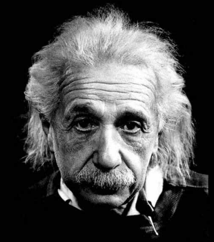
The Art and Science of the Detection of Gravitation waves at the Virgo interferometer

S. Katsanevas; Director
European Gravitational Observatory

The Physics

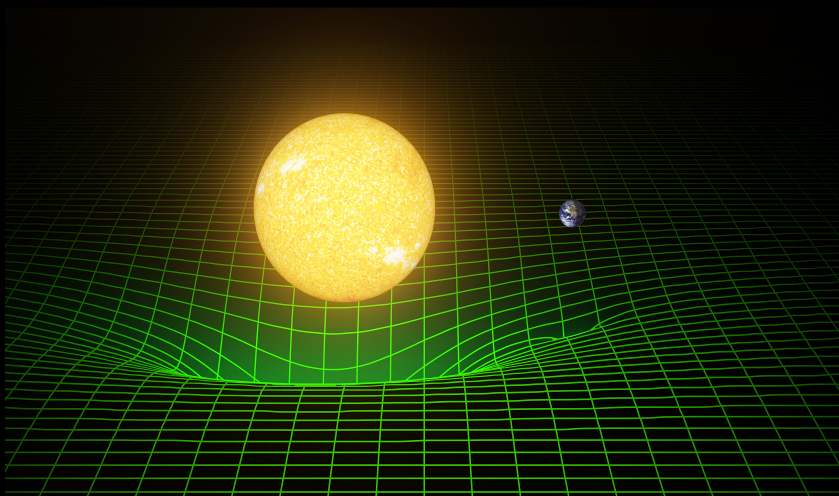


Einstein's Theory of Gravity 1915

Space-Time is a deformable medium

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

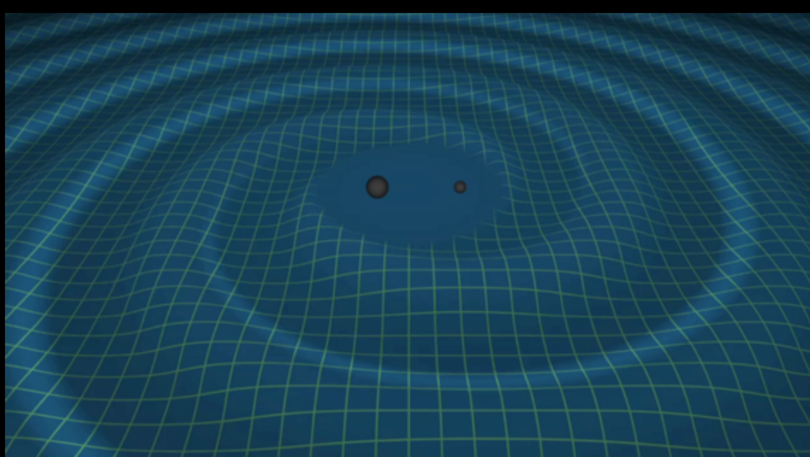
Waves can be produced by violent phenomena



Spacetime Mass-Energy

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

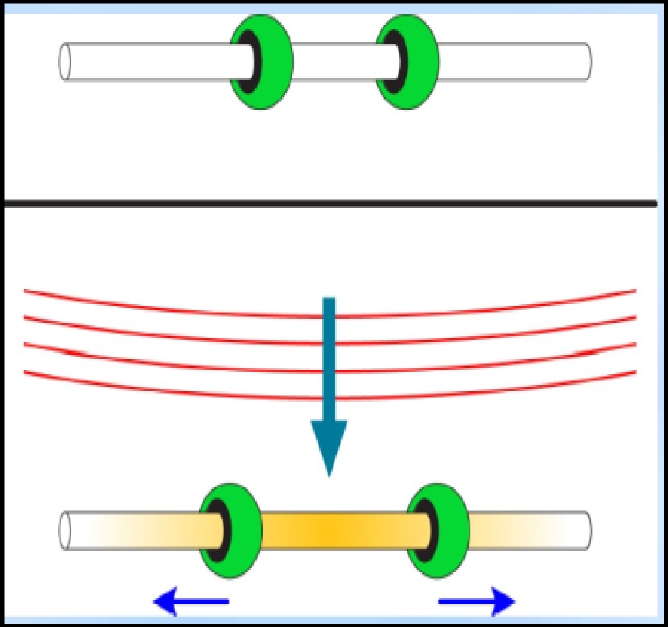
$\sim 10^{-43}$



Papers redicting gravitational waves 1916-1918

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.

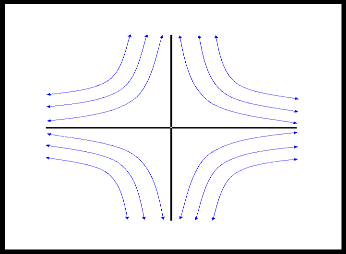


In January 1957, the U.S. Air Force sponsored the *Conference on the Role of Gravitation in Physics*, a.k.a. the Chapel Hill Conference, a.k.a. GR1.

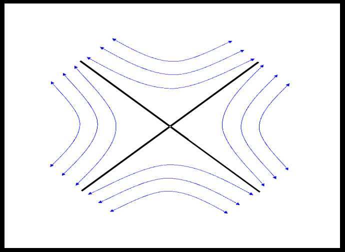
The "gravitational wave problem" was solved there, and the quest to detect gravitational waves was born. (Pirani, Feynman and Babson)

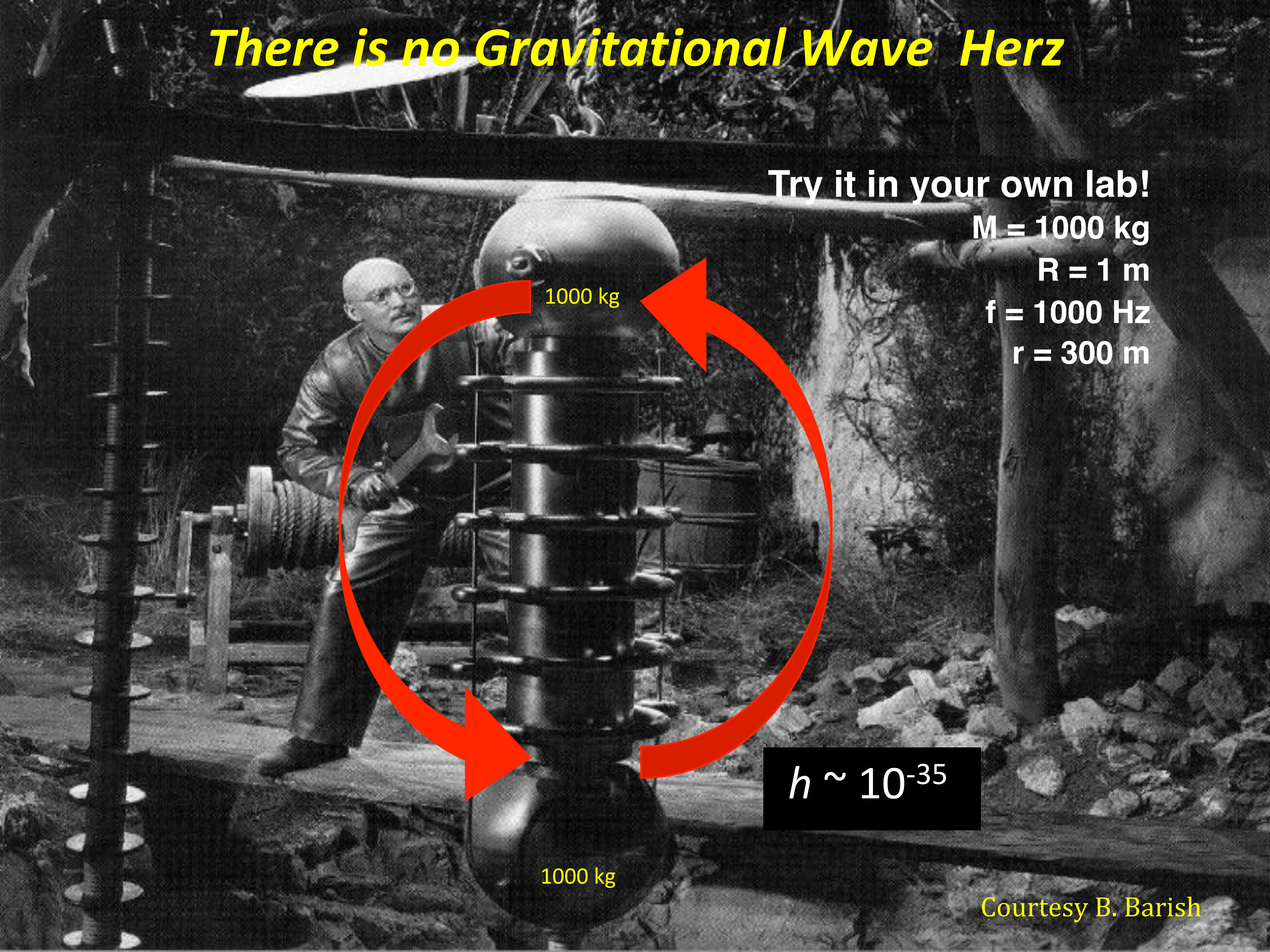
Sticky bead argument (Feynman)

h_+

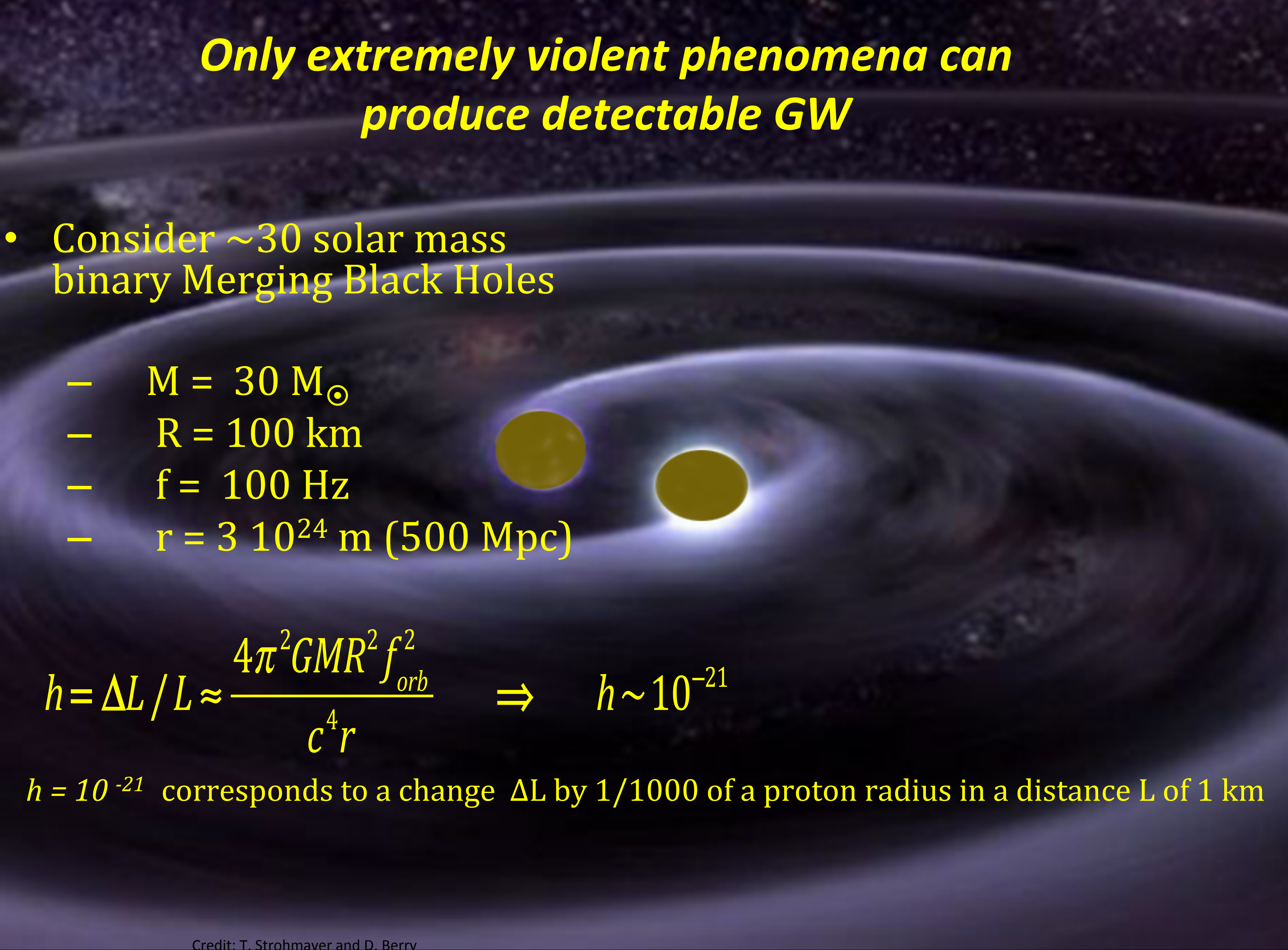


h_x




There is no Gravitational Wave Herz
Try it in your own lab!
M = 1000 kg
R = 1 m
f = 1000 Hz
r = 300 m
1000 kg
1000 kg
h ~ 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)

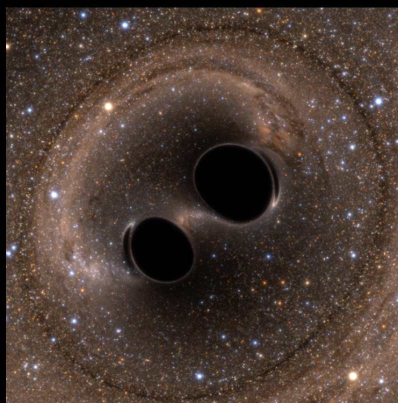
$$h = \Delta L / L \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \quad \Rightarrow \quad h \sim 10^{-21}$$

$h = 10^{-21}$ 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

The Astrophysical Gravitational-Wave Source Catalog

Short ➔ long

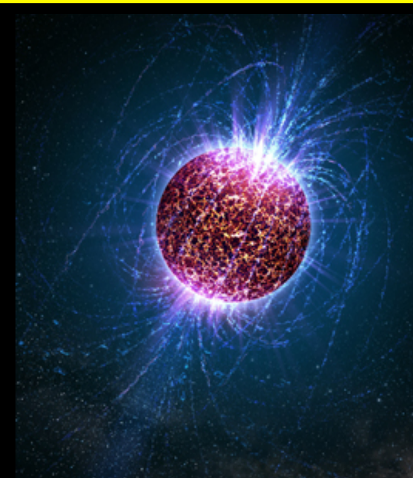


Coalescing Binary Systems CBC

✓ Black hole – black hole

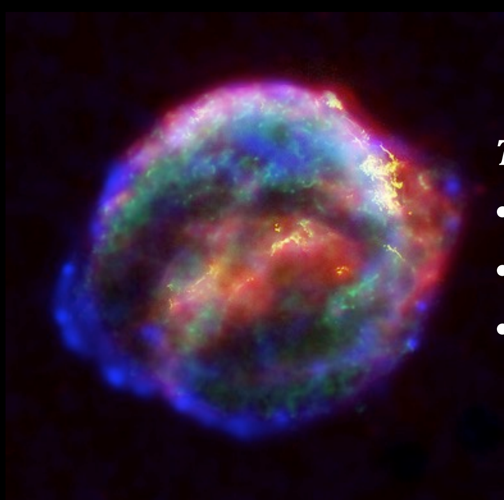
✓ Neutron star – neutron star

- BH-NS
- Analytical waveform



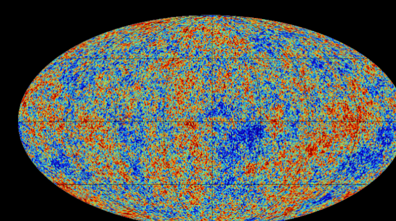
Continuous Sources

- Spinning neutron stars
- monotone waveform



Transient 'Burst' Sources

- core collapse supernovae
- cosmic strings
- unmodeled waveform

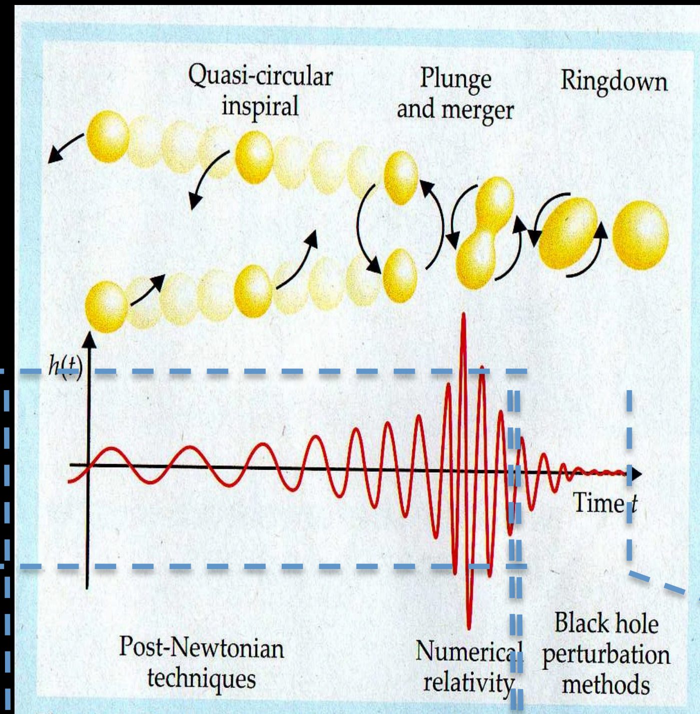


Cosmic GW Background

- residue of the Big Bang,
- stochastic, incoherent background

Transient Burst and Continuous sources the next goal

Known ➔ unknown form



Amplitude

Distance
Inclination angle

Frequency evolution

Chirp” mass
Mass ratio
Initial Spins

Frequency and decay time

Final mass
Final spin

CBC signals I

The signal at the lowest order:

Spiraling phase

$$h_+^{TT}(t) = \frac{4(GM)^{5/3}}{Rc^4} \frac{1+\cos^2 i}{2} \left(\pi f(t)\right)^{2/3} \cos\phi(t)$$

$$h_\times^{TT}(t) = \frac{4(GM)^{5/3}}{Rc^4} \cos i \left(\pi f(t)\right)^{2/3} \sin\phi(t)$$

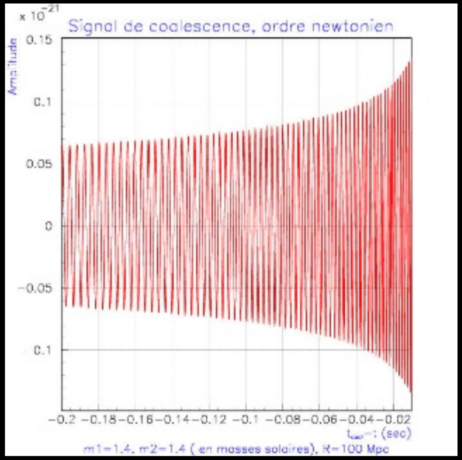
i: angle of the event w.r.t the interferometre axis

where

- Chirp mass: $M = \mu^{3/5} M_{tot}^{2/5}$
- frequency: $f(t) = \frac{1}{\pi}\left(\frac{256}{5}\frac{(GM)^{5/3}}{c^5}(t_c - t)\right)^{-3/8}$

t_c : time of coalescence

- Phase: $\phi(t) = -2\left(\frac{G^{5/3}}{c^5}\right)^{-3/8}\left(\frac{t_c - t}{5M}\right)^{5/8} + cste$



$$h(t) \propto \left(t_c - t\right)^{-1/4}$$

A "**chirp**"

