EGO EUROPEAN GRAVITATIONAL OBSERVATORY

The art and science of Gravitational waves

Το συμπαν για ολους

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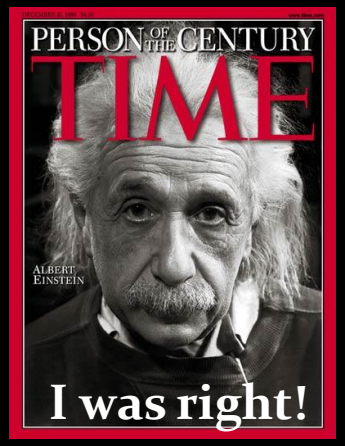
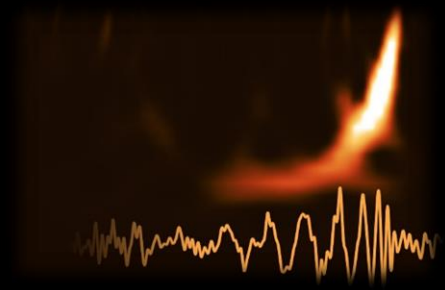
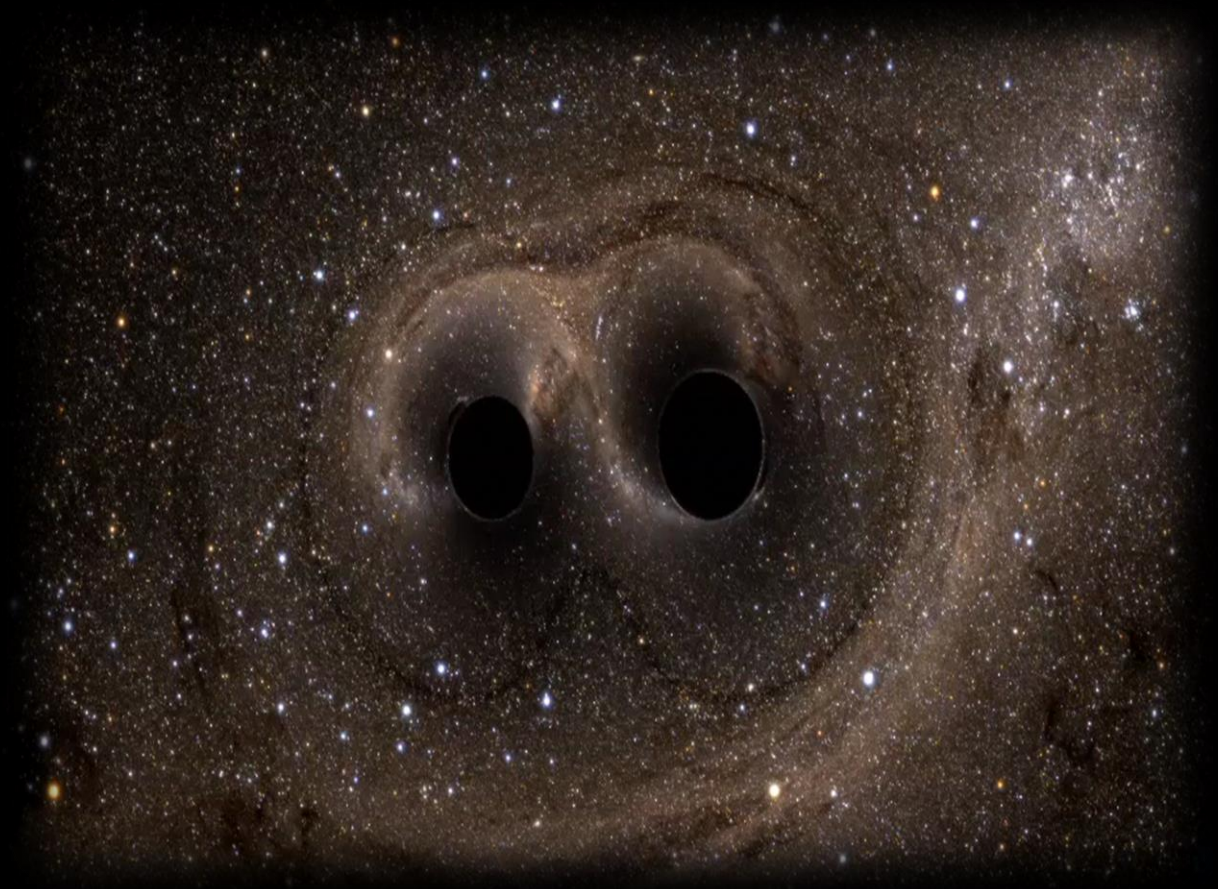
European Gravitational Observatory

September 14th 2015: first Gravitational Waves detection!







Theoretical Framework

The majority of Presocratics opt for a for restitution of the cosmos as transformations of primordial matter-element (water, air, fire).

Anaximander poses the formless (*apeiron*) as primordial element:

".. it is neither water nor any other of the so-called elements, but a substance different from them, which is apeiros (formless) , from which arise all the heavens and the different cosmos within them. And into that from which things take their rise they pass away once more, "as is ordained; for they make reparation and satisfaction to one another for their injustice according to the order of time," as he says in these somewhat poetical terms. — Phys. Op. fr. 2 (R. P. 16)."

They also opt, in their majority, for the eternity of time, using the « sufficient reason argument » if matter was formed at some point and some time, why this specific point and tis specific time ?

- Some modern quantum mechanics theories consider space-time as an emergent property of entangled matter

What is space-time ?

In Ancient Greek, there are many words to denote space:

- *topos* : place or space at the boundary of an object
- *chora:* space of localisation/separation of objects
- *apeiron:* formless or limitless space
- *kenon*: void or empty space
- *chaos:* unstructured space…

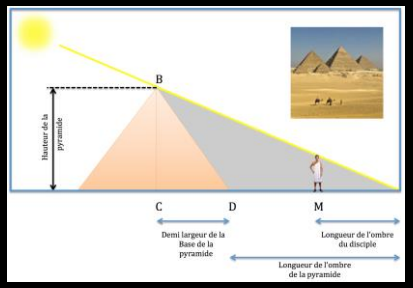
and equally many words to denote time:

- *chronos, aion, kairos…*

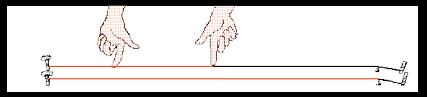
The history of myth, art, science and philosophy has visited these notions again and again shifting the attention from one to the other.

Beginnings for the exploration of space and time :

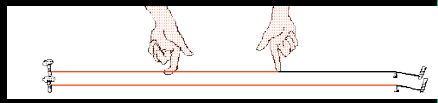
- **Space: Light/Shadow** Thales measuring the height of the pyramid using a stick or "gnomon" (a time instrument)
  - Uses an "instrument" the gnomon to measure the inaccessible by means of the accessible. Same method used later for earth radius by Eratosthenes, and also distances of Moon, Star and the Stars.
  - Supposes the invariance of form inside space (similarity triangles) ➔ Geometrical ratio
  - Shadow also at the mythical beginning of Art (Pliny and the daughter of Boutades)



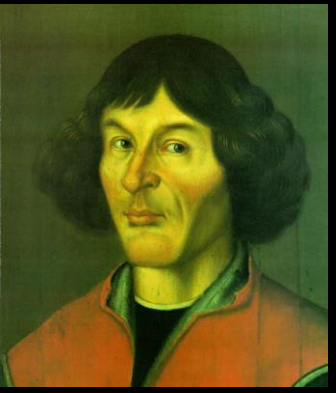
- **Time: Harmony/Disharmony** Pythagoras passing outside a "forger's house and realising that the harmonic sounds are a matter of harmonic ratios: octave (1/2), quinte (2/3) etc..
  - Every periodic movement emits a sound therefore the periodic movement of the planets emits ➔ *Celestial harmony*
  - Our souls are pleased harmony, ➔ Our cosmic insertion.
  - Everything is nmber ➔ arithmetic ratio



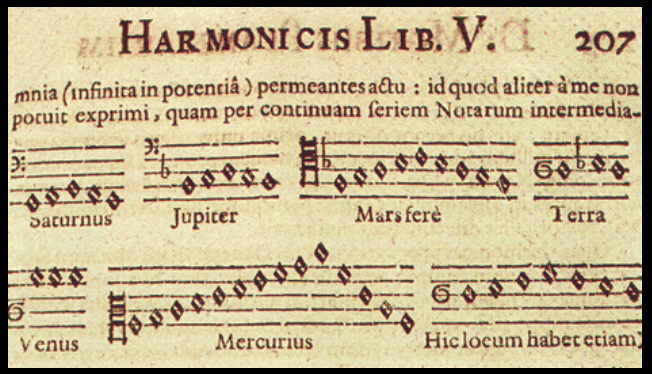
½ octave



2/3 quinte



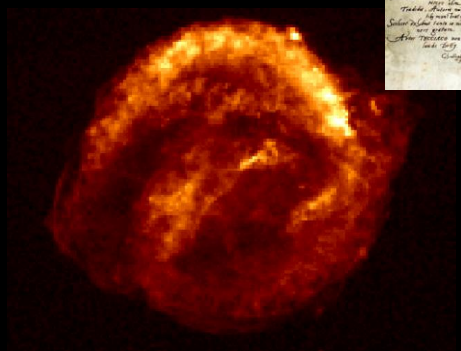
Kepler
Ellipses and violent phenomena



- Kepler in the Mysterium Cosmographicum tries to apply the theories of symmetry of both Pythagoras (harmonics) and Plato (polyhedra). By abandoning them and sticking closer to the data of Tyho Brahe he discovers the elliptical orbits

- E. Panofsky: He made the discovery because he was a Mannerist spirit and not classicist like Galileo (in *"Galileo as an art critic"*)

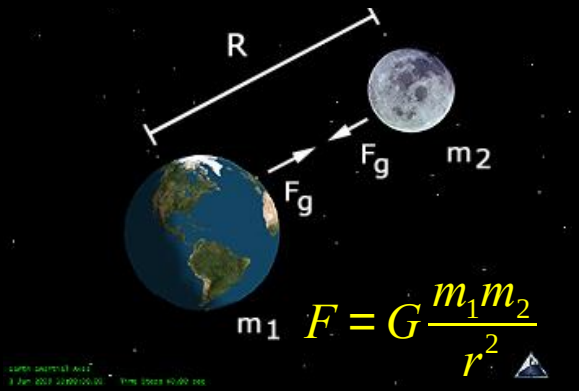
- Another discovery: the sky is not as calm as we thought: 2 supernovae appear, one of which takes Kepler's name (1604)
- The cosmos can be dissonant

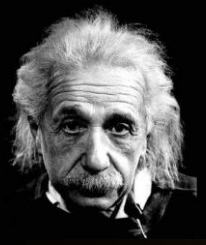


Galileo et Newton

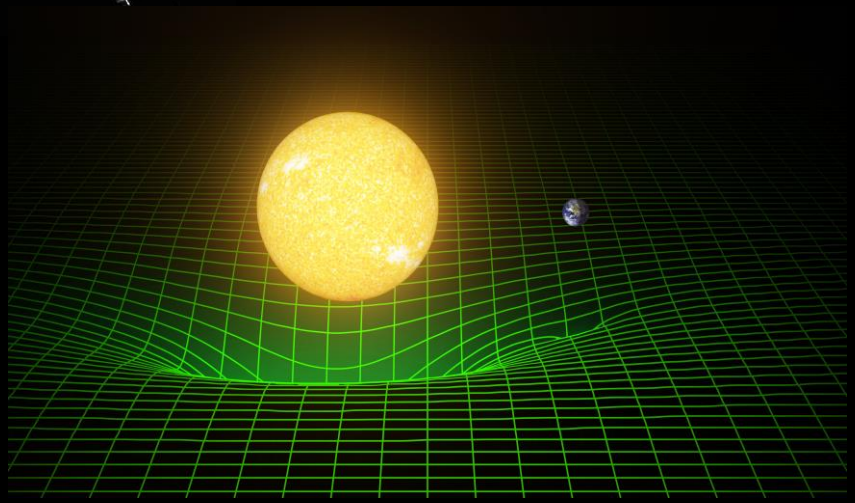
Galileo. The lunar spots are not "marbled texture" but real shadows produced by sunlight. (Influence of perspective?) . Therefore the moon is of the same substance as the earth. Unification of the two regions (sub and sur-lunary)

Newton and the universal law of gravity *"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.*





Einstein's Theory of Gravity 1915



Space-Time is a deformable medium. Mass and Energy deform space-time around them and inversely they follow the deformed paths inside it.

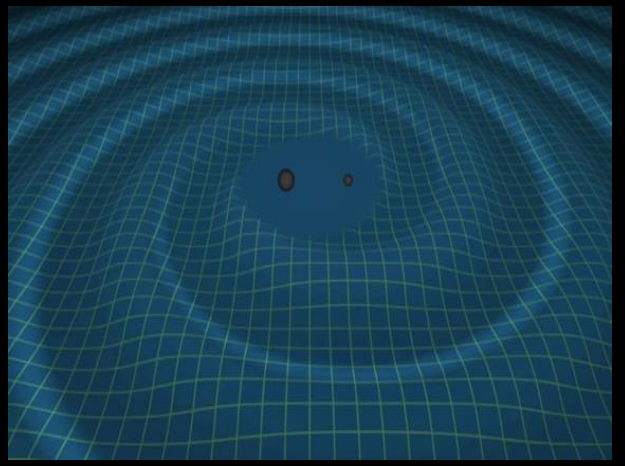
Papers predicting gravitational waves 1916-1918 !

Only extremely violent phenomena can produce detectable GW

BBH of 30 $M_\odot$, 500Mpc

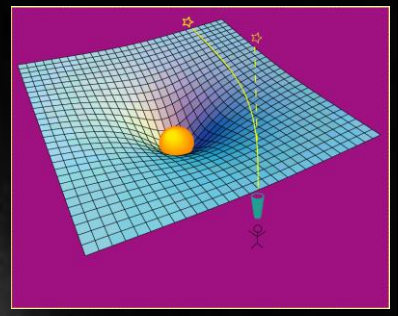
$$h = \Delta L / L \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \quad \Rightarrow \quad h \sim 10^{-21}$$

ΔL by 1/1000 of a proton radius in a distance L of 1 km



Mass « lenses » light . The shadow of gravity.

6 November 1919
Eddington-Dyson announce the results of the solar eclipse confirming Einstein



LIGHTS ALL ASKEW IN THE HEAVENS

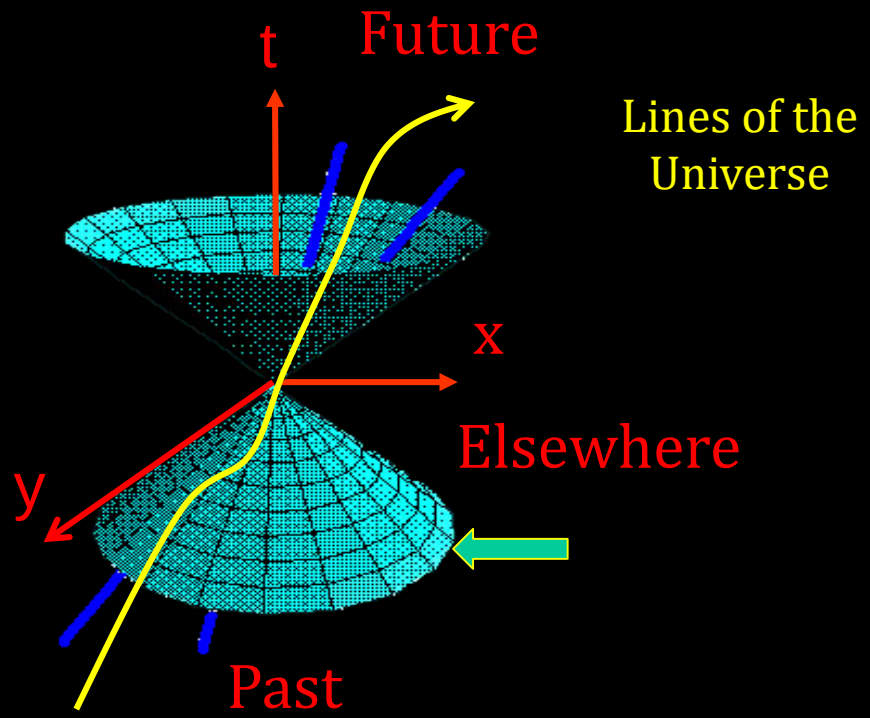
Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

Einstein: Unification of space-time

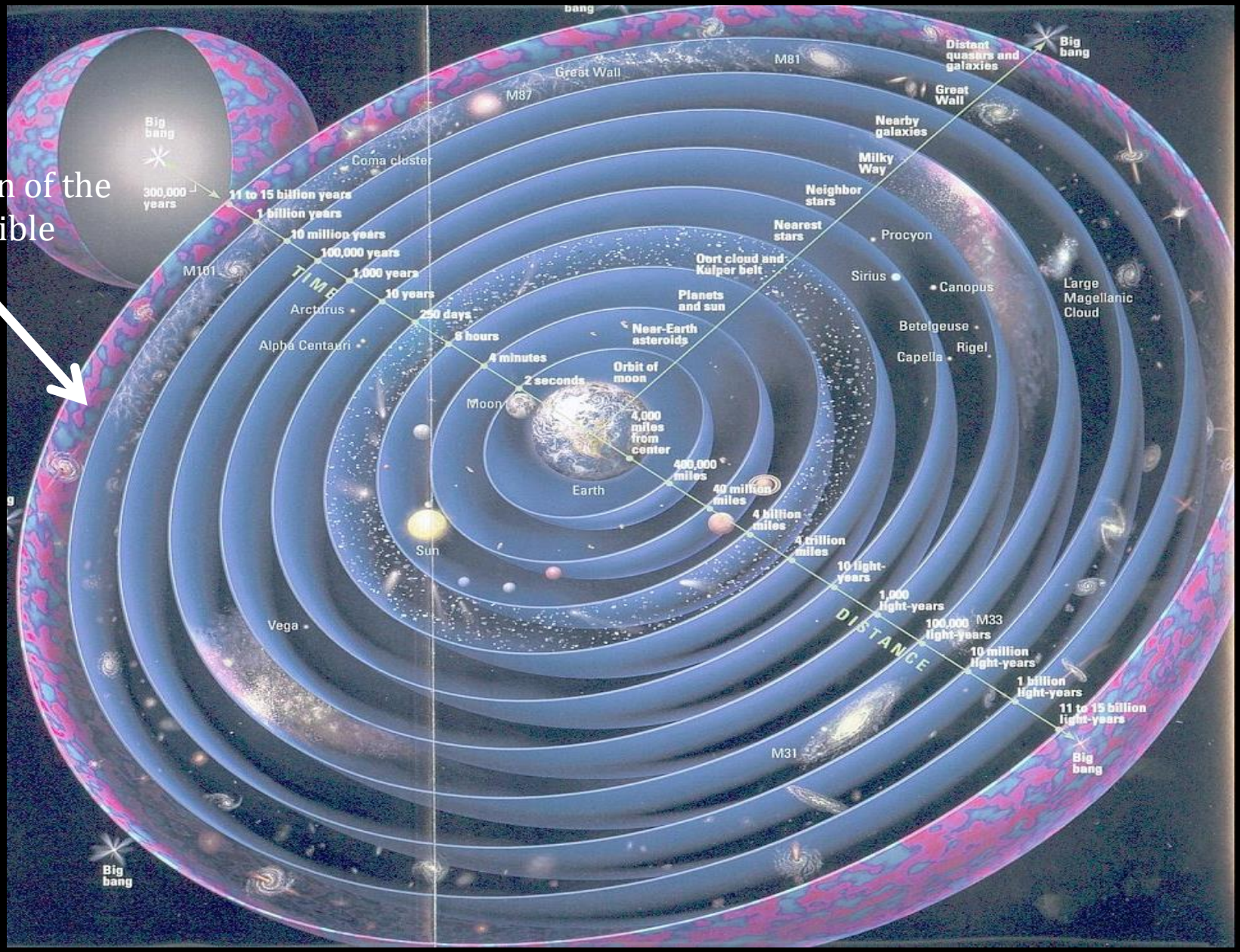
. « *Henceforth, space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality* » *Minkowski*



A strange clepsydra

The Horizon of the past
The horizon of an electromagnetic plasma (the recombination wall)

Horizon of the e.m visible



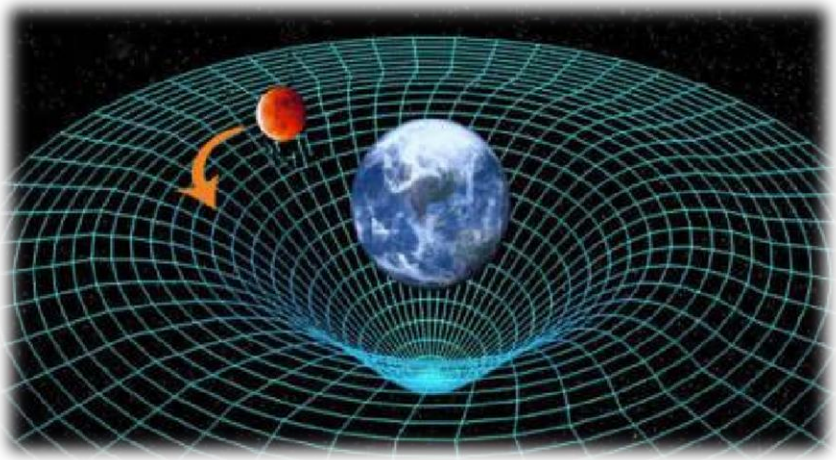
The «Revolution» in Gravitation

Einstein's fields equations

$$G_{\mu\nu}(g) = 8\pi T_{\mu\nu}$$

GEOMETRY

MASS-ENERGY DISTRIBUTION

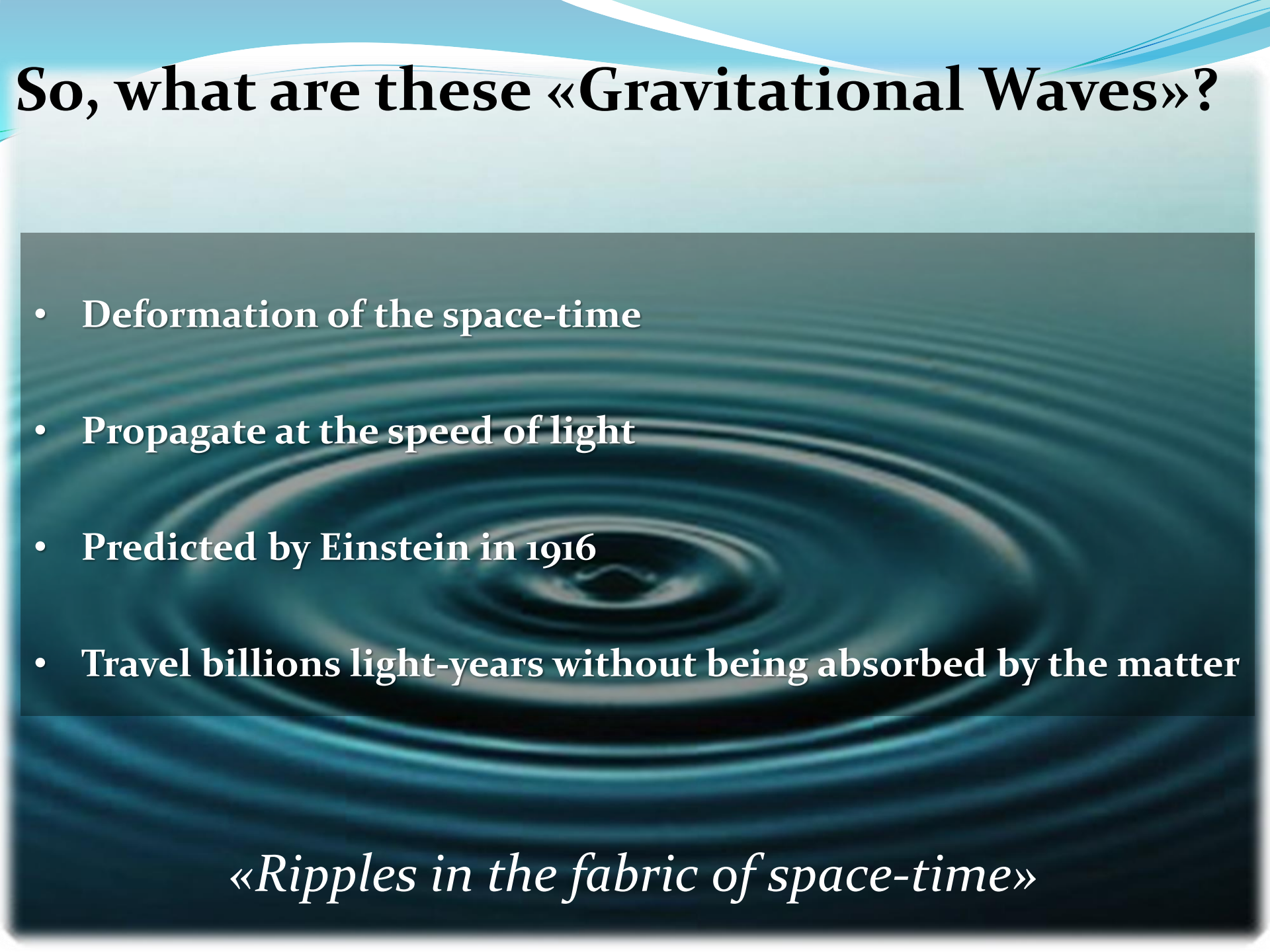


"Matter tells spacetime how to curve, spacetime tells matter how to move."

John A. Wheeler

So, what are these «Gravitational Waves»?

- Deformation of the space-time
- Propagate at the speed of light
- Predicted by Einstein in 1916
- Travel billions light-years without being absorbed by the matter



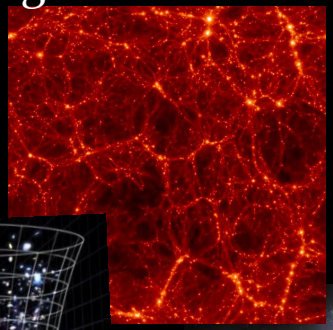
«Ripples in the fabric of space-time»

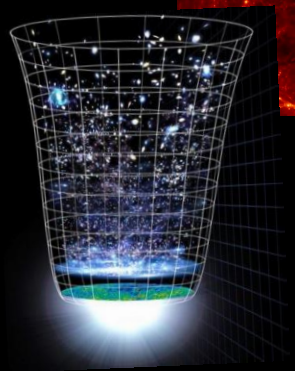
Gravitational Waves sources

All accelerated non-symmetrical masses produce Gravitational Waves…

…but only astrophysical sources can produce detectable effects!

