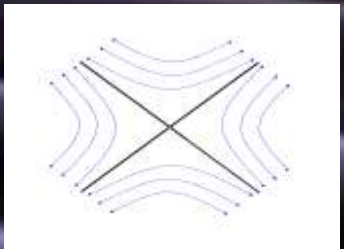
$h \sim 10^{-35}$

Courtesy B. Barish

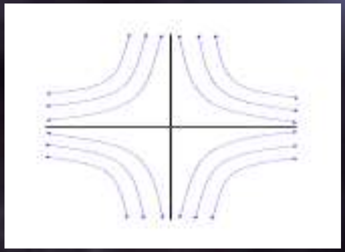
Only extremely violent phenomena can produce detectable GW

- Consider ~30 solar mass binary Merging Black Holes
  - $M = 30\ M_{\odot}$
  - $R = 100$ km
  - $f = 100$ Hz
  - $r = 3\ 10^{24}$ m (500 Mpc)

h_x



h_+

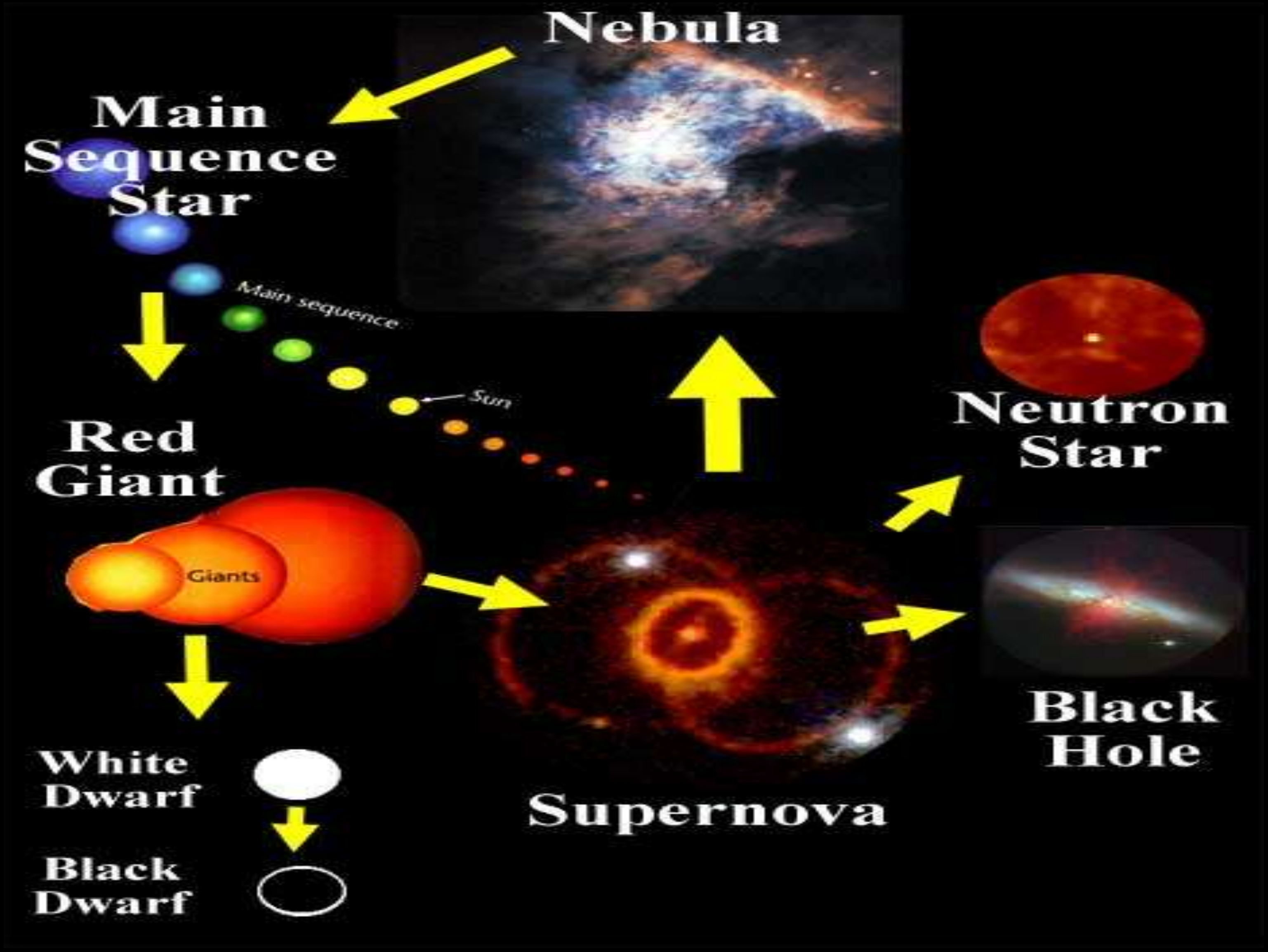


$$h = \Delta L / L \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \quad \Rightarrow \quad h \sim 10^{-21}$$

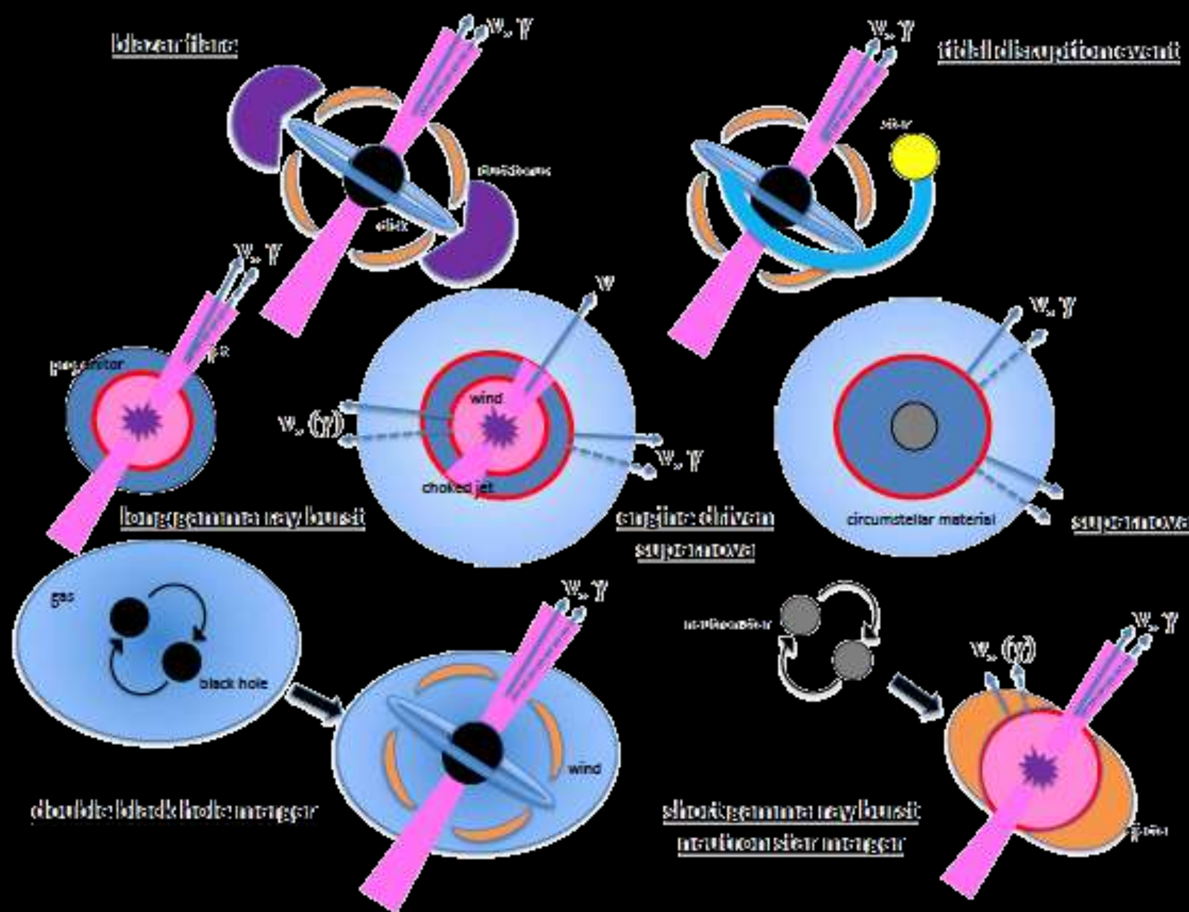
$h = 10^{-21}$ corresponds to a change ΔL by 1/1000 of a proton radius in a distance L of 1 km

Credit: T. Strohmayer and D. Berry

What are the violent phenomena?
First exemple: the end of stars



What are the violent phenomena?
Binary coalescences, tidal effects, jets

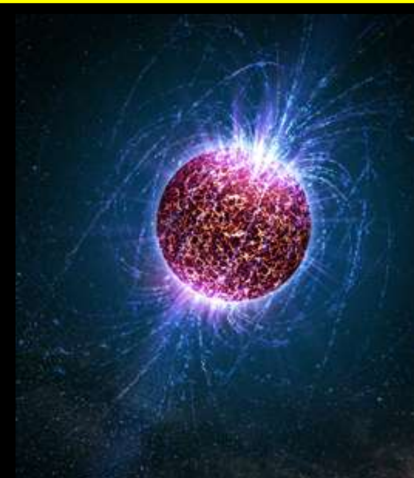


The Astrophysical Gravitational-Wave Source Catalog

Short → long

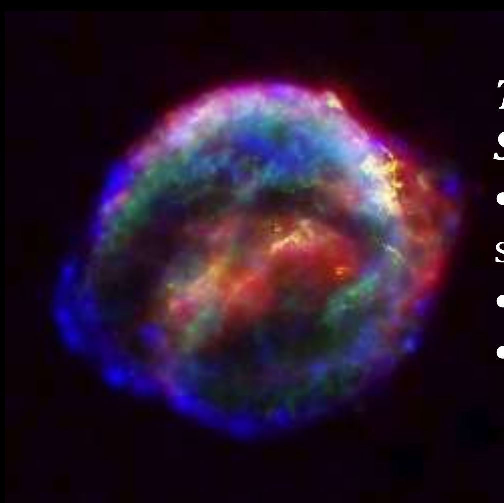
Coalescing Binary Systems CBC

- ✓ Black hole – black hole
- ✓ Neutron star – neutron star
- BH-NS
- Analytical waveform



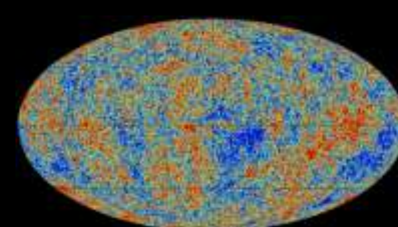
Continuous Sources

- Spinning neutron stars
- Monotone waveform



Transient 'Burst' Sources

- core collapse supernovae
- cosmic strings
- unmodeled waveform



Cosmic GW Background

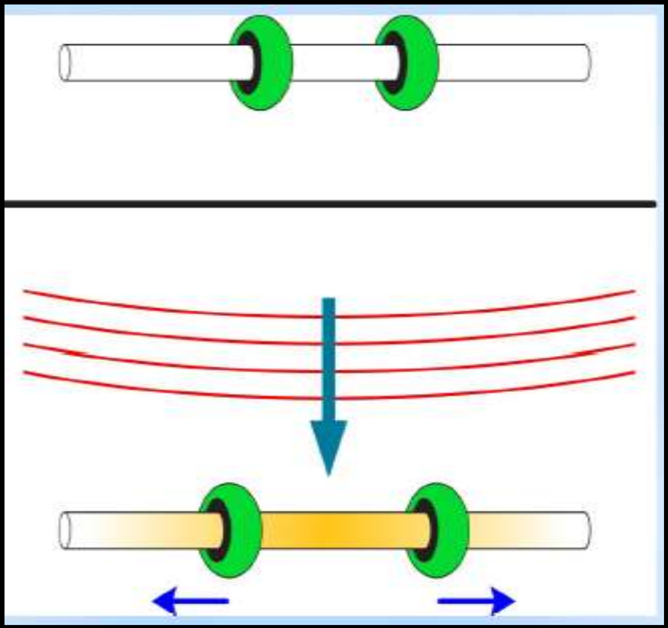
- Residue of the Big Bang,
- Stochastic, incoherent background

Known → unknown form

Transient Burst and Continuous sources the next goal!

Gravitational Waves detection

How can we detect them ?



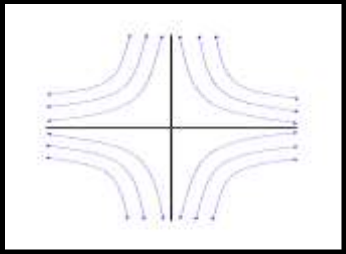
Could the waves be a coordinate effect only, with no physical reality? Einstein didn't live long enough to learn the answer.

In January 1957, the U.S. Air Force sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1.

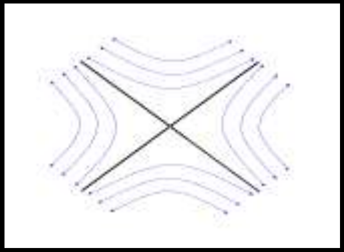
The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born. (Pirani, Feynman and Babson)

Sticky bead argument (Feynman)

h_+

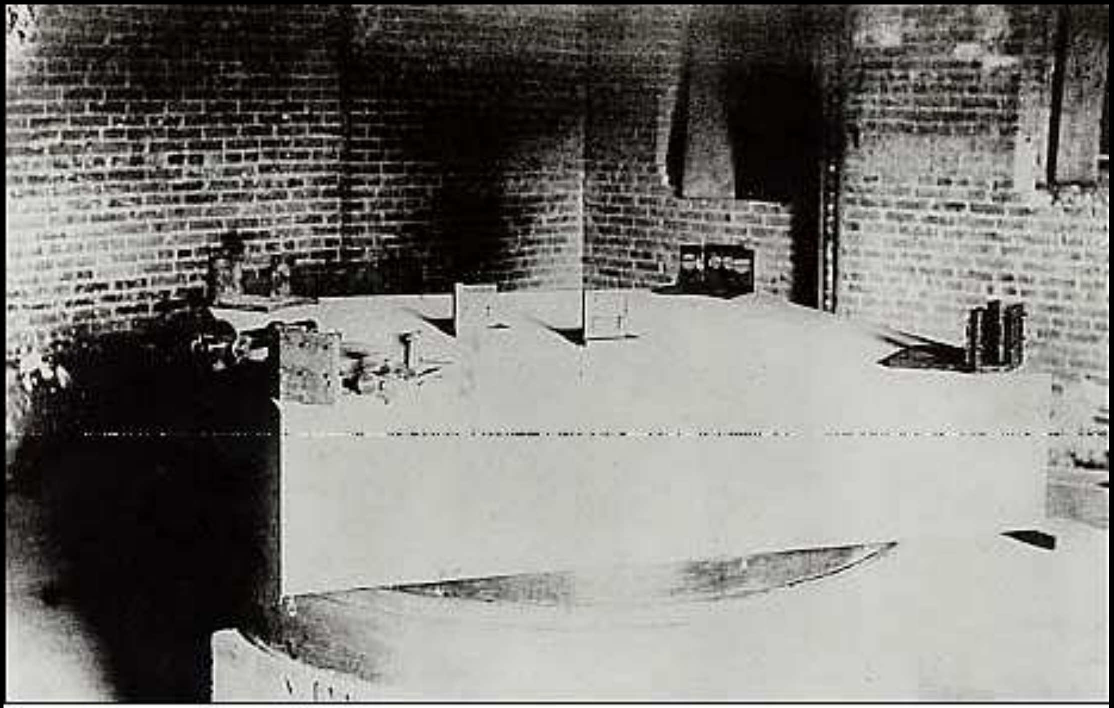


h_x



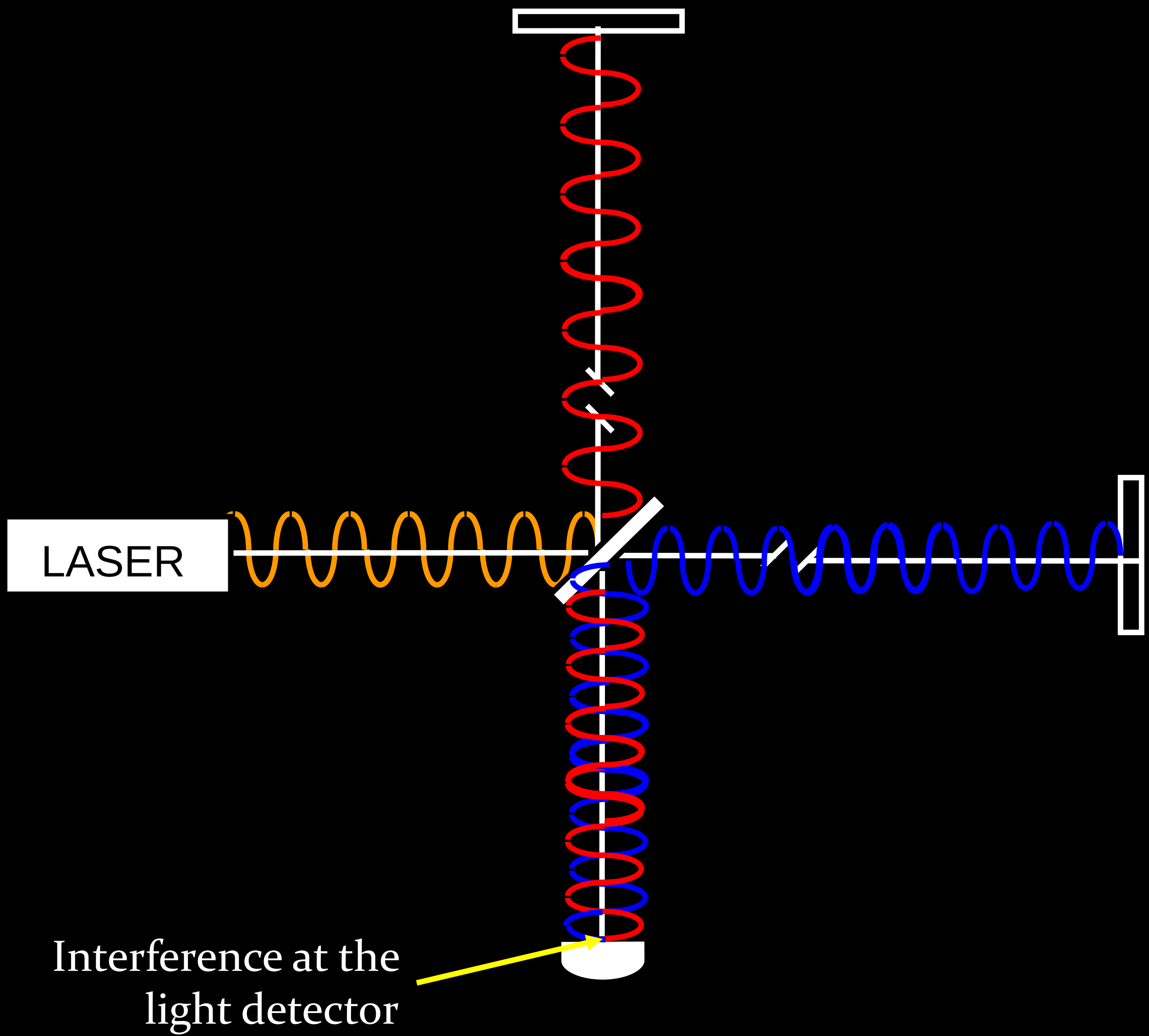
The simplest way to measure the distance between free masses is to use light and exploit the **interference** effect.