CBC signals II

The signal at the lowest order:

Absolute distance

CBC => Standard sirens

Spiraling phase

$$h_+^{TT}(t) = \frac{4(GM)^{5/3}}{Rc^4}\frac{1+\cos^2 i}{2}\left(\pi f(t)\right)^{2/3}\cos\phi(t)$$

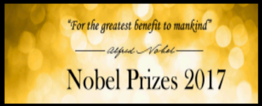
$$h_\times^{TT}(t) = \frac{4(GM)^{5/3}}{Rc^4}\cos i\left(\pi f(t)\right)^{2/3}\sin\phi(t)$$

Phase includes

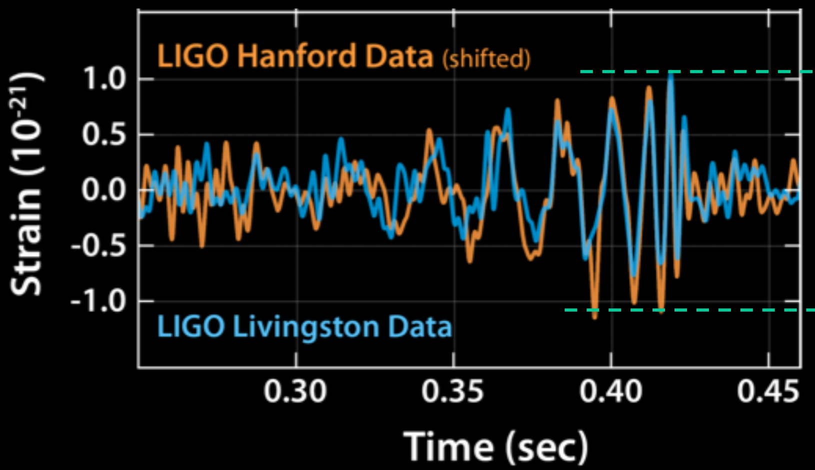
- **GR dynamics**
- **Matter effects (NS EOS)**
- **Fundamental physics (GR extensions, graviton mass…)**

Measure of phase => tests of GR, constraints on NS EOS etc…

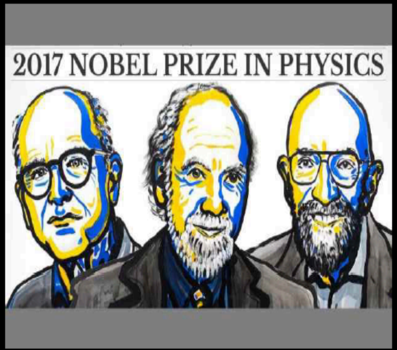
The first GW event: 14 September 2015



2017 October 3



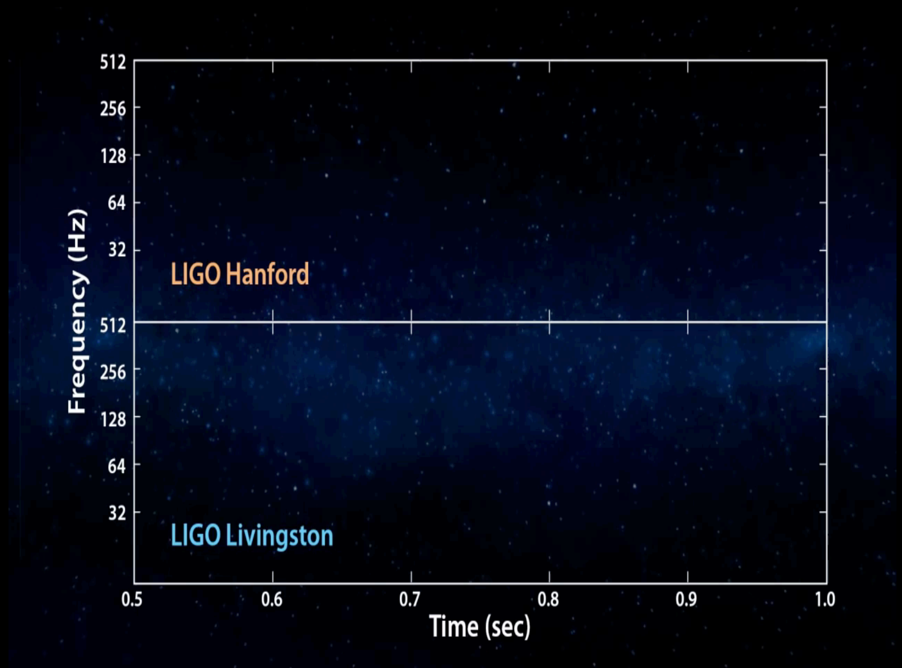
h ~ 10^{-21}
L ~ 4 x 10^{-18} m



Rainer Weiss Barry C. Barish Kip S. Thorne

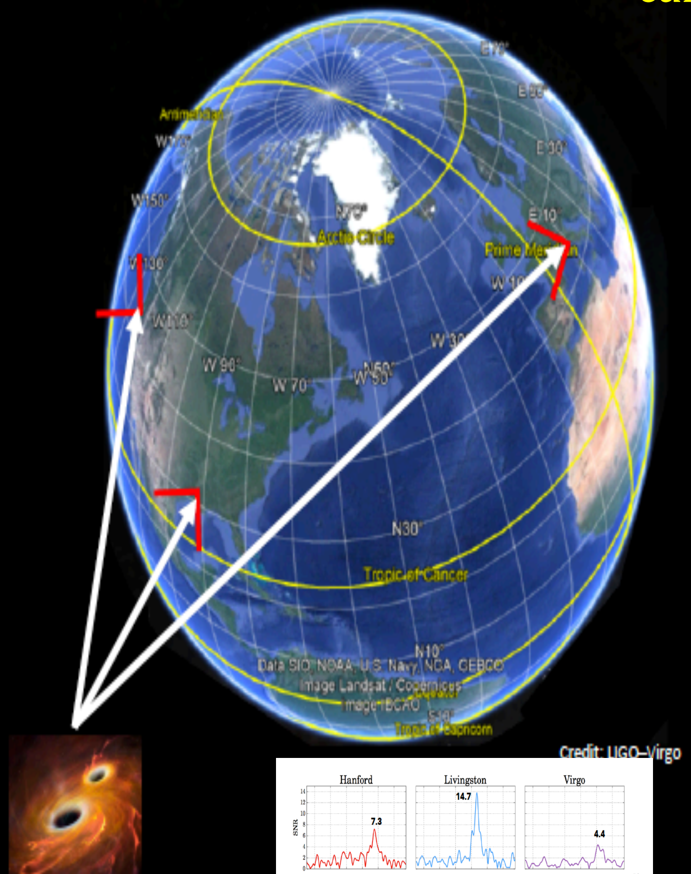
"for decisive contributions to the LIGO detector and the observation of gravitational waves".

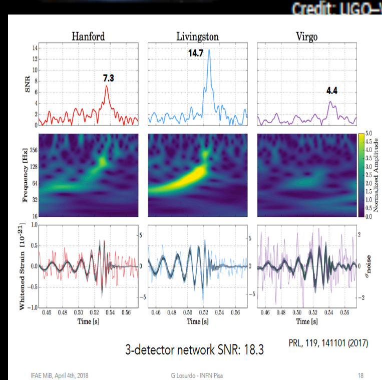
Power ~ 4 x 10^{49} W



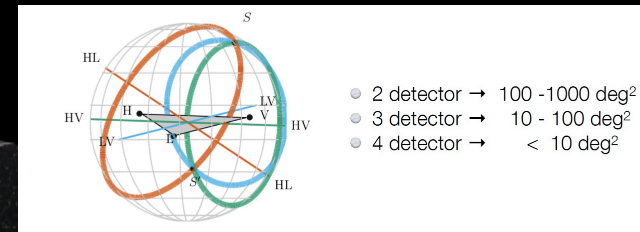
The first GW ‘triangulated event: 14 August 2017

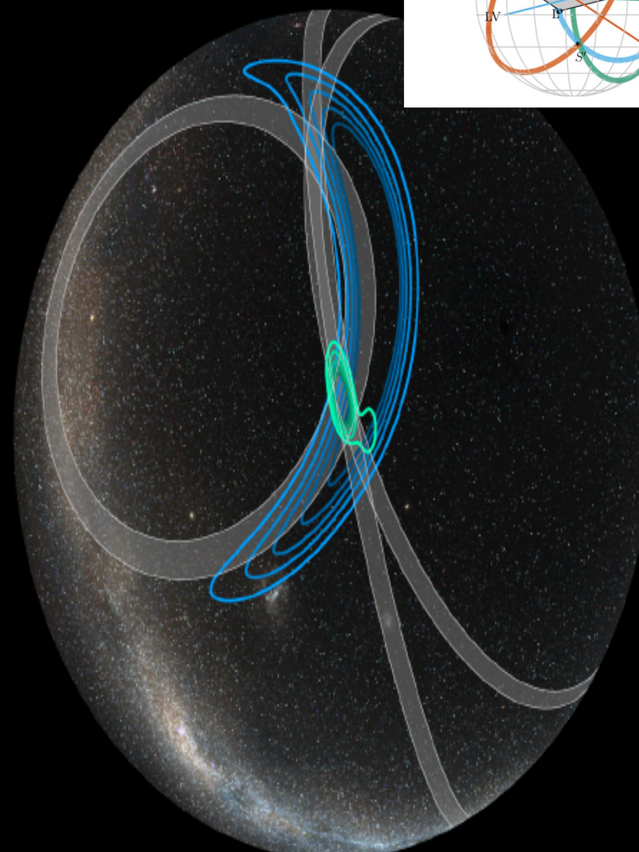
Gravitational Astronomy
can start





Credit: LIGO-Virgo





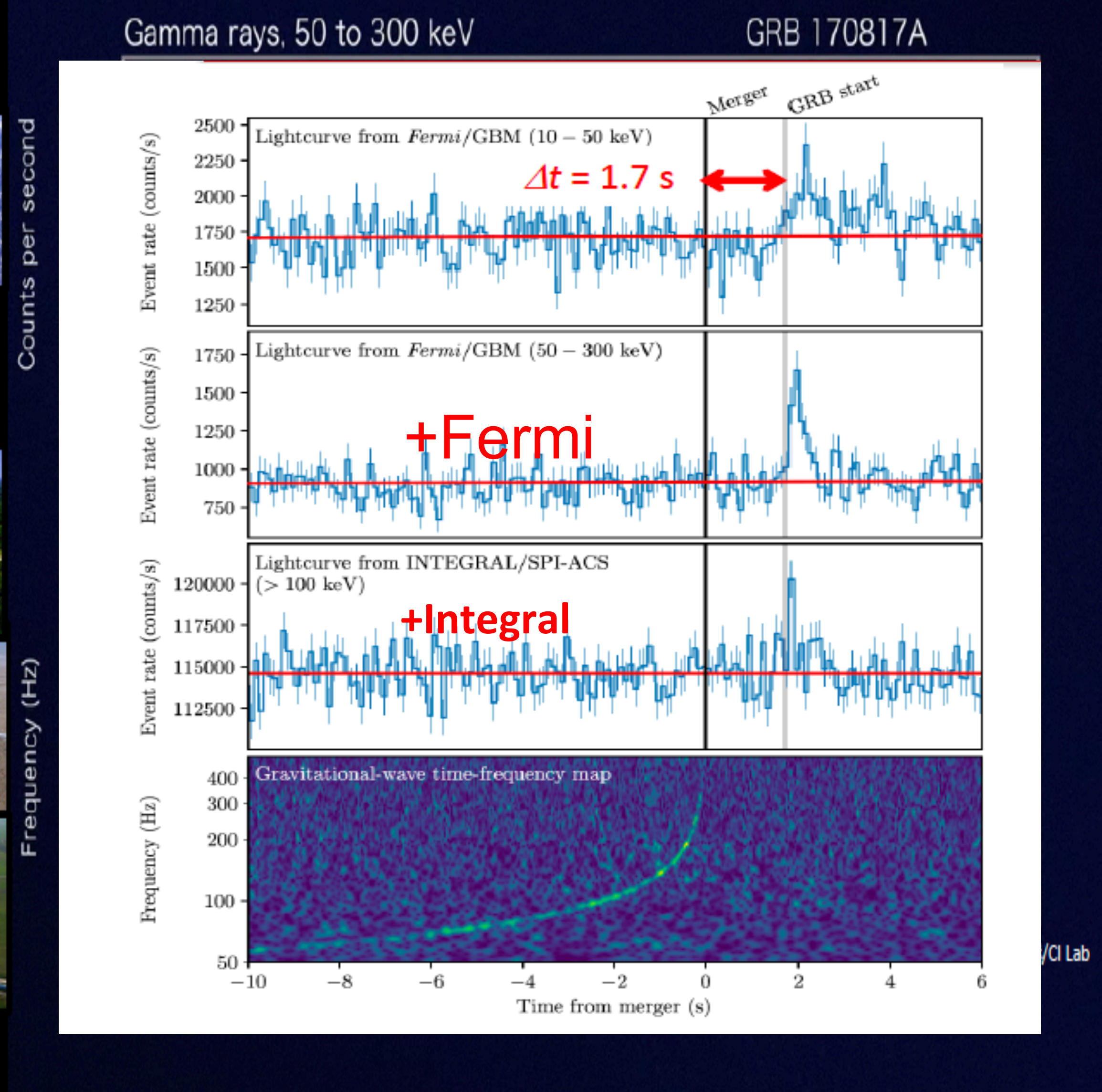
Credit: Leo Singer

LH 1160 square degrees
LHV 60 square degrees

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

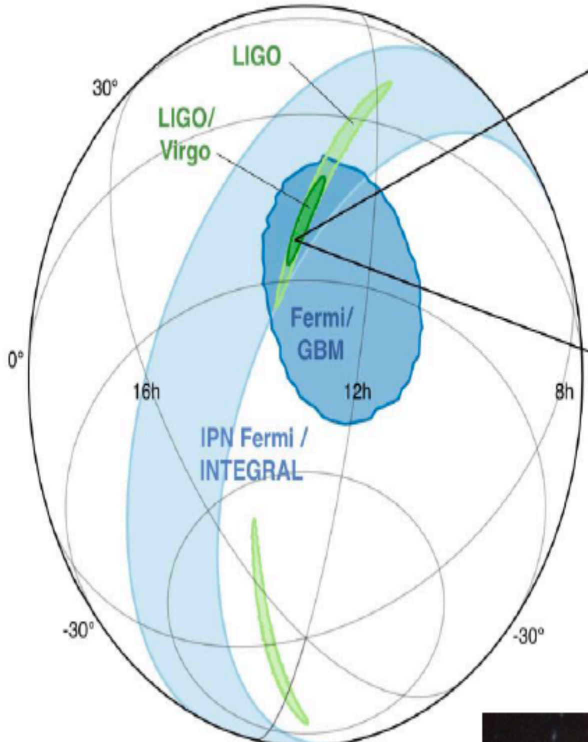
Also measure
of GR
polarisations

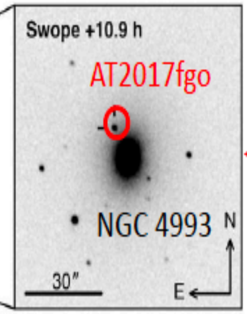
The first multimessenger event 17 August 2017



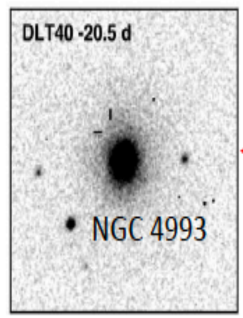
A binary neutron star merger at 40 Mpc

Discovery of Optical Counterpart (AT2017fgo) and Host Galaxy (NGC 4993)



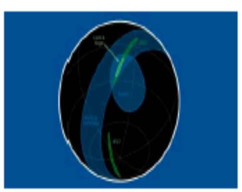


The 1M2H team was the first to discover the optical counterpart AT2017fgo in the host galaxy NGC 4993 with the 1m Swope telescope 10.9 hr after the merger time



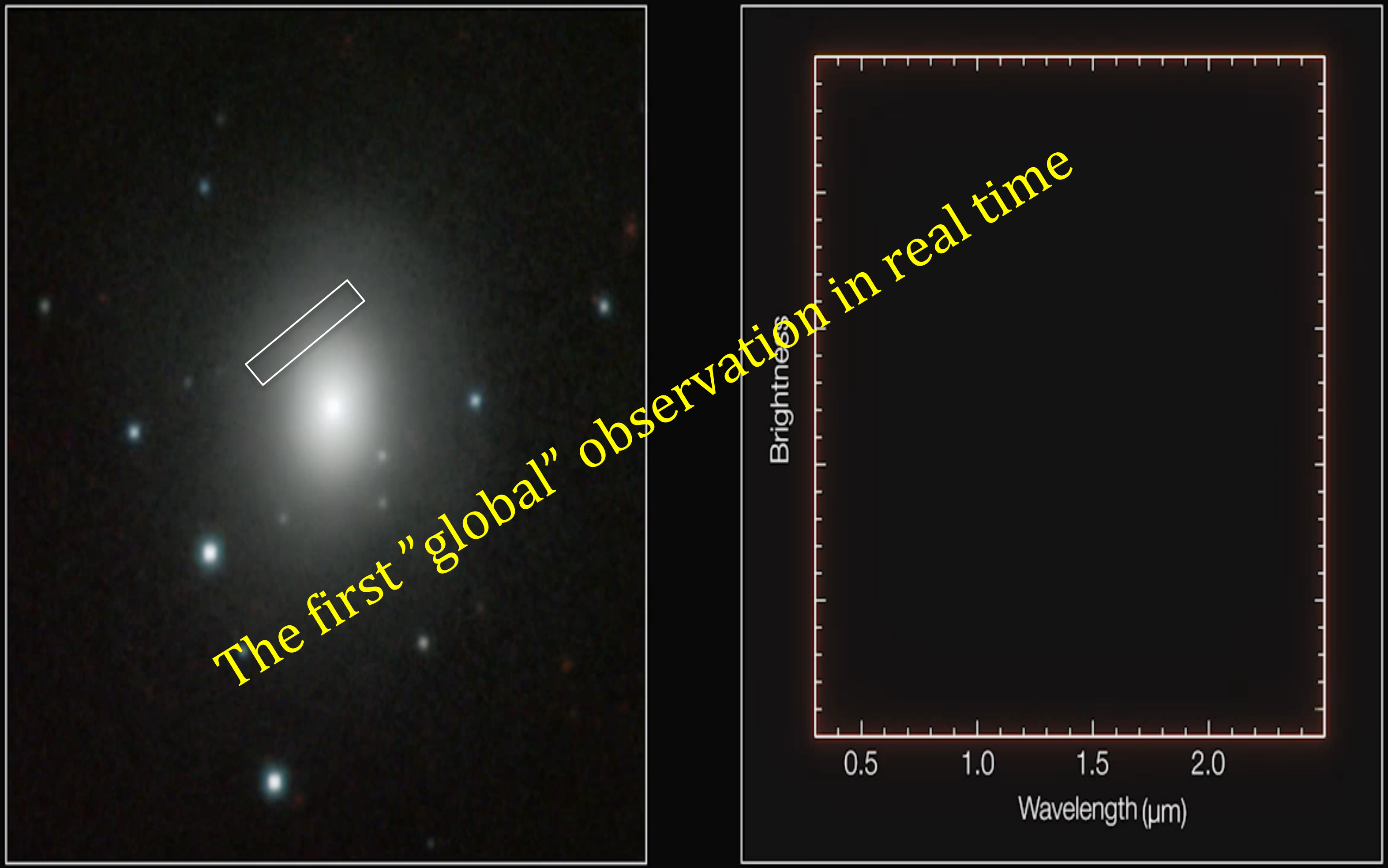
The DLT40 pre-discovery image from 20.5 days prior to merger

