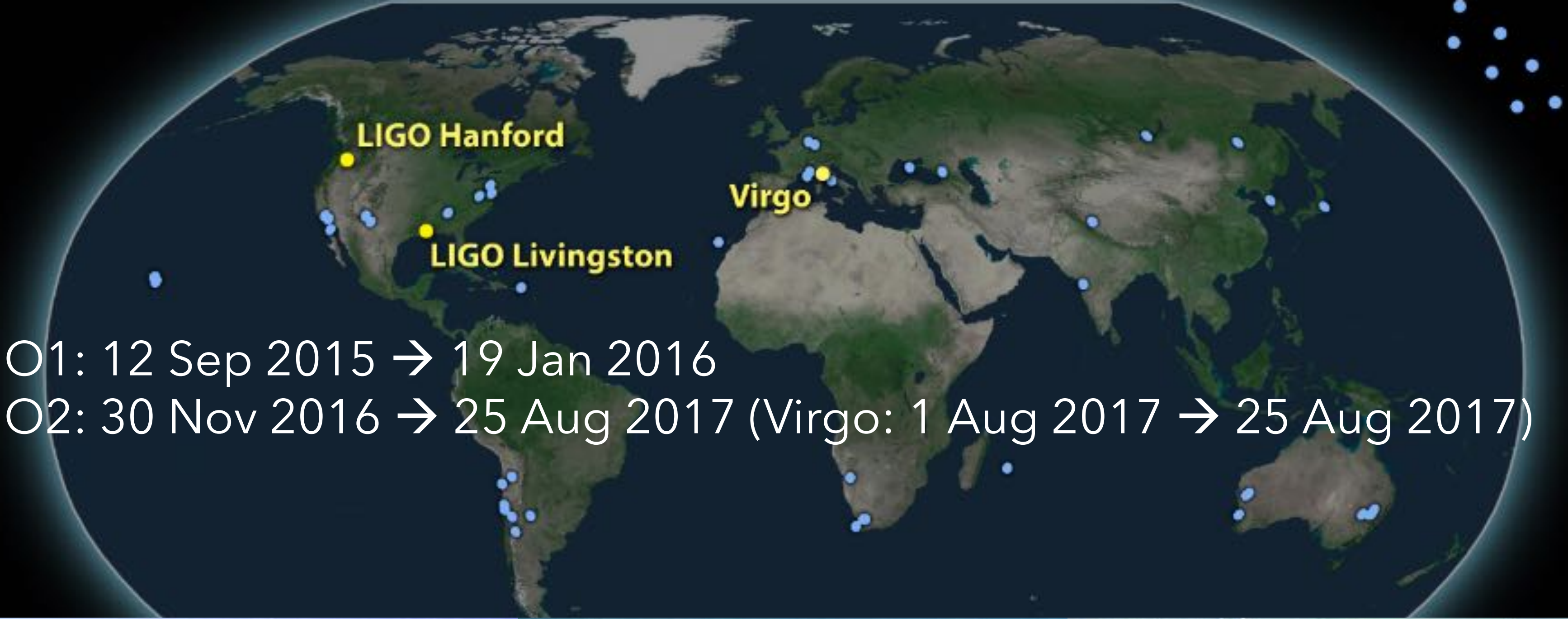
Galileo, 1610

PHYSICS with CURRENT and FUTURE GW EXPERIMENTS

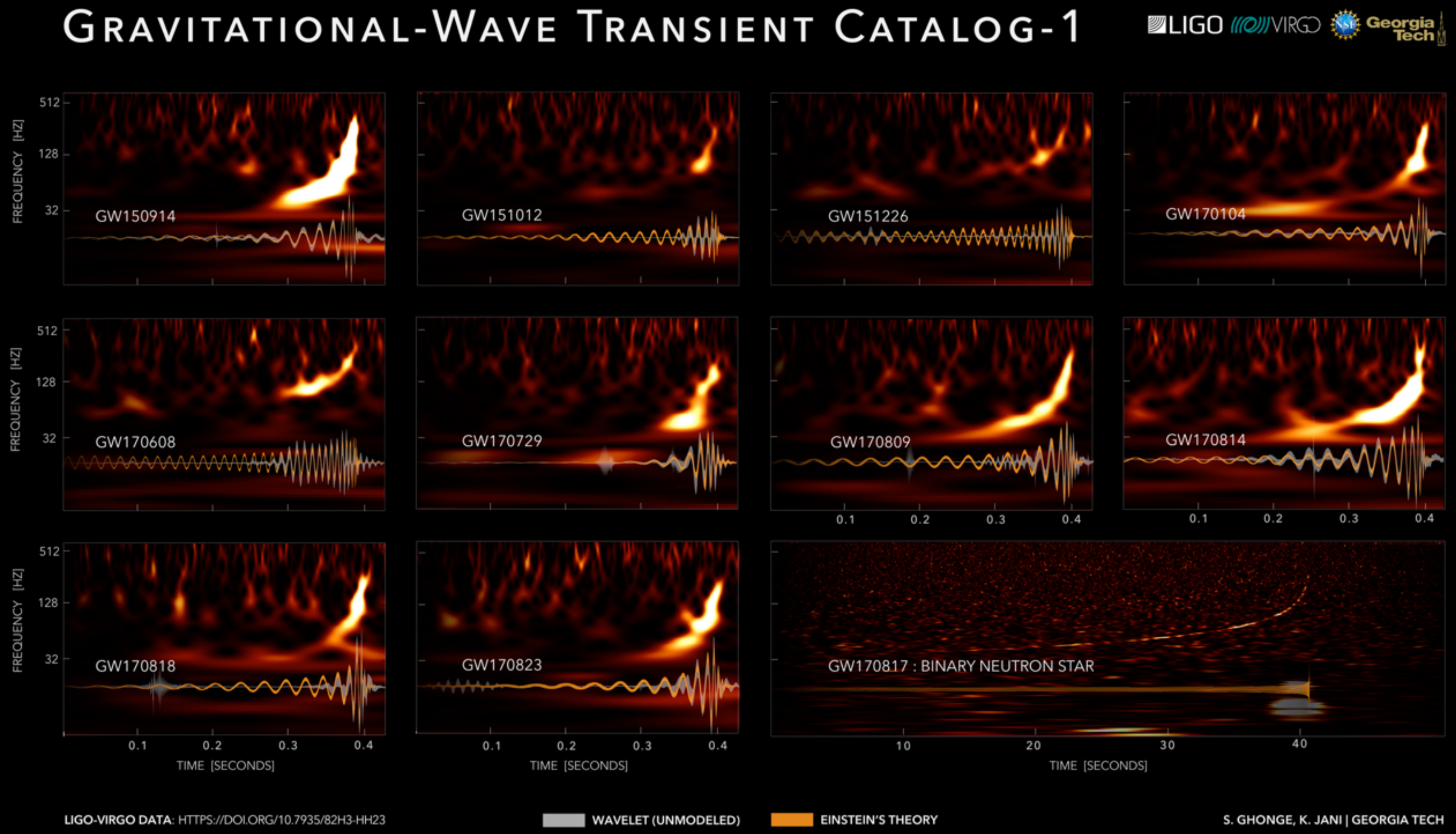
Giovanni Losurdo – INFN Pisa

Slide credits: E Chassand-Mottin, P Schmidt, G Gemme, M Punturo



O1: 12 Sep 2015 → 19 Jan 2016
O2: 30 Nov 2016 → 25 Aug 2017 (Virgo: 1 Aug 2017 → 25 Aug 2017)



B. P. Abbott, et al., (LIGO Virgo Collaboration), "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs" , PRX, 9, 031040 (2019)

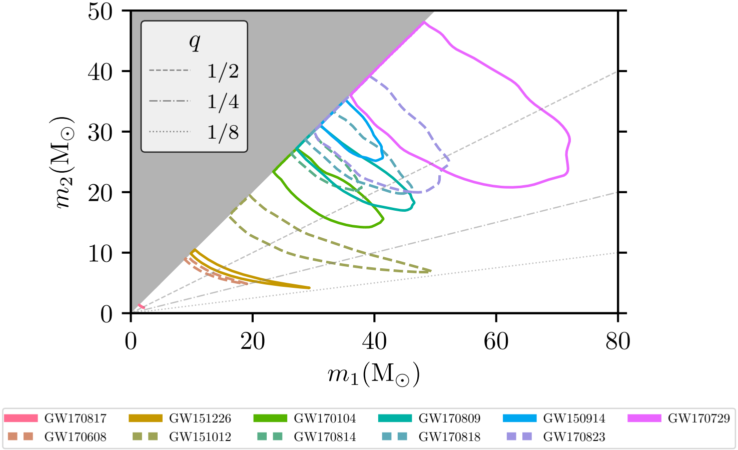
The Catalog

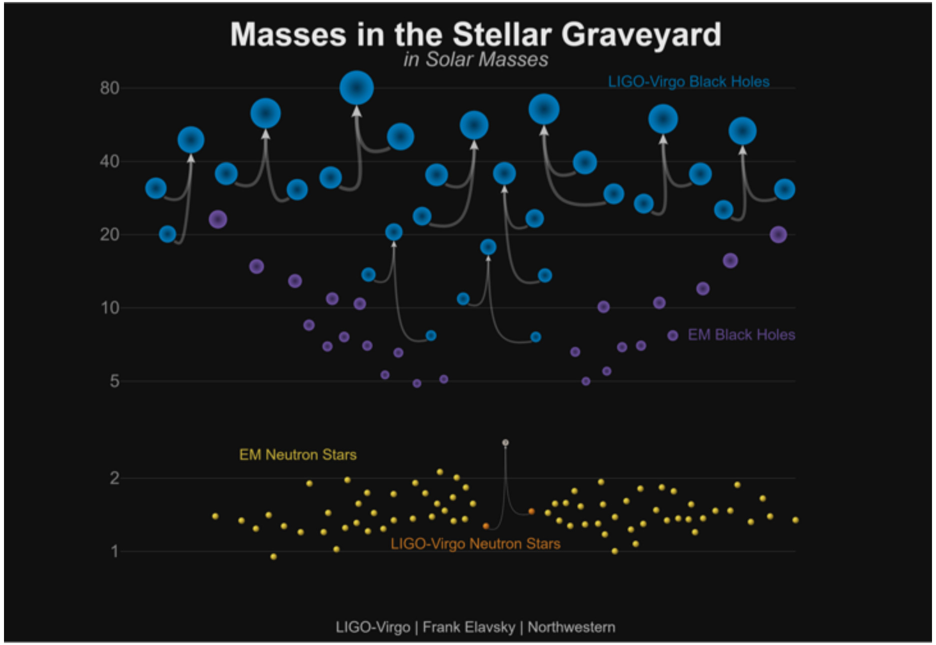
B. P. Abbott, et al. (LIGO Virgo Collaboration), PRX, 9, 031040 (2019)

