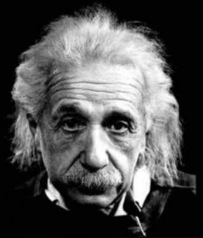
EGO EUROPEAN GRAVITATIONAL OBSERVATORY

Gravitational waves

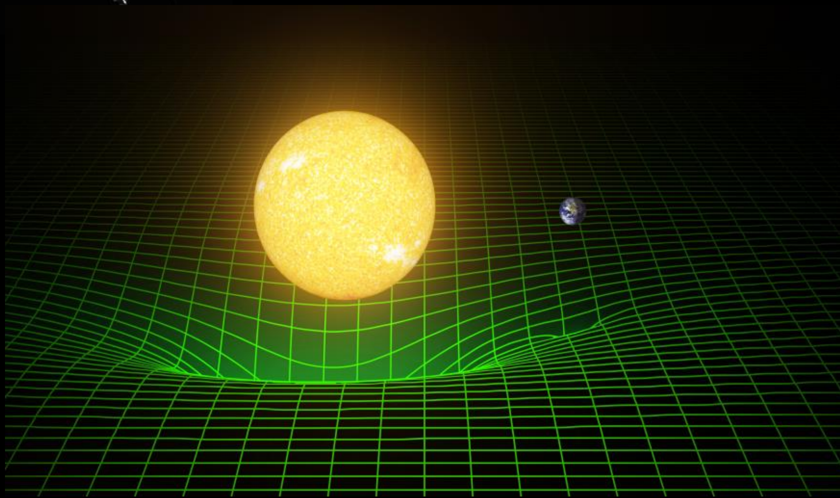
Scientific symposium
20th anniversary of the Auger observatory

J. Casanueva
European Gravitational Observatory

The physics



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.

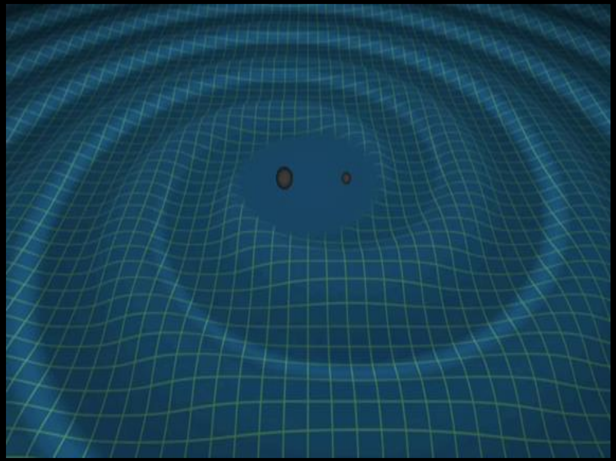
Papers predicting gravitational waves 1916-1918 !

Only extremely violent phenomena can produce detectable GW

BBH of 30 $M_{\odot}$, 500Mpc

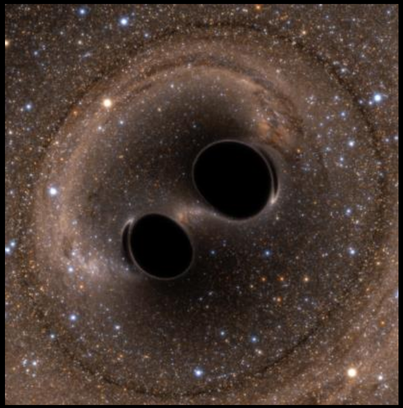
$$h = \Delta L / L \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \Rightarrow h \sim 10^{-21}$$

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



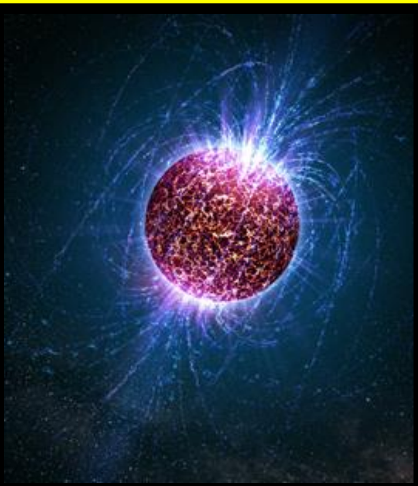
The Astrophysical Gravitational-Wave Source Catalog

Short ➔ long



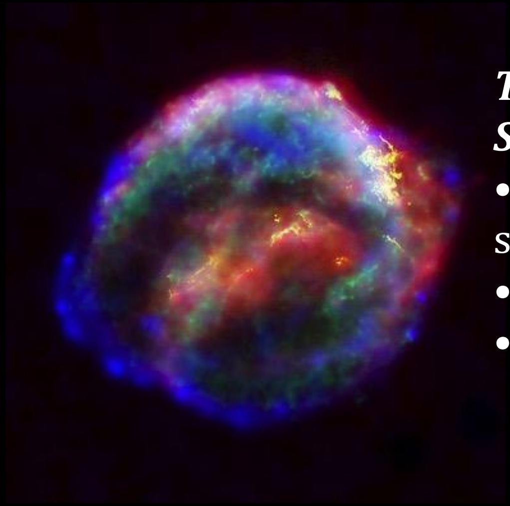
Coalescing Binary Systems CBC

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



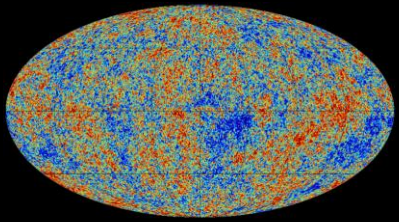
Continuous Sources

- Spinning neutron stars
- Monotone waveform



Transient 'Burst' Sources

- core collapse supernovae
- cosmic strings
- unmodeled waveform



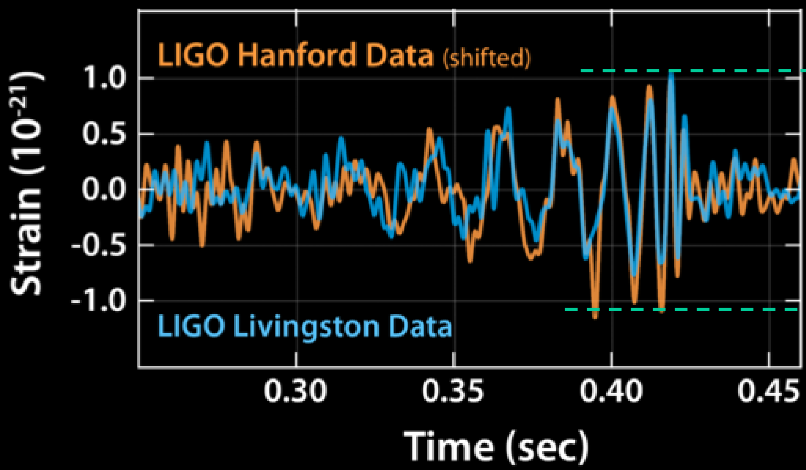
Cosmic GW Background

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

Known ➔ unknown form

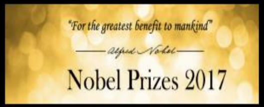
Transient Burst and Continuous sources the next goal!

The first GW event: 14 September 2015

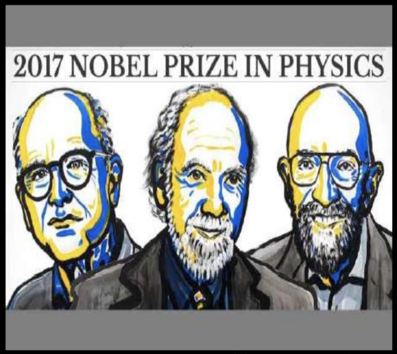


h ~ 10^{-21}
L ~ 4 x 10^{-18} m

Power ~ 4 x 10^{49} W



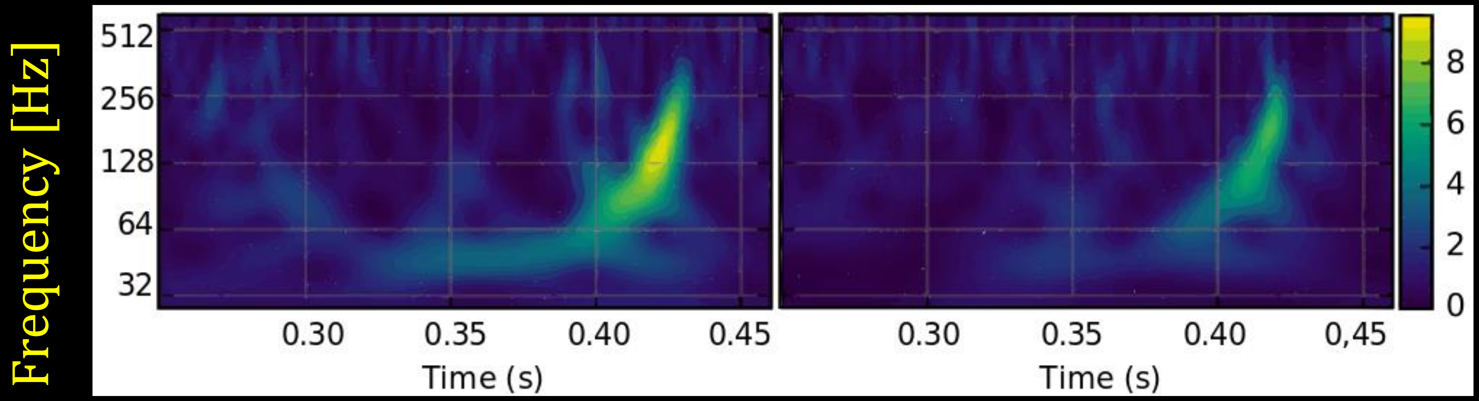
2017 October 3



Rainer Weiss | Barry C. Barish | Kip S. Thorne

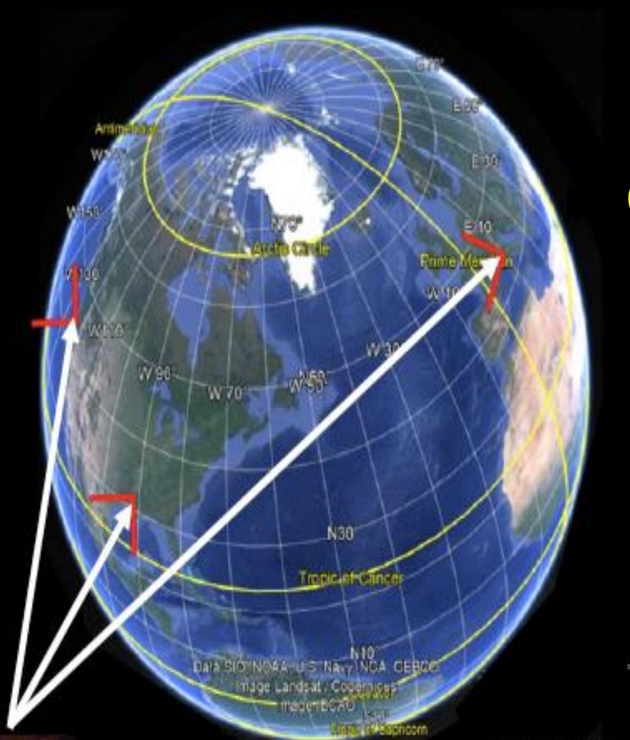
"for decisive contributions to the LIGO detector and the observation of gravitational waves".