Localization of the gravitational-wave, gamma-ray, and optical signals



European Southern Observatory Very Large Telescope

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

GW170817

17/08/2017
12:41:04

Signal from BNS : GW170817

+2 s — Detection from Fermi/ GBM of a short gamma-ray burst (GRB170817A)

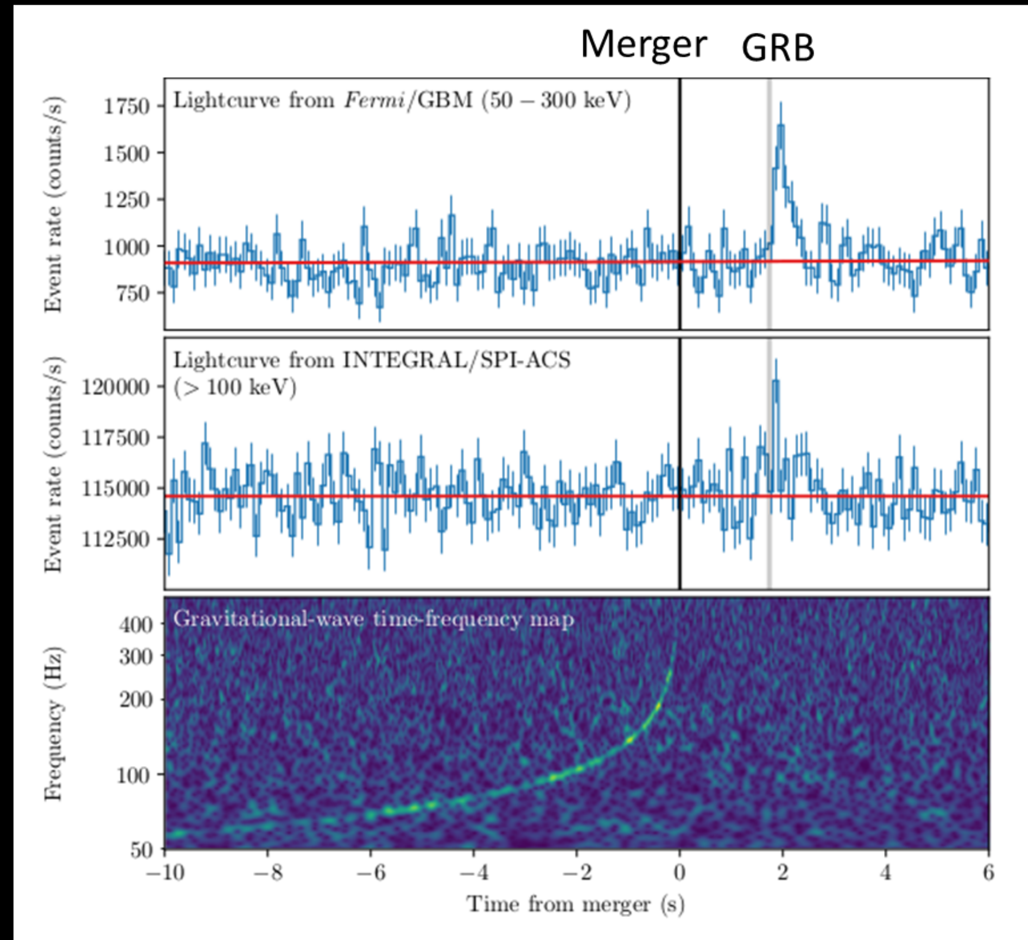
+16 s — GRB alert sent

+40 min — Sent alert on GW side

BEGINNING OF THE MULTI-MESSENGER CAMPAIGN

+1h20min — First reports from temporal coincidences with GW170817

Report from Integral/SPI-ACS Detected GRB170817A



« Gravitational waves and Gamma-rays from binary neutron star merger: GW170817 and GRB170817A », Abbott et al., ApJ, 2017

GW170817

17/08/2017
12:41:04 — GW170817

+2 s — GRB170817A

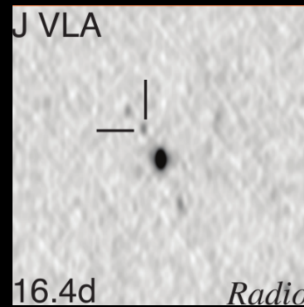
+5h — Localisation with GW
Distance 40 Mpc

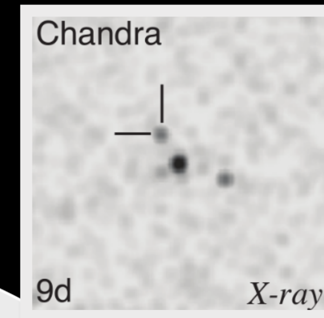
+11h — **Discovery of kilonova AT2017gfo by Swope**
Find host galaxy : NGC4993
START CAMPAIGN ON AT2017GFO

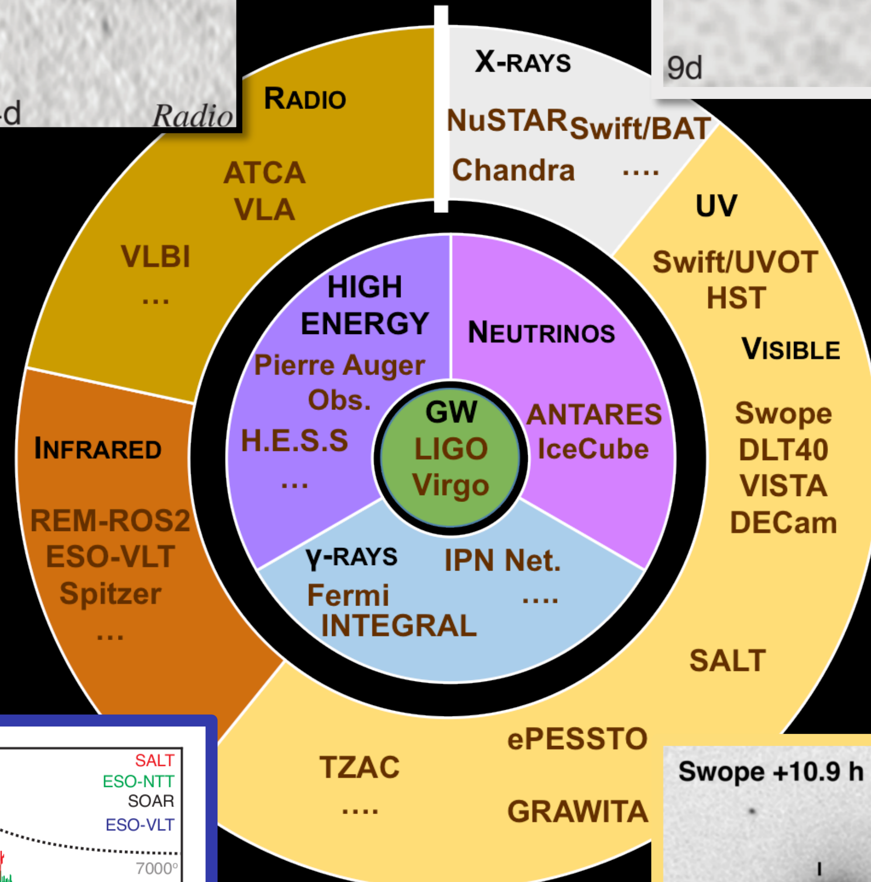
+1.2j — First spectra of the kilonova

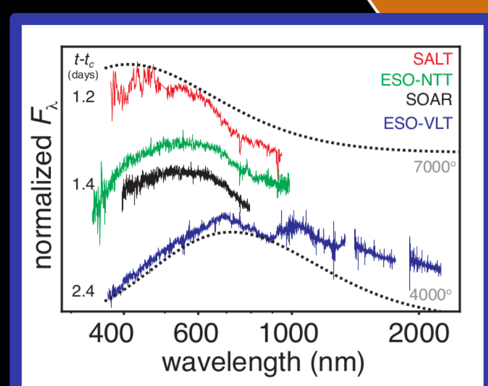
+9j — Discovery of an X-ray counterpart

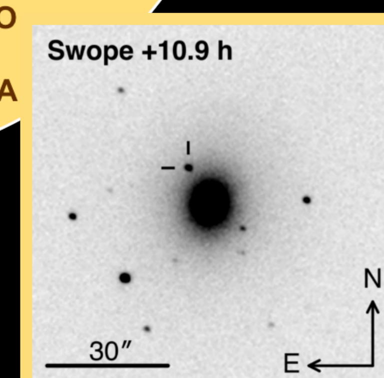
+16j — First radio signal found with VLA











« Multi-messenger observations of a binary neutron star merger », Abbott et al., ApJ, 2017

Kilonova

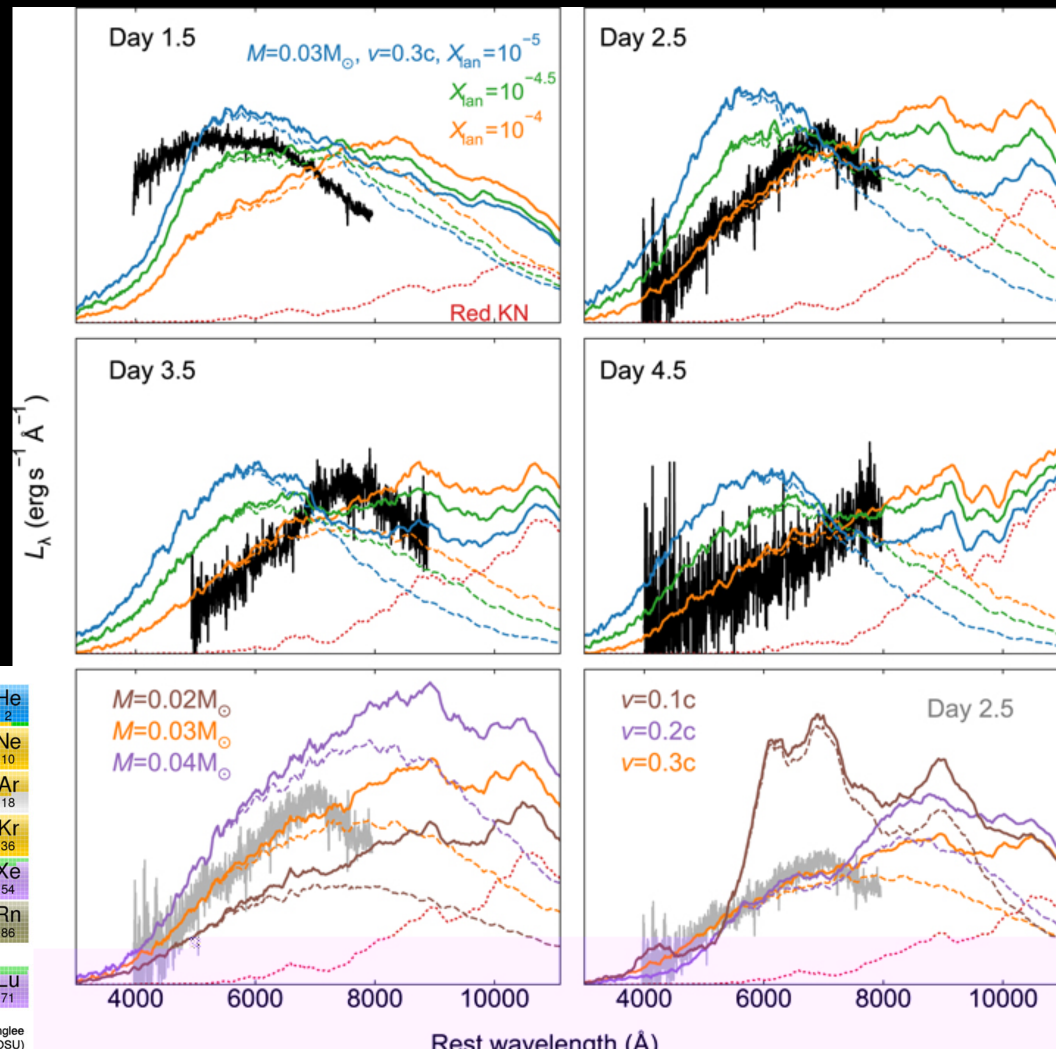
Predictions Vs observations

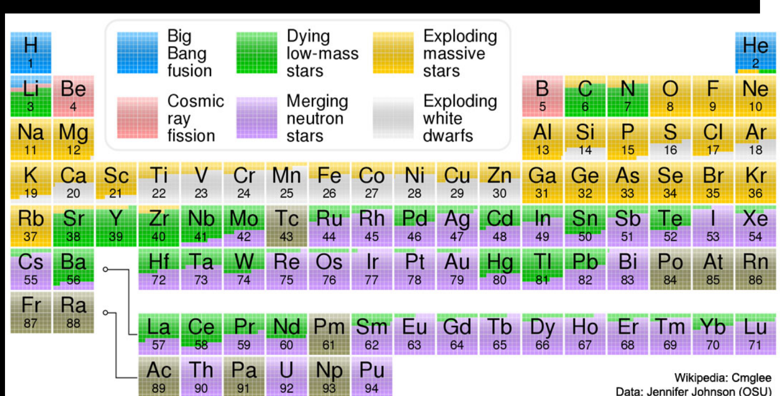
Spectrum : blue->red as time

Favors ejecta $v \sim 0.3\, c$.

Eject mass ~ 0.03 $M_\odot$
(LIGO-Virgo estimate ~10^{-3}-10^{-2} $M_\odot$ from GW observations only)

