Gravitational Waves, General Relativity and Fundamental Physics

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The first observation of a binary black hole merger: status and **future prospects**,
Albert Einstein Institute, Hannover, Germany, May 23-26, 2016

GW150914: An incredibly small signal lost in the noise

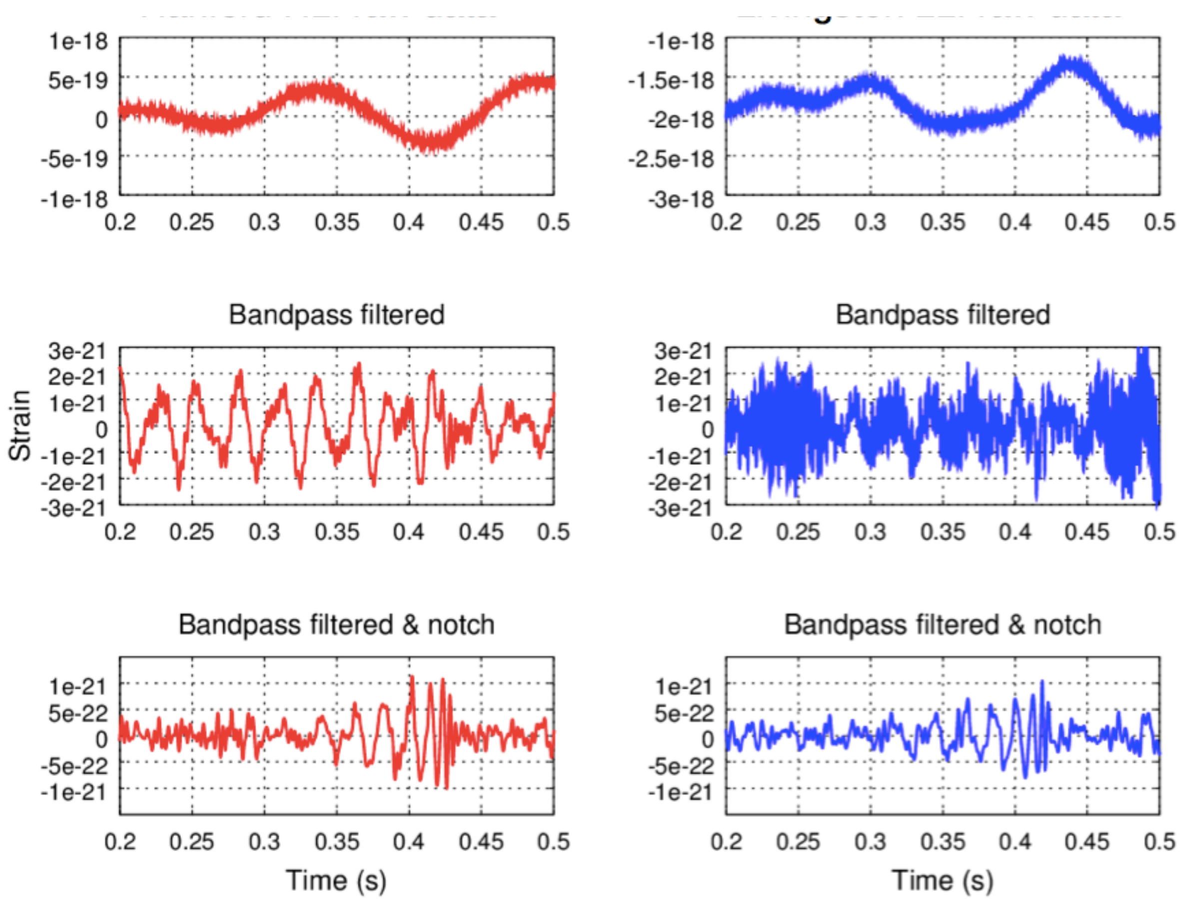
$$h(t)$$

Chassande-Mottin,
Acad Sciences,
5 April 2016

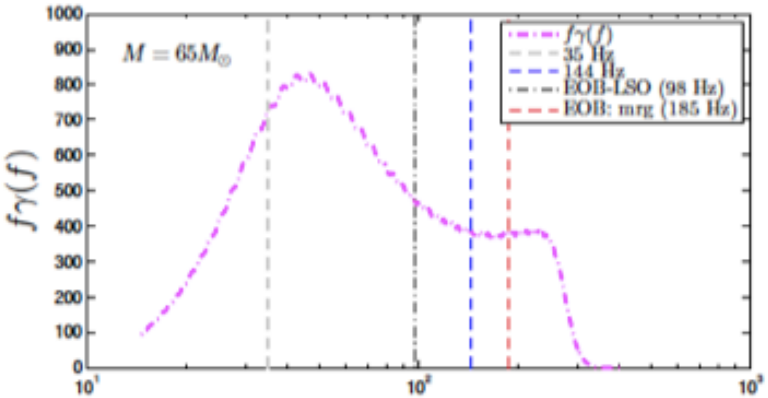
Two levels of signal search:

