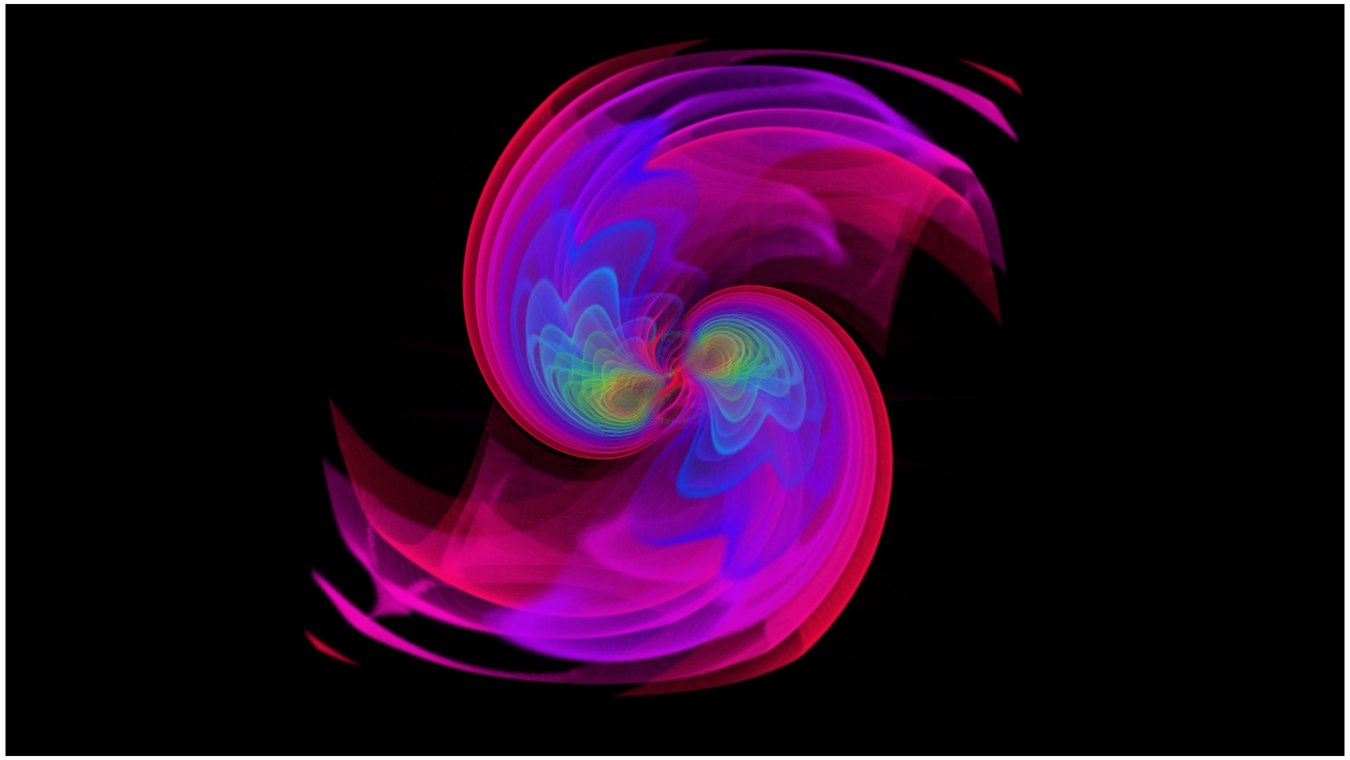

The New Era of Gravitational Wave Physics & Astrophysics

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(Albert Einstein Institute)

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CERN Colloquium, CERN, Geneva *April 20, 2017*

Outline

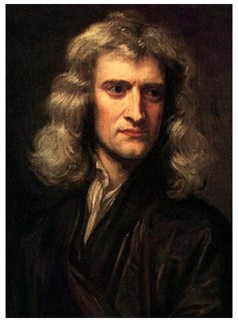
- **Detection** of **gravitational waves** by Advanced LIGO.

- The **science from GW experiments** stems on our **ability** to make **precise predictions: theoretical groundwork** to **identify** and **interpret** the signals.

- Astrophysics. **Tests of general relativity** in the **strong-field, highly dynamical regime**. Probing matter at **supranuclear densities**. **Cosmology**.

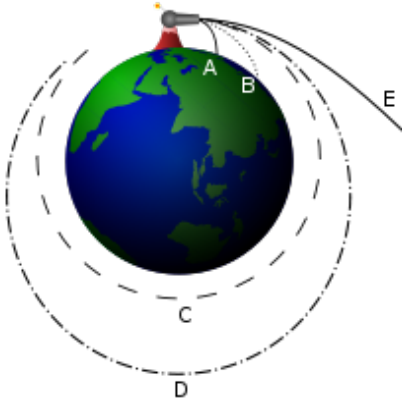
- The **bright future** of gravitational-wave astronomy comes with **new theoretical challenges**.

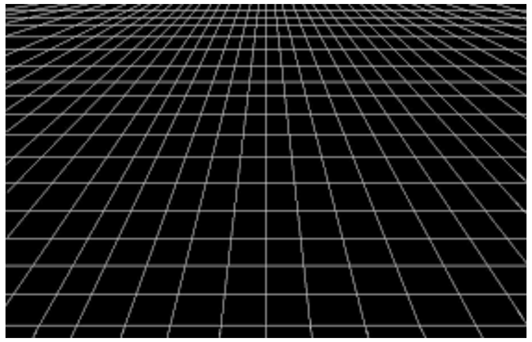
Newton gravity versus Einstein theory of General Relativity



Newton's gravity

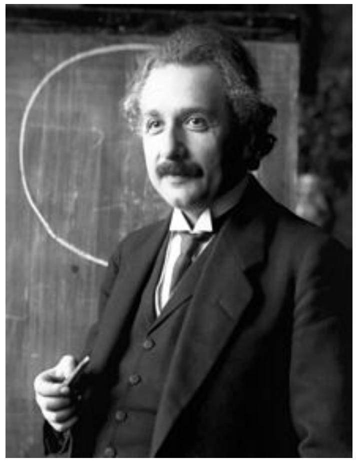
(1687)





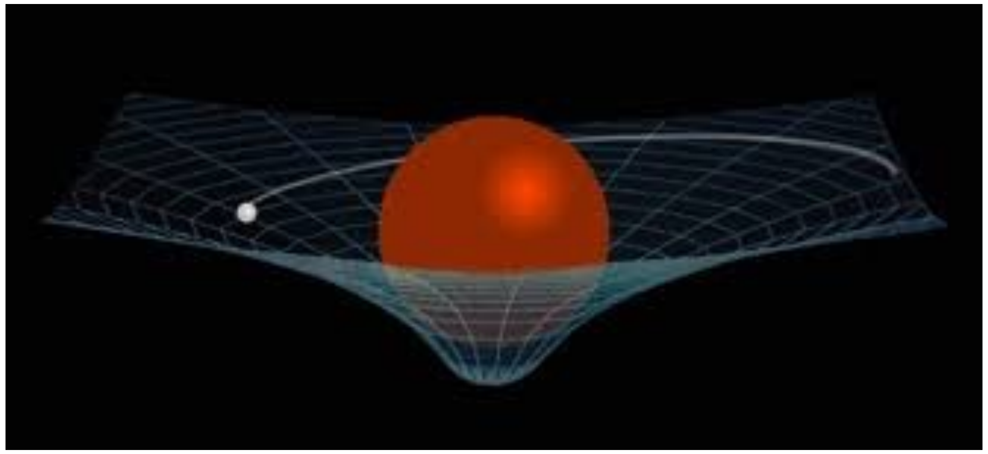
In Newton's gravity space and time are given a priori.

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



General Relativity

(1915)



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

Einstein geometric gravity.

Gravitational waves: signatures of dynamical spacetime

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

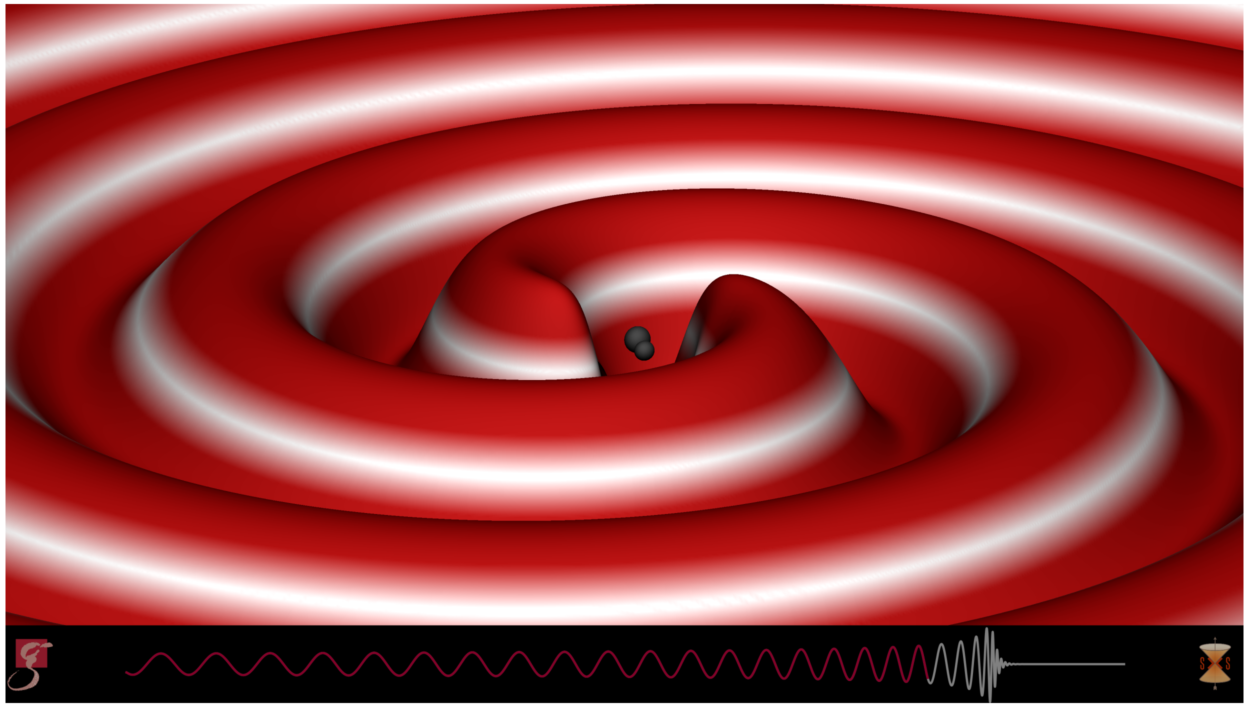
Linearized gravity (weak field): $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ $\quad |h_{\mu\nu}| \ll 1$

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

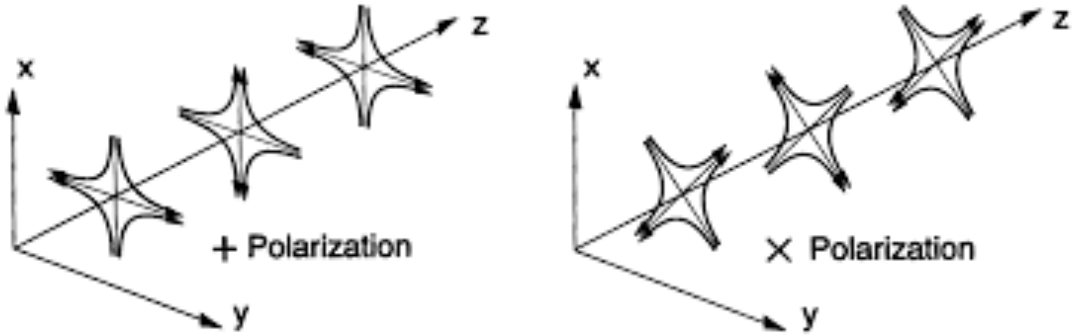
Distribution of **mass deforms spacetime** geometry in its neighborhood.

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

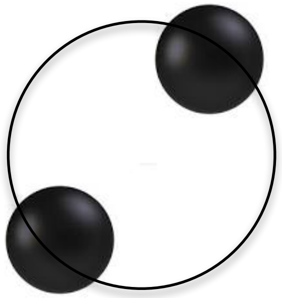
What makes gravitational waves unique astronomical messengers

- 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 **strength**: $h \sim \epsilon \frac{G}{c^2} \frac{(E_{\rm kin}/c^2)}{D}$

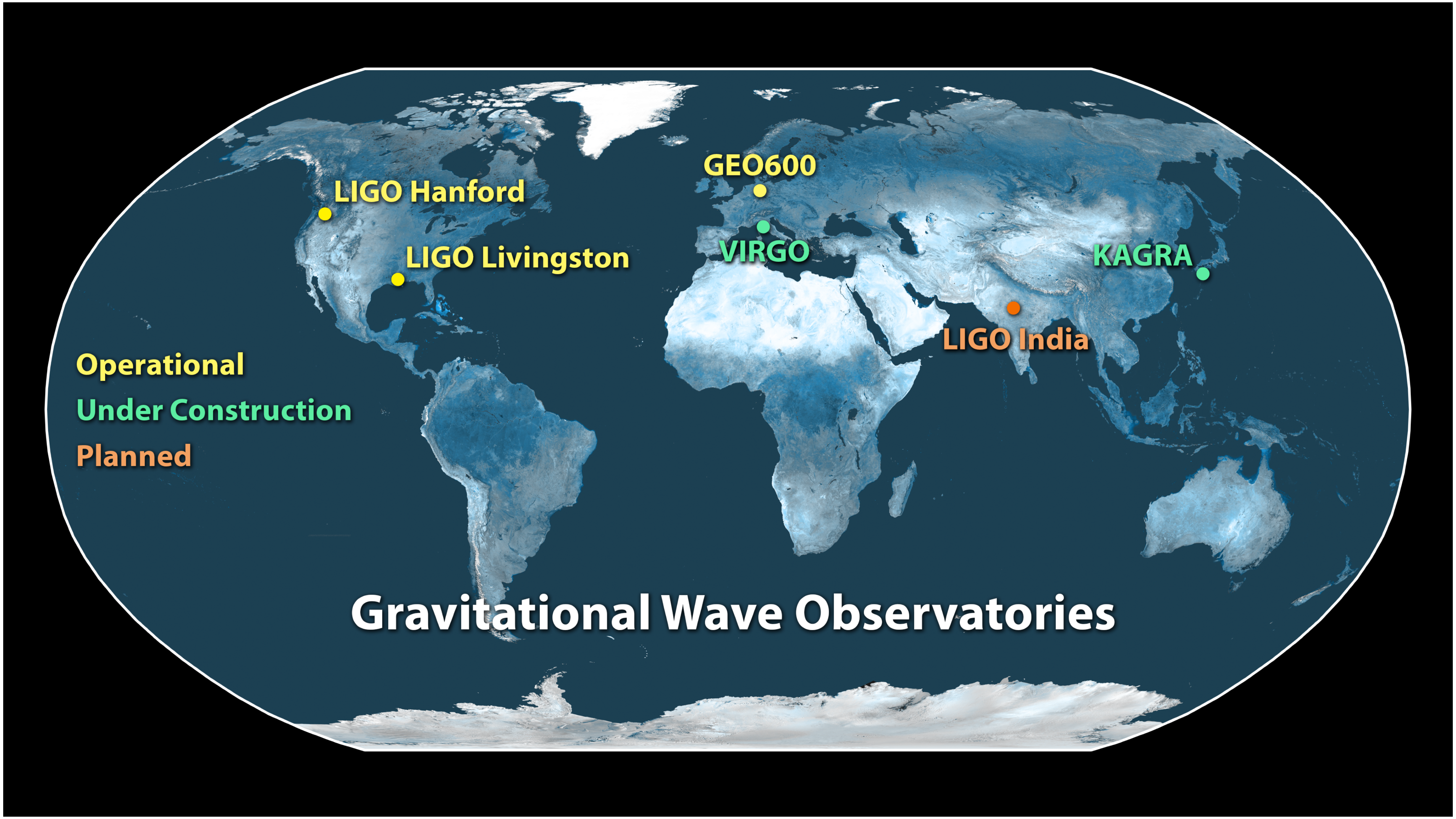
- Typical **luminosity**: $\mathcal{L}_{\rm GW} \sim \epsilon^2 \frac{c^5}{G} \left(\frac{v}{c}\right)^{10}$ $\qquad \frac{c^5}{G} \sim 10^{59} \mathrm{erg/sec}$



(binary)

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

International network of gravitational-wave detectors

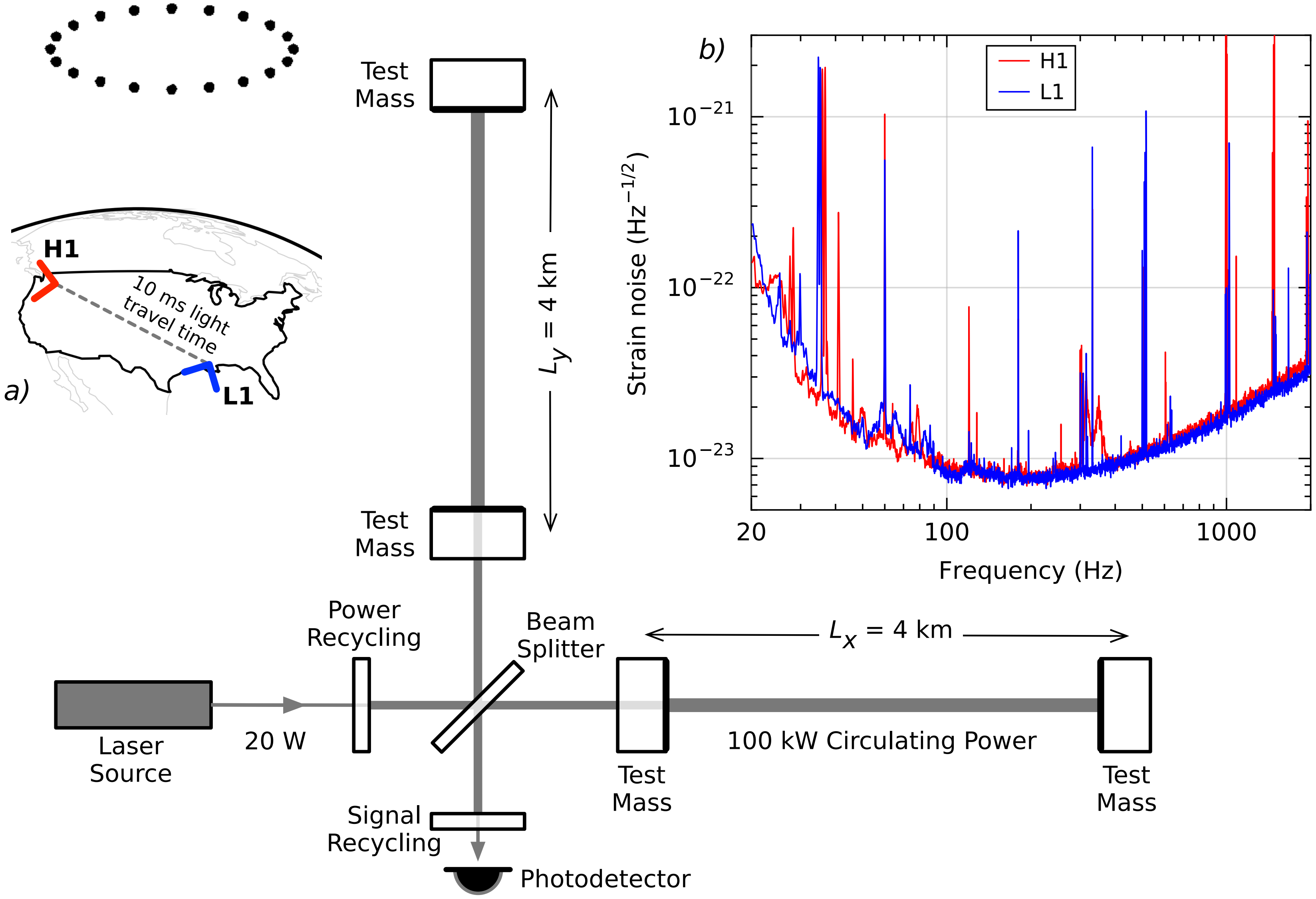


The two LIGO detectors

LIGO in Washington (H1)

LIGO in Louisiana (L1)

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

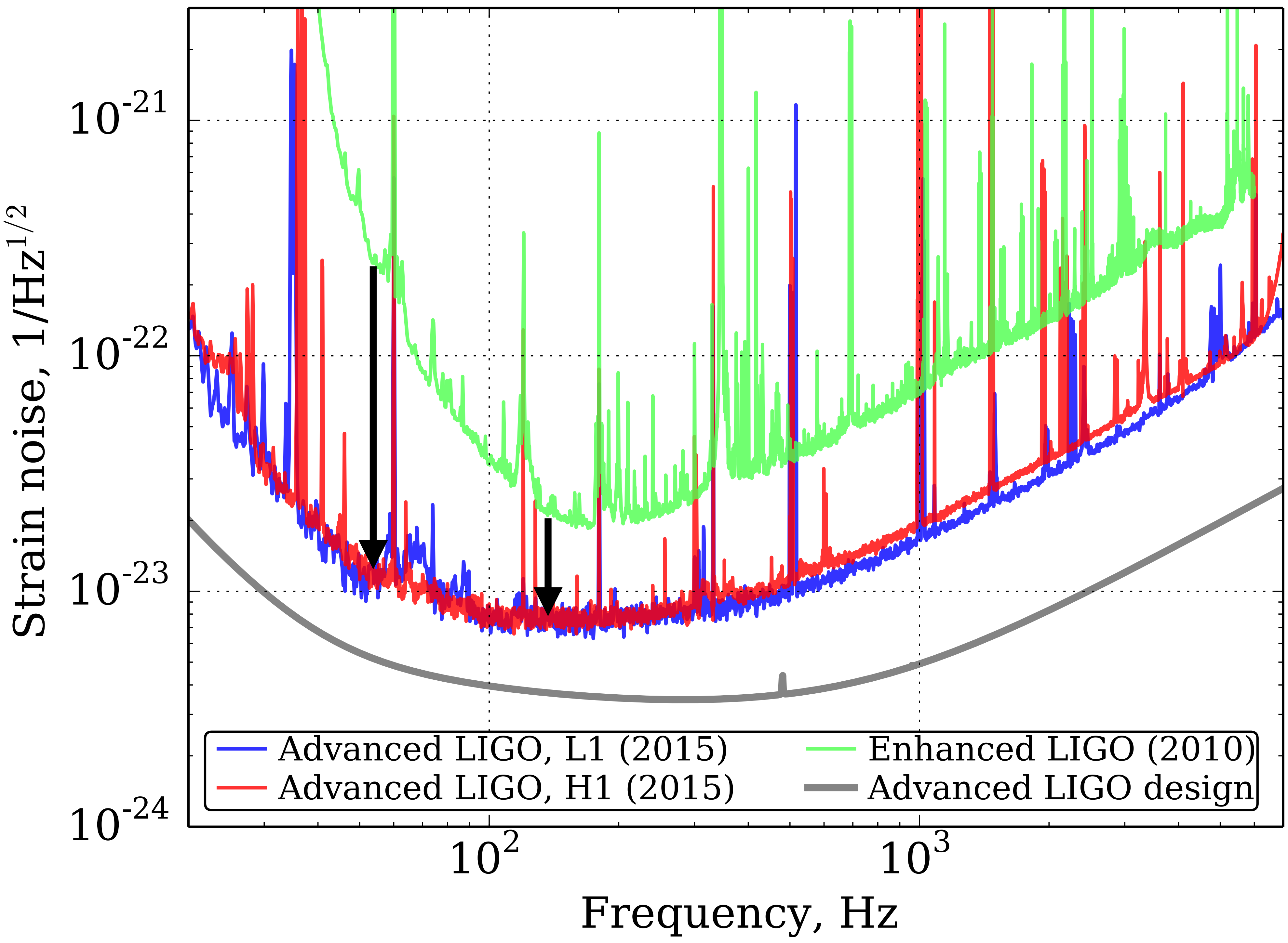


$$\Delta L = L\, h \sim 10^{-16}\ \mathrm{cm}$$

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

LIGOs measures (tiny) relative changes in separation of mirrors **(phase shifts of light at beamsplitter of 10^{-9} rad!)**

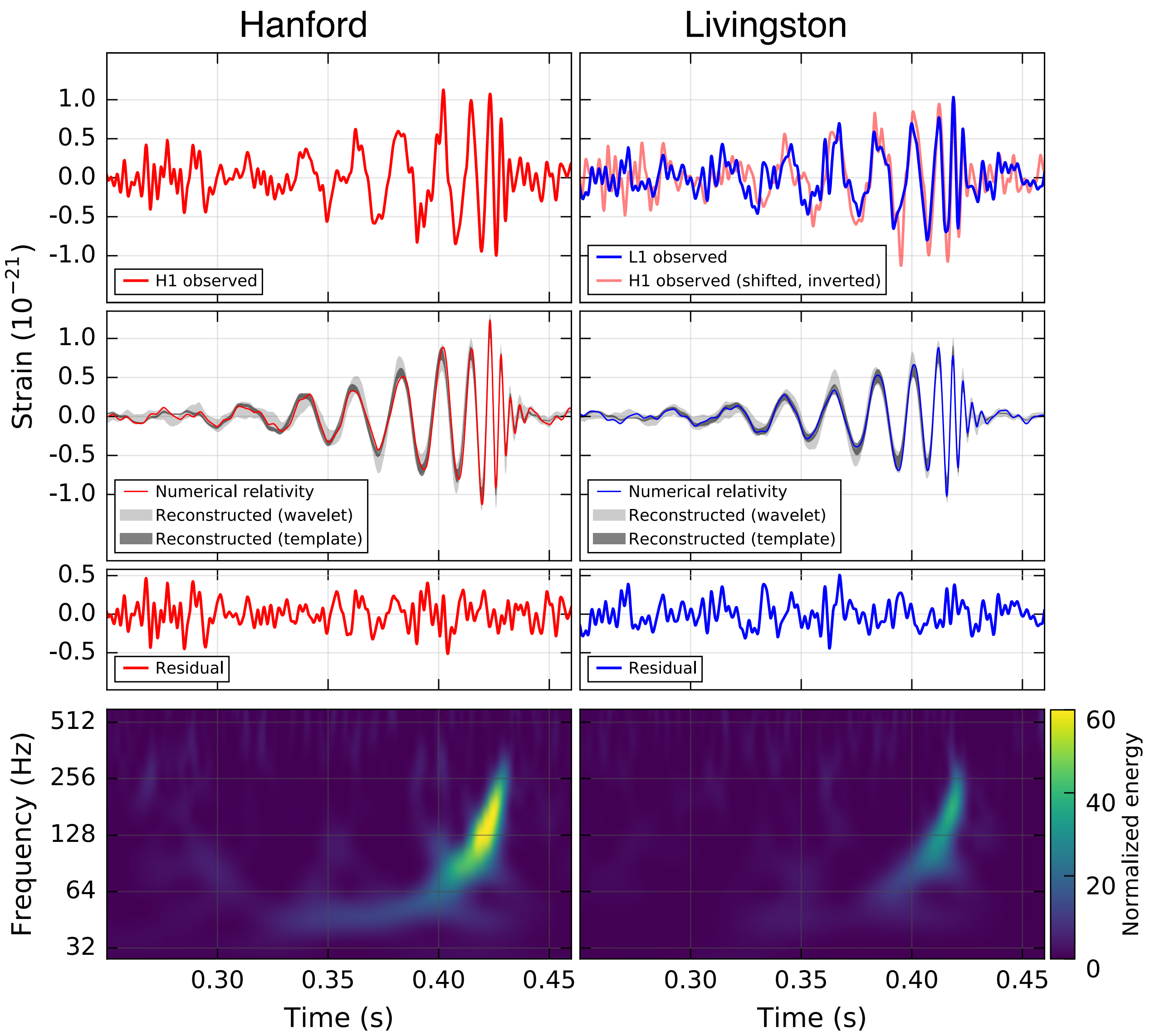
Evolution of sensitivity from Enhanced to Advanced LIGO



