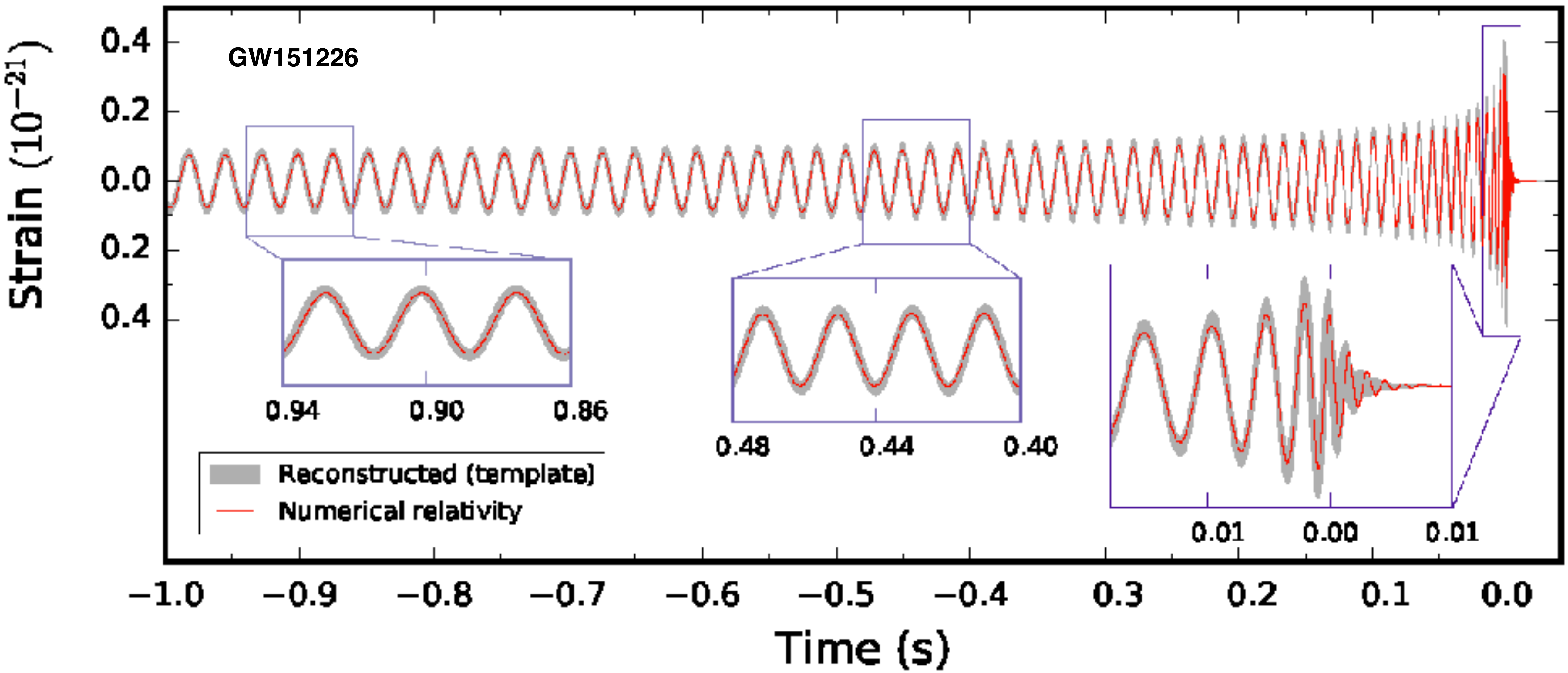
CA18108 - Quantum gravity phenomenology in the multi-messenger approach

Status and prospects for gravitational waveforms in GR and modified GR



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October 3rd, 2019

OUTLINE

I. Motivation

II. Sources and Detectors

III. Gravitational Waveforms in General Relativity

IV. Gravitational Waveforms in Modified Gravity

V. Remarks and Conclusions

Motivation

Motivation

✳ Let us assume we have a data stream from a given Gravitational Wave Detector that contains a gravitational wave signal from a given astrophysical/cosmological source. It can be splitted as:

$$s(t) = h(t, \overrightarrow{\lambda}) + n(t)$$

Where h is the signal (detector response to the GW), λ are the physical parameters (intrinsic and extrinsic), and n is the noise.

✳ We assume that the noise is Gaussian and Stationary:

$$< \tilde{n}(f)\, \tilde{n}(f')^* > = \frac{1}{2}\delta(f - f')\, S_n(f)$$

Where ~ denotes Fourier transformation, < > ensemble average, and * complex conjugation. On the right-hand side we have introduced the so-called (single-sided) noise spectral density, which contains all the information about the detector noise.

Motivation

✳ Then, the probability for the noise to have some realization is:

$$P\left(n = n_o\right) \;\propto\; e^{-\frac{1}{2}(n_o \,|\, n_o)}$$

where we have introduced the following scalar product:

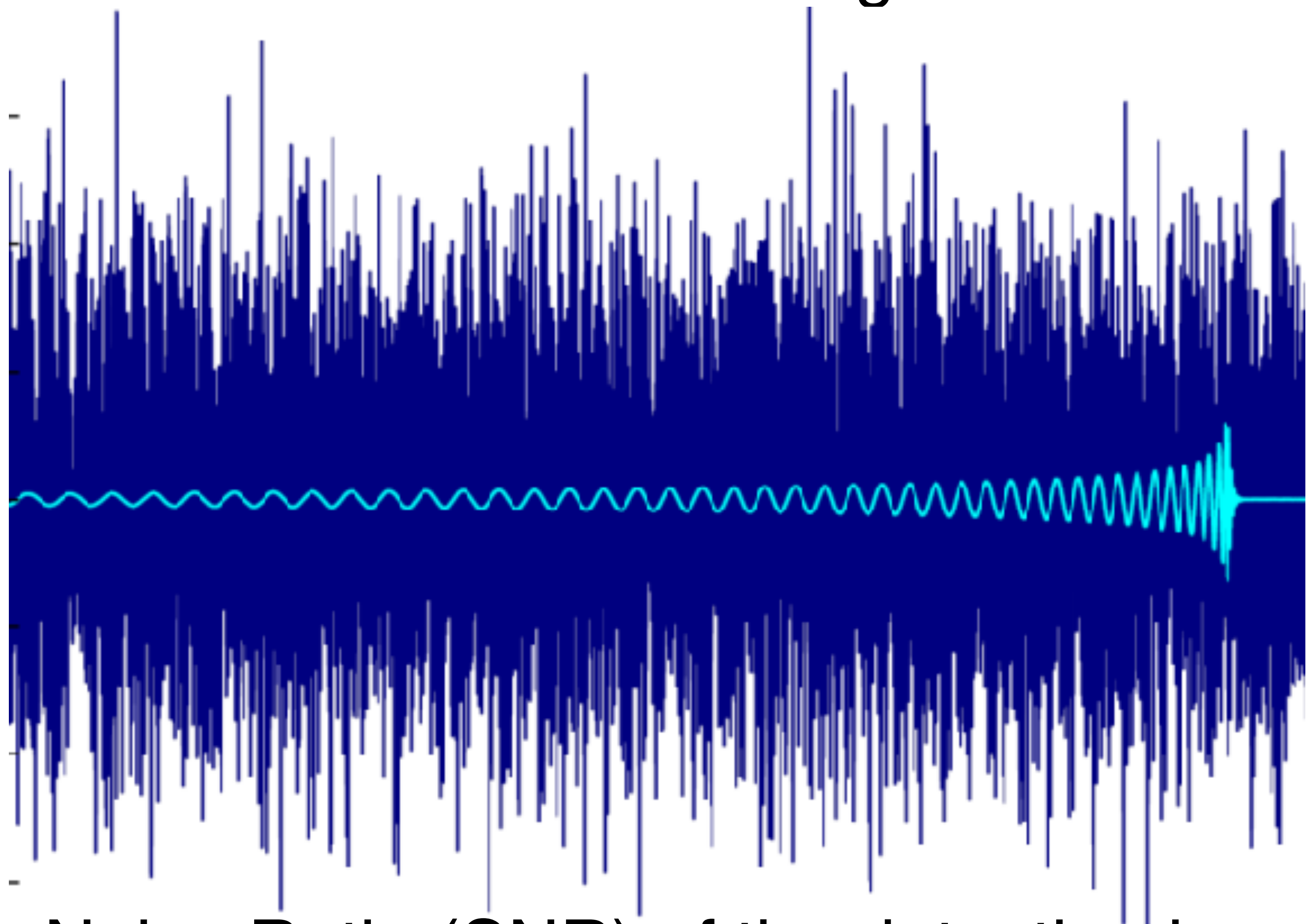
$$\left(h_1 \,|\, h_2\right) = 2\int_0^\infty df\, \frac{\tilde{h}_1^*(f)\tilde{h}_2(f) + \tilde{h}_1(f)\tilde{h}_2^*(f)}{S_n(f)}$$

✳ Therefore, the likelihood that the true parameter values are given by a particular λ, or in other words, the likelihood that our signal is present in the data stream is just given by:

$$P\left(s \,|\, h\right) = P(s \,|\, \vec{\lambda}) \;\propto\; e^{-\frac{1}{2}\left(s(t) - h(t,\,\vec{\lambda}) \,|\, s(t) - h(t,\,\vec{\lambda})\right)}$$

Motivation

* Then, in many cases it is crucial to have *a priori* **theoretical models** $h(t, \vec{\lambda})$ to extract the Gravitational Wave signals from the data, in particular in those situations where the signal is much below the noise.



* The Signal-to-Noise Ratio (SNR) of the detection is approximately given by:

$$\mathrm{SNR}[h(t, \vec{\lambda})] = \sqrt{\left(h(t, \vec{\lambda}) \,|\, h(t, \vec{\lambda}) \right)}$$

Motivation

✳ The other important use of the theoretical models (the **gravitational waveforms**) is parameter estimation (of the physical parameters λ). In the context of Bayesian parameter estimation the posterior probability distribution function (PDF) provides complete information about the parameters of the signal:

$$P(\vec{\lambda}\,|\,s) = \frac{P(\vec{\lambda}) \times P(s\,|\,\vec{\lambda})}{P(s)}$$

Priors

Likelihood

Evidence: Normalization constant (marginalized likelihood)

Motivation

* Let us consider that $\overrightarrow{\lambda}_{\rm T}$ are the "true" values of the physical parameters $\overrightarrow{\lambda}$, and that $\overrightarrow{\lambda}_{\rm ML} = \overrightarrow{\lambda}_{\rm T} + \delta\overrightarrow{\lambda}$ are the best fit parameters in the presence of some realization of the noise. Then, for large SNR, the parameter-estimation errors $\delta\overrightarrow{\lambda}$ have the Gaussian probability distribution:

$$P(\delta\overrightarrow{\lambda}\,|\,s) \;\propto\; e^{-\frac{1}{2}\Gamma_{ij}\,\delta\lambda^i\,\delta\lambda^j}$$

where Γ_{ij} is the so-called Fisher information matrix, defined by

$$\Gamma_{ij} = \left(\frac{\partial h}{\partial\lambda^i}\,\middle|\,\frac{\partial h}{\partial\lambda^j}\right)\Bigg|_{\overrightarrow{\lambda}_{\rm ML}}$$

Motivation

✳ For large SNR, the variance-covariance matrix is given by:

$$< \delta\lambda^i \, \delta\lambda^j > \; = \; \left(\Gamma^{-1}\right)^{ij} \; + \; \mathcal{O}(\mathrm{SNR}^{-1})$$

and the “error” in a given parameter λ^i is defined as:

$$\Delta\lambda^i \;\equiv\; \sqrt{< \delta\lambda^i \, \delta\lambda^i >}$$

Motivation

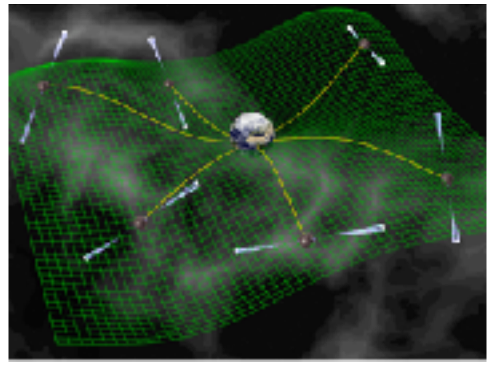
✳ Obvious Principle for GW modeling:

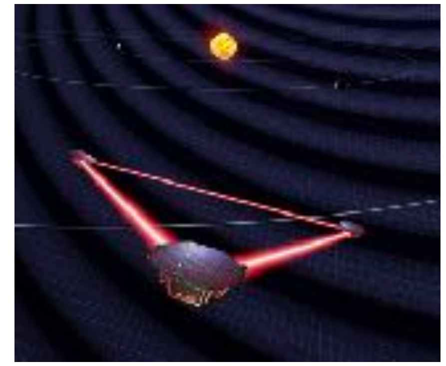
You get what you put in!