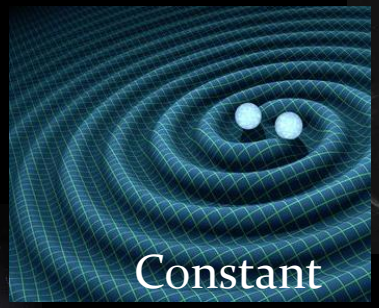
Universe's Dark Matter
Large Scale Structure





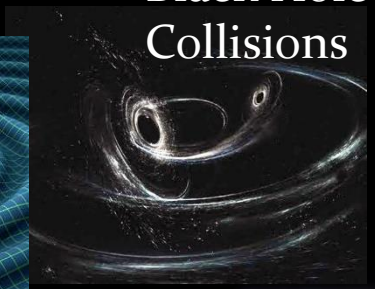
The Big Bang and
the Entire Universe

Galaxy
Collisions

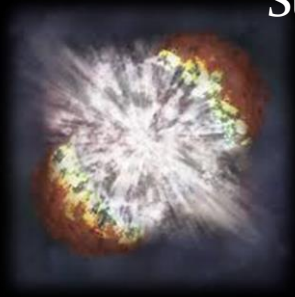


Constant
"Noise" of GWs
from Binaries

Black Hole
Collisions

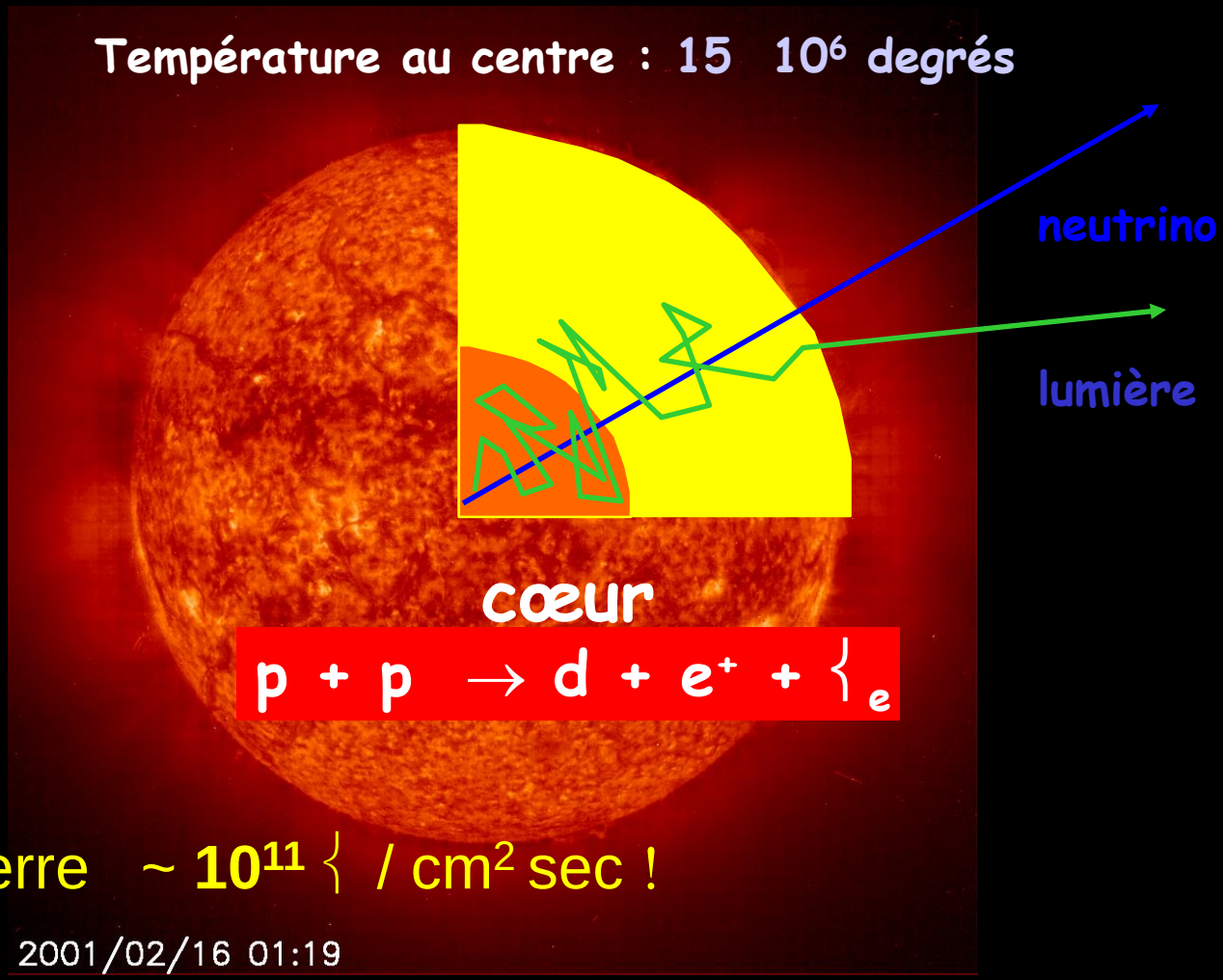


Supernovae



Neutron Star
Collisions

Le soleil équilibre entre gravitation et fusion



Sur la Terre ~ **10^{11}** ν / cm^2 sec !

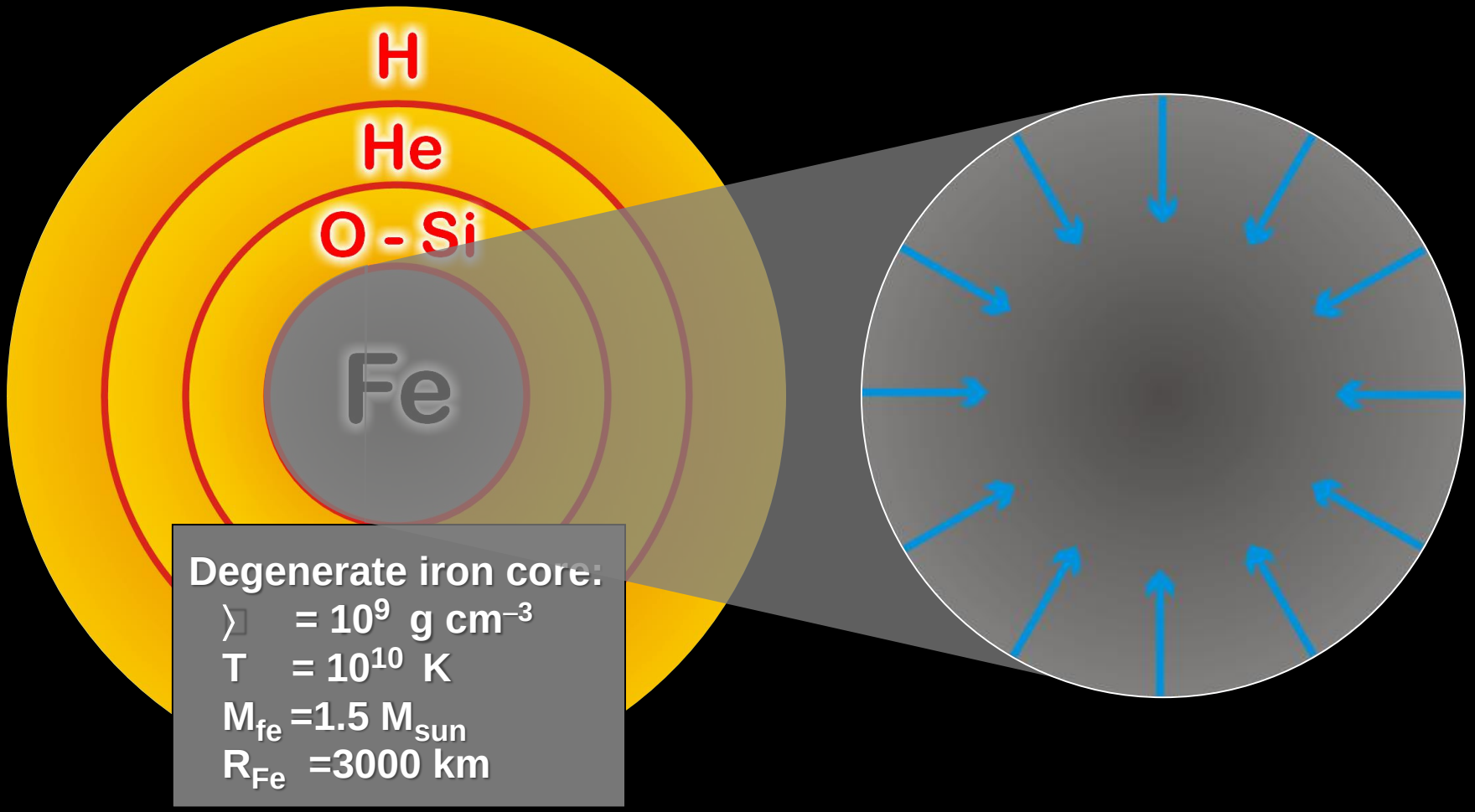
Λα τερρε ετ λεσ χορπσ χοσμιθυεσ θυασι–τρανσπαρεντσ αυξ νευτρινοσ

Evolution et fin de vie d'une étoile: Supernova

Explosion

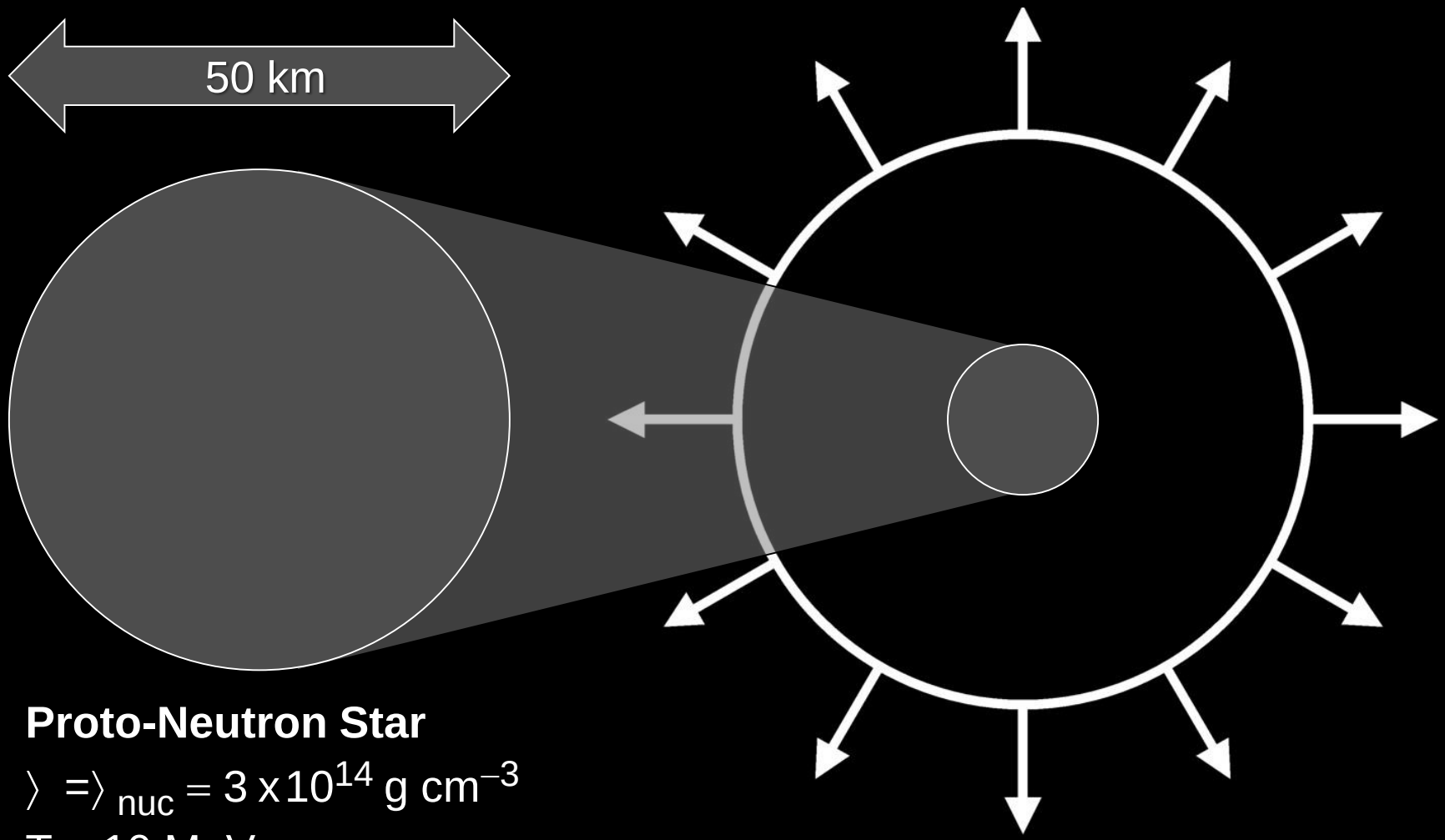
structure onion

Collapse (implosion)



Newborn Neutron Star

Explosion

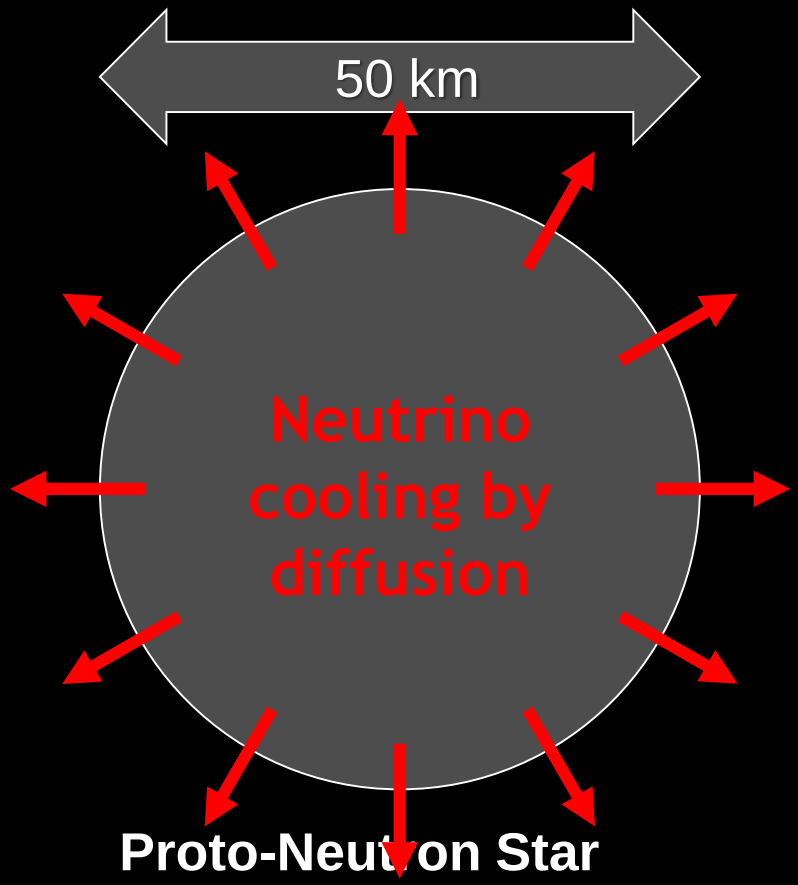


Proto-Neutron Star

$\rho = \rho_{nuc} = 3 \times 10^{14}$ g cm^{-3}

T = 10 MeV

Newborn Neutron Star



$\rangle = \rangle_{nuc} = 3 \times 10^{14}$ g cm^{-3}

T =10 MeV

Gravitational binding energy

$E_b = 3 \times 10^{53}$ erg $= 17\% \, M_{SUN} \, c^2$

This shows up as

99%	Neutrinos
1%	Kinetic energy of explosion
0.01%	Photons, outshine host galaxy

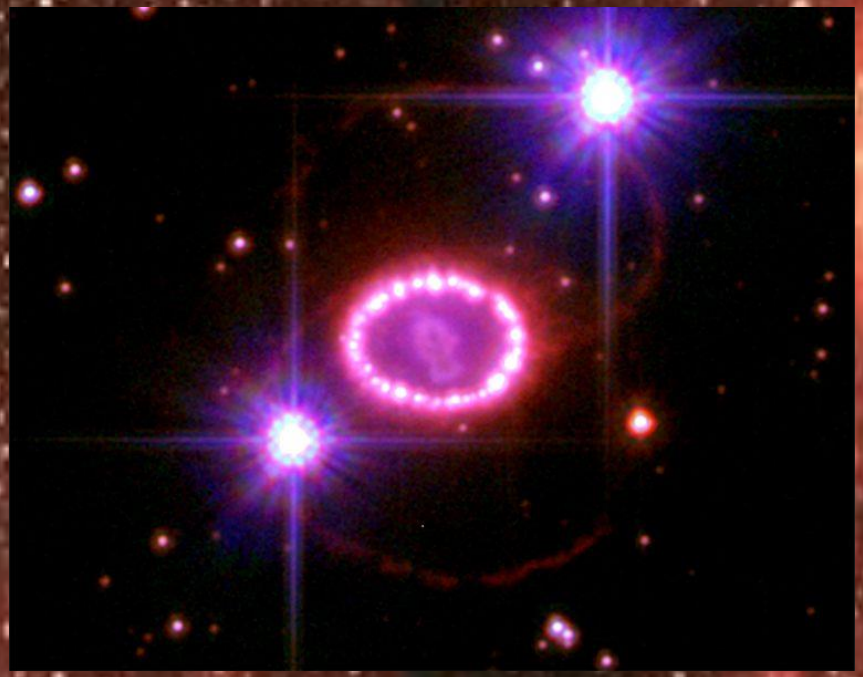
Neutrino luminosity

$L_\nu \quad 3 = 10^{53}$ erg / 3 sec

$3 = 10^{19} \, L_{SUN}$

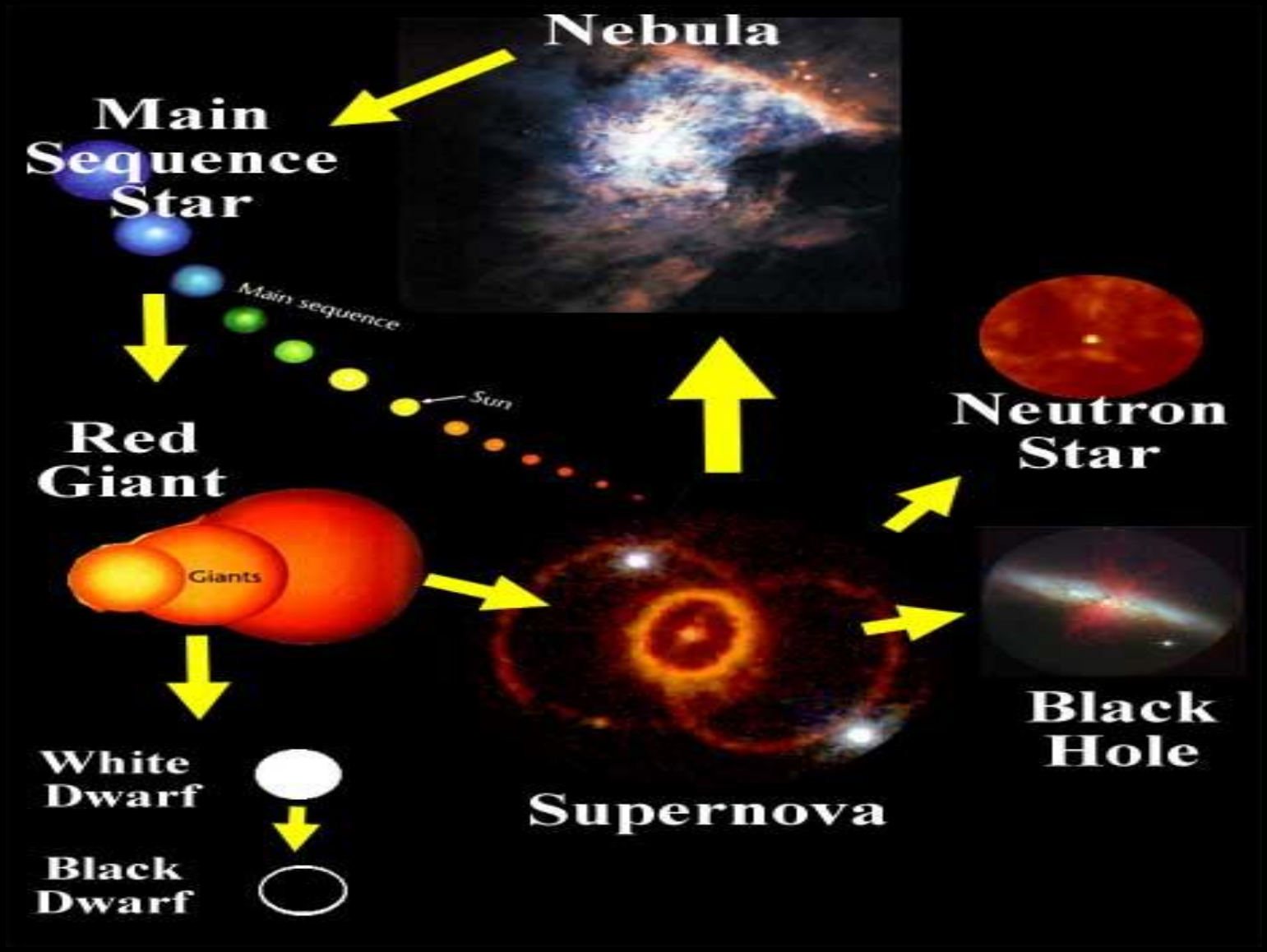
While it lasts, outshines the entire visible universe

Un supernova qui a induit changement des mentalités 1987A



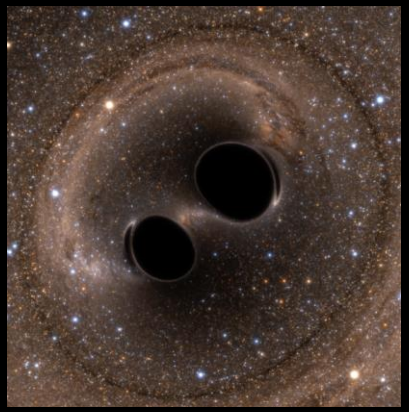
La détection de 1987A en neutrinos
Naissance de l'Astroparticule. Nobel Koshiba

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



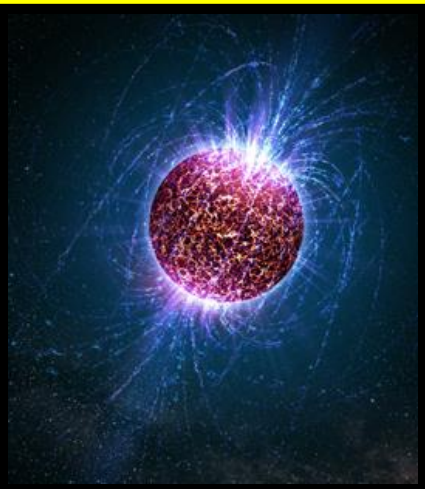
The Astrophysical Gravitational-Wave Source Catalog

Short➔ long



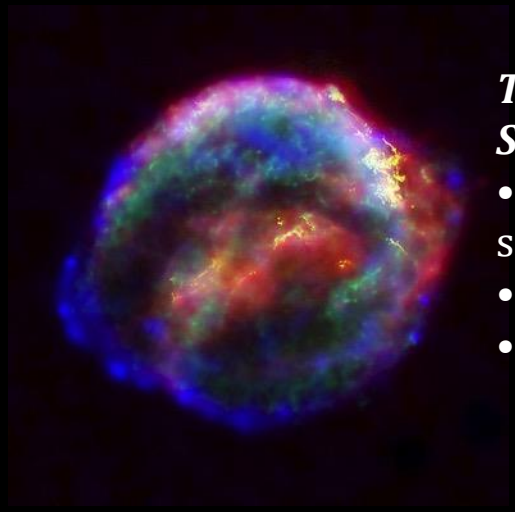
Coalescing Binary Systems CBC

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



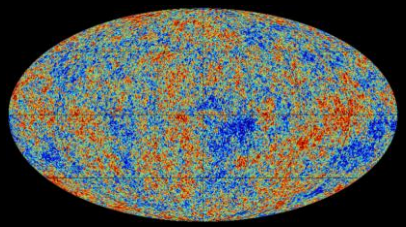
Continuous Sources

- • Spinning neutron stars
- • Monotone waveform



Transient 'Burst' Sources

- • core collapse supernovae
- • cosmic strings
- • unmodeled waveform



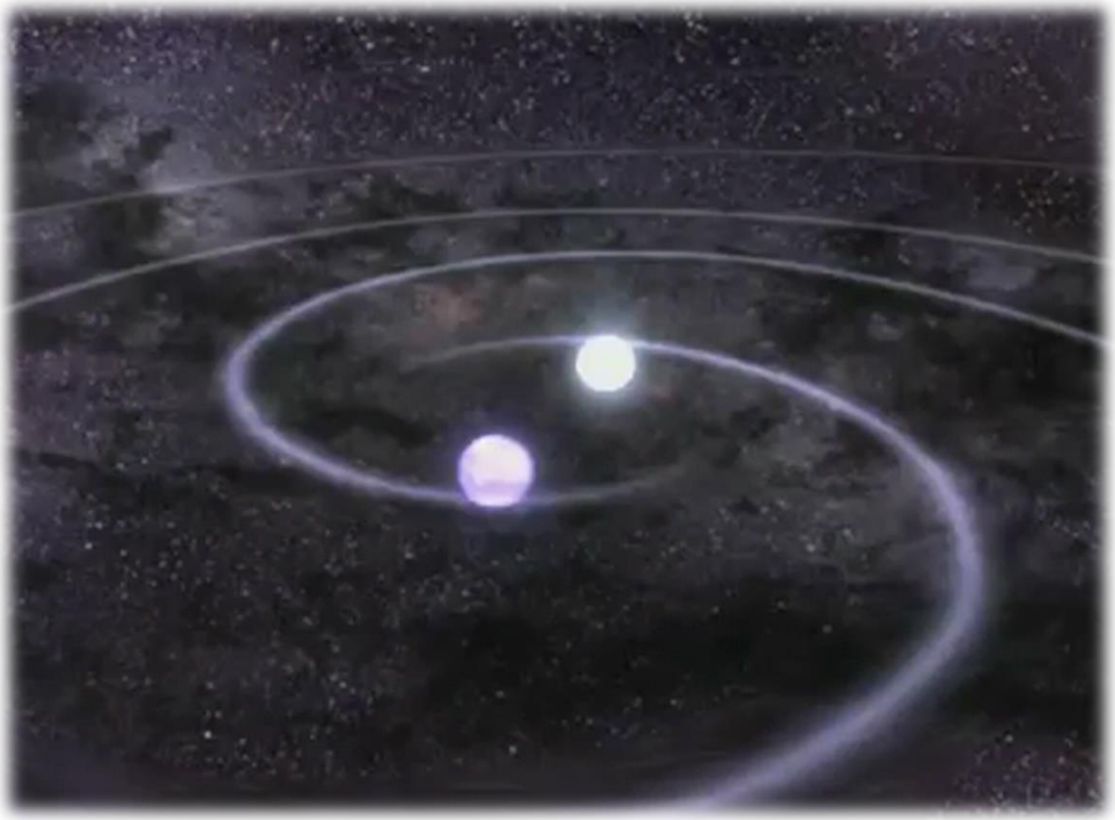
Cosmic GW Background

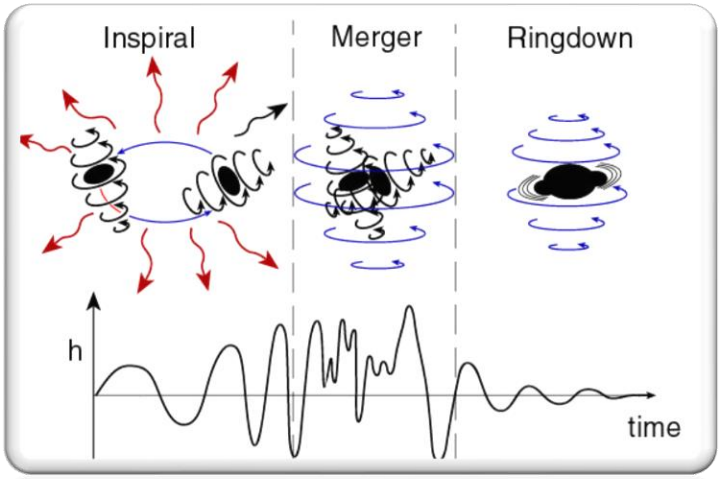
- • Residue of the Big Bang,
- • Stochastic, incoherent background

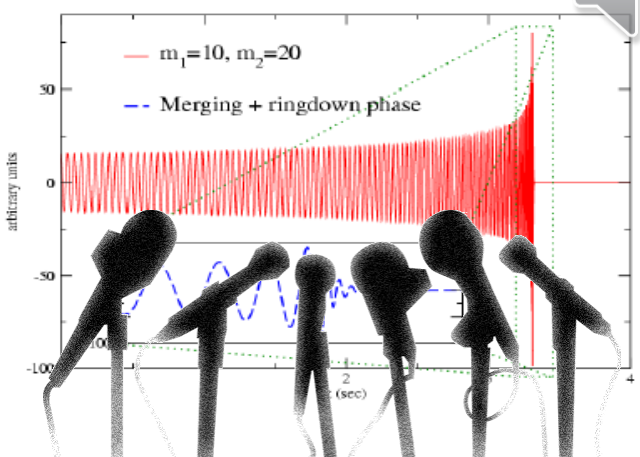
Known ➔ unknown form

Transient Burst and Continuous sources the next goal!