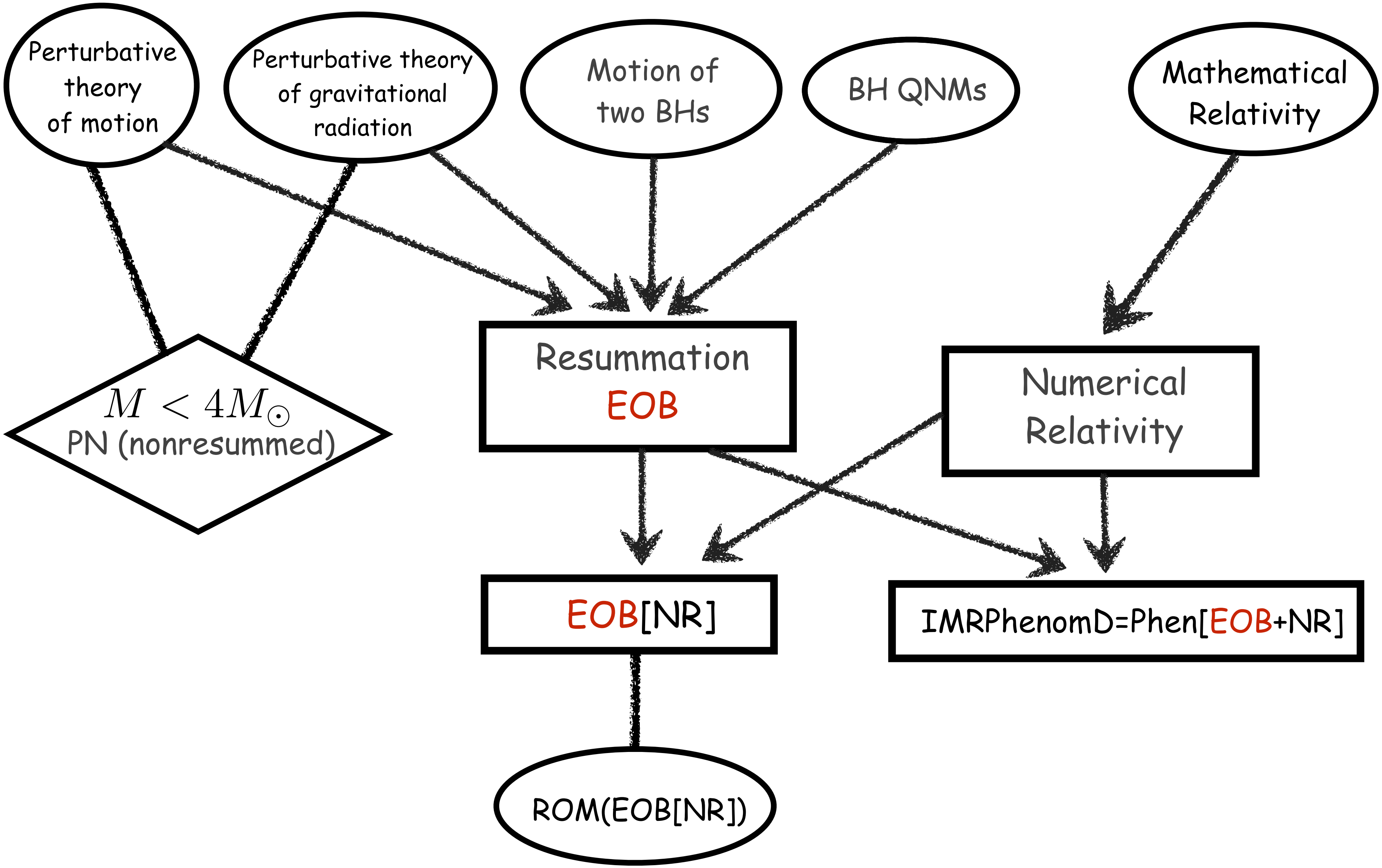
1. time-frequency analysis (Wilson, Daubechies-Jaffard-Journe, Klimenko et al.)
2. Wiener's matched filter analysis (EOB[NR] and Phenom[EOB+NR])

