Gravitational waves: physics at the extreme

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IFT Xmas Workshop, Instituto de Fisica Teorica, Madrid, December 14, 2018

LSC LIGO Scientific Collaboration

VIRGO

Gravity

Gravity is the least understood fundamental interaction with many open questions. Should we not now investigate general relativity experimentally in entirely new ways?

Gravity

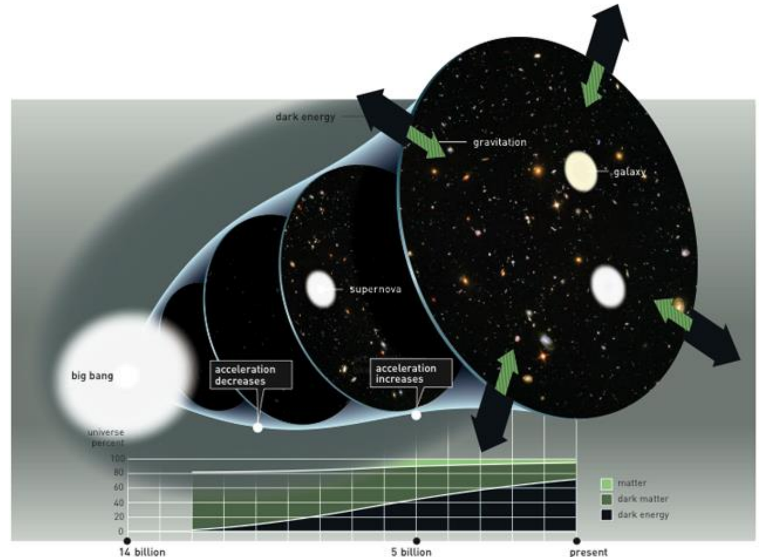
- Main organizing principle in the Universe
  - Structure formation
- Most important open problems in contemporary science
  - Acceleration of the Universe is attributed to Dark Energy
  - Standard Model of Cosmology features Dark Matter
  - Or does this signal a breakdown of general relativity?

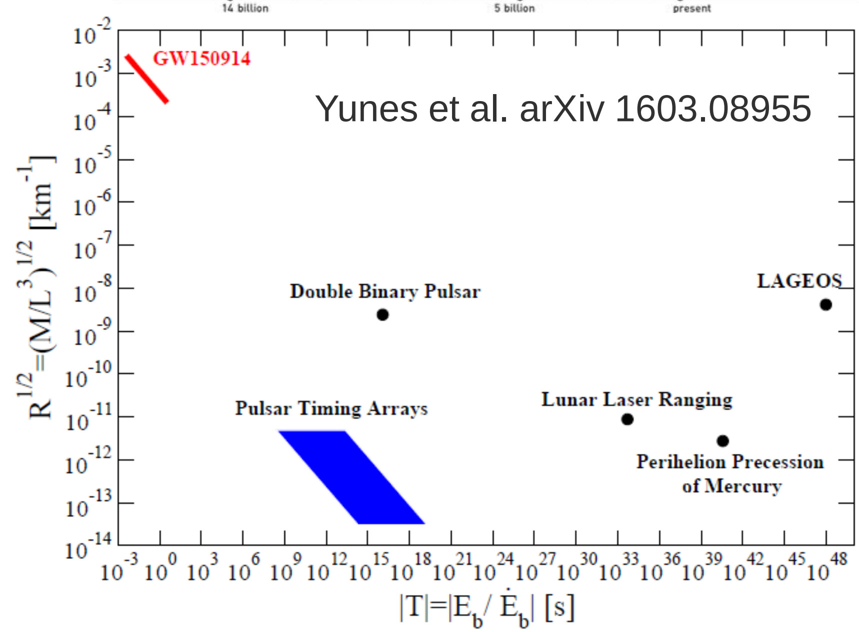
Large world-wide intellectual activity

- 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
- Fundamental physics: black holes, spacetime, horizons
- Cosmology: Hubble parameter, Dark Matter, Dark Energy



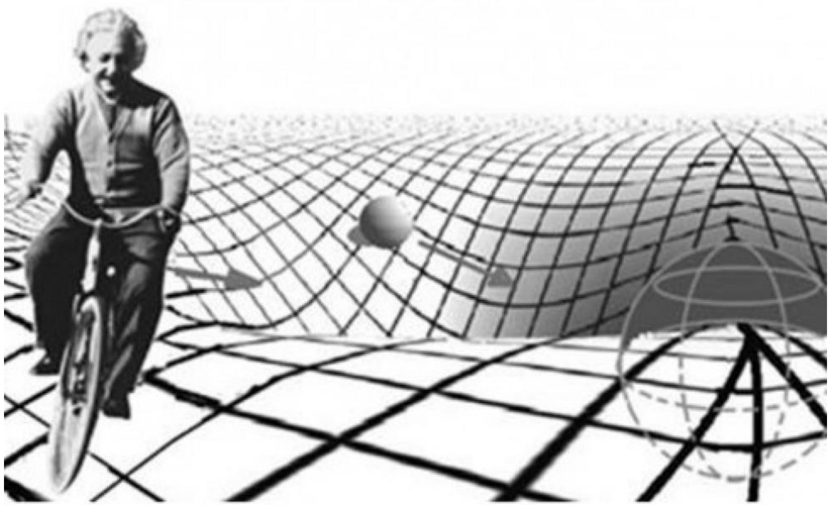


Einstein's theory of general relativity

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

Einstein's Gravity

- Space and time are physical objects
- Gravity as a geometry: curvature of spacetime



Predictions

- Light bends around the Sun
- Expansion of the Universe
- Black holes, wormholes, structure formation, …
- Gravitational waves: curvature perturbations in the spacetime metric that propagate with the speed of light

688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

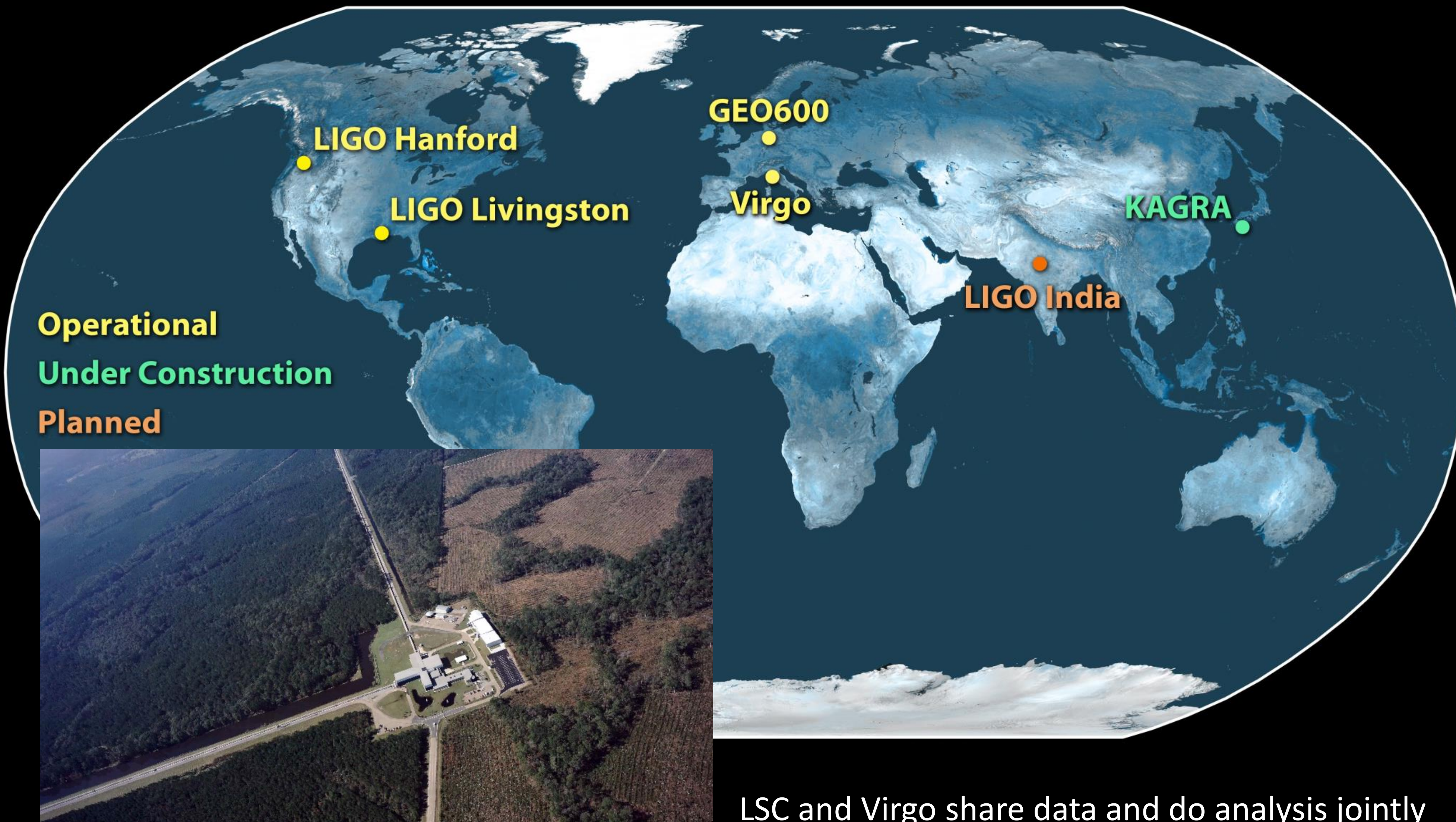
ein. Man erhält aus ihm also die Ausstrahlung A des Systems pro Zeiteinheit durch Multiplikation mit $4\pi R^2$:

$$A = \frac{\varkappa}{24\pi}\sum_{\alpha\beta}\left(\frac{\partial^3 J_{\alpha\beta}}{\partial t^3}\right)^2. \qquad (21)$$

Würde man die Zeit in Sekunden, die Energie in Erg messen, so würde zu diesem Ausdruck der Zahlenfaktor $\frac{1}{c^4}$ hinzutreten. Berücksichtigt man außerdem, daß $\varkappa = 1.87 \cdot 10^{-27}$, so sieht man, daß A in allen nur denkbaren Fällen einen praktisch verschwindenden Wert haben muß.

Gleichwohl müßten die Atome zufolge der inneratomischen Elektronenbewegung nicht nur elektromagnetische, sondern auch Gravitationsenergie ausstrahlen, wenn auch in winzigem Betrage. Da dies in Wahrheit in der Natur nicht zutreffen dürfte, so scheint es, daß die Quantentheorie nicht nur die Maxwellsche Elektrodynamik, sondern auch die neue Gravitationstheorie wird modifizieren müssen.

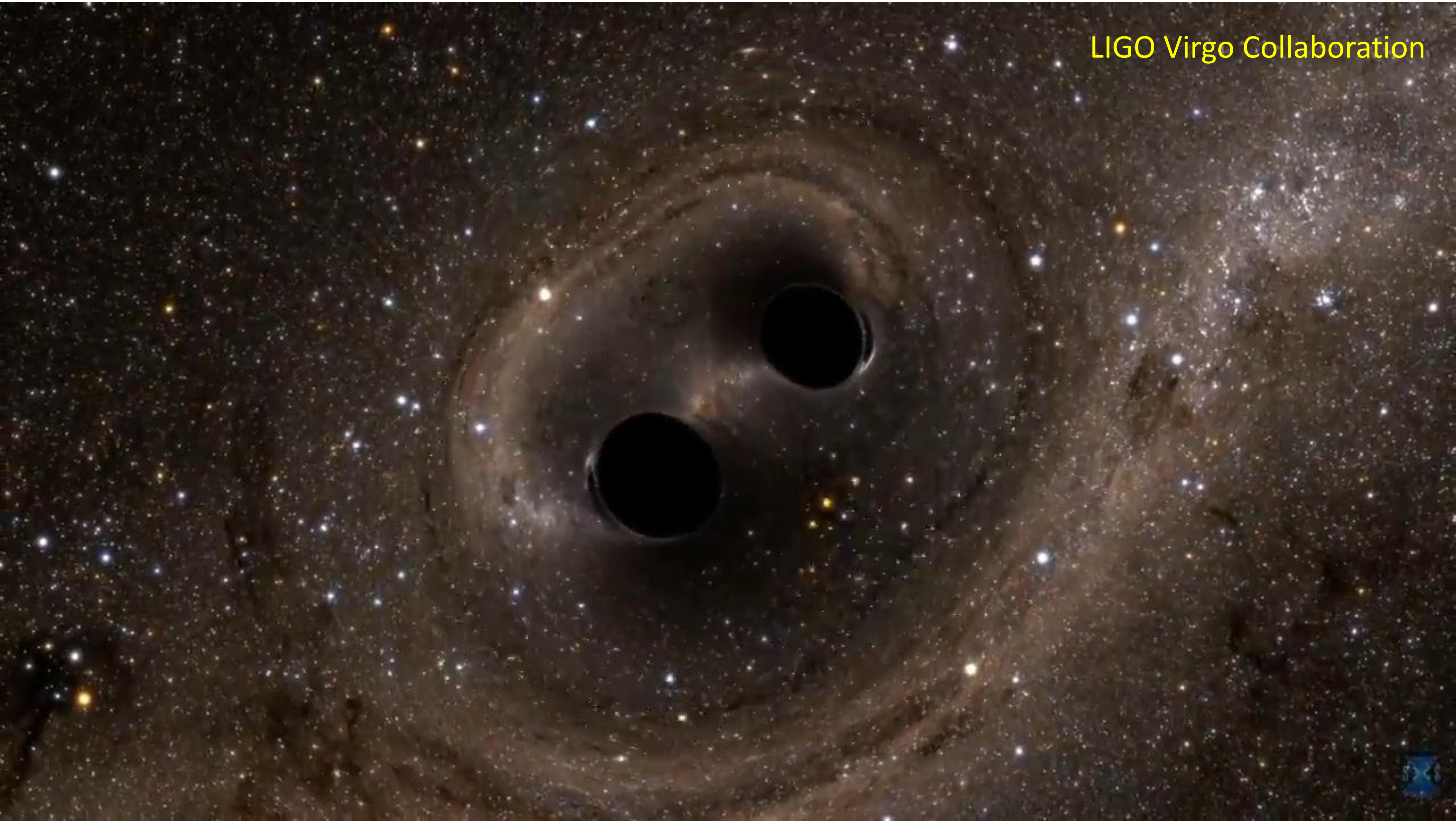
Towards a global GW research infrastructure



LSC and Virgo share data and do analysis jointly

Event GW150914

On September 14, 2015 we detected for the first time gravitational waves (vibrations in the fabric of space and time) from the collision of two black holes



February 2016: LIGO discovery of gravitational waves

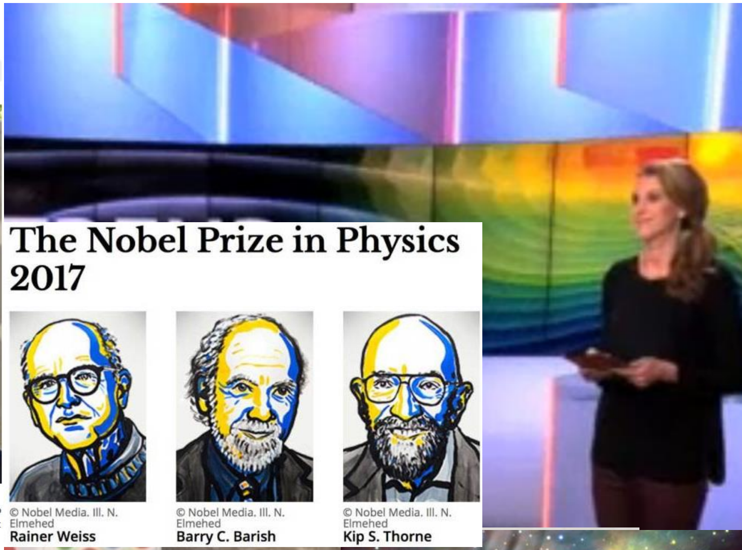
Tiny vibrations in space can now be observed by using the kilometer-scale laser-based interferometers of LIGO and Virgo. This enables an entire new field in science

José Antonio Font analiza en una conferencia el premio Nobel de Física de 2017

GABINETE DE PRENSA 22 de noviembre de 2017

José Antonio Font.

El director del Departamento de Astronomía y Astrofísica de la Universitat de València, José Antonio Font, analizó el premio Nobel de Física de 2017, en el MuVim. 'Arrugas del espacio-tiempo y estallidos de luz' era el título de la conferencia de Font dentro de els Debats del Magnànim. El acto fue presentado por el catedrático Vicent Martínez.



Editor: Pablo Sebastián
Consejero E.: José Oneto
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Ciencia | Ciencia y tecnología

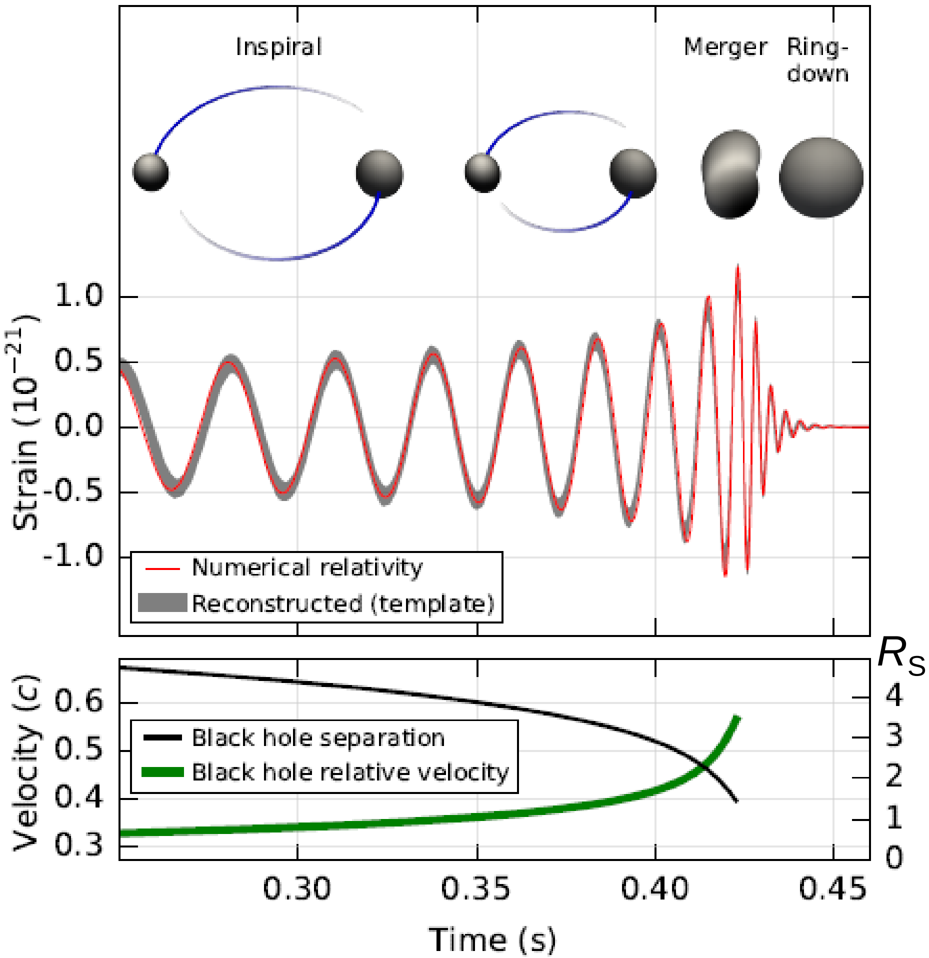
Detectan por primera vez ondas gravitacionales tras la fusión de dos estrellas de neutrones

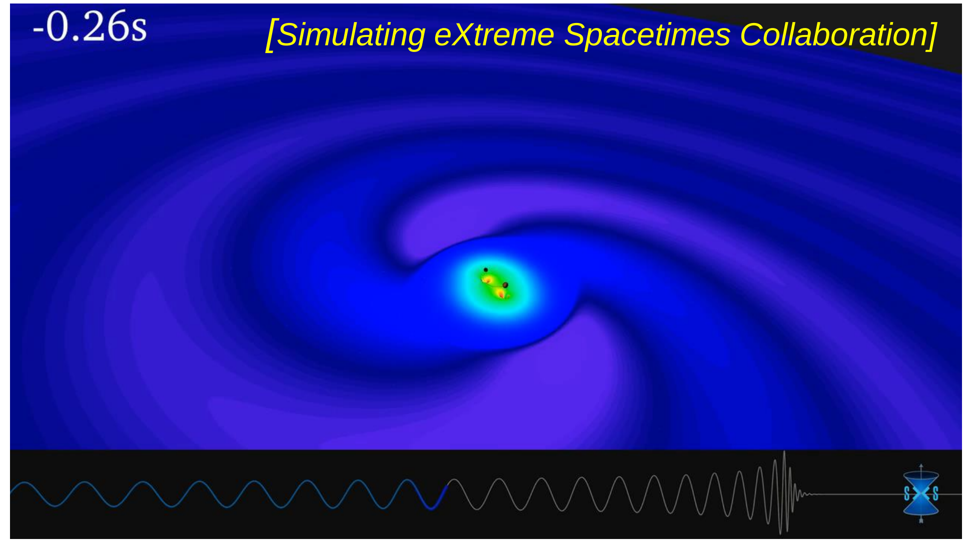
REPÚBLICA/EP | 16/10/2017

Astrónomos de todo el mundo, entre ellos españoles, han podido observar por primera vez tanto ondas gravitacionales como luz (radiación electromagnética) de un mismo evento, la fusión de dos estrellas de neutrones, lo que abre una nueva era en la observación del Universo.

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





- Chirp $\dot{f} \approx f^{11/3} M_S^{5/3}$
- Maximum frequency $f_{\mathrm{ISCO}} = \frac{1}{6^{3/2}\pi M}$
- Orbital phase (post Newtonian expansion)

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

- Strain $h \approx \frac{M_S^{5/3} f^{2/3}}{r} = \frac{\dot{f}}{r f^3}$

Scientific achievements: properties of black holes

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

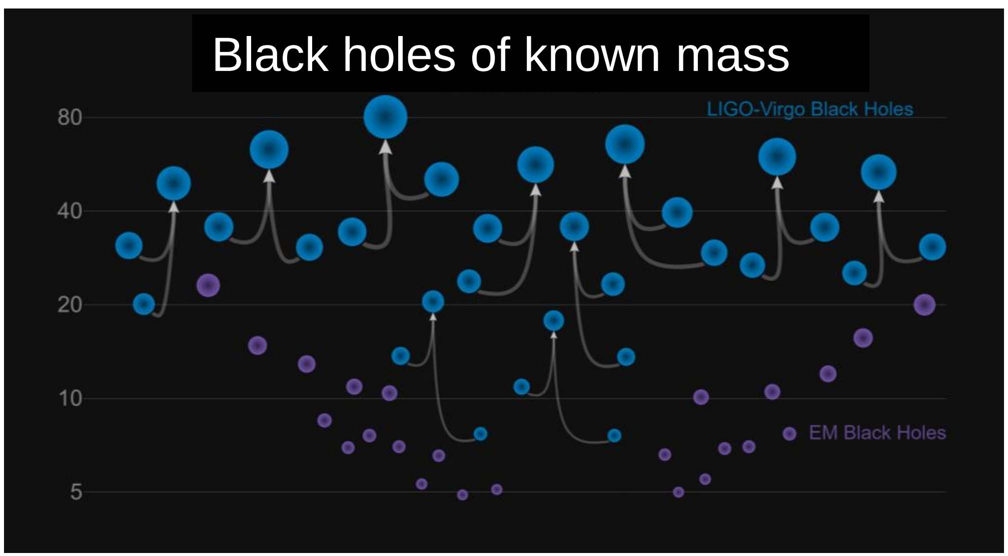
Abbott et al. ApJ 851 (2017) L35

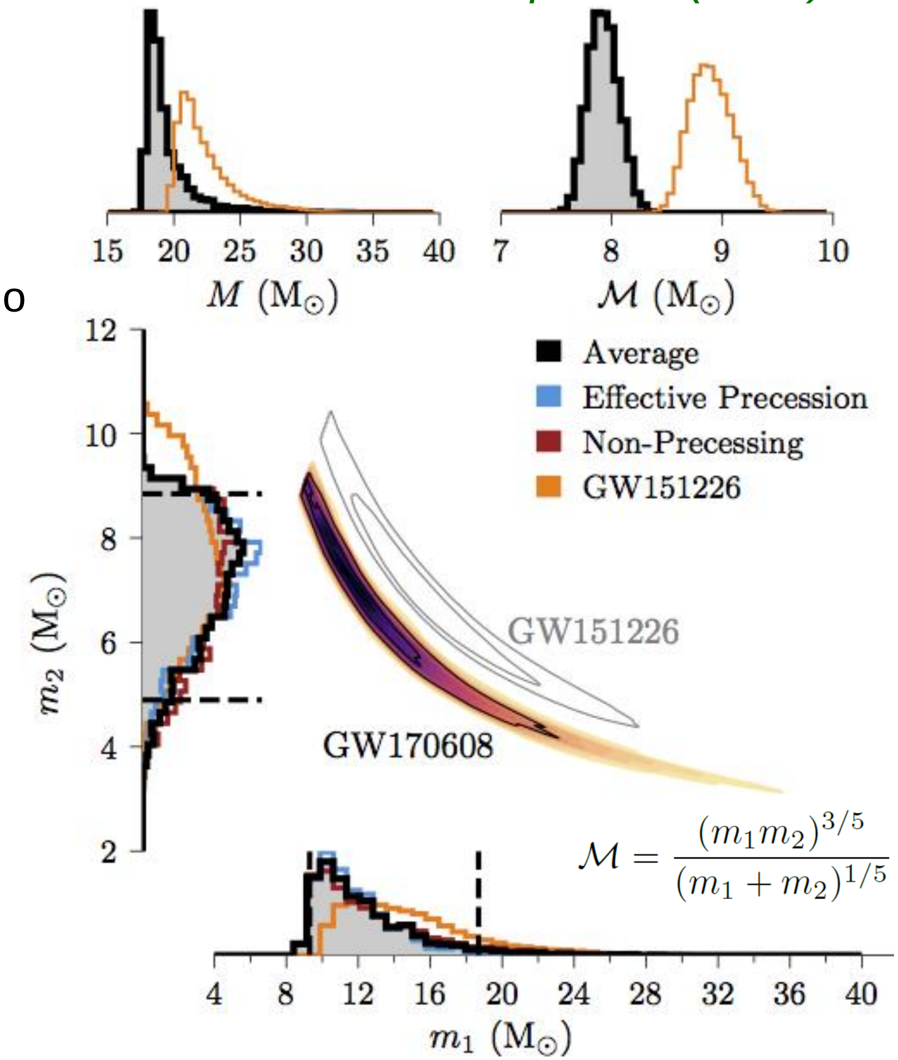
LVC reported on 10 BBH mergers (and 1 BNS)