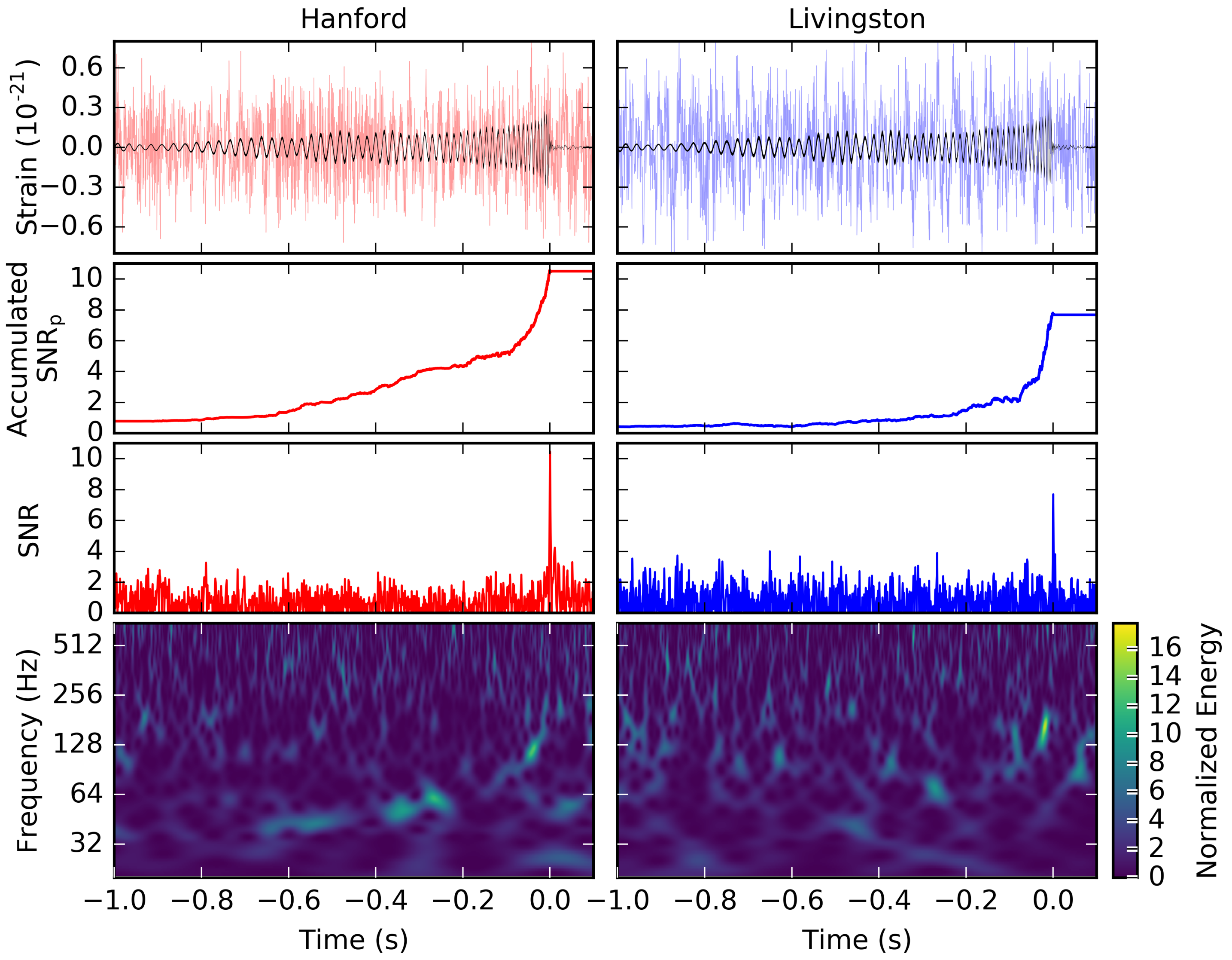
(Martynov et al. arXiv:1604.00439)

LIGO detections during O1: GW150914 & GW151226

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



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

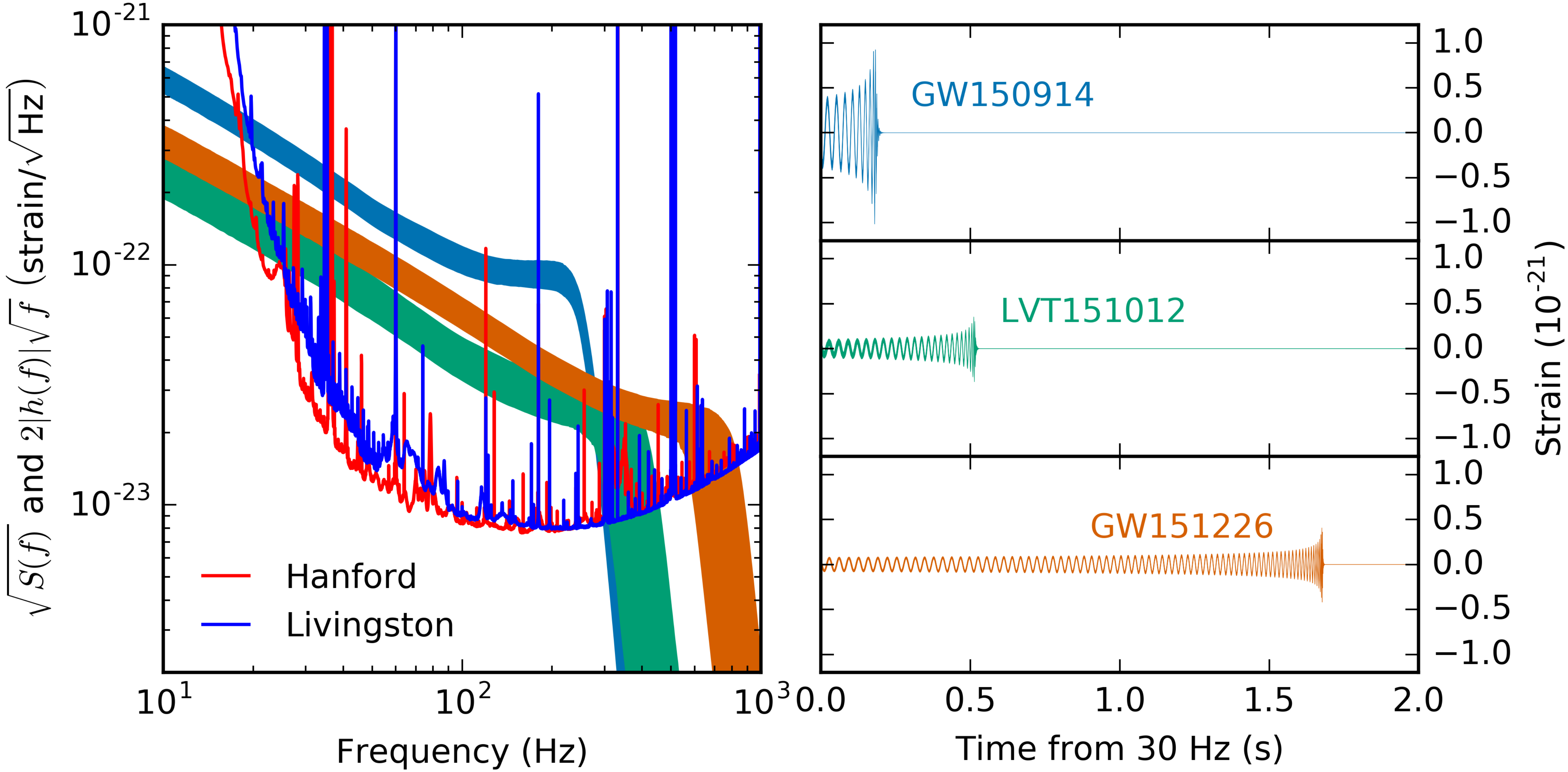


- **GW150914**: SNR=23 (very loud), 10 GW cycles, **0.2 sec.**

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

What LIGO detected: binary black-hole coalescences

(Abbott et al. arXiv:1606.04856)

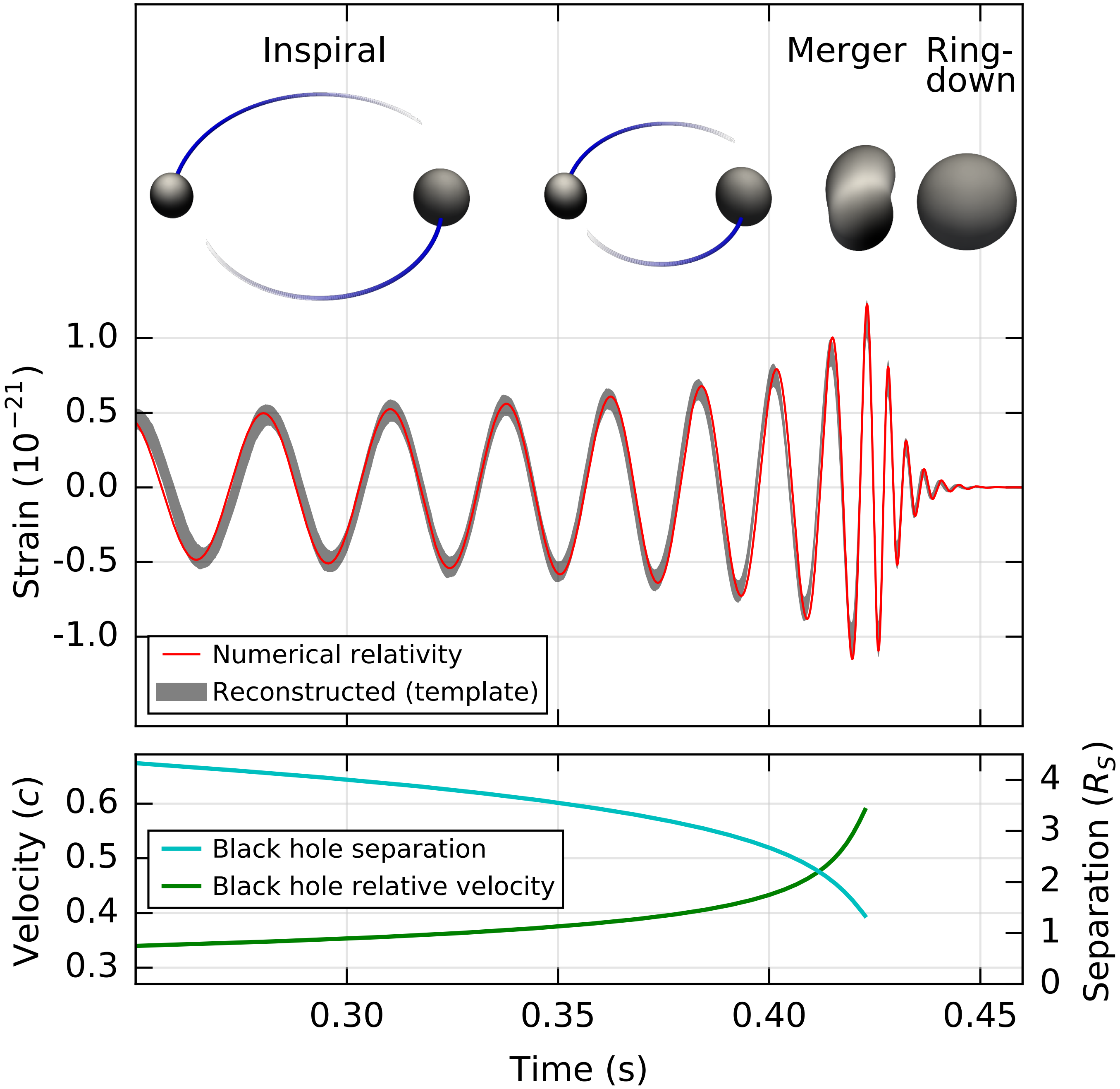


- **GW150914**: **merger in detector's band**, more massive binary
- **GW151226**: **inspiral-plunge in detector's band,** lower mass binary

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

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

Binary was composed of two compact objects, no neutron star

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

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

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

- We **measured**:

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

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

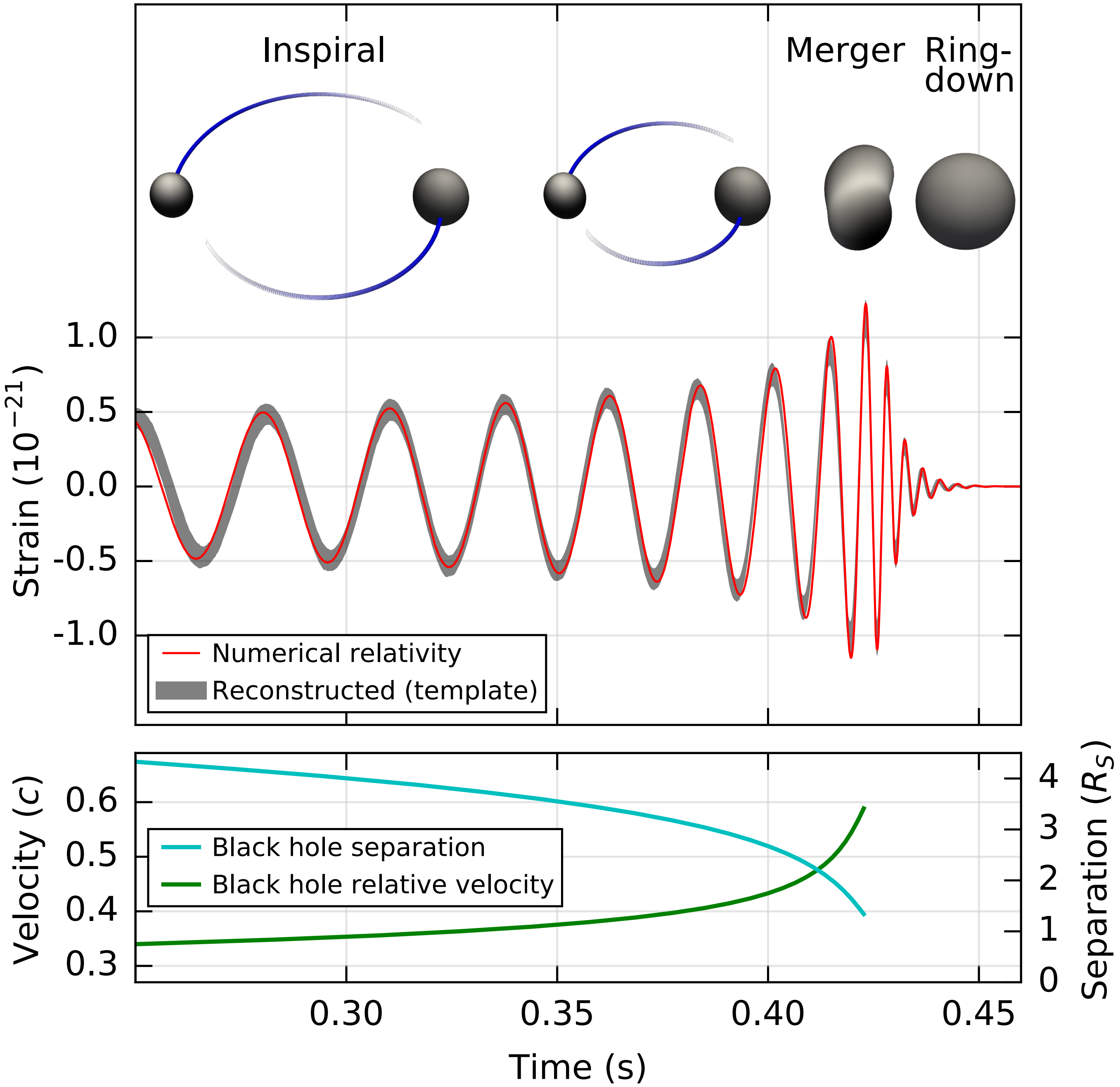
$$\Rightarrow r \simeq 350 \text{km}, 2M \sim 210 \text{km}$$

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

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

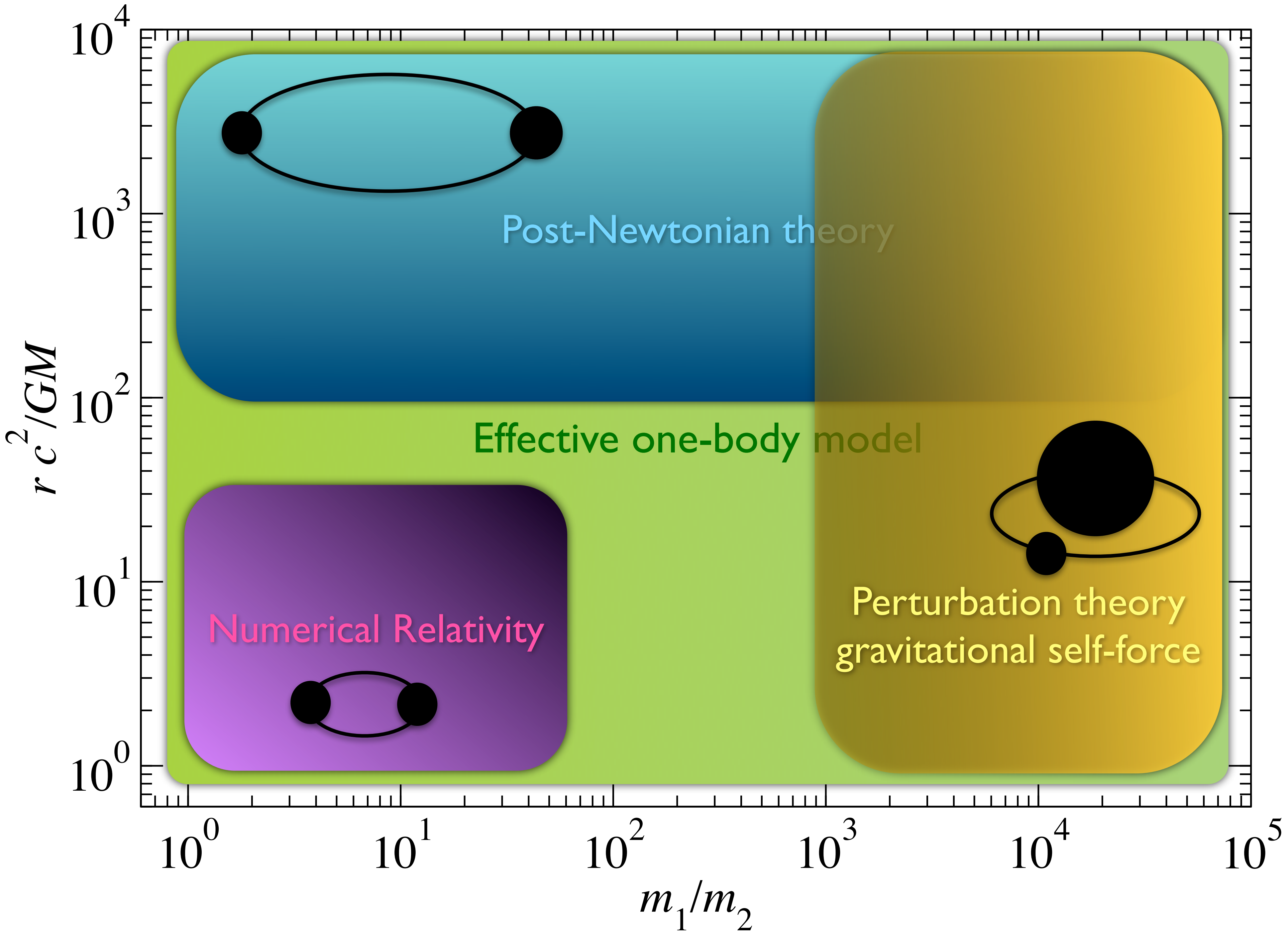
binary would **merge** at **lower frequencies**!

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



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

Waveform modeling to detect and infer source's properties



(AB & Sathyaprakash 14)

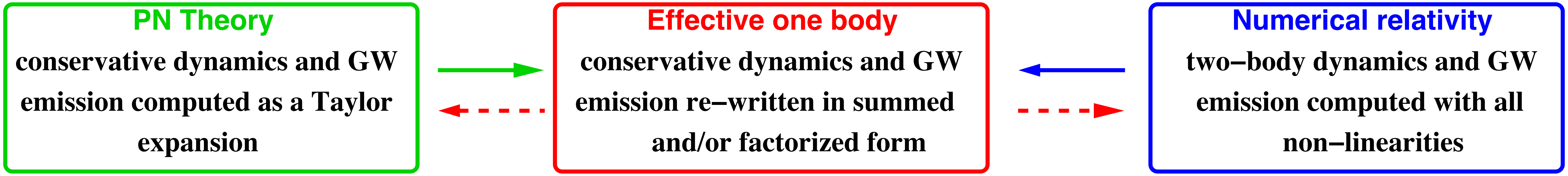
- Two parameters determine the **range of validity** of each method:

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

The effective-one-body (EOB) approach

- **EOB** approach **introduced before NR** breakthrough

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

- **EOB** model uses best information available in PN theory, but **resums PN terms** in suitable way to describe accurately dynamics and radiation during inspiral and plunge.

- **EOB** assumes **comparable-mass** description is **smooth deformation of test-particle limit**. It employs non-perturbative ingredients and **models analytically merger-ringdown** signal.

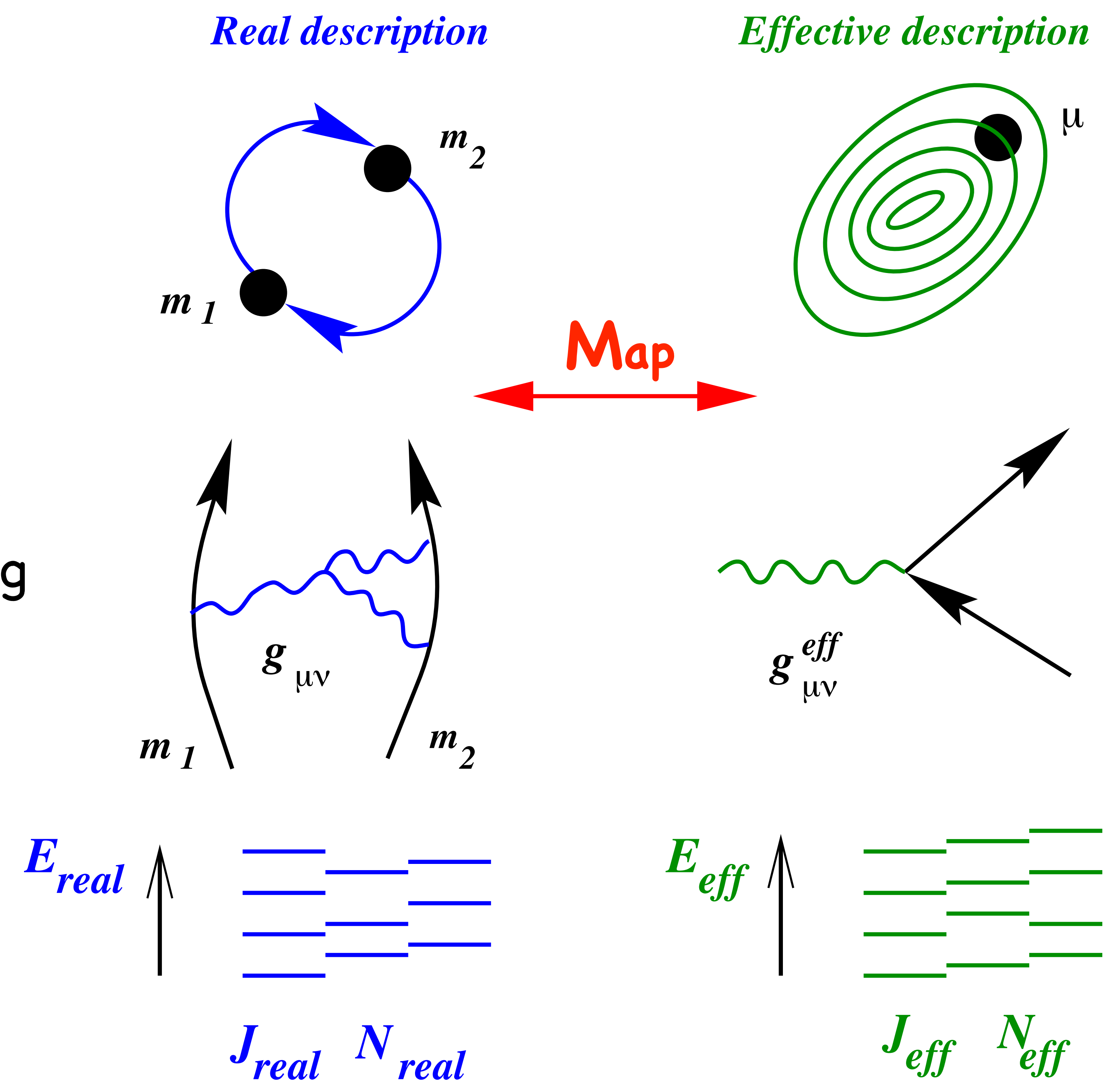
The effective-one-body approach in a nutshell

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

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

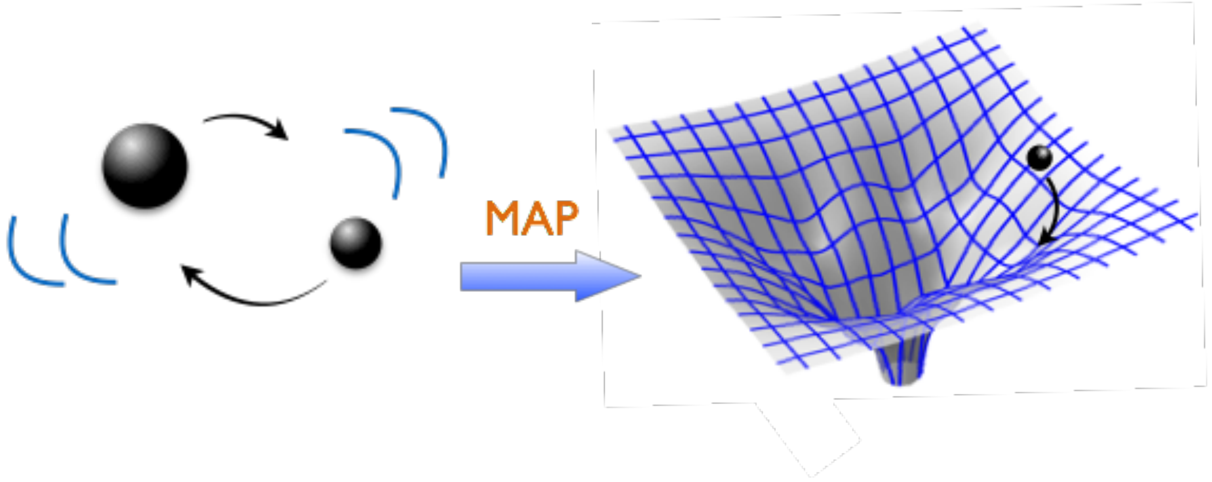
- **Two-body dynamics is mapped** into dynamics of **one-effective body** moving **in deformed black-hole spacetime**, deformation being the mass ratio.

- Some key **ideas** of EOB model were **inspired by quantum field theory** when describing energy of comparable-mass charged bodies.