Observing run O1



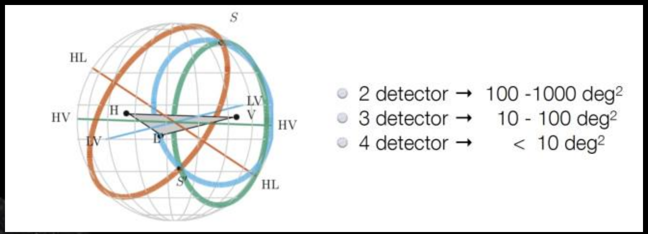
Normalized amplitude

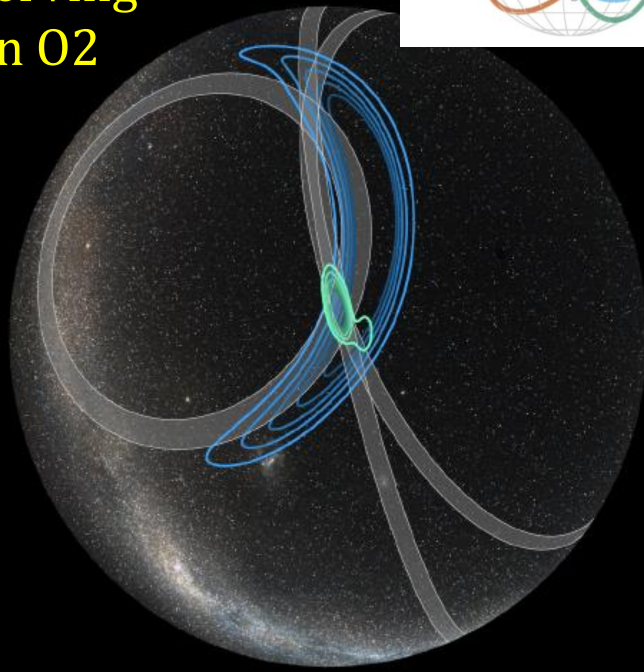
The first GW triangulated event: 14 August 2017



Credit: LIGO–Virgo

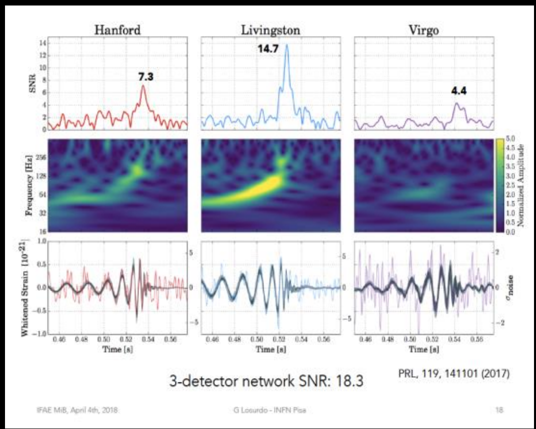
Observing run O2





Credit: Leo Singer

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



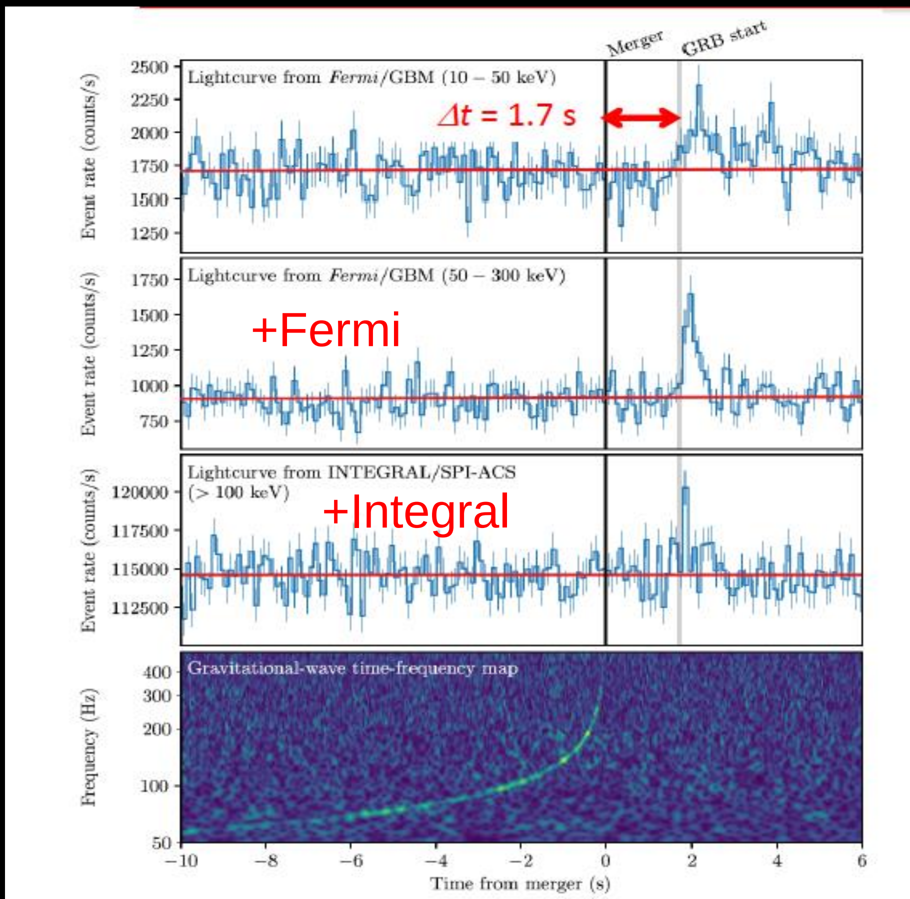
LH 1160 square degrees
LHV 60 square degrees

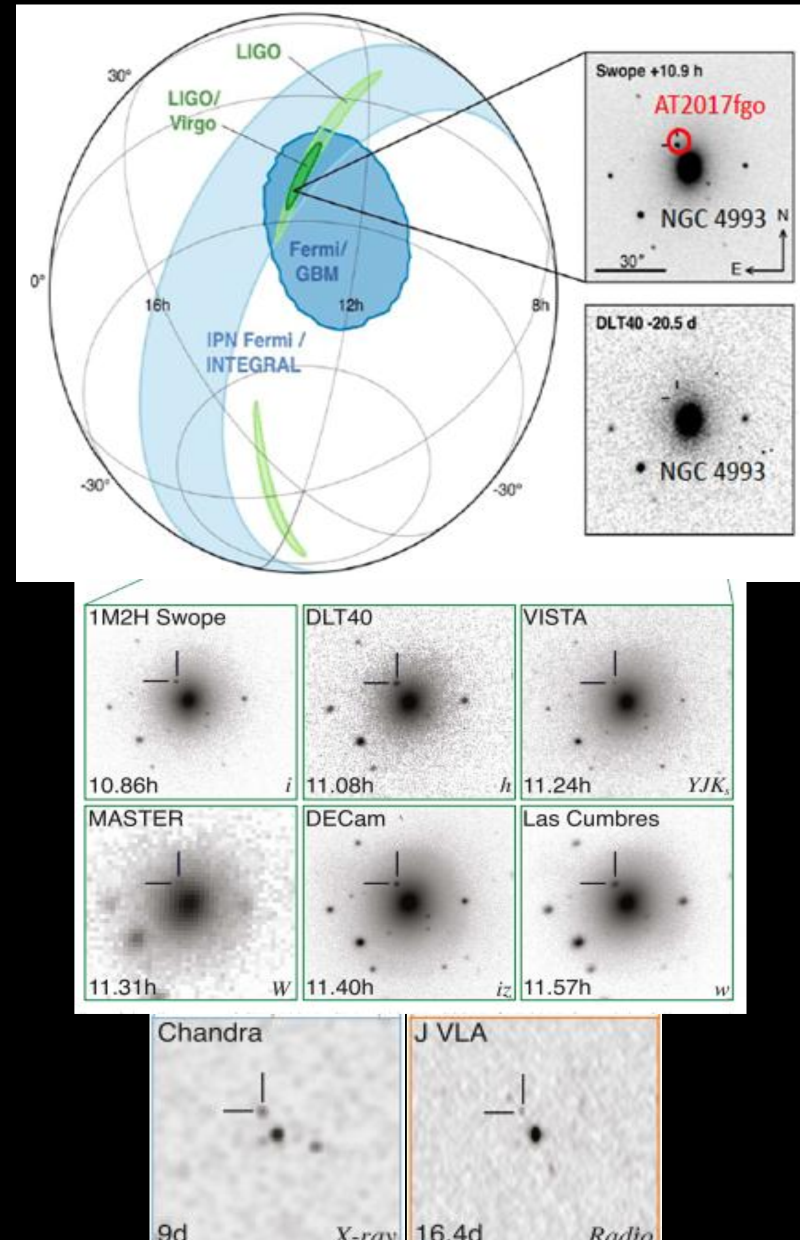
Also measure of GR polarisations

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





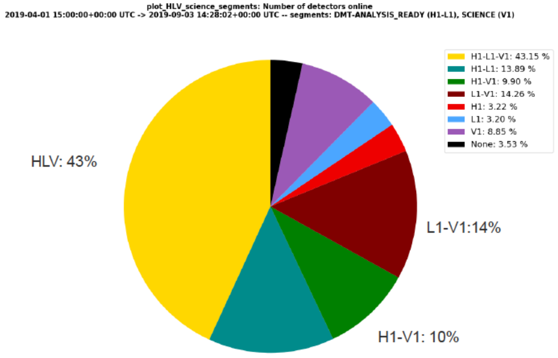
Start of multi messenger astronomy!