Michelson interferometer



Michelson & Morley's 1887 interferometer
built in the basement of Western Reserve
Photo: Case Western Reserve Archive

Basics of interferometry

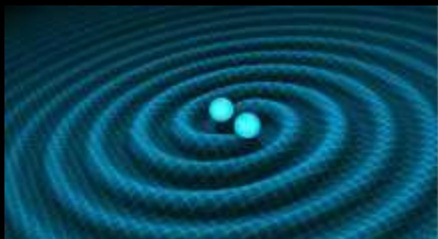


The VIRGO interferometer

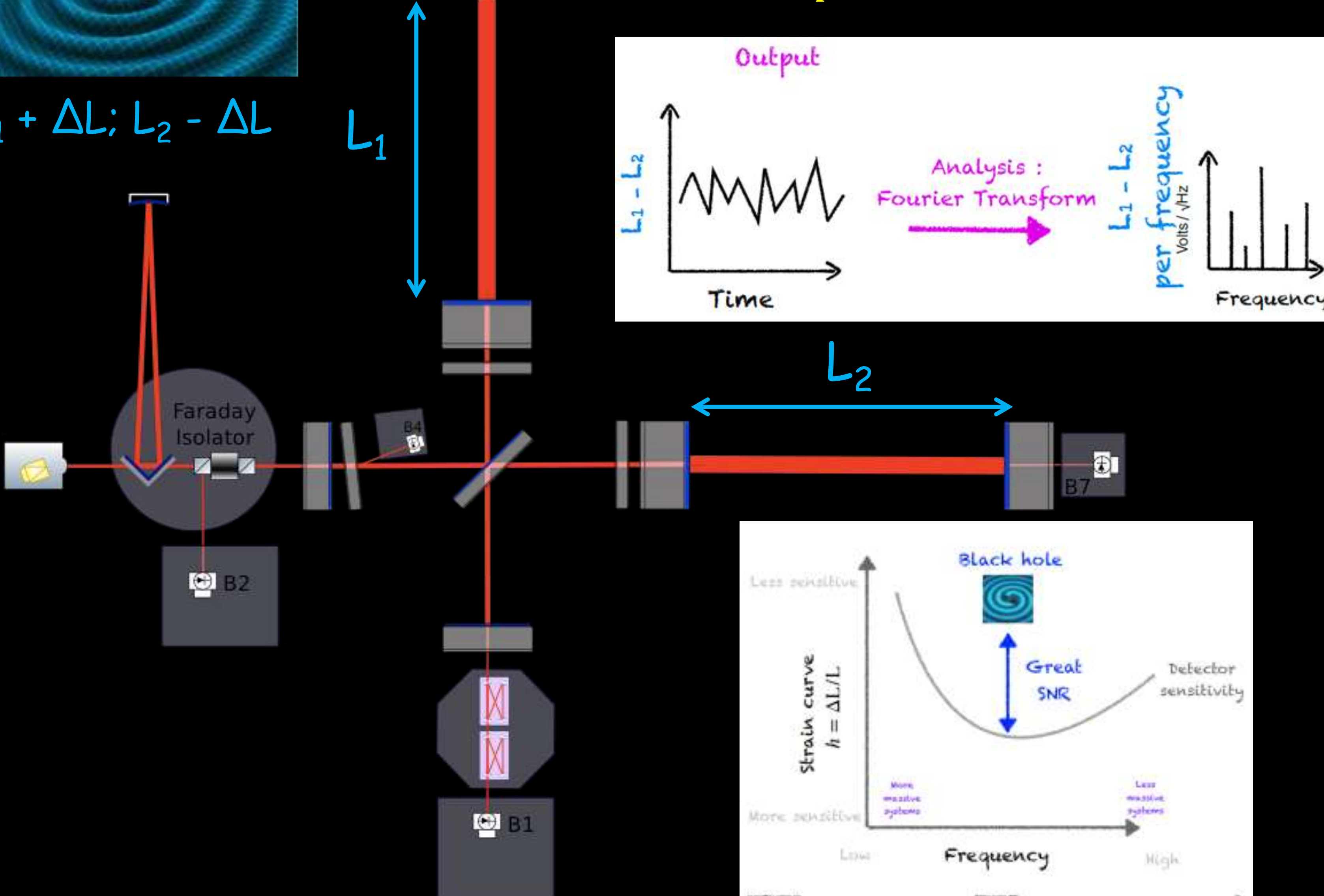
The Advanced Virgo antenna

The most stable « standard » meter on earth

Sensitive to space deformations of 10^{-18} m



$L_1 + \Delta L; L_2 - \Delta L$



“Satanic” Noise (A. Giazotto)

Sources at different frequencies: a complex task at different technology fronts

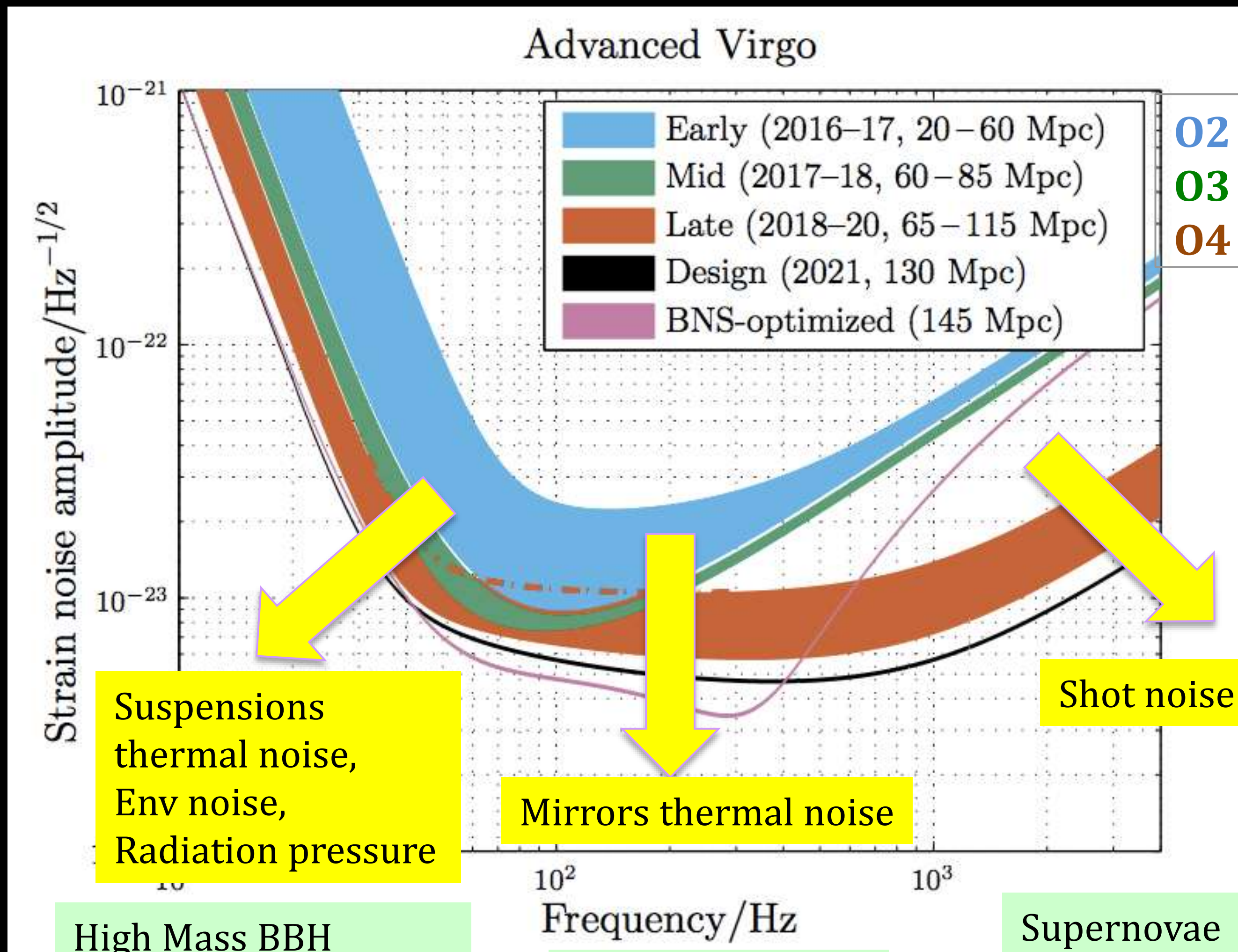
Residual gas (phase noise)

Residual laser noise

Stray-light

Seismic vibration

Newtonian noise

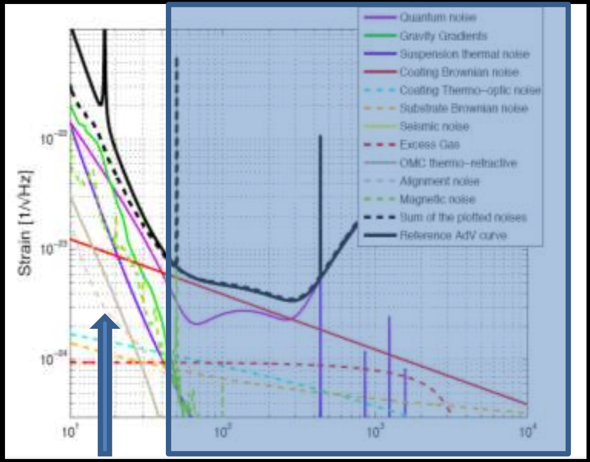


High Mass BBH
NS periodic emission

BBH mergers
BH ring down

Supernovae
NS transients

Low frequency Noise

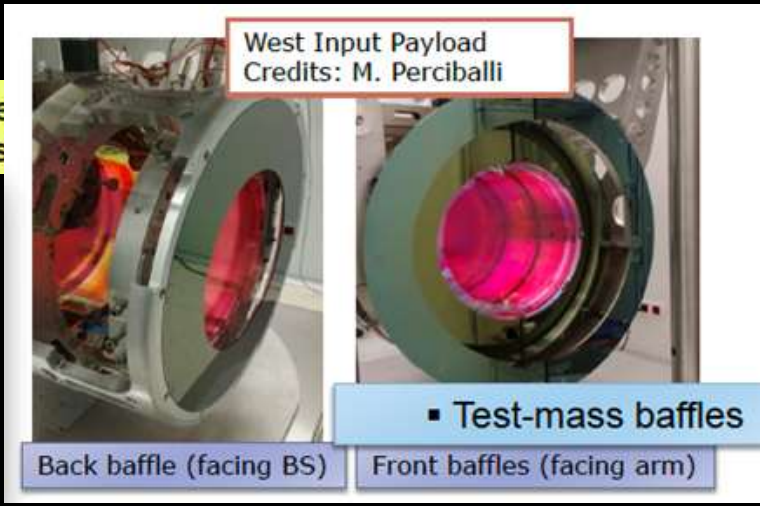


- **Seismic noise**
  - Reduced by suspending the mirrors from extreme vibration isolators (attenuation > 10^12) -> ***Superattenuator***
- Newtonian Noise
  Ultimate limit for ground-based detectors: gravity gradient noise
  It cannot be shielded -> active cancellation is needed based on sensor
- Technical noises of different nature are the real challenge in this range, ex. **Stray light**

▪ A tiny amount of stray light coupling with the fundame
vibrations of infrastructures will bury any gravitational s

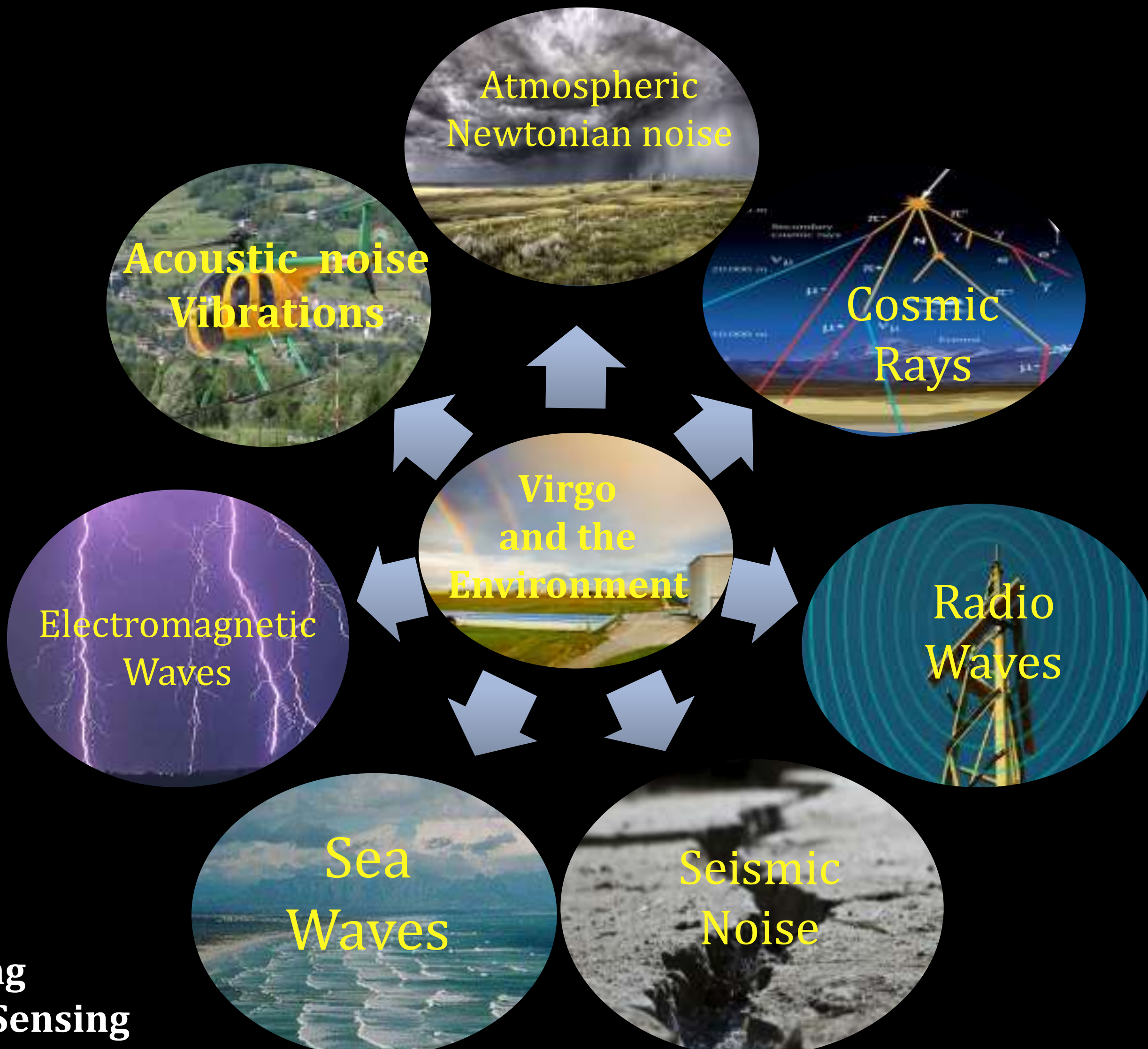
- Install ***baffles***: material that absorb photons

once emitted, a photon has to be caught!



