From 2nd generation GW detectors towards Einstein Telescope

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BGL 17: 10th Bolyai-Gauss-Lobachevsky Conference on Non-Euclidean Geometry and its Applications, Gyöngyös, Hungary, August 21-25, 2017

LIGO Scientific Collaboration

Advanced Virgo

Einstein's theory of general relativity

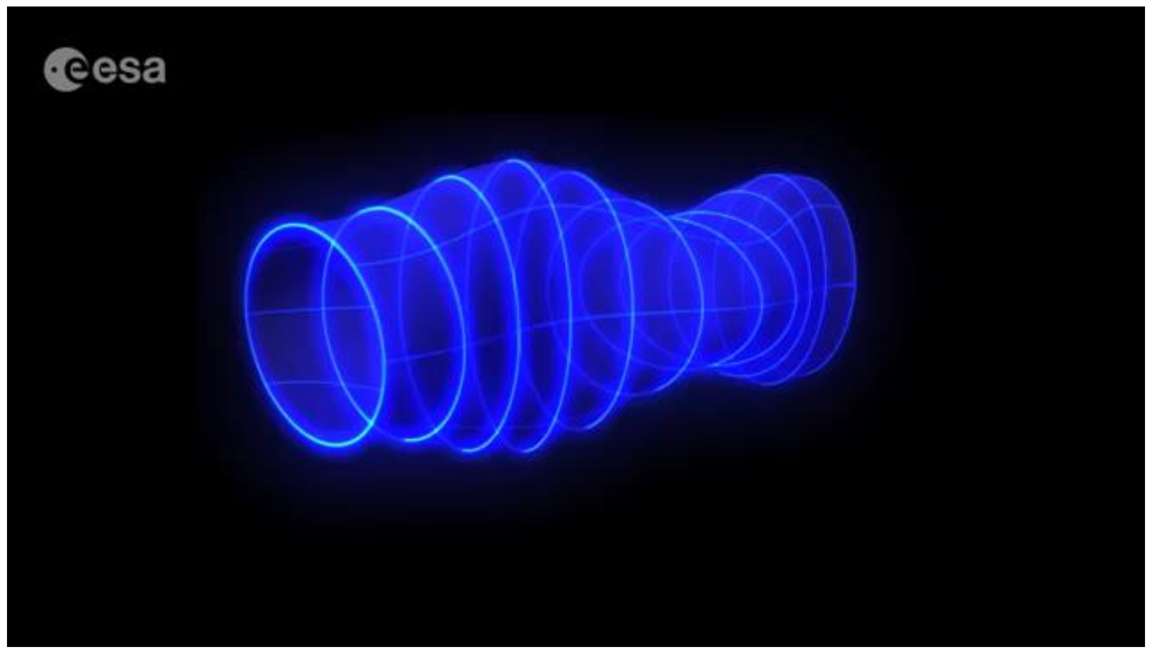
Einstein discovers deep connections between space, time, light, and gravity

Einstein's Gravity

- Space and time are physical objects, and gravity is curvature in the geometry of spacetime due to mass

Predictions

- Light bends around the Sun, expansion of the Universe
- Black holes, wormholes, structure formation, …
- Gravitational waves are *perturbations of the spacetime metric,* moving at the speed of light. It alternately stretches and shrinks with a characteristic strain



Sources of gravitational waves

Gravitational waves can be emitted by astrophysical systems with rapidly changing mass distribution

Binary systems with black holes and/or neutron stars, supernovae, spinning neutron starts, etc.

We have observed about 1600 pulsars (NS) in our Milky Way. Thus NS exist and there are probably billions of NS per galaxy

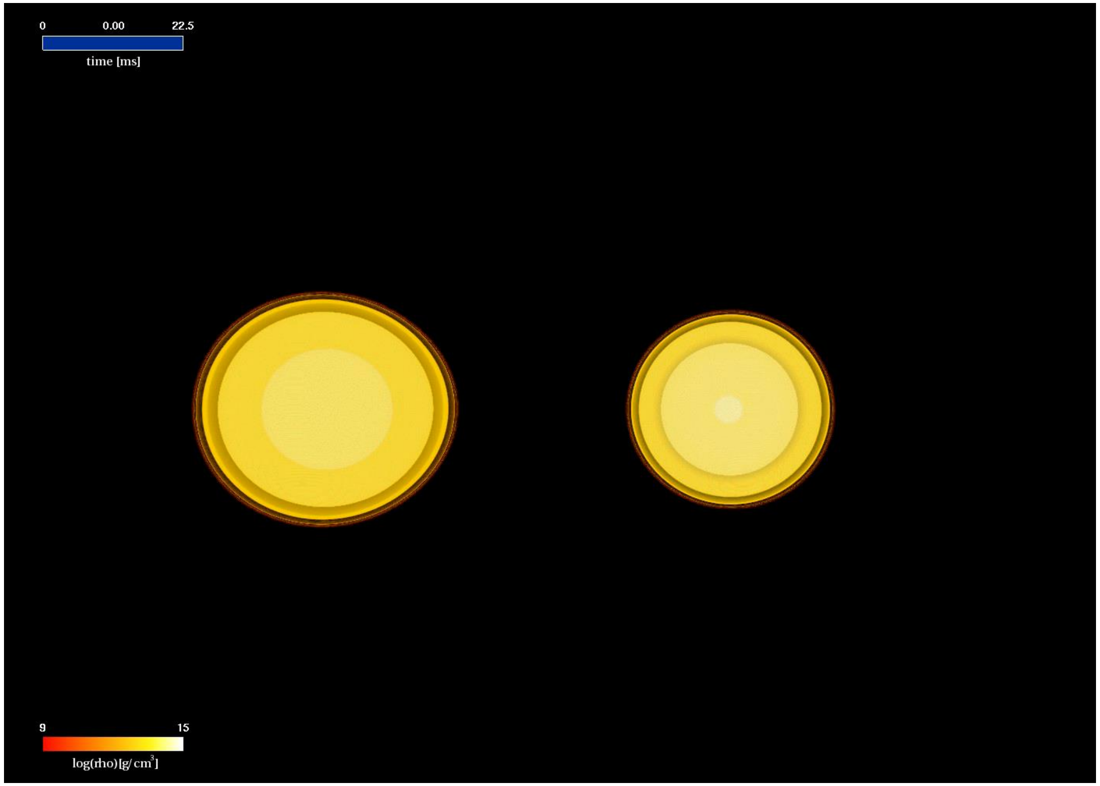
We also discovered 9 binary neutron stars (BNS), *e.g.* Hulse Taylor BNS

These systems undergo strong quadrupole-type acceleration

After a certain time, both NS will collide

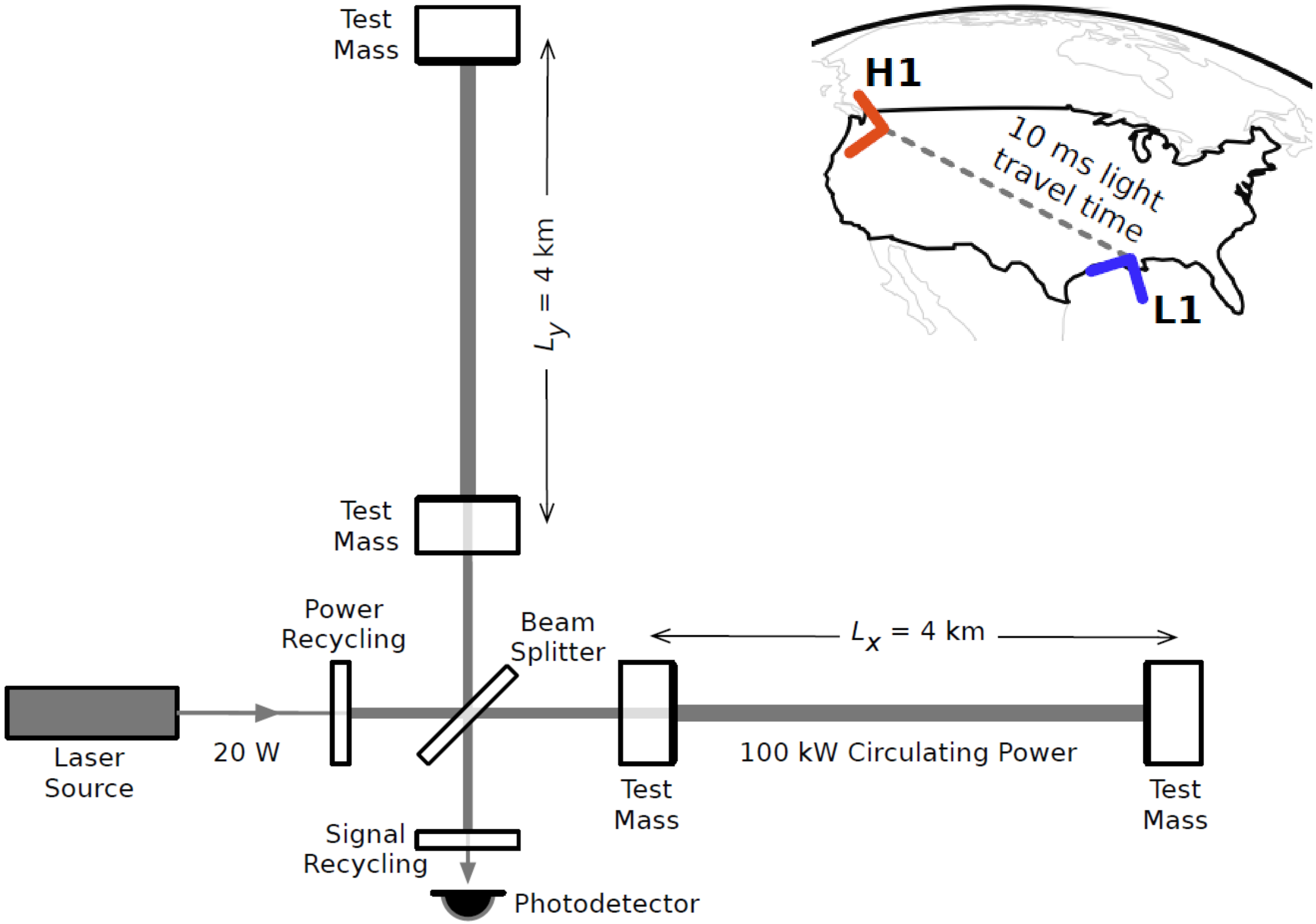
A black hole may be created

Expected strain at Earth 10^{-21} or smaller



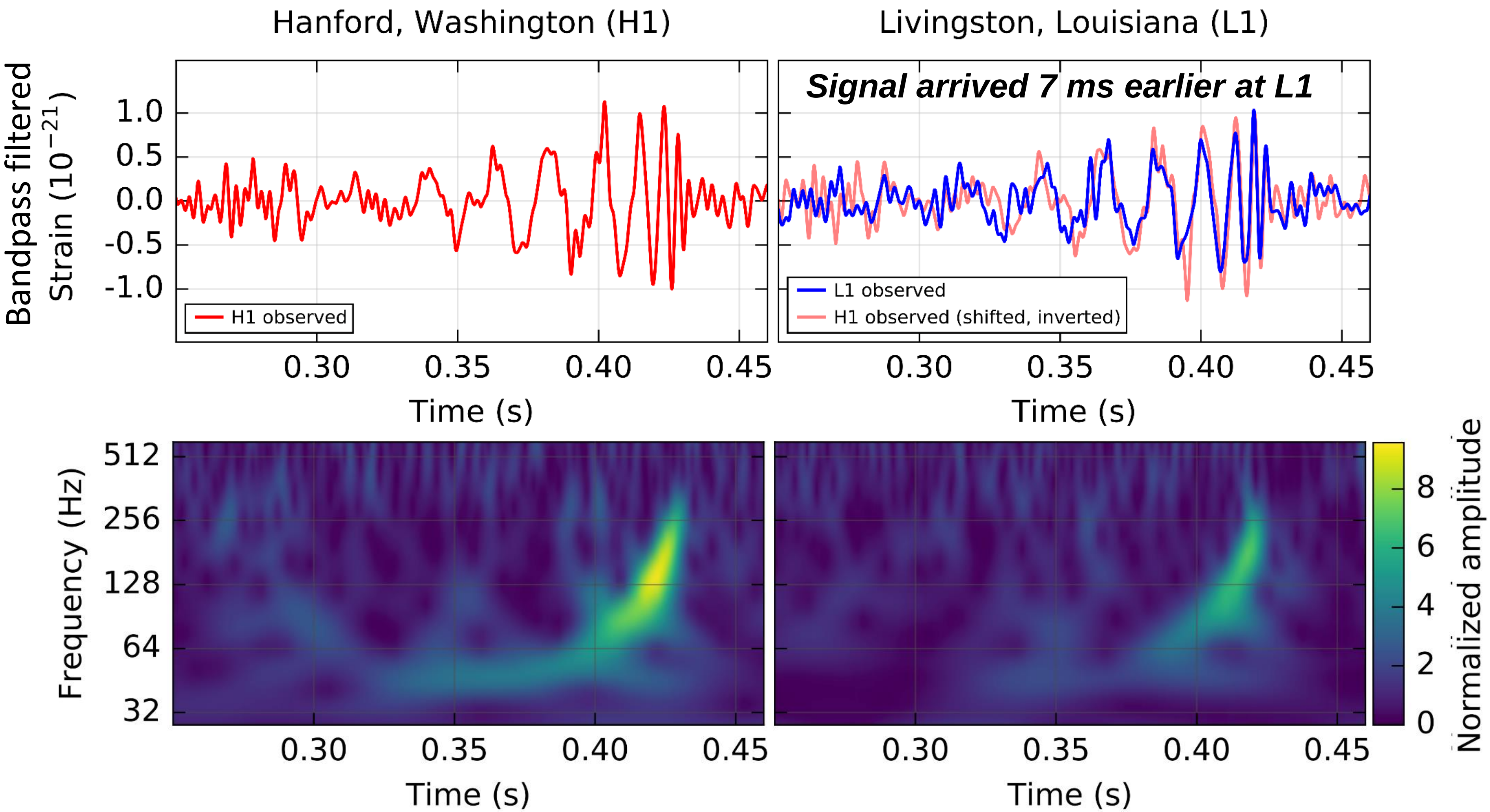
The Advanced LIGO detectors

Only the LIGO detectors of the LIGO Virgo Consortium were operational in 2015. GEO600 had insufficient sensitivity to detect the event, while Virgo joined the network in Summer 2017