Information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms

Event	$m_1/M_\odot$	$m_2/M_\odot$	$\mathcal{M}/M_\odot$	$\chi_{\rm eff}$	$M_{\rm f}/M_\odot$	$a_{\rm f}$	$E_{\rm rad}/(M_\odot c^2)$	$\ell_{\rm peak}/({\rm erg\,s^{-1}})$	$D_{\rm L}/{\rm Mpc}$	z	$\Delta\Omega/{\rm deg}^2$
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$-0.01^{+0.12}_{-0.13}$	$63.1^{+3.3}_{-3.0}$	$0.69^{+0.05}_{-0.04}$	$3.1^{+0.4}_{-0.4}$	$3.6^{+0.4}_{-0.4}\times10^{56}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$	194
GW151012	$23.2^{+14.0}_{-5.4}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.2}$	$0.04^{+0.28}_{-0.19}$	$35.7^{+9.9}_{-3.7}$	$0.67^{+0.13}_{-0.11}$	$1.5^{+0.5}_{-0.5}$	$3.2^{+0.8}_{-1.7}\times10^{56}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$	1491
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$0.18^{+0.20}_{-0.12}$	$20.5^{+6.4}_{-1.5}$	$0.74^{+0.07}_{-0.05}$	$1.0^{+0.1}_{-0.2}$	$3.4^{+0.7}_{-1.7}\times10^{56}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$	1075
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$-0.04^{+0.17}_{-0.20}$	$49.4^{+5.2}_{-3.9}$	$0.66^{+0.09}_{-0.11}$	$2.2^{+0.5}_{-0.5}$	$3.2^{+0.7}_{-1.0}\times10^{56}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$	912
GW170608	$11.2^{+5.4}_{-1.9}$	$7.5^{+1.5}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$0.04^{+0.19}_{-0.06}$	$17.9^{+3.4}_{-0.7}$	$0.69^{+0.04}_{-0.04}$	$0.8^{+0.1}_{-0.1}$	$3.4^{+0.5}_{-1.3}\times10^{56}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$	524
GW170729	$50.7^{+16.3}_{-10.2}$	$34.4^{+8.9}_{-10.2}$	$35.8^{+6.3}_{-4.9}$	$0.37^{+0.21}_{-0.26}$	$80.3^{+14.5}_{-10.3}$	$0.81^{+0.07}_{-0.13}$	$4.9^{+1.6}_{-1.7}$	$4.2^{+0.8}_{-1.5}\times10^{56}$	2760^{+1290}_{-1350}	$0.48^{+0.18}_{-0.21}$	1069
GW170809	$35.2^{+8.3}_{-5.9}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$0.07^{+0.17}_{-0.16}$	$56.4^{+5.2}_{-3.7}$	$0.70^{+0.08}_{-0.09}$	$2.7^{+0.6}_{-0.6}$	$3.5^{+0.6}_{-0.9}\times10^{56}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$	310
GW170814	$30.7^{+5.5}_{-2.9}$	$25.6^{+2.8}_{-4.0}$	$24.3^{+1.4}_{-1.1}$	$0.07^{+0.12}_{-0.11}$	$53.6^{+3.2}_{-2.5}$	$0.73^{+0.07}_{-0.05}$	$2.8^{+0.4}_{-0.3}$	$3.7^{+0.5}_{-0.5}\times10^{56}$	560^{+140}_{-210}	$0.12^{+0.03}_{-0.04}$	99
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	$0.00^{+0.02}_{-0.01}$	≤ 2.8	≤ 0.89	≥ 0.04	$\geq 0.1\times10^{56}$	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$	22
GW170818	$35.5^{+7.5}_{-4.7}$	$26.9^{+4.4}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$-0.09^{+0.18}_{-0.21}$	$59.8^{+4.8}_{-3.7}$	$0.67^{+0.07}_{-0.08}$	$2.7^{+0.5}_{-0.5}$	$3.4^{+0.5}_{-0.7}\times10^{56}$	1020^{+430}_{-370}	$0.20^{+0.07}_{-0.07}$	35
GW170823	$39.5^{+10.1}_{-6.6}$	$29.4^{+6.5}_{-7.1}$	$29.3^{+4.2}_{-3.1}$	$0.08^{+0.19}_{-0.22}$	$65.6^{+9.3}_{-6.5}$	$0.71^{+0.08}_{-0.09}$	$3.3^{+0.9}_{-0.8}$	$3.6^{+0.6}_{-0.9}\times10^{56}$	1860^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$	1780

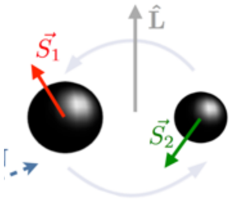
Masses



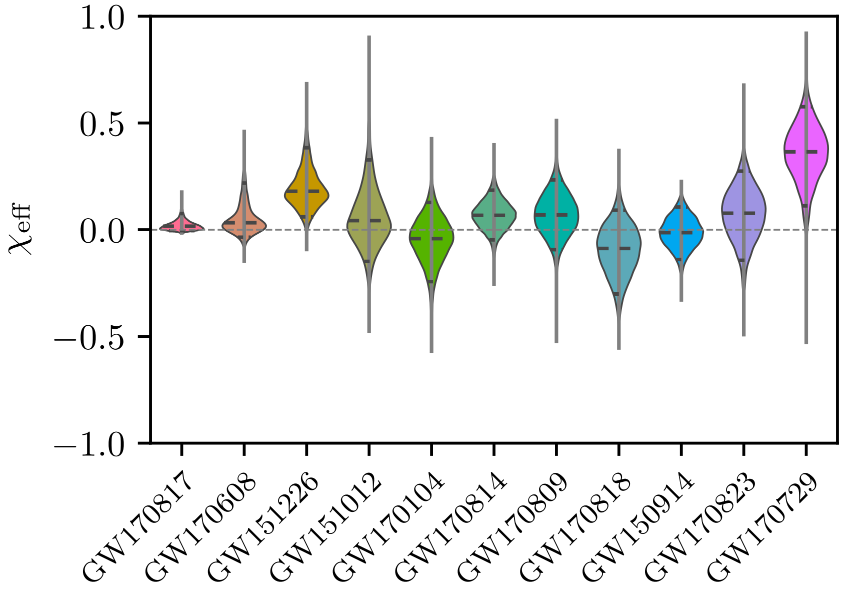


- Wide range of BH masses
  - More BBH towards the heavy end, none in either mass gaps
  - GW170729: heaviest (~80 $M_\odot$) and furthest (z~0.5)
- BNS remnant in the mass gap

BH Spins



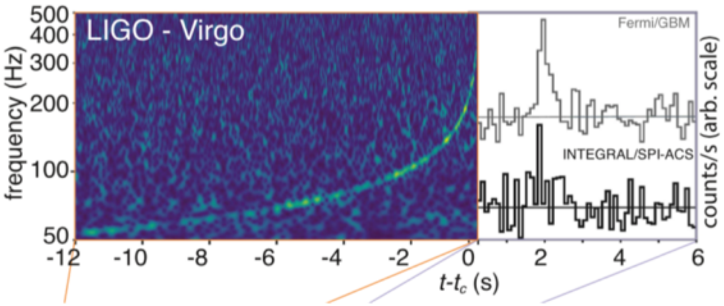
$$\chi_{\rm eff} = \frac{(m_1\vec{\chi}_1 + m_2\vec{\chi}_2)\cdot \hat{L}_N}{M}$$



- Key signatures to discriminate BH populations: shed light on formation mechanism
- GW170729 has a clear indication of a net positive $\chi_{\rm eff}$
- Precession remains unconstrained for all events

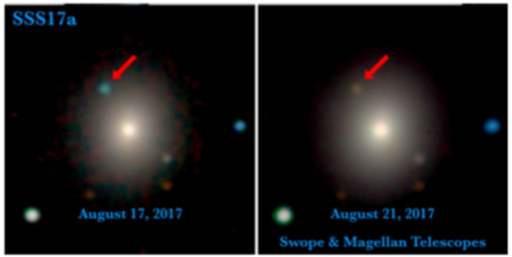
GW170817

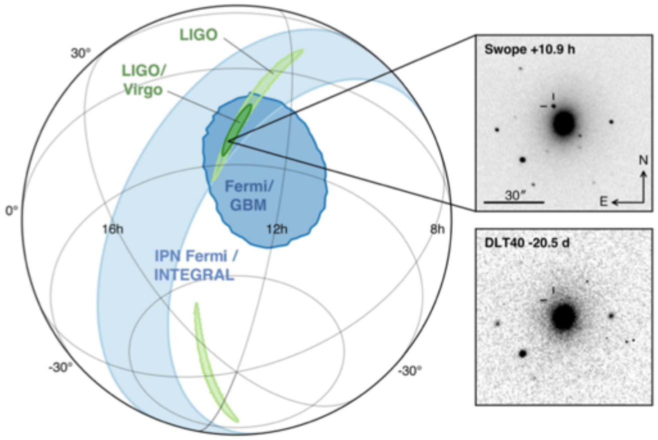
ApJL 2017 and ref. therein



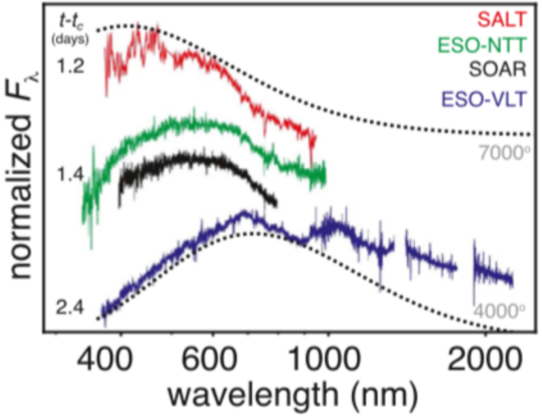
Aug 17, 2017
GW fron BNS detected by LIGO/Virgo
Fermi GBM detects sGRB after 1.7 s

Multiwavelength observation of the source: kilonova

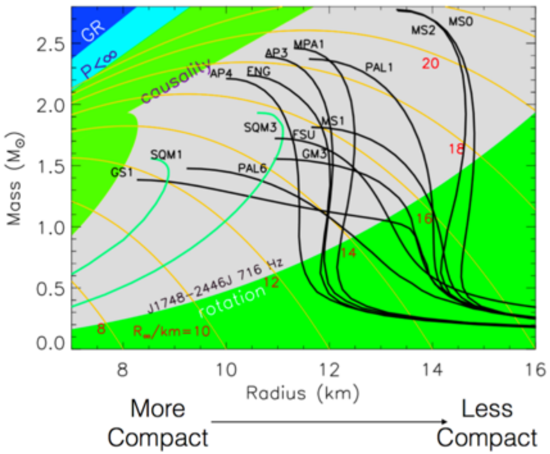




GCN sent after ~27'
Event localized within ~30° sq
Optical counterpart first observed by SWOPE after ~11h

