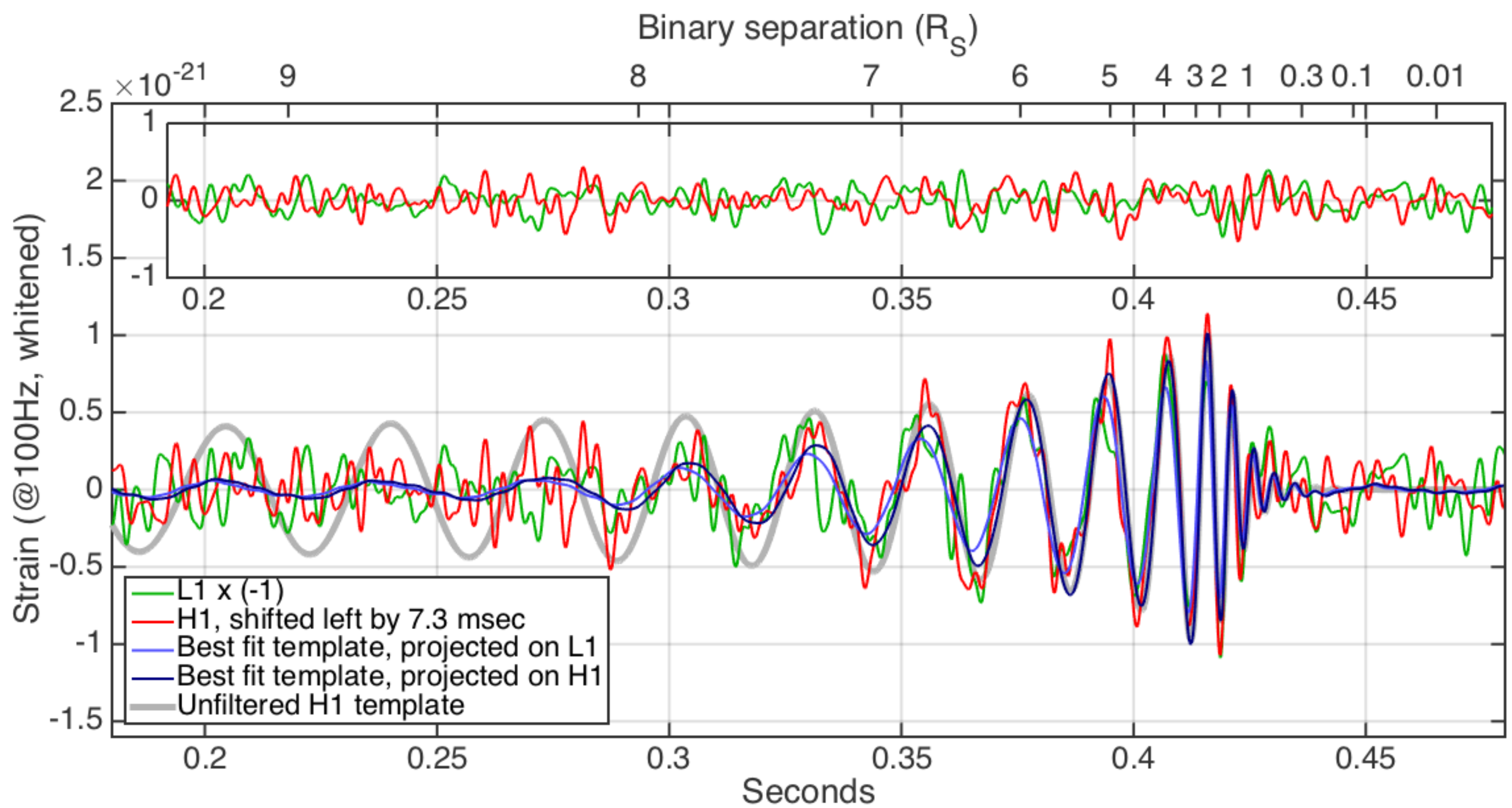

A Glimpse of Gravitational-Wave Astrophysics

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  Albert Einstein Institute
- **Department of Physics, University of Maryland**

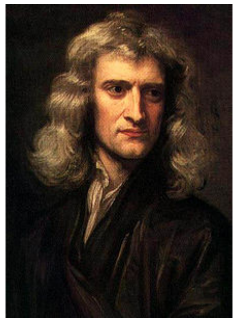
University of Maryland 1856

MAX-PLANCK-GESELLSCHAFT

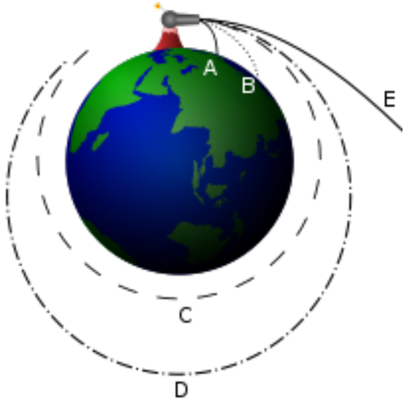
Outline

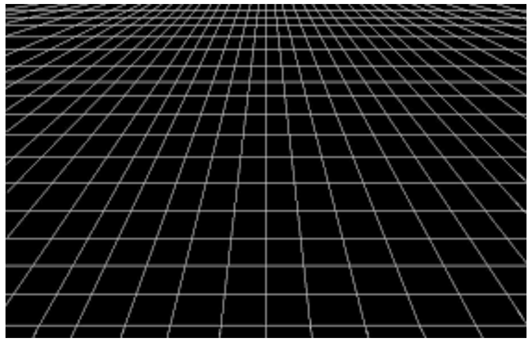
- The **new astronomical messengers: gravitational waves.**
- **LIGO observations** of gravitational waves from **binary black hole coalescences**.
- **Science with gravitational waves**: astrophysics, cosmology and fundamental physics.
- The **bright future** of gravitational-wave astronomy.

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



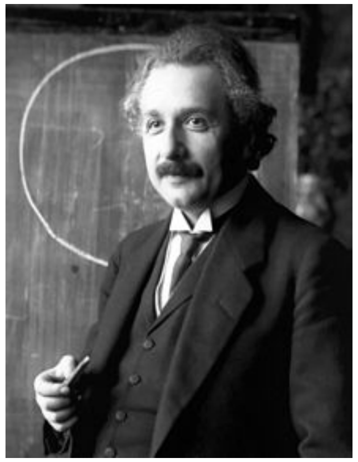
Newton's gravity
(1687)



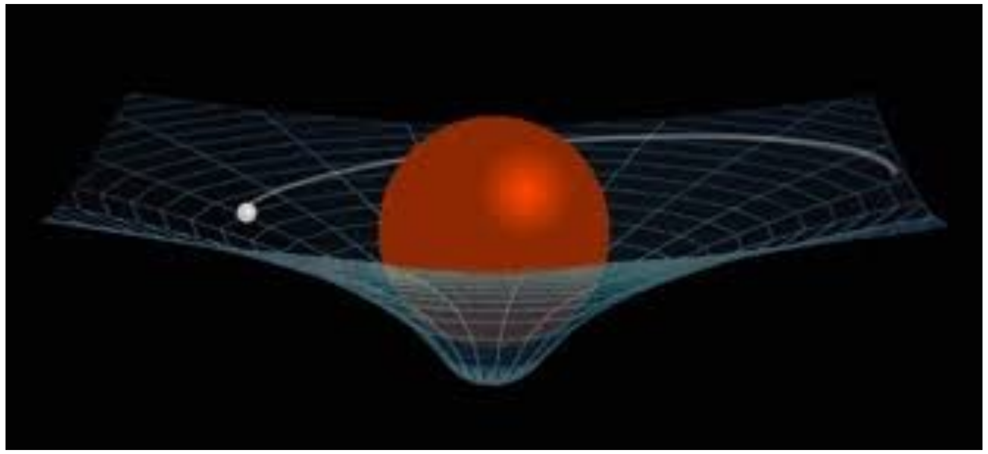


In Newton gravity **space and time** are given **a priori**.

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



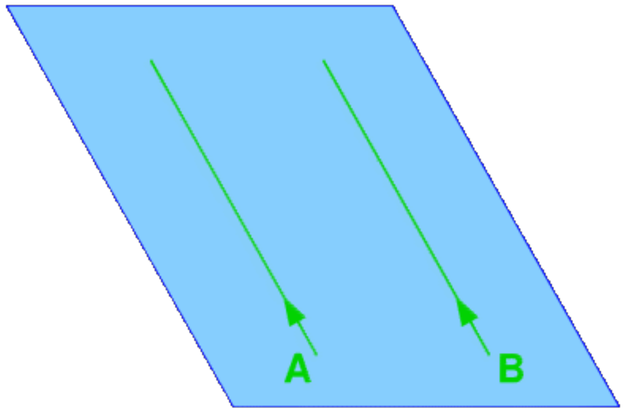
General Relativity
(1915)

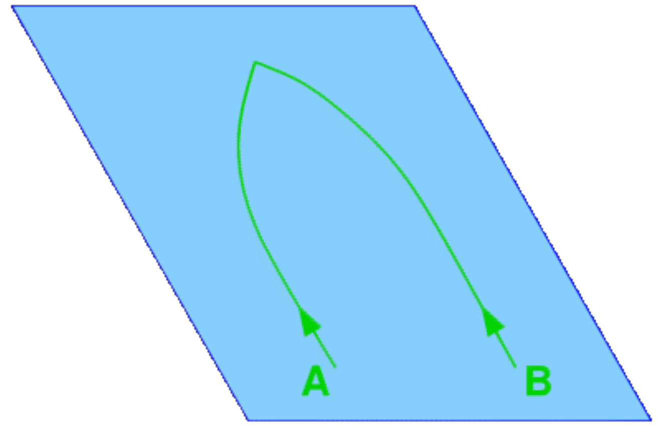


Space-time is a **dynamic** and **elastic entity** both **influencing and influenced by** the distribution of **mass-energy** that it contains.

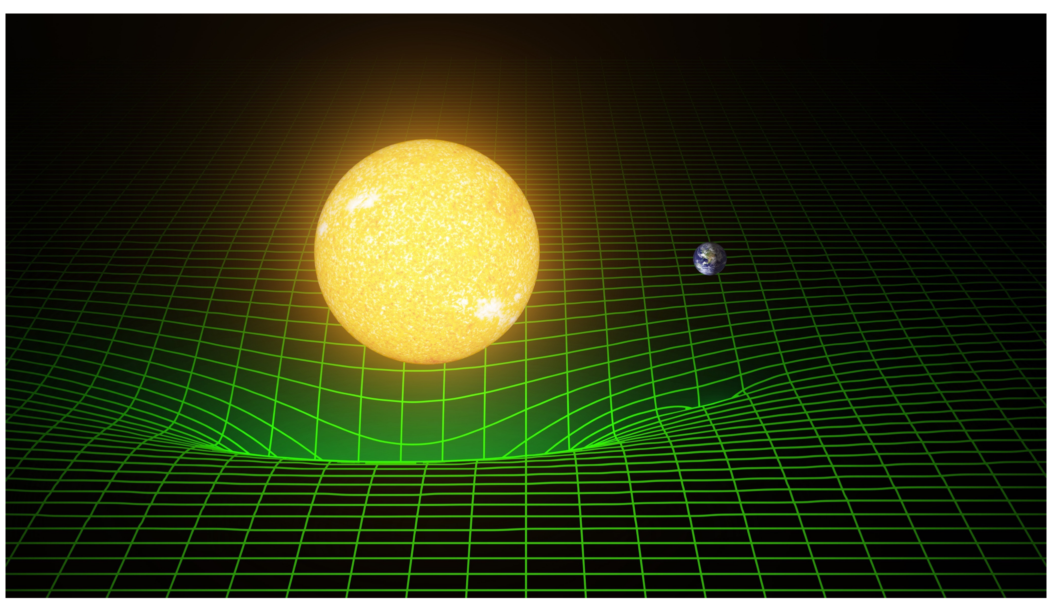
Einstein **geometric gravity**.

Einstein's geometric gravity





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

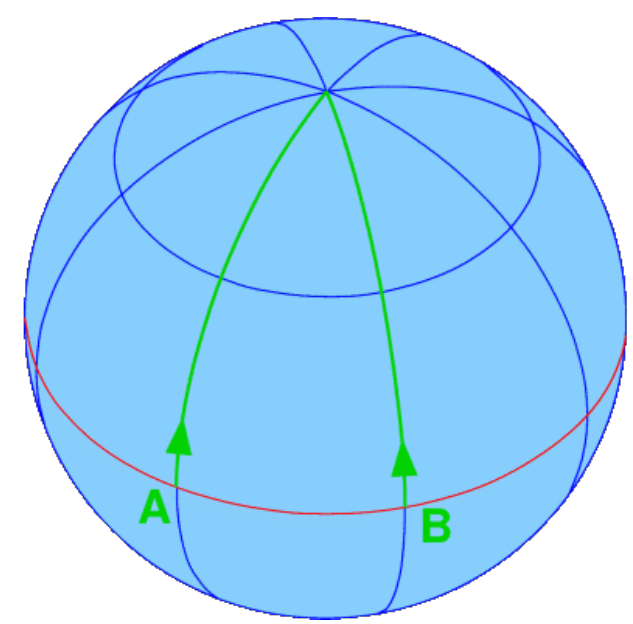


Gravity is the effect of **"curvature" (or warp)** in the geometry of space-time **caused by** the presence of any **object with mass/energy.**

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

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

credit: Einstein online



Gravitational waves: one of greatest predictions of GR

- In 1916 Einstein predicted **existence of gravitational waves:**

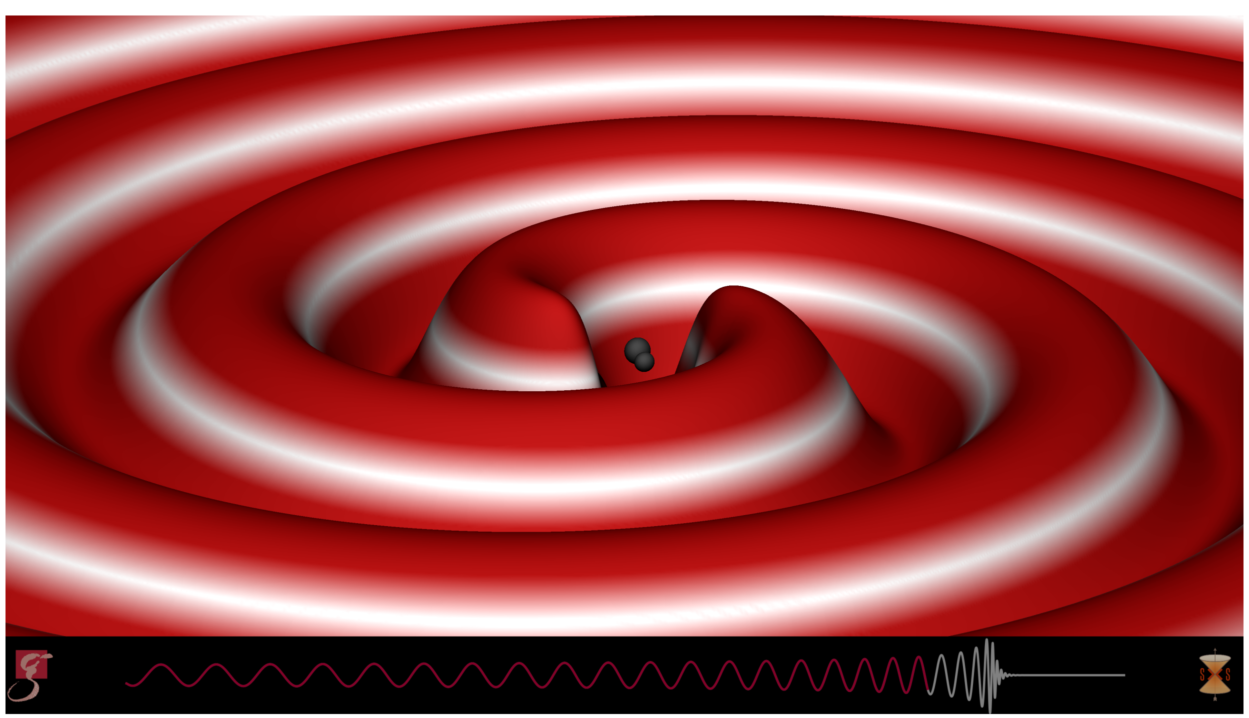
Linearized gravity (weak field): $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ $\qquad |h_{\mu\nu}| \ll 1$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} \longrightarrow \Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

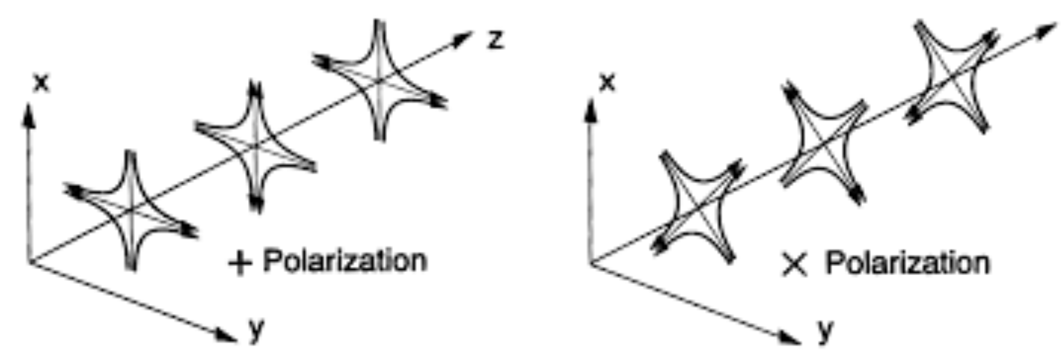
Distribution of **mass deforms spacetime** geometry in its neighborhood.

Deformations propagate away at finite speed **in form of waves** whose oscillations reflect temporal variation of matter distribution.

(visualization: Haas @ AEI)



Ripples in the curvature of **spacetime**



Two radiative degrees of freedom

First paper by Einstein on gravitational waves: 1916

Approximative Integration of the Field Equations of Gravitation

by A. Einstein

For the treatment of the special (not basic) problems in gravitational theory one can be satisfied with a first approximation of the $g_{\mu\nu}$. The same reasons as in the special theory of relativity make it advantageous to use the imaginary time variable $x_4 = it$. By "first approximation" we mean that the quantities $\gamma_{\mu\nu}$, defined by the equation

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu}, \tag{1}$$

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

This expression would get an additional factor $\frac{1}{c^4}$ if we would measure time in seconds and energy in Erg. Considering furthermore that $\kappa = 1.87 \cdot 10^{-27}$, it is obvious that A has, in all imaginable cases, a practically vanishing value.

Nevertheless, due to the inneratomic movement of electrons, atoms would have to radiate not only electromagnetic but also gravitational energy, if only in tiny amounts. As this is hardly true in nature, it appears that quantum theory would have to modify not only MAXWELLIAN electrodynamics, but also the new theory of gravitation.

Second paper by Einstein on gravitational waves: 1918

The important question of how gravitational fields propagate was treated by me in an academy paper one and a half years ago.[1] However, I have to return to the subject matter since my former presentation is not sufficiently transparent and, furthermore, is marred by a regrettable error in calculation.

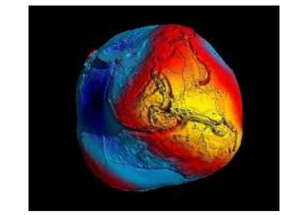
If one forms the mean value of S over all directions of space for a fixed value of $A_{\mu\nu}$, one obtains the mean density $\bar{S}$ of the radiation. Finally, $\bar{S}$ multiplied by $4\pi R^2$ is the energy loss (per time unit) of the mechanical system due to gravitational waves. The calculation finds

$$4\pi R^2 \bar{S} = \frac{\kappa}{80\pi}\left[\sum_{\mu\nu} \dddot{\mathfrak{J}}_{\mu\nu}^{\,2} - \frac{1}{3}\left(\sum_{\mu} \dddot{\mathfrak{J}}_{\mu\mu}\right)^2\right]. \qquad (30)$$

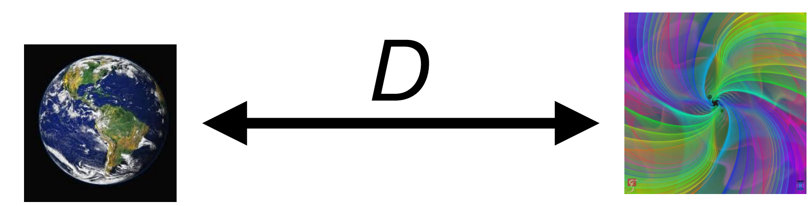
wrong by a factor 2!

This result shows that a mechanical system which permanently retains spherical symmetry cannot radiate; this is in contrast to the result of the previous paper, marred by an error in calculation.

What makes gravitational waves unique astronomical messengers

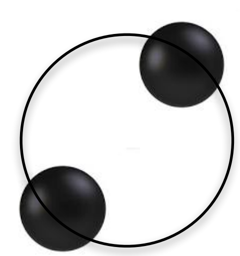


- GW sources **dominated by gravity**
- Produced by variation in time of **quadrupole moment**: $h_{ij} \sim \frac{G}{c^4} \frac{\ddot{Q}_{ij}}{D}$
- Typical GW **strength**: $h \sim \epsilon \frac{G}{c^2} \frac{(E_{\rm kin}/c^2)}{D}$



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

  Similar or larger to the one of **whole visible Universe**!