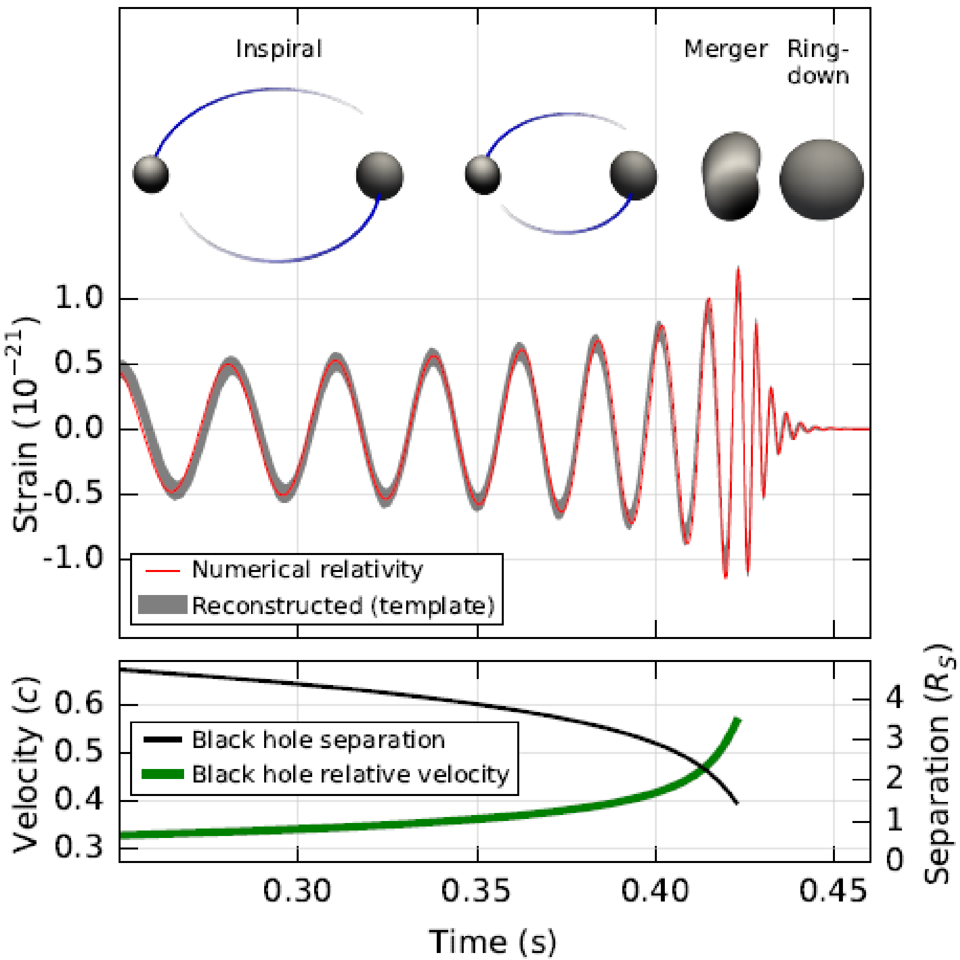
Event GW150914

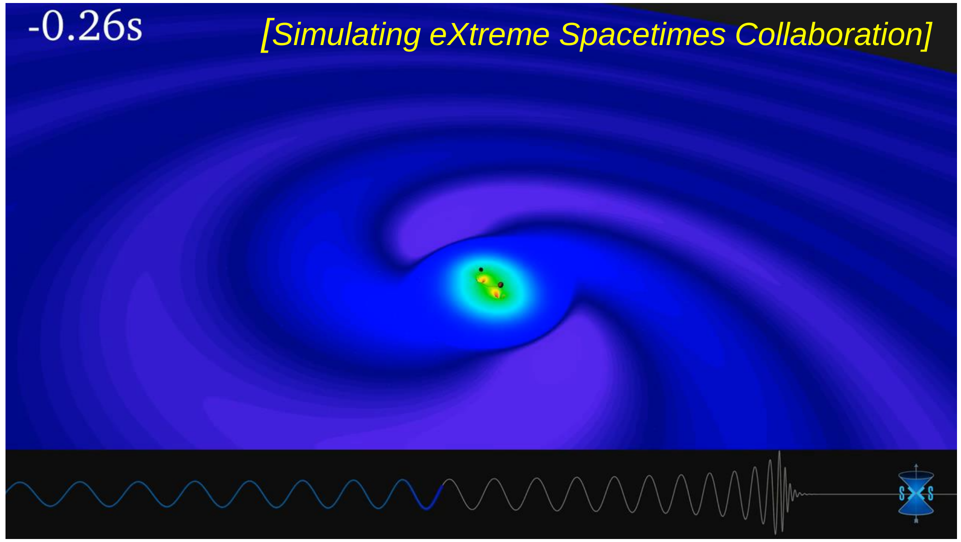
Chirp-signal from gravitational waves from two coalescing black holes were observed with the LIGO detectors by the LIGO-Virgo Consortium on September 14, 2015 *(Abbott et al. 2016, PRL 116, 061102)*



Binary black hole merger GW150914

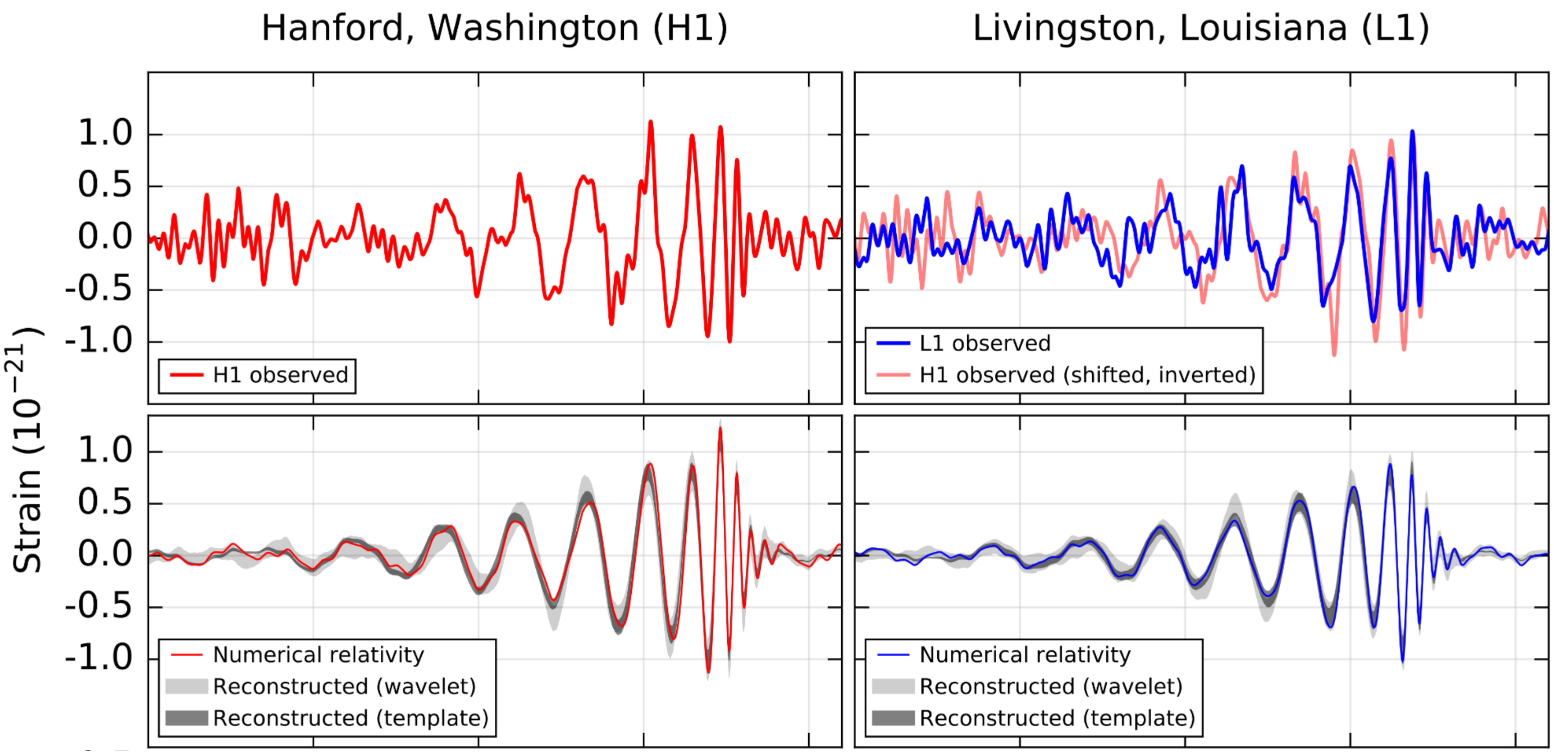
The system will lose energy due to emission of gravitational waves. The black holes get closer and their velocity speeds up. Masses and spins can be determined from inspiral and ringdown phase





Binary black hole merger GW150914

Matches well to BBH template when filtered the same way

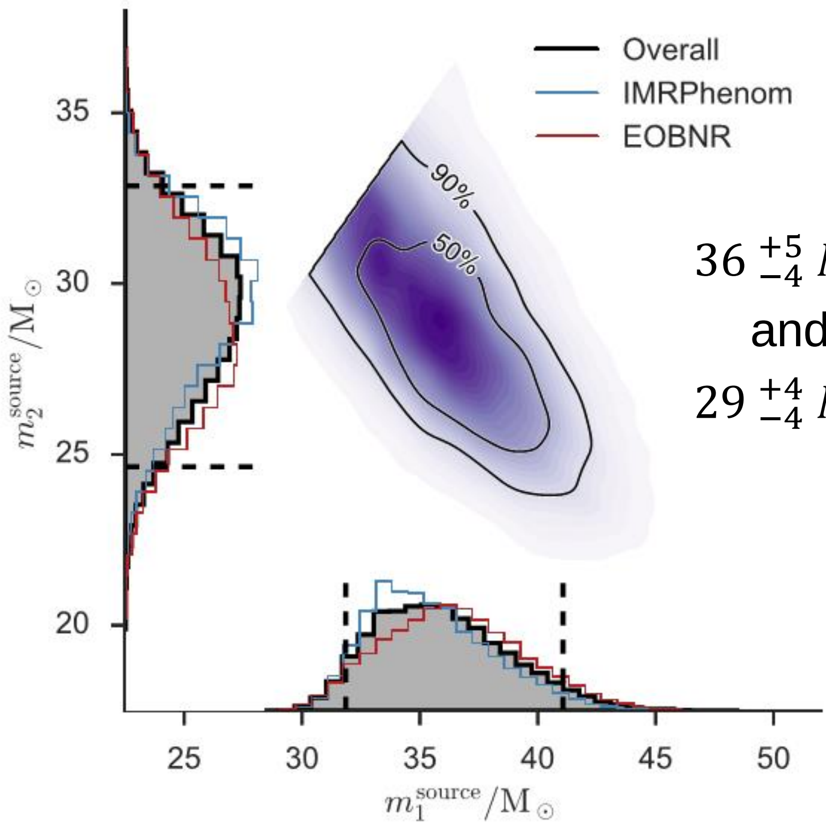


[Abbott et al. 2016, PRL 116, 061102]

Some properties of GW150914

These are surprising heavy for stellar-remnant black holes

Masses



$36\,^{+5}_{-4}\,M_\odot$
and
$29\,^{+4}_{-4}\,M_\odot$

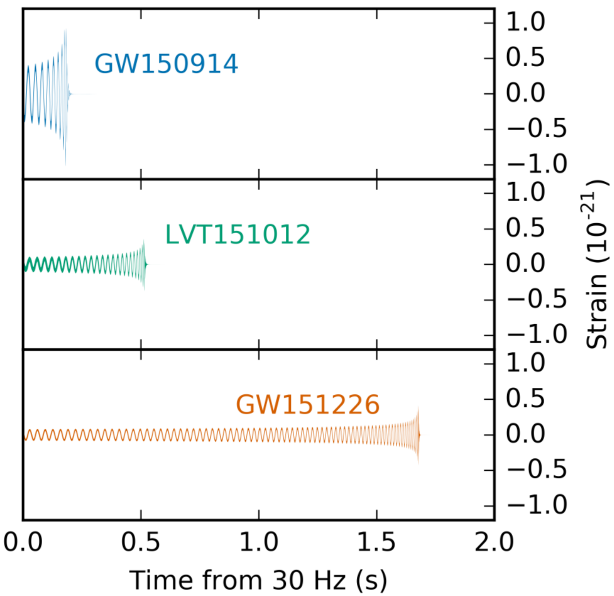
[Abbott et al. 2016, ApJL 833, L1]