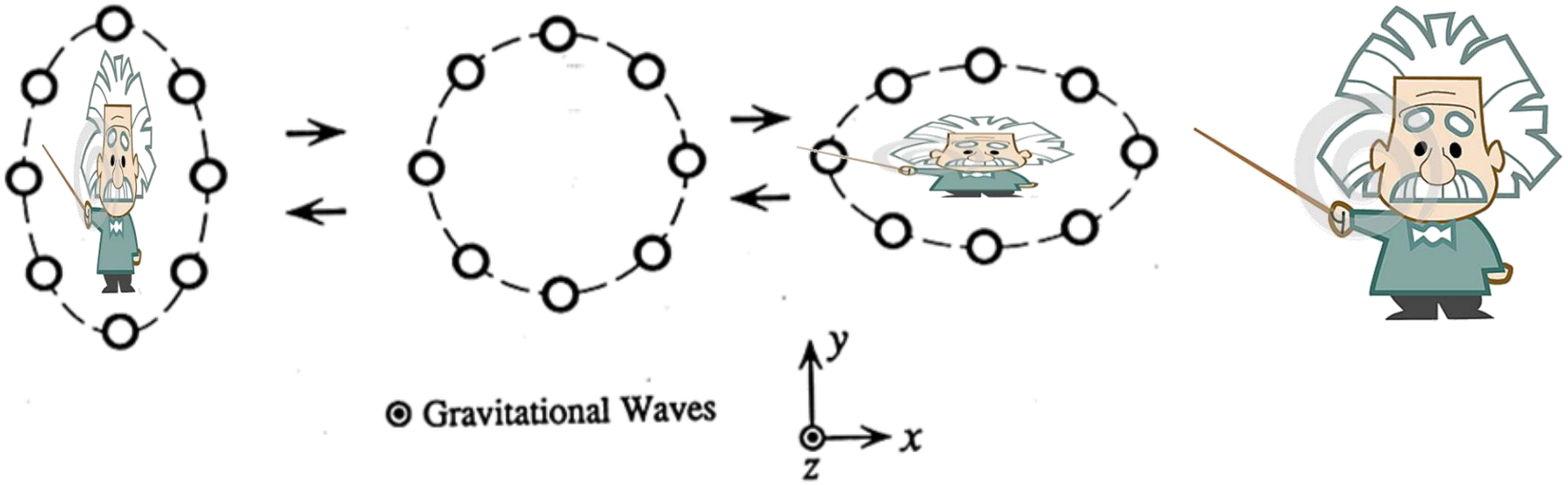
An example: coalescing binaries



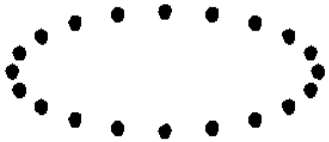


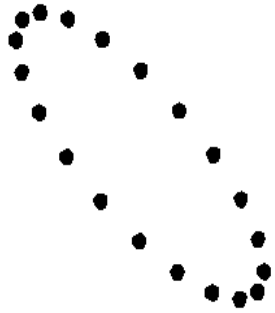


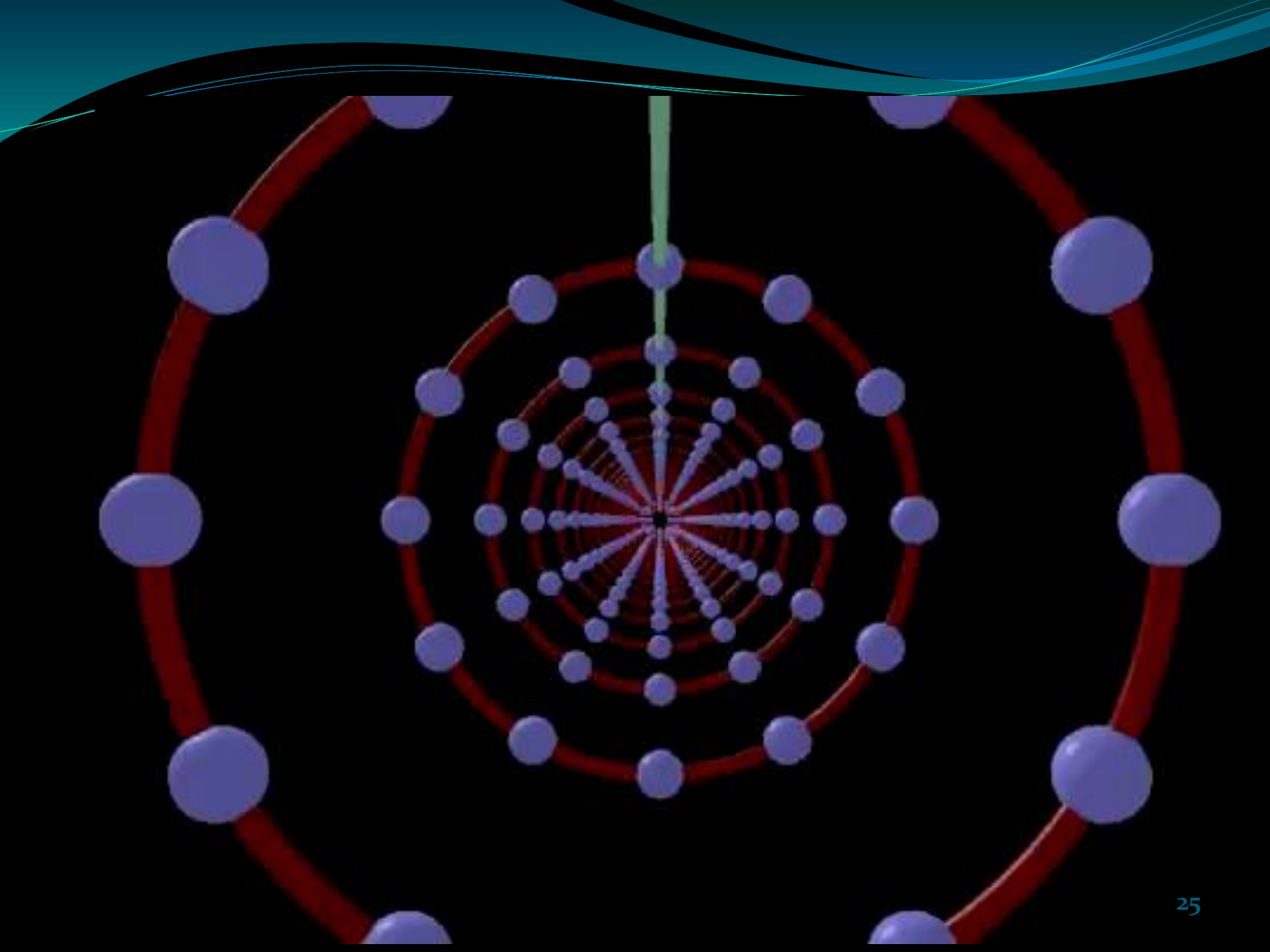
Gravitational Waves effect on the matter



+ polarization	polarization



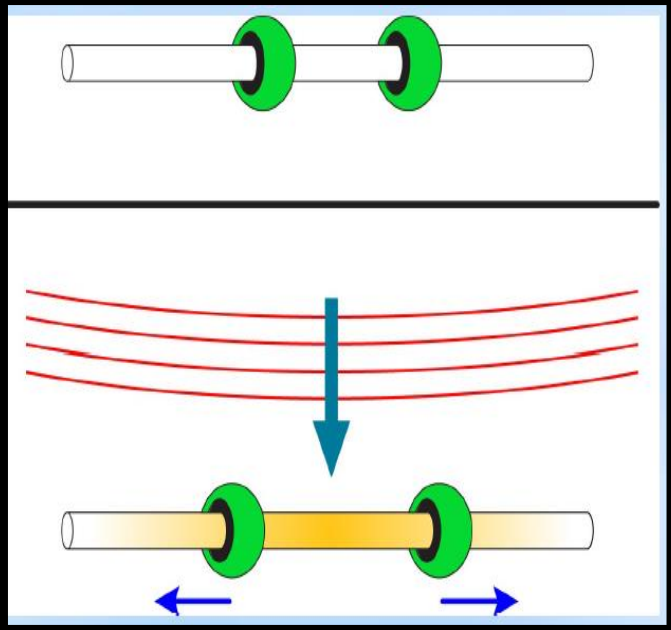




Gravitational Waves detection

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.

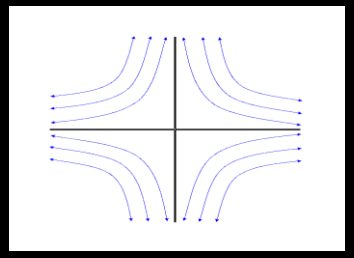


In January 1957, the U.S. Air Force sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1.

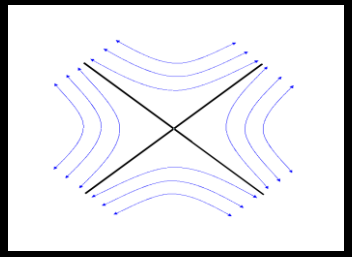
The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born. (Pirani, Feynman and Babson)

Sticky bead argument (Feynman)

h_+

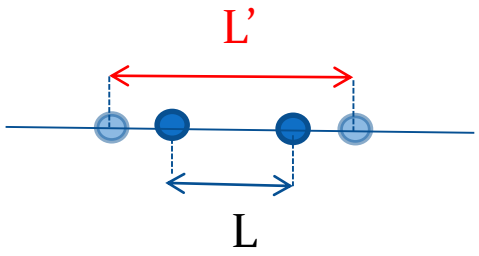


h_x



The effect of Gravitational Waves on free falling masses

Induced variation



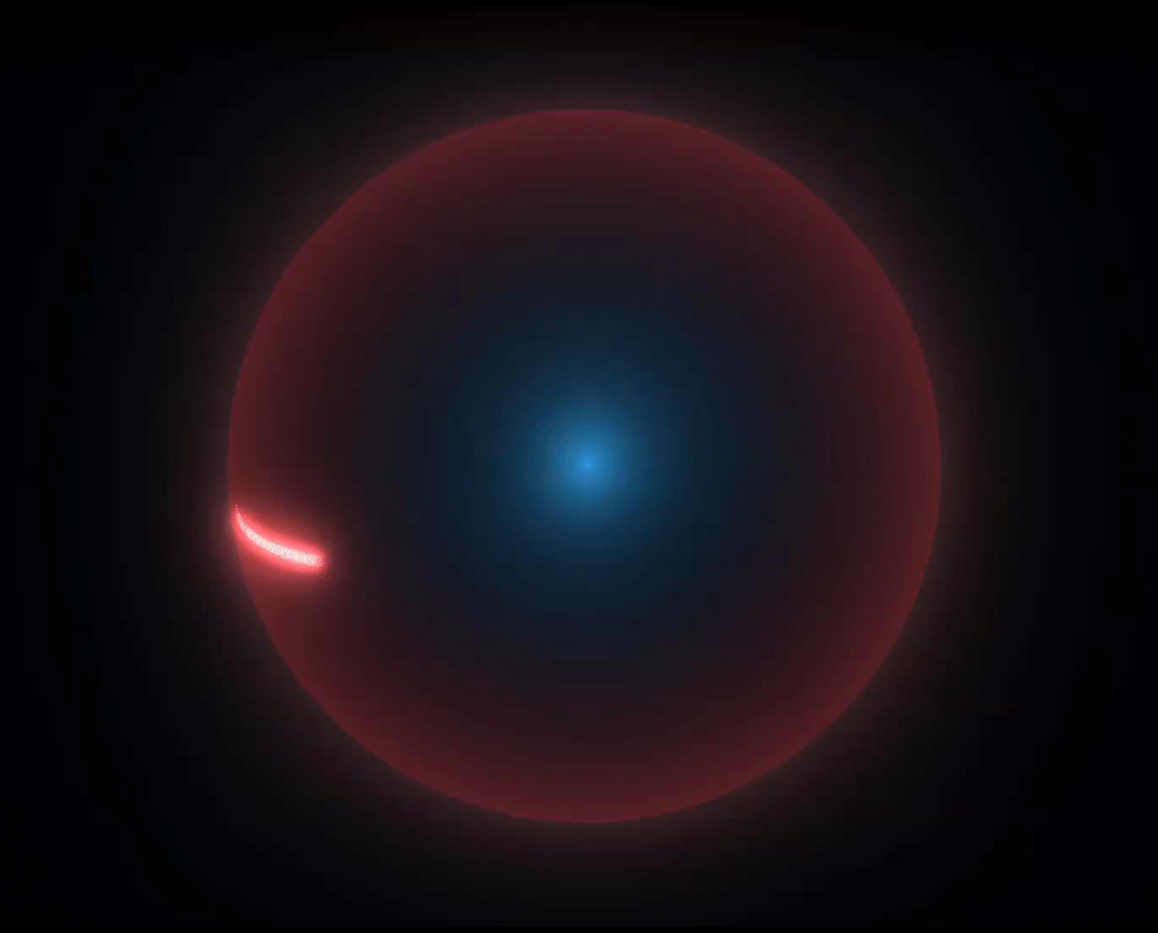
Gravitational wave coming perpendicularly to the screen

Very weak amplitude:

The distance between two masses separated by ~km will change by **m**

"That is comparable to a hair's-width change in the distance from the Sun to Alpha Centauri, its nearest star".

How big is the effect of a gravitational wave compared to the atomic size?



How «small» is small?

Suppose that we pour a glass of wine in the ocean

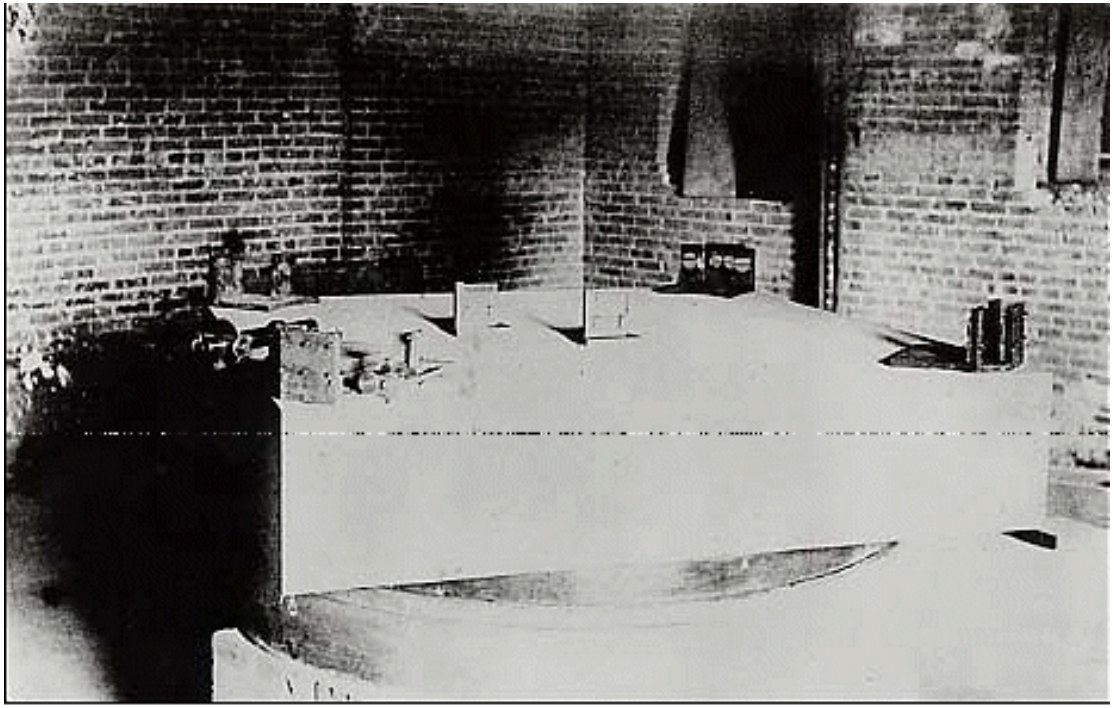
How much does the ocean level change?

That's the order of magnitude of the effect that we want to detect!

How to measure such a small effect?

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

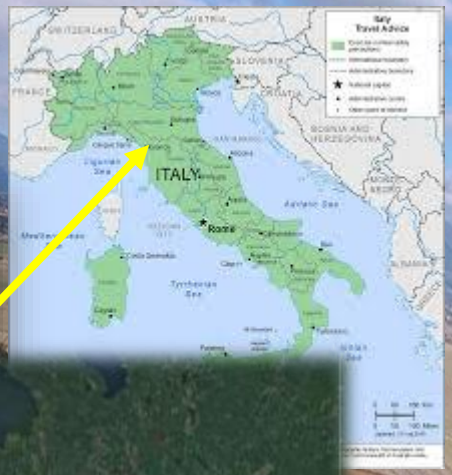
Michelson interferometer



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

The VIRGO interferometer

The VIRGO interferometer



European collaboration

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

Advanced Virgo

- Virgo is a European collaboration with about 500 members, > 30 laboratories
- Advanced Virgo (AdV): upgrade of the Virgo interferometric detector. Participation by scientists from France, Italy, Belgium, The Netherlands, Poland, Hungary, Spain, Germany

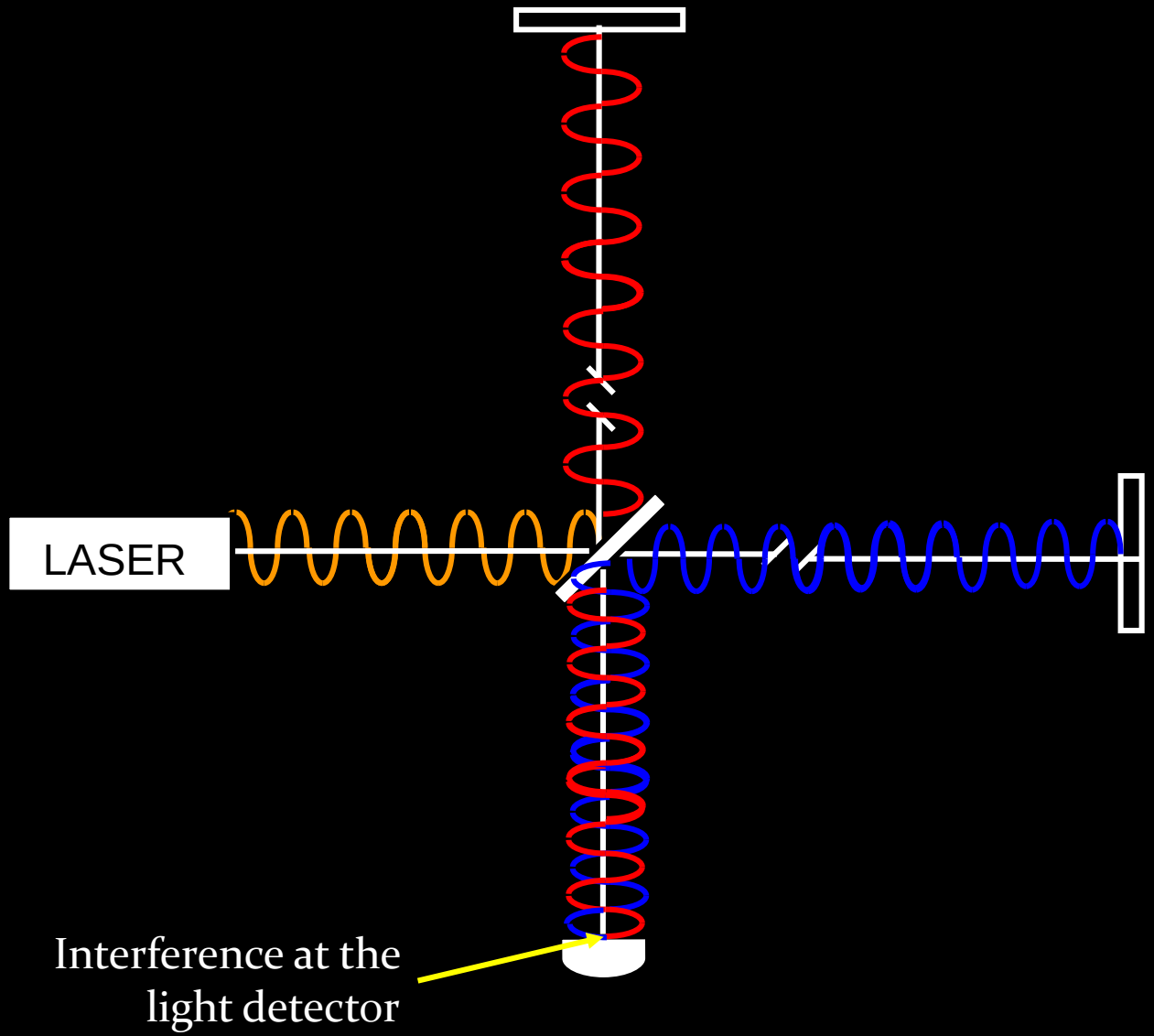
European Gravitational Observatory

(EGO – CNRS, INFN, Nikhef (obs.))

EGO is a consortium with the goal of promoting research in the field of gravitation in Europe.

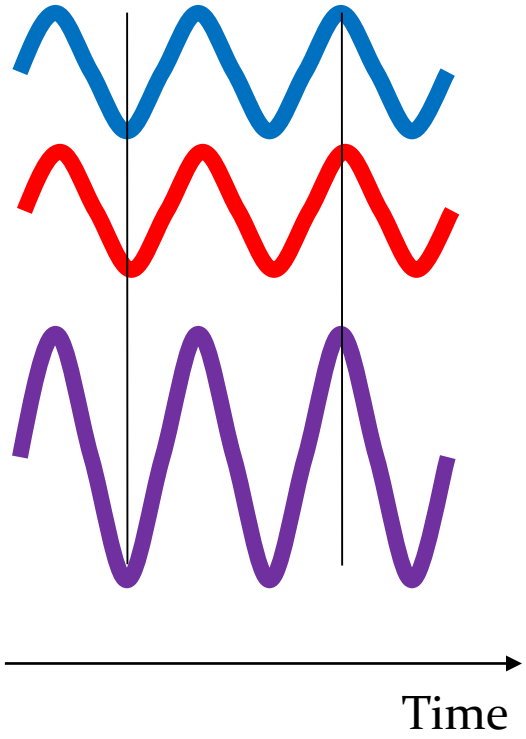
- ***Construction, maintenance, operation and upgrade of the Virgo interferometer***
- Maintenance, operation and upgrade of the site infrastructures including a computing center
- Representation of the consortium
- Promotion of interdisciplinary studies
- Promotion of R&D
- Outreach and education