Observing runs

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

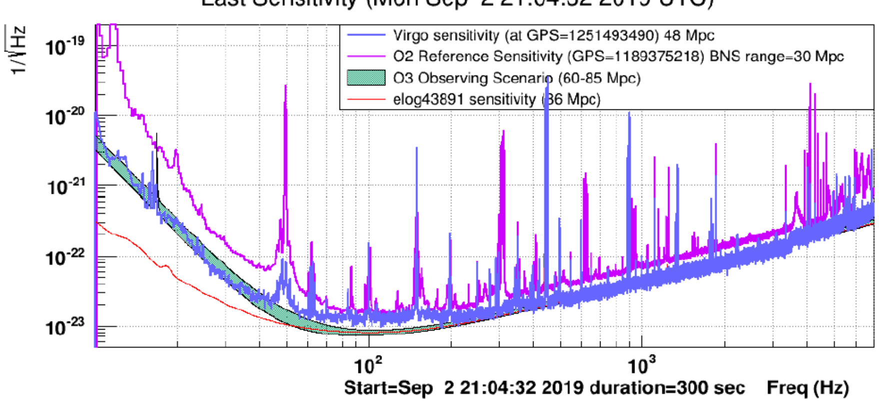
O3 Summary: number of detectors online

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

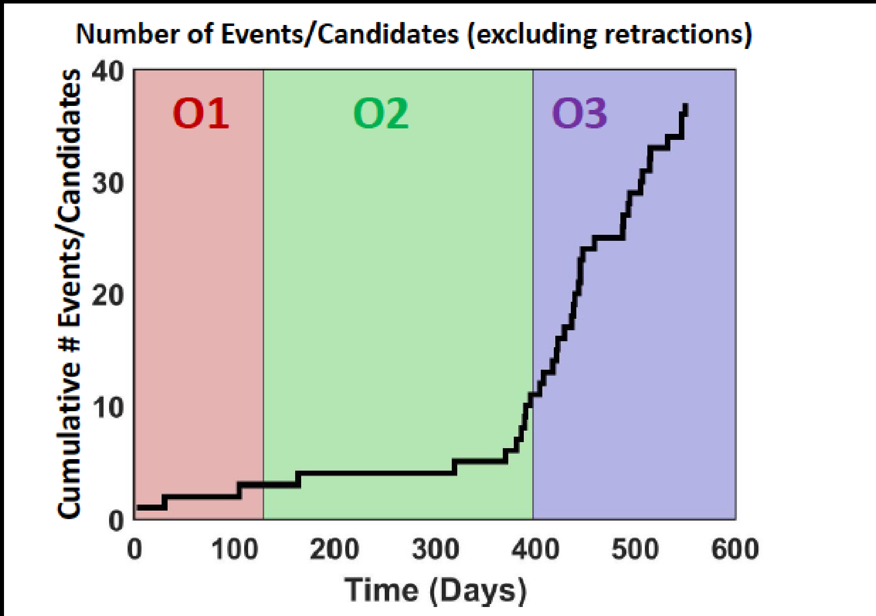


Virgo sensitivity: best value about 50 Mpc

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

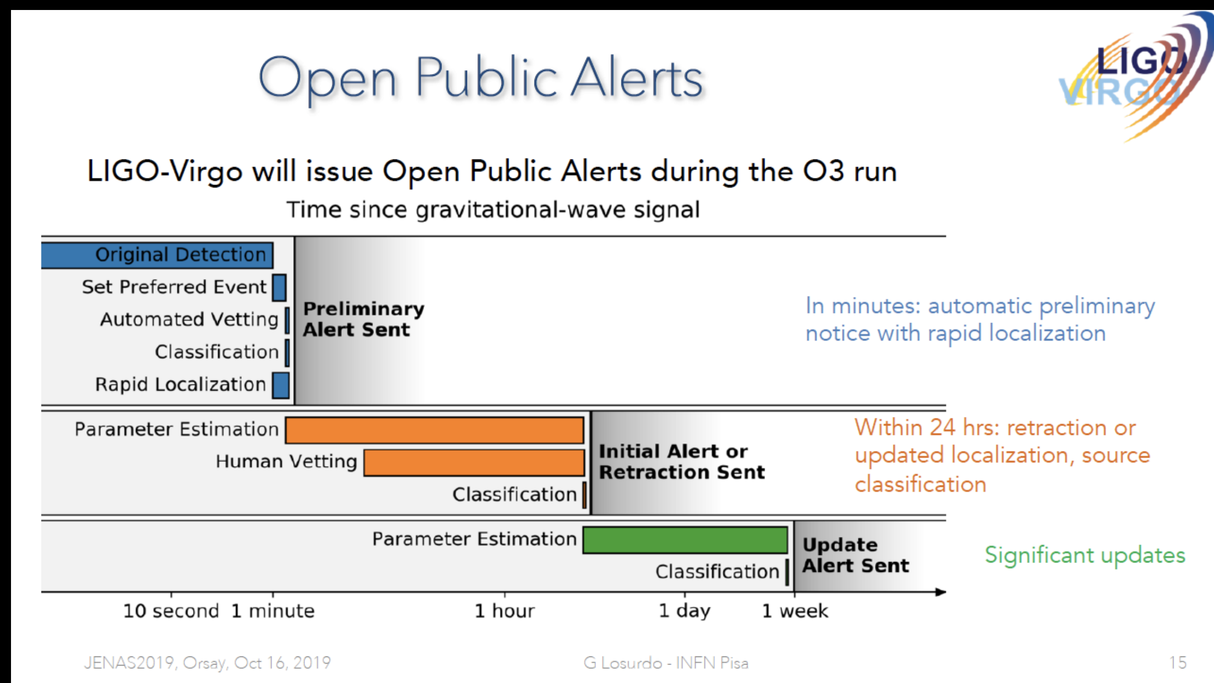
BBH: 53 [9.7, 101] /Gpc^3 /y

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

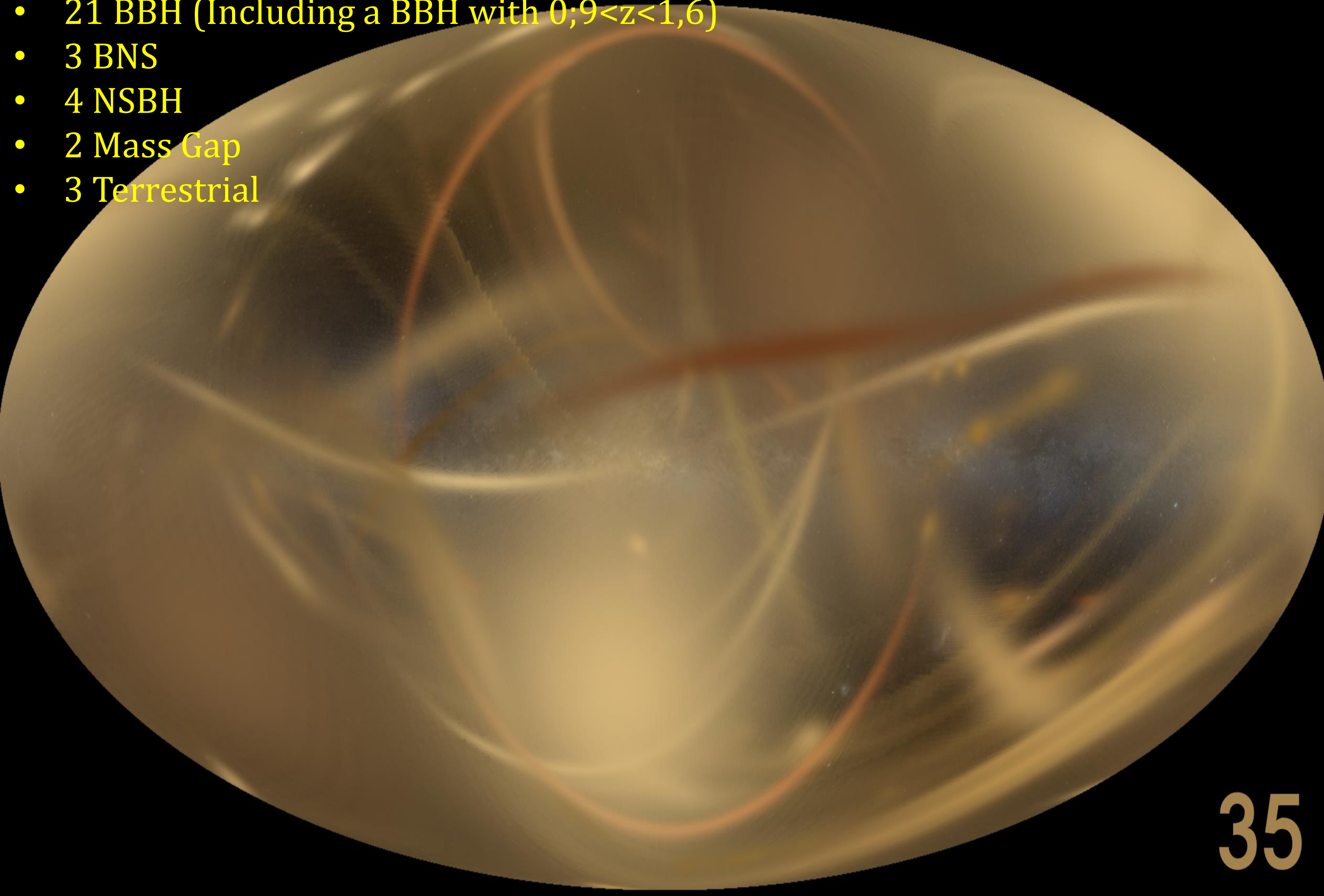
- 10 BBH
- 1 BNS



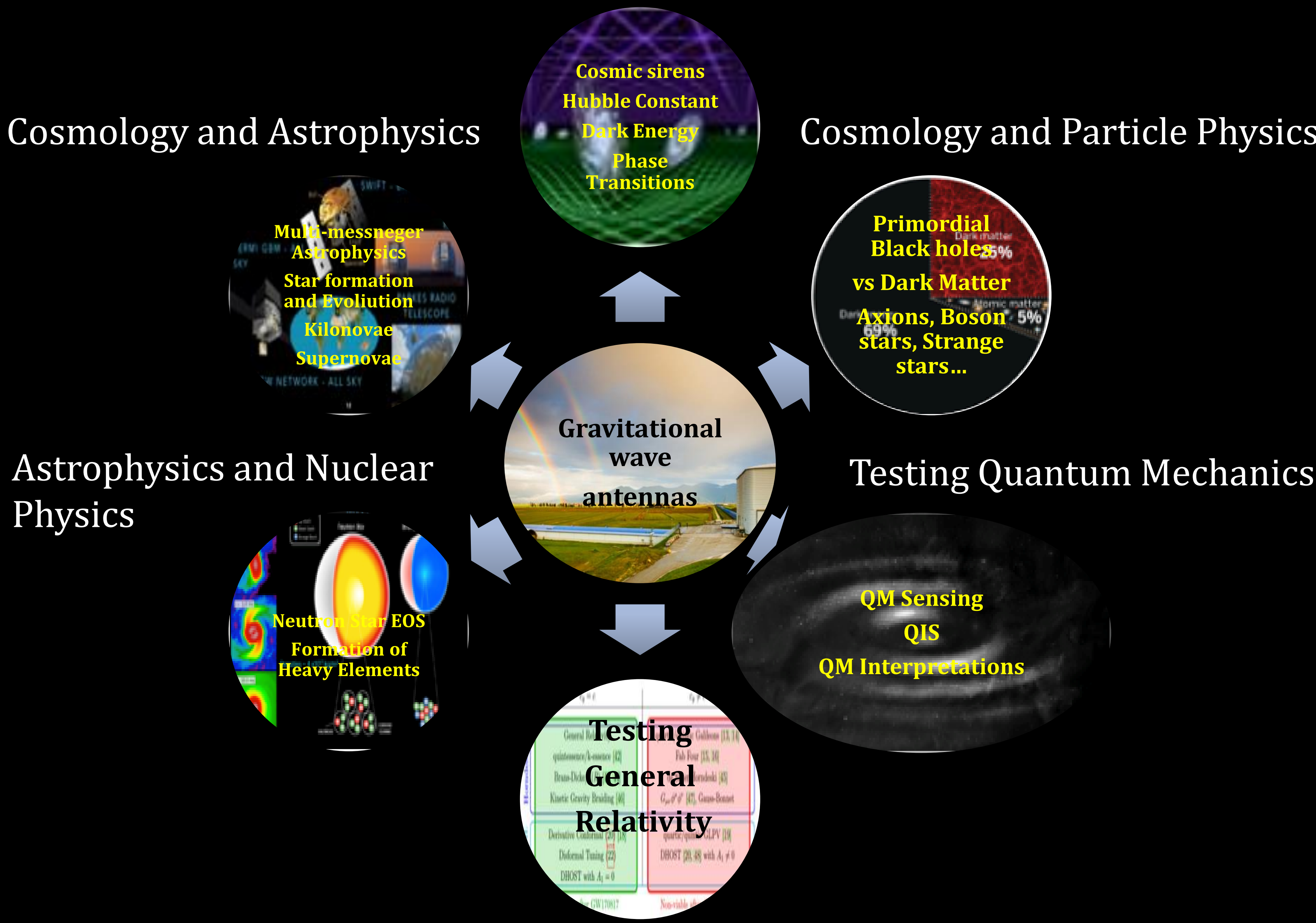
Alerts: LIGO-Virgo currently generate 50% of GCN traffic

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

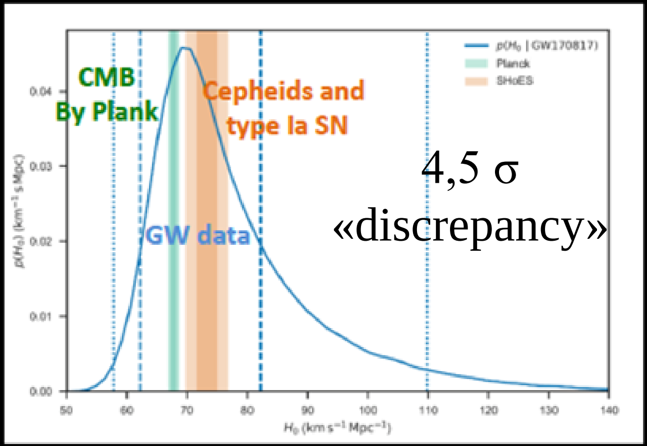


GW and Fundamental Science



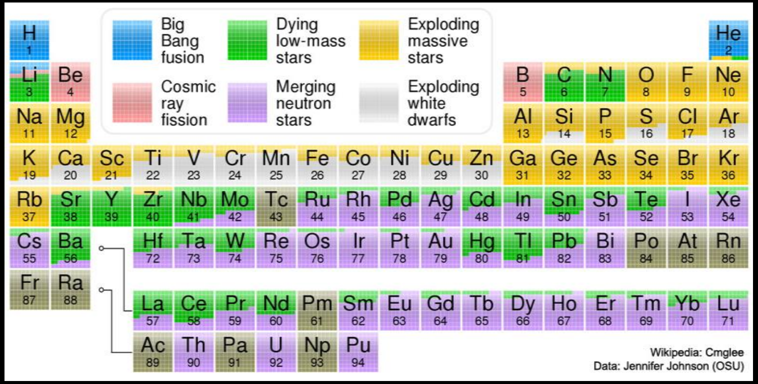
GW and Fundamental Science

Hubble constant



Test the speed of gws

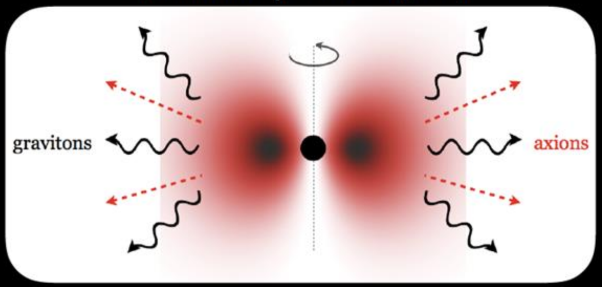
$$-3\cdot10^{-15} \leq \frac{v_{GW}-c}{c} \leq 7\cdot10^{-16}$$

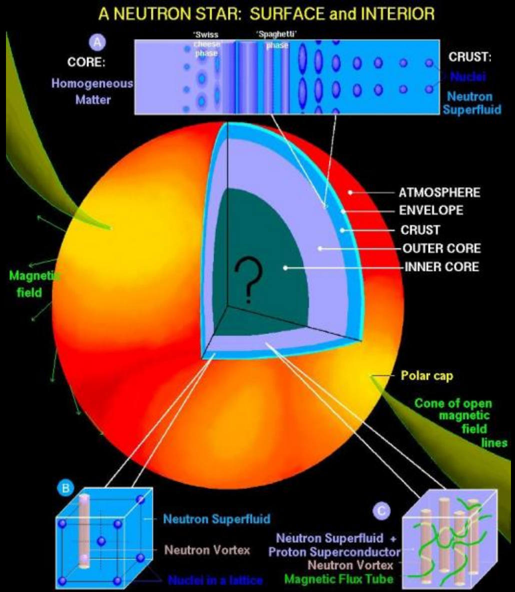


Kilonova: formation of heavy elements (Sd)