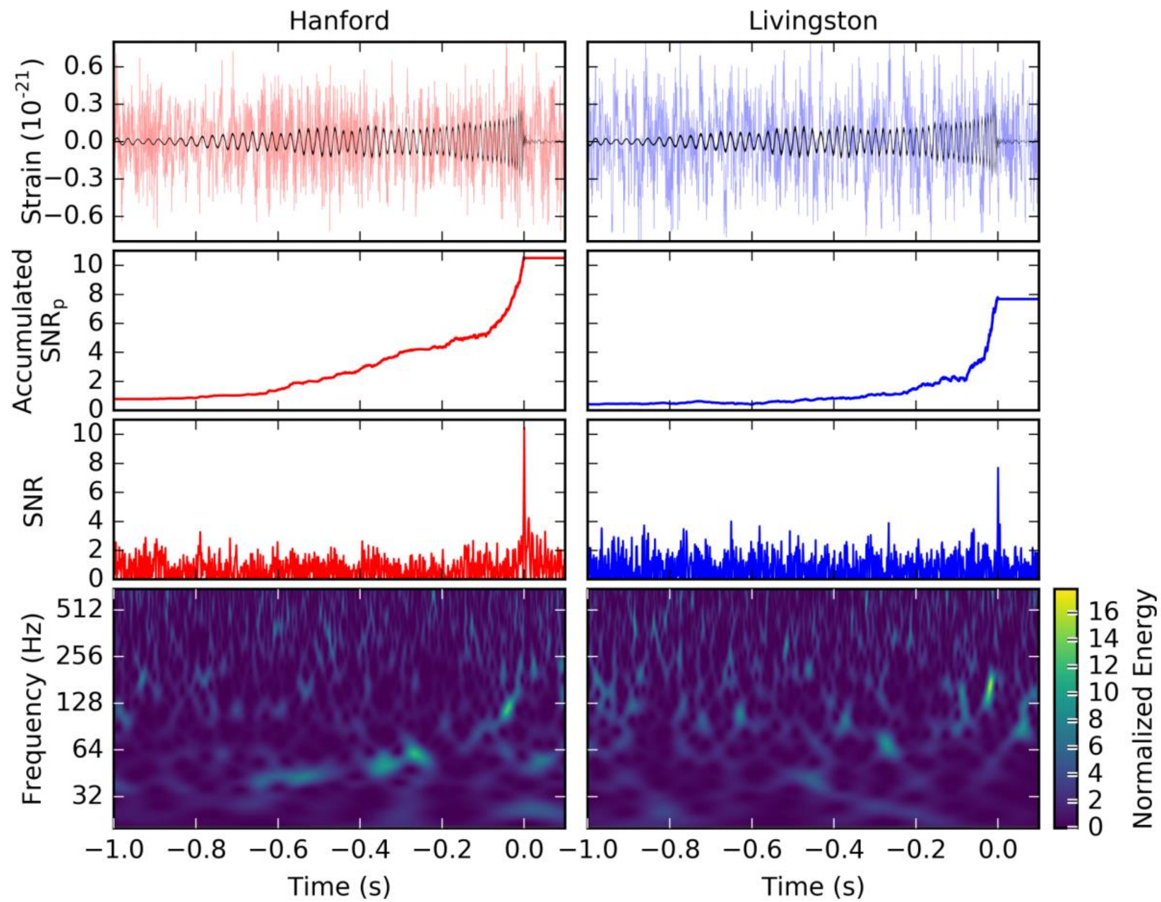
- Final BH mass: $62 \pm 4\ M_\odot$
- Energy radiated: $3.0 \pm 0.5\ M_\odot c^2$
- Peak power $\sim 200\ M_\odot c^2/s$!
- Distance: $410\ ^{+160}_{-180}\ \mathrm{Mpc}$
  $= 1.3 \pm 0.5$ billion light-years
- ➔ Redshift $z \approx 0.09$
- We can't tell if the initial black holes had any "spin" (intrinsic angular momentum), but the spin of the final BH is
- $0.67\ ^{+0.05}_{-0.07}$ of maximal spin allowed by GR ($\frac{Gm^2}{c}$)

More from the first observing run

Analysis of the complete O1 run data revealed one additional significant binary black hole coalescence signal, GW151226, and a so-called trigger LVT. Matched filtering was essential for detecting GW151226

Another signal consistent with GR but qualitatively different
- Longer duration,
- lower amplitude,
- more "cycles" in band





[Abbott et al. 2016, PRL 116, 241103]

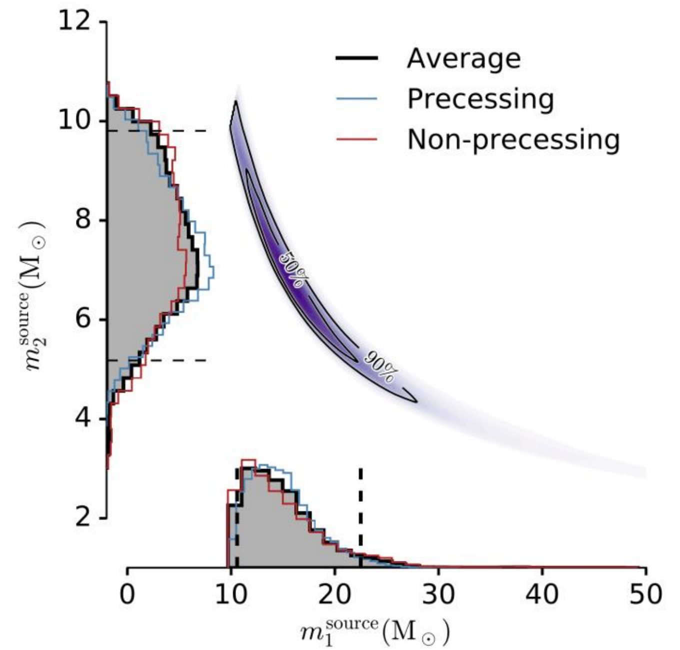
Properties of GW151226

GW151226 has lower mass than GW150914… and nonzero spin!

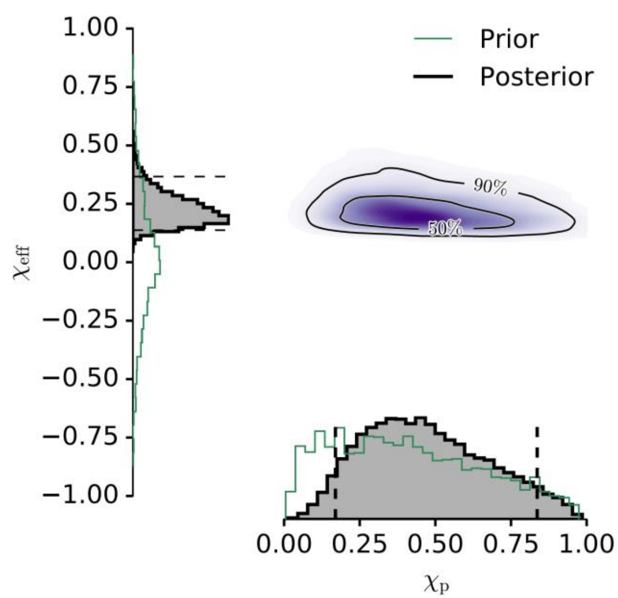
[Abbott et al. 2016, PRL 116, 241103]

Initial masses: $14.2\,^{+8.3}_{-3.7}$ and $7.5 \pm 2.3\ M_\odot$
Final BH mass: $20.8\,^{+6.1}_{-1.7}\ M_\odot$
Energy radiated: $1.0\,^{+0.1}_{-0.2}\ M_\odot c^2$

Luminosity distance: $440\,^{+180}_{-190}$ Mpc



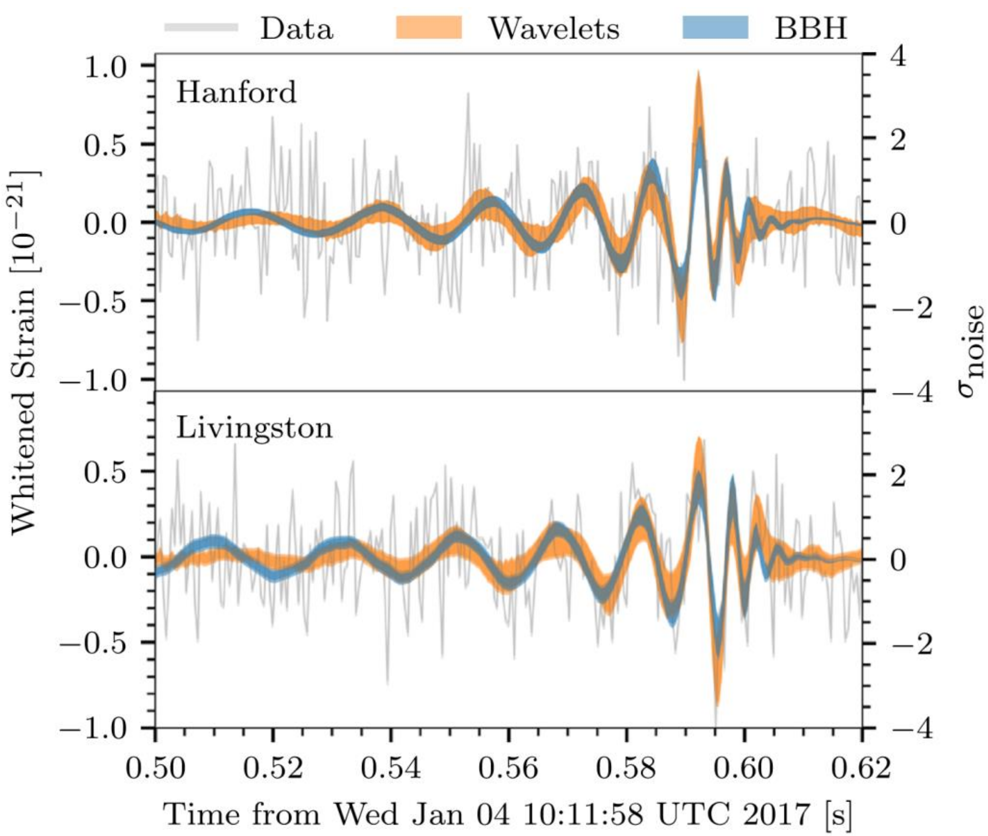
Effective signed spin combination definitely positive
⇒ at least one of the initial BHs has nonzero spin
(we can't tell how the spin is divided up between them due to waveform degeneracy)

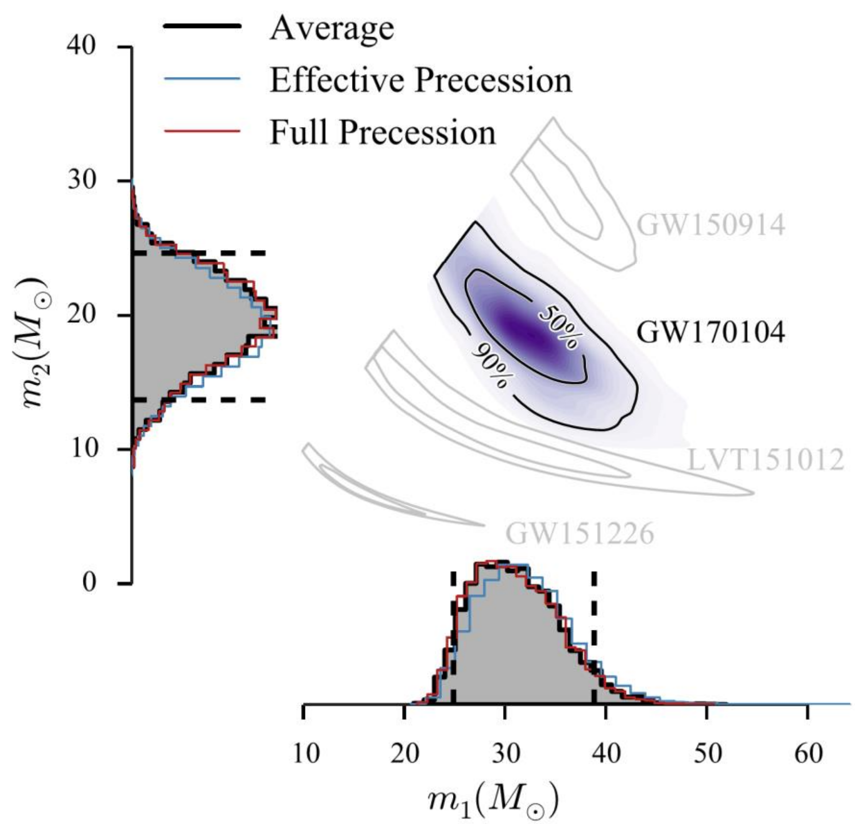


First event from O2 run: GW170104

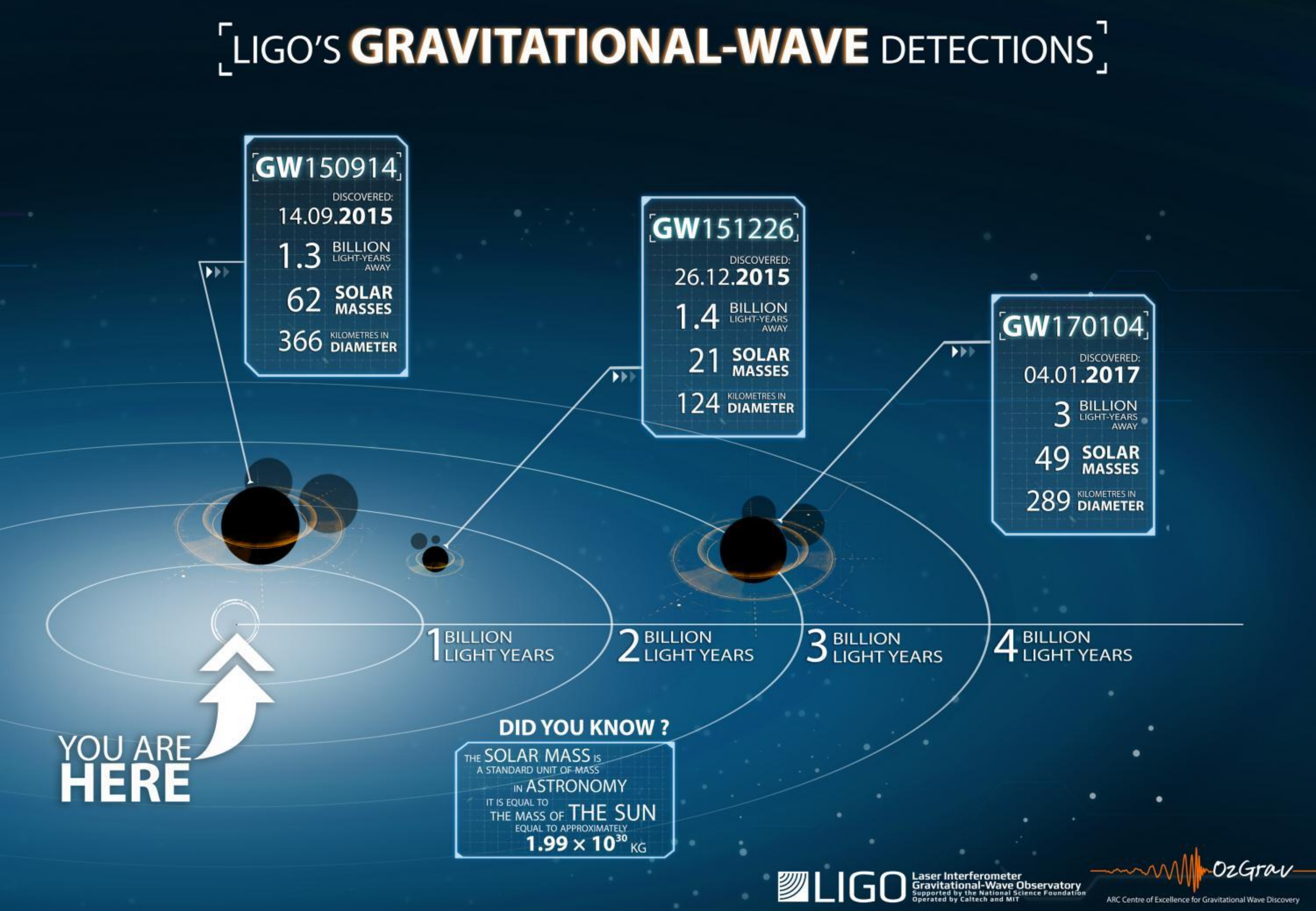
Another binary black hole merger with masses in between GW150914 and GW151226.
Event is about twice as far away as GW150914 and GW151226