Basics of interferometry



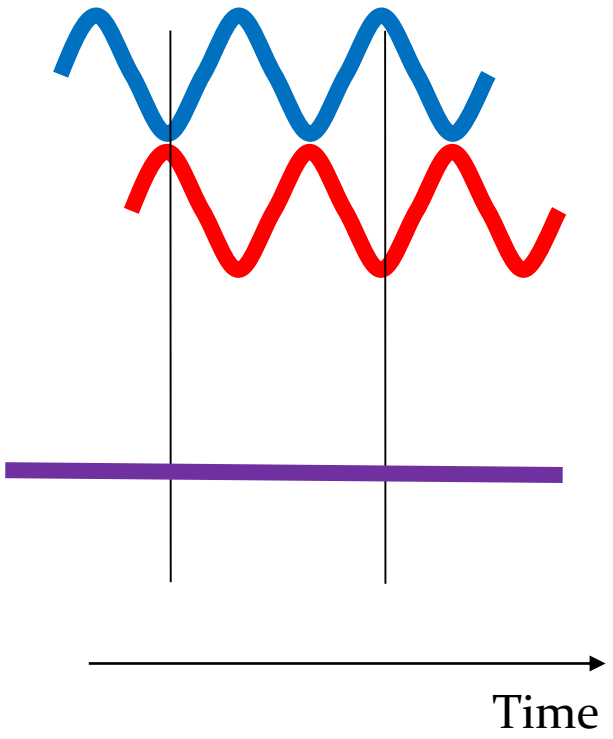
Interference

- Constructive interference



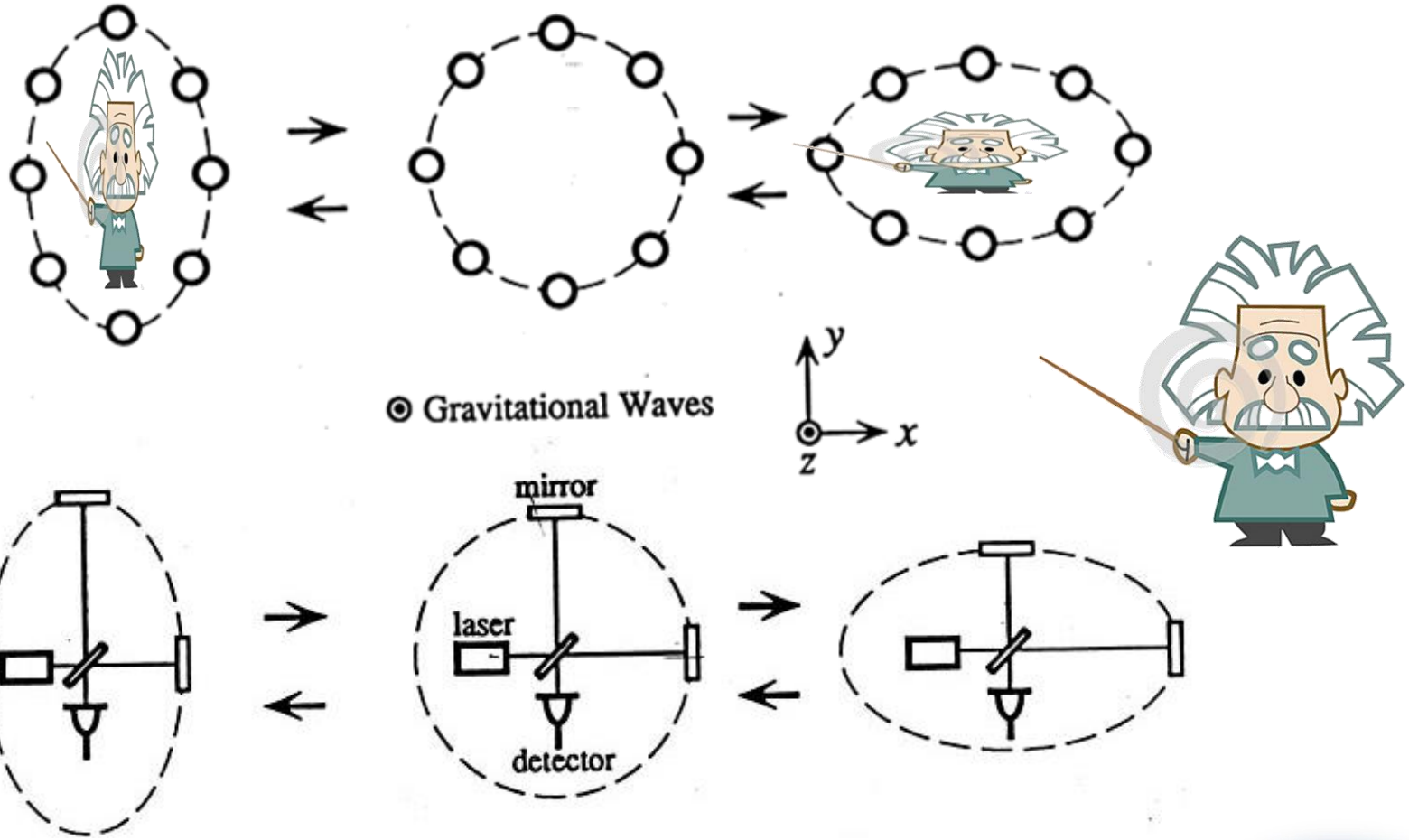
«More» light at the output detector

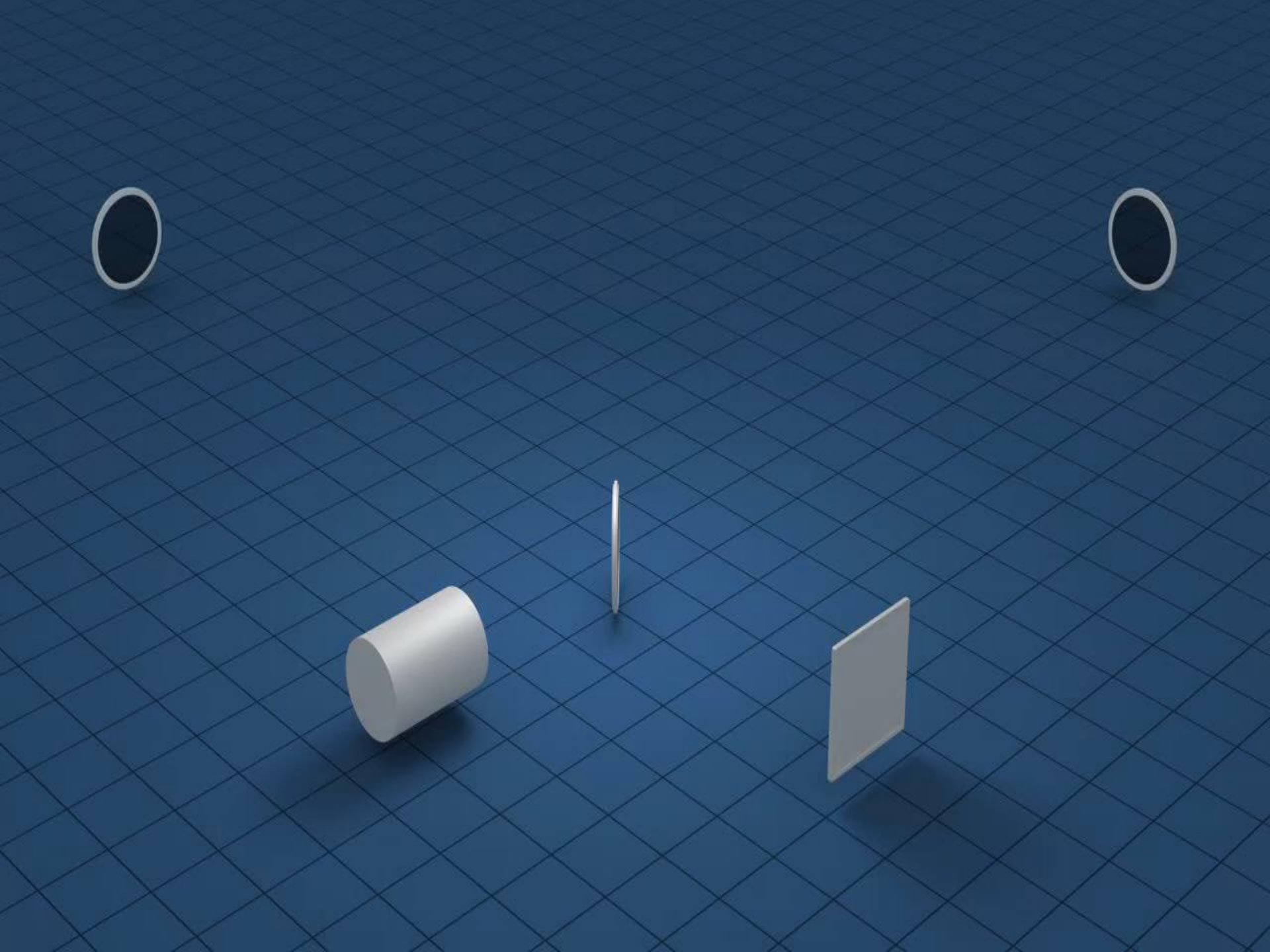
- Destructive interference



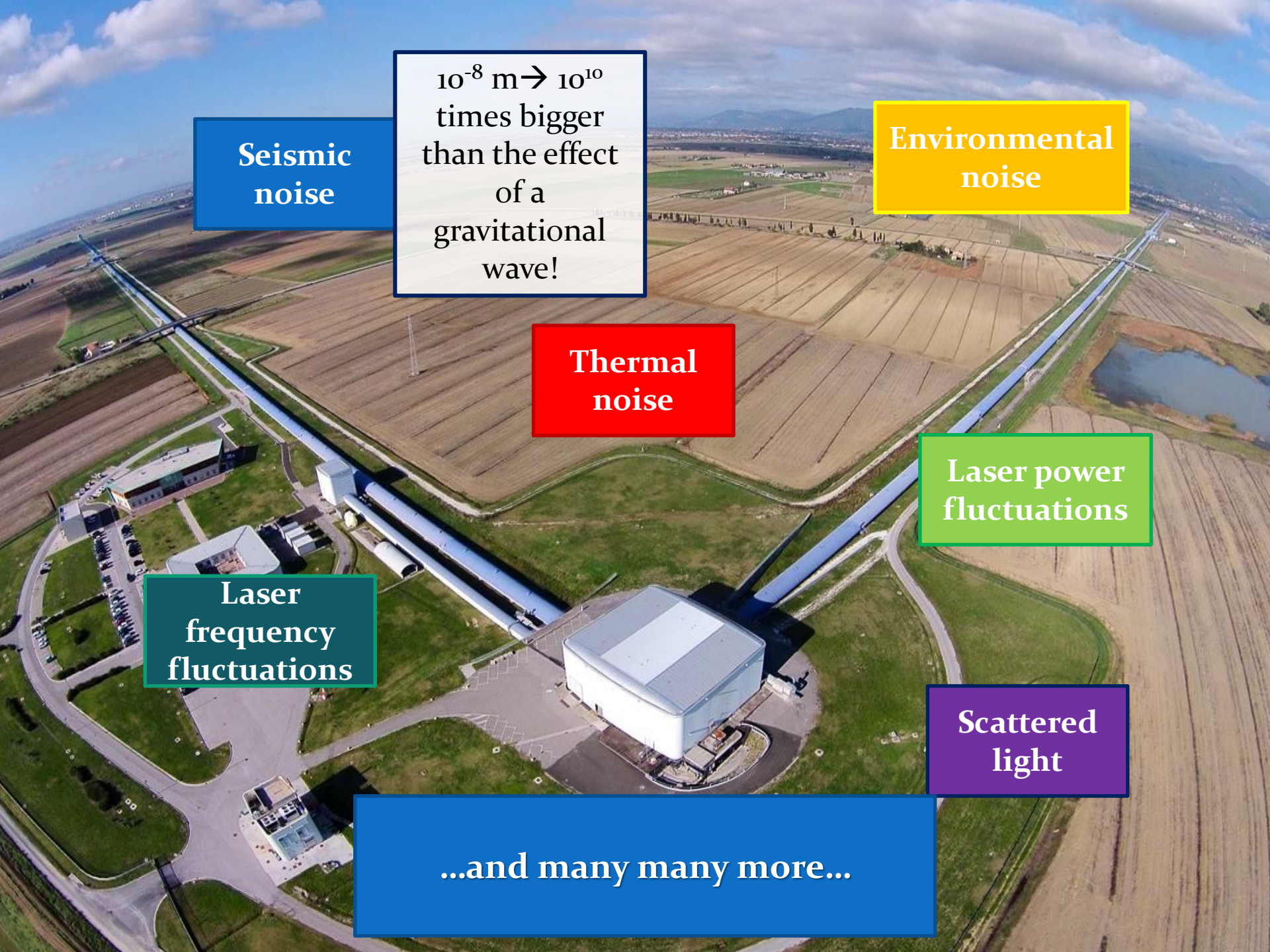
No light at the output detector (DARK)

Why do we use an interferometer?

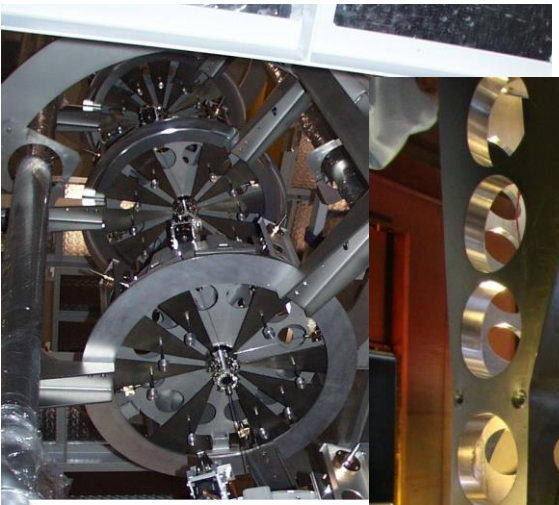


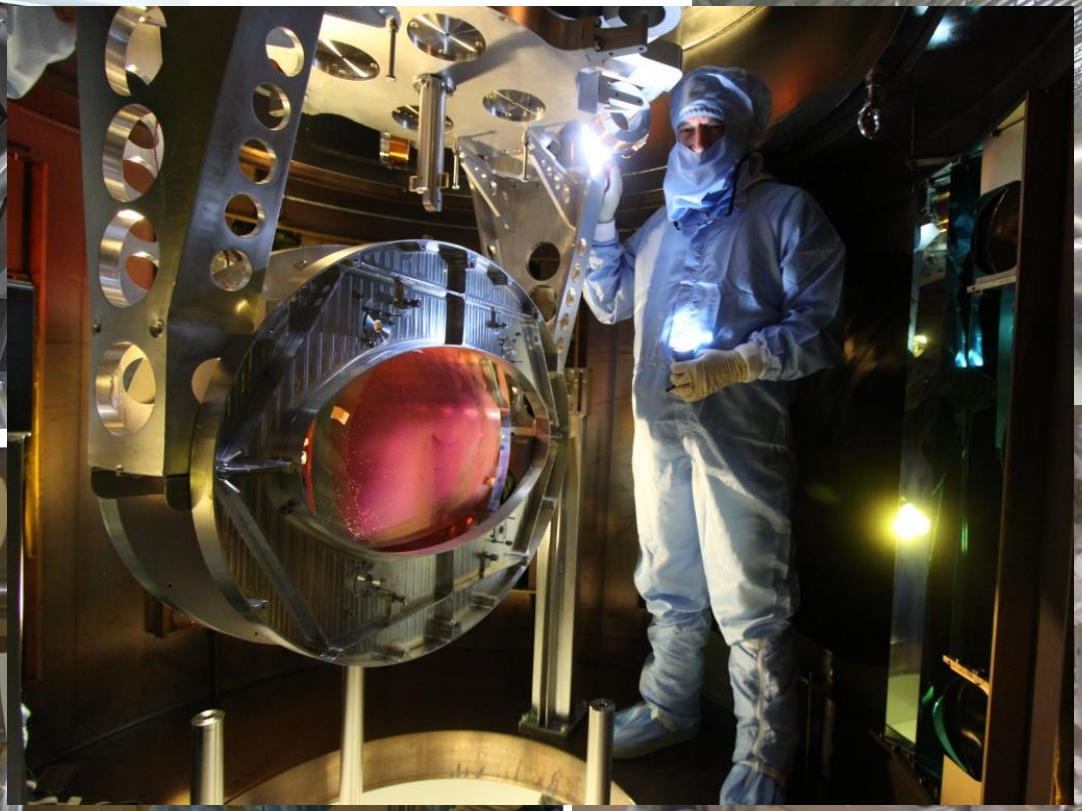


A challenge against noise

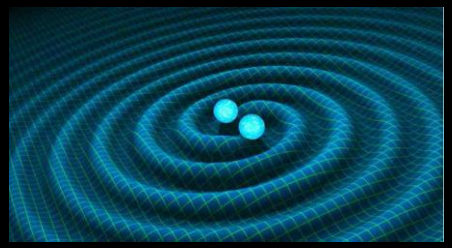

Seismic noise
10^{-8} m→ 10^{10} times bigger than the effect of a gravitational wave!
Environmental noise
Thermal noise
Laser power fluctuations
Laser frequency fluctuations
Scattered light
...and many many more...

What does a *real* interferometer look like…



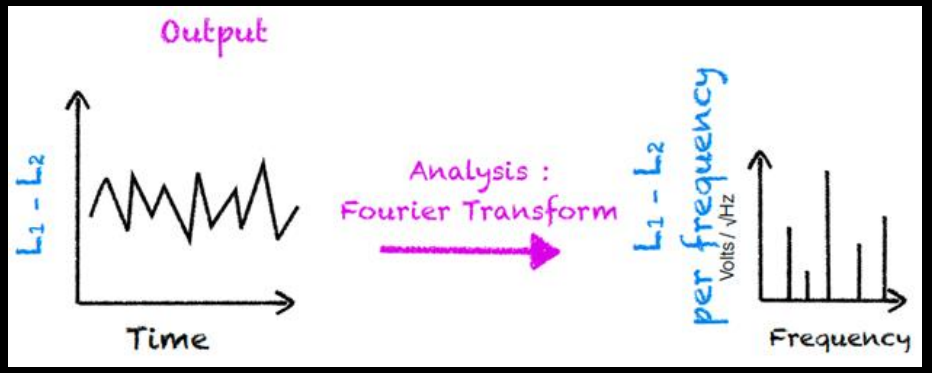


The Advanced Virgo antenna



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

The most stable « standard » meter on earth
Sensitive to space deformations of 10^{-18} m



“Satanic” Noise (A. Giazotto)

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

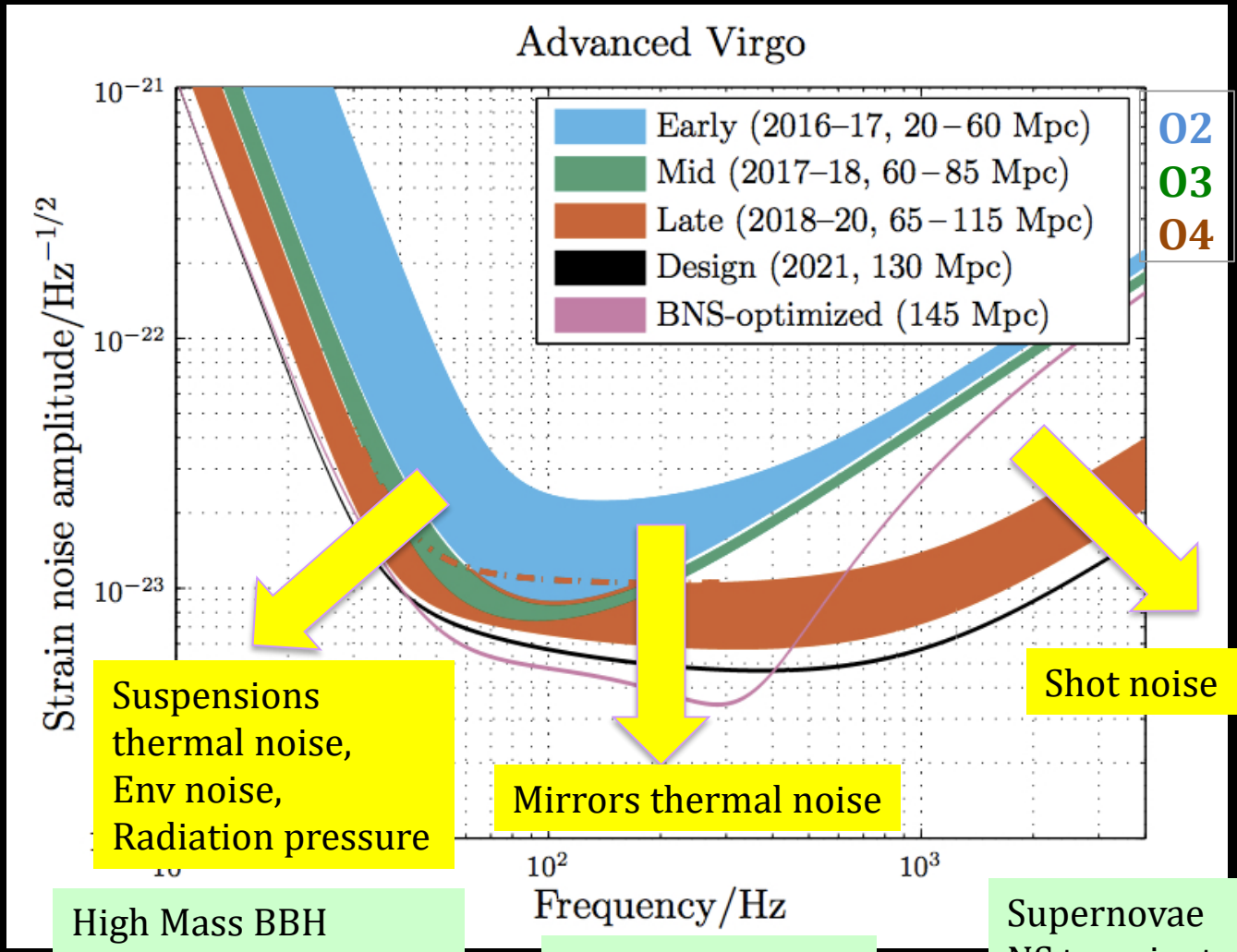
Residual gas (phase noise)

Residual laser noise

Stray-light

Seismic vibration

Newtonian noise



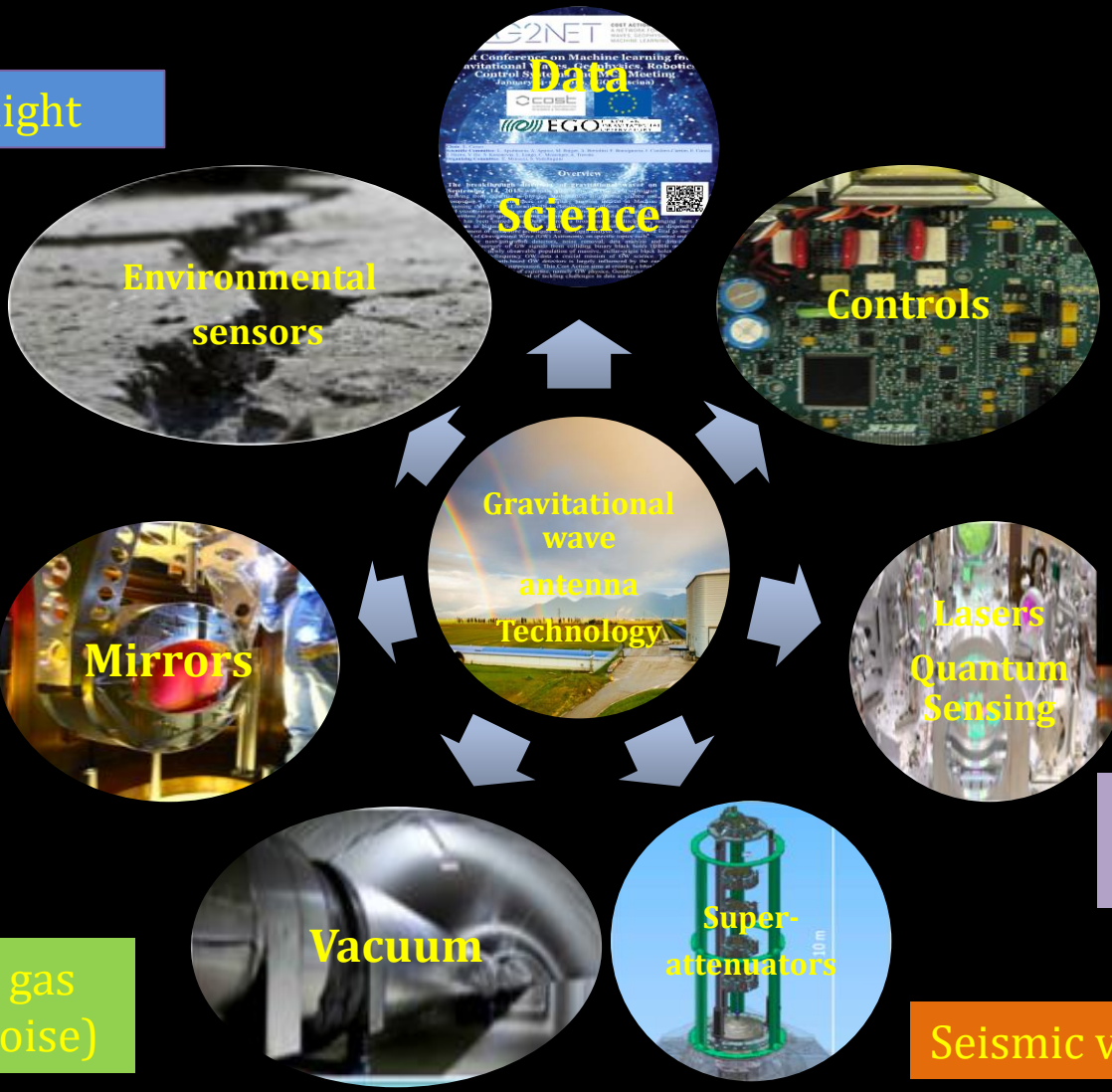
High Mass BBH
NS periodic emission

BBH mergers
BH ring down

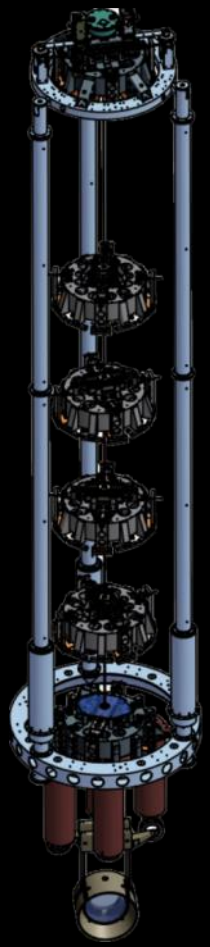
Supernovae
NS transients

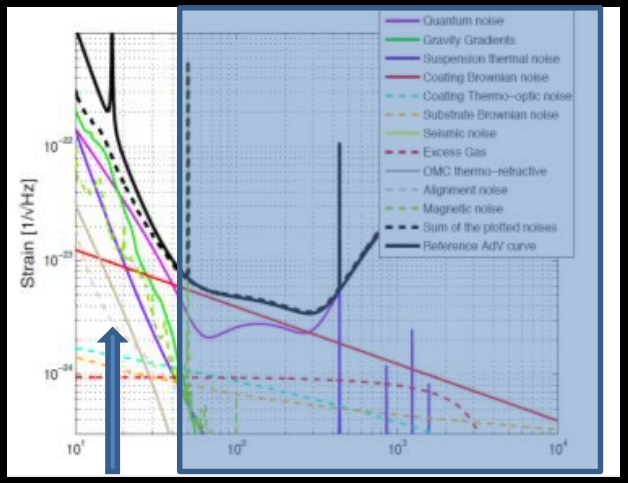
EGO/Virgo and Technology

State of the art, challenges on many fronts:



Low frequency Noise



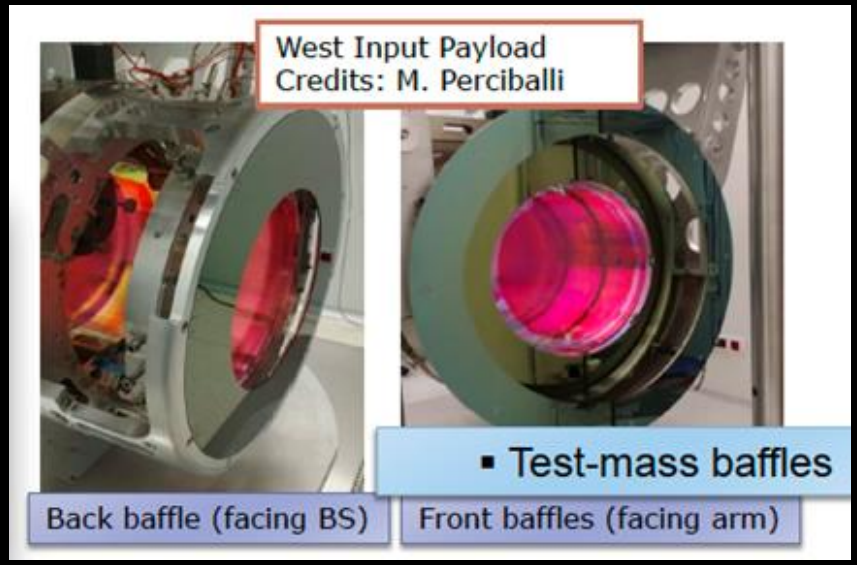


- **Seismic noise**
  - Reduced by suspending the mirrors from extreme vibration isolators (attenuation > 10^12) -> ***Superattenuator***
- Technical noises of different nature are the real challenge in this range, ex. **Stray light**

▪ A tiny amount of stray light coupling with the fundamental mode after "probing" the vibrations of infrastructures will bury any gravitational signal

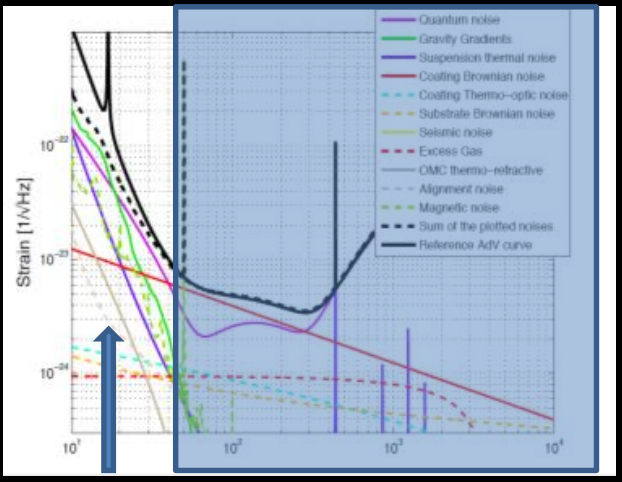
- Install ***baffles***: material that absorb photons

once emitted, a photon has to be caught!