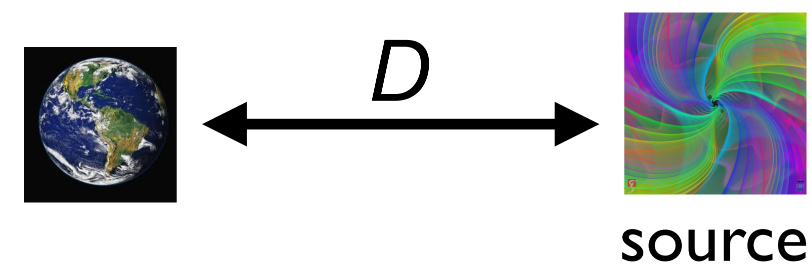


binary system

- Propagation unaffected by matter/energy: **pristine probes**

Multipolar decomposition of waves (at linear order in G)

- Multipolar expansion in terms of mass moments (I_L) and mass current moments (J_L) of source:



can't oscillate can't oscillate can't oscillate

$$h \sim \frac{G I_0}{c^2 D} + \frac{G \dot{I}_1}{c^3 D} + \frac{G \ddot{I}_2}{c^4 D} + \frac{G \dot{J}_1}{c^4 D} + \frac{G \ddot{J}_2}{c^5 D} + \cdots$$

- EM & GR: electric dipole moment & mass dipole moment

$$I_1 : \quad \mathbf{d} = \sum_i m_i \mathbf{x}_i \Rightarrow \dot{\mathbf{d}} = \sum_i m_i \dot{\mathbf{x}}_i = \mathbf{P}$$

conservation of linear momentum

- EM & GR: magnetic dipole moment & current dipole moment

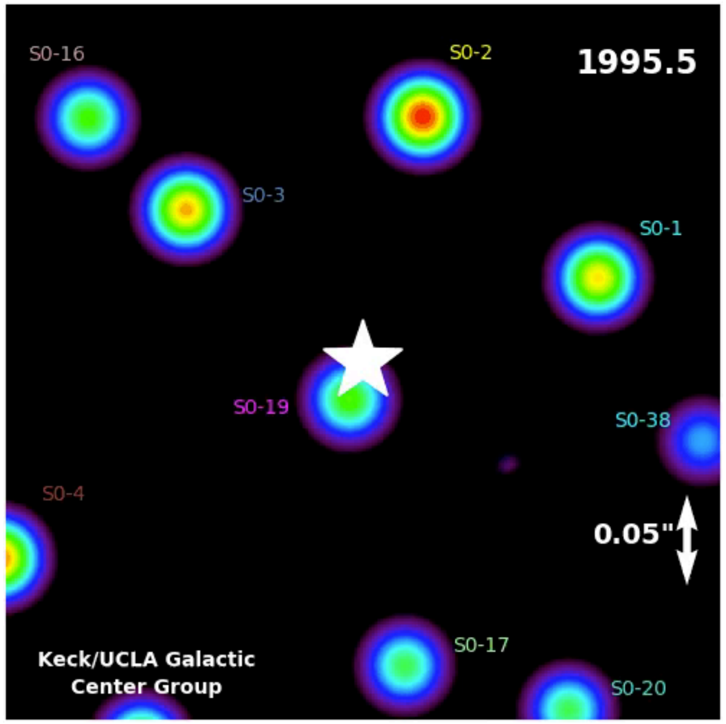
$$J_1 : \quad \mu = \sum_i m_i \mathbf{x}_i \times \dot{\mathbf{x}}_i = \mathbf{L}$$

conservation of angular momentum

Orbiting black holes are the strongest GW sources

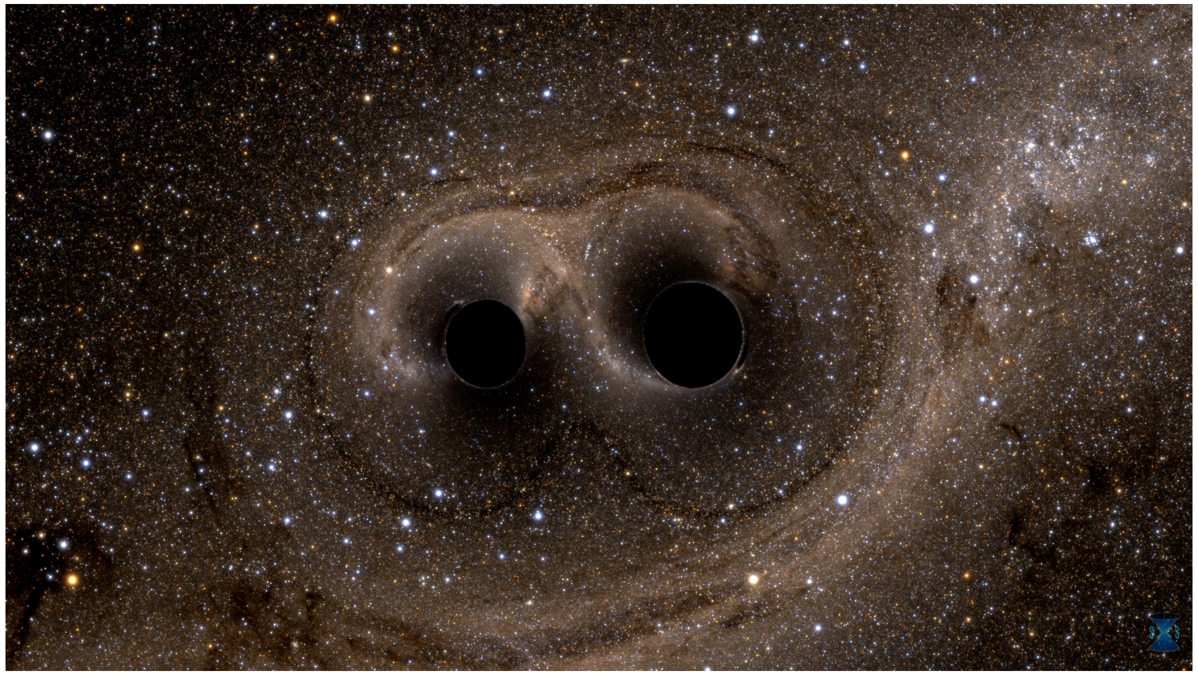
Supergiant star--Cygnus X-1 binary system

credit: Ghez's group



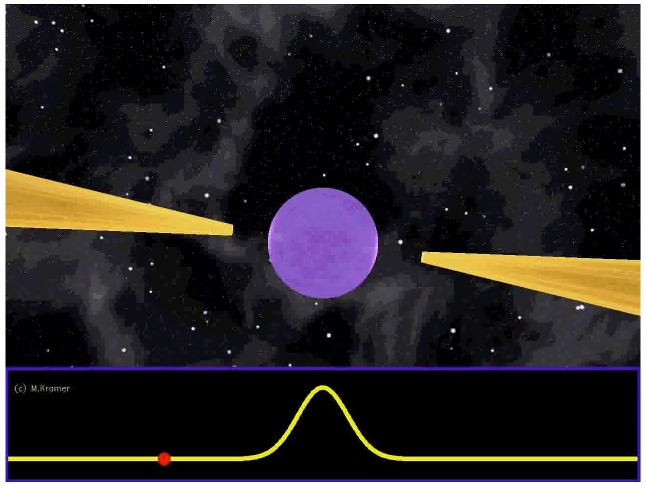
Black hole of 4 million solar masses in our galaxy's center!

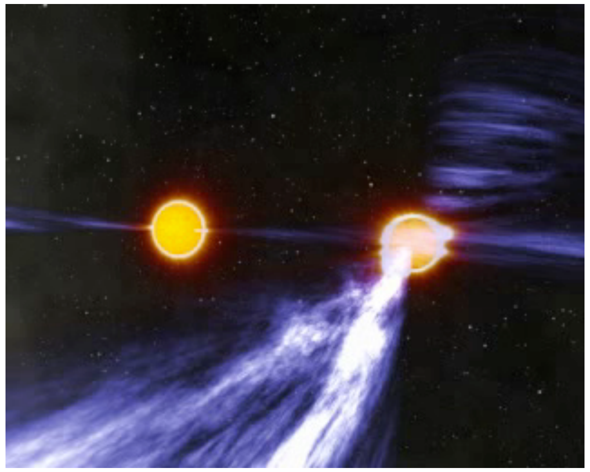
(visualization credit: Cornell U)



Binary black hole

Gravitational waves do exist: we knew it from binary pulsars





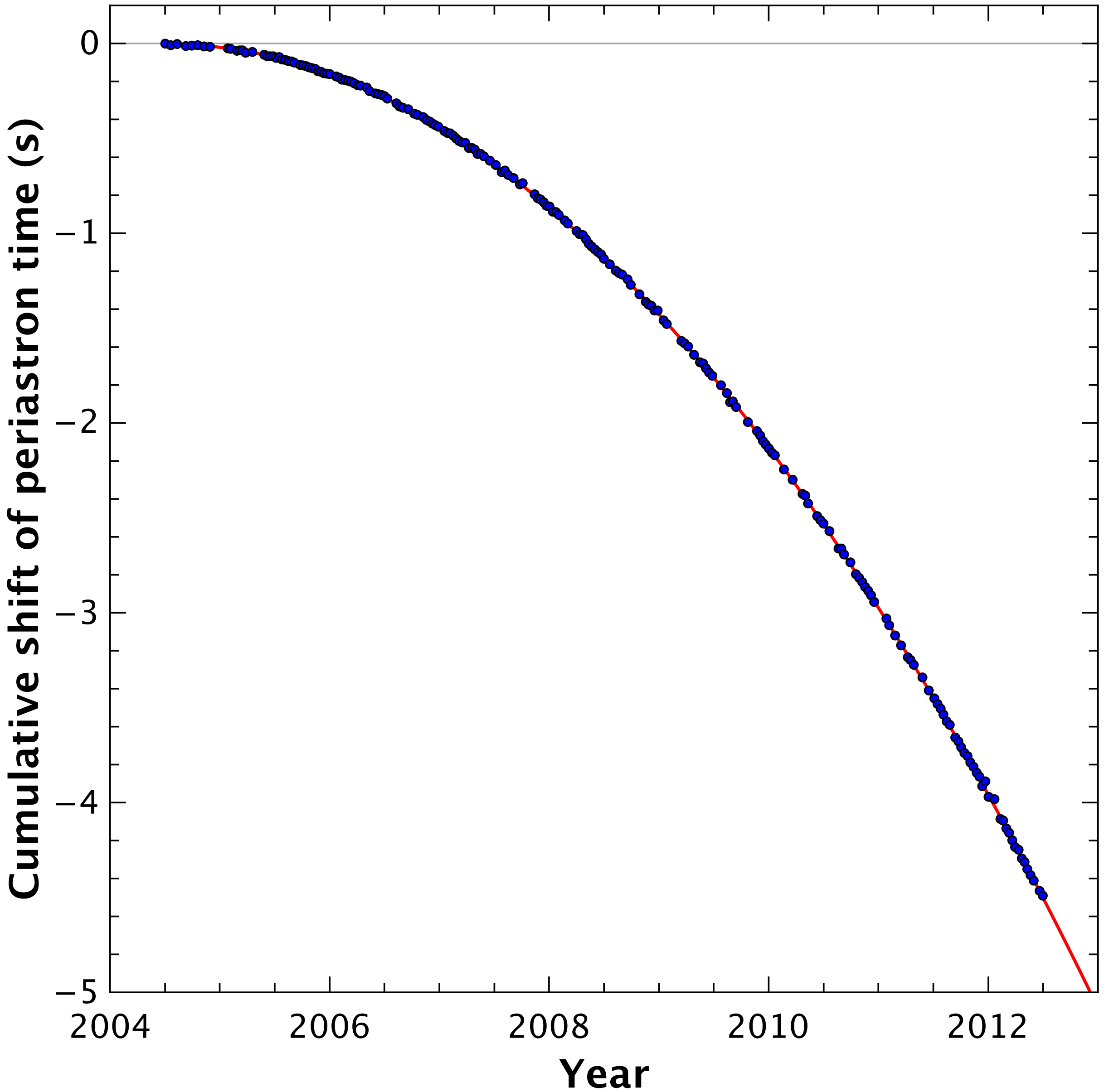
credit: Kramer's group

- **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.

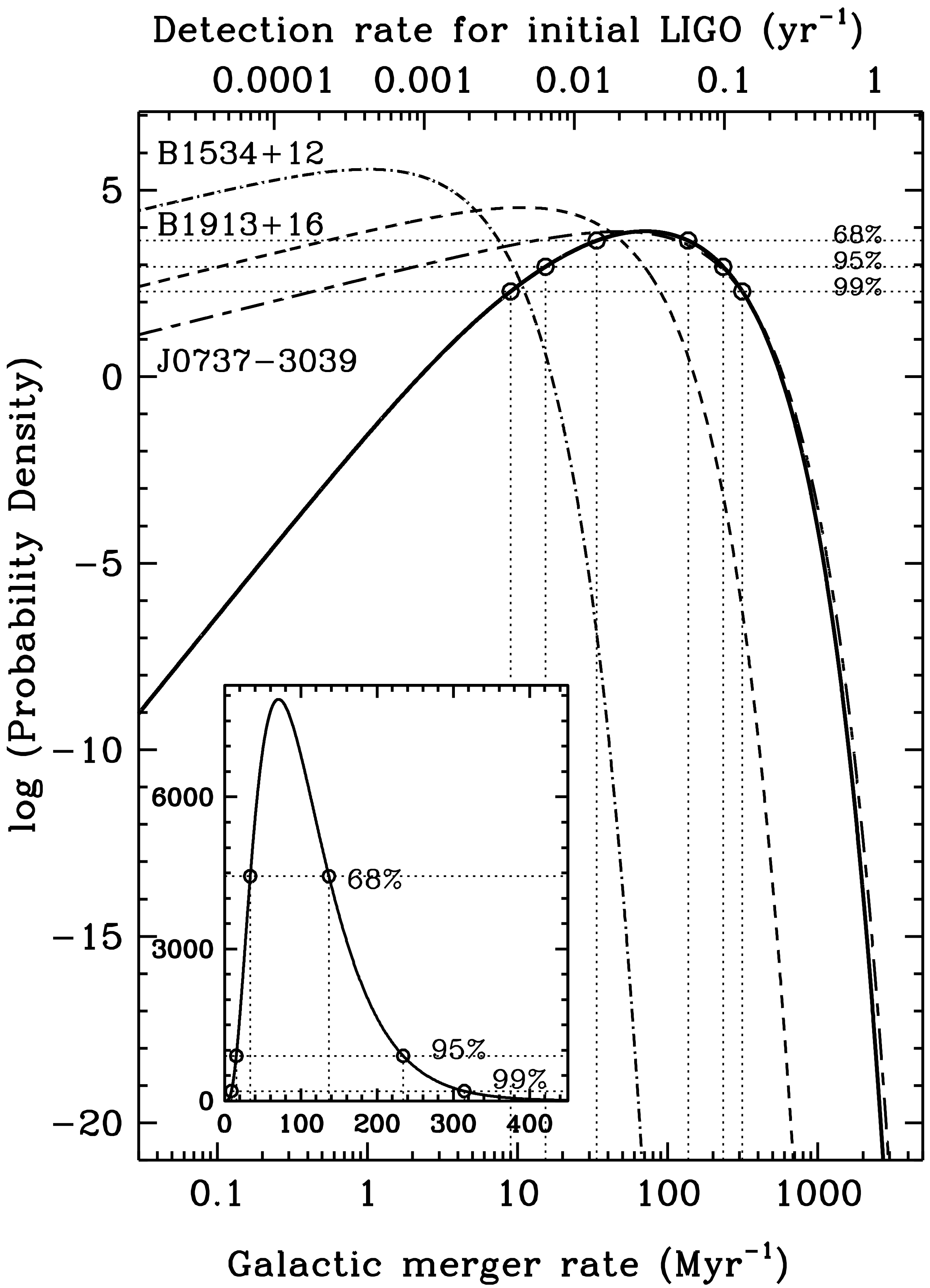
- Before LIGO detections, this was the **strongest evidence** for **existence of gravitational radiation**.

Nobel prize to Hulse & Taylor in 1993



(Kramer et al. 2017)

Some binary pulsars merging in Hubble time

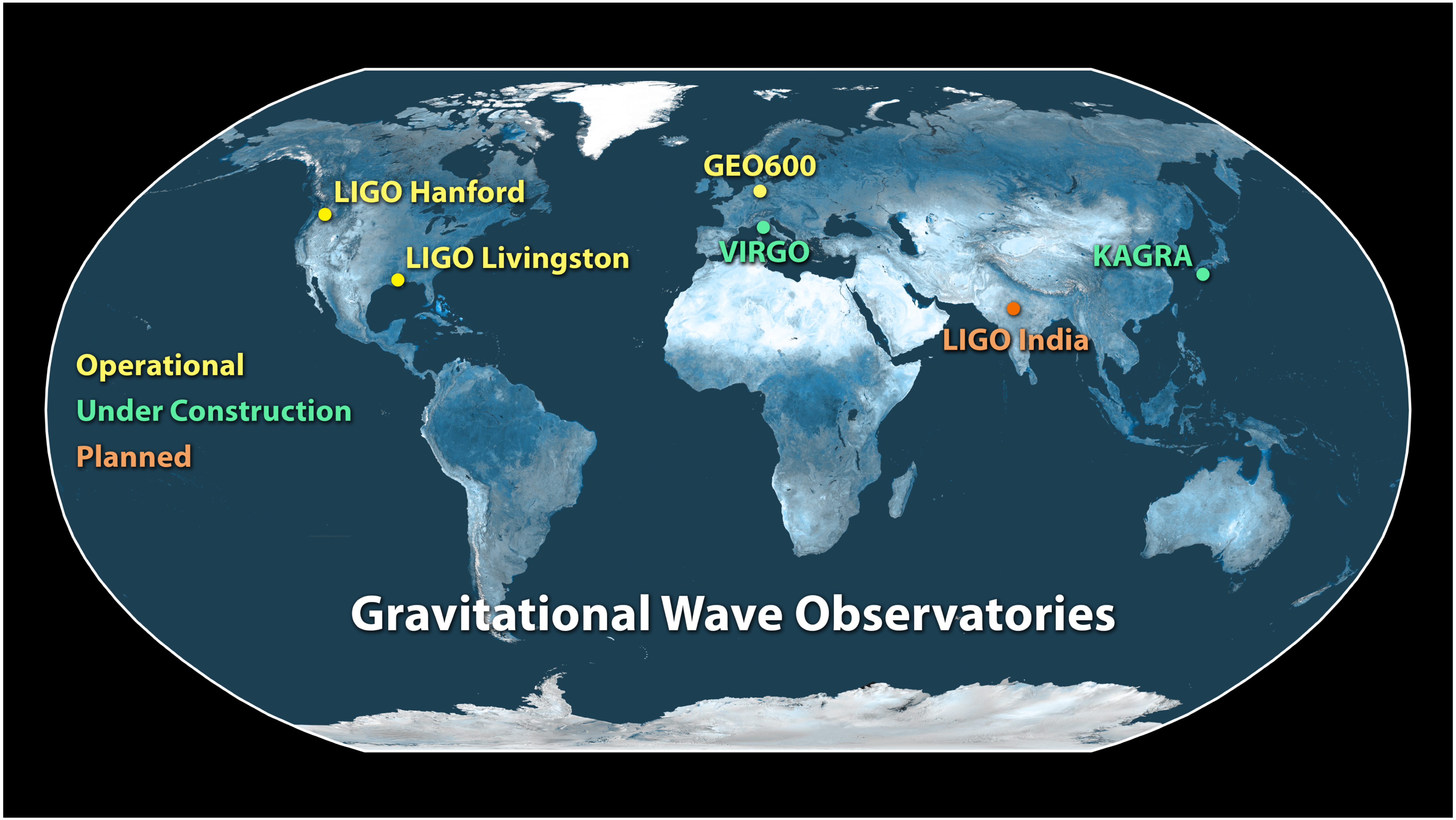


(Kim et al. 2006)

PSR name	P^a (ms)	P_b (hrs)	T_{life} (Gyr)
B1913+16	59.03	7.75	0.37
B1534+12	37.90	10.10	2.93
J0737-3039	22.70	2.45	0.23
J1756-2251	28.46	7.67	2.03
J1906+0746	114.14	3.98	0.082

- Observations are used to estimate **BNS merger rate in Milky-Way-galaxy**; rate is scaled to deduce **rates for LIGO**.
- Observations are used to **constrain pop. synthesis, dynamical capture estimates**, which predict rates for BNS, NS-BH, BBH.
- So far, **no observation** of binary pulsars with a **BH companion.**

International network of gravitational-wave detectors



LIGO Scientific Collaboration: about 800 members!

LIGO

LIGO Scientific Collaboration

LSC

LIGO Scientific Collaboration & Virgo Collaboration: 1004 members!