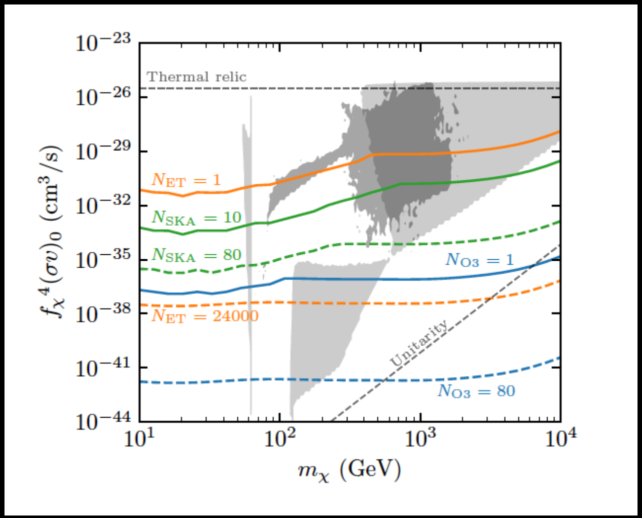
Gravitational atoms and BH super radiance

Arvanitaki+ Phys. Rev. D83 (2011)





Dark matter: Primordial Black Holes



Super dense matter studies measuring tidal deformability of neutron star mergers

The detector

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

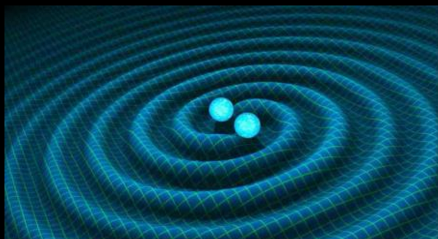
European support

2011 The first Astroparticle Physics European Consortium (APPEC) priority roadmap included Advanced Virgo

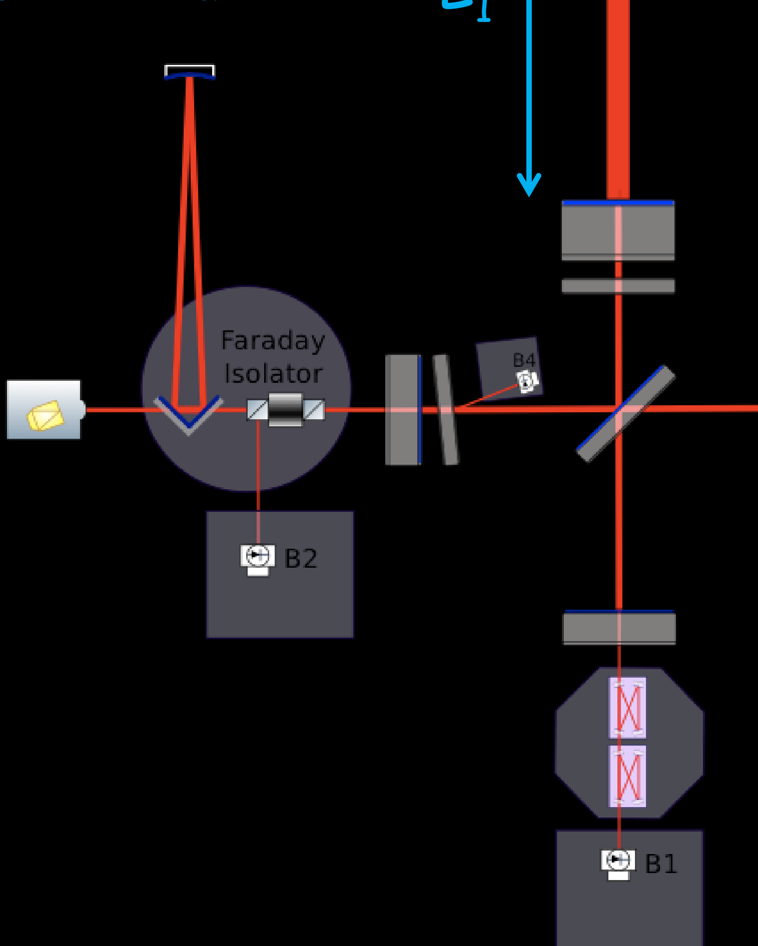
From the APPEC input to CERN European strategy:

I. Cooperation with respect to dark matter searches….
II. The development of the synergies between the PP community and the next generation of observatories of Multi-messenger Physics and in particular the third-generation gravitational-wave observatory Einstein Telescope (ET), on science, infrastructure, detector R&D, computing and governance.
III. Vigorous continuation of CERN ν platform .
IV. The support of European Centre for AstroParticle Theory (EuCAPT)

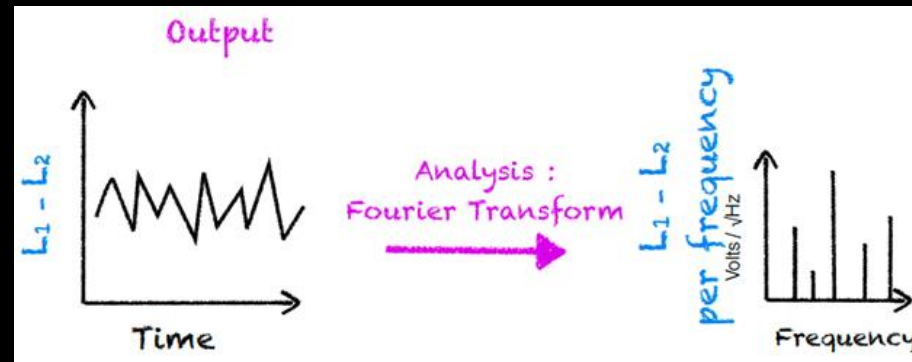
The Advanced Virgo antenna

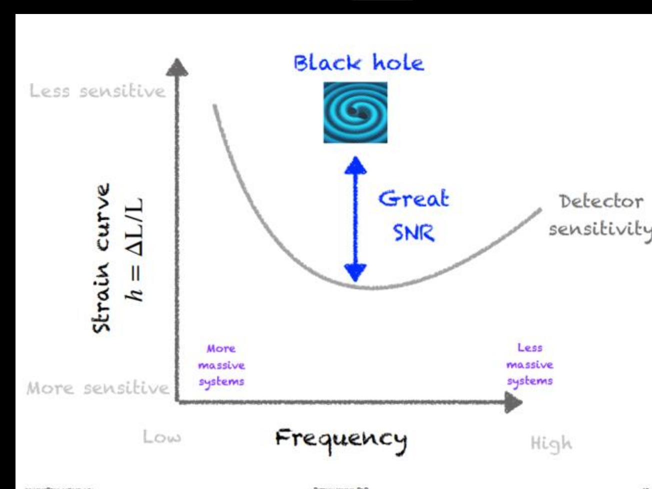


$L_1 + \Delta L$; $L_2 - \Delta L$



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

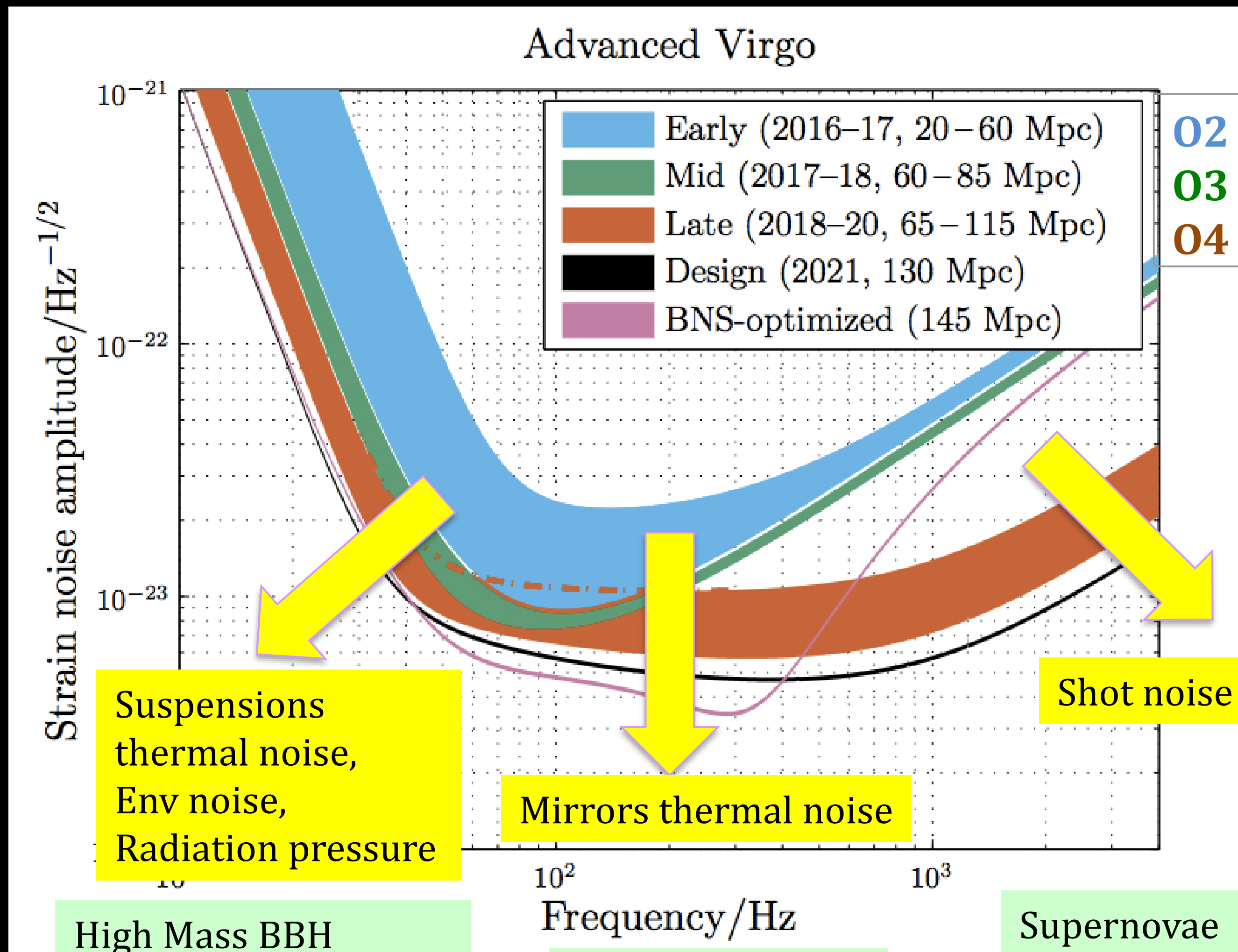
Residual gas (phase noise)

Residual laser noise

Stray-light

Seismic vibration

Newtonian noise



High Mass BBH
NS periodic emission

BBH mergers
BH ring down

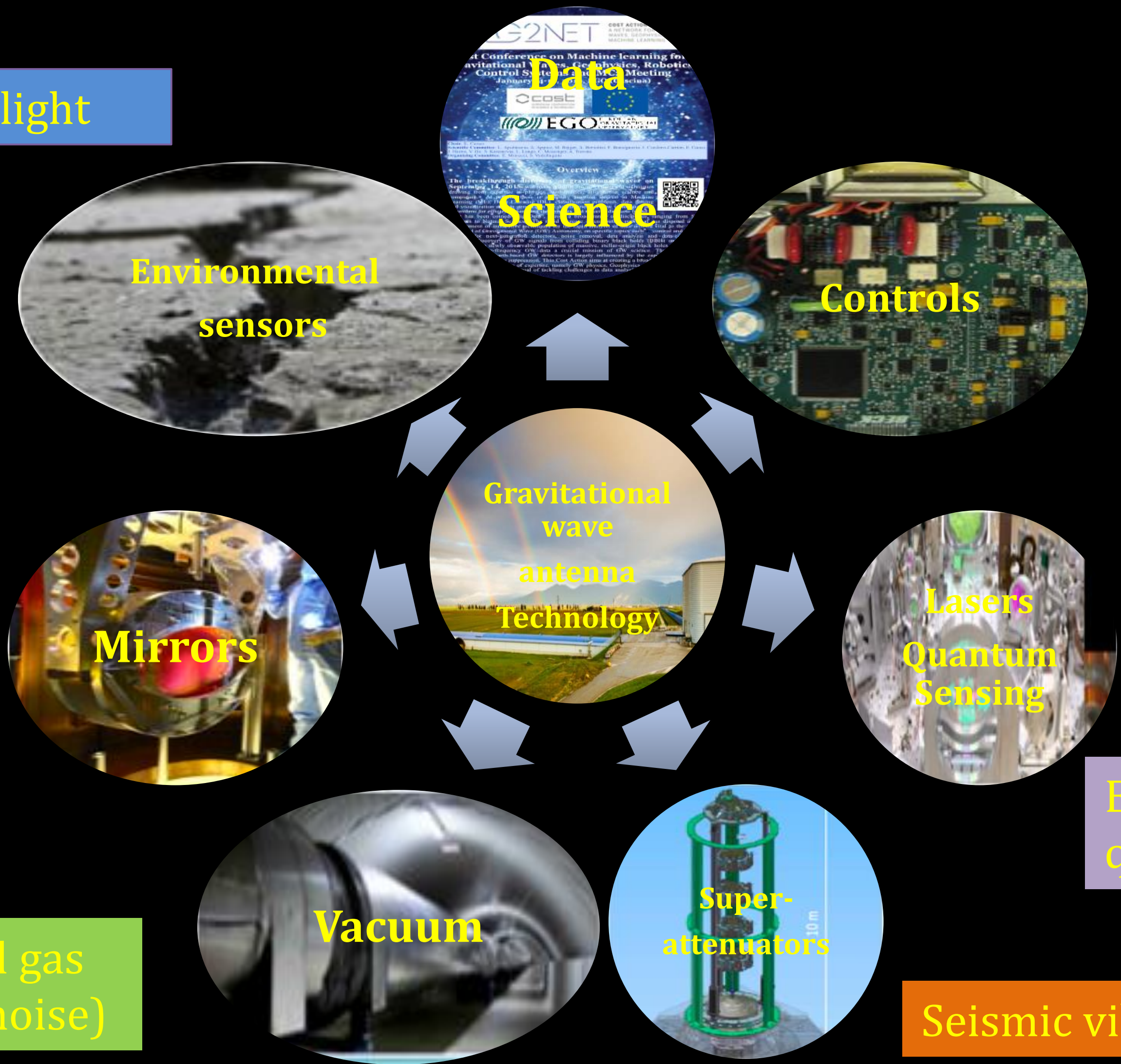
Supernovae
NS transients

EGO/Virgo and Technology

State of the art, challenges on many fronts:

Stray-light

Newtonian noise



Residual laser noise

Thermal noise (coating + suspension)

Radiation pressure fluctuation

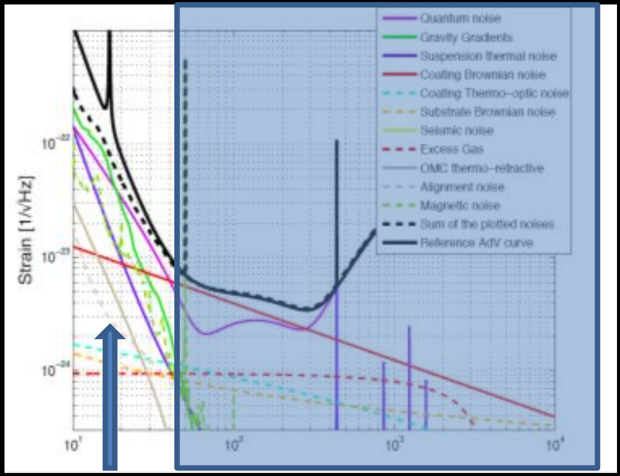
EM field quantum noise

Residual gas (phase noise)

Seismic vibration

Low frequency Noise

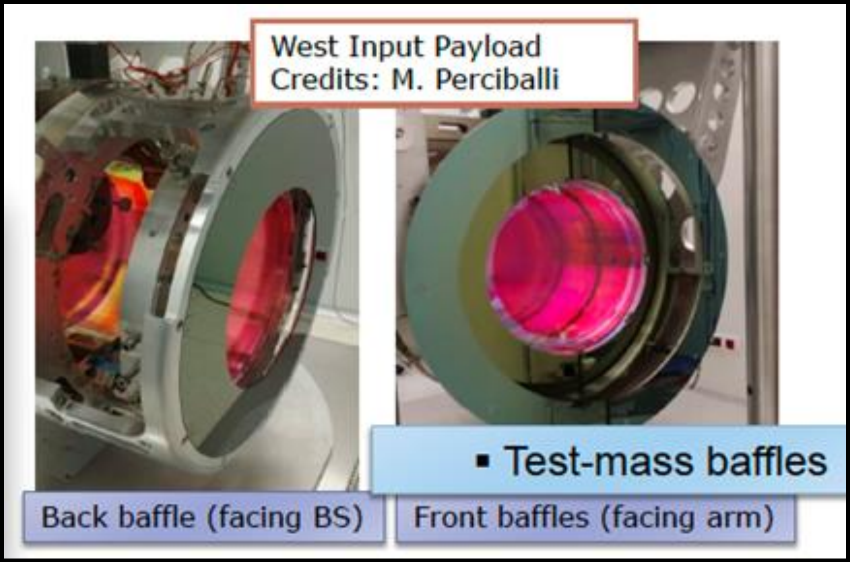
- **Seismic noise**
  - Reduced by suspending the mirrors from extreme vibration isolators (attenuation > 10^12) -> ***Superattenuator***



- Technical noises of different nature are the real challenge in this range, ex. **Stray light**

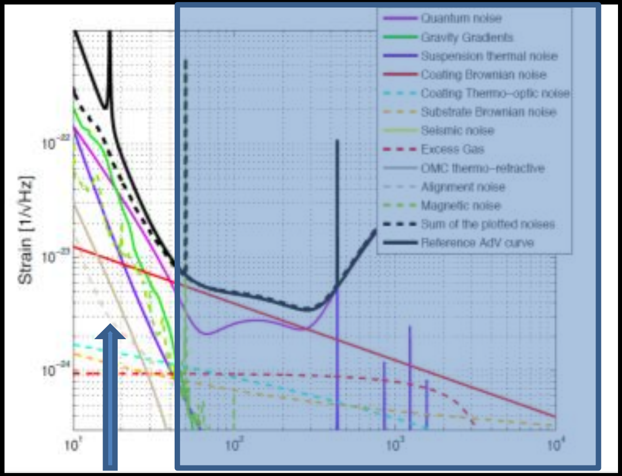
▪ A tiny amount of stray light coupling with the fundamental mode after "probing" the vibrations of infrastructures will bury any gravitational signal

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



once emitted, a photon has to be caught!

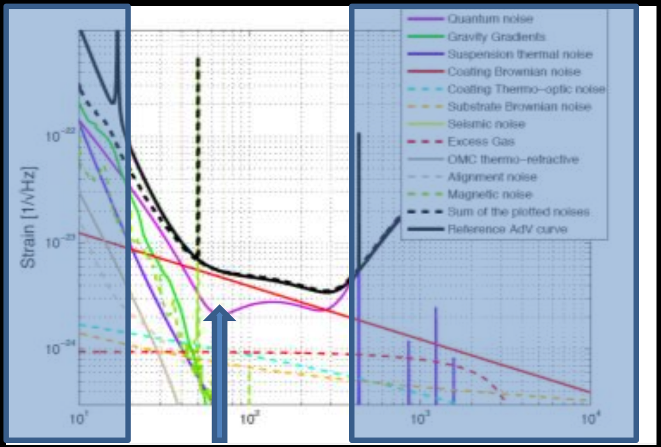
Low frequency Noise

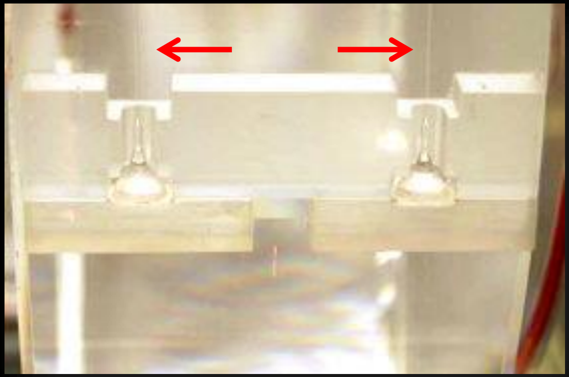


- Future: Newtonian Noise Cancellation
  - Ultimate limit for ground-based detectors: gravity gradient noise
  - It cannot be shielded -> active cancellation is needed based on sensors

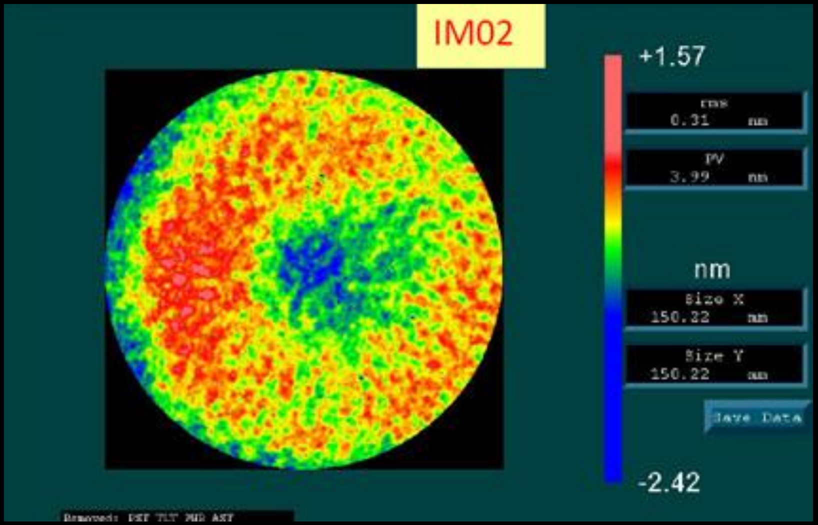
Mid frequency Noise

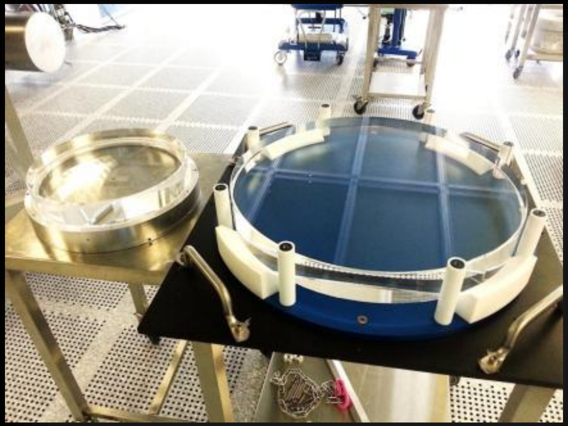
- Thermal noise
  - Coming from mirror coatings and suspensions
- Reduced by:
  - ***Larger beam spot*** (sample larger mirror surface)
  - Test masses suspended by fused silica fibers (low mechanical losses)
  - Mirror coatings engineered for low losses





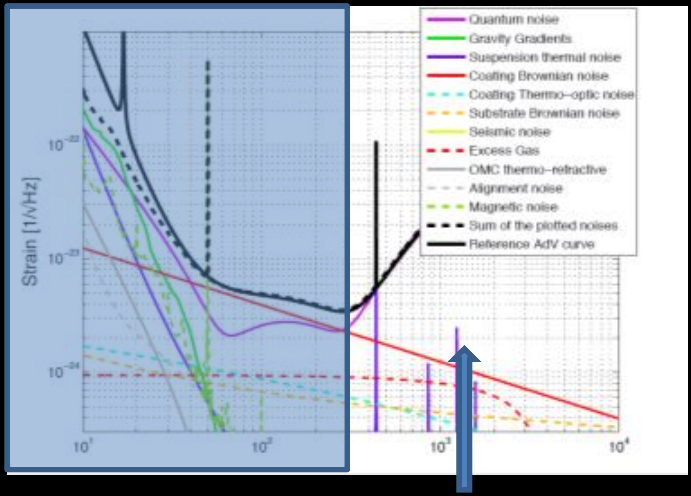
LMA is able to achieve the best coatings in the world for laser interferometry