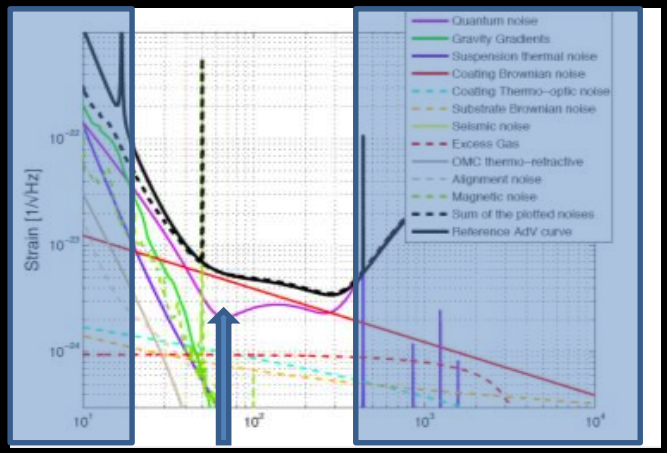
Low frequency Noise

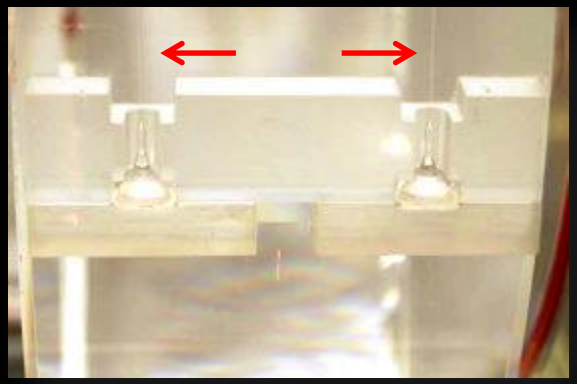
- Future: Newtonian Noise Cancellation
  - Ultimate limit for ground-based detectors: gravity gradient noise
  - It cannot be shielded -> active cancellation is needed based on sensors



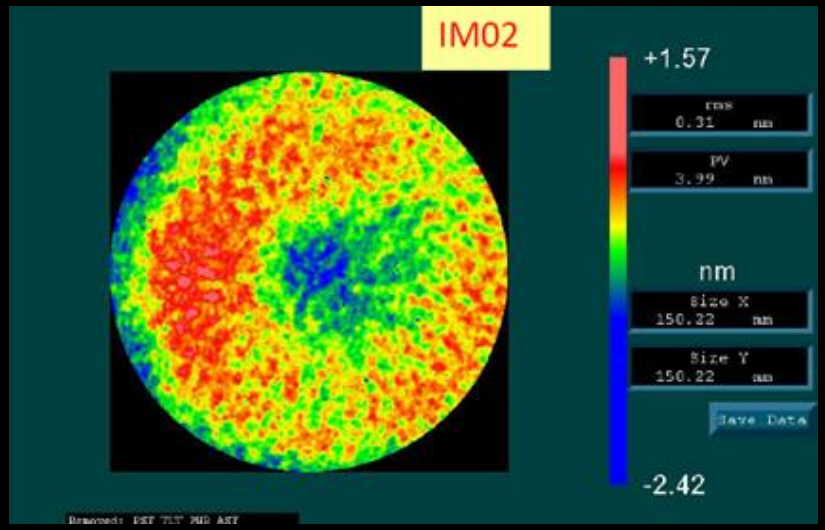
Mid frequency Noise

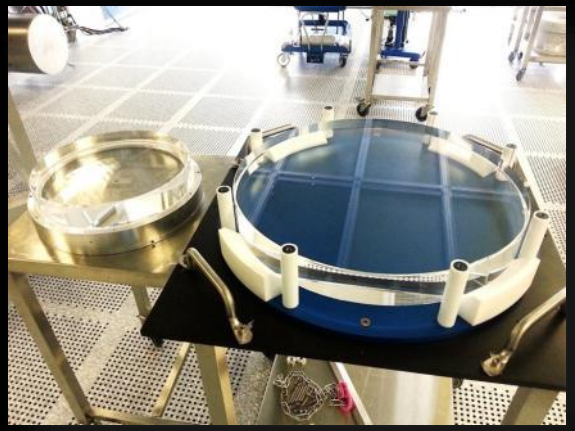
- Thermal noise
  - Coming from mirror coatings and suspensions
- Reduced by:
  - ***Larger beam spot*** (sample larger mirror surface)
  - Test masses suspended by fused silica fibers (low mechanical losses)
  - Mirror coatings engineered for low losses





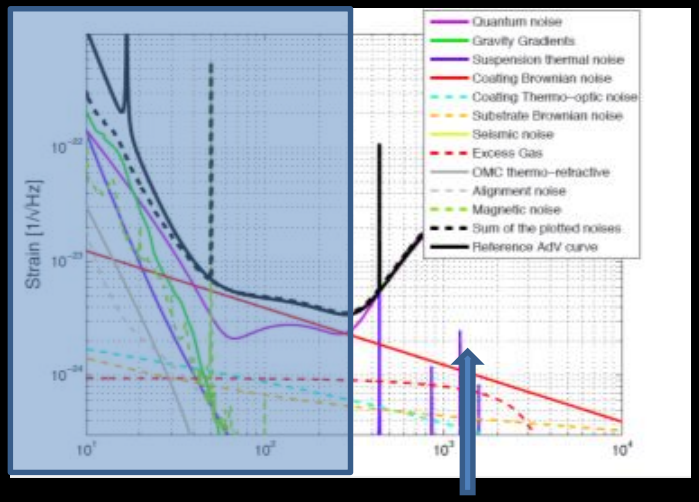
LMA is able to achieve the best coatings in the world for laser interferometry



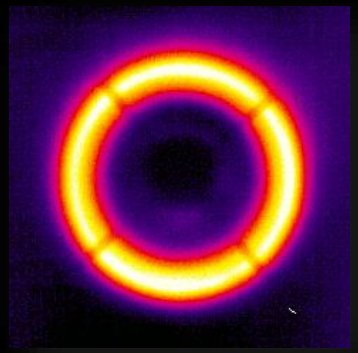


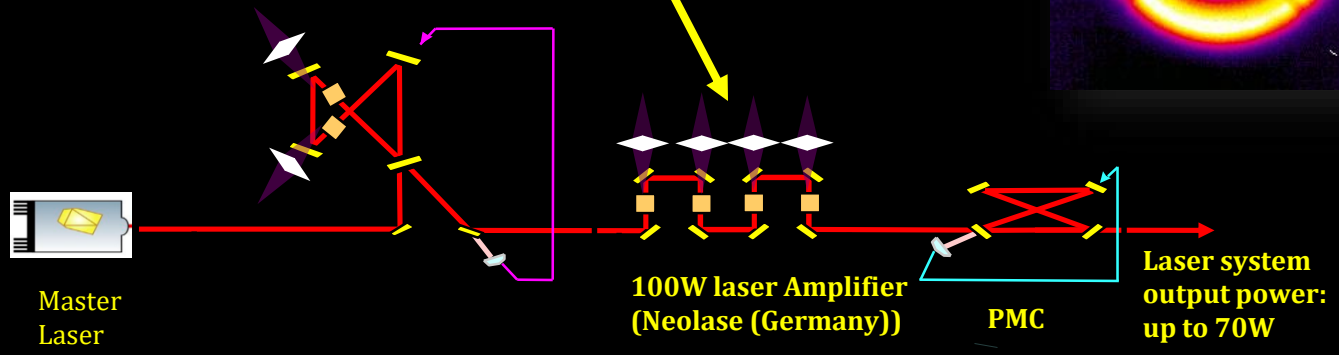
High frequency Noise

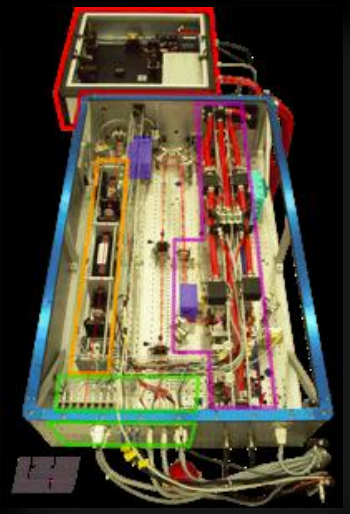
- Laser Shot noise
  - Improved by increasing the power: so far 28W
- Requires:
  - Heavy, low absorption optics (substrates, coatings)
  - Sophisticated systems to correct for thermal aberrations
  - Sophisticated injection system



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





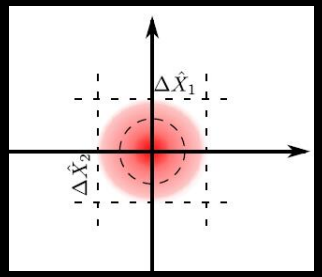


New laser amplifiers (solid state, fiber)

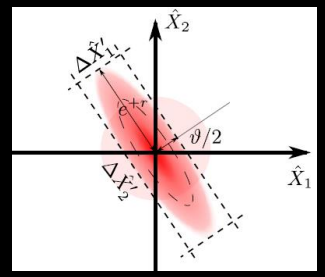
High frequency Noise

- Laser Shot noise
  - Improved by injecting squeezed light

Coherent vacuum state

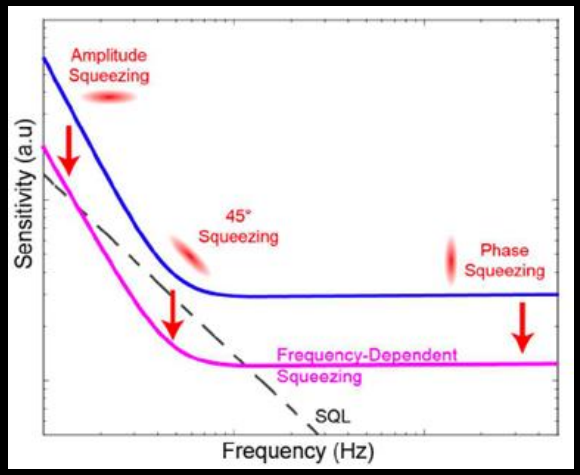


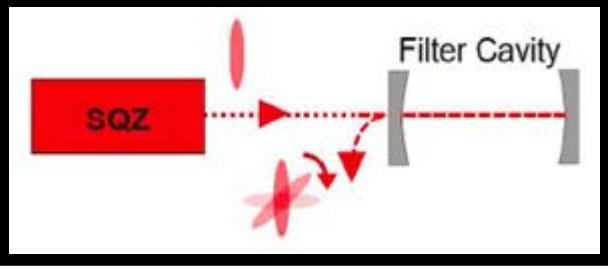
Squeezed vacuum state



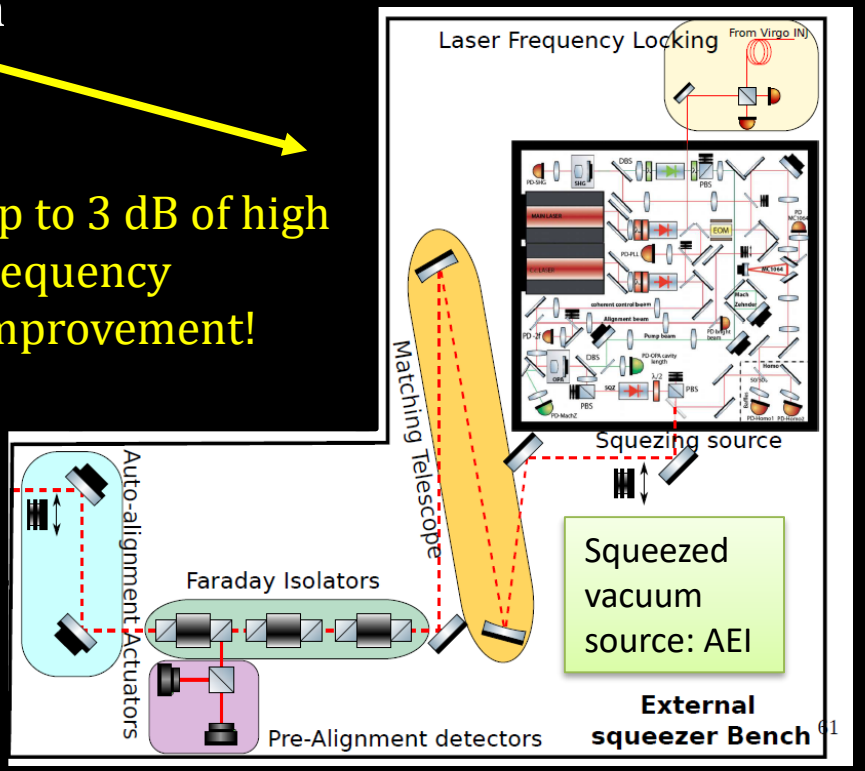
- Requires: Very complex optical design

- Future: Frequency Dependent Squeezing





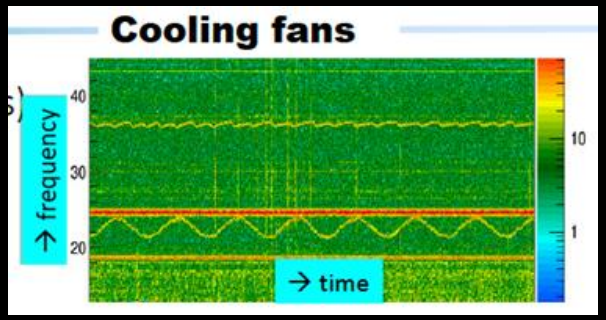
Up to 3 dB of high frequency improvement!



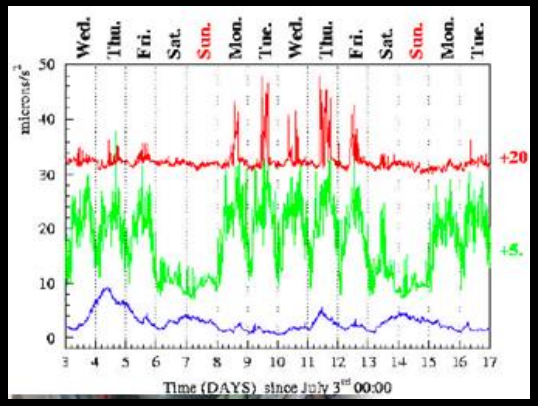
GW environmental noise

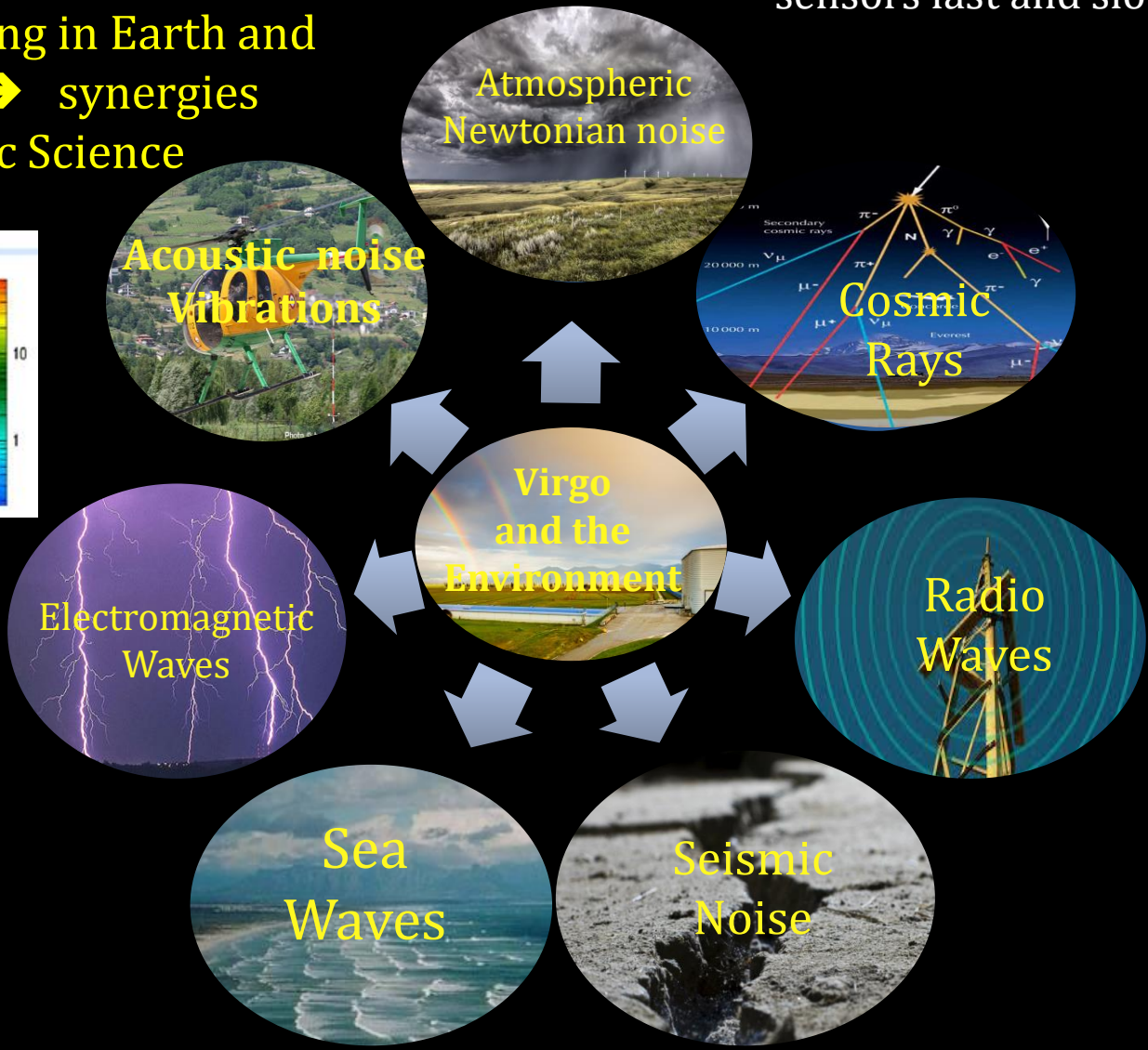
Close to 2000 environmental sensors fast and slow

- Virgo needs to understand very well environment noise
- Highest ever embedding in Earth and Astospheric science ➔ synergies with Geo/Atmospheric Science



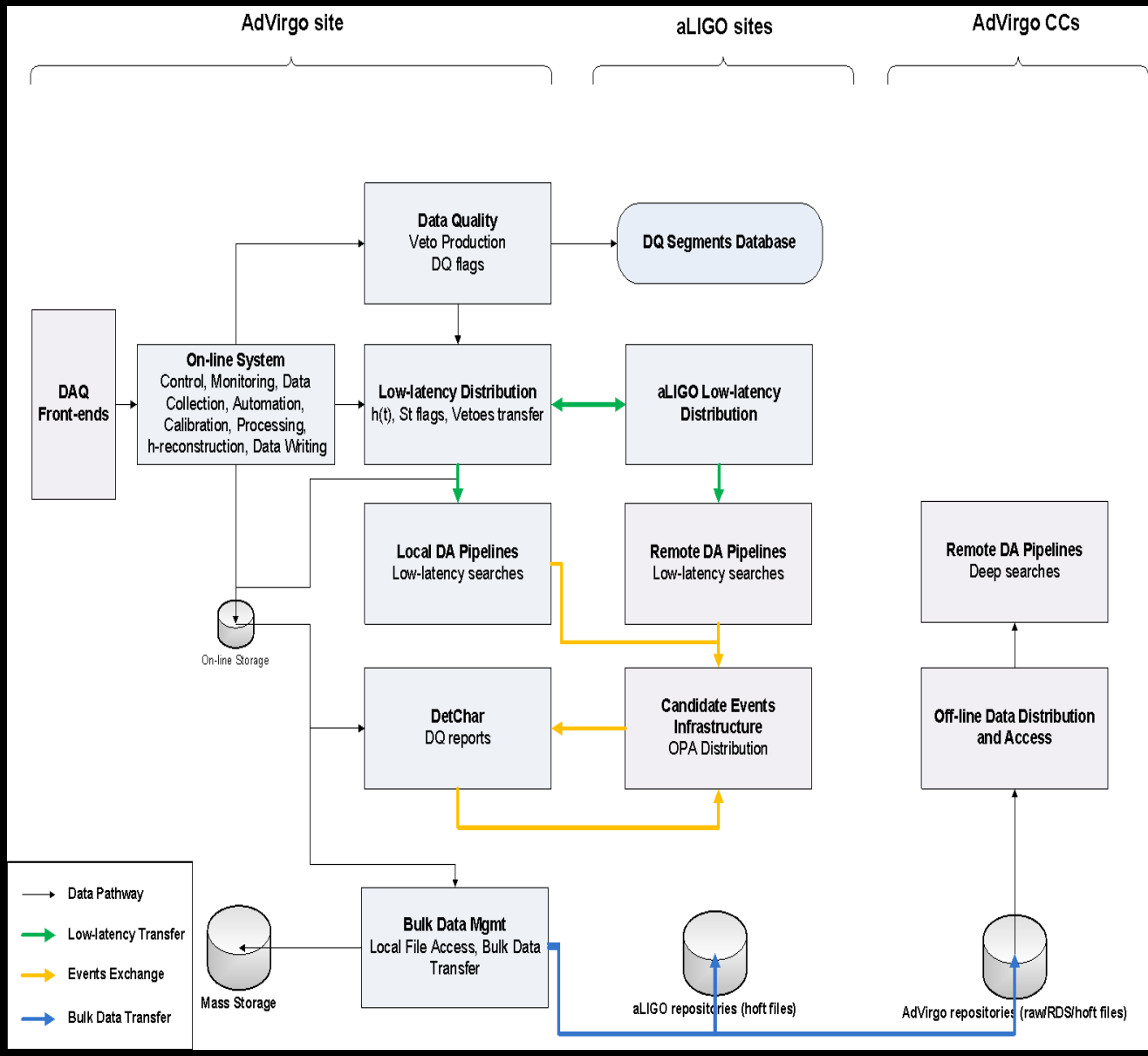
Traffic noise





A global network for computing

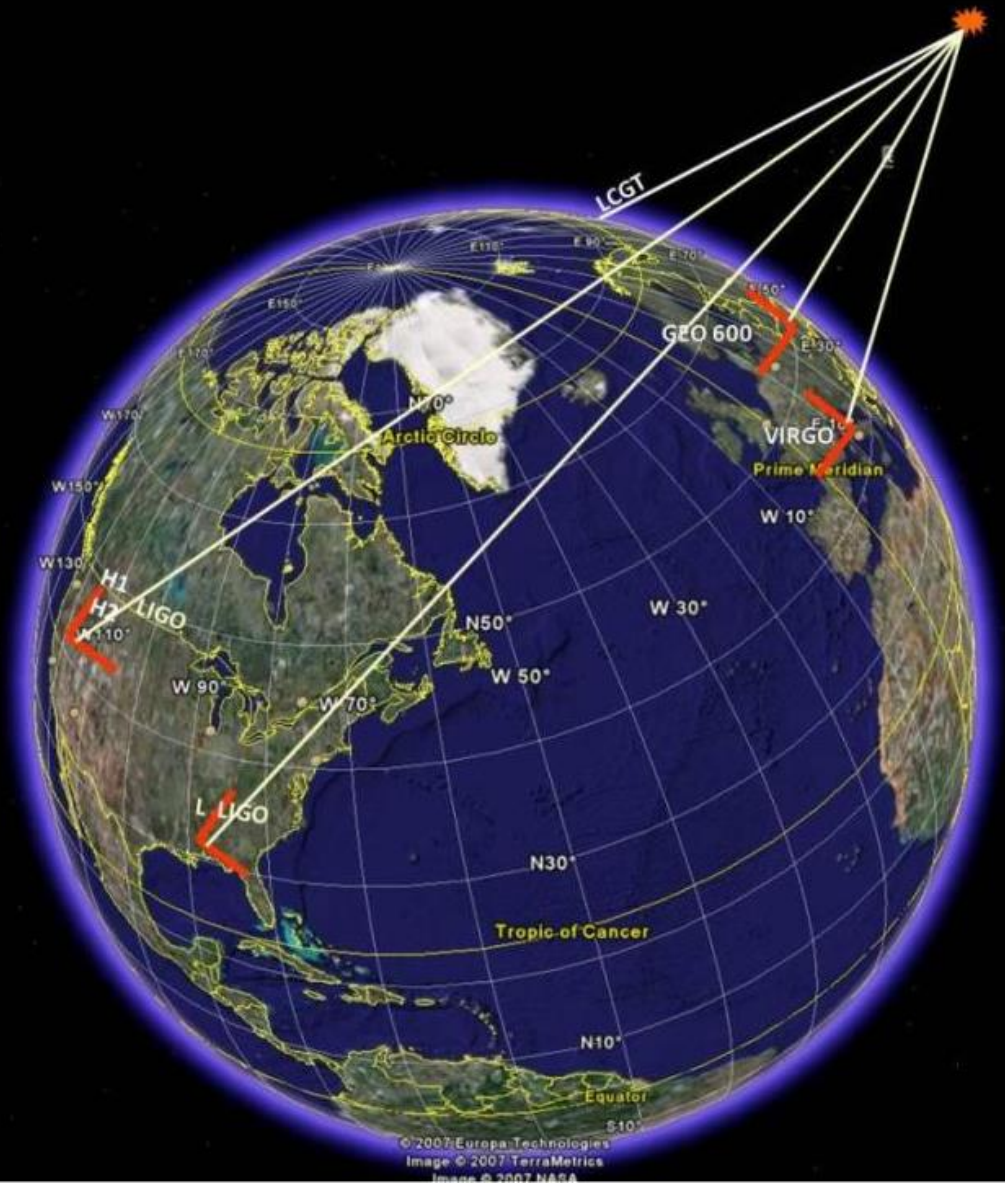
1. The signal arrives
2. Data composed into frames
3. Calibration of the data
4. Veto, DQ flags production
5. h(t) transfer
6. Low-latency matched-filter pipelines
7. Upload to GraceDB
8. Data written into on-line storage
9. Low-latency data quality
10. Low-latency sky localization
11. GCN Circular sent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



The detectors network and the beginning of the multi-messenger astronomy

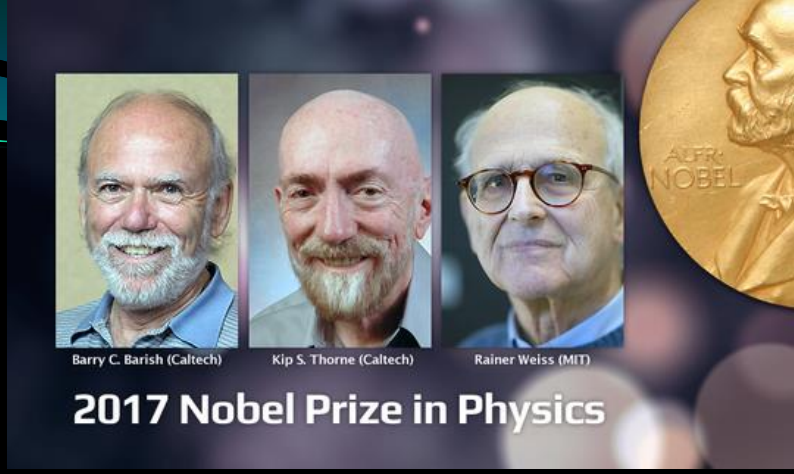
Gravitational waves detector network

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

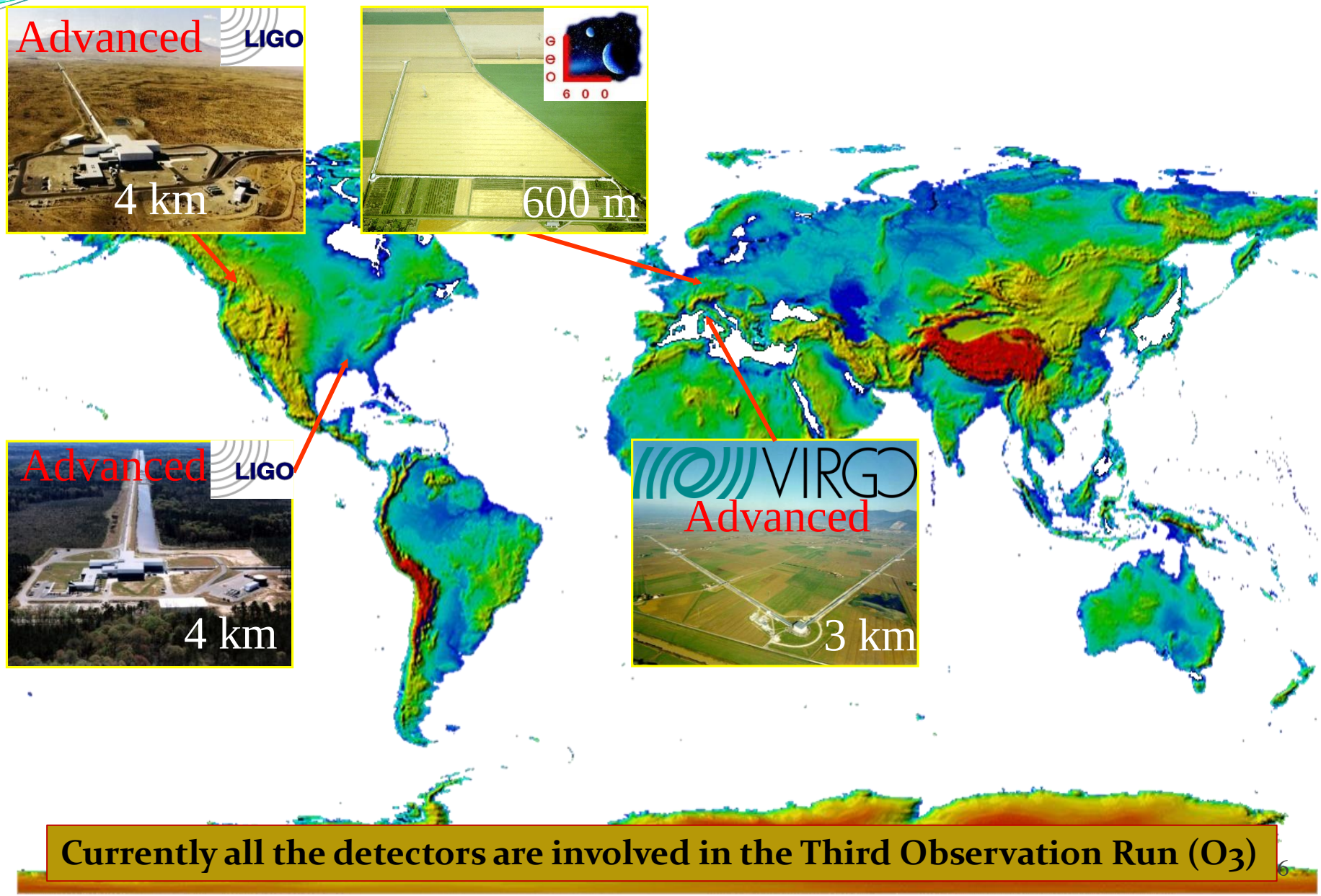


Laser **I**nterferometer

L I G O

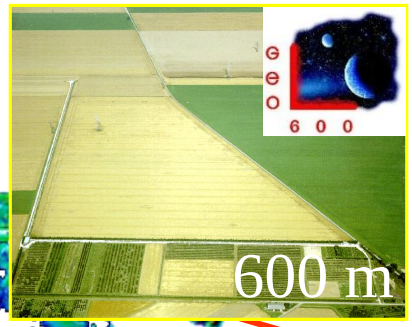
Gravitational wave **O**bservatory

Worldwide detector network

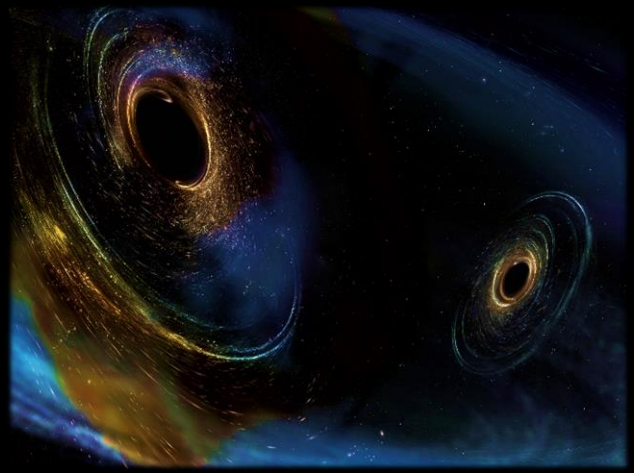


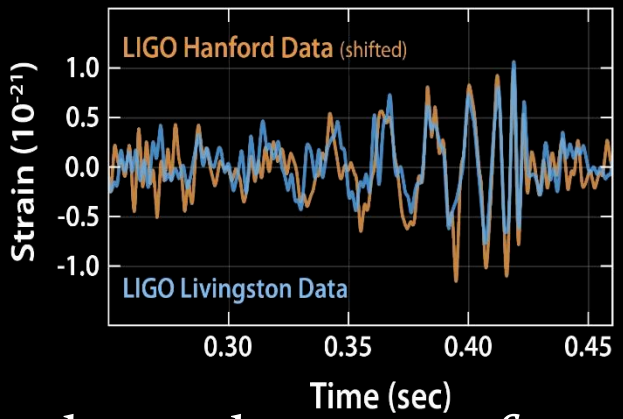
Currently all the detectors are involved in the Third Observation Run (O3)