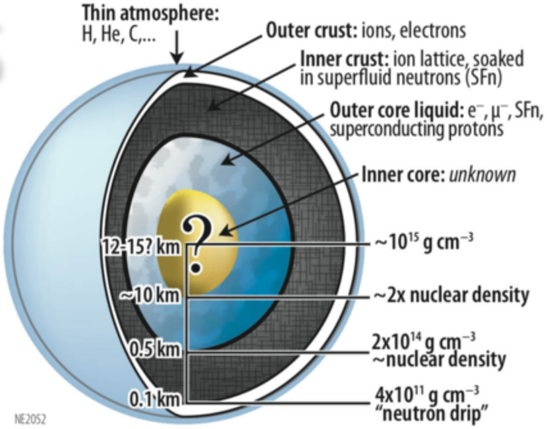


GW170817: NUCLEAR PHYSICS



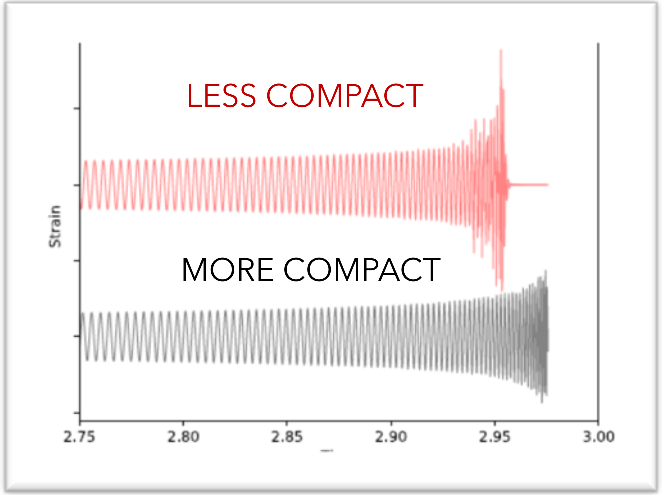
Lattimer, arXiv:1305.3510

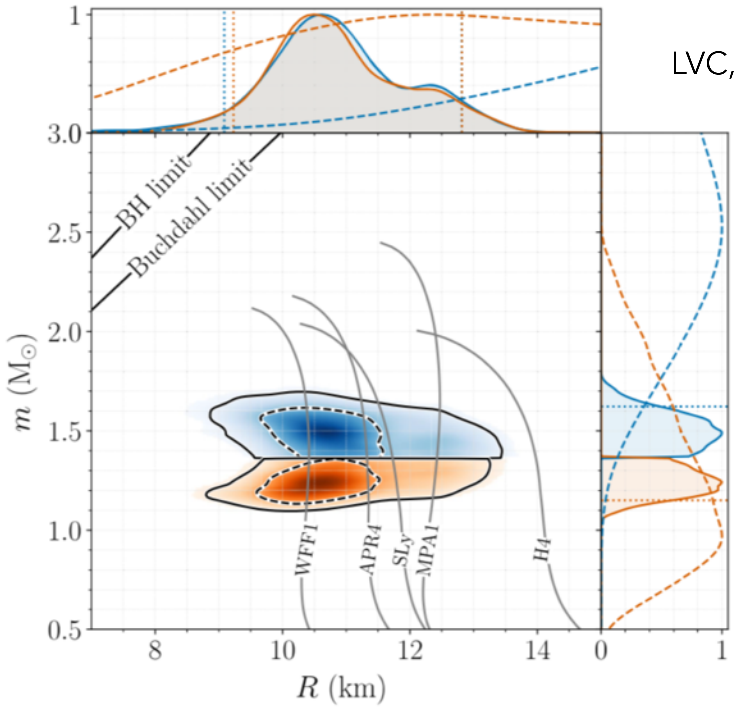
INTERNAL STRUCTURE AND COMPOSITION (LARGELY UNKNOWN) ENCODED IN THE EQUATION OF STATE



Each NS is deformed by the tidal field of the companion

Deformations leave an imprint on the GW emission

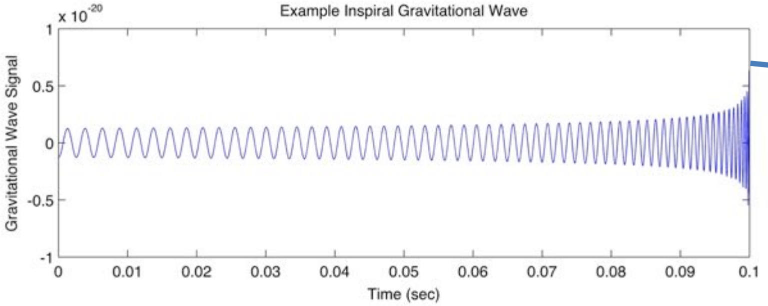




LVC, PRL 121, 161101 (2018)

LIGO/VIRGO are measuring the NS radius/mass. Improving the accuracy (better SNR, more events) will allow to determine the EOS

GW170817: COSMOLOGY



$$H_0 d_L = cz$$

$$H_0 = 70^{12.0}_{-8.0} \text{ km s}^{-1}\text{Mpc}$$

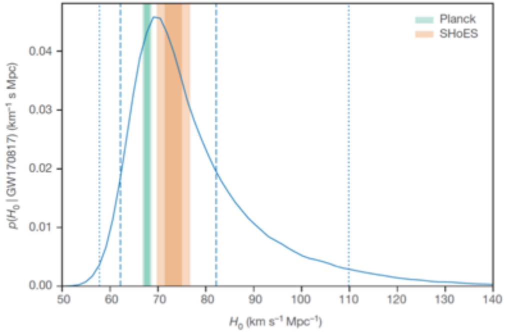
Abbott et al.,Nature, 24471 (2017)

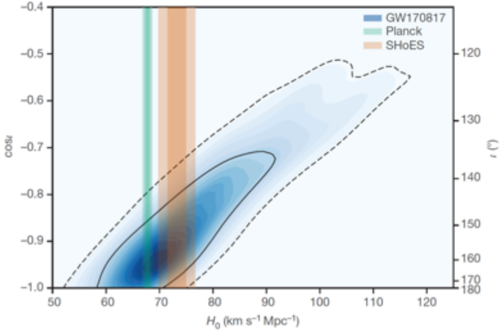
From GW: redshifted mass and luminosity distance

$$\Psi(f) \propto 2\pi f t_c - \Phi_c - \frac{\pi}{4} + \frac{3}{128}\left(\pi \mathcal{M}_z f\right)^{-5/3}\left[1 + \ldots\right]$$

$$\tilde{h}_+(f) \propto A_0 \frac{\mathcal{M}_z^{5/6}}{D_L}\left[1 + \cos^2 \iota\right] f^{-7/6} e^{i\Psi(f)}$$

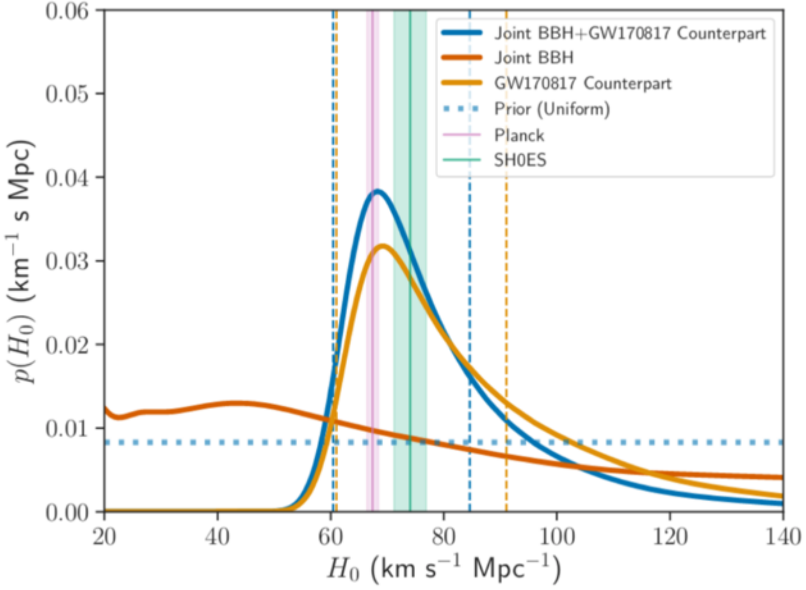
Inclination angle introduces degeneracy, which will be removed by measuring the 2 polarizations





New measurement of H_0 using the O1+O2 detections and galaxy catalogs

arxiv:1908.06060



$$H_0 = 68^{+14}_{-7} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

GW170817: FUNDAMENTAL PHYSICS

- GW170817 provides a stringent test of the speed of gravitational waves

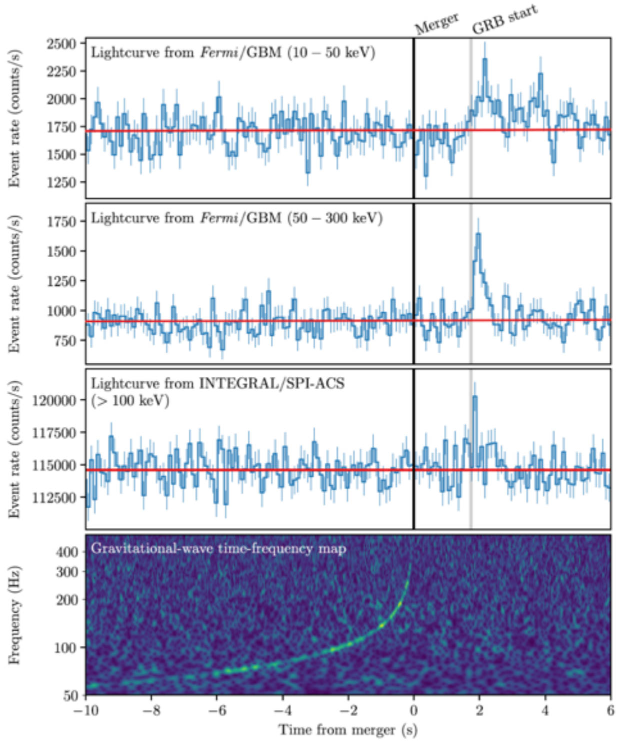
$$\frac{v_{GW} - c}{c} \approx \frac{c}{D}(\Delta t_{obs} - \Delta t_{start})$$

- Δt =1.7±0.5 s over ~130 Myrs

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

Assuming D=26 Mpc (lowest value)

Assuming sGRB emitted 10 s after GW



Abbott et al., ApJL., 848:L13 (2017)

More science from O1-O2

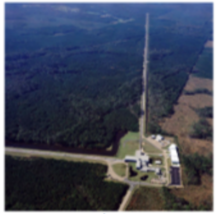
- Updated merger rates: LVC, GWTC-1, PRX 2019
  - BNS: [110,3840] $Gpc^{-3}\ y^{-1}$
  - BBH: [9.7,101] $Gpc^{-3}\ y^{-1}$
  - NSBH merger rate 90% upper limit of 610 $Gpc^{-3}\ y^{-1}$
- Propagation of GW (dispersion): $m_g \leq 4.7\times10^{-23}\ \mathrm{eV/c^2}$ LVC, arXiv 1903.04467
- Polarization tests LVC, PRL 2017
- Tests of the nature of the BNS remnant LVC, arXiv 1908.01012
- Data available: https://www.gw-openscience.org/catalog

Gravitational Wave Open Science Center

Getting Started
Data
- Catalogs
- Bulk Data

Tutorials
Software
Detector Status
Timelines
My Sources
GPS ↔ UTC
About the detectors
Projects
Acknowledge GWOSC

LIGO Hanford Observatory, Washington
(Credits: C. Gray)



LIGO Livingston Observatory, Louisiana
(Credits: J. Giaime)

Virgo detector, Italy
(Credits: Virgo Collaboration)

The Gravitational Wave Open Science Center provides data from gravitational-wave observatories, along with access to tutorials and software tools.

Get started!