LIGO VIRGO

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

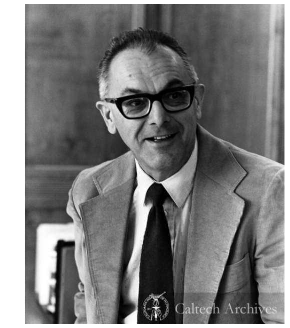
Joe Weber, University of Maryland

Heinz Billing, and Garching group

Kip Thorne, Caltech

Rai Weiss, MIT

Ron Drever, Caltech



Rochus Vogt, Caltech

Barry Barish, Caltech

- 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

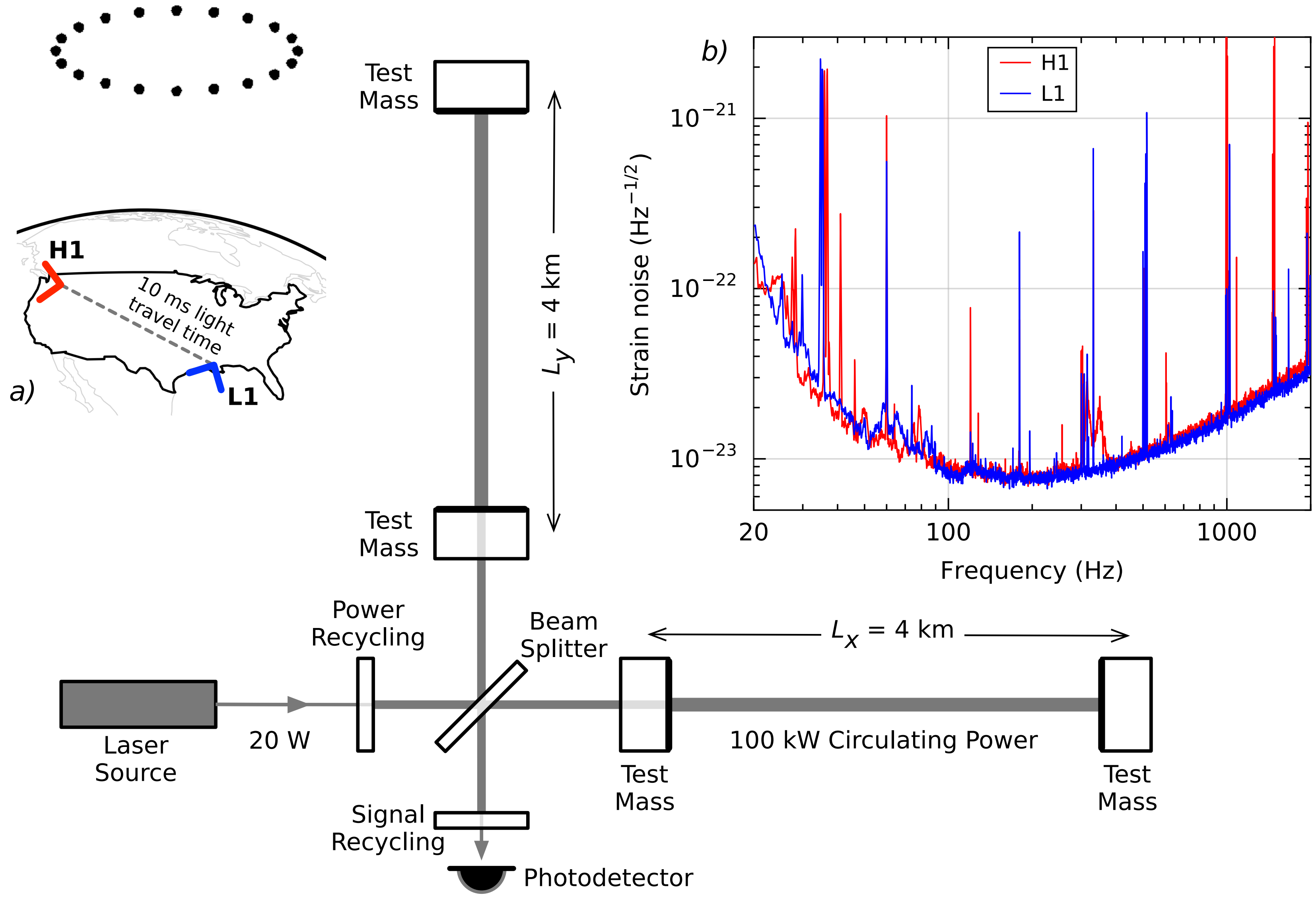
Total cost of LIGOs: about 1.1 billion dollars

The two LIGO detectors

LIGO in Washington (H1)

LIGO in Louisiana (L1)

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

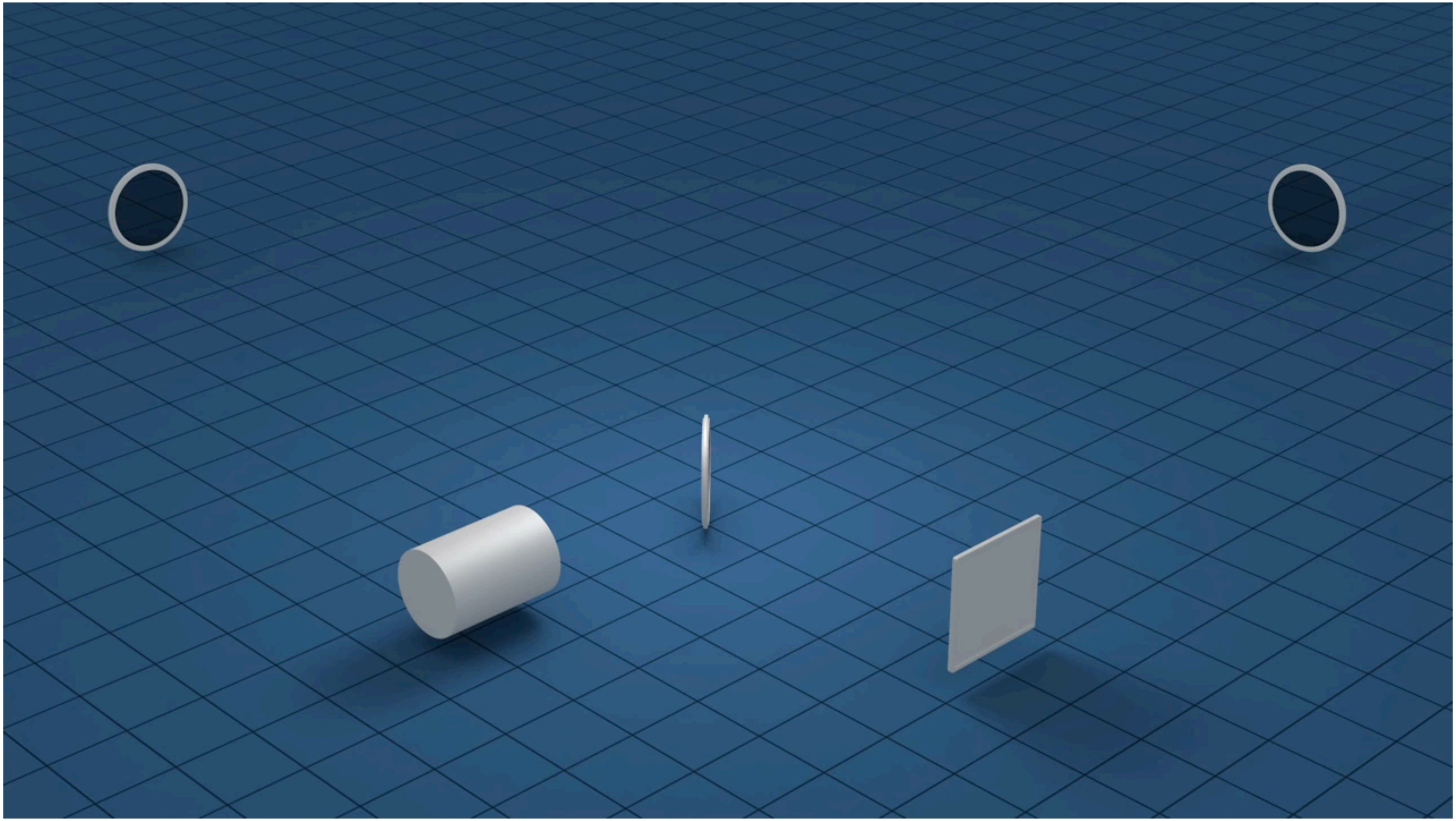


$$\Delta L = L\,h \sim 10^{-16}\,\mathrm{cm}$$

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

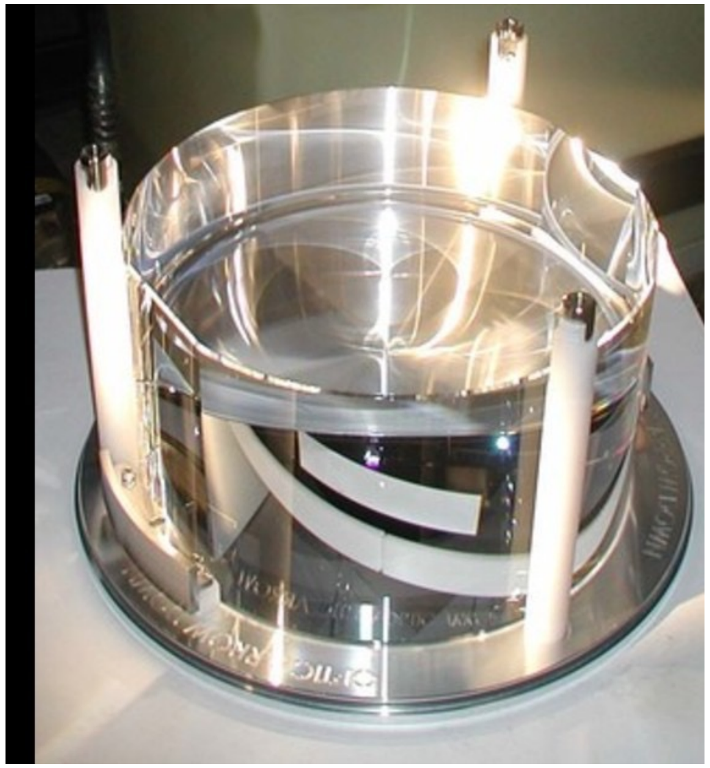
LIGOs measures **displacements of mirrors** at about a **ten-thousandth** of a **proton's diameter.**

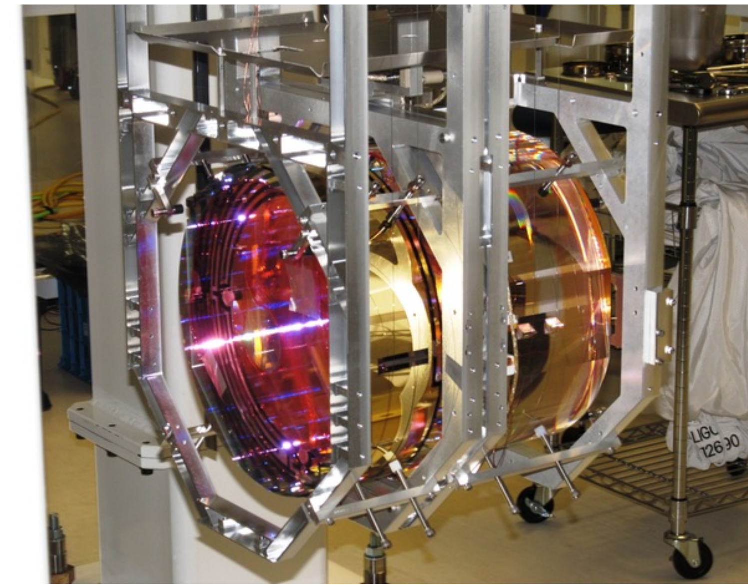
How LIGO works



LIGO Scientific Collaboration

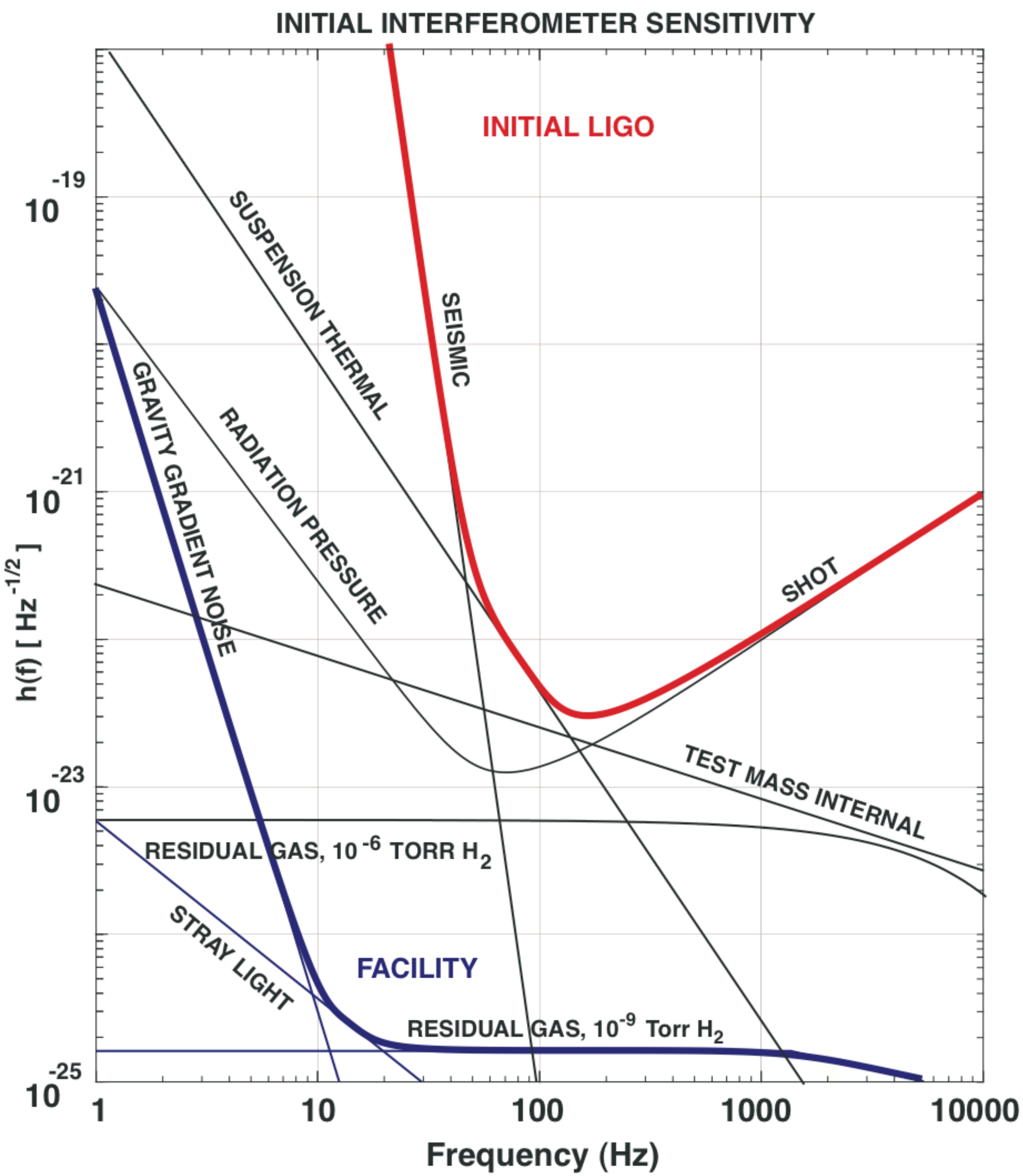
A glimpse inside the LIGO facility



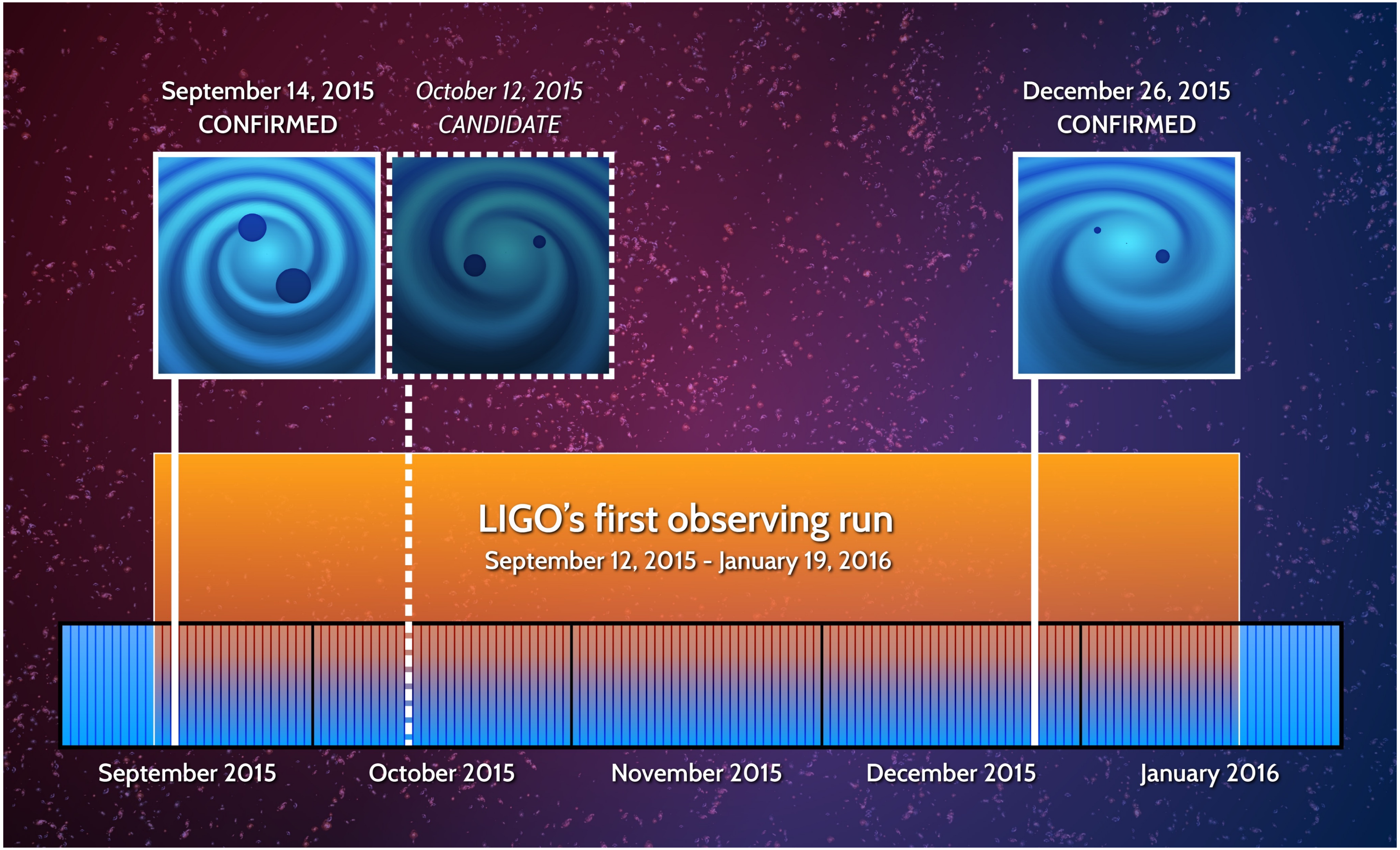


LIGO Scientific Collaboration

Typical noises in ground-based gravitational-wave detectors



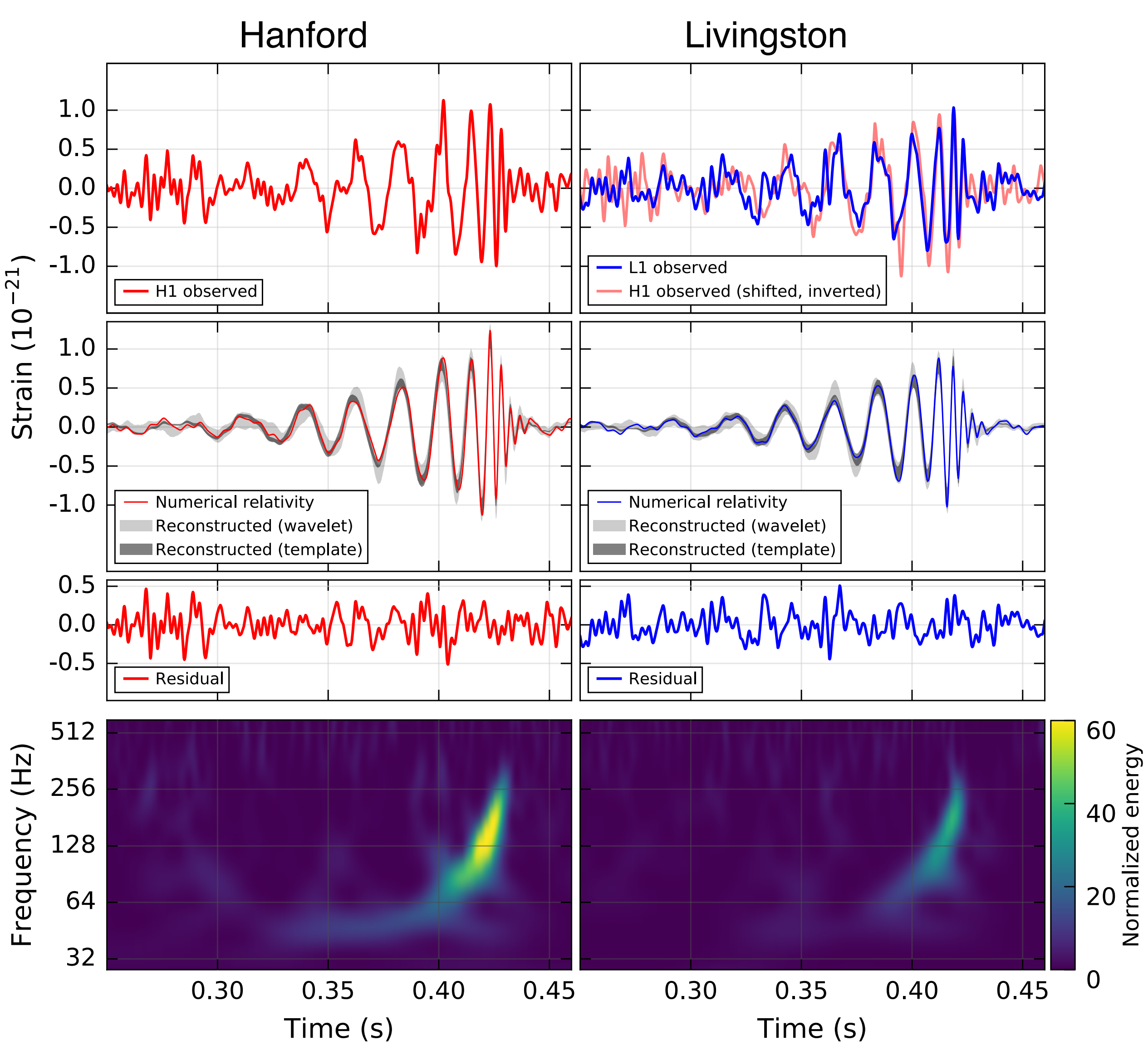
Events during the first observing run (O1) of LIGOs