GW detectors deeply imbedded in Geosphere

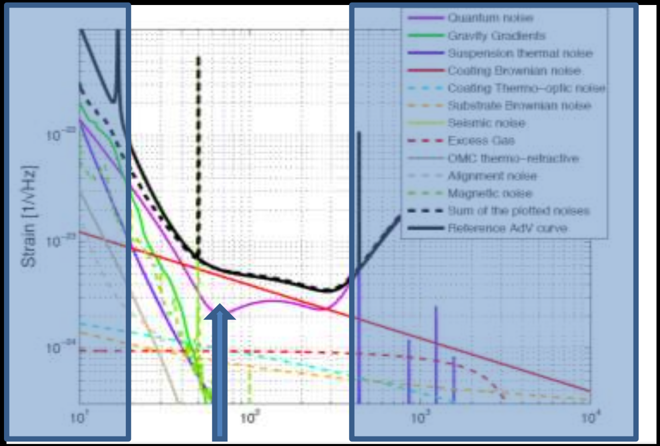
APOGEIA
EU-proposal
Coordinator



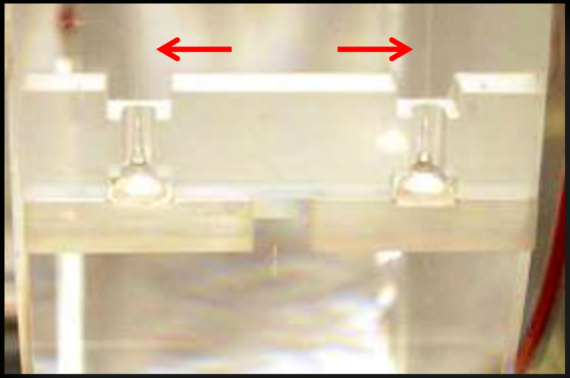
A priority of EGO
EU programs

- **Seismic Sensing**
- **Atmospheric Sensing**
- **Ecology (cost erosion and biotopes)**

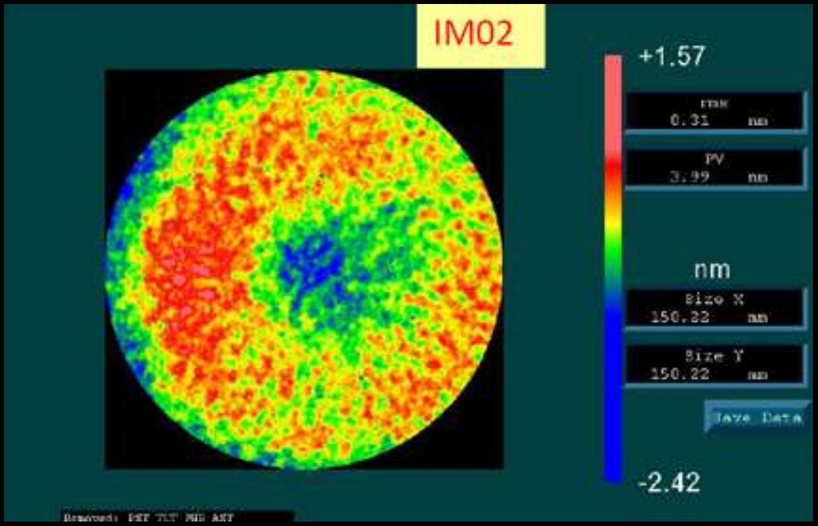
Mid frequency Noise

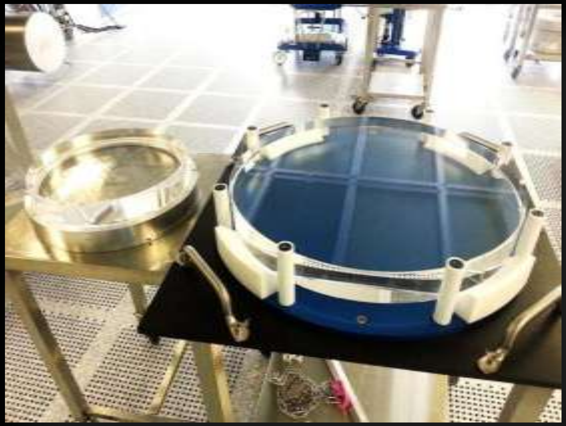


- Thermal noise
  - Coming from mirror coatings and suspensions
- Reduced by:
  - ***Larger beam spot*** (sample larger mirror surface)
  - Test masses suspended by fused silica fibers (low mechanical losses)
  - Mirror coatings engineered for low losses

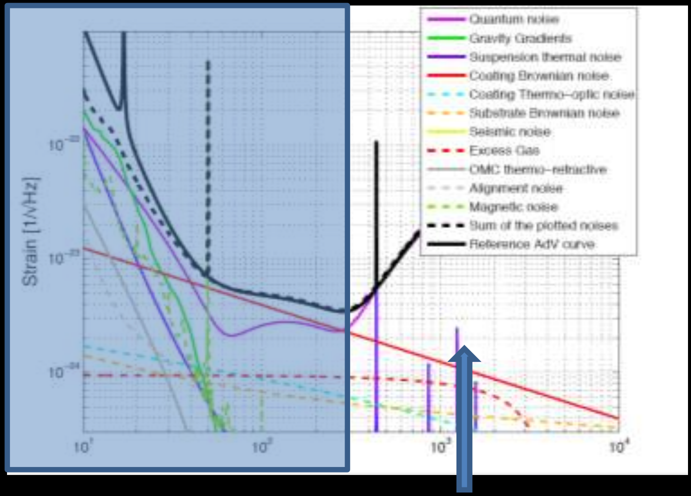


LMA is able to achieve the best coatings in the world for laser interferometry

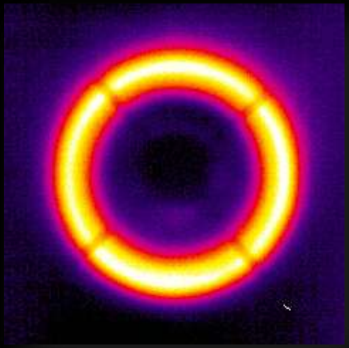




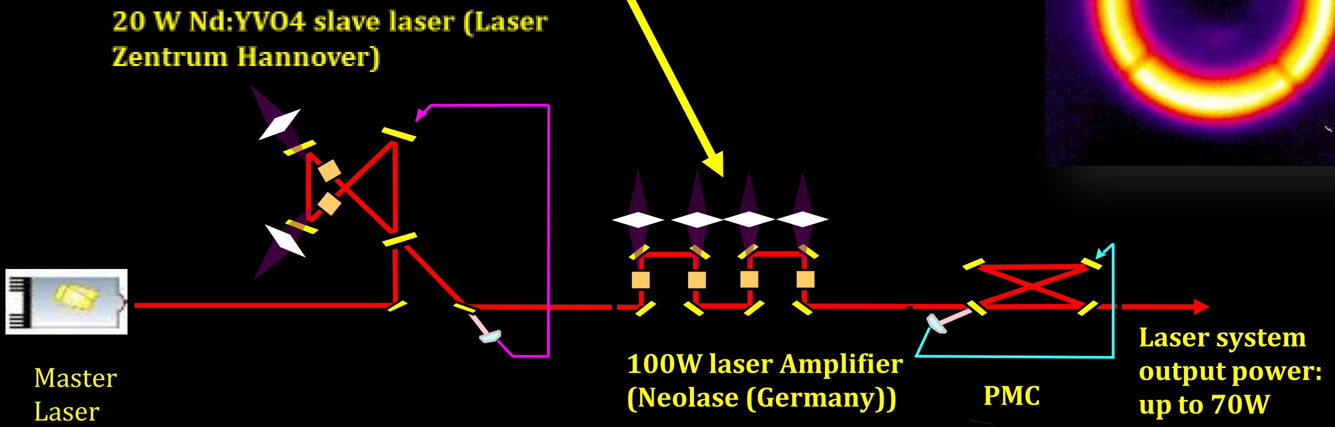
High frequency Noise

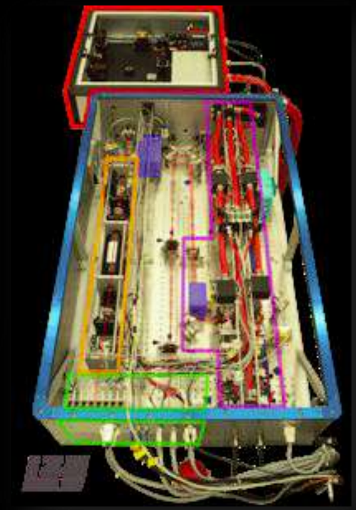


- Laser Shot noise
  - Improved by increasing the power: so far 28W
- Requires:
  - Heavy, low absorption optics (substrates, coatings)
  - Sophisticated systems to correct for thermal aberrations
  - Sophisticated injection system



- Future:
  - ***>100W input***, ~1 MW in the cavities



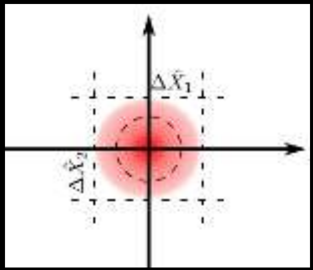


New laser amplifiers (solid state, fiber)

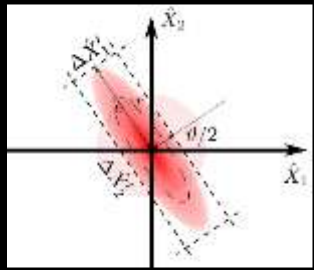
High frequency Noise

- Laser Shot noise
  - Improved by injecting squeezed light
- Requires: Very complex optical design

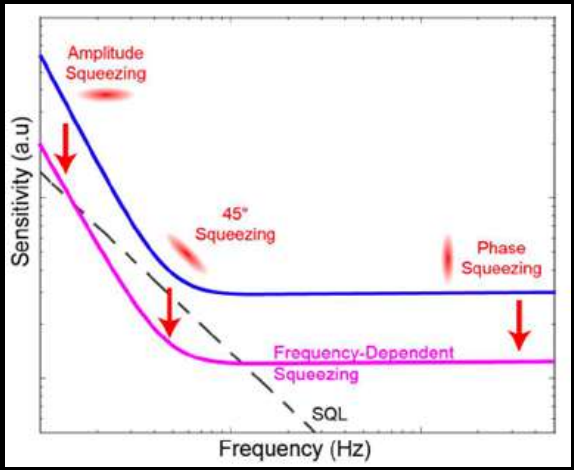
Coherent vacuum state

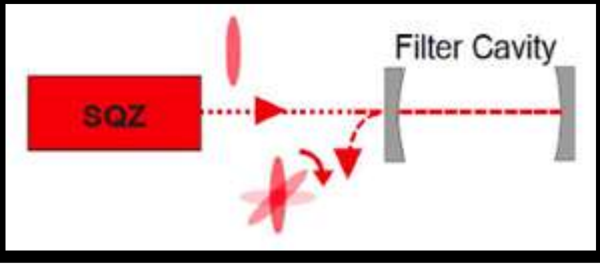


Squeezed vacuum state

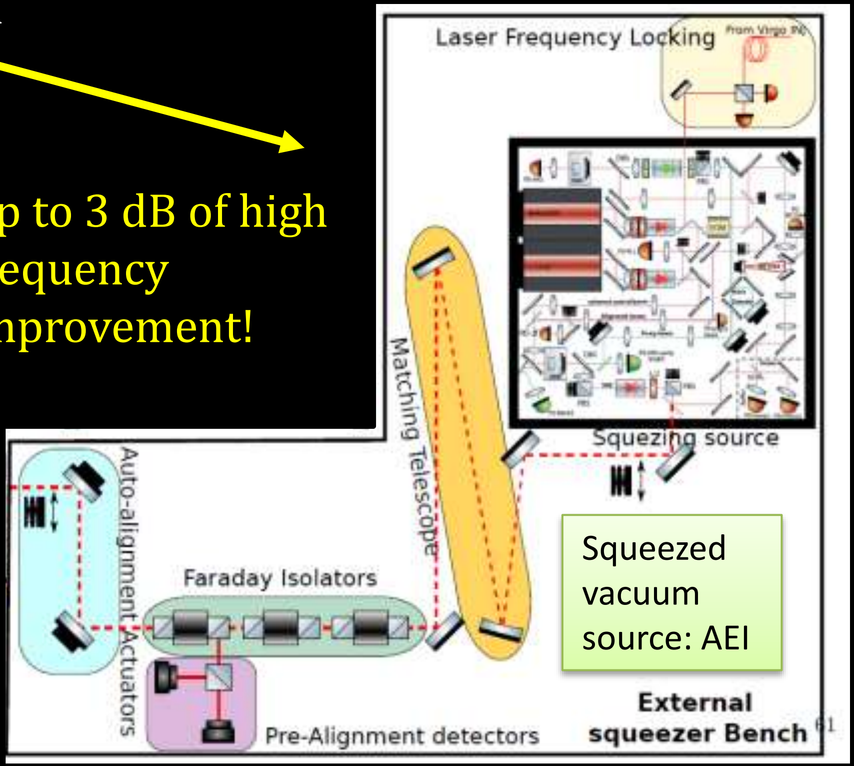


- Future: Frequency Dependent Squeezing

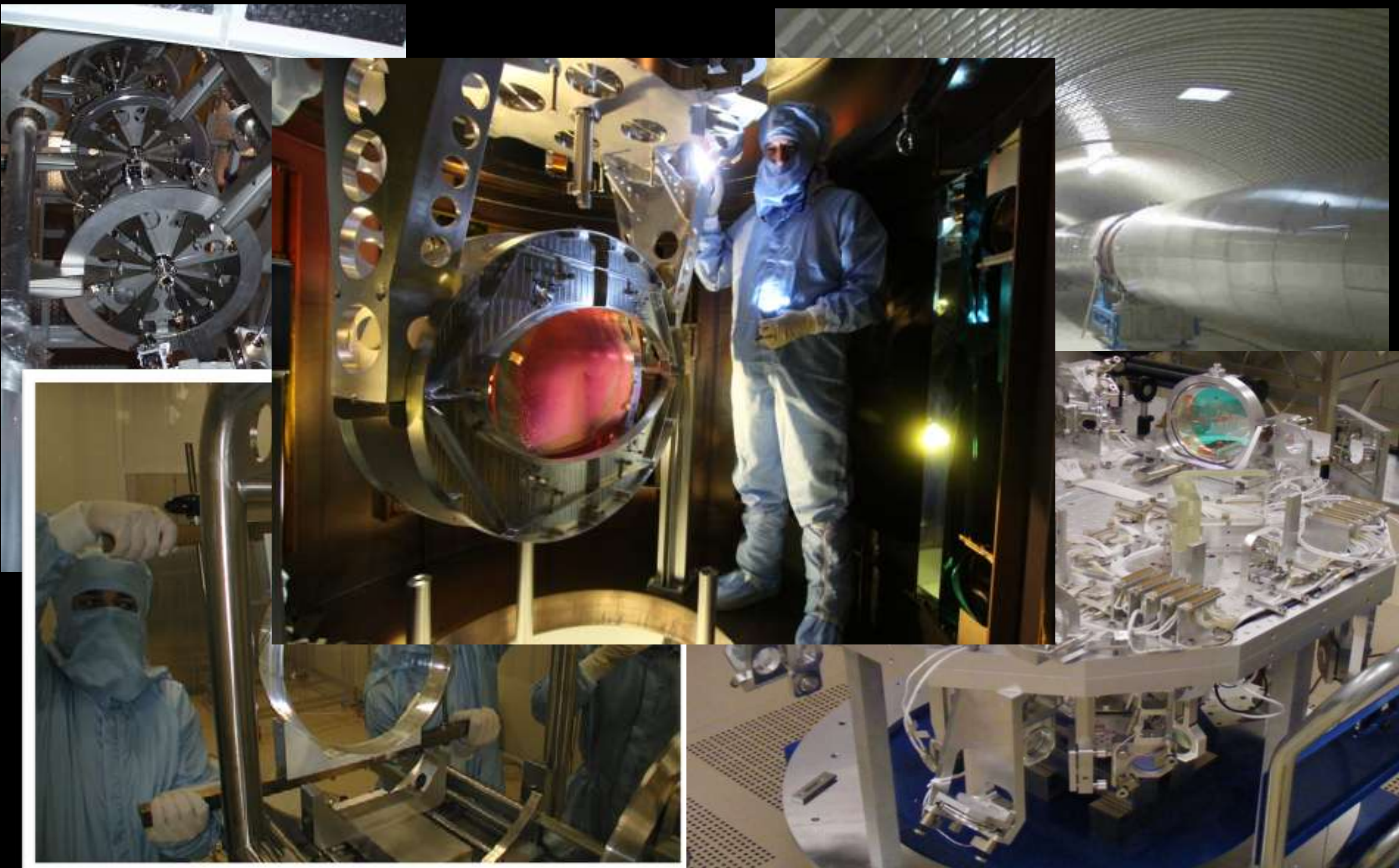




Up to 3 dB of high frequency improvement!