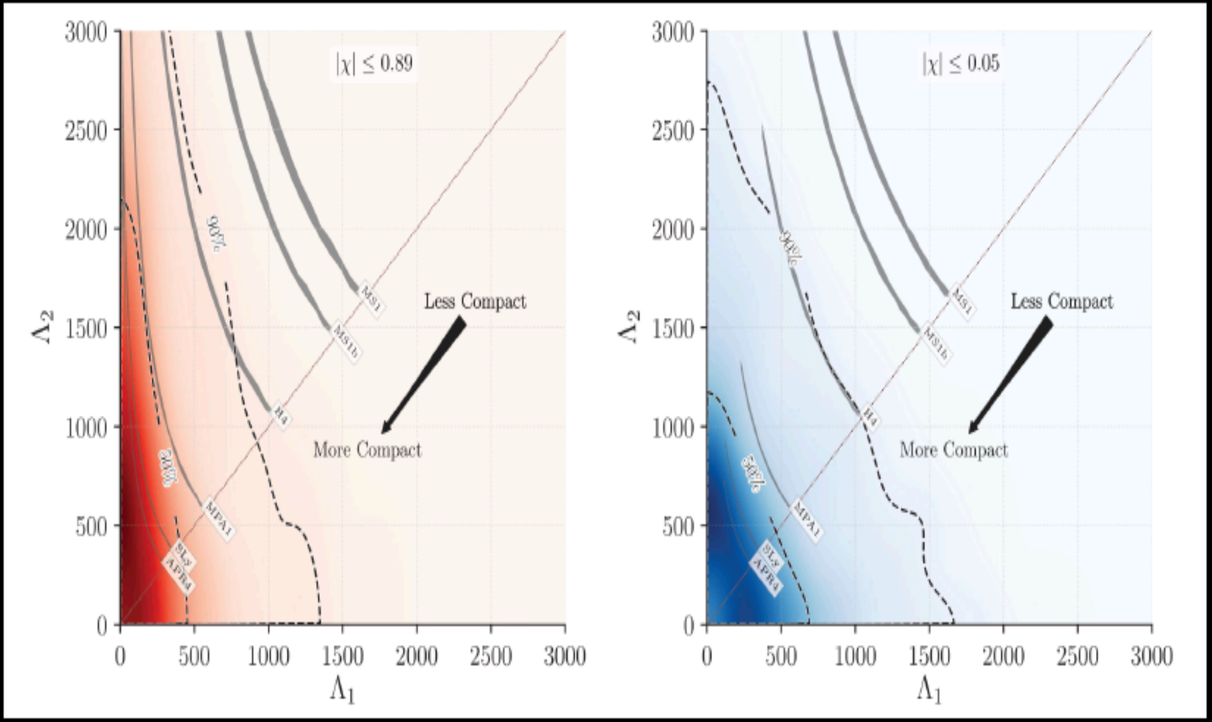
Initially poor in lanthanids

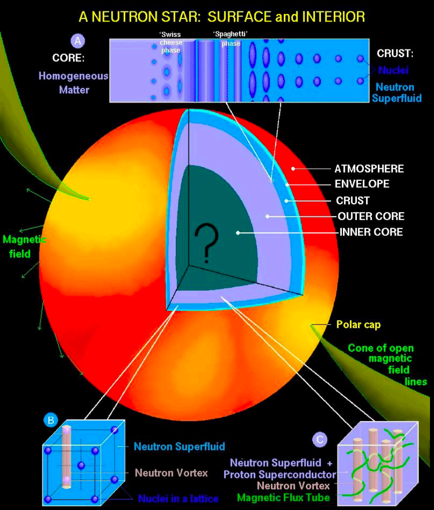




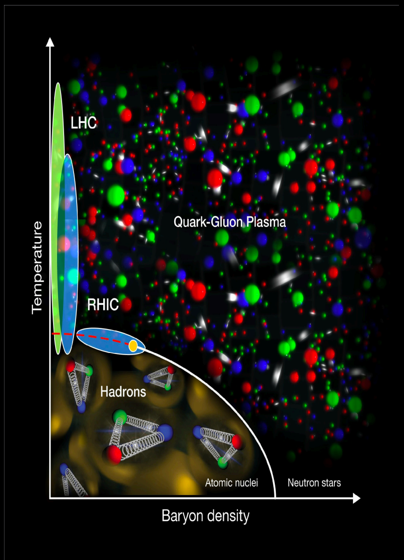
Nicholl et al. 2017

NS LABORATORY FOR STUDYING SUPER-DENSE MATTER

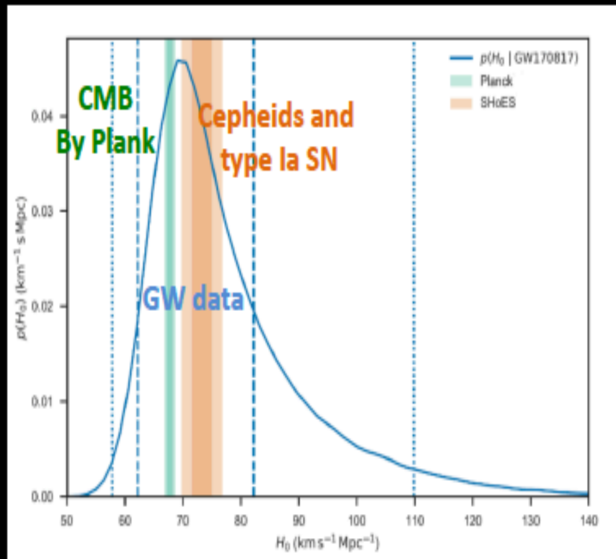




TIDAL DEFORMABILITY = $\Lambda = (2/3)k_2[(c^2/G)(R/m)]^5$



GRAVITATIONAL-WAVE COSMOLOGY

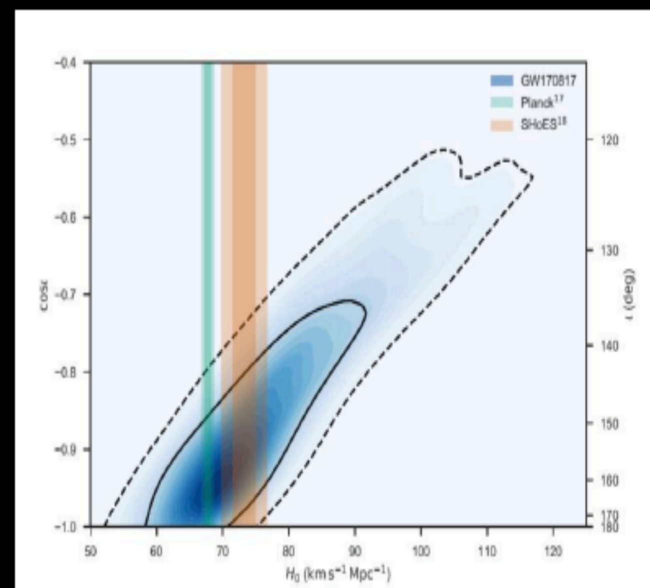


$v_H = H_0 d$ Combining the distance

measured from GWs $d = 43.8^{+2.9}_{-6.9}\,\mathrm{Mpc}$

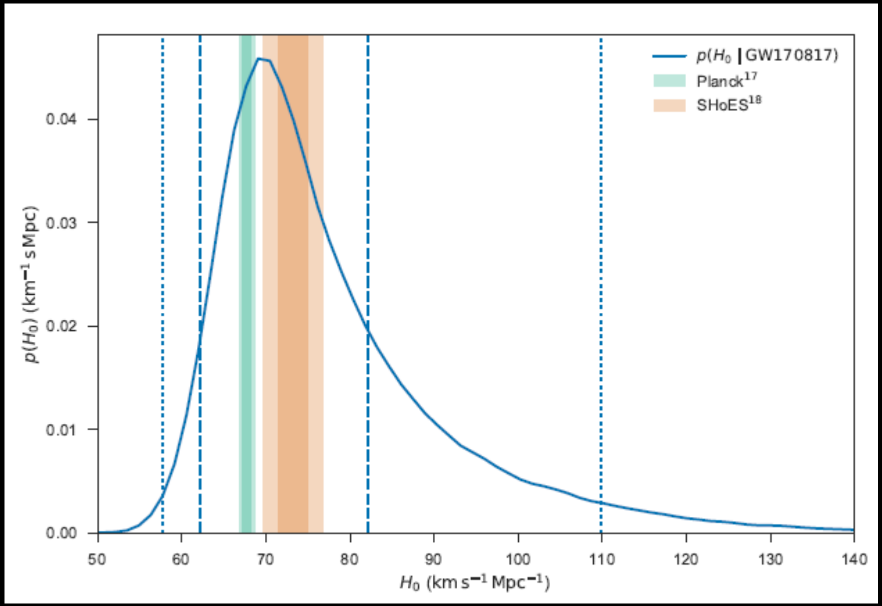
and NGC4993 recession velocity

$\rightarrow H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$



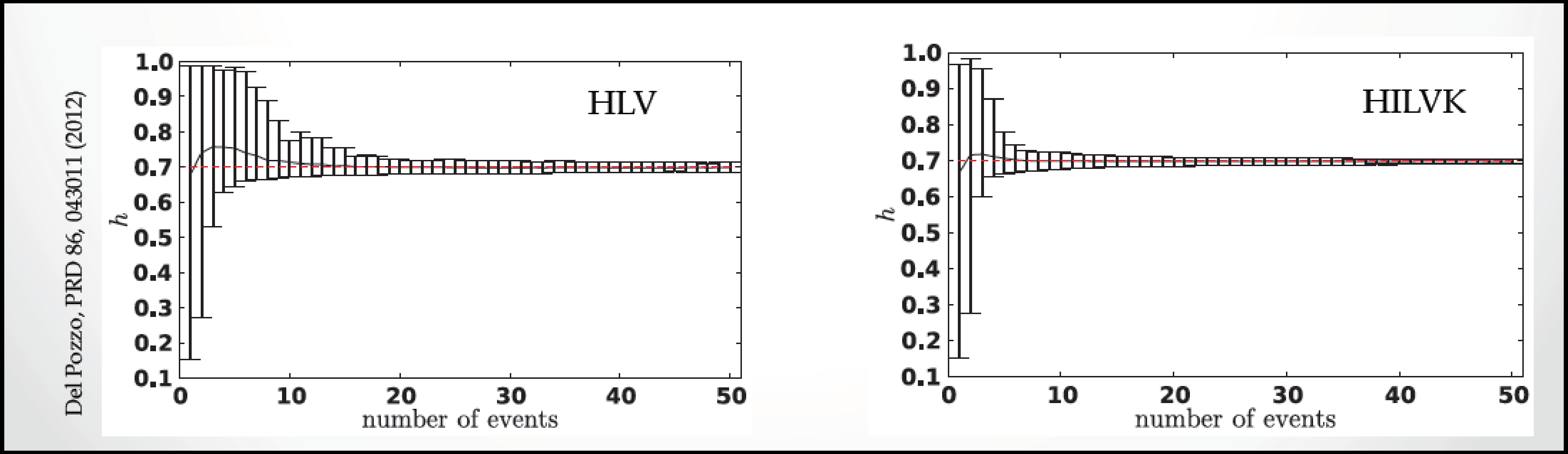
Abbott et al. 2017, Nature, 551, 85A

Hubble constant measurement



Planck data 67.74 ± 0.46 km/s/Mpc
Supernovae 73.24 ± 1.74 km/s/Mpc
➢ 3s « discrepancy ».
More GW events may allow to see clearer!

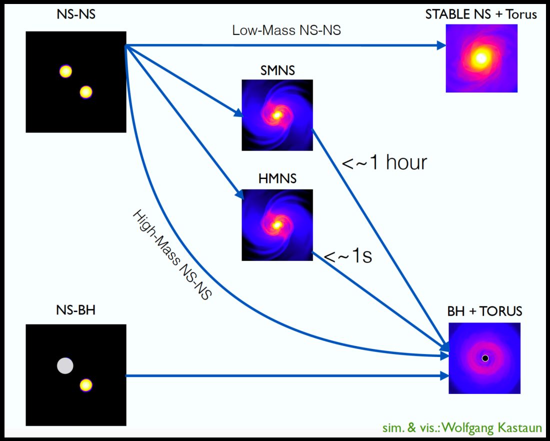
A few tens of evens => < 1% accuracy



GW170817 parameters

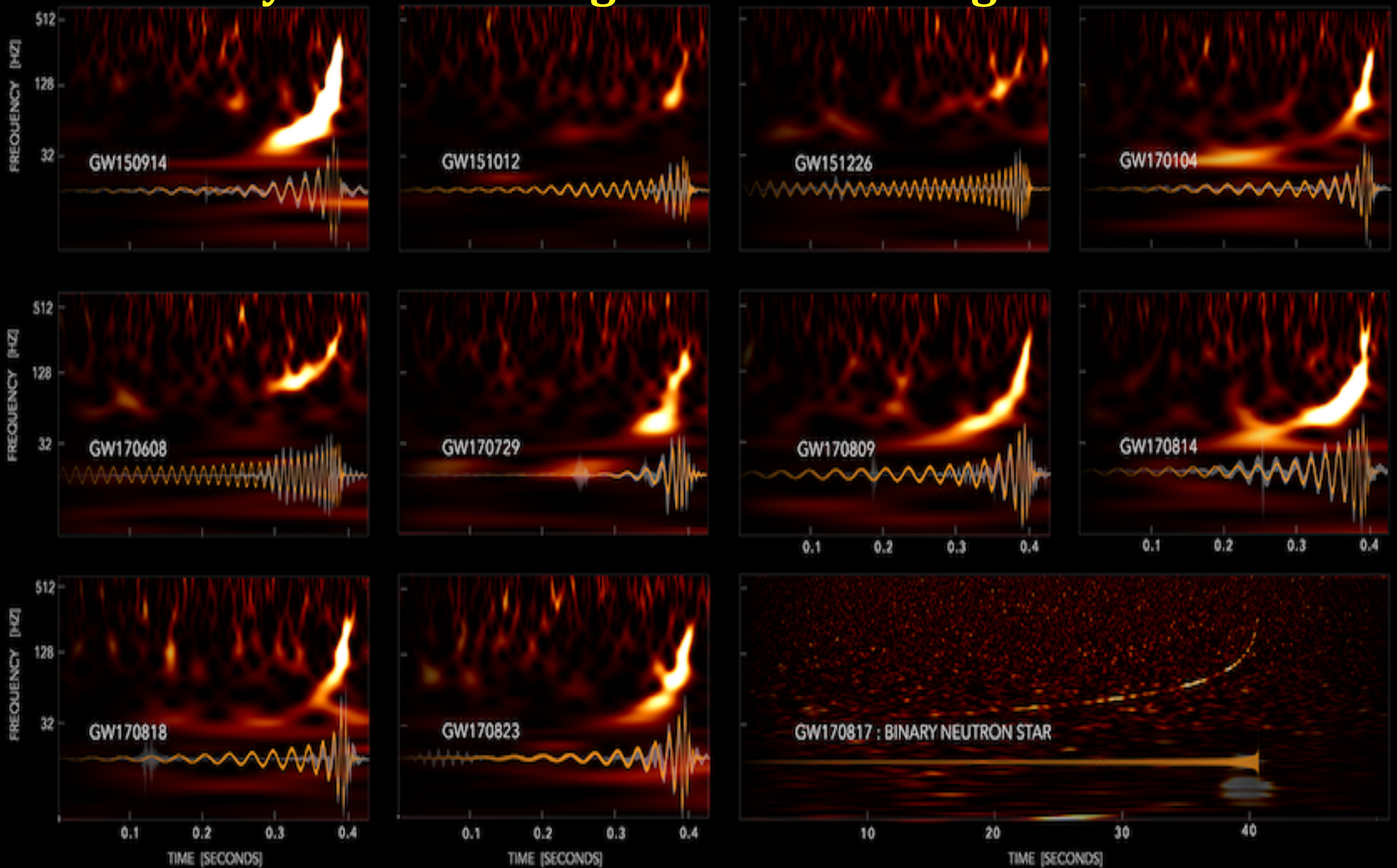
	Low-spin priors ($\|\chi\| \leq 0.05$)	High-spin priors ($\|\chi\| \leq 0.89$)
Primary mass m_1	$1.36 - 1.60\ M_\odot$	$1.36 - 2.26\ M_\odot$
Secondary mass m_2	$1.17 - 1.36\ M_\odot$	$0.86 - 1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002}\ M_\odot$	$1.188^{+0.004}_{-0.002}\ M_\odot$
Mass ratio m_2/m_1	0.7 – 1.0	0.4 – 1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01}\ \mathrm{M}_\odot$	$2.82^{+0.47}_{-0.09}\ \mathrm{M}_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025\ \mathrm{M}_\odot\, c^2$	$> 0.025\ \mathrm{M}_\odot\, c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Misalignment of total angular momentum and line of sight	$\leq 56°$	$\leq 55°$
using counterpart location	$\leq 30°$	$\leq 30°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

Questions about the product of the merger



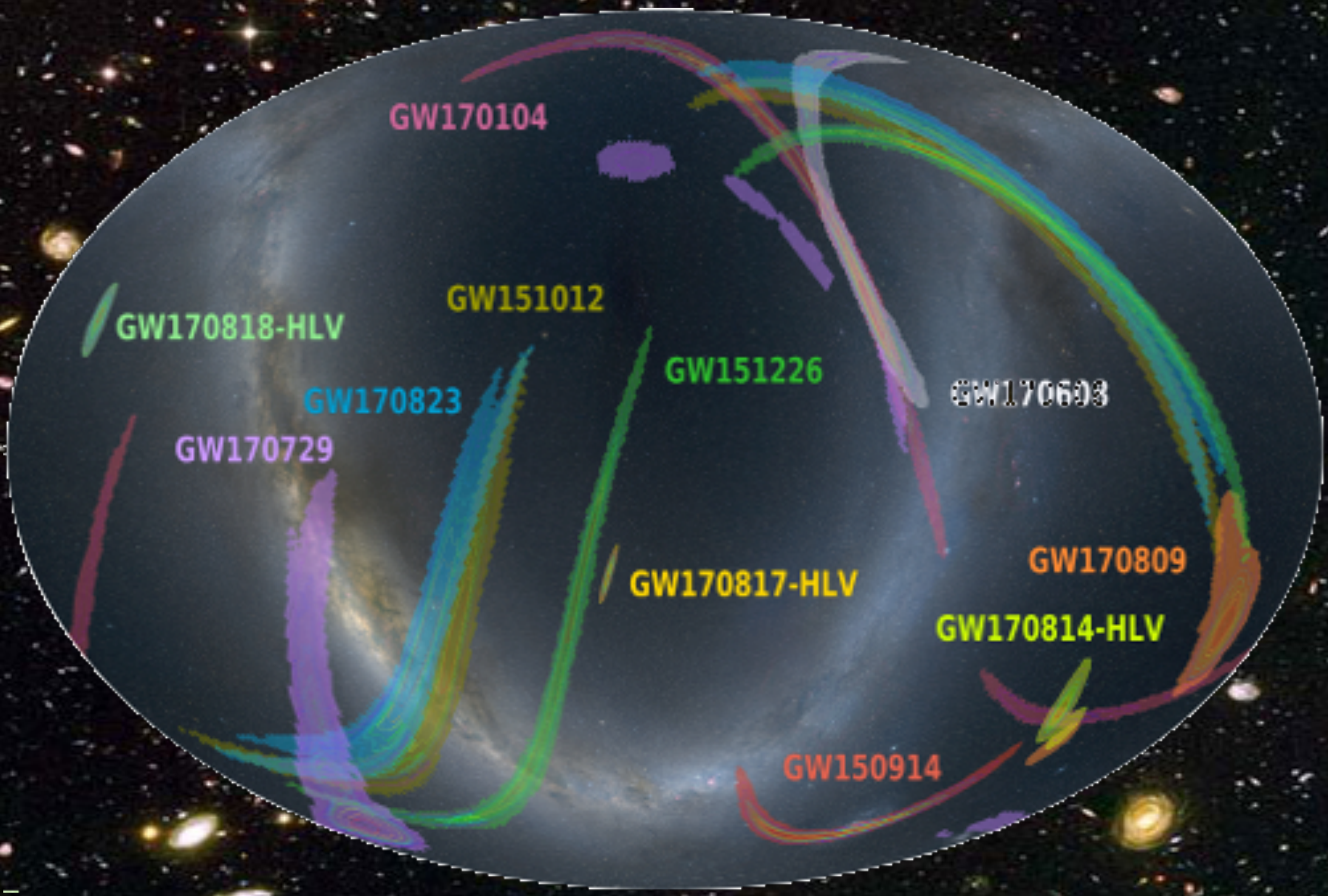
Gravitational-Wave Transient Catalog-1

Today :10 BBH mergers 1 BNS merger



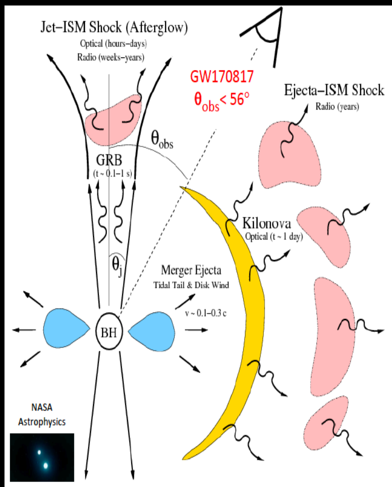
Merger rates of BNS: 920 [110, 3840] BBH: 53 [9.7, 101] Gpc-3 y-1

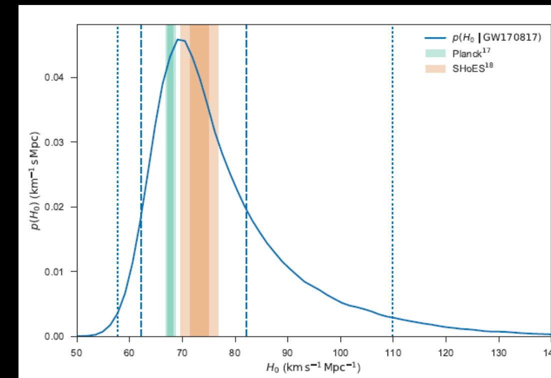
Pascal :« Le silence eternel de ces espaces infinis m’effraie… »



Well, no more, the 14th september 2015 we have heard the sound of the Universe

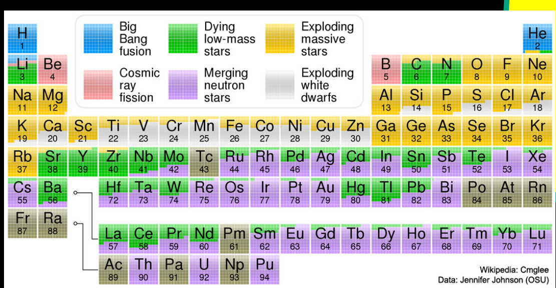
Multiple impact: Cosmology, Astrophysics, Nuclear Physics, Particle Physics, General Relativity

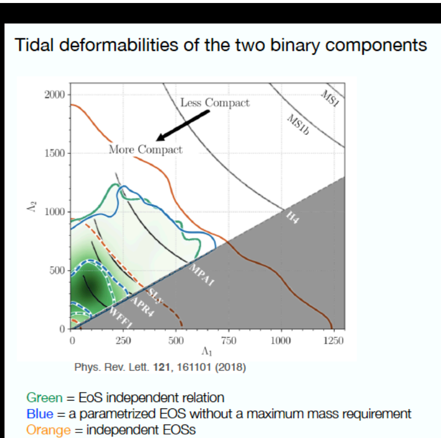




Hubble constant measurement
Test of the GRB kilonova model
Neutron star EOS constraints
Production of heavy elements
Speed of GW w.r.t v_{em}
Test of equivalence principle
Test of Lorenz Invariance
Multiple tests of Modified Gravity

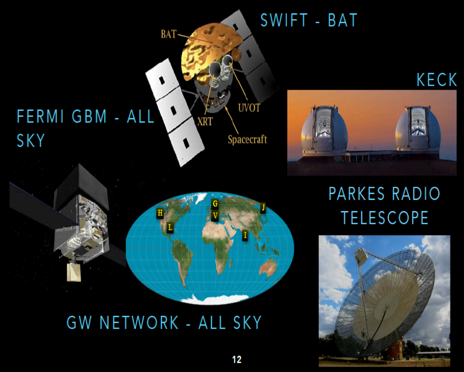
$$-3\ 10^{-15} \leq \frac{v_{GW} - v_{EM}}{v_{EM}} \leq +7\ 10^{-16}$$





	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^\mu\phi^\nu$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal (20) [18] Disformal Tuning (22) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

GW Science

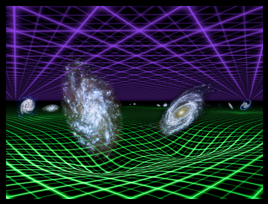


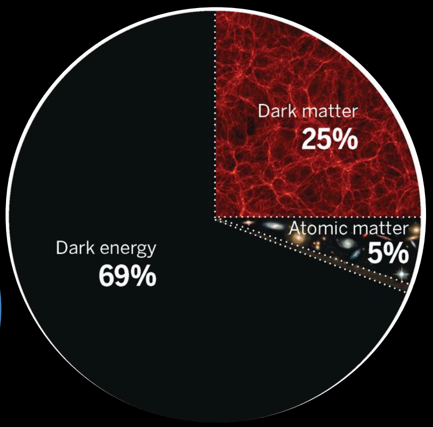
Cosmology

Expansion of the Universe

Dark Energy

CMB





Multi-messneger Astrophysics

Star formation and Evoliution

Kilonovae

Supernovae

Dark Matter

Black Holes?

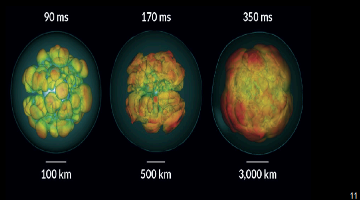
Axions?