÷ 500



$$\frac{d\rho^2}{d\ln f} = \frac{f|\tilde{h}(f)|^2}{S_n(f)}$$



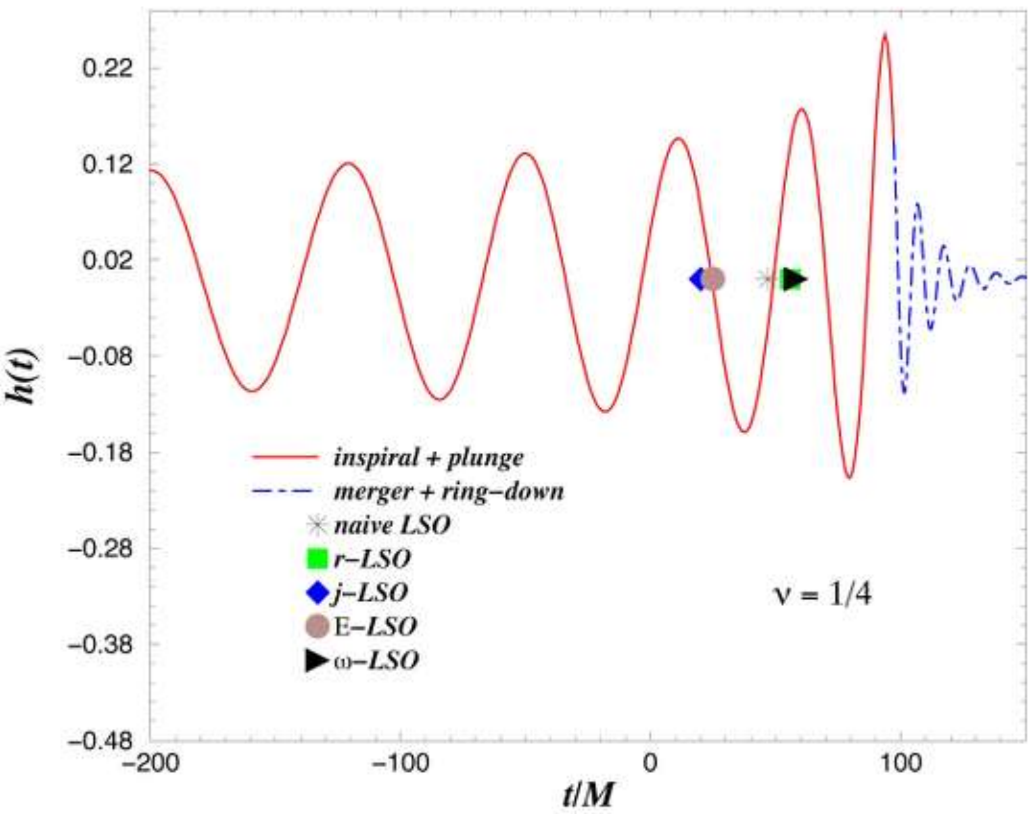


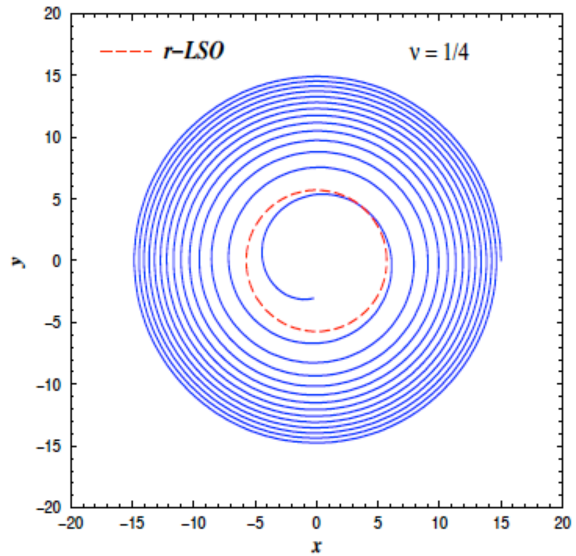
Perturbative theory of motion
Perturbative theory of gravitational radiation
Motion of two BHs
BH QNMs
Mathematical Relativity
$M < 4M_\odot$
PN (nonresummed)
Resummation
EOB
Numerical Relativity
EOB[NR]
IMRPhenomD=Phen[EOB+NR]
ROM(EOB[NR])

EFFECTIVE ONE BODY (EOB) FORMALISM

Buonanno-Damour 99,00; Damour-Jaranowski-Schaefer 00; Damour 01; Damour-Iyer-Nagar 08; after 2005: interfacing with NR: Buonnano et al. ; Damour-Nagar et al

Buonanno-Damour 2000





- Blurred transition from inspiral to plunge
- Final black-hole mass
- Final black hole spin
- Complete waveform

$$\nu = \frac{m_1 m_2}{(m_1 + m_2)^2} = \frac{\mu}{M}$$

TWO-BODY/EOB "CORRESPONDENCE":

BREZIN-ITZYKSON-ZINN-JUSTIN + THINK QUANTUM-MECHANICALLY (J.A. WHEELER)

Real 2-body system
(in the c.o.m. frame)
(m_1, m_2)

1:1 map

An effective particle
in some effective metric

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

$$g_{\mu\nu}^{\text{eff}}$$

$$\mathcal{E} = f(E)$$

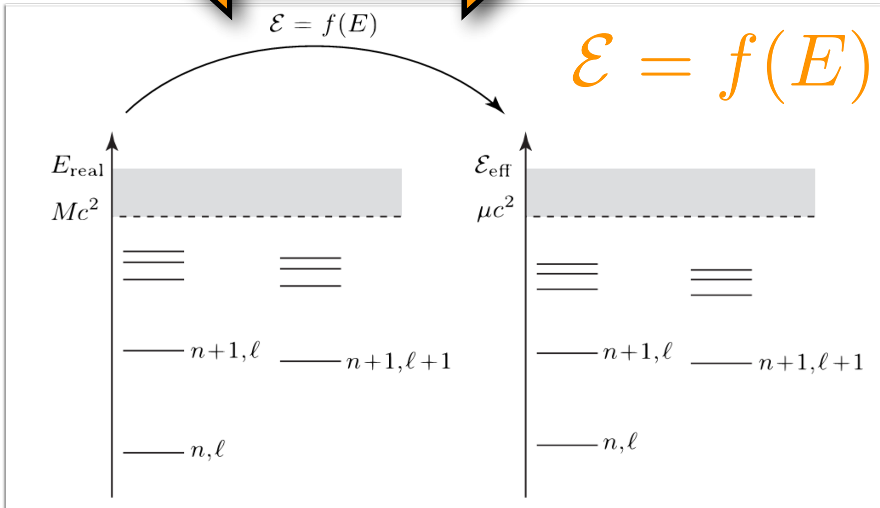


Figure 1: Sketch of the correspondence between the quantized energy levels of the real and effective conservative dynamics. n denotes the 'principal quantum

$$\mu^2 + g_{\text{eff}}^{\mu\nu} \frac{\partial S_{\text{eff}}}{\partial x^\mu} \frac{\partial S_{\text{eff}}}{\partial x^\nu} + \mathcal{O}(p^4) = 0$$