Worldwide detector network



The first binary Black Hole detection



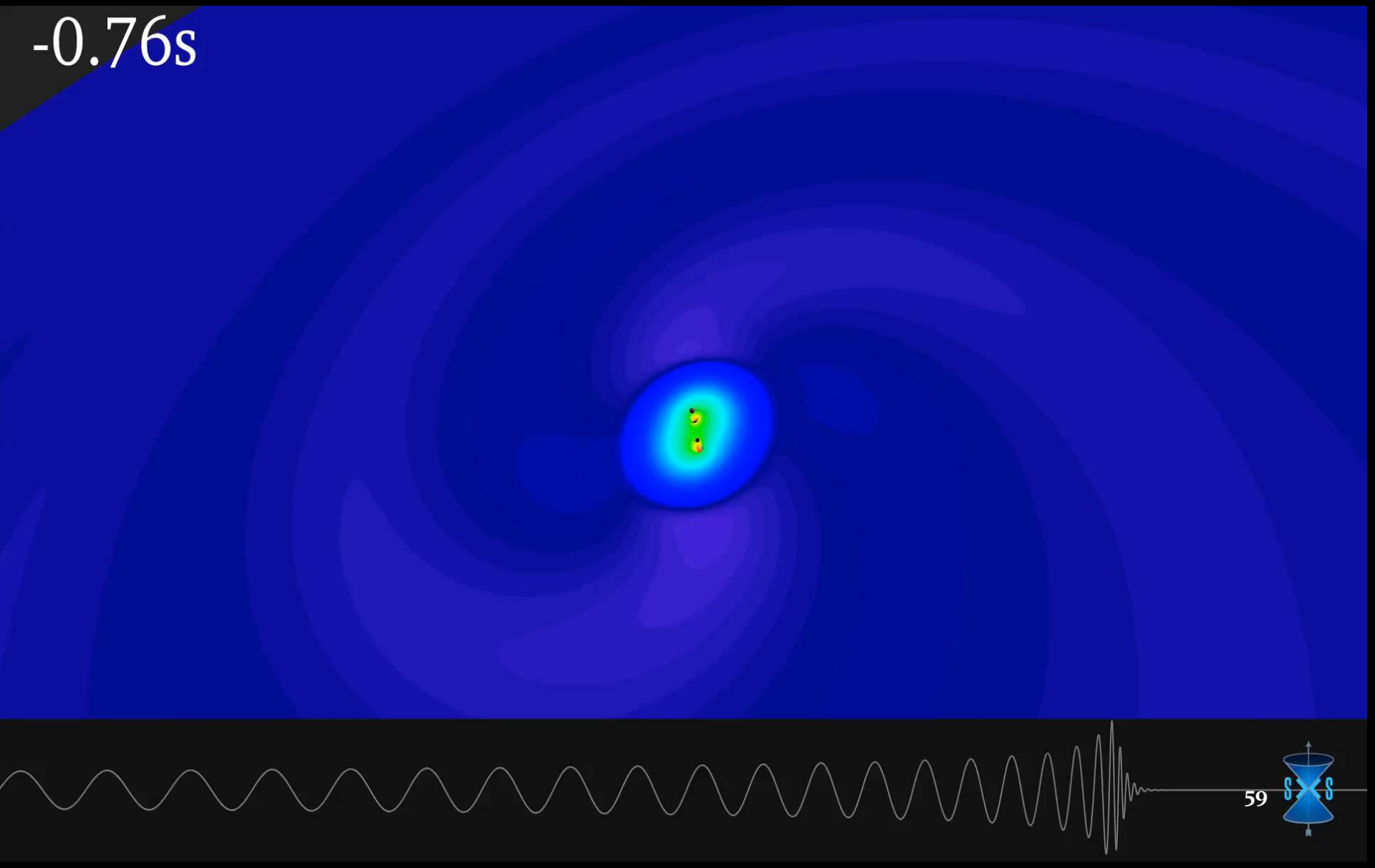


- The Gravitational Wave was produced by the coalescence of two BLACK HOLES 1,3 billion years ago

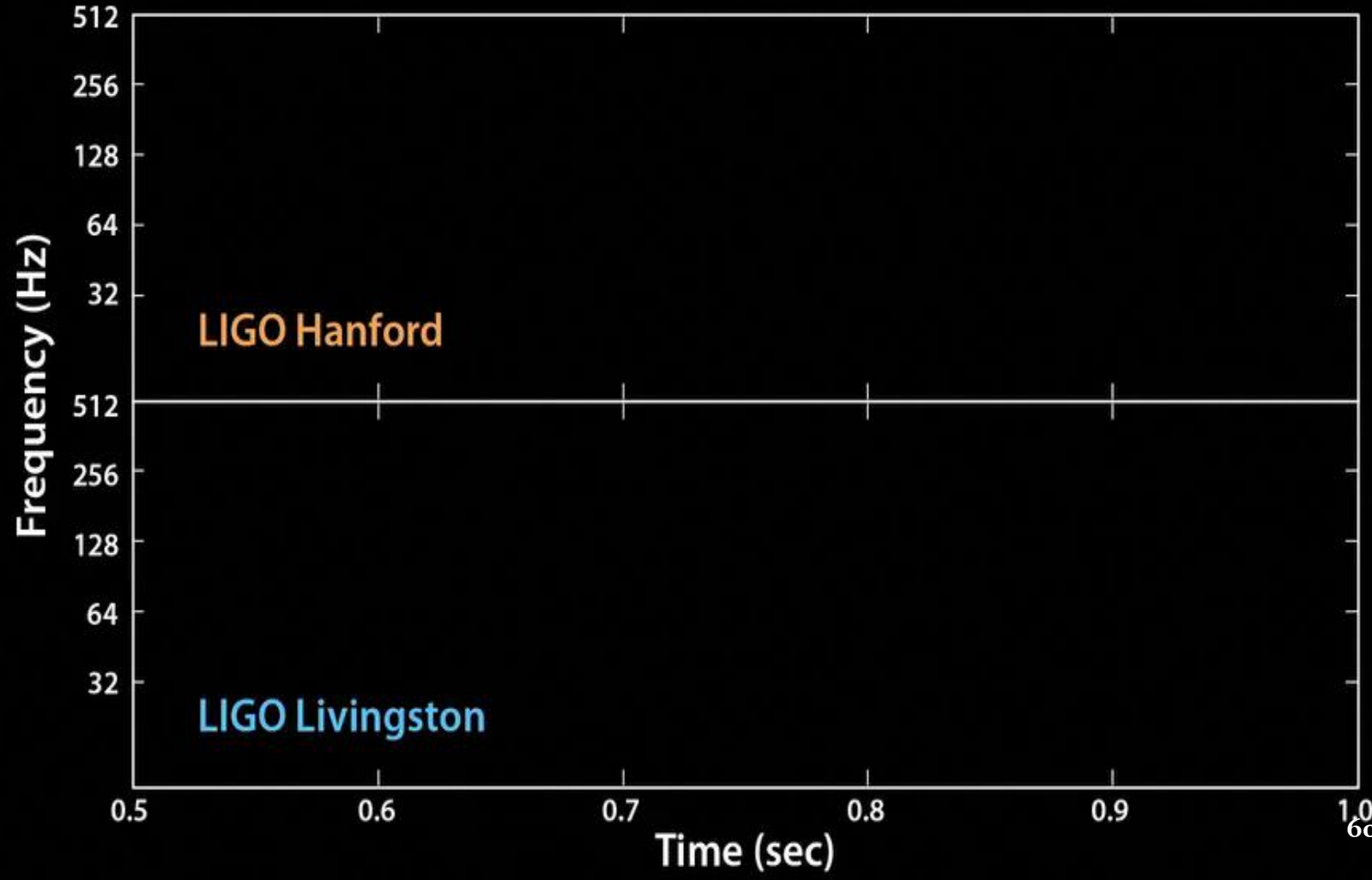
Multicellular life development on Earth

- Two, ~30 solar mass objects concentrated in about 100km diameter colliding in *a fraction of a second*

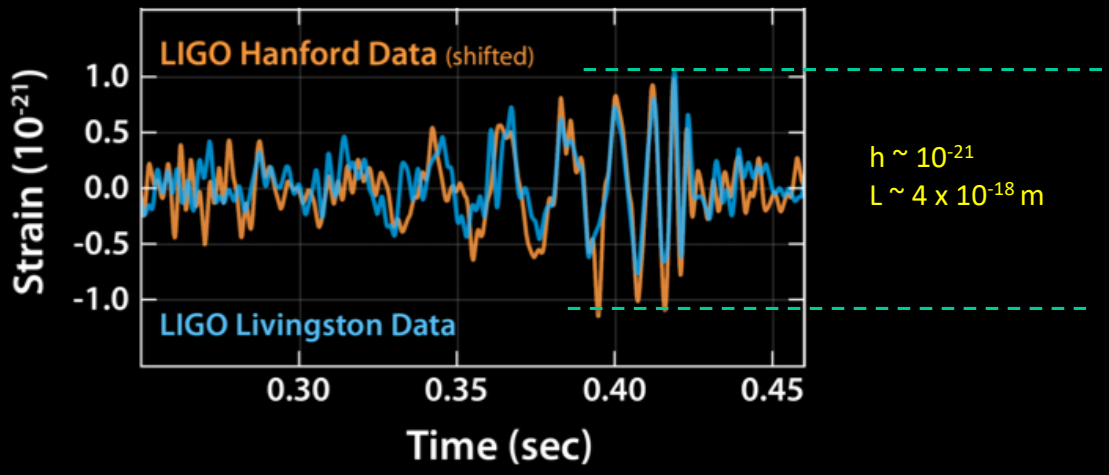
- Traveling at 60% of the speed of light
  - 650 000 000 kilometers per hour! (From here to the moon in 10 seconds!)


-0.76s

The whispers of the Universe



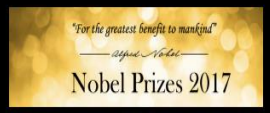
The first GW event: 14 September 2015



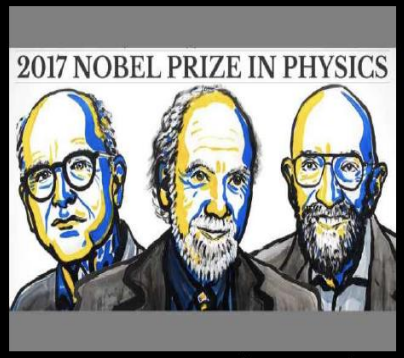
$h \sim 10^{-21}$

$L \sim 4 \times 10^{-18}$ m

Power ~ 4 x 10^{49} W

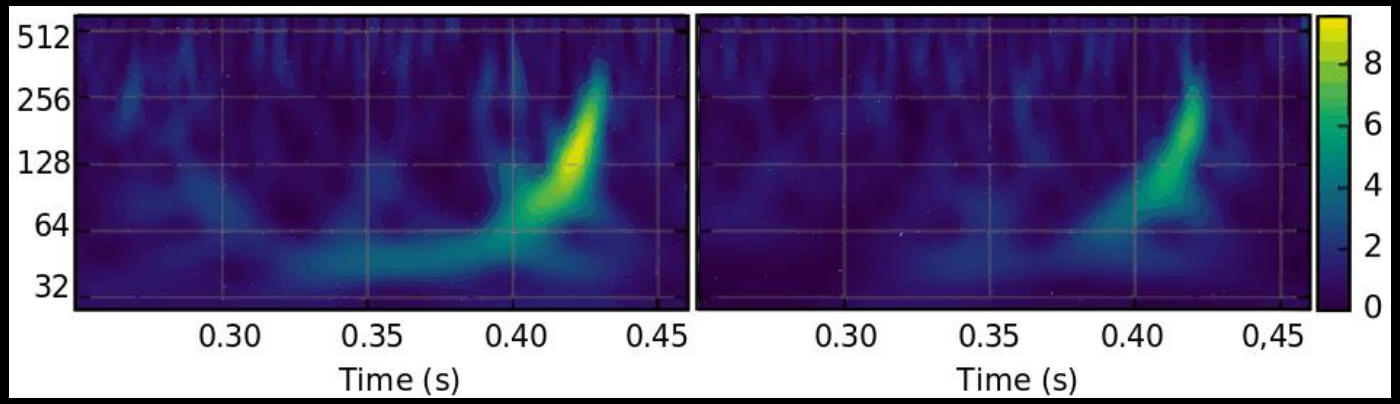


2017 October 3

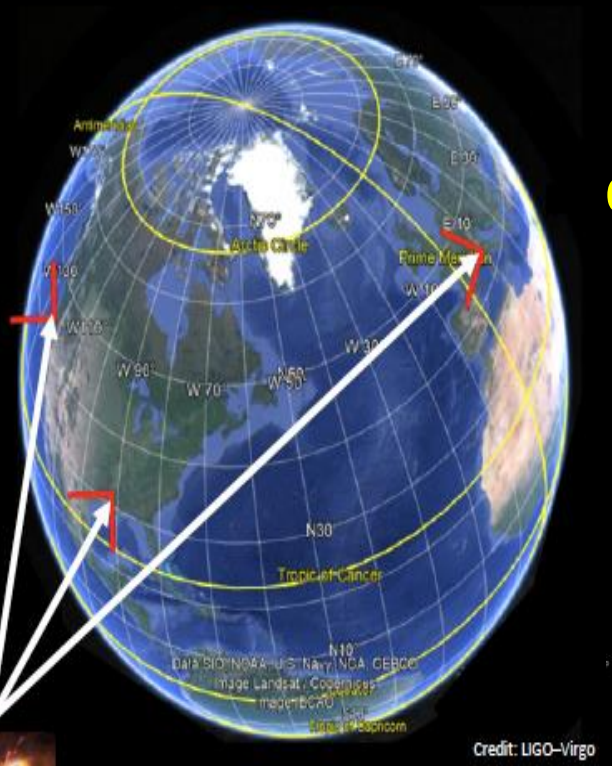


"for decisive contributions to the LIGO detector and the observation of gravitational waves".

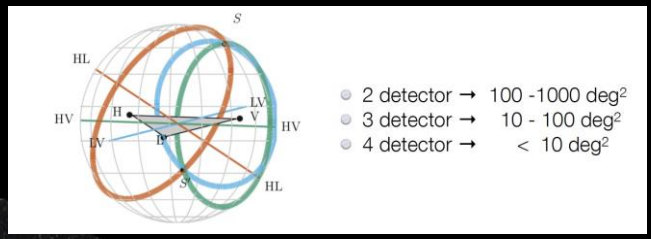
Observing run O1

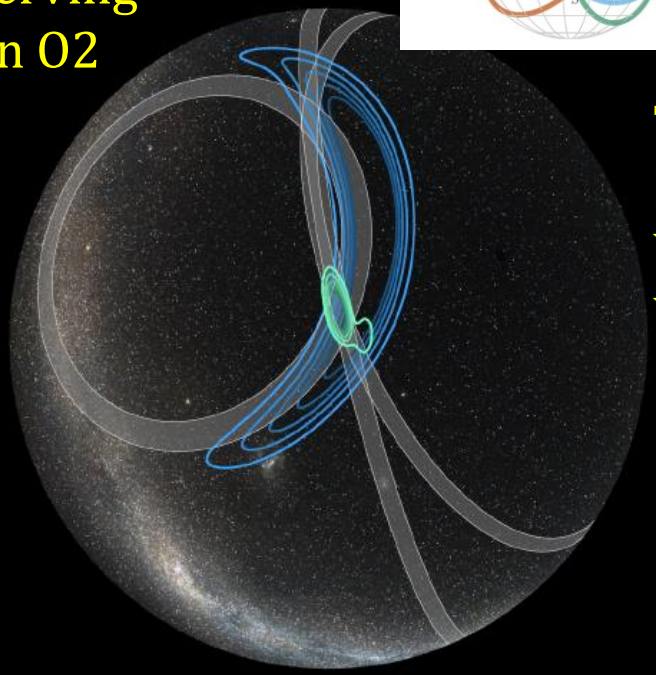


The first GW triangulated event: 14 August 2017

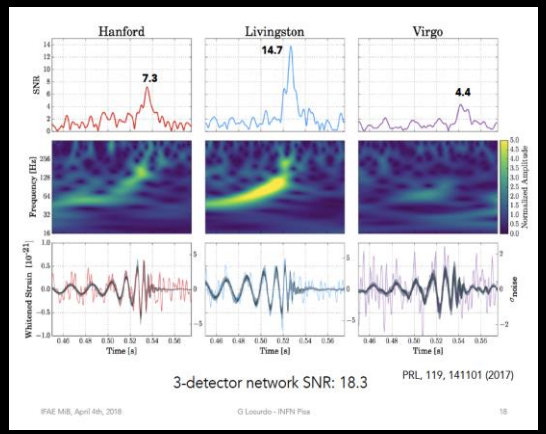


Observing run O2





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



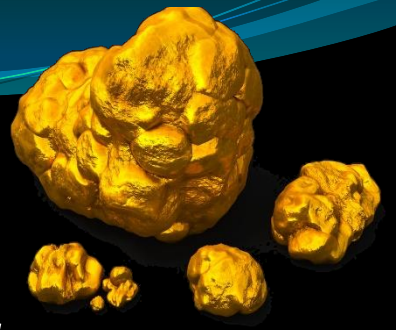
LH 1160 square degrees
LHV 60 square degrees

Also measure of GR polarisations

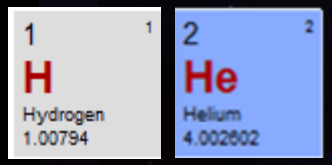
Gravitational Astronomy can start!

GW170817

The origin of gold

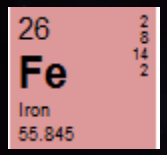


The merging of these two massive objects gave rise to very rapid nuclear reactions forming heavier elements than the ones which formed at the beginning of the Universe life



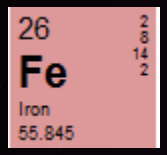
Came out from the heat of the primordial Universe

Up to



Formed during fusion in the stars nuclei

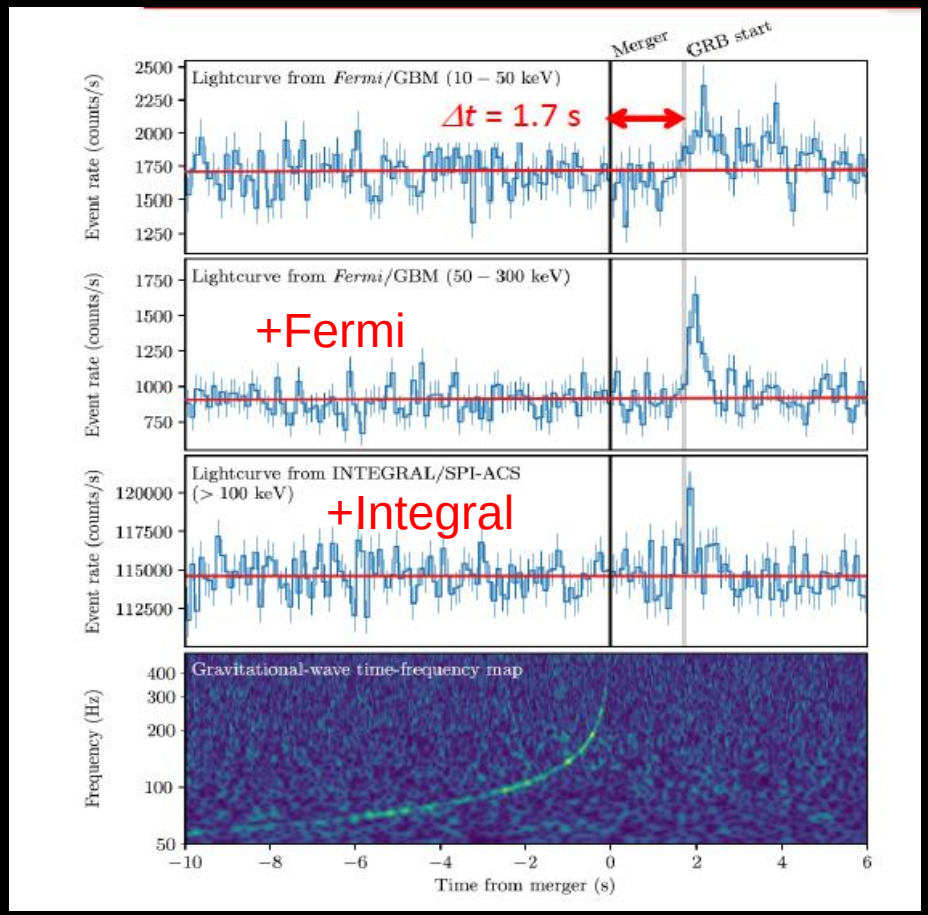
After

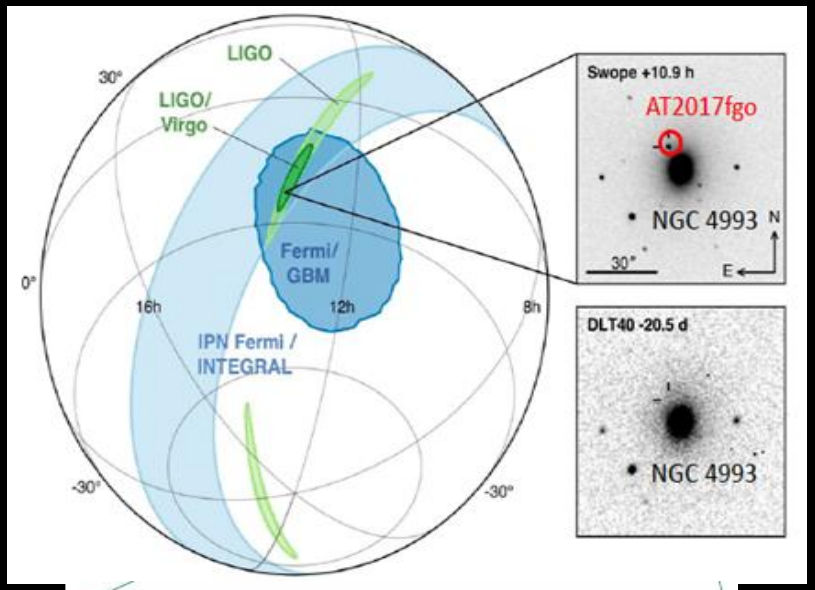


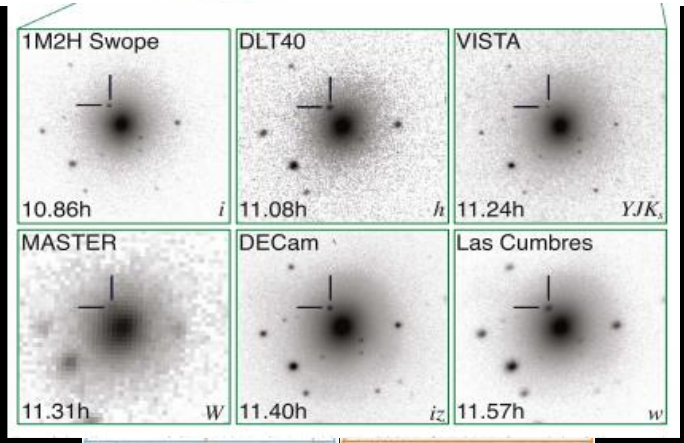
Need to catch more nucleons to form heavier elements. This process can happen either slowly (*s* process) or fast (*r* process). This latter kind of process produces radioactive nuclei which can decay and produce elements like **gold**

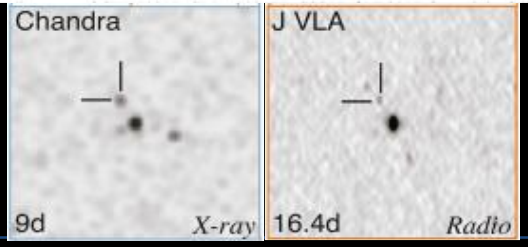
The first GW from a BNS: 17 August 2017

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



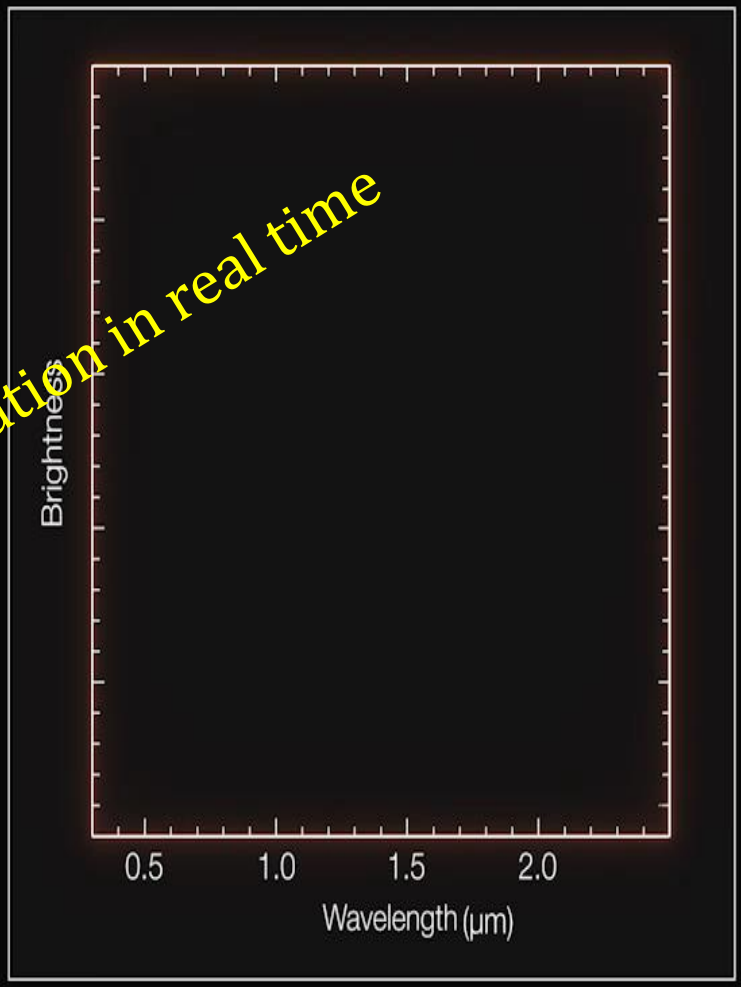






Start of multi messenger astronomy!