Effective spin parameter $\chi_{\text{eff}} = -0.12^{+0.21}_{-0.30}$



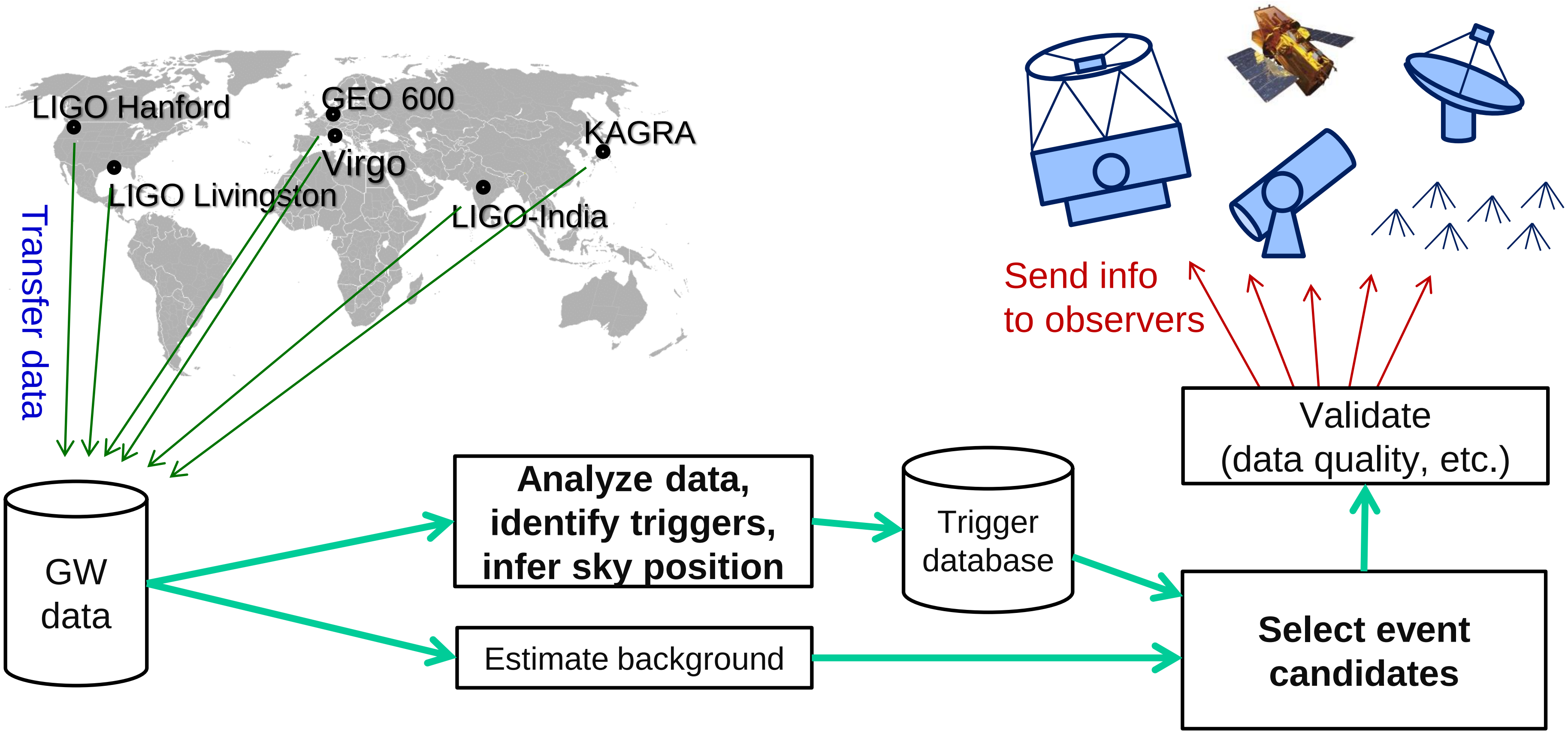


[Abbott et al. 2017, PRL 118, 221101]


LIGO'S GRAVITATIONAL-WAVE DETECTIONS
GW150914
DISCOVERED:
14.09.2015
1.3 BILLION LIGHT-YEARS AWAY
62 SOLAR MASSES
366 KILOMETRES IN DIAMETER
GW151226
DISCOVERED:
26.12.2015
1.4 BILLION LIGHT-YEARS AWAY
21 SOLAR MASSES
124 KILOMETRES IN DIAMETER
GW170104
DISCOVERED:
04.01.2017
3 BILLION LIGHT-YEARS AWAY
49 SOLAR MASSES
289 KILOMETRES IN DIAMETER
1 BILLION LIGHT YEARS
2 BILLION LIGHT YEARS
3 BILLION LIGHT YEARS
4 BILLION LIGHT YEARS
YOU ARE HERE
DID YOU KNOW ?
THE SOLAR MASS IS A STANDARD UNIT OF MASS IN ASTRONOMY
IT IS EQUAL TO THE MASS OF THE SUN
EQUAL TO APPROXIMATELY
1.99 × 10^30 KG
LIGO Laser Interferometer Gravitational-Wave Observatory
Supported by the National Science Foundation
Operated by Caltech and MIT
OzGrav
ARC Centre of Excellence for Gravitational Wave Discovery

Generating and distributing prompt alerts

LIGO & Virgo have signed MOUs with >90 groups for EM/neutrino follow-up, in addition to a number of triggered / joint search MOUs



Swift: NASA E/PO, Sonoma State U., Aurore Simonnet

Towards multi-messenger astronomy

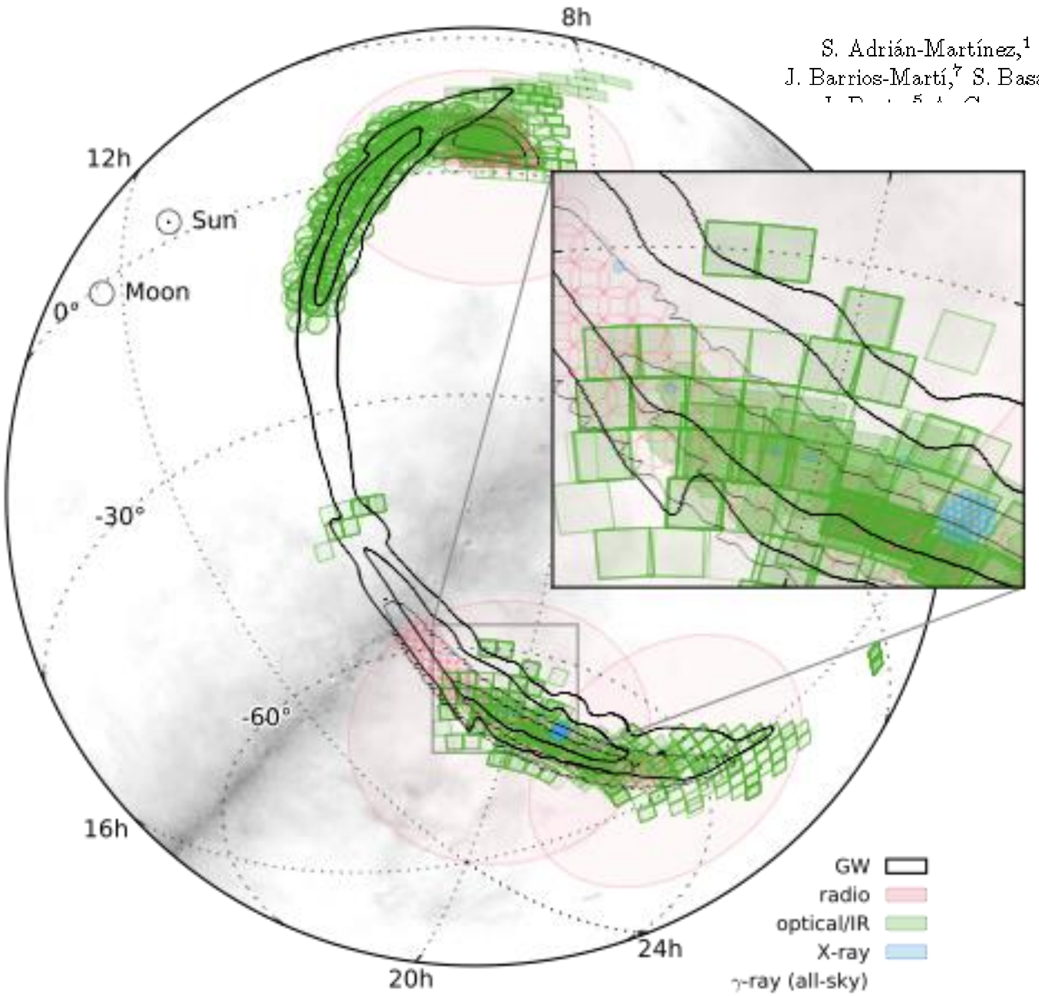
Sky map for GW150914 was sent to astronomers (agreements with more than 90 groups), and they looked. However, in GR we do not expect any EM emission from binary black holes

High-energy Neutrino follow-up search of Gravitational Wave Event GW150914 with ANTARES and IceCube

S. Adrián-Martínez,[1] A. Albert,[2] M. André,[3] G. Anton,[4] M. Ardid,[1] J.-J. Aubert,[5] T. Avgitas,[6] B. Baret,[6] J. Barrios-Martí,[7] S. Basa,[8] V. Bertin,[5] S. Biagi,[9] R. Bormuth,[10,11] M.C. Bouwhuis,[10] R. Bruijn,[10,12] J. Brunner,[5]

arXiv 1602.05411

http://astrog80.astro.cf.ac.uk/Gravoscope/

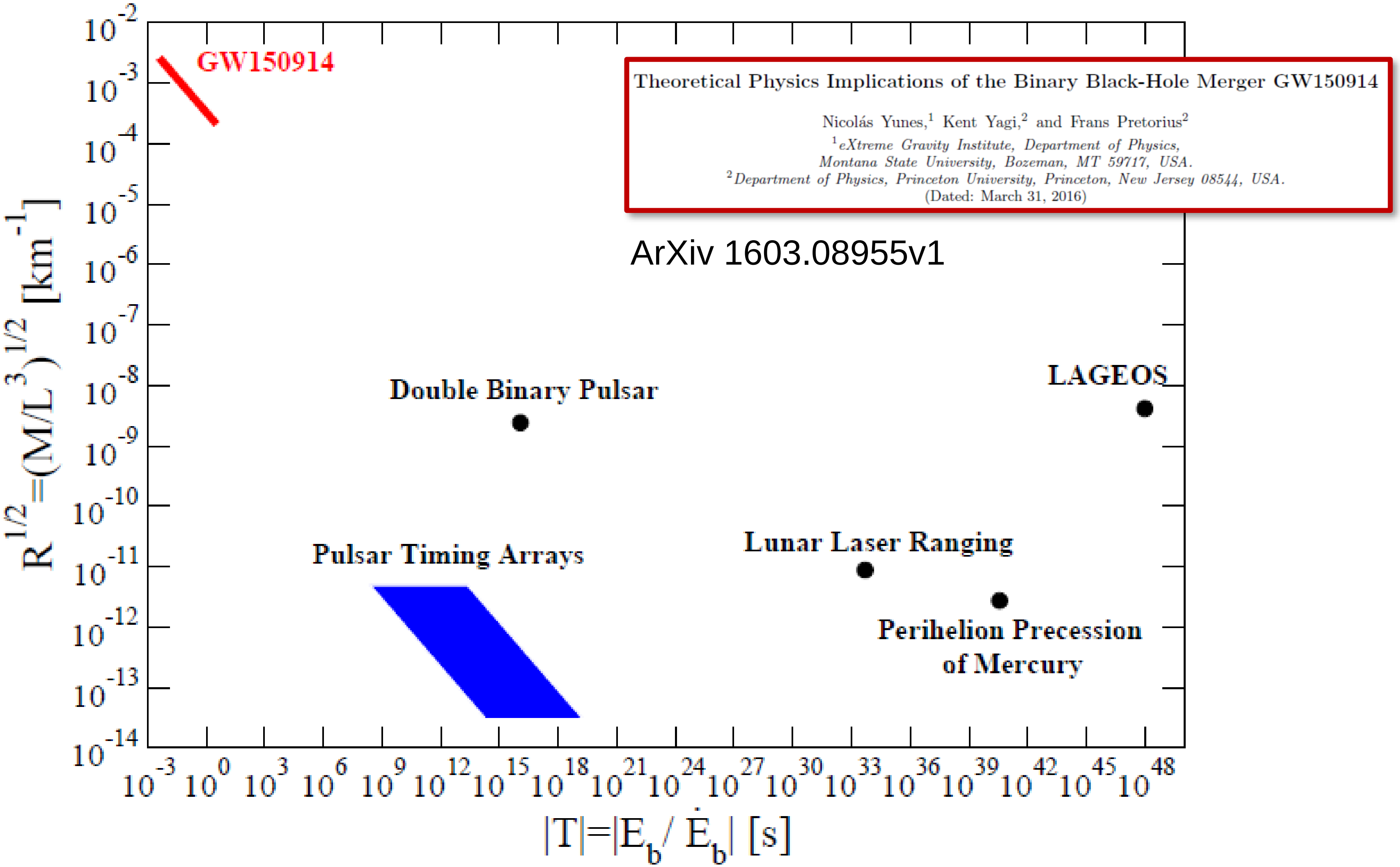


Footprints of Tiled Observations

Group	Area (deg^2)	Contained probability (%) cWB[a]	LIB[b]	LALInf[c]
Swift	2	0.6	0.8	0.1
DES	94	32.1	13.4	6.6
INAF	93	28.7	9.5	6.1
J-GEM	24	0.0	1.2	0.4
MASTER	167	9.3	3.3	6.0
Pan-STARRS	355	27.9	22.9	8.8
SkyMapper	34	9.1	7.9	1.7
TZAC	29	15.1	3.5	1.6
ZTF	140	3.1	2.9	0.9
(total optical)	759	76.5	46.8	23.9
LOFAR-TKSP	103	26.6	1.3	0.5
MWA	2615	97.8	71.8	59.0
VAST	304	25.3	1.7	6.3
(total radio)	2623	97.8	71.8	59.0
(total)	2730	97.8	76.8	62.1

