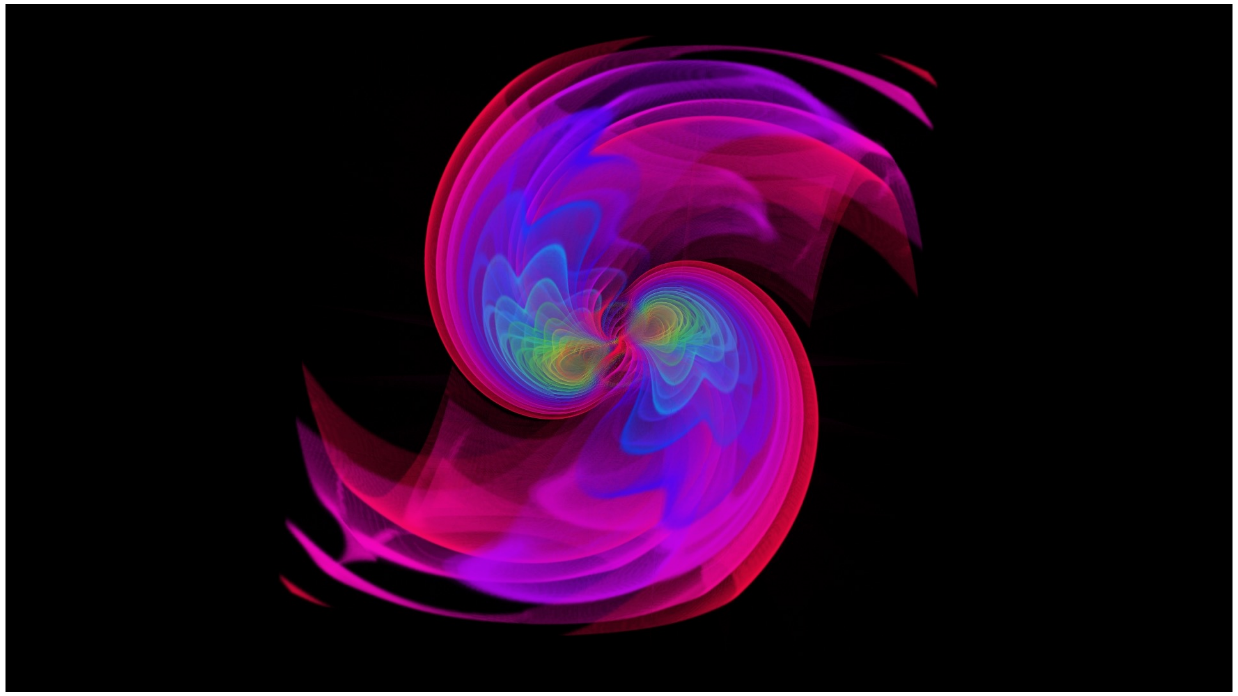


Sounds of Silence:
Listening to the Universe with Gravitational Waves

Alessandra Buonanno

Max Planck Institute for Gravitational Physics

(Albert Einstein Institute)

Department of Physics, University of Maryland

MAX-PLANCK-GESELLSCHAFT

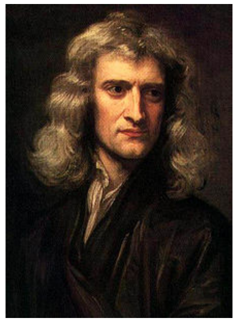
UNIVERSITY OF MARYLAND 18 56

Paco Yindurain Colloquium, Department of Physics, UAM, Madrid **September 27, 2017**

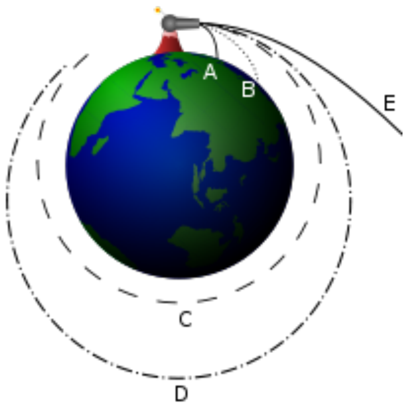
Outline:

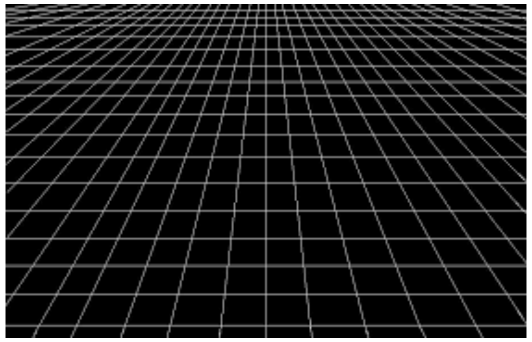
- The theory of General Relativity by Albert Einstein, where space & time can fluctuate.
- All kinds of "pandemonium" in the Universe can ring space & time: how gravitational waves are produced.
- A campaign to record the sky began more than a half century ago: the quest for gravitational waves & the theoretical groundwork to predict their shapes.
- LIGO discoveries: A few billion hundred-million light years away black holes collided in darkness launching very loud gravitational-wave trains into the Universe.
- It is now possible not only to "see" but also to "hear" the Universe through gravitational waves: what we learned and what we will learn.

Newton's gravity versus Einstein's theory of General Relativity



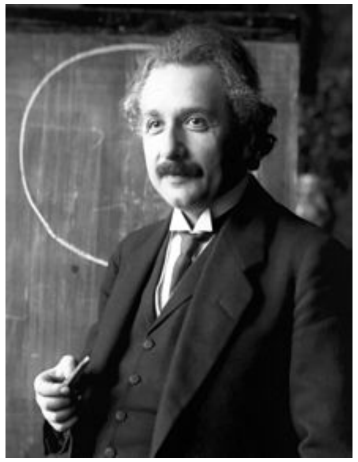
Newton's gravity
(1687)



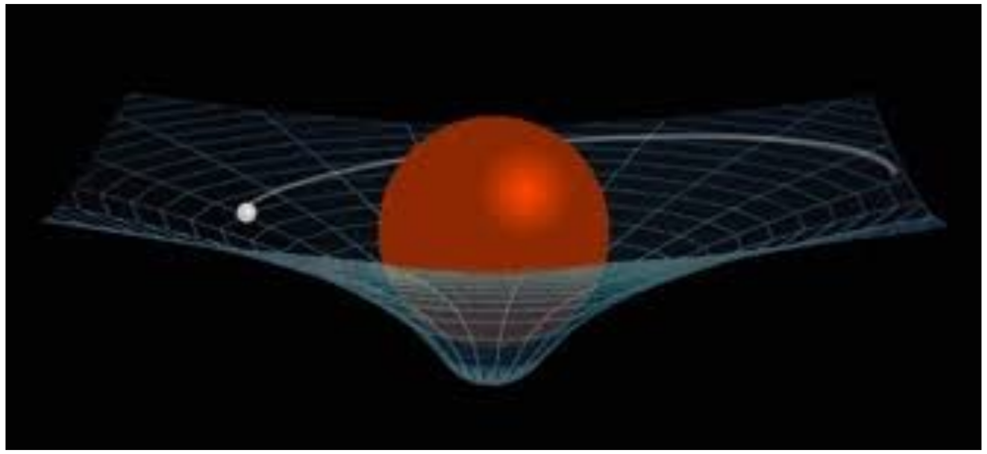


In Newton's gravity space and time are given a priori.

Time is absolute: it flows at the same rate everywhere, always.



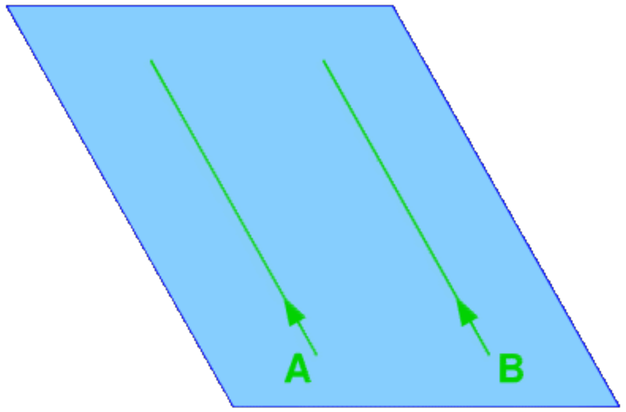
General Relativity
(1915)



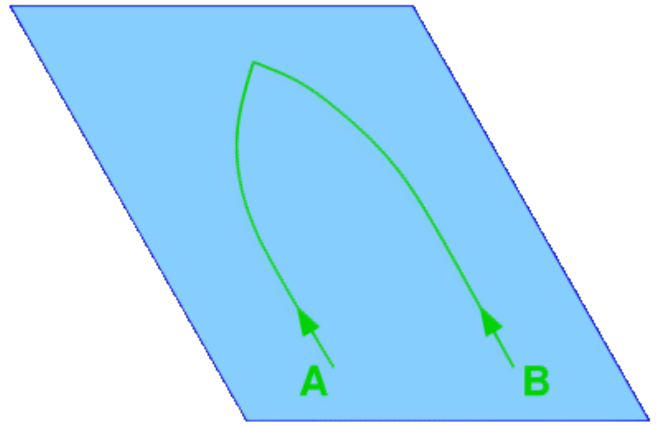
Space-time is a dynamic and elastic entity both influencing and influenced by the distribution of mass-energy that it contains.

Einstein's geometric gravity.

Einstein's geometric gravity

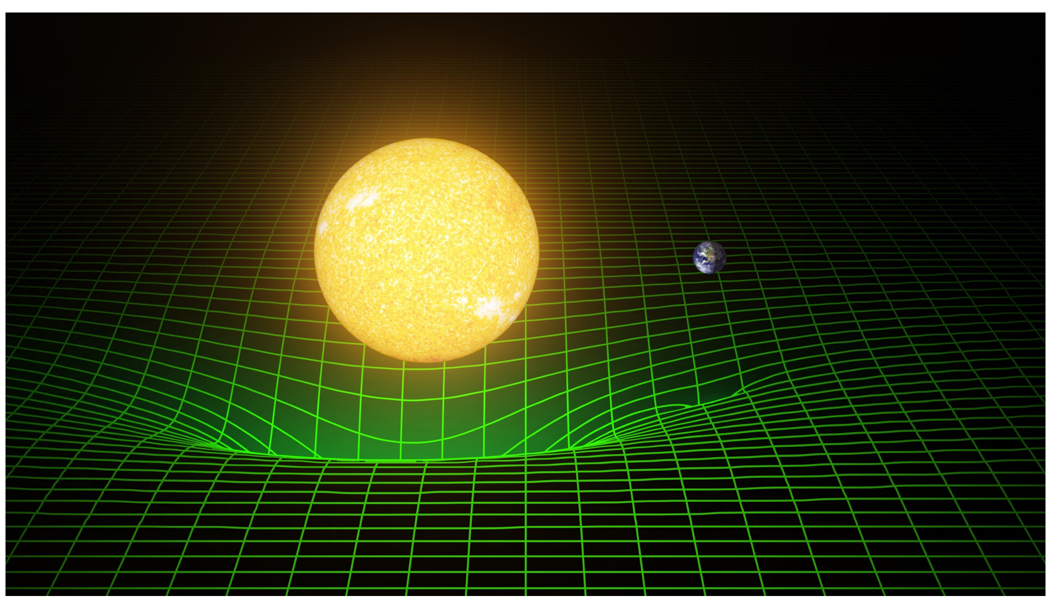


No forces between bodies A and B: bodies move along straightest possible lines.



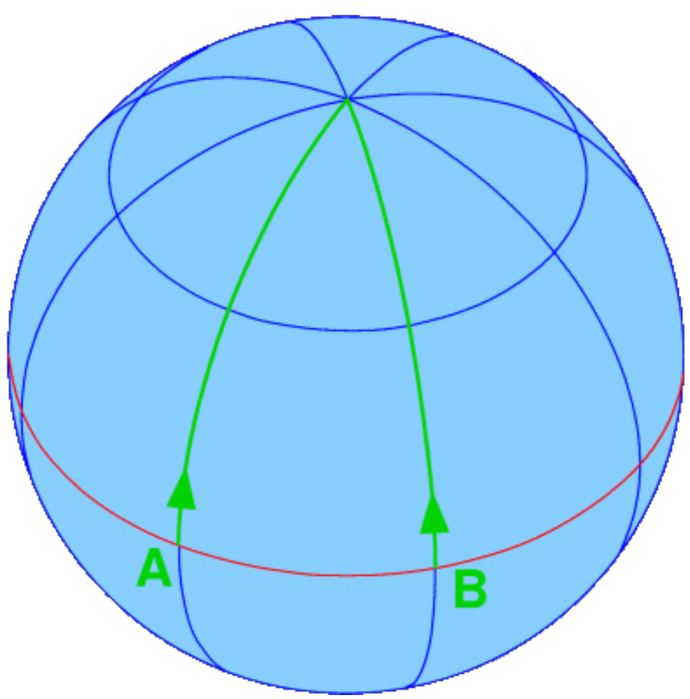
Bodies A and B no longer move along parallel lines. Why?

- Newton's gravity: there is a force between bodies A and B, thus they don't move along straightest possible lines.
- Einstein's geometric gravity: no force, bodies still move on straightest possible lines, but on a sphere not a plane!



Gravity is the effect of "curvature" (or warp) in the geometry of space-time caused by the presence of any object with mass/energy.

credit: Einstein online



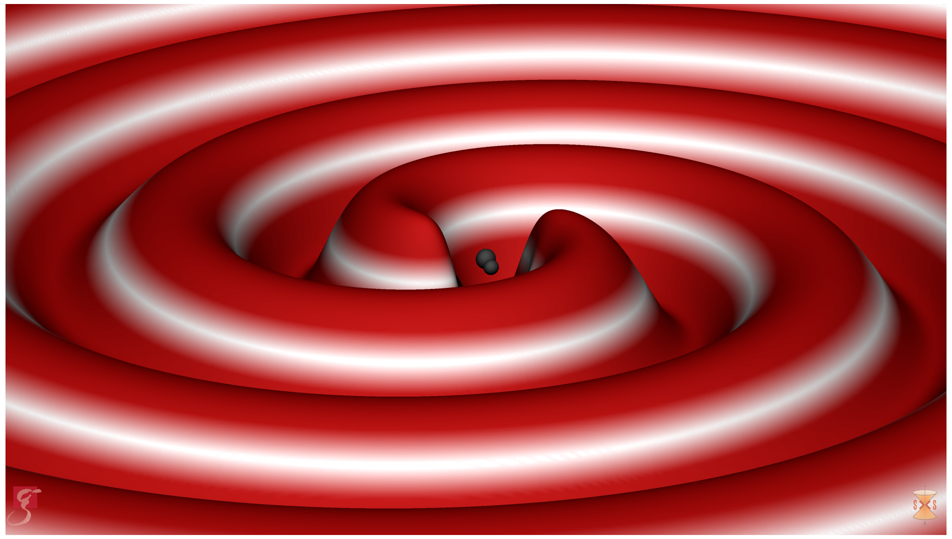
Gravitational waves: the signature of dynamical spacetime

Geometry of space-time is dynamic, not fixed!

1916: Einstein predicted existence of gravitational waves

Distribution of mass deforms space-time in its neighborhood. This deformation propagates away in form of waves whose oscillations reflect temporal variation of matter distribution.

Ripples in fabric of space-time



(credit: Haas @ AEI)

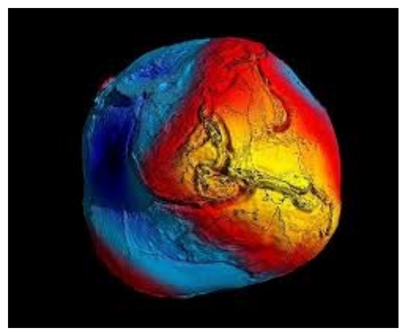
Ripples in the water

Gravitational waves are very weak. We need large and "compact" bodies moving at high velocities! We need black holes …

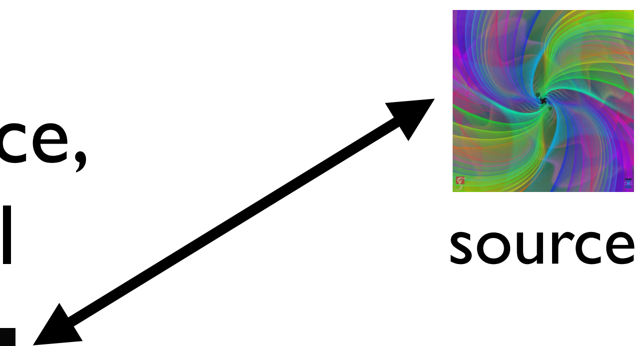
How gravitational waves are produced and typical strength

- GW sources are **dominated by gravity**

- GW are produced by variation in time of **"quadrupole moment"**:



- The **farther** is the source, the **weaker** is the signal on Earth



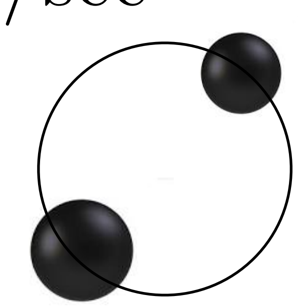
source

- Typical **GW power**:

$$\mathcal{L}_{\rm GW} \sim \epsilon^2 \, \frac{c^5}{G} \left(\frac{v}{c}\right)^{10} \qquad \frac{c^5}{G} \sim 10^{59} {\rm erg/sec}$$

$$\mathcal{L}_{\rm EM}^{\rm Sun} \sim 10^{26} {\rm Watts} \qquad \mathcal{L}_{\rm GW} \sim 10^{52} \; {\rm Watts}$$

(binary)



GW power can be similar or larger than the one of **whole visible Universe**!

- GW propagation (almost) unaffected by matter/energy: **pristine probes**

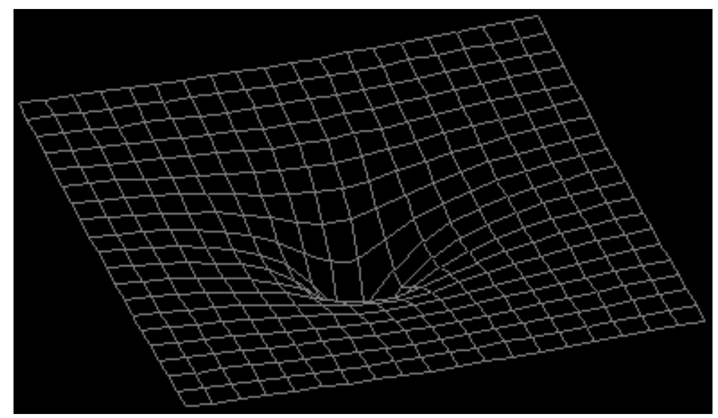
Black holes are ideal candidates. What are they?

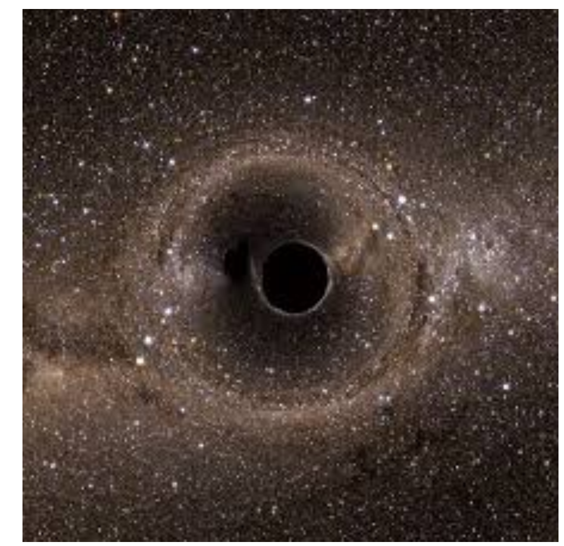
A black hole is made of warped space and time. No matter!

Neither light nor anything else can escape black-hole "horizon".

black-hole mass: 10 Msun
black-hole radius: 30 km!

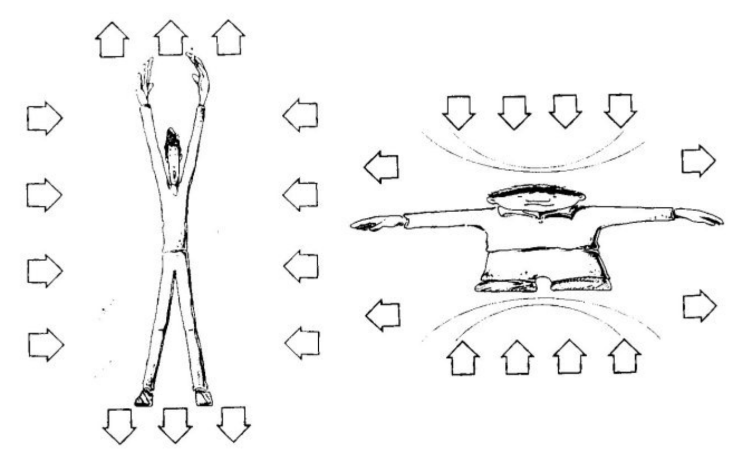
Sun mass: 1 Msun $=10^{30}$ kg
Sun radius: 700,000 km!





Black hole gravitational pull twists and bends geometry of space around the hole, in the same way a heavy ball placed on a sheet of rubber twists and bends the sheet's geometry.

In the hole's vicinity no longer true that circumference = radius (2 π) !



When falling into a black hole …

When (stellar-mass) black holes collide, space-time rings …

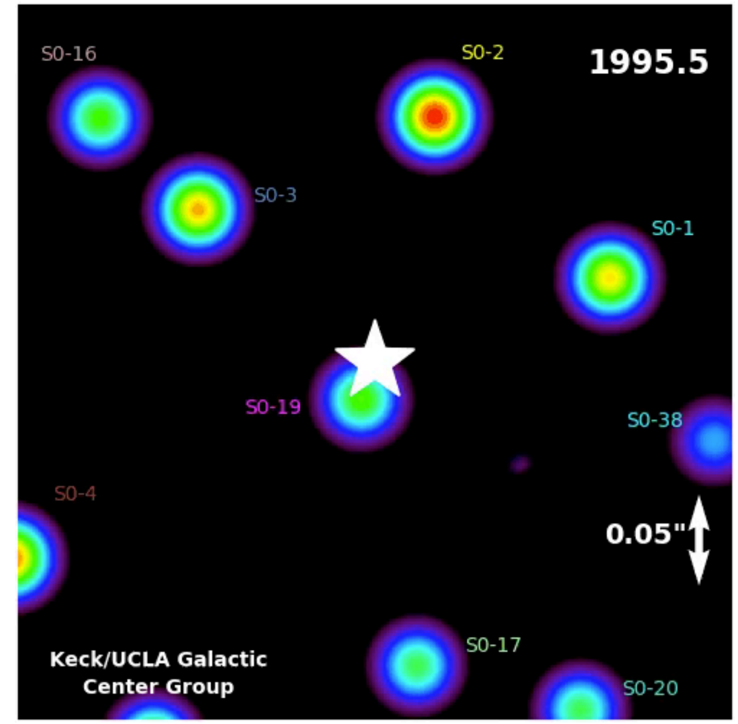
Credit: AEI/Milde Marketing

None of the energy emitted by the collision comes out as light.
No telescope will ever see the events, but we can “hear” them …

Black holes orbiting each other are the strongest sources of gravitational waves

Supergiant star--Cygnus X-1 binary system

credit: Ghez's group

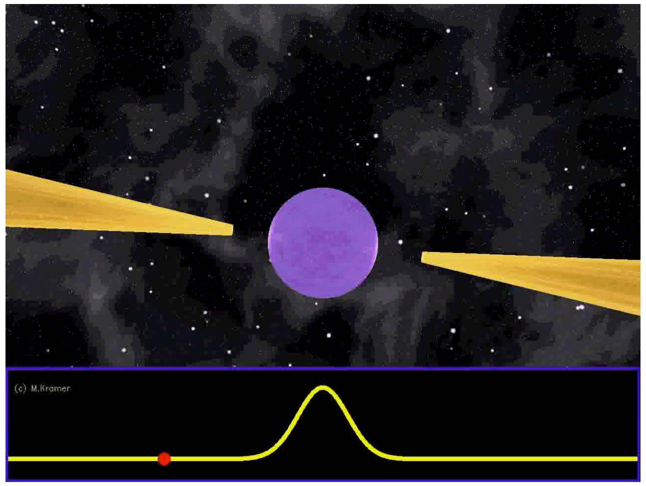


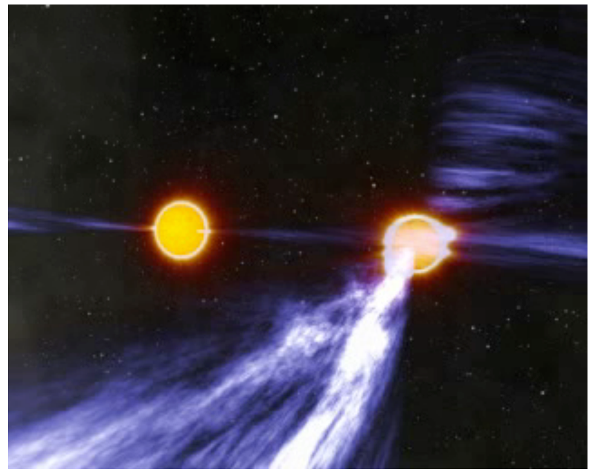
Black hole of 4 million solar masses in our galaxy's center!