Other stars

Gravitational wave

antennas

Physics



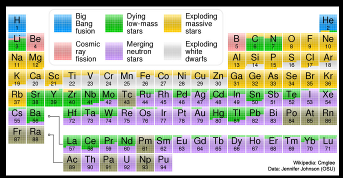
Nuclear Physics

Neutron Star

Equation of state

Nuclear Physics

Formation of Heavy Elements

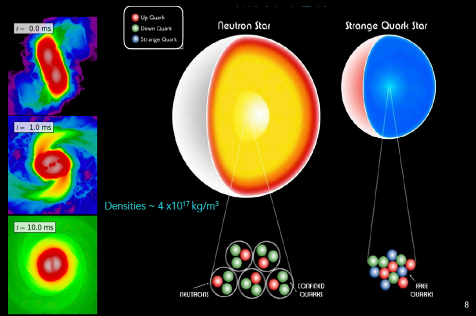


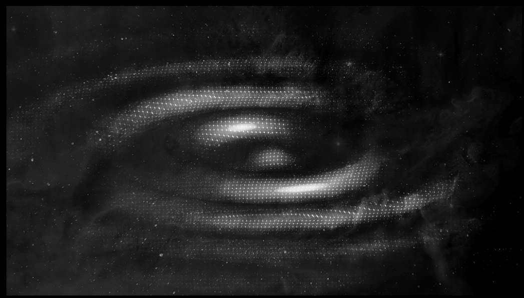
Alernative Theories of

Gravity

Alternative Theories of

Quantum Mechanics





The Interferometer

30 years of EGO/Virgo History

1989 Virgo proposal

1993-1994 CNRS and INFN approve VIRGO (+5y)

1997 Construction starts near Pisa (+7y)

2000 Foundation of EGO (CNRS, INFN) (+11y)

2003 Inauguration of Virgo (+14y)

2004-2006 Commissioning of Virgo

2006 Netherlands joins EGO as an Observer

2007 Start of Virgo science runs (+18y)

2007 LIGO-Virgo “a single machine”

2009 EGO Council approves AdVirgo (+20y)

2010 Polish, Hungarian and Spanish groups join AdVirgo

2017 First detection (+8y, +28y)

2019 O3 one year RUN (+10y,+30y)

Total cost (US costing, including HR) near 0.5 BE

Alain Brillet

Adalberto Giazotto

Inauguration Virgo 2003

Advanced Virgo

Virgo is a European collaboration with about 400 members

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector. Participation by scientists from France, Italy, Belgium, The Netherlands, Poland, Hungary, Spain, Germany

25 laboratories, 340 authors @ Feb2019

- 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

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*

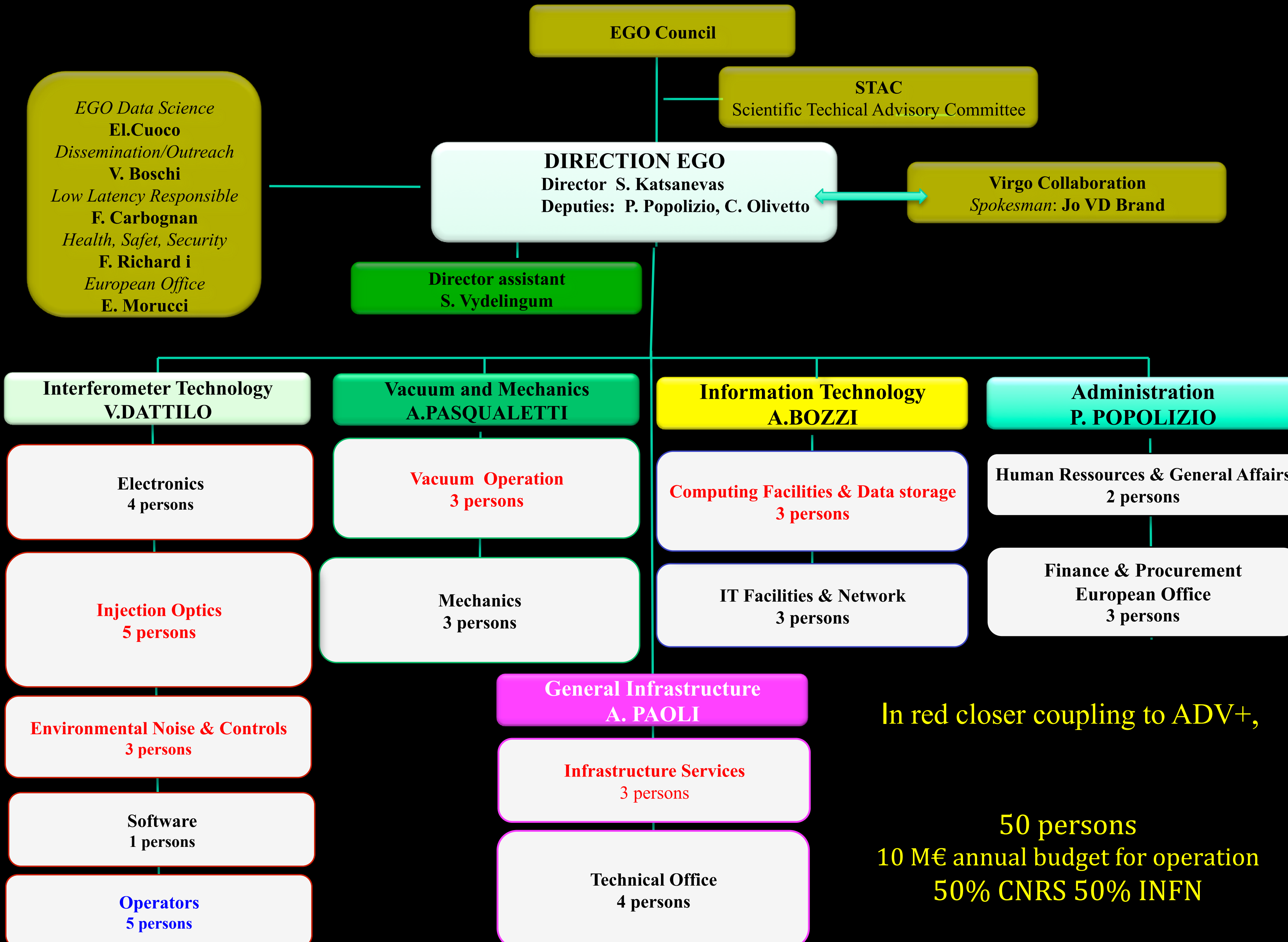
  II. Maintenance, operation and upgrade of the site infrastructures including a computing center

  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)

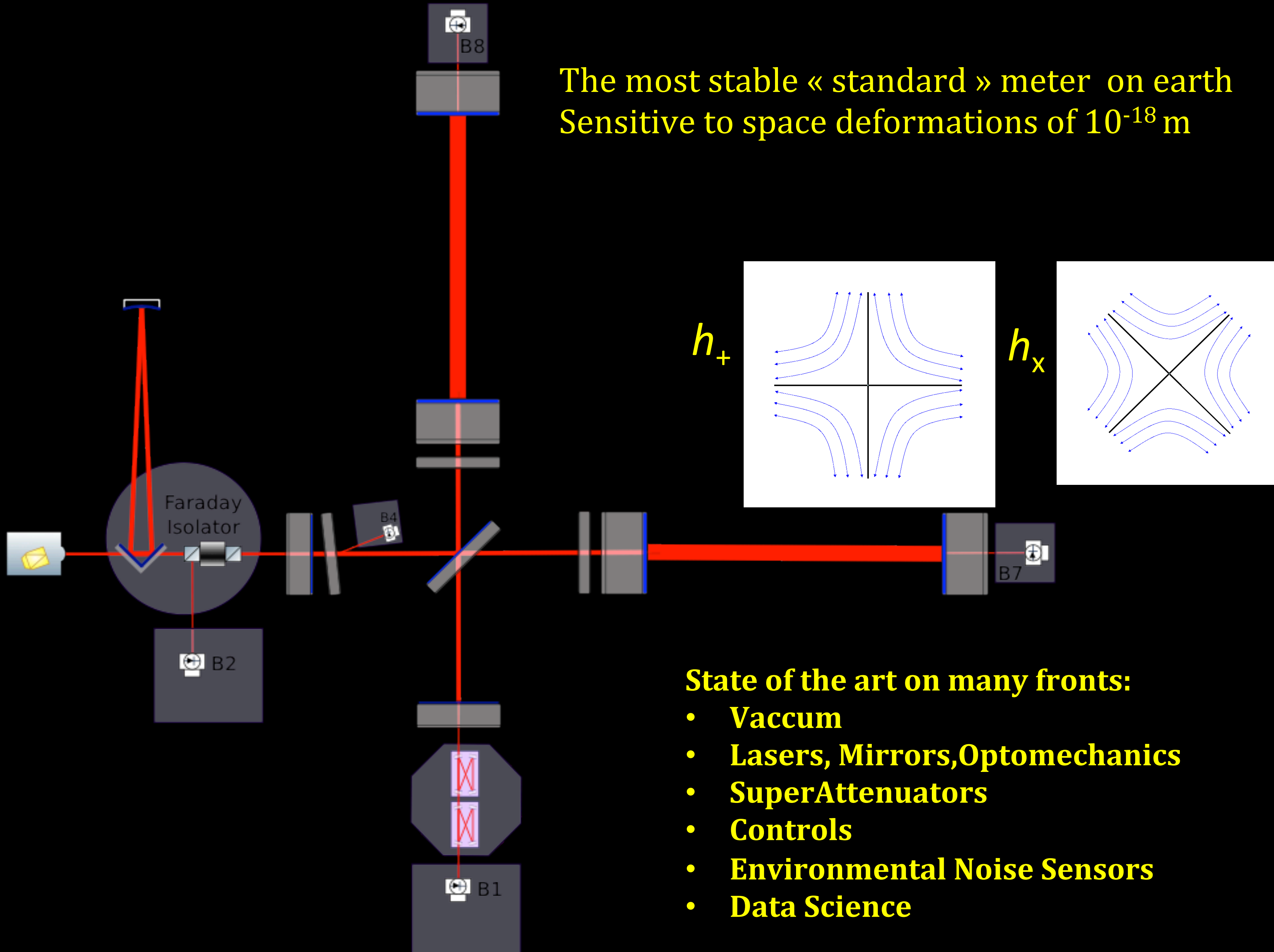
  VI. Outreach and education



EGO Council
STAC
Scientific Techical Advisory Committee
EGO Data Science
El.Cuoco
Dissemination/Outreach
V. Boschi
Low Latency Responsible
F. Carbognan
Health, Safet, Security
F. Richard i
European Office
E. Morucci
DIRECTION EGO
Director S. Katsanevas
Deputies: P. Popolizio, C. Olivetto
Virgo Collaboration
Spokesman: Jo VD Brand
Director assistant
S. Vydelingum
Interferometer Technology
V.DATTILO
Vacuum and Mechanics
A.PASQUALETTI
Information Technology
A.BOZZI
Administration
P. POPOLIZIO
Electronics
4 persons
Vacuum Operation
3 persons
Computing Facilities & Data storage
3 persons
Human Ressources & General Affairs
2 persons
Injection Optics
5 persons
Mechanics
3 persons
IT Facilities & Network
3 persons
Finance & Procurement
European Office
3 persons
Environmental Noise & Controls
3 persons
Software
1 persons
Operators
5 persons
General Infrastructure
A. PAOLI
Infrastructure Services
3 persons
Technical Office
4 persons
In red closer coupling to ADV+,
50 persons
10 M€ annual budget for operation
50% CNRS 50% INFN

The Advanced Virgo antenna

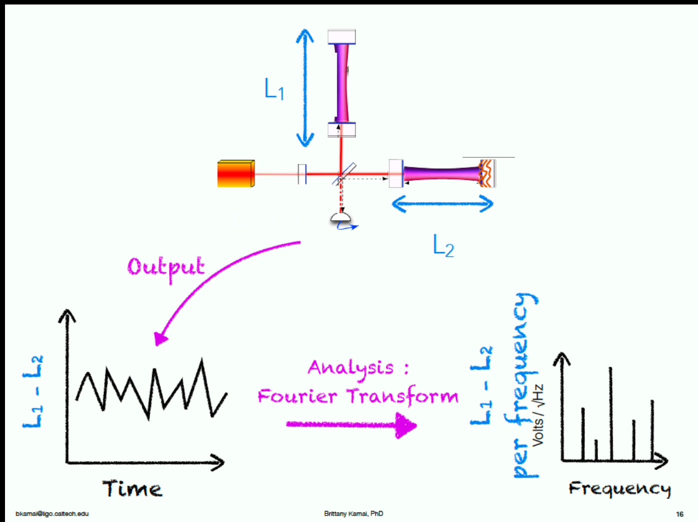
The most stable « standard » meter on earth
Sensitive to space deformations of 10^{-18} m

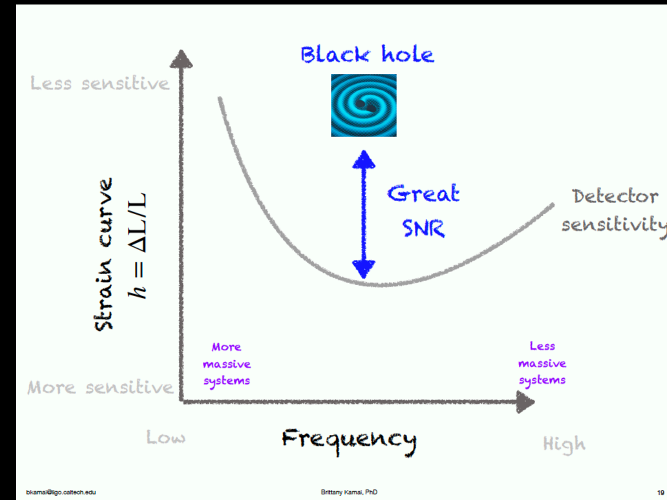


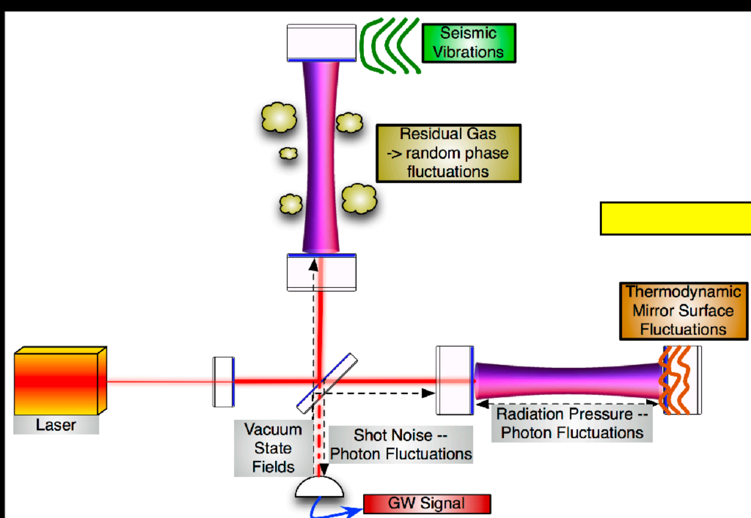
State of the art on many fronts:

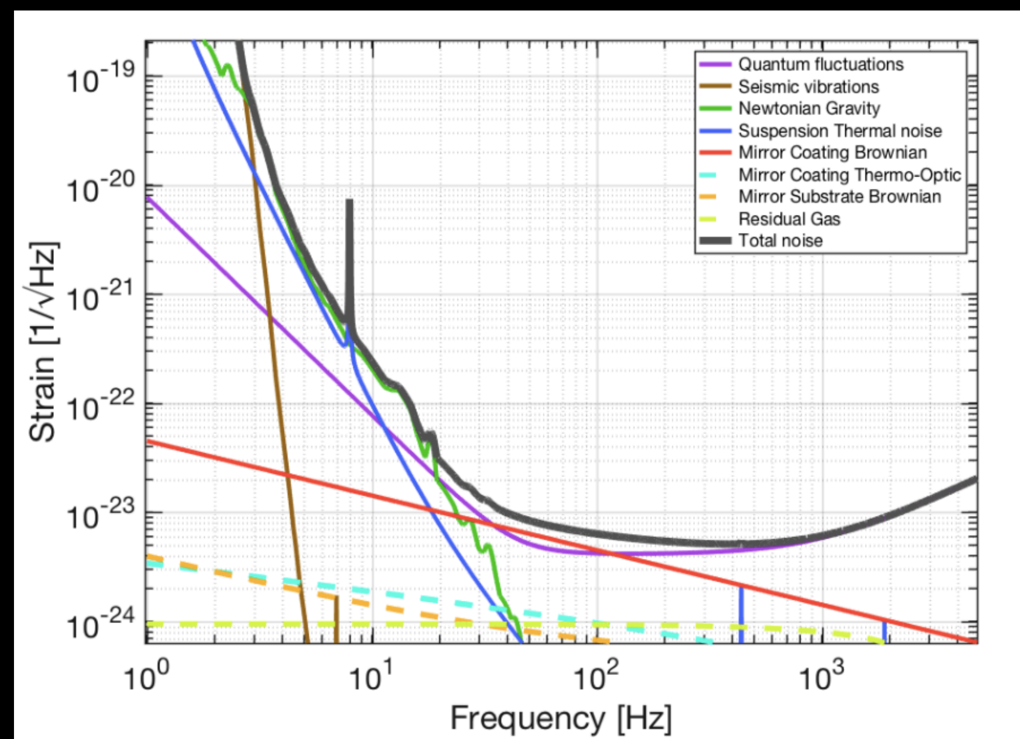
- **Vaccum**
- **Lasers, Mirrors,Optomechanics**
- **SuperAttenuators**
- **Controls**
- **Environmental Noise Sensors**
- **Data Science**