Download data

GWTC-1: Catalog of Compact Binary Mergers

Join the email list

Explore the open data web course

LIGO and Virgo's portal for
- Bulk data
- Event 1-hour time-series data, etc.
- Pointers to papers, data behind figures, posterior samples
- Pointers to analysis codes
- Pointers to Workshop materials

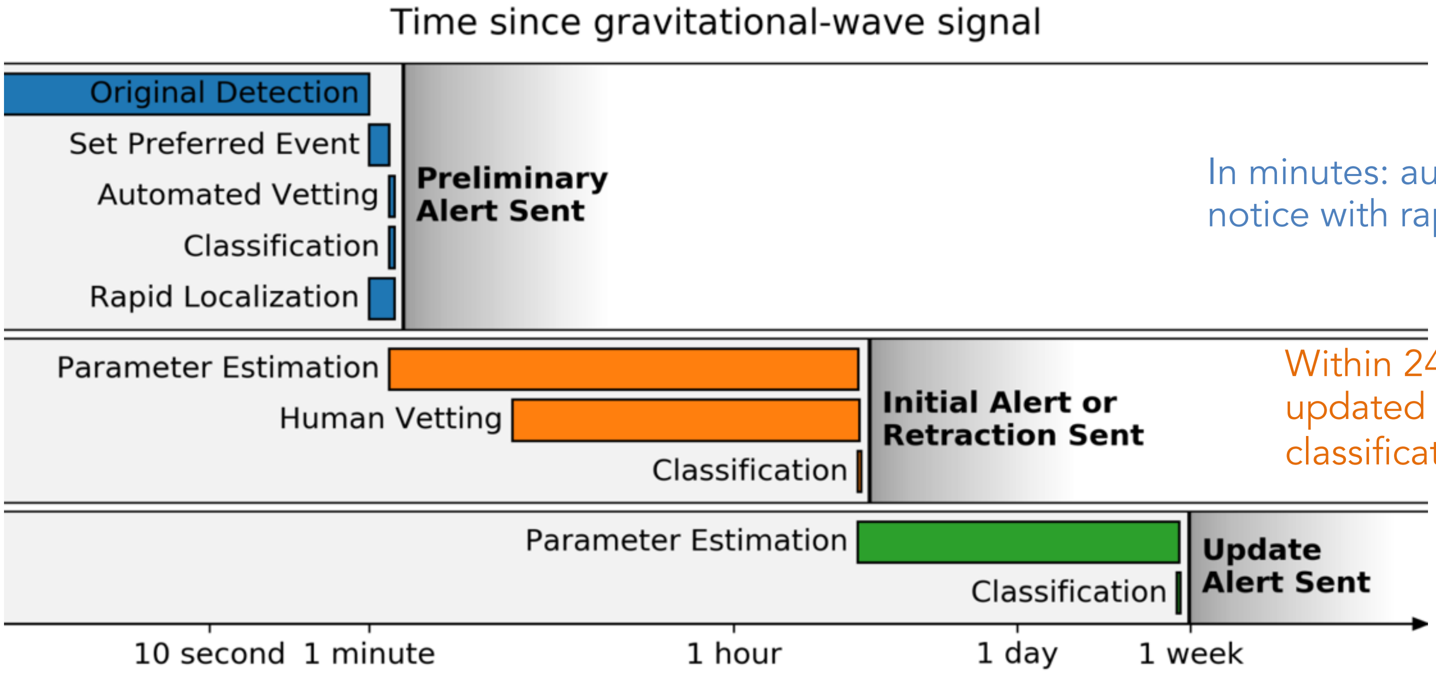
The O3 run

O3a: Apr 1 2019 → Oct 1 2019

O3b: Nov 1 2019 → May 1 2020 (with KAGRA)

Open Public Alerts

LIGO-Virgo will issue Open Public Alerts during the O3 run



In minutes: automatic preliminary notice with rapid localization

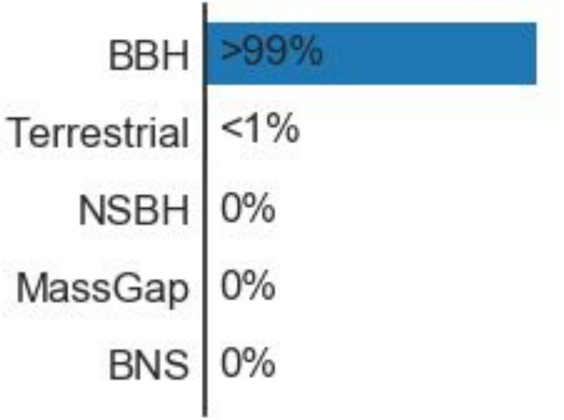
Within 24 hrs: retraction or updated localization, source classification

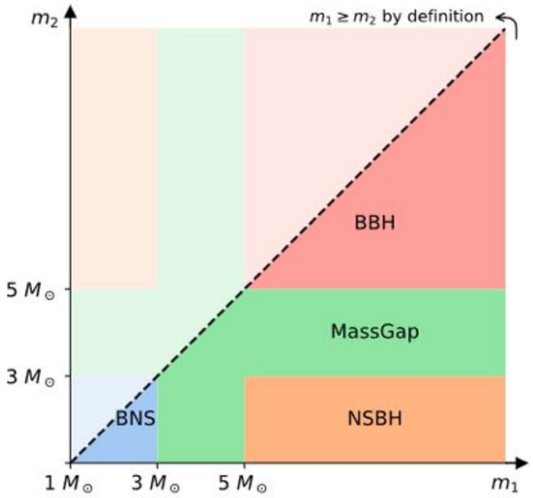
Significant updates

Open Public Alerts

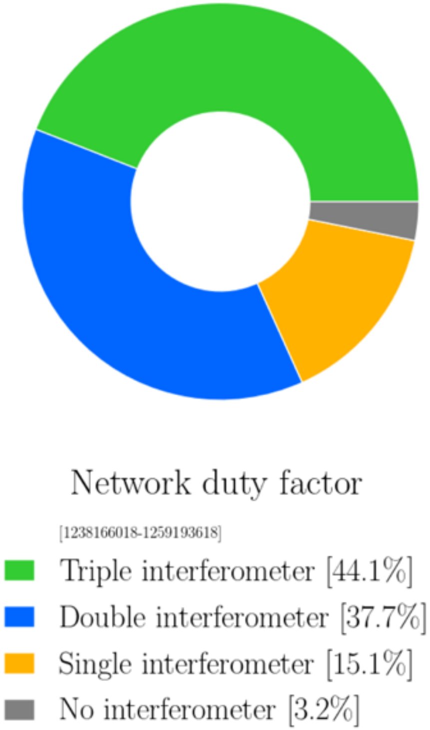
- **Localization:** 3D map for follow-up
- **Classification:** Five numbers, summing to unity, giving probability that the source belongs to five categories
  - This assumes that terrestrial and astrophysical events occur as independent Poisson processes

arXiv:1903.06881

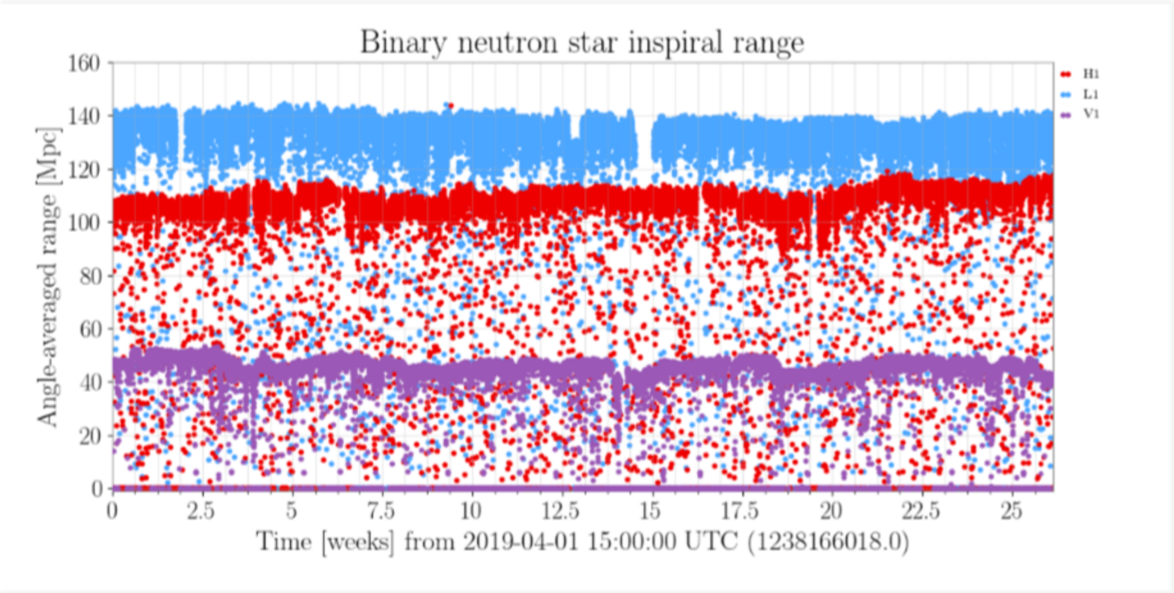




O3



Network duty factor
[1238166018-1259193618]
Triple interferometer [44.1%]
Double interferometer [37.7%]
Single interferometer [15.1%]
No interferometer [3.2%]



Binary neutron star inspiral range
Angle-averaged range [Mpc]
Time [weeks] from 2019-04-01 15:00:00 UTC (1238166018.0)
H1
L1
V1

O3a – Summary of public alerts

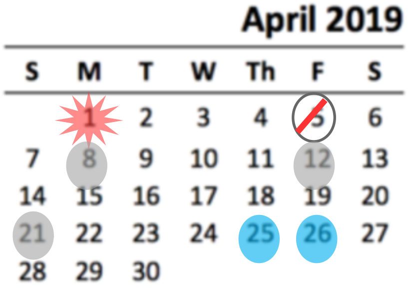
BBH

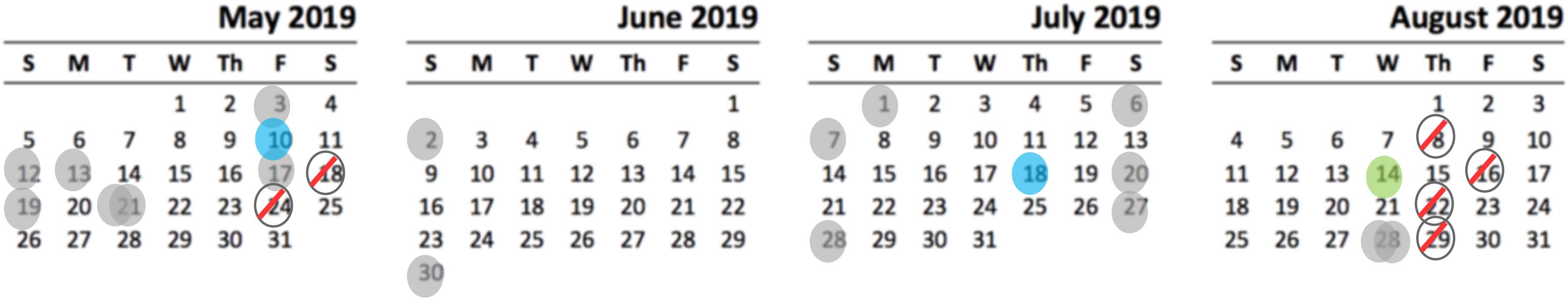
BNS

NSBH

Mass Gap

Retracted

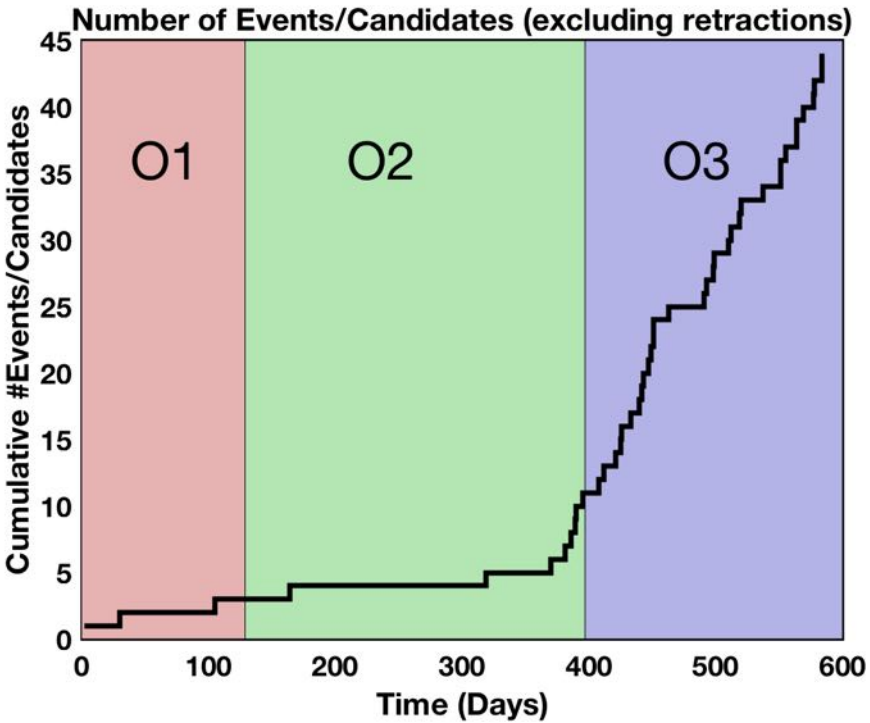




Observation Run	Network	Expected BNS Detections	Expected NSBH Detections	Expected BBH Detections
O3	HLV	2^{+8}_{-2}	0^{+19}_{-0}	15^{+19}_{-10}
O4	HLVK	8^{+42}_{-7}	2^{+94}_{-2}	68^{+81}_{-38}