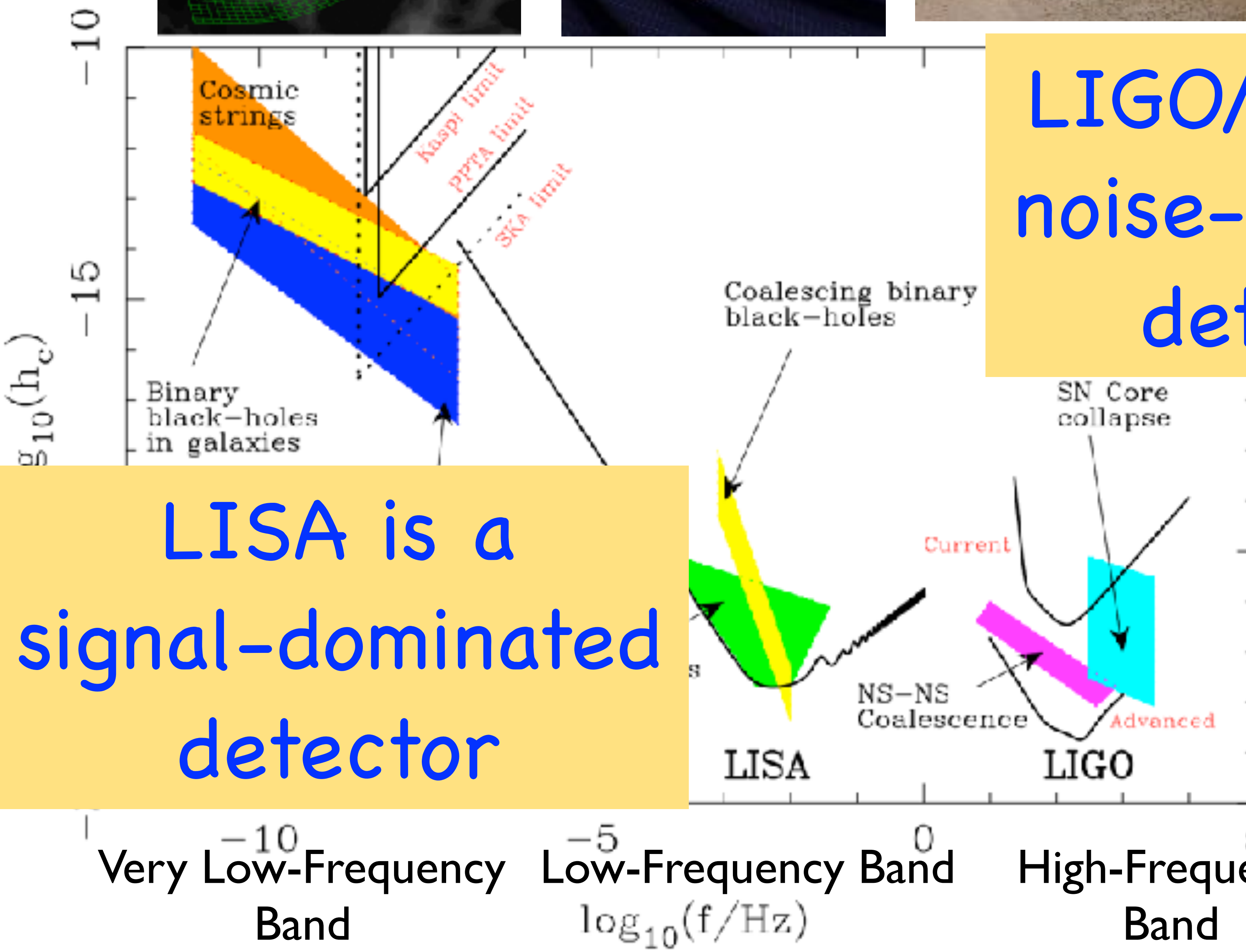
You get, at most, what you put in!

Sources
and
Detectors

Sources and Detectors







LIGO/Virgo are noise-dominated detectors

LISA is a signal-dominated detector

Very Low-Frequency Band

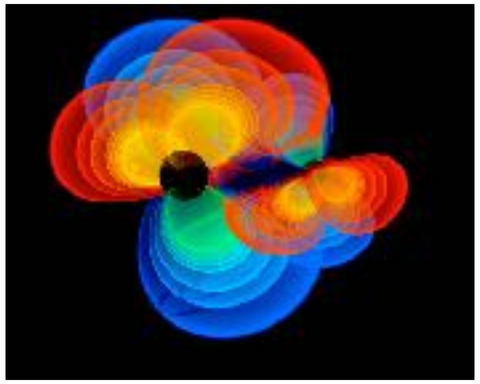
Low-Frequency Band

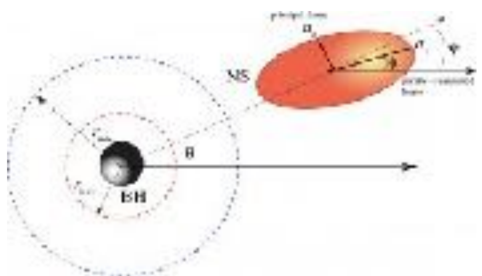
High-Frequency Band

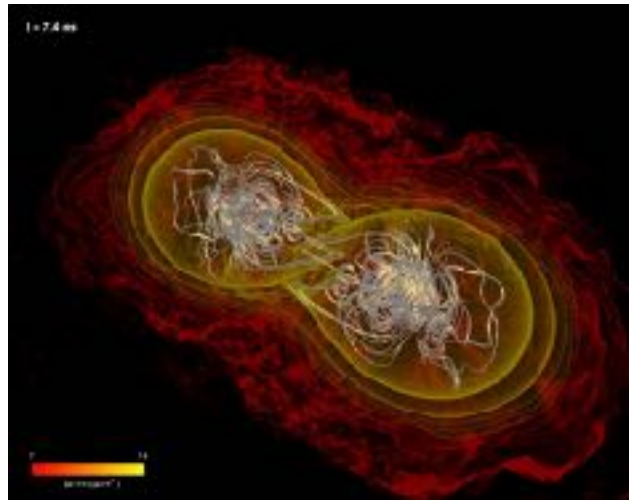
$$f_{\rm GW} \downarrow \;(\lambda_{\rm GW} \uparrow) \;\Rightarrow\; L_{\rm arm} \uparrow$$

Gravitational Wave Sources (HF Band)