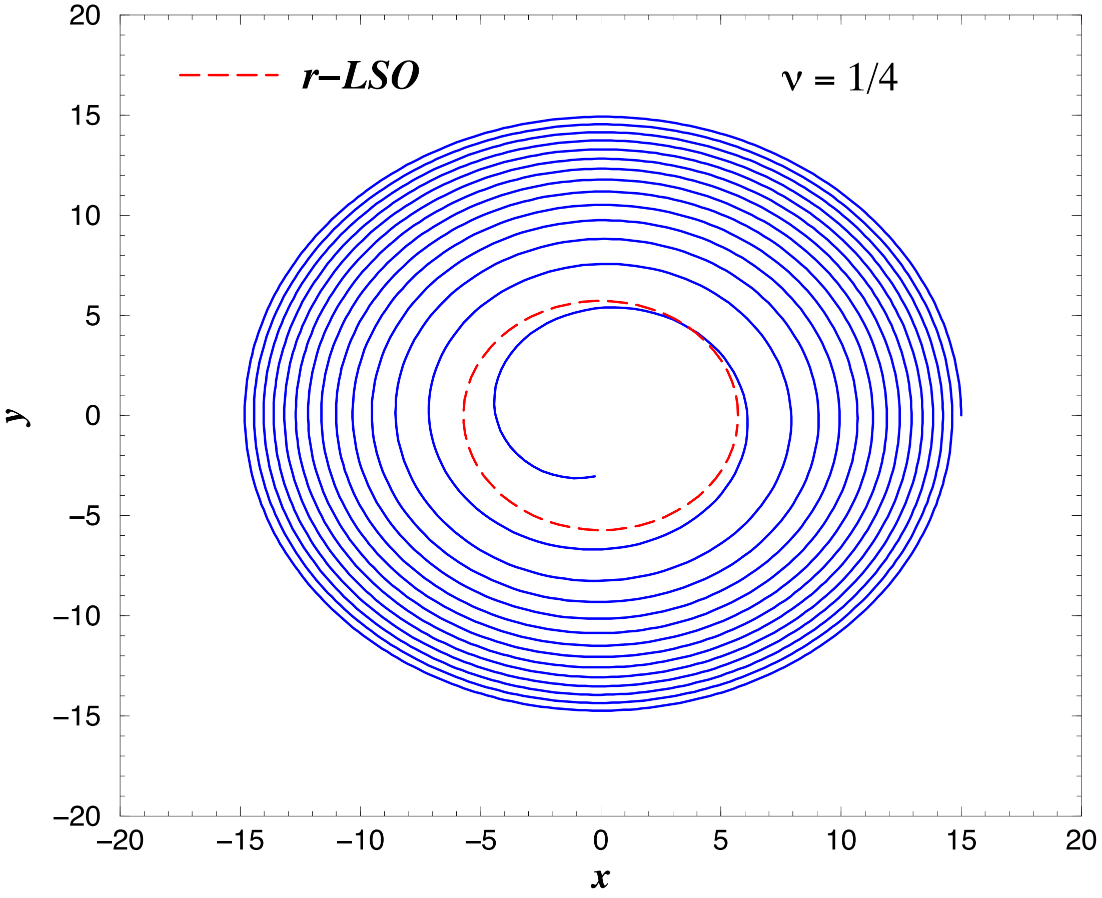
(AB & Damour PRD59 (1999) 084006)

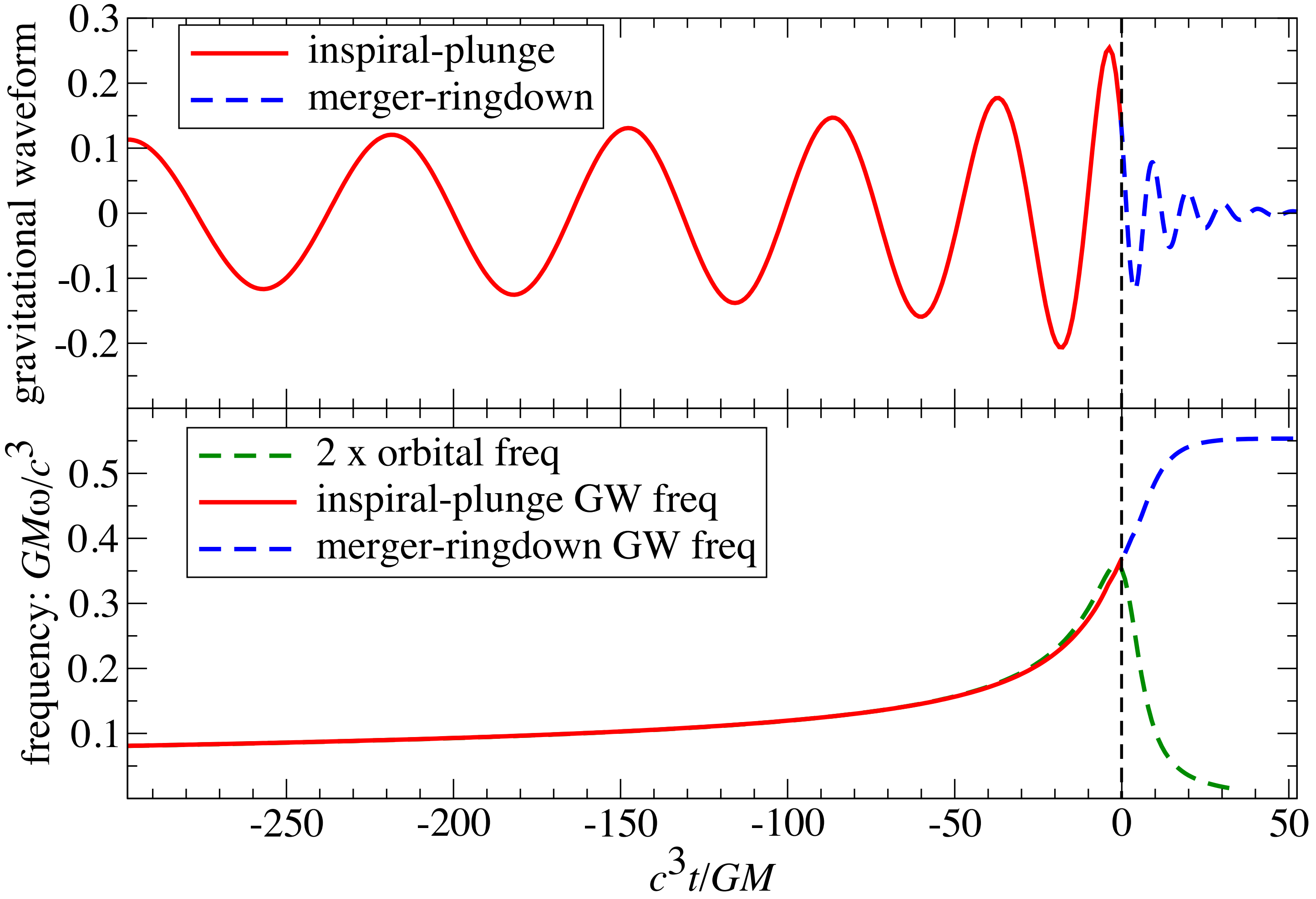
EOB inspiral-merger-ringdown analytic waveform



$$E_{\rm real}^2 = m_1^2 + m_2^2 + 2 m_1 m_2 \left(\frac{E_{\rm eff}}{\mu} \right)$$

(see also Brezin, Itzykson & Zuber 70)





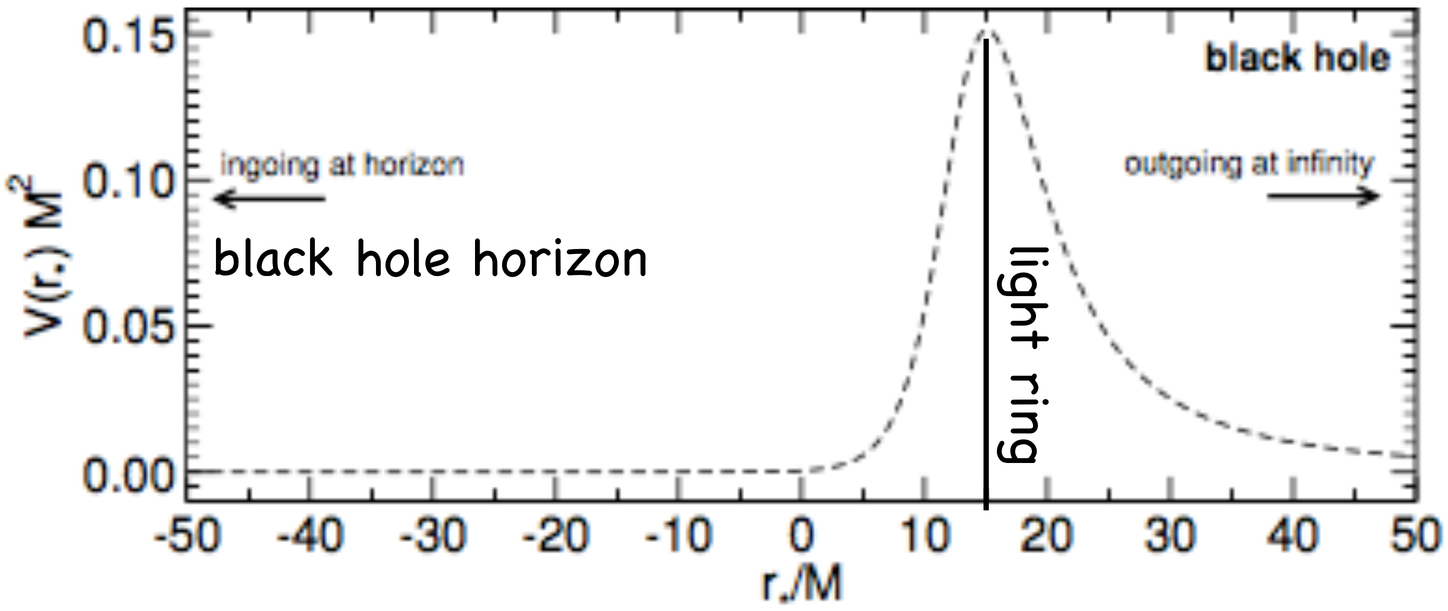
(AB & Damour, PRD59 (1999) 084006, PRD62 (2000) 064015)

On the simplicity of merger signal

equation of gravitational perturbations
in black-hole spacetime

(Regge & Wheeler 56, Zerilli 70,
Teukolsky 72)

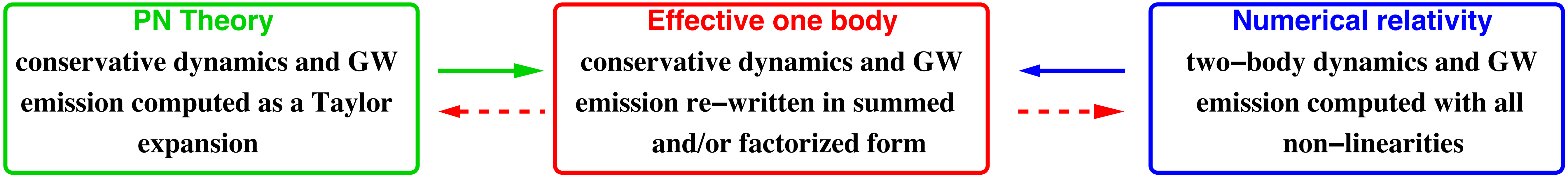
$$\frac{\partial^2\Psi}{\partial t^2} - \frac{\partial^2\Psi}{\partial r_\star^2} + V_{\ell m}\Psi = S_{\ell m}$$



- **Peak** of black-hole potential **close to "light ring".**
- Once particle is inside potential, **direct gravitational radiation** from its motion is **strongly filtered** by potential barrier (**high-pass filter**).
- Only **black-hole spacetime vibrations** (quasi-normal modes) **leaks out** black-hole potential.

Waveforms combining analytical & numerical relativity

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



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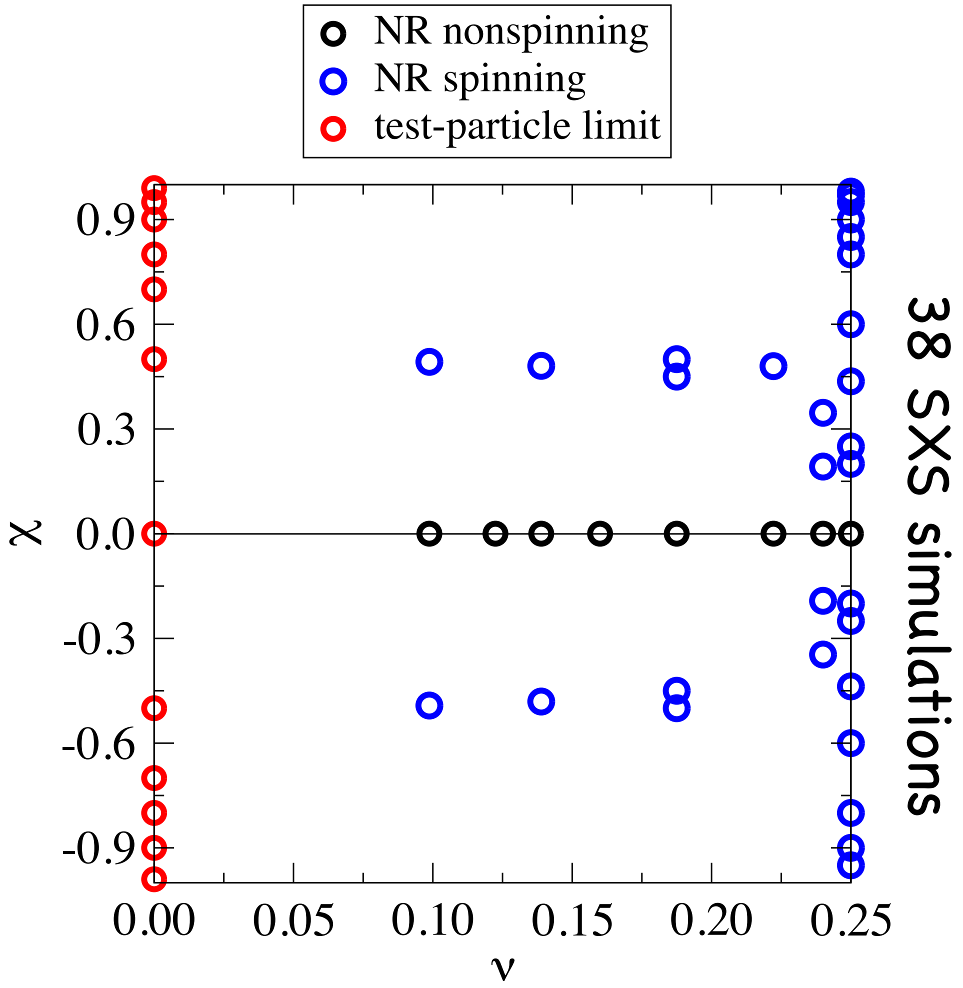
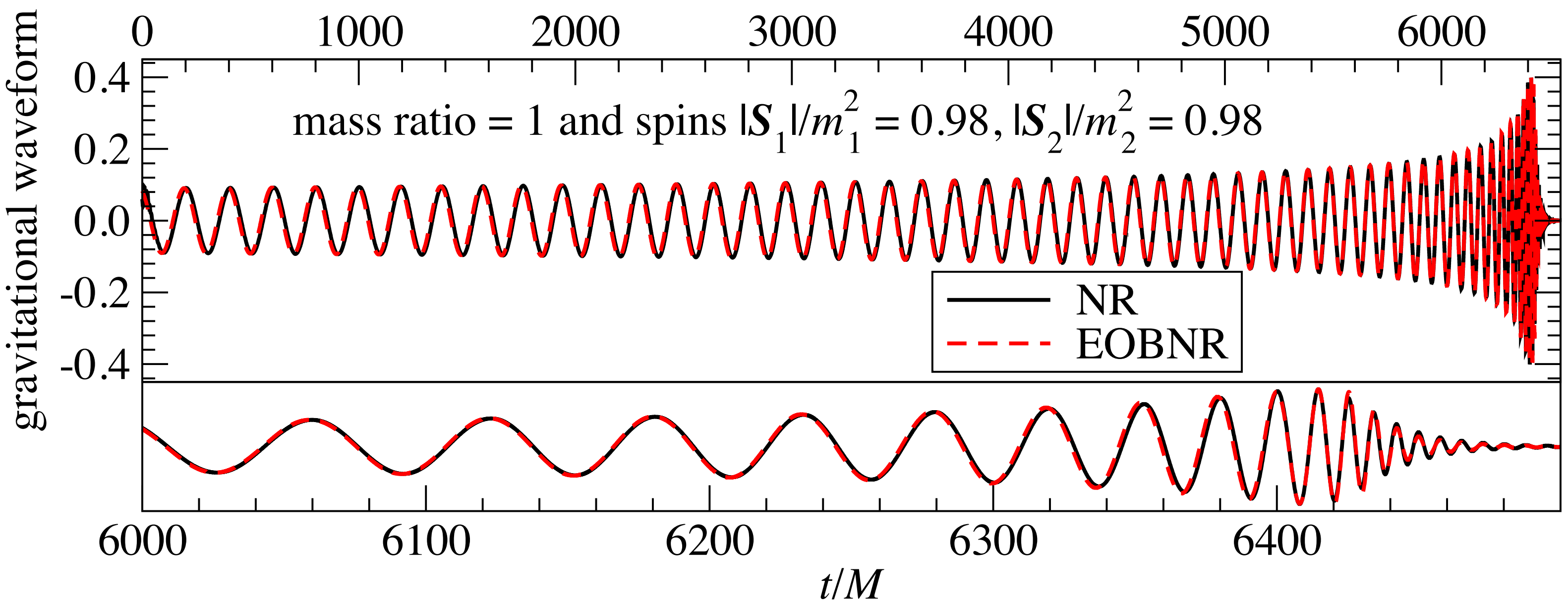


(Taracchini, AB, Pan, Hinderer & SXS 14, Puerrer 15)

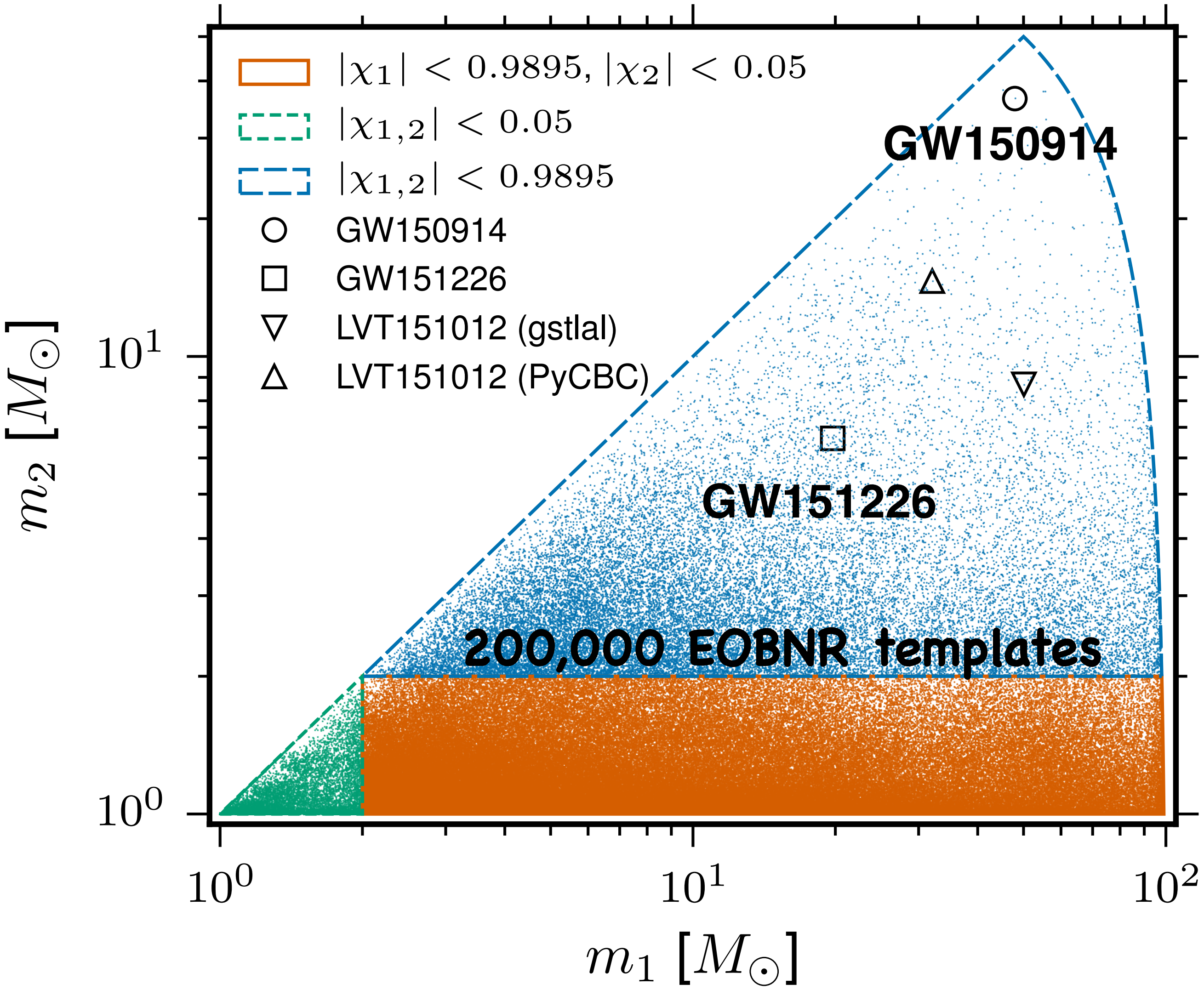


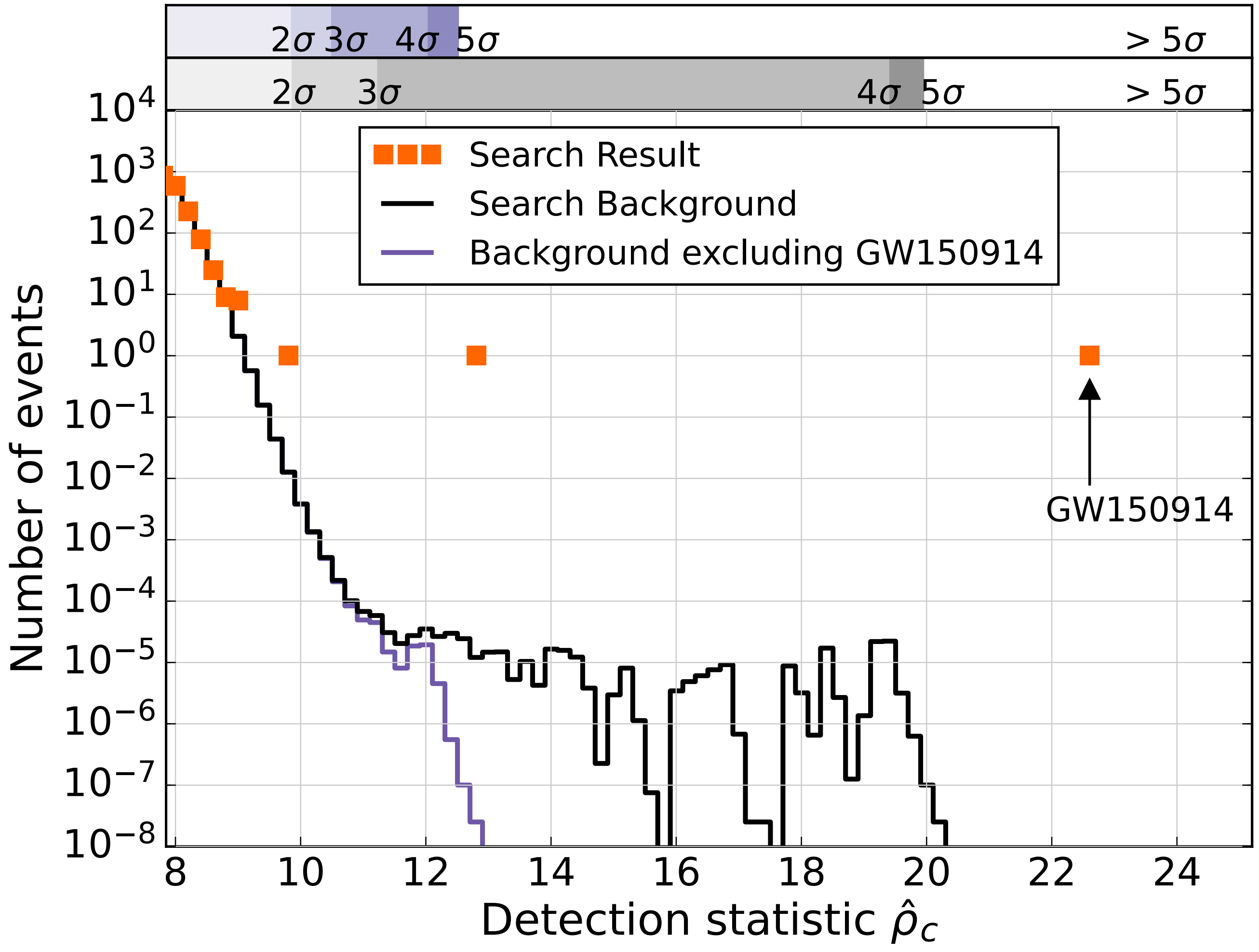
- **Inspiral-merger-ringdown phenomenological** waveforms fitting EOB & NR (IMRPhenom) (Khan et al. 16, Hannam et al 16)

Detection confidence with modeled search in O1

- **Matched filtering** employed

(Abbott et al. arXiv:1606.04856)

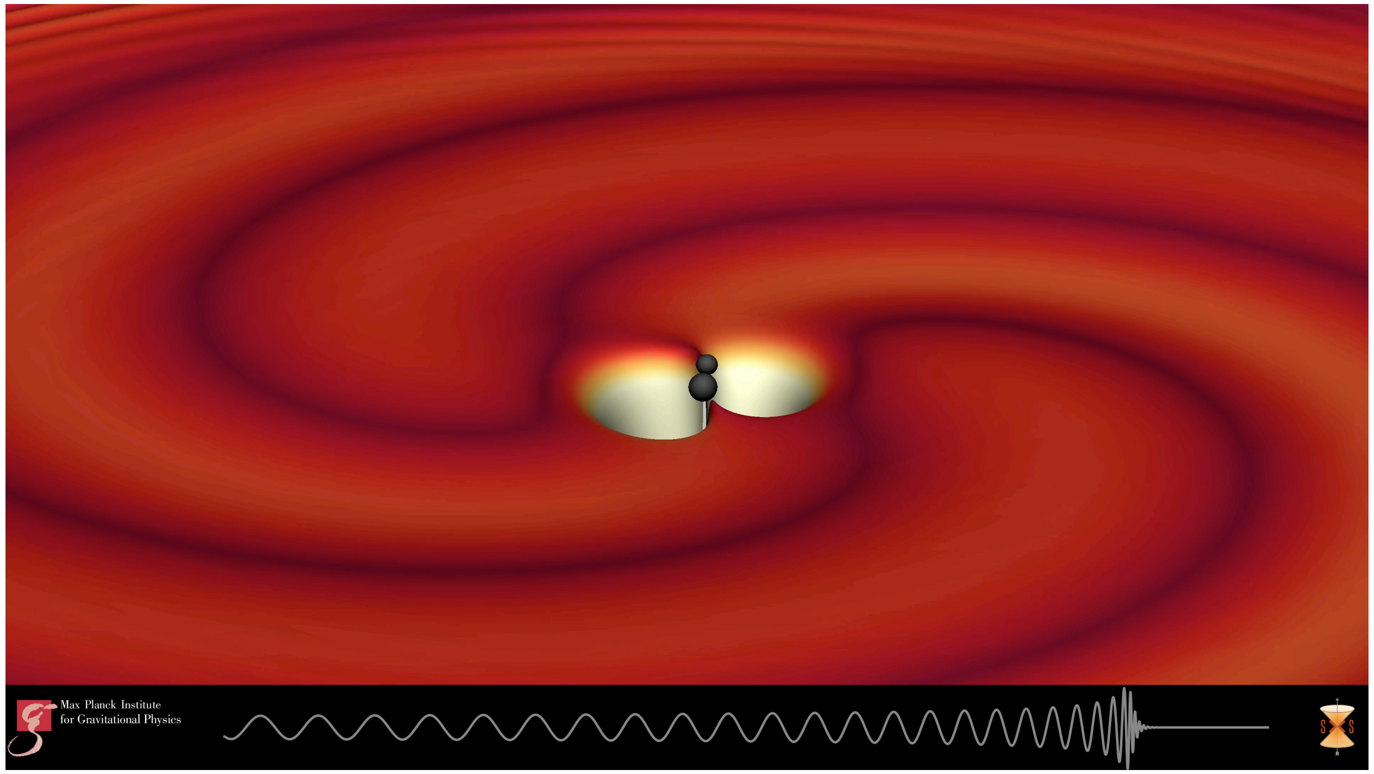




- **Confidence (FAP) > 5.3σ (< $2x10^{-7}$)** that GW150914 & GW151226 were "real" gravitational-wave signals.
- **Minimal-assumption search** reached high detection confidence **(> 4.6σ) only for GW150914.**

Numerical-relativity simulation of a binary black-hole merger with parameters close to GW150914

(visualization credit: Haas @ AEI)



(Ossokine, AB & SXS project)

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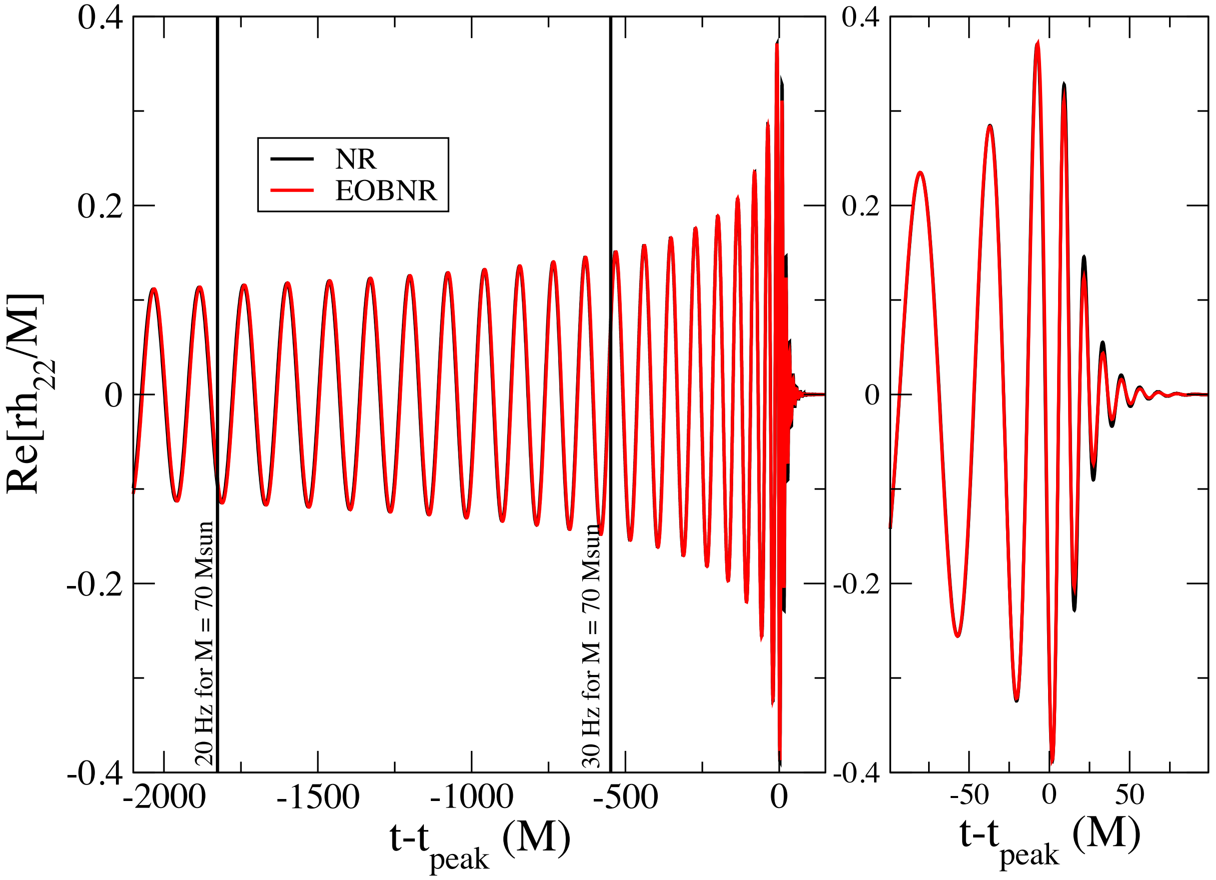


- **Waveform models** very closely **match** the **exact solution** from Einstein equations around GW150914 & GW151226.