What does a *real* interferometer look like…



EGO/Virgo and Technology

State of the art, challenges on many fronts:

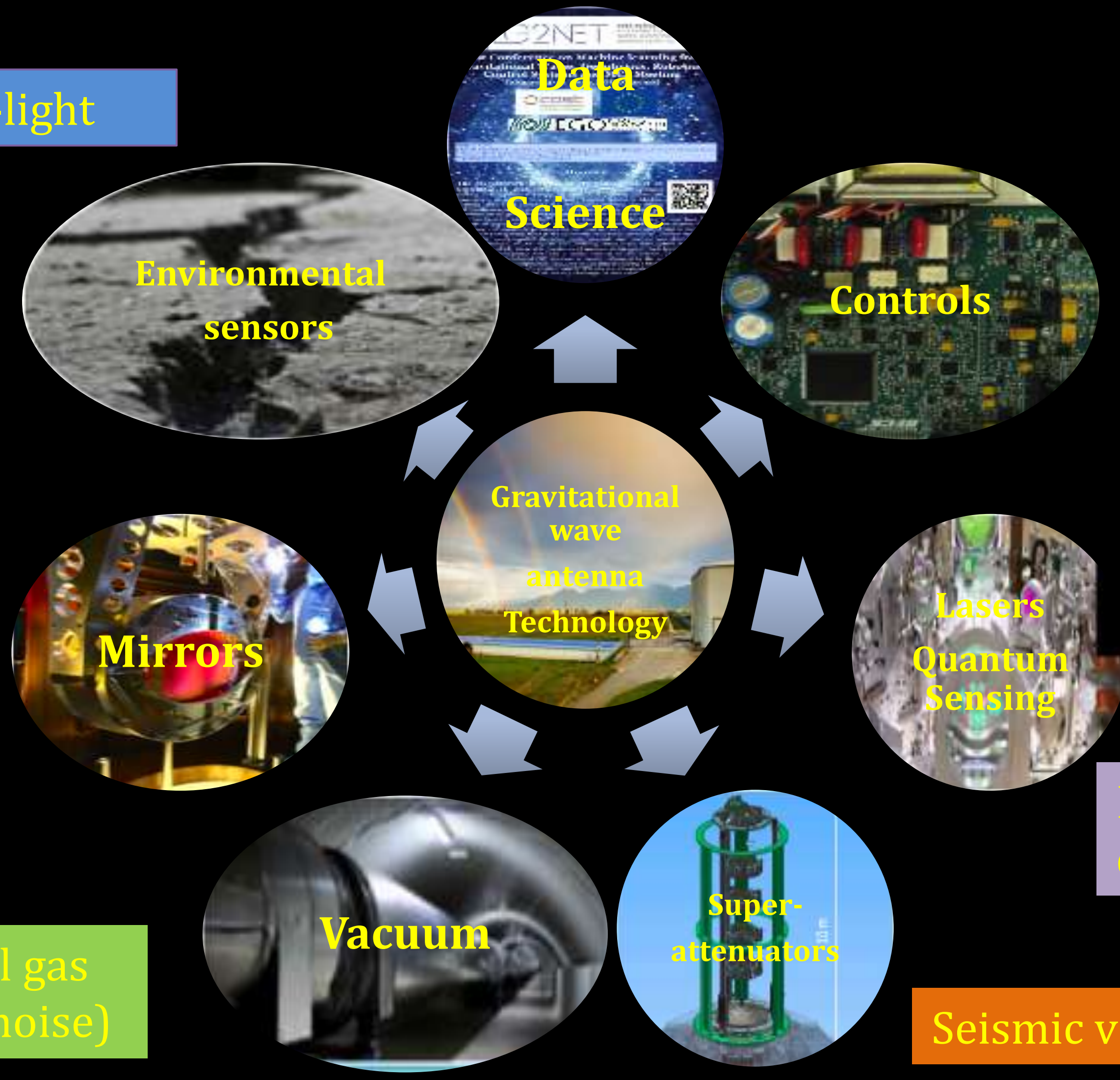
Stray-light

Newtonian noise

Residual laser noise

Thermal noise (coating + suspension)

Radiation pressure fluctuation



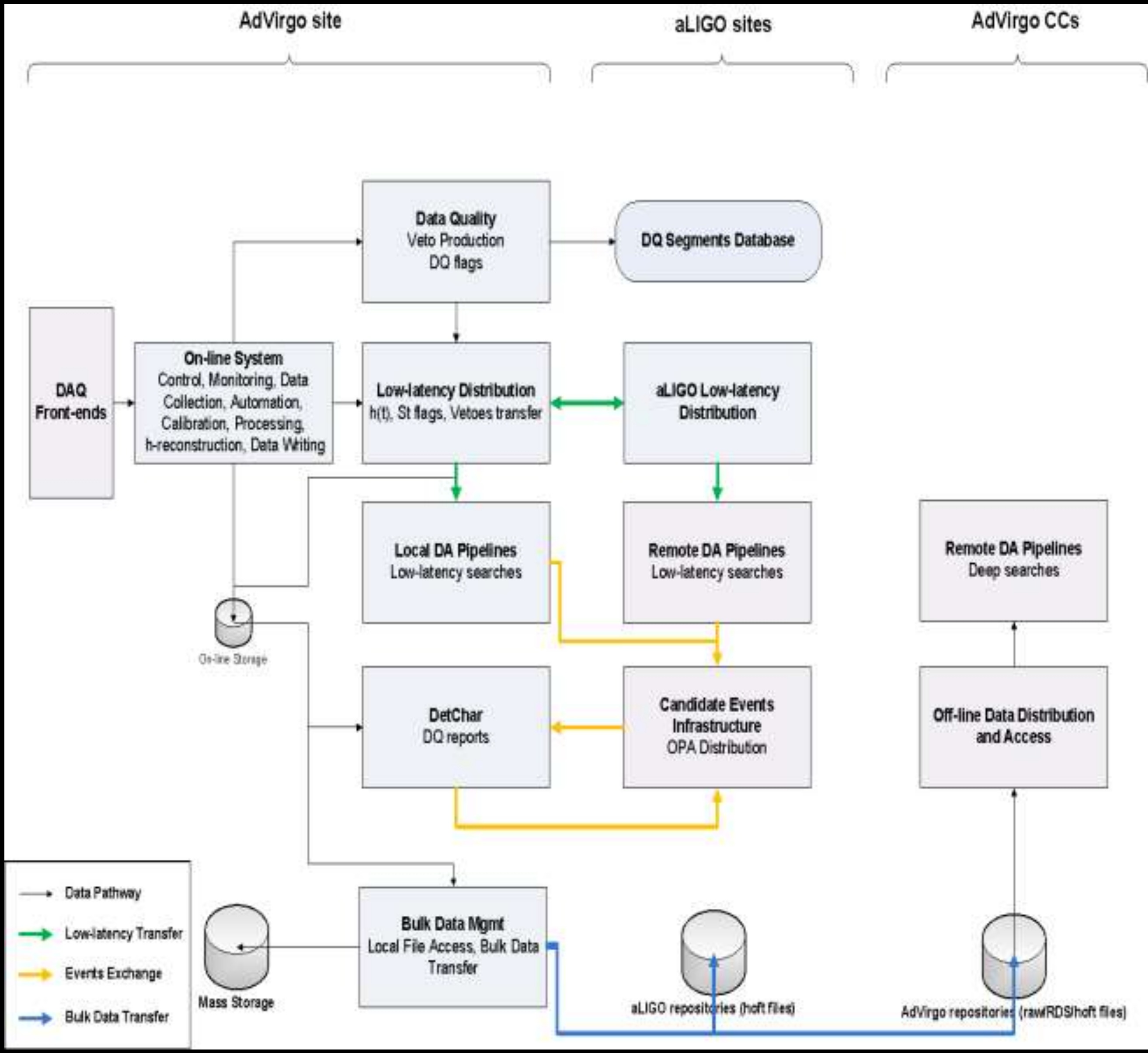
EM field quantum noise

Residual gas (phase noise)

Seismic vibration

A global network for computing

1. The signal arrives
2. Data composed into frames
3. Calibration of the data
4. Veto, DQ flags production
5. h(t) transfer
6. Low-latency matched-filter pipelines
7. Upload to GraceDB
8. Data written into on-line storage
9. Low-latency data quality
10. Low-latency sky localization
11. GCN Circular sent out
12. Data written into Cascina Mass Storage
13. Data transfer toward aLIGO and CCs



30 years of EGO/Virgo History


Alain Brillet


Adalberto Giazotto


Jean-Marie Mackowski

1989 Virgo proposal
1993-1994 CNRS and INFN approve VIRGO (+5y)
1997 Construction starts near Pisa (+8y)
2000 Foundation of EGO (CNRS, INFN) (+11y)
2003 Inauguration of Virgo (+14y)
2004-2006 Commissioning of full detector
2006 Netherlands joins EGO as an Observer
2007-2011 Start of Virgo science runs together with LIGO

1st generation detector: Virgo

2009 EGO Council approves AdVirgo (+20y)
2017 First detection at Virgo (+28y)
2019 O3 one year RUN (+30y)

2nd generation detector: Advanced Virgo


Inauguration Virgo 2003


EGO

European Gravitational Observatory (EGO)

- EGO is a consortium with members CNRS and INFN and NIKHEF as observer with goal the promotion of research in the field of gravitation in Europe.
- Objectives:

I. *Construction, maintenance operation and upgrade of the Virgo interferometer*

II. Maintenance, operation and upgrade of the site infrastructures including a computing center

III. Representation of the consortium at the regional, national , European and global level

IV. Promotion of interdisciplinary studies

V. Promotion of R&D (mostly environmental noise and photonic science)

VI. Outreach and education

Advanced Virgo

- Virgo is a European collaboration with 559 members belonging to 106 institutions in 12 countries

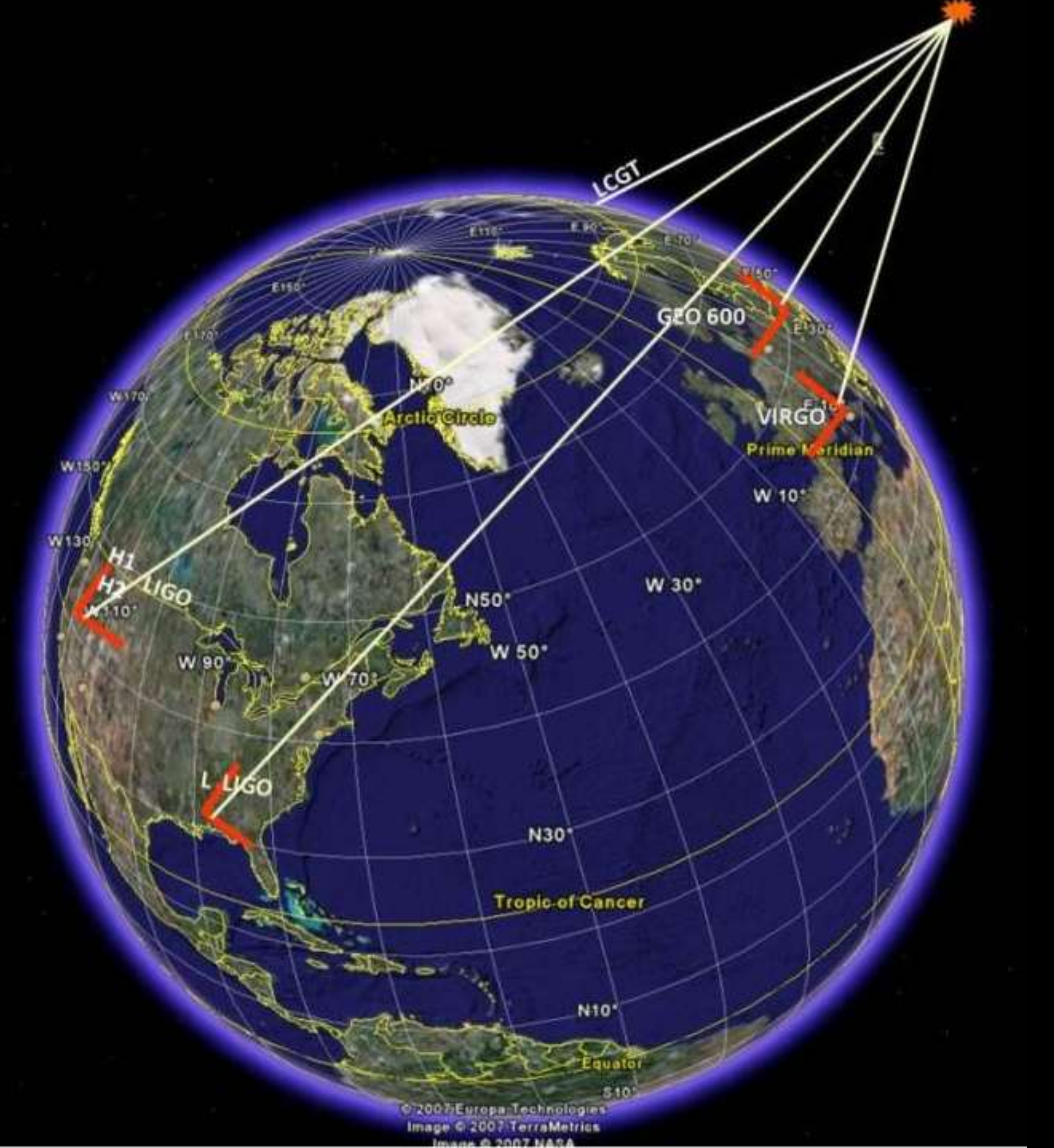
- APC Paris
- ARTEMIS Nice
- EGO Cascina
- IFAE
- INFN Firenze-Urbino
- INFN Genova
- INFN Napoli
- INFN Perugia
- INFN Pisa
- INFN Roma La Sapienza
- INFN Roma Tor Vergata
- INFN Trento-Padova
- LAL Orsay – ESPCI Paris
- LAPP Annecy
- LKB Paris
- LMA Lyon
- Nikhef Amsterdam
- POLGRAW(Poland)
- RADBOUD Uni. Nijmegen
- RMKI Budapest
- UCLouvain
- ULiège
- Univ. of Barcelona
- Univ. of Valencia
- University of Jena

The Science

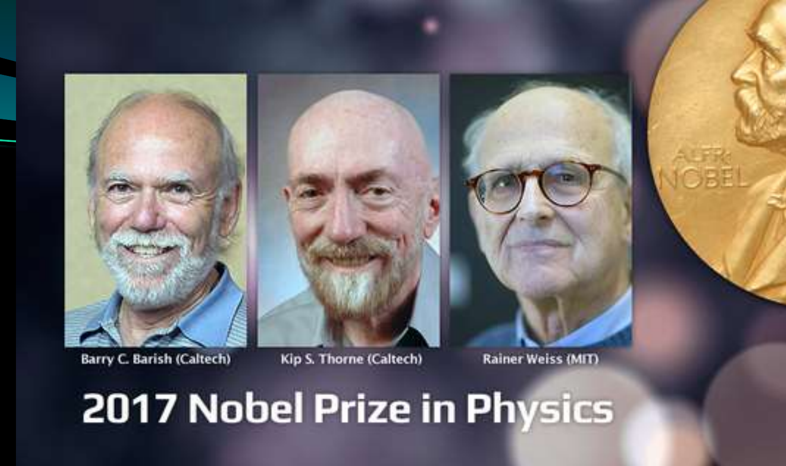
Gravitational waves detector network

Like a single microphone, only one detector, can't tell much about from where a gravitational wave has come. Therefore, having more detectors helps in:

- Identifying the direction to the signal
- Rejecting false signals exploiting coincidence