Sommerfeld's
"Old Quantum Mechanics"
(action-angle variables &
Delaunay Hamiltonian)

$$J = \ell\hbar = \frac{1}{2\pi} \oint p_\varphi d\varphi$$

$$N = n\hbar = I_r + J$$

$$I_r = \frac{1}{2\pi} \oint p_r dr$$

$$H^{\text{classical}}(q,p) \longrightarrow H^{\text{classical}}(I_a) \longrightarrow \boxed{E^{\text{quantum}}(I_a = n_a h) = f^{-1}[\mathcal{E}_{\text{eff}}^{\text{quantum}}(I_a^{\text{eff}} = n_a h)]}$$

EXPLICIT FORM OF THE 3PN EOB HAMILTONIAN

EOB Hamiltonian

$$H_{\mathrm{EOB}} = M\sqrt{1+2\nu\left(\hat{H}_{\mathrm{eff}}-1\right)}$$

$$\nu \equiv \frac{\mu}{M} \equiv \frac{m_1 m_2}{(m_1+m_2)^2}$$

All functions are a ν-dependent deformation of the Schwarzschild ones

$$A(r) = 1 - 2u + 2\nu u^3 + a_4 \nu u^4$$

$$a_4 = \frac{94}{3} - \frac{41}{32}\pi^2 \simeq 18.6879027$$

$$A(r)B(r) = 1 - 6\nu u^2 + 2(3\nu - 26)\nu u^3$$

$$u = GM/(c^2 R)$$

Simple effective Hamiltonian:

$$\hat{H}_{\mathrm{eff}} \equiv \sqrt{p_{r_*}^2 + A(r)\left(1 + \frac{p_\varphi^2}{r^2} + z_3\frac{p_{r_*}^4}{r^2}\right)}$$

$$p_{r_*} = \left(\frac{A}{B}\right)^{1/2} p_r$$

Crucial EOB radial potential

Contribution at 3PN

POST-NEWTONIAN HAMILTONIAN (C.O.M)

$$\hat{H}^{\rm NR}_{\rm real}(\mathbf{q},\mathbf{p}) = \hat{H}_{\rm N}(\mathbf{q},\mathbf{p}) + \hat{H}_{\rm 1PN}(\mathbf{q},\mathbf{p}) + \hat{H}_{\rm 2PN}(\mathbf{q},\mathbf{p}) + \hat{H}_{\rm 3PN}(\mathbf{q},\mathbf{p}), \tag{4.27}$$

where

$$\hat{H}_{\rm N}(\mathbf{q},\mathbf{p}) = \frac{\mathbf{p}^2}{2} - \frac{1}{q}, \quad \text{Newton} \quad \text{(0PN)} \tag{4.28a}$$

$$\hat{H}_{\rm 1PN}(\mathbf{q},\mathbf{p}) = \frac{1}{8}(3\nu-1)(\mathbf{p}^2)^2 - \frac{1}{2}\left[(3+\nu)\mathbf{p}^2 + \nu(\mathbf{n}\cdot\mathbf{p})^2\right]\frac{1}{q} + \frac{1}{2q^2}, \quad \text{(1PN, 1938)} \tag{4.28b}$$

- [Einstein-Infeld-Hoffman]

$$\hat{H}_{\rm 2PN}(\mathbf{q},\mathbf{p}) = \frac{1}{16}\left(1-5\nu+5\nu^2\right)(\mathbf{p}^2)^3 + \frac{1}{8}\left[\left(5-20\nu-3\nu^2\right)(\mathbf{p}^2)^2 - 2\nu^2(\mathbf{n}\cdot\mathbf{p})^2\mathbf{p}^2 - 3\nu^2(\mathbf{n}\cdot\mathbf{p})^4\right]\frac{1}{q}$$
$$+\frac{1}{2}\left[(5+8\nu)\mathbf{p}^2 + 3\nu(\mathbf{n}\cdot\mathbf{p})^2\right]\frac{1}{q^2} - \frac{1}{4}(1+3\nu)\frac{1}{q^3}, \quad \text{(2PN, 1982/83)} \tag{4.28c}$$

- [Damour-Deruelle]

$$\hat{H}_{\rm 3PN}(\mathbf{q},\mathbf{p}) = \frac{1}{128}\left(-5+35\nu-70\nu^2+35\nu^3\right)(\mathbf{p}^2)^4$$
$$+\frac{1}{16}\left[\left(-7+42\nu-53\nu^2-5\nu^3\right)(\mathbf{p}^2)^3 + (2-3\nu)\nu^2(\mathbf{n}\cdot\mathbf{p})^2(\mathbf{p}^2)^2 + 3(1-\nu)\nu^2(\mathbf{n}\cdot\mathbf{p})^4\mathbf{p}^2 - 5\nu^3(\mathbf{n}\cdot\mathbf{p})^6\right]\frac{1}{q}$$
$$+\left[\frac{1}{16}\left(-27+136\nu+109\nu^2\right)(\mathbf{p}^2)^2 + \frac{1}{16}(17+30\nu)\nu(\mathbf{n}\cdot\mathbf{p})^2\mathbf{p}^2 + \frac{1}{12}(5+43\nu)\nu(\mathbf{n}\cdot\mathbf{p})^4\right]\frac{1}{q^2} \quad \text{(3PN, 2000)}$$
$$+\left\{\left[-\frac{25}{8} + \left(\frac{1}{64}\pi^2 - \frac{335}{48}\right)\nu - \frac{23}{8}\nu^2\right]\mathbf{p}^2 + \left(-\frac{85}{16} - \frac{3}{64}\pi^2 - \frac{7}{4}\nu\right)\nu(\mathbf{n}\cdot\mathbf{p})^2\right\}\frac{1}{q^3}$$
$$+\left[\frac{1}{8} + \left(\frac{109}{12} - \frac{21}{32}\pi^2 + \omega_{\rm static}\right)\nu\right]\frac{1}{q^4}. \tag{4.28d}$$