Chirp mass is well inferred

Merger dynamics more sensitive to total mass

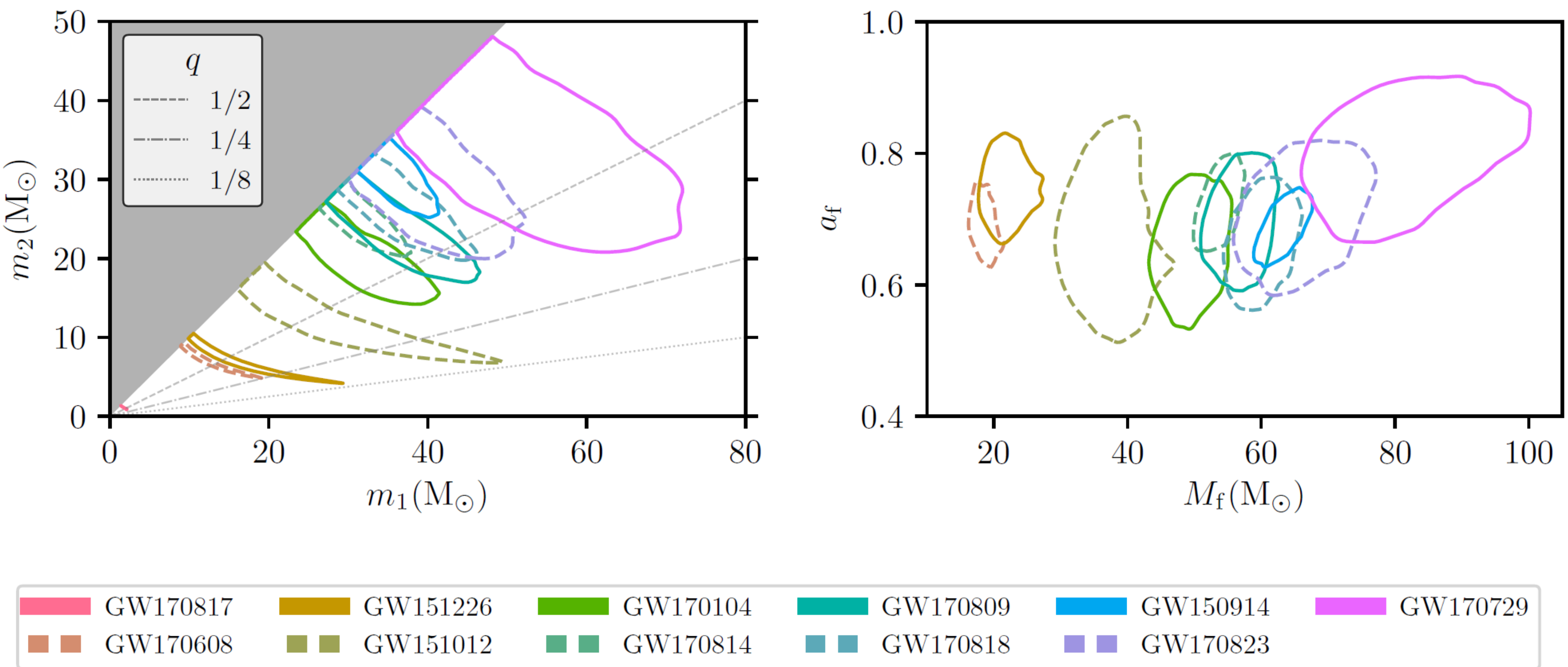
"GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs", The LIGO Virgo Collaboration, [arXiv:1811.12907](https://arxiv.org/abs/1811.12907)





Properties of black holes

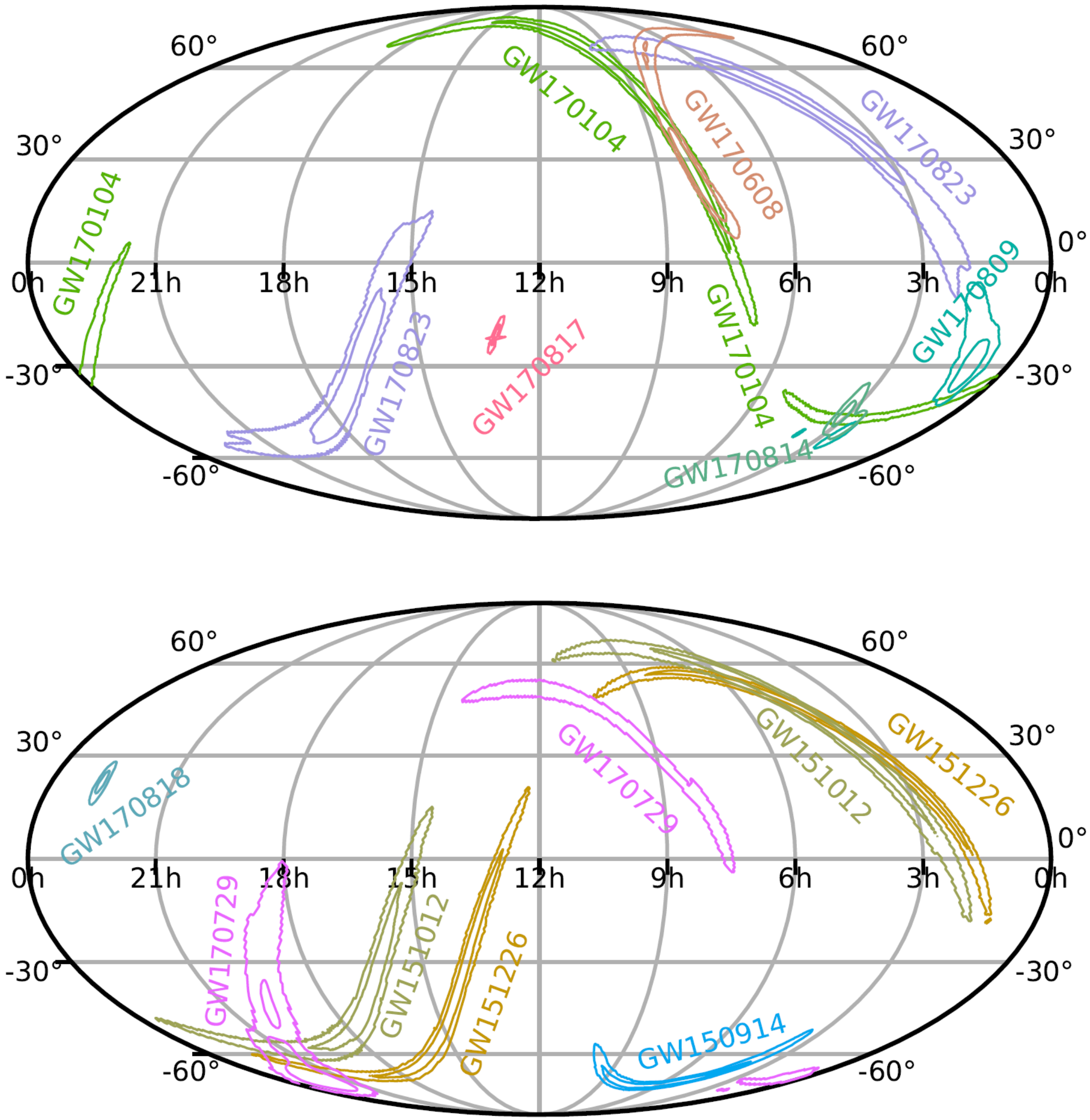
Extract information on masses, spins, energy radiated, position, distance, inclination, polarization. Population distribution may shed light on formation mechanisms



“GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs”, The LIGO Virgo Collaboration, arXiv:1811.12907

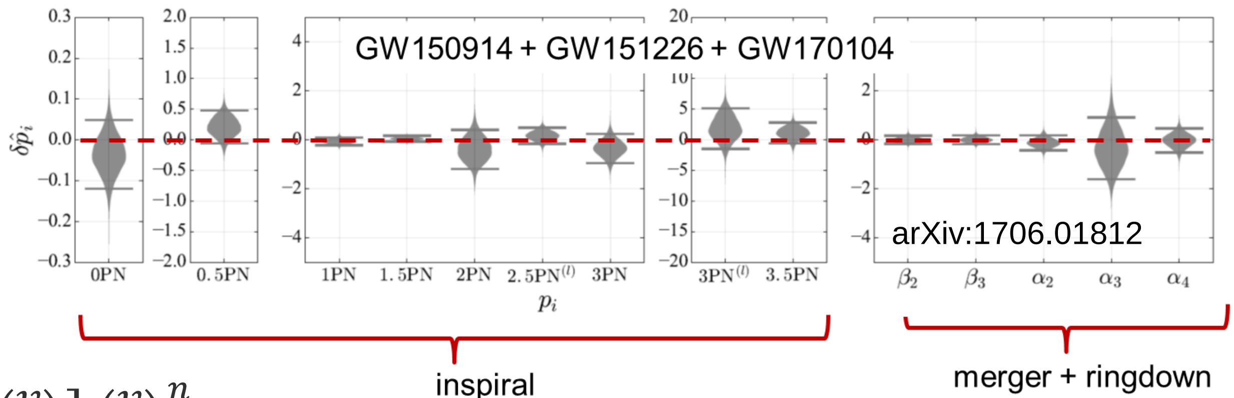
Distributed skymaps

See https://dcc.ligo.org/LIGO-G1801864



Precision tests of GR with BBH mergers

Bayesian analysis increases accuracy on parameters by combining information from multiple events



Inspiral and PN expansion

Inspiral PN and logarithmic terms:
Sensitive to GW back-reaction, spin-orbit, spin-spin couplings, …

Orbital phase (post Newtonian expansion): $h^{\alpha\beta}(f) = h^{\alpha\beta} e^{i\Phi(f)}$

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

Merger terms: numerical GR

Ringdown terms: quasi-normal modes; do we see Kerr black holes?

Towards high precision tests of gravity

Combining information from multiple events and having high-SNR events will allow unprecedented tests of GR and other theories of gravity

Our collaborations set ambitious goals for the future

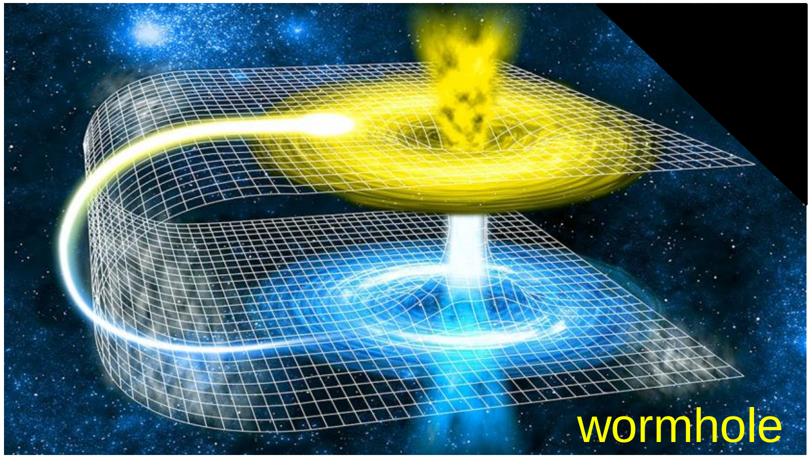
We need to improve:

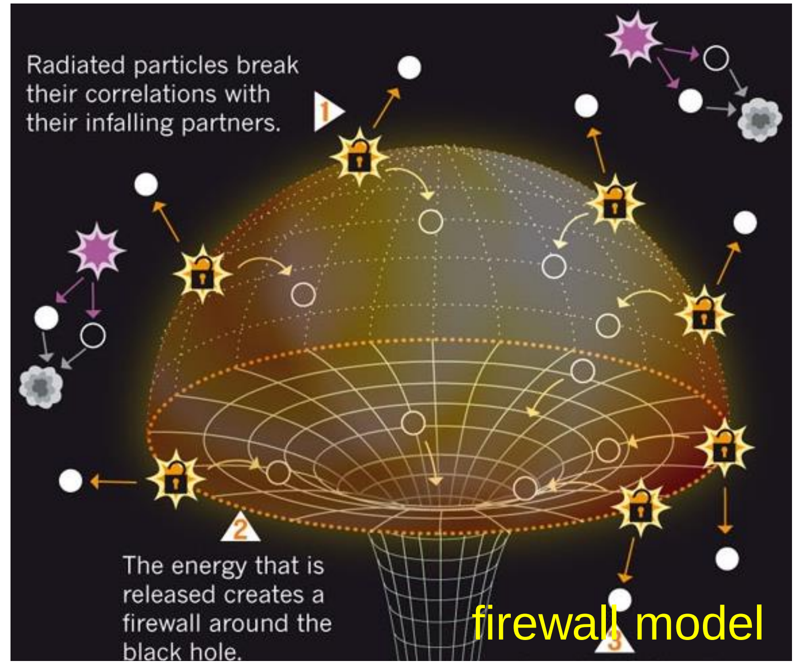
- sensitivity of our instruments over the entire frequency range
- optimize our computing and analysis
- improve our source modeling (NR)

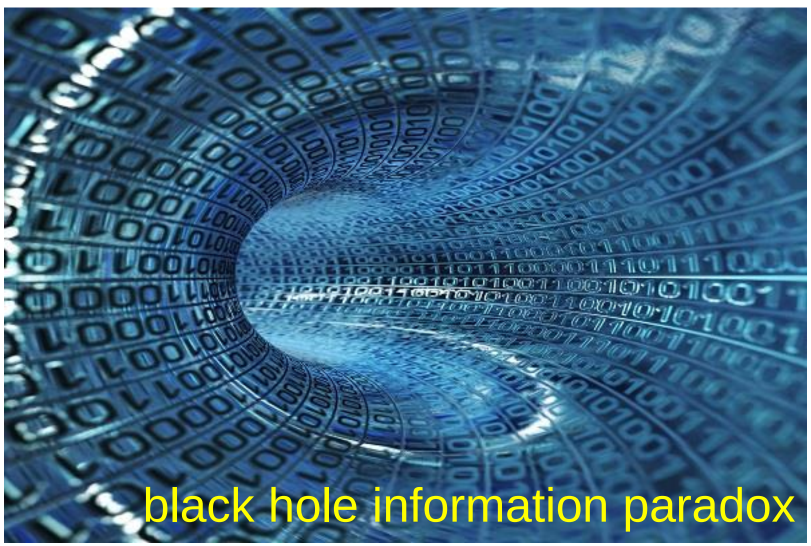
So far, results are in agreement with GR

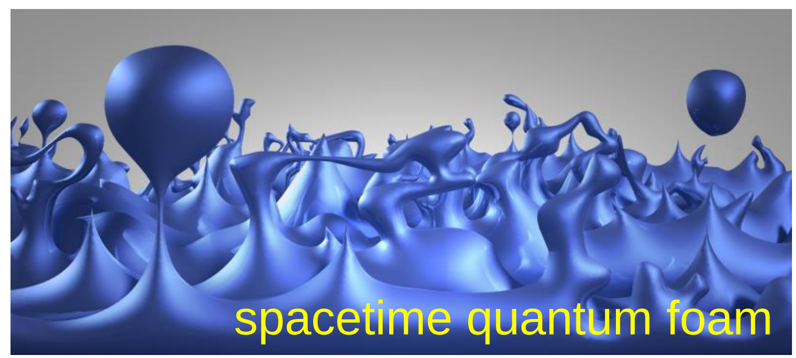
Fundamental physics: did we observe black holes?

Our theories "predict" the existence of other objects, such as quantum modifications of GR black holes, boson stars, gravastars, firewalls, *etc*. Why do we believe we have seen black holes?



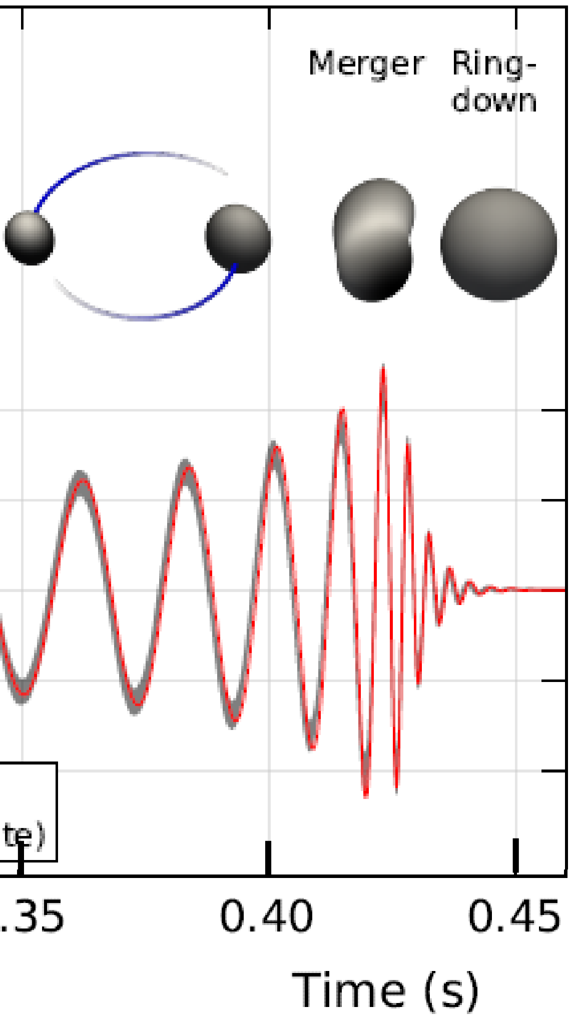


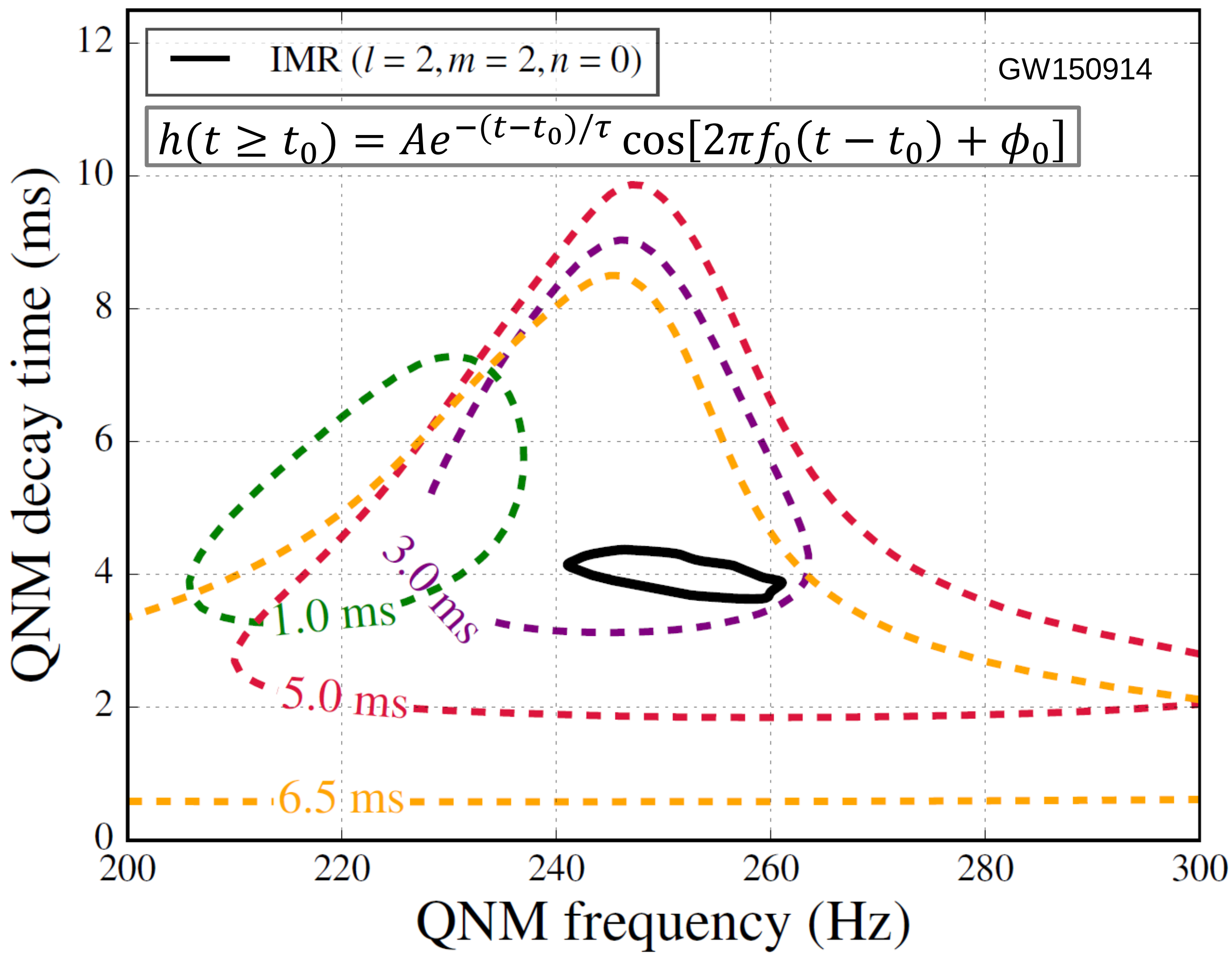




Is a black hole created in the final state?

From the inspiral we can predict that the ringdown frequency of about 250 Hz and 4 ms decay time. This is what we measure (http://arxiv.org/abs/1602.03841). We will pursue this further and perform test of the no-hair theorem





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

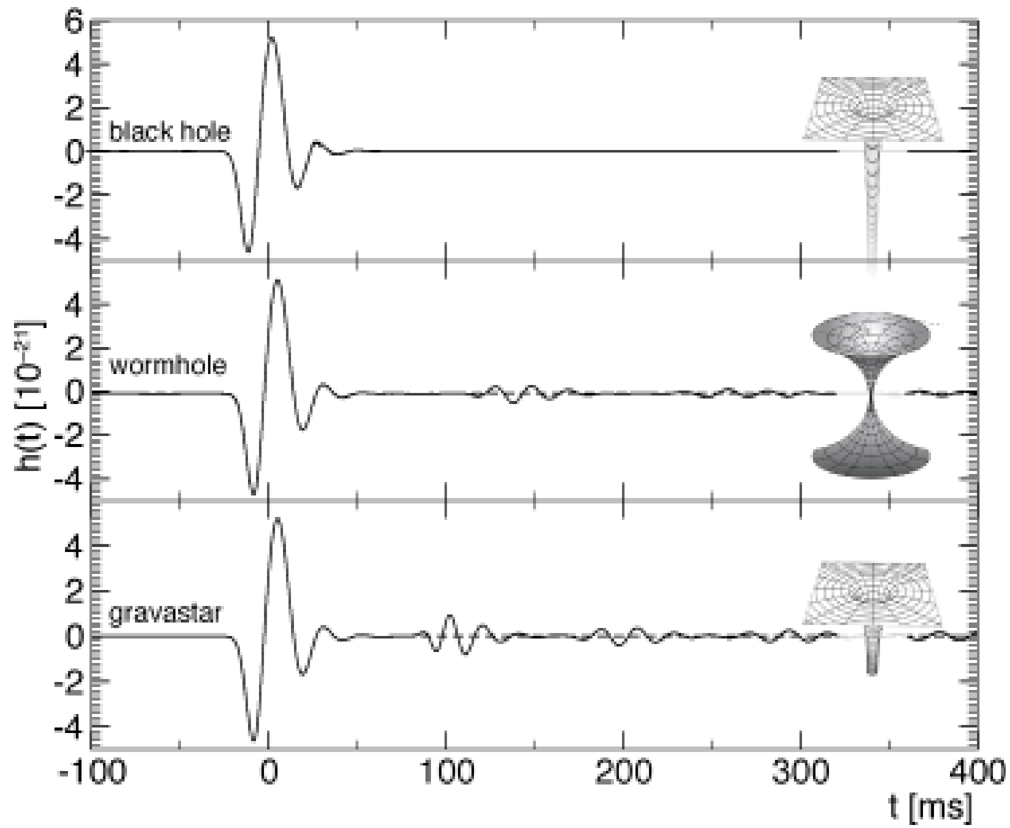
- Dark matter stars

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



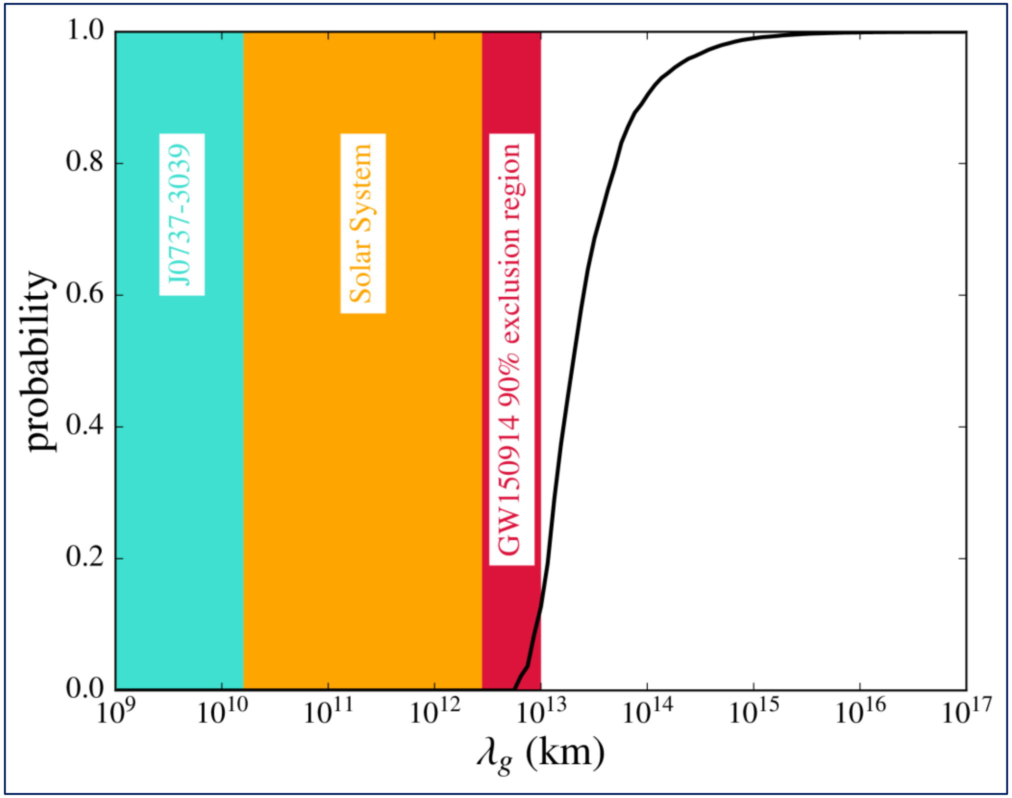
Cardoso et al. PRD 94, 084031 (2016)

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 $E^2 = p^2c^2 + m_g^2c^4$

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

Thus frequency dependent speed

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

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

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

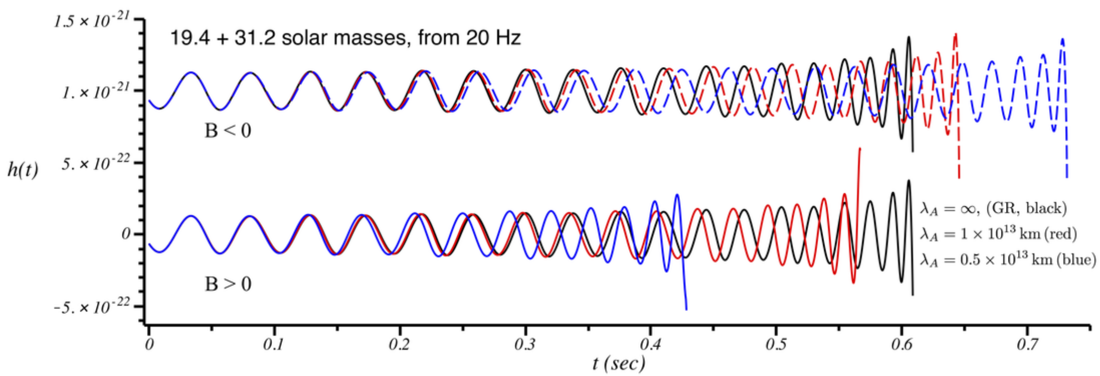
See "*Tests of general relativity with GW150914*"
http://arxiv.org/abs/1602.03841