Compact Binary System Coalescence

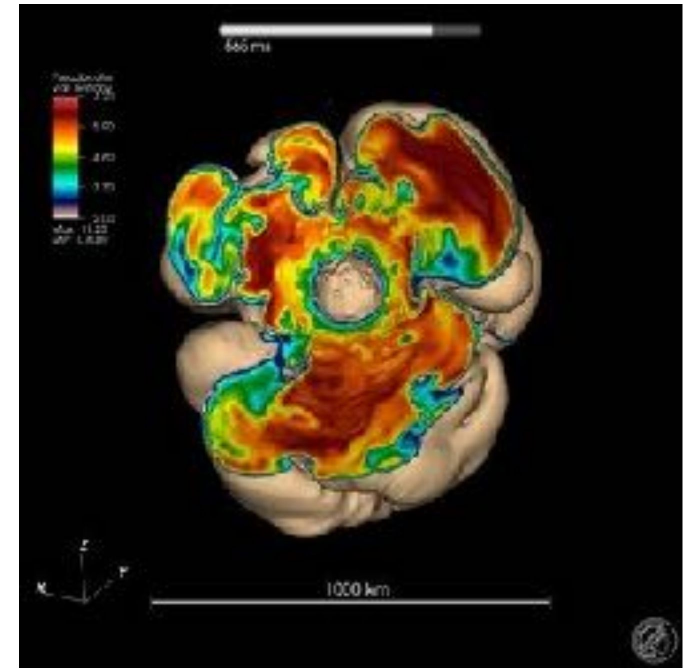




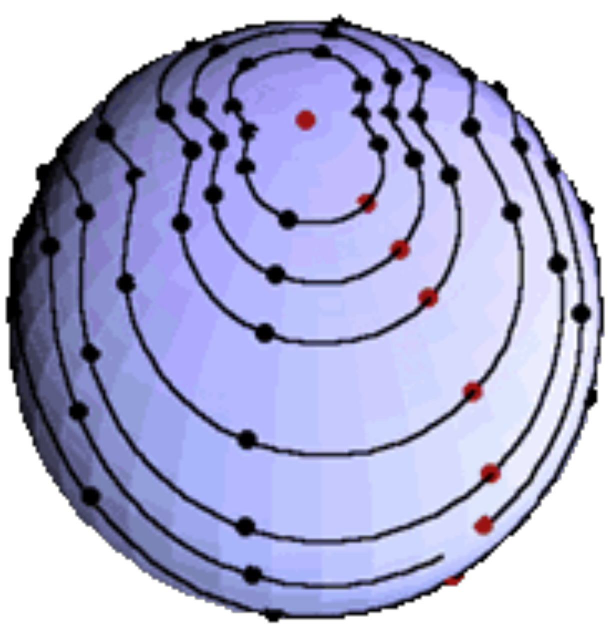


NS-NS, BH-BH, BH-NS

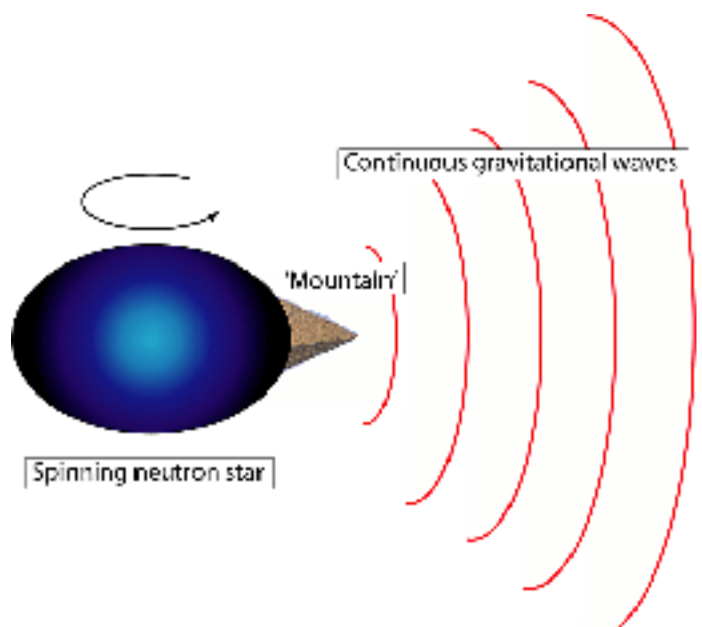
Core Collapse Supernovae



Oscillations of Relativistic Stars

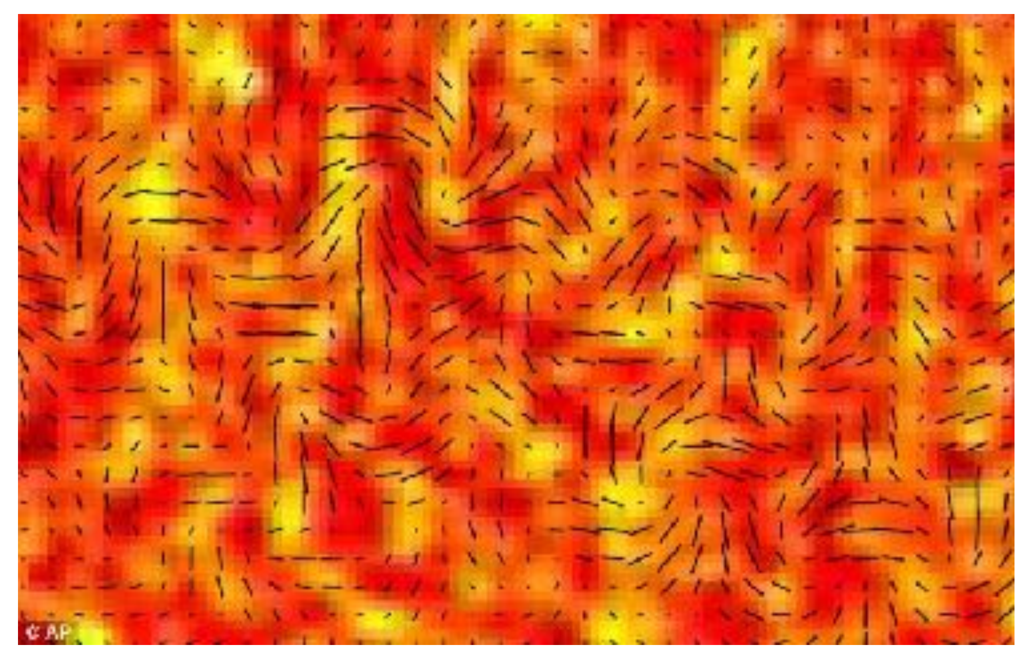


r-Modes

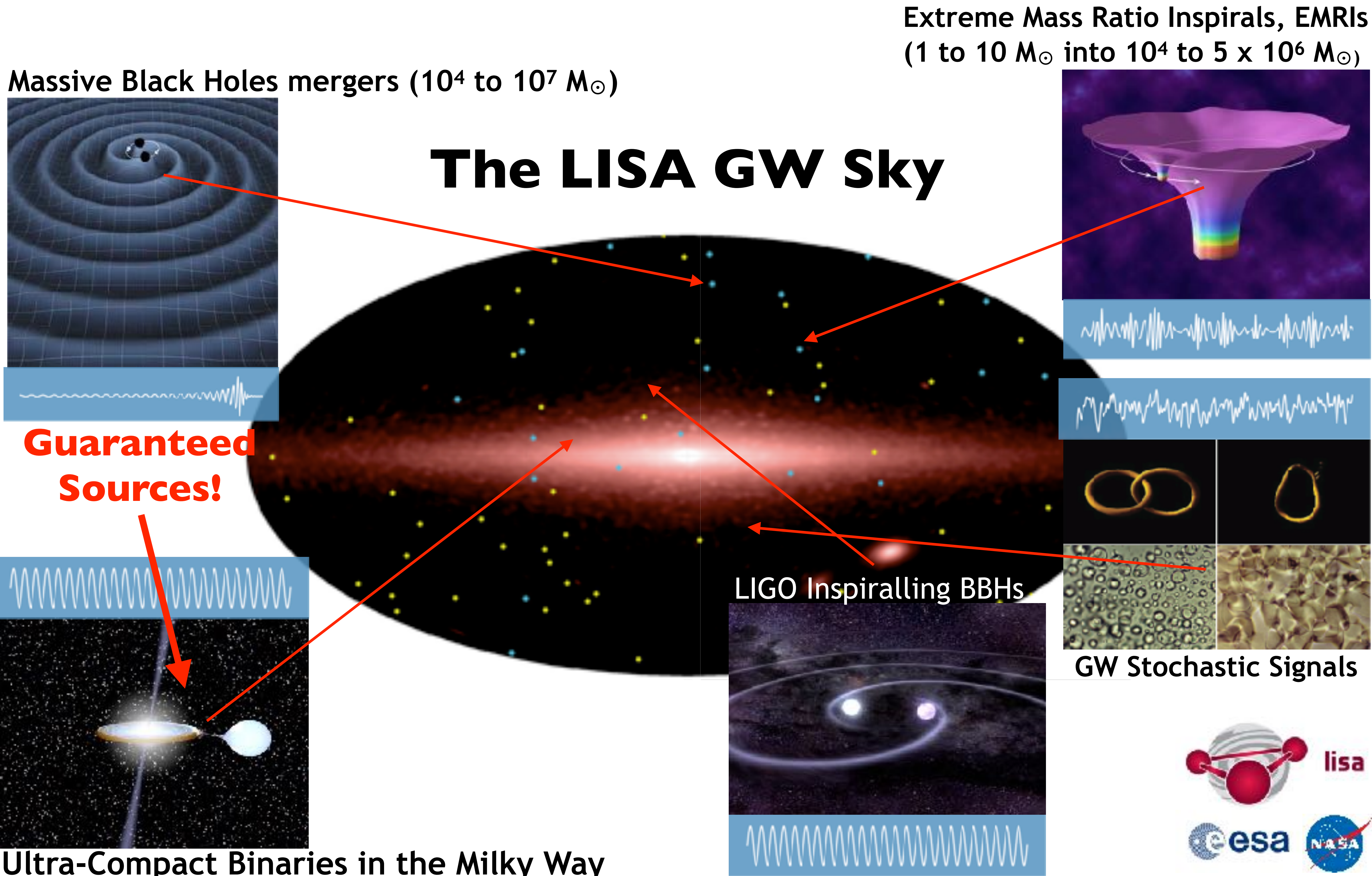


“mountains” in Neutron Stars

Stochastic Signals/ Gravitational Wave Backgrounds

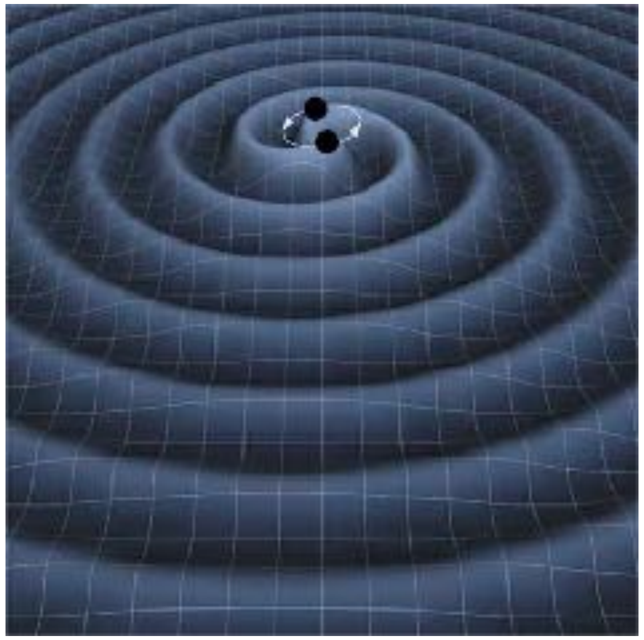


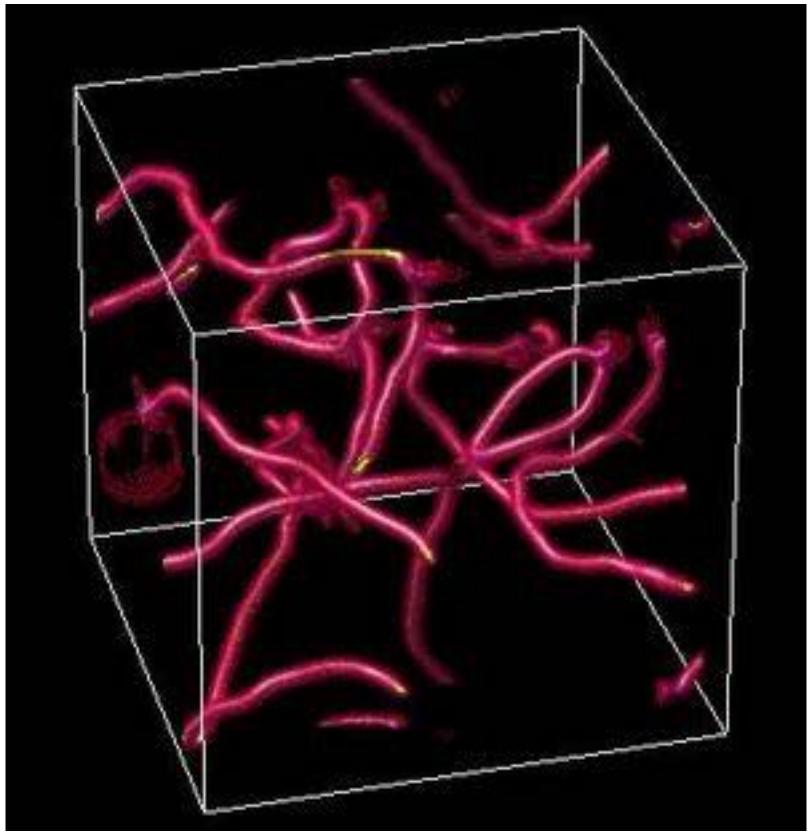
Gravitational Wave Sources (LF Band)



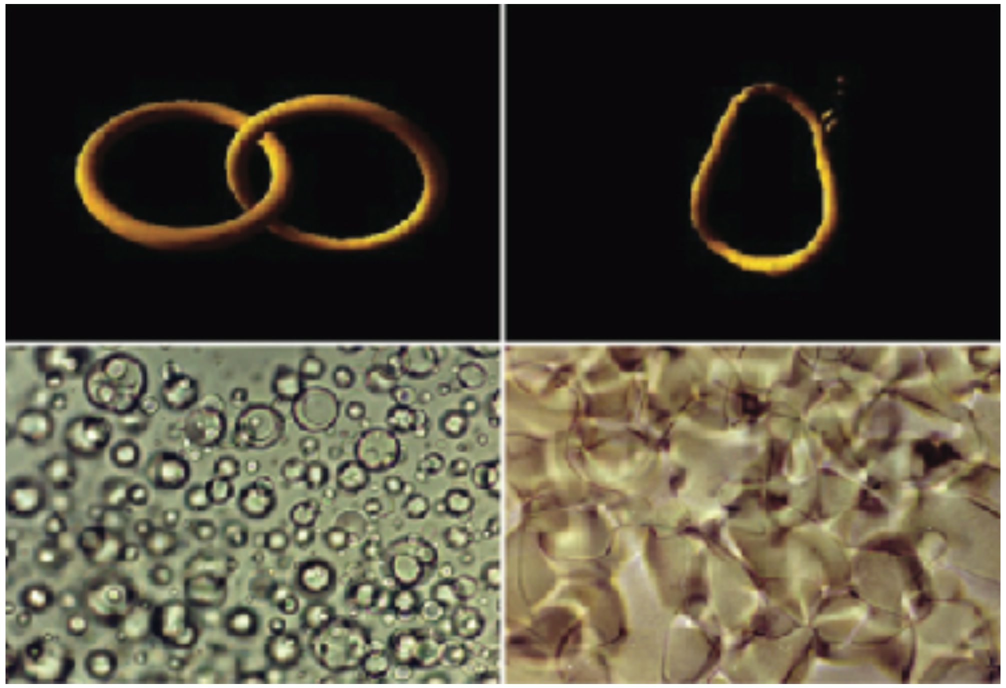
Gravitational Wave Sources (VLF Band)

Stochastic Background from Supermassive Black Holes mergers (10^8 to 10^{10} $M_\odot$)





Cosmic Strings



GW Stochastic Signals

Compact Binary Coalescences

✳ Most probably, the main source of GWs for detectors in the high and low-frequency bands (also in the deciHertz band) are compact binaries in the regime where their dynamics is ruled by GW emission:

✳ Types of Compact Objects:

- **Compact stars:** White Dwarfs, Neutron Stars.
- **Black Holes:** Primordial BHs, Stellar-origin BHs, Intermediate Mass BHs, Supermassive Black Holes.
- **Exotic Objects:** Boson stars, gravastars, etc.