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



The first "global" observation in real time

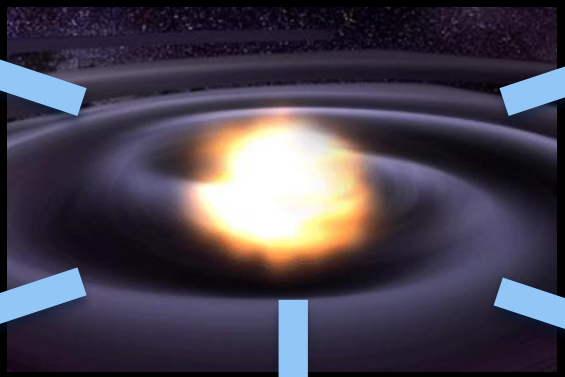
Time: -1225 days

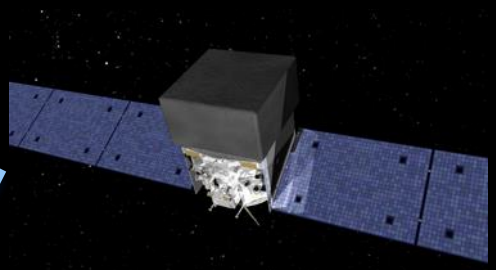
Elena Pian et al. 2017, Nature, 551, 67–70 ESO

Multi-messenger Astronomy with Gravitational Waves

Gravitational Waves

Binary Neutron Star Merger

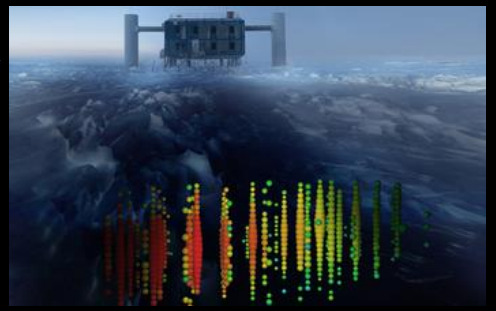




X-rays/Gamma-rays

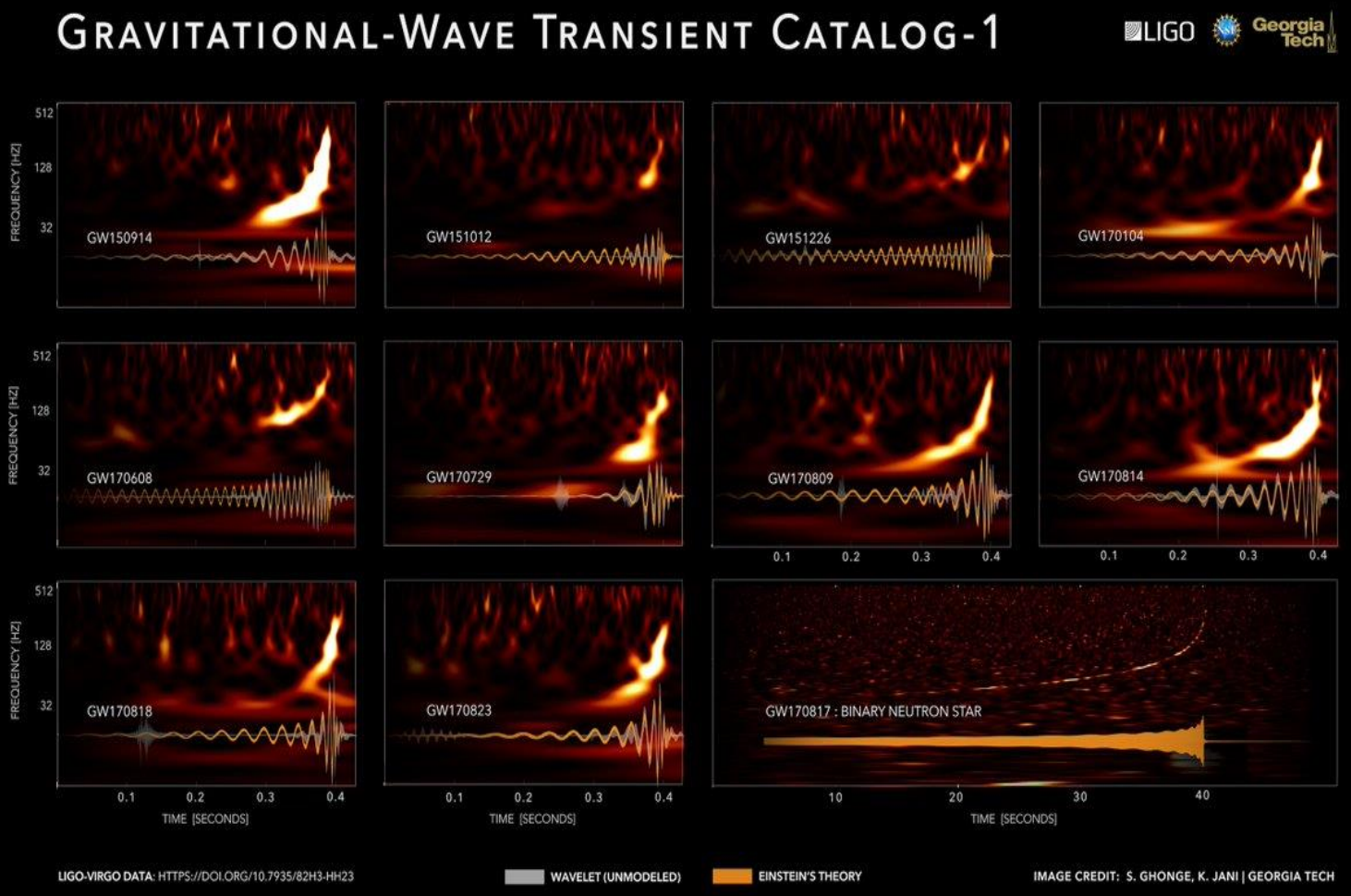
Visible/Infrared Light

Radio Waves



Neutrinos

First Gravitational Waves catalog released

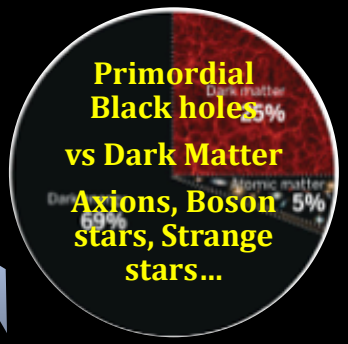


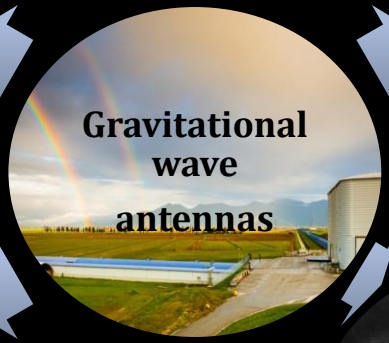
10 Binary Black Holes and 1 Binary Neutron Stars systems detected during first and second Observation Runs

GW and Fundamental Science

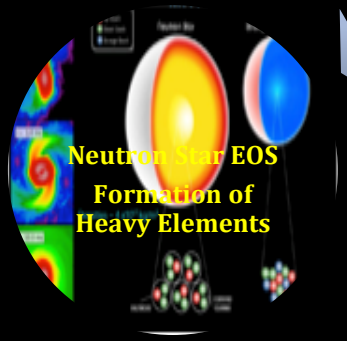
Cosmology and Astrophysics

Cosmology and Particle Physics

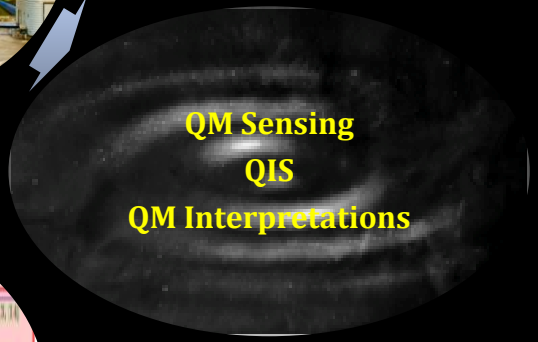


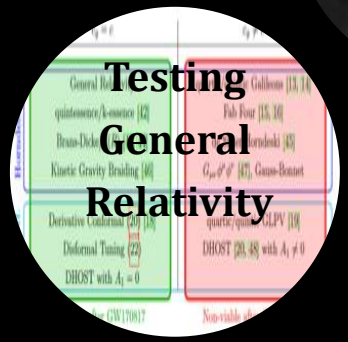


Astrophysics and Nuclear Physics



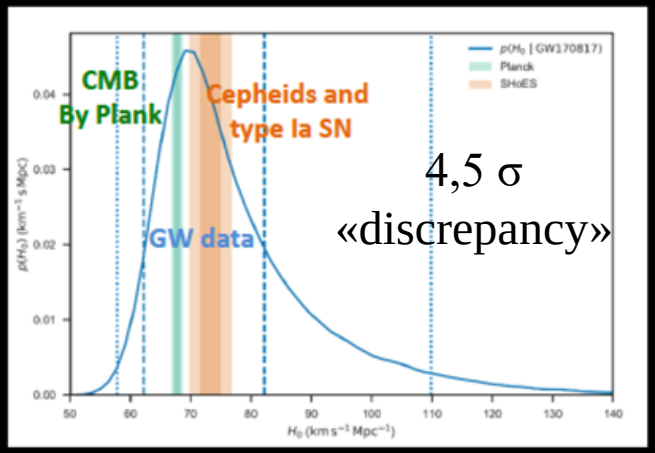
Testing Quantum Mechanics





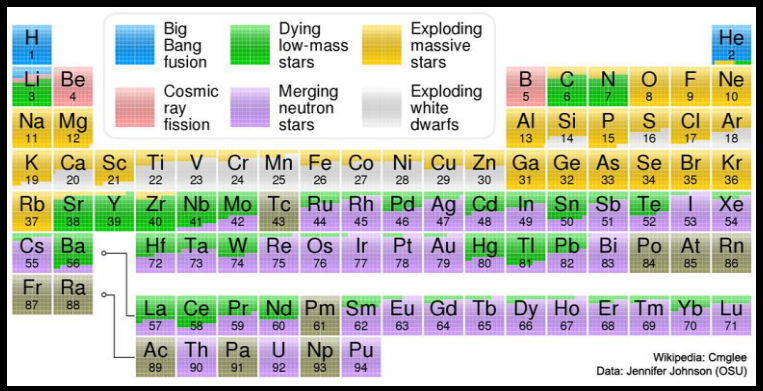
GW and Fundamental Science

Hubble constant



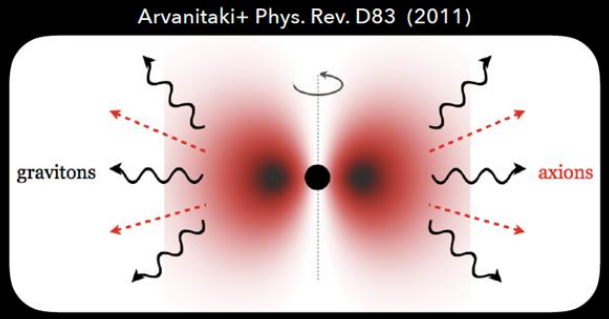
Test the speed of gws

$$-3\cdot10^{-15} \le \frac{v_{GW}-c}{c} \le 7\cdot10^{-16}$$

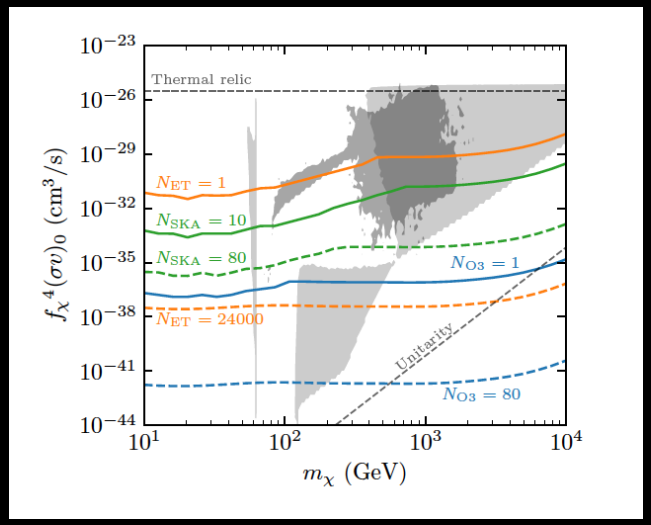


Kilonova: formation of heavy elements (Sd)

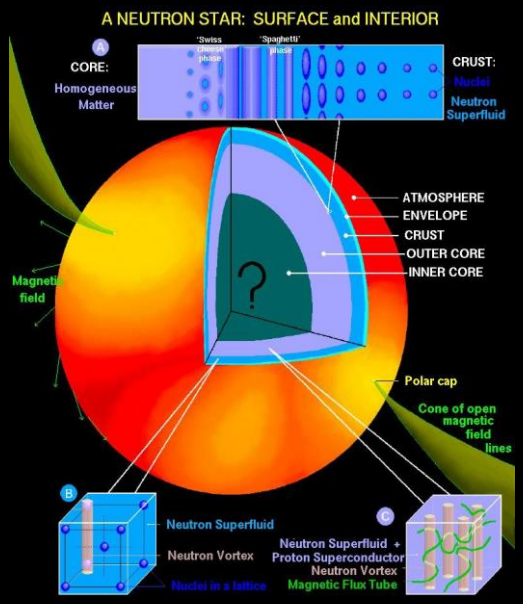
Gravitational atoms and BH super radiance



Dark matter: Primordial Black Holes



Super dense matter studies measuring tidal deformability of neutron star mergers

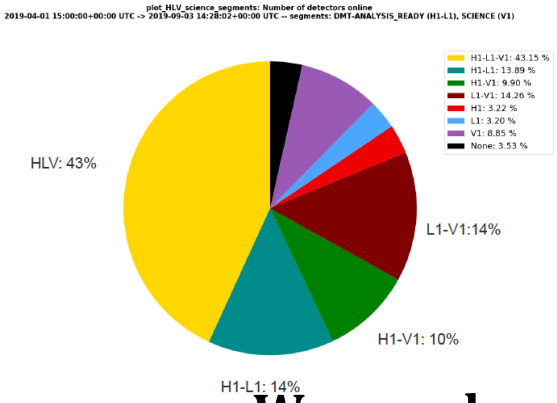


Observing runs

O1 – Sep. 2015 – Jan. 2015
O2 – Nov. 2016 – Aug. 2017
(Virgo joined on Aug. 1st)

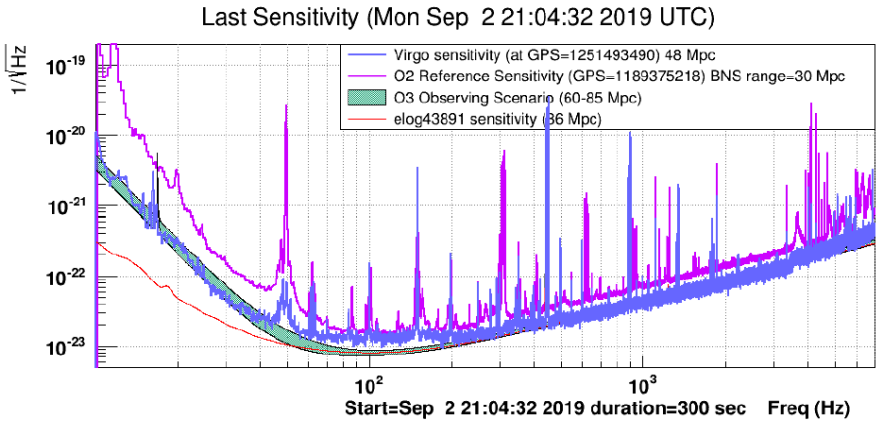
O3 Summary: number of detectors online

H1-L1 double efficiency 57%, H1-L1-V1 double+triple efficiency 82%

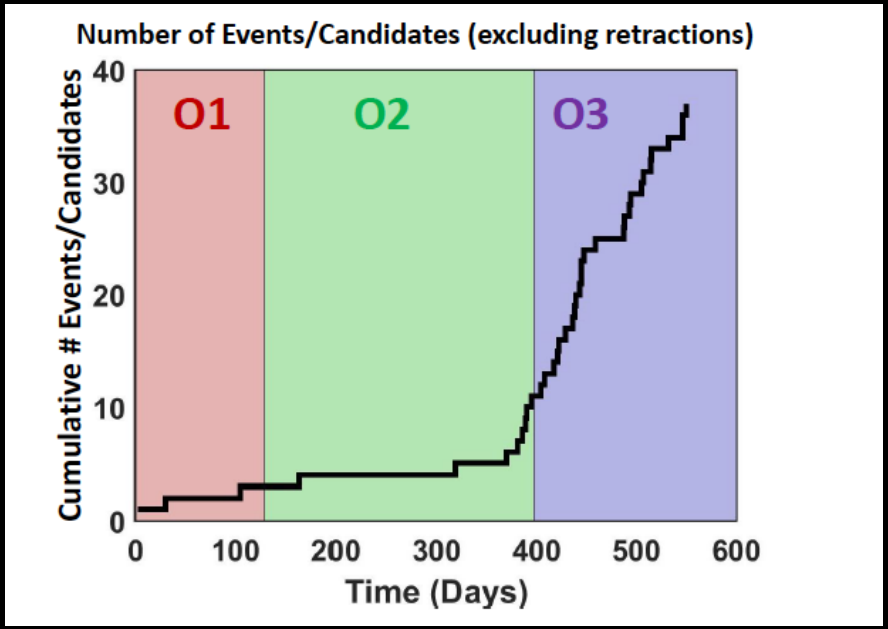


Virgo sensitivity: best value about 50 Mpc

Significant improvement with respect to the best sensitivity obtained in O2. However, we see a flat noise contribution at mid-frequencies, significant noise around 50 Hz. Virgo uses 18 W of power



We are observing (O3) since the 1st of April 2019!



O2 prediction : Merger rates

BNS: 920 [110, 3840]/Gpc^3 /y

BBH: 53 [9.7, 101] /Gpc^3 /y

Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{0}	15^{+19}_{-10}
O3 candidates in 5 months of observations		2	1	20

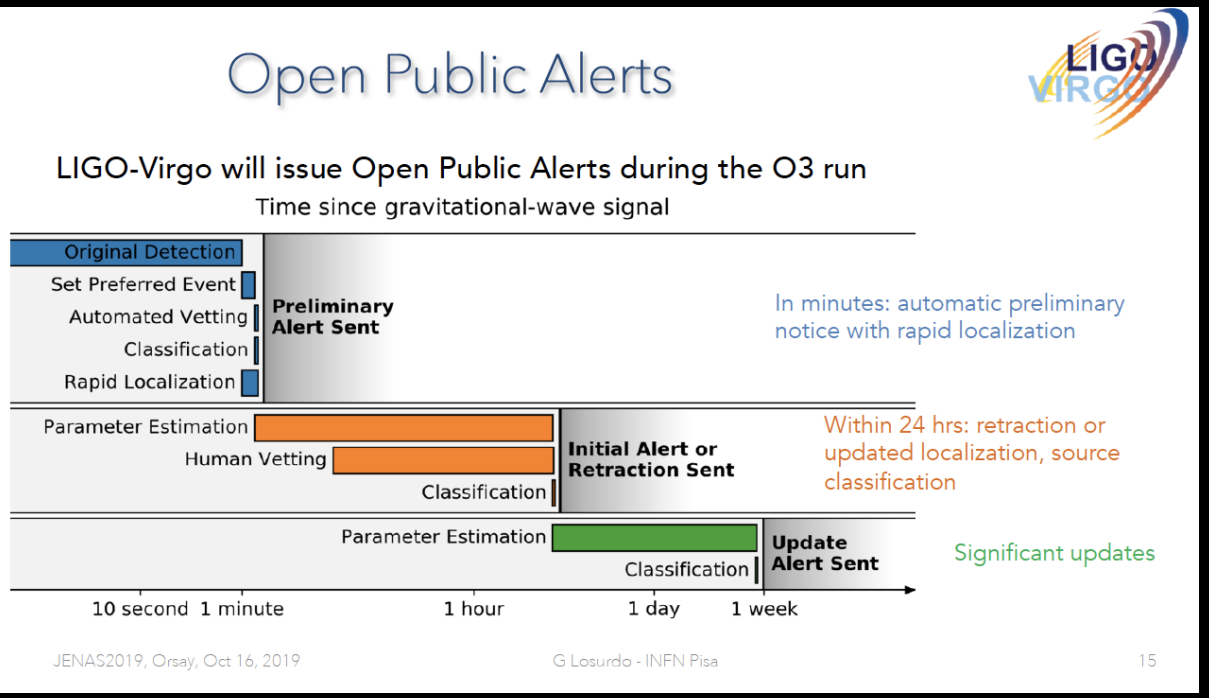
Every online candidate may not qualify as a detection in the catalogue

O1 + O2: 11 detections

- 10 BBH
- 1 BNS

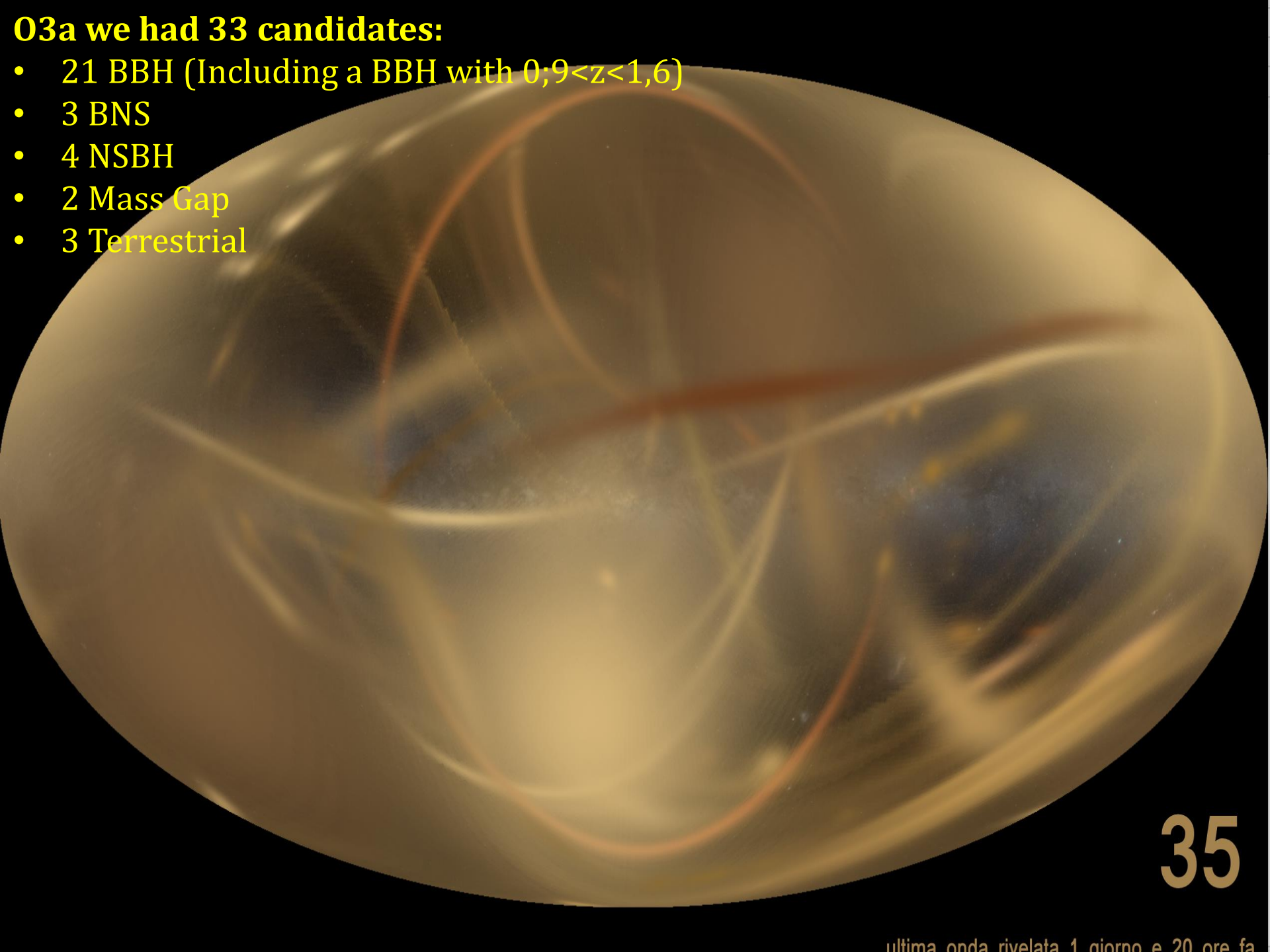
Alerts: LIGO-Virgo currently generate 50% of GCN traffic

Open Public Alerts



O3a we had 33 candidates:

- 21 BBH (Including a BBH with 0;9<z<1,6)
- 3 BNS
- 4 NSBH
- 2 Mass Gap
- 3 Terrestrial

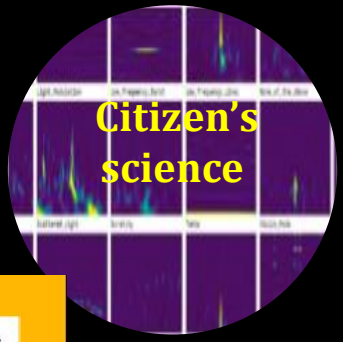


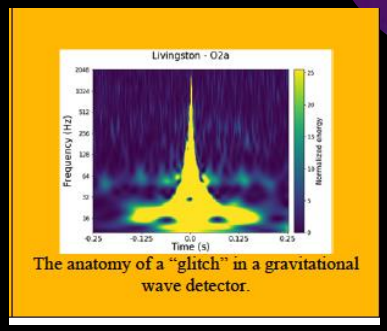
Want to be always informed?

The detector

EGO/Virgo and Society

Multimessenger room : T. Saraceno
"On Air" Palais de Tokyo





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

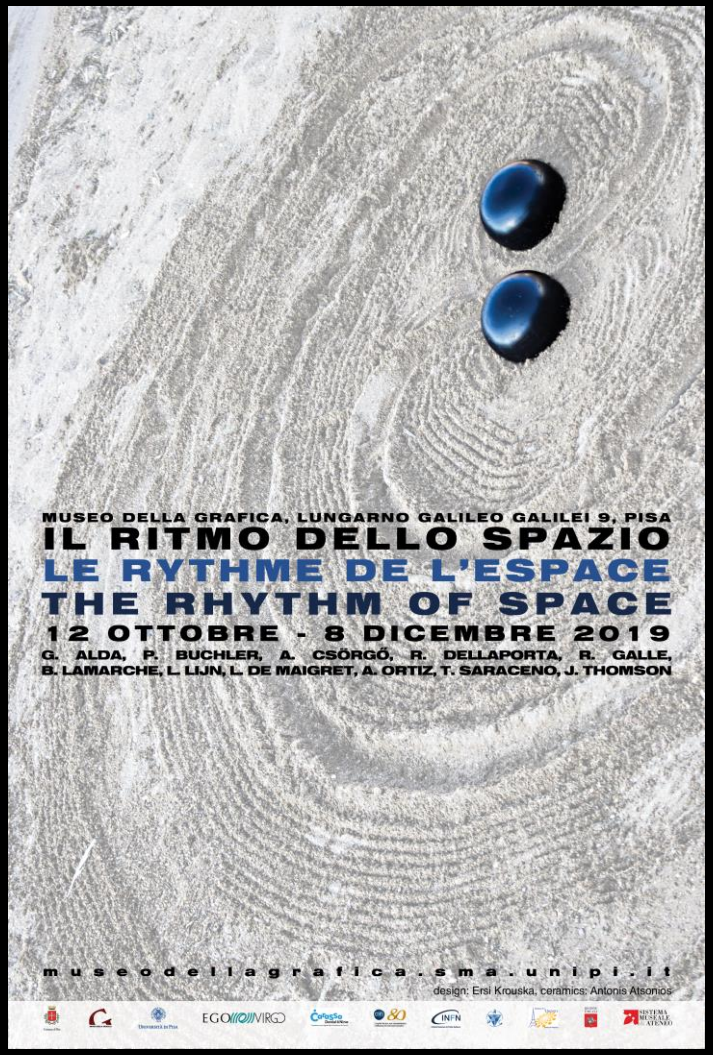
REINFORCE
Classify Glitches

Multisensorial studies with Wanda Diaz-Merced
« The average person looks without seeing, listens without hearing » Leonardo

Most activities funded by EU programs

An exhibition on Art and Science
Rythm of Space

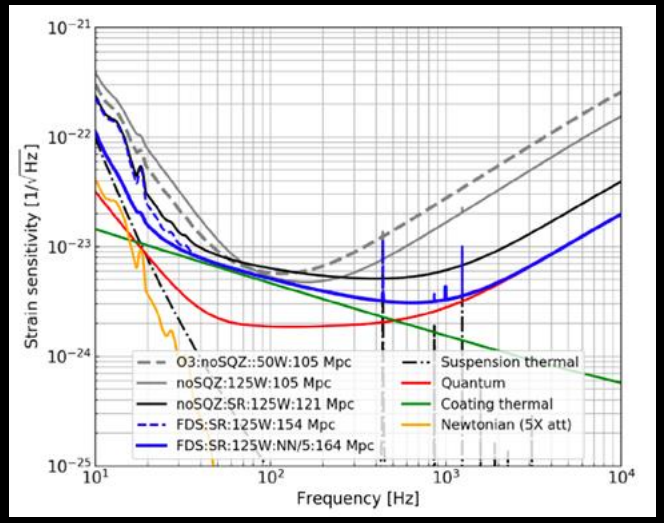
T. Saraceno, L. Lijn, A. Csorgo, B.Lamarche, R. Dellaporta, G. Alda/A. Ortiz...