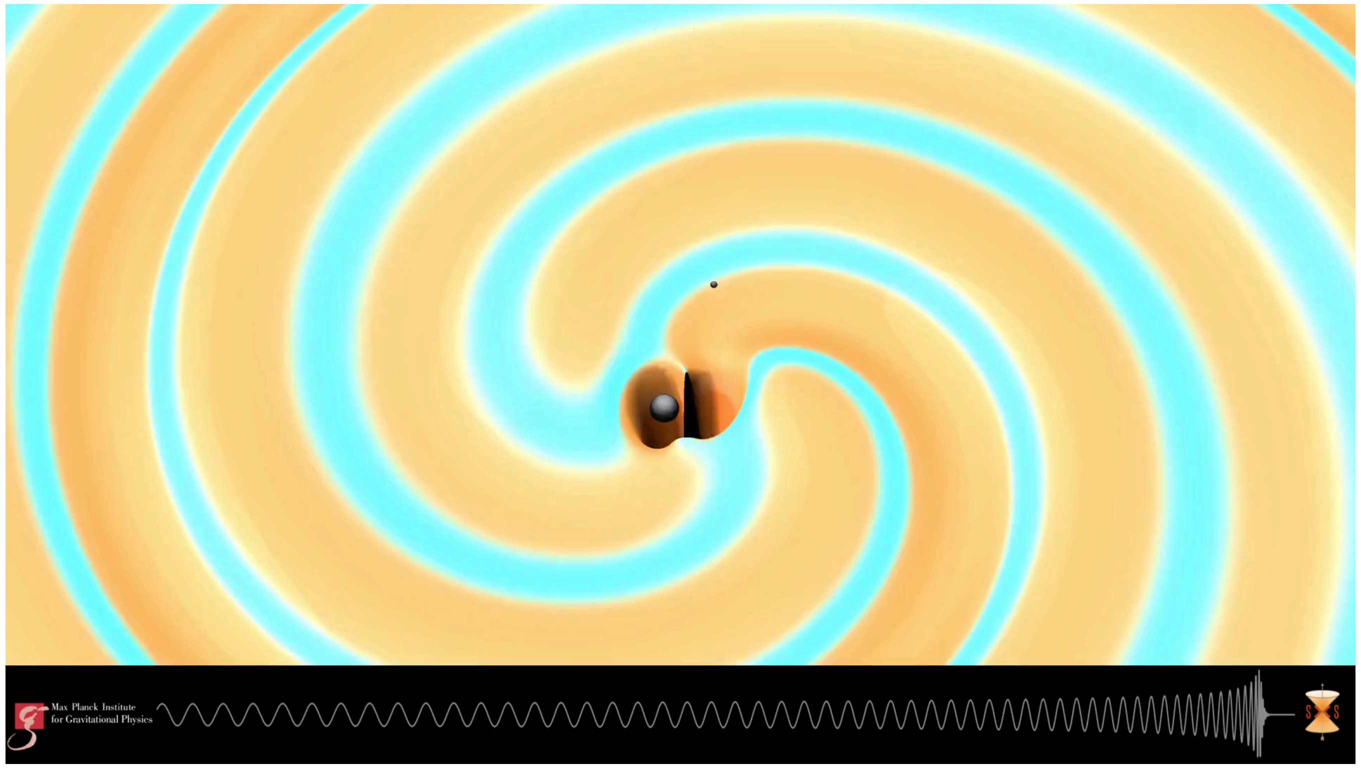
- **Systematics** due to modeling **are smaller than statistical** errors.

(see also Abbott et al. arXiv:1611.07531)

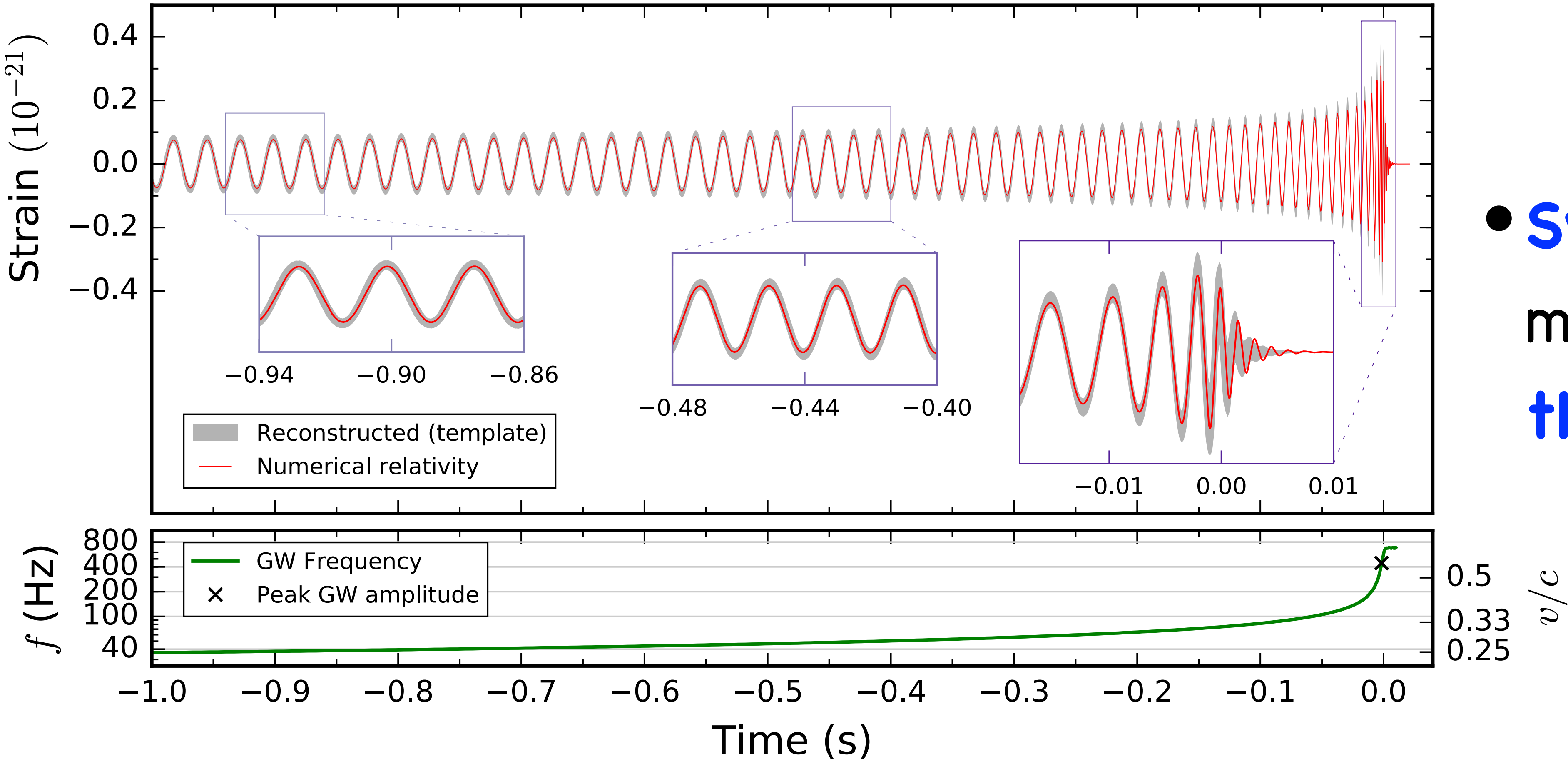
Numerical-relativity simulation of a binary black-hole merger with parameters close to GW151226

(visualization credit: Dietrich, Haas @AEI)

(Ossokine, AB & SXS project)



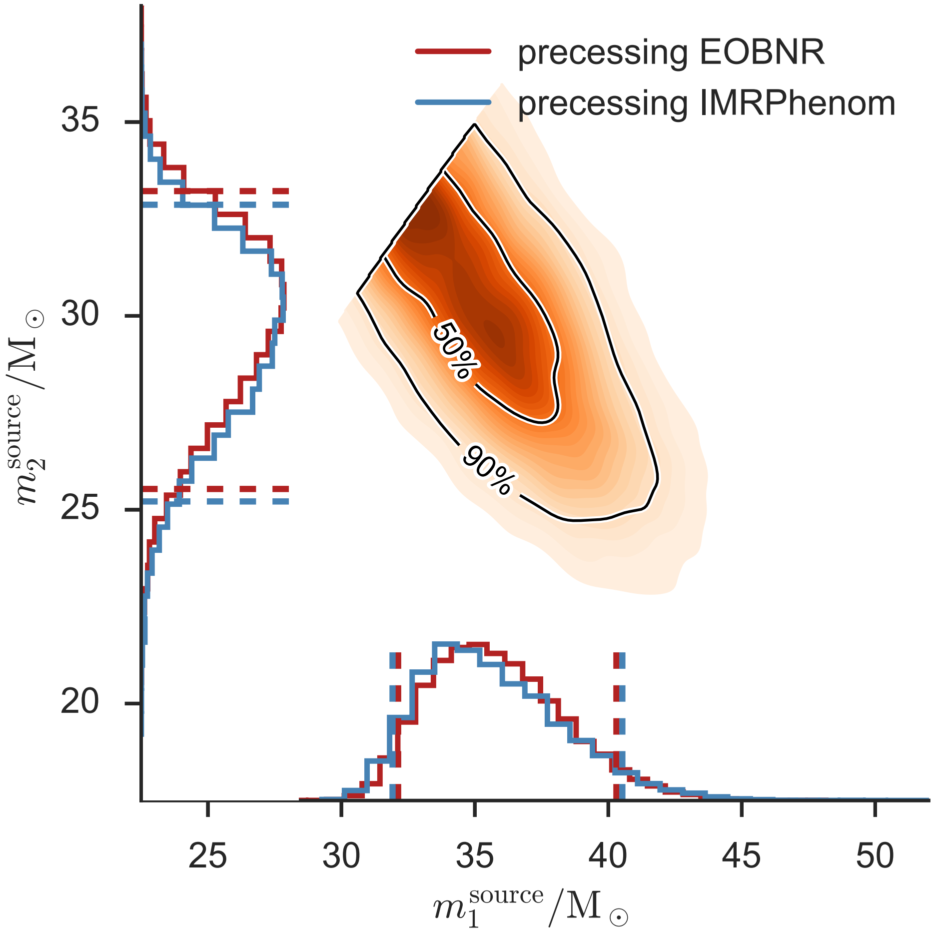
(Abbott et al. PRL 116 (2016) 241103)



- **Systematics** due to modeling **are smaller than statistical** errors.

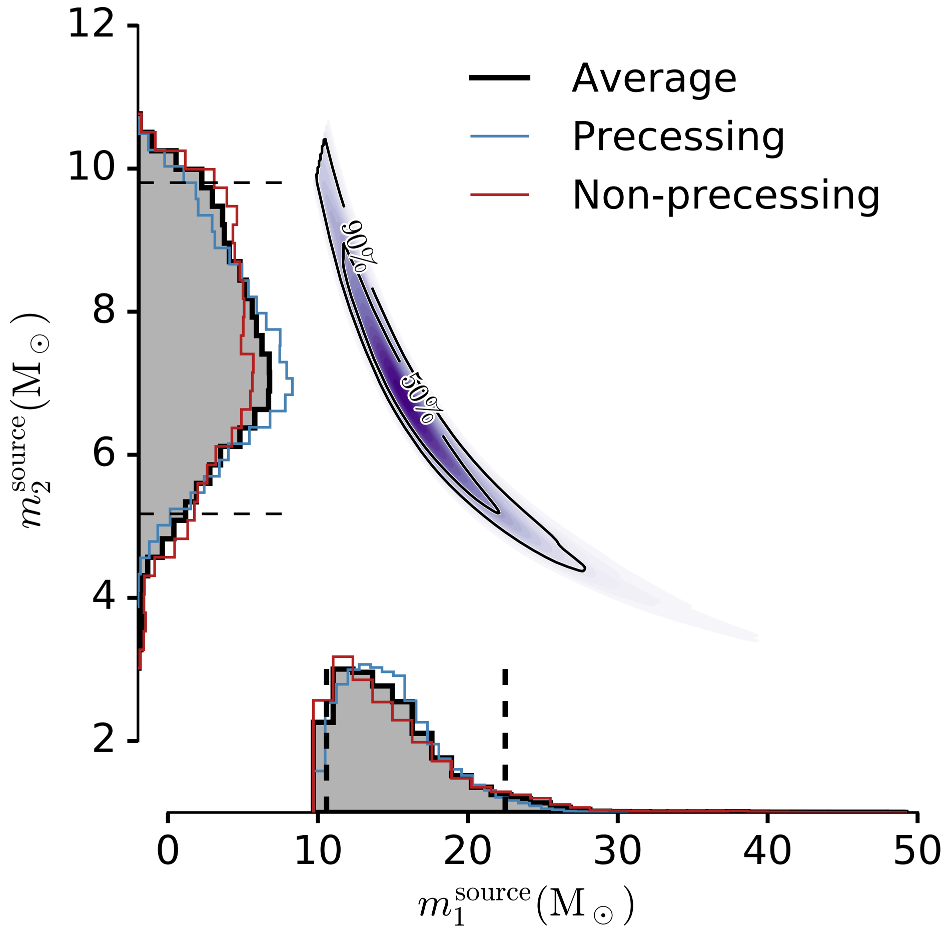
Unveiling binary black holes properties: masses

GW150914



(Abbott et al. arXiv:1606.01210)

GW151226



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

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

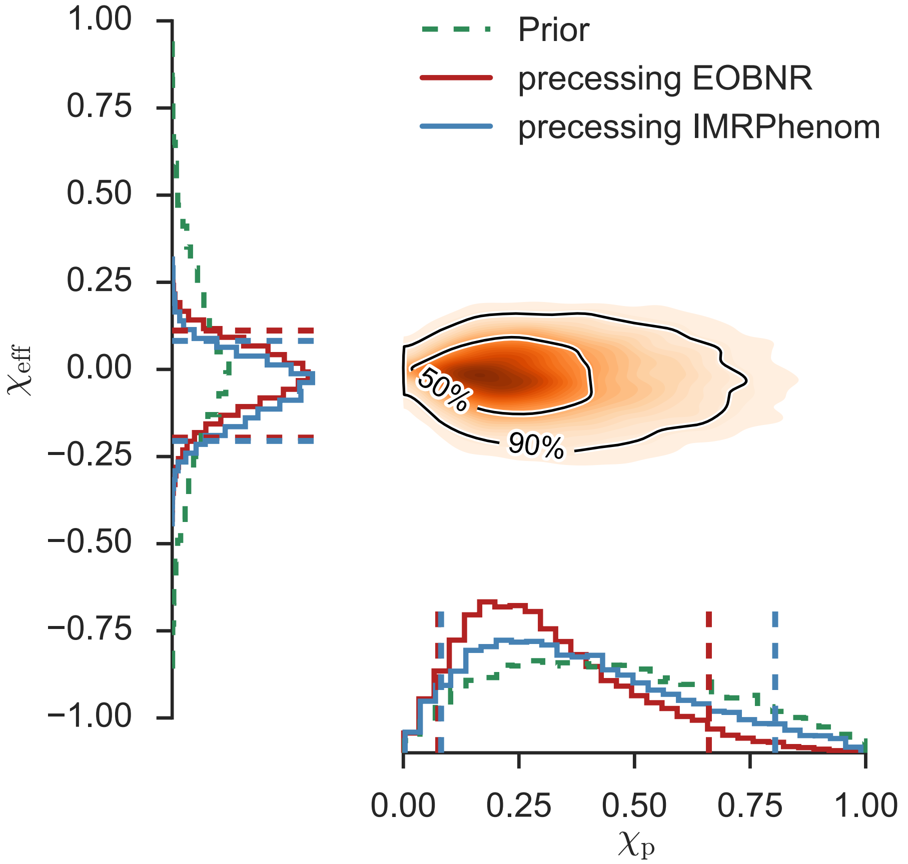
- **GW150914**: merger in band, total mass well measured, good measurement of individual masses.

- **GW150914**: merger outside band, individual masses measured less precisely.

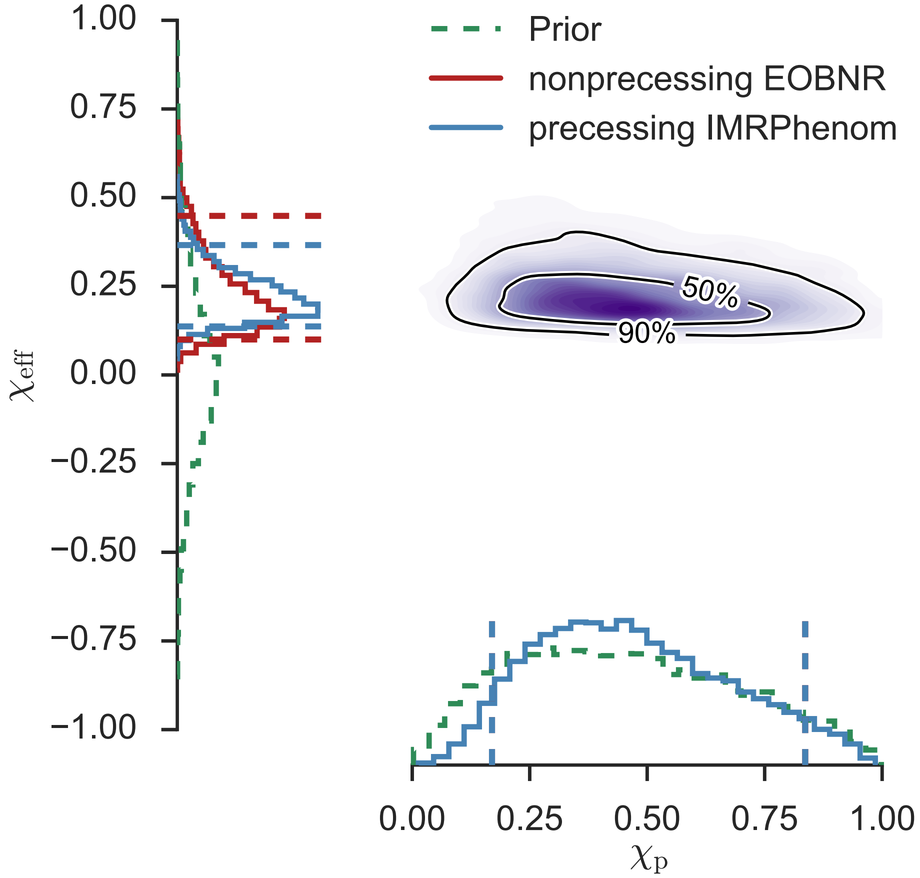
Unveiling binary black-holes properties: spins

(Abbott et al. arXiv:1606.01210)

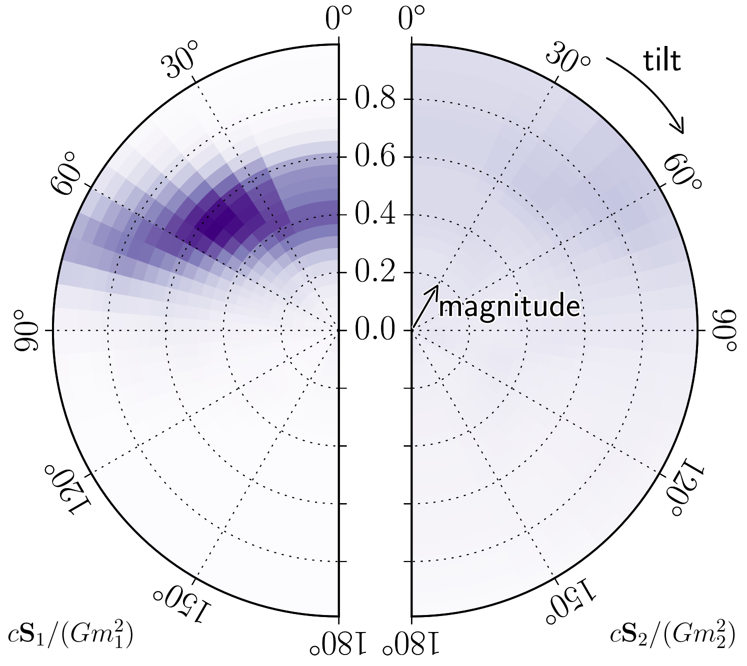
GW150914



GW151226



$$\chi_{\rm eff} = \left(\frac{\mathbf{S_1}}{m_1} + \frac{\mathbf{S_2}}{m_2}\right)\cdot\left(\frac{\hat{\mathbf{L}}}{M}\right)$$

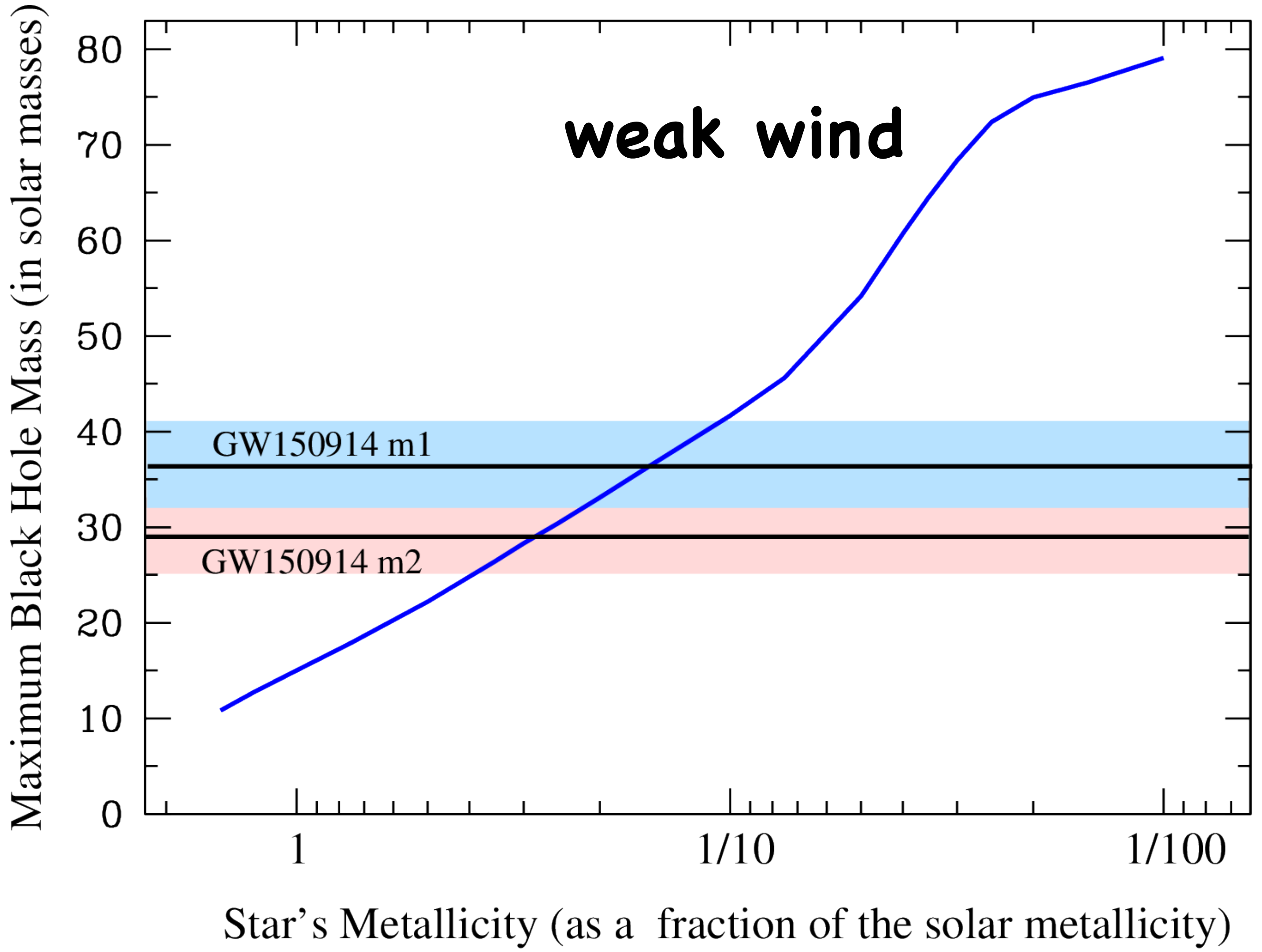


- BHs' **spins not maximal**, and for GW151226 **one BH's spin larger than 0.2** at 99% confidence.
- **Spins < 0.7. No information** about **precession.**

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

Implications for binary formation scenarios

- BHs' observed **heavier than expected for GW150914**. How did they form?
- **Dynamical capture** or **massive** binary stars **undergoing core-collapse** or chemically homogeneous evolving stars or primordial BHs or PopIII stars?

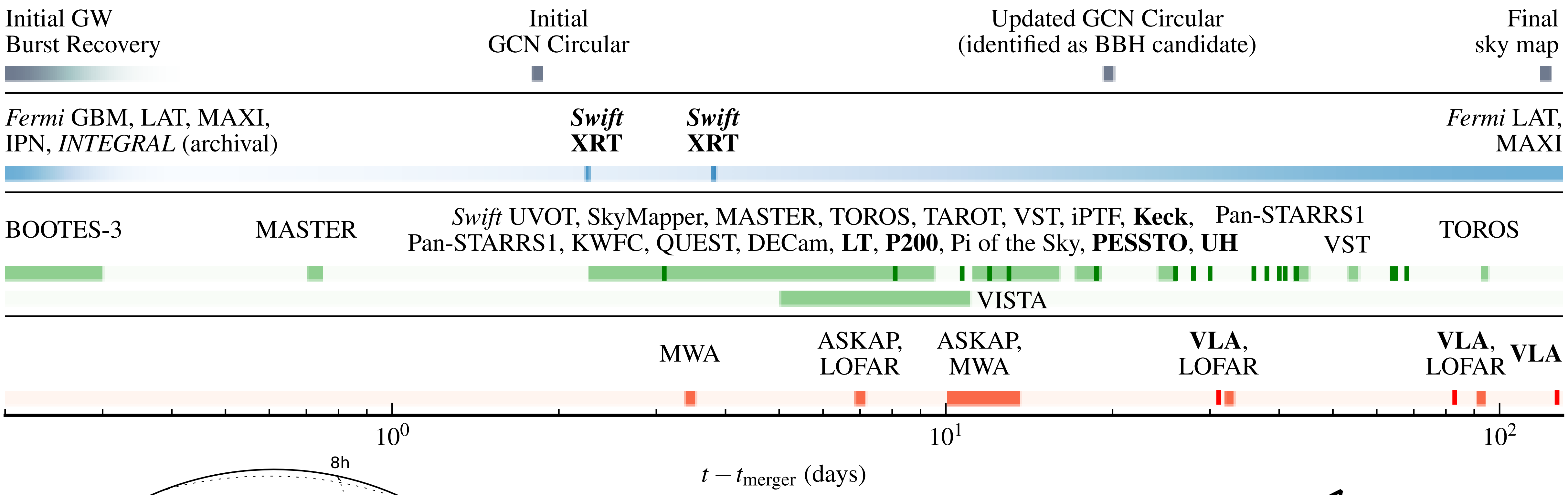


(Abbott et al. ApJ L22 (2016) 818)

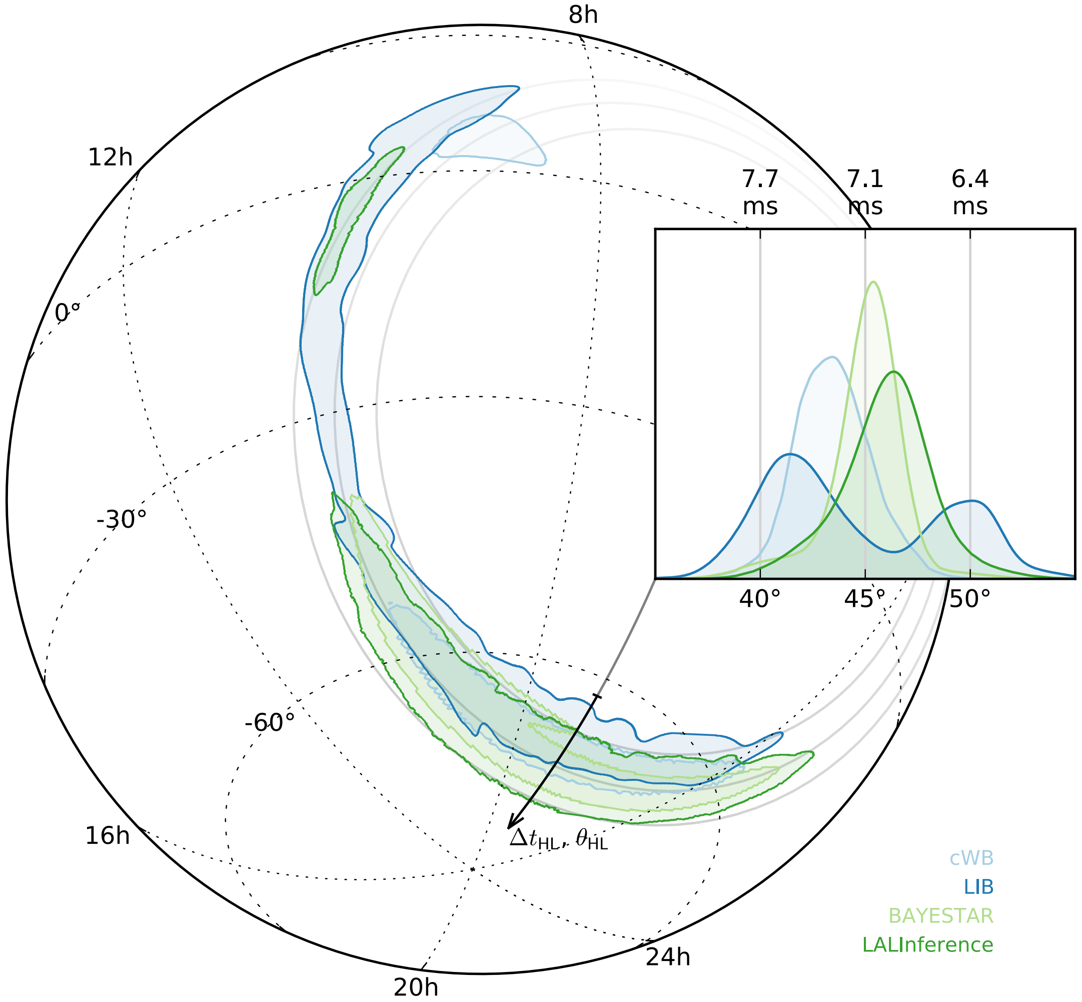
(Lipunov et al 97,
Belczynski et al. 10,
Dominik et al. 15,
Belczynski et al. 15,
Nelemans et al. 01,
Rodriguez et al. 16,
de Mink et al. 09,
Marchant et al. 16,
Bird et al. 16,
de Mink & Mandel 16,
Belczynski et al. 16,
...)