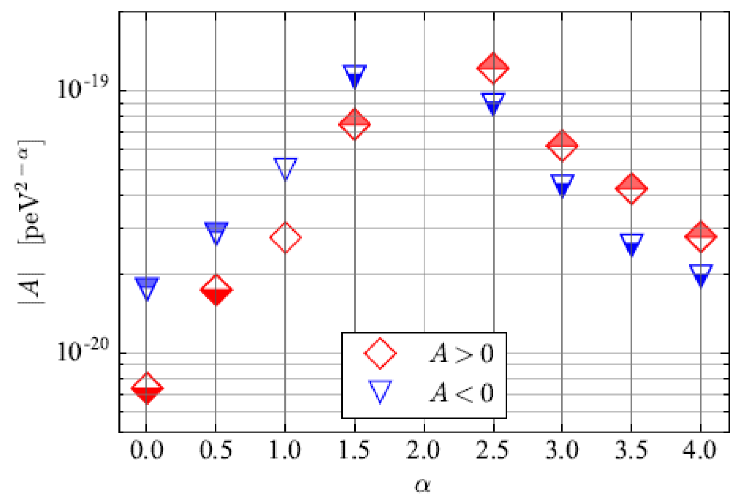
Bounds on violation of Lorentz invariance

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
$$\delta\Psi = \begin{cases} \frac{\pi}{\alpha-1}\frac{AD_\alpha}{(hc)^{2-\alpha}}\left[\frac{(1+z)f}{c}\right]^{\alpha-1} & \alpha \neq 1 \\ \frac{\pi AD_\alpha}{hc}\ln\left(\frac{\pi G\mathcal{M}^{det}f}{c^3}\right) & \alpha = 1 \end{cases} \qquad A \cong \pm\frac{MD_\alpha}{\lambda_A^2}$$





Abbott et al. PRL 118, 221101 (2017)

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)

The Virgo detector joins LIGO in August 2017

Advanced Virgo

Virgo is a European collaboration with more than 300 members

Advanced Virgo (AdV): upgrade of the Virgo interferometric detector

Participation by scientists from France, Italy, Belgium, The Netherlands, Poland, Hungary, Spain, Germany

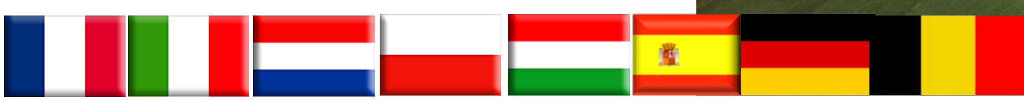
- 24 laboratories, about 280 authors
  - APC Paris
  - ARTEMIS Nice
  - EGO Cascina
  - IFAE Barcelona
  - INFN Firenze-Urbino
  - INFN Genova
  - INFN Napoli
  - INFN Perugia
  - INFN Pisa
  - INFN Roma La Sapienza
  - INFN Roma Tor Vergata
  - INFN Trento-Padova
  - LAL Orsay – ESPCI Paris
  - LAPP Annecy
  - LKB Paris
  - LMA Lyon
  - Nikhef Amsterdam
  - POLGRAW(Poland)
  - RADBOUD Uni. Nijmegen
  - RMKI Budapest
  - UCLouvain
  - ULiege
  - Univ. of Barcelona
  - Univ. of Valencia
  - University of Jena

Advanced Virgo project has been formally completed on July 31, 2017

Part of the international network of 2nd generation detectors

Joined the O2 run on August 1, 2017

8 European countries

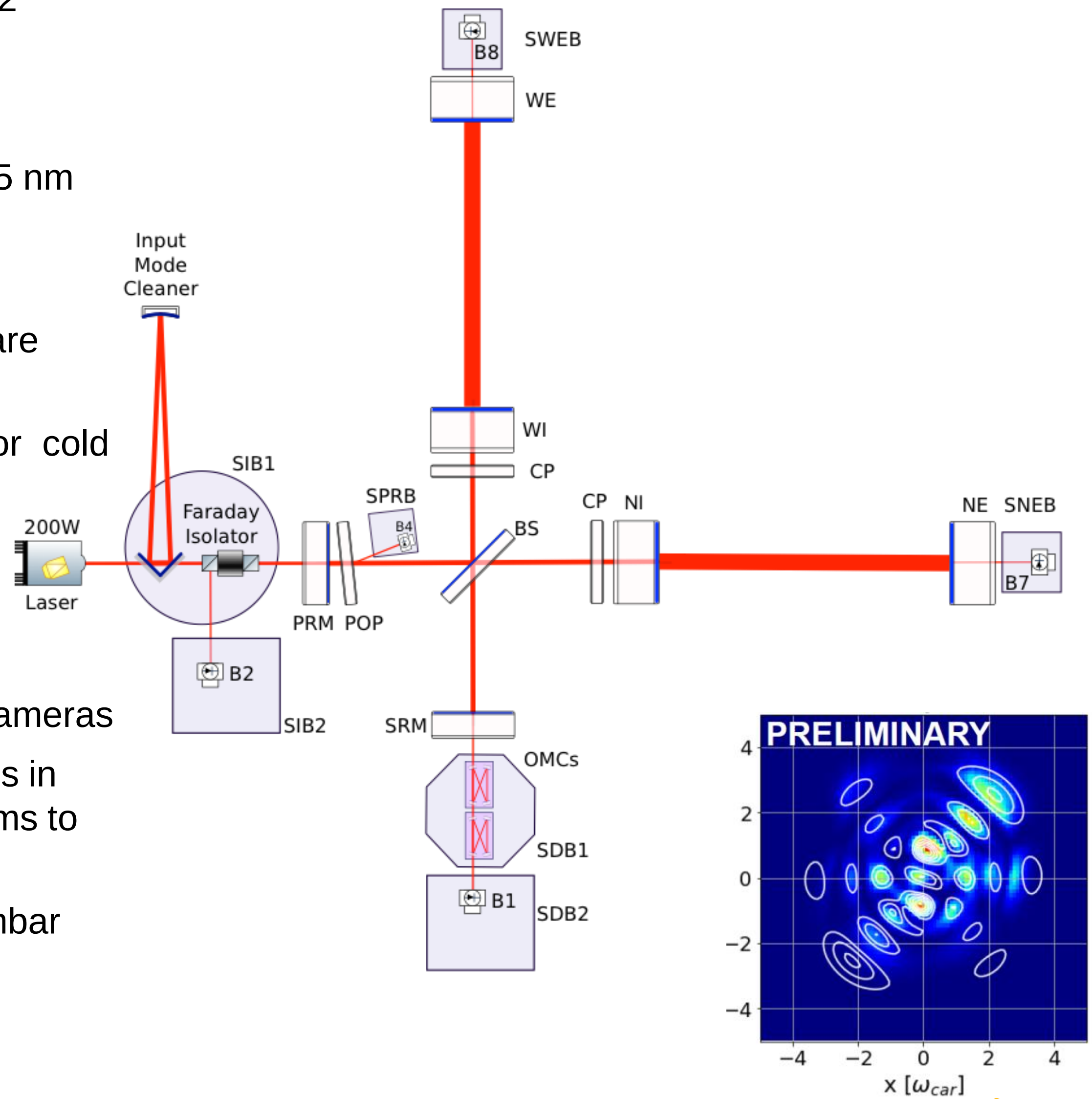


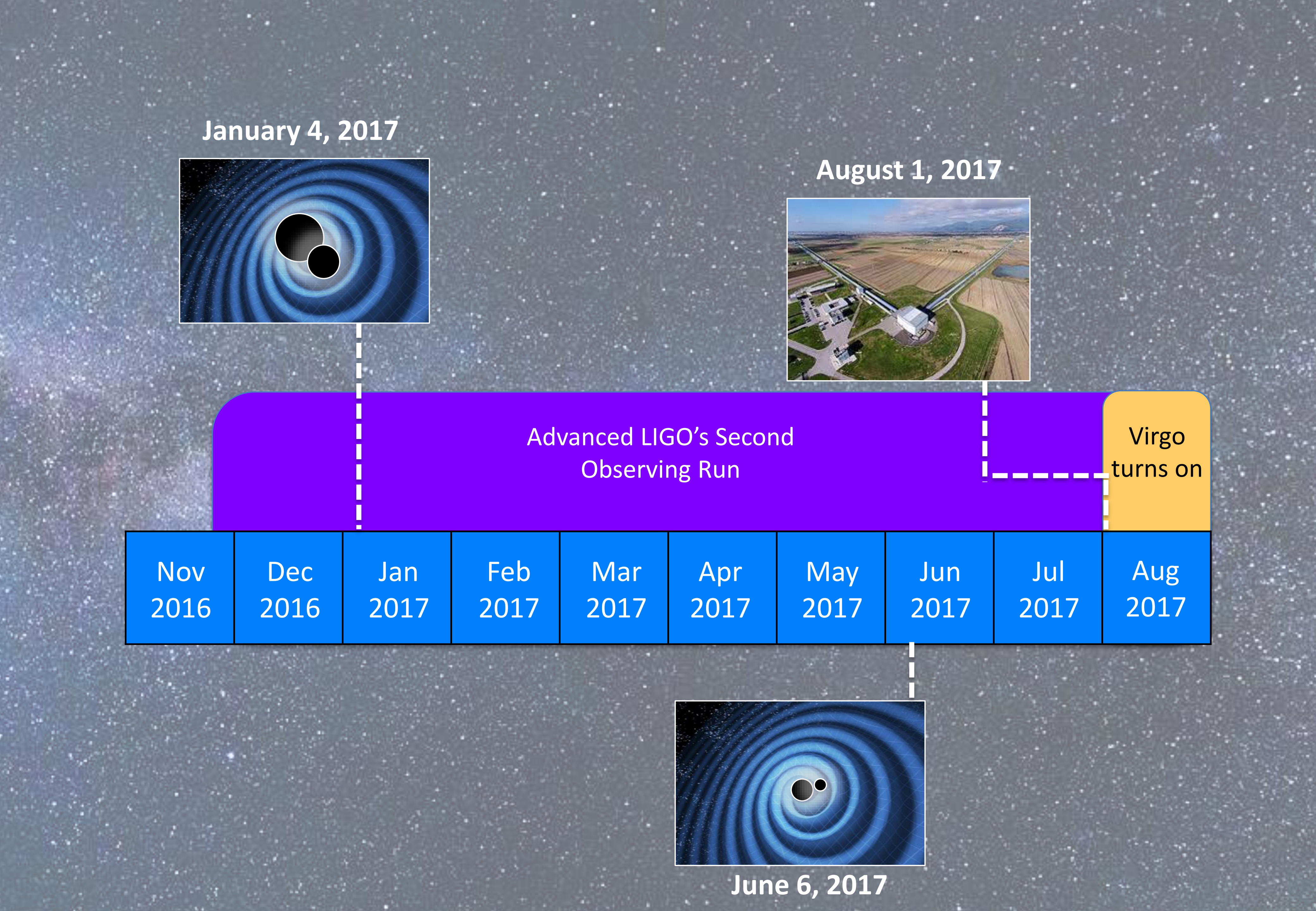
Advanced Virgo

Advanced Virgo started operation on August 1, 2017. It features many improvements with respect to Virgo and Virgo+

Instrumentation improvements for Observing run 2

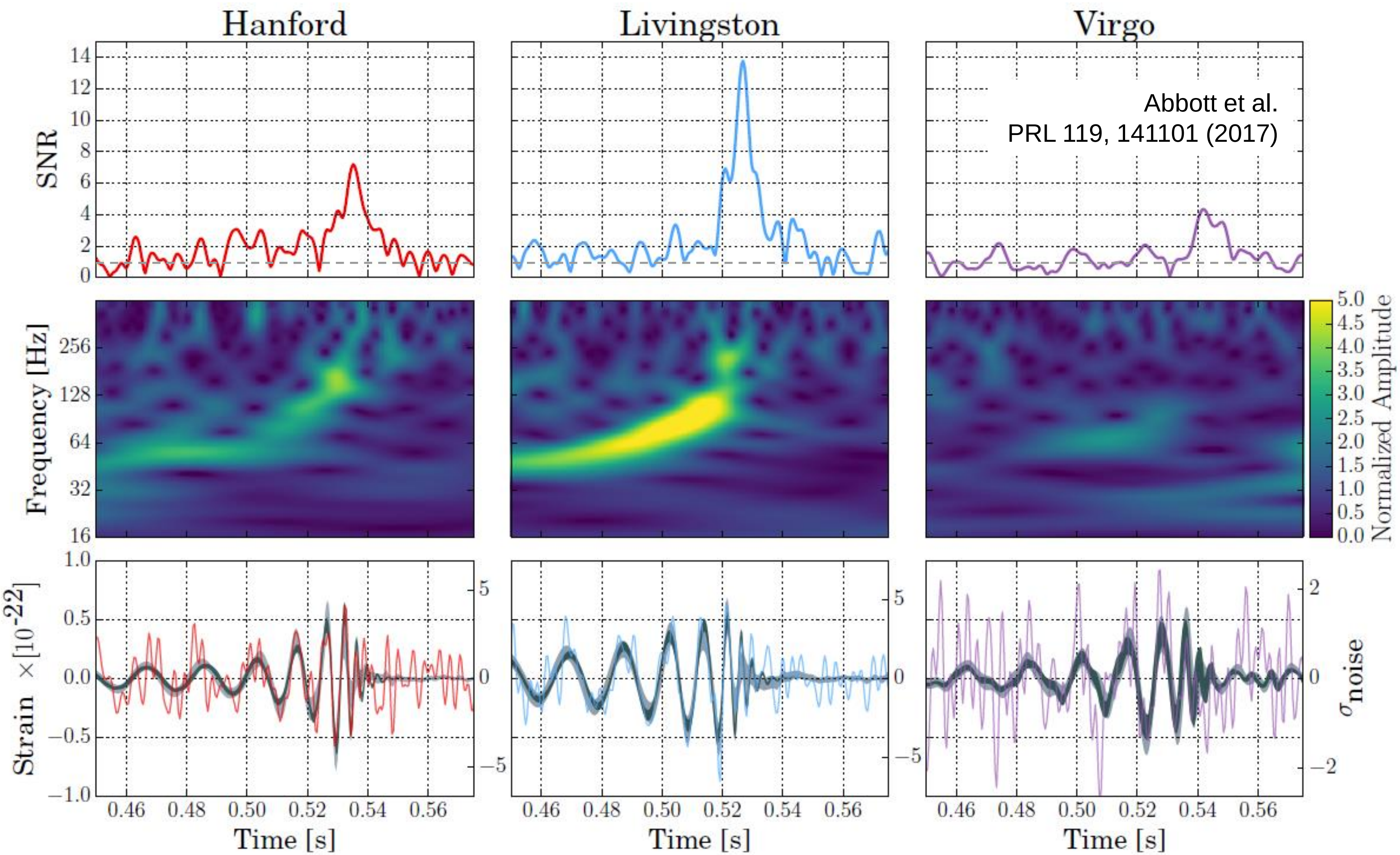
- Larger beam: 2.5x larger at ITMs
- Heavier mirrors: 2x heavier
- Higher quality optics: residual roughness < 0.5 nm
- Improved coatings for lower losses: absorption < 0.5 ppm, scattering < 10 ppm
- Reducing shot noise: arm finesse of cavities are 3 x larger than in Virgo+
- Thermal control of aberrations: compensate for cold and hot defects on the core optics:
  - ring heaters
  - double axicon CO_2 actuators
  - CO_2 central heating
  - diagnostics: Hartmann sensors & phase cameras
- Stray light control: suspended optical benches in vacuum, and new set of baffles and diaphragms to catch diffuse light
- Improved vacuum: 10^{-9} mbar instead of 10^{-7} mbar




January 4, 2017
August 1, 2017
Advanced LIGO's Second Observing Run
Virgo turns on
Nov 2016
Dec 2016
Jan 2017
Feb 2017
Mar 2017
Apr 2017
May 2017
Jun 2017
Jul 2017
Aug 2017
June 6, 2017

First triple detection by Virgo and LIGO

August 14, 2017 three detectors observed BBH. Initial black holes were 31 and 25 solar mass, while the final black hole featured 53 solar masses. About 3 solar mass radiated as pure GWs

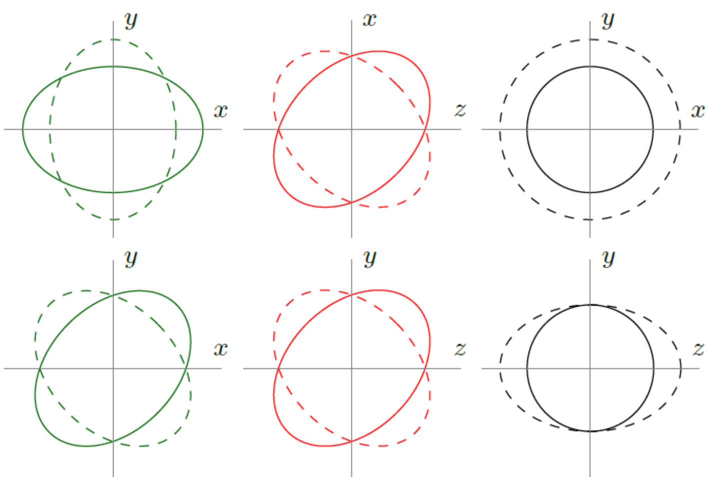


Polarization of gravitational waves

Polarization is a fundamental property of spacetime. It determined how spacetime can be deformed. General metric theories allow six polarizations. General Relativity allows two (tensor) polarizations

GR only allows (T) polarizations

General metric theories also know vector (V) and scalar (S) polarizations



Theory	+	x	x	y	b	l
General Relativity	allowed	allowed	forbidden	forbidden	forbidden	forbidden
GR in noncompactified 4/6D Minkowski	allowed	allowed	allowed	allowed	allowed	allowed
Einstein-Æther	allowed	allowed	allowed	allowed	allowed	allowed
5D Kaluza-Klein	allowed	allowed	allowed	allowed	allowed	forbidden
Randall-Sundrum braneworld	allowed	allowed	forbidden	forbidden	forbidden	forbidden
Dvali-Gabadadze-Porrati braneworld	allowed	allowed	depends	depends	depends	depends
Brans-Dicke	allowed	allowed	forbidden	forbidden	allowed	allowed
f(R) gravity	allowed	allowed	forbidden	forbidden	allowed	allowed
Bimetric theory	allowed	allowed	allowed	allowed	allowed	allowed
Four-Vector Gravity	forbidden	forbidden	allowed	allowed	forbidden	forbidden

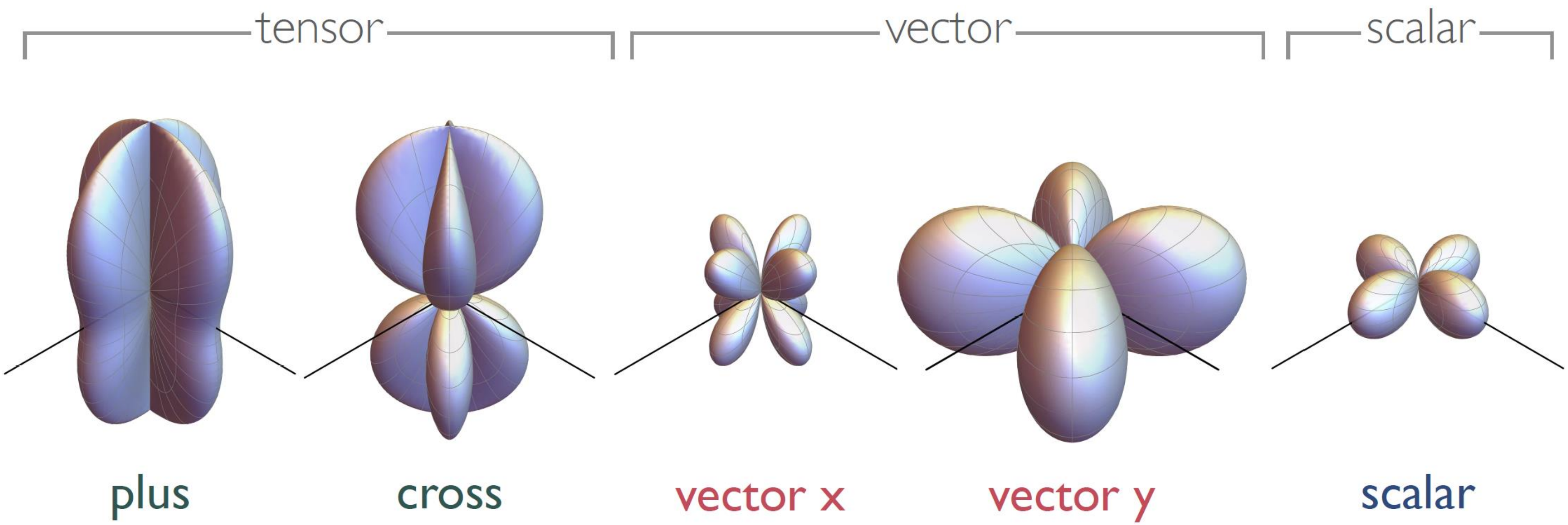
Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther]. allowed / depends / forbidden

First test of polarizations of gravitational waves

According to Einstein's General Relativity there exist only two polarizations. General metric theories of gravity allow six polarizations. GW170814 confirms Einstein's prediction

Angular dependence (antenna-pattern) differs for T, V, S

LIGO and Virgo have different antenna-patterns
This allows for a fundamental of the polarizations of spacetime



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This allows for a fundamental of the polarizations of spacetime

tensor vector scalar

Our analysis favors tensor polarizations in support of General Relativity

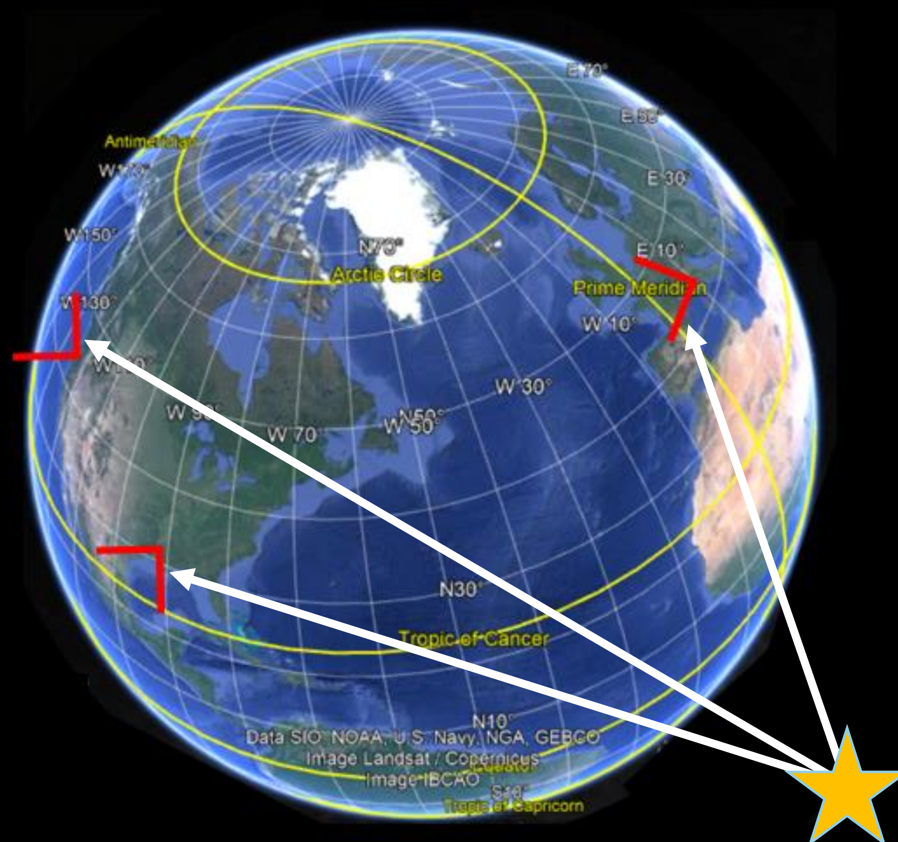
Our data favor tensor structure over vector by about a (Bayes) factor 200

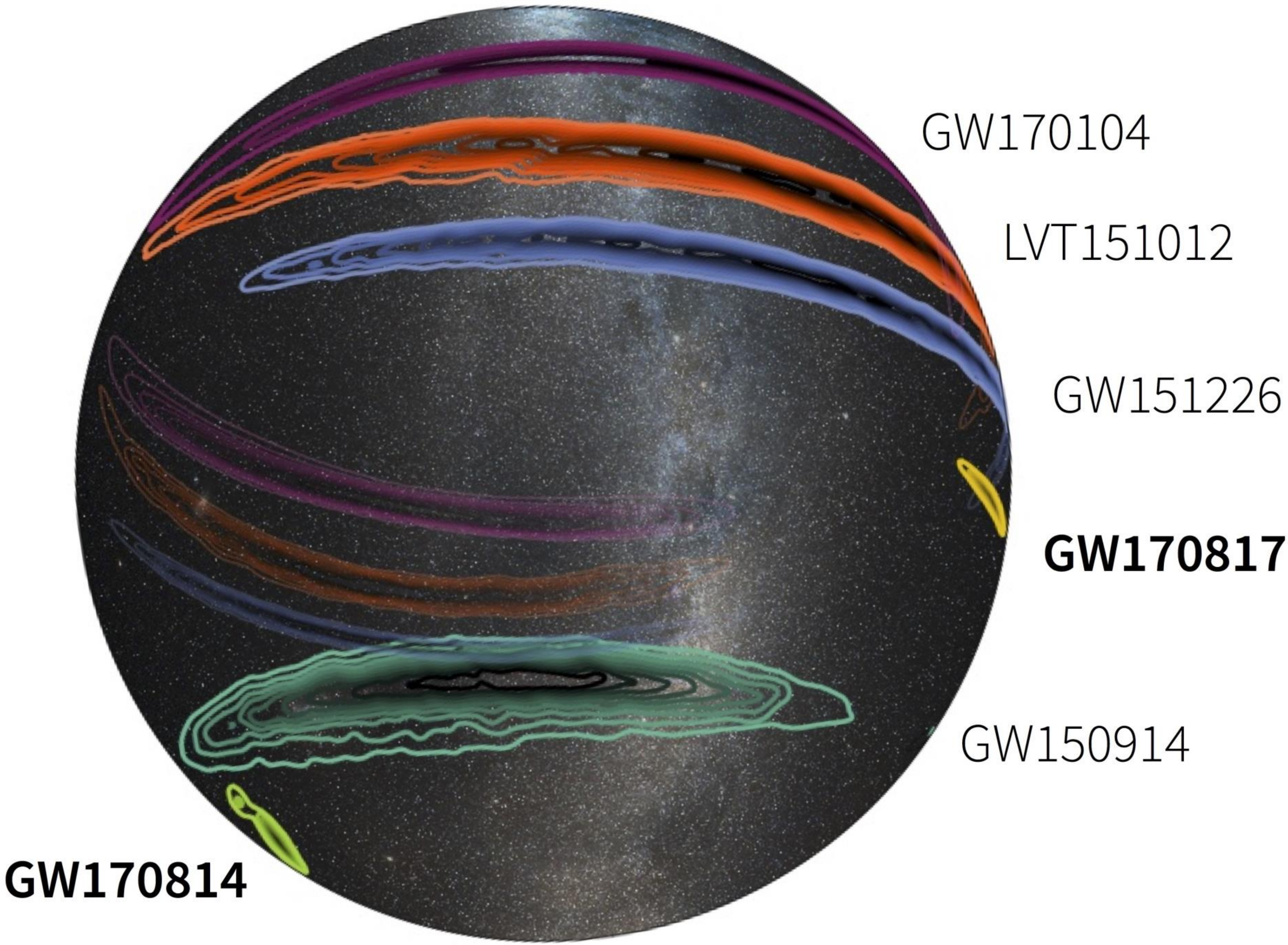
And tensor over scalar by about a factor 1000