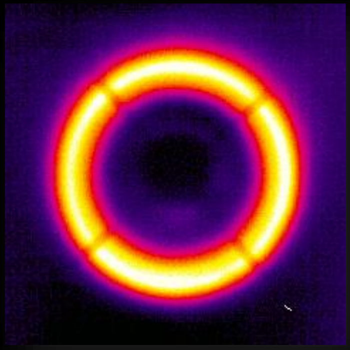


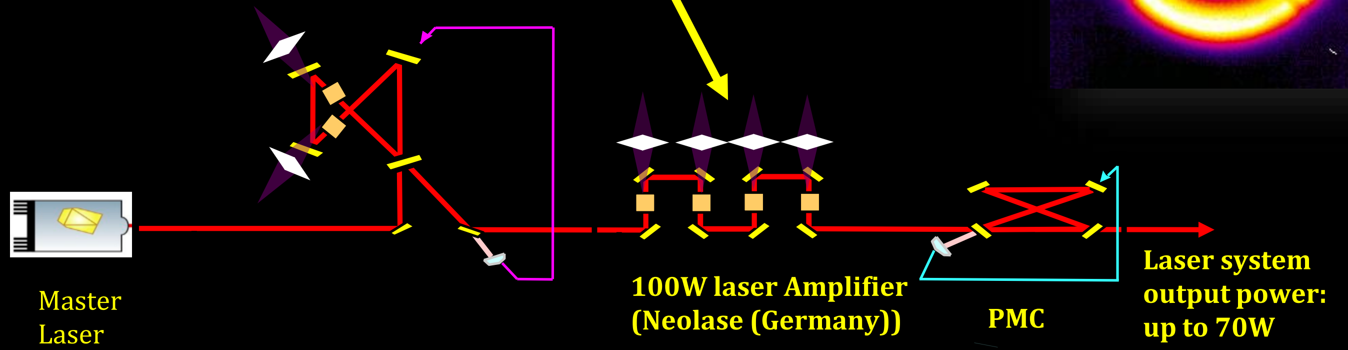
High frequency Noise

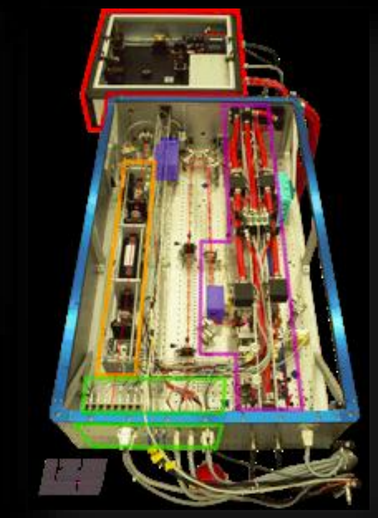
- Laser Shot noise
  - Improved by increasing the power: so far 28W
- Requires:
  - Heavy, low absorption optics (substrates, coatings)
  - Sophisticated systems to correct for thermal aberrations
  - Sophisticated injection system



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





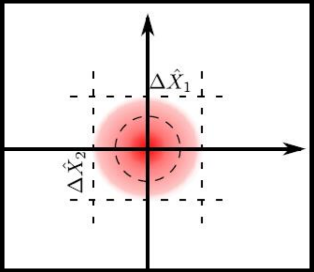


New laser amplifiers (solid state, fiber)

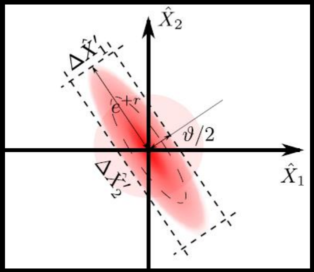
High frequency Noise

- Laser Shot noise
  - Improved by injecting squeezed light

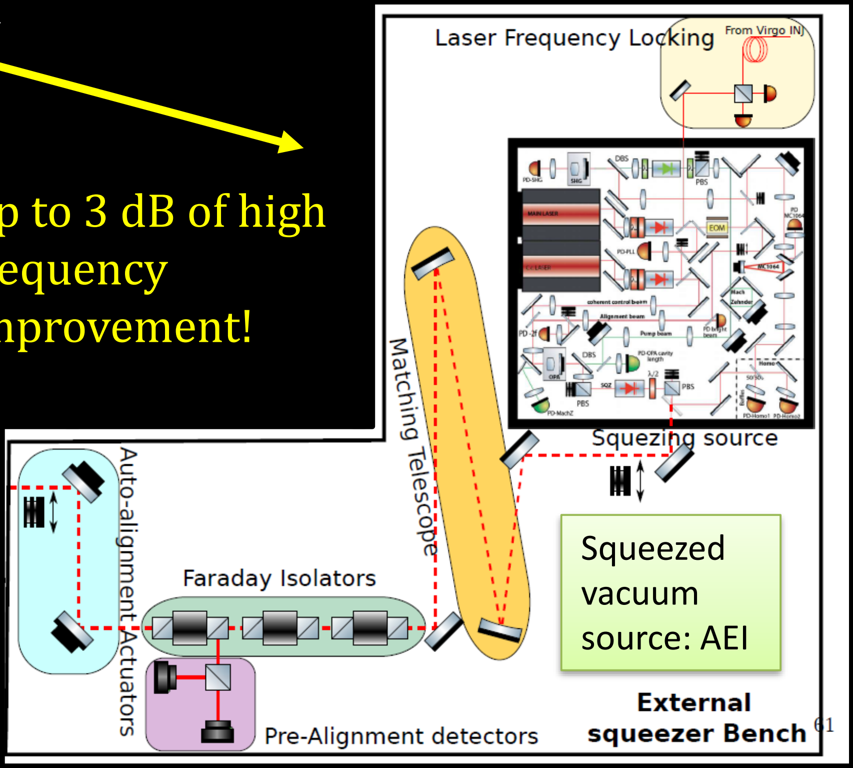
Coherent vacuum state



Squeezed vacuum state

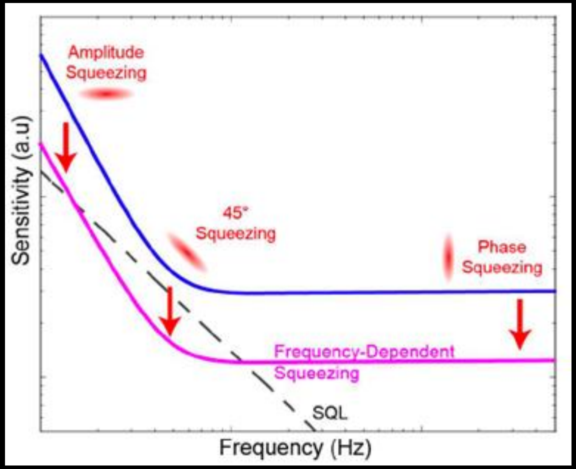


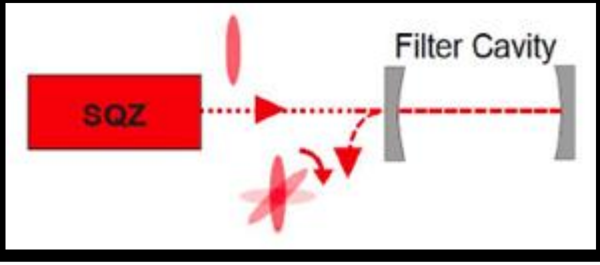
- Requires: Very complex optical design



Up to 3 dB of high frequency improvement!

- Future: Frequency Dependent Squeezing

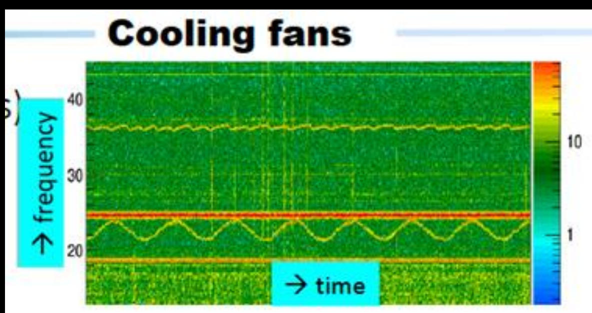




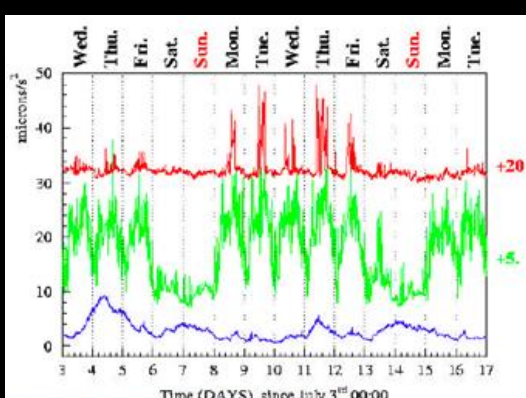
GW environmental noise

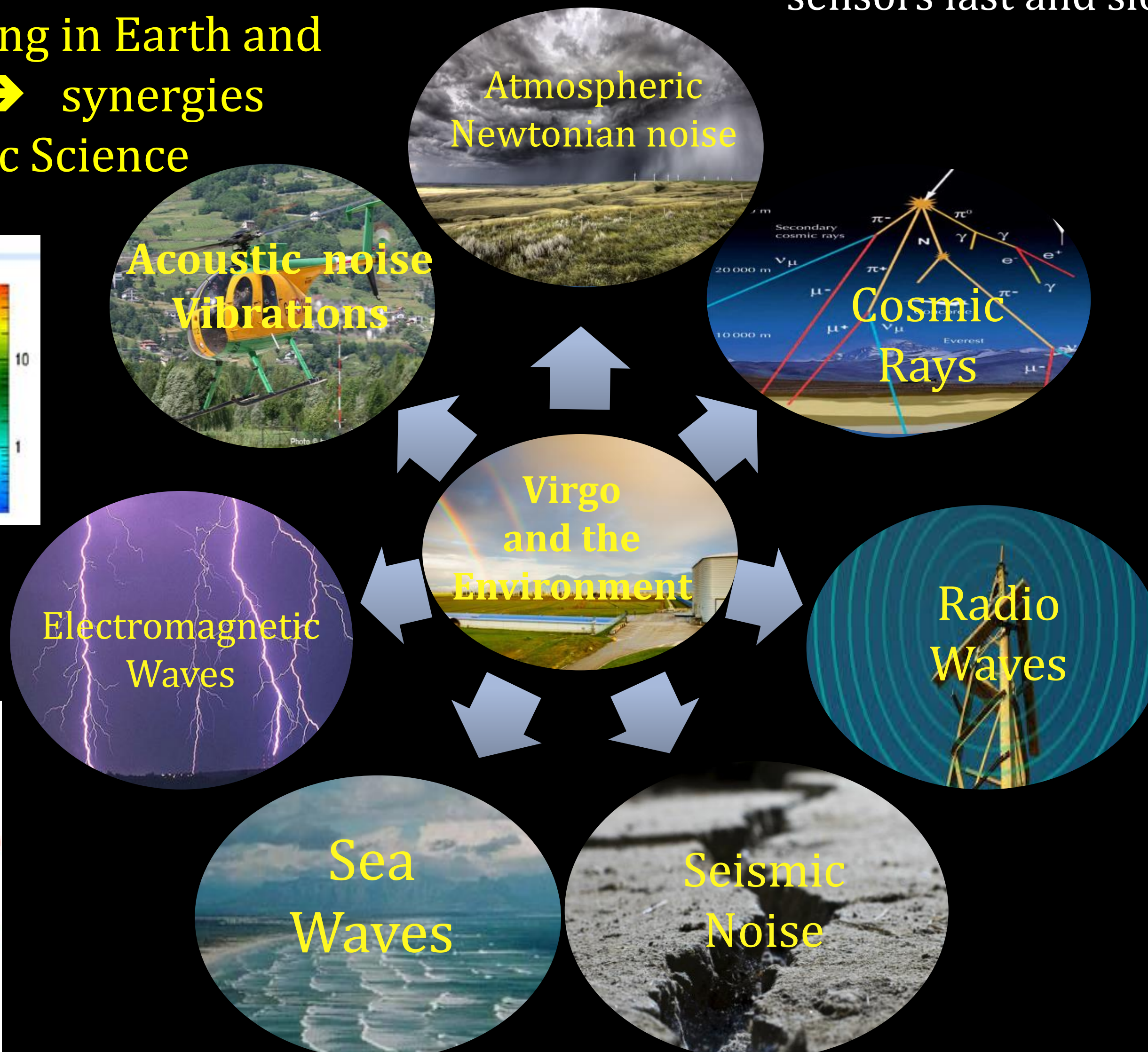
- Virgo needs to understand very well environment noise
- Highest ever embedding in Earth and Astospheric science ➔ synergies with Geo/Atmospheric Science