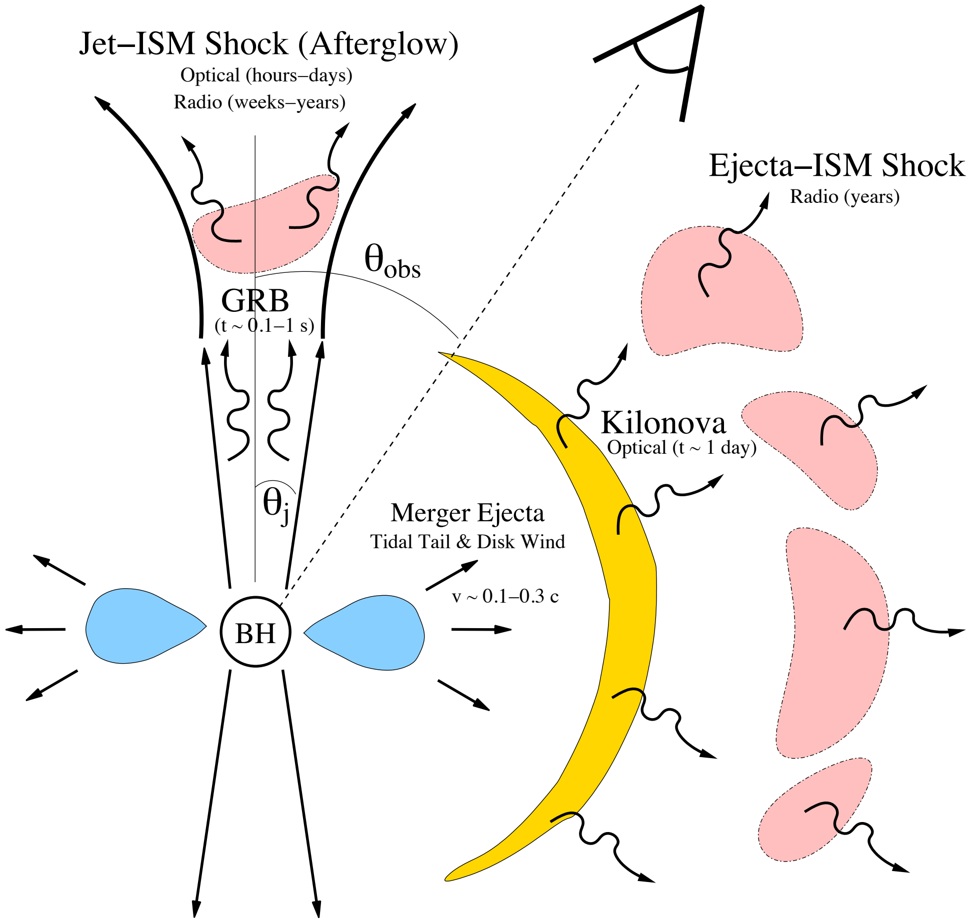
(Heger et al. 03, Mapelli et al. 09, Belczynski et al. 10, Mapelli et al. 13, Spera et al. 15)

First campaign for electromagnetic counterparts



(Abbott et al. APJ L13 (2016) 826)

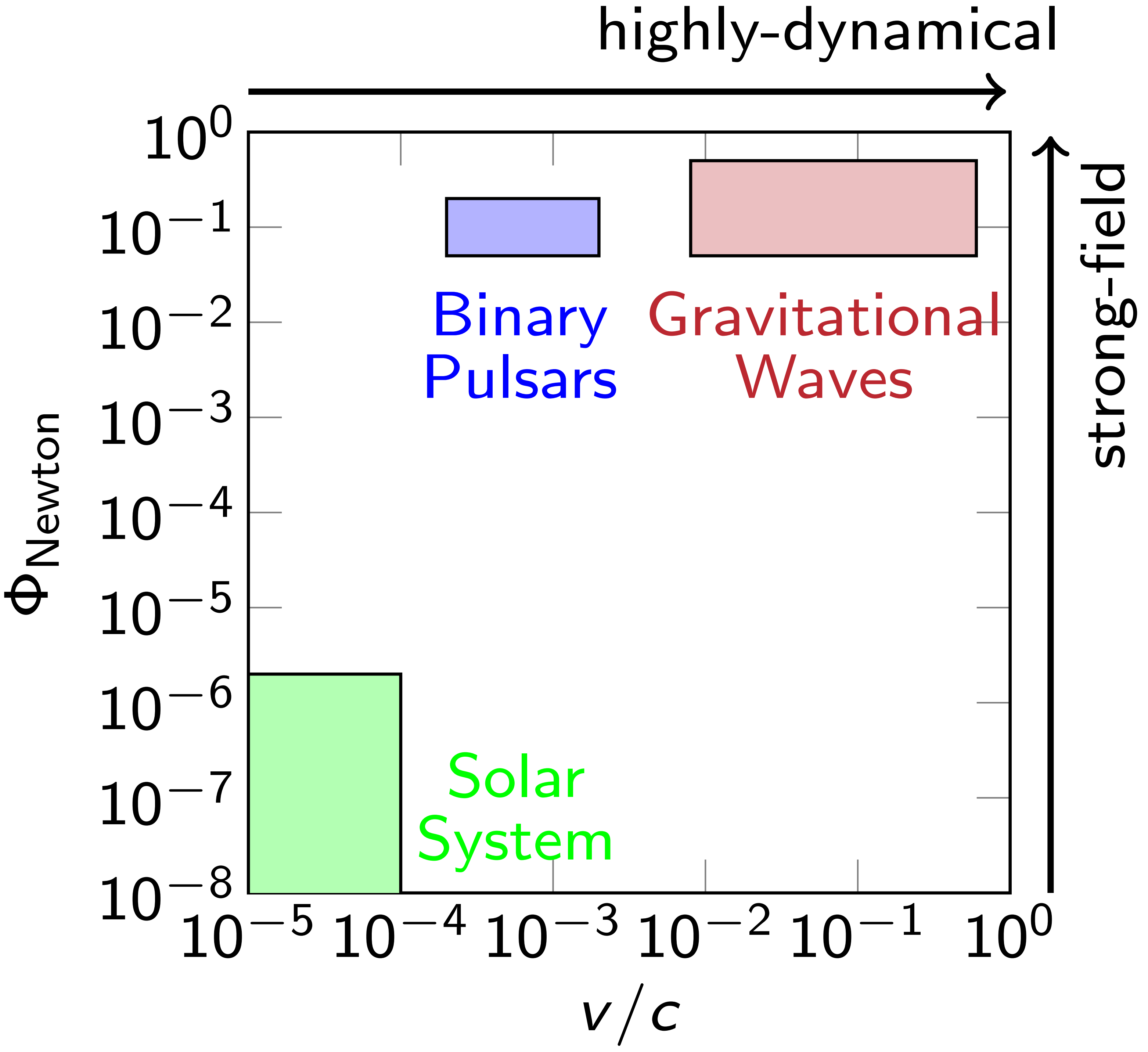




(Berger & Metzger 11)

Tests of GR with LIGO's sources

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



(credit: Sennett)

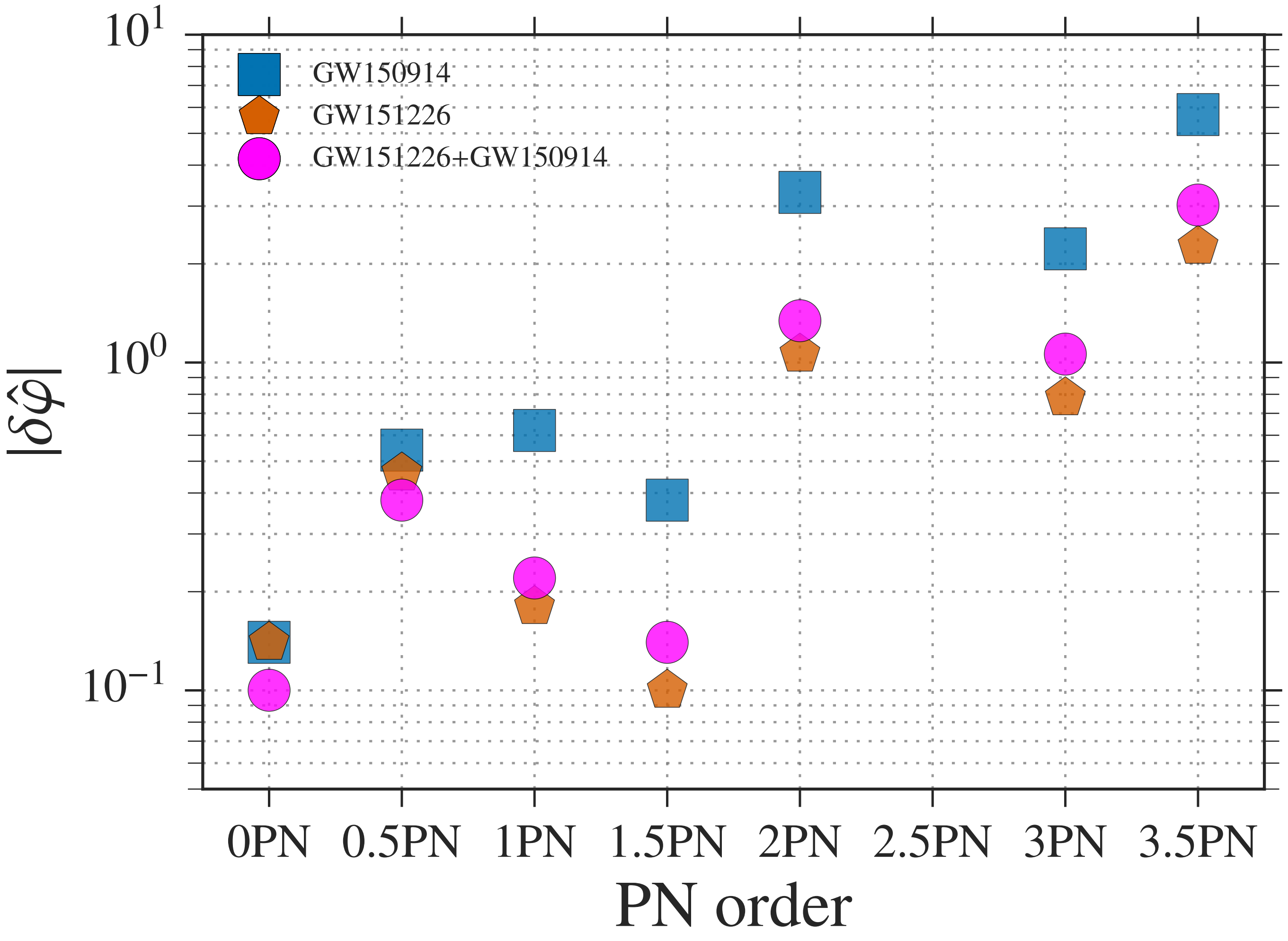
Tests of GR with first LIGO's black holes: inspiral

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

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

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

(Abbott et al. arXiv:1606.04856)

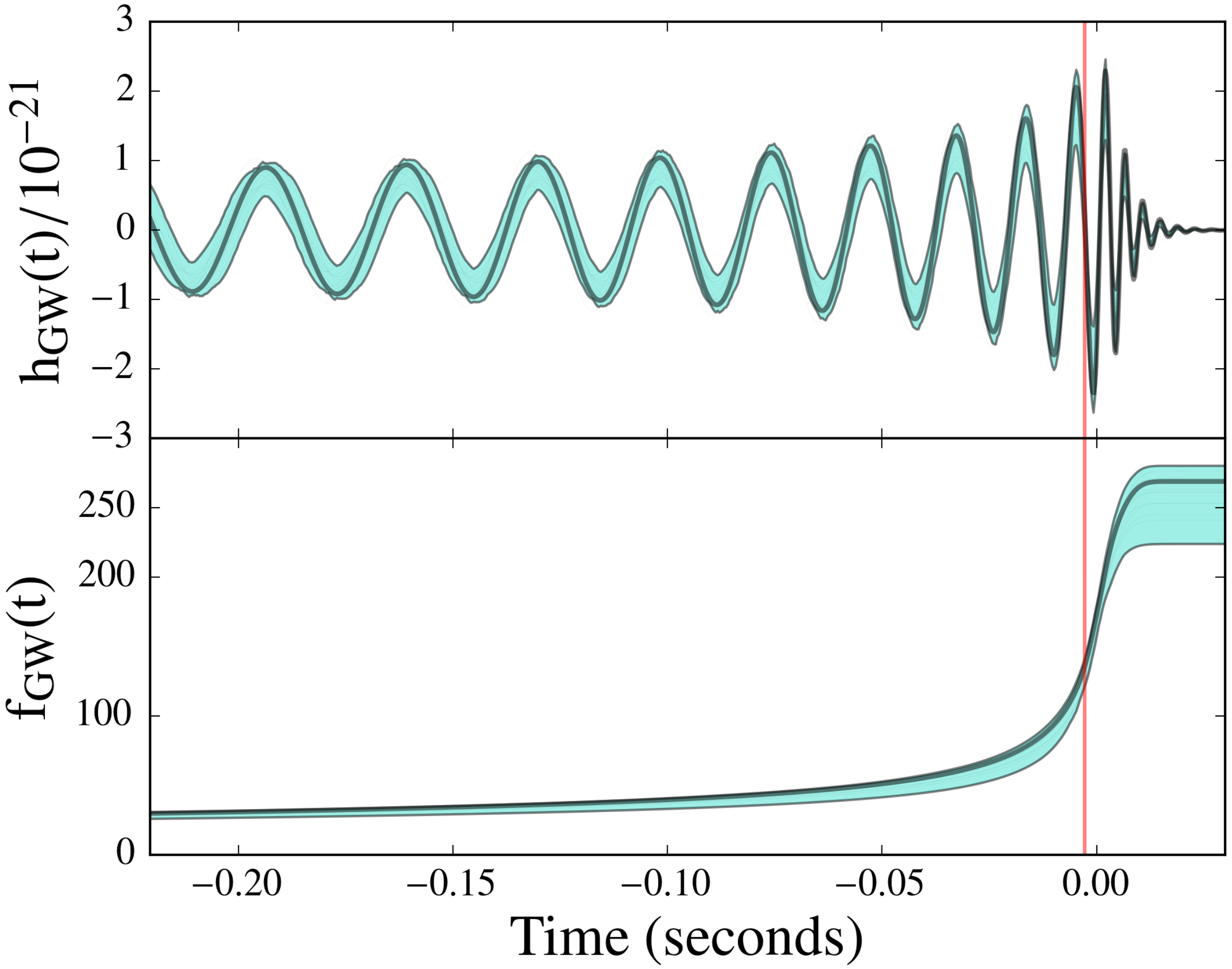


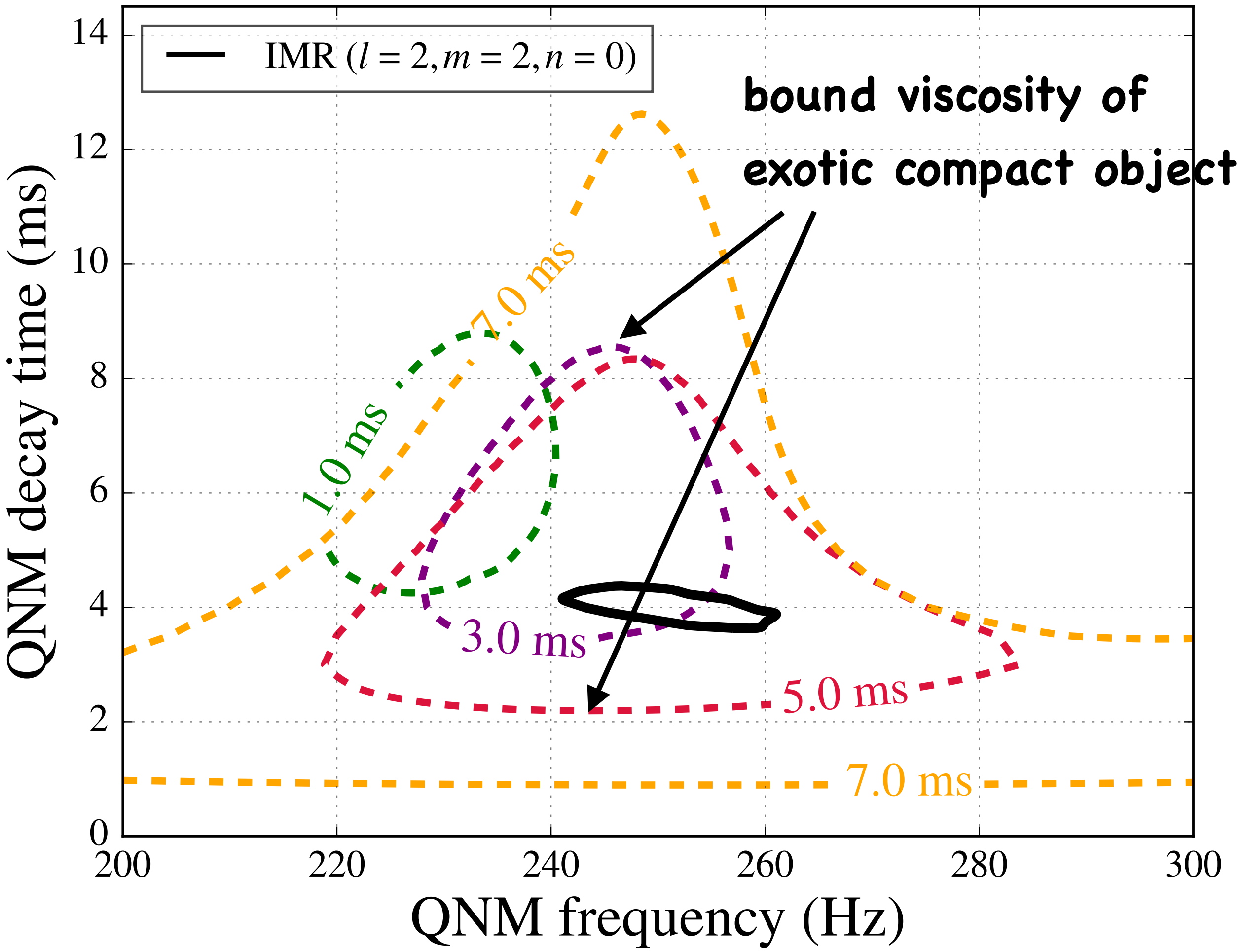
(Arun et al. 06 , Mishra et al. 10, Yunes & Pretorius 09, Li et al. 12)

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

- First **GR test** in the genuinely dynamical, **strong-field regime.**

Could we prove that GW150914's remnant is a BH?





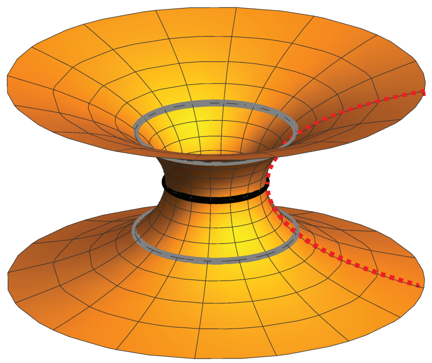
(Abbott et al. PRL 116 (2016) 221101)

- We measured frequency & decay time of **damped sinusoid** in the data after GW150914's peak.

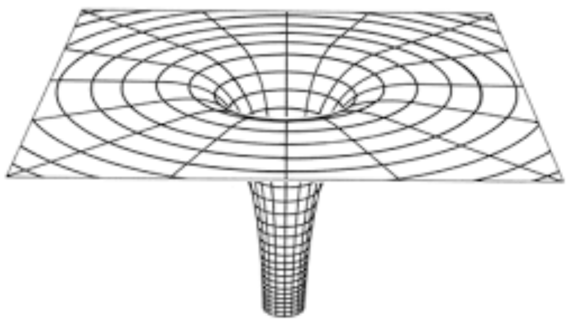
- **Multiple QNMs** need to be measured to extract mass and spin of remnant, test **no-hair theorem** and **second-law black-hole mechanics** (Israel 69, Carter 71; Hawking 71, Bardeen 73).

Can we probe the event horizon from the GW ringdown?

- What determines **ringdown signal**? **Light ring or horizon**?

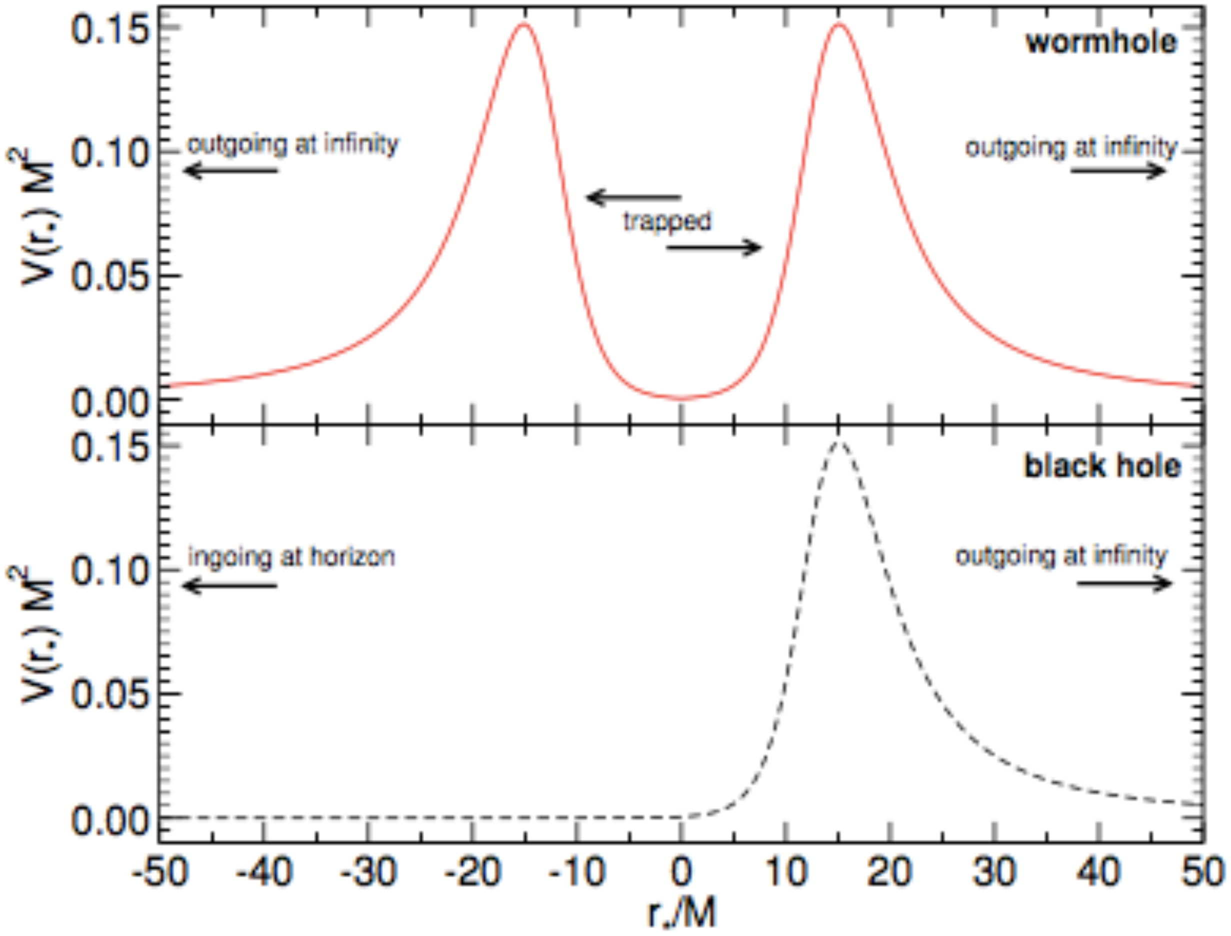


horizonless object

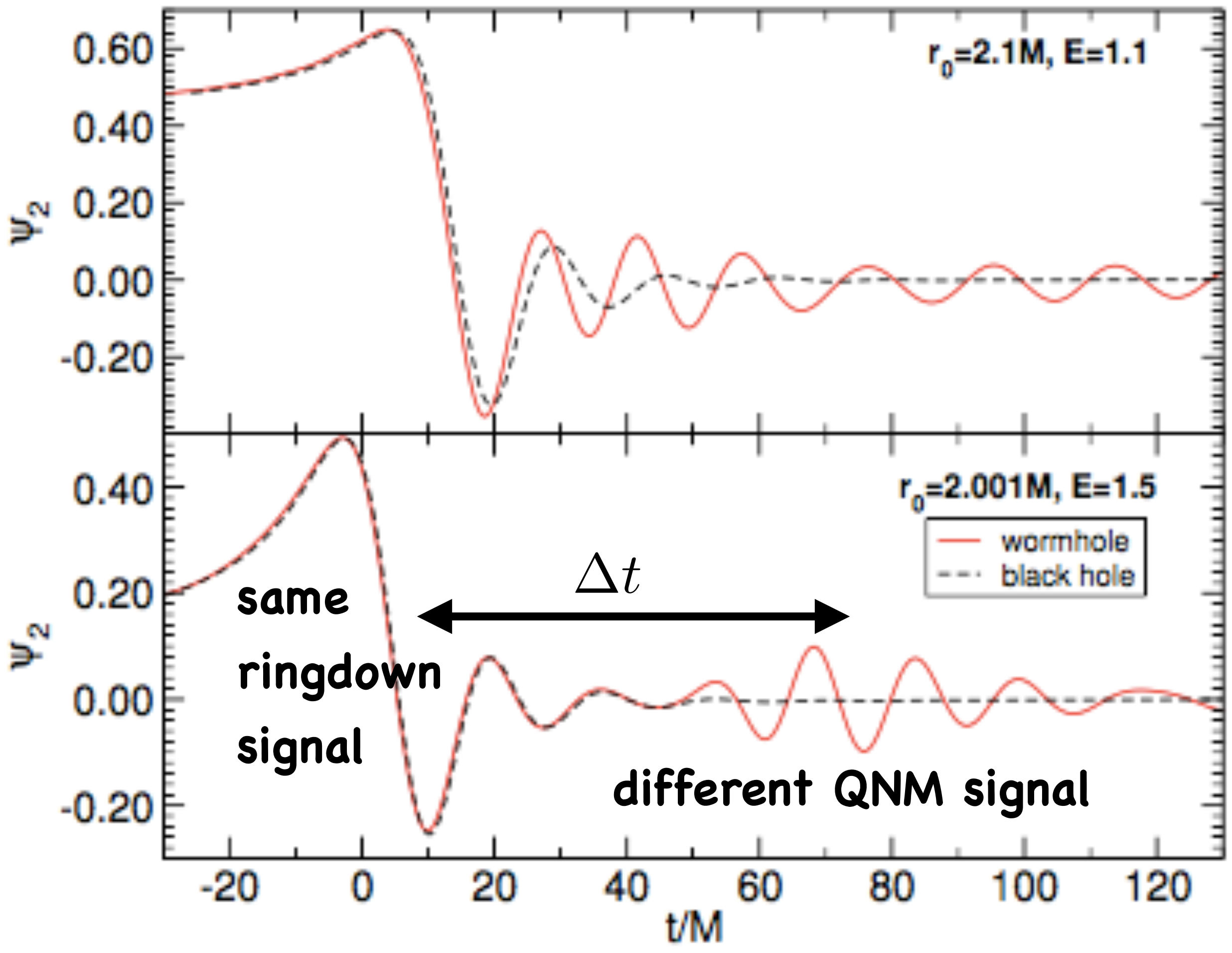


black hole

- **QNM** spectrum **differs** in **BH** and **horizonless object.**
- **Ringdown** and **QNM** signals can be **different in horizonless objects: GW echoes!**