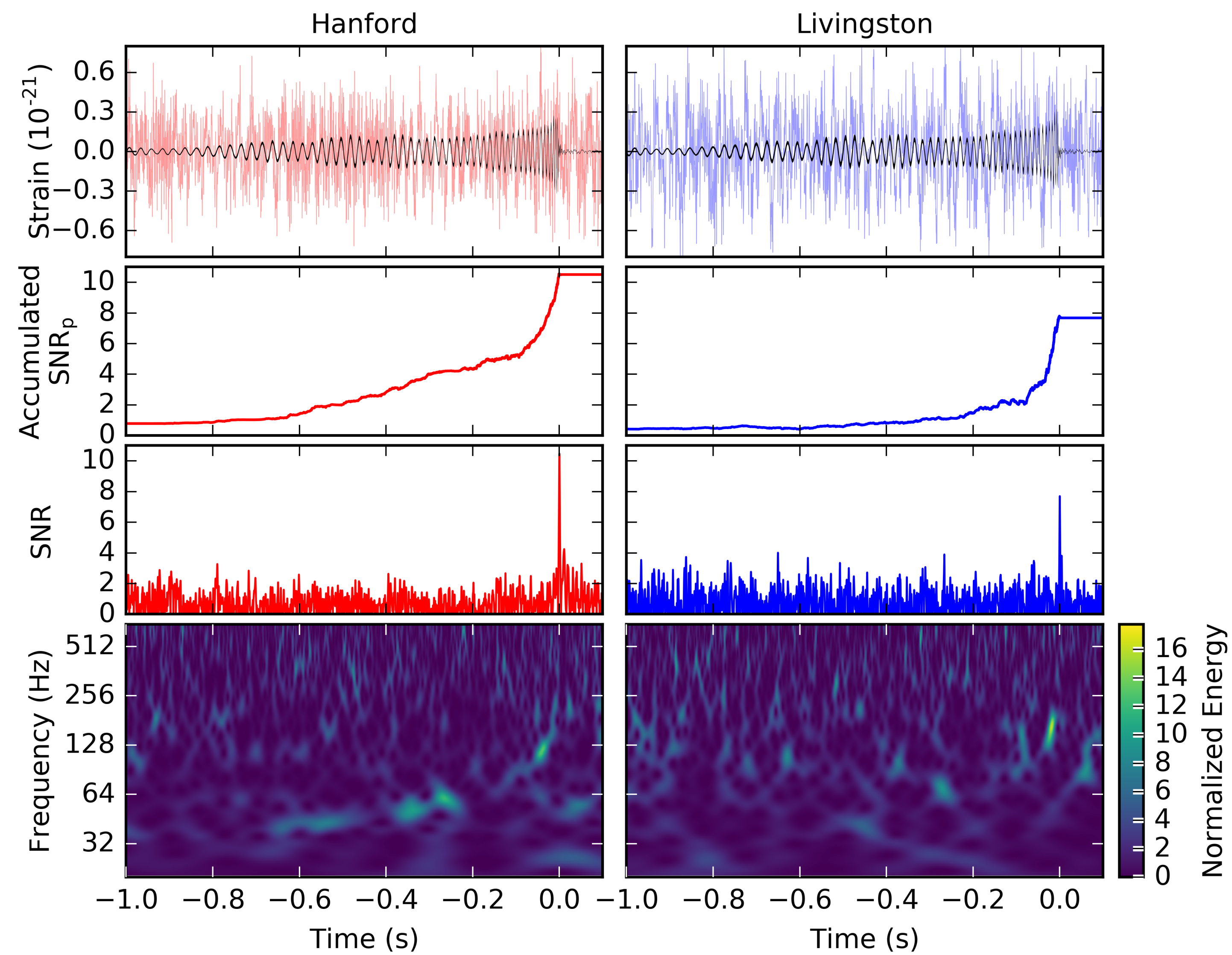


LIGO detections during O1: GW150914 & GW151226

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

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





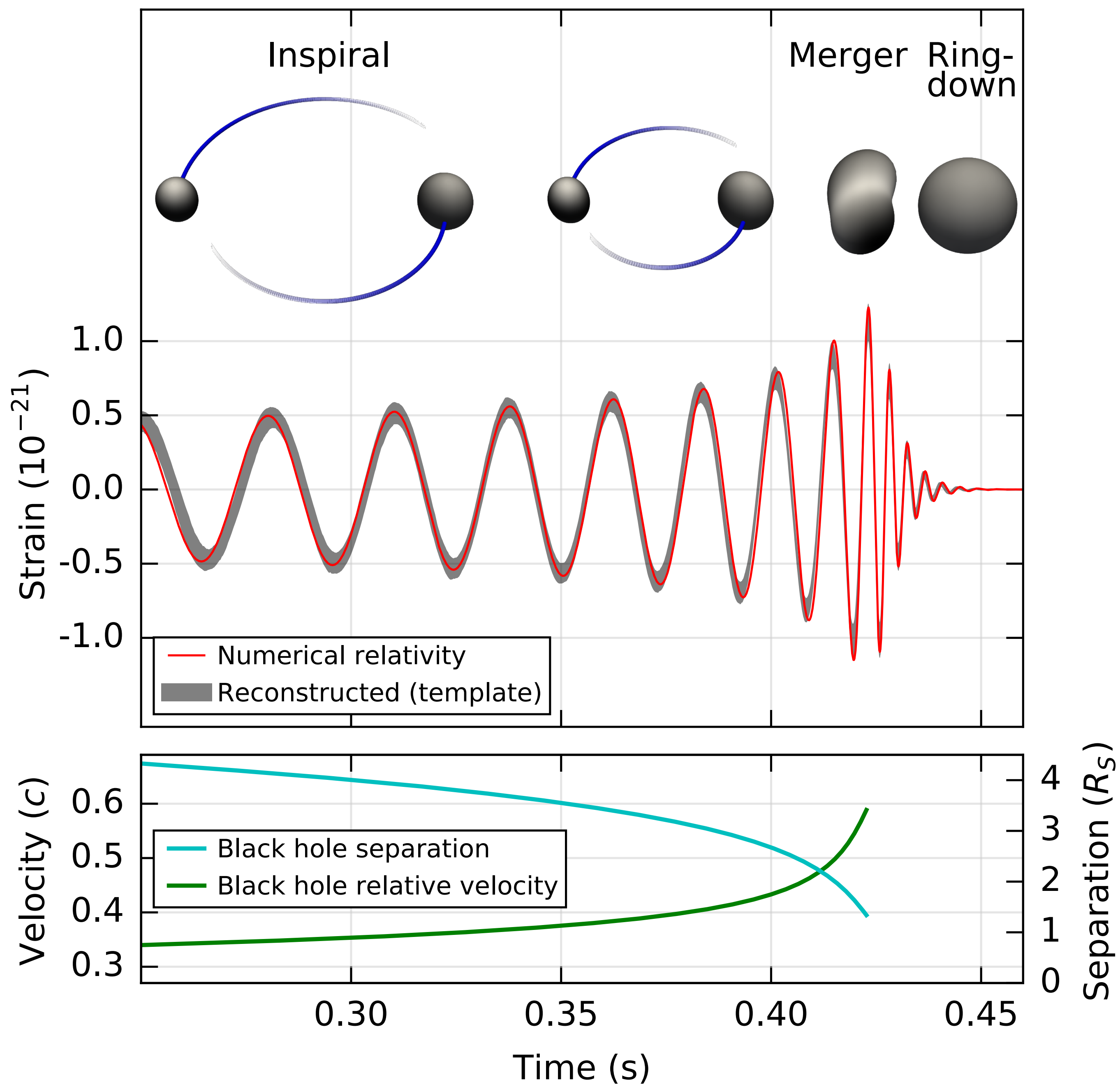
- **GW150914**: SNR=24 (very loud), 10 GW cycles, **0.2 sec.**

- **GW151226**: SNR=13 (quieter), 55 GW cycles, **1.5 sec.**

Characteristics of binary black-hole coalescence

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

- **Early inspiral:** low velocity & weak gravitational field.
- **Late inspiral/plunge:** high velocity & strong gravitational field.
- **Merger:** nonlinear & non perturbative effects; rapidly varying gravitational field
- **Ringdown:** excitation of quasi-normal modes/spacetime vibrations.



Phase/amplitude evolution **encodes unique information** about the source

Binary was composed of two compact objects, no neutron star

$$\nu = \frac{\mu}{M} \qquad 0 \le \nu \le 1/4$$

$$\mu = \frac{m_1 m_2}{M} \qquad M = m_1 + m_2$$

$$\mathcal{M} = \nu^{3/5} M = \left(\frac{5}{96} \pi^{-8/3} f_{\rm GW}^{-11/3} \dot{f}_{\rm GW} \right)^{3/5}$$

- We **measured**:

$$\mathcal{M} \simeq 30 M_\odot \Rightarrow M \ge 70 M_\odot$$

$$f_{\rm GW} \sim 150 {\rm Hz}\,, \omega^2 r^2 = \frac{M}{r}$$

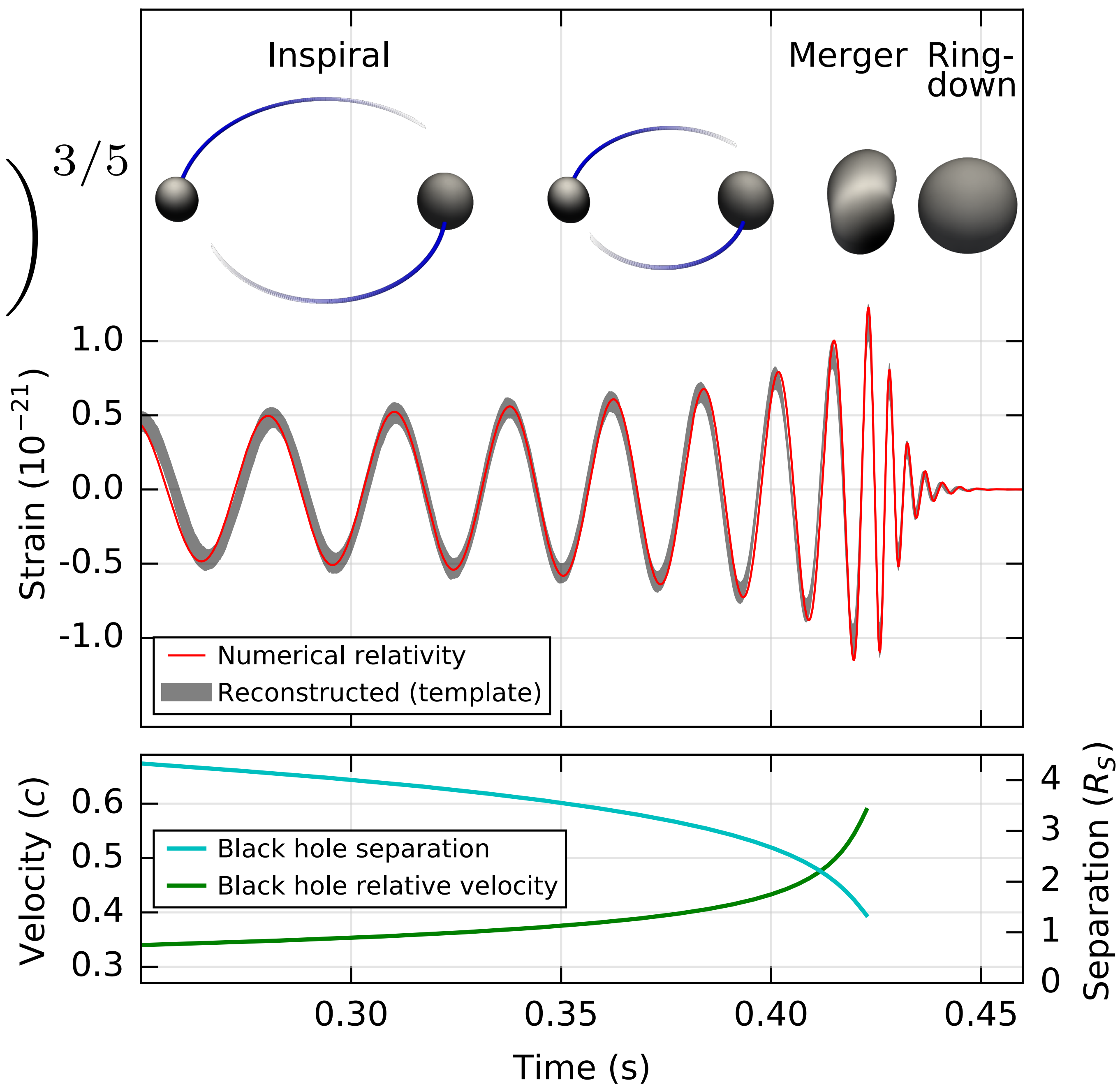
$$\Rightarrow r \simeq 350 {\rm km}, 2M \sim 210 {\rm km}$$

- If **neutron star** were **present**:

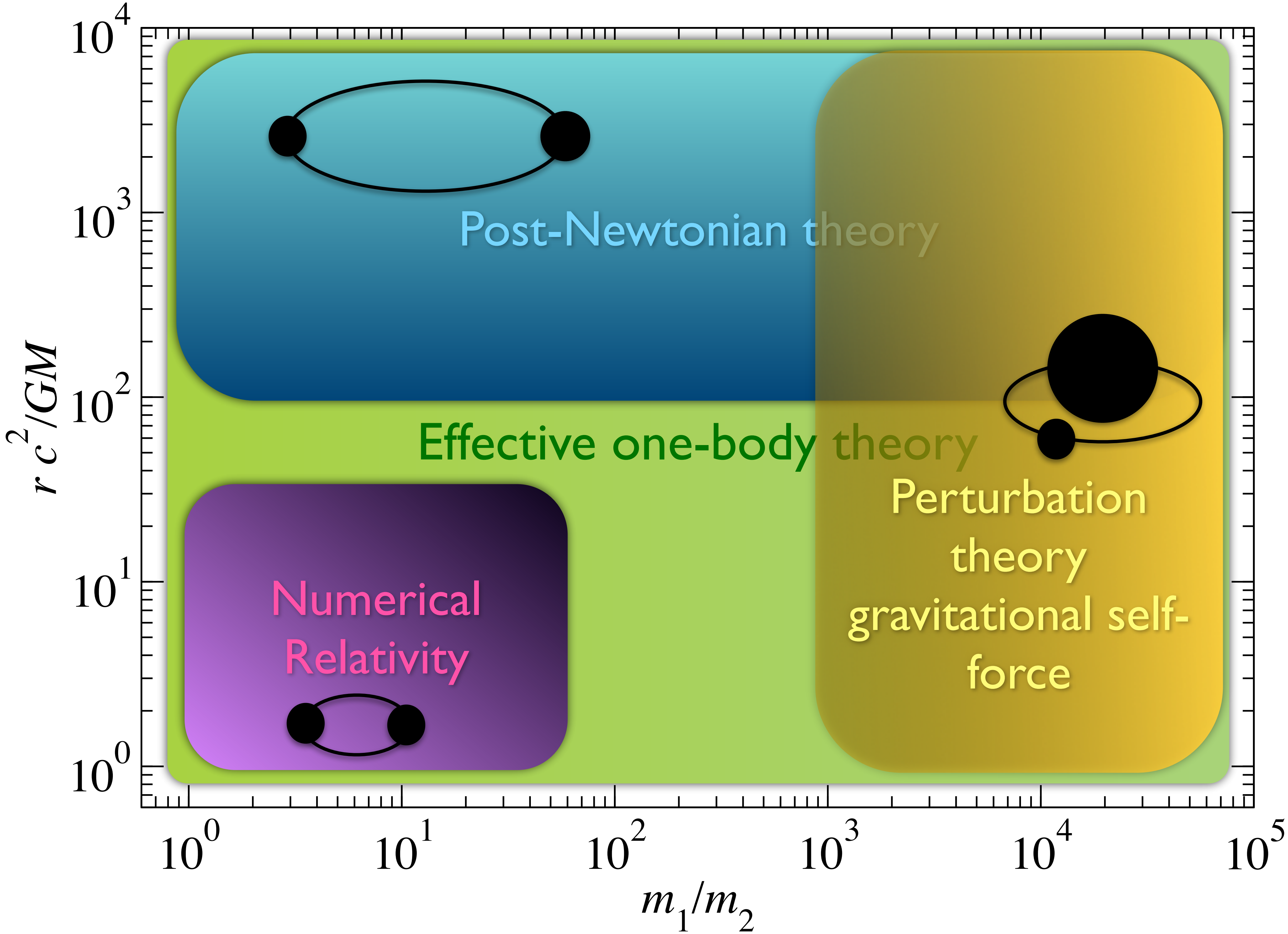
$$m_{\rm NS} \sim 2 M_\odot, m_{\rm BH} \sim 1700 M_\odot$$

binary would **merge** at **lower frequencies**!

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



Waveform modeling to detect and infer source's properties



(AB & Sathyaprakash arXiv:1504.04766)

- Two parameters determine the **range of validity** of each method:

$$\frac{G\,M}{r\,c^2} \sim \frac{v^2}{c^2} \quad \& \quad \frac{m_2}{m_1}$$

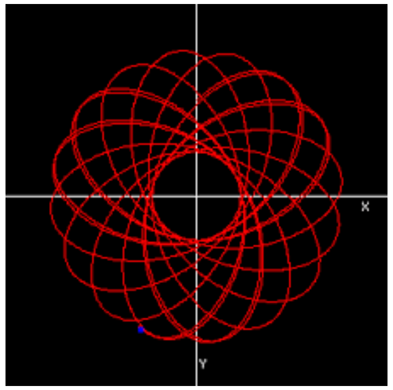
Post-Newtonian approximation

- **First developed in 1917** (Droste & Lorentz 1917, and Einstein, Infeld & Hoffmann 1938)

(Blanchet, Damour, Iyer, Faye, AB, Bohe', Marsat; Jaranowski, Schaefer, Steinhoff; Will, Wiseman; Goldberger, Porto, Rothstein, Levi, Foffa, Sturani; Flanagan, Hinderer, Vines ...)