✳ Types of Binaries:

- **Mass Ratio:** (M1/M2): Comparable/Intermediate Mass Ratio Binaries.
- **Inspiral Stage:** Inspiral vs Inspiral-Merger-Ringdown (IMR)

Gravitational Waveforms
in
General Relativity

Gravitational Waveforms in General Relativity

✴ **Ingredients in the Computation of the Gravitational Waveforms:**

- Equations of Motion for Gravity and the Matter Fields.
  Einstein's Field equations+Energy-Momentum conservation
- Computation of the waveforms (polarizations) for observers in the asymptotically-flat region of the source.

Waveform at the source frame

- Propagation of the GWs emitted:
  Cosmology: ΛCDM
  Non-GR propagation effects

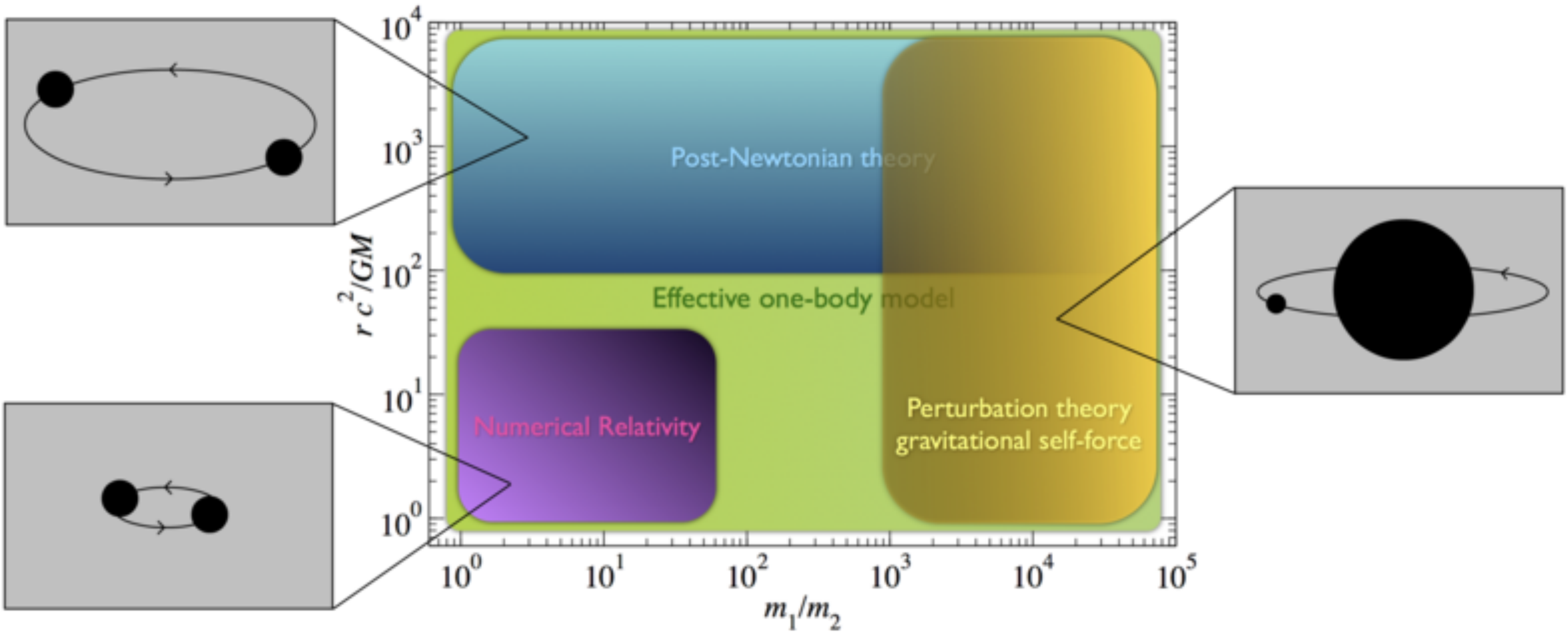
Waveform at the detector

- Relative motion between source and detector
- Detector Response

Waveform at the detector frame-> detector response to GWs

Gravitational Waveforms in General Relativity

✳ **Gravitational Regimes in the GW driven evolution of Binary Systems:**

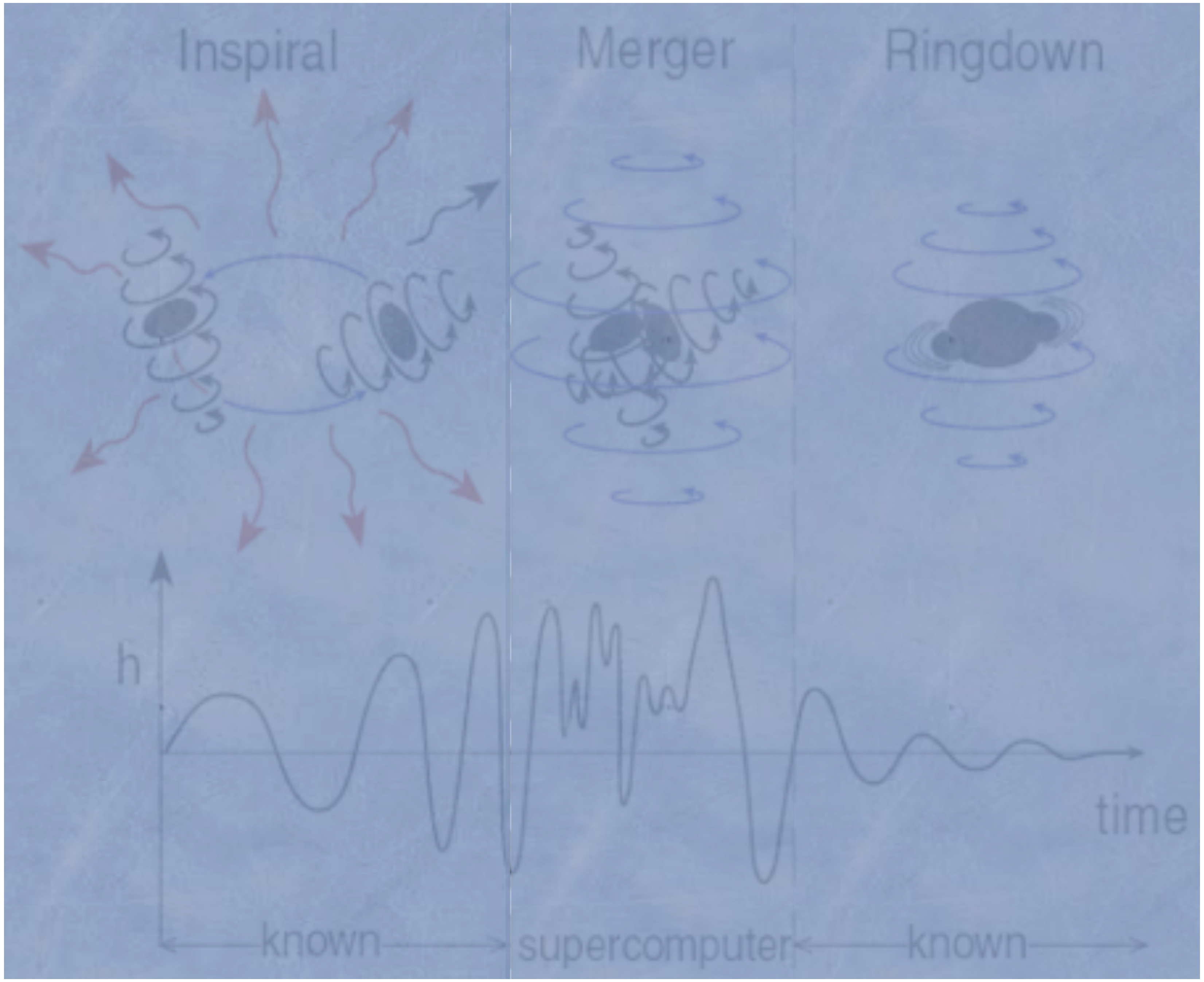


Buonanno & Sathyaprakash 2014

Waveforms for Binary Black Holes in GR

* The case of Binary Black Holes: The last stages of the evolution of a Black Hole Binary will be driven by gravitational-wave emission:

The system here resembles a perturbed single Black Hole. The evolution can be followed using BH perturbation theory (evolution of damped sinusoids, i.e. Quasi-normal modes).



From: Kip Thorne (Caltech)

Waveforms for Binary Black Holes in GR

✳ In 2005 Frans Pretorius (Caltech) produced the first simulations of the last orbits of a Binary Black Hole merger, including merger, ringdown and the extraction of the gravitational waves emitted.