Our partners

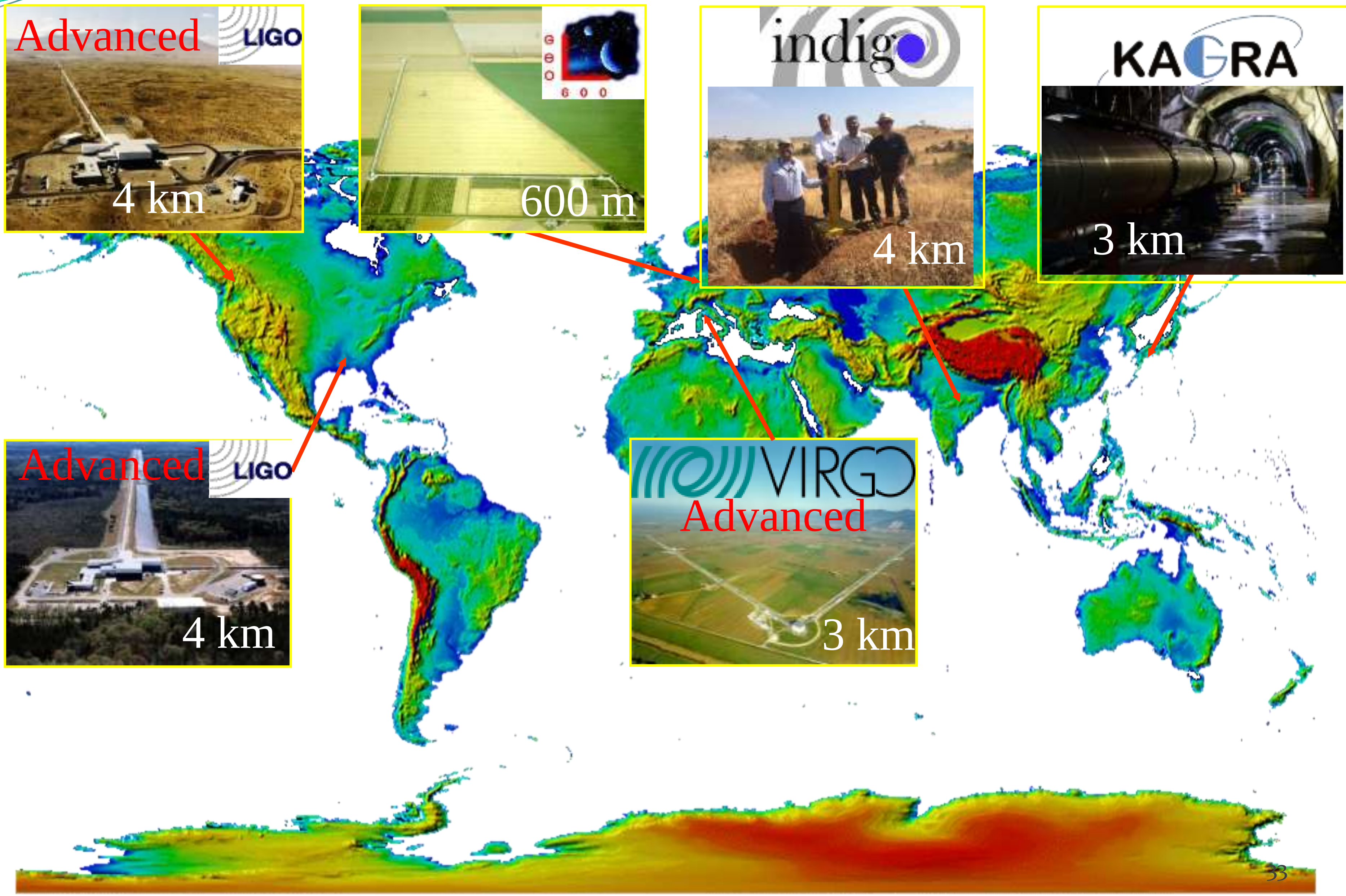


Laser Interferometer

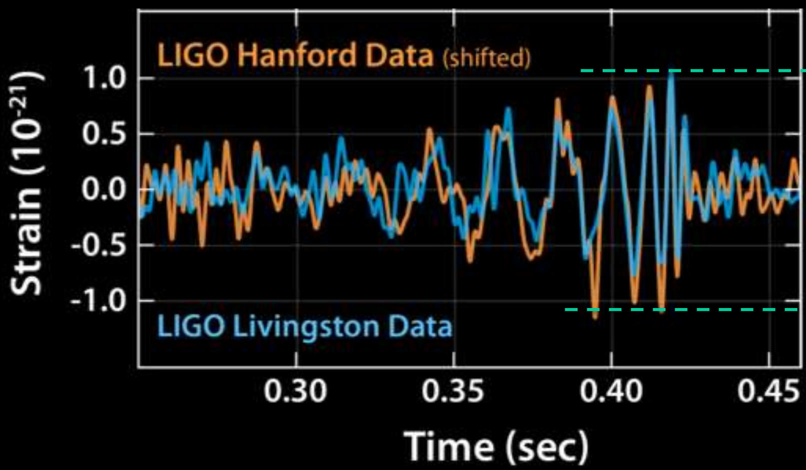
L I G O

Gravitational wave Observatory

Worldwide detector network

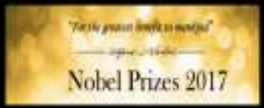


The first GW event: 14 September 2015

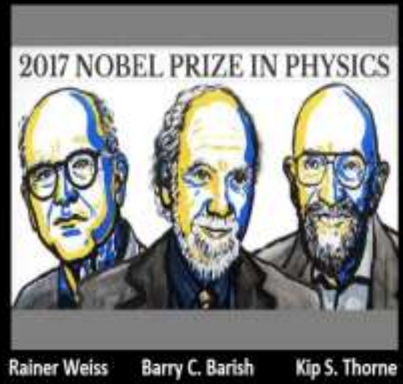


h ~ 10^{-21}
L ~ 4 x 10^{-18} m

Power ~ 4 x 10^{49} W

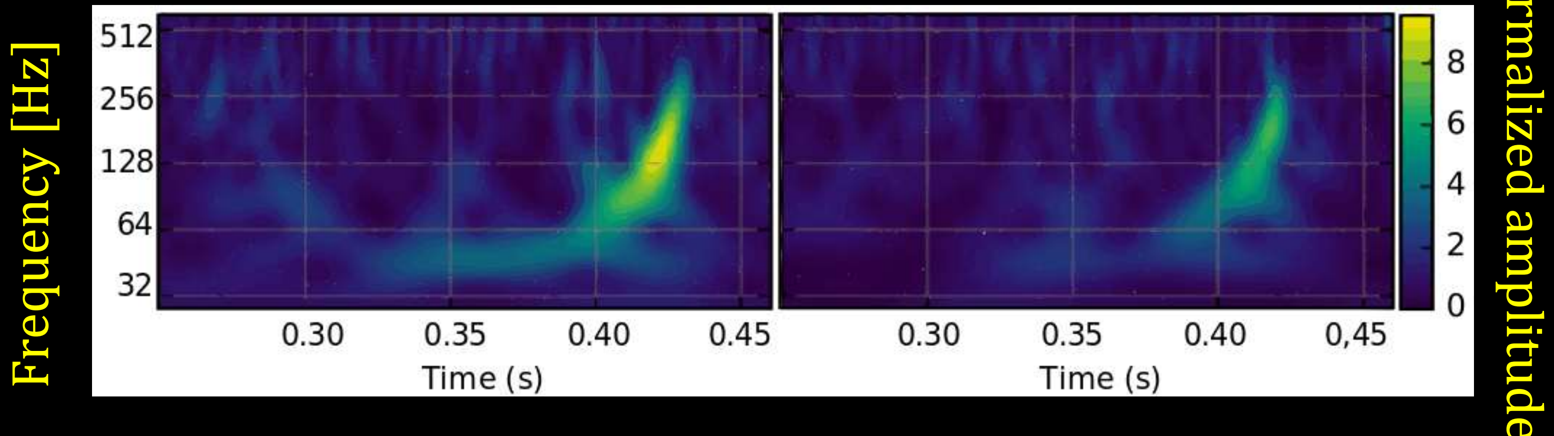


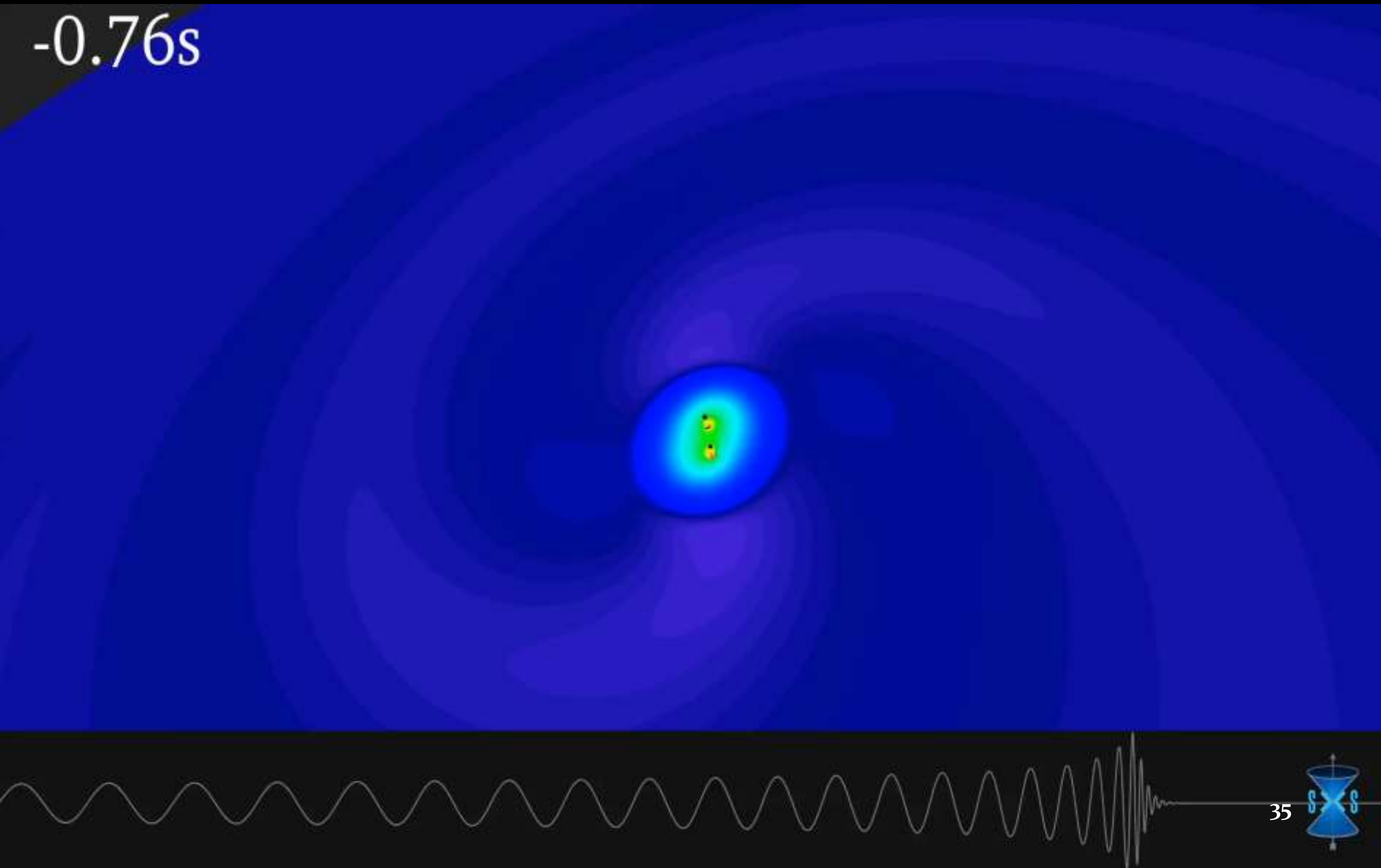
2017 October 3



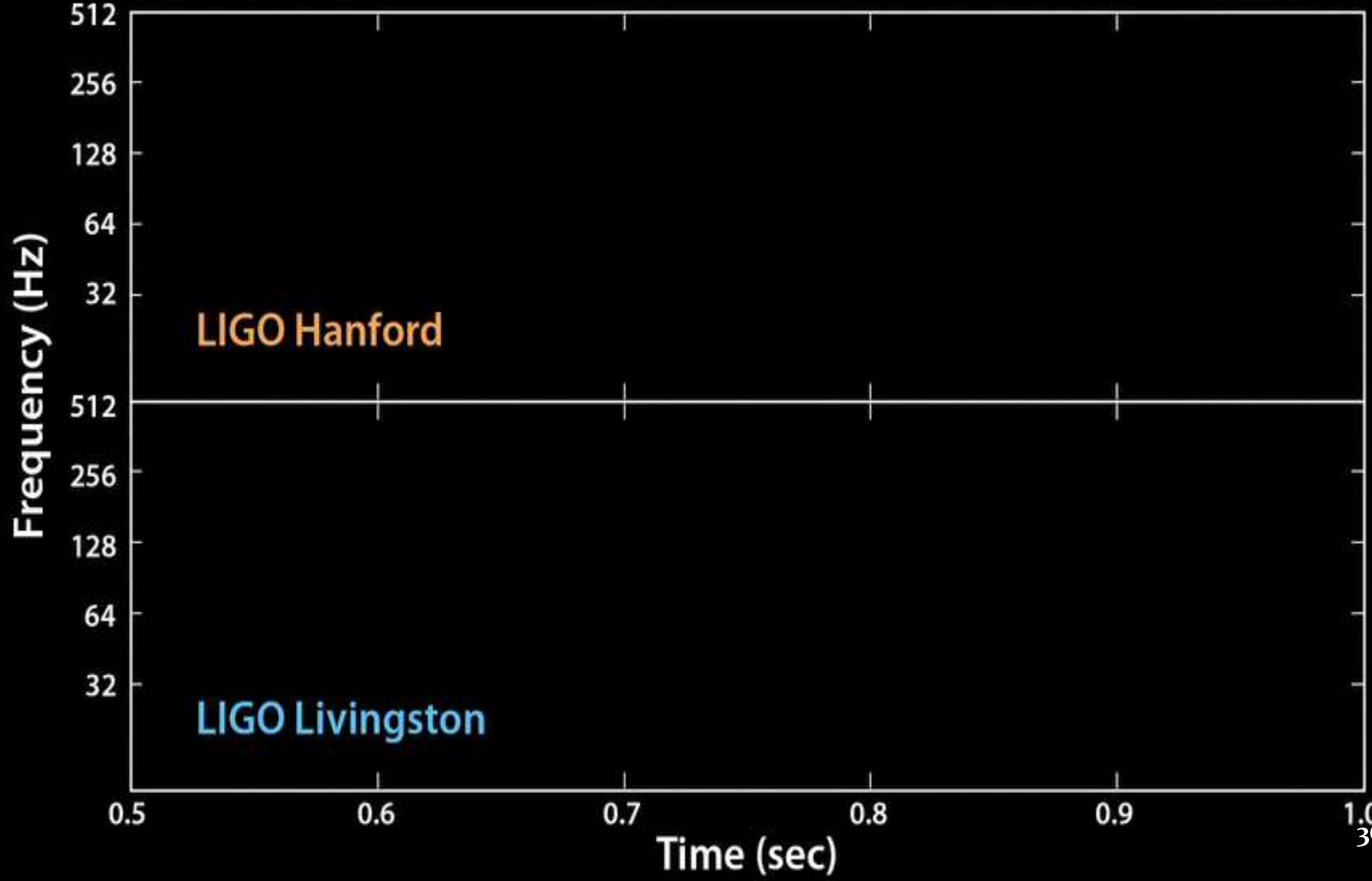
"for decisive contributions to the LIGO detector and the observation of gravitational waves".

Observing run O1

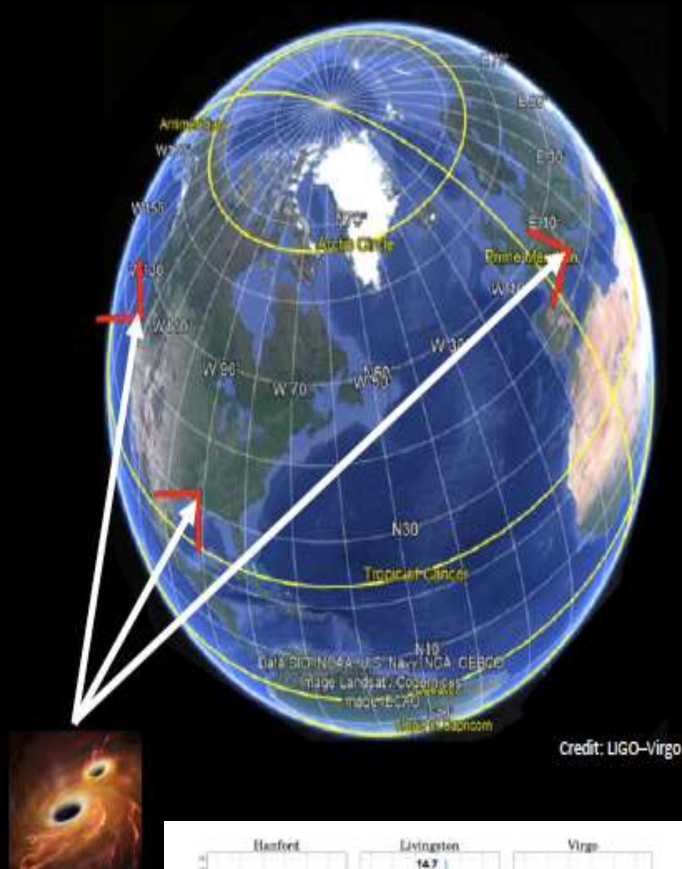



-0.76s

The whispers of the Universe

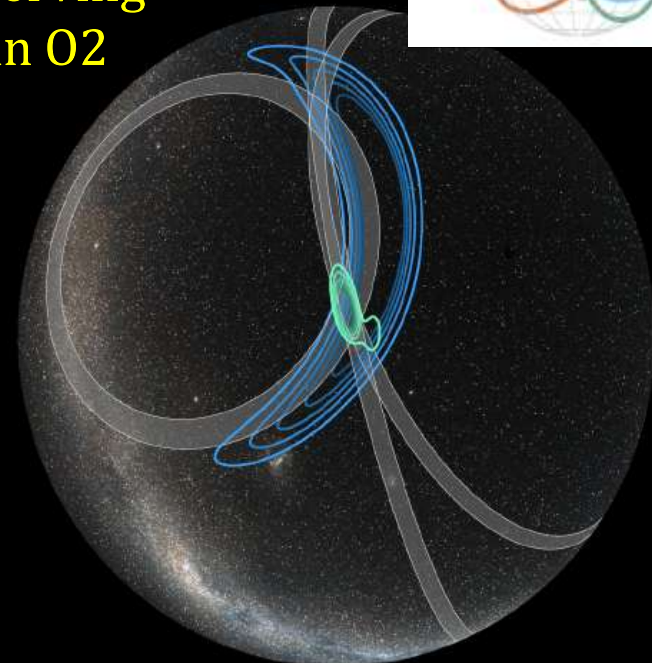


The first GW triangulated event: 14 August 2017

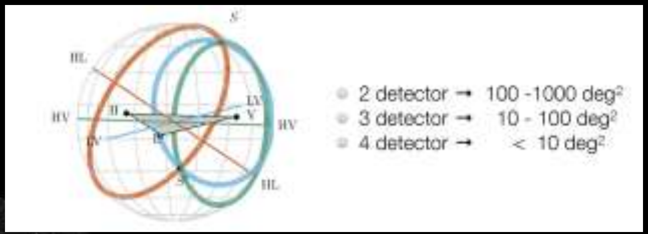


Credit: LIGO–Virgo

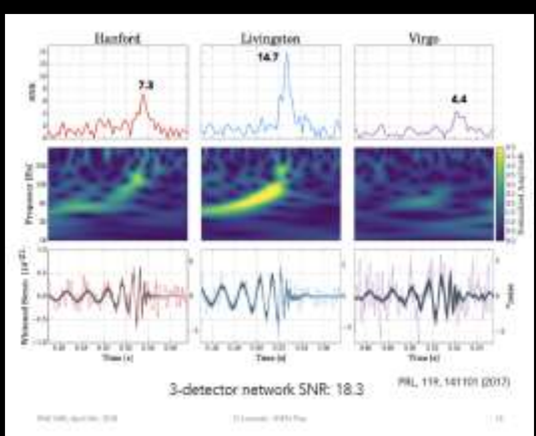
Observing run O2



Credit: Leo Singer



TOF :
HL ~ 10 msec.
VL ~ 26 msec.
VH ~ 27 msec.