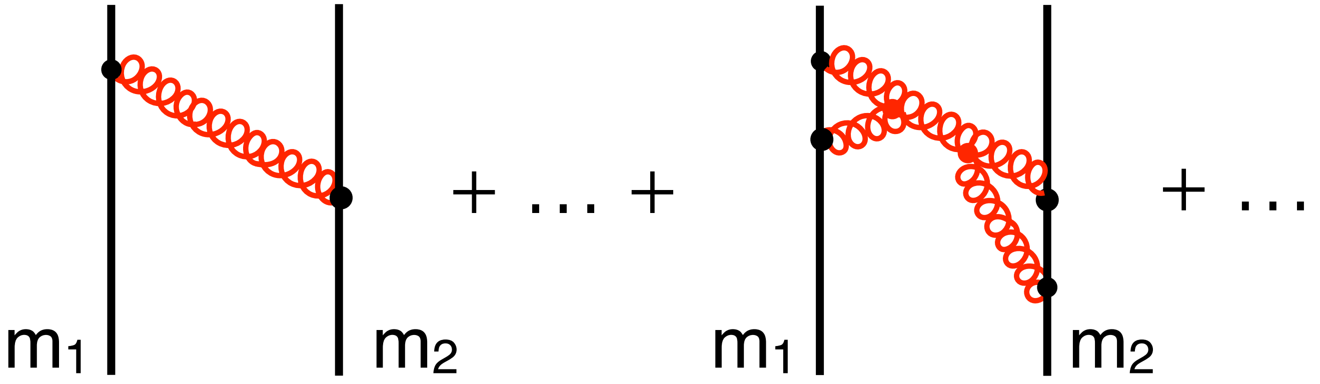
$$\widehat{H}_{\rm N}(\mathbf{r},\mathbf{p}) = \frac{\mathbf{p}^2}{2} - \frac{1}{r}$$

Small parameter is **v/c**



$$\widehat{H}_{\rm 1PN}(\mathbf{r},\mathbf{p}) = \frac{1}{8}(3\nu-1)(\mathbf{p}^2)^2 - \frac{1}{2}\left\{(3+\nu)\mathbf{p}^2 + \nu(\mathbf{n}\cdot\mathbf{p})^2\right\}\frac{1}{r} + \frac{1}{2r^2}$$

$$\widehat{H}_{\rm 2PN}(\mathbf{r},\mathbf{p}) = \frac{1}{16}\left(1-5\nu+5\nu^2\right)(\mathbf{p}^2)^3 + \frac{1}{8}\Big\{\left(5-20\nu-3\nu^2\right)(\mathbf{p}^2)^2 \quad + \ldots$$



$$F_{\rm PN} = -\frac{G\,m_1\,m_2}{r^2}\left(1 + a_{\rm 1PN}\,\frac{v^2}{c^2} + a_{\rm 2PN}\,\frac{v^4}{c^4} + a_{\rm 2.5PN}\,\frac{v^5}{c^5} + a_{\rm 3PN}\,\frac{v^6}{c^6} + a_{\rm 3.5PN}\,\frac{v^7}{c^7} + \cdots\right)$$

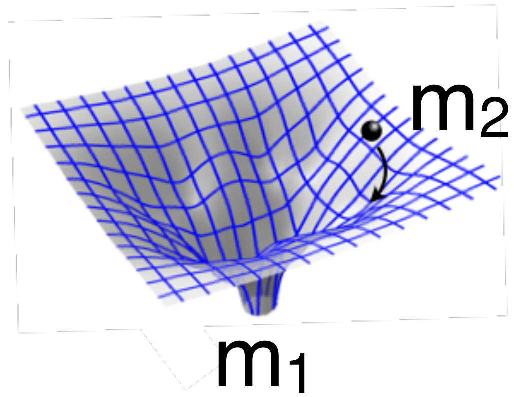
Perturbation theory and gravitational self force (GSF)

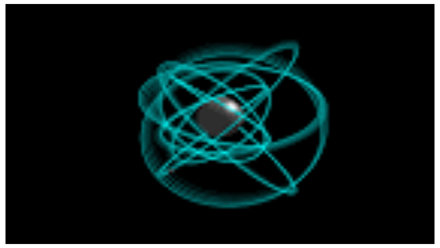
- **First works in 50-70s** (Regge & Wheeler 56, Zerilli 70, Teukolsky 72)

  Small parameter is **m_2/m_1**

  Equation of gravitational perturbations in black-hole spacetime:

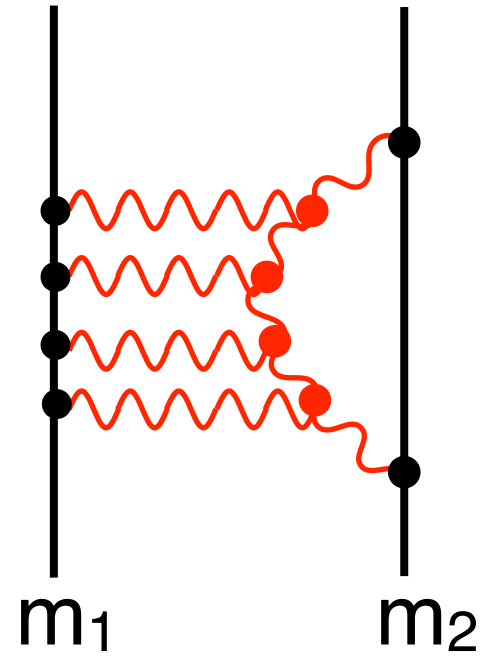
$$\frac{\partial^2 \Psi}{\partial t^2} - \frac{\partial^2 \Psi}{\partial r_\star^2} + V_{\ell m} \Psi = S_{\ell m}$$





  Green functions in Schwarzschild/Kerr spacetimes.

(Fujita, Poisson, Sasaki, Shibata, Khanna, Hughes, Bernuzzi, Harms, ...)



- **GSF:** Accurate modeling of **relativistic dynamics of large mass-ratio** inspirals **requires** to include **back-reaction effects** due to interaction of small object with its own gravitational perturbation field.

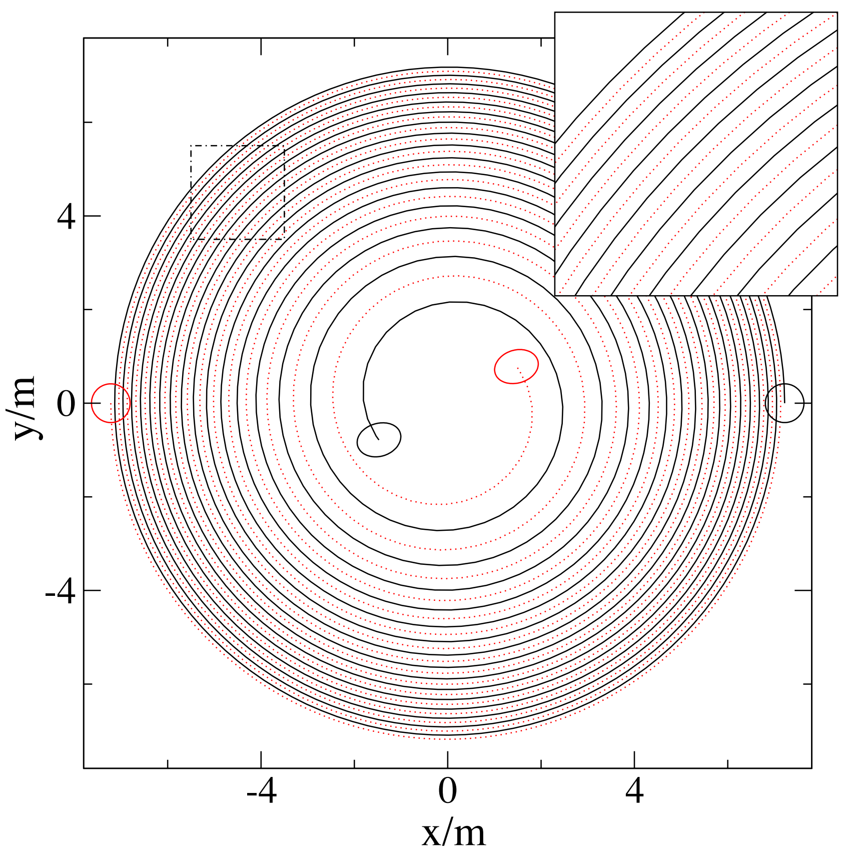
(Deitweiler, Whiting, Mino, Poisson, Quinn, Sasaki, Tanaka, Barack, Ori, Pound, van de Meent...)

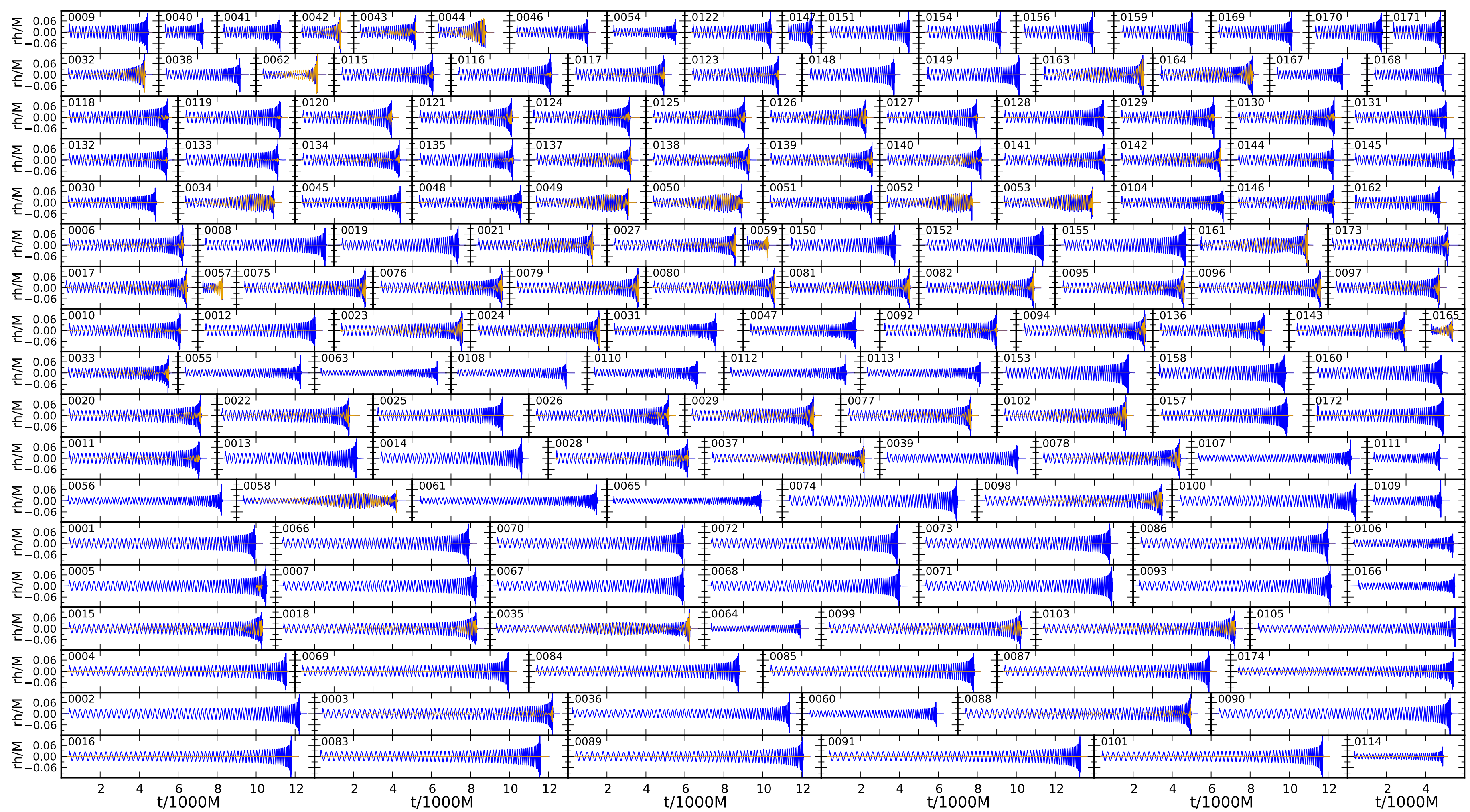
Numerical Relativity

- **Breakthrough** in 2005 (Pretorius 05, Campanelli et al. 06, Baker et al. 06)

Kidder, Pfeiffer, Scheel, Lindblom, Szilagyi; Bruegmann, Hannam, Husa, Tichy; Laguna, Shoemaker; ...

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





- **Simulating eXtreme Spacetime (SXS)** collaboration (Mroue et al. 13)

- **Numerical-Relativity & Analytical Relativity** collaboration (Hinder et al. 13)

Waveforms combining analytical & numerical relativity

- **Effective-one-body** (EOB) theory

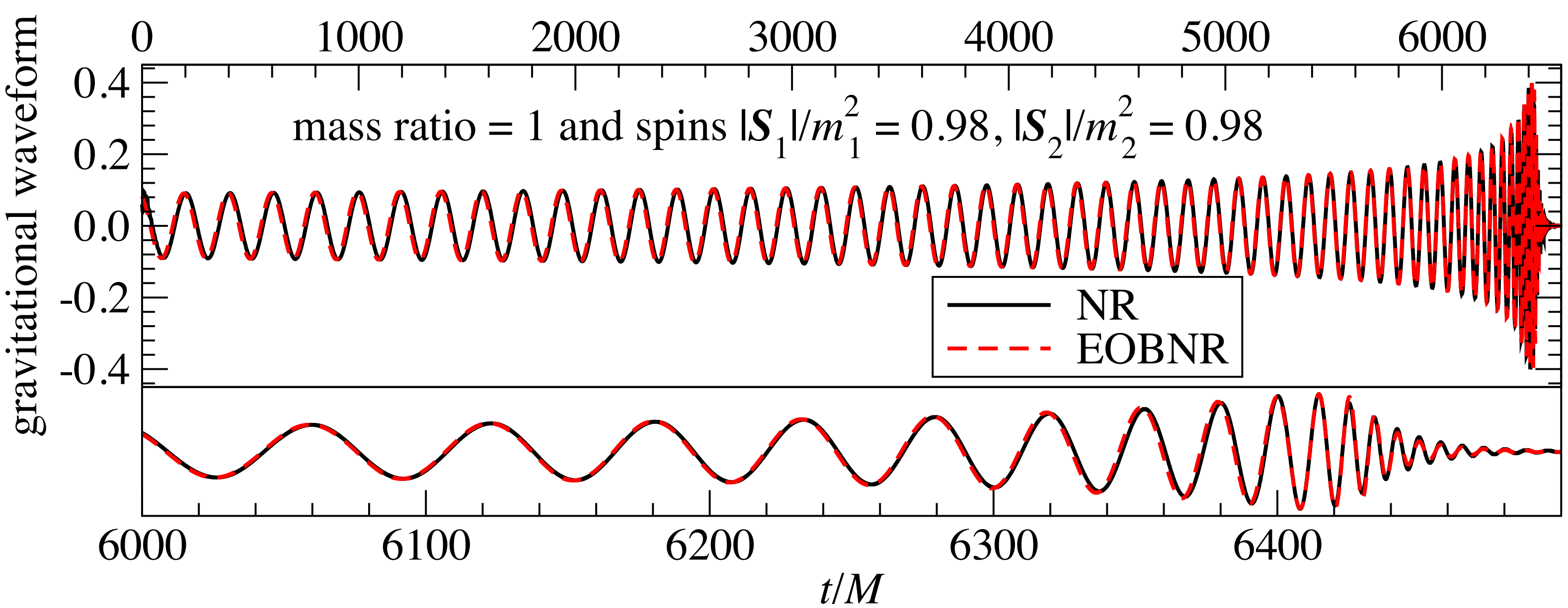
AB, Pan, Taracchini, Bohe', Shao, Barausse, Hinderer, Steinhoff; Damour, Nagar, Bernuzzi, Bini, Balmelli; Iyer, Sathyaprakash; Jaranowski, Schaefer;

PN Theory
conservative dynamics and GW emission computed as a Taylor expansion

Effective one body
conservative dynamics and GW emission re–written in summed and/or factorized form

Numerical relativity
two–body dynamics and GW emission computed with all non–linearities

(Taracchini, AB, Pan, Hinderer & SXS 14, Puerrer 15)



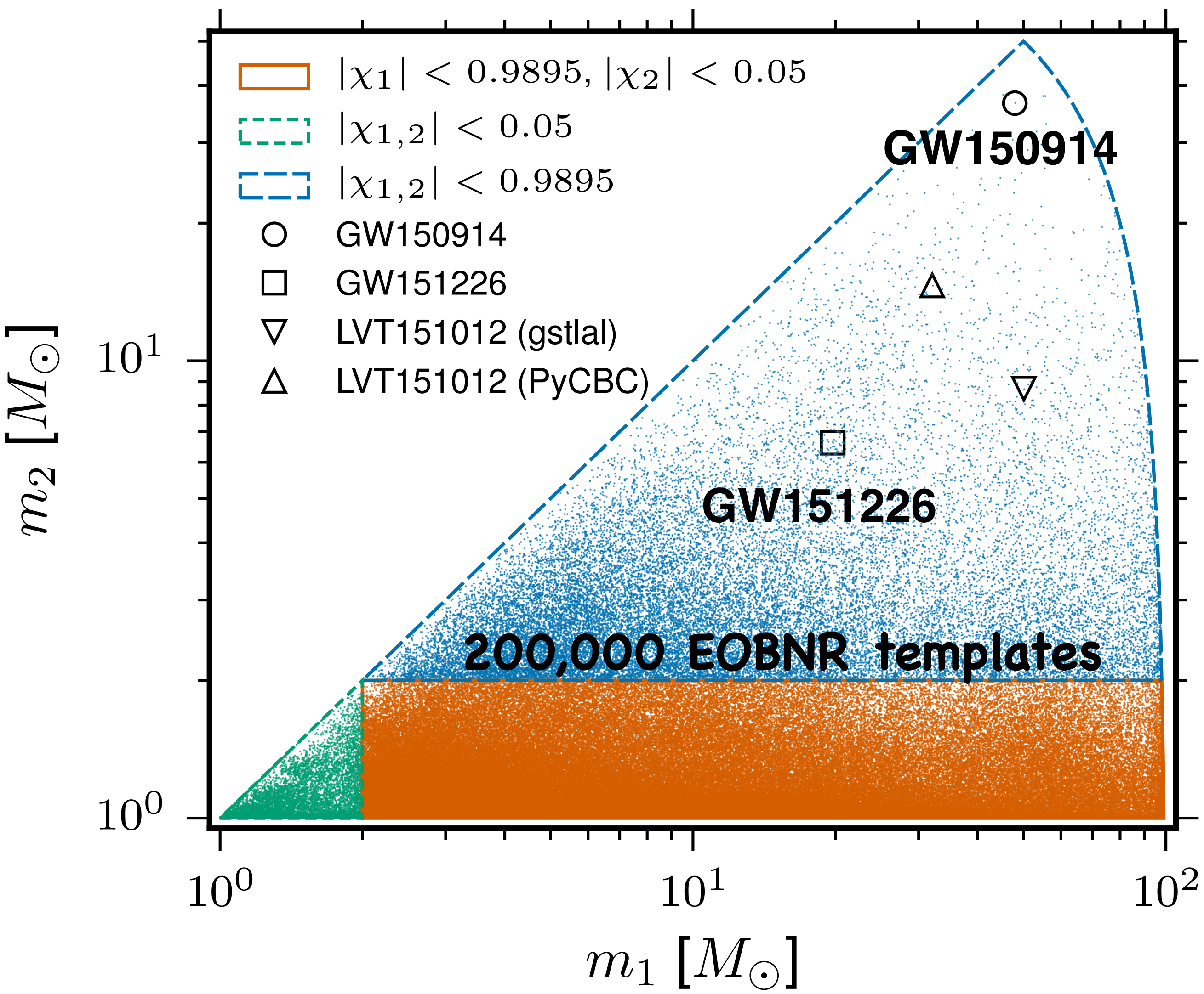
- **Phenomenological approach**

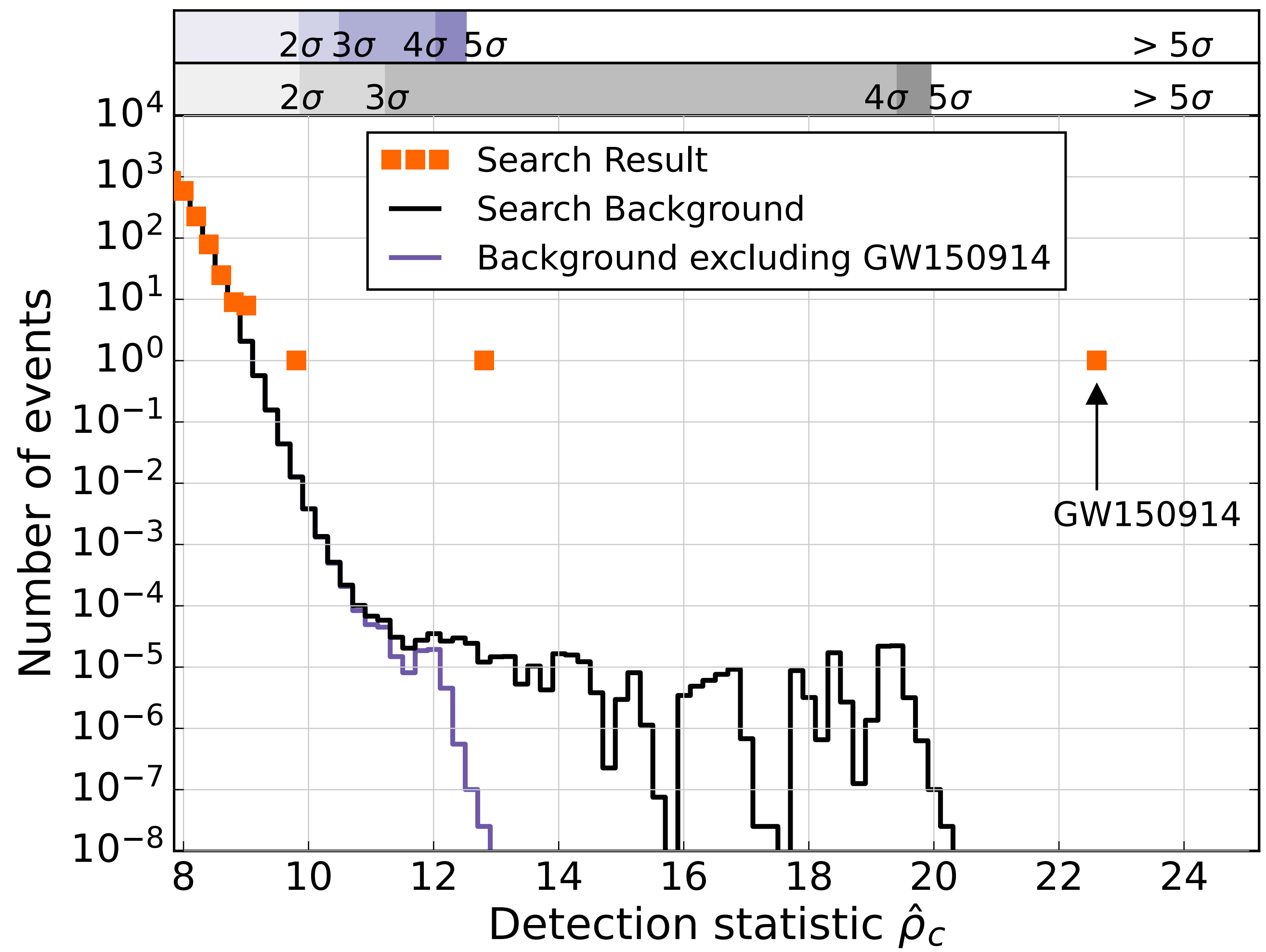
Ajith, Chen; AB, Pan; Hannam, Husa, Khan, Schmidt, Puerrer, Ohme, Bohe';