PRL **95,** 121101 (2005) PHYSICAL REVIEW LETTERS week ending 16 SEPTEMBER 2005

Evolution of Binary Black-Hole Spacetimes

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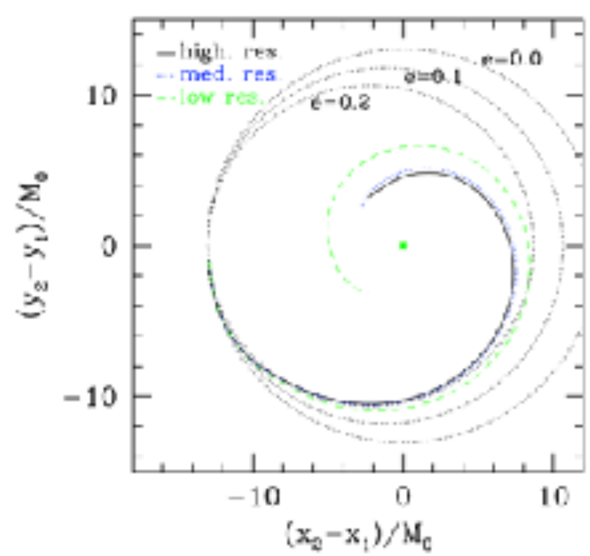
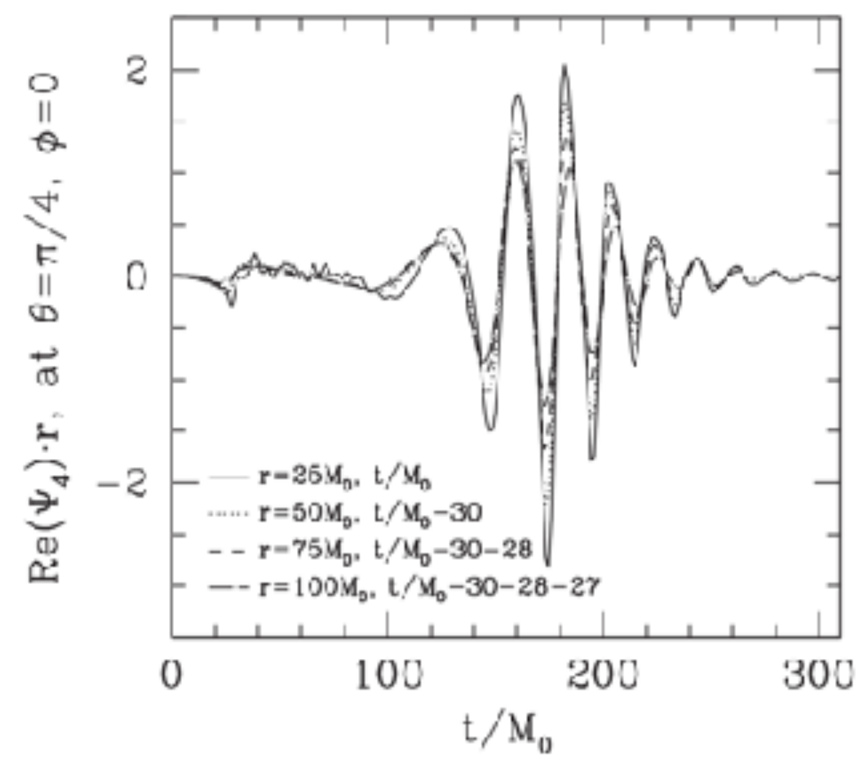
(Received 6 July 2005; published 14 September 2005)

We describe early success in the evolution of binary black-hole spacetimes with a numerical code based on a generalization of harmonic coordinates. Indications are that with sufficient resolution this scheme is capable of evolving binary systems for enough time to extract information about the orbit, merger, and gravitational waves emitted during the event. As an example we show results from the evolution of a binary composed of two equal mass, nonspinning black holes, through a single plunge orbit, merger, and ringdown. The resultant black hole is estimated to be a Kerr black hole with angular momentum parameter $a \approx 0.70$. At present, lack of resolution far from the binary prevents an accurate estimate of the energy emitted, though a rough calculation suggests on the order of 5% of the initial rest mass of the system is radiated as gravitational waves during the final orbit and ringdown.

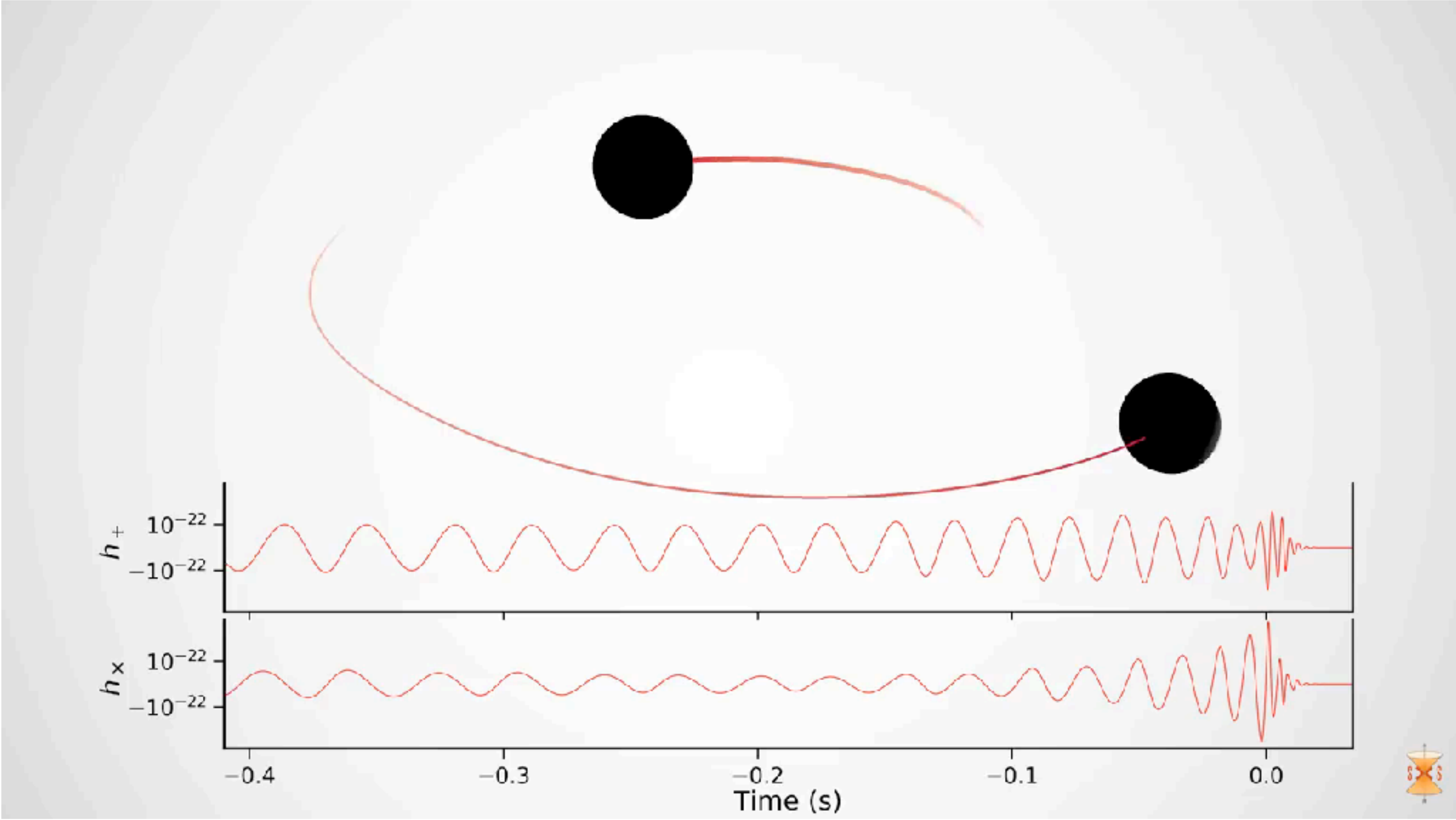
DOI: 10.1103/PhysRevLett.95.121101 PACS numbers: 04.25.Dm, 04.30.Db, 04.70.Bw

Numerical Relativity Breakthrough!





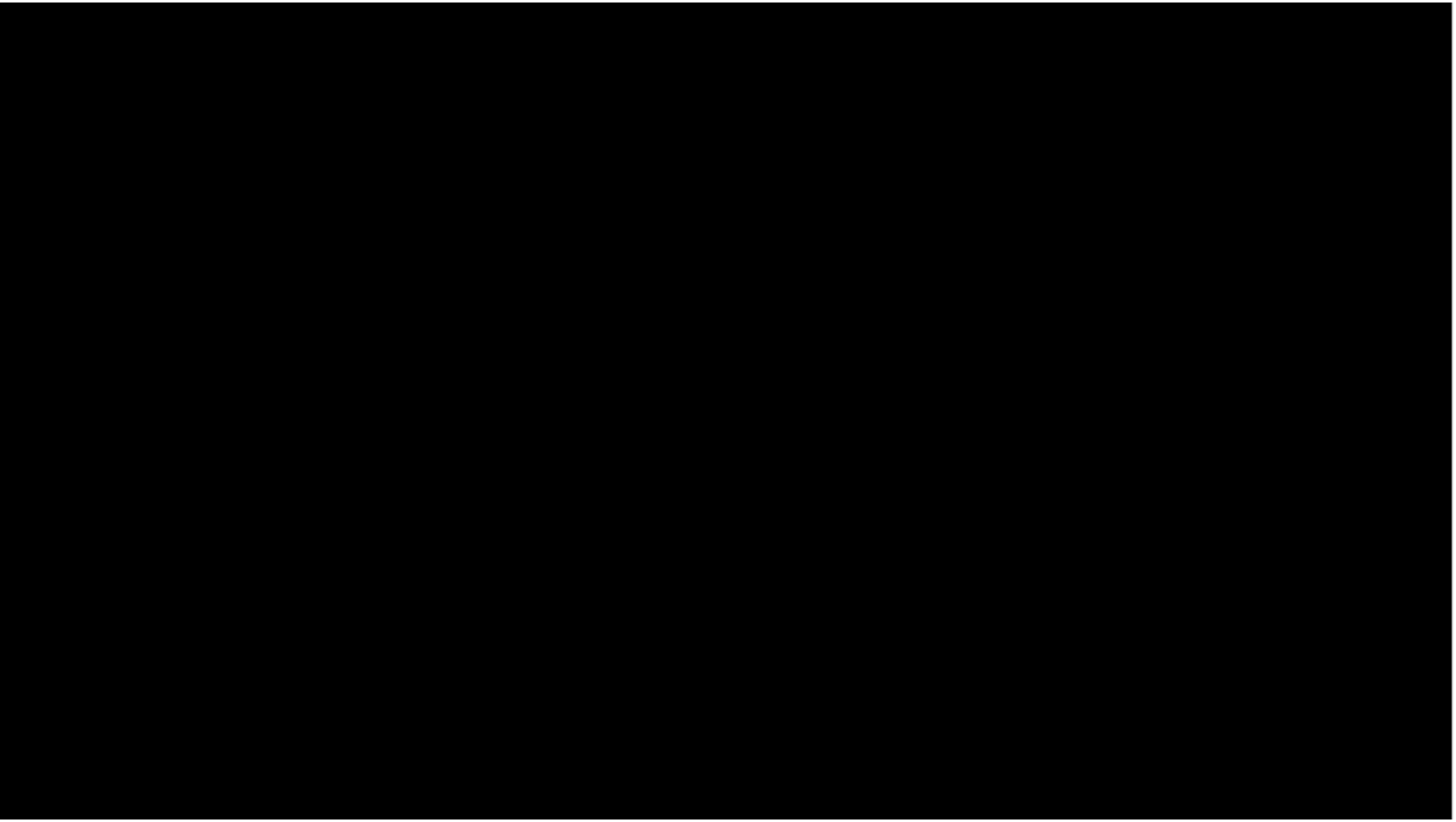
Waveforms for Binary Black Holes in GR



SXS Collaboration

Waveforms for other Compact Binaries in GR

- The case of Binary Neutron Stars was done before the Binary Black Hole case: We need the hydrodynamical equations for the matter composition of Neutron Stars (Equation of State?); shock capturing methods; microphysics; etc.



Simulation of GW170817, the first merger of a BNS detected

Waveforms for other Compact Binaries in GR

- There are also simulations for Black Hole-Neutron Star Binaries.