Close to 2000 environmental sensors fast and slow



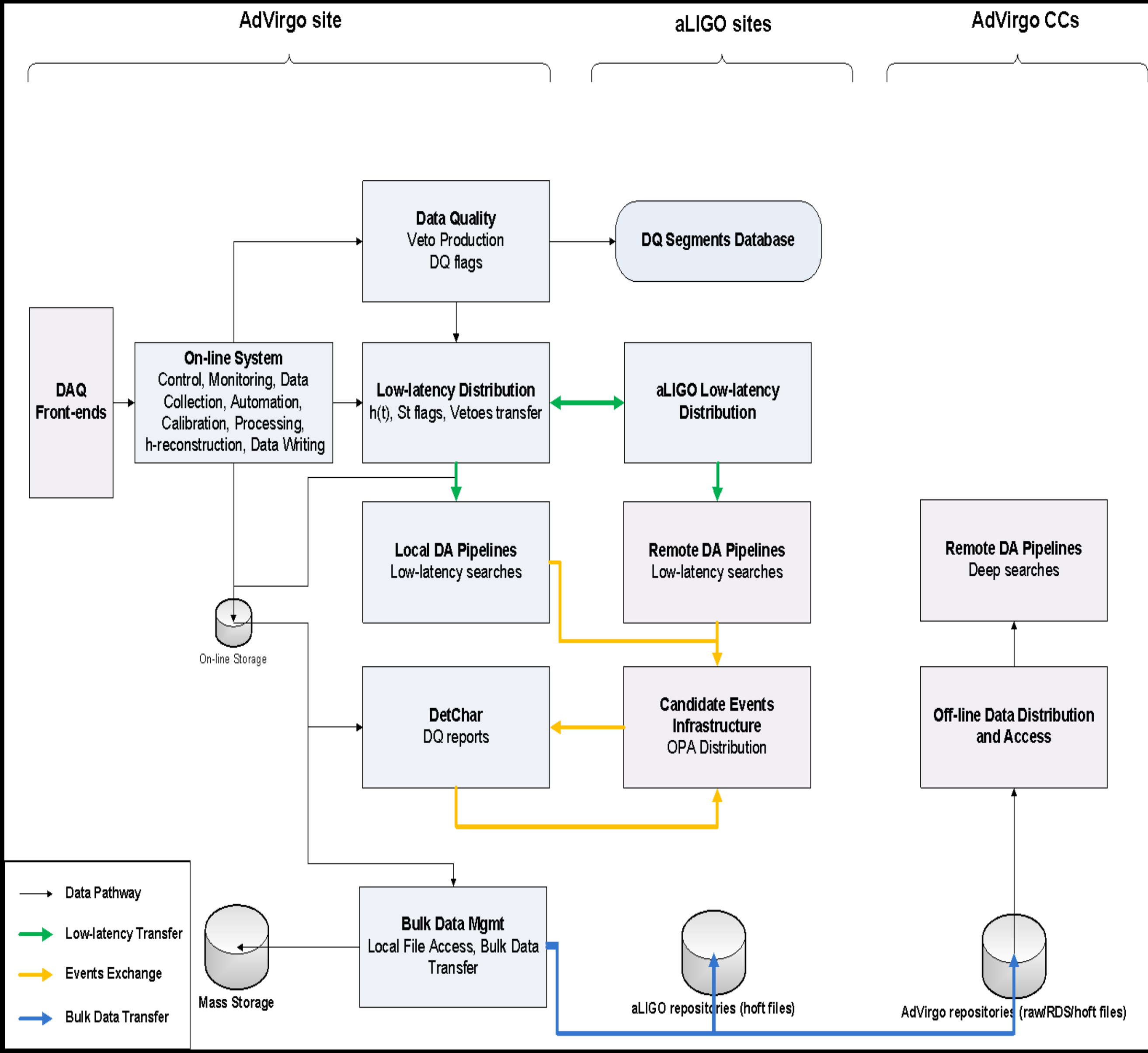
Traffic noise





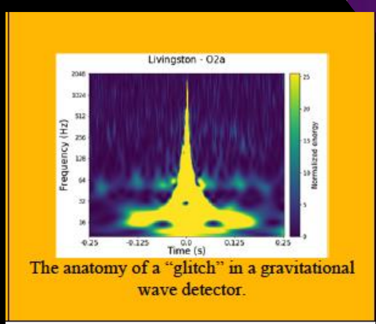
A global network for computing

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

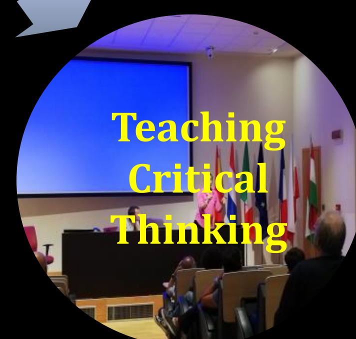


EGO/Virgo and Society

Multimessenger room : T. Saraceno
“On Air” Palais de Tokyo



The anatomy of a “glitch” in a gravitational wave detector.



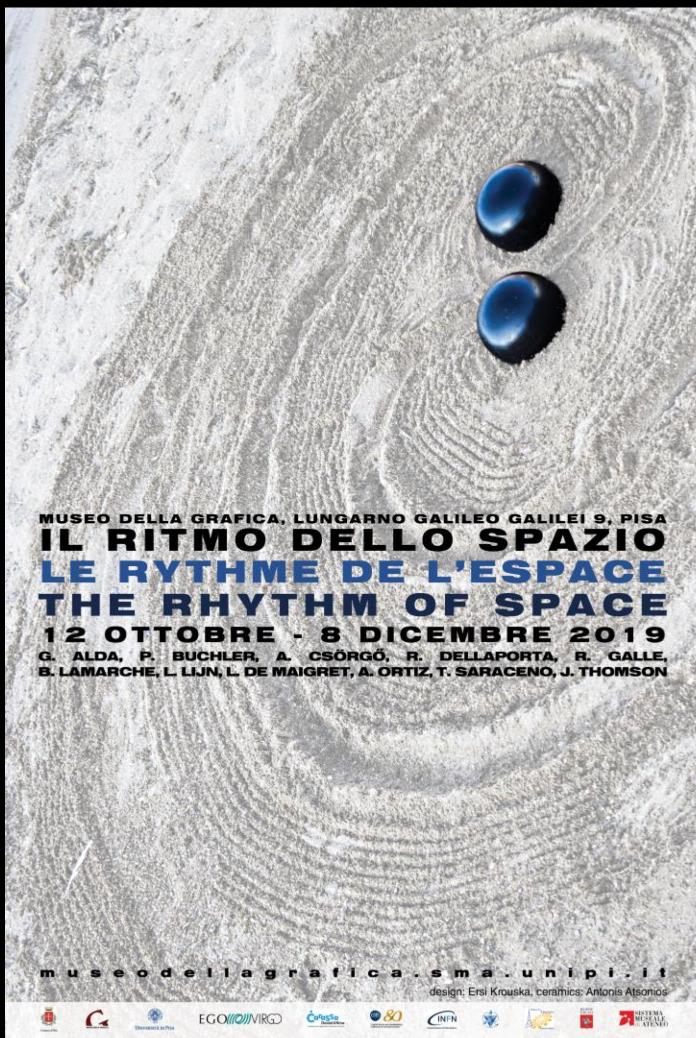
Multisensorial studies with Wanda Diaz-Merced
« The average person looks without seeing, listens without hearing » Leonardo

REINFORCE
Classify Glitches

Most activities funded by EU programs

An exhibition on Art and Science
Rythm of Space

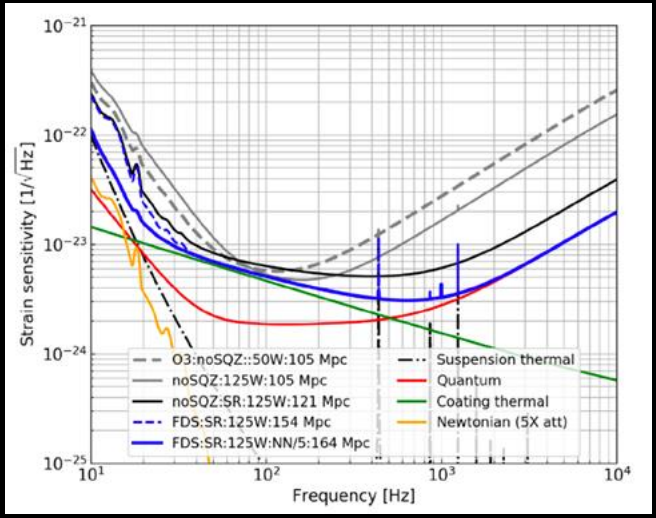
T. Saraceno, L. Lijn, A. Csorgo, B.Lamarche, R. Dellaporta, G. Alda/A. Ortiz...



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

The Future

AdV+

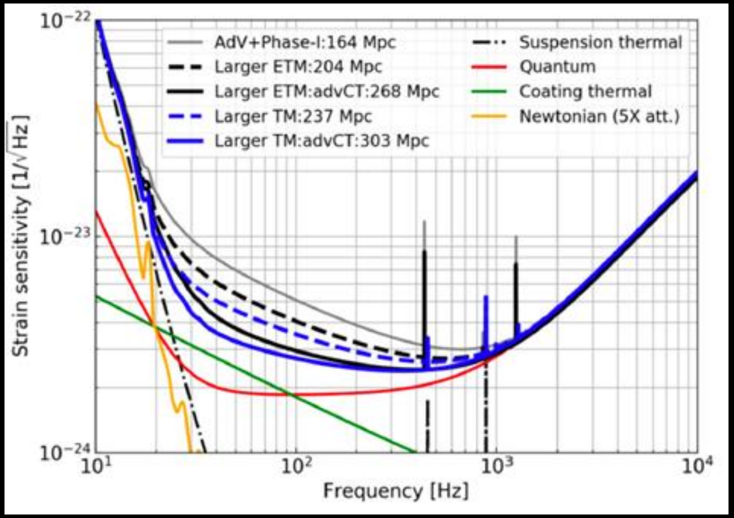


Phase I (O4): reaching the thermal noise wall

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

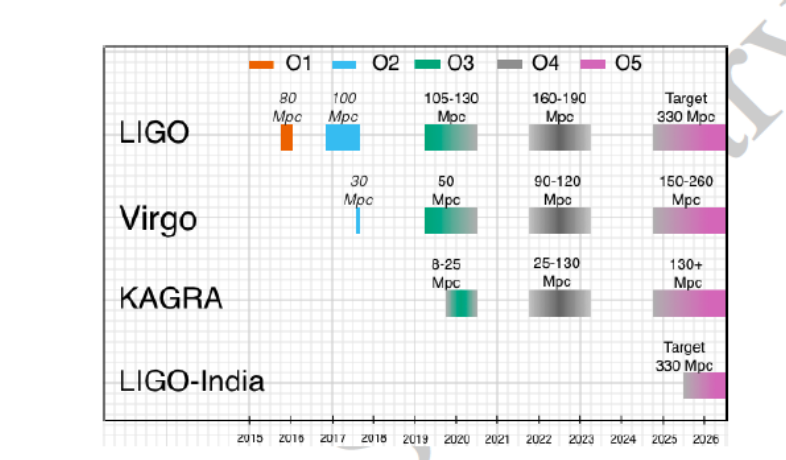


- The sensitivity can improve up to *160 Mpc on Phase I* and up to *300 Mpc on Phase II!*
- This will increase the **number of detections** and the sensitivity to **new phenomena** (Equation of state of Neutron stars for example!)

The next 10 years

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

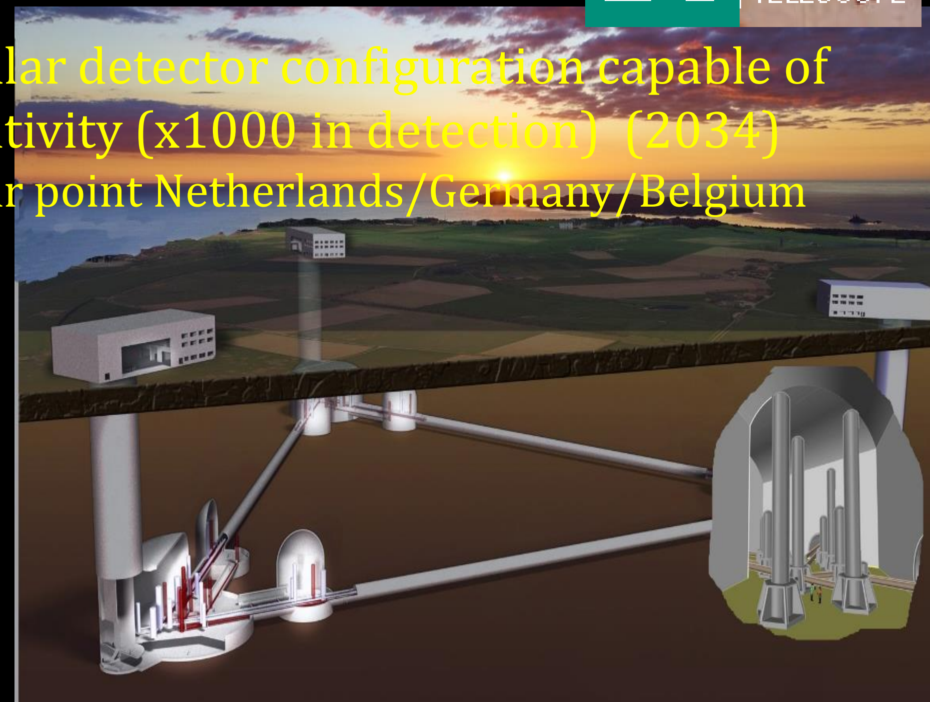
- A global multimessenger network:
  - ✓ GW and EM observatories (optical to radio)
  - ✓ GW and Space satellites (FERMI, INTEGRAl, ATHENA,..)
  - ➢ GW and large surveys (DES, LSST, DESI)
  - ➢ GW and high energy observatories (CTA, KM3NET/ICECUBE, Auger,..)00



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)