(visualization credit: Cornell U)

Binary black hole

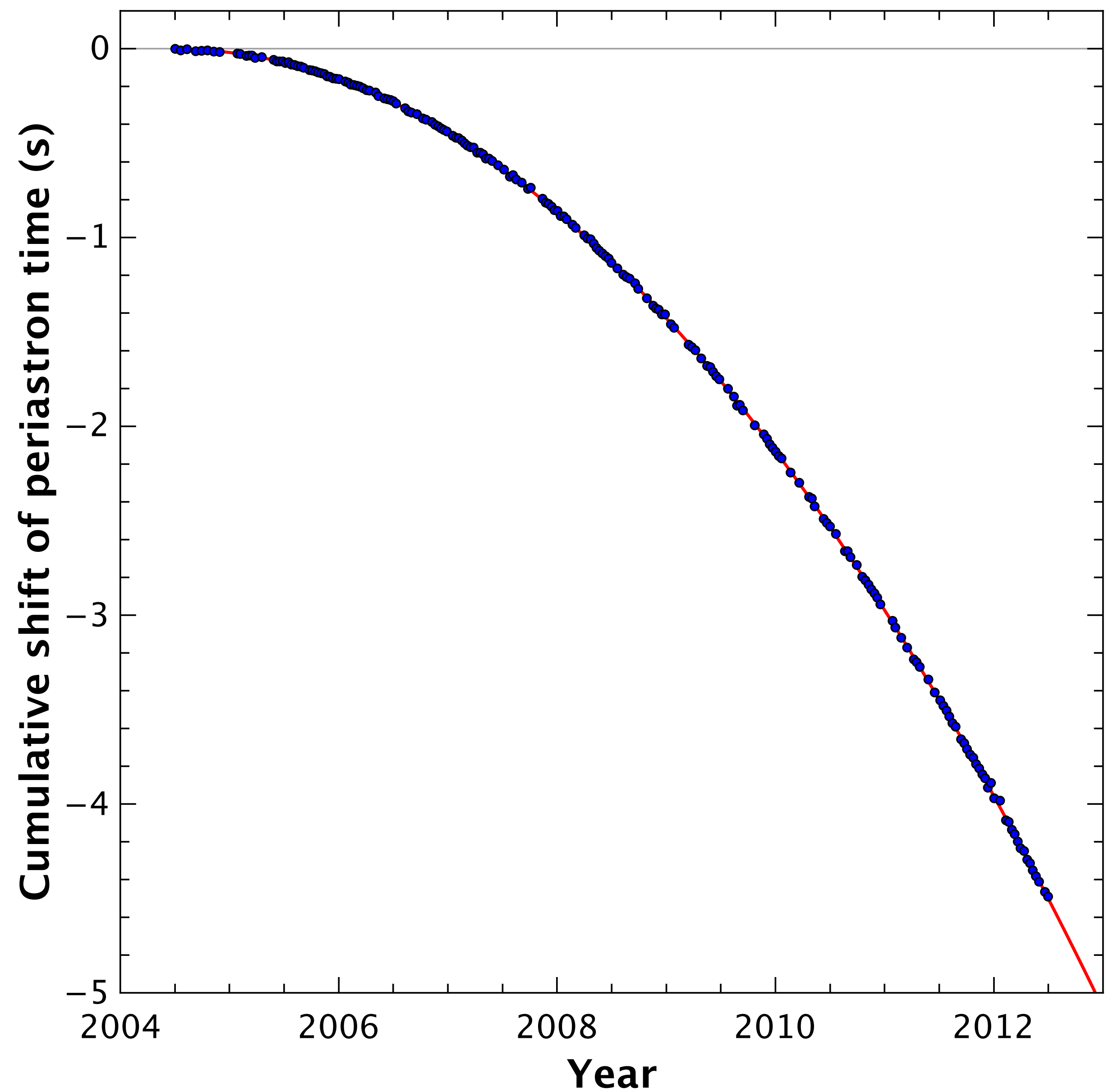
Gravitational waves do exist: we knew it from binary pulsars





credit: Kramer's group

Nobel prize to Hulse & Taylor in 1993



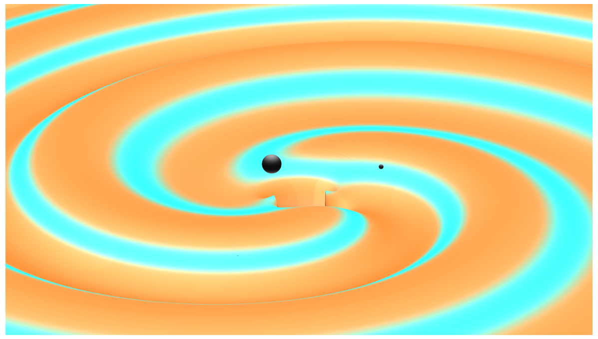
(Kramer et al. 2017)

Double-pulsar binary in close orbit with period of 2.45 hours.

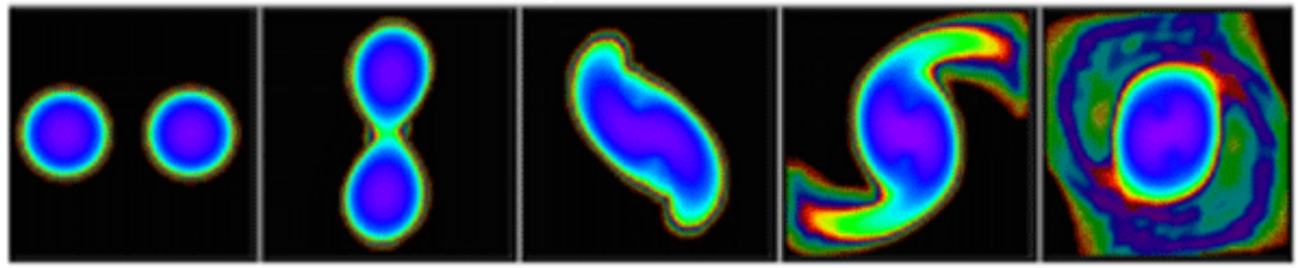
The orbital period slowly decreases at just the rate predicted by general relativity.

Before LIGO detections, this was the strongest evidence for existence of gravitational radiation!

The Transient & Persistent Gravitational-Wave Sky

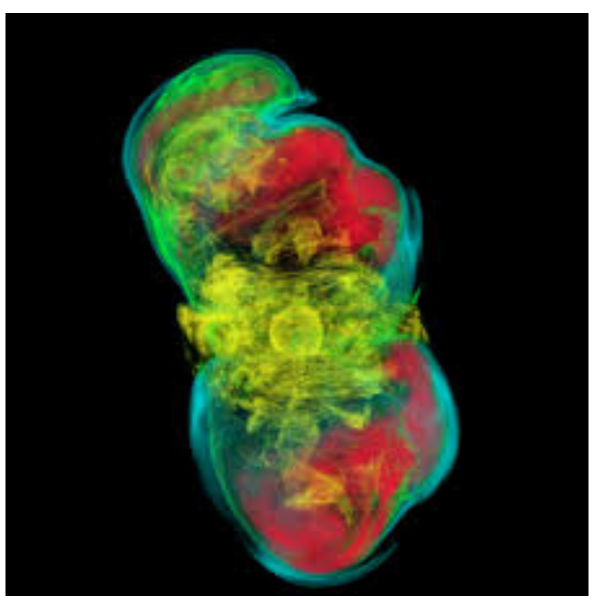


binary black hole

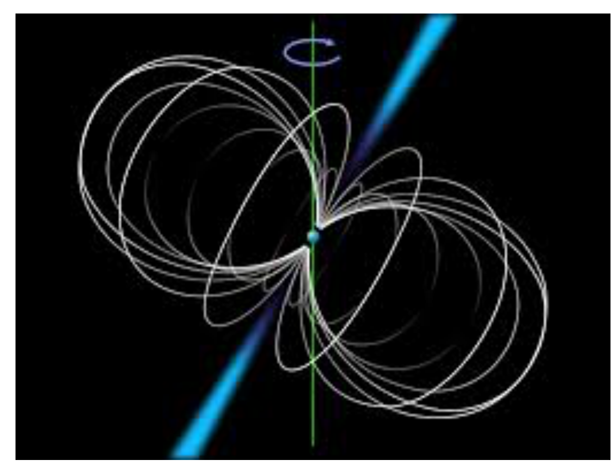


binary neutron star

- GWs from **binaries** are in band for **tens of msec/mins** in **LIGO/Virgo, months/years** in **Einstein Telescope/LISA** and are **continuous signals** in **Pulsar Timing Arrays**.



- **Periodic** GW signals from **pulsars**.

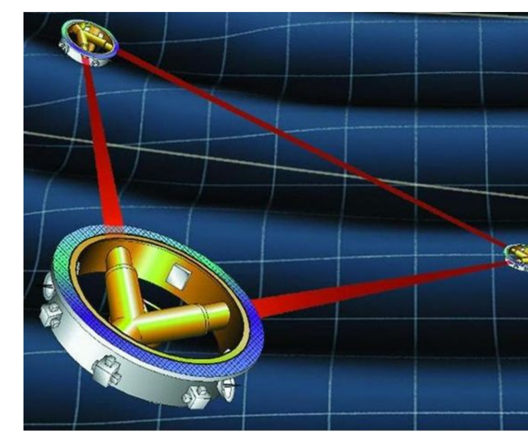


- GW-bursts from **supernovae** are in band for **tens of msec**.

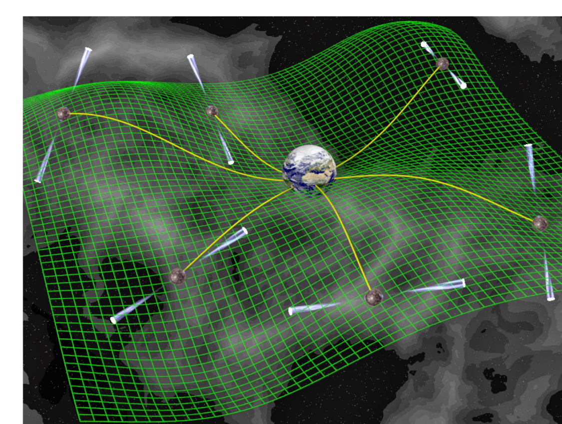
- **Stochastic** GW backgrounds from **early Universe**.

- GW frequency: 10^{-9}–10^{3} Hz

LIGO

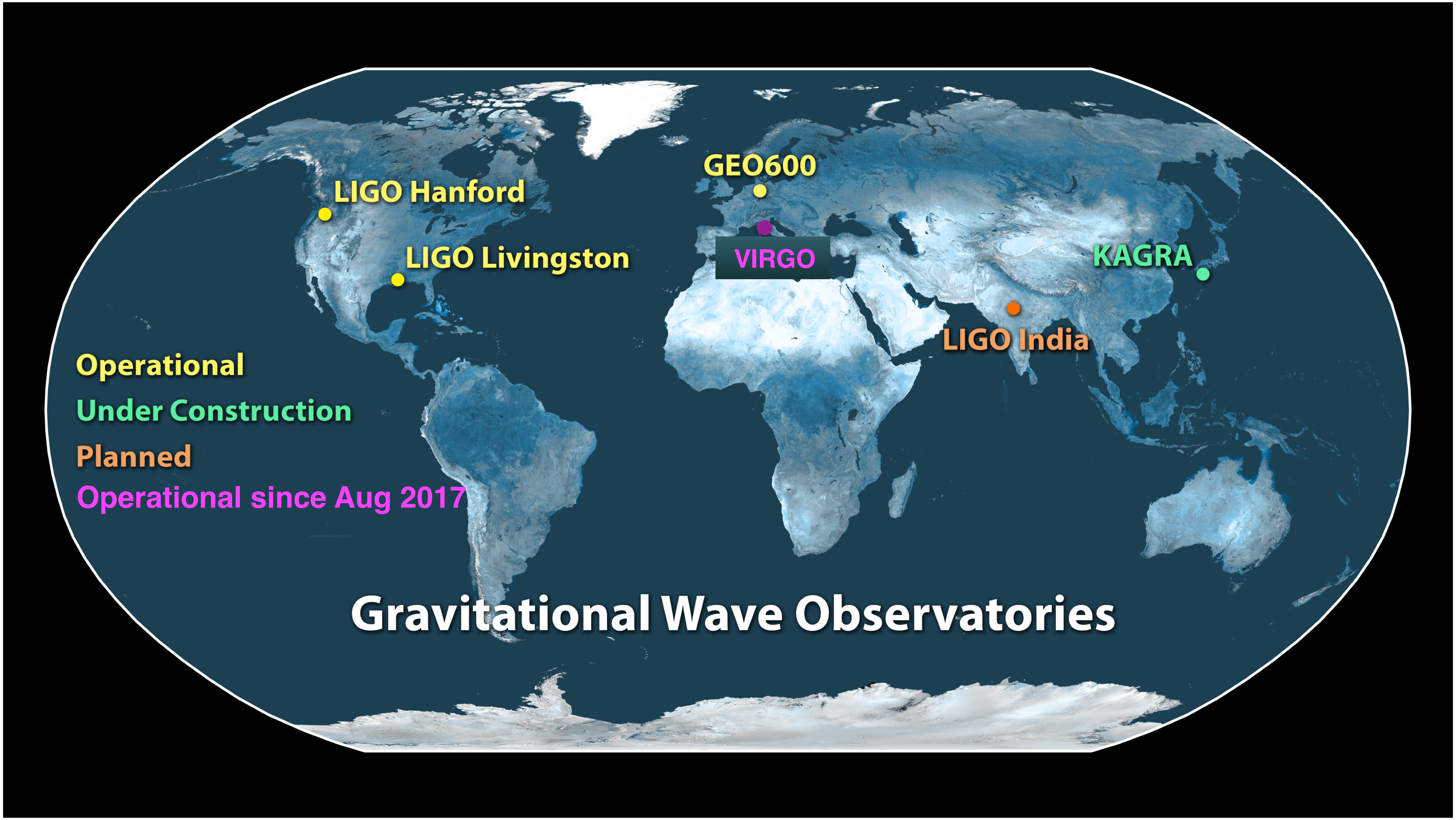


LISA



Pulsar Timing Array

International network of detectors to record the sky



LIGO Scientific Collaboration: about 800 members!

LIGO

LSC

LIGO Scientific Collaboration

LIGO Scientific Collaboration & Virgo Collaboration: 1004 members!

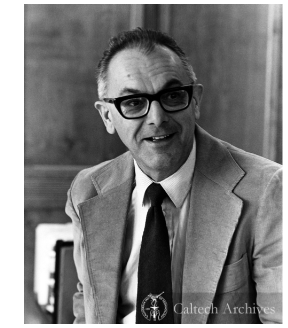
LIGO VIRGO

Several decades of patient and steady work … finally paid off!

Joe Weber, University of Maryland

Heinz Billing, and Garching group

Kip Thorne, Caltech



Rochus Vogt, Caltech

Ron Drever, Caltech

Rai Weiss, MIT

Barry Barish, Caltech

Total cost of LIGOs: about 1.1 billion dollars

- 1960 — First ideas by Weber/ Forward
- 1967 — First detailed interferometer study by Weiss
- 1989 — First LIGO proposal to NSF
- 1994 — Largest funded NSF project in history
- 2004 — Initial LIGO
- 2015 — Advanced LIGO

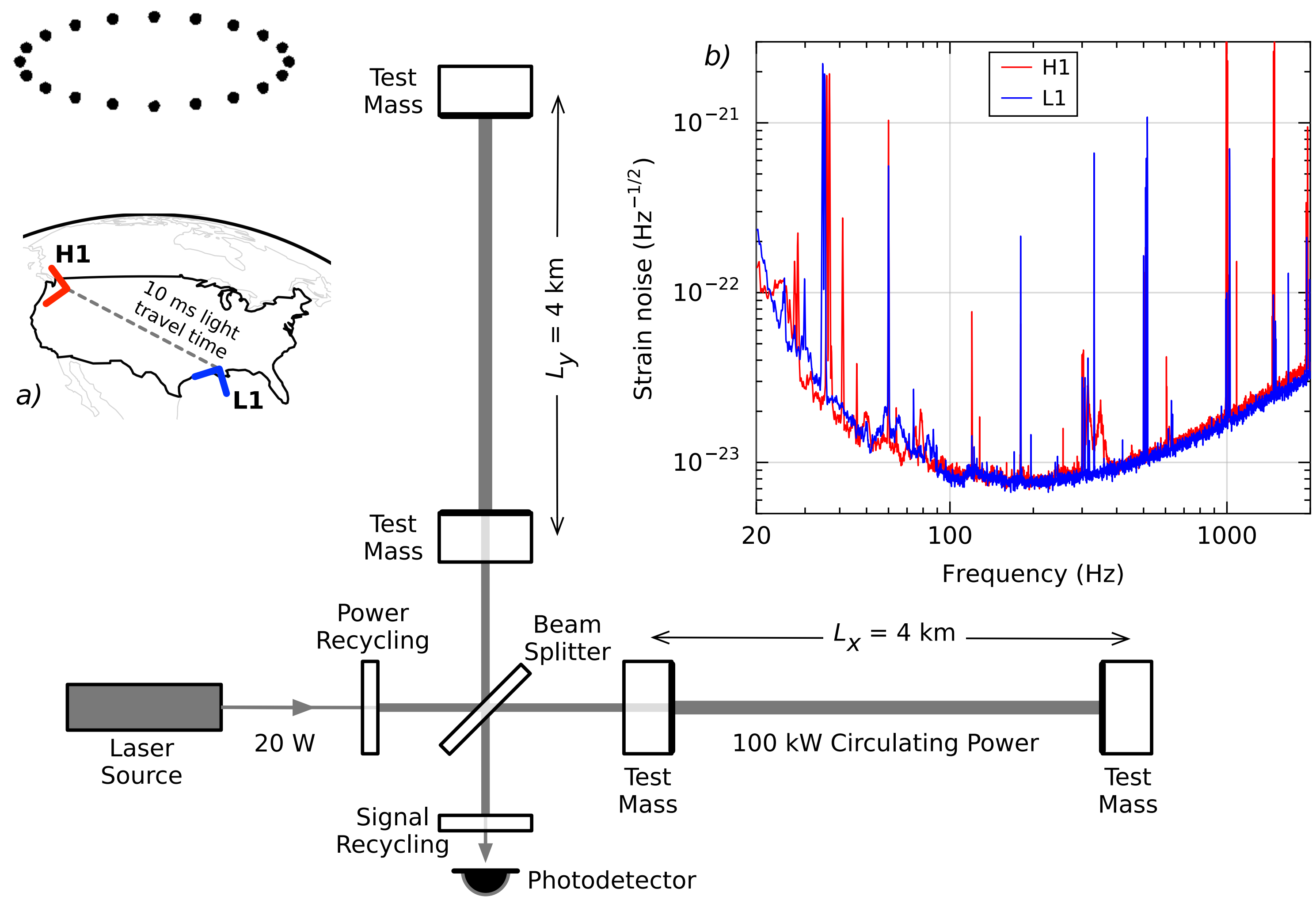
Crucial also theoretical groundwork to solve Einstein equations, and predict shape of gravitational waves from astrophysical sources.

First detections of gravitational waves passing through Earth

LIGO in Washington (H1)

LIGO in Louisiana (L1)

(Abbott et al. PRL 116 (2016) 061102)



$$\Delta L = L\, h \sim 10^{-16}\,\mathrm{cm}$$

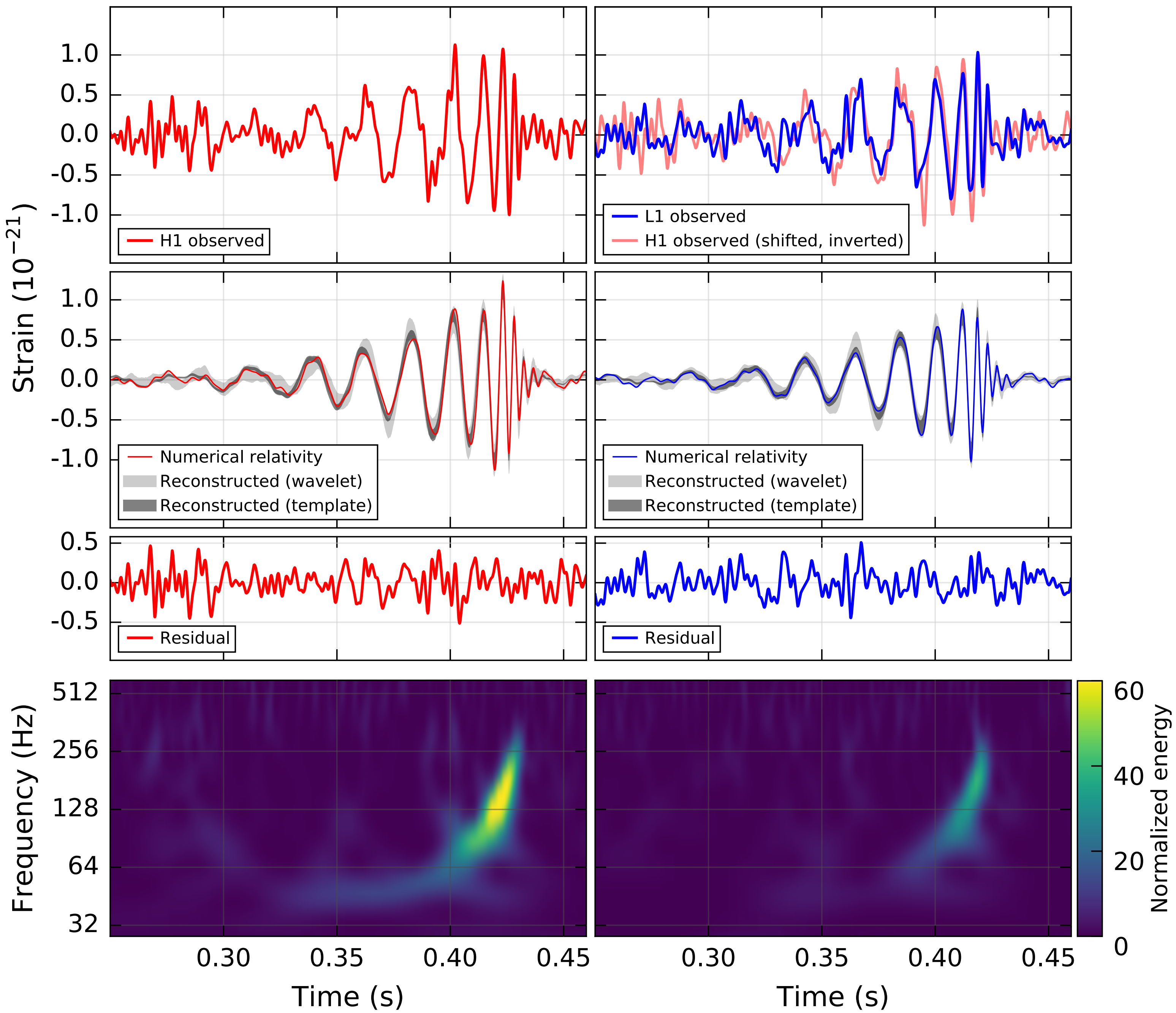
$$L = 4\,\mathrm{km} \Rightarrow h \sim 10^{-21}$$

On Sept 14, Dec 26, 2015 and Jan 4, 2017 GWs were detected!

LIGOs measures displacements of mirrors at about a ten-thousandth of a proton's diameter.

First LIGO Detection: GW150914

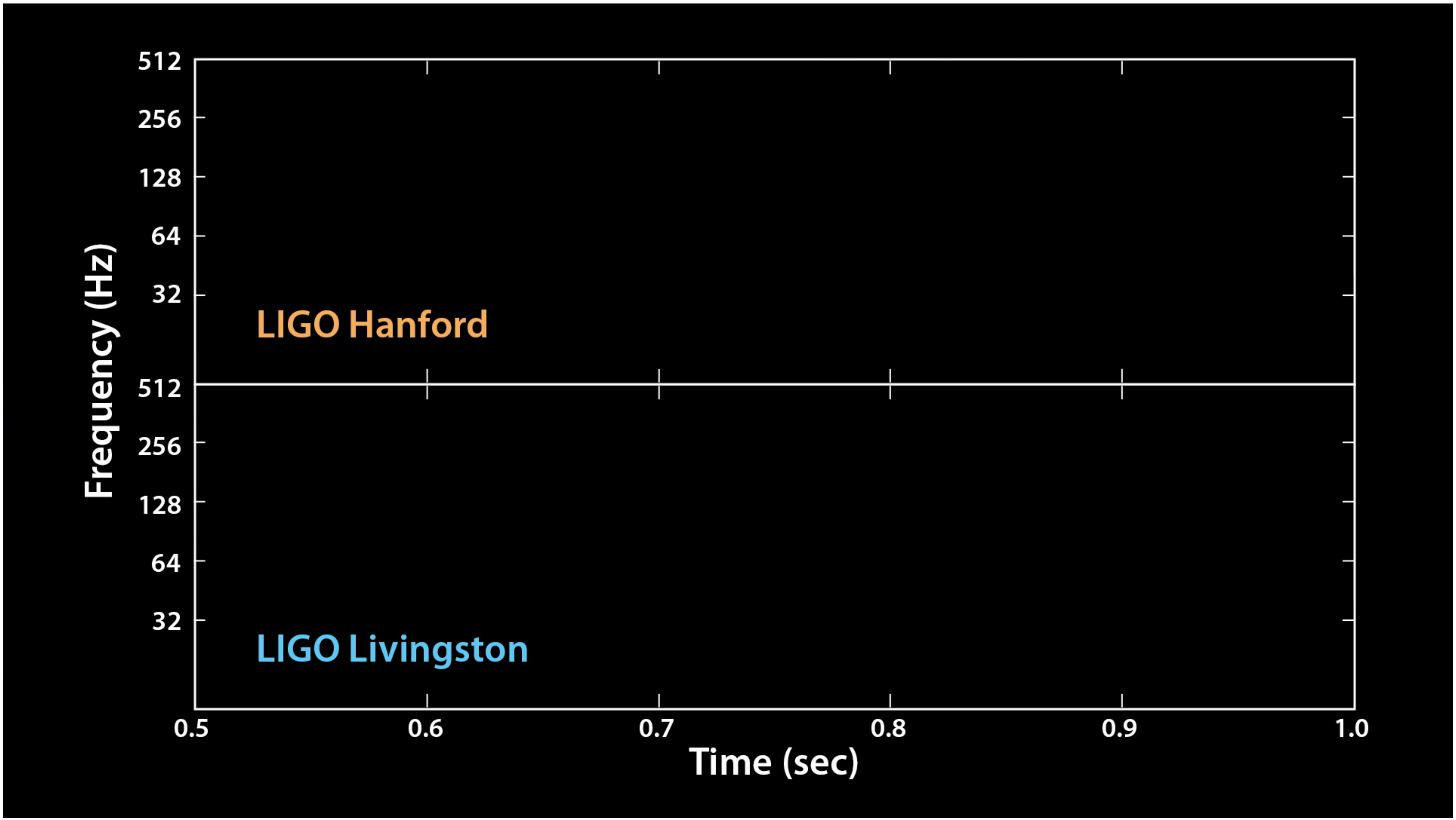
(Abbott et al. PRL 116 (2016) 061102)



Gravitational waves carry fingerprints of the source that has generated them.

When black holes collide they make a sound

"Hearing" the gravitational wave or chirp



LIGO Scientific Collaboration

LIGO discovery made a big splash in the News

“Was that you I heard just now, or was it two black holes colliding?”

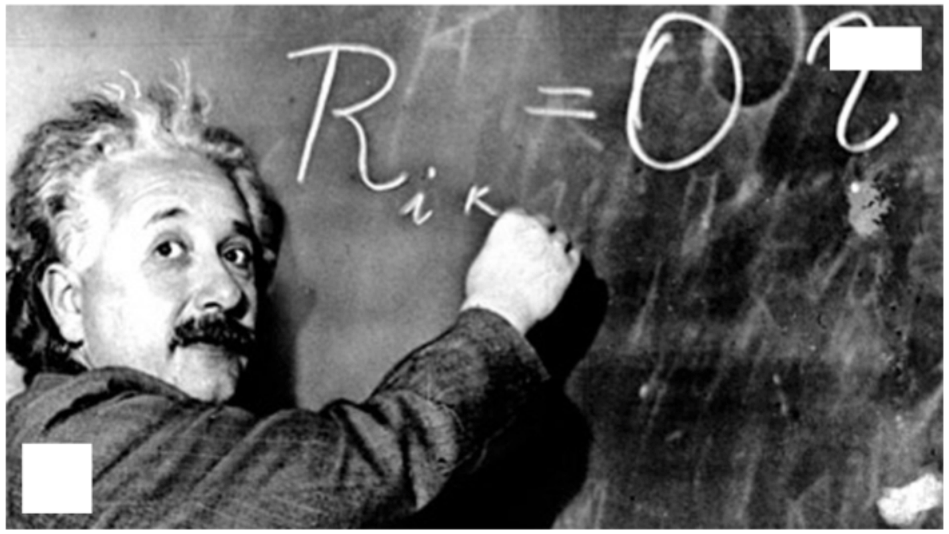
The New Yorker

Descubierta la primera señal de ondas gravitacionales

Un experimento en EE UU asegura ser el primero en confirmar la existencia del "sonido del universo" predicho por Albert Einstein

NUÑO DOMÍNGUEZ

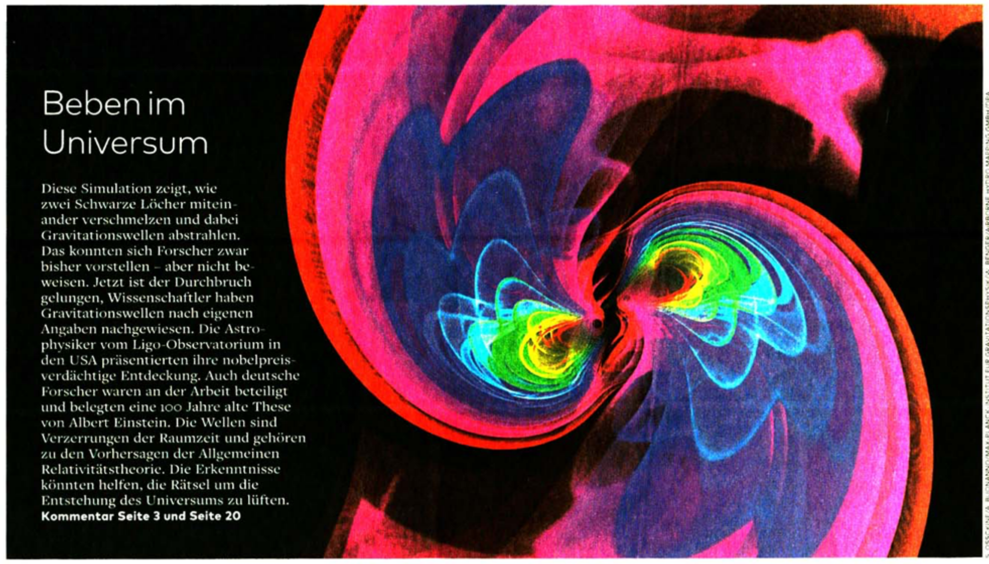
11 FEB 2016 - 19:24 CET



La última gran predicción de Albert Einstein sobre el universo se acaba de confirmar un siglo después: las ondas gravitacionales existen y un experimento en EE UU las ha detectado por primera vez.