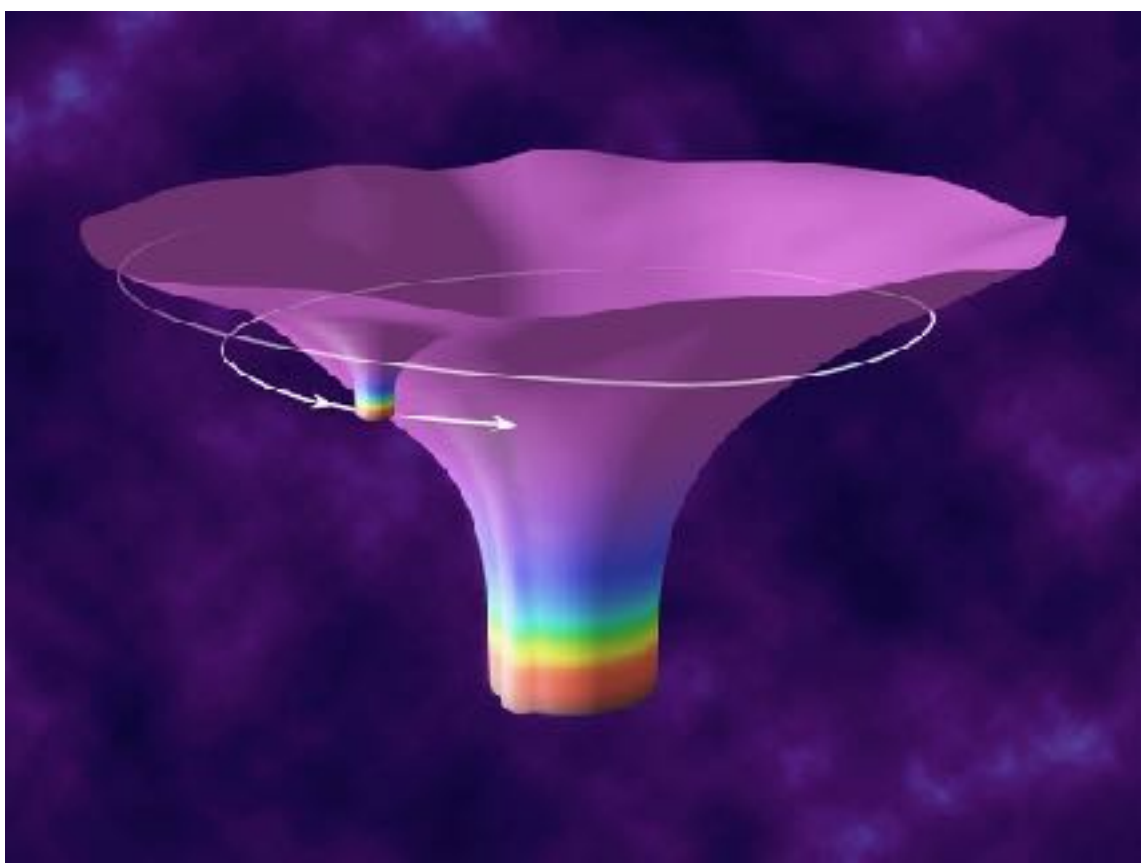
- Boson Star Binary Evolutions

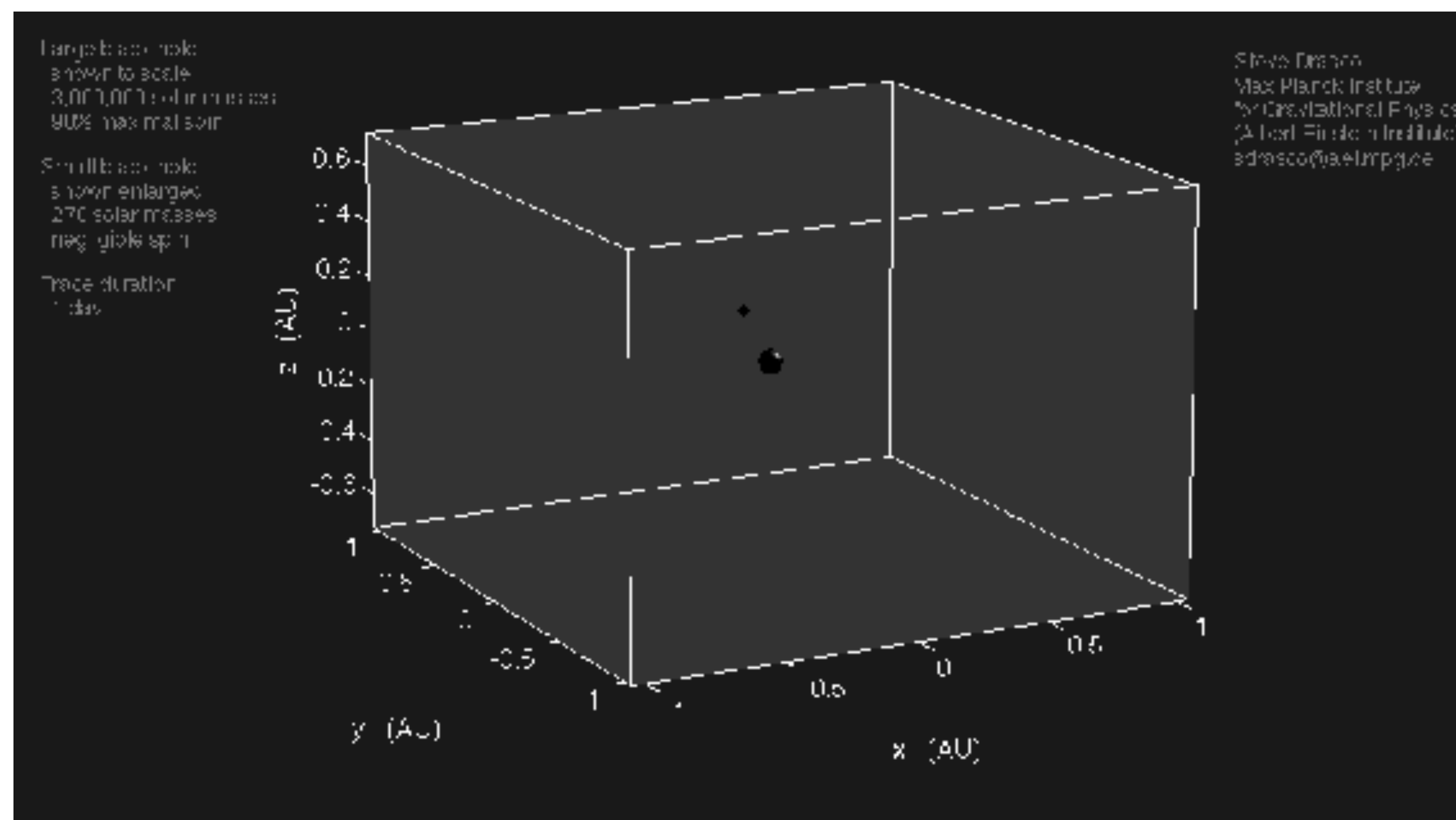
- **REMARK**: In practice, for the data analysis, template banks of gravitational waveforms from different types of phenomenological models that combine the information from different techniques (pN, BHPT, NR, …) are used. These are much cheaper from the computational point of view.

Extreme-Mass-Ratio Inspirals (EMRIs)

- LISA will detect (SNR > 20) 1-2 inspirals of a compact object (a NS or a stellar-mass BH) captured in a highly relativistic orbit around a (super)massive BH ($10^4 < M/M_{\odot} < 5 \times 10^6$) and spiralling through the strongest field regions a few Schwarzschild radii from the event horizon before plunging into it; out to redshift z ~ 0.7, covering a co-moving volume of 70 Gpc^3, a much larger volume than current observations of dormant galactic nuclei.

- The signals are long lasting (~ yrs) so that the SNR is built up as the contribution from many cycles (~ 10^5 cycles during the last year before plunging into the central black hole)





Extreme-Mass-Ratio Inspirals (EMRIs)

- Long and complex signal that carries very precise information about the gravitational multipole moments of the central Black Hole.
- LISA measurement of EMRI signals will provide the best tests of theories of gravity like Scalar-Tensor theories, Chern-Simons, higher-dimensional models (braneworlds), etc.

LISA measurement of EMRI signals will also test alternatives: deviations from the Kerr geometry of the General Relativistic Black Hole (boson stars, gravastars, etc.).

Extreme-Mass-Ratio Inspirals (EMRIs)

- The self-force program (based on BH perturbation theory) is the best approach we have to achieve high-precision waveforms for EMRIs.

- At the moment, it has been recently completed the computation of the 1st-order self-force for Kerr spacetimes. We need to implement it in a consistent evolution of the system and 2nd-order perturbations for gauge-invariant waveform generation.

Extreme-Mass-Ratio Inspirals (EMRIs)

- The parameter error estimations for LISA detections of EMRIs are [Barack & Cutler, PRD, **69**, 082005 (2004)]

$$\Delta(\ln M_\bullet)\,, \quad \Delta\left(\ln m_\star\right)\,, \quad \Delta\left(\frac{S_\bullet}{M_\bullet^2}\right) \;\sim\; 10^{-4}$$

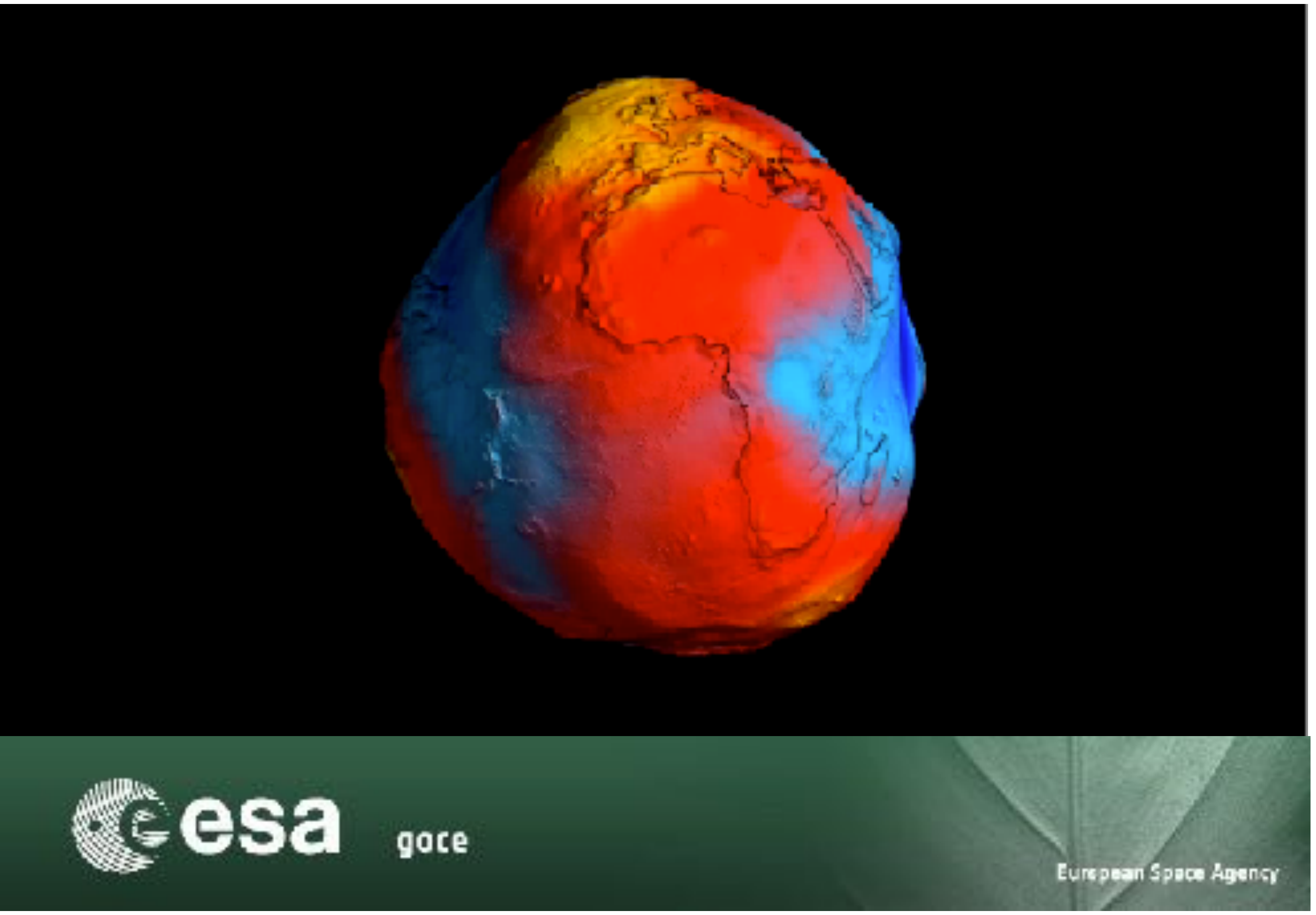
$$\Delta e_0 \;\sim\; 10^{-(3-4)}\,, \quad \Delta\left(\ln\frac{m_\star}{D_\mathrm{L}}\right) \;\sim\; 10^{-(1-2)}$$