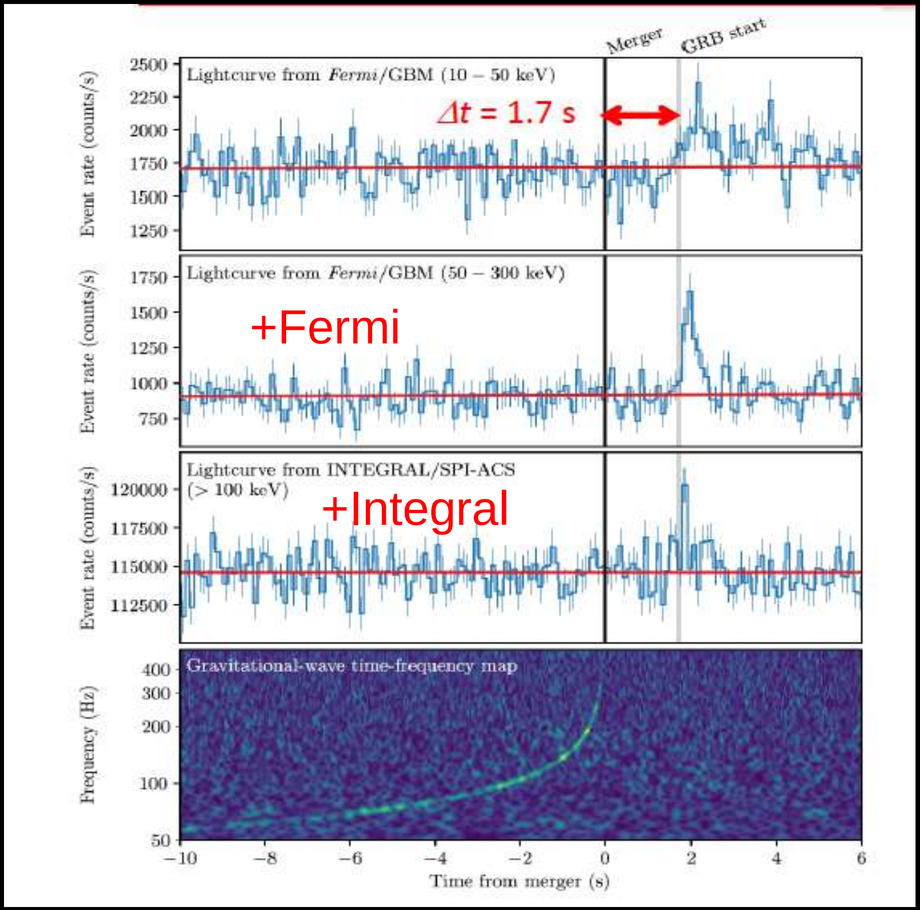
LH 1160 square degrees
LHV 60 square degrees

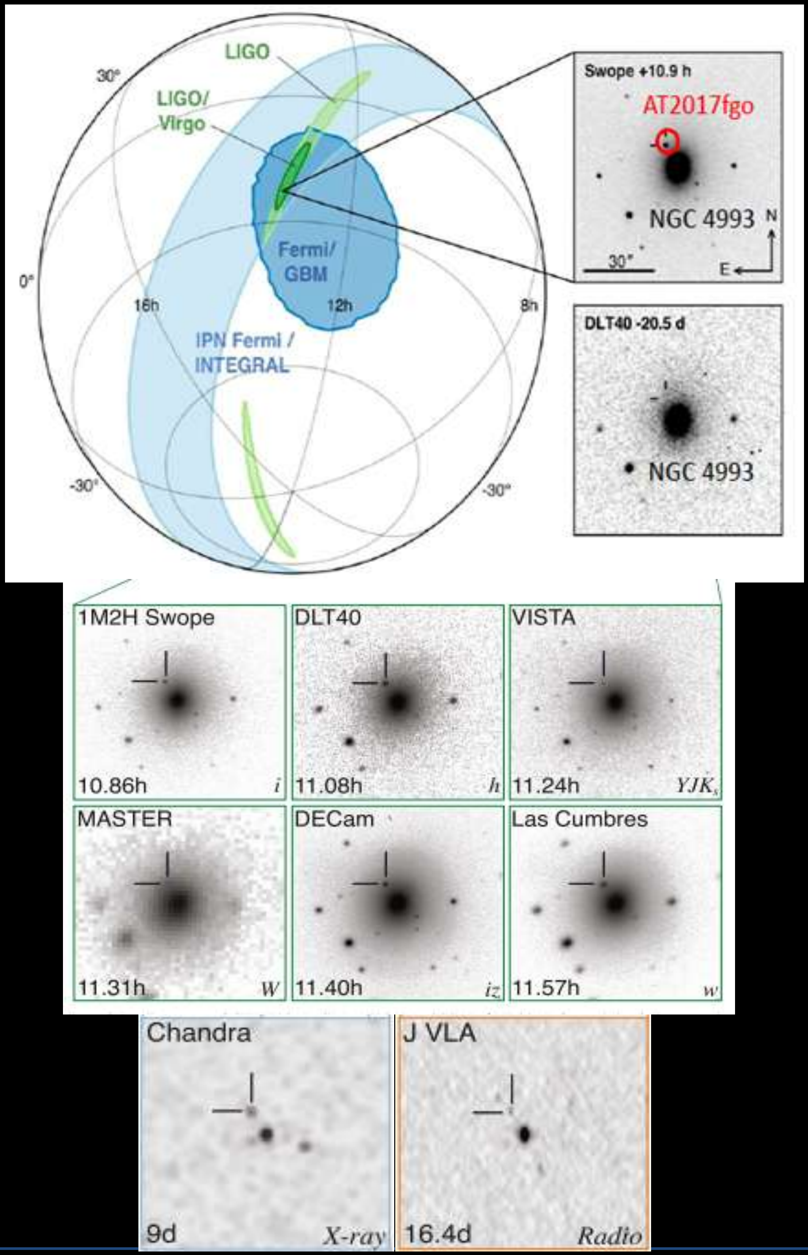
Also measure of GR polarisations

Gravitational Astronomy can start!

The first GW from a BNS: 17 August 2017

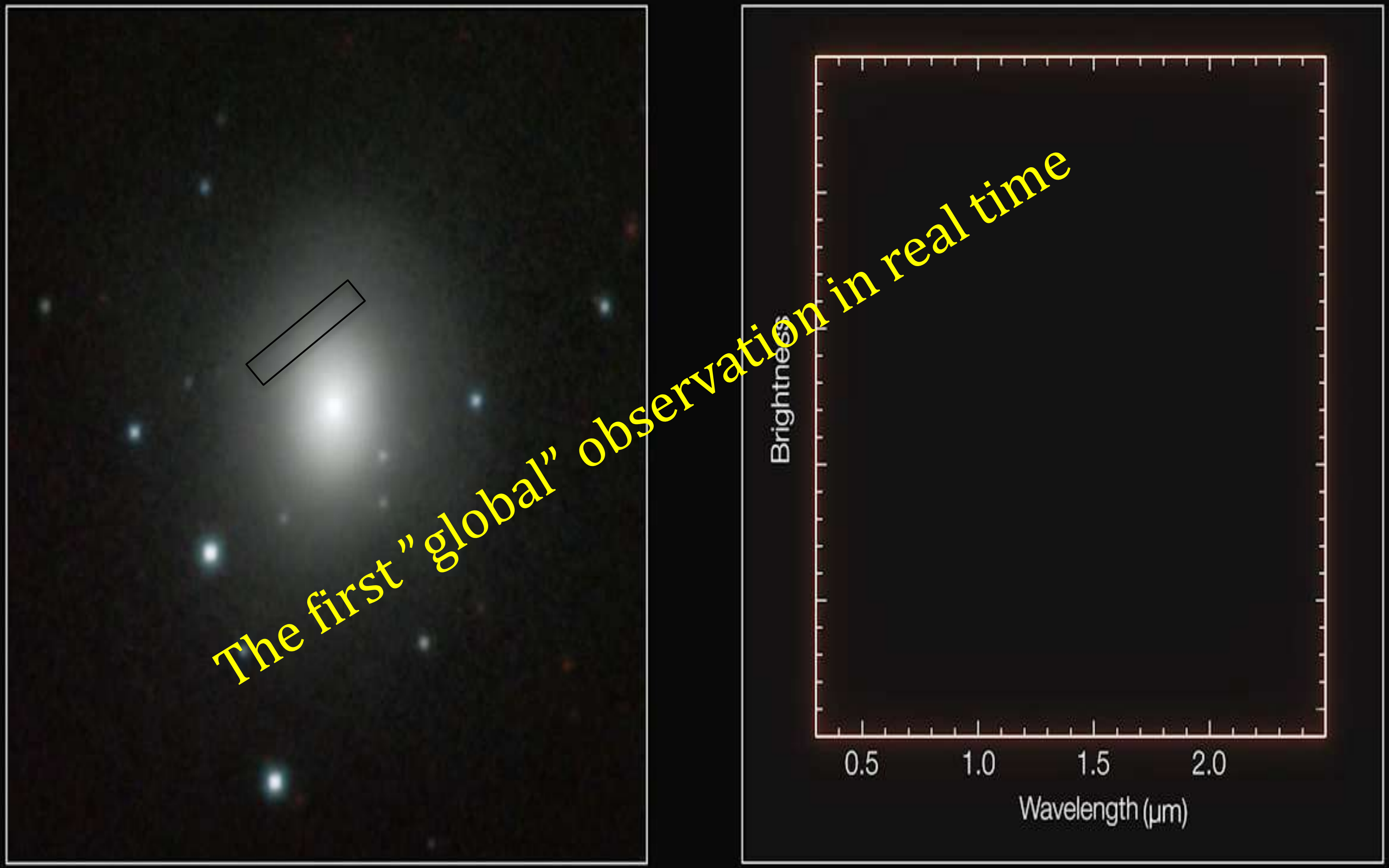
GW170817 a BNS @ 40Mpc:
observed by about 70 observatories
around the world





Start of multi messenger astronomy!

GW170817-GRB170817A-AT2017fgo
Observed by about 70 observatories around the world



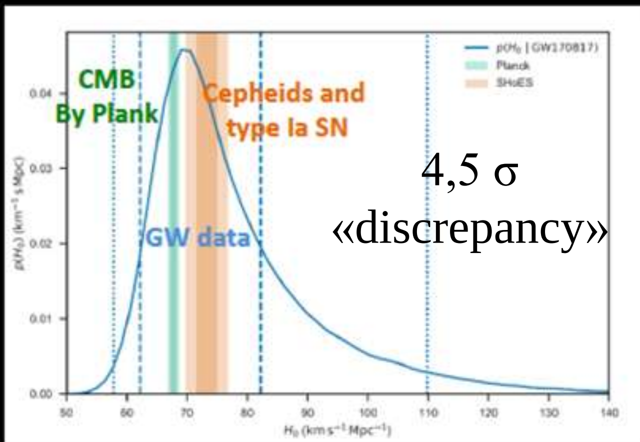
The first "global" observation in real time

Time: -1225 days

Elena Pian et al. 2017, Nature, 551, 67–70 ESO

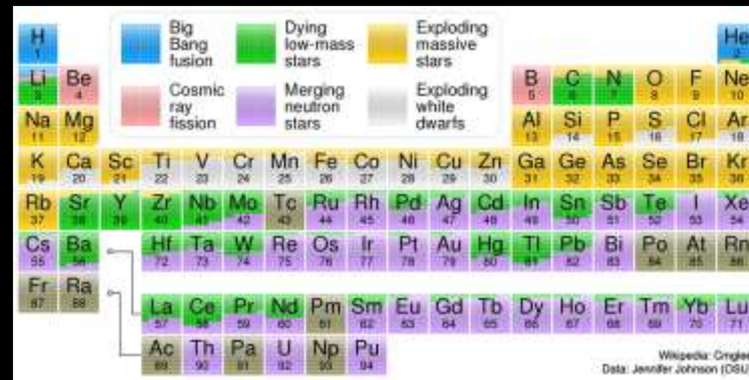
GW and Fundamental Science

Hubble constant



Test the speed of gws

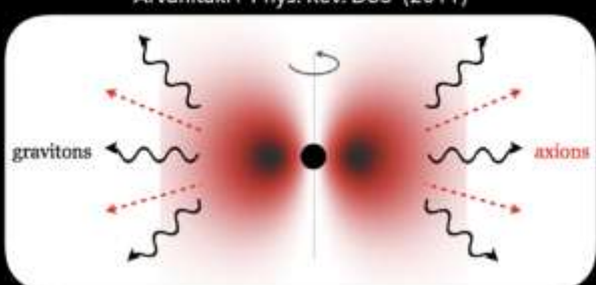
$$-3\cdot 10^{-15} \le \frac{v_{GW}-c}{c} \le 7\cdot 10^{-16}$$

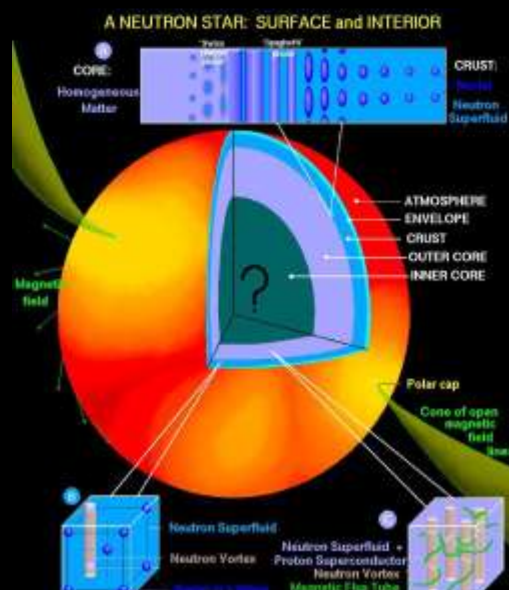


Kilonova: formation of heavy elements (Sd)

Gravitational atoms and BH super radiance

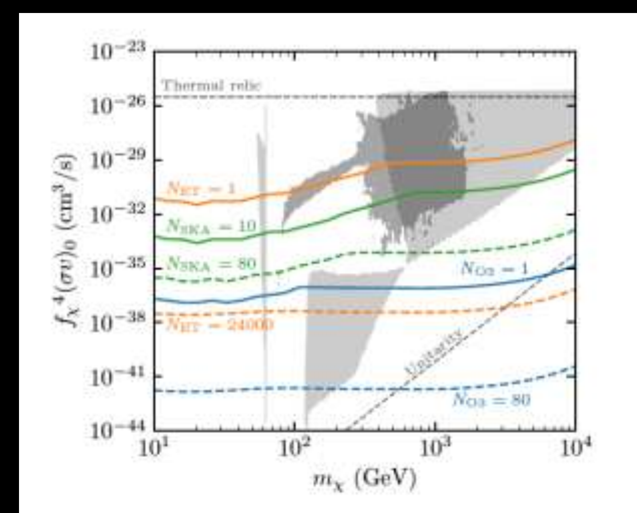
Arvanitaki+ Phys. Rev. D83 (2011)