This is a first test, and for BBH we do not know the source position very well

Virgo allowed source location via triangulation

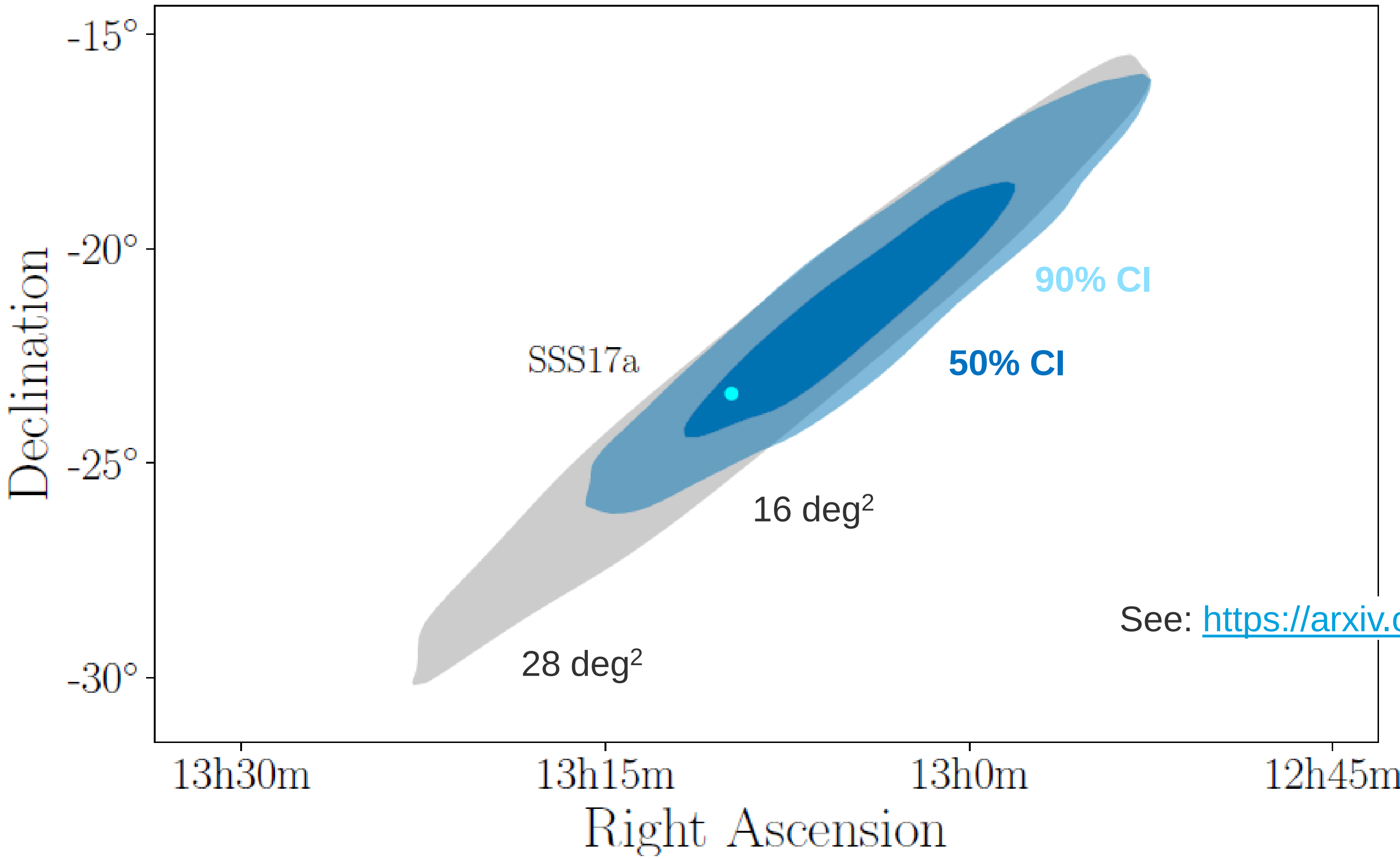
GW170817 first arrived at Virgo, after 22 ms it arrived at LLO, and another 3 ms later LLH detected it




GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814

Localization by Virgo and LIGO

Improved localization of GW170817, with the location of the associated counterpart SSS17a/AT 2017gfo has been obtained. The darker and lighter blue shaded regions correspond to 50% and 90% credible regions respectively, and the gray shaded region shows the previously derived 90% credible region presented in B. Abbott et al., PRL **119**, 161101 (2017)

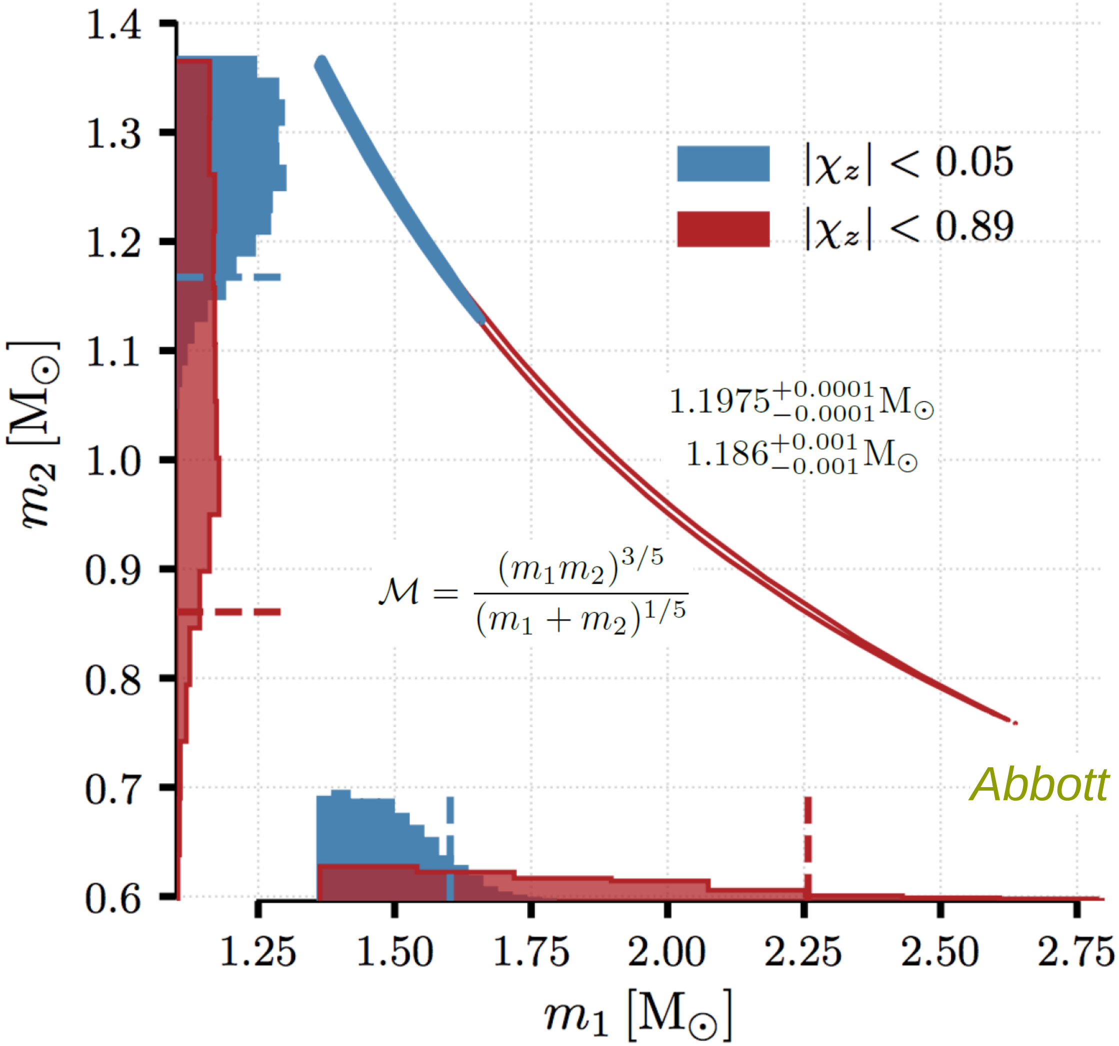


See: https://arxiv.org/abs/1805.11579

GW170817 source properties: BNS chirp mass

Chirp mass can be inferred to high precision. There is a degeneracy between masses and spins

Available rapid waveform models impose limit $|\chi_z| < 0.89$
Observation of **binary pulsars** in our galaxy indicates spins are **not larger than ~0.04**



To lowest approximation $\tilde{h}(f) \propto e^{i\Psi(f)}$

with $\Psi(f) = \frac{3}{4}\left(\frac{G\mathcal{M}}{c^3} 8\pi f\right)^{-5/3} + \ldots$

	Low-spin priors ($|\chi| \leq 0.05$)
Primary mass m_1	$1.36 - 1.60\ M_\odot$
Secondary mass m_2	$1.17 - 1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002}\ M_\odot$
Mass ratio m_2/m_1	$0.7 - 1.0$
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01}\ M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025\ M_\odot c^2$

Abbott et al. PRL 119 (2017) 161101

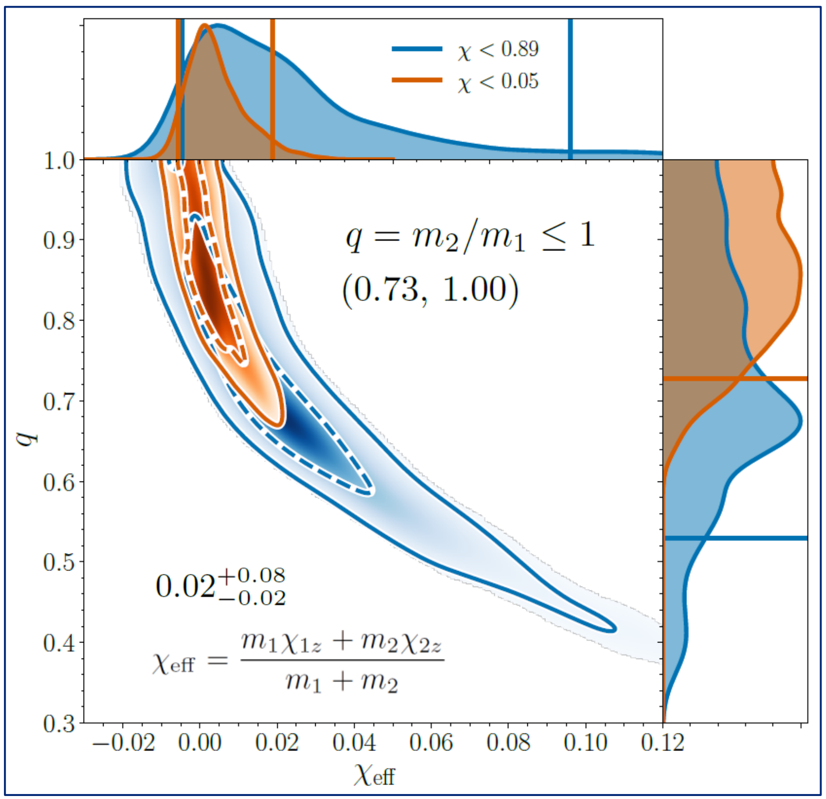
GW170817 inferred properties: spins

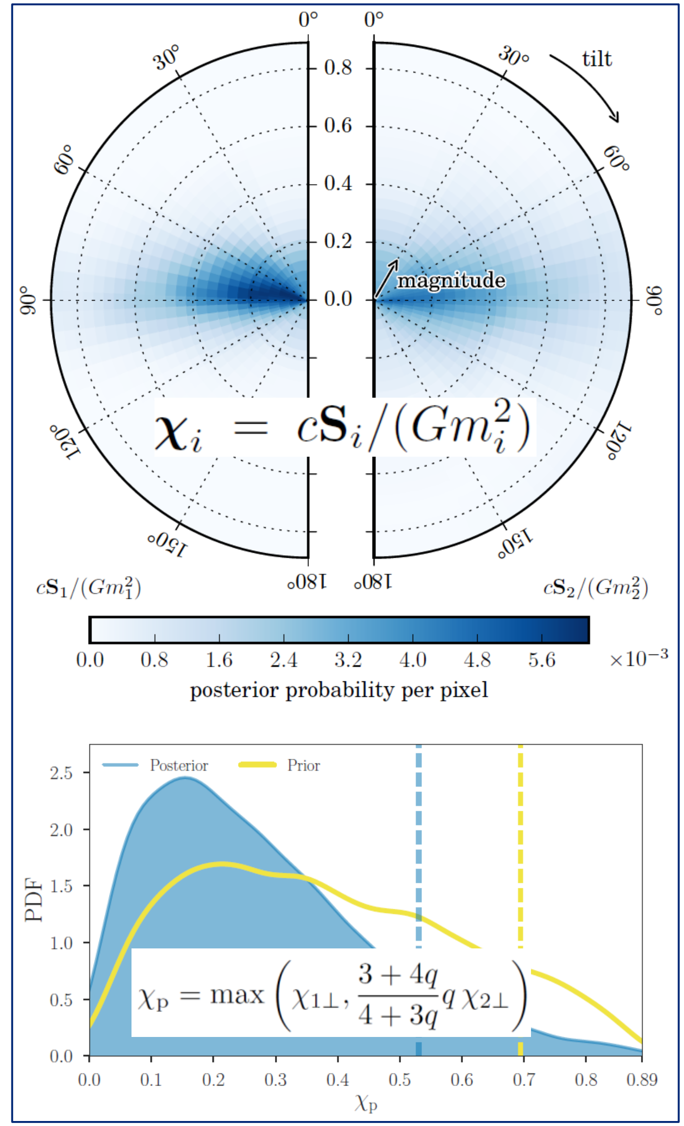
Constrains on mass ratio q, $\chi_{\rm i}$ dimensionless spin, $\chi_{\rm eff}$ effective spin, and $\chi_{\rm p}$ effective spin precession parameter. See https://arxiv.org/abs/1805.11579

No evidence for NS spin

$\chi_{\rm eff}$ contributes to GW phase at 1.5 PN, and degenerate with q

$\chi_{\rm p}$ starts contributing at 2 PN to GW phase





GW170817 properties: inclination angle

Including EM-information allows to constrain the inclination angle of the binary system

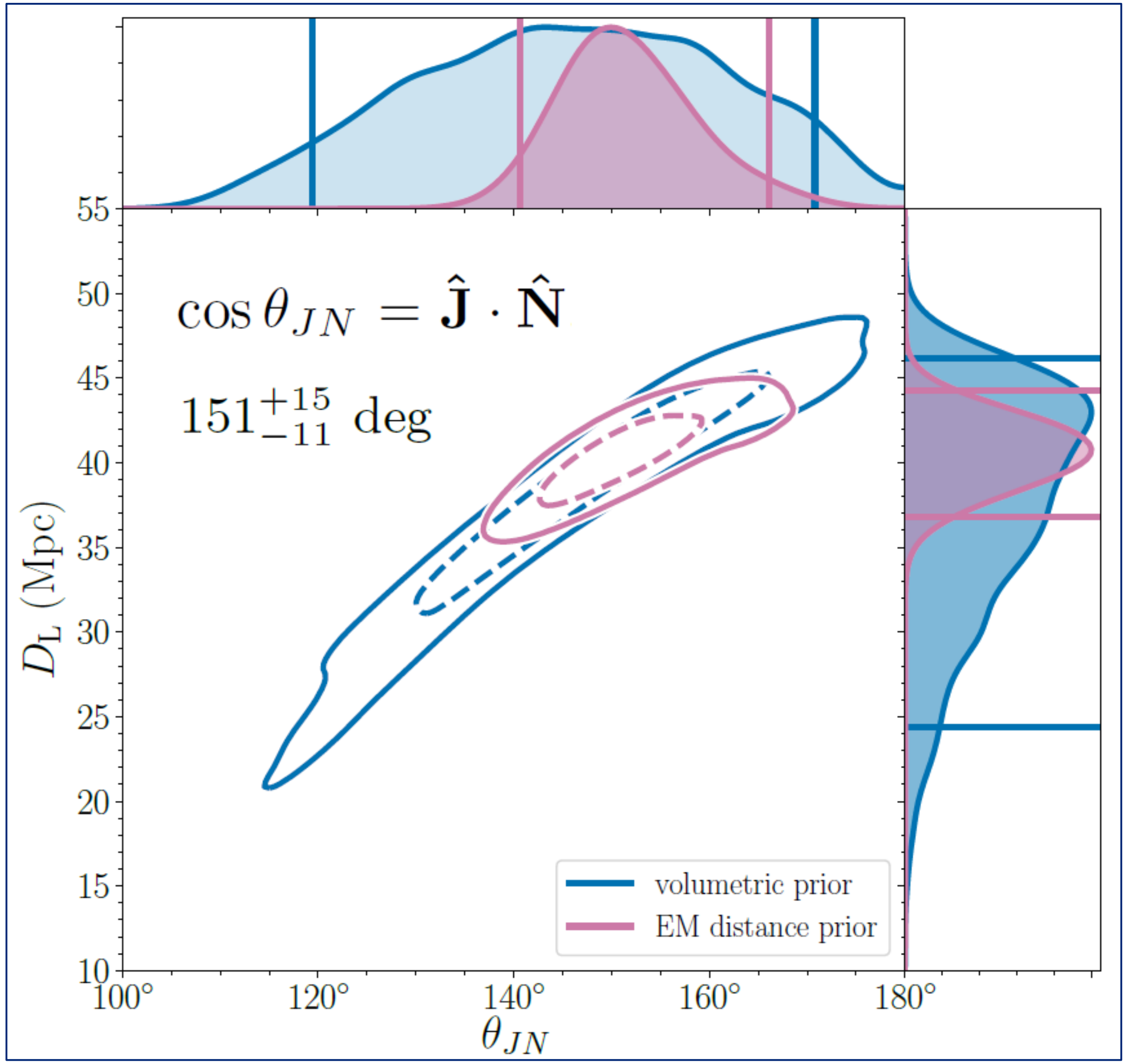
GW amplitude and polarization are dependent on binary inclination angle

Use distance prior from EM follow-up observations

Use volumetric prior from GW measurements

Line of sight vector $\hat{\boldsymbol{N}}$

Binary angular momentum vector $\hat{\boldsymbol{J}}$

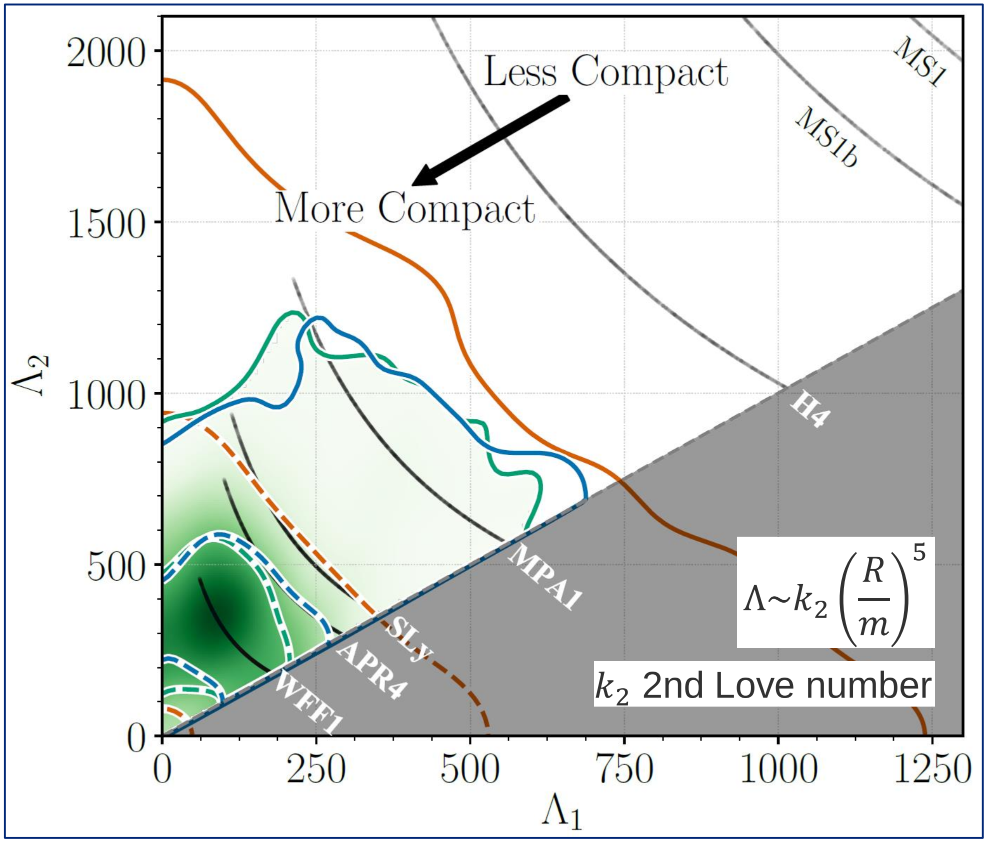


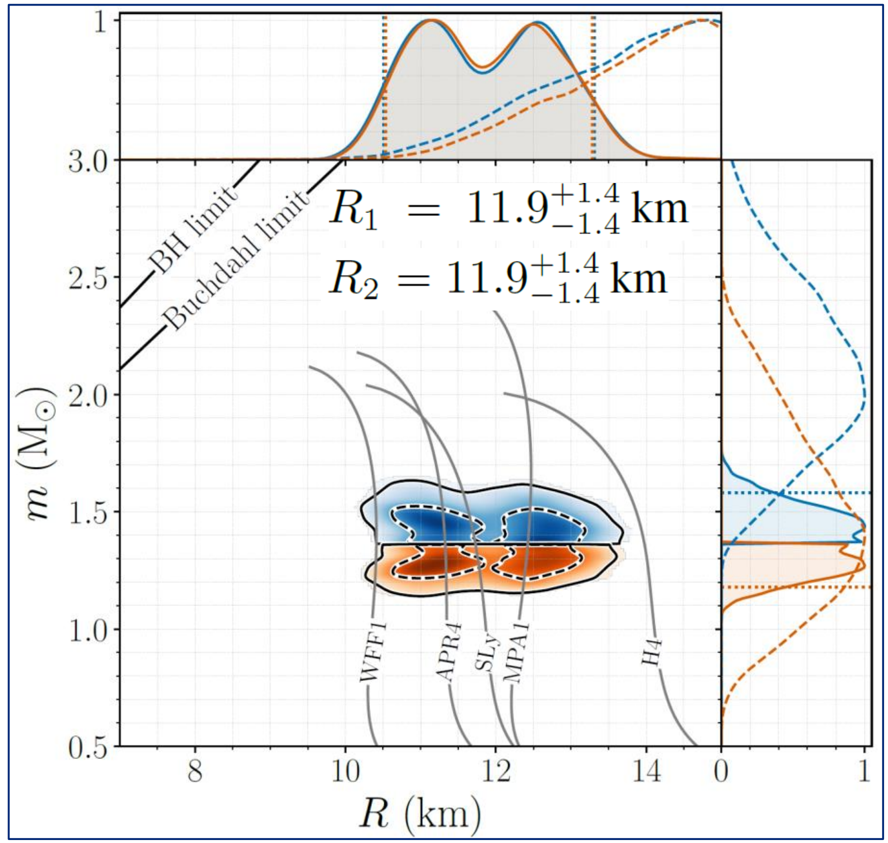
GW170817 properties: tidal deformability, EOS, radii

Tidal deformability gives support for "soft" EOS, leading to more compact NS. Various models can now be excluded. We can place the additional constraint that the EOS must support a NS $1.97\,\mathrm{M}_\odot$

Leading tidal contribution to GW phase appears at 5 PN: $\tilde{\Lambda} = \frac{16}{13}\frac{(m_1+12m_2)m_1^4\Lambda_1 + (m_2+12m_1)m_2^4\Lambda_2}{(m_1+m_2)^5}$

Employ common EOS for both NS (green shading), EOS insensitive relations (green), parametrized EOS (blue), independent EOSs (orange). See: LVC, https://arxiv.org/abs/1805.11581

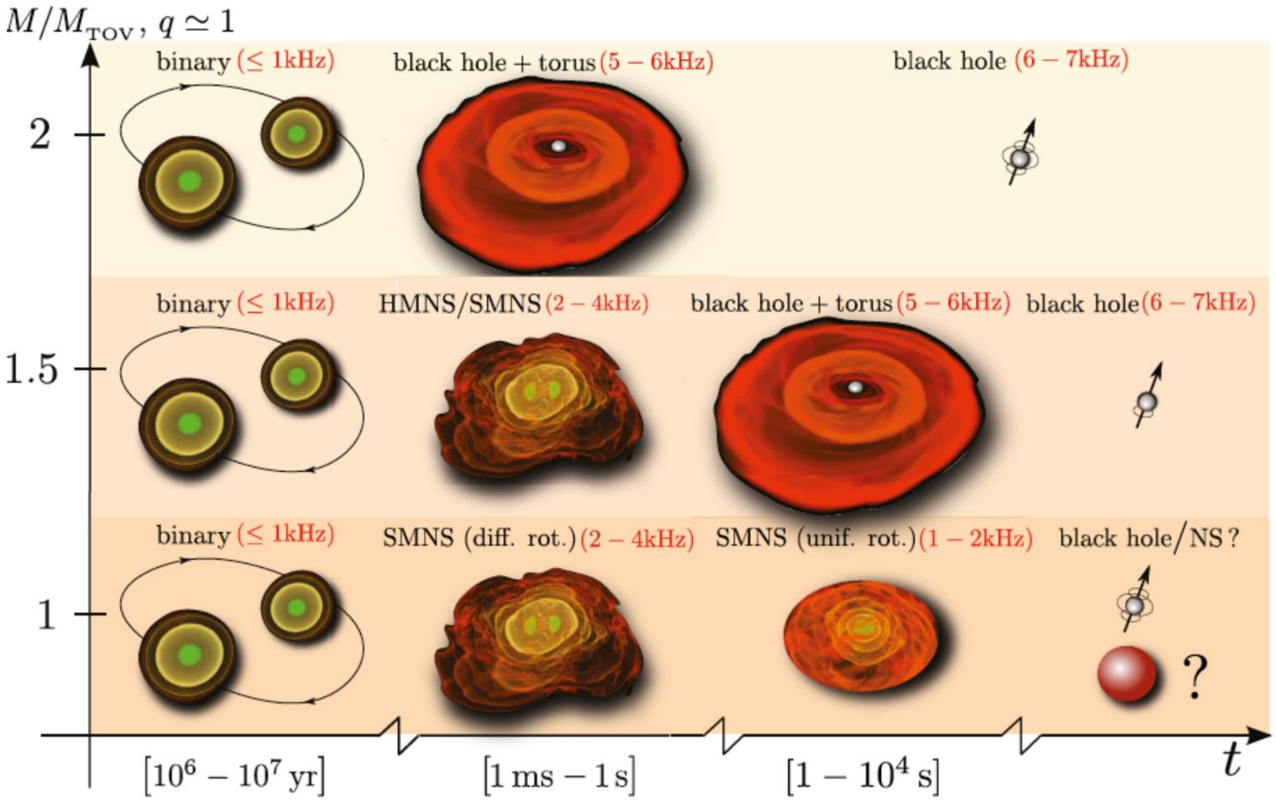




Phys. Rev. Lett., 119:161101, 2017

GW170817 properties: need high frequency sensitivity

Focus on the nuclear physics of Neutron Stars requires good sensitivity at high frequency in the range 1 to 5 kHz (thus high power interferometry)



L. Baiotti, and L. Rezzolla (2017)

Merger remnants:

Hyper-massive neutron star (HMNS) or Super-massive neutron star (SMNS)

Oscillation mode (or GW) frequency is around 2kHz - 4kHz

Encoding rich information about equation of state (EOS) of hot, dense nuclear matter

Having EM counterpart (multi-messenger observation)