The art and science of GW observation

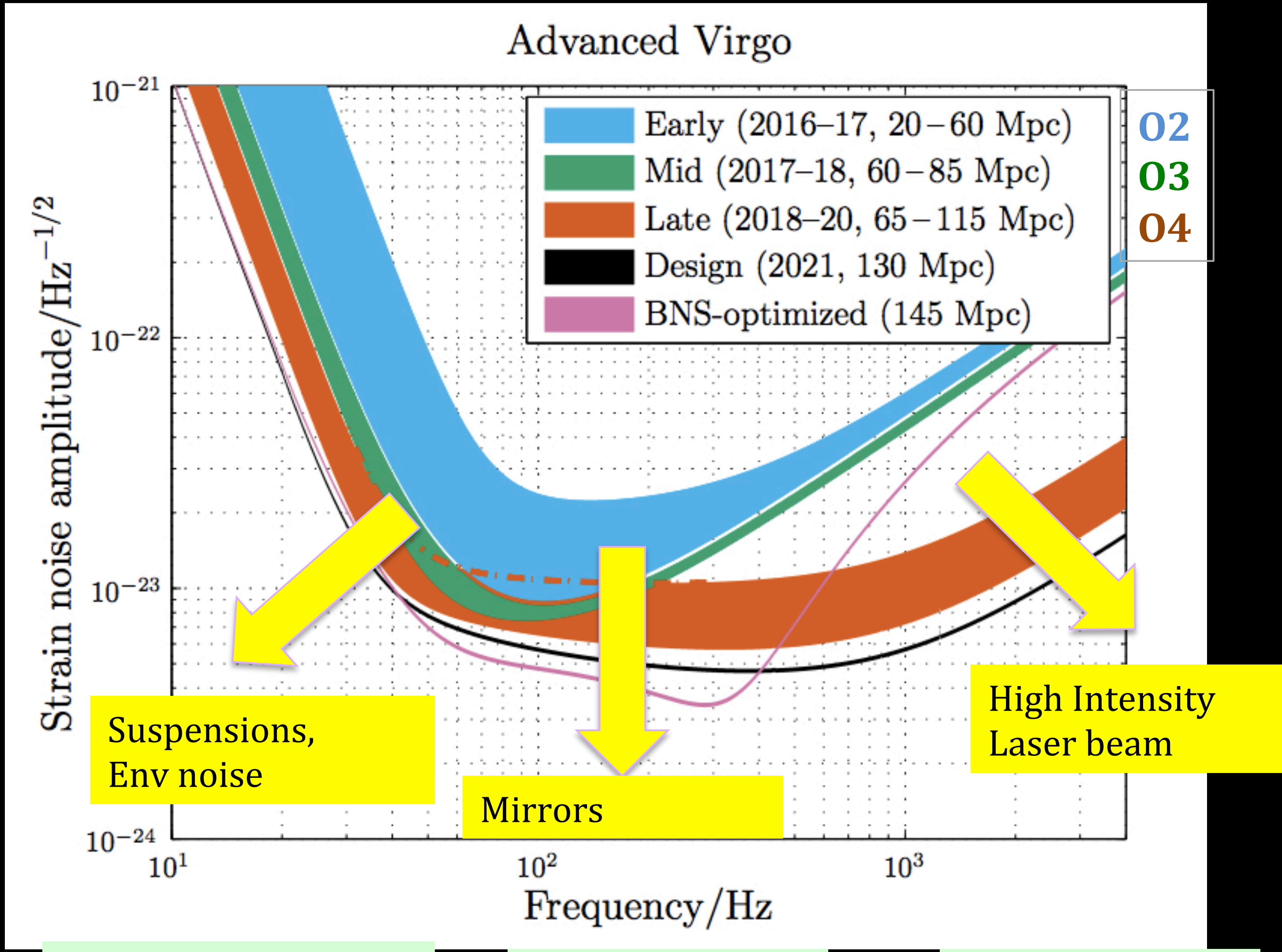








Sources at different frequencies a complex task at different technology fronts

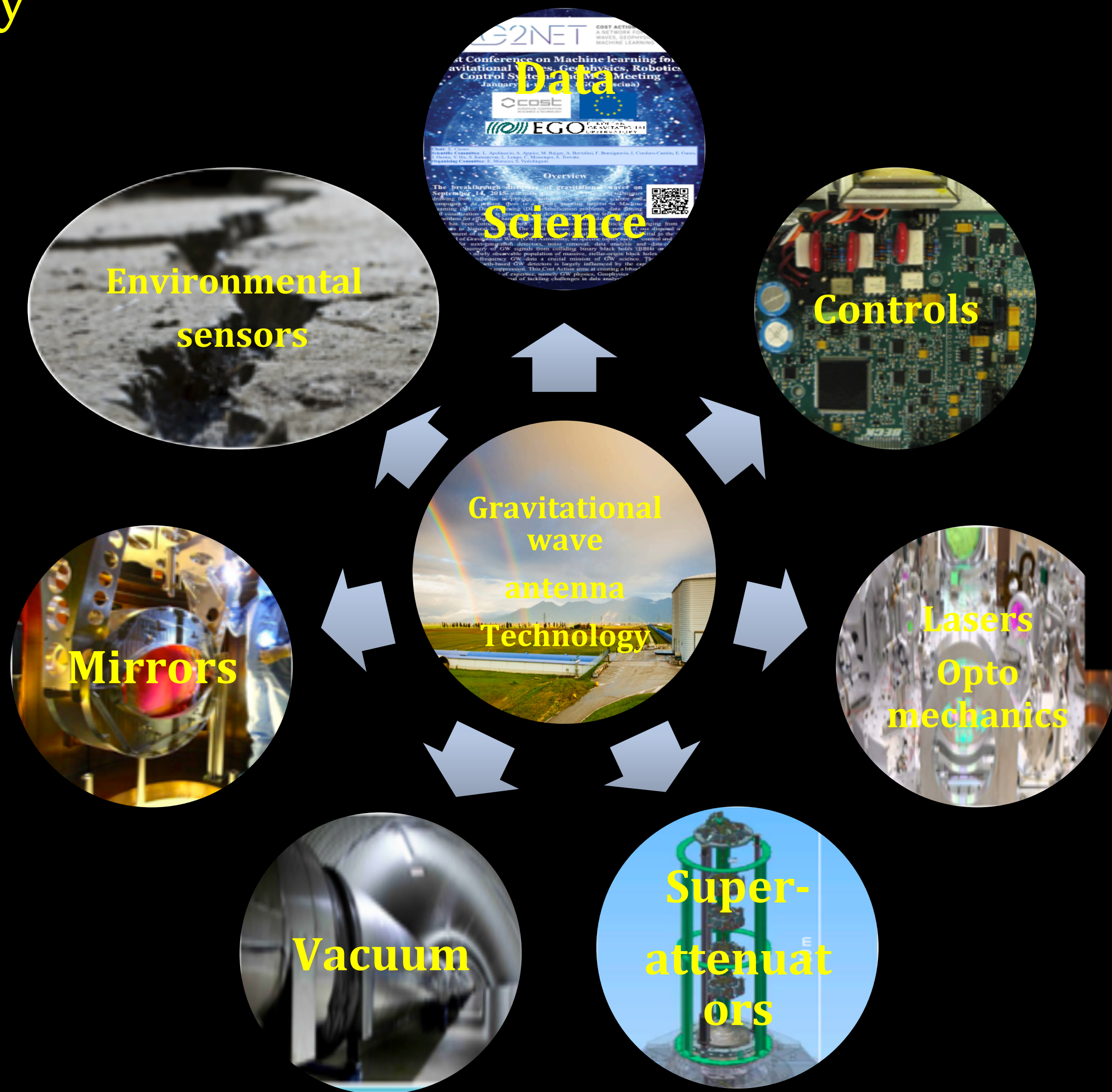


High Mass BBH
NS periodic emission

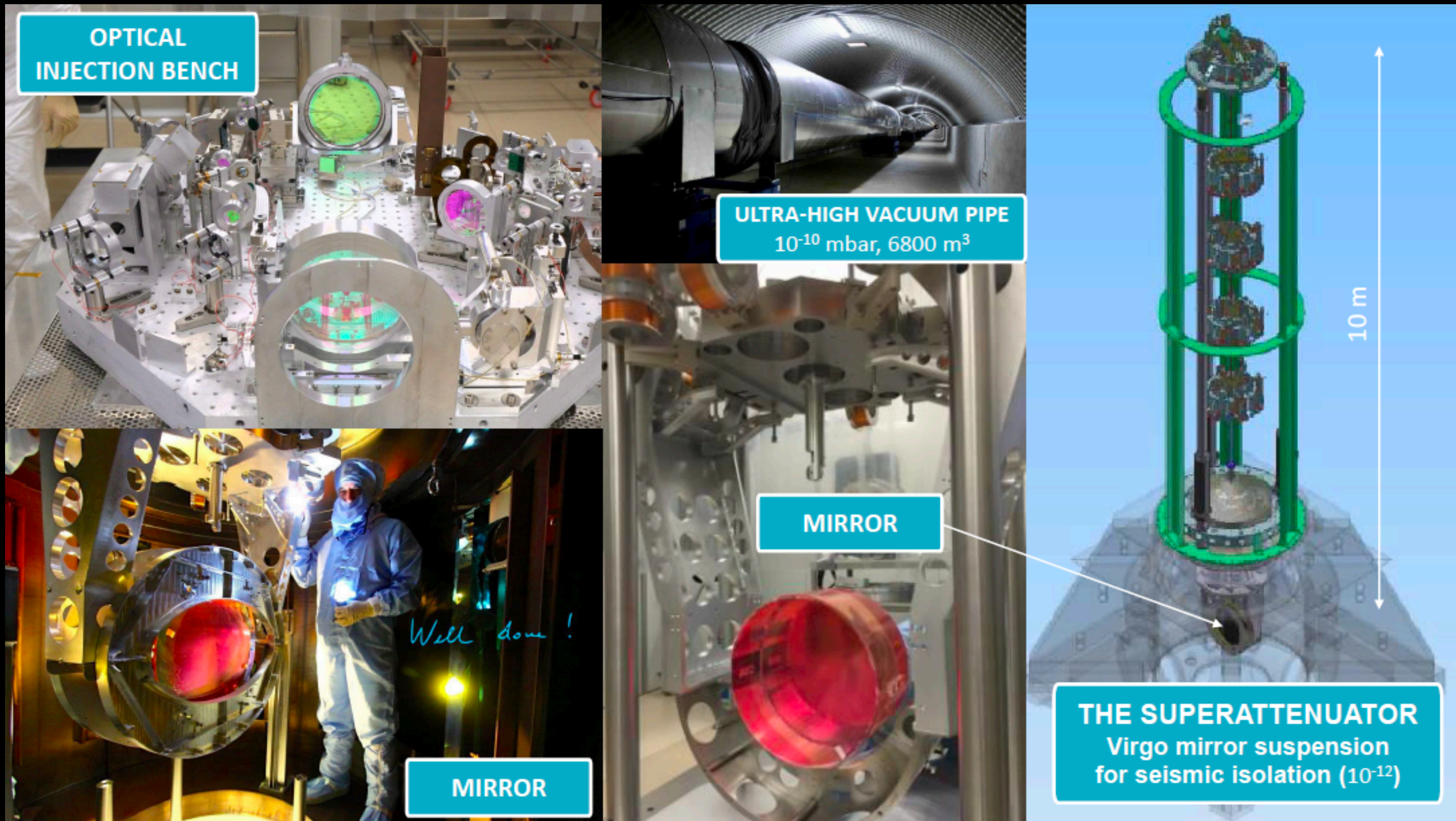
BBH mergers
BH ring down

Supernovae
NS transients

EGO/Virgo and Technology



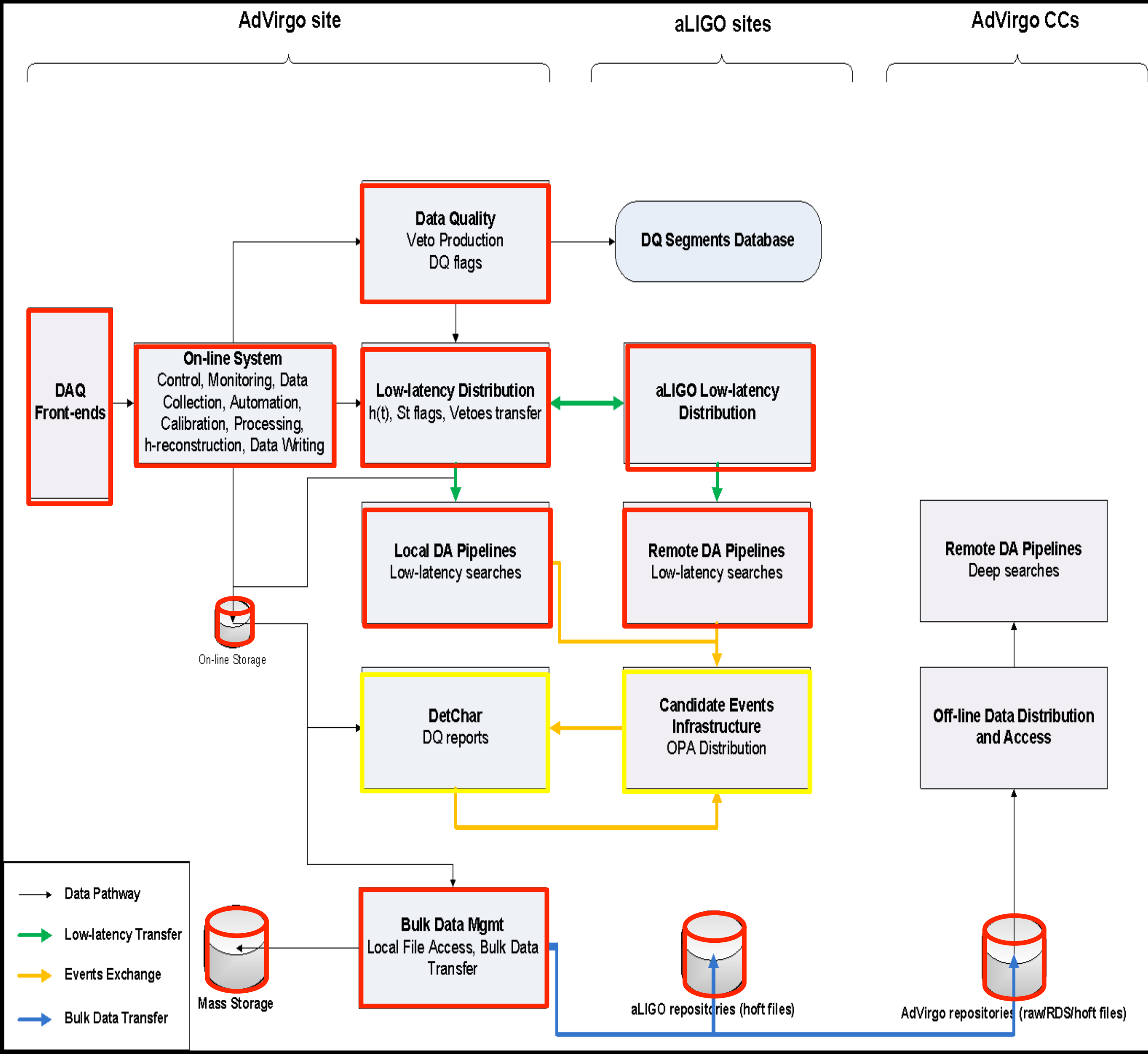
A technological hub



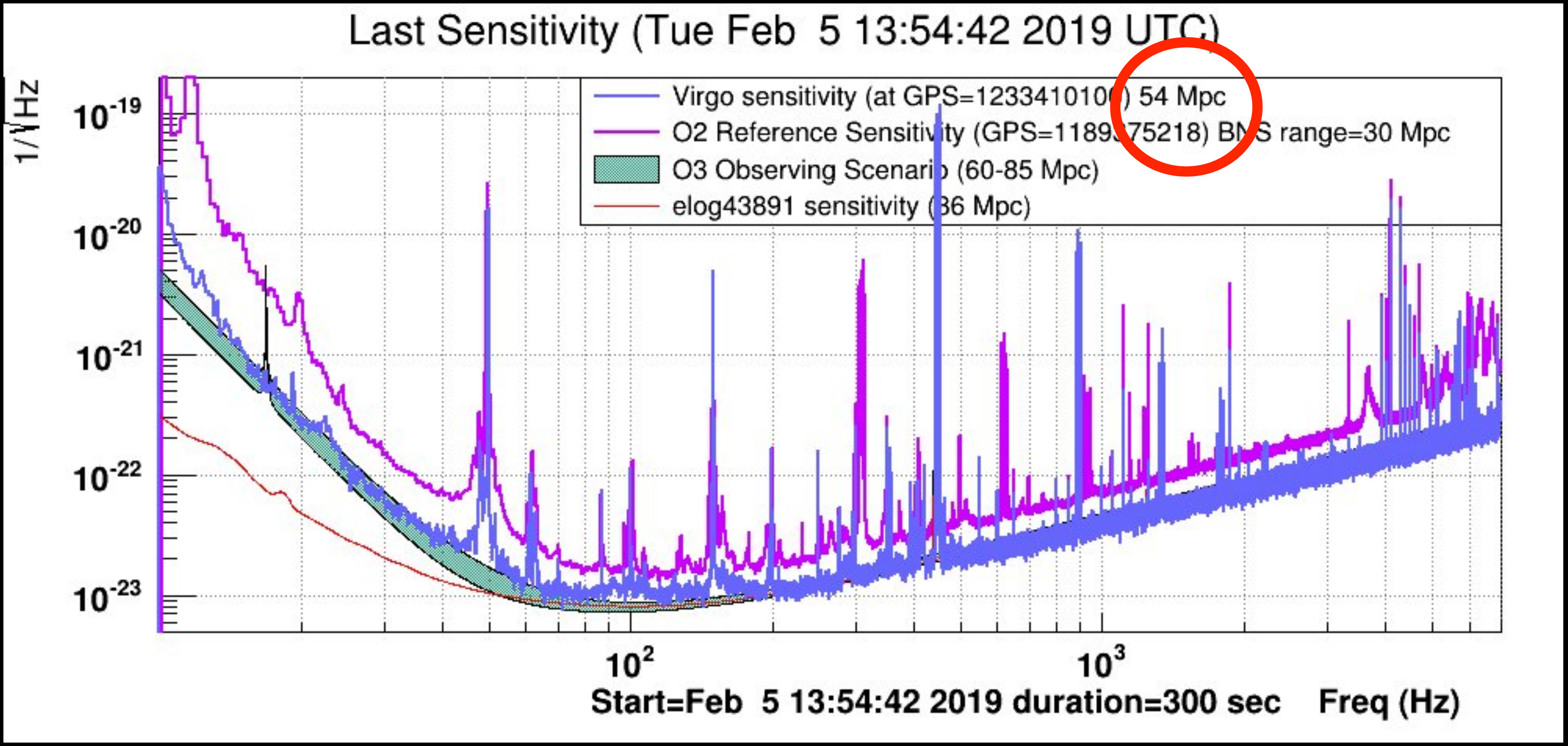
A huge effort over more than 3 decades of technological developments in a) State-of-the-art precision optics; b) Low optical and mechanical dissipation materials and new optical coatings for mirrors c) Low loss electro-optics d)The world's most stable high power lasers, d) High performance seismic vibration filtering e) Advanced environmental noise studies; f) Low noise control systems g) vacuum handling

AdVirgo Data Flow: The GW170814 case

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



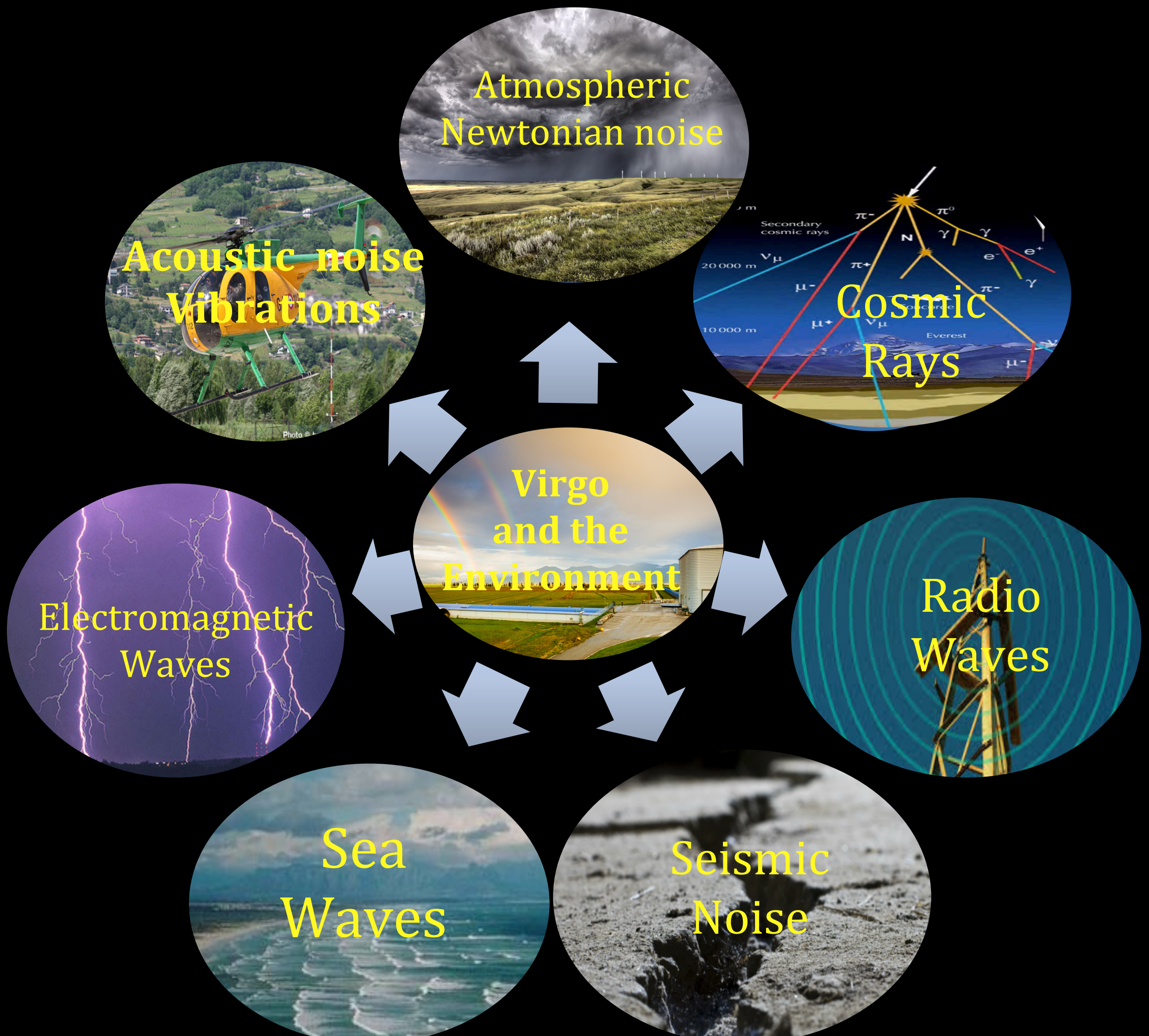
Where we are today
Preparing for the O3 run (end of March 2019)
towards the BNS 60 Mpc sensitivity (200 Mly)