Detection confidence with modeled search in O1

- **Matched filtering** employed

(Abbott et al. arXiv:1606.04856)

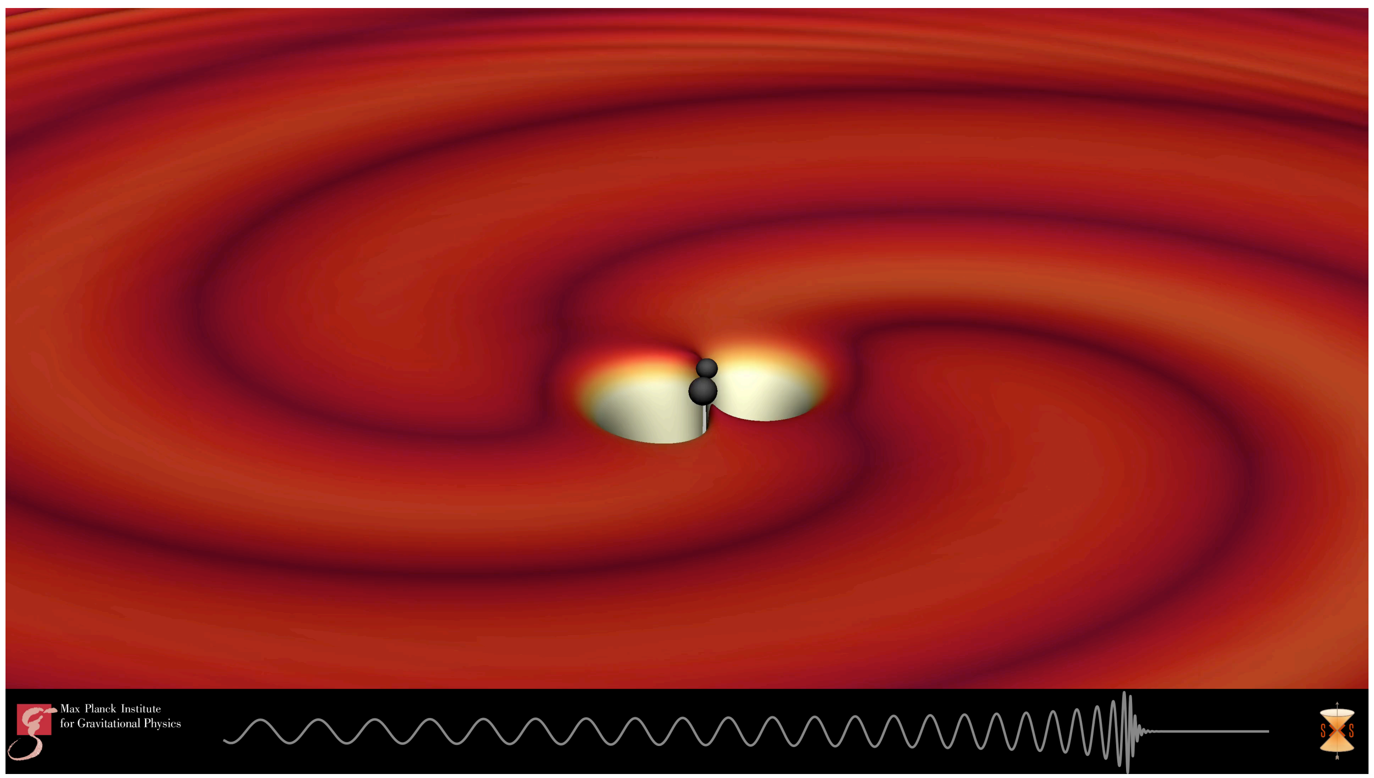




- **Confidence > 5.3σ** that GW150914 & GW151226 were real gravitational-wave signals.
- **Minimal-assumption search** reached high detection confidence **(> 4.6σ) only for GW150914.**

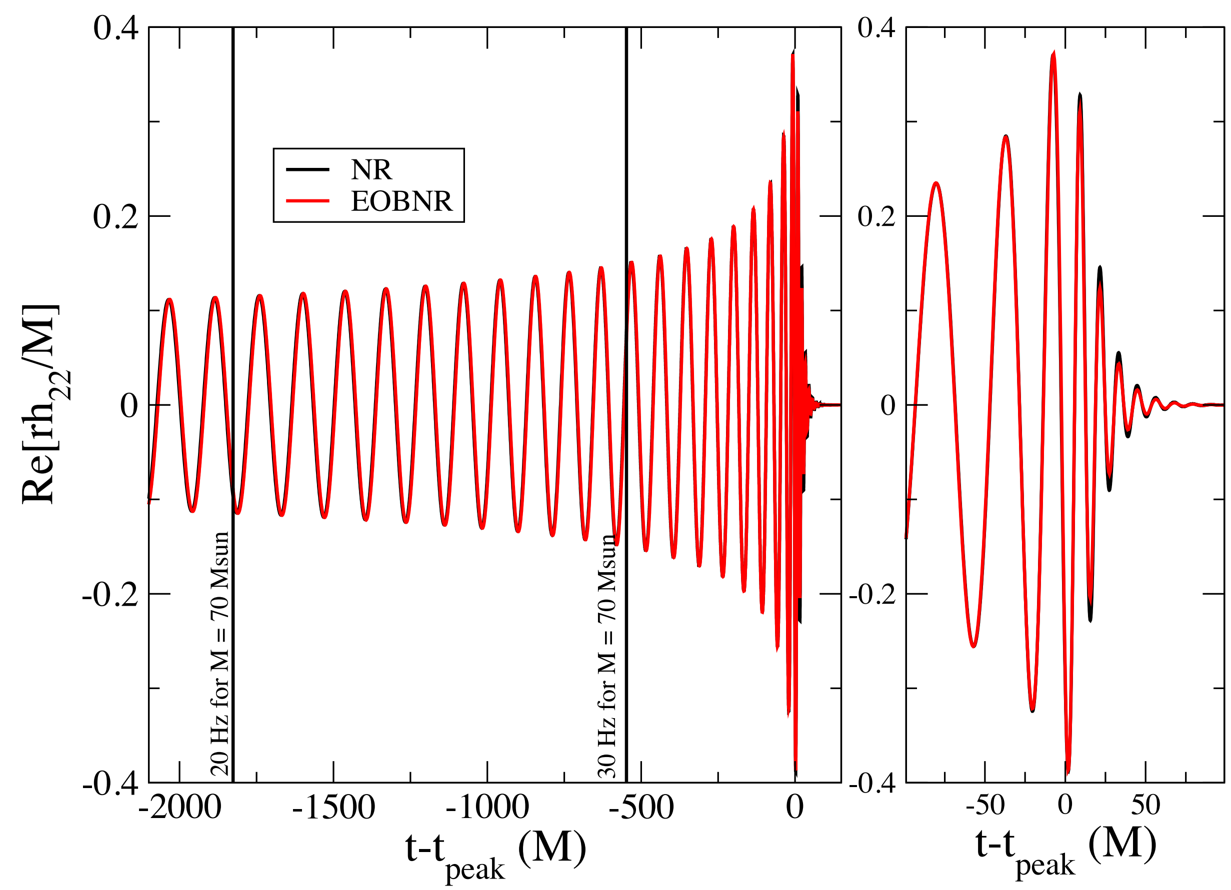
Numerical-relativity simulation of GW150914

(visualization credit: Haas @ AEI)



(Ossokine, AB & SXS project)

(Ossokine, AB & SXS project)

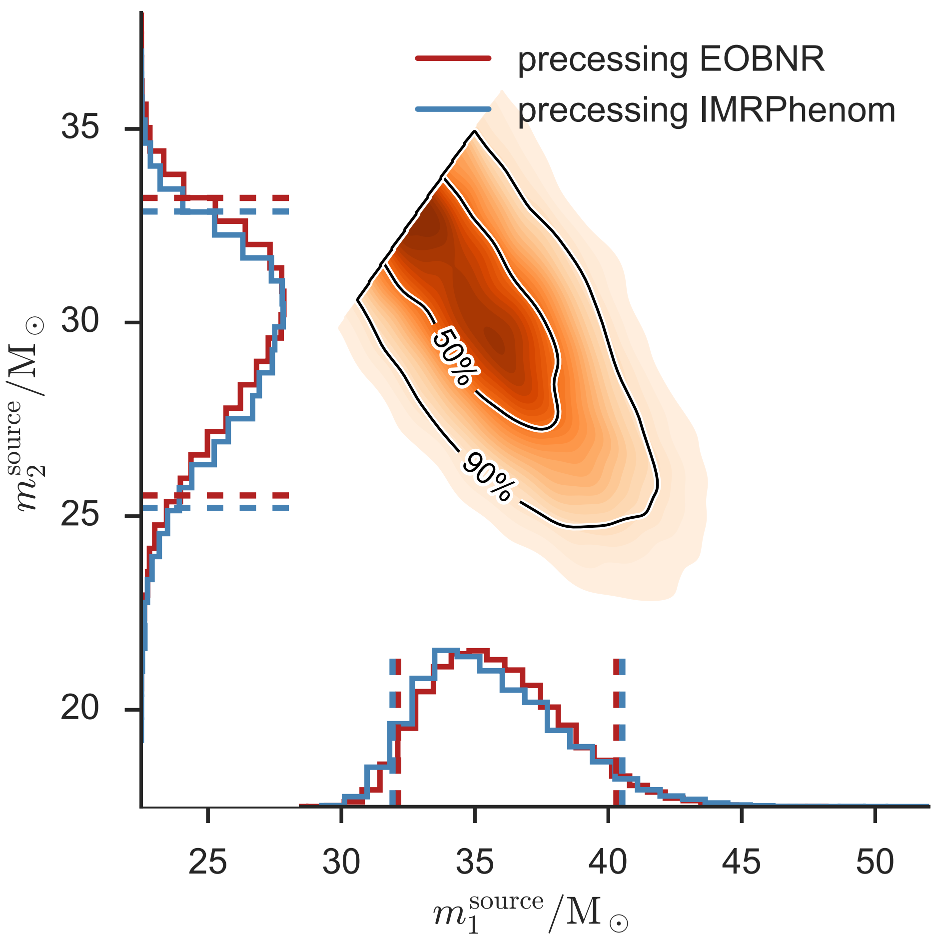


- **Waveform models** very closely **match** the **exact solution** from Einstein equations around GW150914 & GW151226.

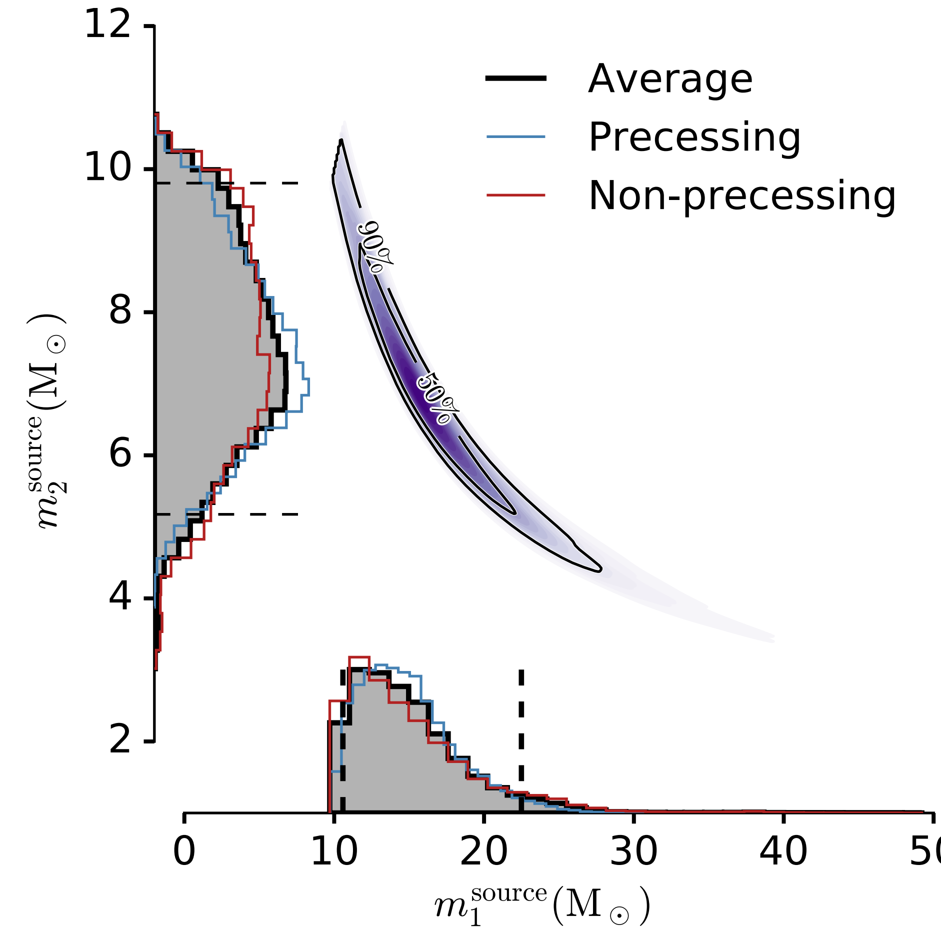
Unveiling binary black holes properties: masses

(Abbott et al. arXiv:1606.01210)

GW150914



GW151226



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

- We **measure best** the **"chirp" mass** $\mathcal{M} = M\,\nu^{3/5}$

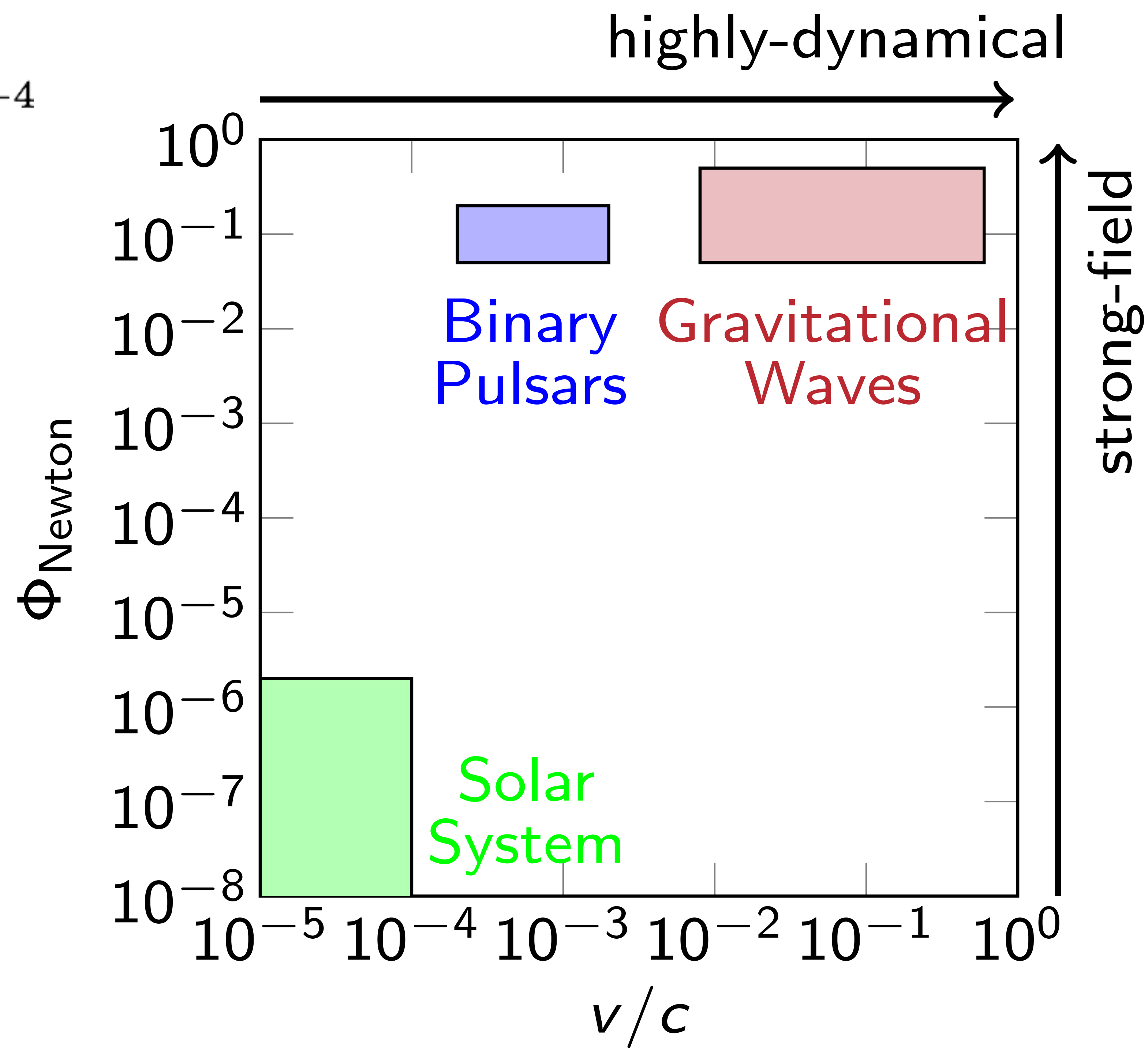
Tests of GR with LIGO's sources

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

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

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

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

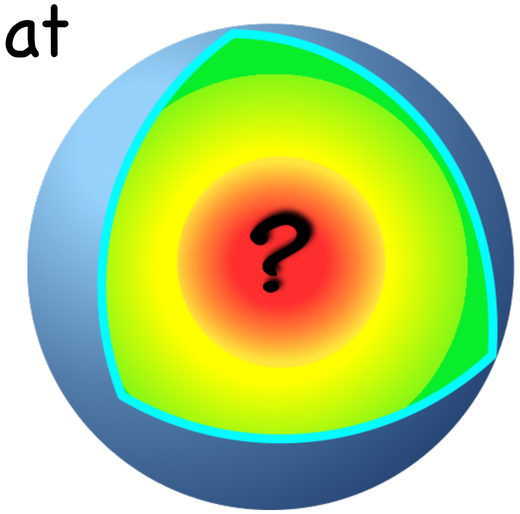


(credit: Sennett)

Can we probe NS's equation of state with LIGO observations?

- **NSs** are **unique laboratories** to study baryonic matter at supra-nuclear density
  - **NS's** characteristics:

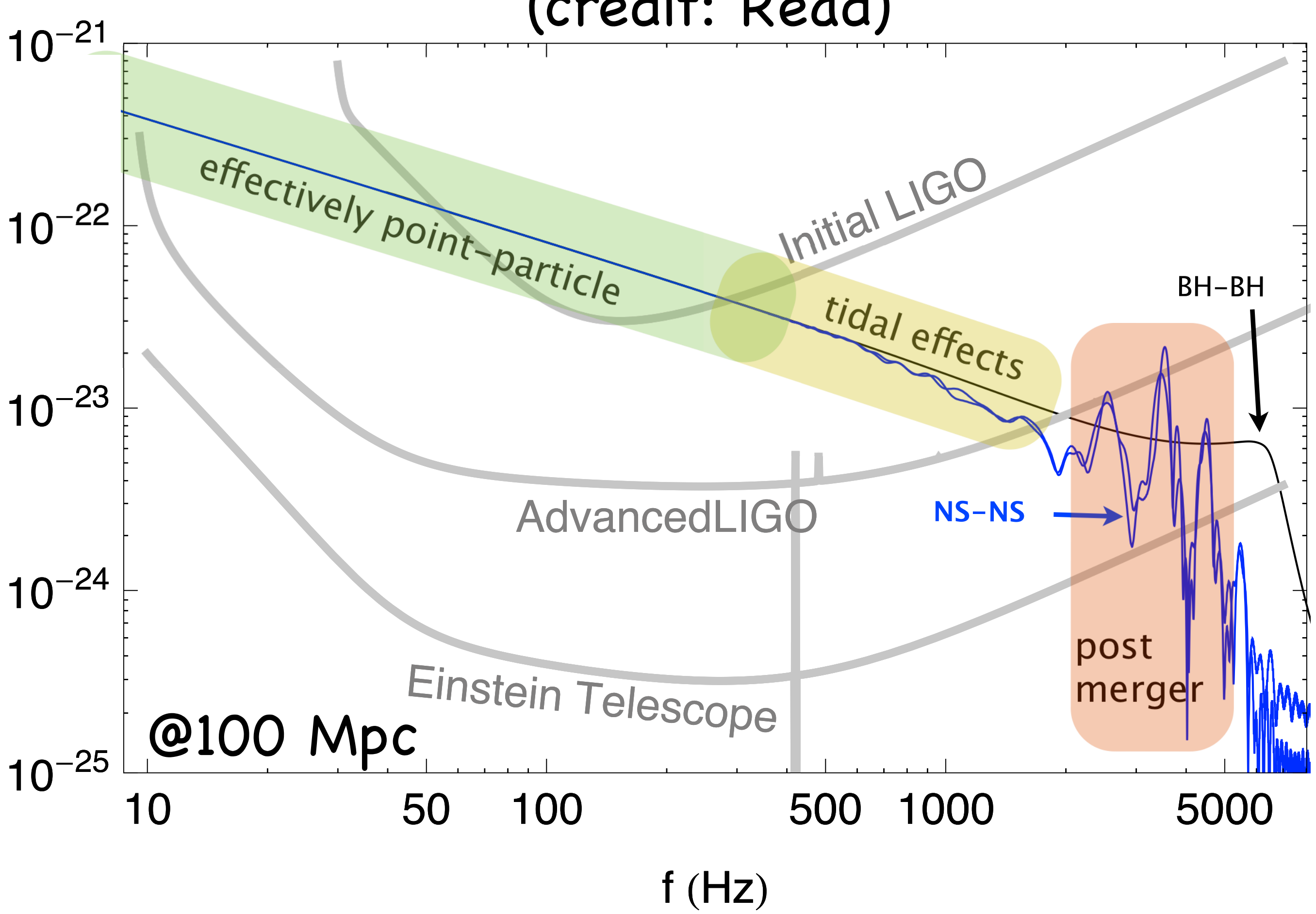
- mass: 1-3 Msun
- radius: 9-15 km
- core density > 10^{14}g/cm^3