- For EMRIs with:

$$M_\bullet = 10^6 M_\odot\,, \quad m_\star = 10 M_\odot\,, \quad \mathrm{SNR}\sim 30$$

Testing Strong Gravity within EMRIs

- For Earth's gravitational field:



$$V(\vec{r}) = -G \sum_{\ell\,,m} \frac{M_{\ell m}}{r^{\ell+1}}\, Y_{\ell m}(\theta,\varphi)$$

$M_{\ell m}$: Multipole moments

GOCE can measure up to

$\ell_{\mathrm{MAX}} \sim 200$

- For a Kerr BH in GR: There are two sets of moments:

$$M_\ell + i\, J_\ell = M_\bullet \left(i\, \frac{S_\bullet}{M_\bullet\, c} \right)^{\ell}$$

- Kerr Hypothesis: "The exterior gravitational field of the dark, compact and very massive objects sitting at the galactic centers can be well described by the vacuum, stationary, and axisymmetric solutions of General Relativity whose multipole moments satisfy the Kerr relations"

- Different measurements of multipole moments provide different tests of the Kerr hypothesis.

Testing Strong Gravity within EMRIs

- This program was pioneered by Ryan [Ryan, PRD, **52**, 5707 (1995); **56**, 1845 (1997)]

TABLE IV. The error $\delta\theta^i$ for each parameter θ^i, when fitting up to the $l_{\max}$th moment, using LISA. We use the abbreviation $L(\cdots)\equiv\log_{10}(\cdots)$. We assume $\mu=10M_\odot$, $M=10^5M_\odot$, $r=3M$, and $S/N=100$.

$l_{\max}$	$L(\delta t_*/\mathrm{sec})$	$L(\delta\phi_*)$	$L(\delta\mu/\mu)$	$L(\delta M/M)$	$L(\delta s_1)$	$L(\delta m_2)$	$L(\delta s_3)$	$L(\delta m_4)$	$L(\delta s_5)$	$L(\delta m_6)$	$L(\delta s_7)$	$L(\delta m_8)$	$L(\delta s_9)$	$L(\delta m_{10})$
0	0.74	−0.25	−5.90	−5.80										
1	1.71	0.33	−4.92	−4.70	−4.53									
2	2.37	1.41	−4.17	−4.01	−3.89	−2.82								
3	2.73	2.52	−3.49	−3.28	−2.94	−2.27	−1.66							
4	4.54	3.80	−2.40	−2.23	−1.97	−0.81	0.07	0.72						
5	5.99	4.74	−0.73	−0.55	−1.12	0.47	0.59	0.95	2.35					
6	6.05	4.87	−0.68	−0.50	−1.00	0.54	0.94	1.53	2.35	2.58				
7	6.07	4.88	−0.66	−0.48	−0.99	0.56	0.94	1.53	2.35	2.81	2.68			
8	6.07	4.88	−0.65	−0.47	−0.98	0.57	0.96	1.56	2.35	2.81	3.16	3.68		
9	6.08	4.91	−0.65	−0.47	−0.96	0.58	1.04	1.67	2.35	2.82	3.20	3.74	4.10	
10	6.08	4.92	−0.64	−0.46	−0.95	0.58	1.05	1.69	2.35	2.82	3.20	3.75	4.17	4.70

- This uses quasi-circular and quasi-equatorial orbits. The conclusion is that a LISA-like detector may be able to estimate 3-5 moments (1-3 tests of the Kerr hypothesis).

Testing Strong Gravity within EMRIs

- Barack & Cutler extended their study [PRD, **75**, 042003 (2007)] to consider a central object with a mass quadrupole. The error estimations for this parameter (using generic orbits) are in the range:

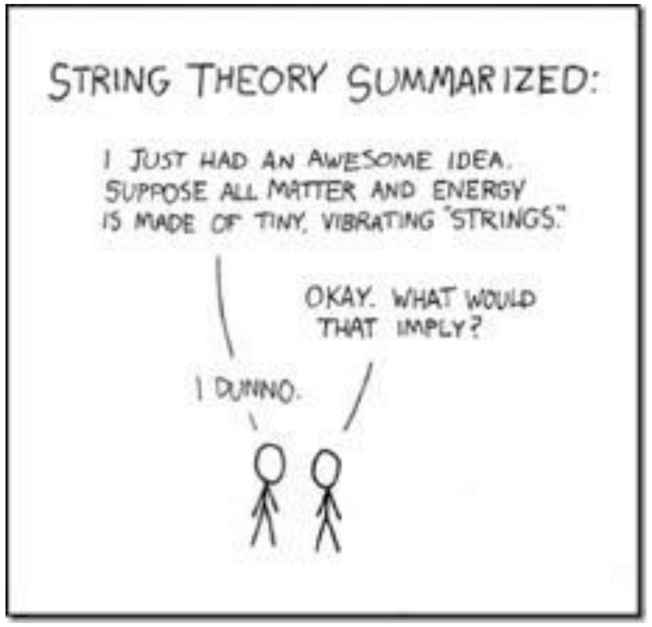
$$\Delta\left(\frac{M_2}{M_0^3}\right) \sim 10^{-(2-4)}$$

which is a considerably better error estimate than Ryan's estimate.

Gravitational Waveforms in Modified Gravity

Testing Strong Gravity beyond General Relativity

- Even to test General Relativity we must use models that consider non-GR dynamics.
- The Landscape of Theories of Gravity is very rich...



Testing Strong Gravity beyond General Relativity

- Not all theories are suitable to consistently study Comapct Binary Coalescence (CBCs).

- We need to check that we can have all the ingredients mentioned above in place for each theory. This means we need theories that allow for the necessary computations.

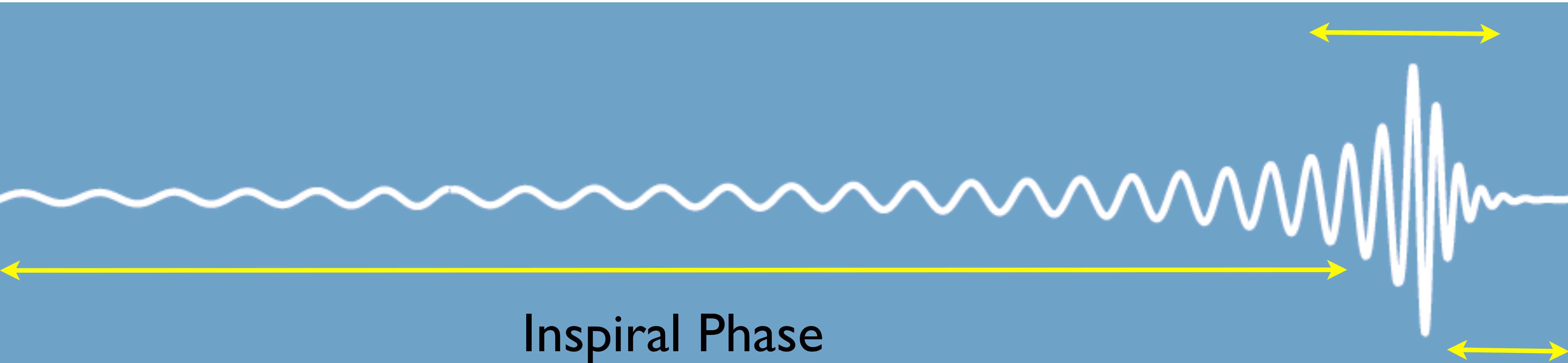
- An alternative would be to introduce modifications from those theories in the GR computations that we already know how to perform them.

- Metric-based theories have some advantages as we can try to profit from the GR knowledge. Possible theories: Scalar-Vector-Tensor theories; f(R,…); Higher-dimensional theories; etc.

Fundamental Physics with Massive Black Hole Mergers

- High precision measurements of Strong Gravity

Merger
(Numerical Relativity)



Inspiral Phase
(post-Newtonian)

Ringdown
(Perturbation Theory)

Thousands of cycles at SNRs 50-1000.

The phase carries information about the propagation of the Gravitational Waves.

Can test theories of gravity that predict massive gravitations, improving present bounds.

Short bursts of Gravitational Waves in the non-linear regime of General Relativity.

It is a very energetic event with a power corresponding to ~ 10^{22} times the power of the Sun.

The asymmetric remnant after the merger settles down to a single (Kerr) Black Hole. In this “relaxation” process the system emits Gravitational Waves that are combinations of the QuasiNormal Modes (QNMs) of the final Black Hole.

The QNMs, according to General Relativity, only depend on the Mass and Spin of the Black Hole (*no hair* conjecture).

The identification of two QNMs provides a test of the geometry of Black Holes (are they really Kerr Black Holes?). The QNM spectrum is sufficiently rich to allow for distinction of different object. eLISA will measure several QNMs with sufficient SNR to carry out these tests.