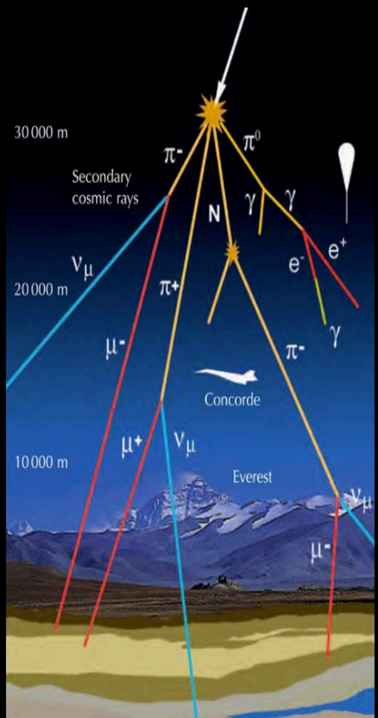
GW synergies

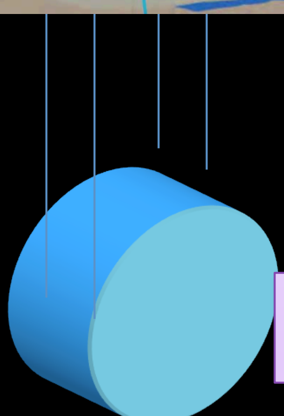
Virgo well isolated from environment

Increase of sensitivity ➔ challenges ➔ synergies with Geo/Atmospheric Science



Cosmic rays





"burst-like" can mimic GW event

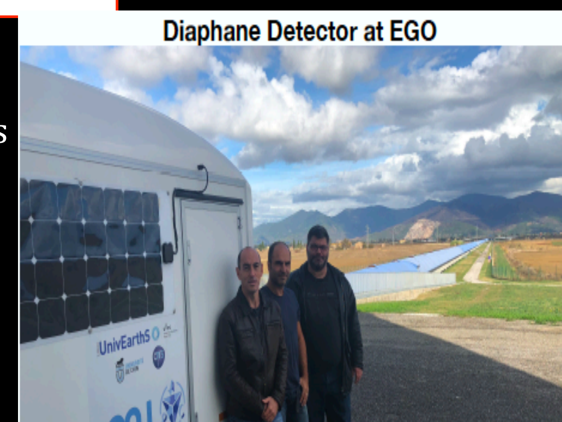
Interactions cosmic ray shower ↔ mirror test masses:

- Elastic interaction: direct momentum transfer
- Inelastic interaction: heating → distortion of mirror surface
- Muons are charged → charge deposit on mirror → Coulomb force fluctuations

Braginsky et al. *Notes about noise in GW antennas created by cosmic rays*, 2006 Phys. Lett. A 350,1 arXiv:gr-qc/0509058

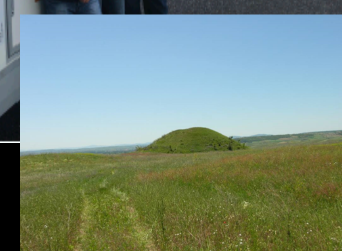
❑ Some effect can be observed for > 2TeV showers
h ≈ 10^-22 (just a few / year)

❑ Certainly of relevance for future 3G detectors
Acquiring experience now helps!



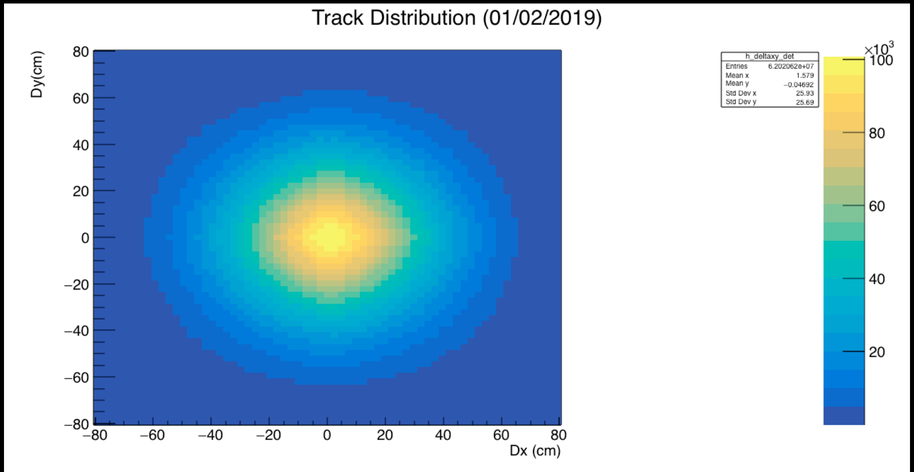
❑ One muon detector installed at EGO, during O3 science run (courtesy of Jacques Marteau – IPN Lyon)

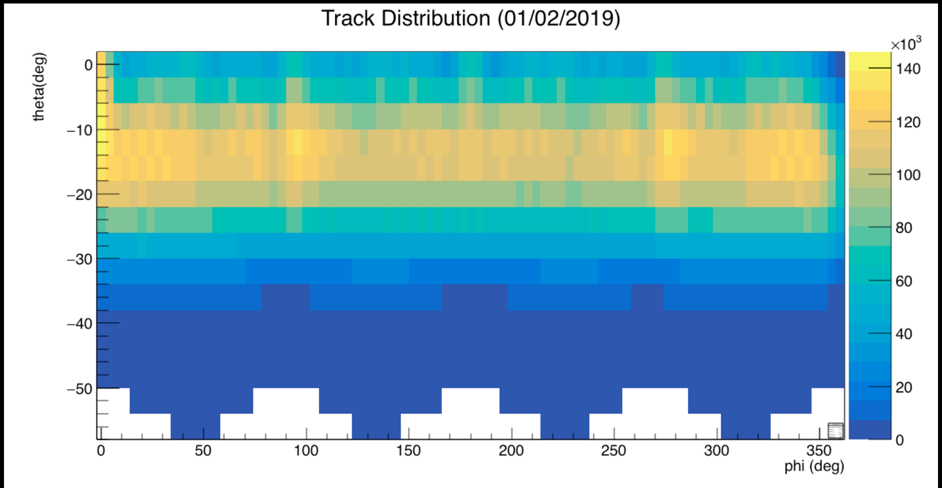
Synergy with Archaeology→



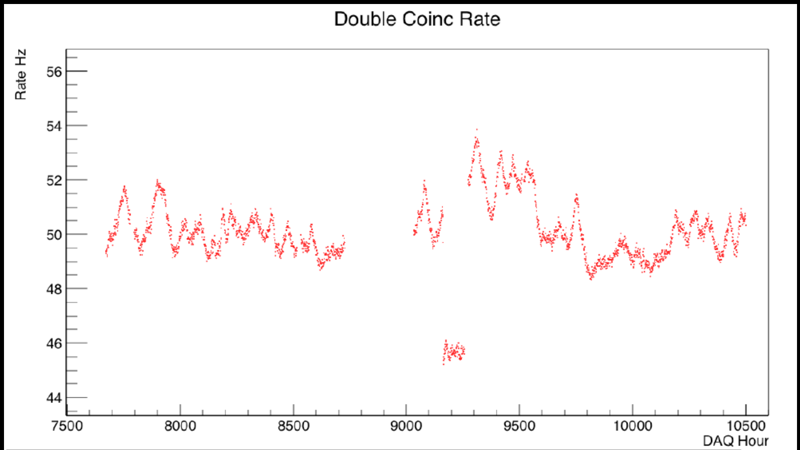
3 months of CR data

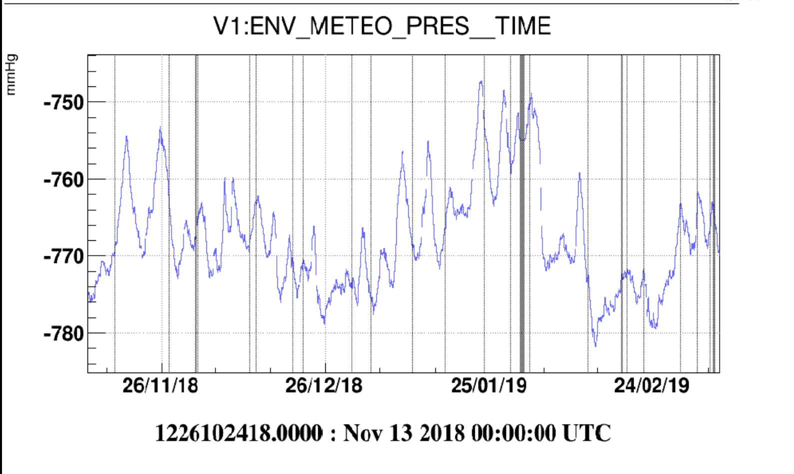
Space



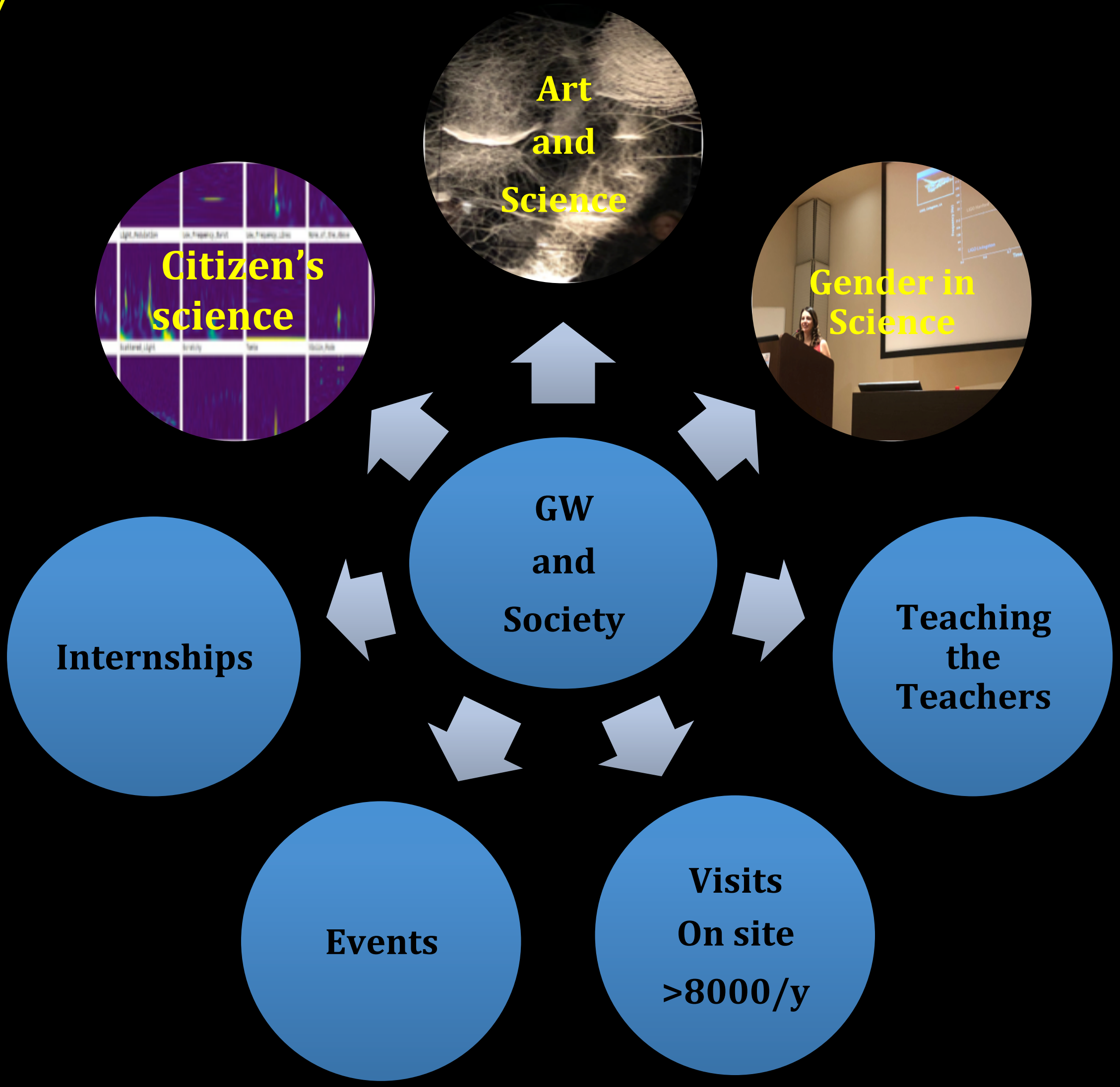


Time

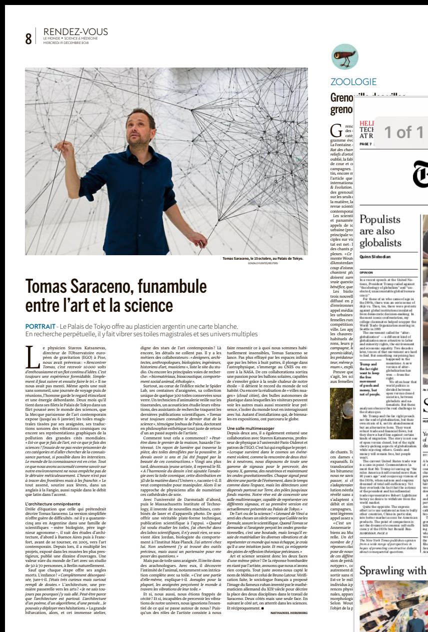




EGO/Virgo and Society



Art and science



8 RENDEZ-VOUS

ZOOLOGIE

Tomas Saraceno, funambule entre l'art et la science

PORTRAIT - Le Palais de Tokyo offre au plasticien argentin une carte blanche. En recherche perpétuelle, il y fait vibrer ses toiles magistrales et ses univers multiples

NENEH CHERRY CONVICTIONS IN HER MELODIES

'GOD WAS ON VACATION' GETTING A LESSON ON THE HOLOCAUST

The New York Times

INTERNATIONAL EDITION

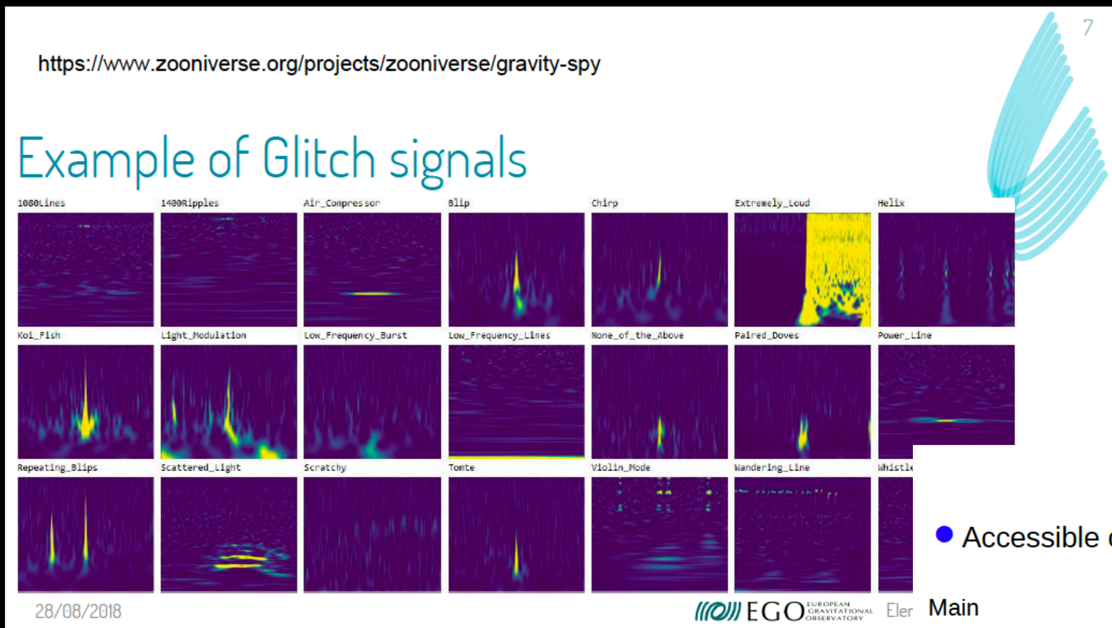
Populists are also globalists

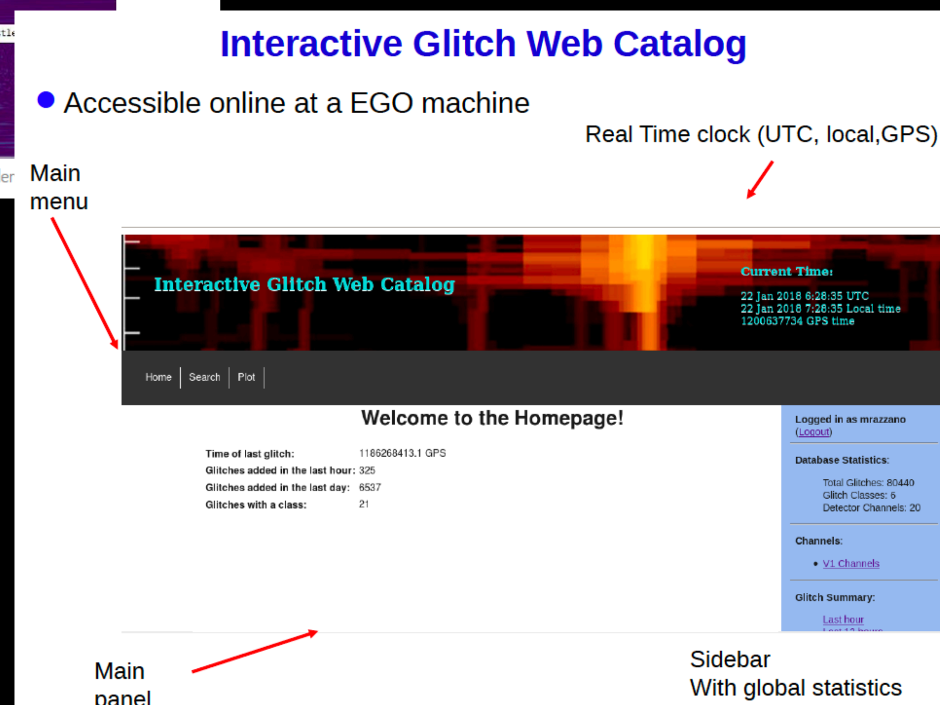
Fertilizer, with a whiff of Russian intrigue