- [Damour, Jaranowski,Schaefer]

...and **4PN** too, [Damour, Jaranowski&Schaefer 2014/2015] - 4 loop calculation

$$\mathbf{q} = \mathbf{q}_1 - \mathbf{q}_2$$

$$\mathbf{p} = \mathbf{p}_1 = -\mathbf{p}_2$$

The first EOB vs NR comparison

Buonanno-Cook-Pretorius 2007

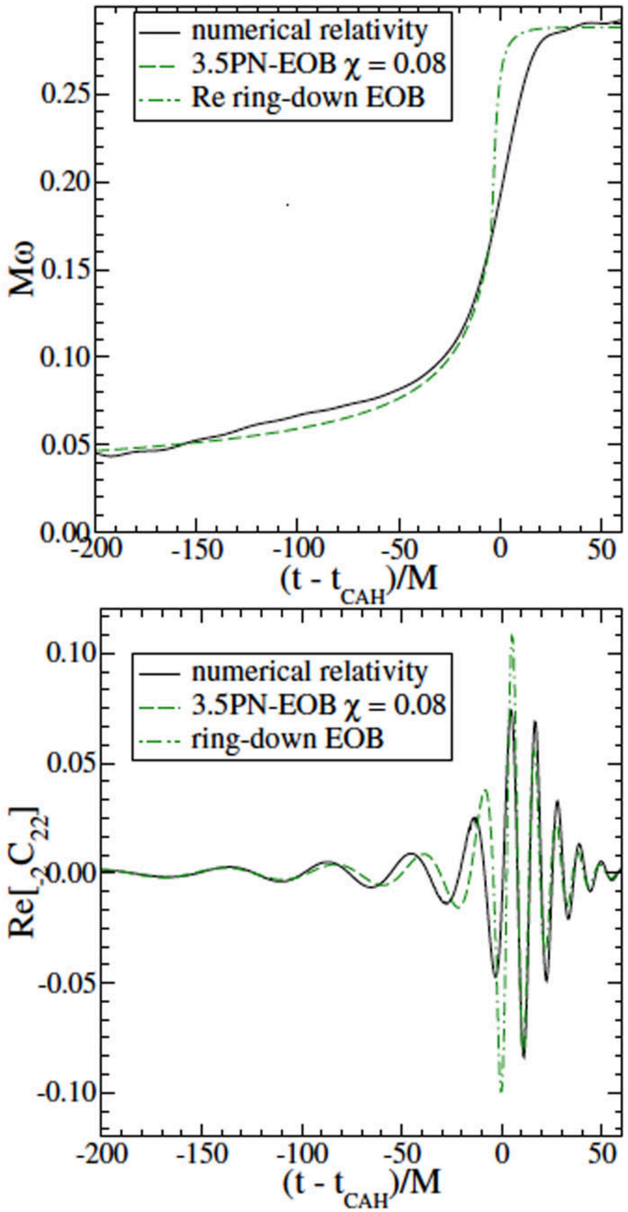
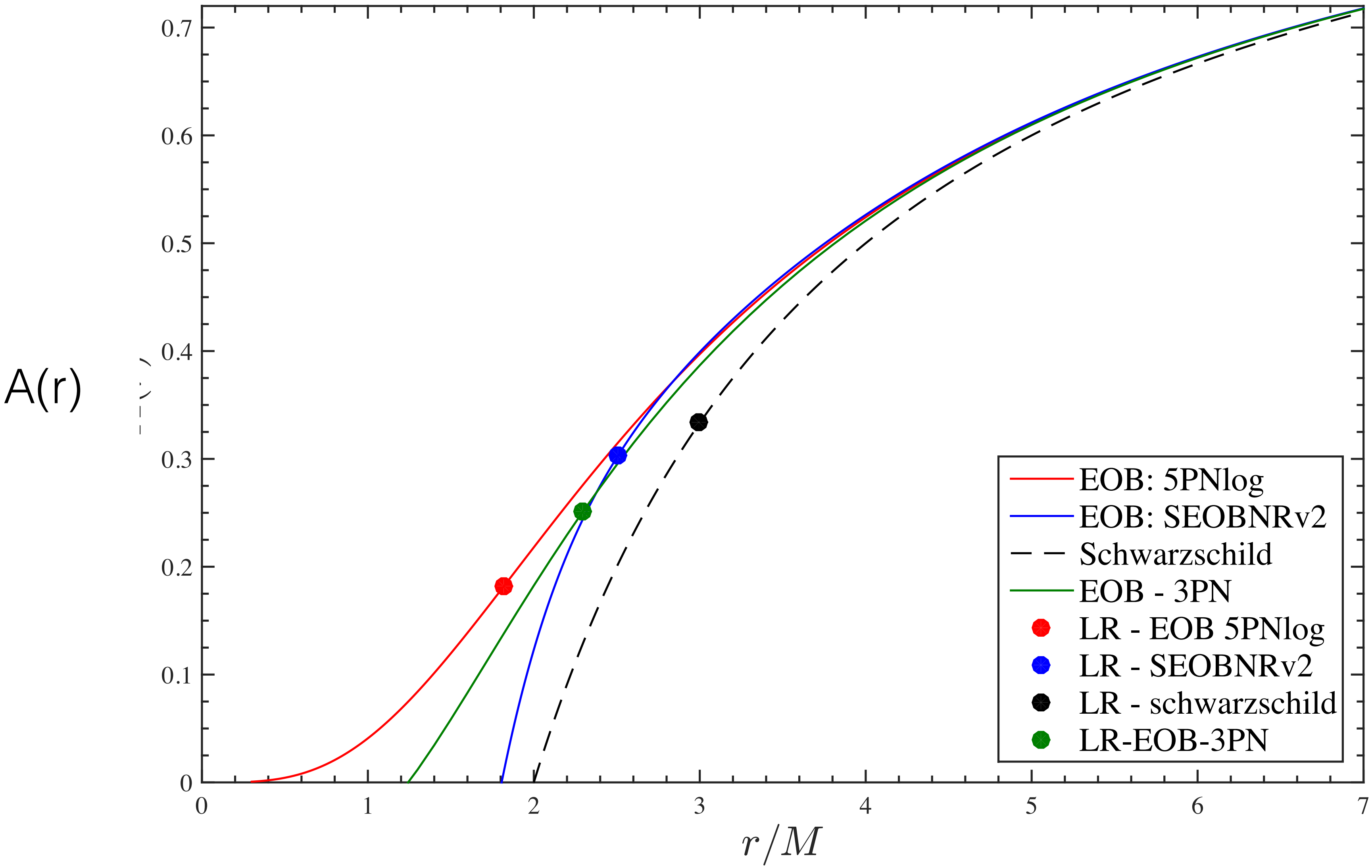