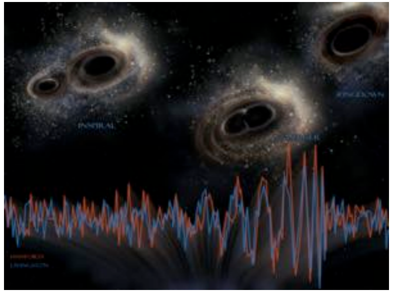
https://arxiv.org/abs/1304.0670

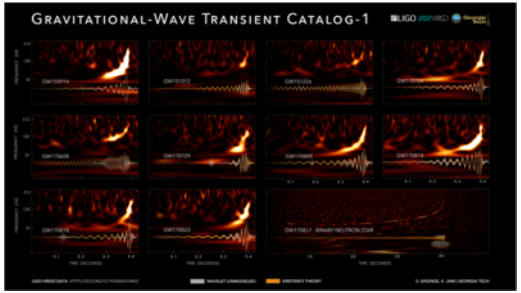
- 33 public alerts (excluding retractions) in O3a
- Most interesting:
  - 3 NSBH (p>50%)
  - 4 BNS (p≳50%)
  - 1 system with a star in the "mass gap"
  - 1 BBH at z ≳1
- Extensive follow-up but no e.m. counterpart in O3a



https://gracedb.ligo.org/latest/

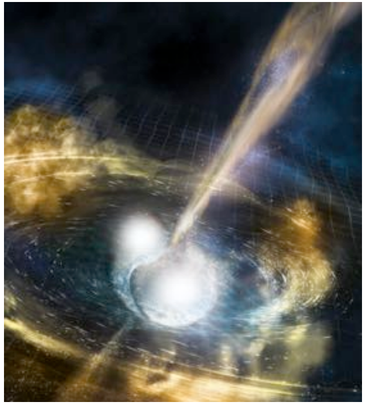
In just 4 years…

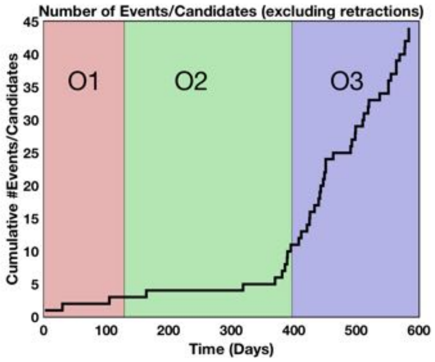




…to population studies

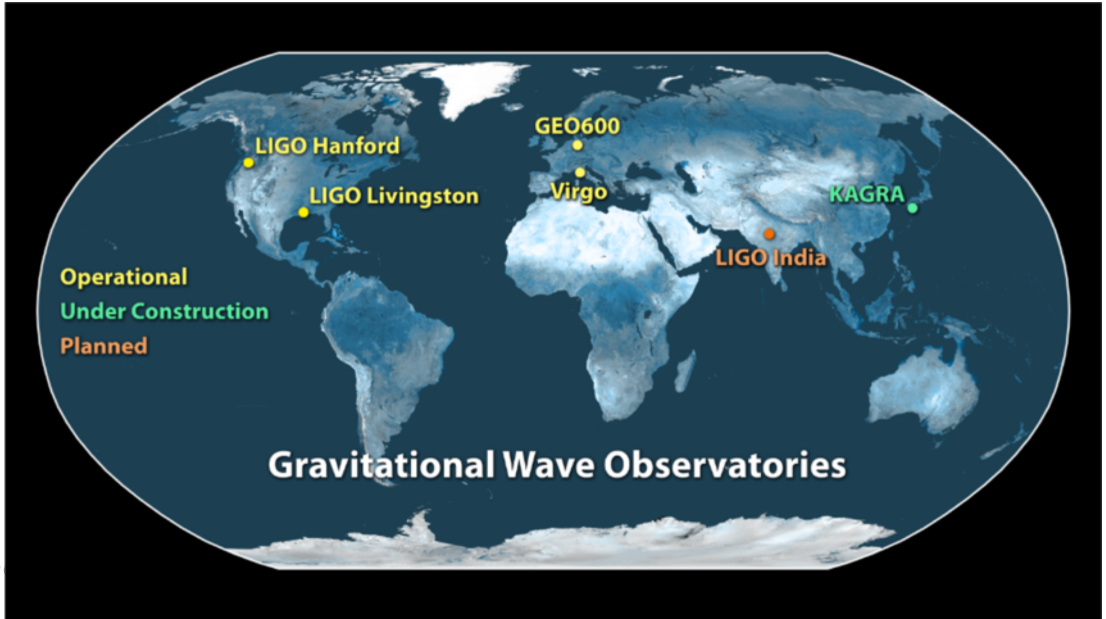
From discovery…



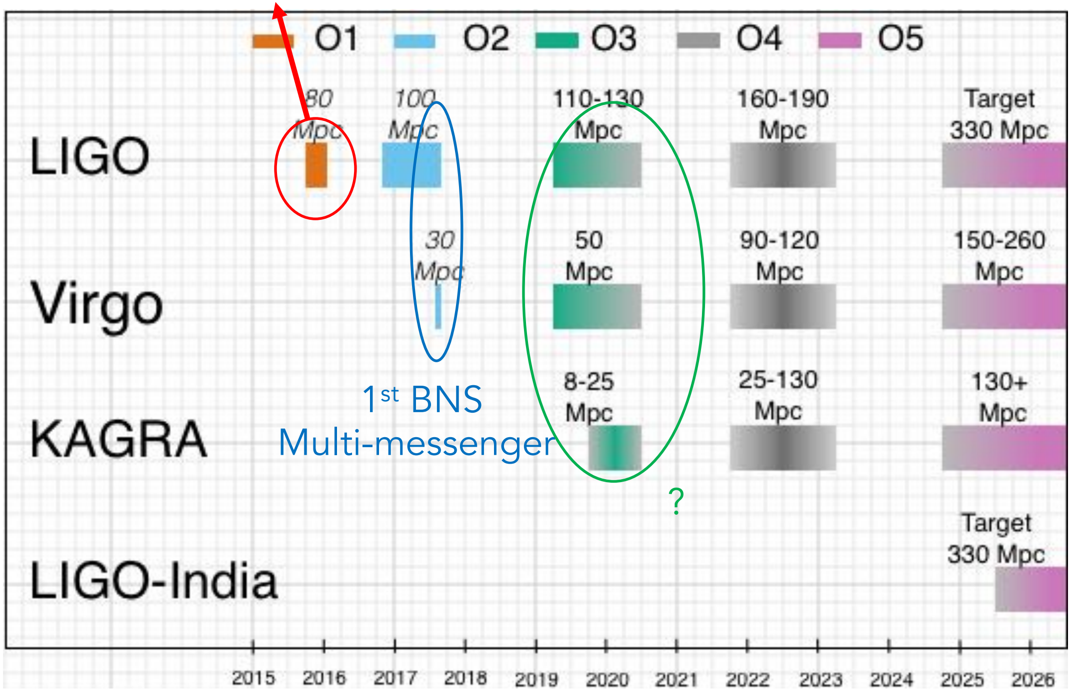


MID-TERM OUTLOOK

- KAGRA to join the network in O3b
- Ligo/Virgo to be further upgraded (A+/AdV+) after O3
- Ligo India to join the network in ~2024

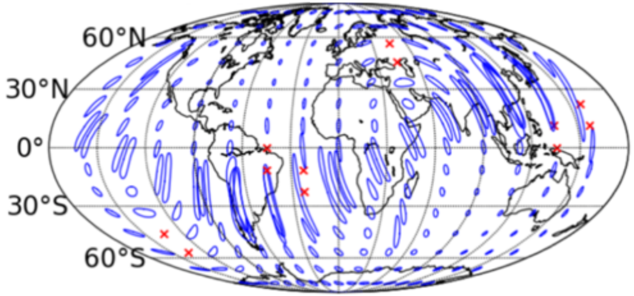


1st GW detection

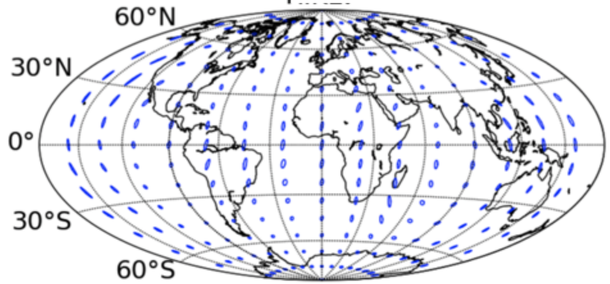


arXiv:1304.0670 (v8 Sept 2019)