DIE WELT

85 37 FREITAG, 12. FEBRUAR 2016



Chirp from black holes validates Einstein

Sound of cosmic collision offers direct evidence of gravitational waves

BY DENNIS OVERBYE

A team of physicists who can now count themselves as astronomers announced on Thursday that they had heard and recorded the sound of two black holes colliding a billion light-years away, a fleeting chirp that fulfilled the last prophecy of Einstein's general theory of relativity.

That faint rising tone, physicists say, is the first direct evidence of gravitational waves, the ripples in the fabric of space-time that Einstein predicted a century ago. And it is a ringing (pun intended) confirmation of the nature of black holes, the bottomless gravitational pits from which not even light can escape, which were the most foreboding (and unwelcome) part of his theory.

More generally, it means that scientists have finally tapped into the deepest register of physical reality, where the weirdest and wildest implications of Einstein's universe become manifest.

Conveyed by these gravitational waves, an energy 50 times greater than that of all the stars in the universe put together vibrated a pair of L-shaped antennas in Washington State and Louisiana known as LIGO on Sept. 14.

If replicated by future experiments, that simple chirp, which rose to the note of middle C before abruptly stopping, seems destined to take its place among the great sound bites of science, ranking with Alexander Graham Bell's "Mr. Watson — come here" and Sputnik's first beeps from orbit.

"We are all over the moon and back," said Gabriela González of Louisiana State University, a spokeswoman for

BLACK HOLES, PAGE 6

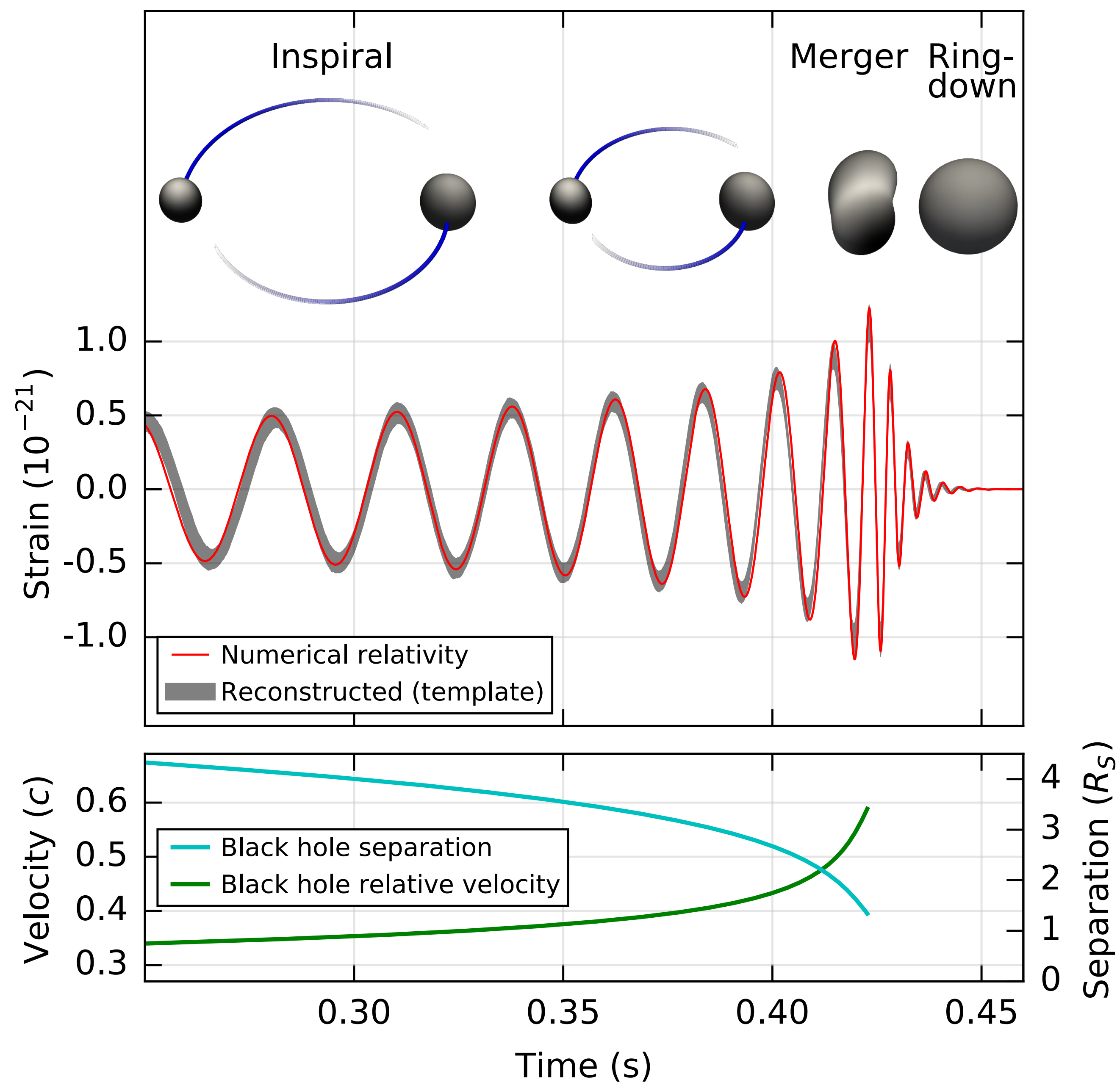
SIMULATING EXTREME SPACETIMES

An artist's rendering of two black holes that collided more than a billion years ago.

The cosmic dance during the final 200 milliseconds

- **Early inspiral:** low velocity & weak gravity.
- **Late inspiral/plunge:** high velocity & strong gravity.
- **Merger:** black holes collide and form a new black hole!
- **Ringdown:** excitation of black-hole frequencies/spacetime vibrations.

(Abbott et al. PRL 116 (2016) 061102)

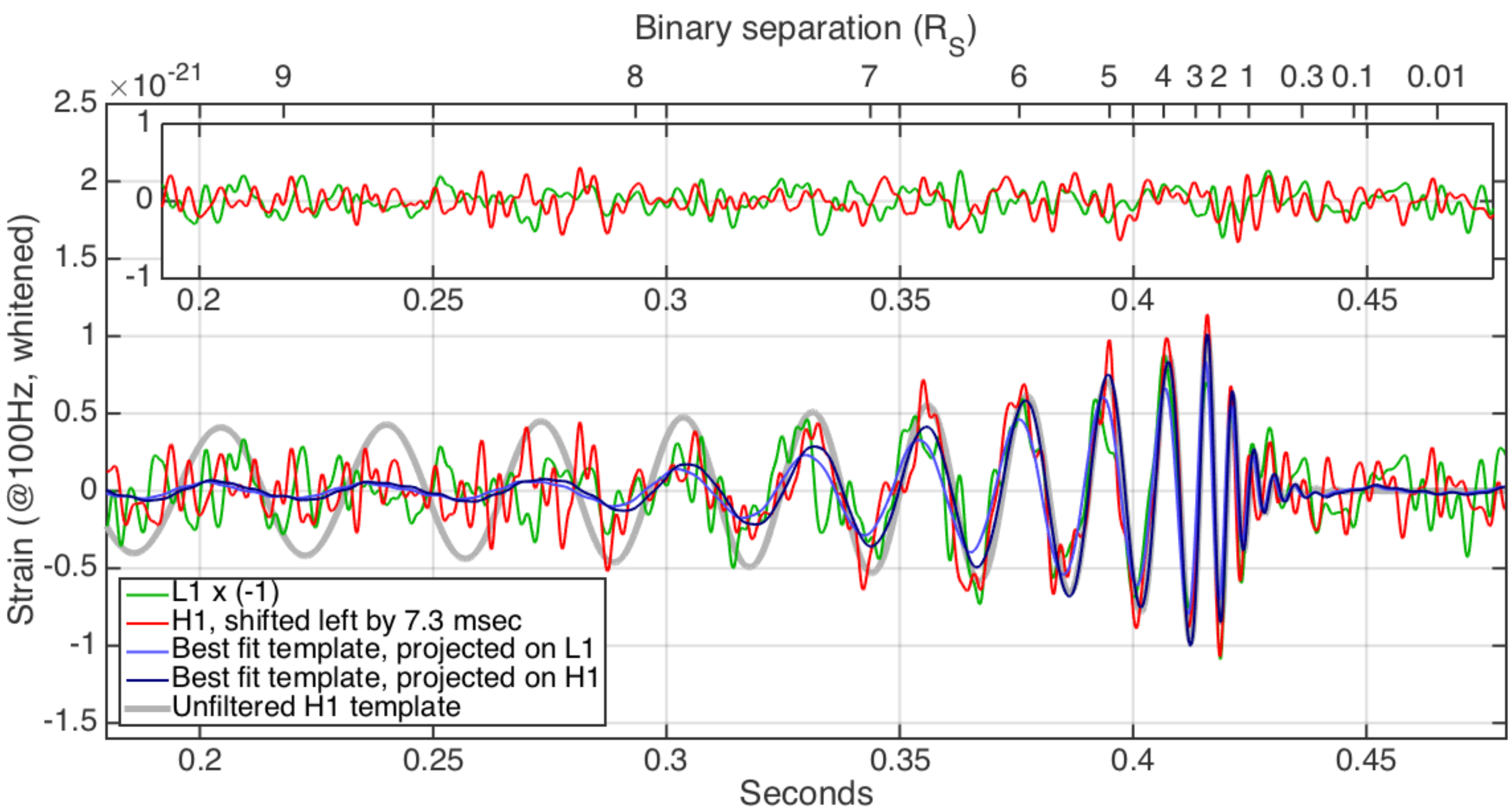


Black holes collide at (almost) speed of light, like fundamental particles.

Black holes of radius of 90 km at separation of 350 km are making 75 orbits per second before merging.

How do we build waveform models?

- **Einstein equations predict gravitational waves from colliding black holes, but it is difficult and time consuming to solve for them!**
- **We combine approximation methods to build highly-accurate waveform models (or templates) and use them to detect and infer black hole properties.**



LIGO-T1500560

Analytical and numerical relativists at work

Model waveforms are built using analytical relativity (i.e., paper & pencil) and numerical relativity (i.e., supercomputers).

Paper & pencil (fast but approximate)

"DATA, DATA EVERYWHERE!"

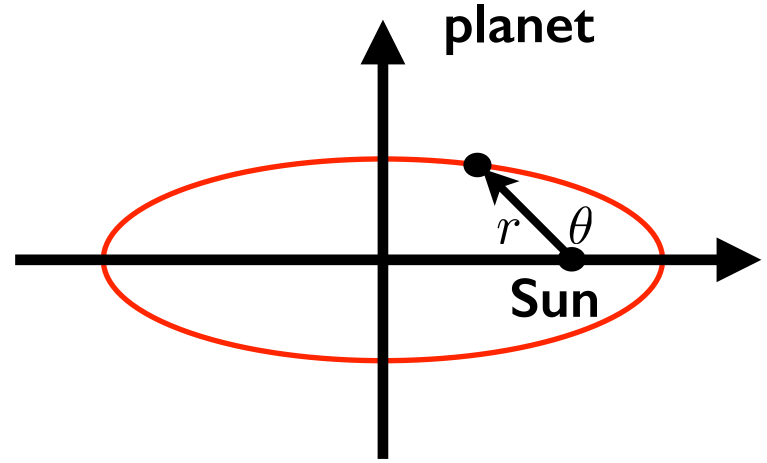
Supercomputers (slow but exact)

Working at the interface between analytical and numerical relativity, one tries to find a law or a pattern hidden in the data and formalize it with an equation or a model.

What is an approximate (analytic) model

- **Newtonian gravity:**

curve for orbit
(numerical)



formula for orbit
(analytical)

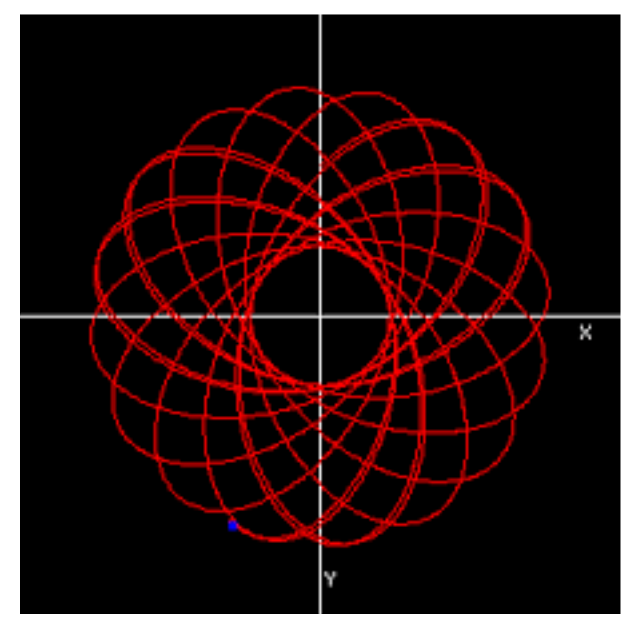
$$r = \frac{p}{1 + \epsilon \cos\theta}$$

- **General Relativity:**

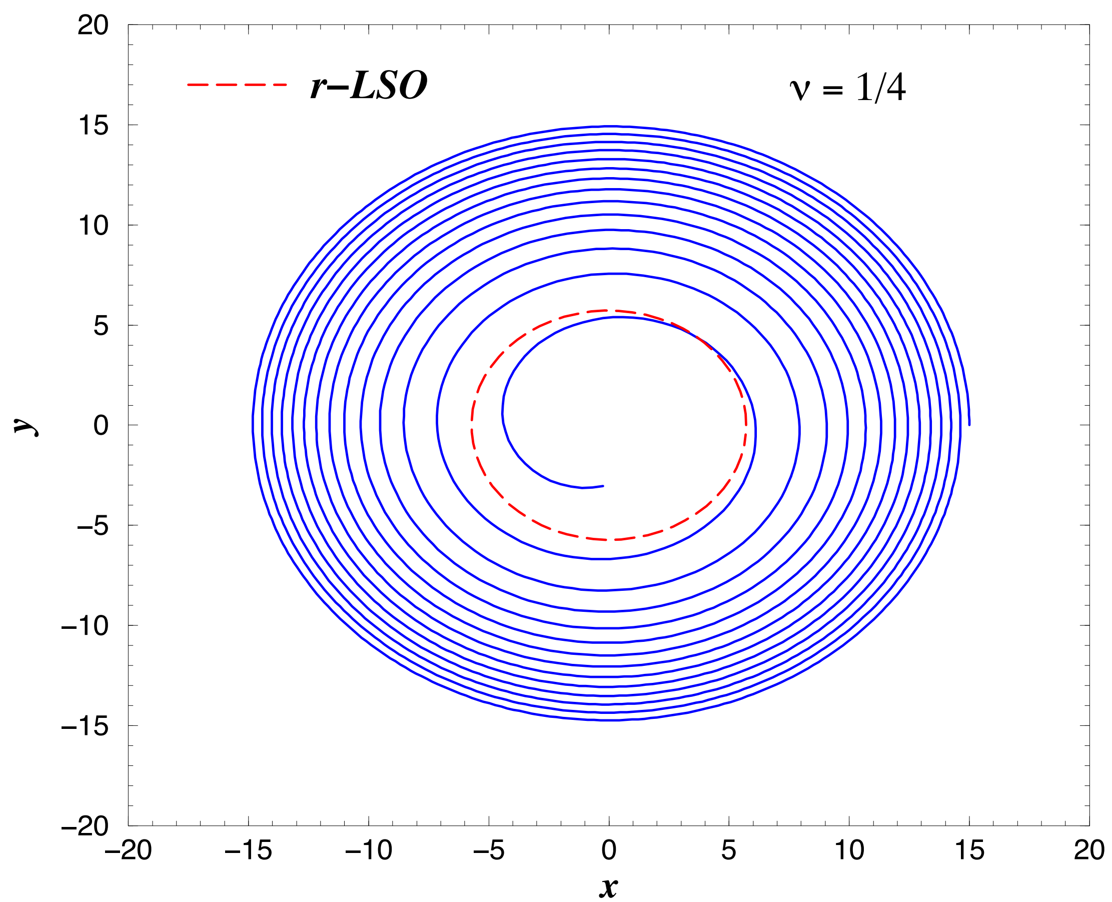
- Impossible to find exact formula for orbit.

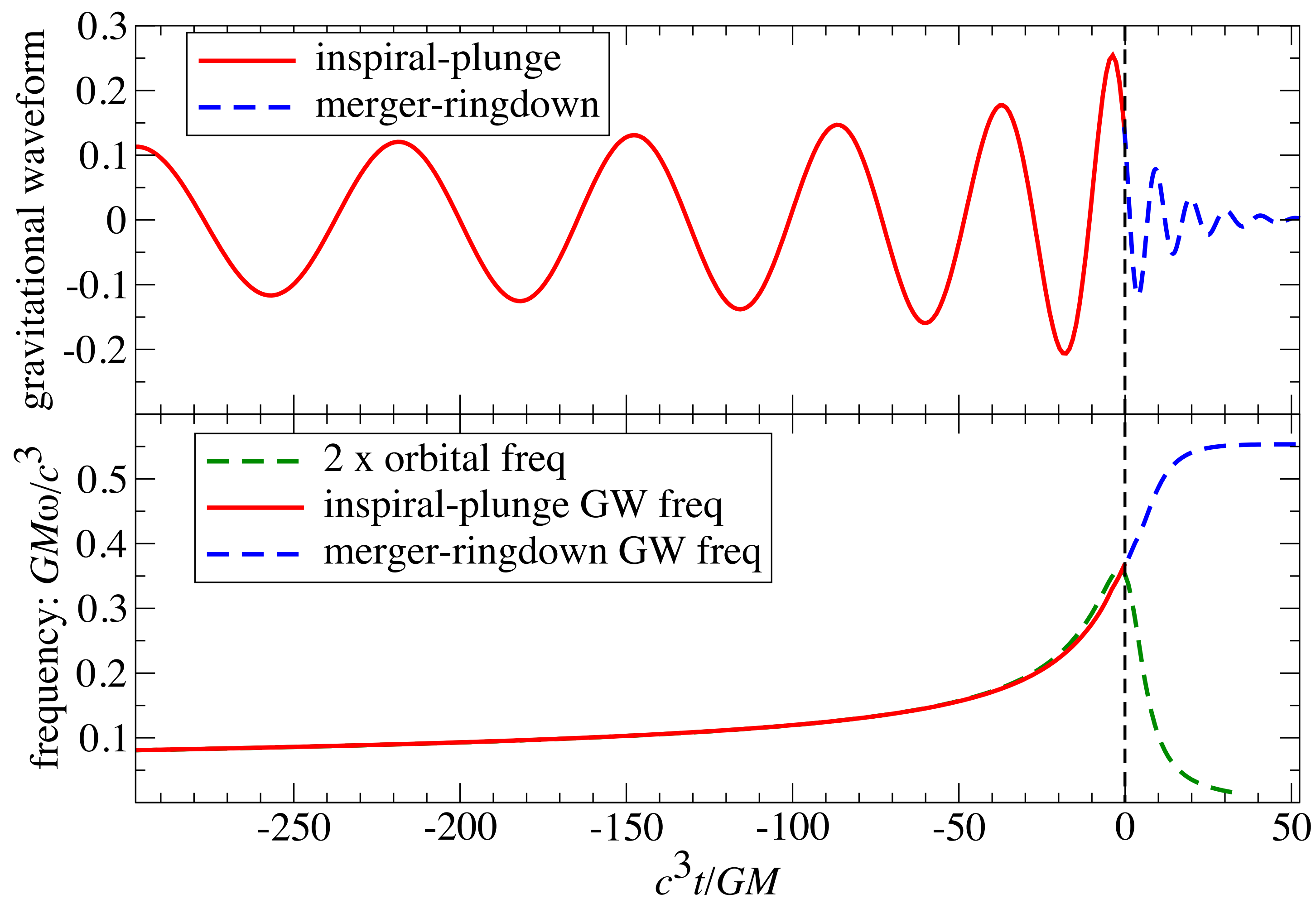
- Ellipse is no longer fixed and it also shrinks over time.

- Possible to find approximate, analytic model for the orbit.



Approximate analytic model for orbit and waveform





(AB & Damour Phys.Rev. D62 (2000) 064015)

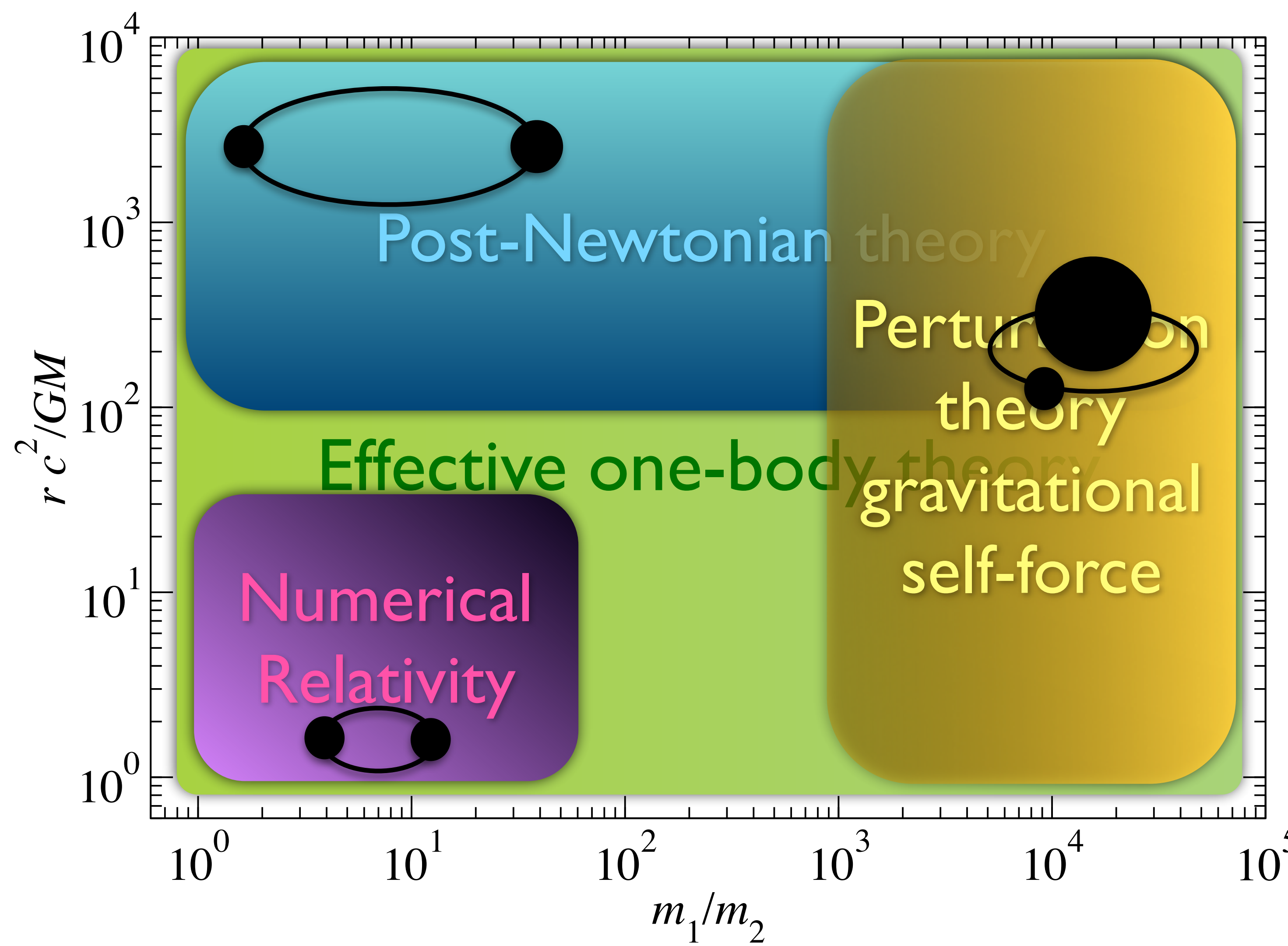
- **Curves computed solving equations and/or using analytic formulas that approximate Einstein equations.**

Solving Two-Body Problem in General Relativity (including Radiation)

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

- **GR** is **non-linear theory**. Complexity similar to QCD.