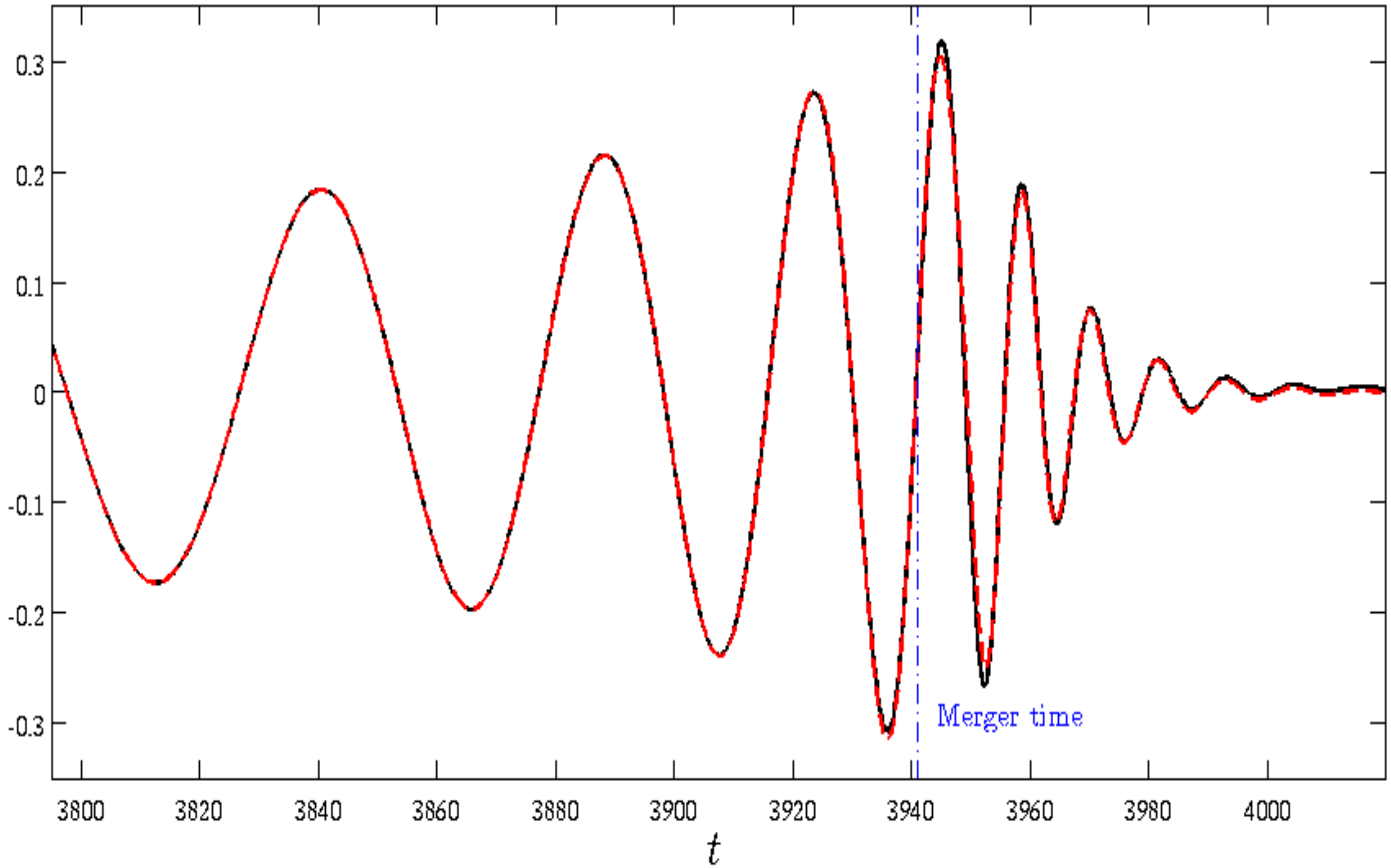
FIG. 21 (color online). We compare the NR and EOB frequency and Re$[{}_{-2}C_{22}]$ waveforms throughout the entire inspiral–merger–ring-down evolution. The data refers to the $d = 16$ run.