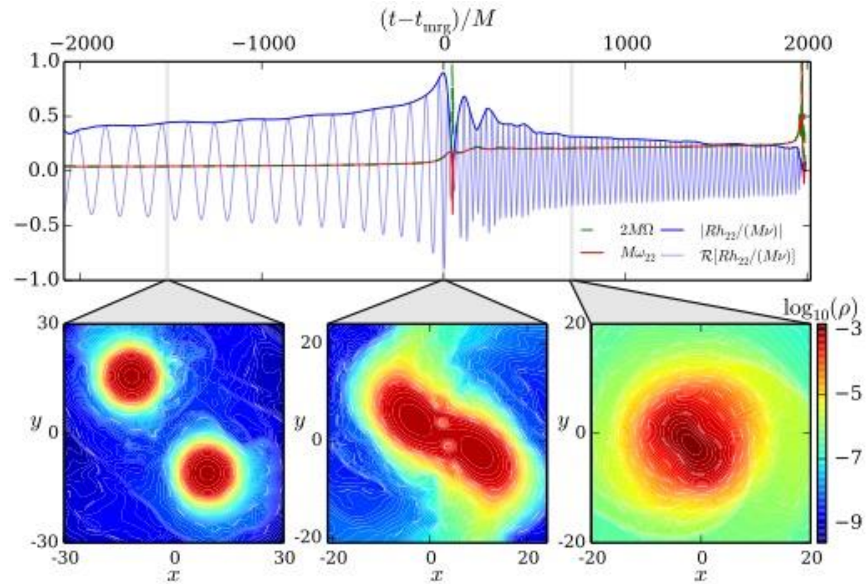
Probing the structure of neutron stars

Tidal effects leave their imprint on the gravitational wave signal from binary neutron stars. This provides information about their deformability. There is a strong need for more sensitive detectors

Gravitational waves from inspiraling binary neutron stars

- When close, the stars induce tidal deformations in each other
- These affect orbital motion
- Tidal effects imprinted upon gravitational wave signal
- Tidal deformability maps directly to neutron star equation of state

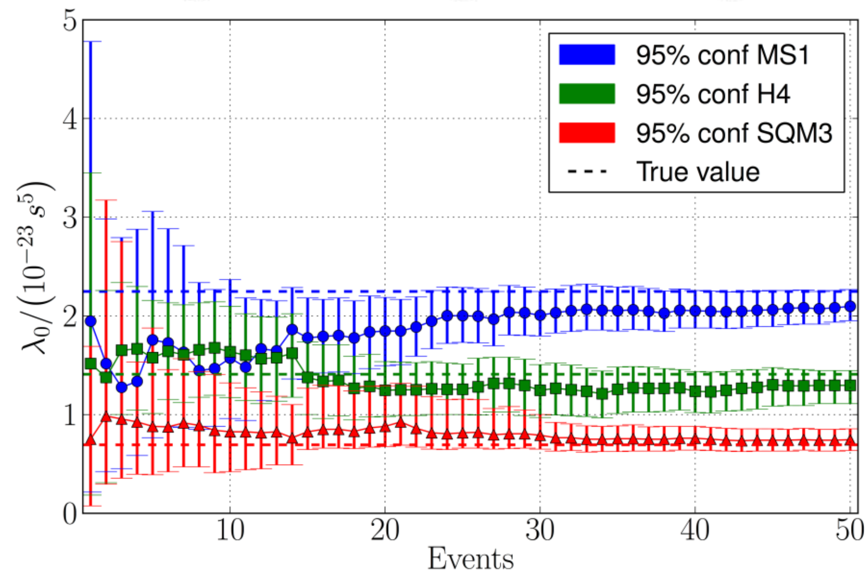
Bernuzzi et al. PRL 115, 091101 (2015)



Measurement of tidal deformations on GW170817

- More compact neutron stars favored
- “Soft” equation of state
- See LVC, https://arxiv.org/abs/1805.11581
- LVC, PRL 119, 161101 (2017)

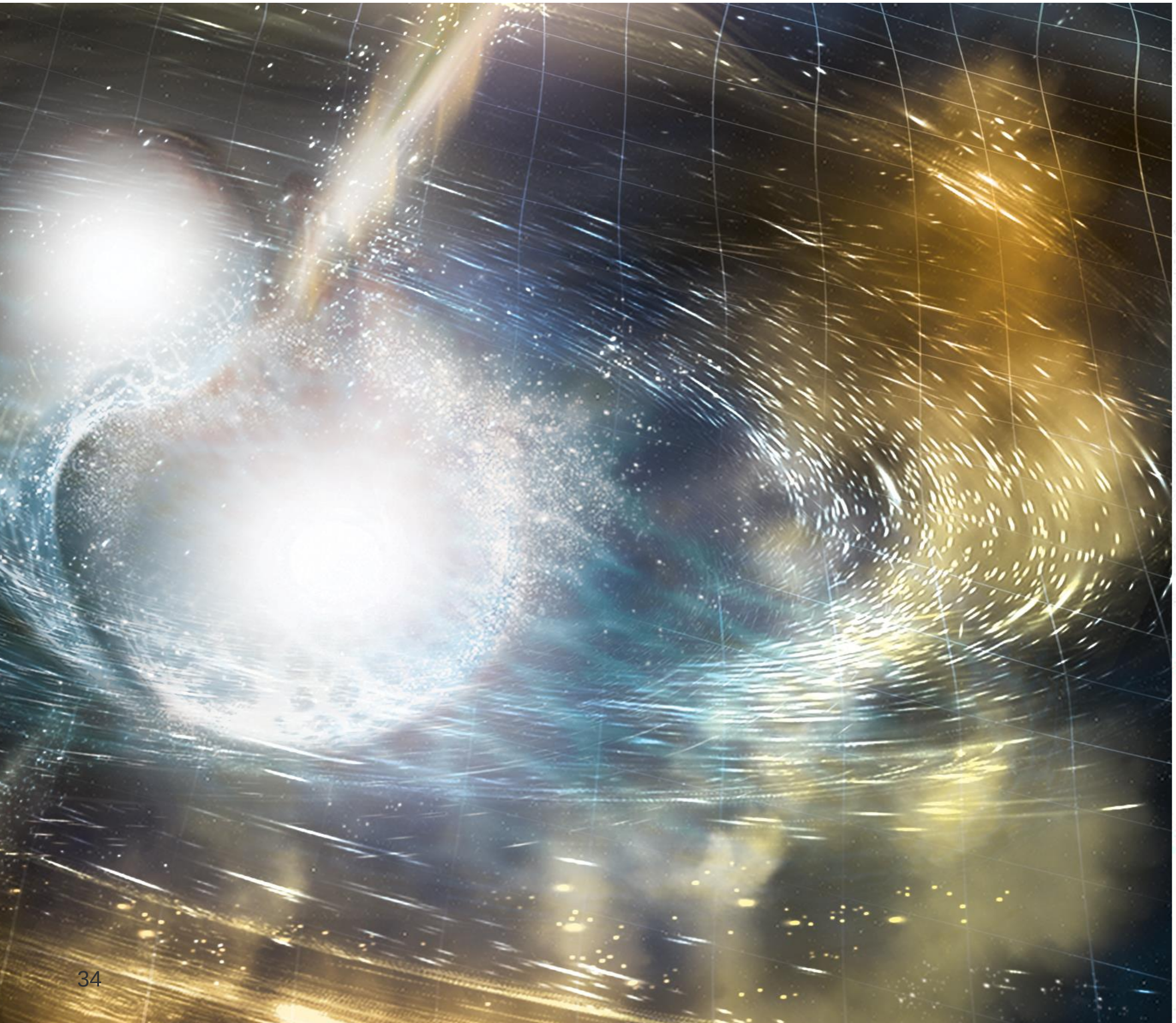
Agathos et al. PRD 92, 023012 (2015)

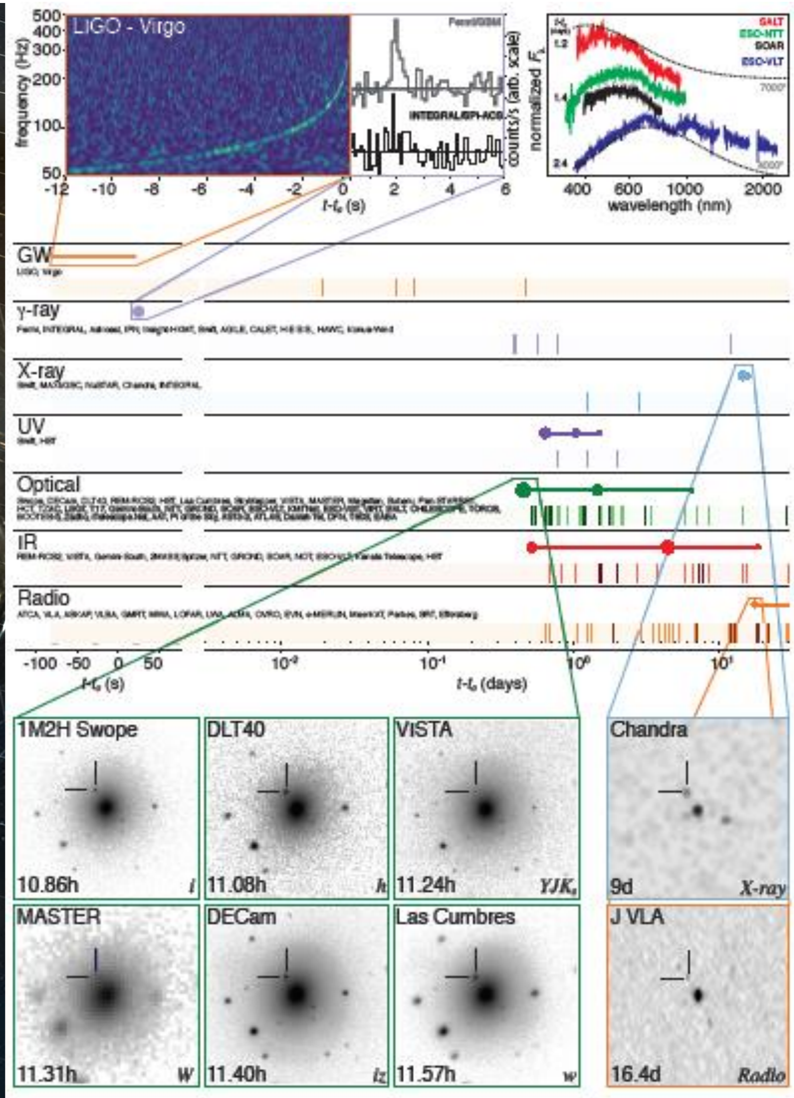


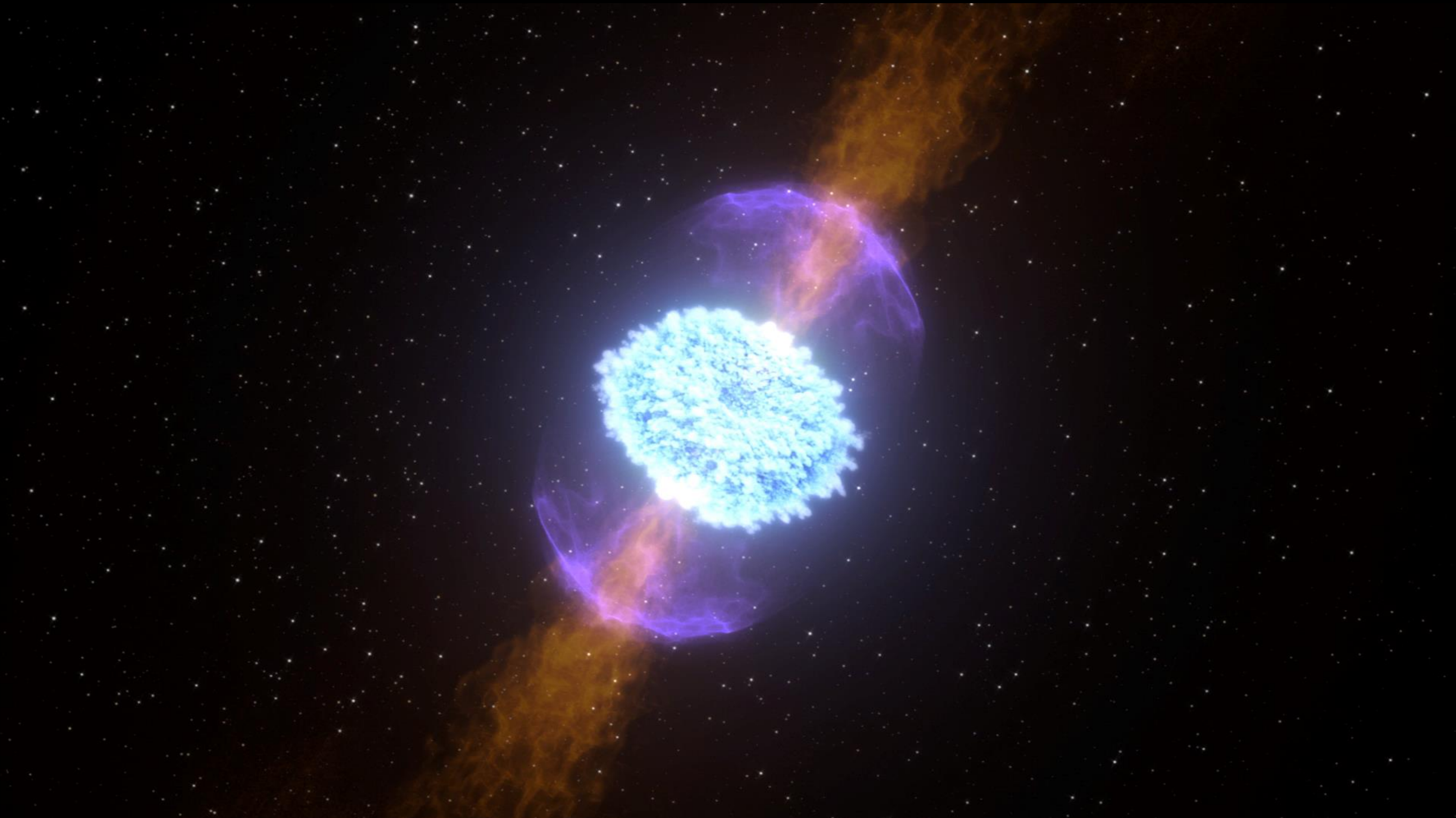
GW170817: start of multi-messenger astronomy with GW

Many compact merger sources emit, besides gravitational waves, also light, gamma- and X-rays, and UV, optical, IR, and radio waves, as well as neutrino's or other subatomic particles. Our three-detector global network allows identifying these counterparts

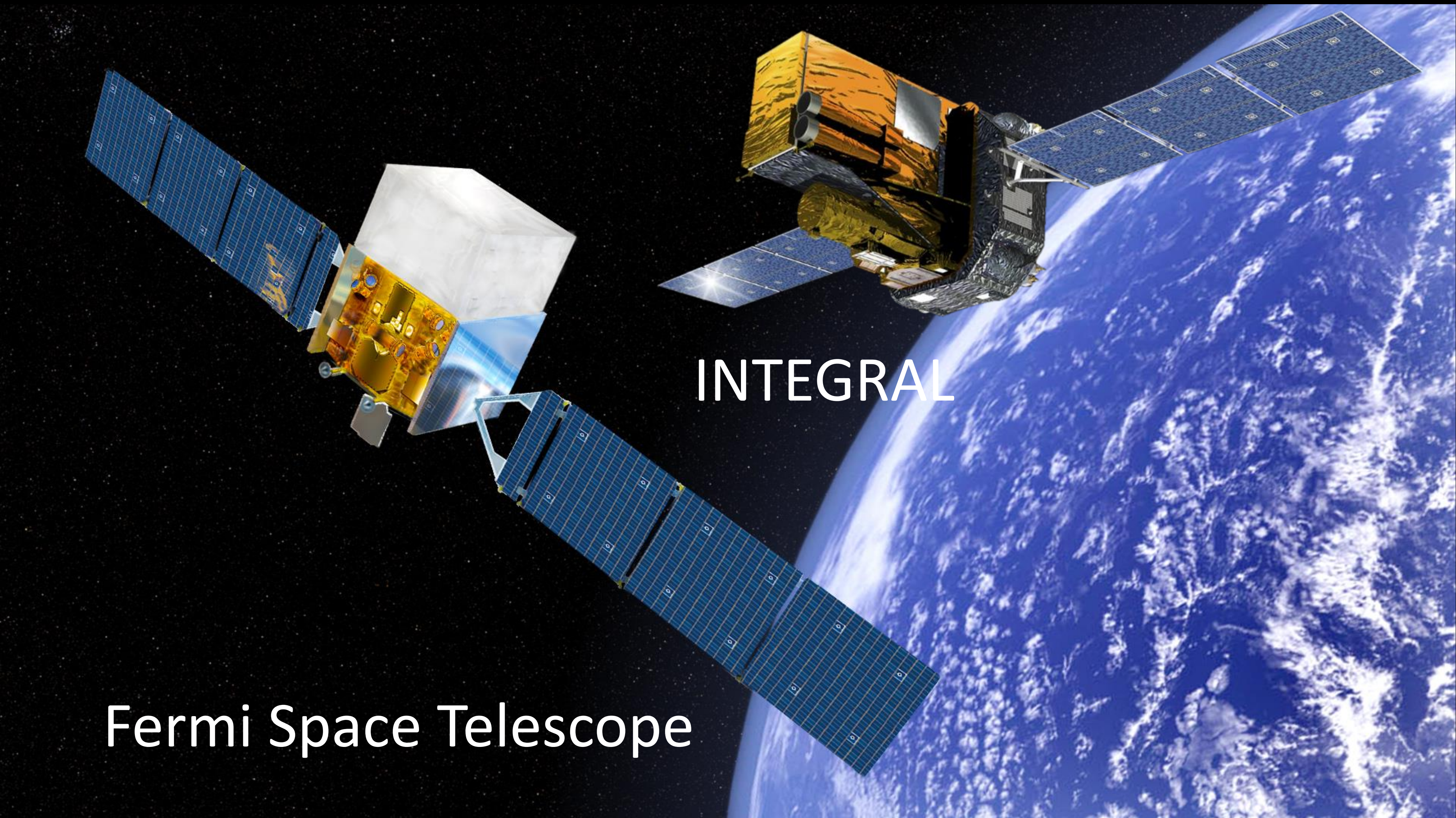
Abbott et al. APJL, 848:L12 (2017)







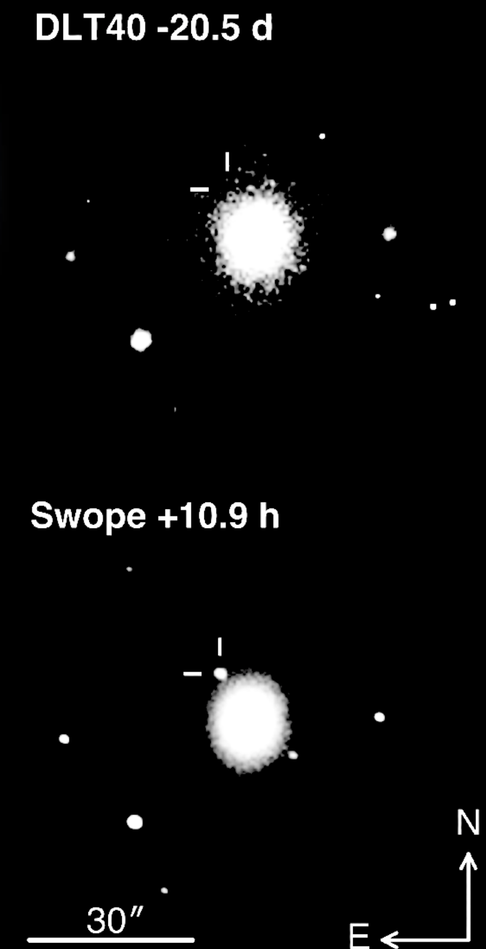
Gamma rays reached Earth 1.7 seconds after GW event

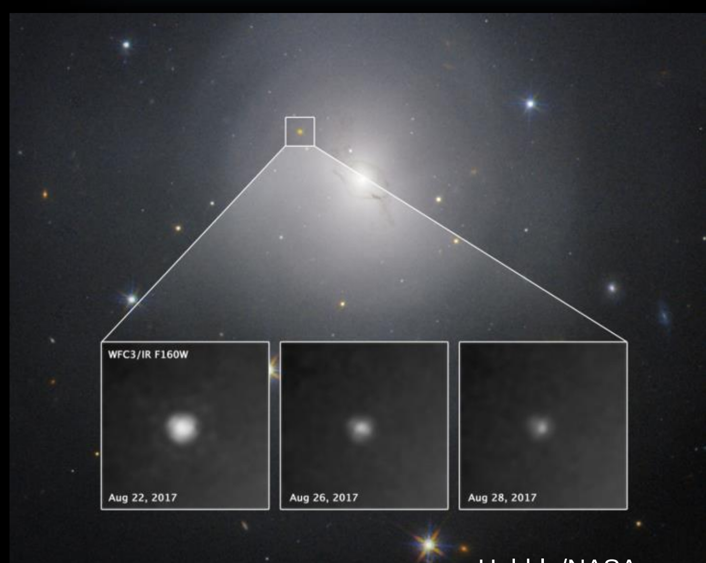


Looking into the heart of a dim nearby sGRB

Gravitational waves identified the progenitor of the sGRB and provided both space localization and distance of the source. This triggered the EM follow-up by astronomers for the kilonova

GW170817 was followed-up by astronomers



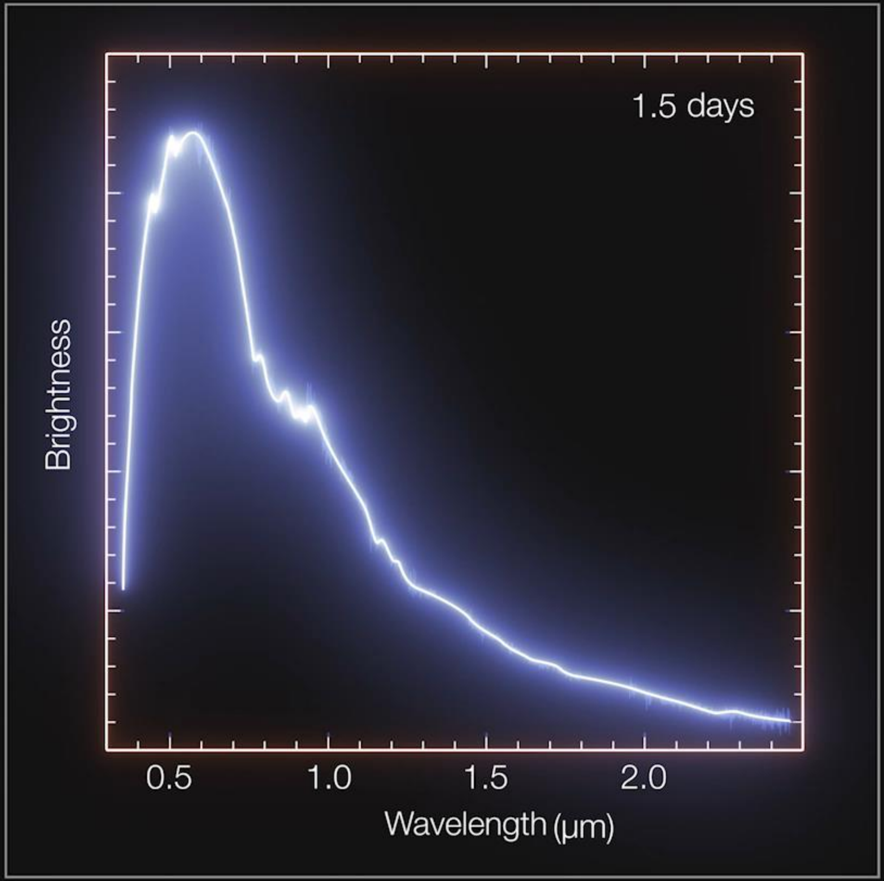


Hubble/NASA

European Southern Observatory

About 70 observatories worldwide observed the event by using space telescope (e.g. Hubble and Chandra) and ground-based telescopes (e.g. ESO) in all frequency bands (UVOIR). We witness the creation of heavy elements by studying their spectral evolution

Since LIGO/Virgo provide the distance and BNS source type, it was recognized that we are dealing with a weak (non-standard) GRB. This led to the optical counterpart to be found in this region



Kilonova description for GW170817

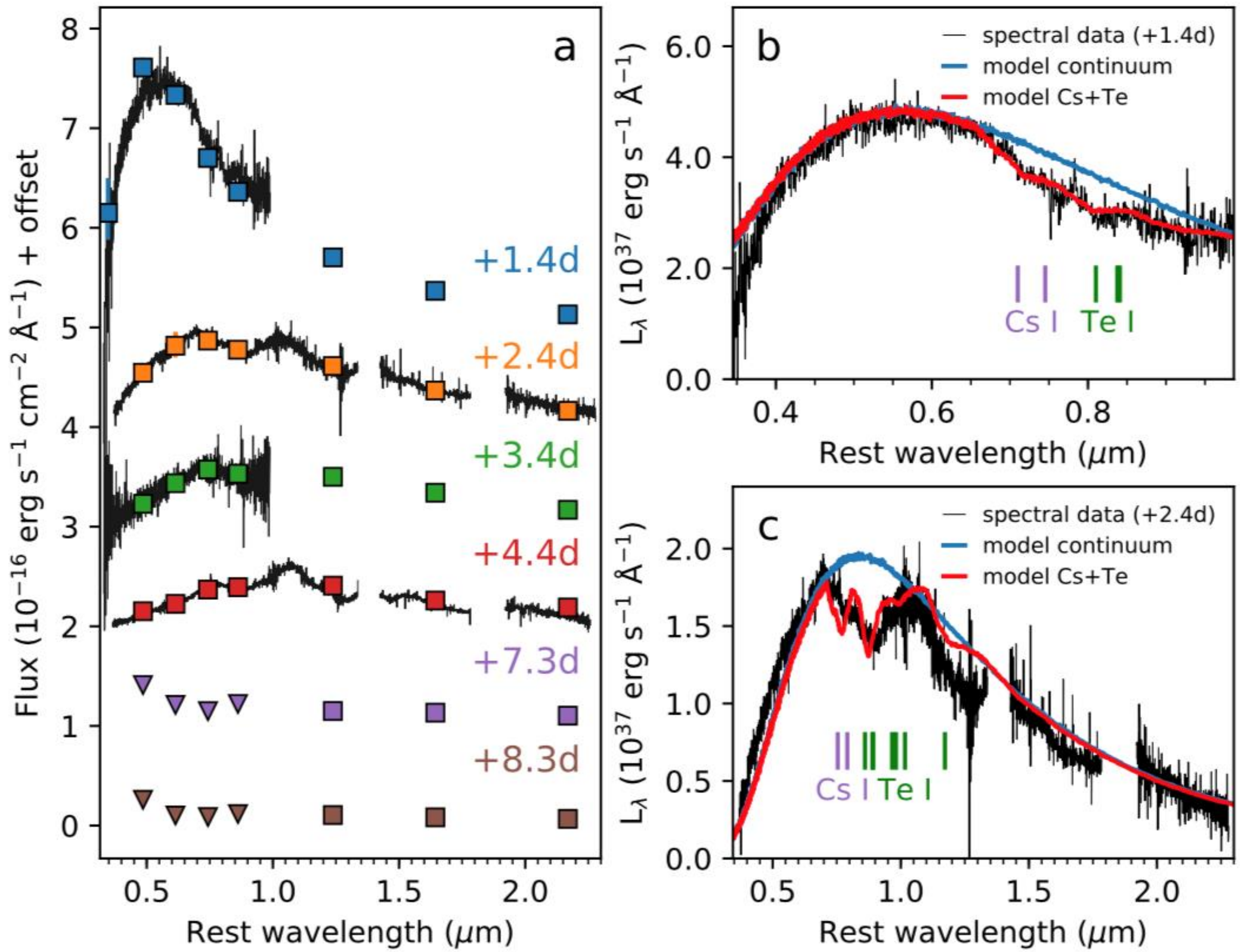
ePESSTO and VLT xshooter spectra with TARDIS radiative transfer models
See Smartt S.J. *et al*., Nature, 551, 75-79, 2017 for more details