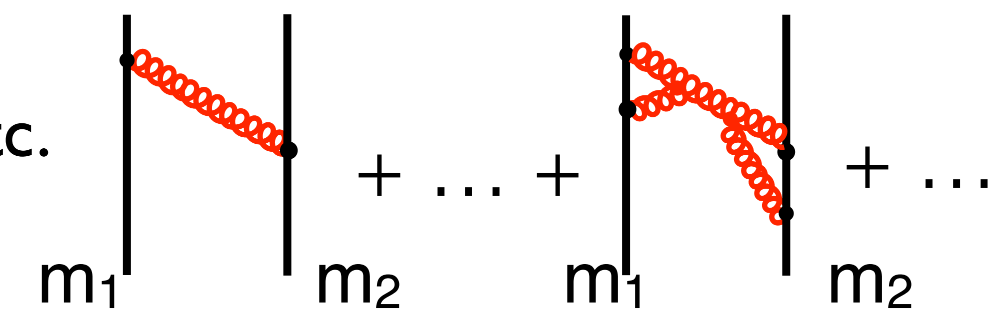
- Einstein's field equations can be solved:
  - **approximately,** but **analytically** (**fast** way)
  - **exactly**, but **numerically** on supercomputers (**slow** way)



(AB & Sathyaprakash 14)

- **Analytical methods**: post-Newtonian/post-Minkowskian expansions, gravitational self-force, effective-one-body theory

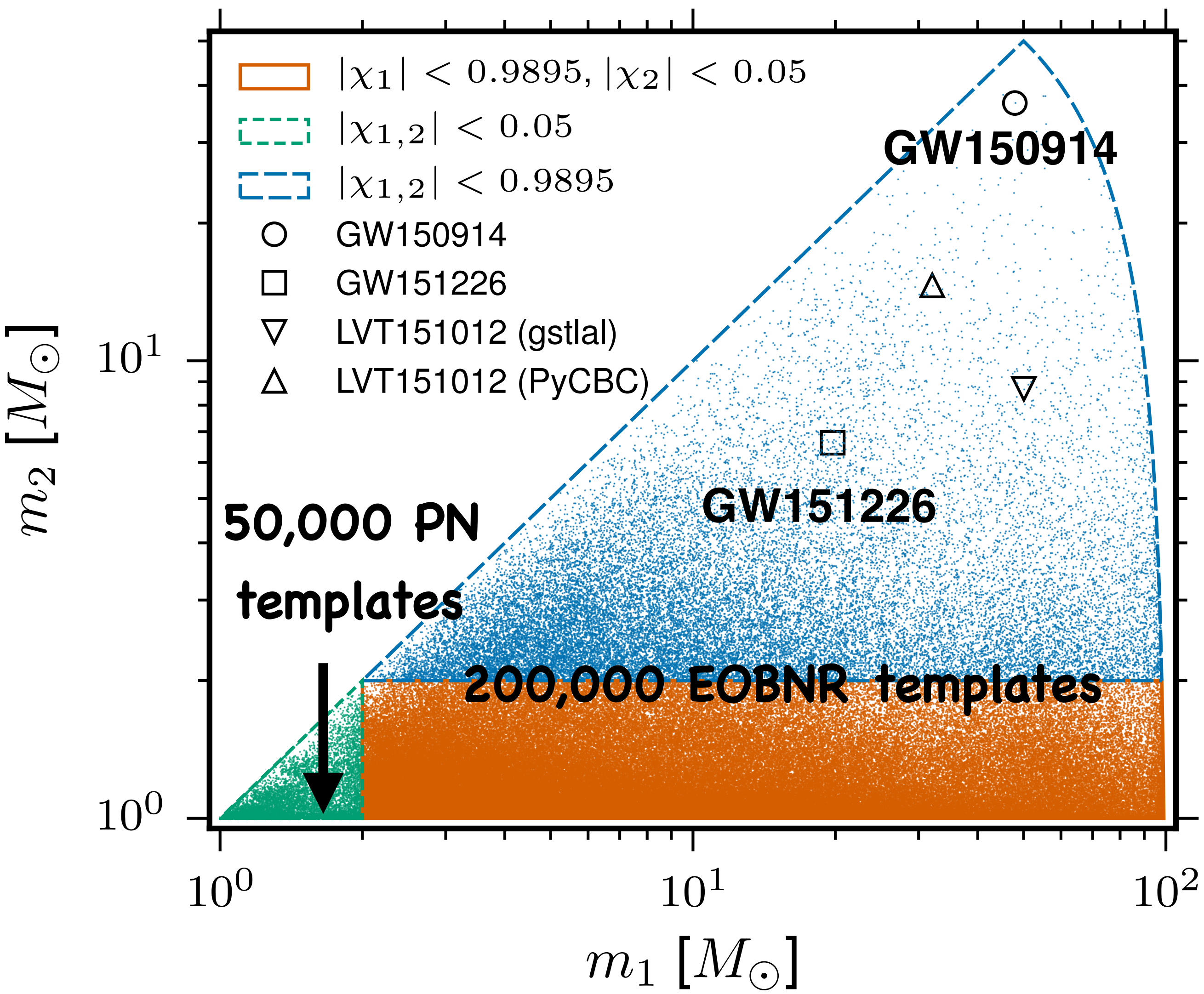
  - **effective field-theory**, **dimensional regularization**, etc.
  - **diagrammatic** approach to organize expansions

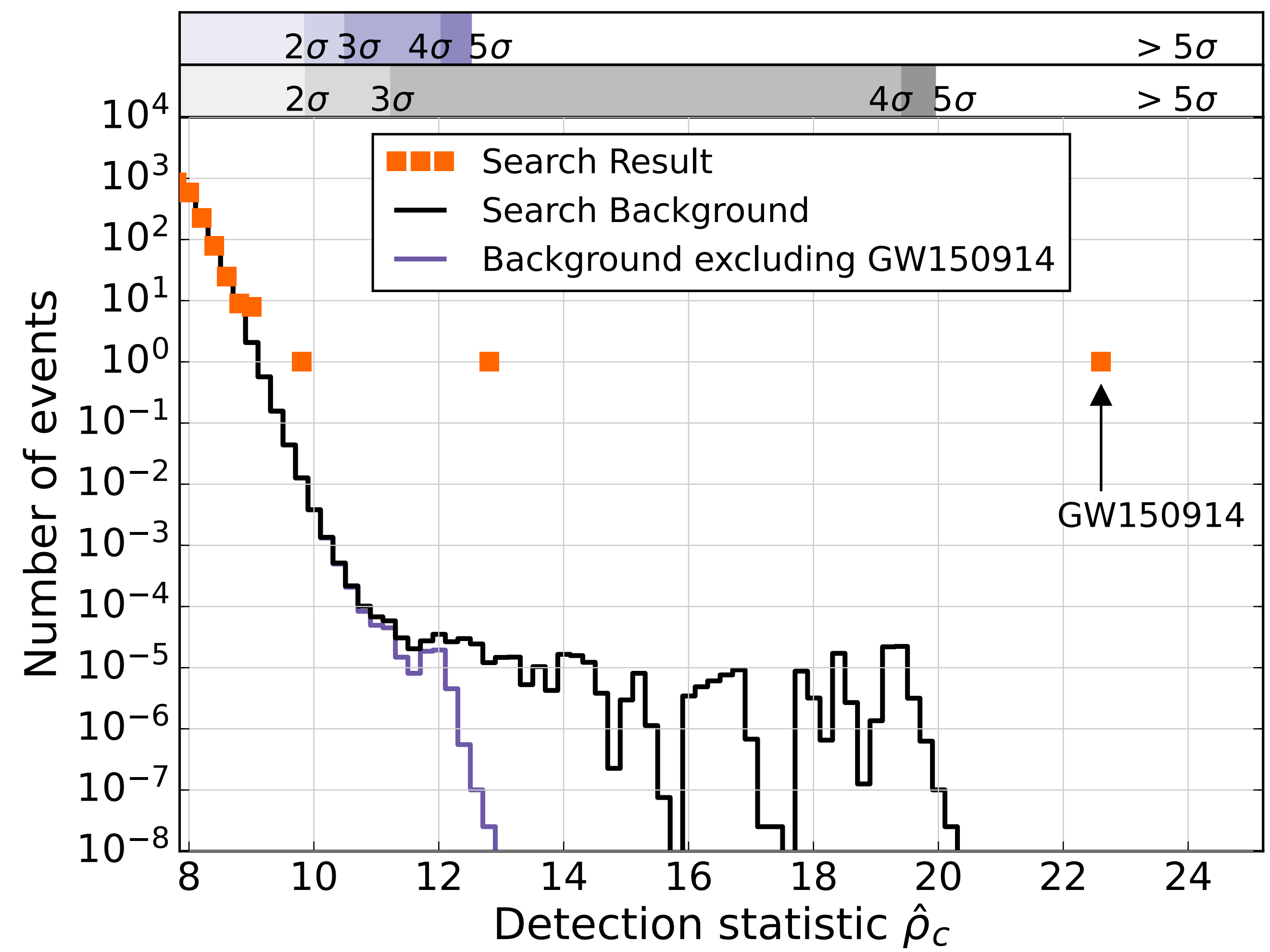


Assessing statistical confidence in LIGO detection

- **Matched filtering** employed

(*Abbott et al.* Phys.Rev. X6 (2016) no.4, 041015)

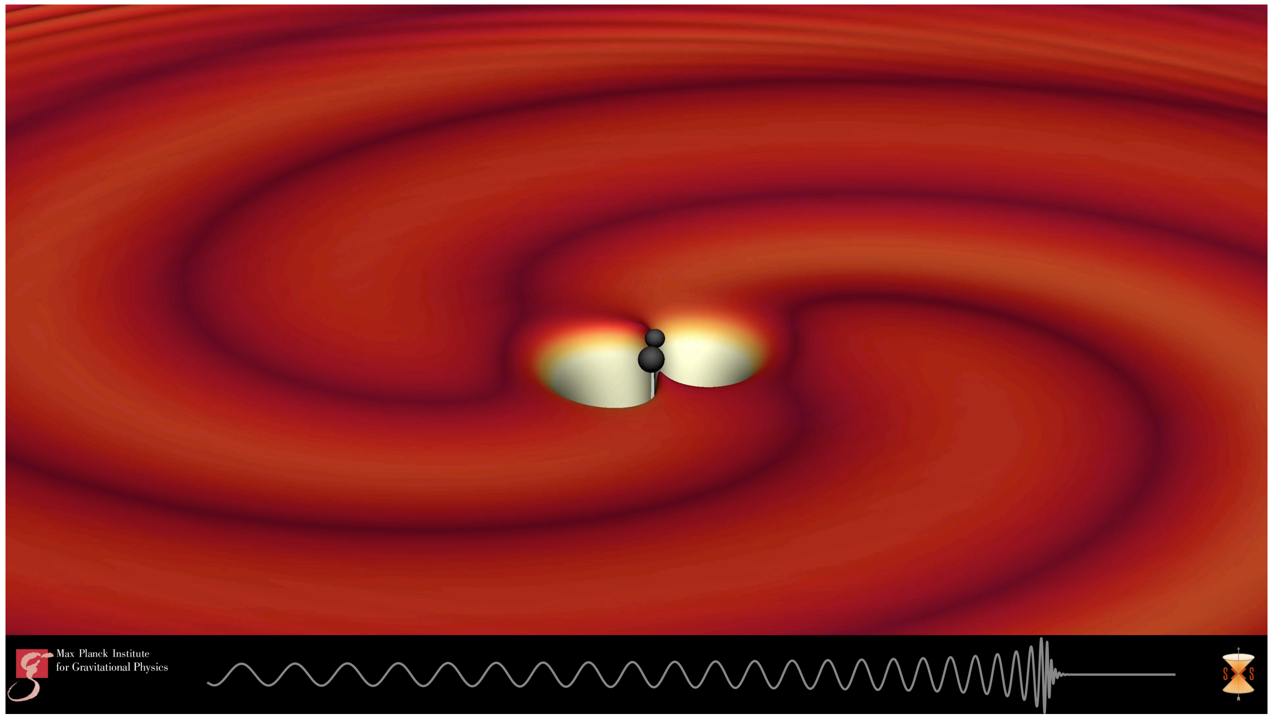




- **Confidence (False Alarm Probability) > 5-sigma (<1/200,000)** **that GW150914, GW151226, GW170104 were produced by gravitational waves instead of instrumental/environment noise.**

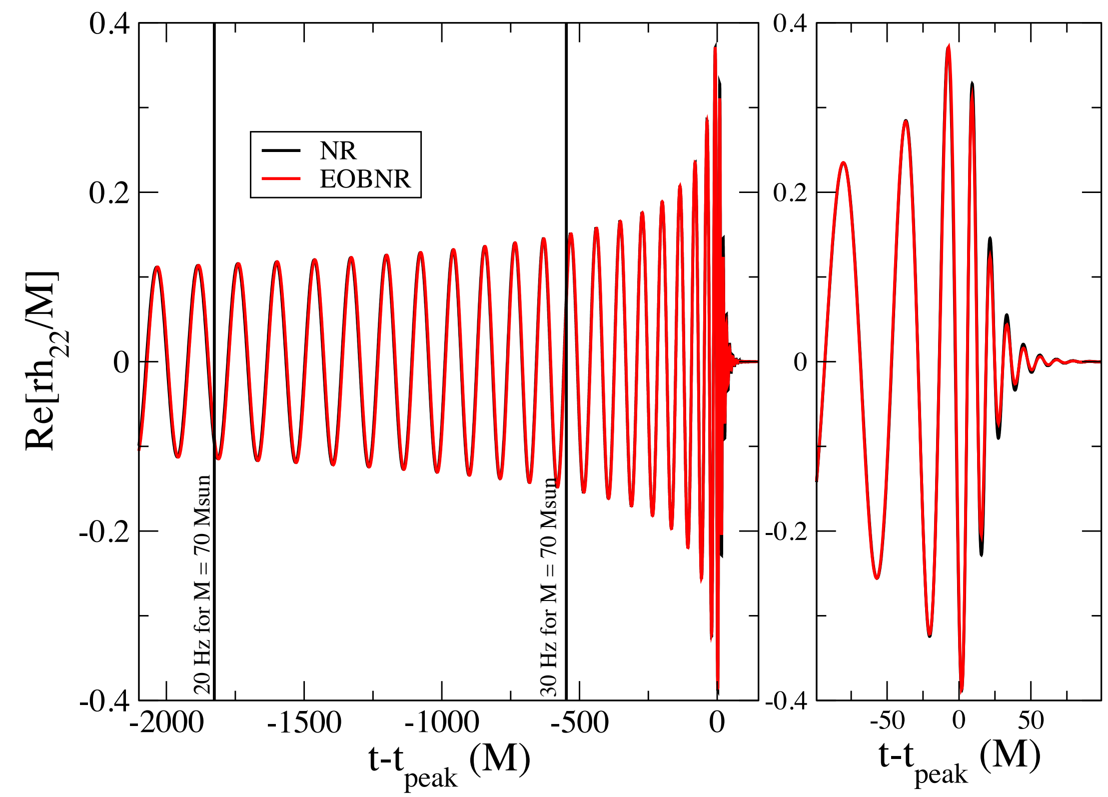
Comparing model with exact solution of Einstein equations

(visualization credit: Haas @ AEI)



(Ossokine, AB & SXS project)

(Ossokine, AB & SXS project)



- Solving **Einstein equations** for two colliding black holes on a **supercomputer.**
- **Three weeks** of computer time **to produce this simulation!**

(computer cluster @ AEI)

Waveform models very closely match the exact solutions from Einstein equations!

Properties of the binary black hole GW150915

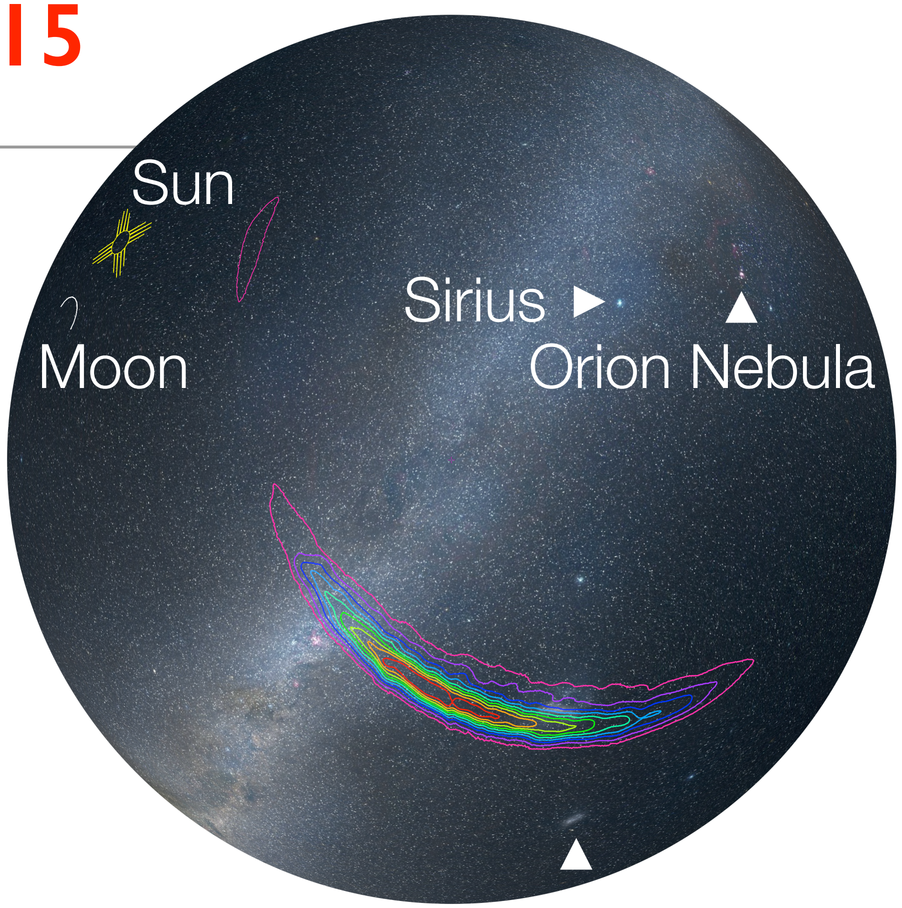
GW150914 took place 1.4 billion light-years away!

Binary black holes:

- m_1= 36 solar mass
- m_2 = 29 solar mass

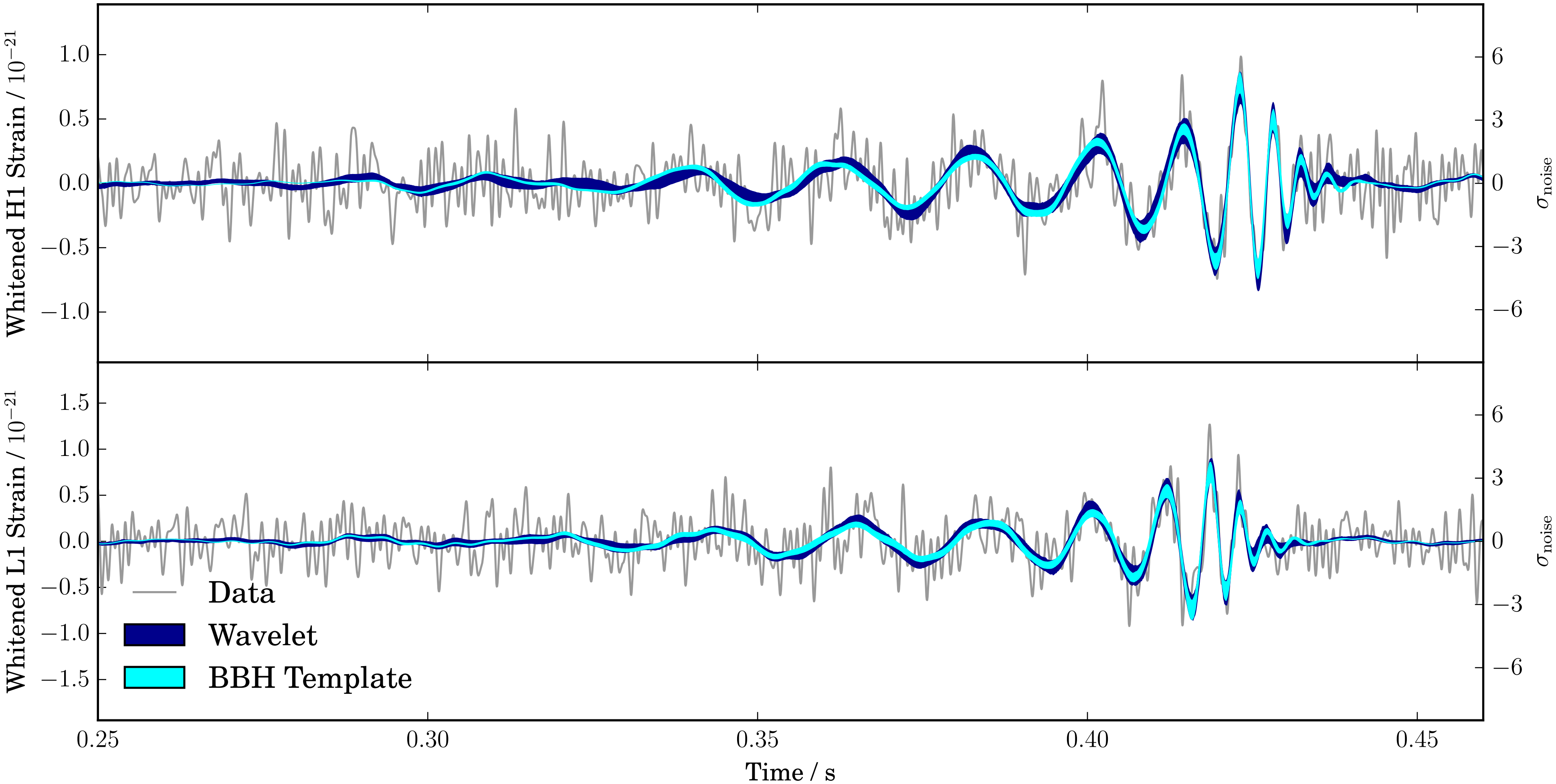
Final black hole:

- m = 62 solar mass
- intrinsic rotation= 67% of maximum value



Small Magellanic Cloud

(Abbott et al. PRL 116 (2016) 241102)

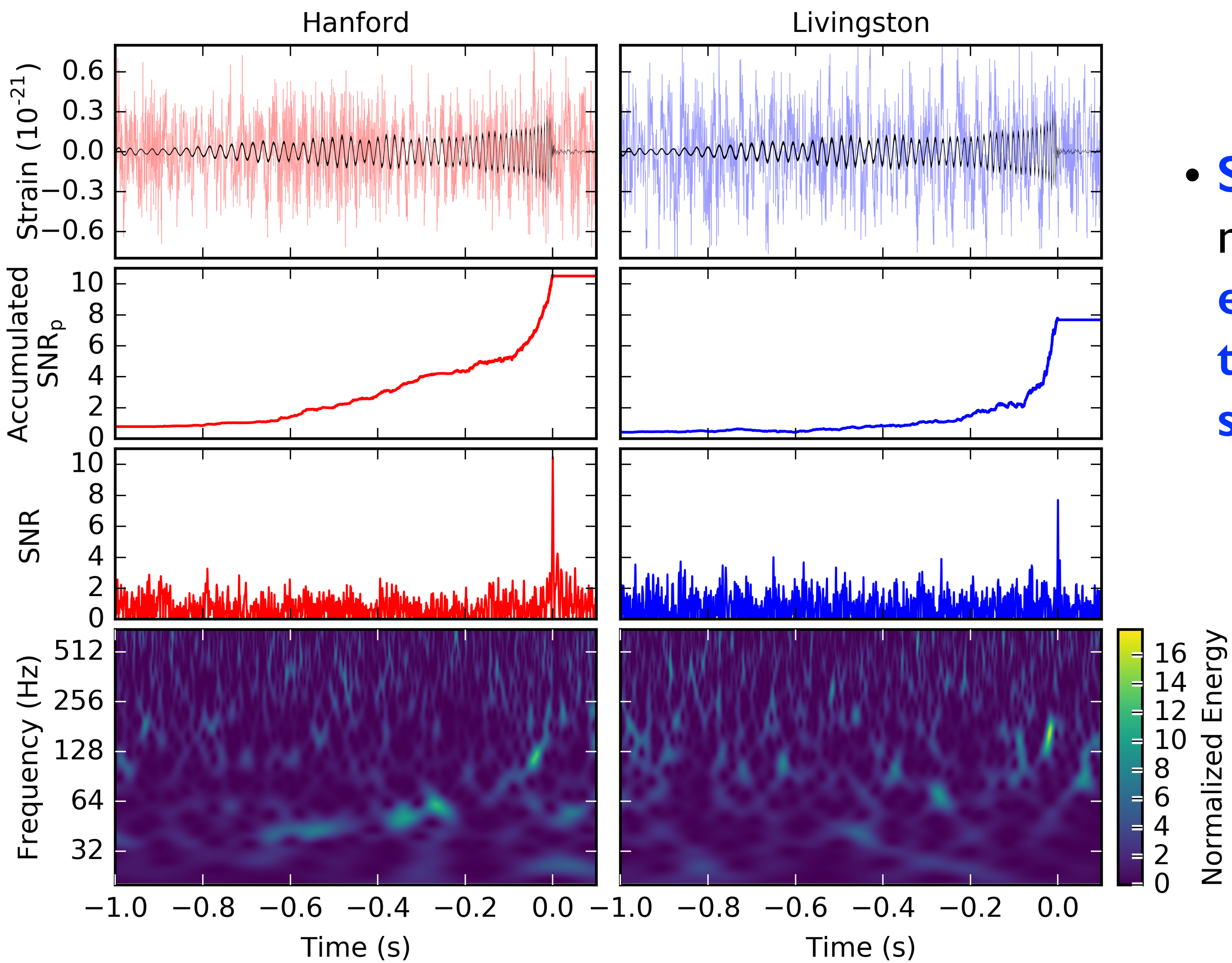


Energy radiated:

- 3 solar masses
- Power: ten times of all stars and galaxies in our Universe

Second gravitational wave detected by LIGOs

(Abbott et al. PRL 116 (2016) 241103)

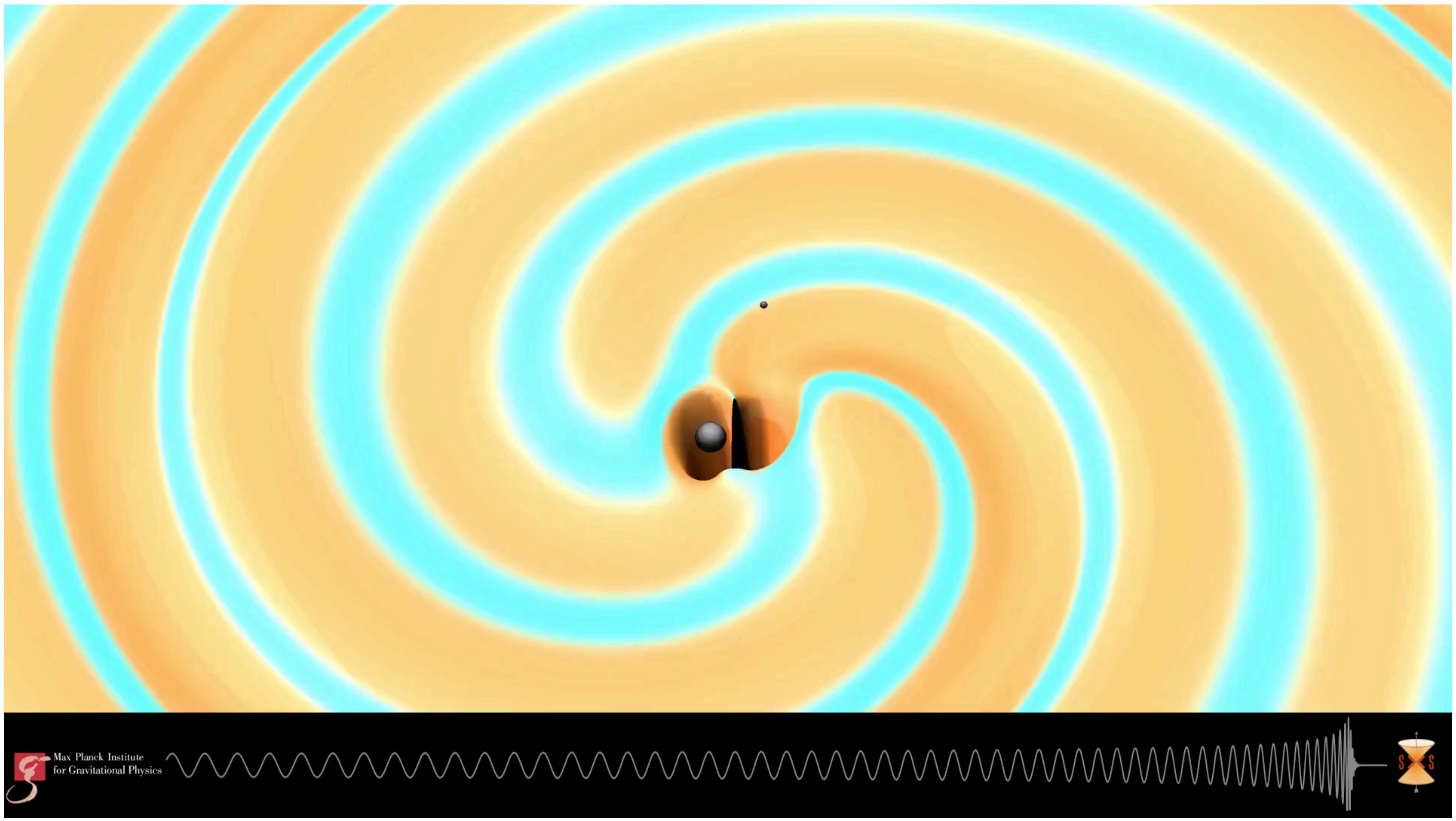


- **Signal processing** (or matched filtering) was **essential to detect the** gravitational-wave **signal!**