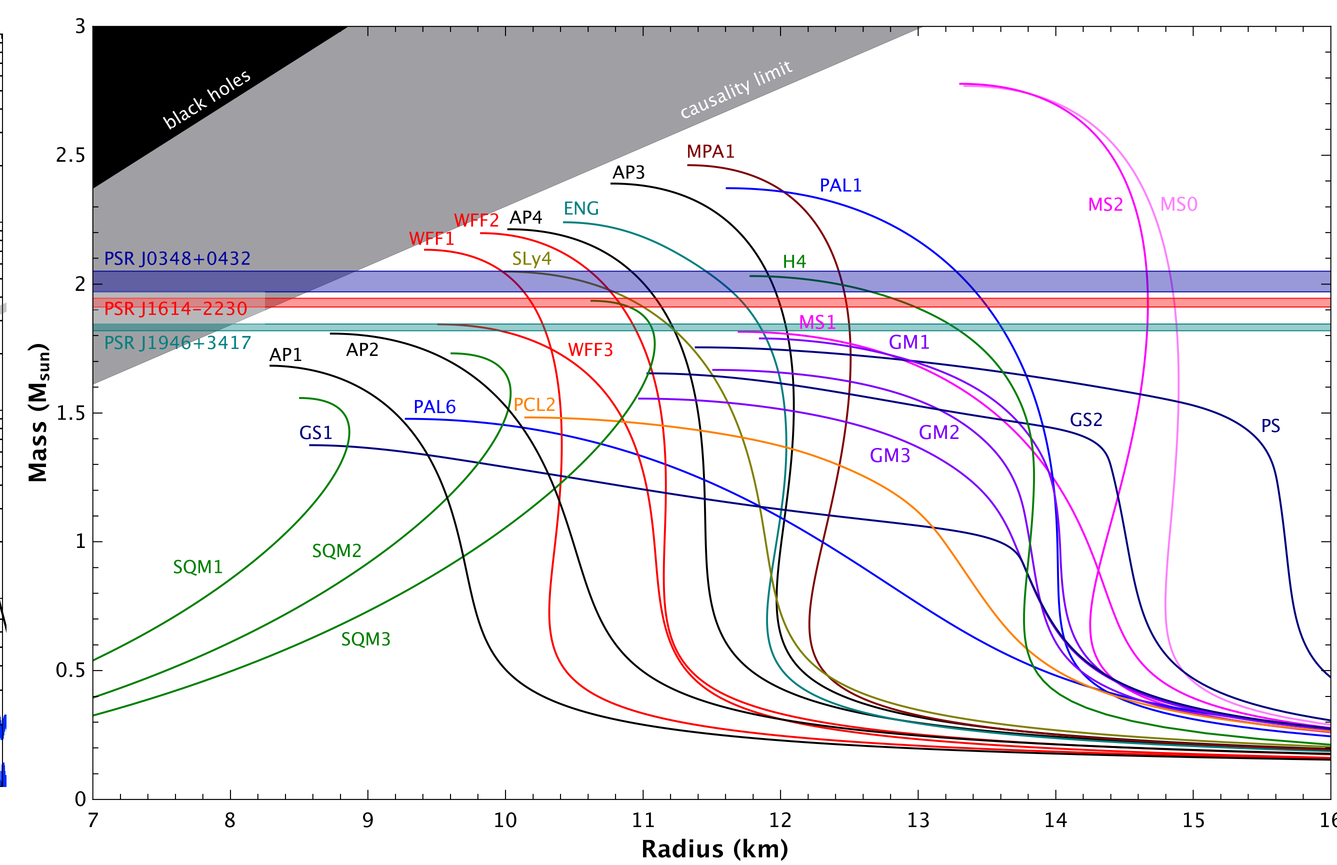
(credit: Hinderer)

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

(credit: Read)

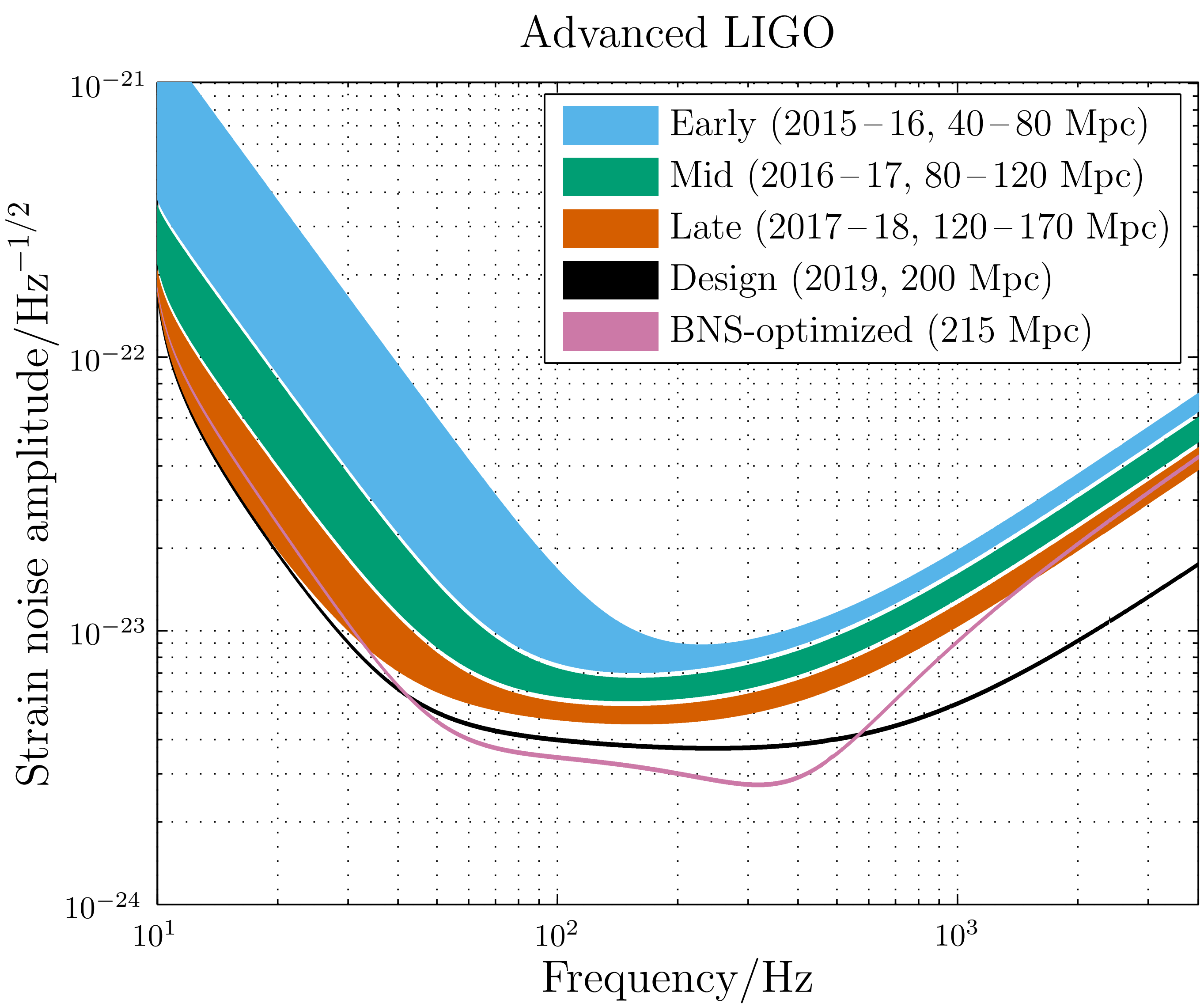


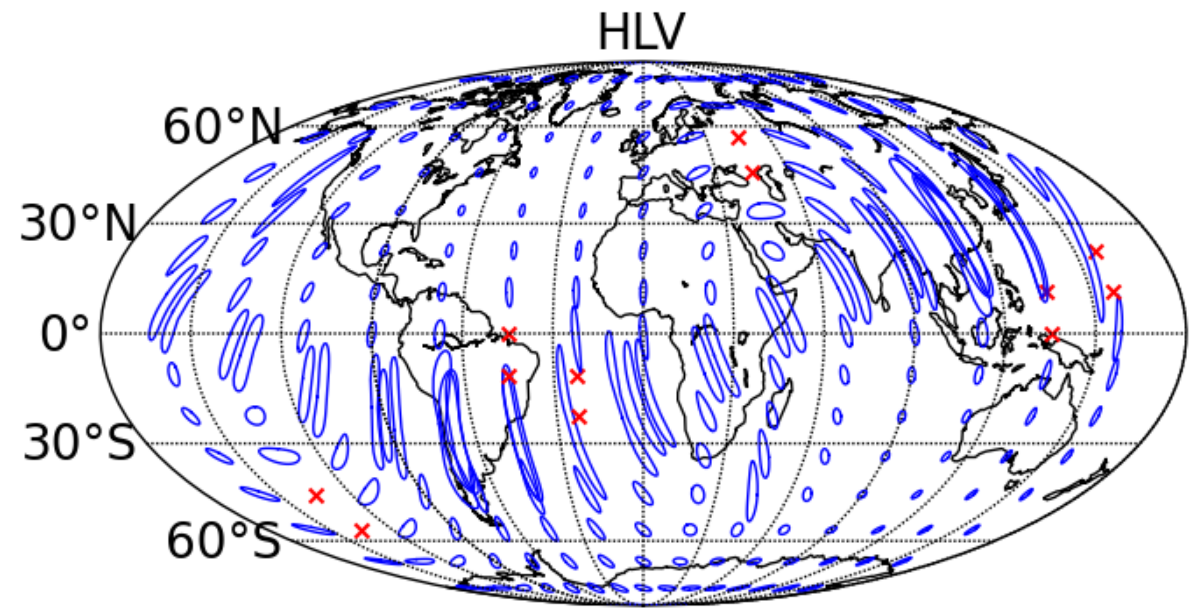
(Antoniadis et al. 16)



Advanced detectors' roadmap and sky localization

(Aasi et al. arXiv:1304.0670)





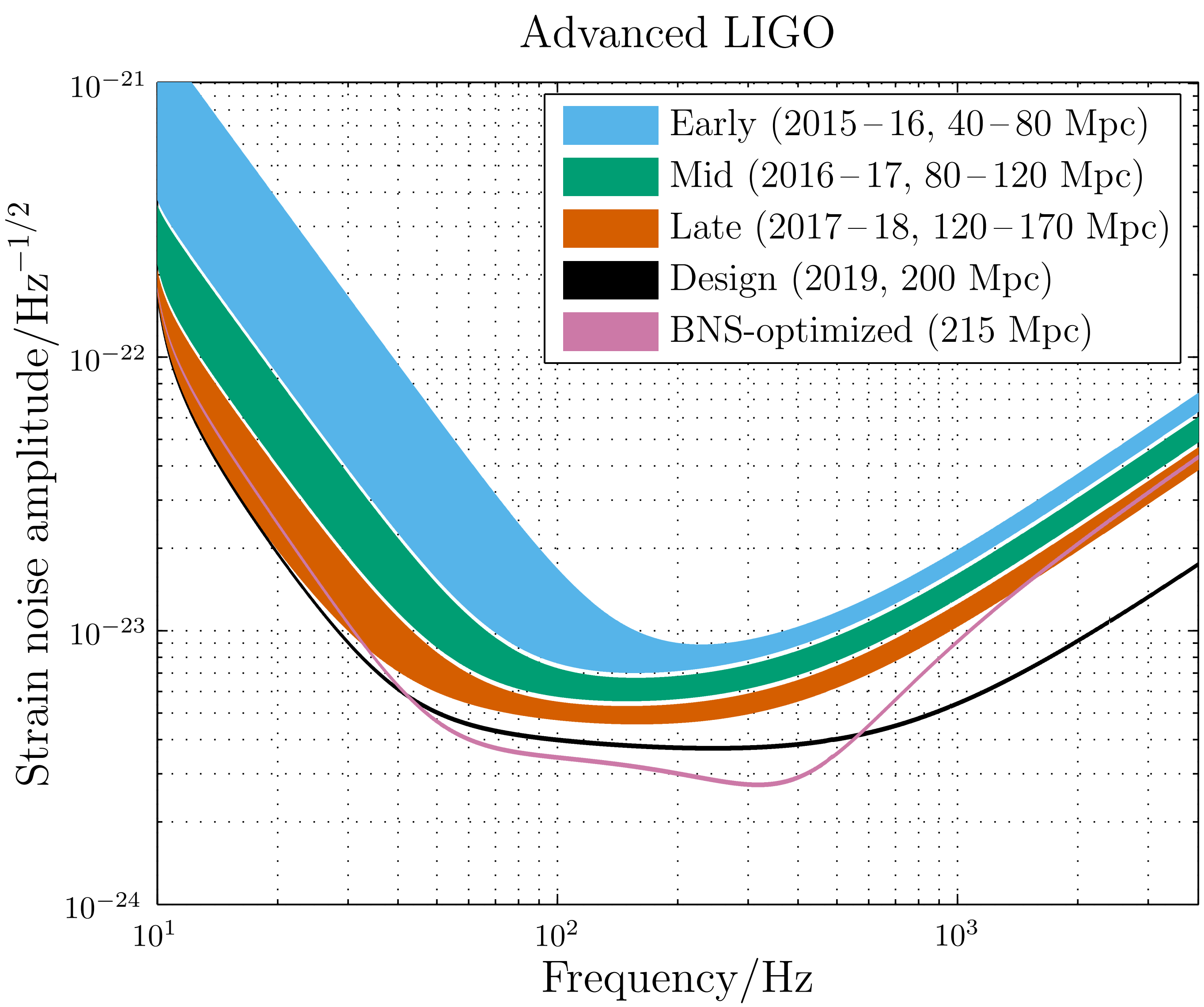
- Few **tens or hundred** square degrees

Detection rates @ **design sensitivity**:

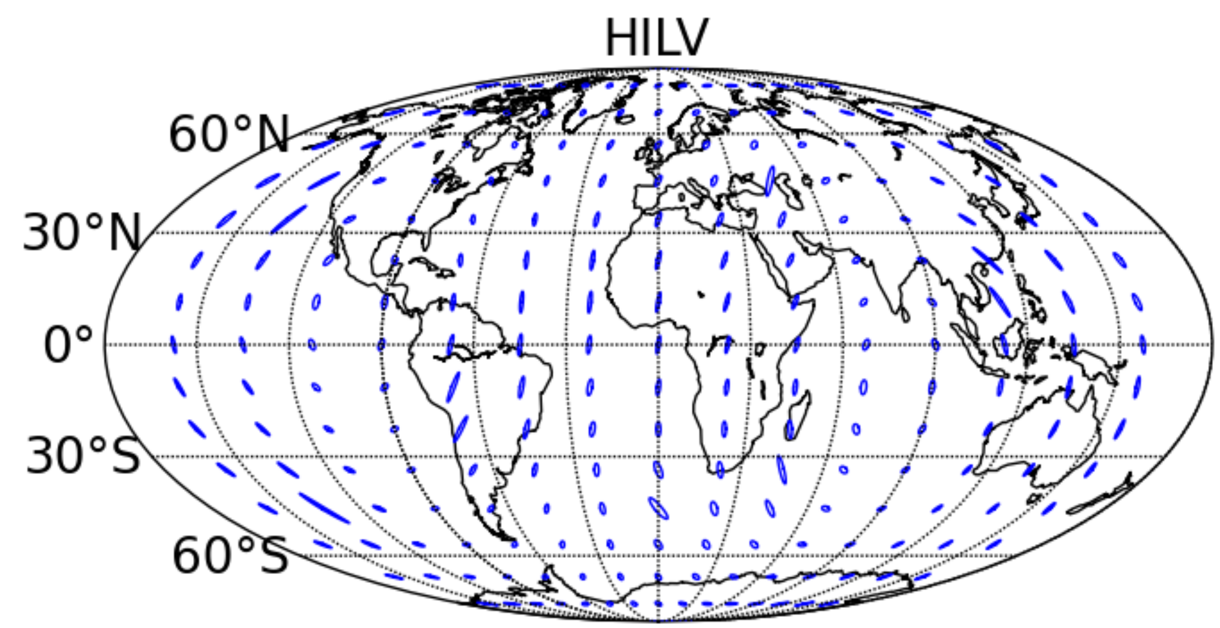
- **Binary neutron stars: 0.2 - 200 per year**
- **Binary black holes: tens to hundreds per year!**

Advanced detectors' roadmap and sky localization

(Aasi et al. arXiv:1304.0670)



with LIGO-India



- **Few** square degrees!

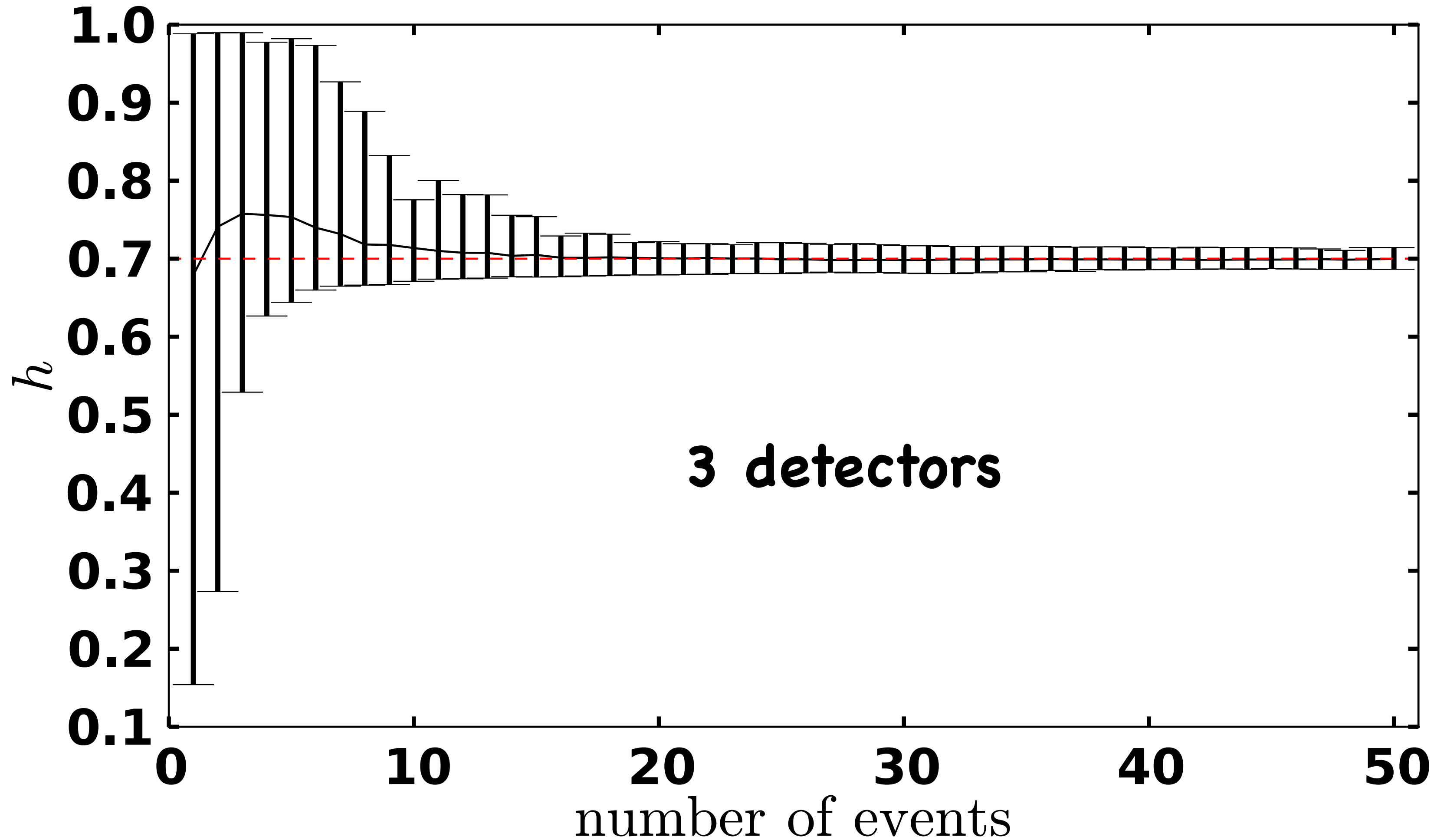
Detection rates @ **design sensitivity**:

- **Binary neutron stars: 0.2 - 200 per year**
- **Binary black holes: tens to hundreds per year!**