The kilonova essentially has a black-body spectrum (6000 K; blue curve in panel C)

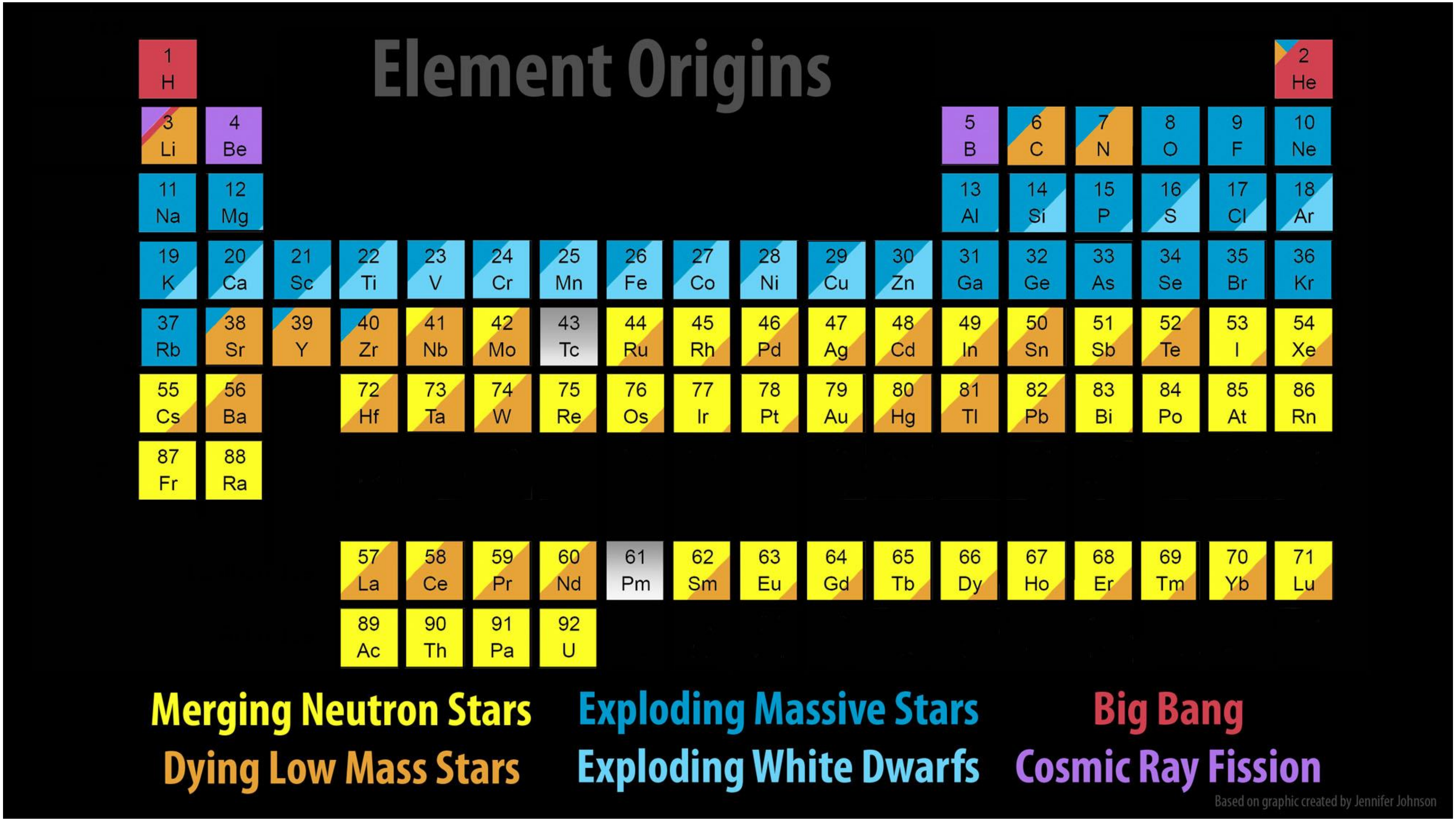
Data shows evidence for absorption lines (see model with tellurium and cesium with atomic numbers 52 and 55)

Formation of Cs and Te is difficult to explain in supernova explosions

The lines are Doppler broadened due to the high speed of the ejected material (about 60,000 km/s)



Many heavy elements were produced in such collisions



Implications for fundamental physics

Gamma rays reached Earth 1.7 s after the end of the gravitational wave inspiral signal. The data are consistent with standard EM theory minimally coupled to general relativity

GWs and light propagation speeds

Identical speeds to (assuming conservative lower bound on distance from GW signal of 26 Mpc)

$$-3 \times 10^{-15} < \frac{\Delta v}{v_{EM}} < +7 \times 10^{-16}$$

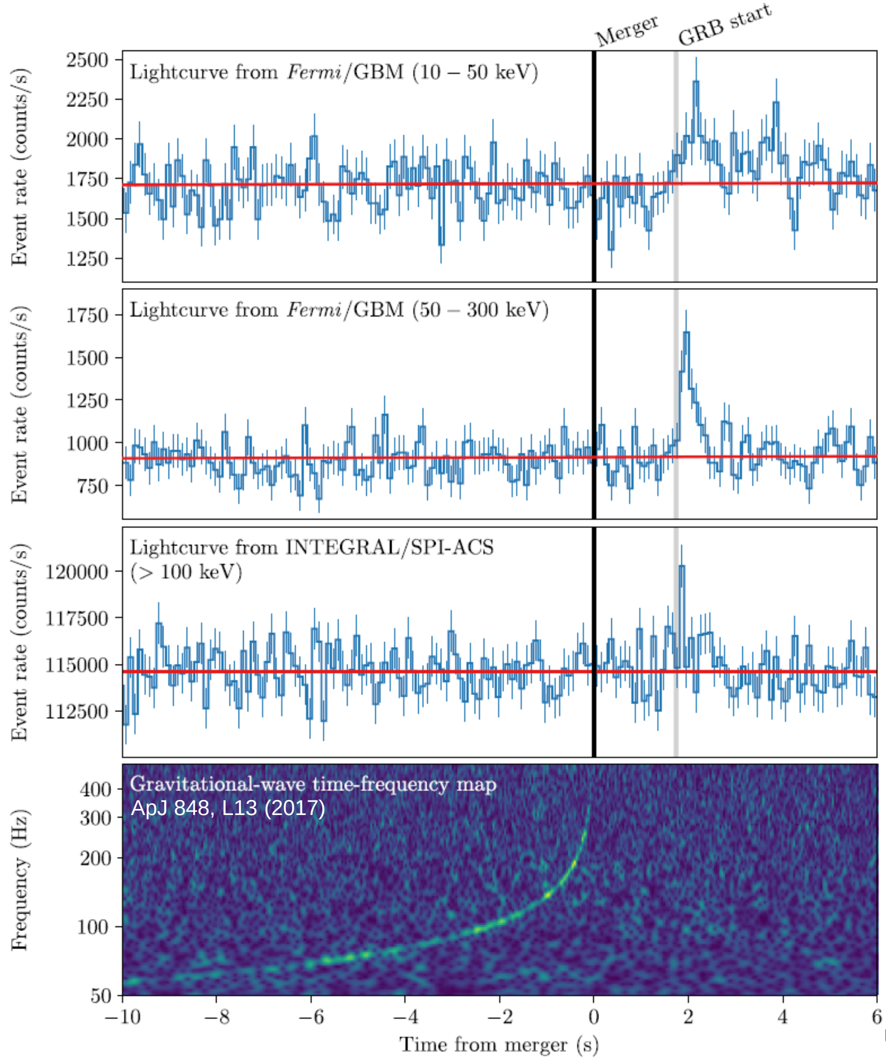
Test of Equivalence Principle

According to General Relativity, GW and EM waves are deflected and delayed by the curvature of spacetime produced by any mass (i.e. background gravitational potential). Shapiro delays affect both waves in the same manner

$$\Delta t_{\text{gravity}} = -\frac{\Delta\gamma}{c^3}\int_{r_0}^{r_e} U(r(t);t)\,dr$$

Constraints on dark energy models

Simultaneous detection of GW and EM signals rules out a class of modified gravity theories (arXiv:1710.05901v2)

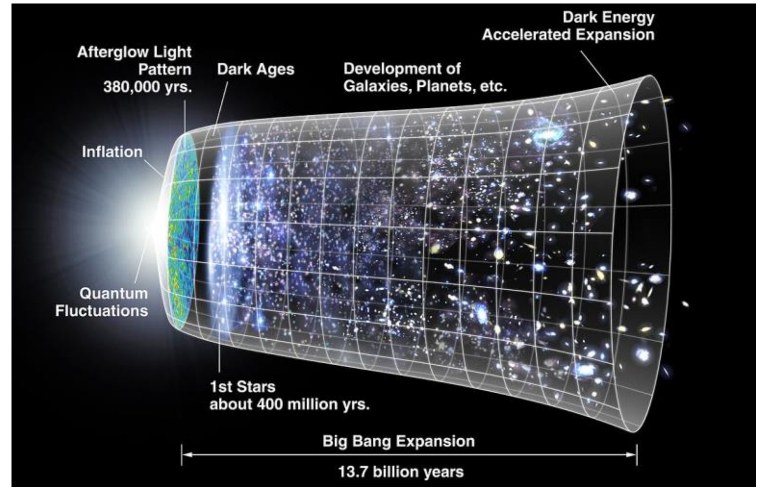


A new cosmic distance marker

Binary neutron stars allow a new way of mapping out the large-scale structure and evolution of spacetime by comparing distance and redshift

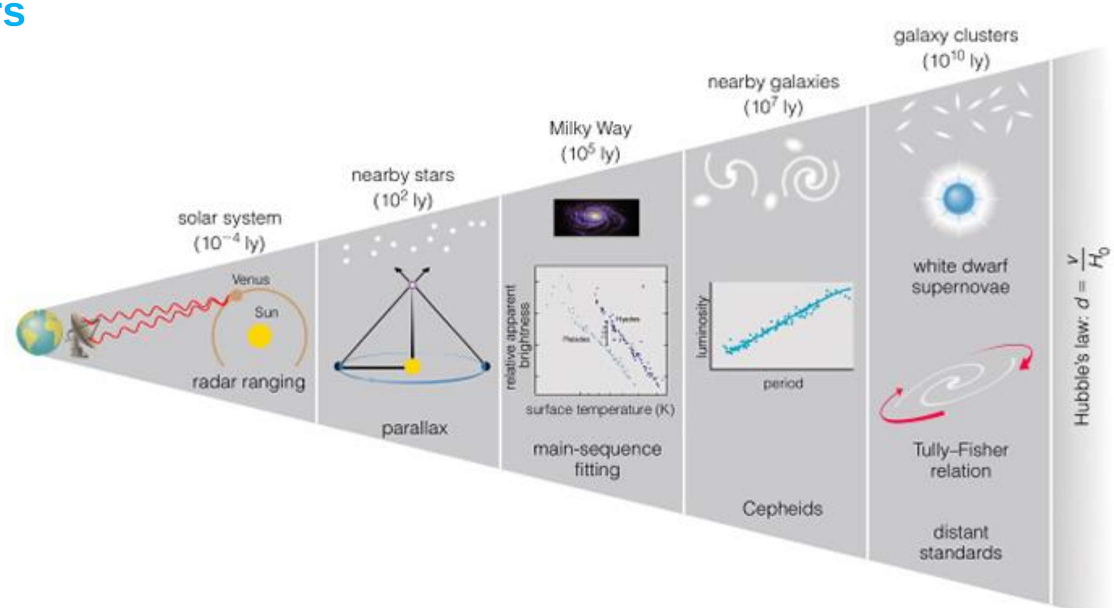
Current measurements depend on cosmic distance ladder

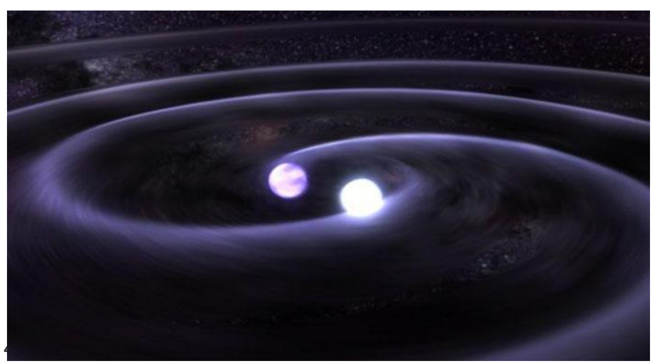
- Intrinsic brightness of *e.g.* supernovae determined by comparison with different, closer-by objects
- Possibility of systematic errors at every “rung” of the ladder



Gravitational waves from binary mergers

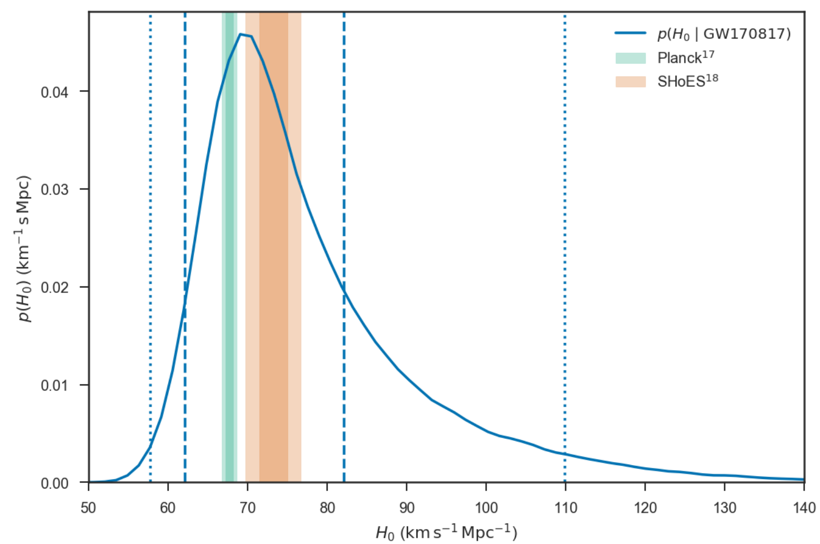
Distance can be measured directly from the gravitational wave signal!





A new cosmic distance marker

A few tens of detections of binary neutron star mergers allow determining the Hubble parameters to about 1-2% accuracy

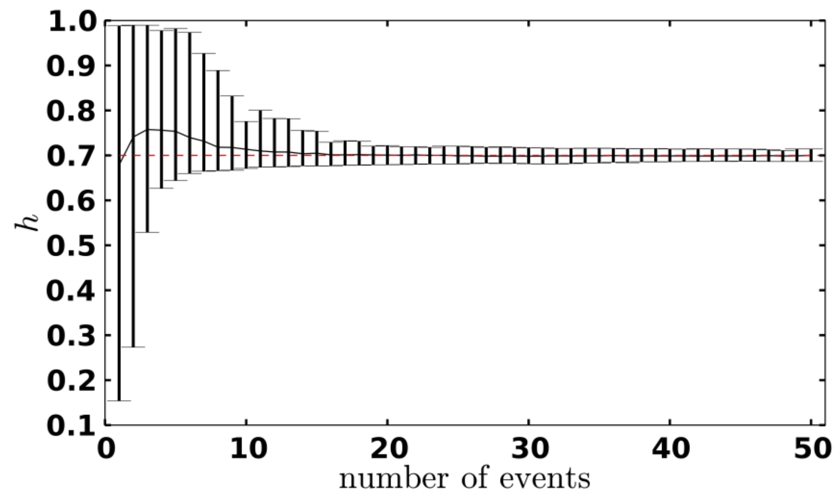


Measurement of the local expansion of the Universe

The Hubble constant

- Distance from GW signal
- Redshift from EM counterpart (galaxy NGC 4993)

LIGO+Virgo *et al*., Nature 551, 85 (2017)



GW170817

- One detection: limited accuracy
- Few tens of detections with LIGO/Virgo will be needed to obtain O(1-2%) accuracy

Bernard Schutz, Nature 323, 310–311 (1986)

Walter Del Pozzo, PRD 86, 043011 (2012)

Third generation observatories allow studies of the Dark Energy equation of state parameter

Scientific impact of gravitational wave science

Multi-messenger astronomy started: a broad community is relying of detection of gravitational waves

Fundamental physics

Access to dynamic strong field regime, new tests of General Relativity
Black hole science: inspiral, merger, ringdown, quasi-normal modes, echo's
Lorentz-invariance, equivalence principle, polarization, parity violation, axions

Astrophysics

First observation for binary neutron star merger, relation to sGRB
Evidence for a kilonova, explanation for creation of elements heavier than iron

Astronomy

Start of gravitational wave astronomy, population studies, formation of progenitors, remnant studies

Cosmology

Binary neutron stars can be used as standard “sirens”
Dark Matter and Dark Energy

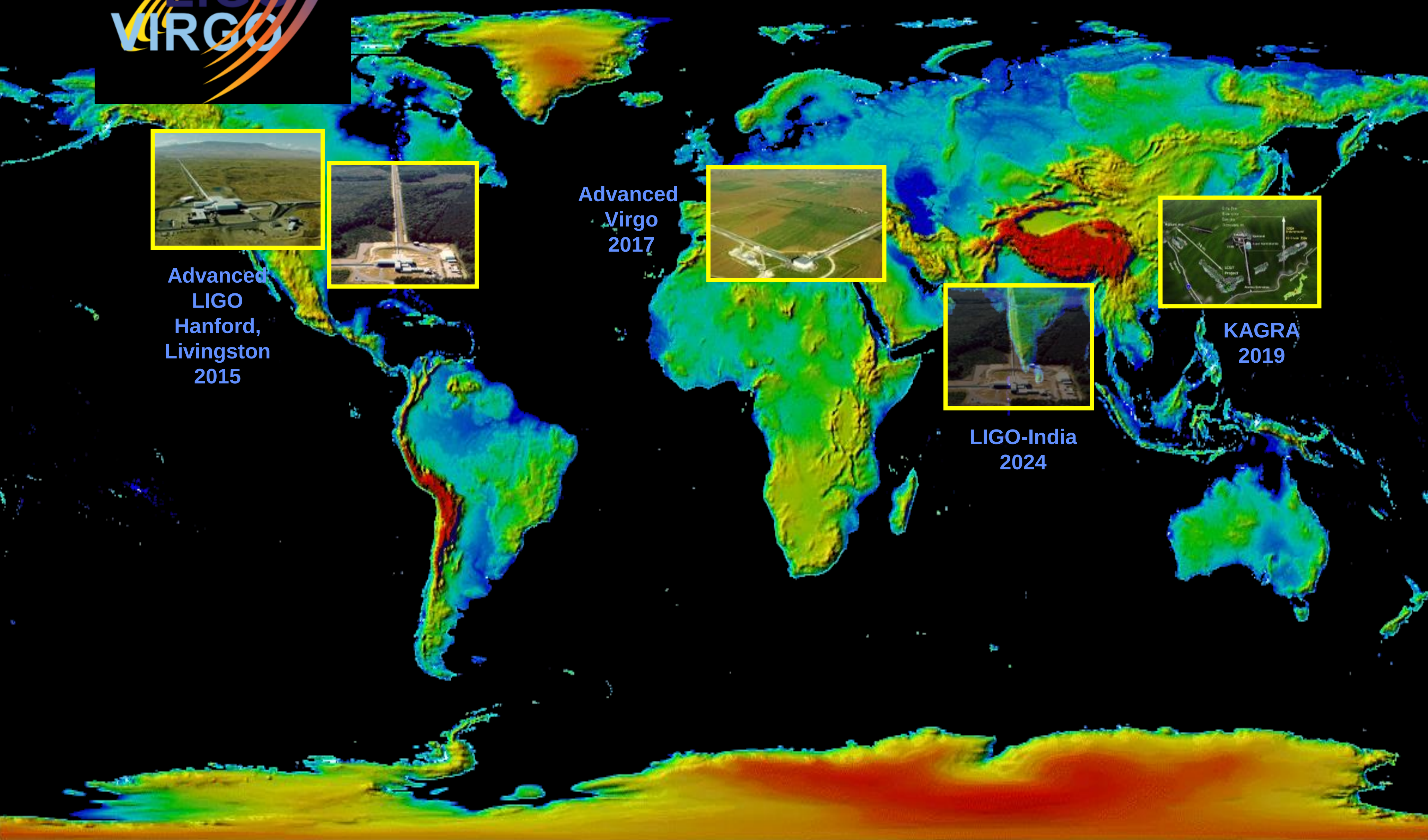
Nuclear physics

Tidal interactions between neutron stars get imprinted on gravitational waves
Access to equation of state

LVC will be back with improved instruments to start the next observation run (O3) early next year

What's next?

The advanced GW detector network

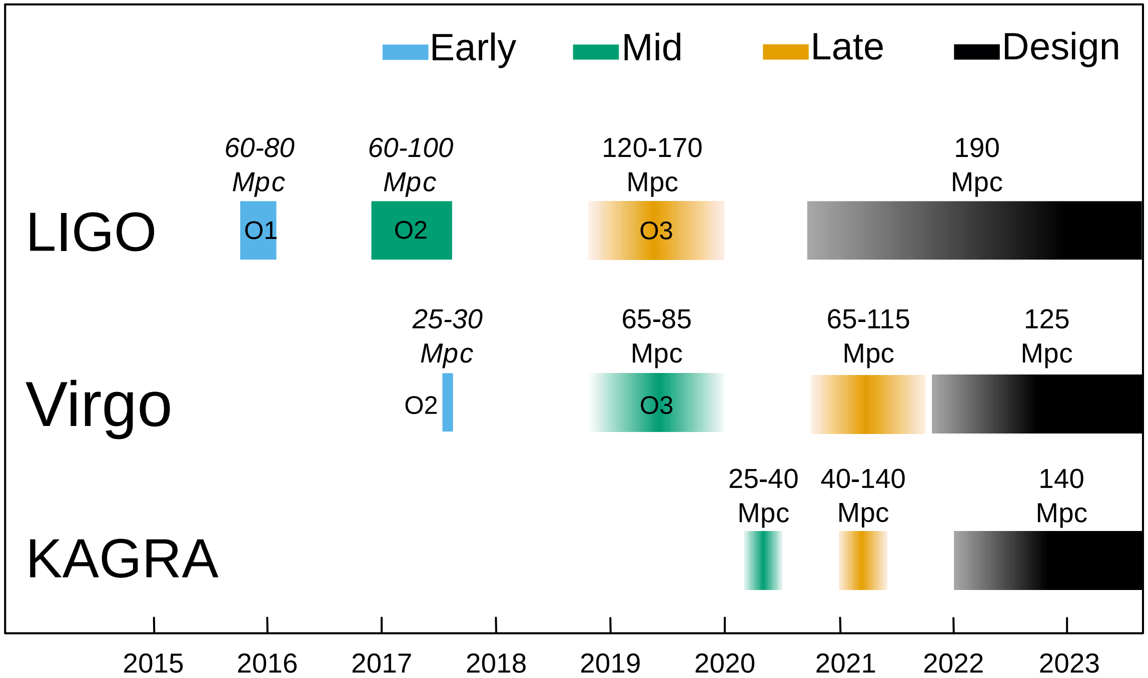


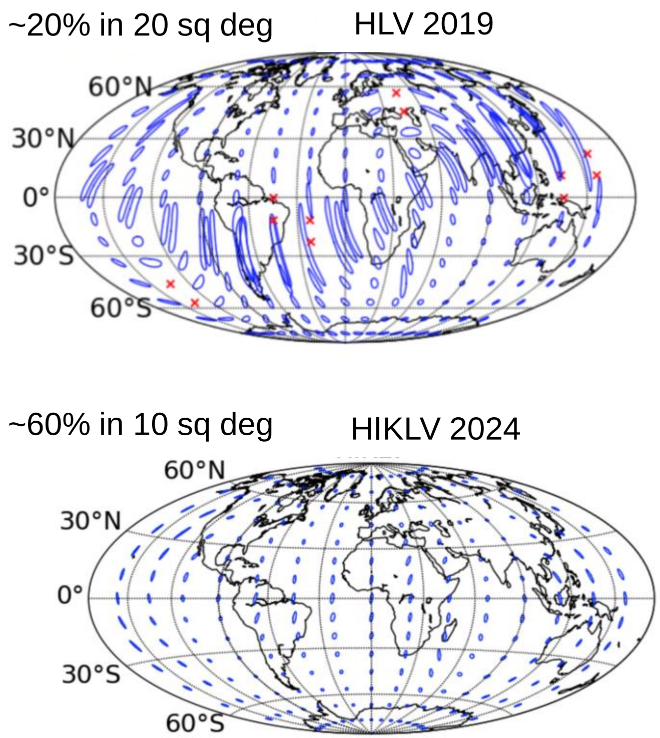
Planned observing timeline

One-year O3 planned to start in April 2019 with about twice the sensitivity in O3 (thus about 2^3 rate).
In O3 LIGO and Virgo will release Open Public Alerts

Observation run O3

Three detectors and perhaps 1 event per week
KAGRA expected to join at the end of O3
Contribute to sky localization and PE





B. P. Abbott et al., *Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA*, 2016, Living Rev. Relativity 19

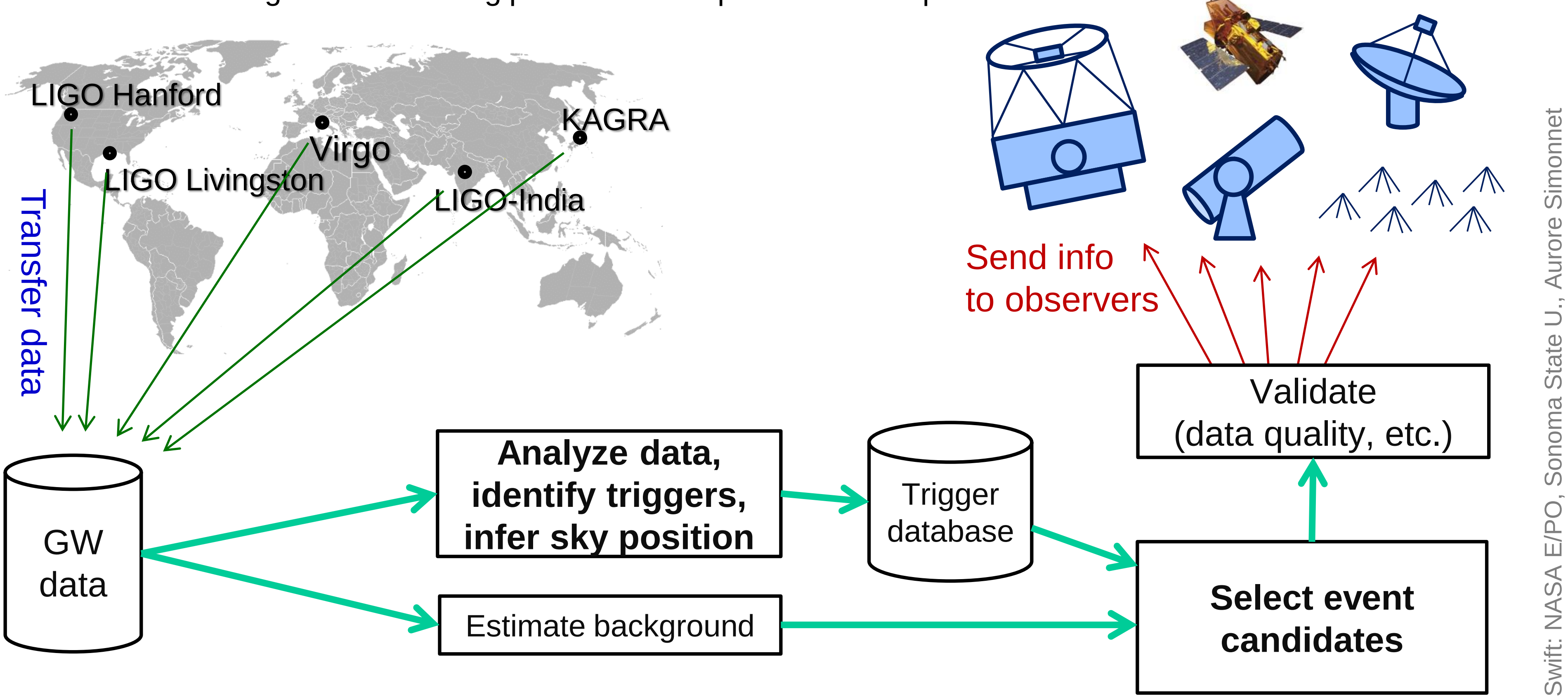
Open Public Alerts in O3 and Multi-Messenger Astronomy