- **GW151226**: **quieter** than first event, **55** gravitational-wave **cycles**, duration of about 1.5 **sec.**

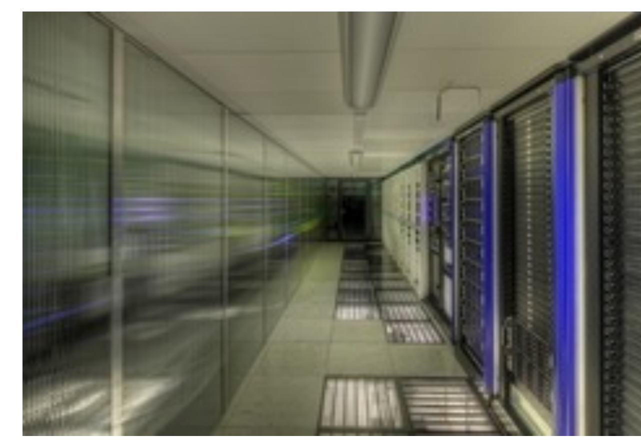
Numerical simulation of the binary black hole: GW151226

(visualization credit: Dietrich, Haas @ AEI)



(Ossokine, AB & SXS project)

- Solving Einstein equations for two colliding black holes on a supercomputer



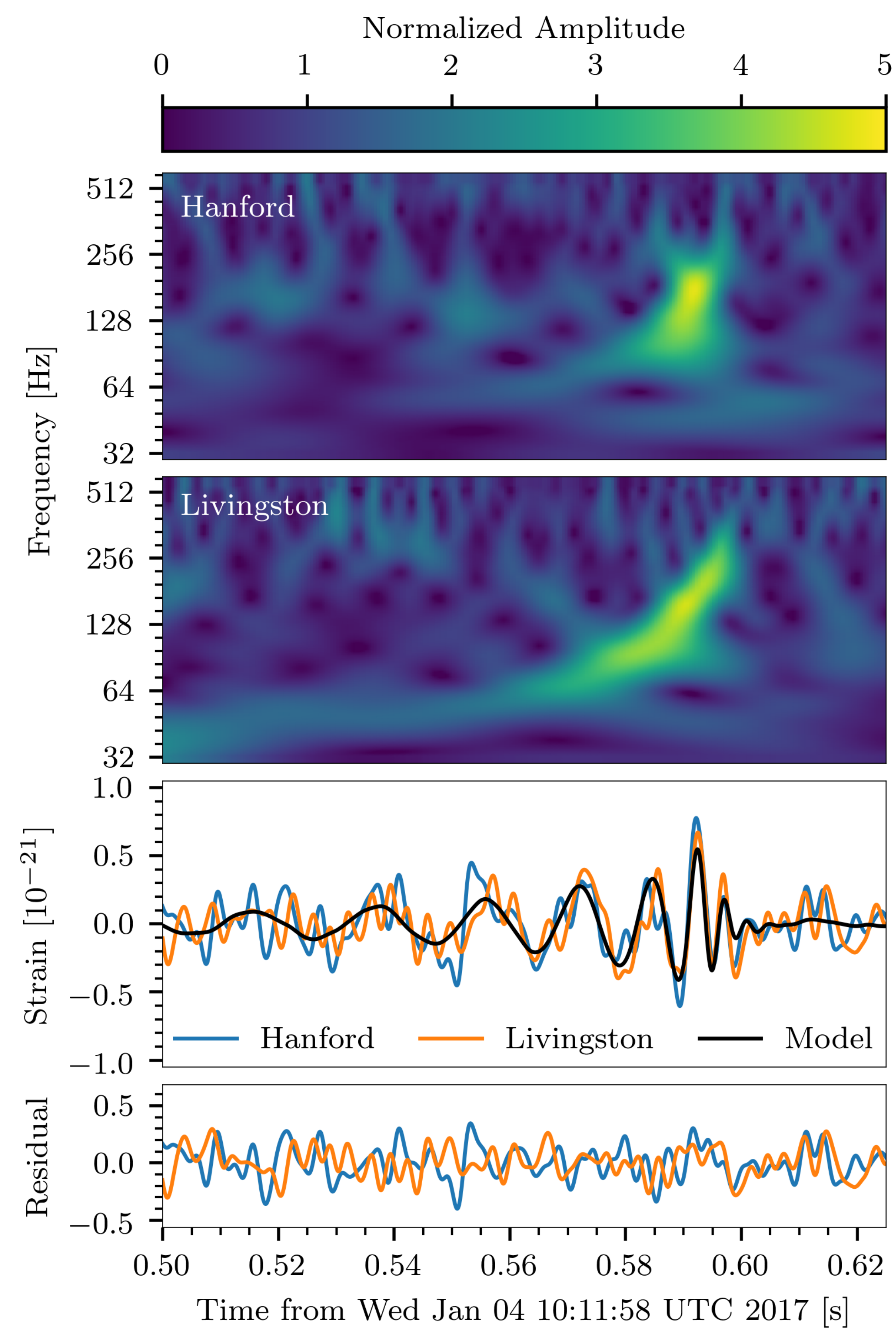
(computer cluster @ AEI)

Three months of computer time to produce this simulation!

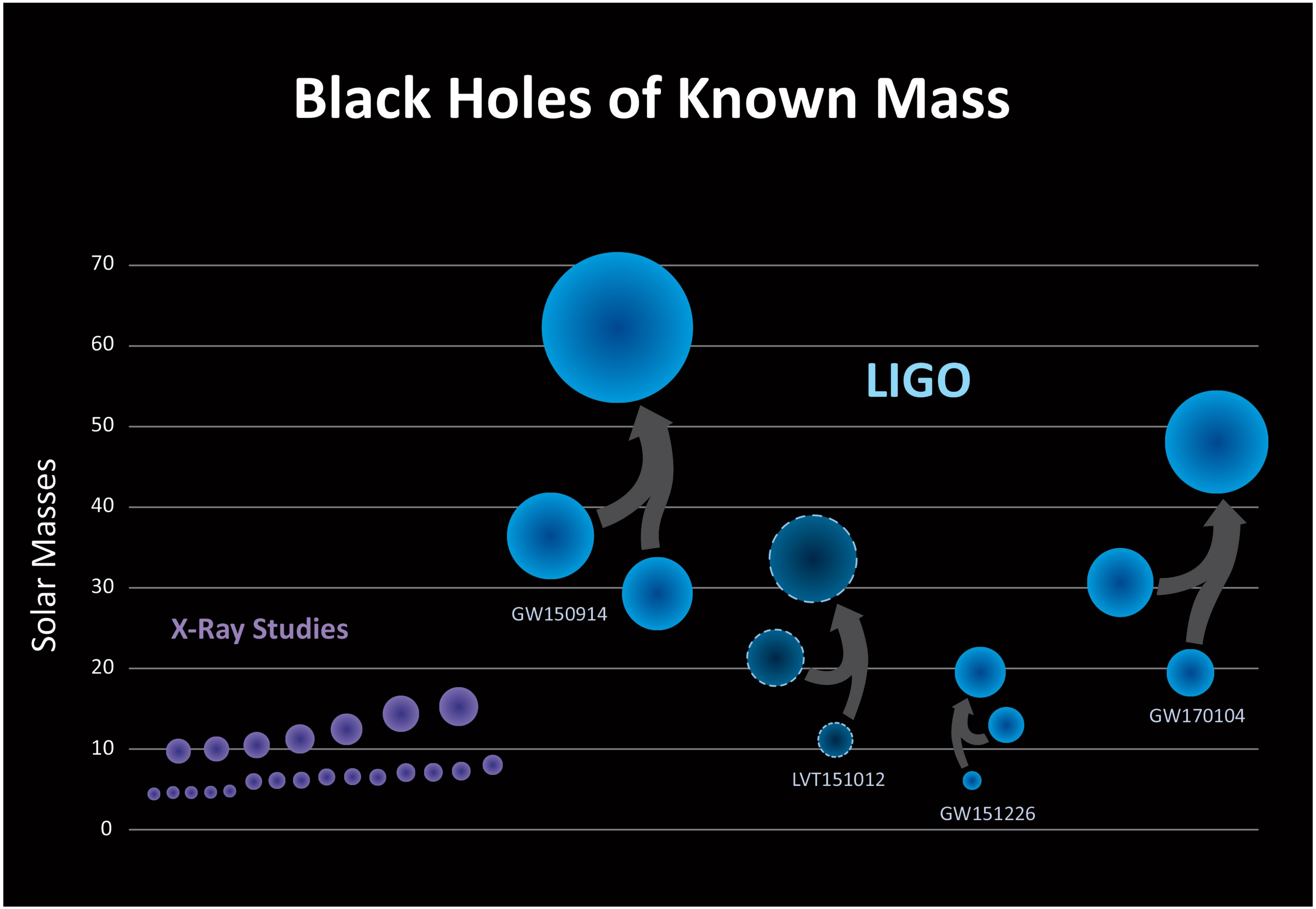
Third gravitational wave detected by LIGOs

(Abbott et al. PRL 118 (2017) 221101)

- GW170104: quieter than first event, 14 gravitational-wave cycles, duration of about 0.3 sec.



Black Holes Discovered through GWs during O1 & O2 (so far)



(credit: *Simonnet*)

Some outstanding questions in astrophysics & fundamental physics

- What are the **properties** of **dynamical spacetime** (gravitational waves)?

- Is **General Relativity still valid** in the highly dynamical, strong-field regime?

- Are **Nature's black holes** the black holes in the theory of **General Relativity**? What are the **astrophysical formation scenarios** of binary black holes?

- How **matter behaves** under **extreme density and pressure**? Can **dark matter** make compact objects?

- What's the **origin** of the **most energetic phenomena** in our Universe? **Rattles and shines:** we will detect **"sounds"** and see **"images".**

- Which physical phenomena took place in the **primordial dark age** of the **Universe**?

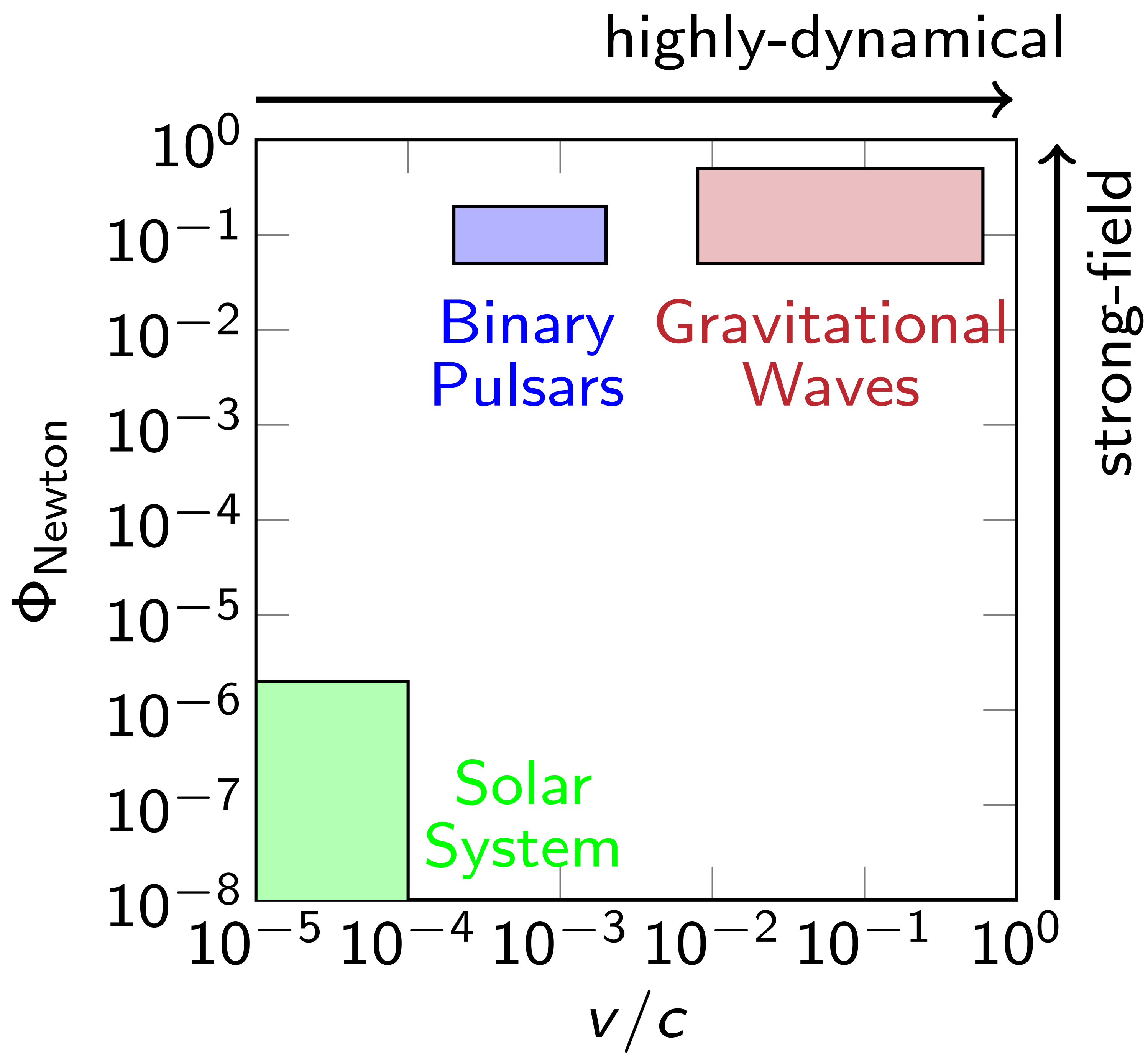
Extreme gravity, dynamical spacetime: tests of General Relativity

Solar system: $\frac{v}{c} \sim 10^{-5} - 10^{-4}$

Binary pulsars: $\frac{v}{c} \sim 10^{-3}$

LIGO/Virgo: $\frac{v}{c} \geq 0.1$

- Given **current tight constraints** on GR (e.g., Solar system, binary pulsars), can **any GR deviation be observed with GW detectors**?



(credit: Sennett)

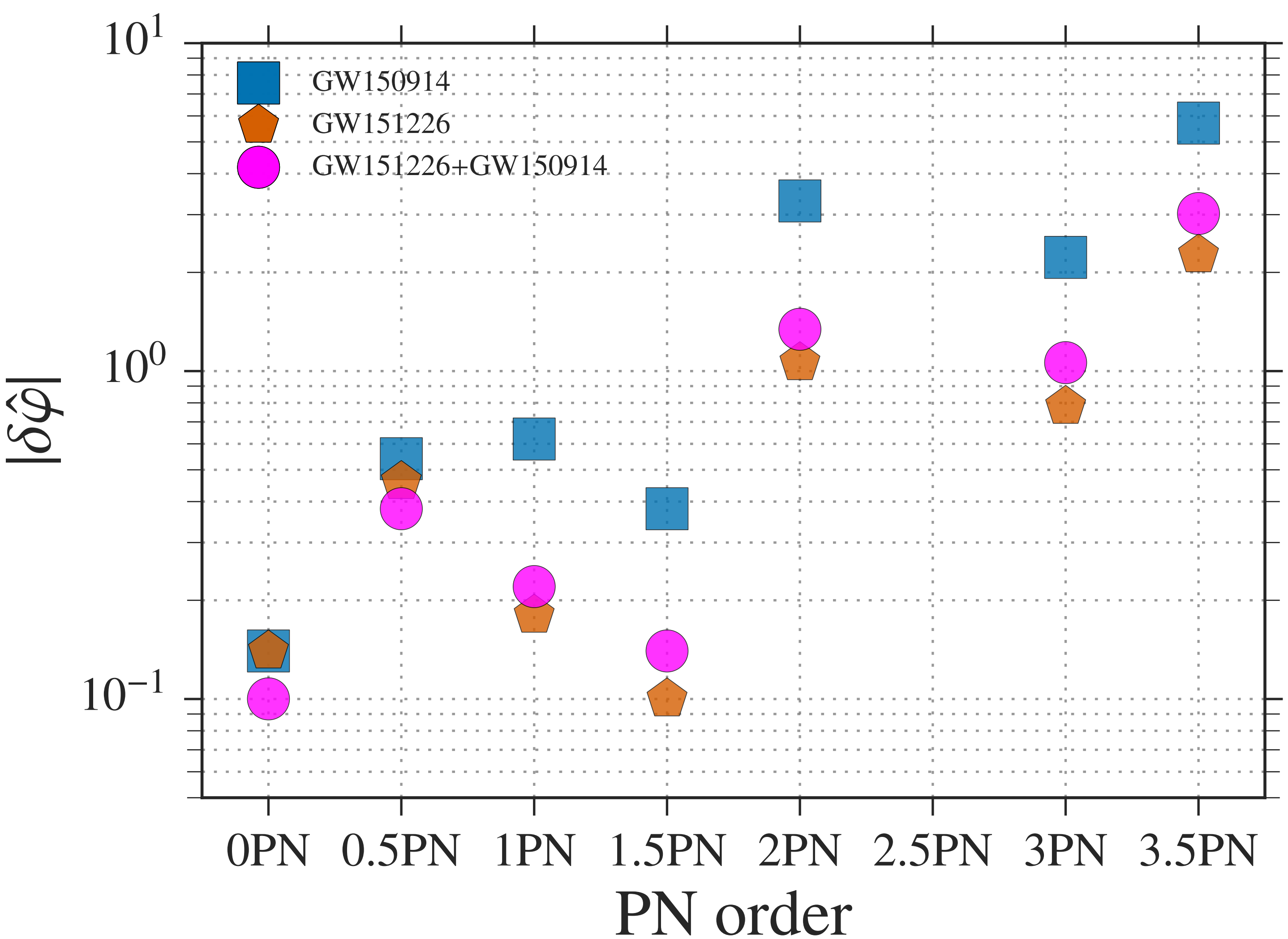
First tests of General Relativity in dynamical, strong Field

- GW150914/GW122615/GW170104's **rapidly varying orbital periods** allow us to **bound higher-order PN coefficients** in gravitational phase.

$$\tilde{h}(f) = \mathcal{A}(f)e^{i\varphi(f)}$$

$$\varphi(f) = \varphi_{\rm ref} + 2\pi f t_{\rm ref} + \varphi_{\rm Newt}(Mf)^{-5/3} + \varphi_{\rm 0.5PN}(Mf)^{-4/3} + \varphi_{\rm 1PN}(Mf)^{-1} + \varphi_{\rm 1.5PN}(Mf)^{-2/3} + \cdots$$

(Abbott et al. PRX6 (2016))



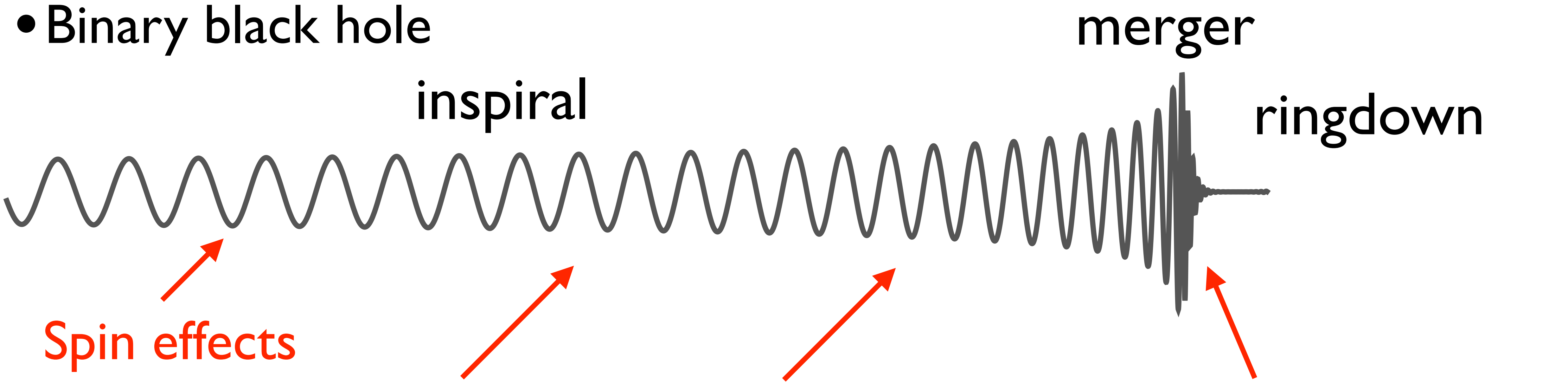
(Arun et al. 06 , Mishra et al. 10, Yunes & Pretorius 09, Li et al. 12)

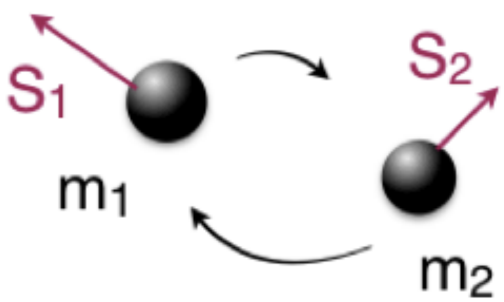
- **PN parameters** describe: **tails** of radiation due to backscattering, **spin-orbit** and **spin-spin** couplings.

- **PN parameters** take **different values** in **modified theories** to GR.

Waveforms encode plethora of physical effects

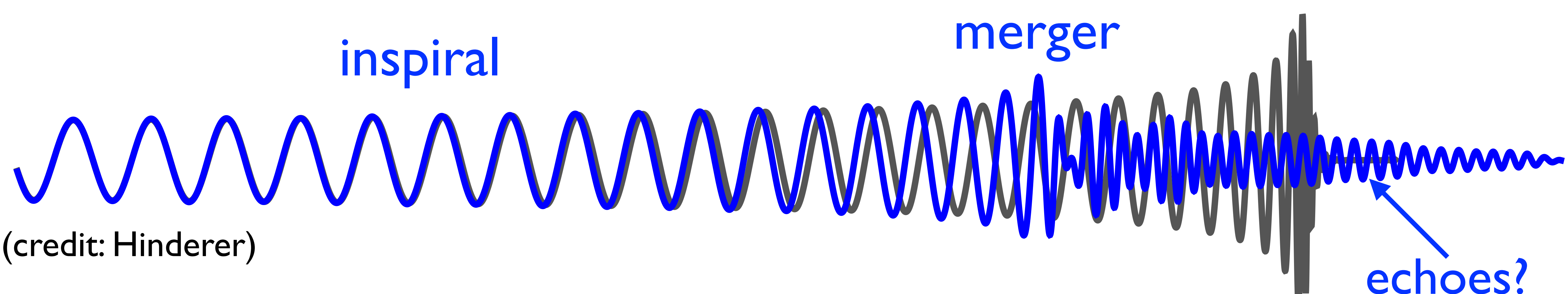
- Binary black hole





(credit: Hinderer)

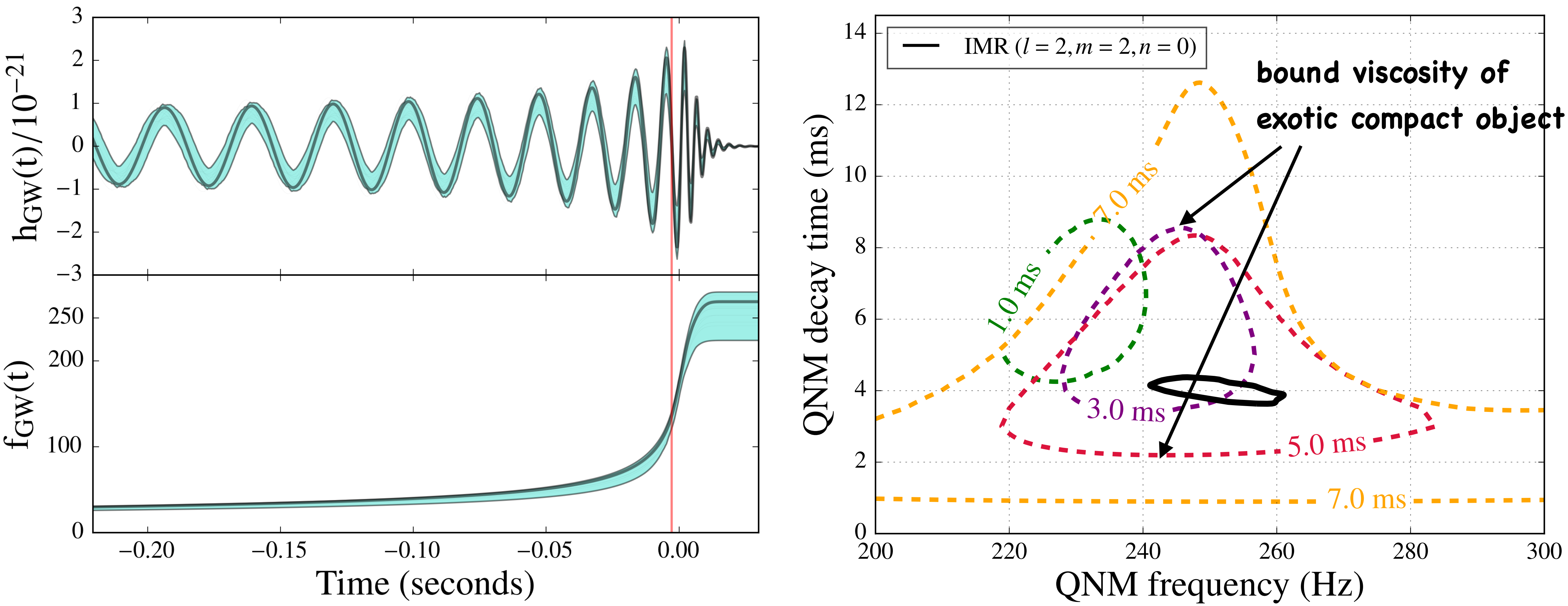
- **Compact-object binary** with **matter** or in **modified theory** to GR?



(credit: Hinderer)

Probing remnant: quasi normal modes (QNMs)

- **Deformed black holes** emits **quasi-normal modes**.
- **Measuring** at least two modes will be **smoking gun** that **Nature's black holes** are black holes of **General Relativity**.



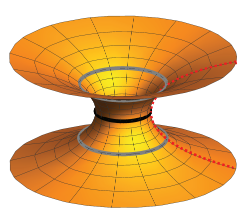
(Abbott et al. PRL116 (2016))

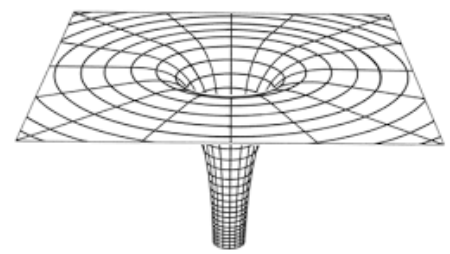
- **Multiple QNMs** can be measured with future detectors, thus testing **no-hair theorem** and **second-law black-hole mechanics** *(Israel 69, Carter 71; Hawking 71, Bardeen 73)*.