Allows to explore GR in the strong-field regime

Curvature-radiation reaction time-scale phase space sampled by relevant experiments. E_b is the characteristic gravitational binding energy and $\dot{E}_b$ is the rate of change of this energy



General Relativity passes first precision tests

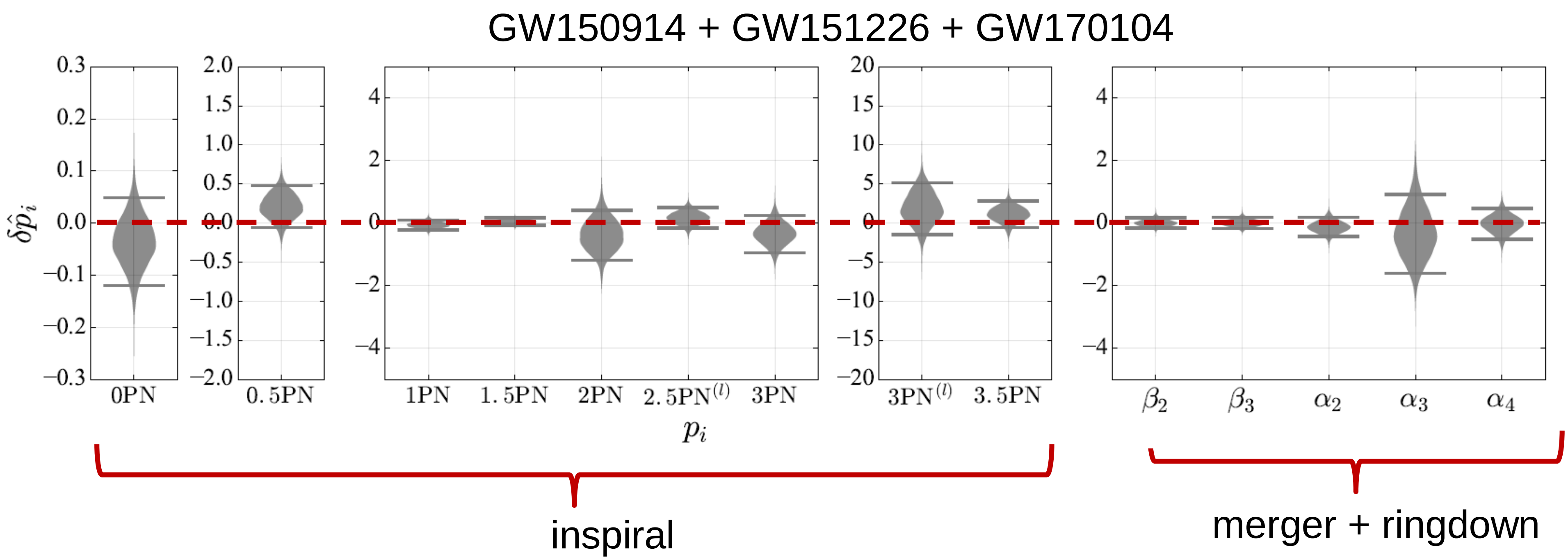
Our Bayesian analysis allows combination of different events in order to improve hypothesis testing

Orbital phase (post Newtonian expansion): $\Phi(v) = \left(\frac{v}{c}\right)^{-5} \sum_{n=0}^{\infty} \left[\varphi_n + \varphi_n^{(l)} \ln\left(\frac{v}{c}\right)\right] \left(\frac{v}{c}\right)^n$

Inspiral PN terms $\varphi_j, j = 0, .., 7$ and logarithmic terms $\varphi_{jl},\ j = 5, 6$

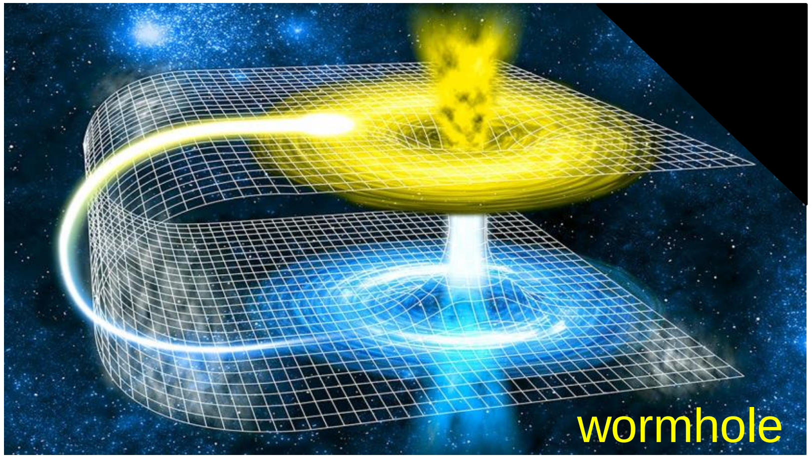
Intermediate and merger-ringdown β_i and α_i

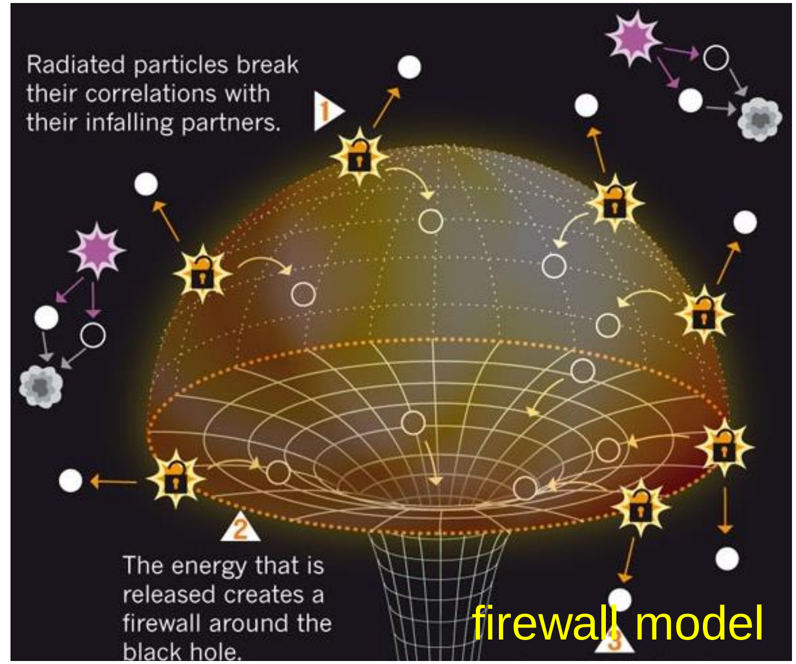
GW back-reaction, spin-orbit, spin-spin couplings, …

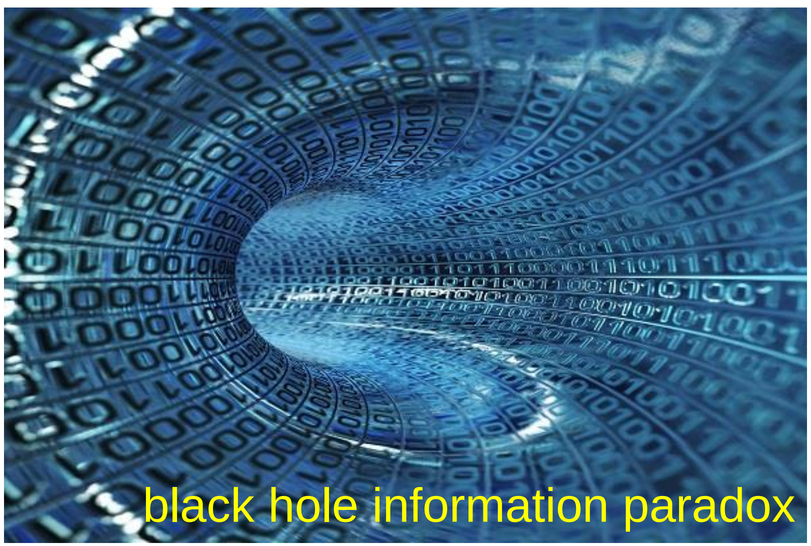


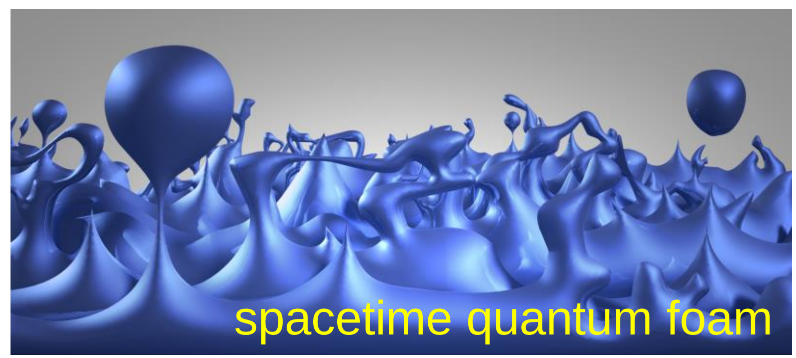
Fundamental physics: did we observe black holes?

Our theories “predict” the existence of other objects, such as wormholes, boson stars, dark matter stars, gravastars, firewalls, *etc*. Why do we believe we have seen black holes?



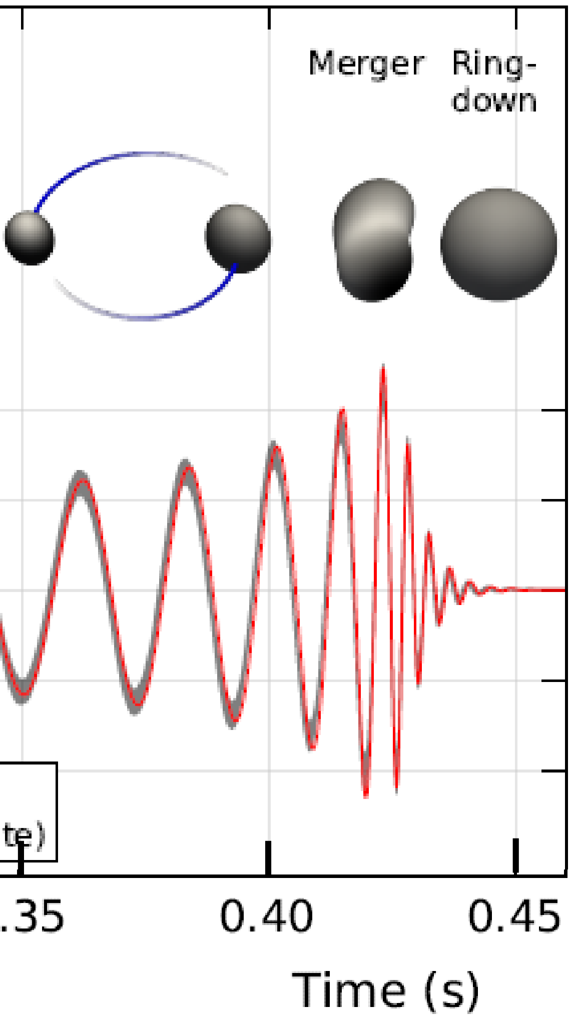


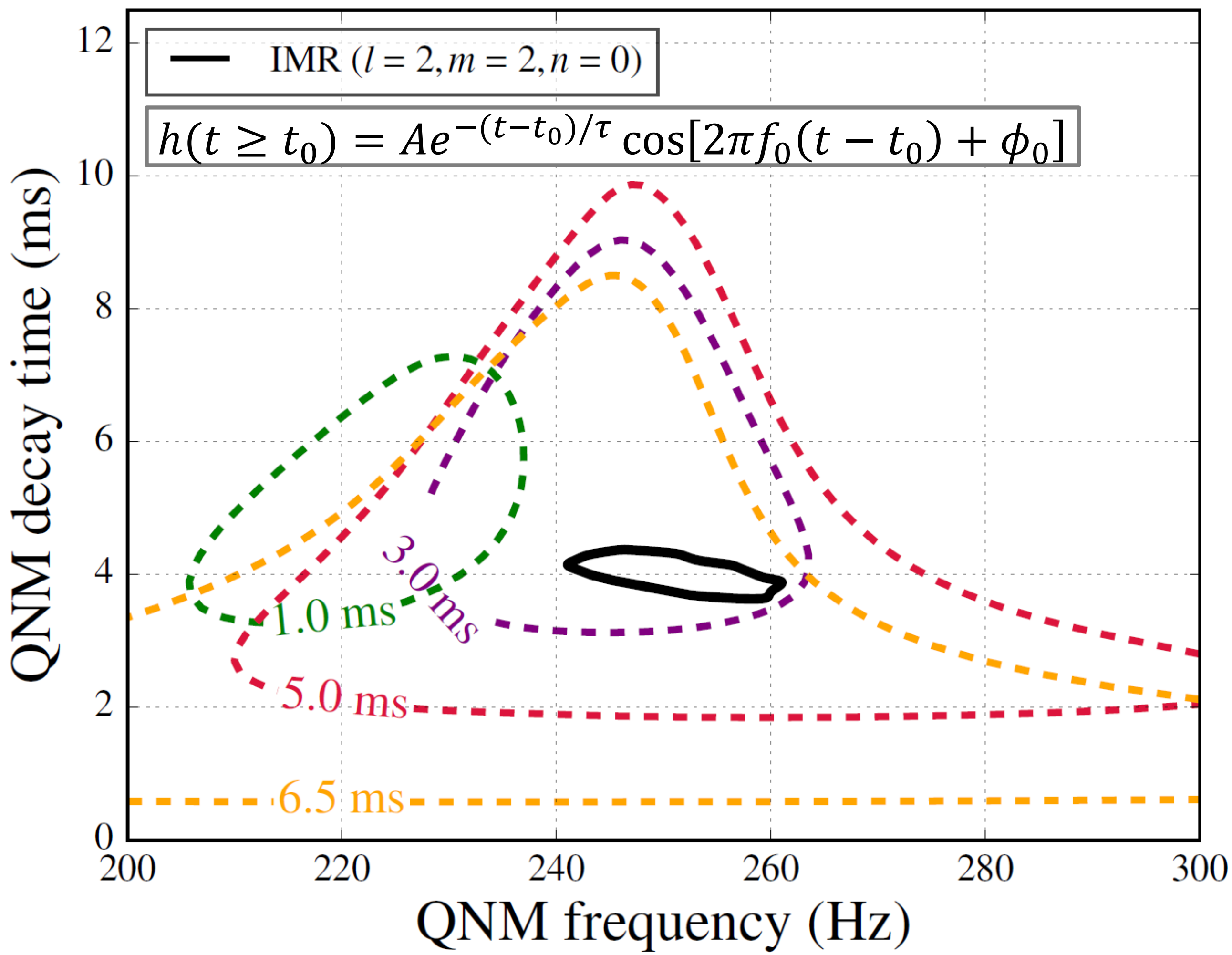




Is a black hole created in the final state?