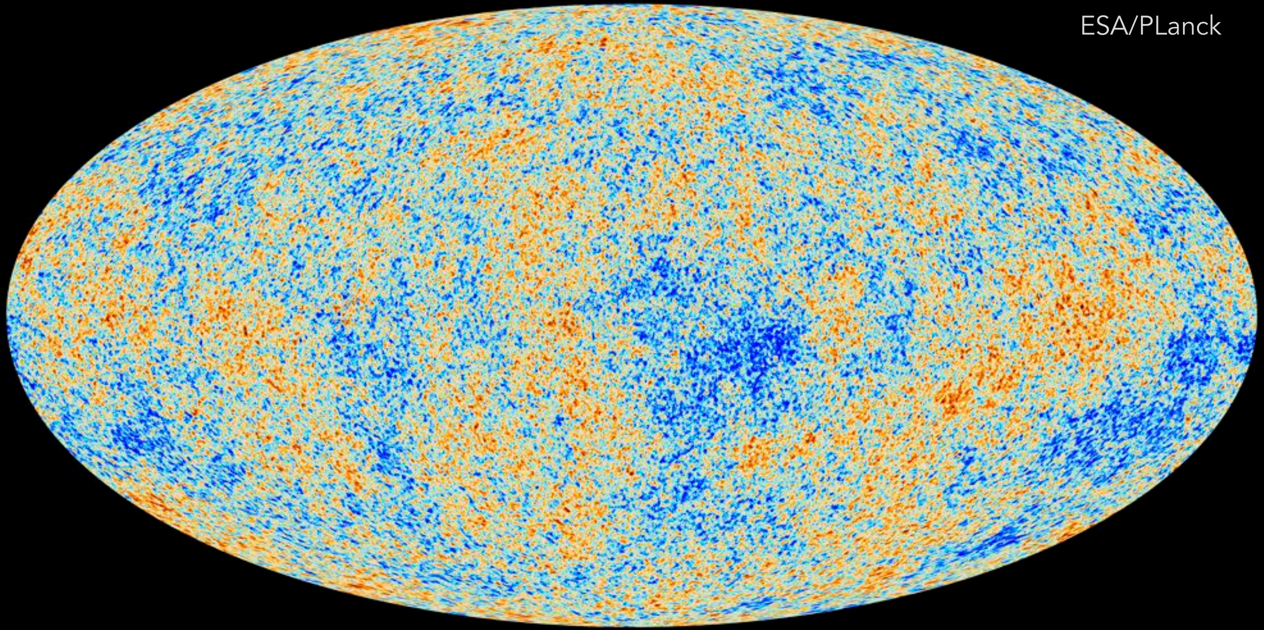
~20% in 20 sq deg HLV 2019



~60% in 10 sq deg HIKLV 2024



Credit: S Fairhurst



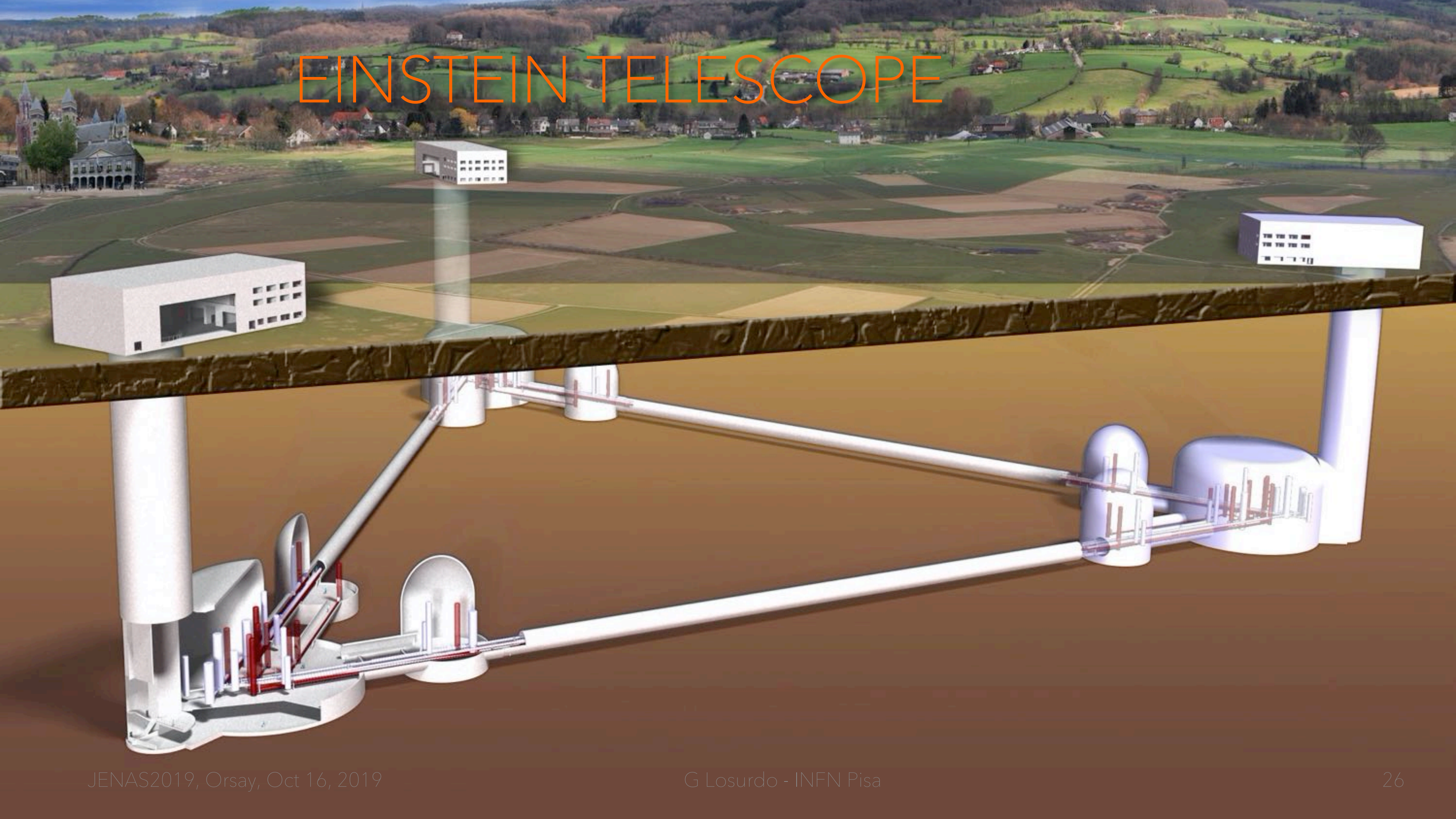
LONG-TERM OUTLOOK

From here to 3G - GWIC

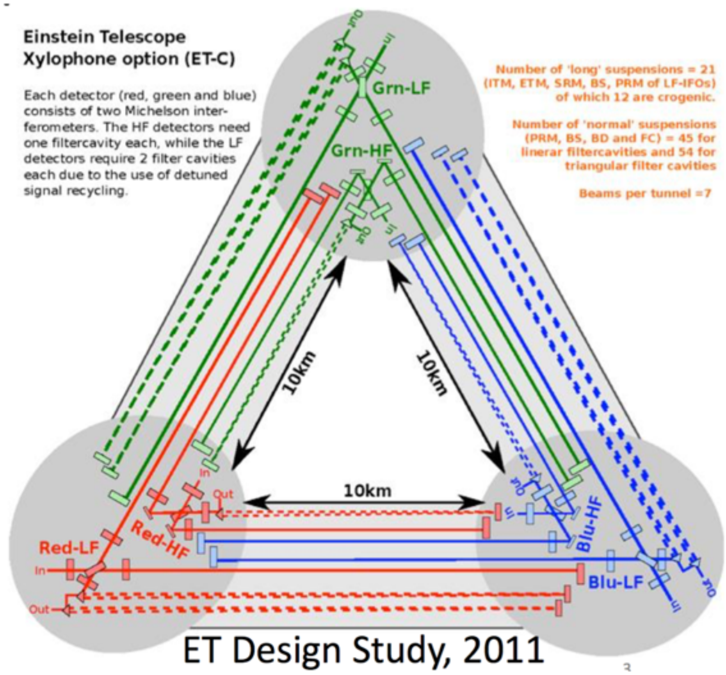
- 2016: subcommittee to look at the 3G in a coordinated way
  - D Reitze, M Punturo co-chairs
- 2019: report of actions/recommendations to be delivered
  - Science drivers for 3G detectors
  - Coordination of the ground-based GW community
  - Networking
  - Funding agencies interfacing and advocacy
  - Investigate 3G detectors governance schemes
  - Computing

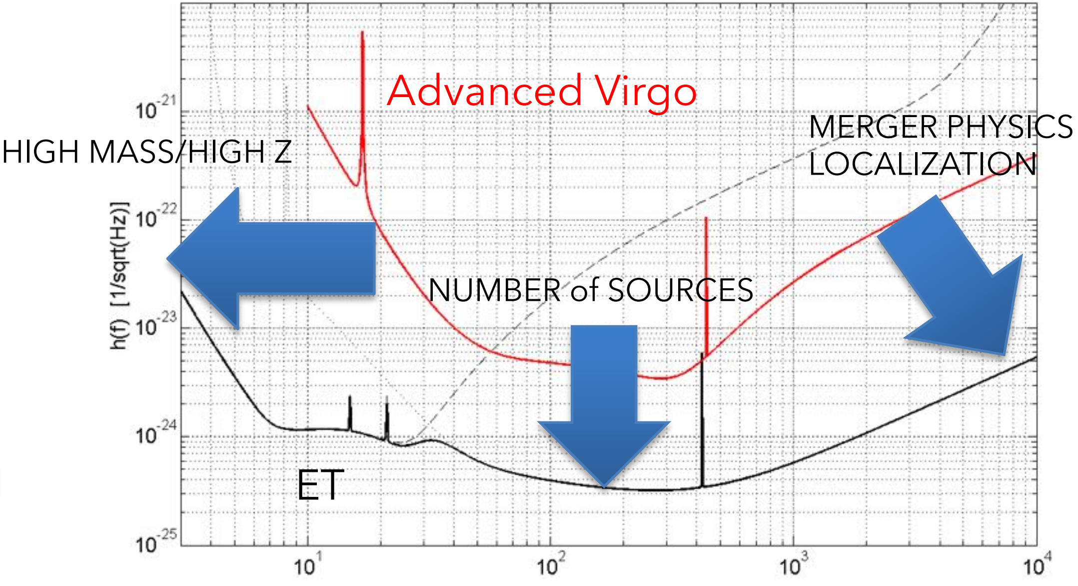
The GW community is engaged in a coherent effort to develop 3G

EINSTEIN TELESCOPE



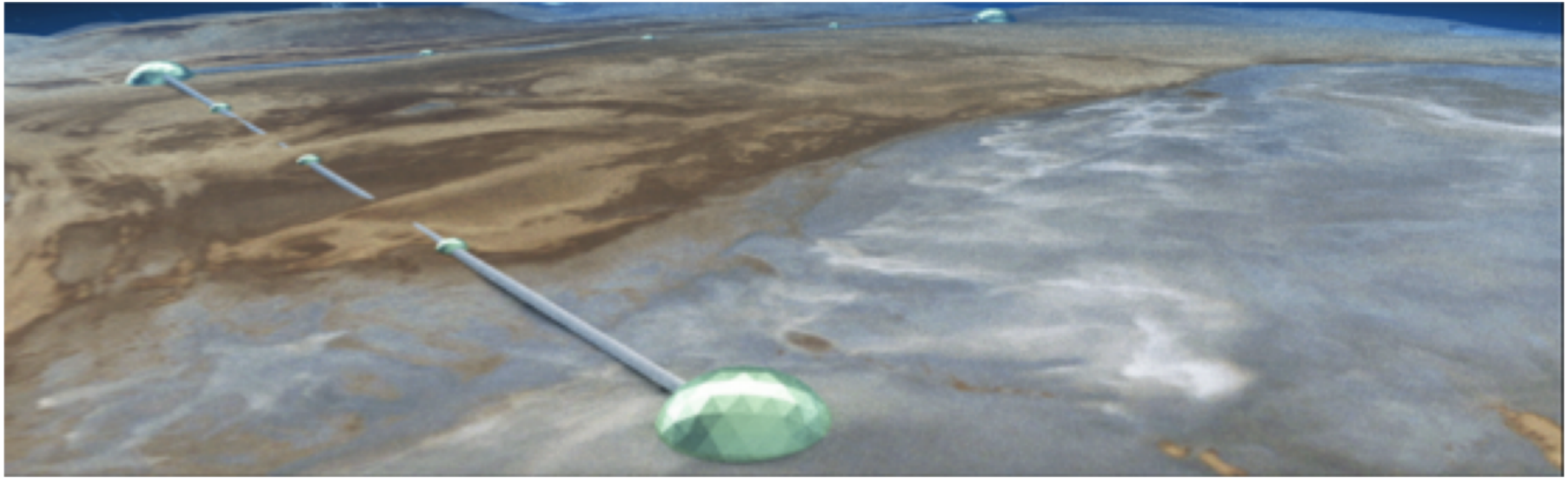
EINSTEIN TELESCOPE





COSMIC EXPLORER

- 3rd generation observatory in the US
- Above ground, L shaped, 40 km
- NSF funded design study under way (www.cosmicexplorer.org)