Remnant: black hole or exotic compact object?

horizonless objects

wormhole



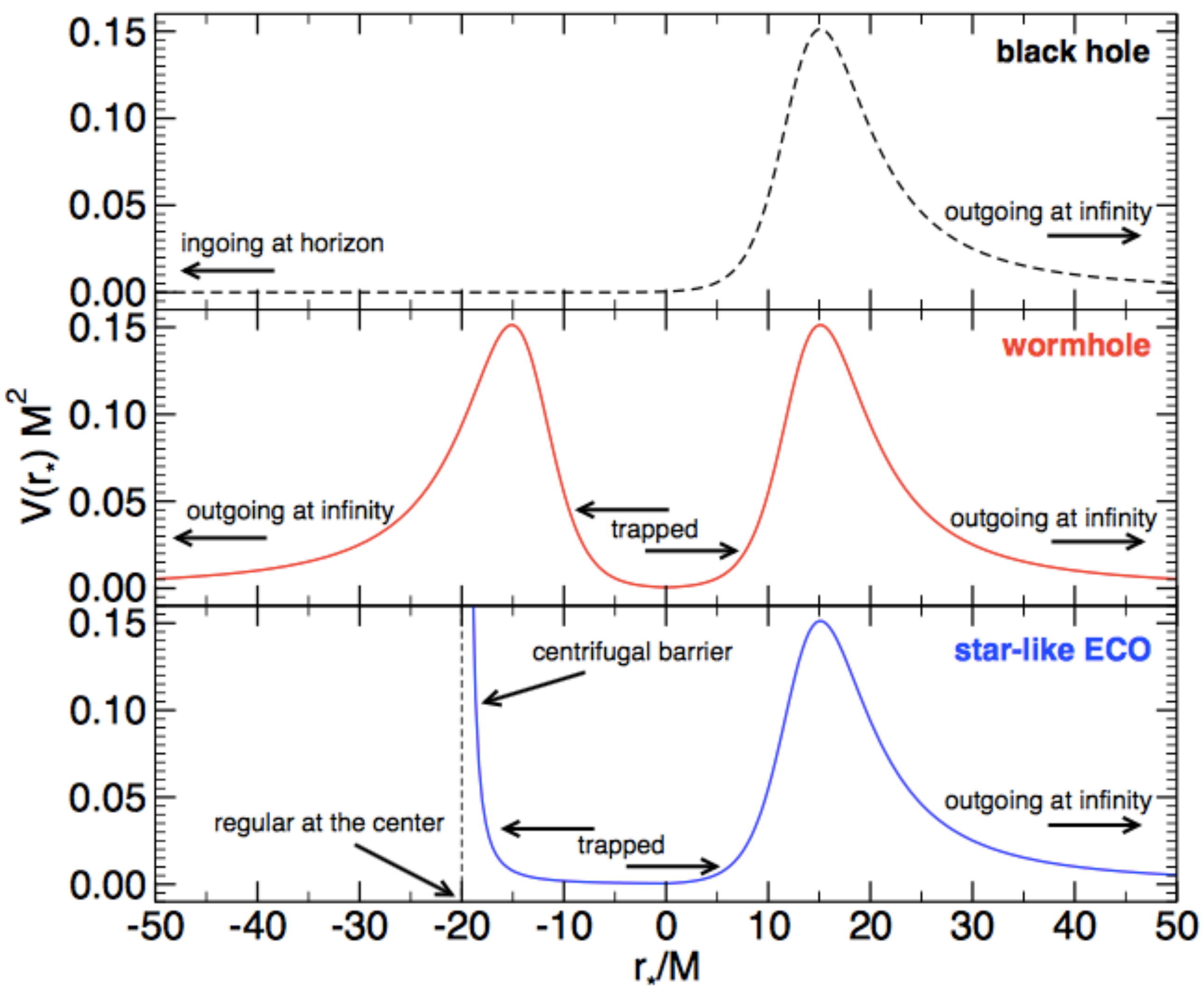


black hole

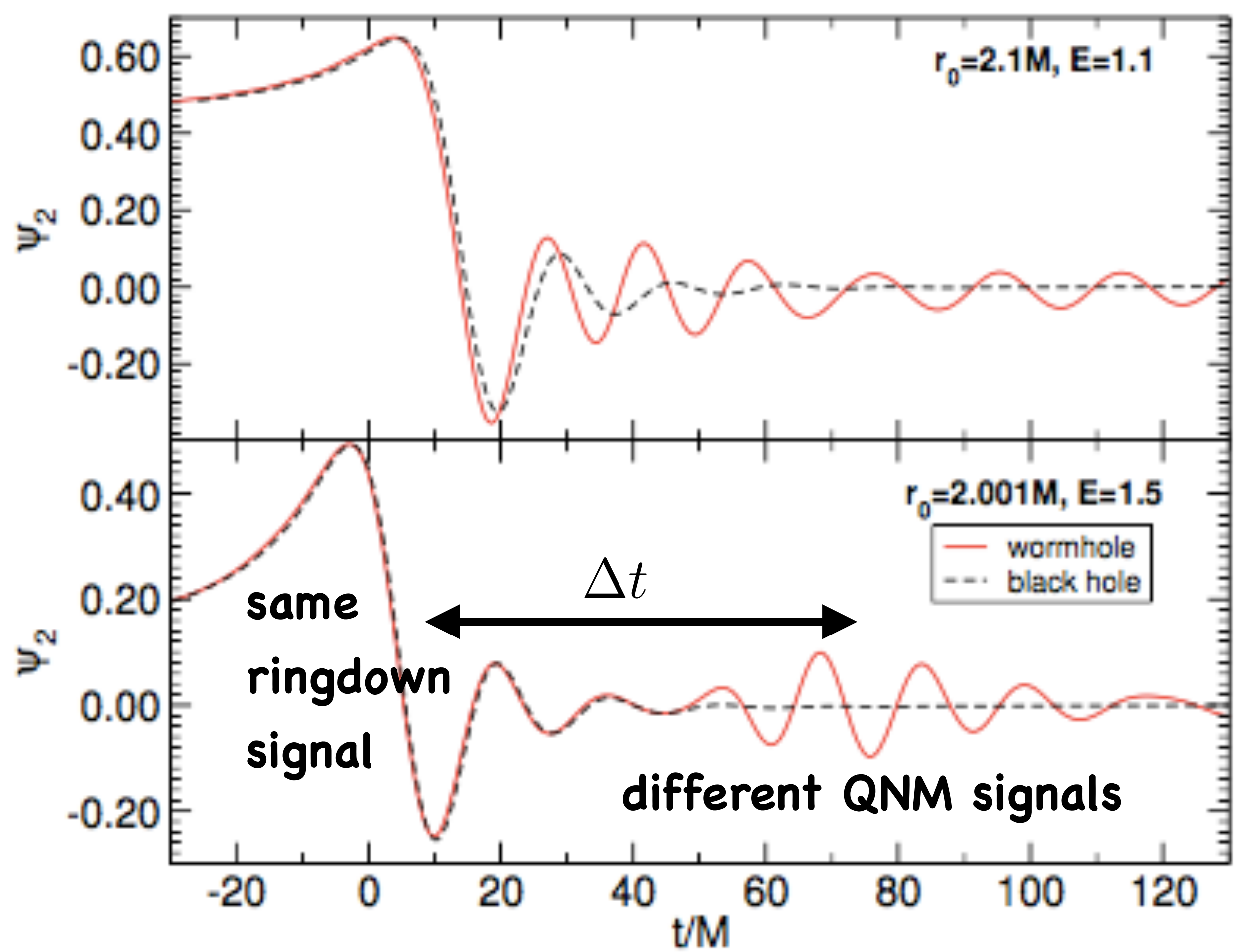
boson stars, fermion stars, etc.
(e.g., Giudice et al. 16)

- If **remnant** is **horizonless,** and/or **horizon is replaced** by **"surface"**, new modes in the spectrum, and ringdown signal is modified: **echoes signals emitted after merger.**

(Cardoso et al. 16)

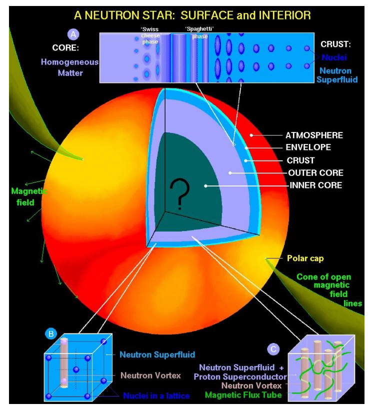


(Damour & Solodukhin 07, Cardoso, Franzin & Pani 16)



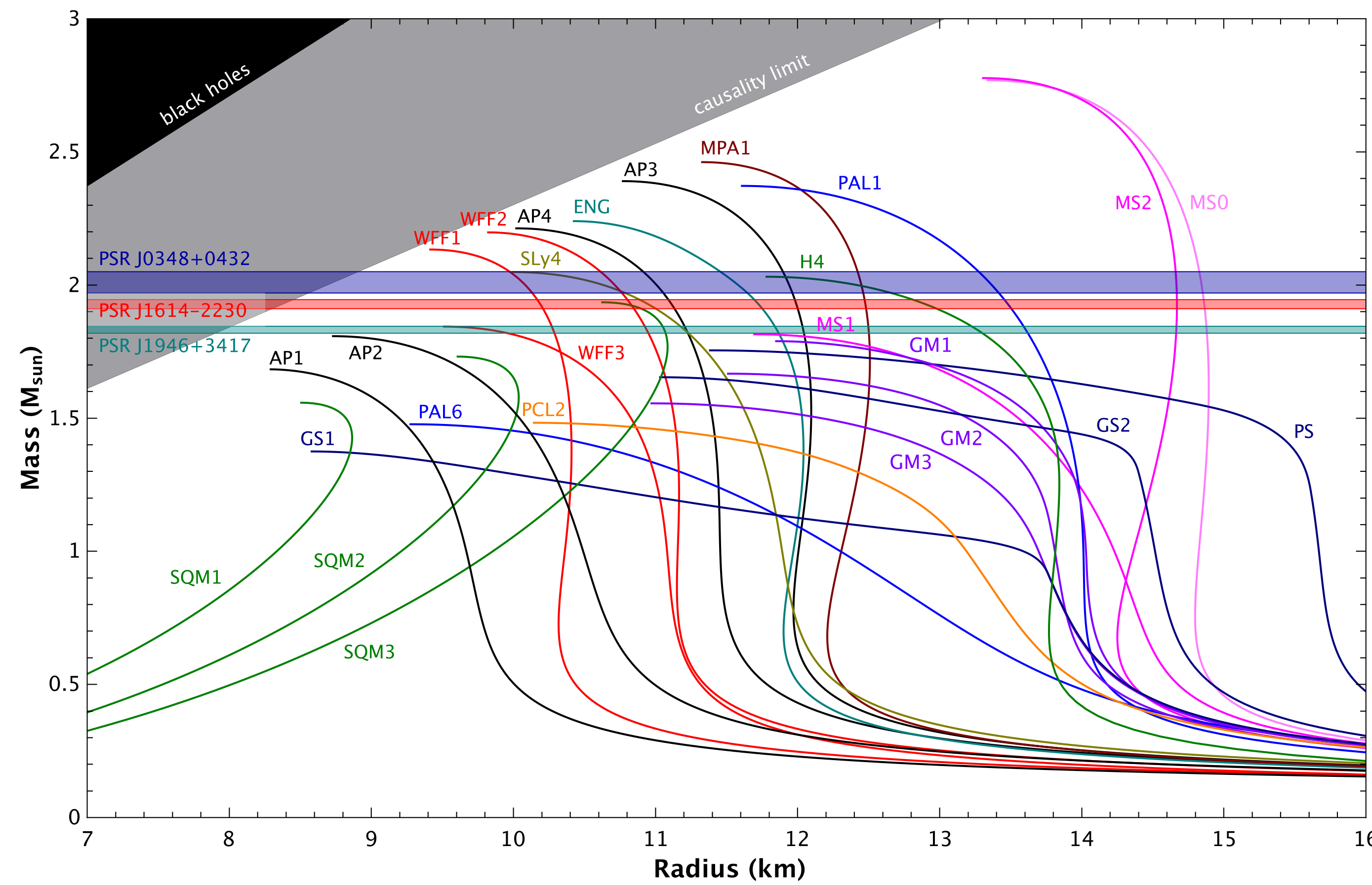
Probing new physics with GWs and neutron stars

(Baade & Zwicky 1934, Gamow 1937, Landau 1938, Oppenheimer & Volkoff 1939, Cameron 1959, Wheeler 1966)

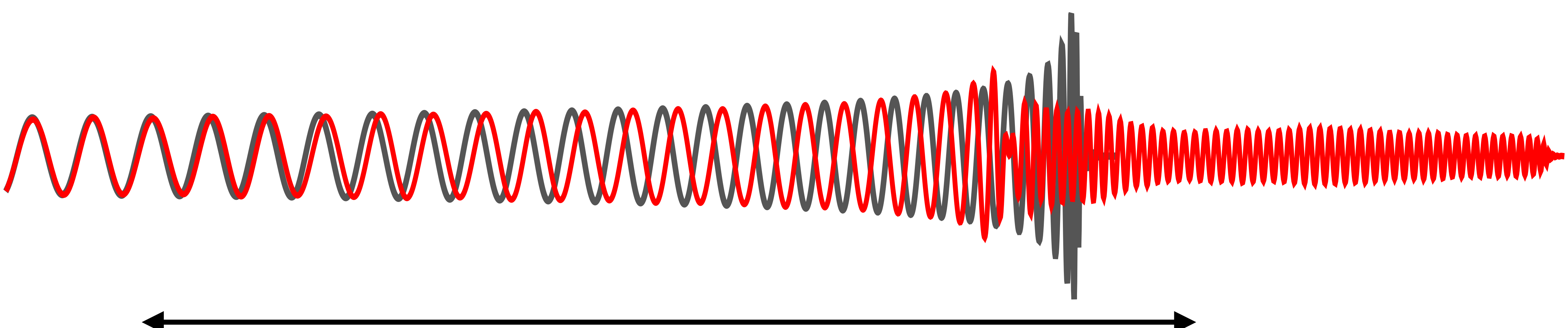


Neutron Star:

- mass: 1-3 Msun
- radius: 9-15 km
- core density > 10^{14}g/cm^3



(Antoniadis et al. 2016)

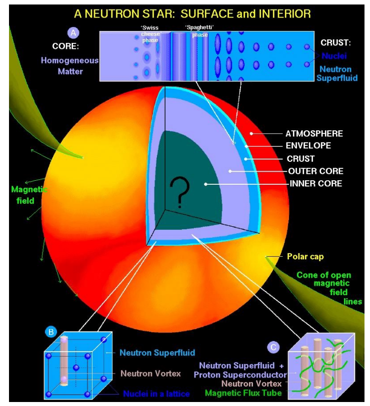


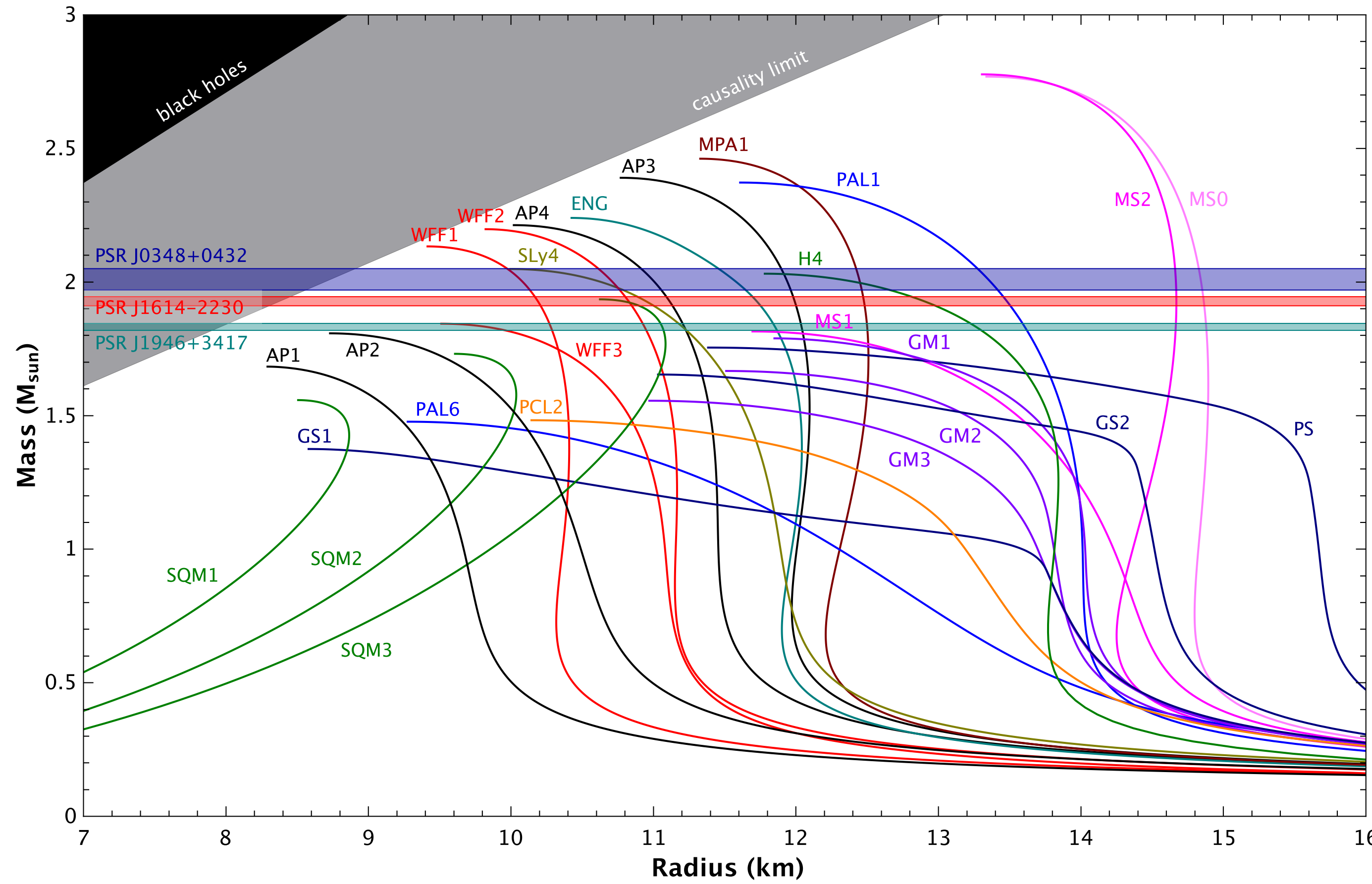
tidal interactions

(credit: Hinderer)

Inferring equation of state of dense matter

(Baade & Zwicky 1934, Gamow 1937, Landau 1938, Oppenheimer & Volkoff 1939, Cameron 1959, Wheeler 1966)



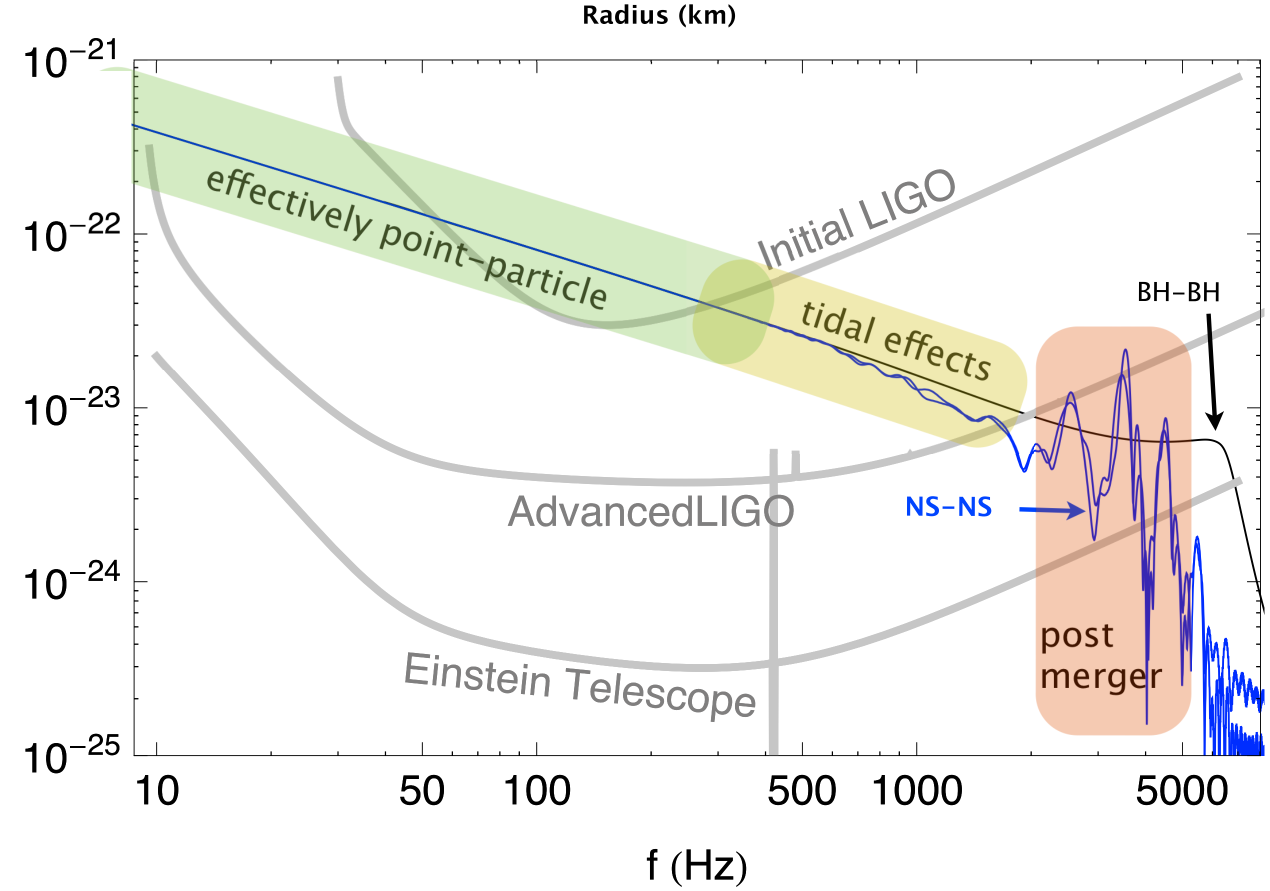


(Antoniadis et al. 2016)

Neutron Star:

- mass: 1-3 Msun
- radius: 9-15 km
- core density > 10^{14}g/cm^3

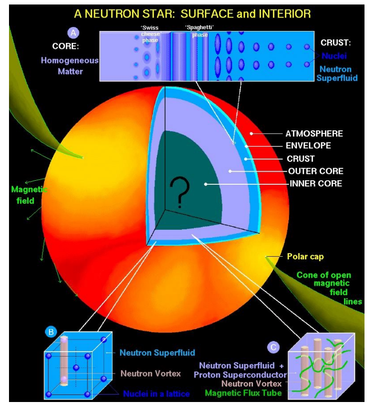
- **NS equation of state** (EOS) affects gravitational **waveform** during **late inspiral, merger** and **post-merger**.