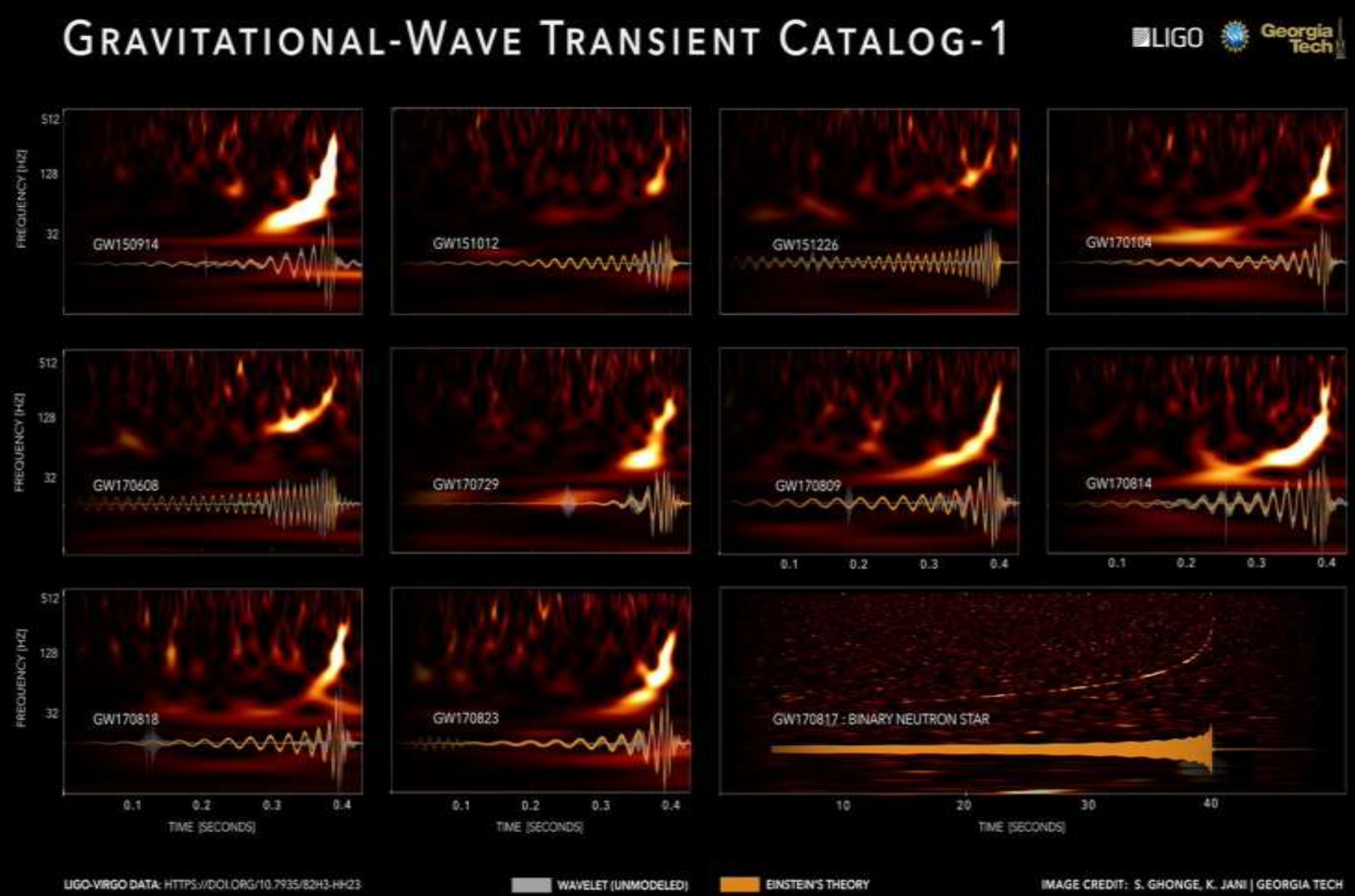


Super dense matter studies measuring tidal deformability of neutron star mergers

Dark matter: Primordial Black Holes



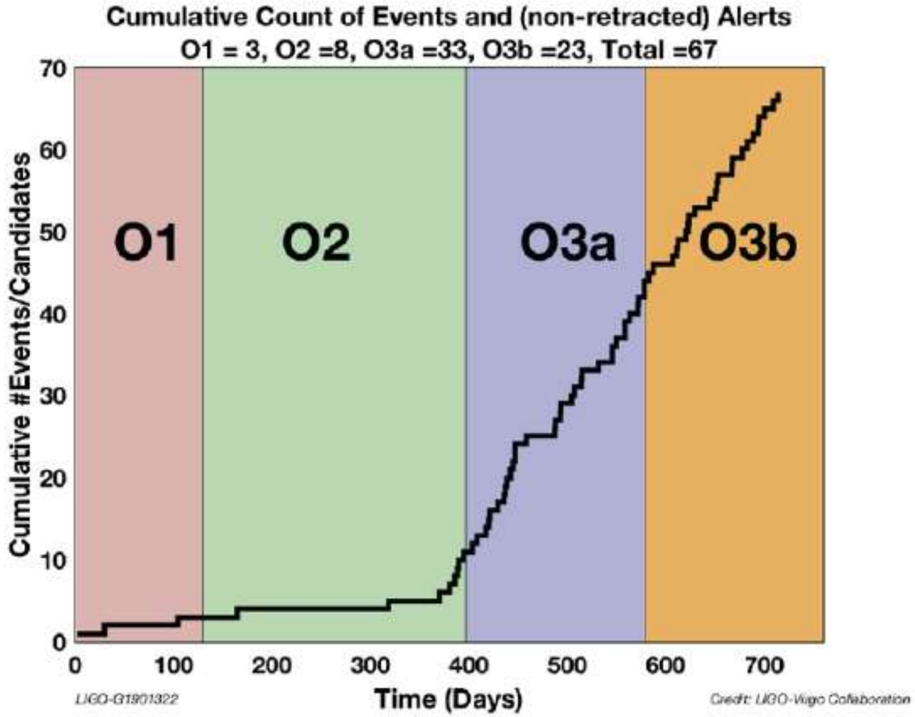
First Gravitational Waves catalog released



10 Binary Black Holes and 1 Binary Neutron Stars systems detected during first and second Observation Runs

April 2019-April 2020 O3 Run

O3 publicly anounced candidate events

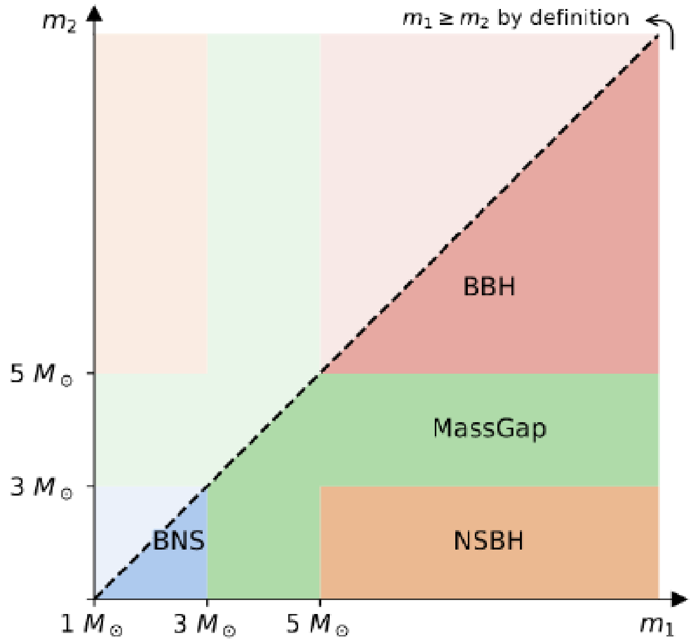


O3 has been a very successful run: **56 candidate events**.

A few confirmed detections (exceptional events) have already been published: **GW190412, GW190425, GW190814.**

O3: Contents of the alert (CBC)

- False Alarm Rate (FAR) estimate of the event candidate.
- Event time and sky localization.
- 3-D skymap with direction dependent luminosity distance.
- Luminosity distance marginalized over whole sky.
- Source classification and properties.



BNS: both masses < $3M_{sun}$

MassGap: $3M_{sun}$ < one mass < $5M_{sun}$

NSBH: one mass < $3M_{sun}$, other mass > $5M_{sun}$

BBH: both masses > $5M_{sun}$

Terrestrial: noise

HasNS: probability one mass consistent with NS.

HasRemnant: probability system ejected NS matter.

GW190412

GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses (LVC, arXiv:2004.08342)

First o
with
masse

First
multip

- New
- Furth

Margin

GW19
knowle

GW190425

GW190425:
3.4 M_{sun} (LV

Most likely **2**
2 interferom

Total mass

GW190814

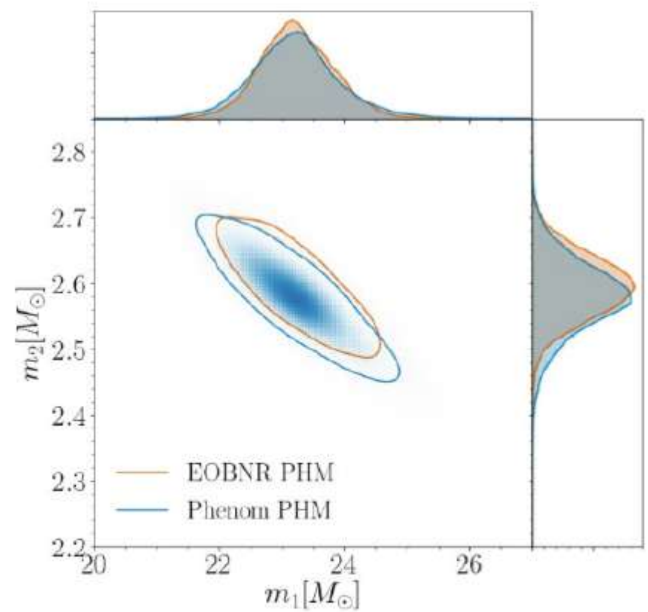
GW190814: Gravitational Waves from the Coalescence of a 23 M_{sun} Black Hole with a 2.6 M_{sun} Compact Object (LVC, ApJL, 896:L44, 2020)

Nature of secondary component uncertain: **BBH or NSBH?**

Difficulties to identify the source:

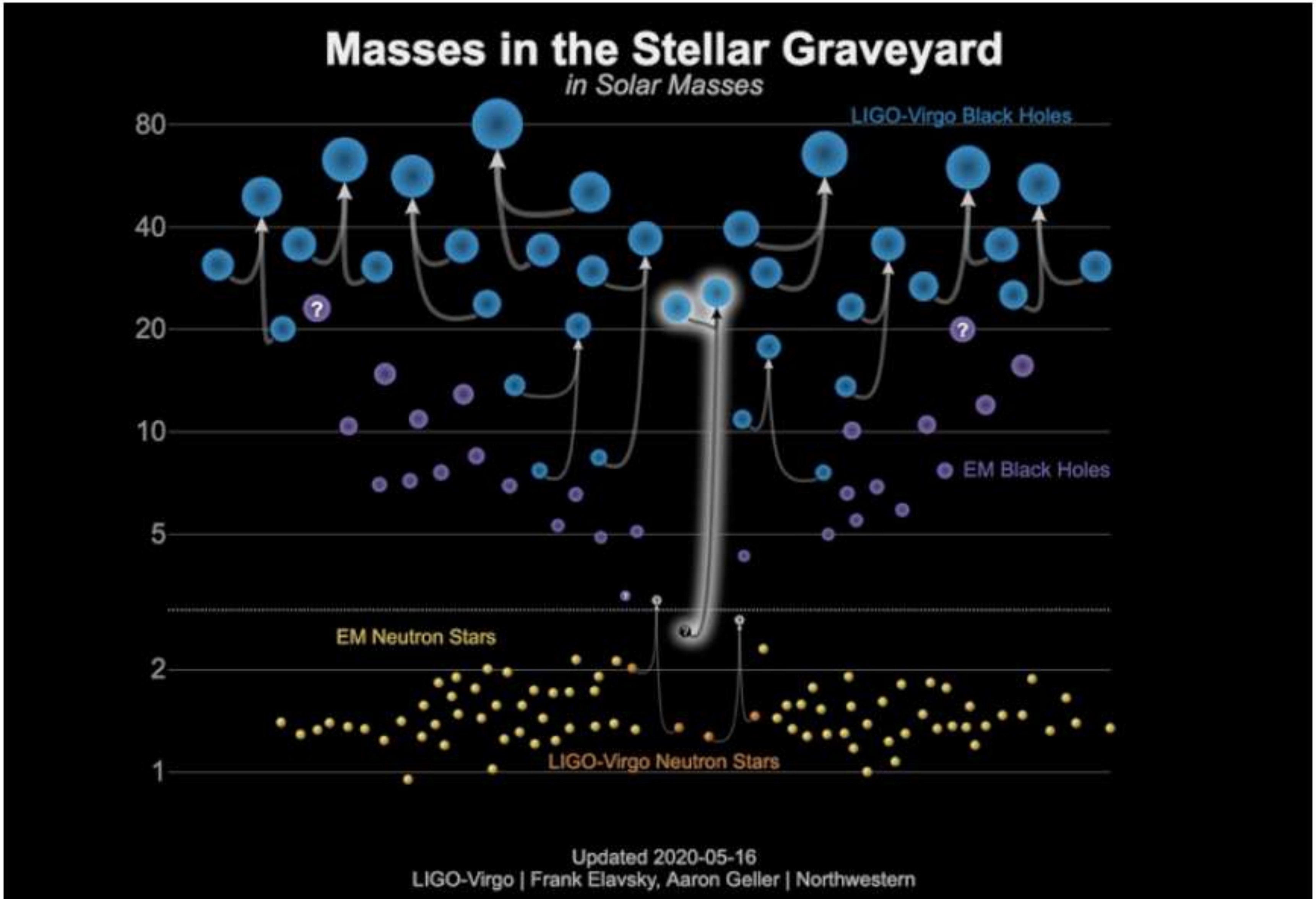
- Asymmetric masses (9:1 ratio)
- No EM counterpart
- No signature of spin-induced quadrupole effects or tides on waveform

Object of **2.6 M_{sun}** compatible with NS or BH depending on maximum mass supported by NS EOS.



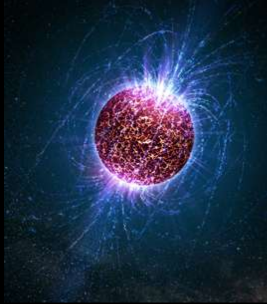
Challenge for formation models.

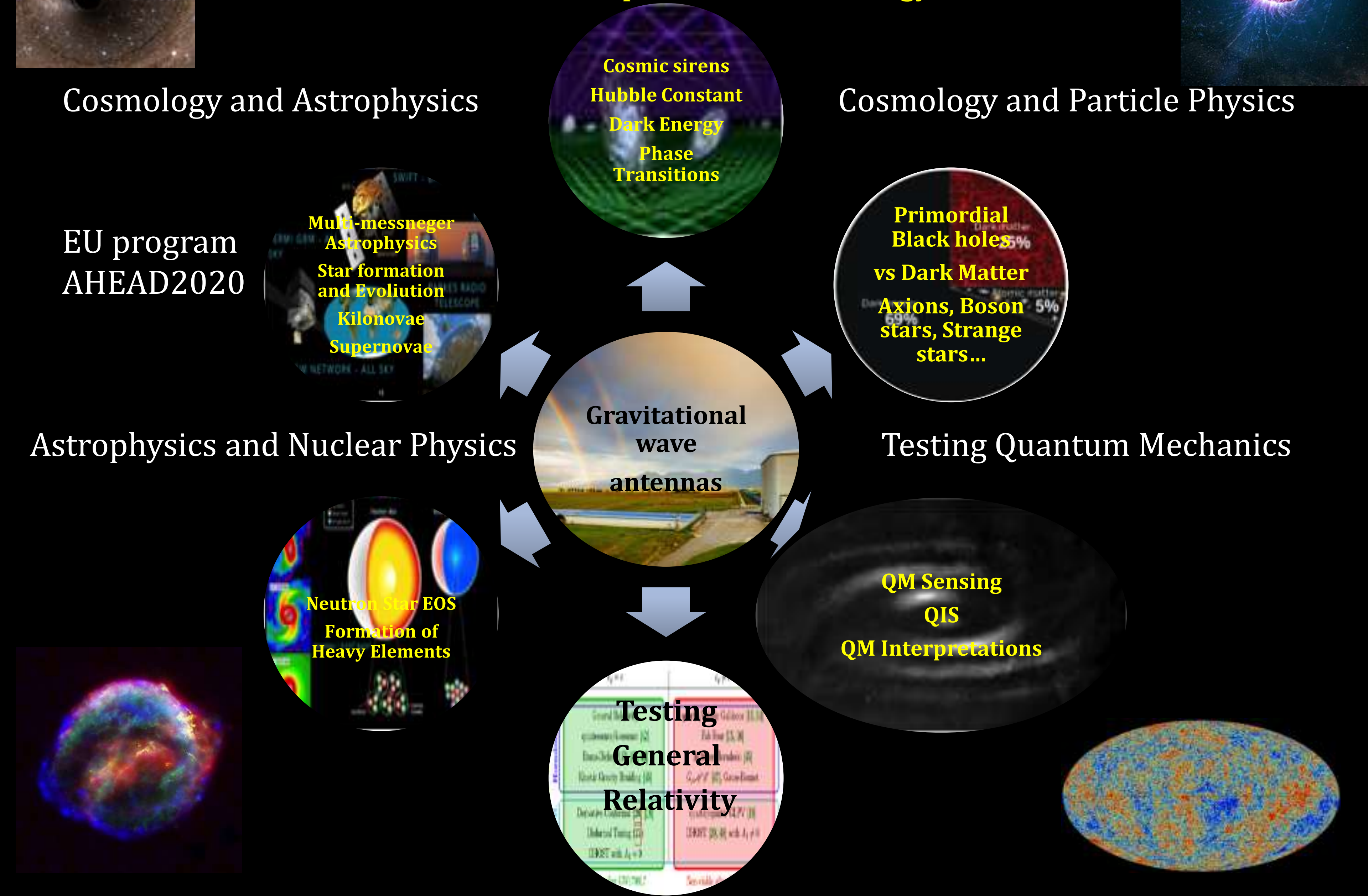
GW190814: compact object in the mass gap