MAIN RADIAL RADIAL EOB POTENTIAL A(R)



NR VS EOB[NR]

non-spinning, equal masses

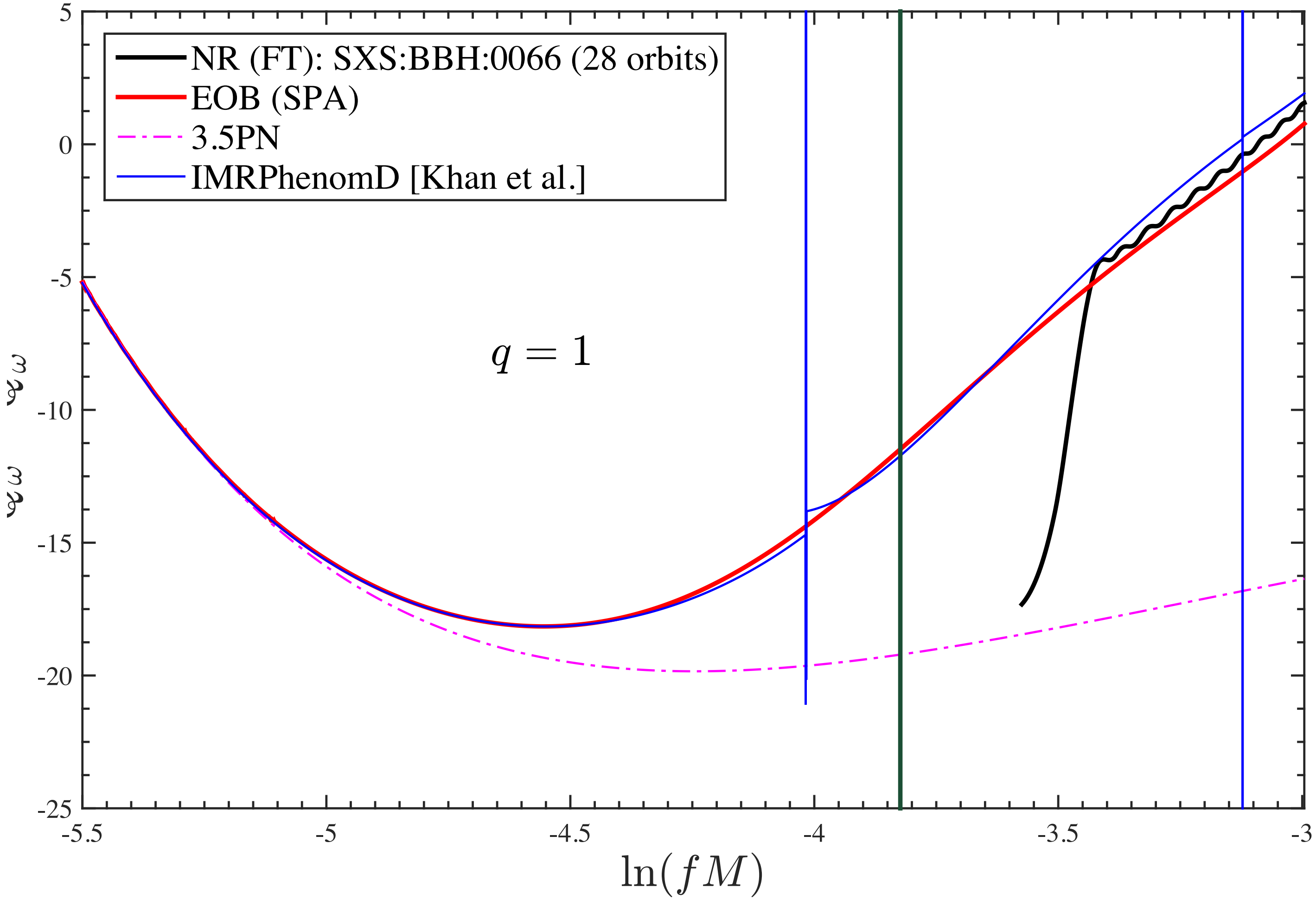


PN, EOB, NR, PHENOMD

There generally exists a gap between PN and NR