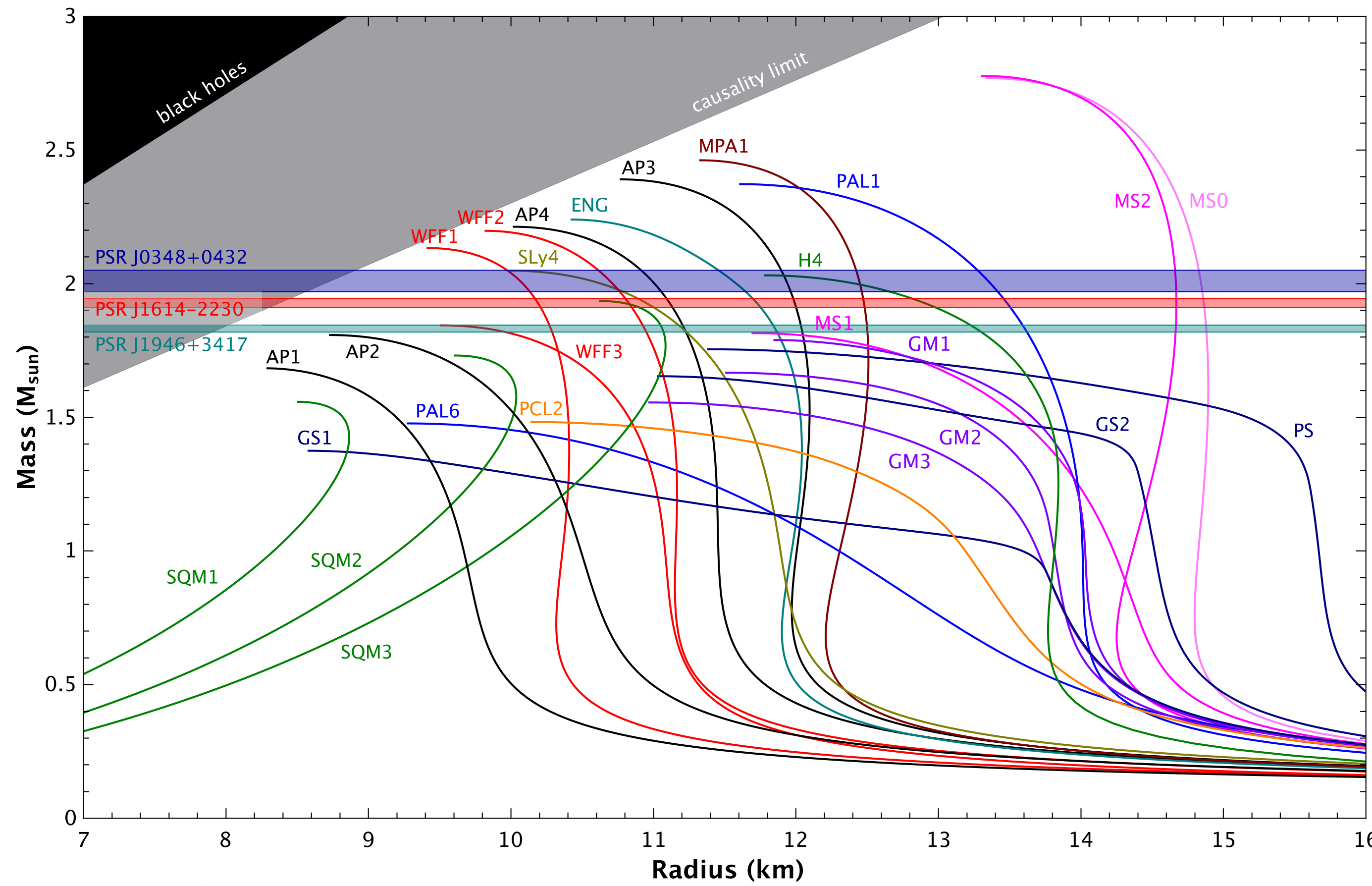


(credt: Read)

Extracting information on EOS from late inspiral

(Baade & Zwicky 1934, Gamow 1937, Landau 1938, Oppenheimer & Volkoff 1939, Cameron 1959, Wheeler 1966)





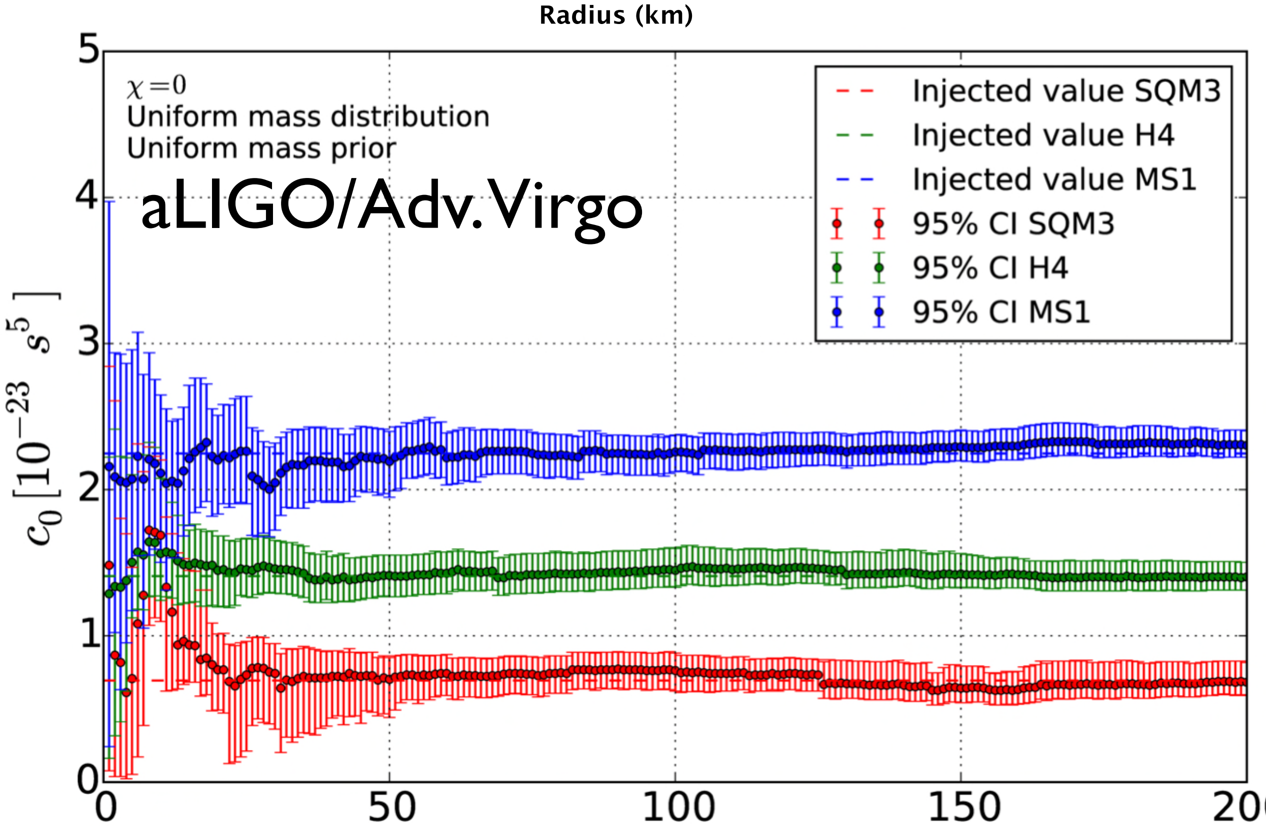
(Antoniadis et al. 2016)

Neutron Star:

- mass: 1-3 Msun
- radius: 9-15 km
- core density > 10^{14}g/cm^3

- **Tidal effects imprinted** on gravitational waveform during inspiral through **parameter** λ.
- λ **measures** star's **quadrupole deformation** in response to companion **perturbing tidal field:**

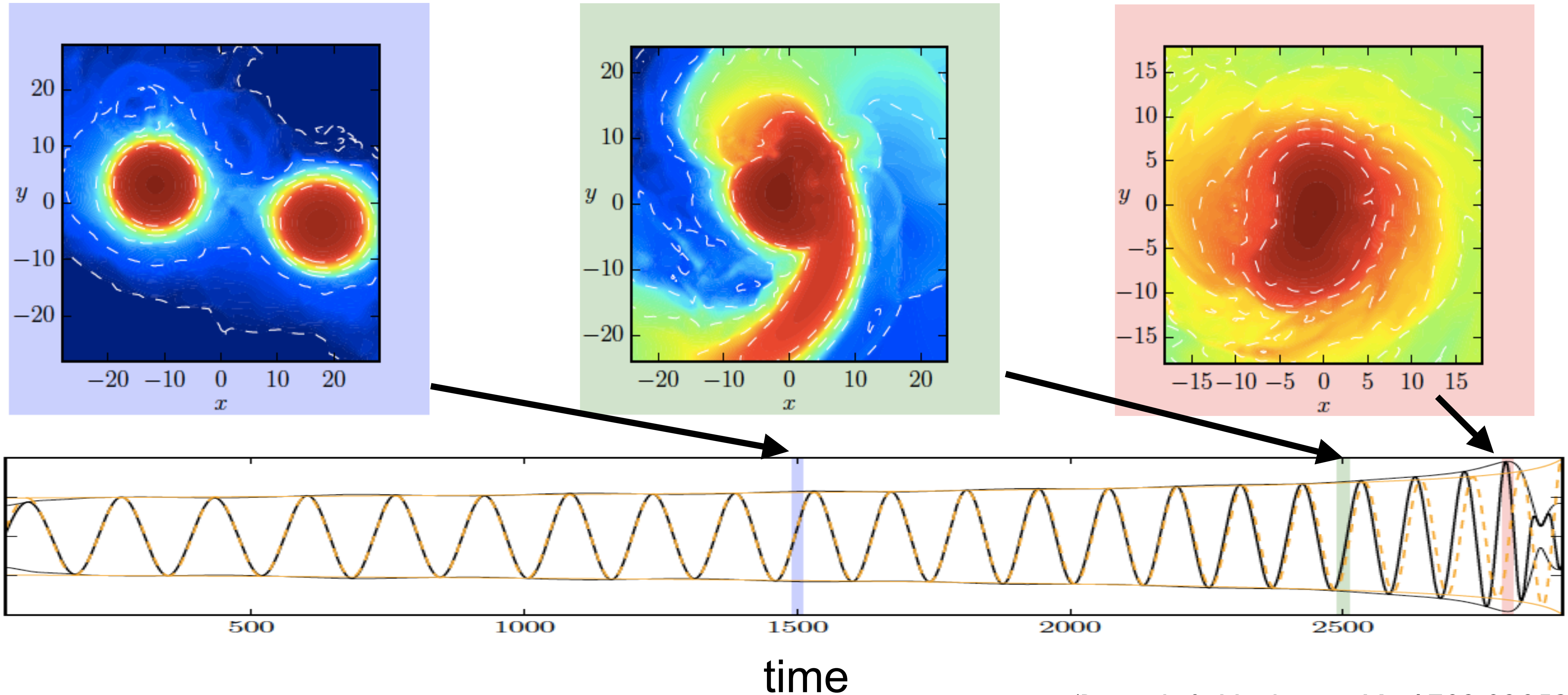
$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$



(Agathos et al. 2015)

Gravitational waveform from a binary neutron star

- Synergy between **analytical and numerical work** is **crucial again.**



(Dietrich & Hinderer arXiv:1702.02053)

(Damour & Nagar 12; Bernuzzi et al. 15; Hinderer et al. 16, Steinhoff et al. 16)

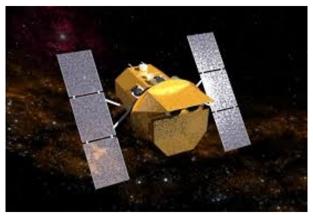
Multi-messenger astrophysics with GW & EM

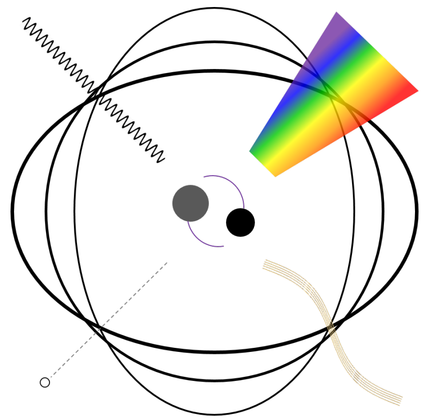
- 95 **astronomical groups** part of **GW-EM** campaign

PTF

Integral

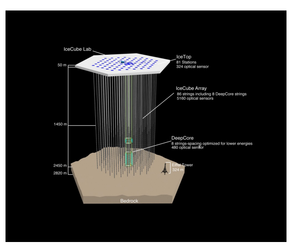
Swift



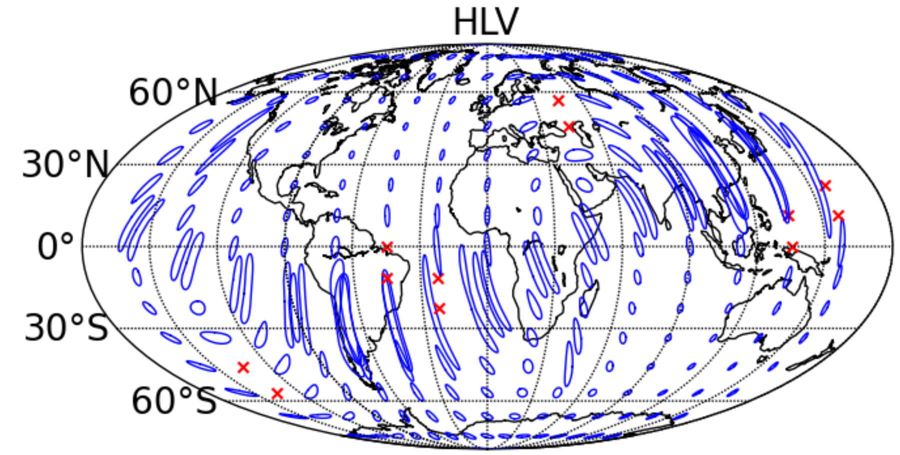


Fermi

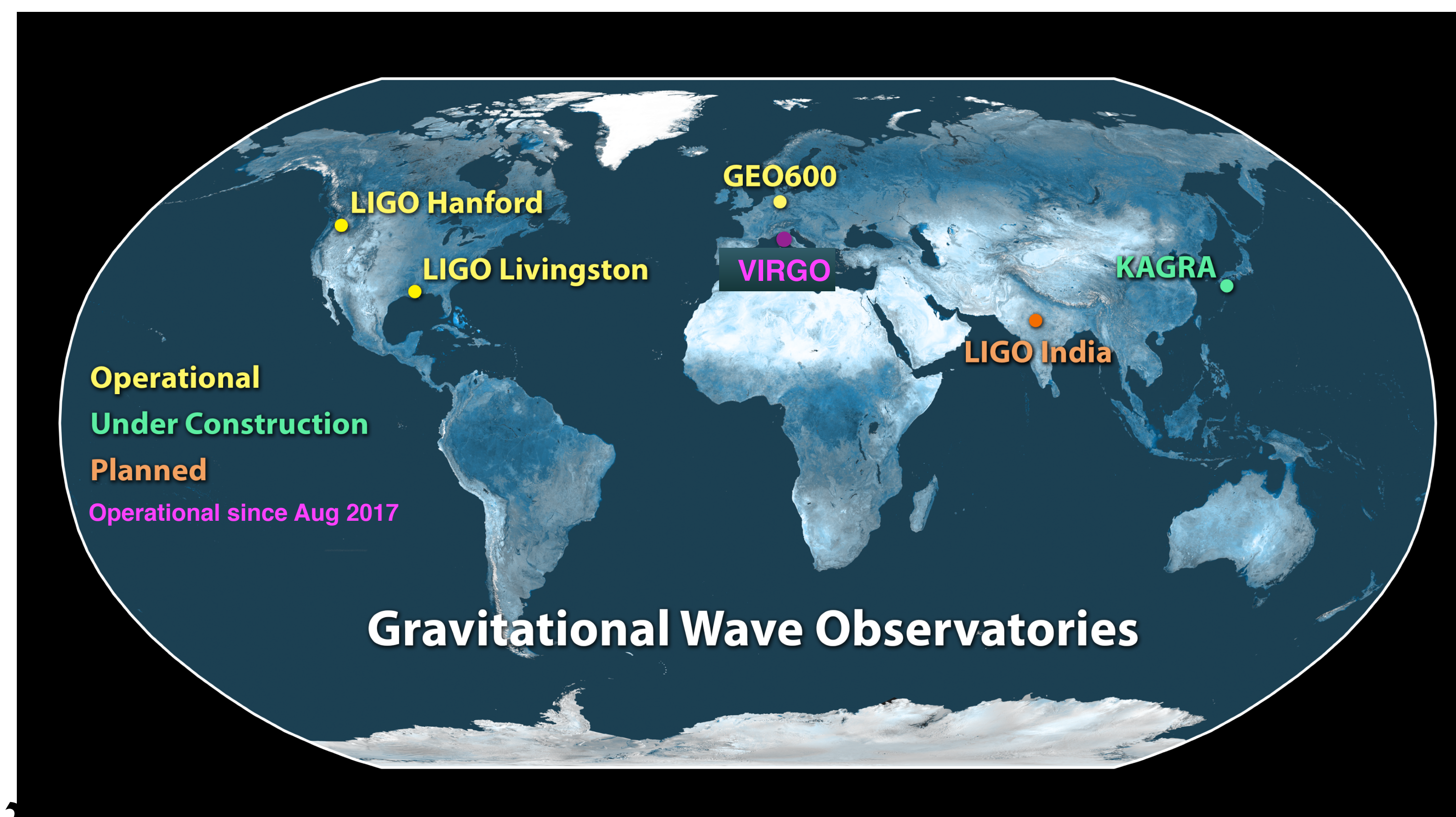
Icecube



(Aasi et al. arXiv:1304.0670)



- Few **tens or hundred** square degrees



- What is the **physics of gravitational collapse** (supernovae)?
- What are the **true luminosity distances** of cosmological sources?
- Do **GWs** propagate at **speed of light**?

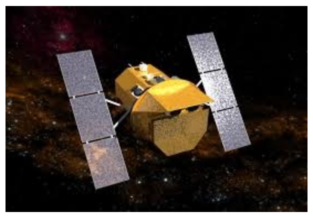
Multi-messenger astrophysics with GW & EM counterparts

- 95 **astronomical groups** part of **GW-EM** campaign

PTF

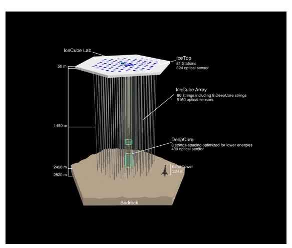
Integral

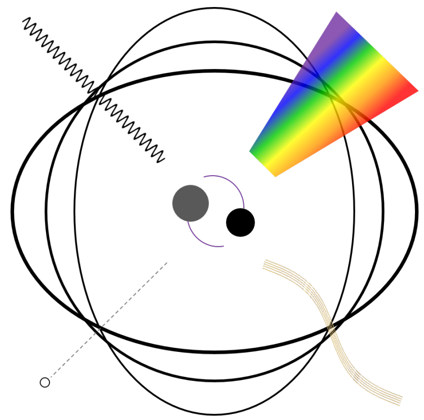
Swift



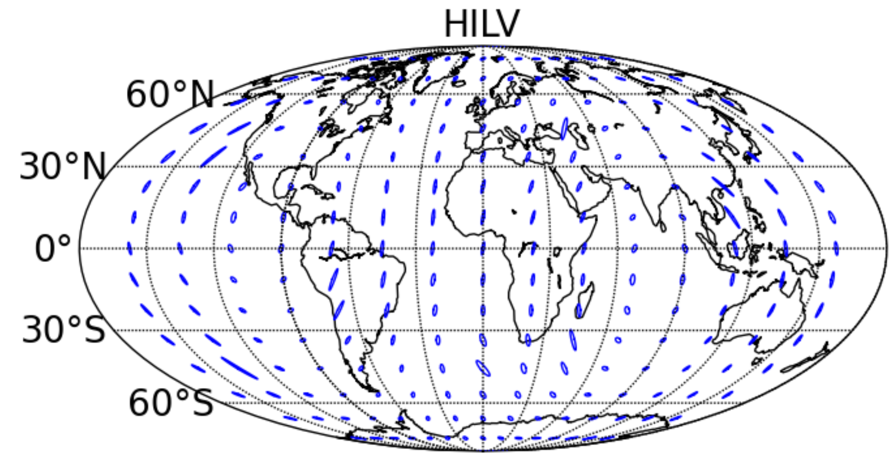
Fermi

Icecube

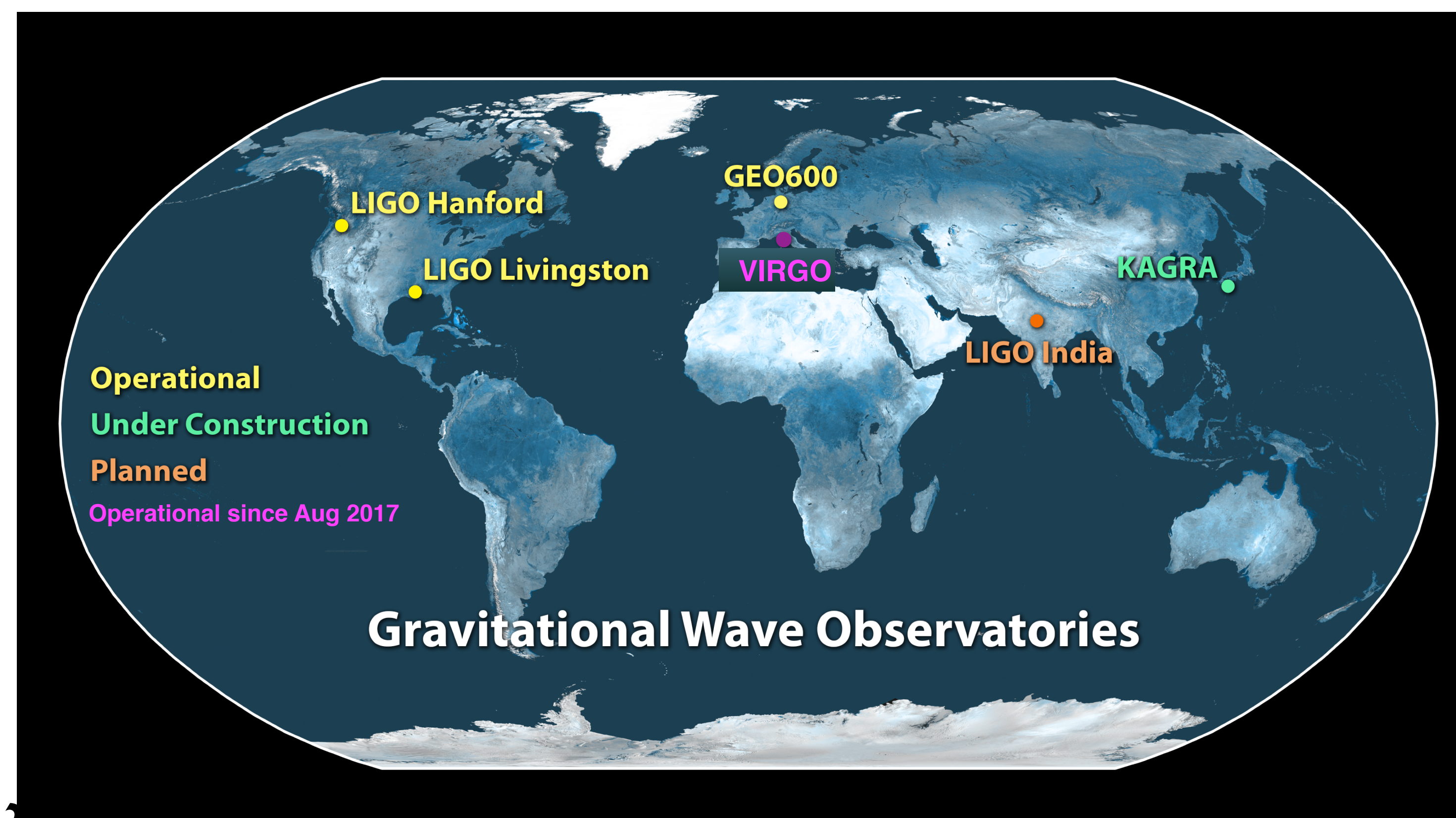




(Aasi et al. arXiv:1304.0670)

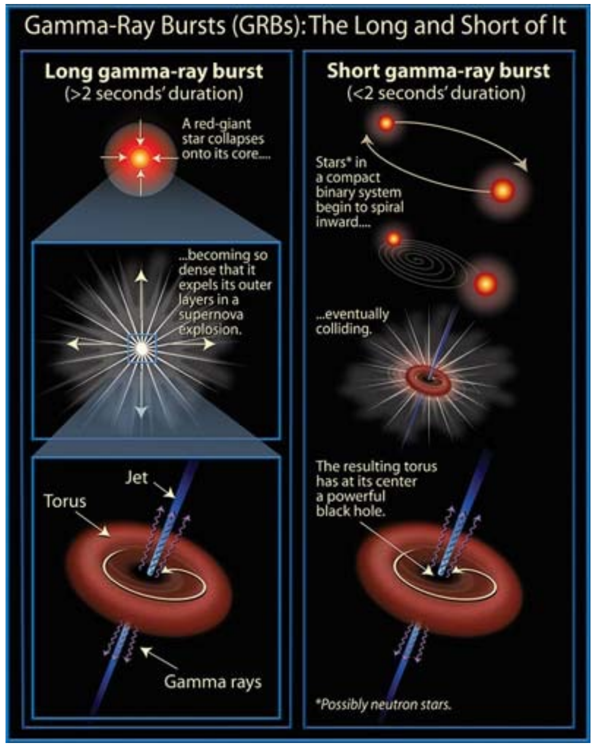


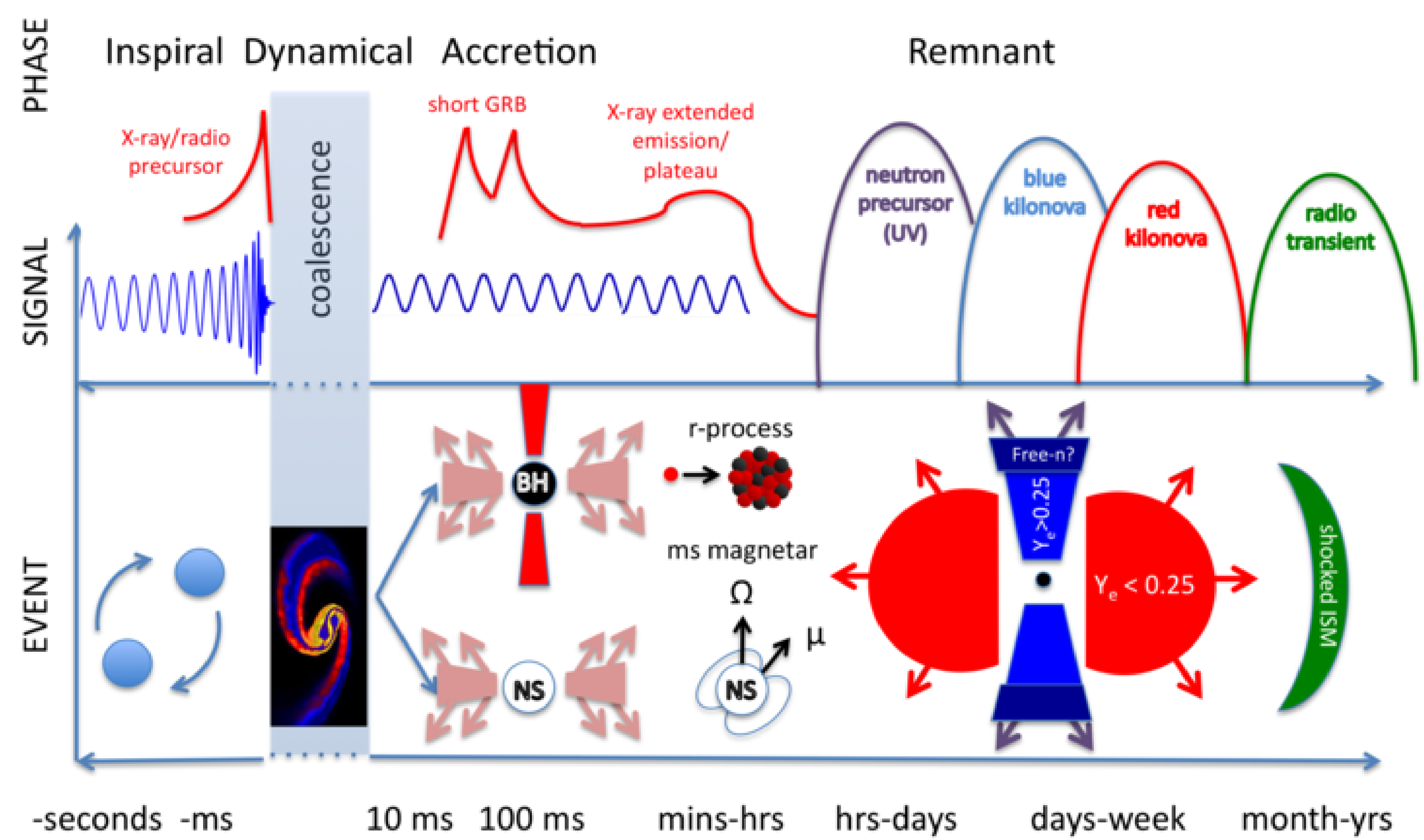
- **Few** square degrees!



- What is the **physics of gravitational collapse** (supernovae)?
- What are the **true luminosity distances** of cosmological sources?
- Do **GWs** propagate at **speed of light**?

Disclosing the origin of most energetic phenomena in universe

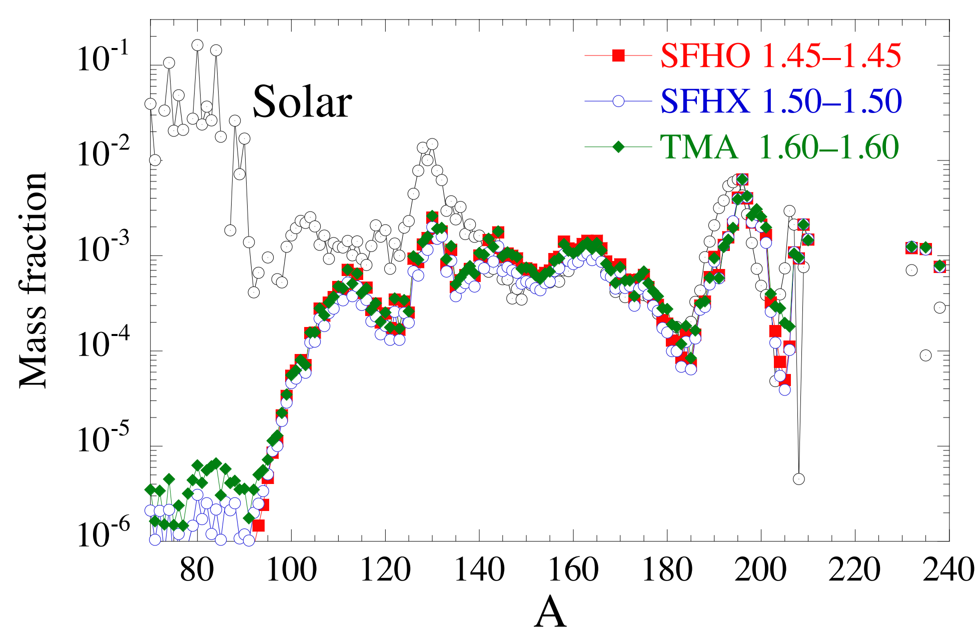


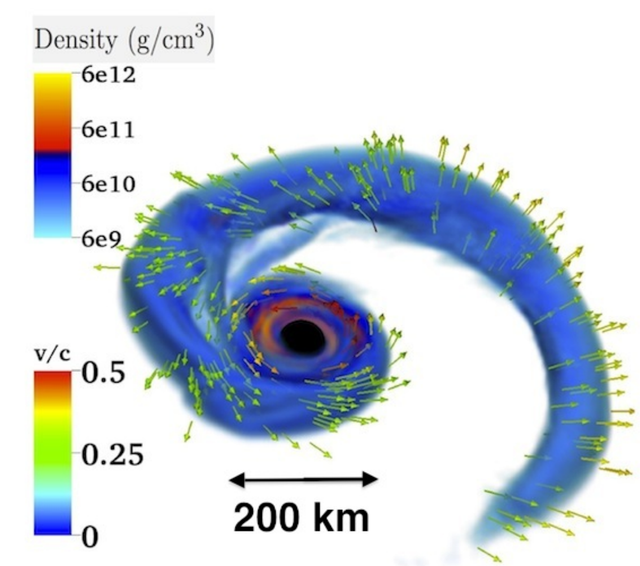


(Fernandez & Metzger 2016)

- Solving the **enigma** of short-hard **GRBs progenitors.**
- Understanding **matter and geometry** in **extreme conditions** of density, temperature, magnetic fields and relativistic motion.
- What's matter **EOS** at **supra-nuclear density**?