(Cardoso, Franzin & Pani 16)



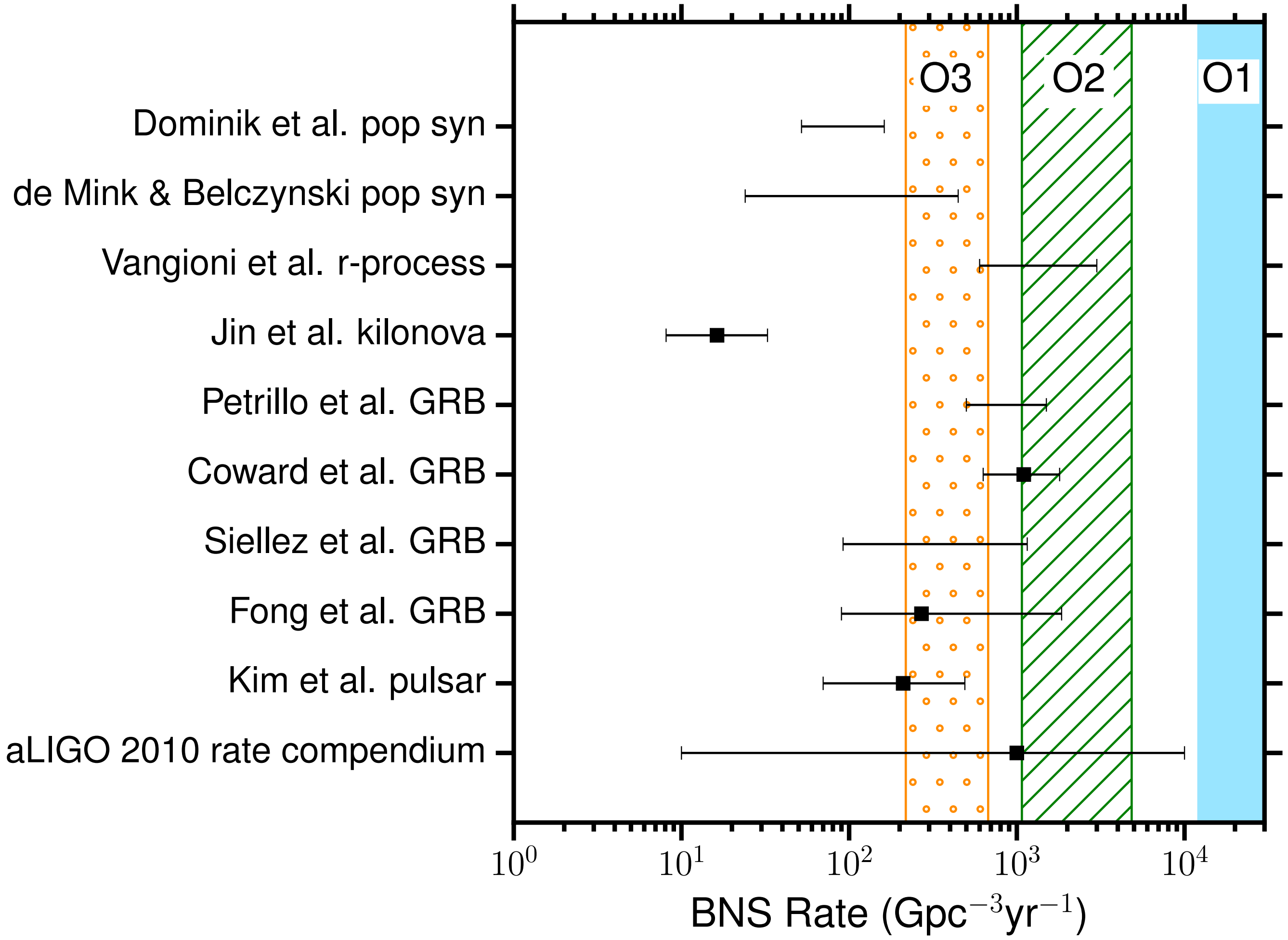
same ringdown signal

Δt

different QNM signal

radial infall

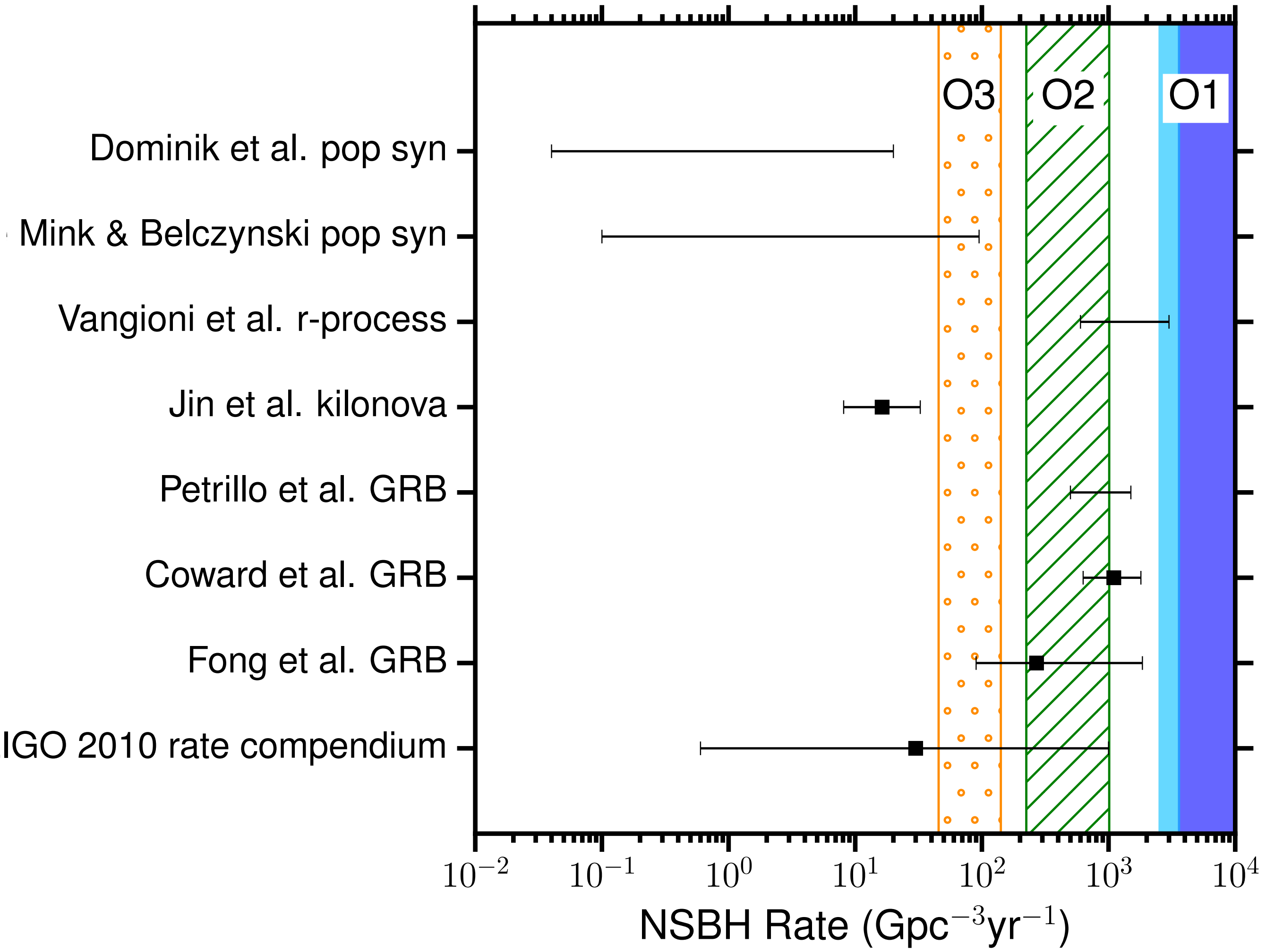
Upper limits on rates of neutron star mergers



(Abbott et al. arXiv:1607.07456)

@90% confidence:

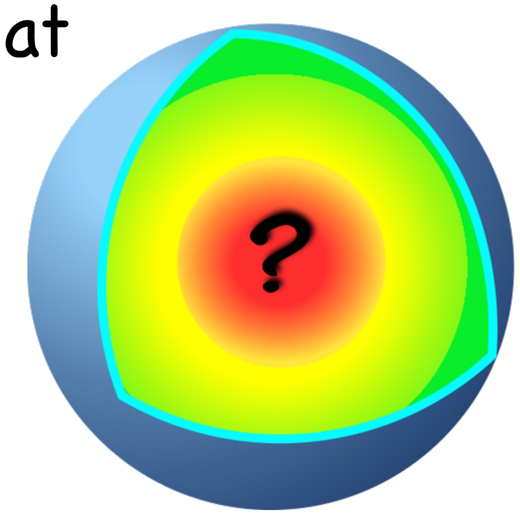
- NSNS rate < $12{,}600/(\mathrm{Gpc})^3/\mathrm{yr}$
- NSBH rate < $3{,}600/(\mathrm{Gpc})^3/\mathrm{yr}$



Probing NS's equation of state with LIGO and Virgo

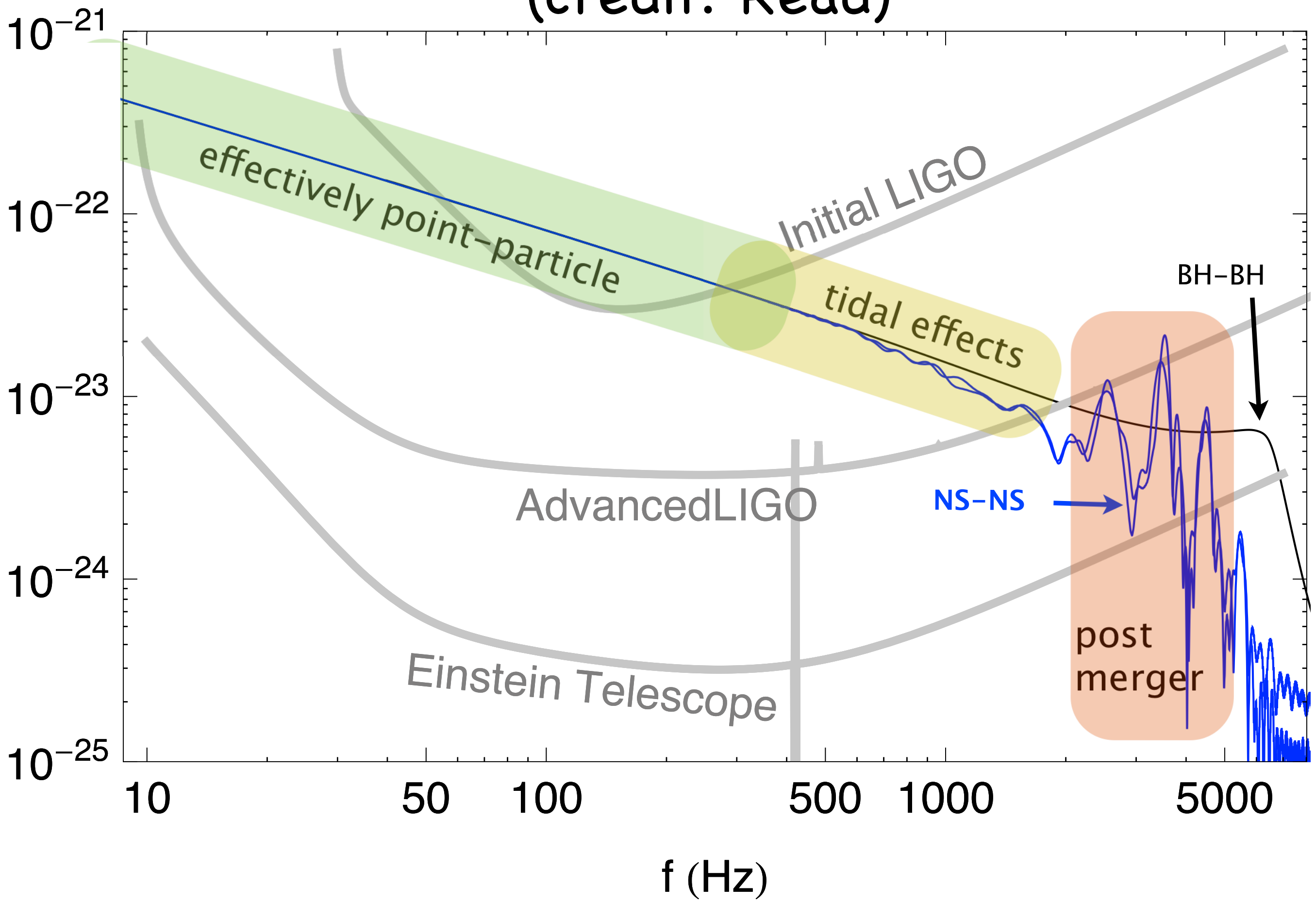
- **NSs** are **unique laboratories** to study baryonic matter at supra-nuclear density
  - **NS's** characteristics:

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

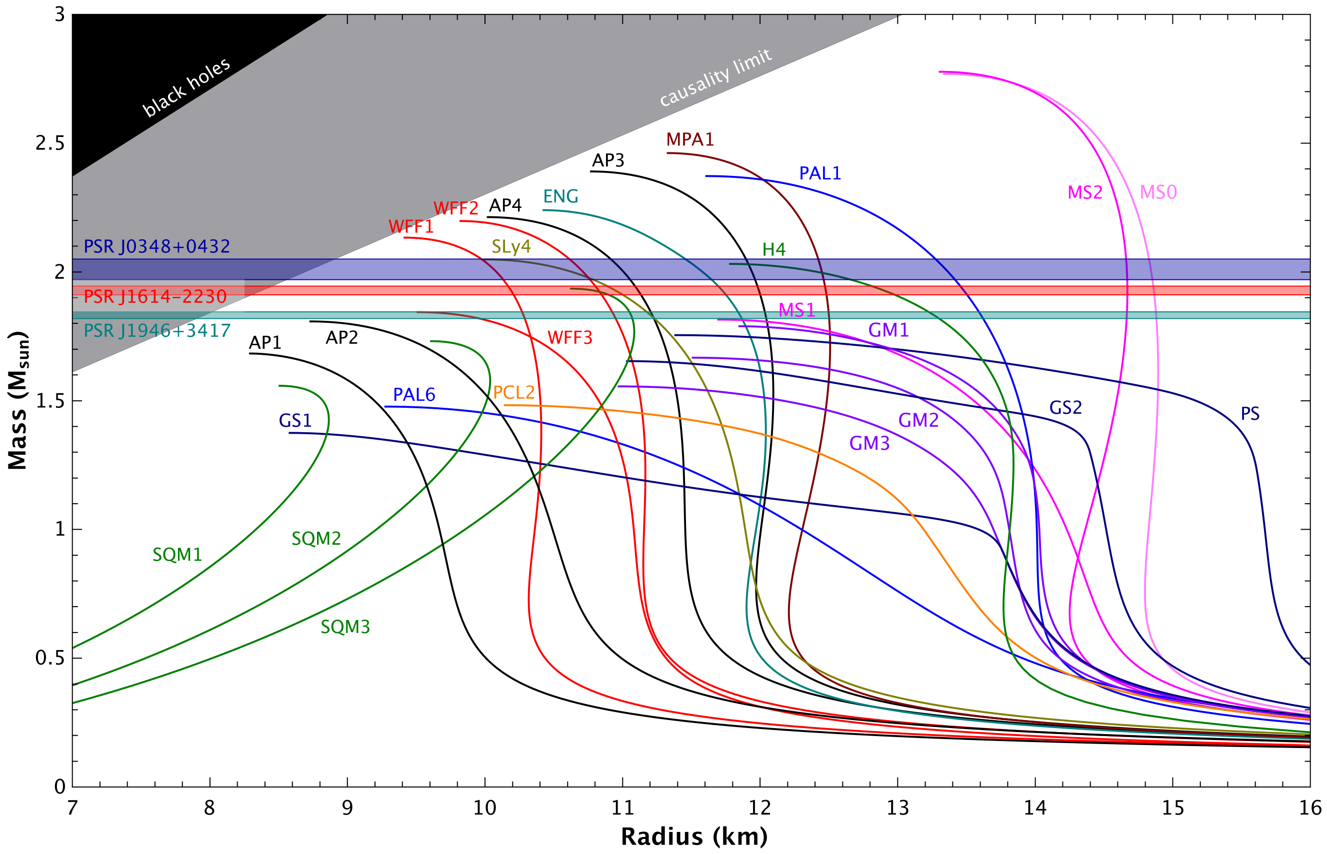


(credit: Hinderer)

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



(credit: Read)

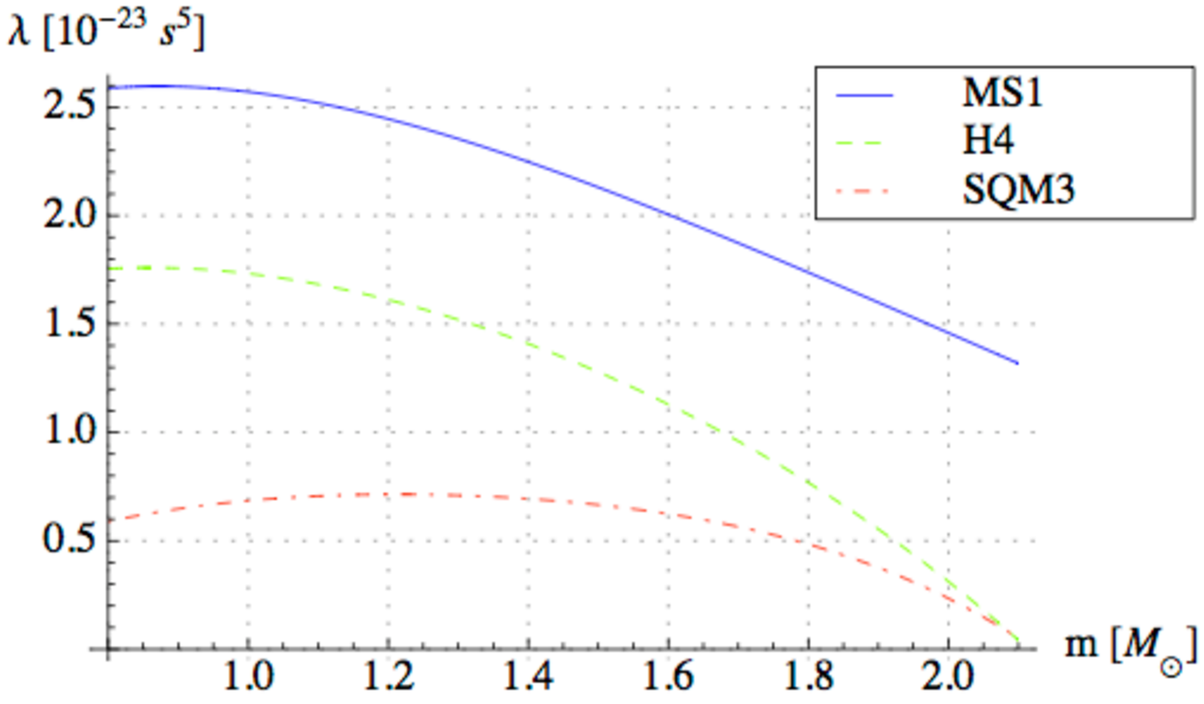


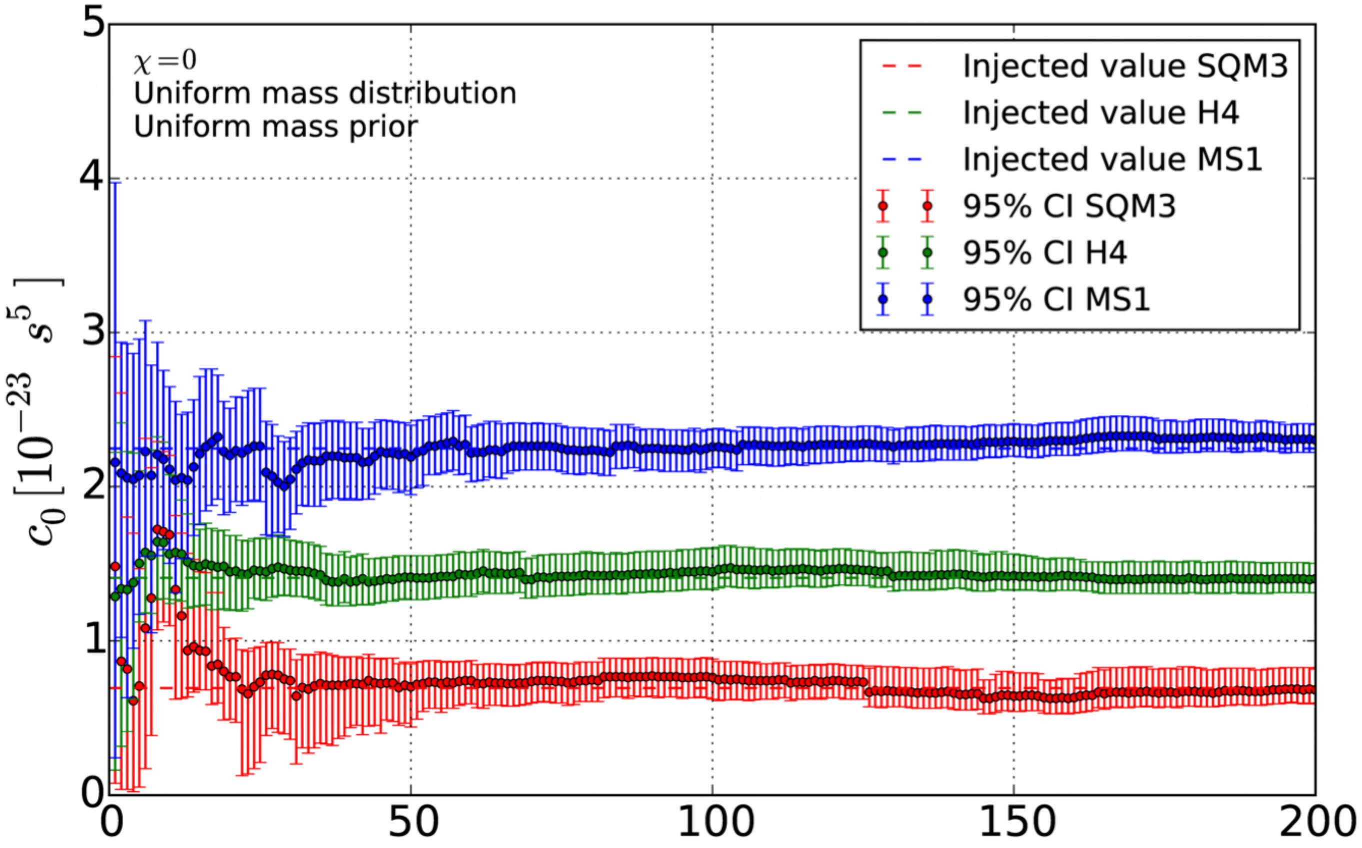
(Antoniadis et al. 16)

With several tens of events, possible to distinguish "some" EOS

- The influence of NS's **internal structure** on waveform is **characterized** by a single (constant) parameter, the **tidal deformability** λ
- λ **measures** star's **quadrupole deformation** in response to the companion **perturbing tidal field**: $Q_{ij} = -\lambda\mathcal{E}_{ij}$

(Kochanek 92, Bildsten & Cutler 92, Lai et al. 93, Lai 94)

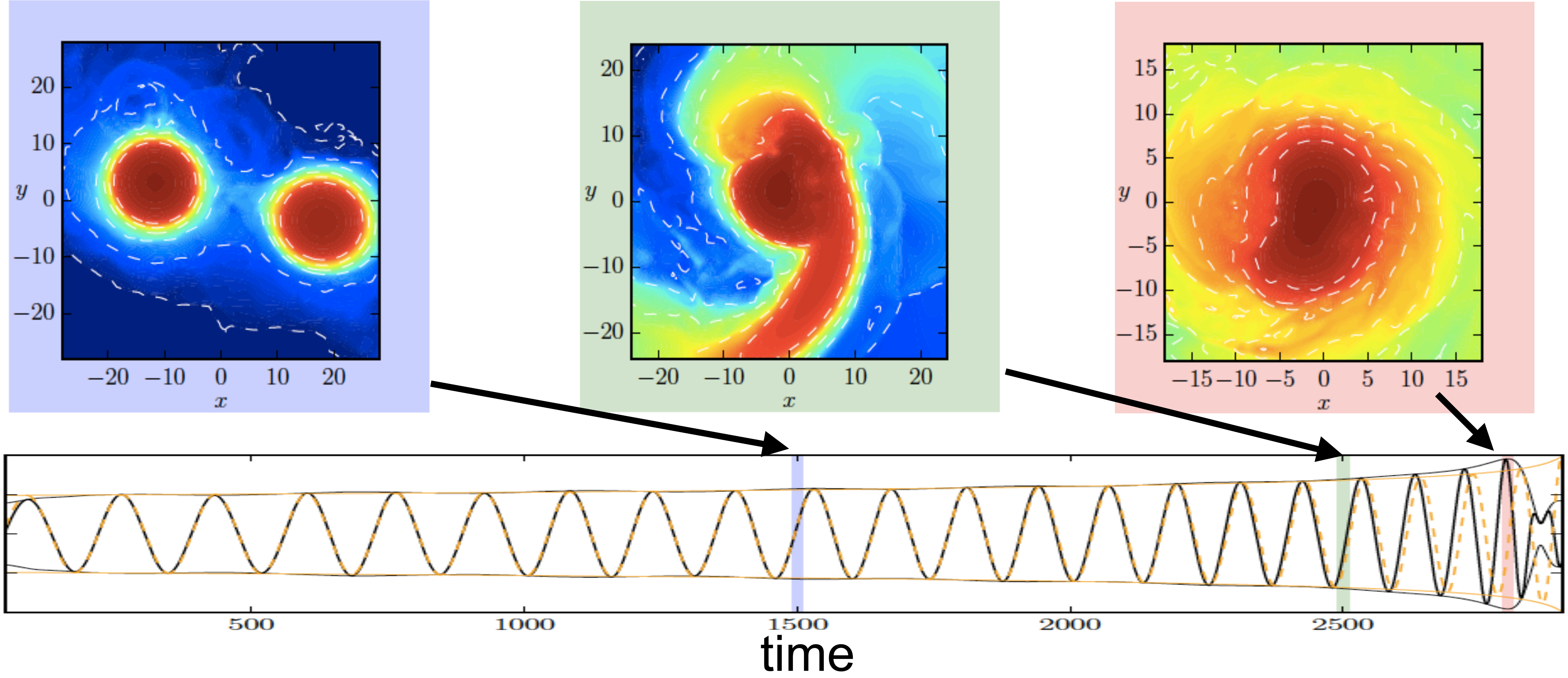




(Agathos et al. 15, Del Pozzo et al. 13 (see also Lackey et al. 14; Lynch et al. 14; Yagi et al. 15))

Waveform modeling for NS-NS binaries up to merger

mass ratio = 1.5, EOS = MS1b



(Dietrich & Hinderer 17)

tidal EOB waveform versus NR waveform

- Results extended to NS-BHs

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

Boson stars as black-hole/neutron-star mimickers

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi} - \nabla^\alpha\Phi\nabla_\alpha\Phi^* - V(|\Phi|^2)\right]$$

- **Boson stars** are self-gravitating configurations of a complex scalar field

	$V(\lvert\Phi\rvert^2)$	$M_{\max}$	Compactness
Mini BS	$\mu^2\Phi^2$	$\left(\frac{85\,\mathrm{peV}}{\mu}\right) M_\odot$	0.08
Massive BS	$\mu^2\Phi^2 + \frac{\lambda}{2}\lvert\Phi\rvert^4$	$\sqrt{\lambda}\left(\frac{270\,\mathrm{MeV}}{\mu}\right)^2 M_\odot$	0.158
Neutron star		$2-4\,M_\odot$	0.3
Solitonic BS	$\mu^2\Phi^2\left(1-\frac{2\lvert\Phi\rvert^2}{\sigma_0^2}\right)^2$	$\left(\frac{\mu}{\sigma_0}\right)^2\left(\frac{700\,\mathrm{TeV}}{\mu}\right)^3 M_\odot$	0.349
Black hole		∞	● 0.5