From the inspiral we can predict that the ringdown frequency should be about 250 Hz.
This is what we measure! (http://arxiv.org/abs/1602.03841)

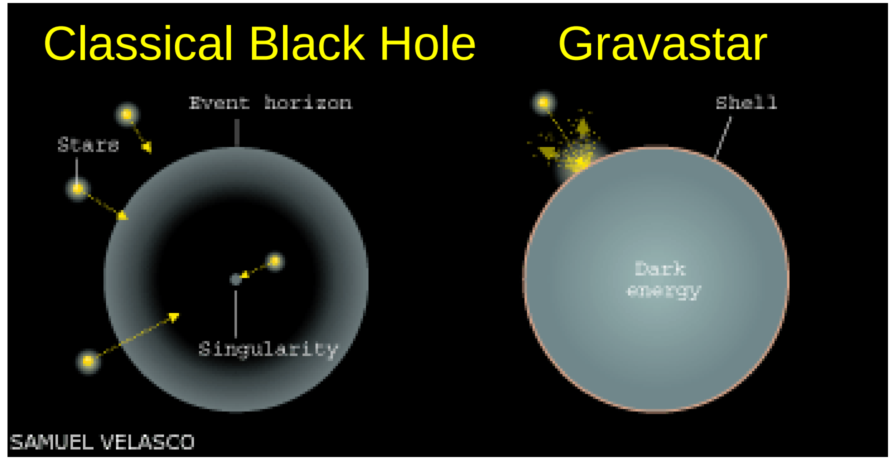




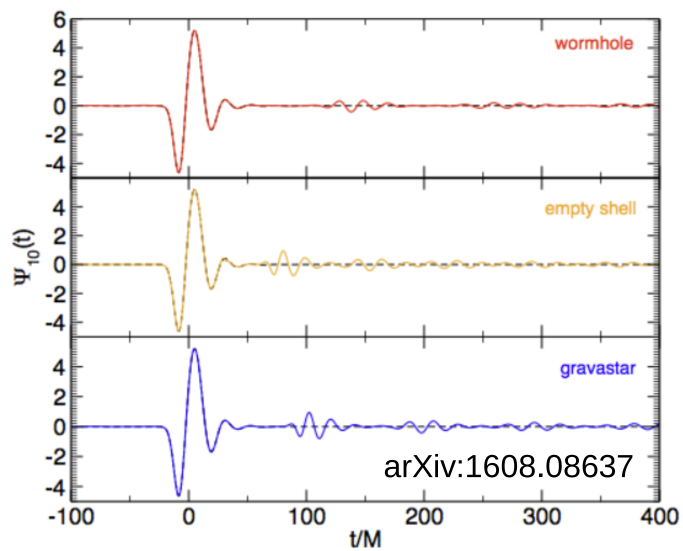
Exotic compact objects

Gravitational waves from coalescence of two compact objects is the Rosetta Stone of the strong-field regime. It may hold the key and provide an in-depth probe of the nature of spacetime

- Quantum modifications of GR black holes
  - Motivated by Hawking's information paradox
  - Firewalls, fuzzballs, EP = EPR, …
- Fermionic dark matter
  - Dark matter stars
- Boson stars
  - Macroscopic objects made up of scalar fields
- Gravastars
  - Objects with de Sitter core where spacetime is self-repulsive
  - Held together by a shell of matter
  - Relatively low entropy object

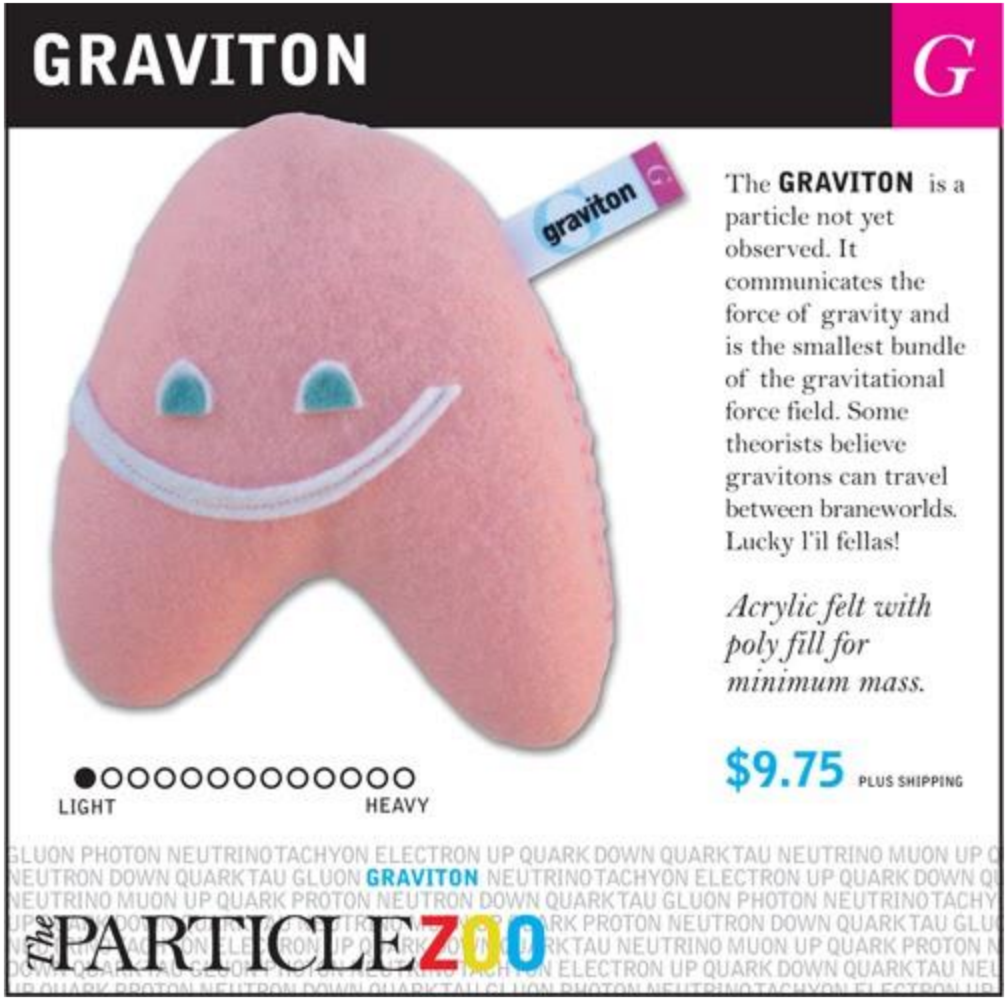


- GW observables
  - Inspiral signal: modifications due to tidal deformation effects
  - Ringdown process: use QNM to check no-hair theorem
  - Echoes: even for Planck-scale corrections $\Delta t \approx -nM \log \frac{l}{M}$



Limit on the mass of the graviton

Bounds on the Compton wavelength $\lambda_g = {}^{h}/_{m_g c}$ of the graviton compared to Solar System or double pulsar tests. Some cosmological tests are stronger (but make assumptions about dark matter)



$$\delta\Phi(f) = -\frac{\pi D c}{\lambda_g^2 (1+z)} f^{-1}$$

Will, Phys. Rev. D **57**, 2061 (1998)

Massive-graviton theory dispersion relation $E^2 = p^2c^2 + m_g^2 c^4$

We have $\lambda_g = h/(m_g c)$

Thus frequency dependent speed

$$\frac{v_g^2}{c^2} \equiv \frac{c^2p^2}{E^2} \cong 1 - h^2c^2/(\lambda_g^2 E^2)$$

$\lambda_g > 10^{13}\mathrm{km}$

$m_g \leq 10^{-22}\mathrm{eV/c^2}$

Michalis Agathos (Nikhef 2016)

See "*Tests of general relativity with GW150914*" http://arxiv.org/abs/1602.03841

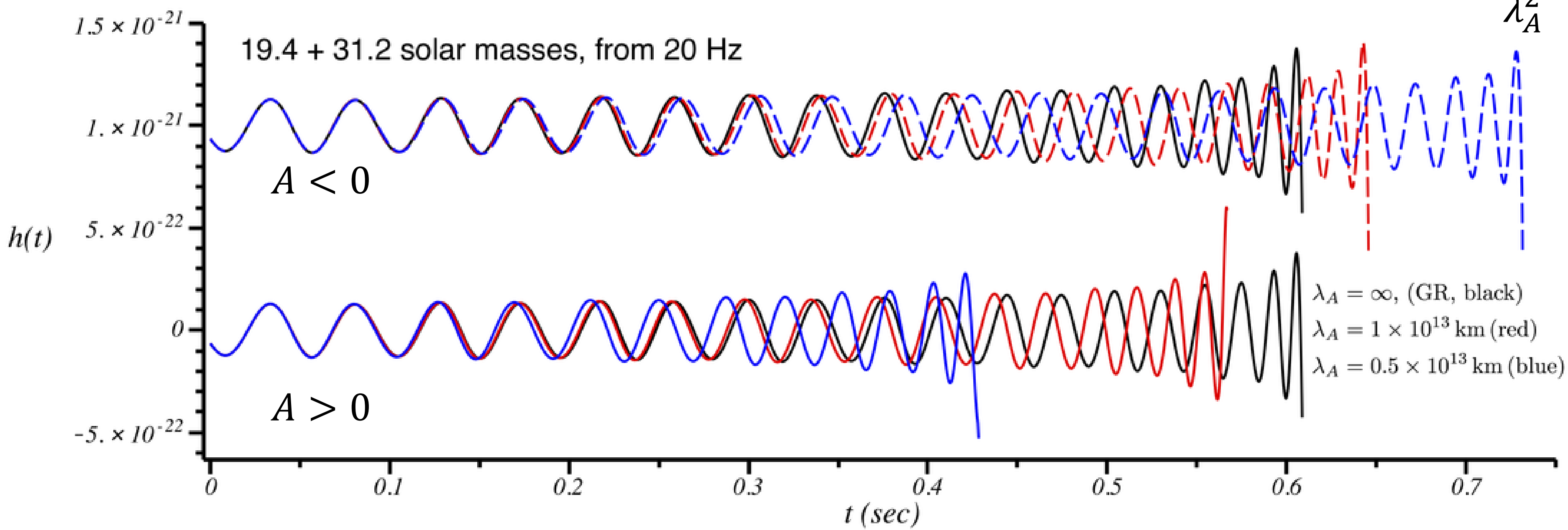
Bounds on violation of Lorentz invariance

First bounds derived from gravitational-wave observations, and the first tests of superluminal propagation in the gravitational sector

Generic dispersion relation $$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \alpha \geq 0 \;\Rightarrow \frac{v_g}{c} \cong 1 + (\alpha - 1)AE^{\alpha-2}/2$$

Gravitational wave phase term $$\delta\Psi = \begin{cases} \frac{\pi}{\alpha-1}\frac{AD_\alpha}{(hc)^{2-\alpha}}\left[\frac{(1+z)f}{c}\right]^{\alpha-1} & \alpha \neq 1 \\ \frac{\pi AD_\alpha}{hc}\ln\left(\frac{\pi G\mathcal{M}^{det}f}{c^3}\right) & \alpha = 1 \end{cases}$$

$$A \cong \pm\frac{MD_\alpha}{\lambda_A^2}$$



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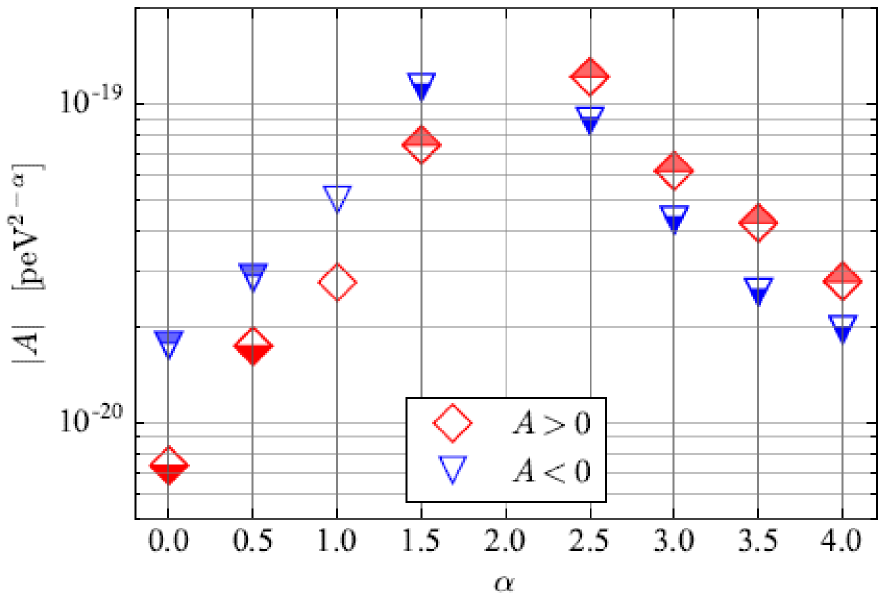