Inspiral

- **The Parameterized Post-Einsteinian (PPE) Formalism.** [Yunes & Pretorius PRD, **80** 122003 (2009)]
- Detectors are more sensitive to than phase than to the amplitude. Phenomenogical modification:

$$\tilde{h}^{\mathrm{I}}(f) = \tilde{h}^{\mathrm{I}}_{\mathrm{GR}}(f)\left(1 + \alpha\, u^{a}\right) \exp(i\beta\, u^{b}) \qquad \left[u \equiv (\pi \mathcal{M}_c f)^{1/3}\right]$$

Theories	GR Pillars	Theoretical Mechanism	PPE a	PPE b	PN Order	PPE (α,β)
time-varying G	Strong Equivalence Principle	Anomalous Acceleration	-8	-13	-4 PN	$(\alpha_{\dot{G}}, \beta_{\dot{G}})$
RS-II Braneworld	4D	Anomalous Acceleration	-8	-13	-4 PN	$(\alpha_{\mathrm{ED}}, \beta_{\mathrm{ED}})$
Scalar-Tensor (including Brans-Dicke)	Strong Equivalence Principle	(Monopole) Scalar Field	-2	-7	-1 PN	$(\alpha_{\mathrm{ST}}, \beta_{\mathrm{ST}})$
Einstein-dilaton Gauss-Bonnet	Strong Equivalence Principle	(Monopole) Scalar Field	-2	-7	-1 PN	$(\alpha_{\mathrm{EdGB}}, \beta_{\mathrm{EdGB}})$
dynamical Chern-Simons	Parity Invariance	(Dipole) Scalar Field	$+4$	-1	$+2$ PN	$(\alpha_{\mathrm{dCS}}, \beta_{\mathrm{dCS}})$
Einstein-Æther, Hořava-Lifshitz	Lorentz Invariance	Vector Field	-2	-7	-1 PN	$\left(\alpha^{(-1)}_{\text{Æ}}, \beta^{(-1)}_{\text{Æ}}\right)$
			0	-5	0 PN	$\left(\alpha^{(0)}_{\text{Æ}}, \beta^{(0)}_{\text{Æ}}\right)$

- There are similar parametrizations for merger and ringdown

Waveforms for Binary Black Holes in Modified Gravity

GW Propagation

- **The Parameterized Post-Einsteinian (PPE) Formalism.** [Yunes & Pretorius PRD, **80** 122003 (2009)]

$$\tilde{h}^{\rm I}(f) = \tilde{h}^{\rm I}_{\rm GR}(f)\left(1 + \alpha\, u^{a}\right) \exp(i\beta\, u^{b}) \qquad \left[u \equiv (\pi \mathcal{M}_c f)^{1/3}\right]$$

Theories	PPE a	PN Order	PPE b	PN Order	PPE (α, β)
Massive Gravity	—	—	-3	$+1$ PN	
Double Special Relativity	—	—	$+6$	$+5.5$ PN	
Extra Dimension, Hořava-Lifshitz	—	—	$+9$	$+7$ PN	$\left(0, A\, D\, \mathcal{M}^{-b/3}\right)$
Multifractional Spacetime	—	—	3–6	4–5.5 PN	
Standard Model Extension ($d = 4, 5, \ldots$)	—	—	$3(d-3)$	$(3d-4)/2$ PN	
Parity-violating Theories	$+3$	$+1.5$PN	$+6$	$+5.5$ PN	$(\alpha_{\rm PV}, \beta_{\rm PV})$

Late Inspiral and Merger (Numerical Relativity)

- Late Inspiral and Merger of Binary Black Holes in Scalar-Tensor Theories of Gravity [Healy, Bode, Haas, Pazos, Laguna, Shoemaker, Yunes. arXiv: 1112.3928].

- Numerical binary black hole collisions in dynamical Chern-Simons gravity [Okounkova, Stein, Scheel & Teukolsky. arXiv:1906.08789]

Ringdown

• Black Hole solutions and their quasi-normal modes have been studied in many different theories (high-volume literature about this).

Testing Strong Gravity beyond General Relativity with EMRIs

- EMRIs in Chern-Simons Modified Gravity (CSMG) [CFS & Yunes, PRD, **84**, 064106 (2011); Canizares, Gair & CFS, arXiv:1205.1253].
- This is a theory with a gravitational parity-violating term. It can be seen as a low-energy limit of string theory or of loop quantum gravity. It can also be taken as a gravitational correction in the spirit of effective field theories.

$$G_{\mu\nu} + \frac{\alpha}{\kappa} C_{\mu\nu} = \frac{1}{2\kappa}\left(T^{\rm mat}_{\mu\nu} + T^{(\vartheta)}_{\mu\nu}\right),$$

$$\beta \Box\vartheta = \beta \frac{dV}{d\vartheta} - \frac{\alpha}{4} {}^{*}R\,R,$$

$$T^{(\vartheta)}_{\mu\nu} = \beta\left[(\nabla_\mu\vartheta)(\nabla_\nu\vartheta) - \frac{1}{2} g_{\mu\nu}(\nabla^\sigma\vartheta)(\nabla_\sigma\vartheta) - g_{\mu\nu}V(\vartheta)\right]$$

$C^{\mu\nu}$ (the so-called *C-tensor*) in Eq. (4) can be split into two parts, $C^{\mu\nu} = C_1^{\mu\nu} + C_2^{\mu\nu}$, where

$$C_1^{\alpha\beta} = (\nabla_\sigma\vartheta)\,\epsilon^{\sigma\delta\nu(\alpha}\nabla_\nu R^{\beta)}{}_\delta\,,$$
$$C_2^{\alpha\beta} = (\nabla_\sigma\nabla_\delta\vartheta)\; {}^{*}R^{\delta(\alpha\beta)\sigma}\,. \quad (7)$$

Testing Strong Gravity beyond General Relativity with EMRIs

- EMRIs in Chern-Simons Modified Gravity (CSMG) [CFS & Yunes, PRD, **84**, 064106 (2011); Canizares, Gair & CFS, arXiv:1205.1253].
- Two very important features:

(i) Kerr is not a solution. The new solution will only depart from Kerr near the horizon… (we do not know the full solution). The deviations are controlled by a unique parameters that is universal:

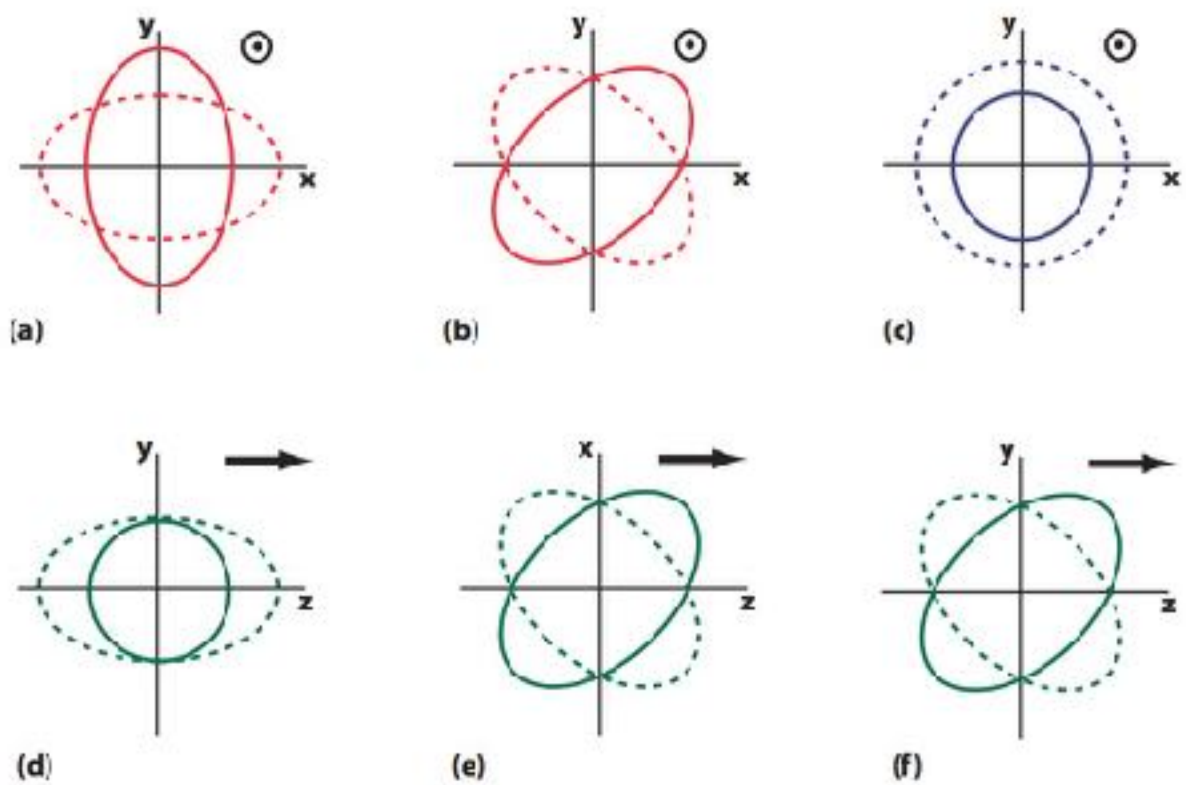
$$\xi = \frac{\alpha^2}{\beta \kappa_{\rm N}}$$

(ii) The effective energy-momentum tensor of the GWs is formally as in GR. There are also contributions to the radiation reaction mechanism from the CS scalar field.

Testing Strong Gravity beyond General Relativity with EMRIs

- EMRIs in Chern-Simons Modified Gravity (CSMG) [CFS & Yunes, PRD, **84**, 064106 (2011); Canizares, Gair & CFS, arXiv:1205.1253].

- How is the propagation of GWs and their effect on test masses?



- GR has only two independent polarization [(a) and (b) in the figure]

- Assuming "weak" GWs, the same happens in the case of CSMG.

Testing Strong Gravity beyond General Relativity with EMRIs

- EMRIs in Chern-Simons Modified Gravity (CSMG) [CFS & Yunes, PRD, **84**, 064106 (2011); Canizares, Gair & CFS, arXiv:1205.1253].

- Two observations:

(I) The "no-hair conjecture" remains the same as in GR, since the only new parameter entering the metric depends on "fundamental" constants of the theory.

(II) The Kerr relation between multipole moments of the BH is modified, but starting at l=4 (at the order approximation used to build the MBH metric).

Testing Strong Gravity beyond General Relativity with EMRIs

- EMRIs in Chern-Simons Modified Gravity (CSMG) [CFS & Yunes, PRD, **84**, 064106 (2011); Canizares, Gair & CFS, arXiv:1205.1253].

- Assuming that CSMG is the correct theory of gravity we have obtained the following error parameter estimations [Fisher analysis]:

System	$M_\bullet$	$a/M_\bullet$	e_0	$a\cdot\xi/M_\bullet^5$
A	$5\cdot 10^5$	0.25	0.25	$5\cdot 10^{-2}$
B	10^6	0.25	0.25	$5\cdot 10^{-2}$

System A

$$\Delta\log M_\bullet \sim 5\cdot 10^{-3}\,,\qquad \Delta a \sim 5\cdot 10^{-6}\,,$$
$$\Delta e_0 \sim 3\cdot 10^{-7}\,,\qquad \Delta\log(a\cdot\xi) \sim 4\cdot 10^{-2}\,,$$

System B

$$\Delta\log M_\bullet \sim 6\cdot 10^{-4}\,,\qquad \Delta a \sim 3\cdot 10^{-6}\,,$$
$$\Delta e_0 \sim 10^{-7}\,,\qquad \Delta\log(a\cdot\xi) \sim 2\cdot 10^{-2}\,,$$

Testing Strong Gravity beyond General Relativity with EMRIs

- EMRIs in Chern-Simons Modified Gravity (CSMG) [CFS & Yunes, PRD, **84**, 064106 (2011); Canizares, Gair & CFS, arXiv:1205.1253].

- Assuming that GR is the correct theory of gravity we have obtained the following bound on the CS parameter:

$$\xi^{1/4} < 1.4 \cdot 10^4 \mathrm{km}$$

This result, a prediction for LISA measurements, is almost four orders of magnitude better than the bound imposed by Solar System experiments (LAGEOS & Gravity Probe B).

Remarks and Conclusions

Remarks and Conclusions

- Gravitational Wave Astronomy provides access for the first time in history to the radiative non-linear regime of Gravity (up to BH horizon scales).

- This allows for a number of tests of Gravity, both within GR (e.g. no hair conjecture) and outside General Relativity (tests of deviations of GR).

- Both detection and parameter estimation for Compact Binary Coalescence events requires precise and effective gravitational waveforms.

- In GR has taken more than 40 years to bring under control some of the problems related with the modeling.

Remarks and Conclusions

- Gravitational Wave Astronomy is very exciting but:

“We get what we put in”

Many of the strong field tests of gravity require a lot of theoretical developments.

Many Thanks for your attention!