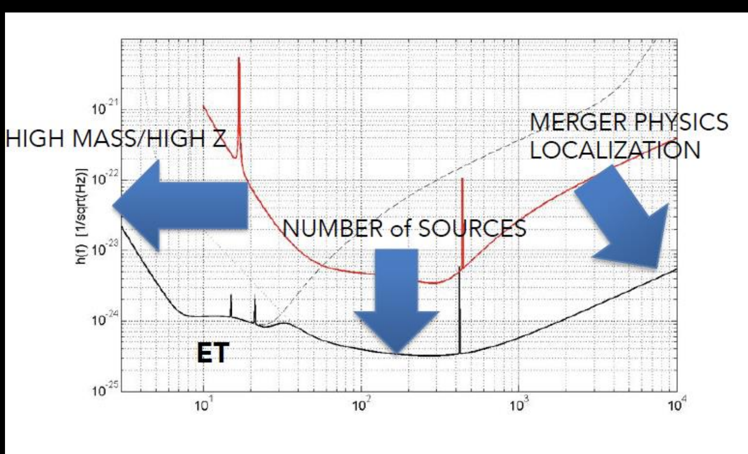
Two candidate sites: Sardinia, Triangular point Netherlands/Germany/Belgium



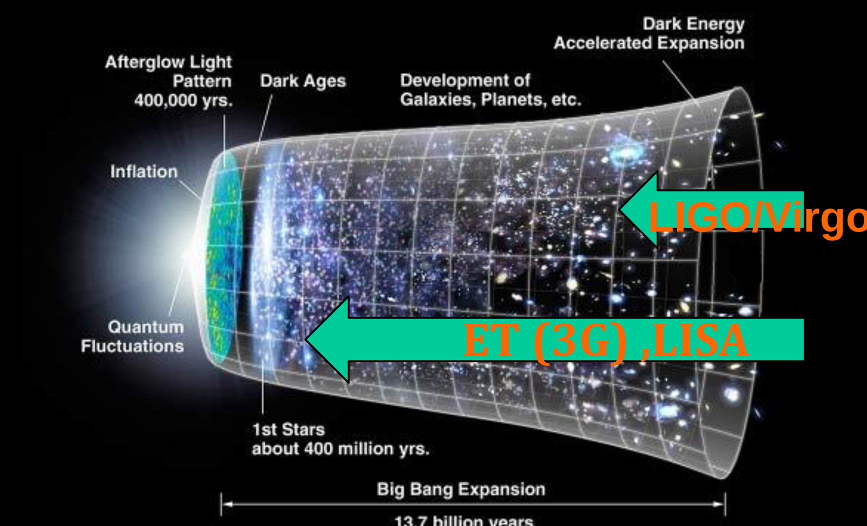
Tentative planning:

- 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…

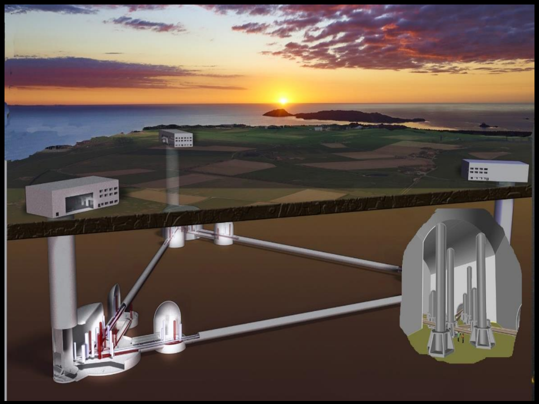
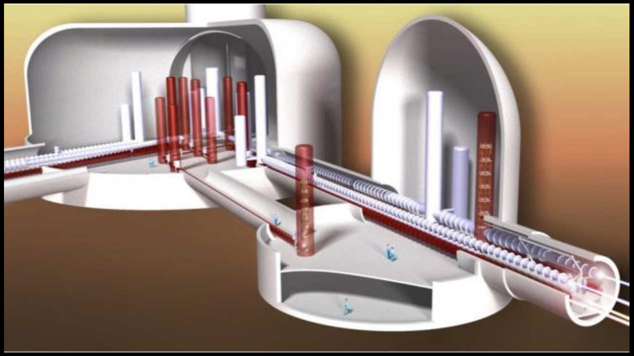
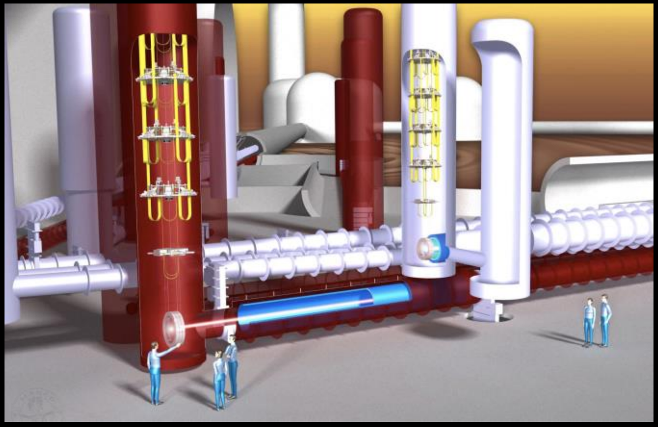


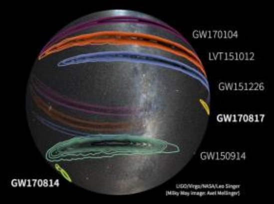
Cosmic Explorer (US): L shaped, above ground, 40 km; design study on-going



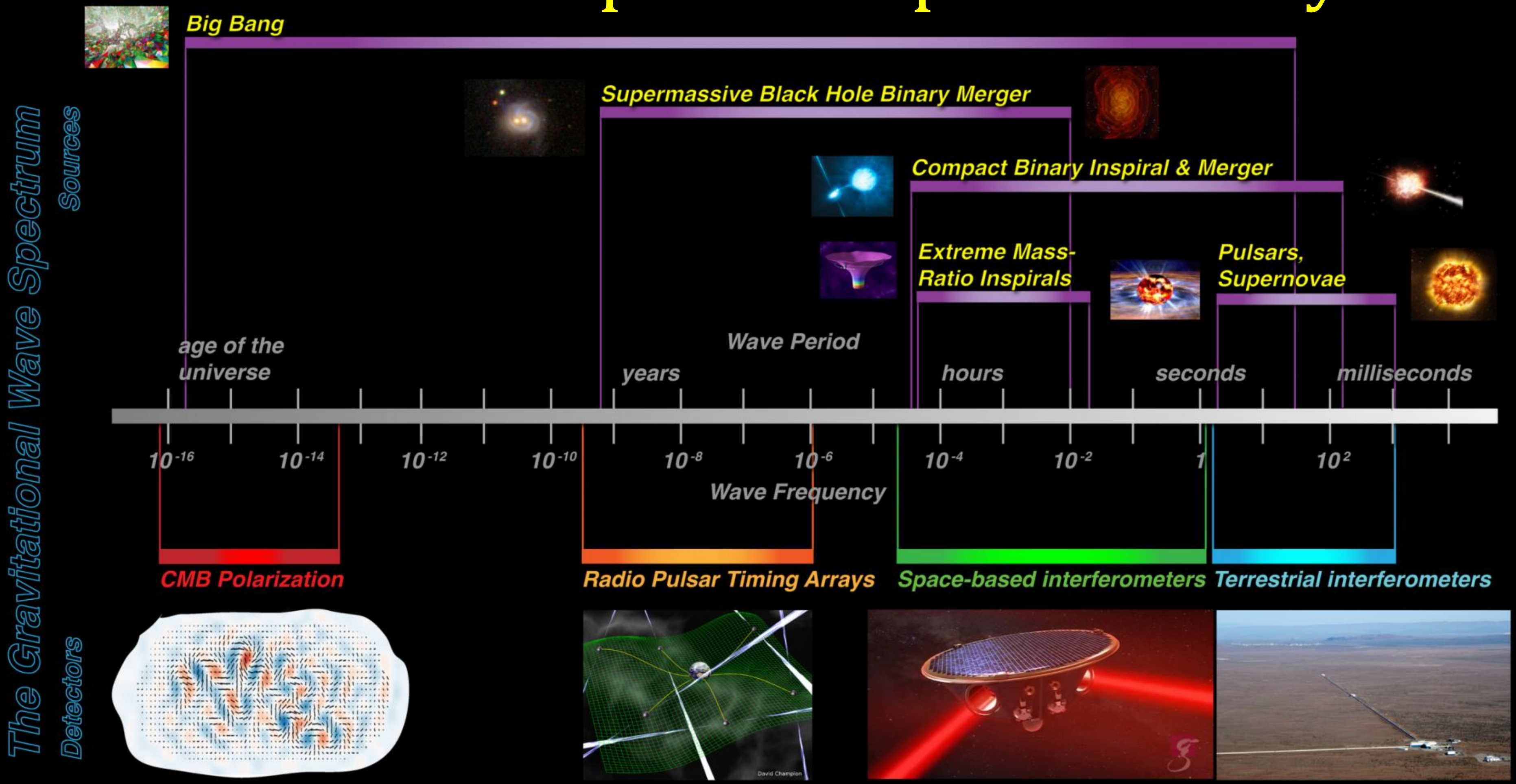
The importance of civil infrastructures

- 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

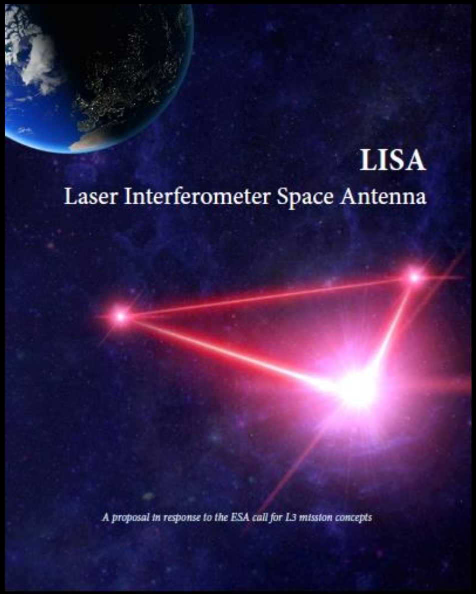


Gravitational Waves
Ground-Space complementarity



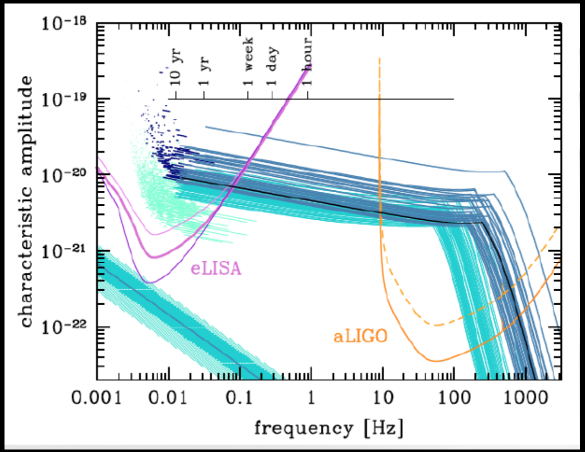
LISA

A spatial mission ESA: LISA (1994➔ 2034)

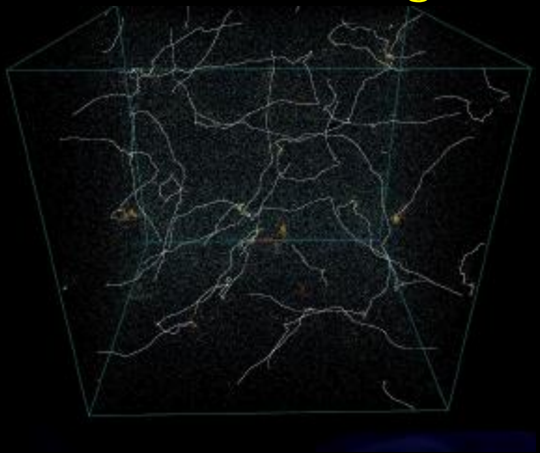


1. 1993-1994 1e proposition (6 sat)
2. 1997 Final configuration(3 satellites)
3. 2017 Start of phase 0
4. Discussions of participation NASA
5. 2018-2020 Phase A
6. 2030-2034 Launch (duration 4 (+6) y)

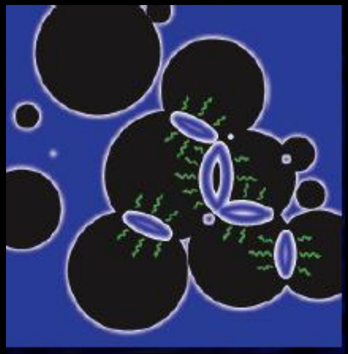
A detector of Super Massive Black Holes ➔ evolution of galaxies, dark matter…



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

I also bring the greetings and wishes for another 20 productive years full of discoveries by the EGO director Stavros Katsanevas

Greetings addressed to the Auger collaboration as well as to his homonymous detector, hopefully still collecting cosmic rays in the Argentinian pampa