Inference of cosmological parameters in future LIGO searches

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

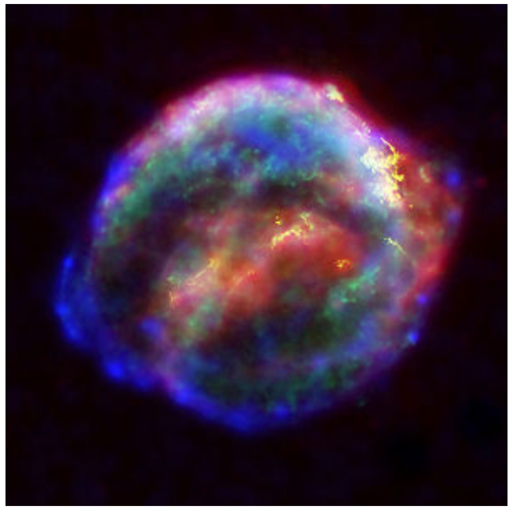
(Schutz 1986)



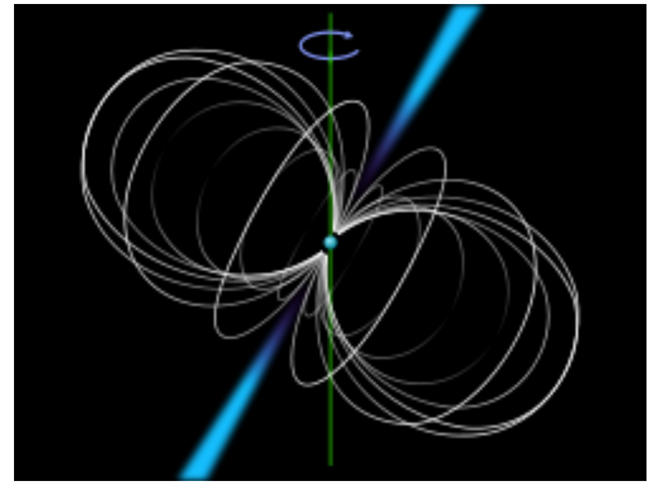
(Del Pozzo 12)

- LIGOs will measure **Hubble constant** H_0 with accuracy of **5%** at 95% confidence **after 40-50 GW observations with 3 detectors.**

Other sources of gravitational waves



Kepler's supernova
SN1604

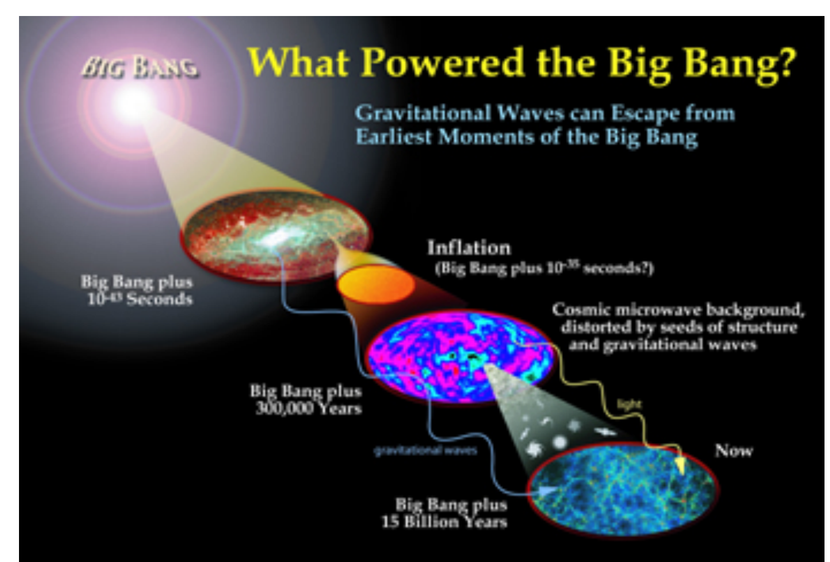


optical/X-ray image
of the Crab Nebula

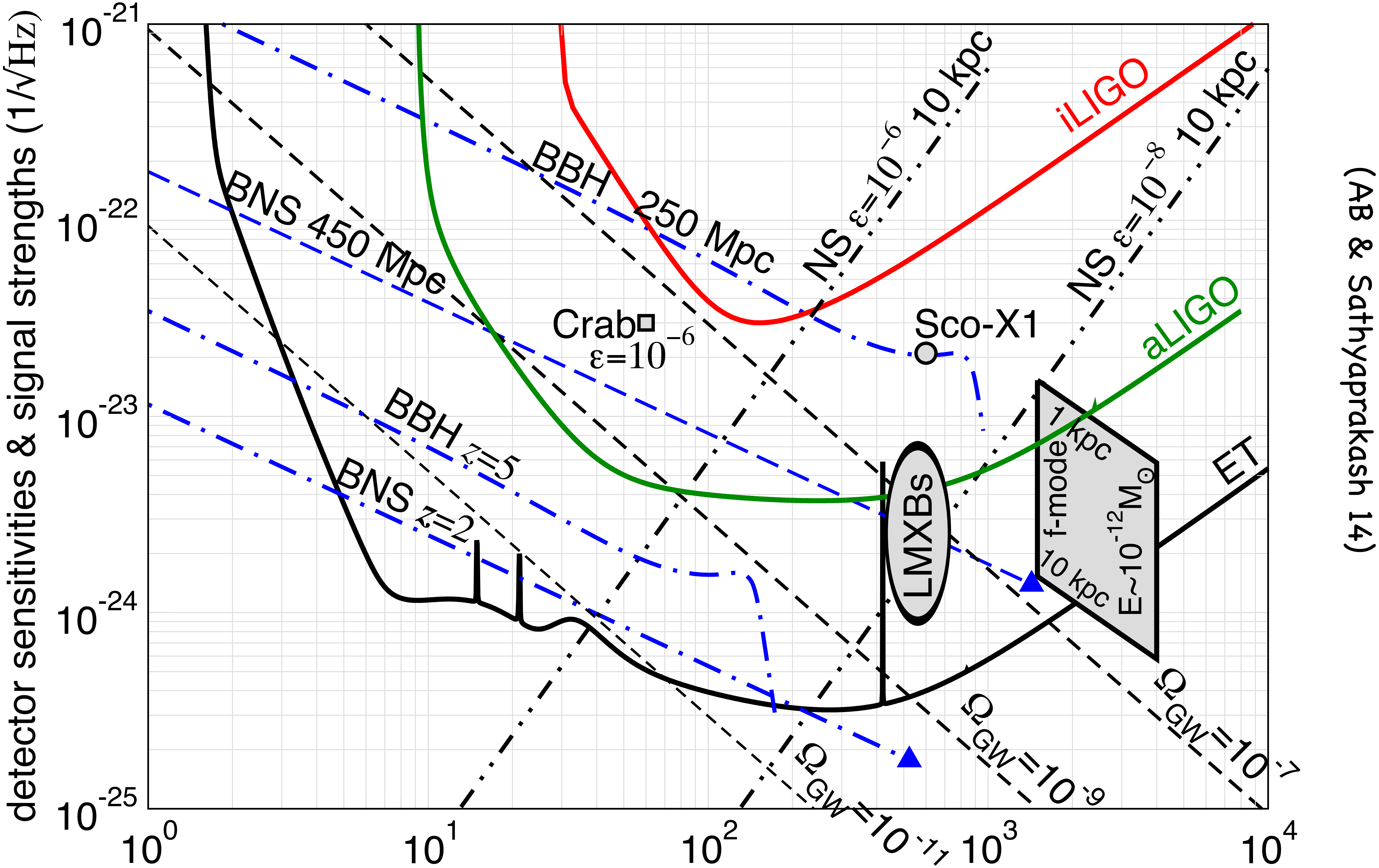
- **Core of massive star** ceases to generate energy from nuclear fusion and **undergoes sudden collapse** forming a neutron star.
- **GW signal** is **unshaped burst** lasting for **tenths of millisecond**.

- Pulsars emit radio waves with **stable period**.
- **"Mountains"** on pulsars are **cm in height**!
- **GW signal** is **continuous and periodic**.

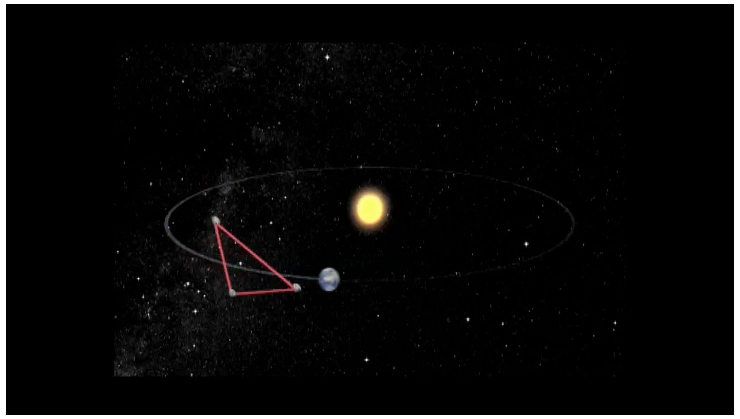
- **Snapshot** of the "very" **early Universe**.
- **Stochastic GW background produced** during rapid expansion of Universe **after Big Bang**.



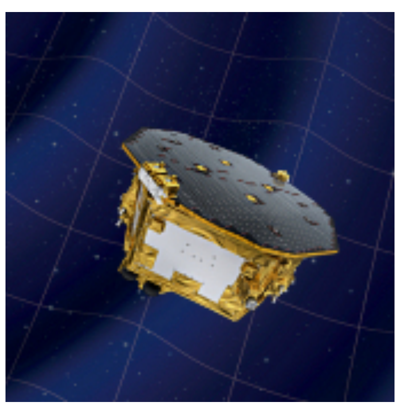
The future of GW astronomy on the ground

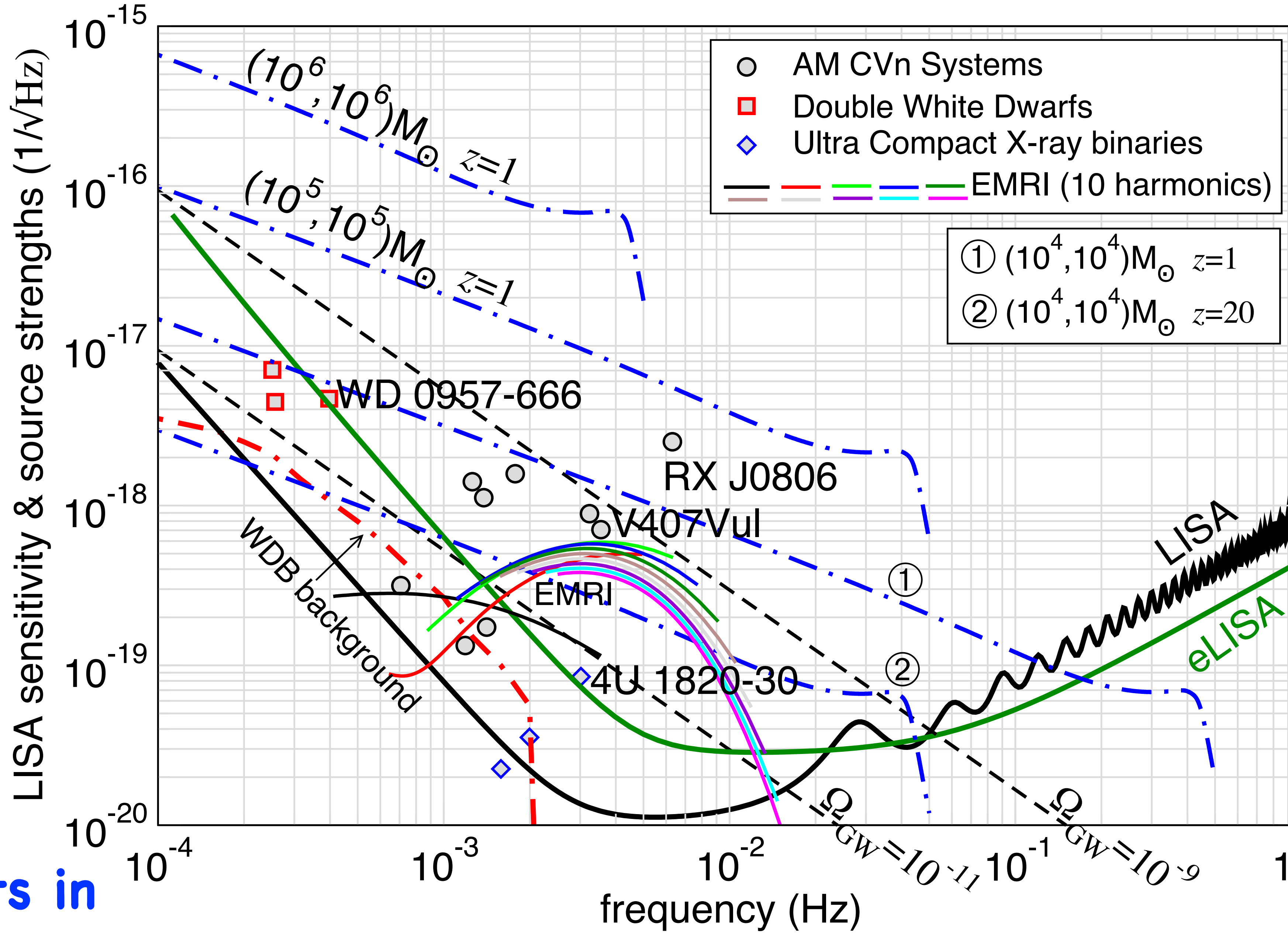


The future of GW astronomy lies also in space: LISA (2034)



Crdit: AEI/Milde Marketing



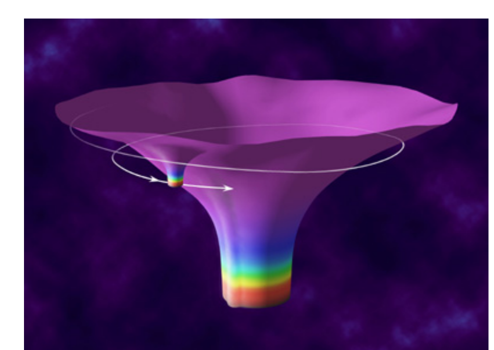


(AB & Sathyaprakash 14)

- **LISA Pathfinder results in 2016:** **extremely successful technology mission. LISA works!**

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

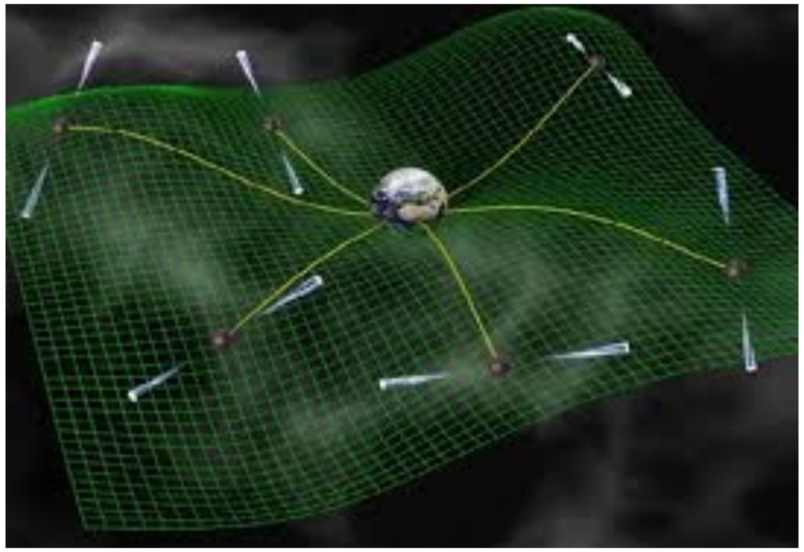
SBBH



EMRI

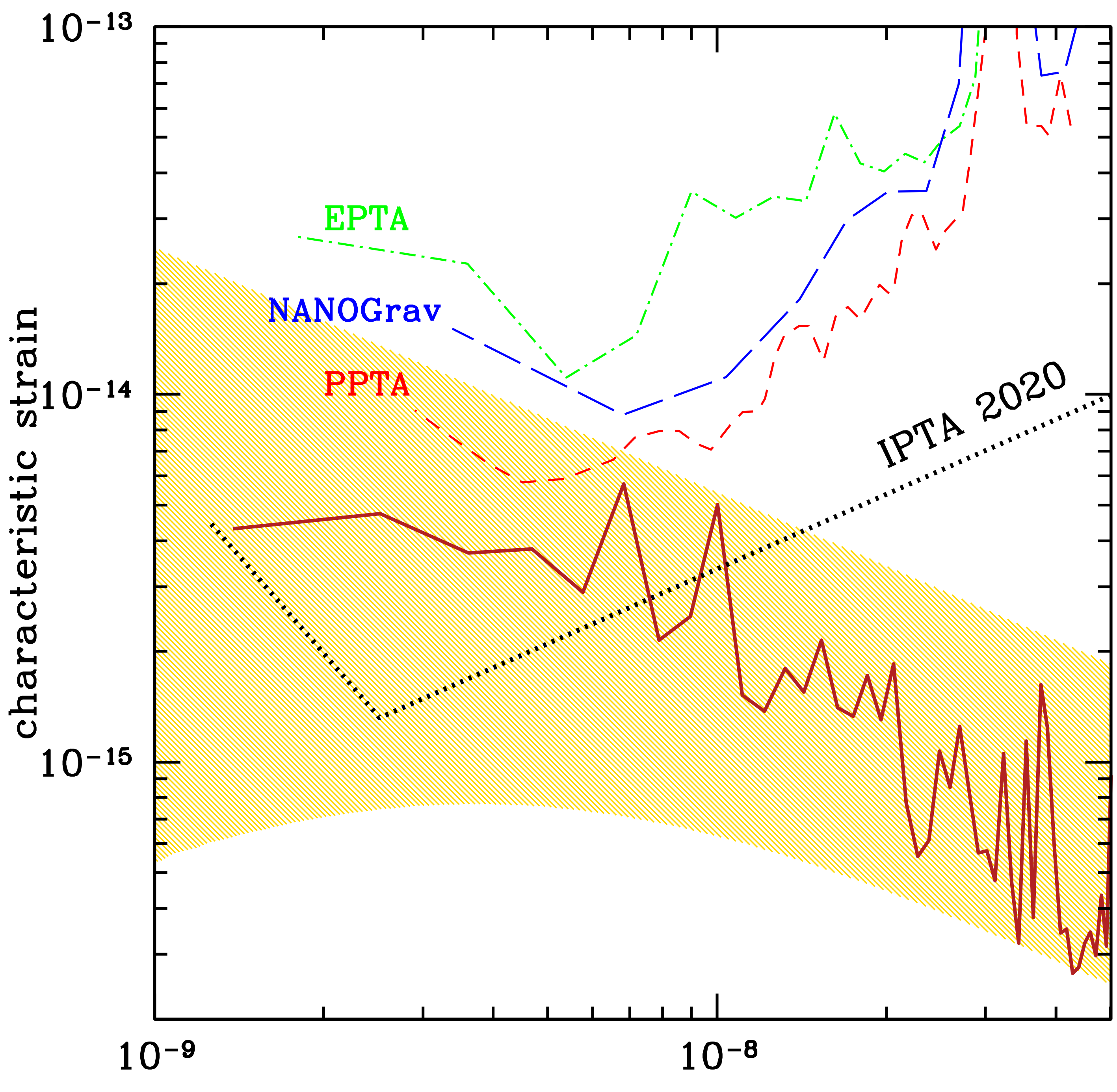
Pulsar Timing Array

NANOGrav, EPTA, PPTA



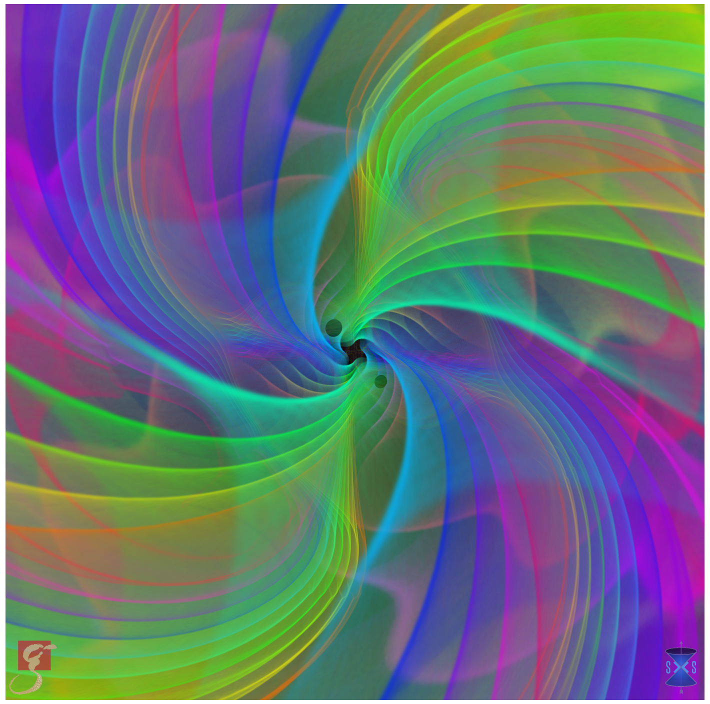
GW frequency: 10^{-9} - 10^{-7} Hz

- At low frequencies, a superposition of GW signals from **supermassive black holes** produces a **stochastic GW background**.
- **GW background** from **fundamental** and **cosmic strings**.



(credit: Sesana)

The new astronomical messengers: gravitational waves



- We can now **probe** the **most extreme astrophysical objects** in the universe, and learn **how they formed**.

- We can now **learn about gravity** in the genuinely **highly dynamical, strong field** regime.

- We can now **unveil properties of neutron stars** unaccessible in other ways.

- We can now provide the **most convincing evidence** that **black holes in our Universe** are the objects **predicted** by GR.

- **Unique science** done so far and even more exciting science in next years and decades **if able to make precise theoretical predictions.**