In Observation Run O2, the LIGO-Virgo Collaboration had MOUs with 95 collaborations in astronomy and astro-particle physics. Multi-messenger astronomy requires rapid follow-up of interesting triggers and fast distribution of science data between partners distributed over the globe

In our next observation run O3 we will release Open Public Alerts

- GW event rate rapidly increases as sensitivity improves (note that GW-amplitude is measured; Rate $\sim S_{GW}^3$)
- Also computing needs grow as templates get longer

Moreover LIGO-Virgo make a strong push towards open data and open science

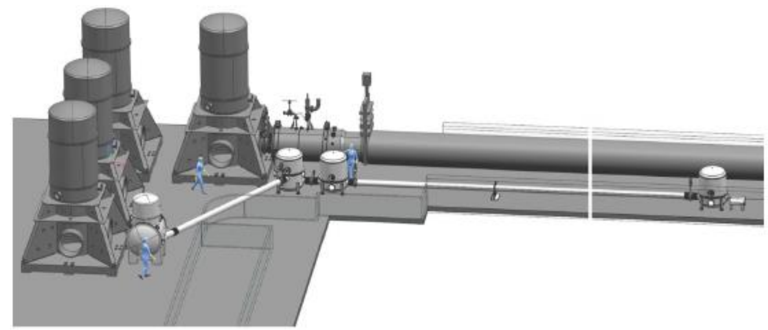


AdV+ as the next incremental step forward in sensitivity

AdV+ is the European plan to maximize Virgo's sensitivity within the constrains of the EGO site. It has the potential to increase Virgo's detection rate by up to an order of magnitude

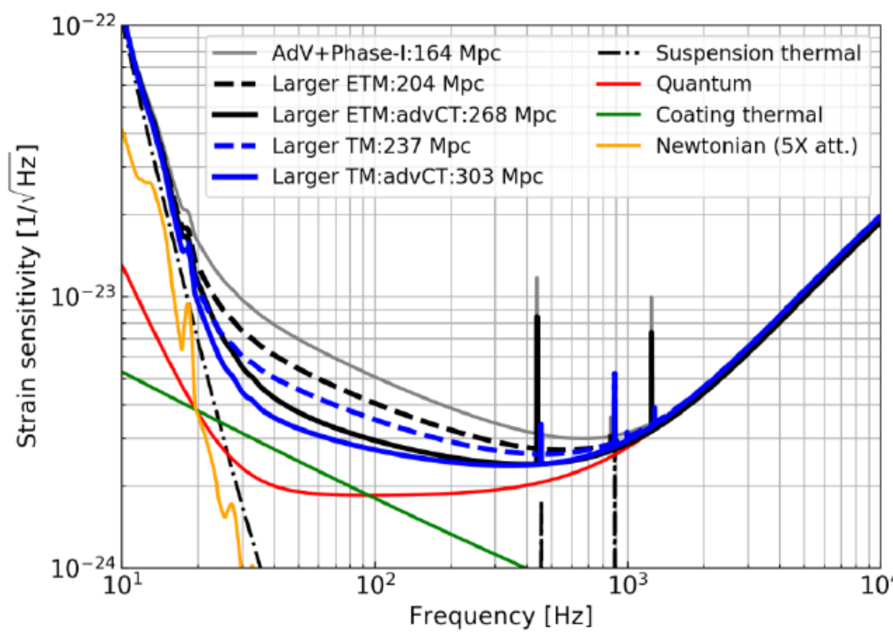
AdV+ features

- Maximize science
- Secure Virgo's scientific relevance
- Safeguard investments by scientists and funding agencies
- Implement new innovative technologies
- De-risk technologies needed for third generation observatories
- Attractive for groups wanting to enter the field



Upgrade activities

- Tuned signal recycling and HPL: 120 Mpc
- Frequency dependent squeezing: 150 Mpc
- Newtonian noise cancellation: 160 Mpc
- Larger mirrors (105 kg): 200-230 Mpc
- Improved coatings: 260-300 Mpc



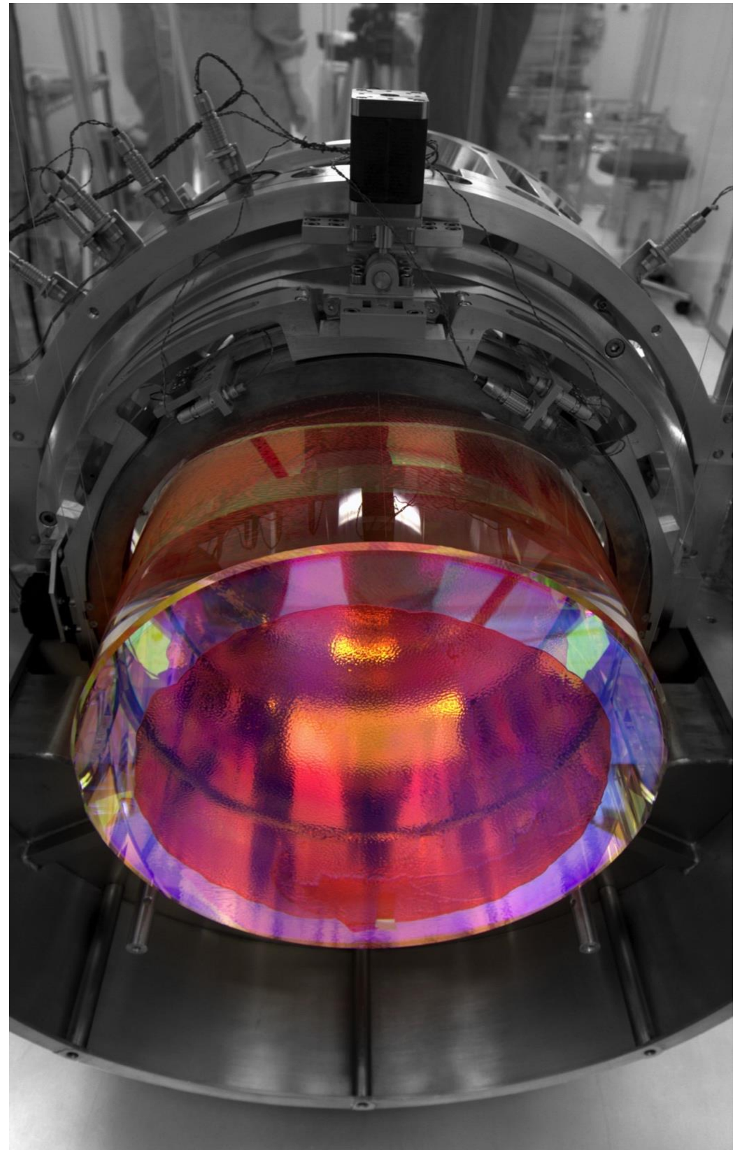
Injection of squeezed light states

Employ frequency dependent squeezing to overcome quantum noise at low and high frequencies

Virgo squeezer from AEI, Hanover

AdV+ upgrade and extreme mirror technology

Laboratoire des Matériaux Avancés LMA at Lyon produced the coatings used on the main mirrors of the two working gravitational wave detectors: Advanced LIGO and Virgo. These coatings feature low losses, low absorption, and low scattering properties



Features

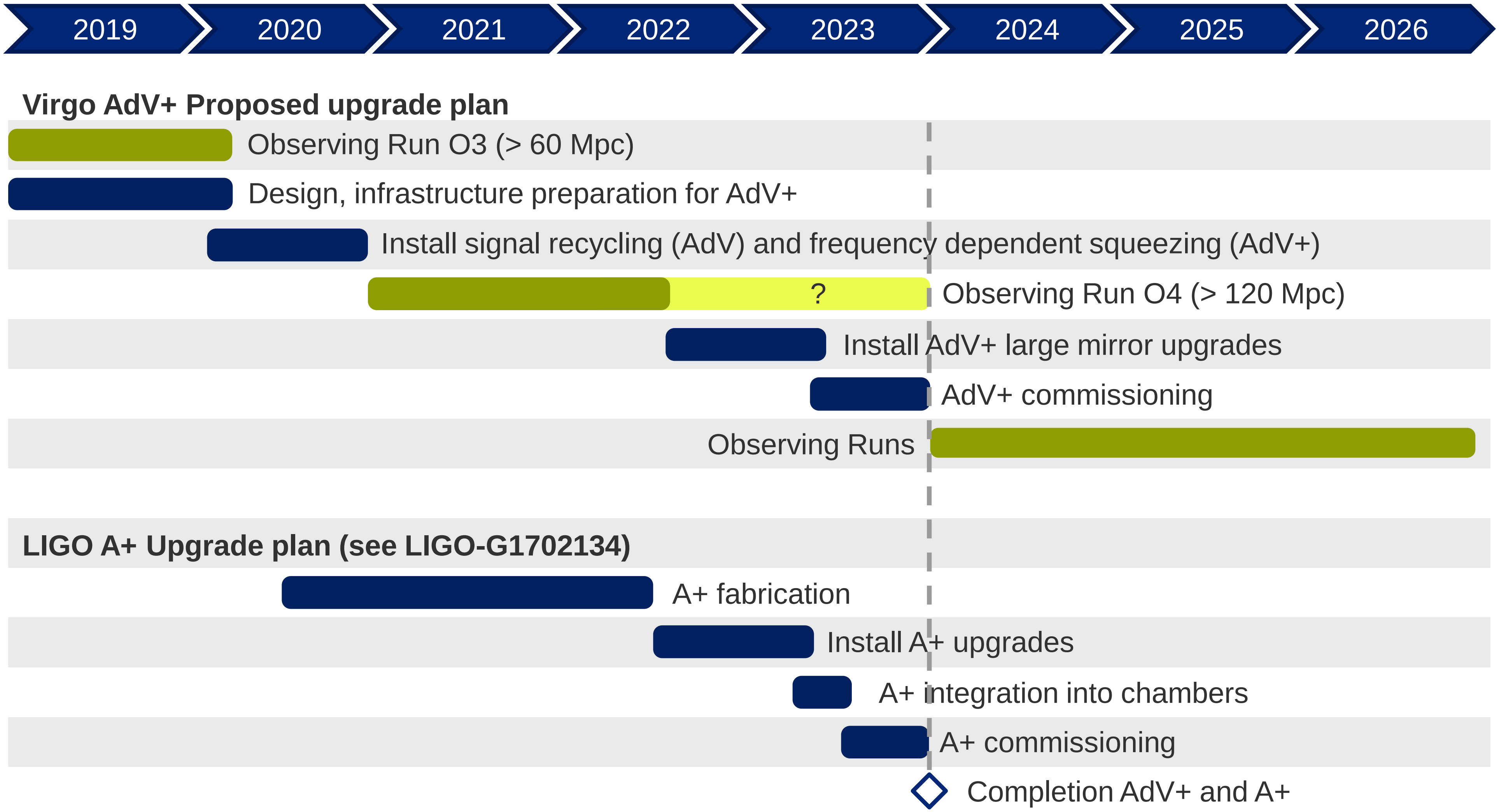
- Flatness < 0.5 nm rms over central 160 mm of mirrors by using ion beam polishing (robotic silica deposition was investigated)
- Ti:Ta_2O_5 and SiO_2 stacks with optical absorption about 0.3 ppm

Expand LMA capabilities for next generation

LMA is the only coating group known to be capable of scaling up

AdV+ to be carried out in parallel with LIGO's A+ upgrade

Five year plan for observational runs, commissioning and upgrades



Note: duration of O4 has not been decided at this moment

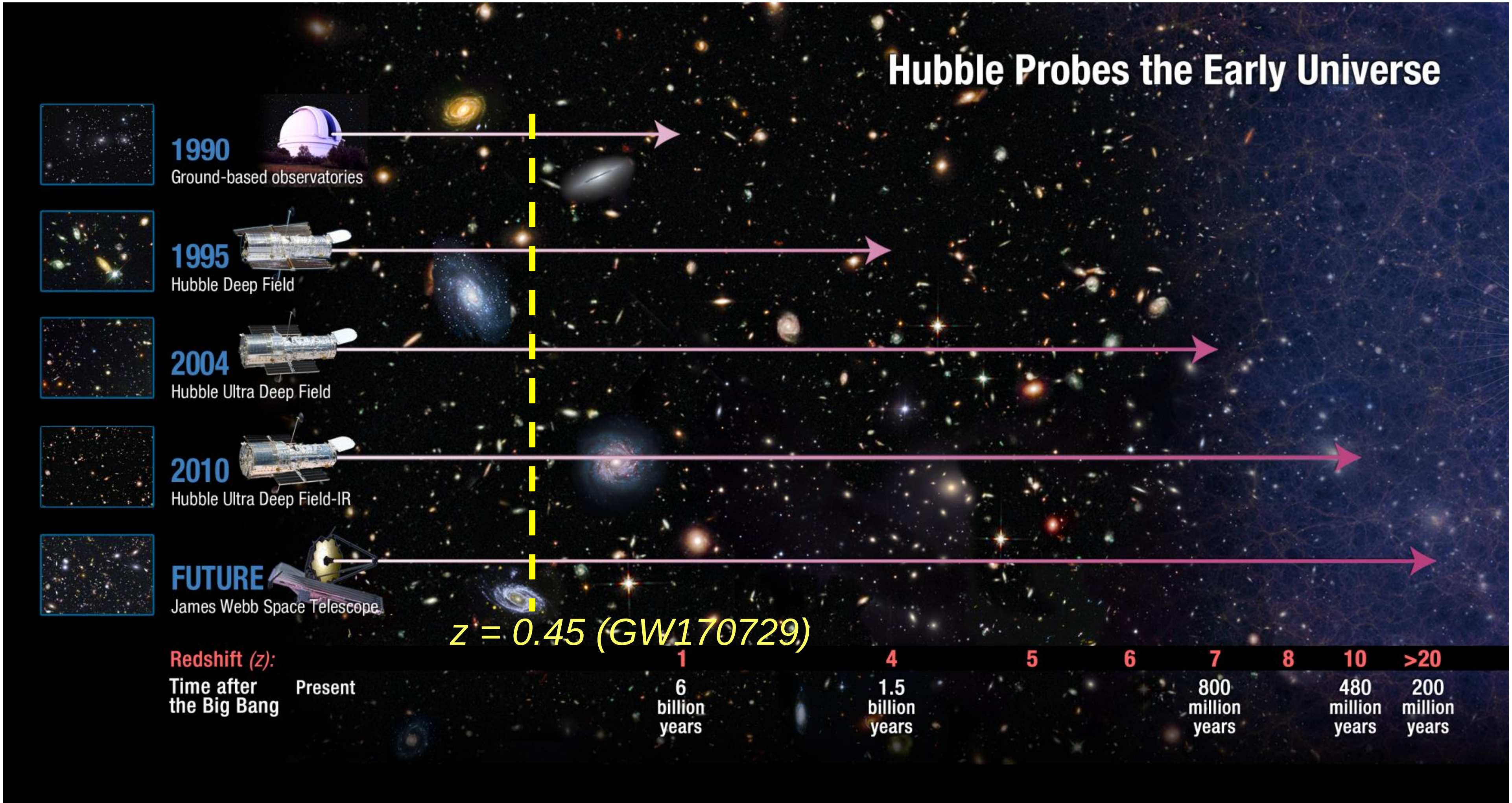
AdV+ is part of a strategy to go from 2^{nd} generation to Einstein Telescope

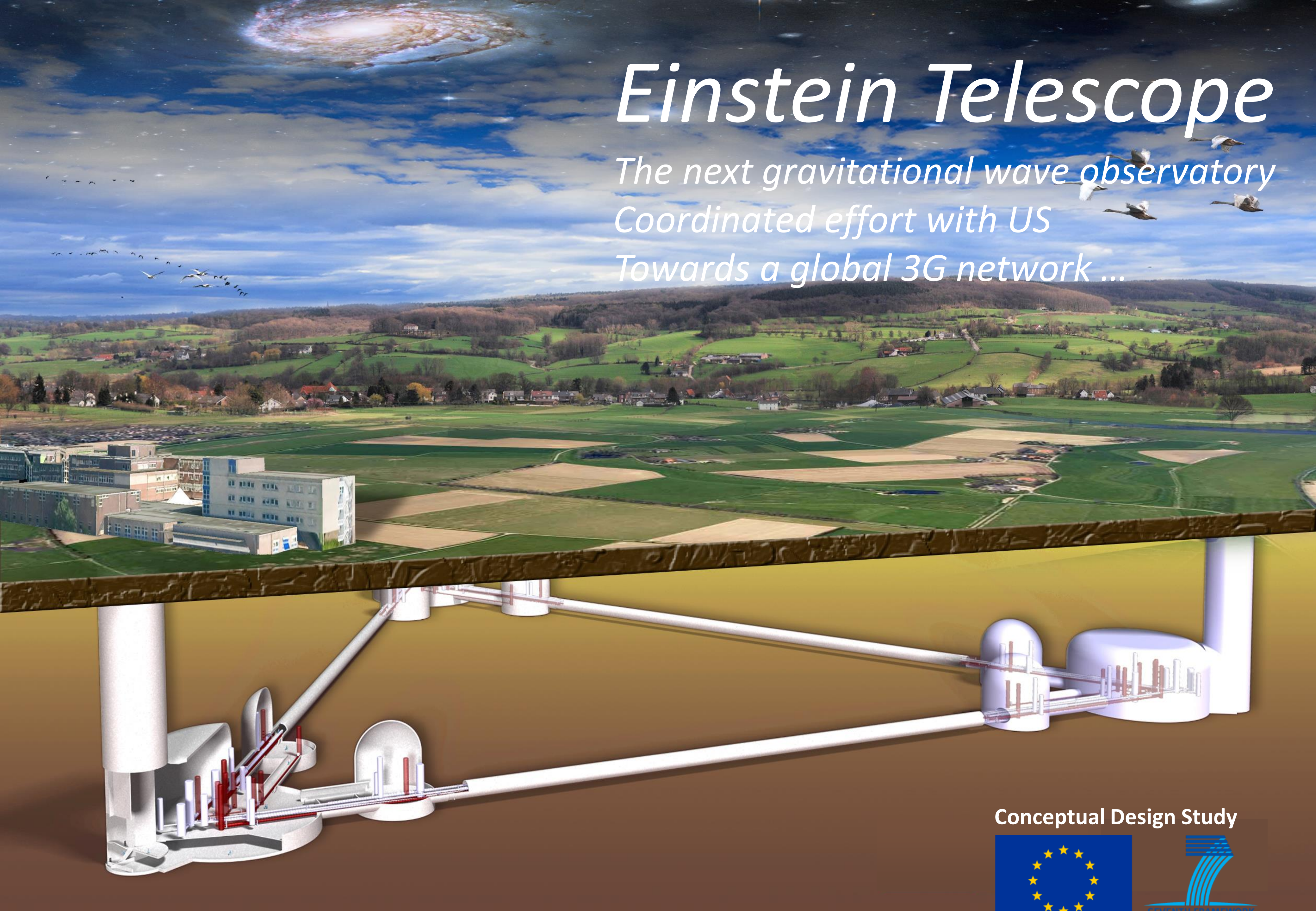
Einstein Telescope: observing all mergers in the Universe

This cannot be achieved with existing facilities and requires a new generation of GW observatories

We want to collect high statistics (*e.g.* millions of BBH events), high SNR, distributed over a large z-range ($z < 20$)

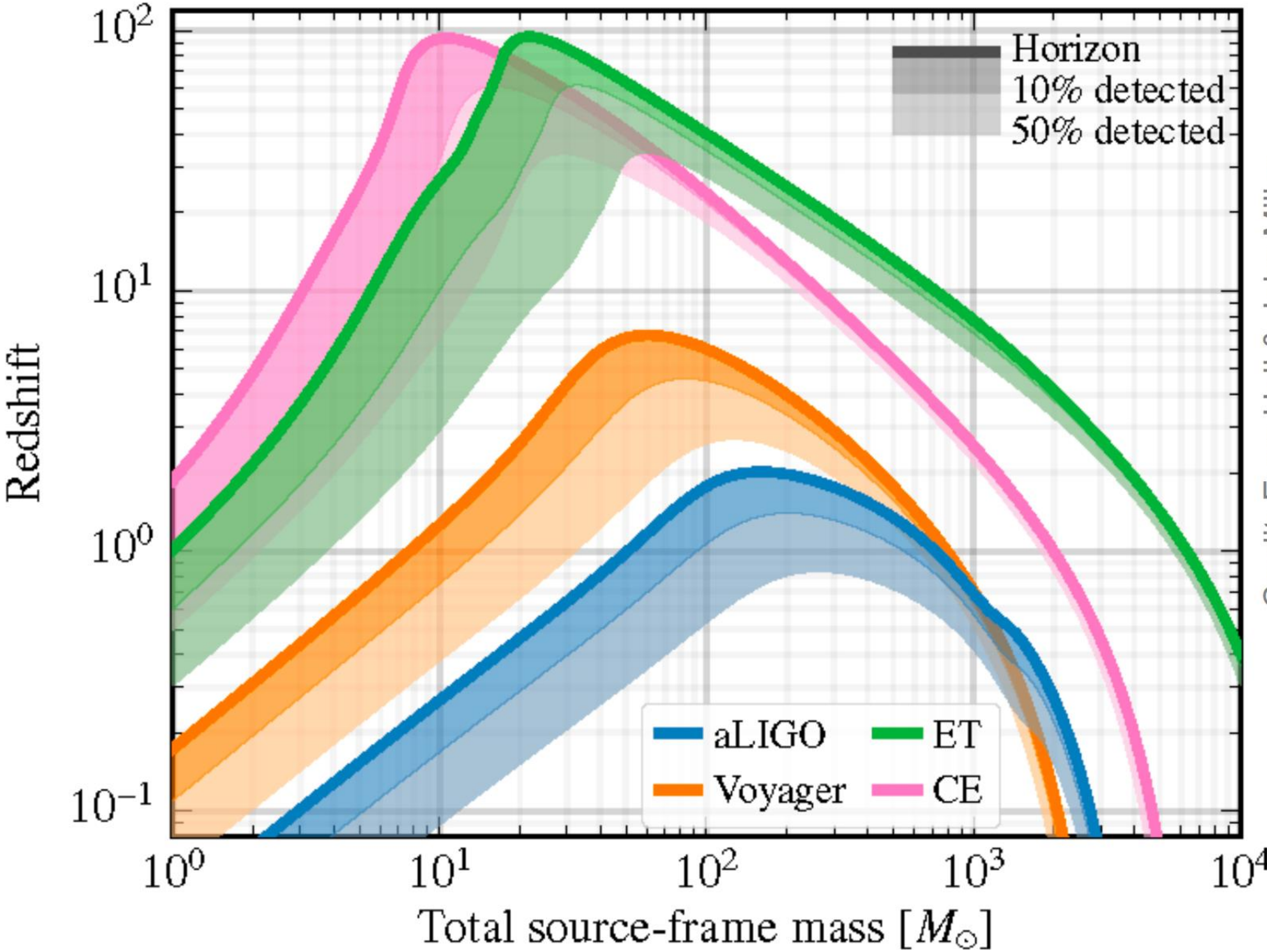
This allows sorting data versus redshift, mass distributions, *etc*. Early warning, IMBH, early Universe, CW, …



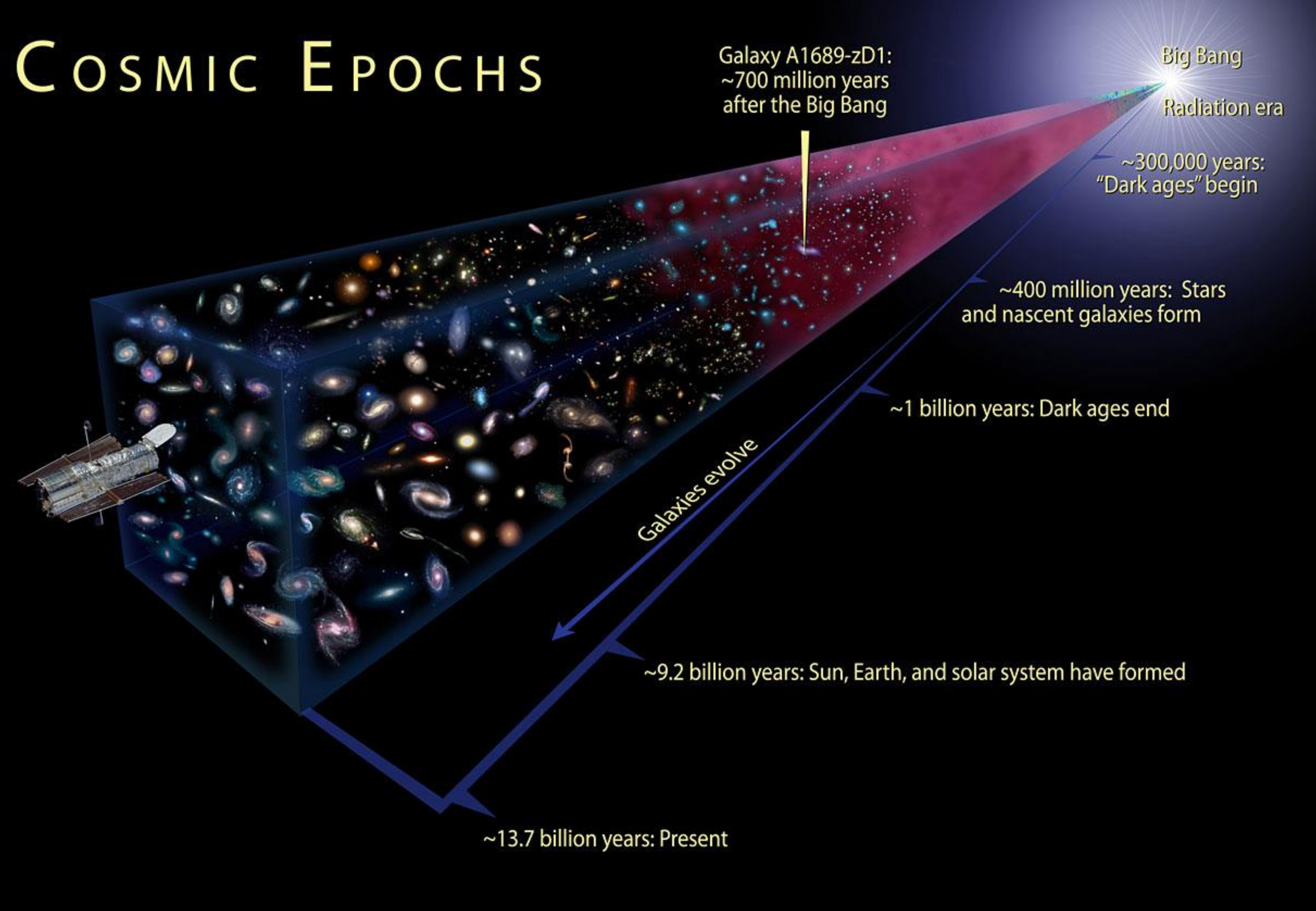

Einstein Telescope
The next gravitational wave observatory
Coordinated effort with US
Towards a global 3G network …
Conceptual Design Study