- **r-processes** (nucleosynthesis) in **neutron-star mergers**.

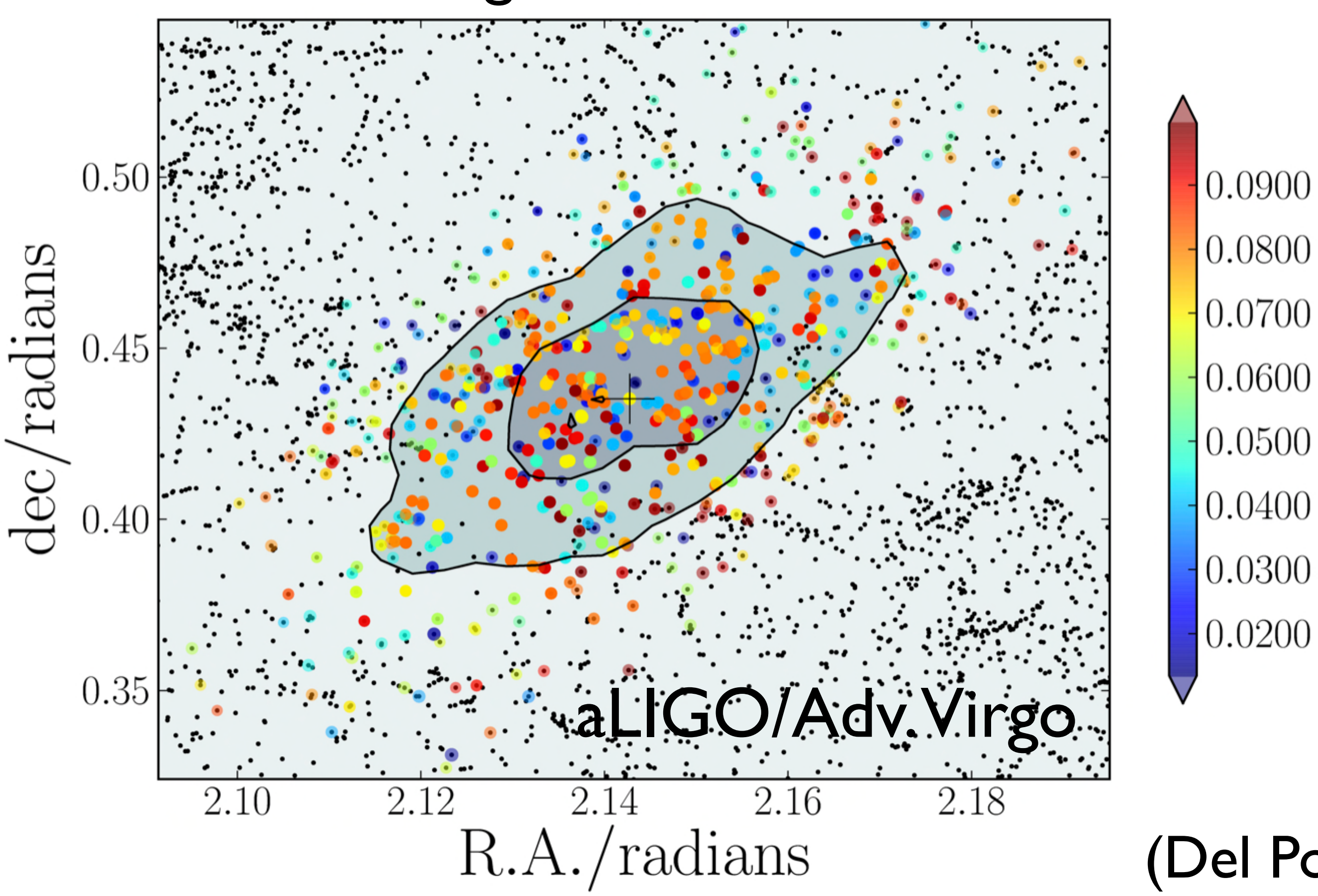




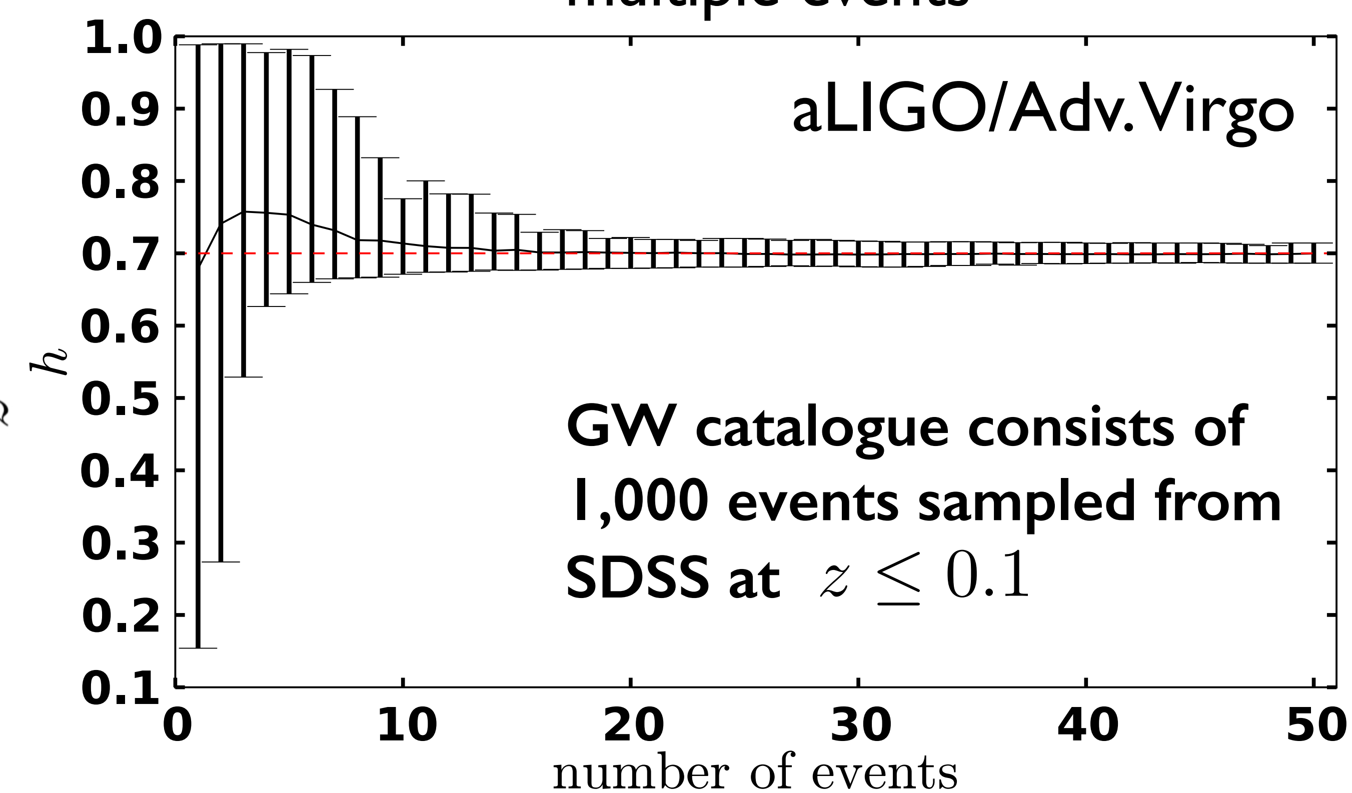
Cosmography: inference of cosmological parameters

- **Wide-field galaxy surveys** can provide (**sky positions** and) **redshifts.** (Schutz 1986)

single GW event



multiple events



(Del Pozzo 2012)

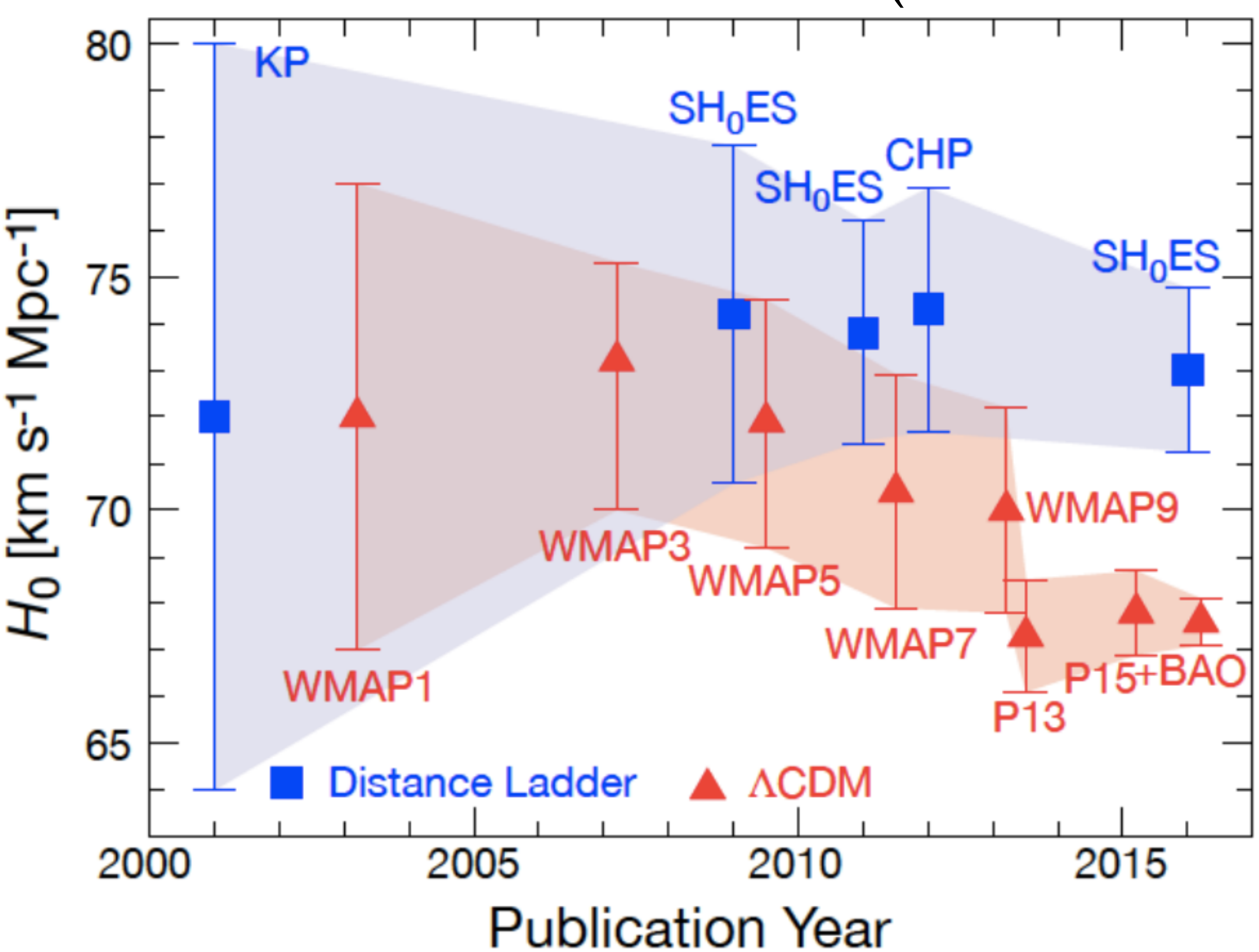
- aLIGO/Adv.Virgo: measurement of **Hubble constant** H_0 with accuracy of **5%** at 95% confidence **after 40-50 GW observations with 3 detectors.**

- Results will **depend on knowledge of clusters' catalogues** at redshifts larger than 1.

Cosmography with spacetime sirens: other considerations

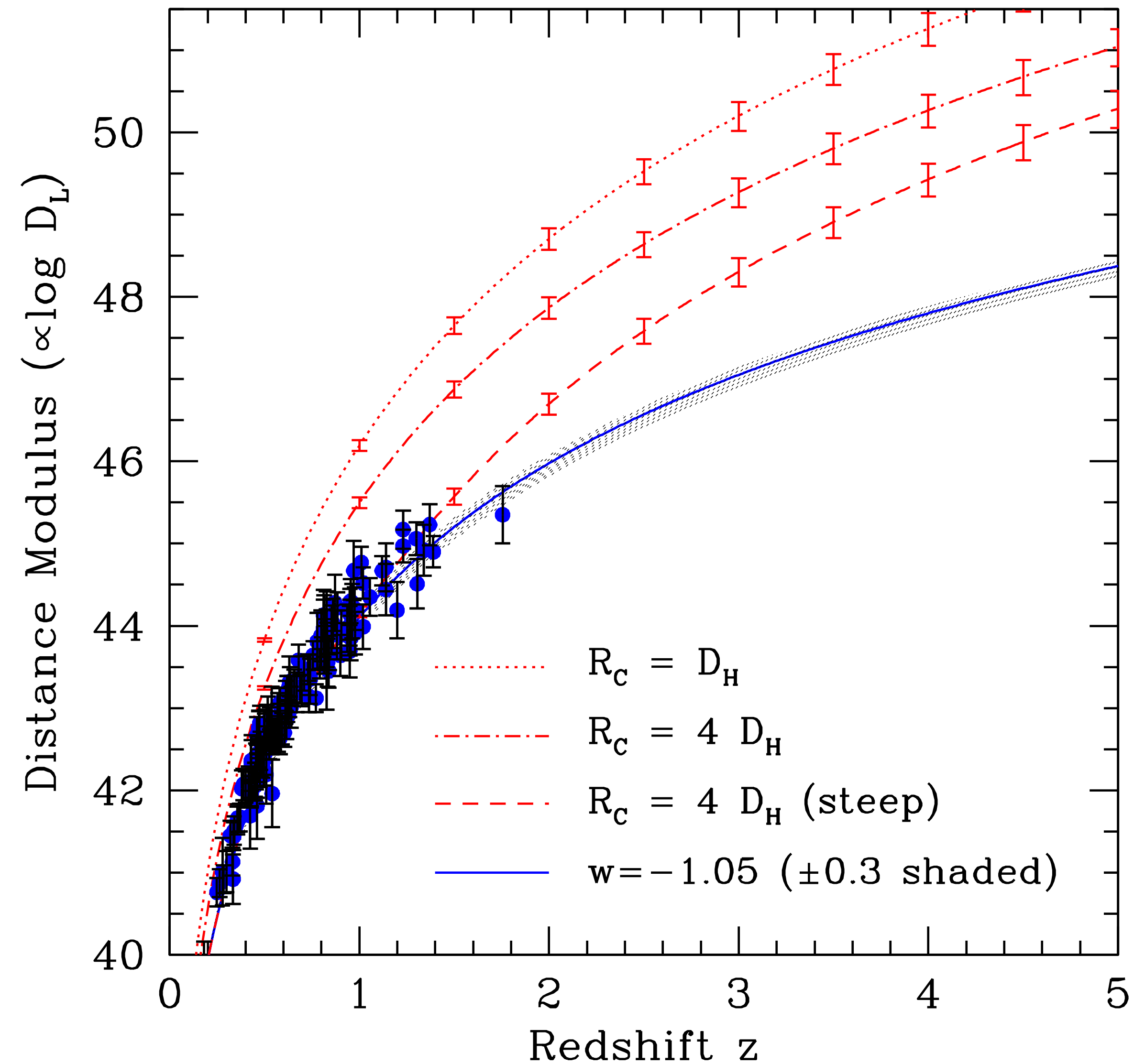
- **Current measurements** of H_0 show some **tension**.

(Freedman 2017)



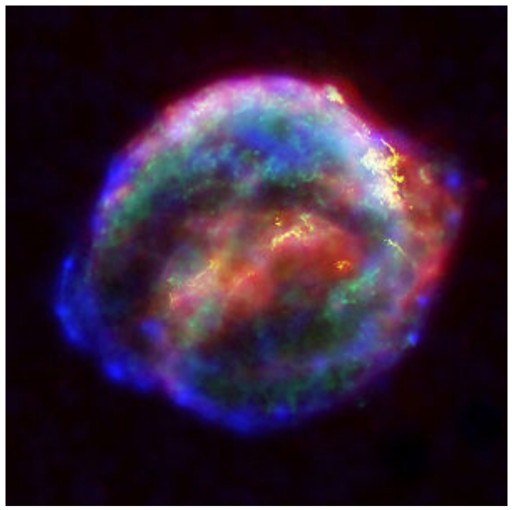
- Testing **extra-dimensions** with GW standard sirens.

(Deffayet & Menou 2007)



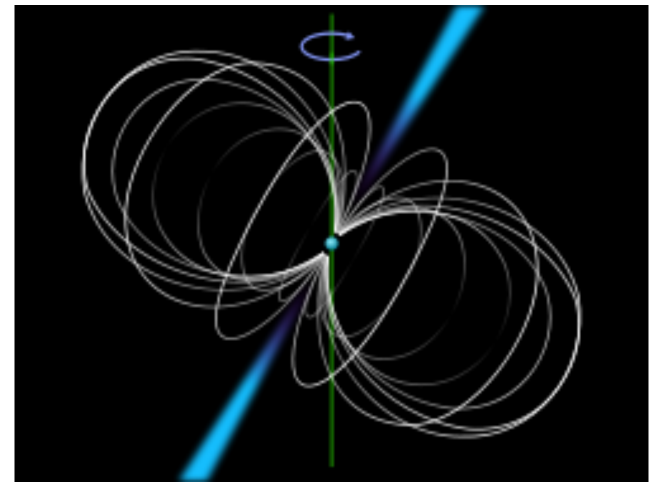
- Mapping **expansion rate of Universe** on scales of **hundreds Mpc** will **provide** a **completely independent estimate** of **Hubble parameter**.

All kinds of turmoil in the Universe can ring space-time



Kepler's supernova SN1604

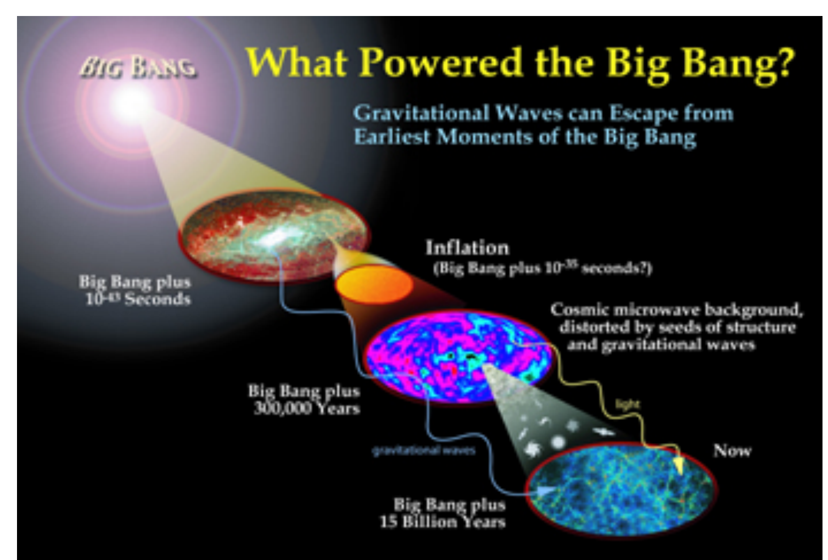
- Core of massive star ceases to generate energy from nuclear fusion and undergoes sudden collapse forming a neutron star.
- GW signal is unshaped burst lasting for tenths of millisecond.



optical/X-ray image of the Crab Nebula

- Pulsars emit radio waves with extremely stable period.
- Typical "mountains" on a pulsar are 1cm in height!
- GW signal is continuous and periodic.

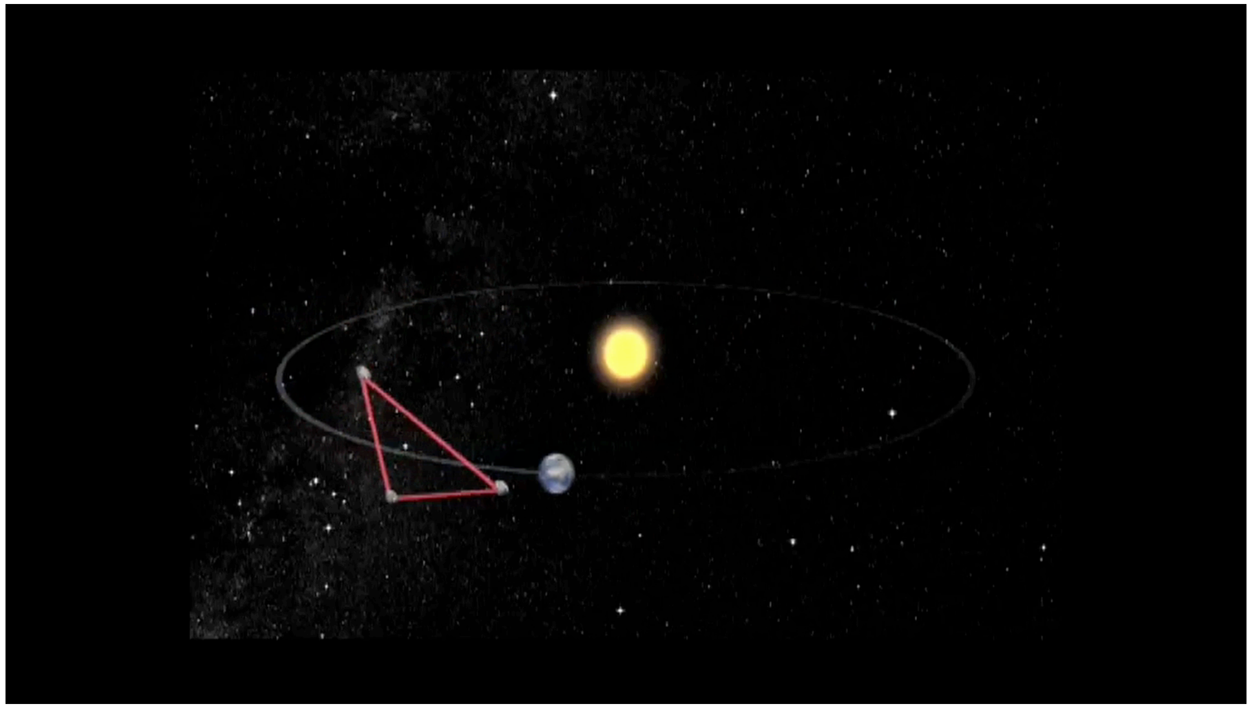
- Snapshot of the "very" early Universe.
- Stochastic GW background produced during rapid expansion of Universe after Big Bang.



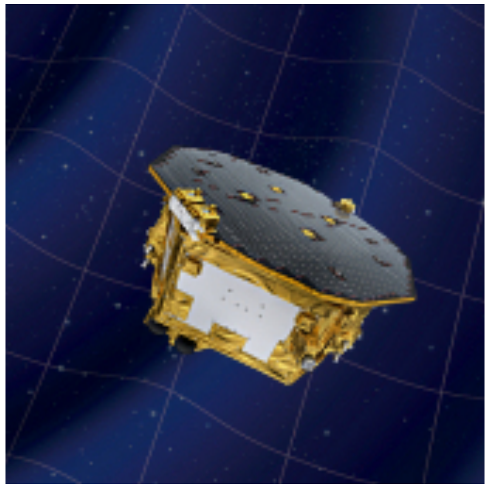
Detecting gravitational waves in space: LISA

- Laser Interferometer Space Antenna (LISA): ESA mission for 2034 **(2028?)**

Credit: AEI/Milde Marketing



(Armano et al. PRL 116 (2016) 231101)



- **LISA Pathfinder (technology mission) completed: extremely successful. LISA works!**

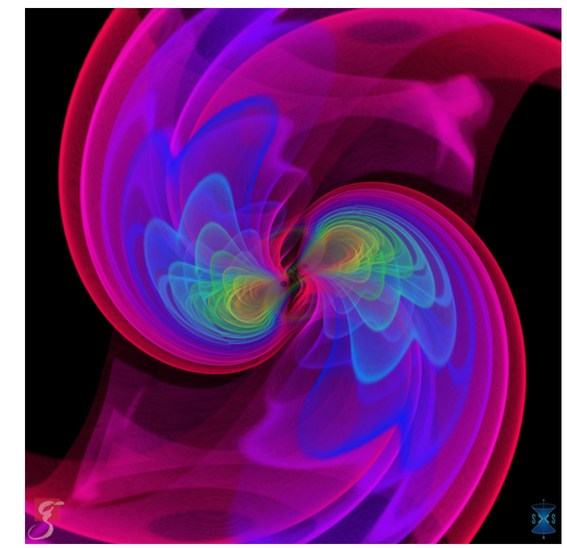
Merging galaxies: NGC4038 and NGC4039

- **When galaxies collide, the supermassive black holes at their centers can interact and merge, emitting the strongest gravitational-wave signals.**

- **Ringing of space-time can be observed continuously over one-two years!**

New Era of Precision Gravitational-Wave (astro)Physics

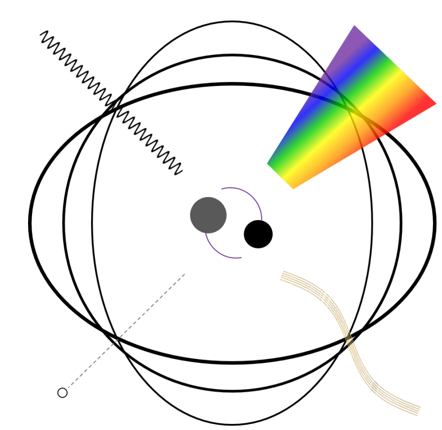
- GW observations by LIGO/Virgo opened a new era of scientific discovery.



- Gravitational interaction powers most luminous, spectacular objects and phenomena (GRBs, pulsars, supernovae, black-hole and neutron-star mergers, and evolution of early Universe).

- We will probe extreme gravity and astrophysics.

- We will solve outstanding questions in fundamental physics and cosmology.



- As for any new observational tool, gravitational (astro)physics will likely unveil phenomena and objects never imagined before.