Saudi Arabia's war grinds on

Sprawling with spiders, and other masterpieces

LIGO and Virgo
Citizen's Science : Gravity Spy





Also Machine Learning and Citizen's Science

Coming Soon

IL RITMO DELLO SPAZIO
LE LUCI E I SUONI DELL'UNIVERSO
DA MARCONI ALLE ONDE GRAVITAZIONALI

THE RHYTHM OF SPACE
Lights and sounds of the Universe
From Marconi to Gravitational waves

Ottobre-Novembre 2019
Museo della Grafica – Palazzo Lanfranchi, Pisa

EGO and EUROPE

- EGO an APPEC Functional Center
  - Key role for the APPEC contribution to European Strategy for Particle Physics
  - Promoting multi-messenger Physics in Europe from the institutional point of view
  - Start of a common roadmap Astroparticle-Geoscience for large infrastructures and Technology (first APPEC-GEO-8 meeting 11-12 February 22019 in Paris)

EU programs

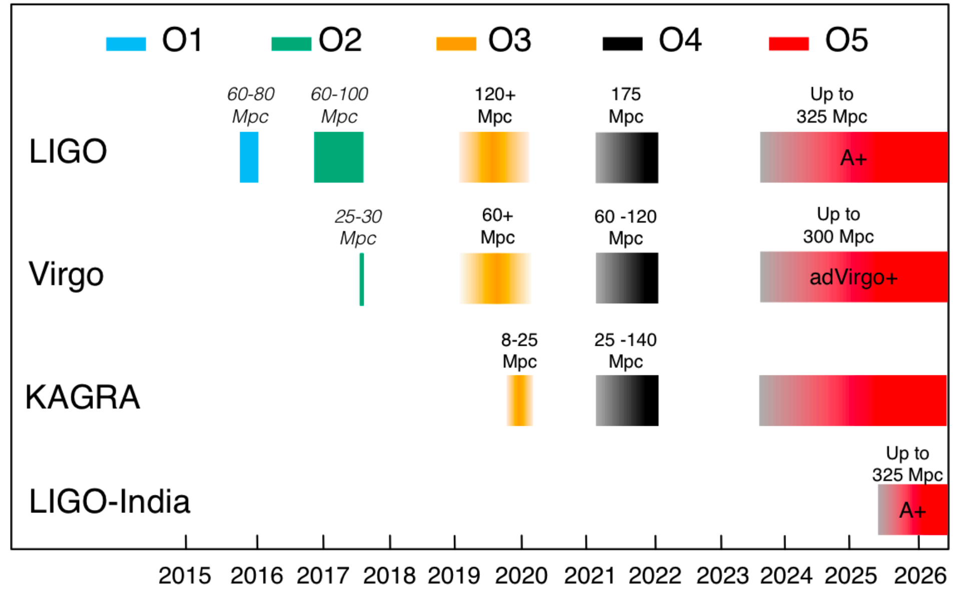
- **CURRENT**
  - **G2NET** Machine learning in Astroparticle and Geoscience (coordinator)
  - **ESCAPE** Data analysis, EOSC
  - **FRONTIERS** Outreach and education

- **SUBMITTED (news ca july)**
  - **AHEAD2** for Multimessenger Physics
  - **EU-MMO** for Multimessenger Physics data analysis
  - **REINFORCE** Swafs Citizen's Science (coordinator)

The Future

An international program
A+/AdV+/KAGRA/LIGO India
The next 10 years

- ➔ > x100 sources
- ➔ A global international network
- ➔ A global Multimessenger network



LIGO Scientific Collaboration:

- 1263 collaborators (including GEO)
- 20 countries
- 9 computing centres
- ~1.5 G$ of total investment

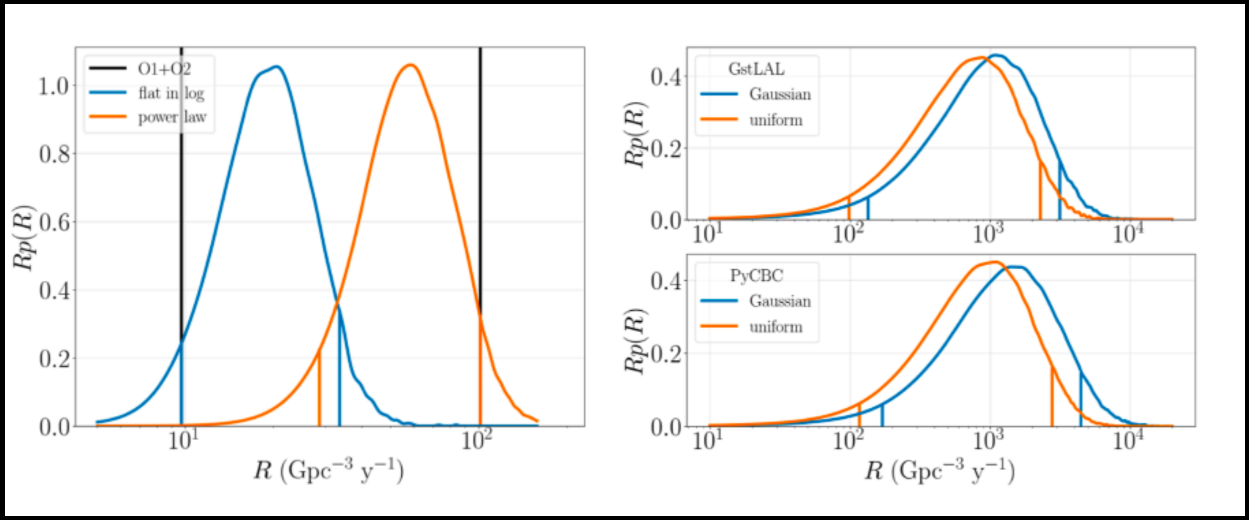
Virgo Collaboration:

- 343 collaborators
- 6 countries
- 6 computing centres
- ~0.42 G€ of total investment

KAGRA Collaboration:

- 260 collaborators
- 12 countries
- 5 computing centres
- ~16.4 G¥ of construction costs

BBH and BNS merger rates



Current sensitivity : merger rates of

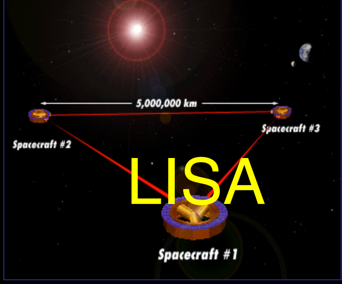
- BNS: 920 [110, 3840] Gpc-3 y-1
- BBH: 53 [9.7, 101] Gpc-3 y-1

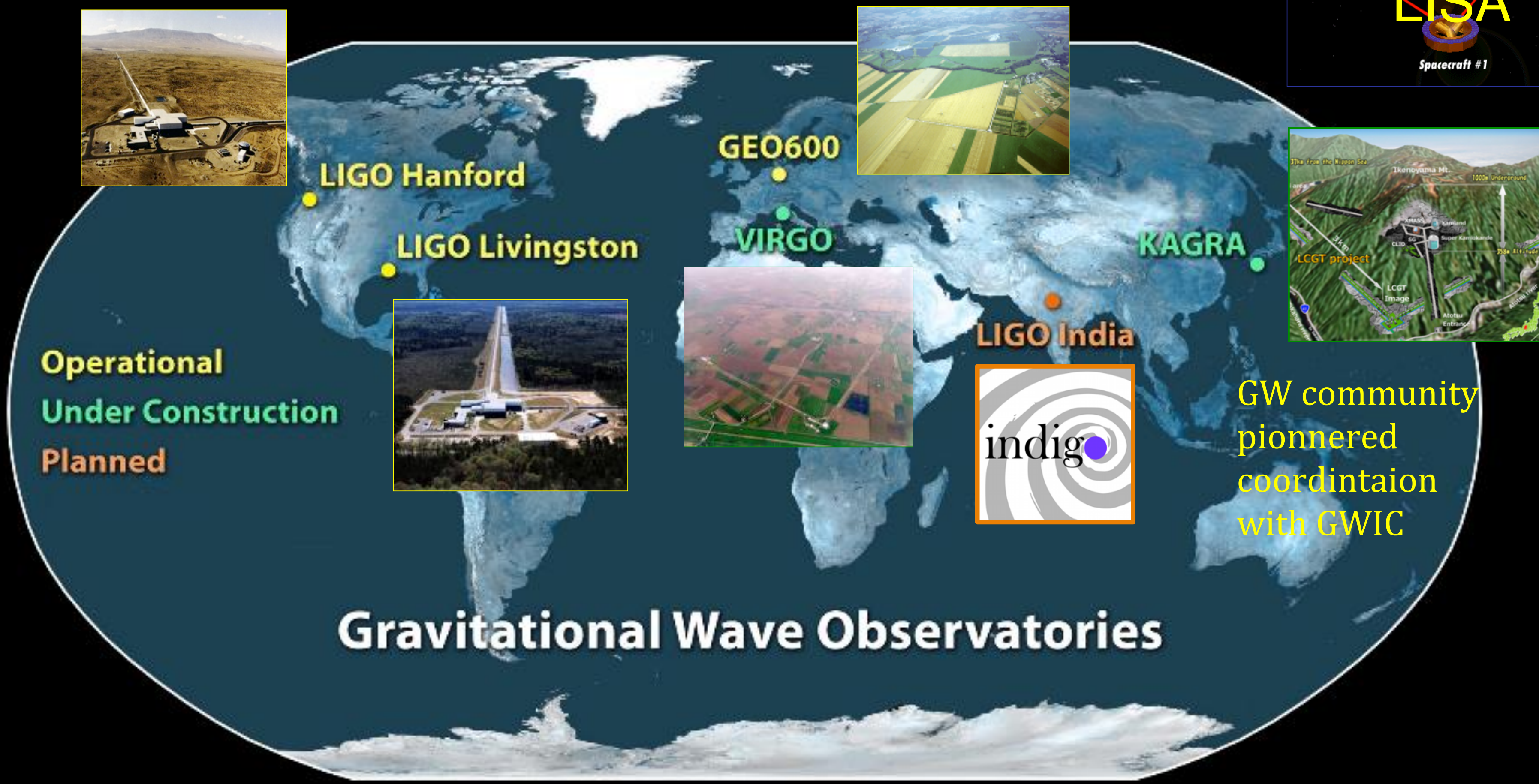
- At the end of ADV+/A+ upgrade
  - ➔ x100 sources
- 3G sensitivities
  - ➔ x1000 sources over AdV+/A+

Network	N(detected) $[\mathrm{yr}^{-1}]$	Median loc. [sq.deg]	N(<1 sq.deg.) $[\mathrm{yr}^{-1}]$	N(<10 sq.deg.) $[\mathrm{yr}^{-1}]$	N(<100 sq.deg.) $[\mathrm{yr}^{-1}]$
HLV	25	9	0	13	25
HLVKI	51	4	3	44	51
3aLIGO	34	11	1	15	33
1ET+2aLIGO	240	11	5	110	240
1CE+2aLIGO	290	17	4	91	280
3Voy	2500	20	18	550	2300
1ET+2Voy	14000	20	100	2700	13000
1ET+3Voy	19000	12	290	7700	19000
1CE+2Voy	18000	32	110	3000	17000
1CE+3Voy	24000	16	290	7600	24000
1CE+1ET+1Voy	260000	37	1000	28000	240000
1ET+2CE	620000	13	13000	240000	600000
3ET	240000	6	11000	170000	240000
3CE	860000	14	15000	310000	840000

Table 7.1: Detections per year and localization estimates for various 3G configurations. Binary neutron star sources were uniformly distributed in comoving volume. We assume a local co-moving BNS rate of 1000 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$.

A new challenge: worldwide collaboration





GW community pionnered coordintaion with GWIC

Between GW but also with em CR and neutrino observatories
(GW, CTA, KM3NET/ICECUBE, Auger)
New infrastructures, new detectors, computing, data access…
How will it be supported in the construction phase and funded ?
APPEC highest priority

Also a large complemntarity with space present (ISS, AMS,…) and future (ATHENA,…)

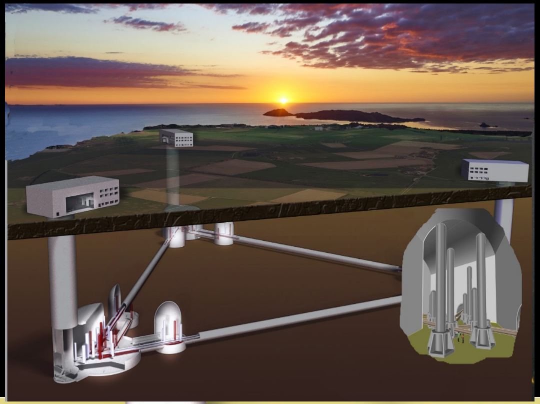
Towards the third generation

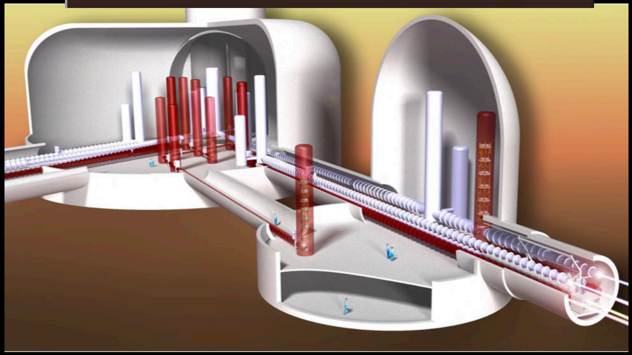
ET is an underground10km long triangular detector configuration capable of achieving a factor of 10 increase in sensitivity (x1000 in detection) (2034)
Two candidate sites: Sardinia, Triangular point Netherlands/Germany/Belgium

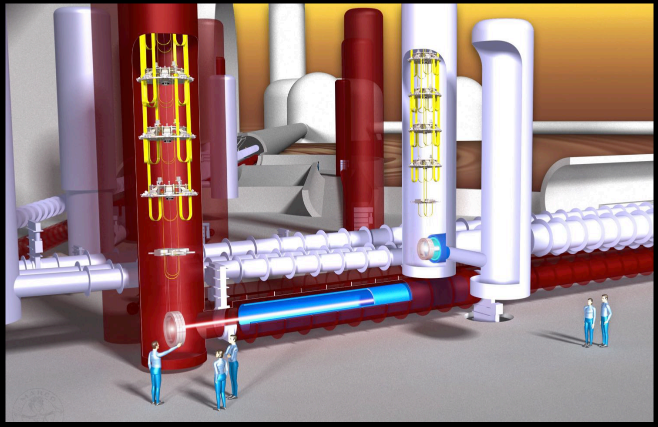
2021-2022 Site selection
2023-2024 Technical design report
2025 beginning of the construction
2030-2031 beginning of the commissioning phase

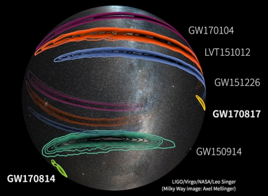
The importance of civil infrastructures

- 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

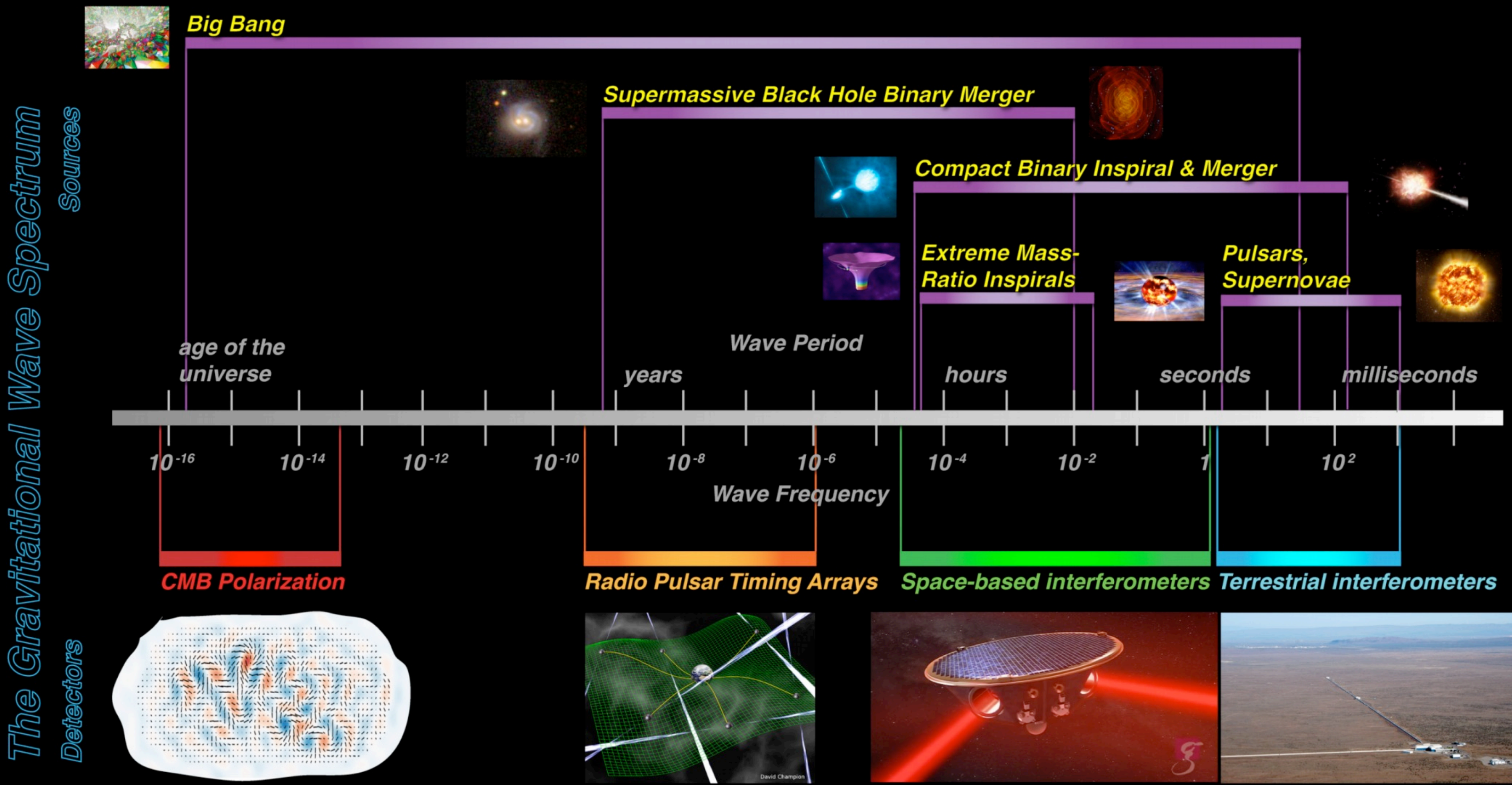








Gravitational Waves
Ground-Space complementarity



Conclusions

- GW address many fields of fundamental science: from Astrophysics and Cosmology to Particle and Nuclear Physics but also and photonic/ optomechanics/QM challenges.

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

- There is a continuous path of upgrades from adV (2017) to ET (2032-34). GW is a field where there is rare continuity between observation, upgrade and design of a new infrastructure.
  - But, the proper pace has to be kept in the process

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

- 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 and it is an enabling element in the above policy