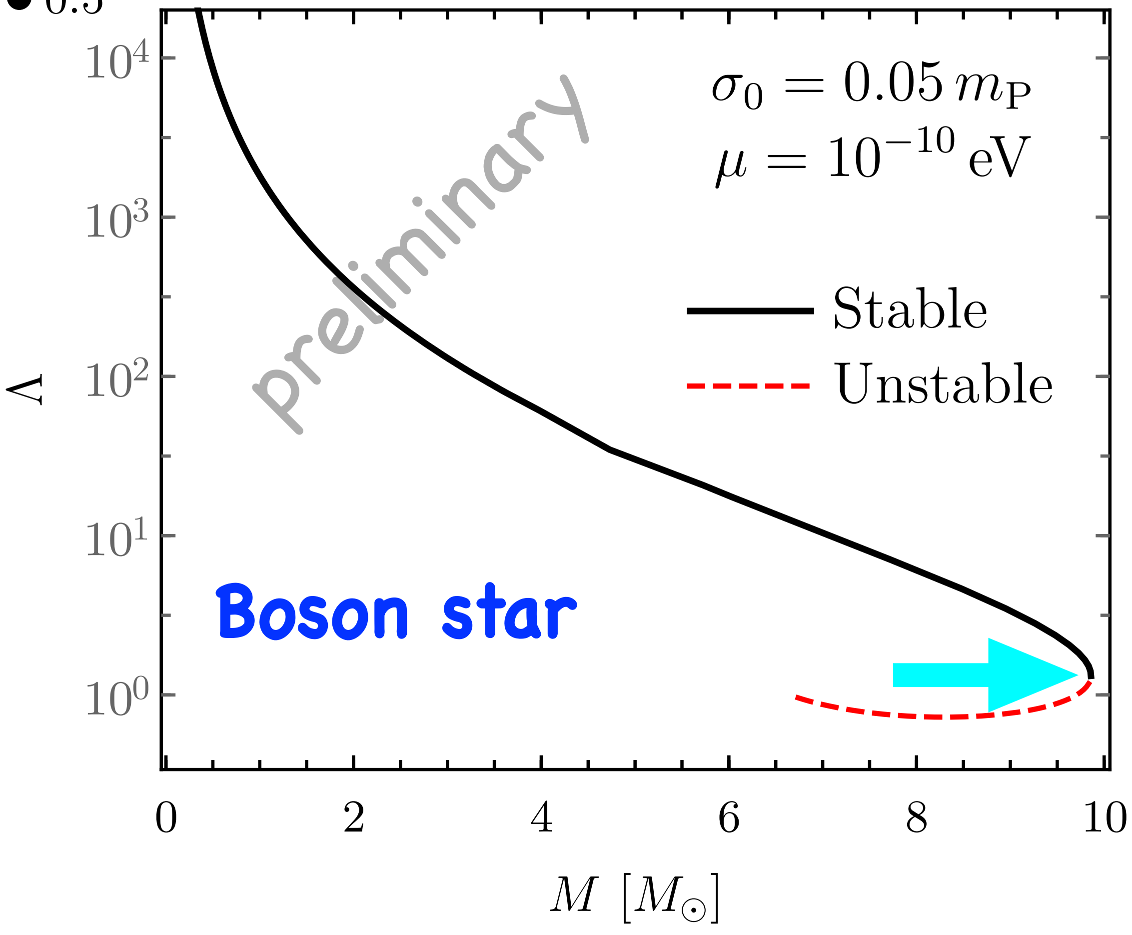
(credit: Sennett)

$$\mathcal{C} = \frac{GM}{Rc^2}$$

(Sennett et al. in preparation, see also Cardoso et al. 17)

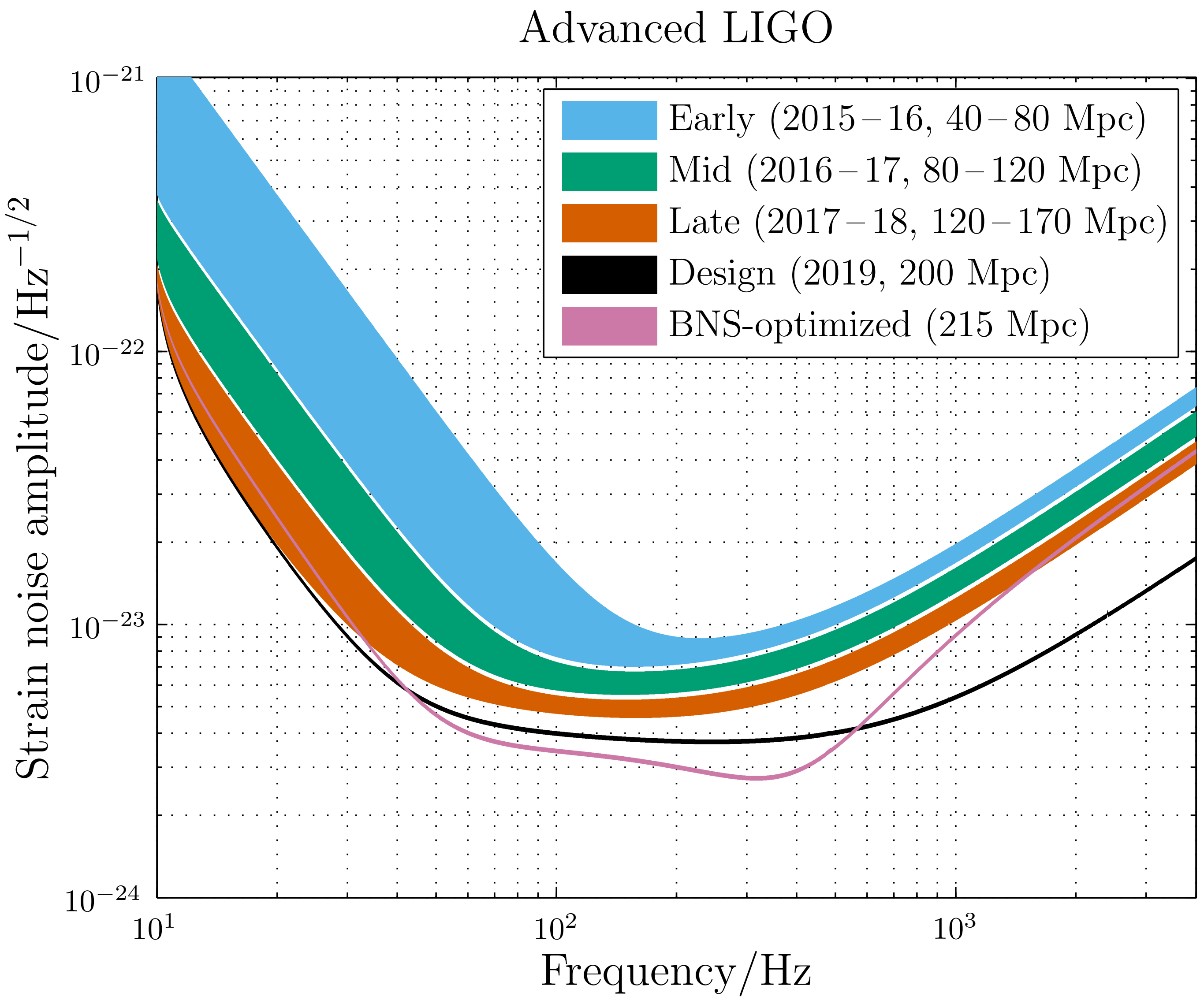
$$\Lambda = \lambda/M^5$$

- **Black holes:** $\Lambda = 0$
- **Neutron stars:** $\Lambda_{\min} \sim 10$
- **Boson stars:** $\Lambda_{\min} \sim 1$

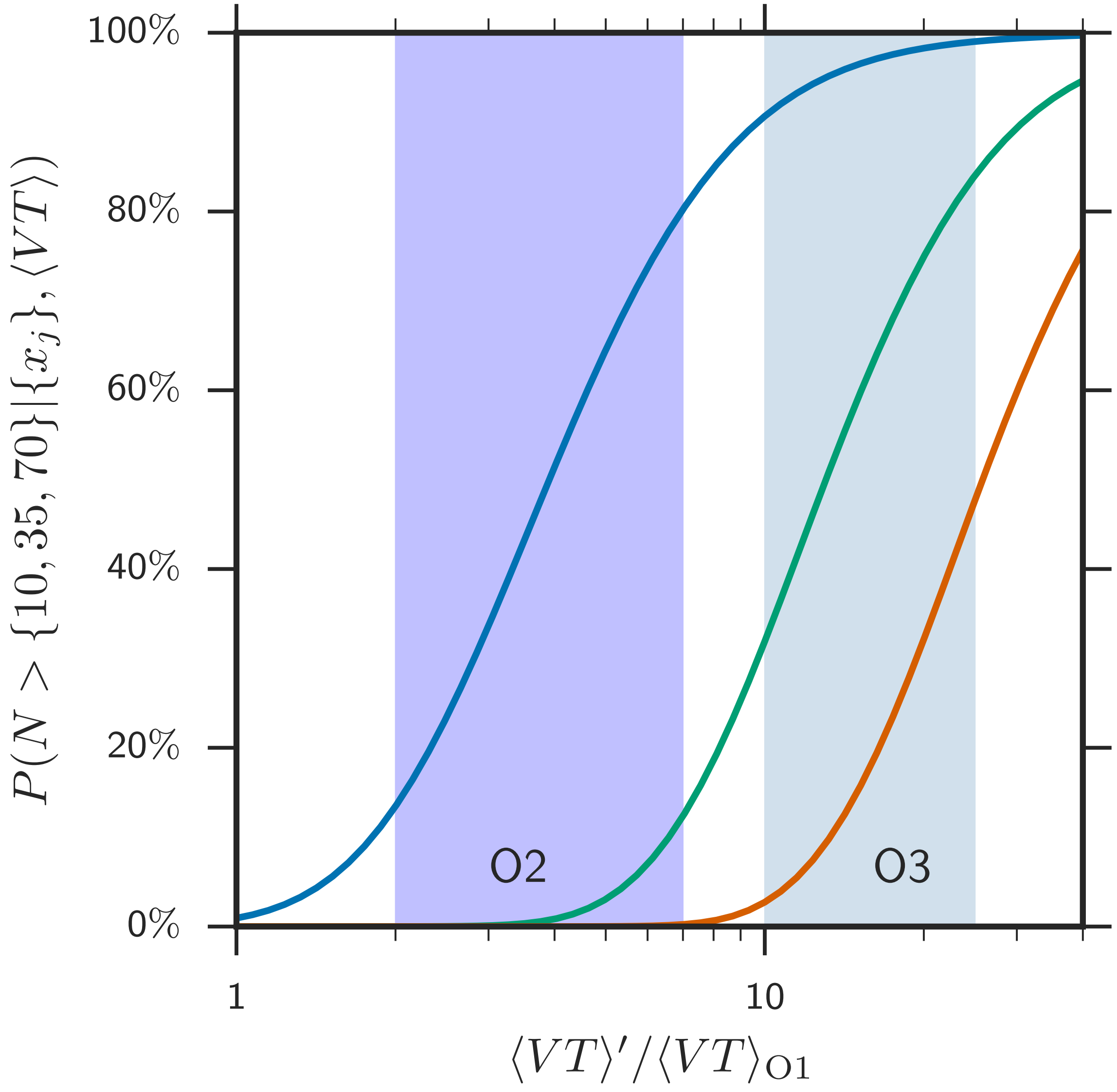


Advanced detectors' roadmap and rates

(Aasi et al. arXiv:1304.0670)



- BBH rates: 9 - 240 /(Gpc)^3/yr



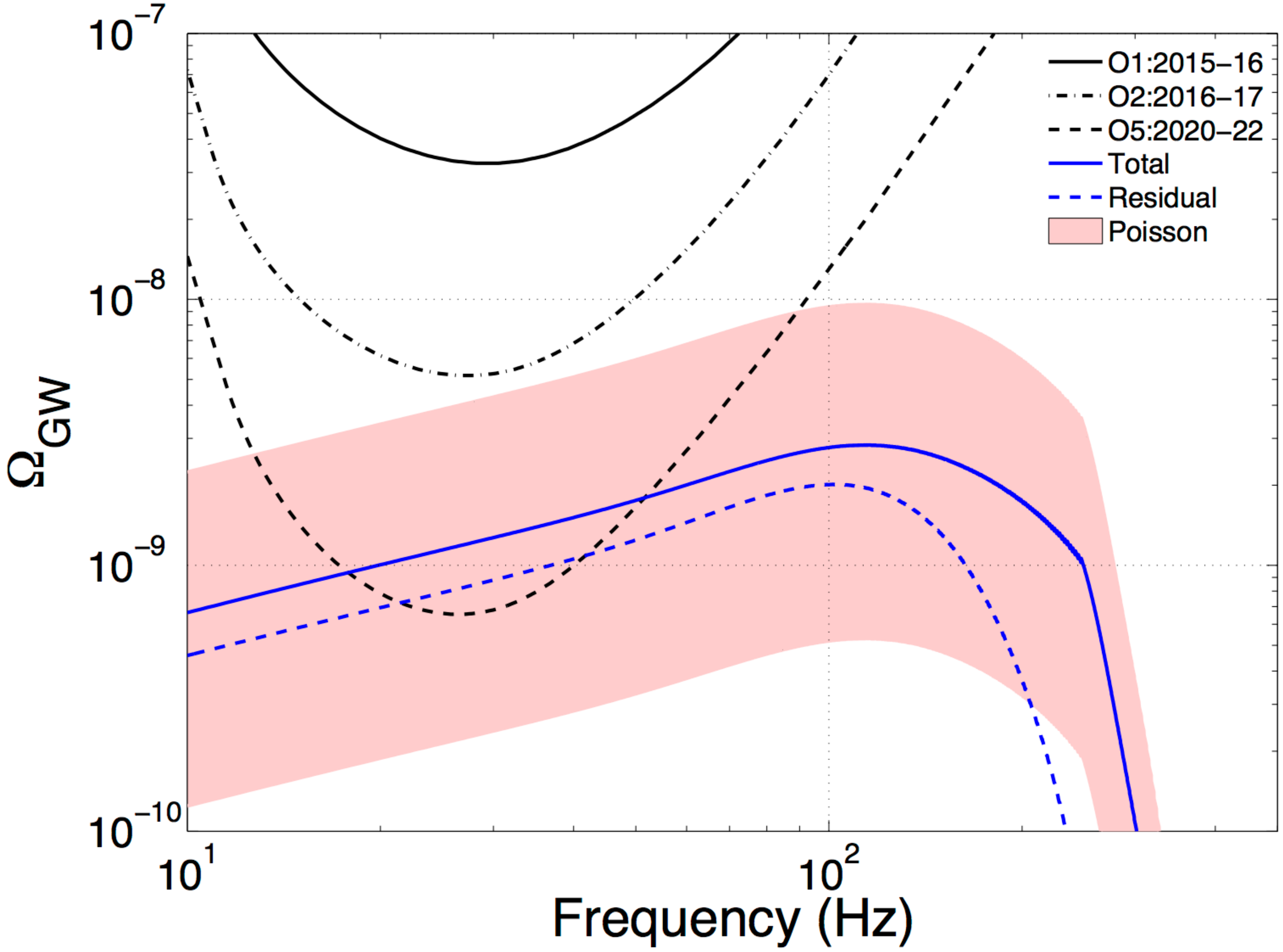
(Abbott et al. arXiv:1606.04856)

Detection rates @ **design sensitivity**:

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

Gravitational-wave stochastic background from binary black-holes

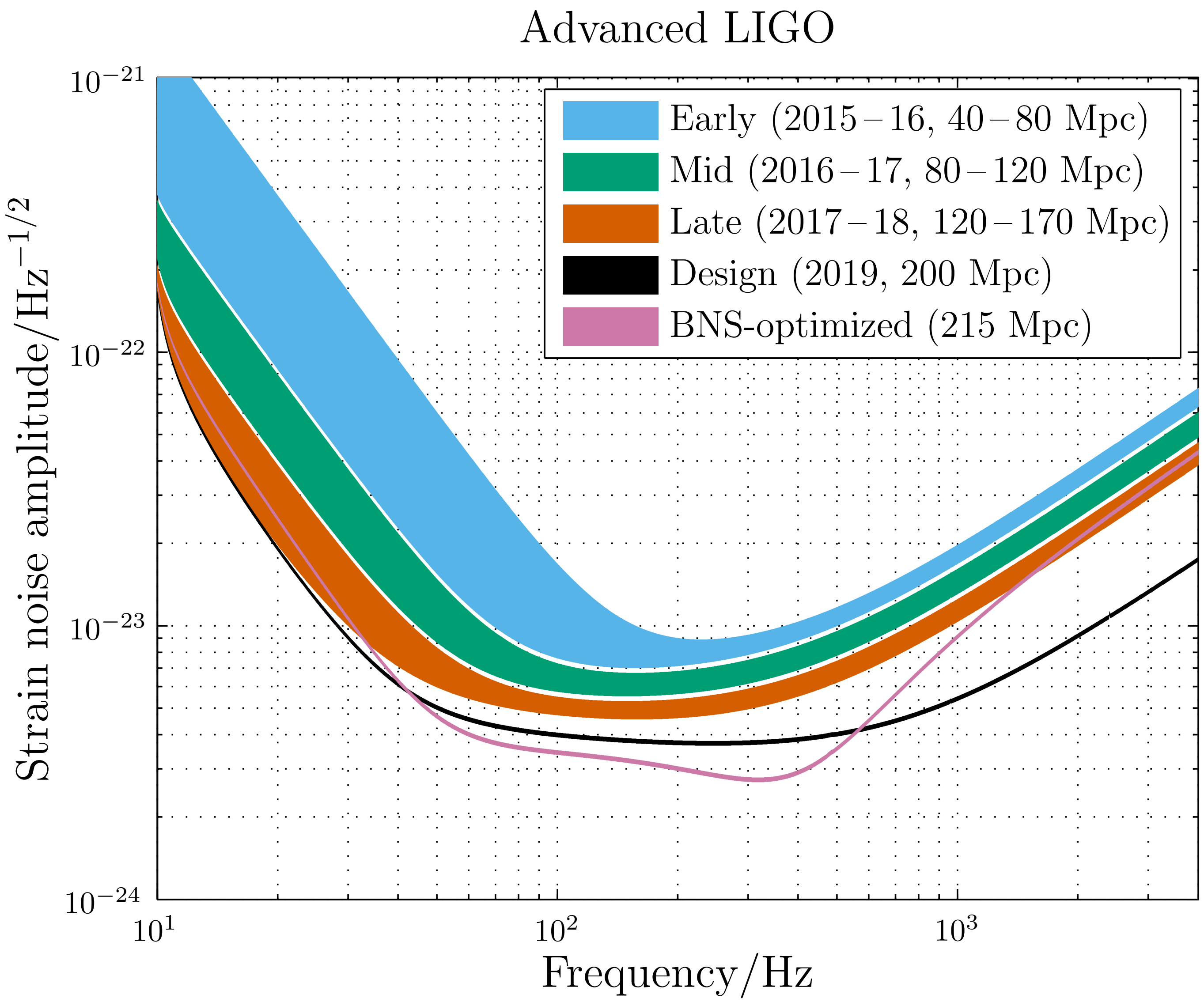
- **Larger** BH **masses** & **higher** BH coalescence **rate**, imply **brighter** astrophysical GW stochastic **background than expected.**

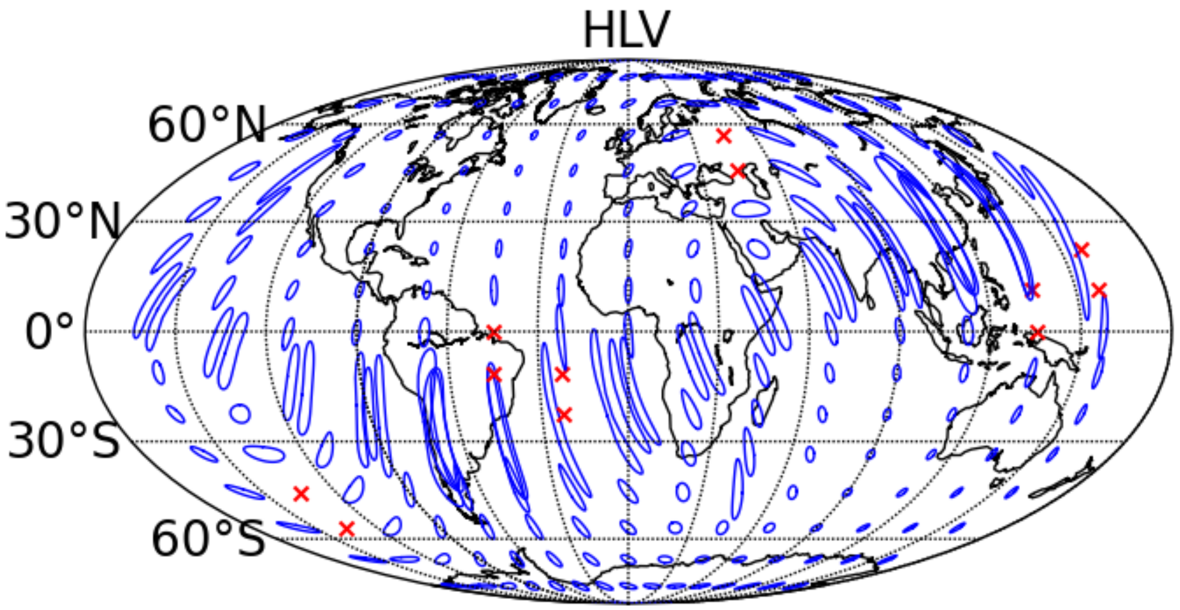


(Abbott et al. PRL 116 (2016) 131102)

Advanced detectors' roadmap and sky localization

(Aasi et al. arXiv:1304.0670)





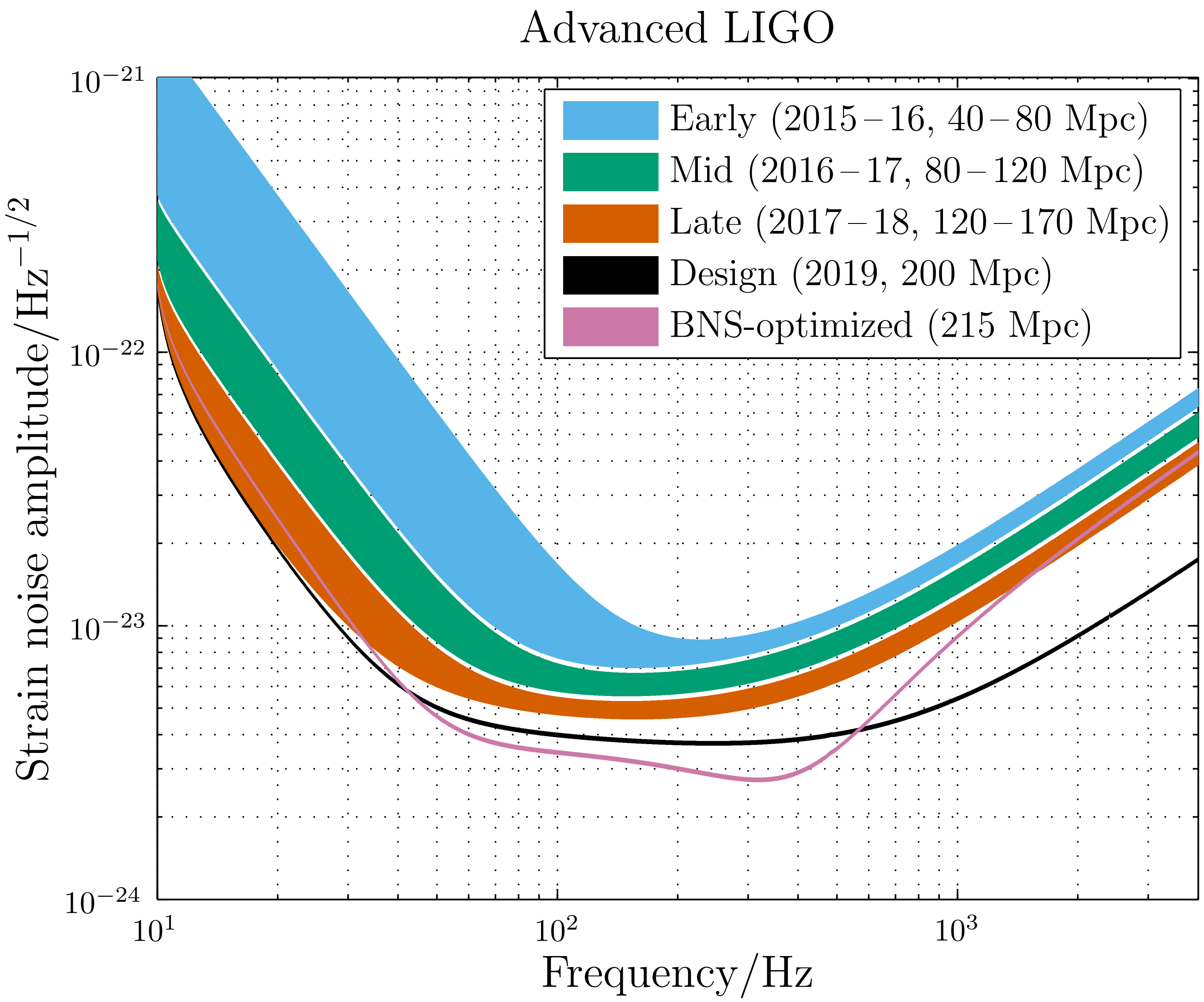
- Few **tens or hundred** square degrees

Detection rates @ **design sensitivity**:

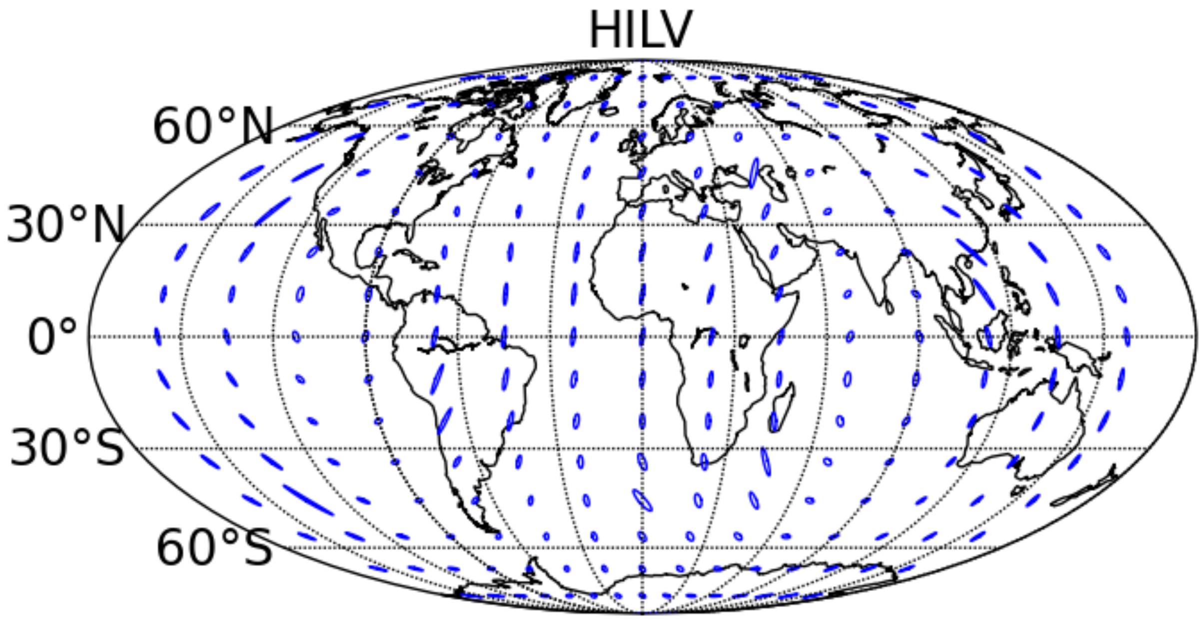
- **Binary neutron stars: 0.2 - 200 per year**
- **Binary black holes: tens to hundreds per year!**

Advanced detectors' roadmap and sky localization

(Aasi et al. arXiv:1304.0670)



with LIGO-India



- **Few** square degrees!