GW and Fundamental Science

From APPEC input to EU PP Strategy



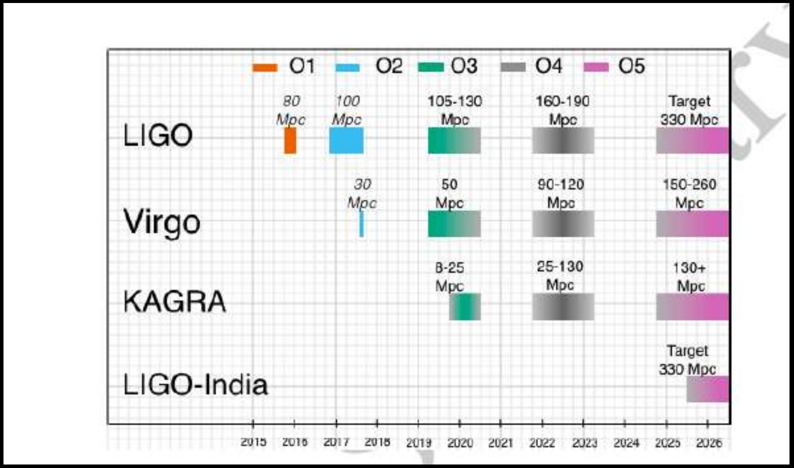


The Future

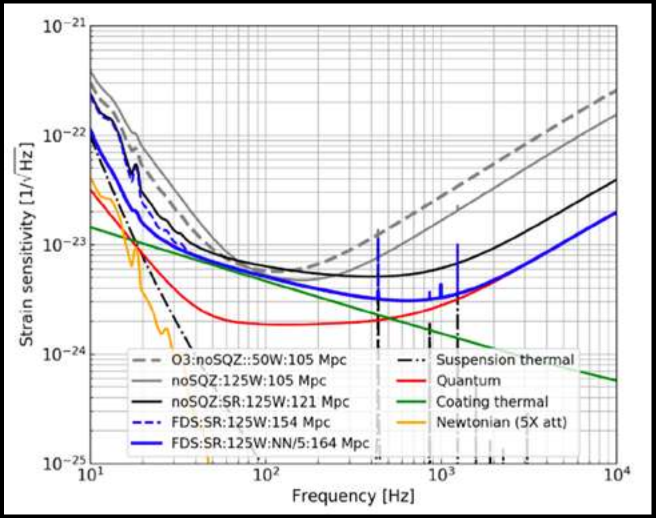
The next 10 years

- An international gw network: A+, AdV+, KAGRA, LIGO India (> 100 sources)
  - Recent signature of an MoU with KAGRA

- A global multimessenger network:
  - ✓ GW and EM observatories (optical to radio)
  - ✓ GW and Space satellites (FERMI, INTEGRAl, ATHENA,..)
  - ➢ GW and large surveys (DES, LSST, DESI)
  - ➢ GW and high energy observatories (CTA, KM3NET/ICECUBE, Auger,..)00



AdV+

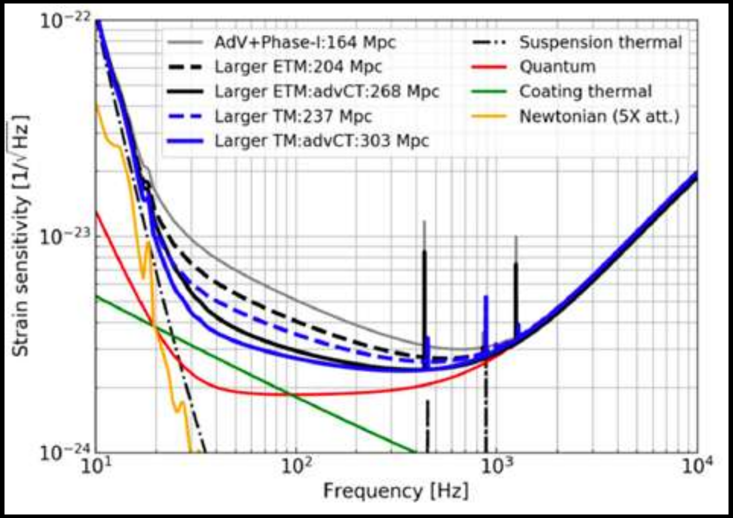


Phase I (O4): reaching the thermal noise wall

1. Signal Recycling
2. High power laser
3. Frequency Dependent squeezing
4. Newtonian Noise Cancellation

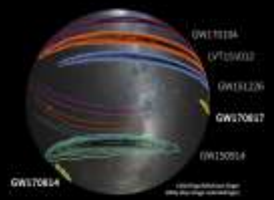
Phase II (O5): pushing the thermal noise wall down

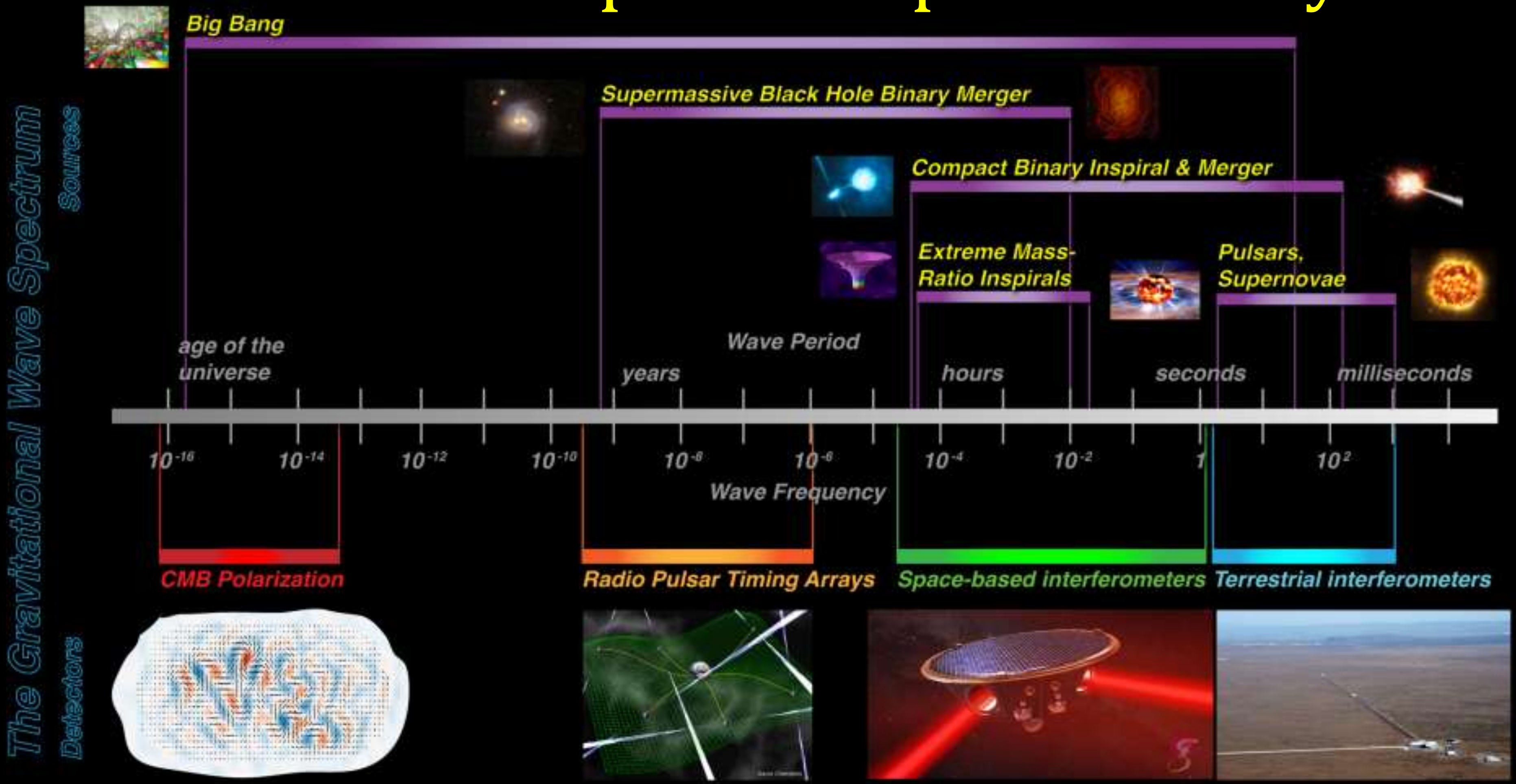
1. Further increase of laser power
2. Larger beams and larger end test masses (~ 100 kg)
3. Better coatings



- The sensitivity can improve up to *160 Mpc on Phase I* and up to *300 Mpc on Phase II!*
- This will increase the **number of detections** and the sensitivity to **new phenomena** (Equation of state of Neutron stars for example!)

Gravitational Waves
Ground-Space complementarity

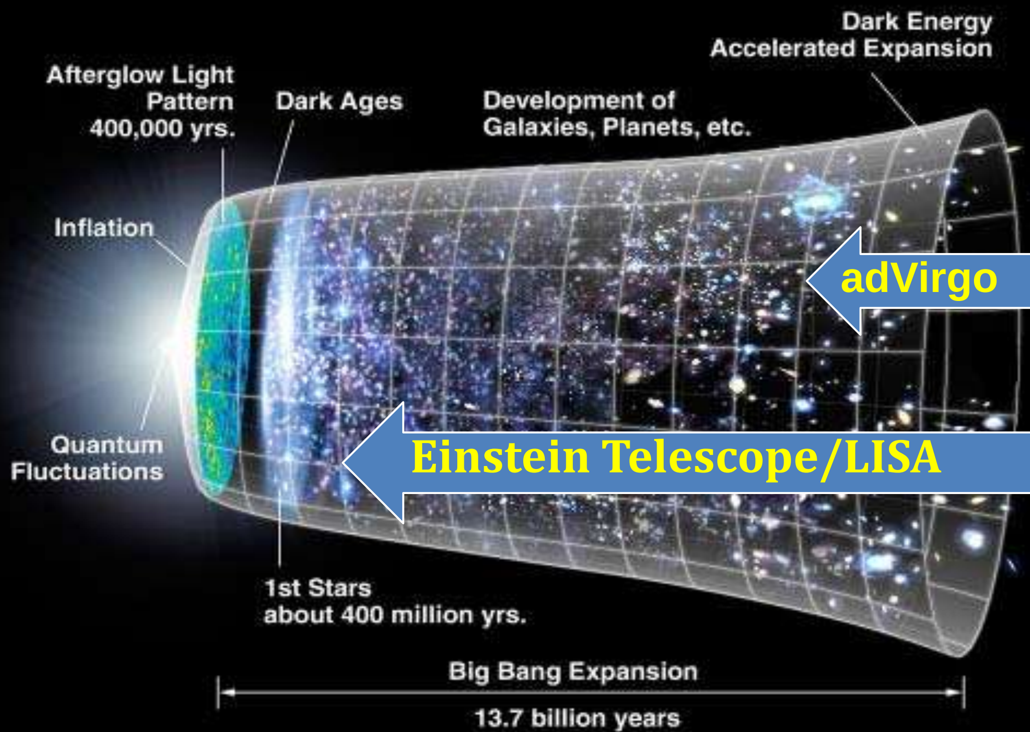


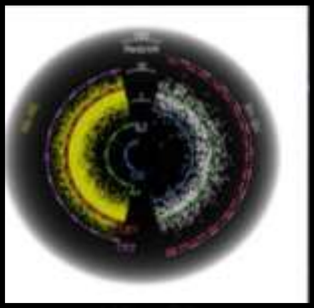


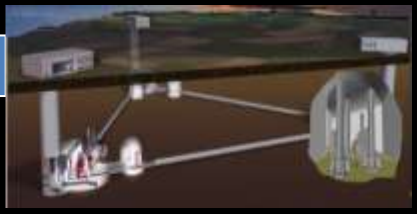
LISA

The next 20 years

	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
AdV	O4 prep		O4 run x10 sources	O5 prep	O5 prep	O5 run x10 sources									
Einstein Telescope	ESFRI roadmap		ET preparation												ET run x1000 sources

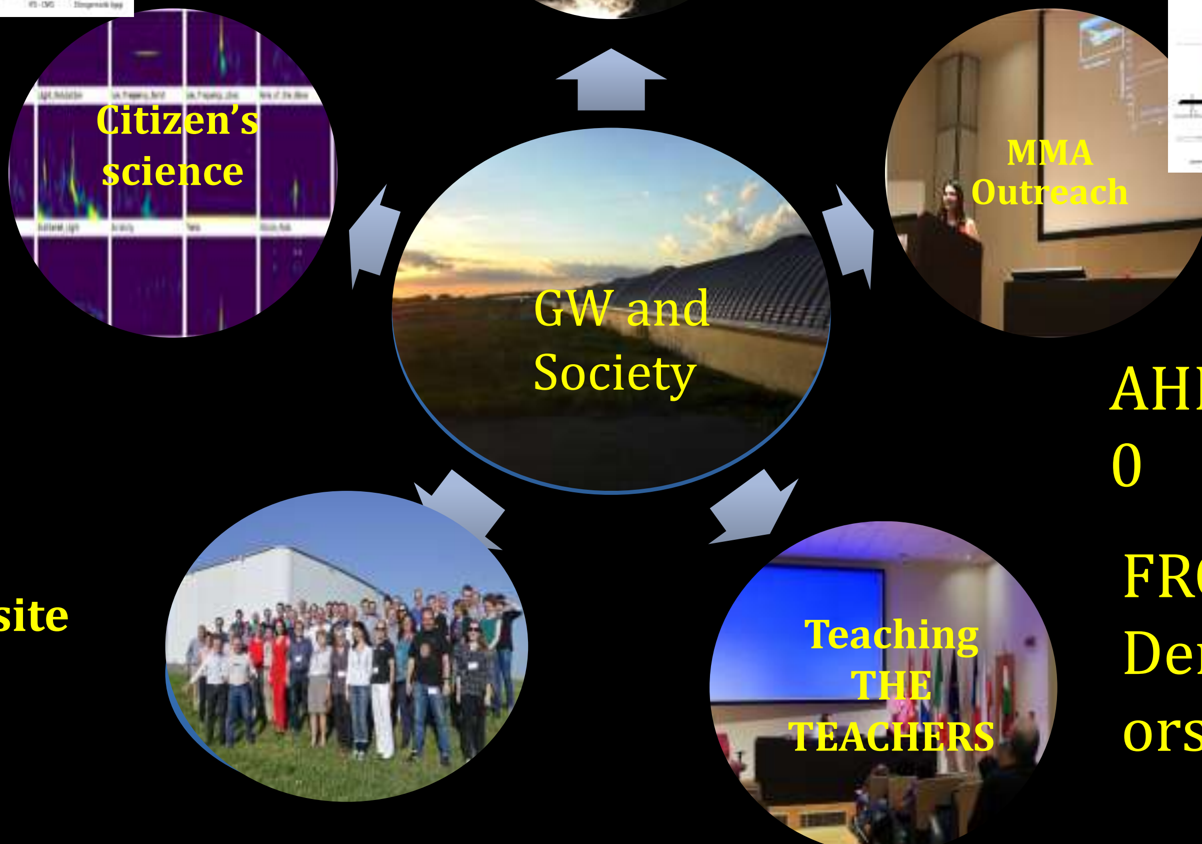






EGO/Virgo and Society

EU program
Ccoordinator
Multisensorial
studies



AHEAD2020

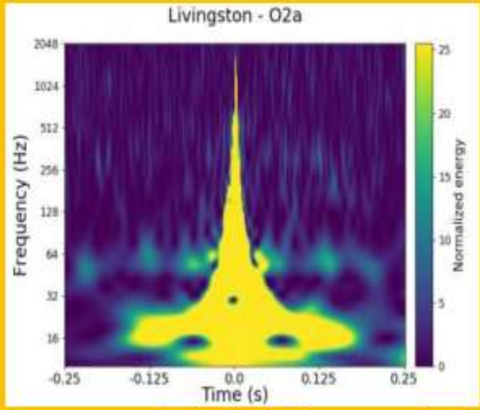
FRONTIERS
Demonstrators

Visits on the site
>8000/y

Many activities funded by EU programs, Private Foundations

Citizen's Science REINFORCE
GRAVITATIONAL WAVE NOISE HUNTING

Gravitational Wave noise hunting will develop a cutting-edge citizen-science programme by providing public access to GW antenna data, including environmental data, for an open-data project. The sensitivity of GW detectors is limited by several types of noise and requires recognition on how they affect GW data is crucial to understand their origin and eliminate them. The result of this activity of noise hunting and profiling is crucial to be more sensitive to GW Signals, including those that are not modelled by general relativity formula, such as those from the explosion of supernovae. Citizen scientists will contribute to this activity by looking at chunks of data and identify the presence of noise, and this outcome will serve as a basis to train machine learning algorithms that will automatically recognize and isolate noise in GW data. The same approach can also be used for seismic applications and/or earthquake. The team is already working in collaboration with the team of GravitySpy, a highly successful citizen science project base on recognition of transient noise sources called *glitches*. The experience of the LIGO Gravity-SPY programme[1] will be central here. The University of Oxford has many Zooniverse resources and technologies than can be usefully deployed here. In the framework of the "Gravitational Wave noise hunting" demonstrator, the option is to develop multi-messenger techniques in citizen's science will be investigated.



The anatomy of a "glitch" in a gravitational wave detector.

Originalities:

- Sonification: Increase inclusion, increase multi-modal apprehension of signal to noise
- Critical Thinking (with Nobel Prize Saul Perlmutter)

An exhibition on Art and Science
Rythm of Space

T. Saraceno, L. Lijn, A. Csorgo, B.Lamarche, R. Dellaporta, G. Alda/A. Ortiz...

Scientists and artists are the world's noticers. Their job is simply to notice what other people cannot.
Franck Oppenheimer

Conclusions

- GWs address many fields of **fundamental science**: from Astrophysics and Cosmology to Particle and Nuclear Physics but also photonic/opto-mechanics/QM challenges.

- **Multi-messenger** science has started and GW is a determining partner

- There is a continuous path of upgrades from AdV/A+ to ET/CE. GW is a field where there is rare continuity between observation, upgrade and design of a new infrastructure.

- There is a rich and developing field of **synergies with Geosciences and Atmospheric sciences**

- There is an equally important field of synergy with **quantum sensing**

- GW **Computing** is at the fore-font of recent developments

- There is a great potential of **outreach/education/engagement**, or societal impact accompanying these developments