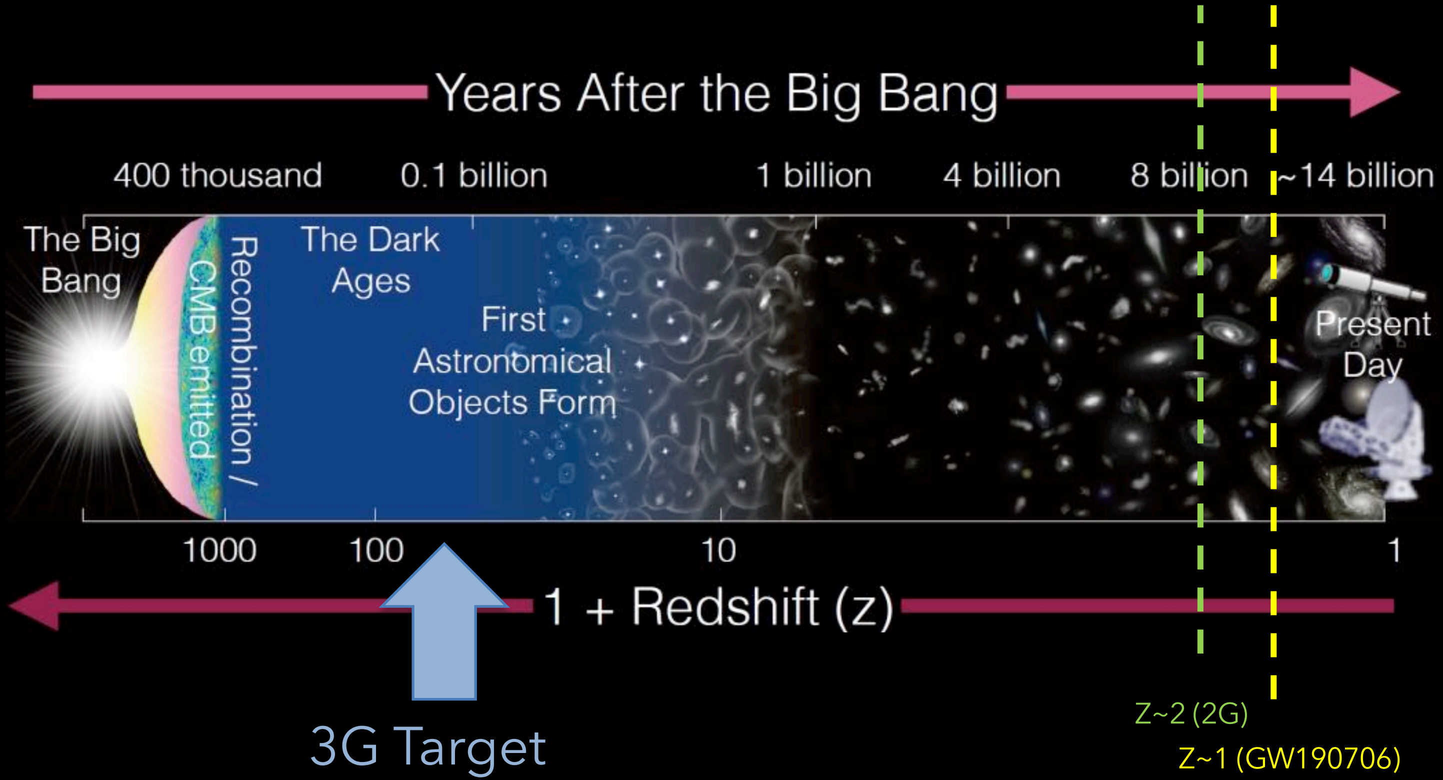
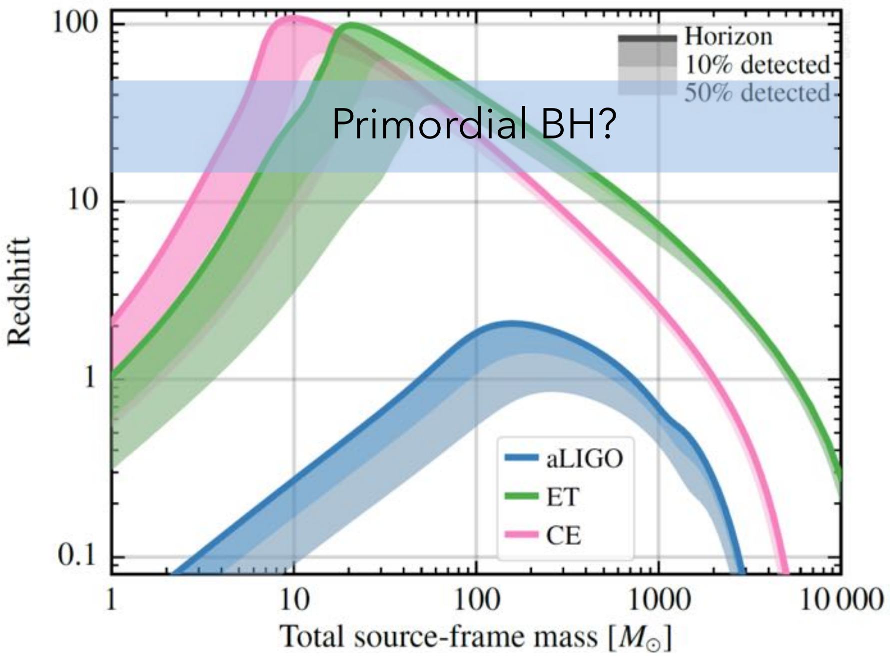
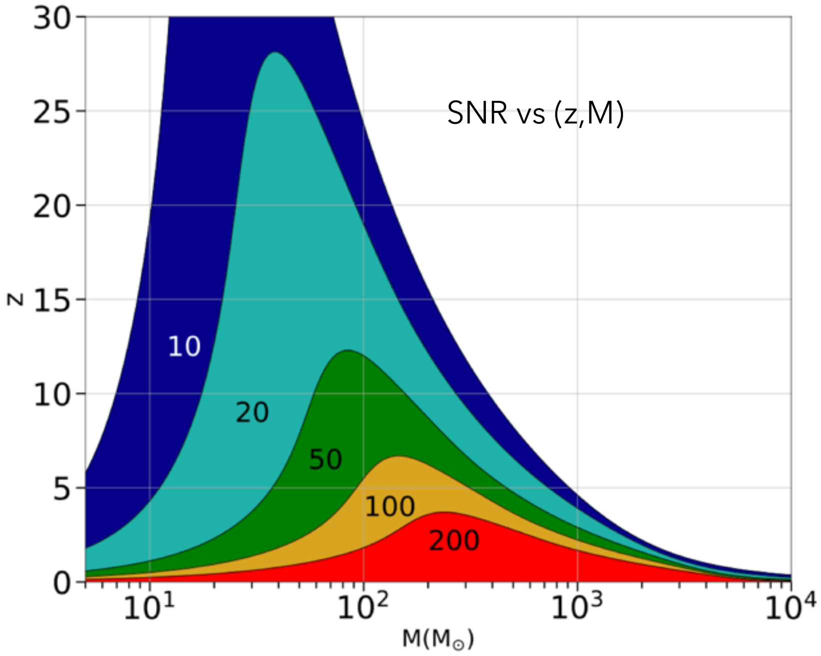


Image credit: NAOJ/ALMA http://alma.mtk.nao.ac.jp/

3G SCIENCE POTENTIAL

From the ET Science Case

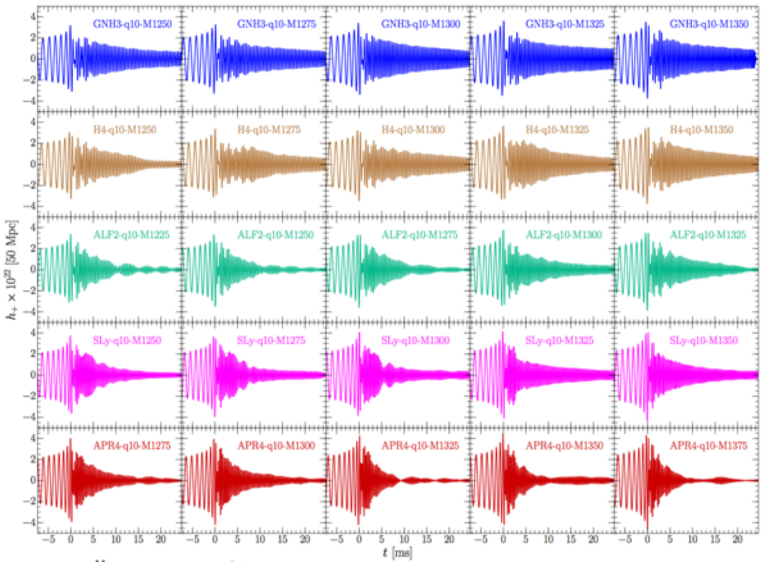




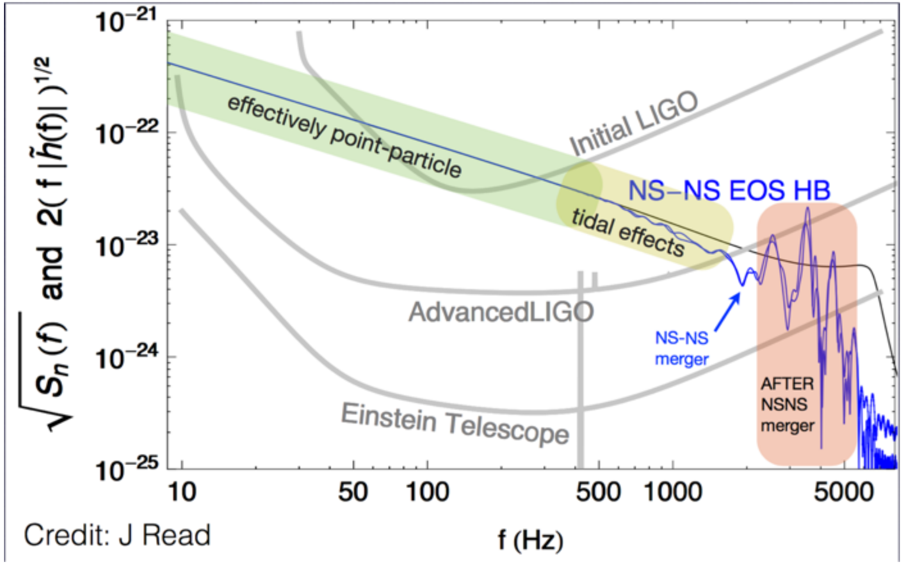
The combination of distances and masses explored, sheer number of detections, and detections with very high SNR will provide a wealth of data that have the potential of triggering revolutions in astrophysics, cosmology and fundamental physics.

NUCLEAR PHYSICS

NS: WE ARE ABLE TO COMPUTE THE WAVEFORMS FOR THE VARIOUS EOS



Takami, Rezzolla, Baiotti (2014)



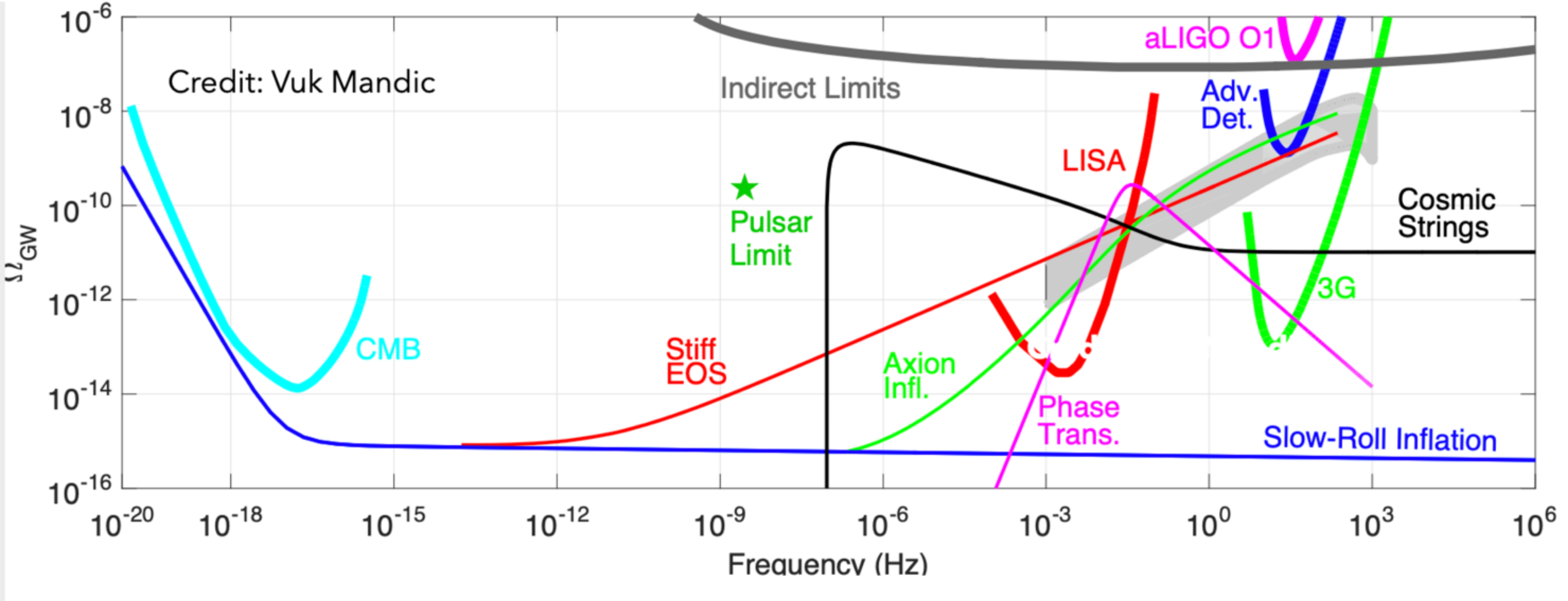
A 3G DETECTOR IS NEEDED TO MEASURE WHICH EOS IS THE RIGHT ONE