Einstein Telescope has excellent sensitivity

Einstein Telescope and Cosmic Explorer can observe the entire universe



Credit: Evan Hall & John Miller

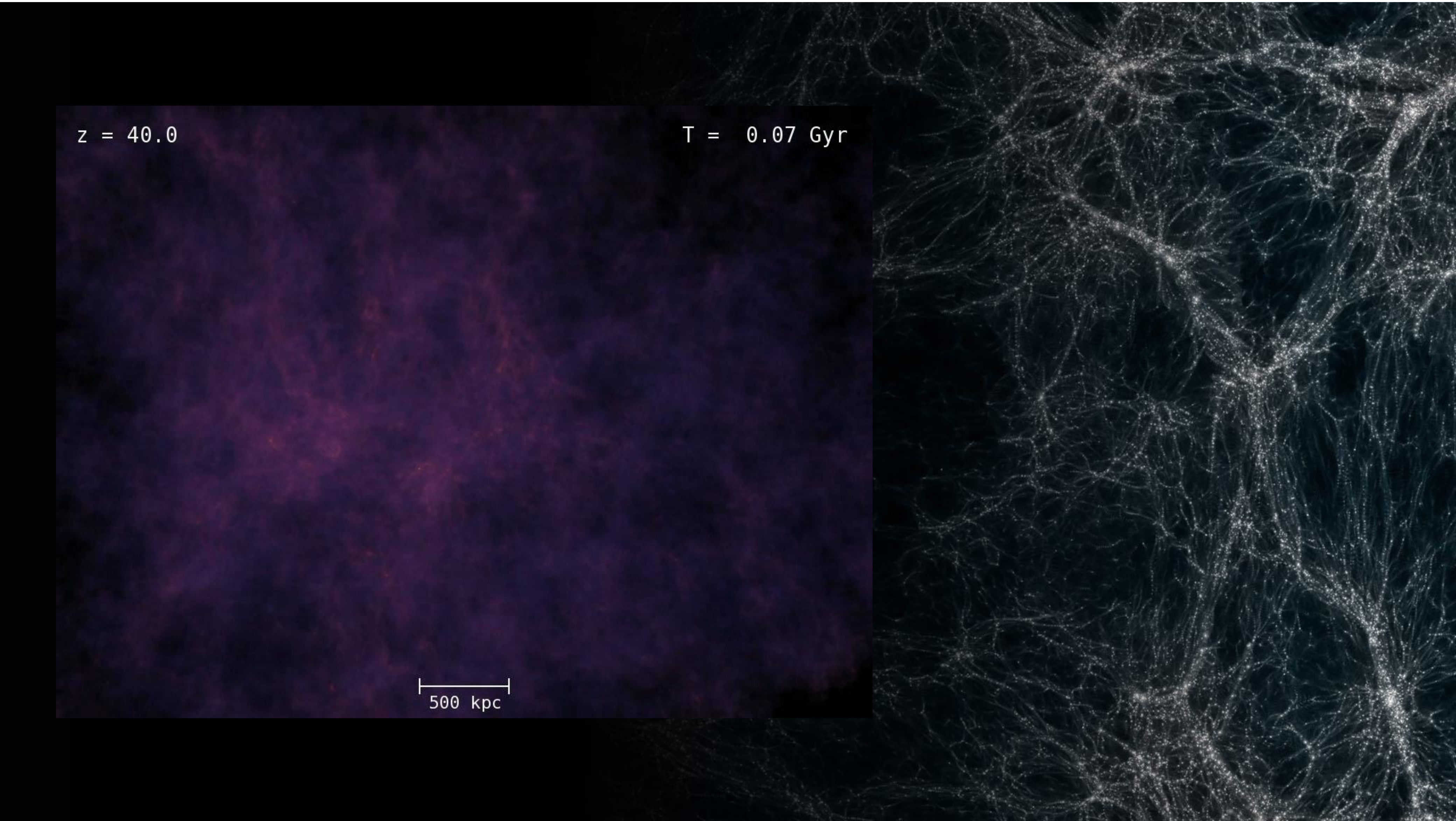

Cosmic Epochs
Galaxy A1689-zD1: ~700 million years after the Big Bang
Big Bang
Radiation era
~300,000 years: "Dark ages" begin
~400 million years: Stars and nascent galaxies form
~1 billion years: Dark ages end
Galaxies evolve
~9.2 billion years: Sun, Earth, and solar system have formed
~13.7 billion years: Present

Einstein Telescope

Einstein Telescope can observe BBH mergers up to a redshift of 100. This allows a new approach to cosmography. Study primordial black holes, BH from population III stars (first metal producers), *etc*.

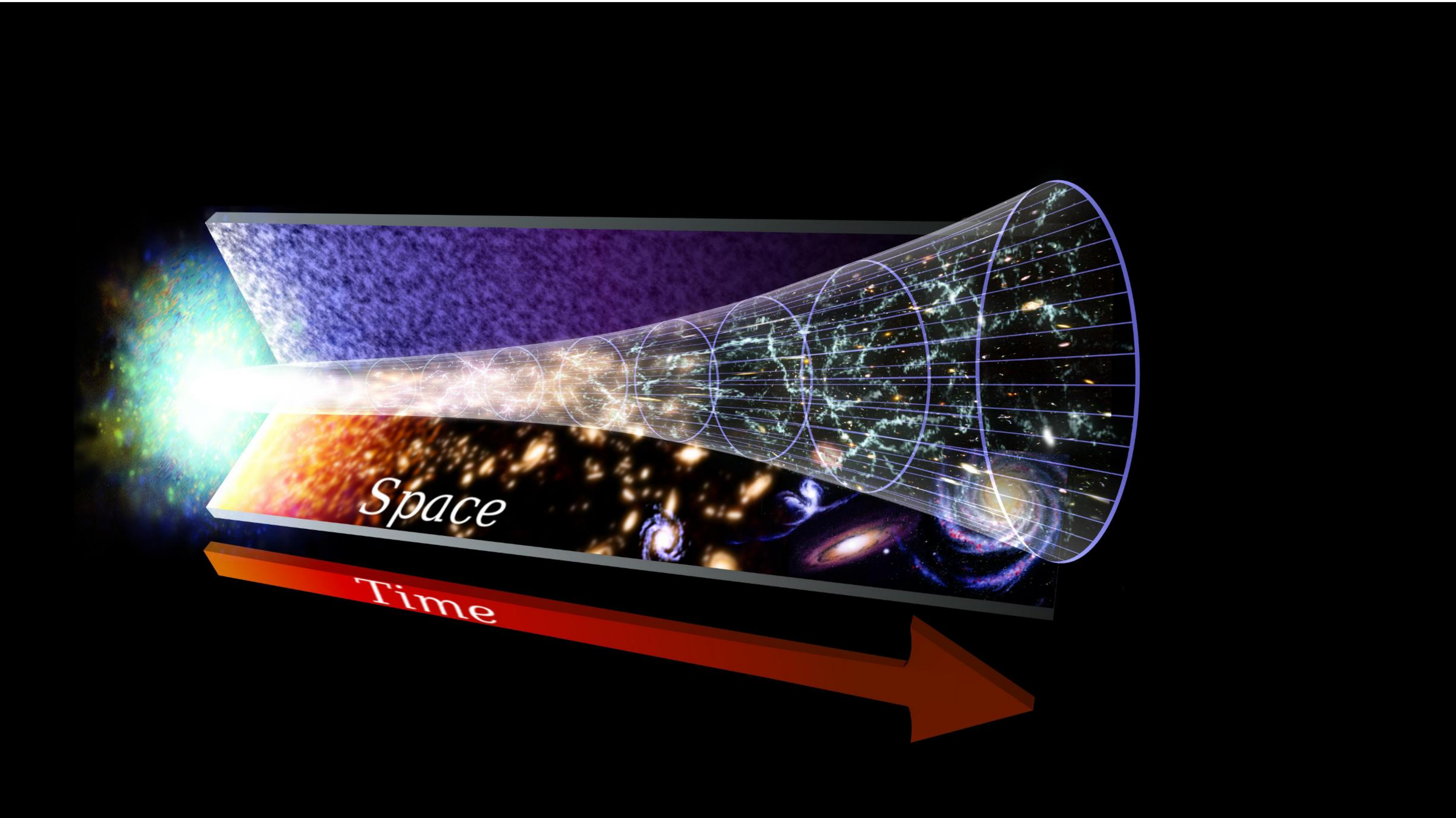
Einstein Telescope

Einstein Telescope can observe BBH mergers up to a redshift of 100. This allows a new approach to cosmography. Study primordial black holes, BH from population III stars (first metal producers), *etc*.



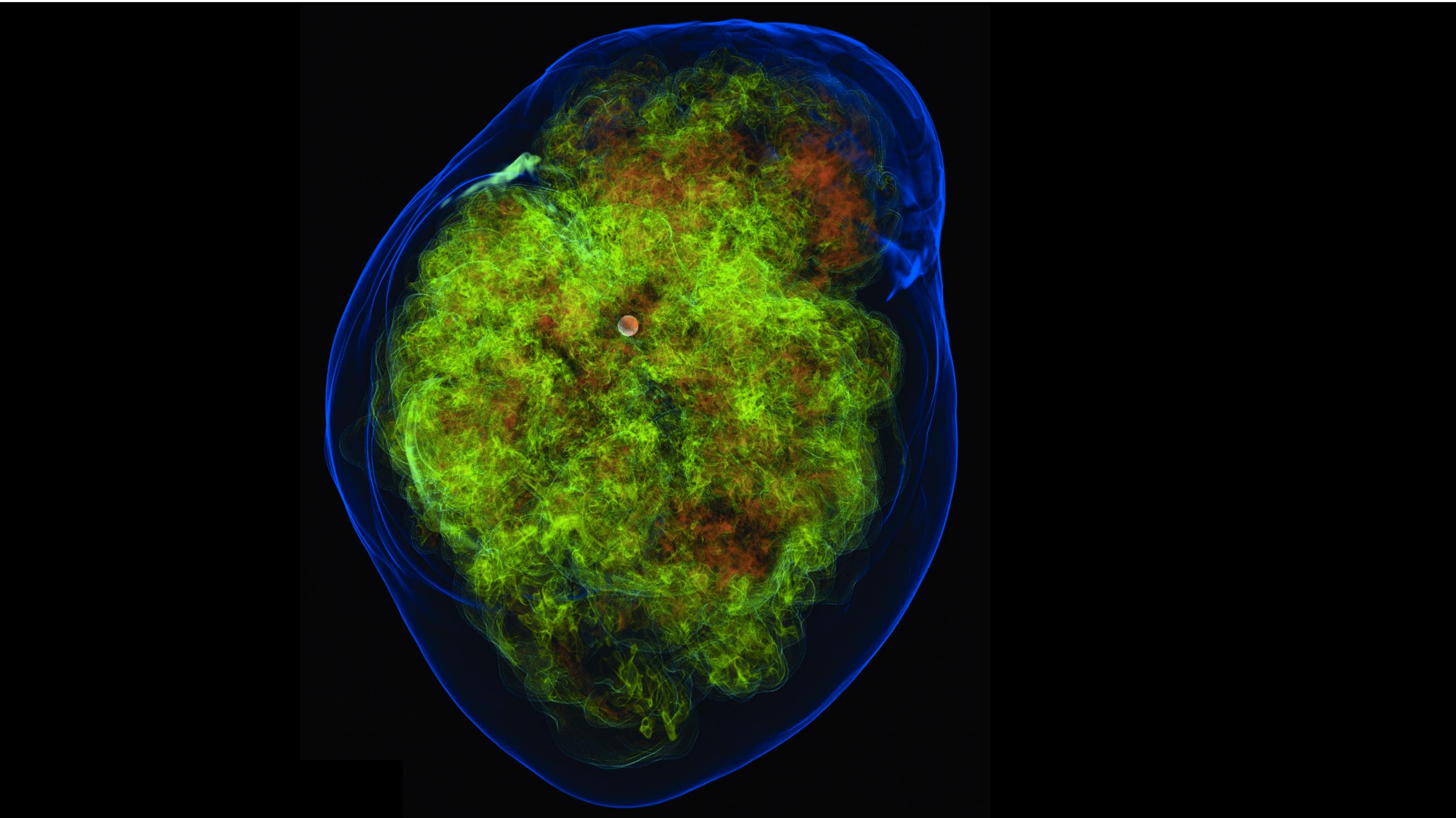
Dark energy: what is ripping the universe apart?

Einstein Telescope will use CBC events as standard “sirens”. This allows a new type of cosmography. Moreover the equation of state parameter for Dark Energy can be measured



Physics of supernovae

Study progenitor mass, proto neutron star (NS) core oscillations, core rotation rate, mass accretion rate from shock, geometry of core collapse, effects of NS Equation of State, fate of collapse: NS or BH



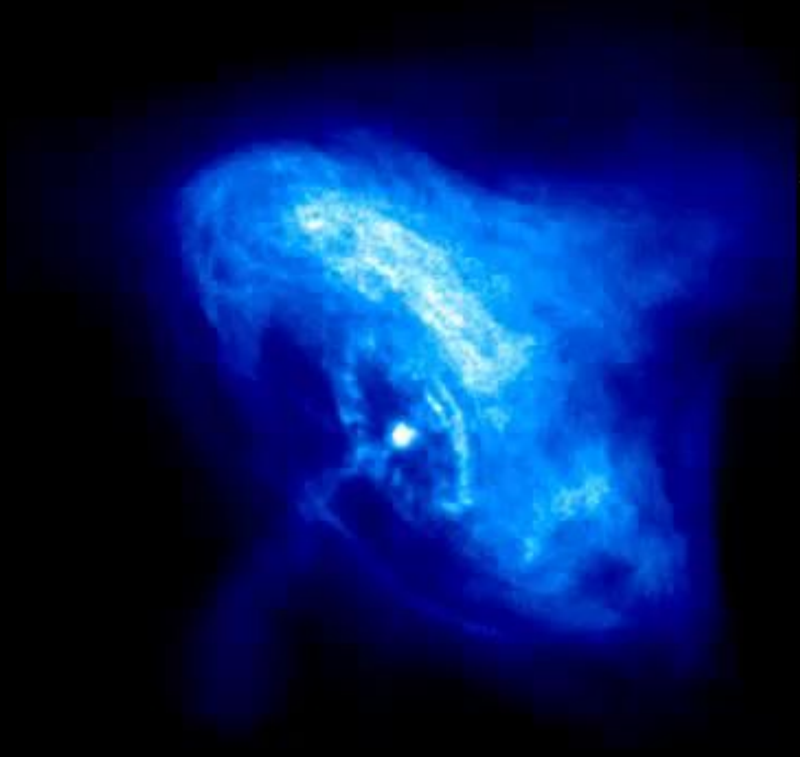
Physics of neutron stars

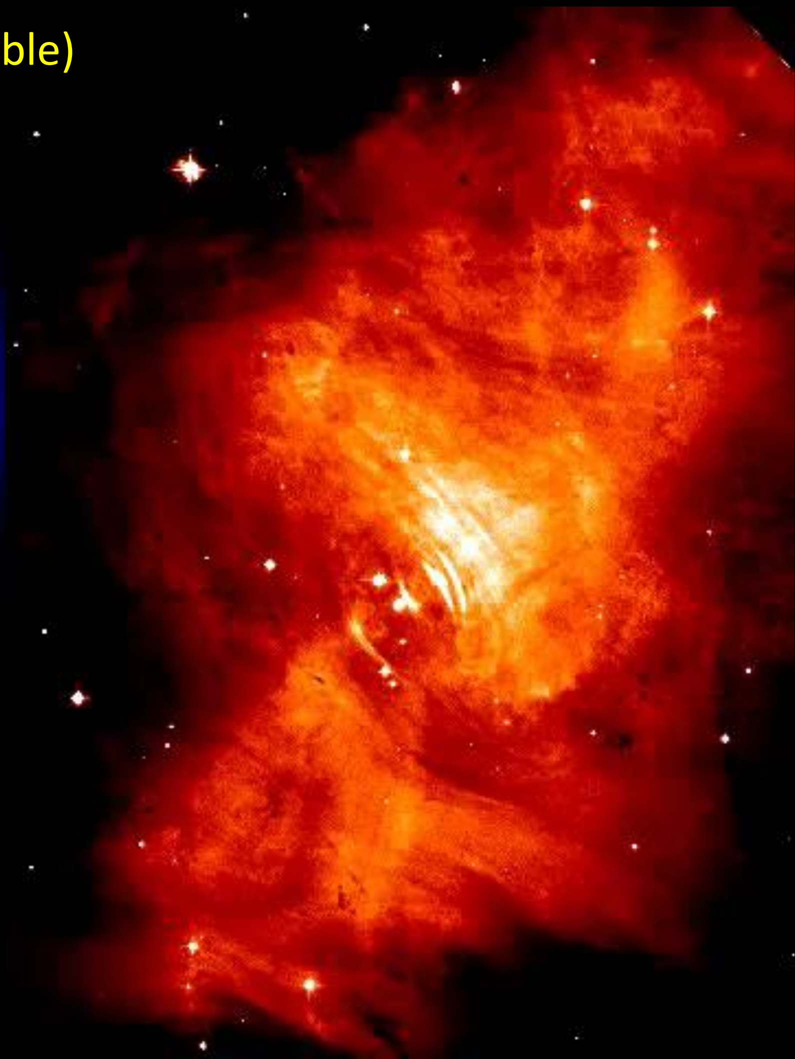
Deformation due to elastic stresses or magnetic field not aligned to the rotation axis, free precession around rotation axis, excitation of long-lasting oscillations (e.g. *r*-modes), deformation due to matter accretion (e.g. LMXB)

SN1054 (Crab) composite movie (X + visible)

X-Ray Image Credit: NASA/CXC/ASU/J.Hester *et al.*

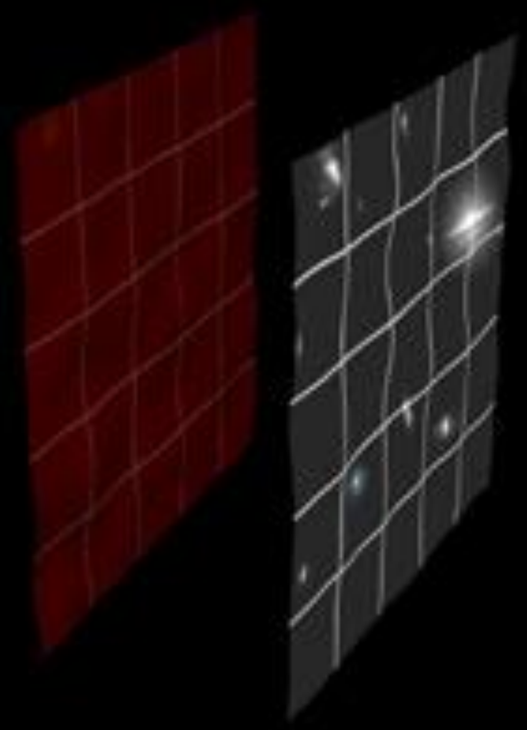
Optical Image Credit: NASA/HST/ASU/J.Hester *et al.*

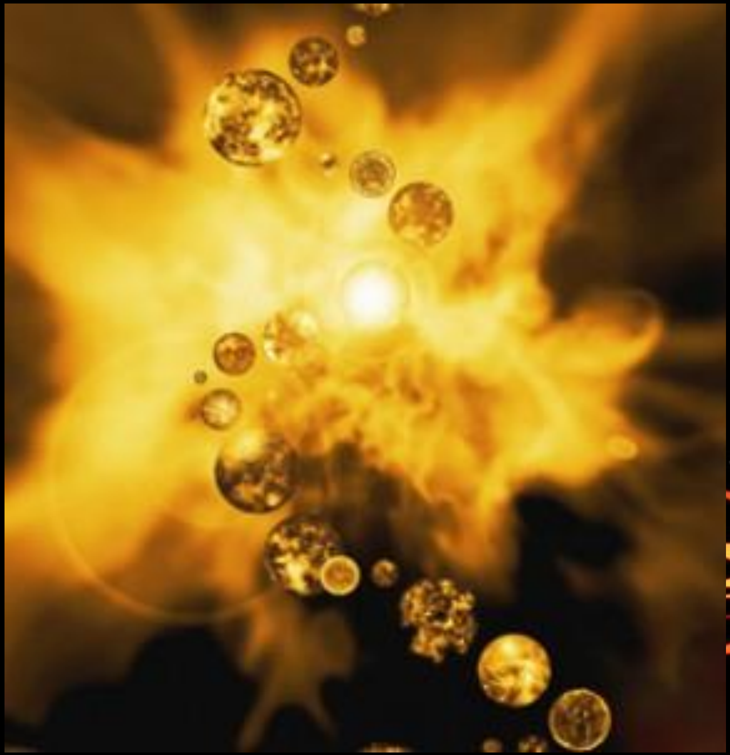


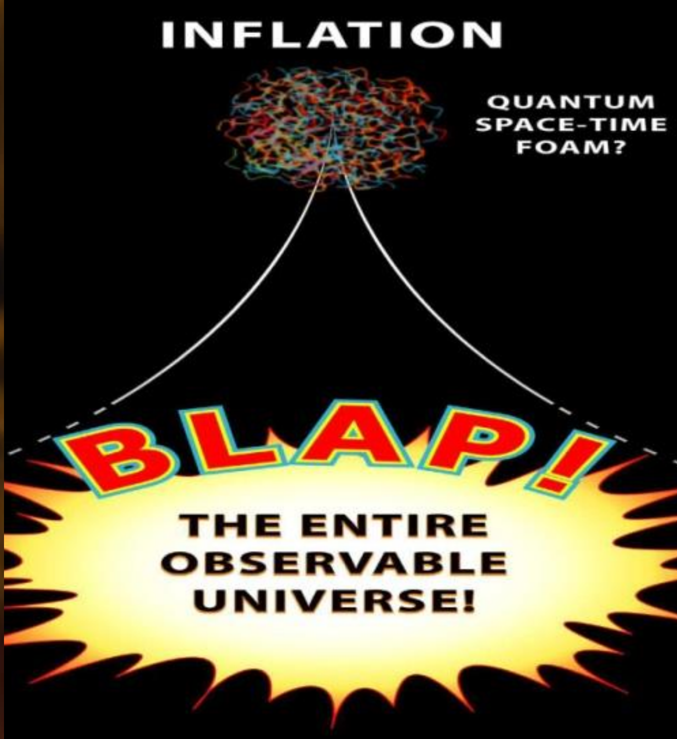


Physics from the early Universe

A stochastic background of gravitational waves may be observed from the earliest stages of the Universe

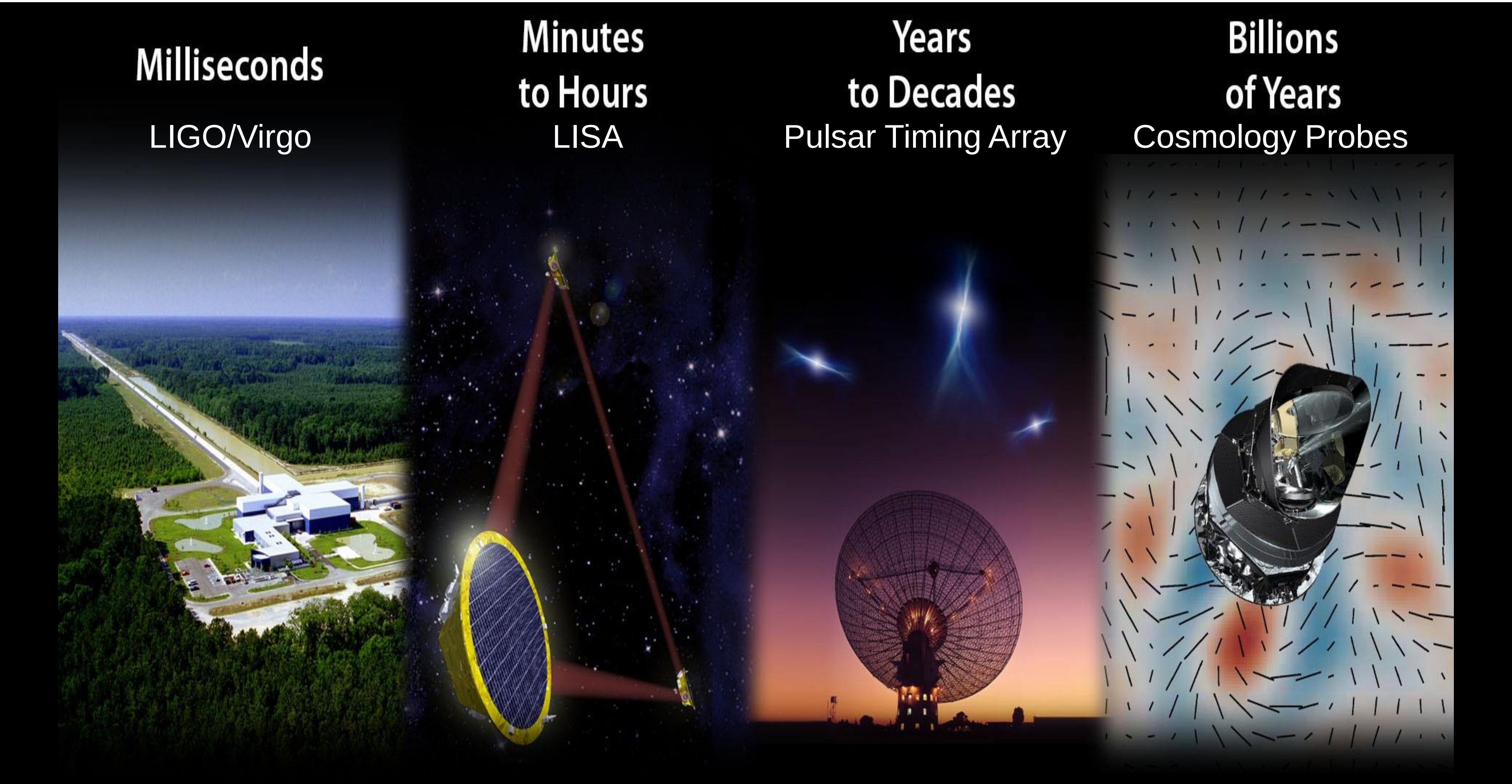






The beginning of a new field

New instruments cover a wide range of frequency, new discoveries, new synergies



Bright future for gravitational wave research

LIGO and Virgo are operational. KAGRA in Japan next year, LIGO-India under construction. ESA launches LISA in 2034. Einstein Telescope CDR financed by EU, strong support by APPEC

Gravitational wave research

- LIGO and Virgo operational
- KAGRA to join next year
- LIGO-India under construction (2025)
- ESA selects LISA, NASA rejoins
- Pulsar Timing Arrays, such as EPTA and SKA
- Cosmic Microwave Background radiation

Einstein Telescope

- Design financed by EU in FP7
- APPEC gives GW a prominent place in the new Roadmap and especially the realization of ET

Next steps for 3G

- Organize the community and prepare a credible plan for EU funding agencies
- ESFRI Roadmap (2020)
- Support ET: http://www.et-gw.eu/index.php/letter-of-intent