Note: $1\ \mathrm{peV} \simeq h \times 250\ \mathrm{Hz}$

Top filled: superluminal speed

$$E^2 = p^2c^2 + Ap^\alpha c^\alpha, \alpha \geq 0$$

$$\Rightarrow \frac{v_g}{c} \cong 1 + (\alpha - 1)AE^{\alpha-2}/2$$

Several modified theories of gravity predict specific values of α:

massive-graviton theories (α = 0, A > 0), multifractal spacetime (α = 2.5),

doubly special relativity (α = 3), and Horava-Lifshitz and extradimensional theories (α = 4)

See "GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2"

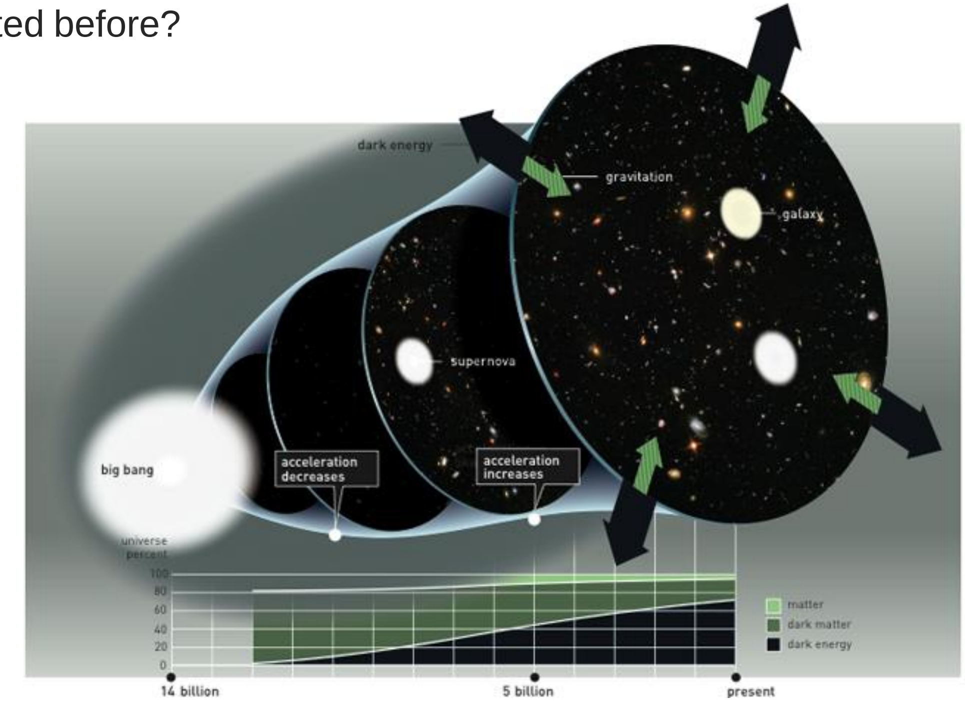
http://arxiv.org/abs/1706.01812

What does it all mean? What’s next?

Gravity

Gravity is the least understood fundamental interaction with many open questions. Should we not now investigate general relativity experimentally, in ways it was never tested before?

- Gravity
  - Main organizing principle in the Universe
    - Structure formation
  - Most important open problems in contemporary science
    - Acceleration of the Universe is attributed to dark energy
    - Standard Model of Cosmology features dark matter
    - Or does this signal a breakdown of general relativity?
- Large world-wide intellectual activity
  - Theoretical: combining GR + QFT, cosmology, …
  - Experimental: astronomy (CMB, Euclid, LSST), particle physics (LHC), dark matter searches (Xenon1T), …



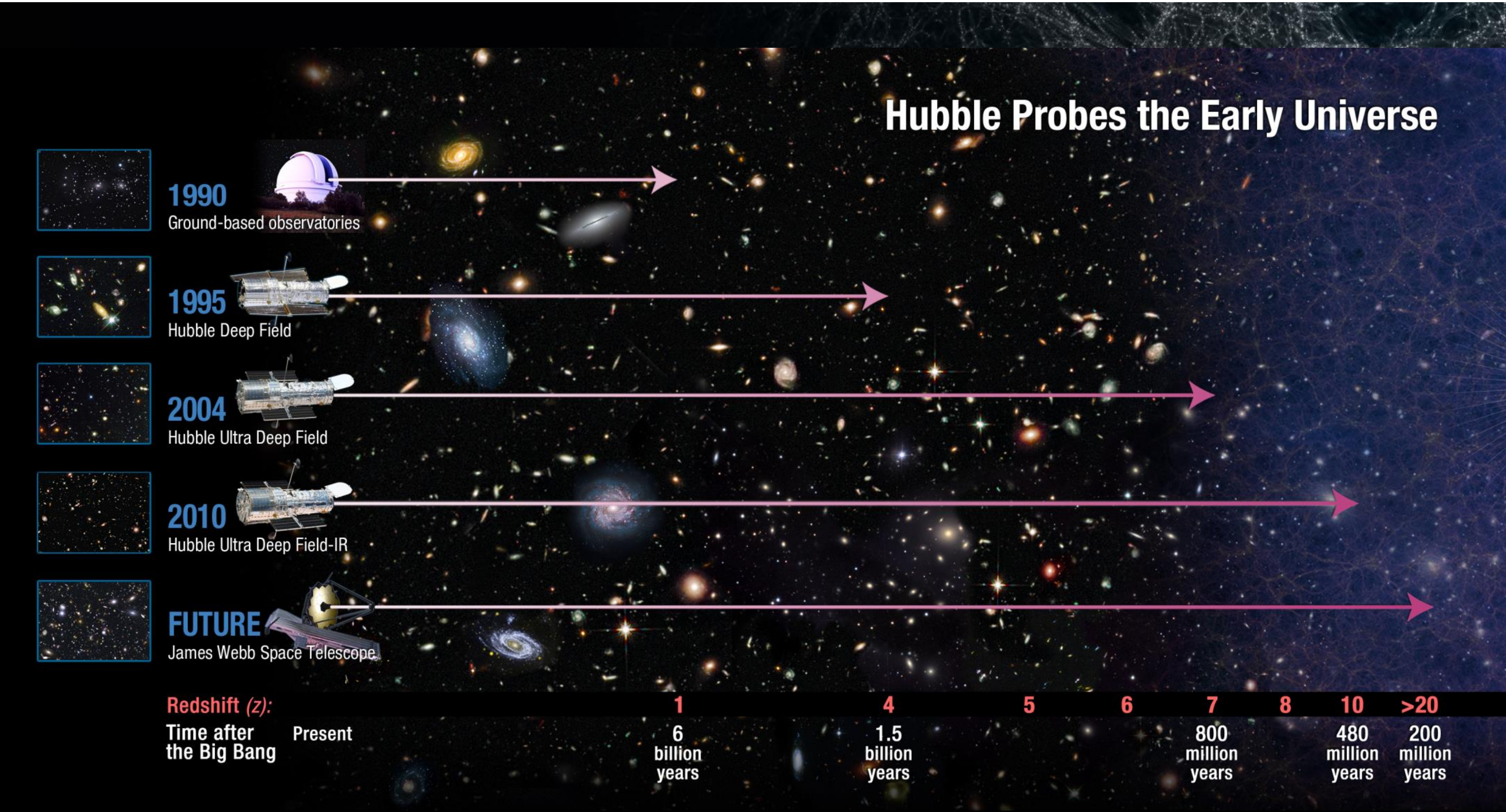
- Gravitational waves
  - Dynamical part of gravitation, all space is filled with GW
  - Ideal information carrier, almost no scattering or attenuation
  - The entire universe has been transparent for GWs, all the way back to the Big Bang
- Gravitational wave science can impact
  - Fundamental physics: black holes, spacetime, horizons
  - Cosmology: dark energy

Global GW Detector Network

Current state-of-the-art: Second-generation (“advanced”) laser interferometers. Virgo joined O2 on August 1, 2017

Probing the early Universe

It is important to study the early Universe in the “dark ages”, before first stars have formed. For example, Einstein Telescope can observe BBH mergers up to redshifts of about 20



Questions

Science drives the design requirements for 3G

[1] Do we want to observe all BBH mergers in the Universe?

- Do we want to collect high statistics (e.g. a million BBH events) distributed over a large z-range ($z < 20$)?
- Do we really need 3G, or is an upgrade of existing facilities within site constrains sufficient?

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- Are our waveform models robust for stacking, e.g. to sub-per-mille precision on PN terms?
- Can we face-up to the computing challenge?
- Do we prefer events a few high-SNR events (thus long arms), or can we combine lower SNR events?

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[3] Do we want to <u>constantly</u> observe the <u>entire</u> sky with high <u>pointing</u> precision?

- Correlate high statistics GW data with other (e.g. EM) observations (SKA-II, LSST, Theseus, …)
- One L-shaped sensitive instrument, or one triangular detector? Or do we need a 3G network?

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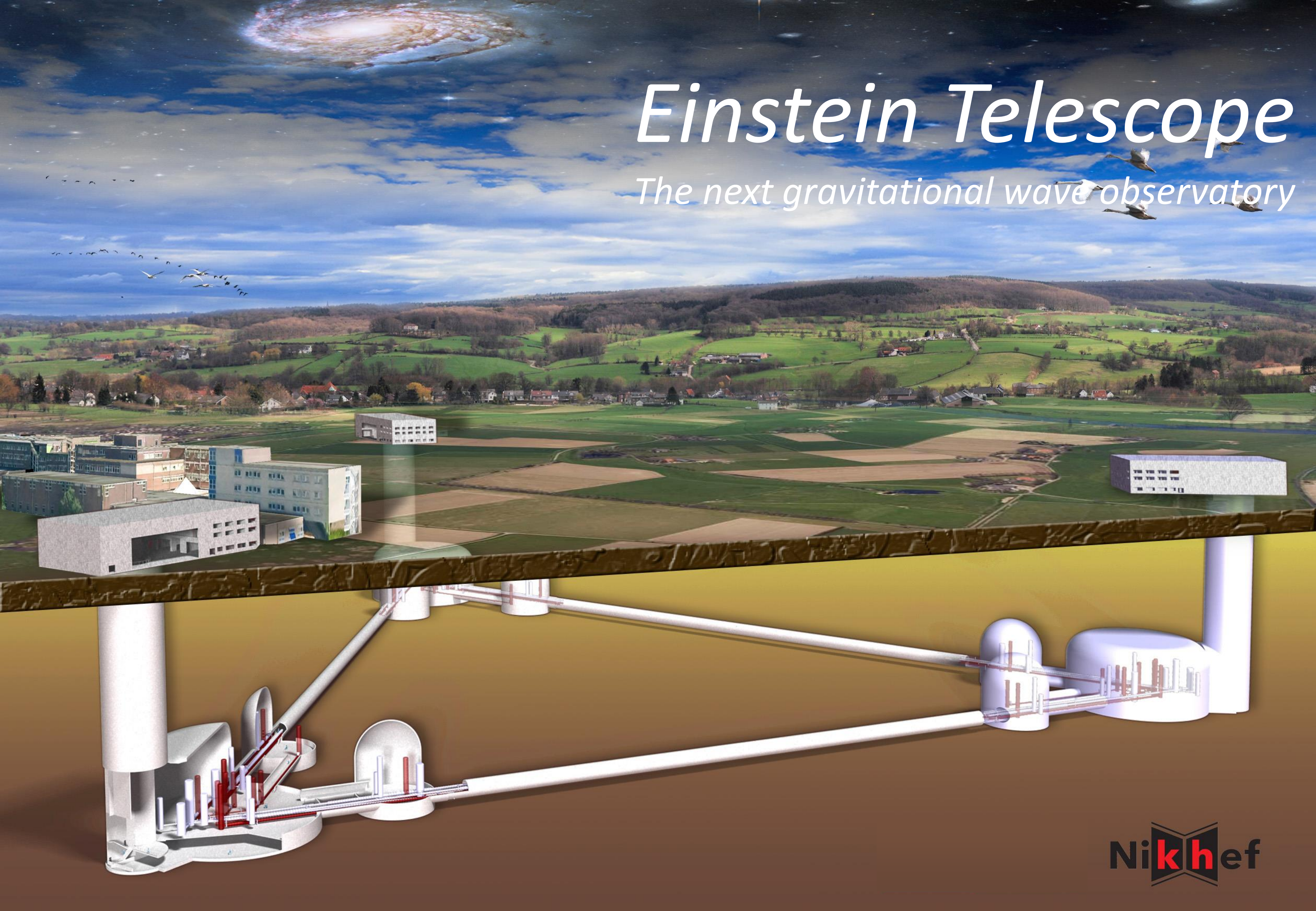
[4] For how long do we want to observe our signals?

- How important is it to predict a merger about 1 minute in advance to prepare for EM follow-up?
- Importance of studying spin-precession effects? What about IMRIs? Sensitivity for high-z events?
- What should be our low-frequency cut-off? Do we need to go underground for seismic and Newtonian noise?



Einstein Telescope
The next gravitational wave observatory
Nikhef

How to get from 2G to 3G?