COSMOLOGY

$$d_L(z) = \frac{1+z}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_M (1+z')^3 + \frac{\rho_{\mathrm{DE}}(z')}{\rho_0}}}$$

- GW170817 has already demonstrated the possibility to measure H_0 with GW standard sirens
- Multi-messenger observations at high redshift with 3G will make possible to measure $\rho_{DE}(z)$
- Possibility to explore models beyond ΛCDM

COSMOLOGY

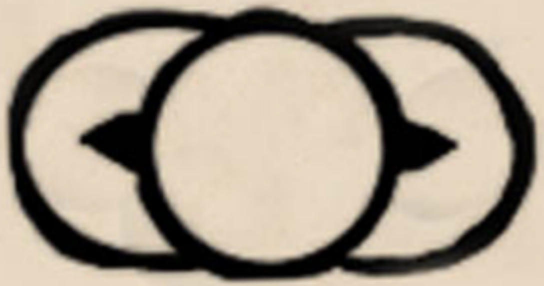


Credit: Vuk Mandic
Indirect Limits
aLIGO O1
Adv.
Det.
LISA
Pulsar
Limit
Cosmic
Strings
3G
CMB
Stiff
EOS
Axion
Infl.
Phase
Trans.
Slow-Roll Inflation
Ω_{GW}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-16}
10^{-20}
10^{-18}
10^{-15}
10^{-12}
10^{-9}
10^{-6}
10^{-3}
10^{0}
10^{3}
10^{6}
Frequency (Hz)

Galileo, 1610

Galileo, 1610

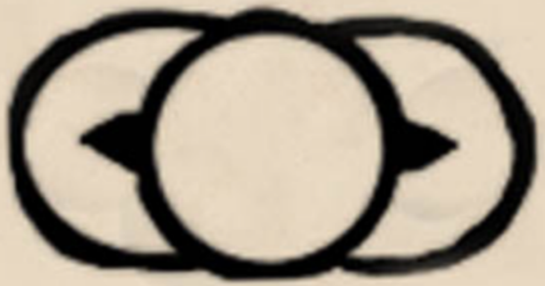
Galileo, 1616

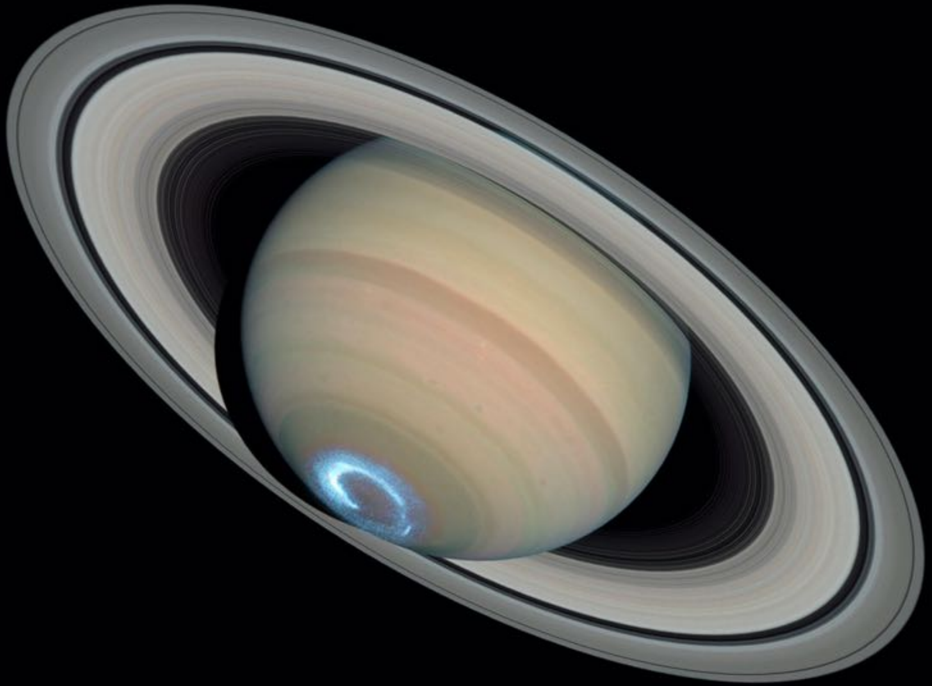


WE HAVE THE RIGHT INSTRUMENT.
NOW WE NEED TO MAKE IT BETTER AND BETTER AND BETTER…

Galileo, 1610

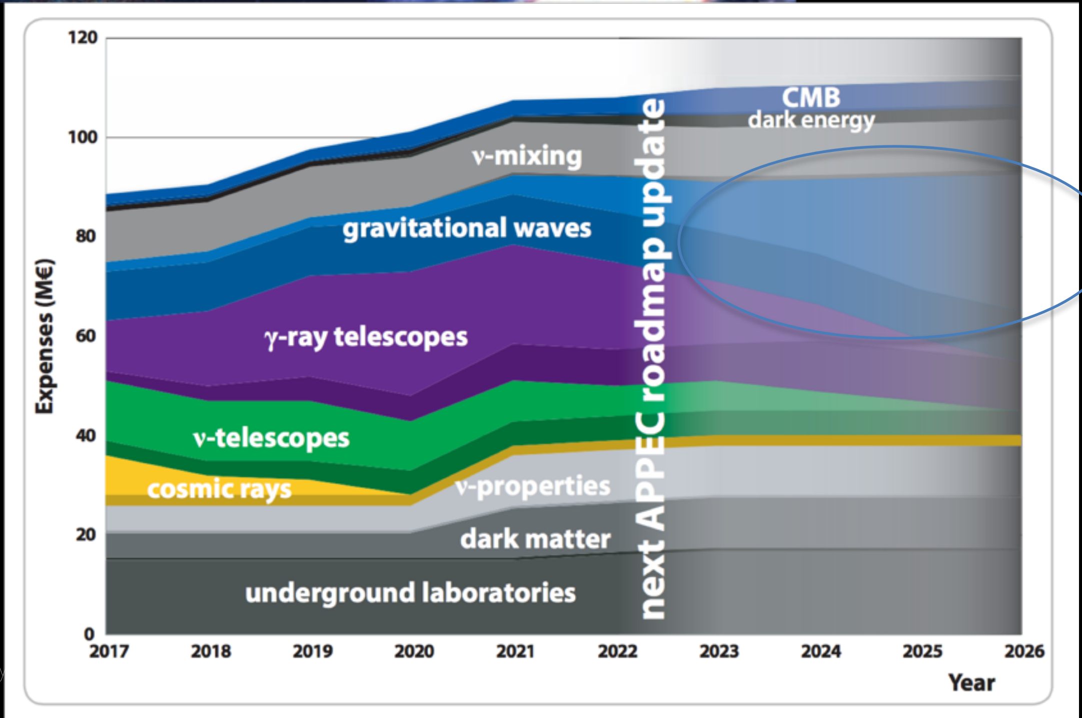
Galileo, 1616





HST, 400 yrs later

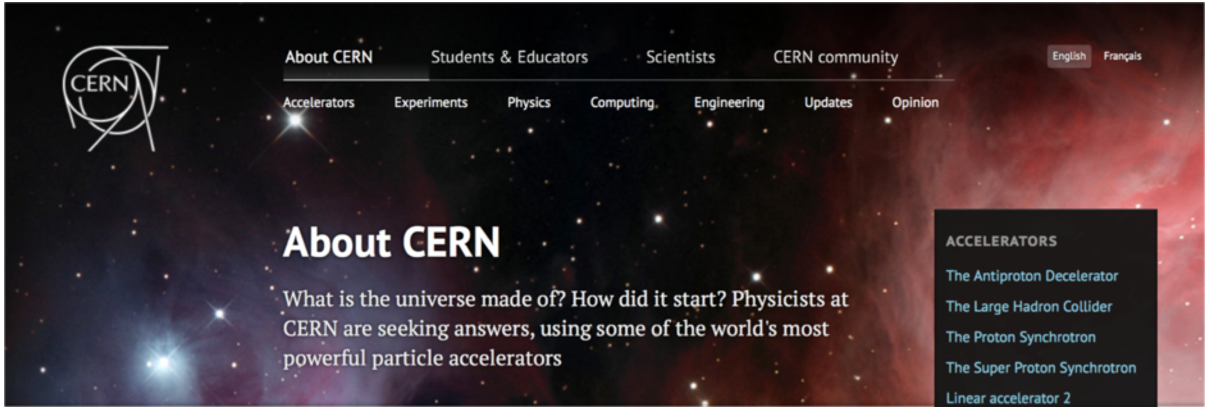
APPEC European Astroparticle Physics Strategy 2017-2026



ET: the big investment for the next decade (recommendation…)

THE POSSIBLE ROLE OF CERN

- The GW community looks at CERN as a model to many extents
- We have a lot to learn from CERN:
  - Model of governance
  - Management of big projects
  - Technology: underground infrastructure, vacuum, cryogenics, computing
- A commitment of CERN on ET (in some form) might be a game changer



From the Physics Briefing Book

https://home.cern/news/news/cern/briefing-book-2020-update-european-strategy-particle-physics

The future generation of GW ground-based detectors, which in Europe is the Einstein Telescope project, has the unique potential **to strengthen the synergy between cosmology, particle, nuclear, astroparticle physics and astrophysics science domains** since: 1) It tests the nature of gravity (…) 2) It explores the nature of dark matter in a complementary way to colliders and underground direct search experiments (…); 3) It provides an independent measure of the Hubble constant either solving the current tension between its *far* and *near* determinations or alternatively opening a portal to new physics (…); 4) It reveals phase transition from nucleons to free quarks giving insight into the QCD phase diagram, explores the state of ultra-dense nucleons and the origin of heavy elements (…); 5) It studies the primordial Universe, through primordial stochastic backgrounds, early-Universe phase transitions, cosmic strings (…); 6) It probes the nature of space-time at the interface with quantum mechanics, through the study of alternative gravity and quantum gravity theories.

ET science not only reflects CERN's own pursuit of fundamental physics, but strong synergies exist concerning the precision engineering that was required to build and operate the LHC.

CONCLUDING REMARKS

- A new field of research has been opened promising access to fundamental physics, nuclear physics, astrophysics, cosmology, dark sector, …
- Time to invest on the development of 3G technologies, infrastructure, detectors
- Einstein Telescope: a EU project for a 3G detector of GW
  - Very strong science case
  - Cost ~1.5 G€
  - Timeline >2030
- A great chance to ensure EU leadership in the field