Detection rates @ **design sensitivity**:

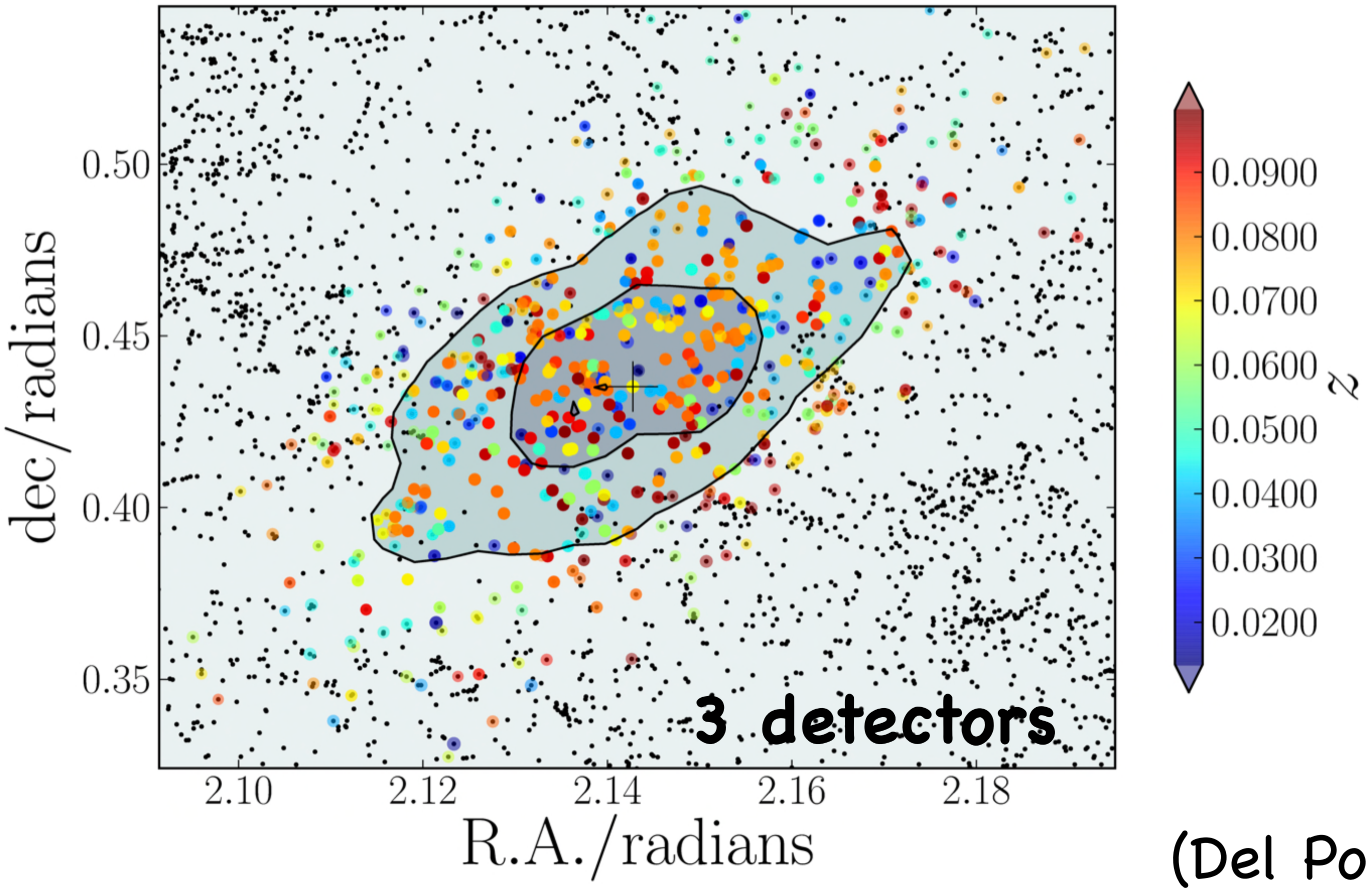
- **Binary neutron stars: 0.2 - 200 per year**
- **Binary black holes: tens to hundreds per year!**

Inference of cosmological parameters in future LIGO searches

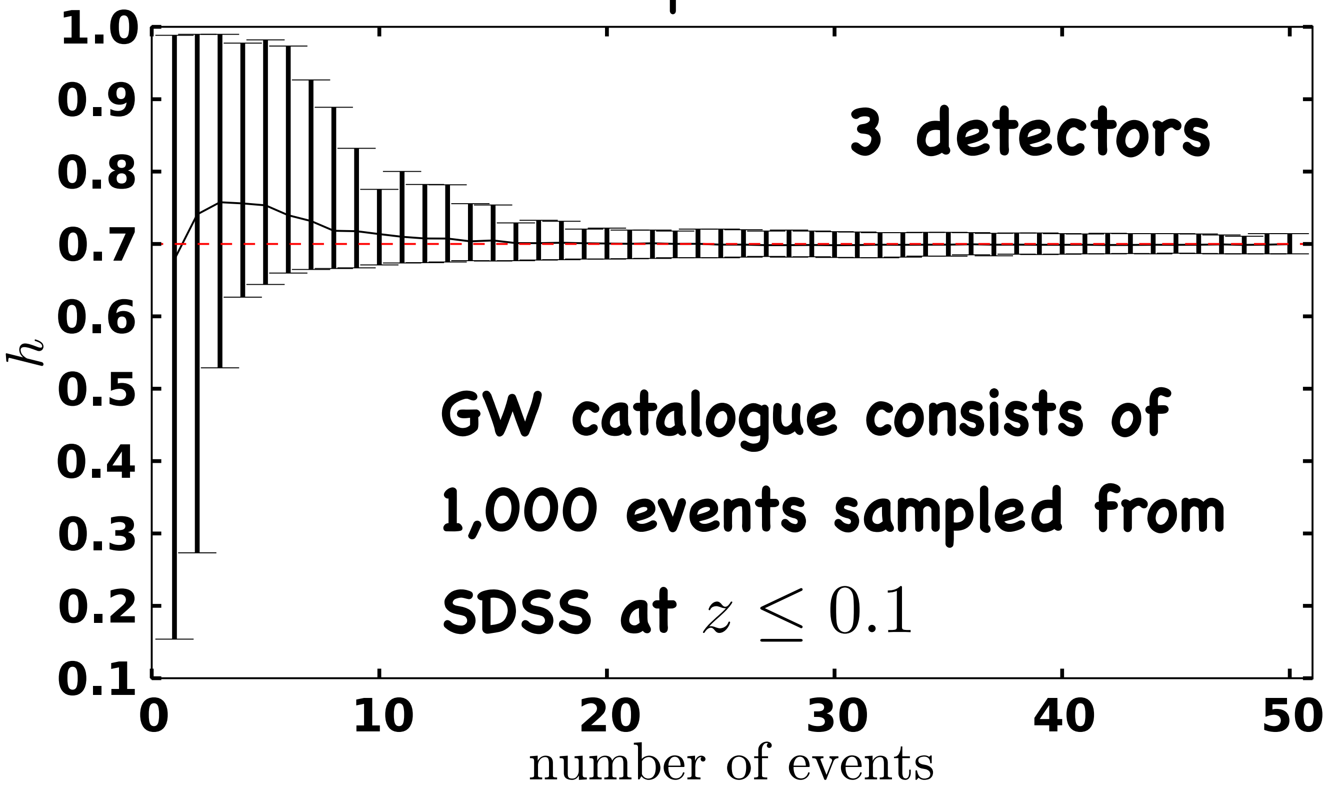
- **Wide-field galaxy surveys** can provide (**sky positions** and) **redshifts**

(Schutz 1986)

single GW event



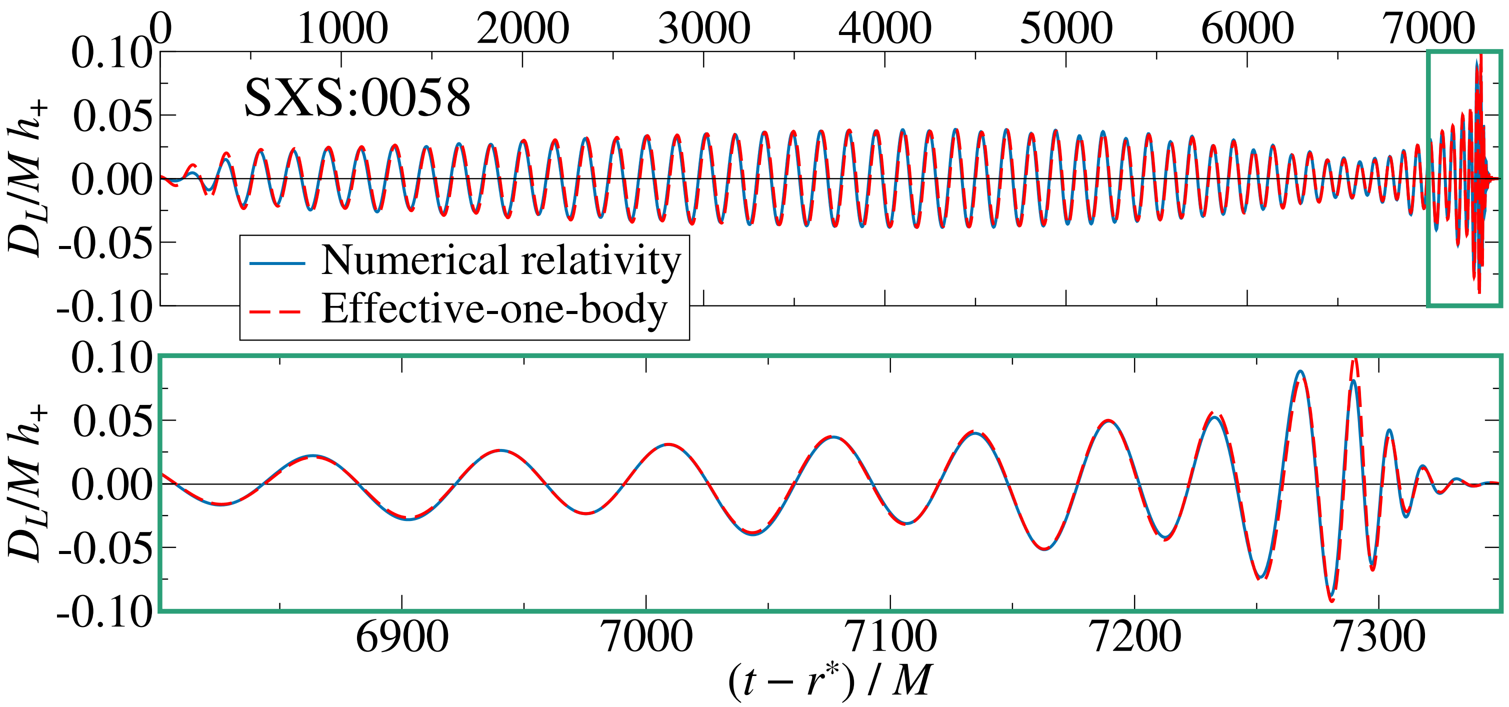
multiple events



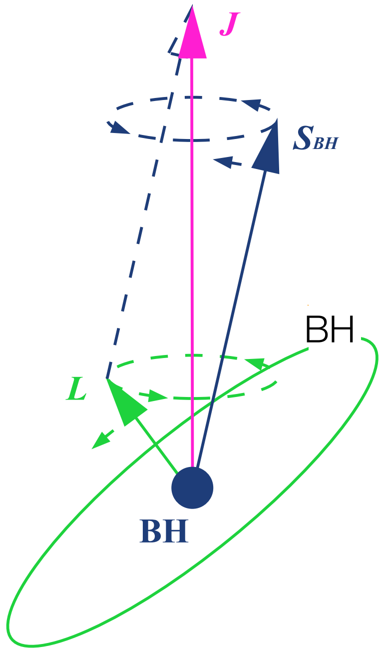
(Del Pozzo 12)

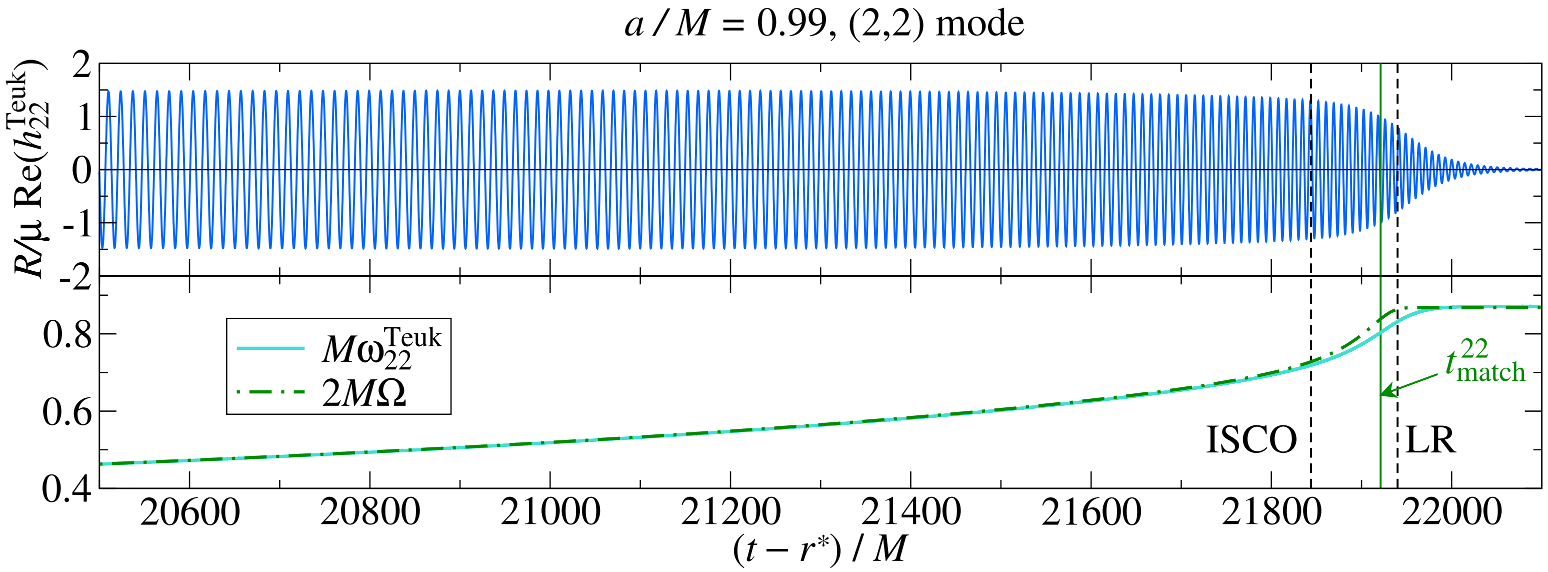
- Measurement of **Hubble constant** H_0 with accuracy of **5%** at 95% confidence **after 40-50 GW observations with 3 detectors.**

More challenges: spin-precession, extremal BHs, eccentricity …



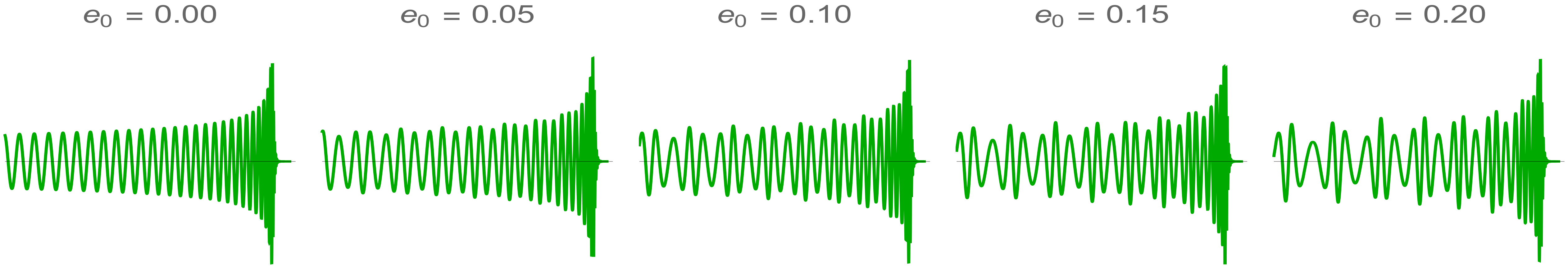
(Babak et al. 16)



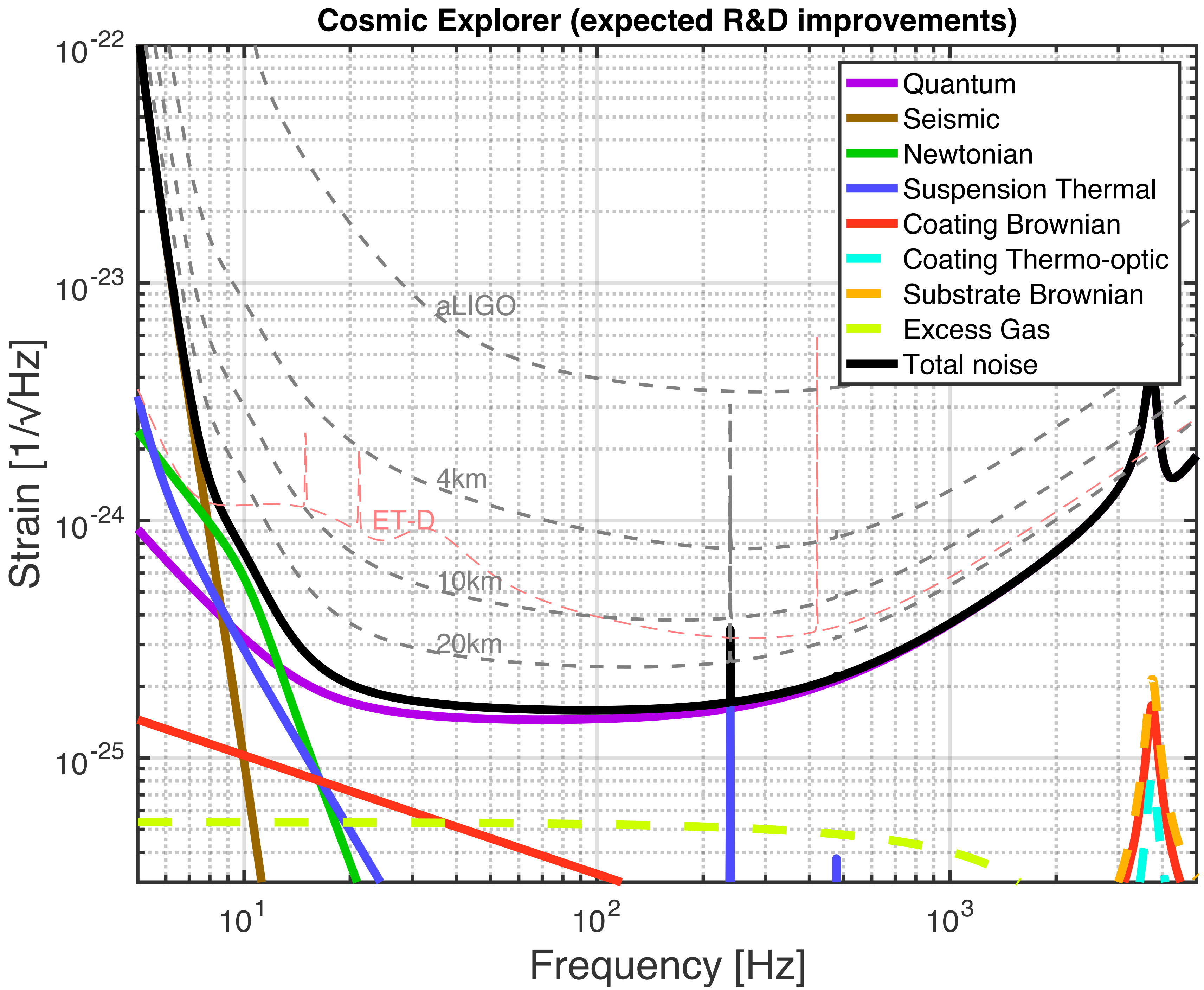


(Taracchini et al. 13)

(Hinder et al. in prep)



Looking more ahead: Einstein Telescope & Cosmic Explorer

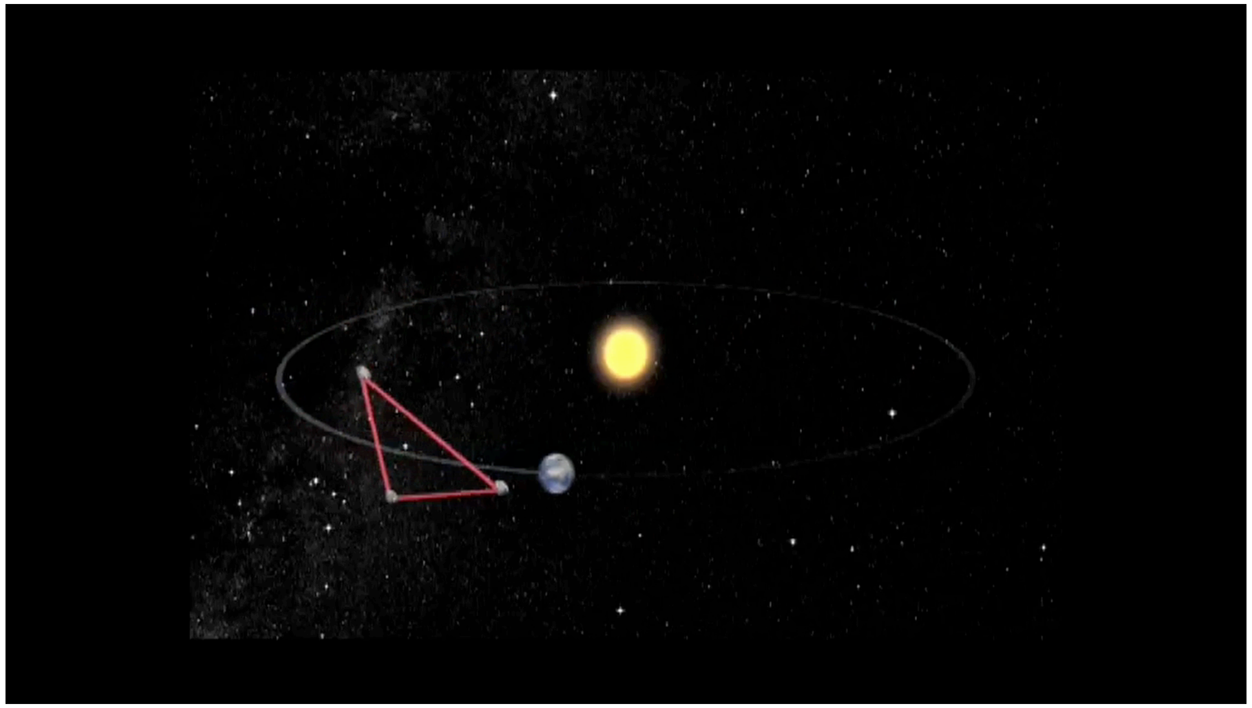


(Abbott et al. arXiv:1607.08697)

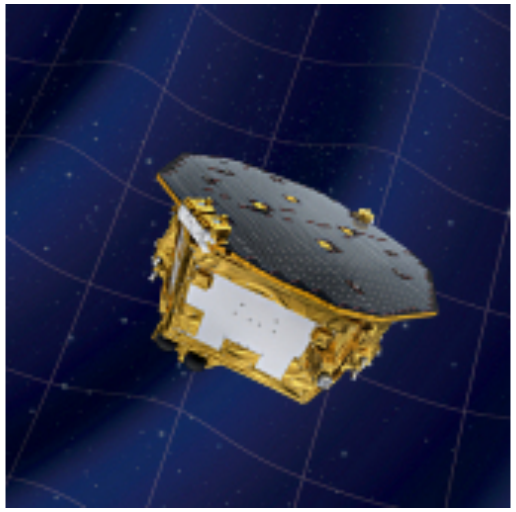
- Observing **binary coalescences with high SNR** (> 20) even **at high redshift** (z > 10) or SNR > 100 and z < 2!

Detecting gravitational waves in space

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

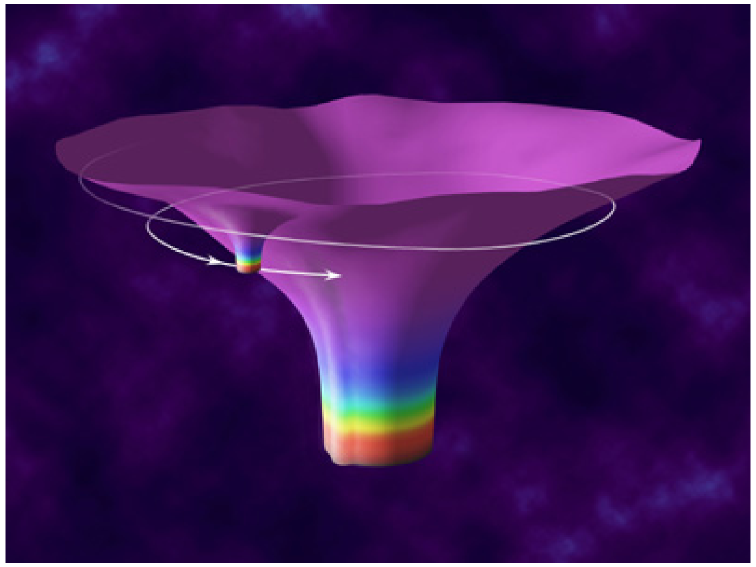


Credit: AEI/Milde Marketing



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

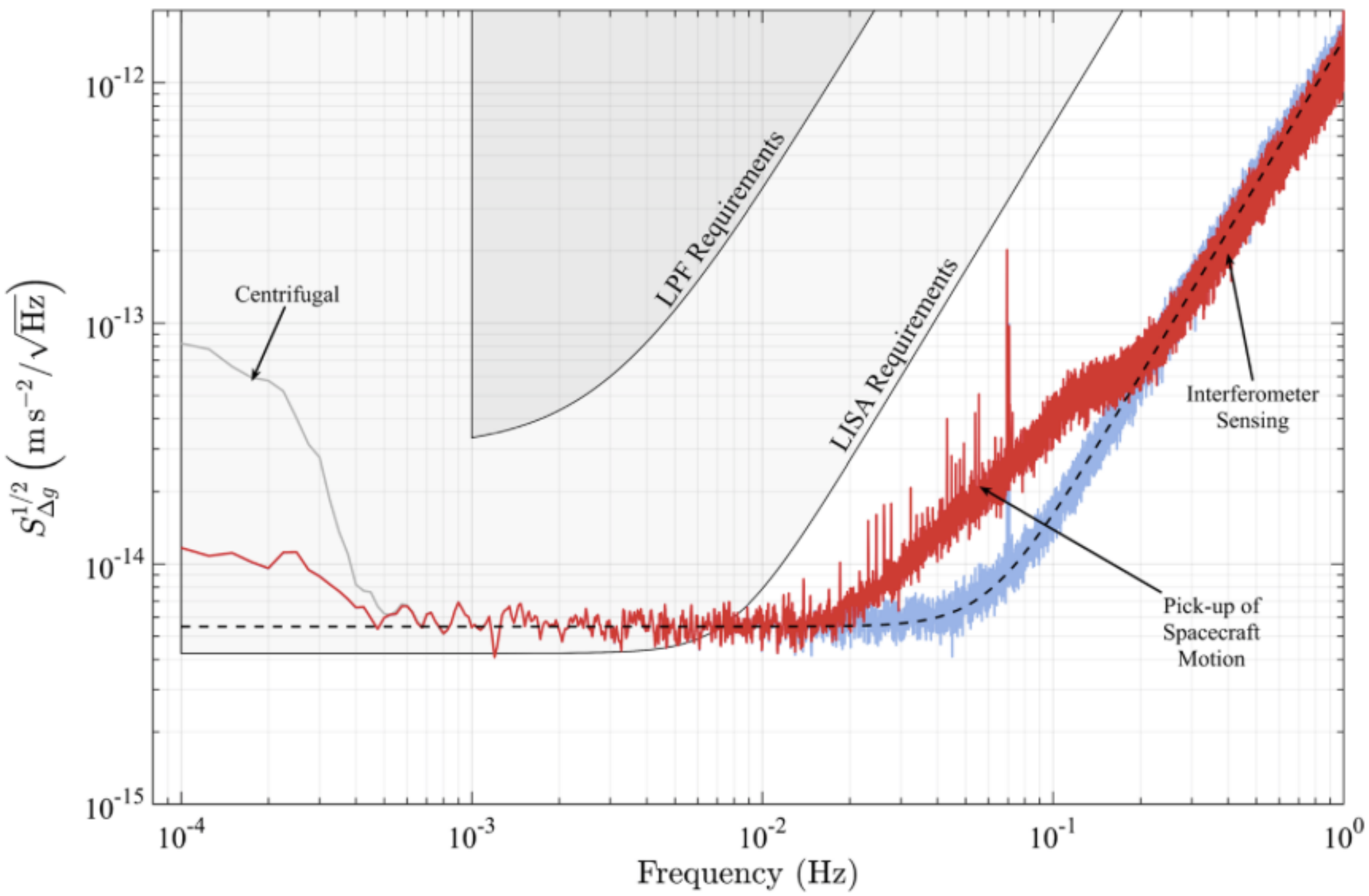
Merging galaxies: NGC4038 and NGC4039



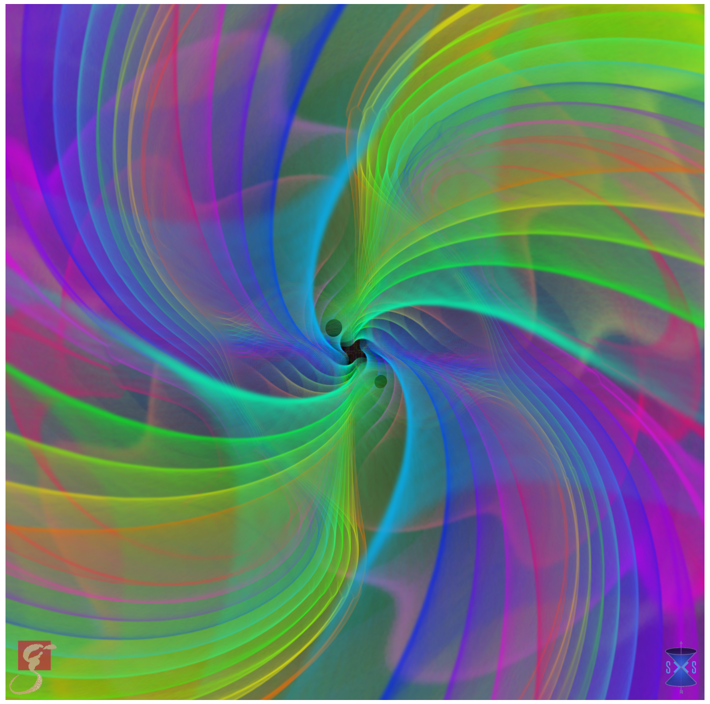
LISA Pathfinder: the "stillest" place in the Universe

- **Sub-femto-g free fall!**

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



The new era of precision gravitational-wave astrophysics



- 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 **compact objects in our Universe** are **black holes** as predicted in GR.

- **To take full advantage of discovery potential** in next years and decades **we need** to make **precise theoretical predictions.**