Vision beyond Advanced Virgo

The collaboration has discussed a path from Advanced Virgo to Einstein Telescope

Sensitivity of Advanced Virgo will be improved further within current infrastructure limits

- Additional hardware implementations are planned: MS, FDS, HPL, SR
  - Main limits: mirror thermal noise and quantum noise
- New ideas are under study
  - Larger beam and larger mirrors, and better coatings
  - Newtonian noise subtraction, and improved suspensions

Phased approach

- Phase I: achieve design sensitivity (2017 – 2021)
- Phase II: achieve maximum sensitivity within infrastructure limits (2021 – 2025)
- Phase III: optimize AdV in view of a new available infrastructure (> 2025)

From Advanced Virgo to Einstein Telescope

- Scientific excellence with the network of advanced detectors: LIGO, Virgo, KAGRA
- Vigorous and international R&D program focused on third generation with spin-off to advanced detectors
- Position Virgo as an attractive international gateway to GW science

Strategic decision of EU agencies on their commitment for ground-based GW science is required

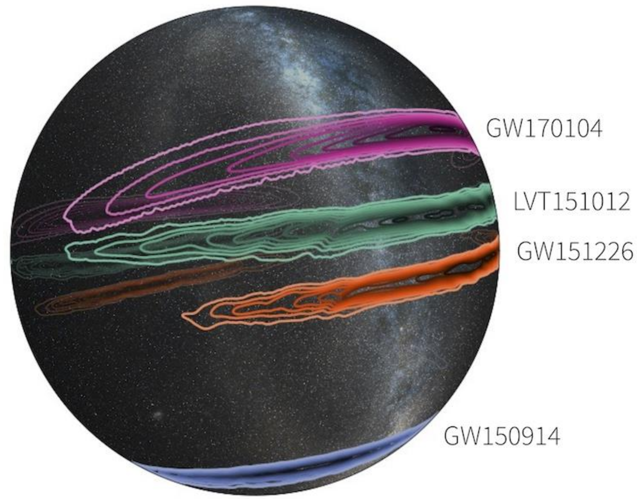
- Important roles for ApPEC and GWIC

Virgo as a node in the GW global network

We made a promise to deliver Virgo as the third node in a world-wide network for GW detection

Added scientific value of Virgo in the network

- Increase of sky coverage
- Improvement of sky location of sources
- Measurement of GW polarization
- Improvement in distance measurement
- Three-fold coincidence measurement for increased robustness
- Improvement in parameter estimation



Sensitivity evolution in BNS range (see VIR-0136A-16)

• Early	2016 – 17	20 – 60 Mpc
• Mid	2017 – 18	60 – 85 Mpc
• Late	2018 – 20	65 – 115 Mpc
• Design	2021	130 Mpc
• BNS-optimized		145 Mpc

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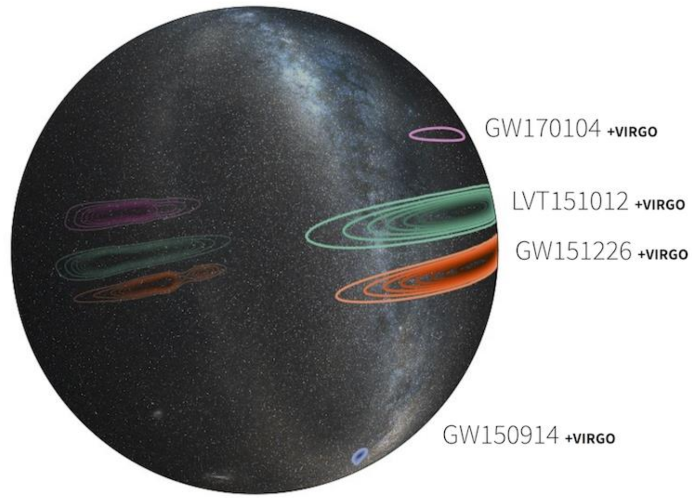

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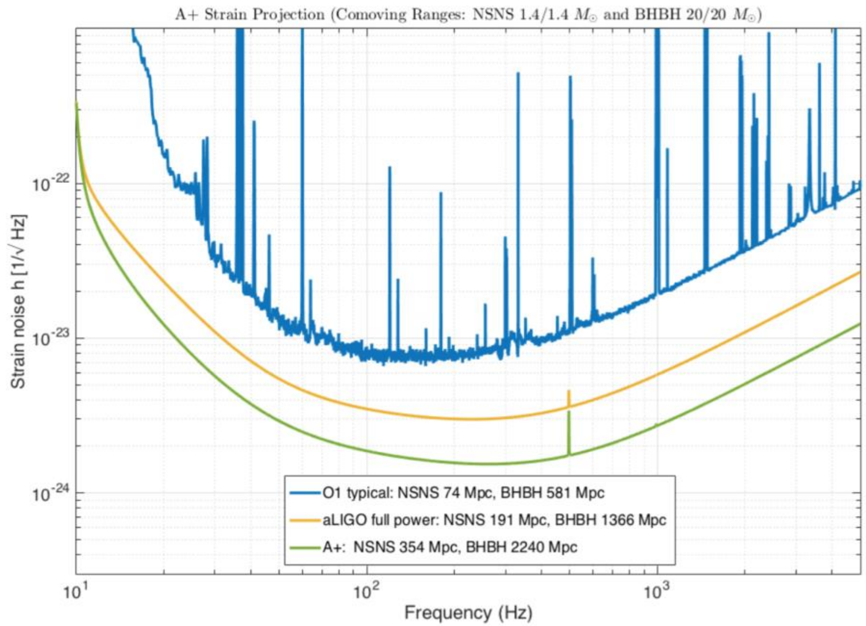
Multi-messenger astronomy

- BNS, BHNS

Upgrade path for 2G

LIGO and Virgo are thinking to mid and long-term upgrades to exploit the current facilities. Laser power, FDS, reduction of coating loss angle. But also heavier test masses, … Towards z = 1 for BBH



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Prospects for doubling the range of Advanced LIGO

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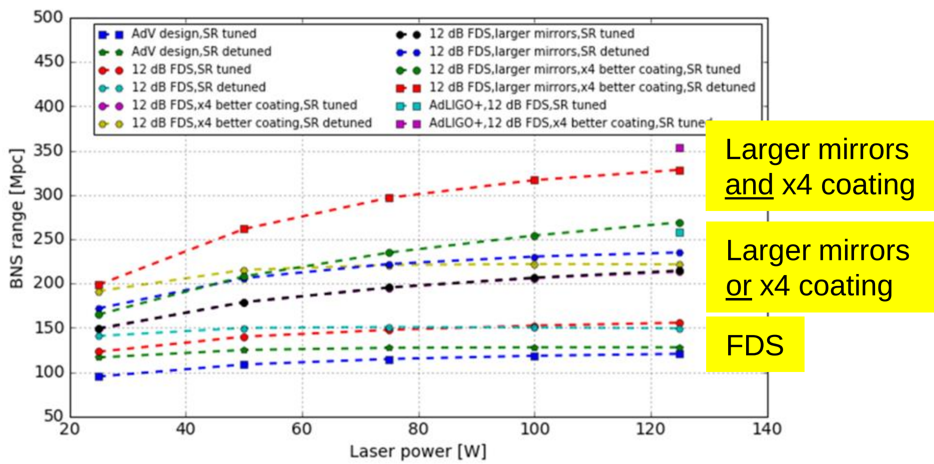


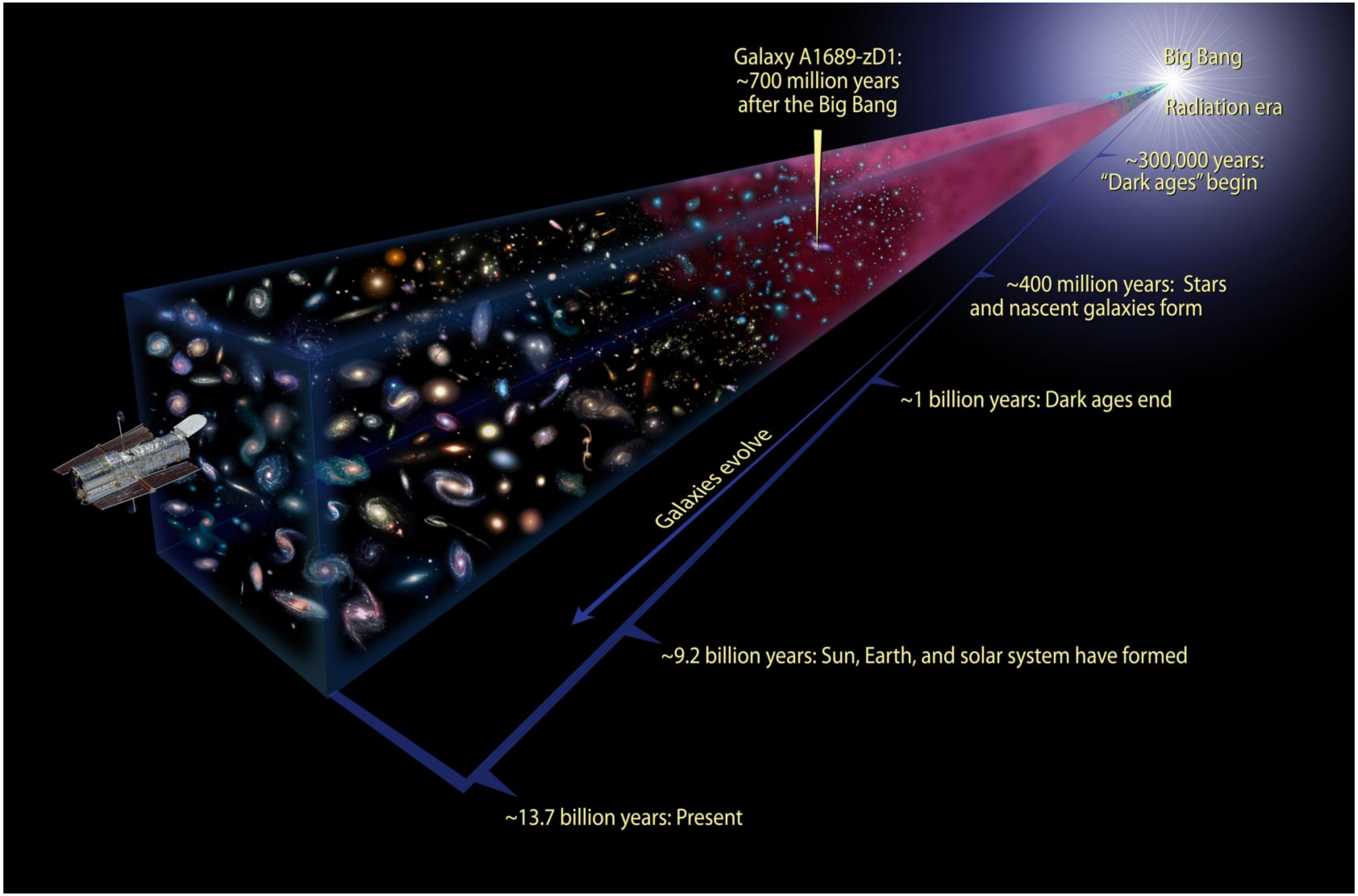
A Vision Beyond the Advanced Virgo Project

VIR-0136A-16

The VIRGO collaboration
September 2016

How far do you want to go?

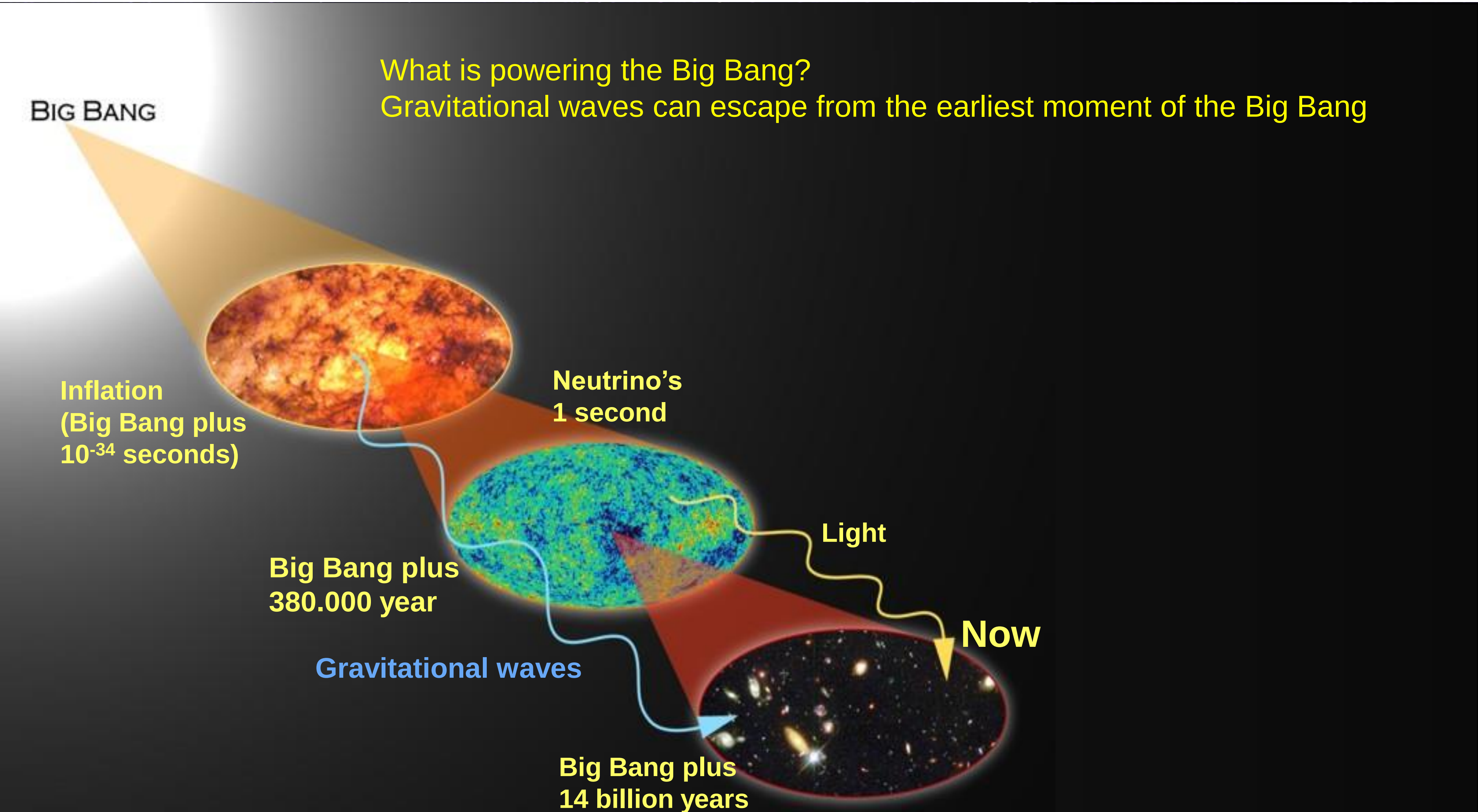
Einstein Telescope can observe BBH mergers up to red shifts of about 20. Explore the dark ages …



Credit: NASA, ESA, and A. Feild (STScI)

Einstein Telescope: science program

A facility for precision gravitational physics and gravitational wave astronomy for the 21st century.
An infrastructure where key technologies can be improved continuously




Thank you!