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

The Future

AdV+

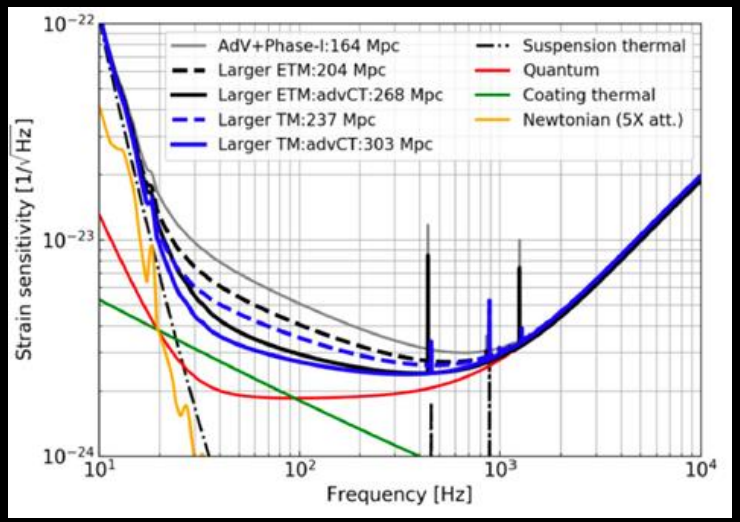


Phase I (O4): reaching the thermal noise wall

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

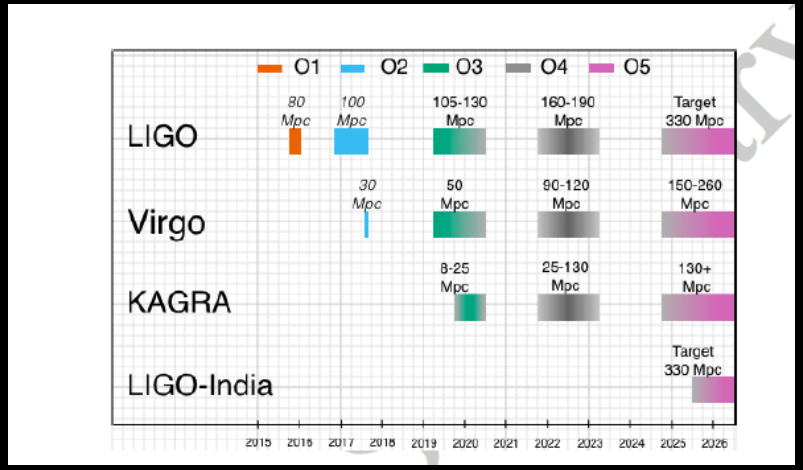


- The sensitivity can improve up to *160 Mpc on Phase I* and up to *300 Mpc on Phase II!*
- This will increase the **number of detections** and the sensitivity to **new phenomena** (Equation of state of Neutron stars for example!)

The next 10 years

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

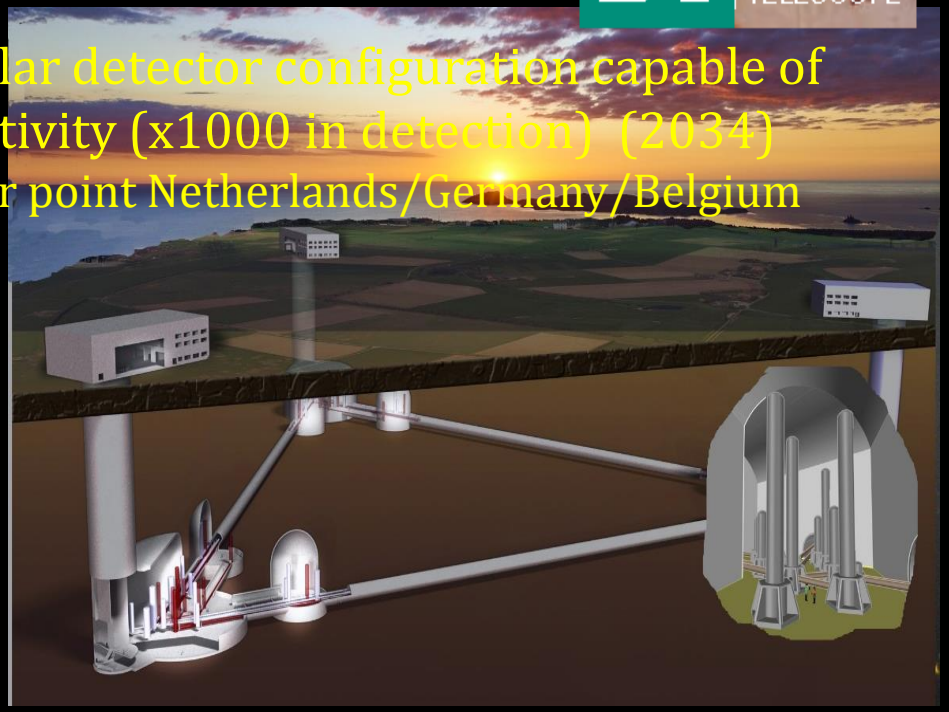
- A global multimessenger network:
  - ✓ GW and EM observatories (optical to radio)
  - ✓ GW and Space satellites (FERMI, INTEGRAl, ATHENA,..)
  - ➢ GW and large surveys (DES, LSST, DESI)
  - ➢ GW and high energy observatories (CTA, KM3NET/ICECUBE, Auger,..)00



Towards the third generation

ET is an underground10km long triangular detector configuration capable of achieving a factor of 10 increase in sensitivity (x1000 in detection) (2034)

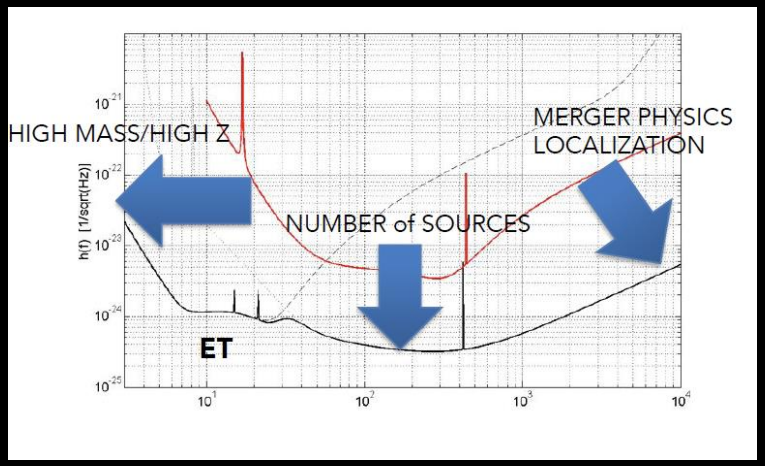
Two candidate sites: Sardinia, Triangular point Netherlands/Germany/Belgium

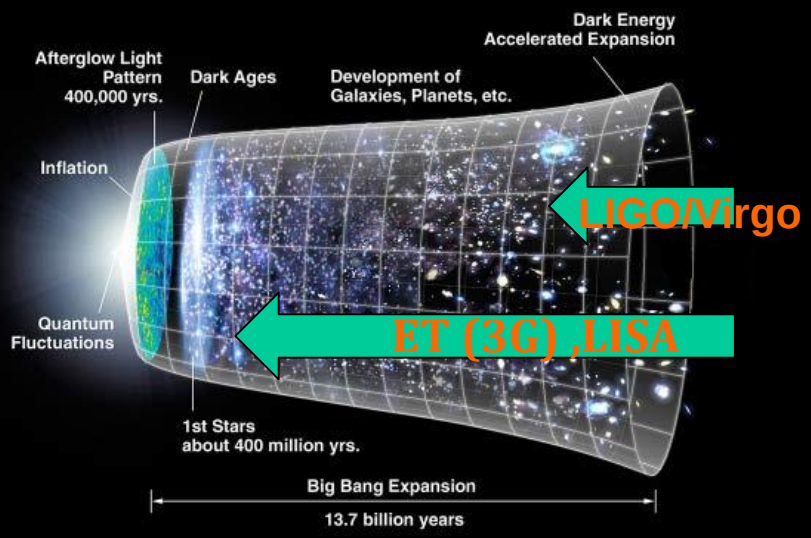


Tentative planning:

- 2021-2022 Site selection
- 2023-2024 Technical design report
- 2025 Beginning of the construction
- 2030-2031 Beginning of the commissioning phase

Perspectives: Equation of State, increase of sources…

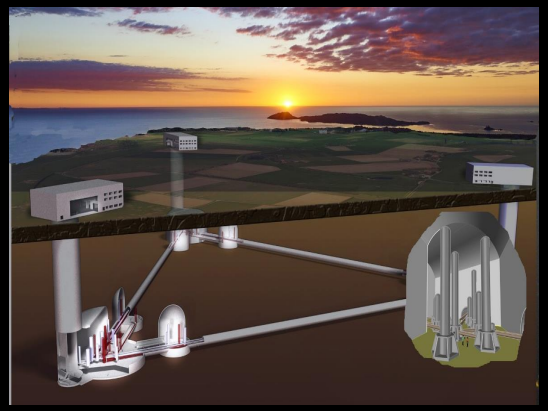


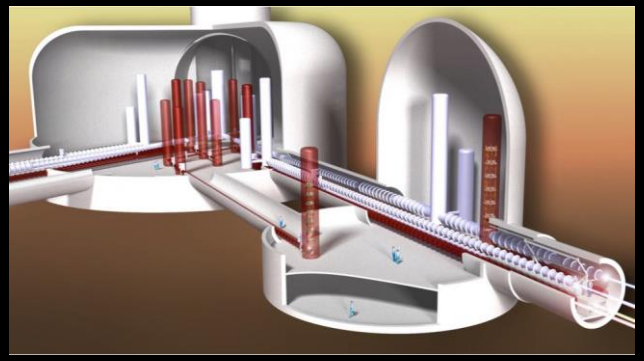


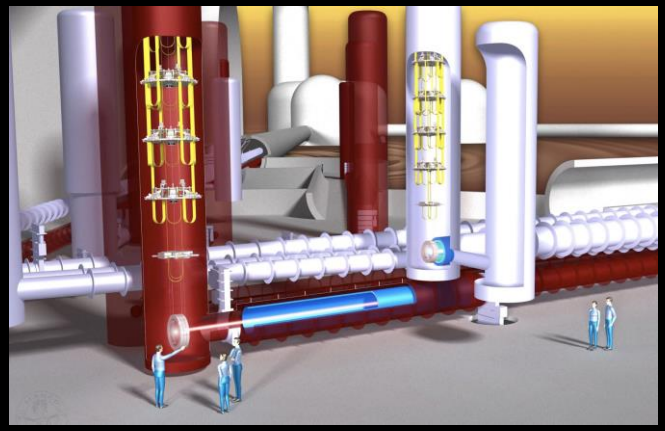
Cosmic Explorer (US): L shaped, above ground, 40 km; design study on-going

The importance of civil infrastructures

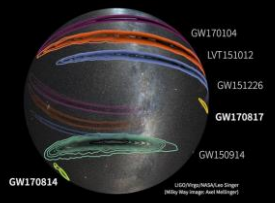
- The interlinked sensor network monitoring and mitigating noise of the interferometers is at the avant-garde of the technological front of “smart infrastructures”
- The environmental studies can become a source of innovation in geological and atmospheric matters (early warnings, earth, cloud and sea monitoring). Synergies.
- The 3G civil-infrastructure is a large part (>90%) of the cost of 3G, there are technological, innovation synergies to be developed with other fields (HEP , ν) with the same concerns of civil infrastructure





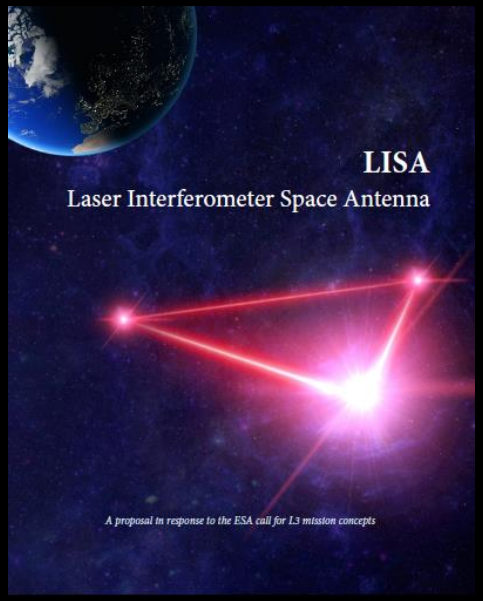


Gravitational Waves
Ground-Space complementarity



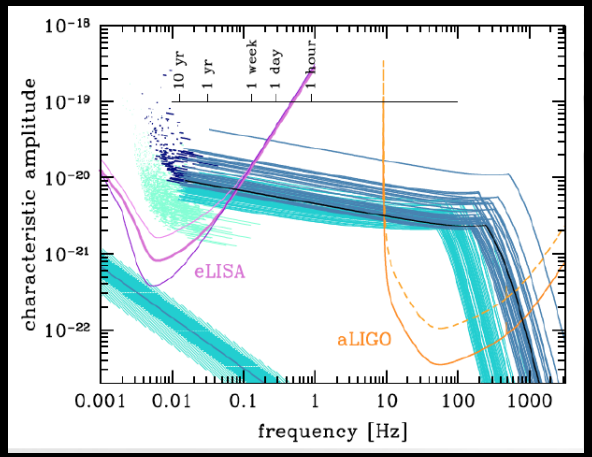
LISA

A spatial mission ESA: LISA (1994➔ 2034)

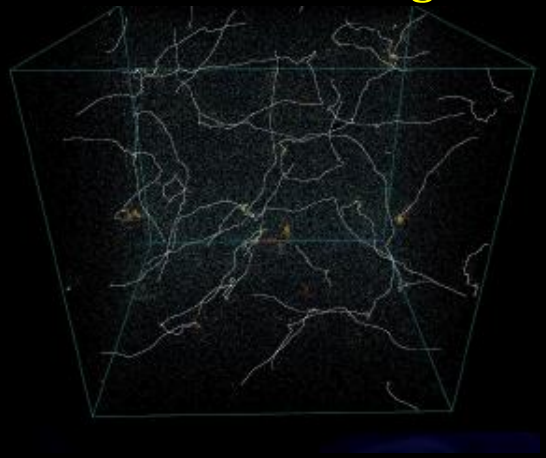


1. 1993-1994 1^{e} proposition (6 sat)
2. 1997 Final configuration(3 satellites)
3. 2017 Start of phase 0
4. Discussions of participation NASA
5. 2018-2020 Phase A
6. 2030-2034 Launch (duration 4 (+6) y)

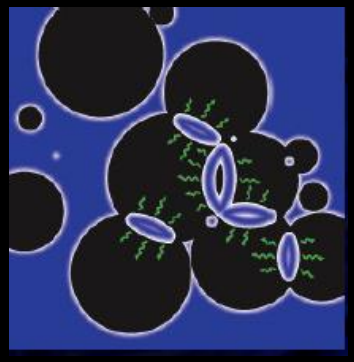
A detector of Super Massive Black Holes ➔ evolution of galaxies, dark matter…



Terrestrial GW alert



Cosmic strings

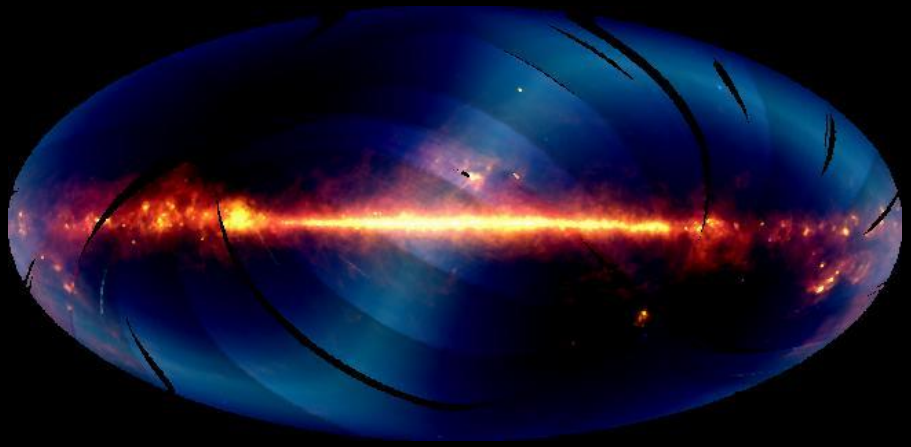


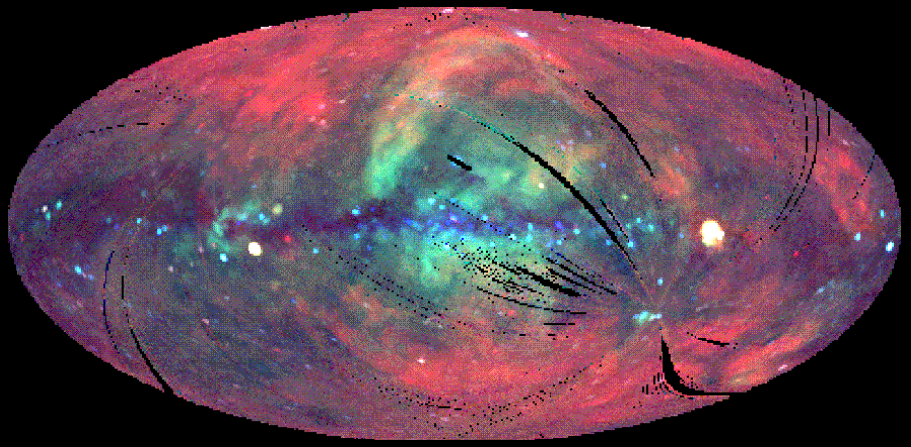
Phase transitions

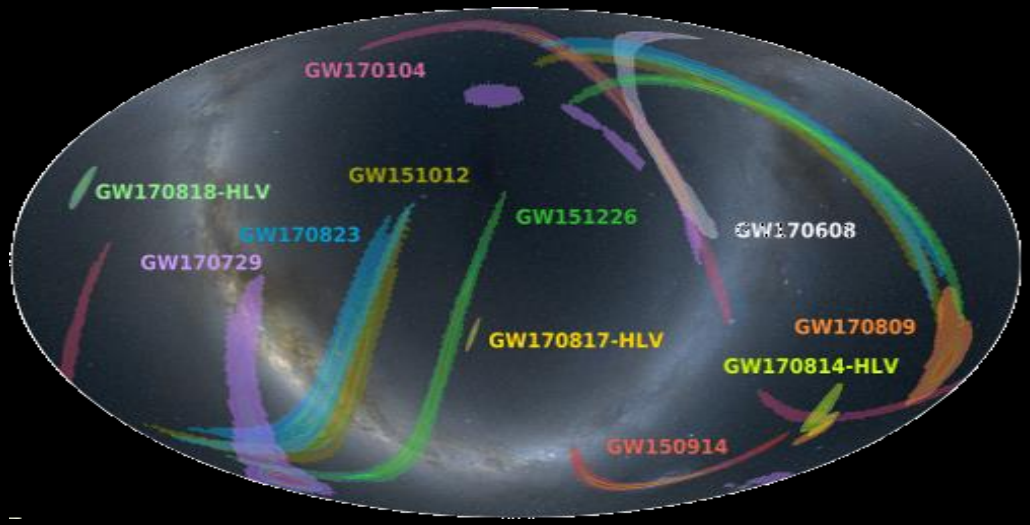
Conclusions

- 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

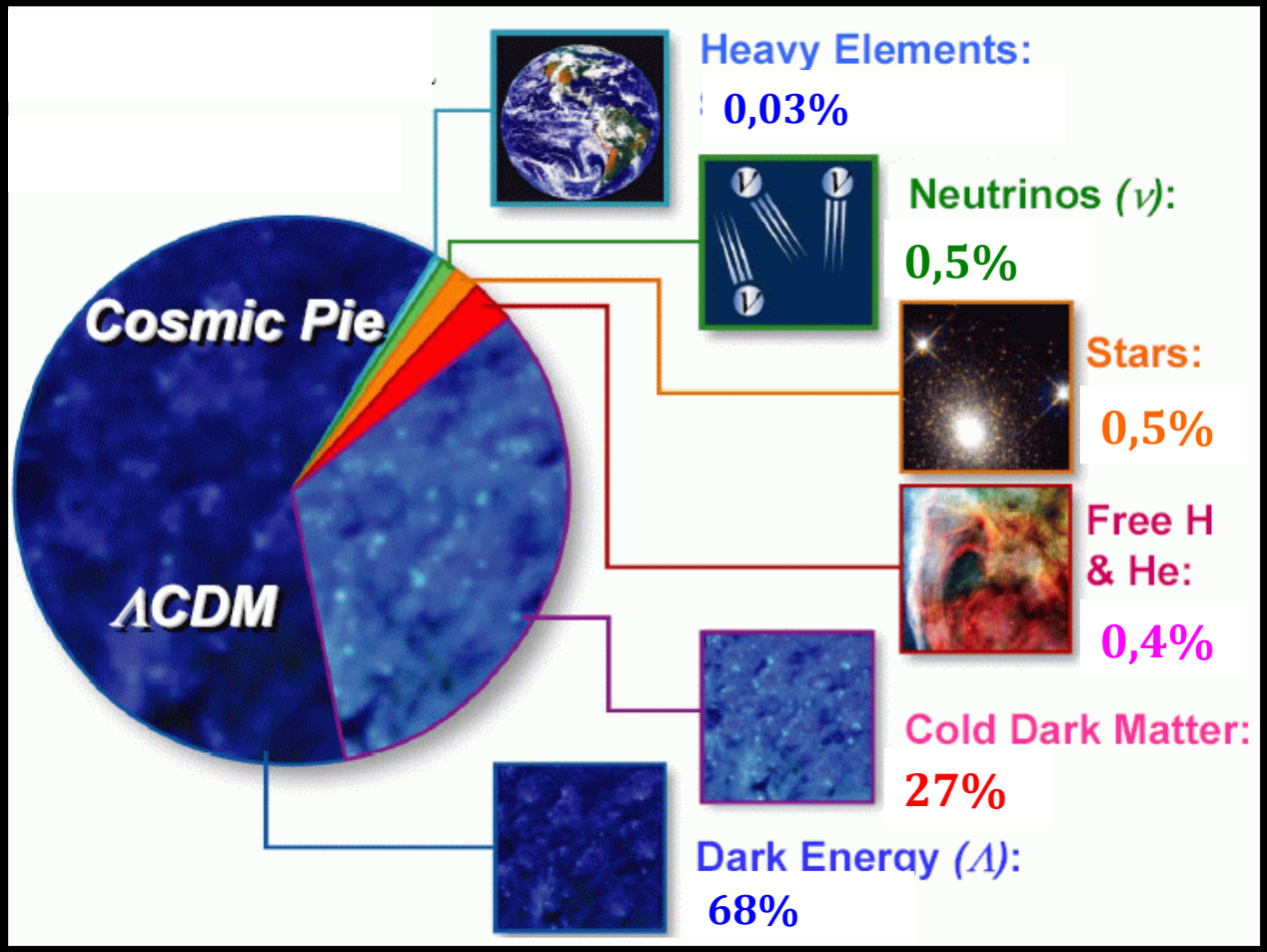
Pressing question 1:
How structure is formed from the quark to the Cosmos ?
Compare the multi-messenger cartographies





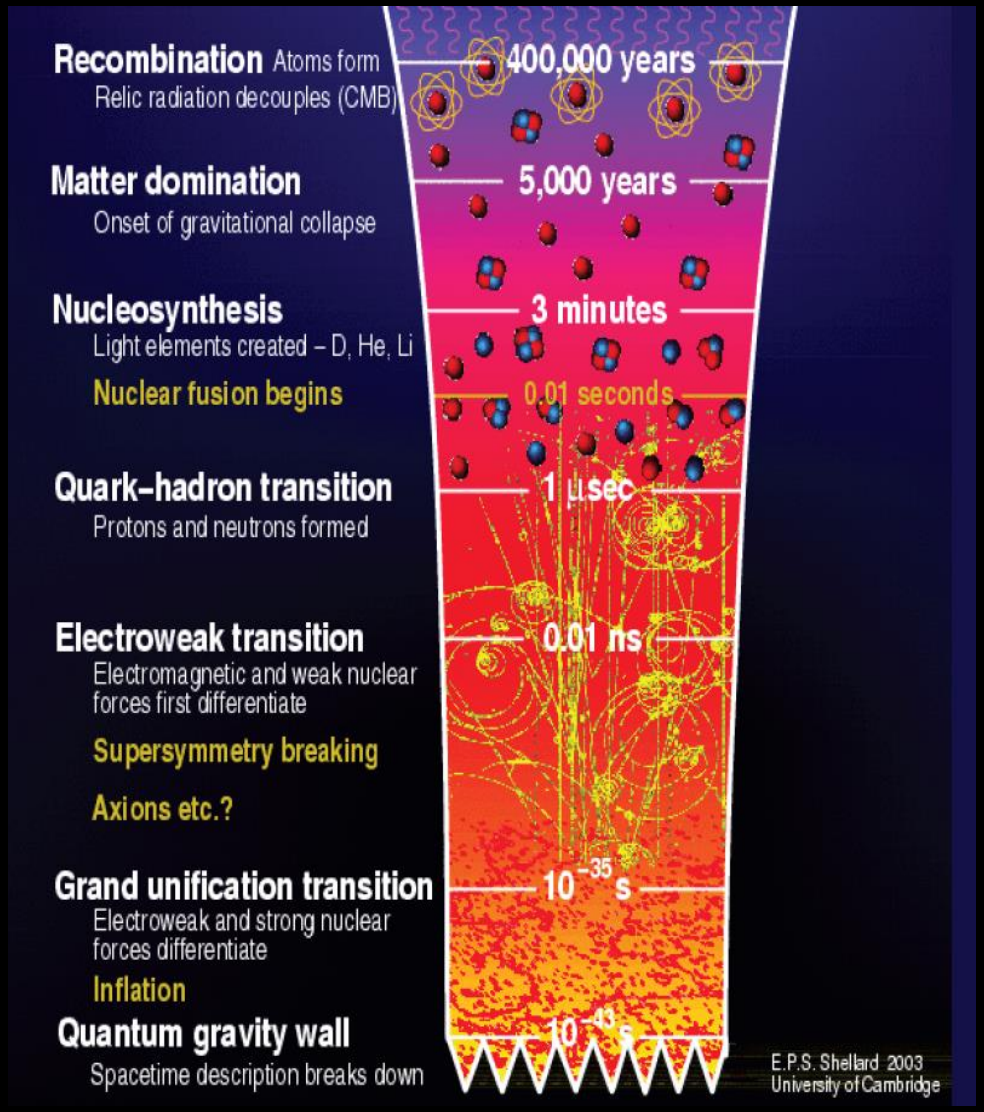


Pressing question 2
What is the nature of dark matter and energy ?



Pressing question 3 :
What lies behind the Horizon of a black hole ?

Pressing question 4 :
What lies behind the Horizon of the electromagnetic wall of recombination ?



Last question: What lies behind the enigmatic smile of Art and Science ?

Cronin and Hawking at a visit at the Louvre November 2006

✓Η έννοια κόσμος, για τους αρχαίους, σημαίνει ταυτόχρονα στολίδι, διακόσμηση αλλά και την λαμπρότητα γενικωτερα, το σύμπαν η την ολότητα των πραγμάτων, πολιτική διακυβέρνηση βασισμένη στο νόμο, αρχή τάξης και αρμονίας που διέπει τόσο τις σχέσεις ανάμεσα στα όντα όσο και την σχέση ανάμεσα στα στοιχεία κάθε όντος, αρετή που επιτρέπει σε κάθε όν να γίνει αυτό που είναι και να διατηρηθεί αυτό που είναι. Κ. Παπαιωάννου