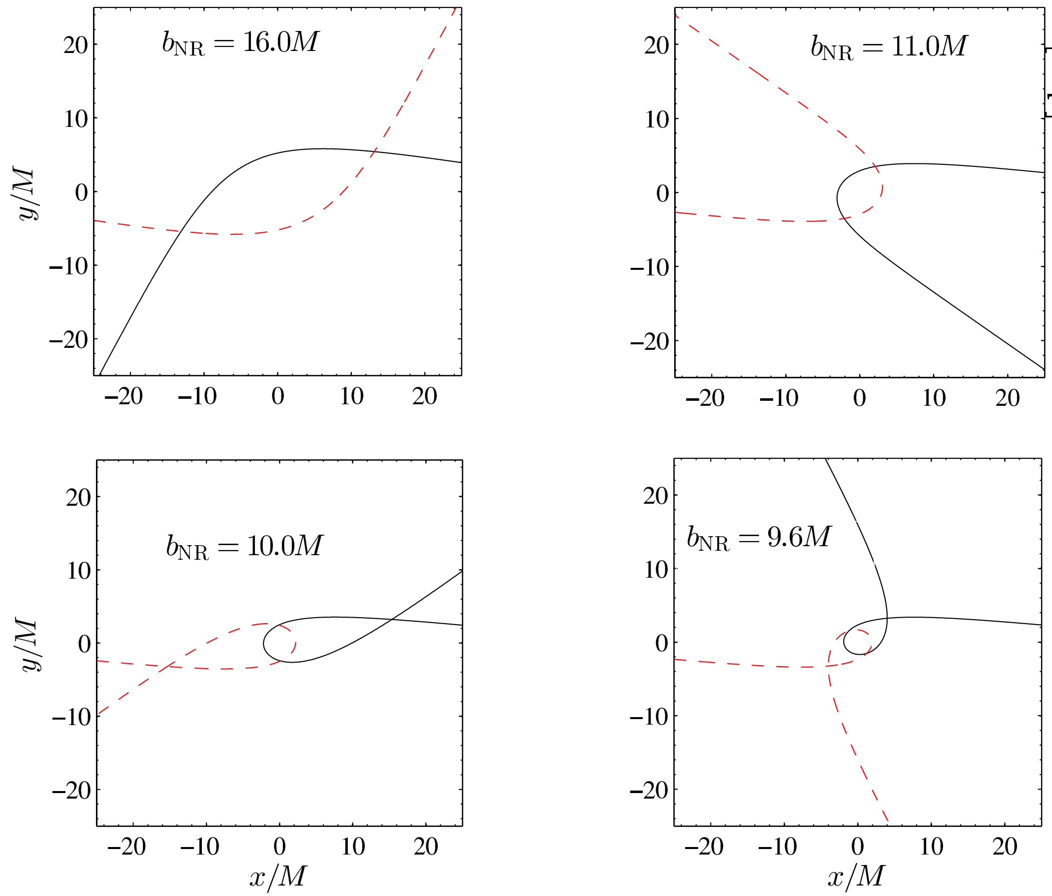
Dimensionless « quality factor » of GW phase $Q_\omega = f^2 \frac{d^2\psi(f)}{df^2} \approx \frac{\omega^2}{\dot{\omega}}$

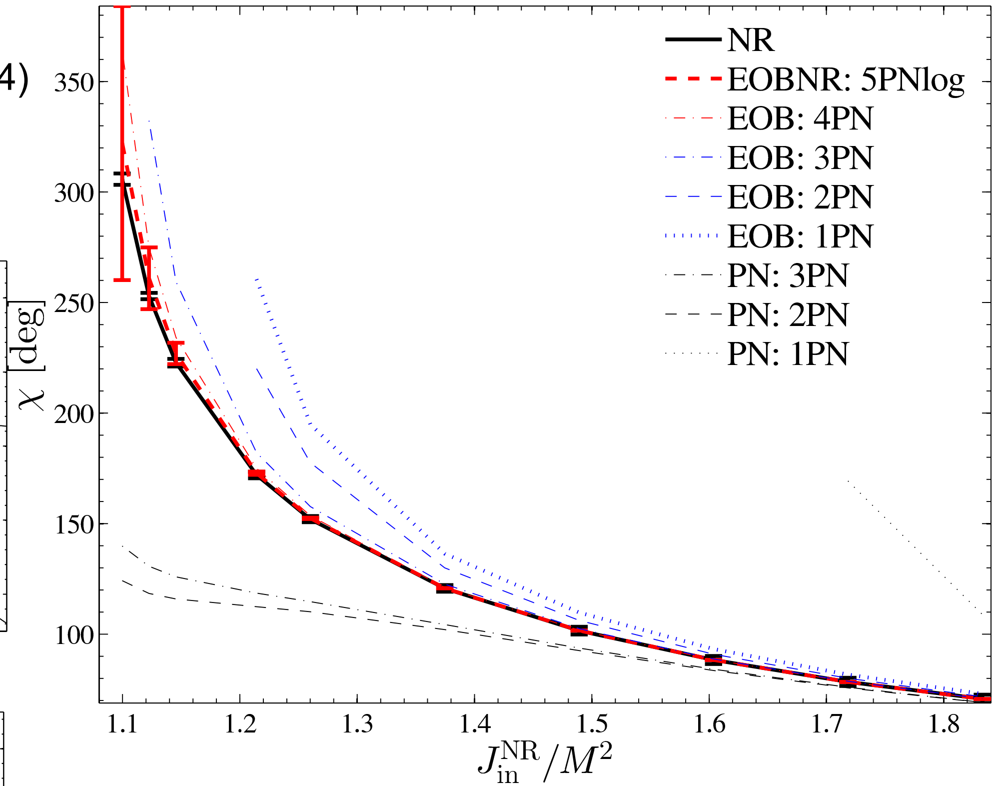
$Q_\omega - Q_\omega^N$

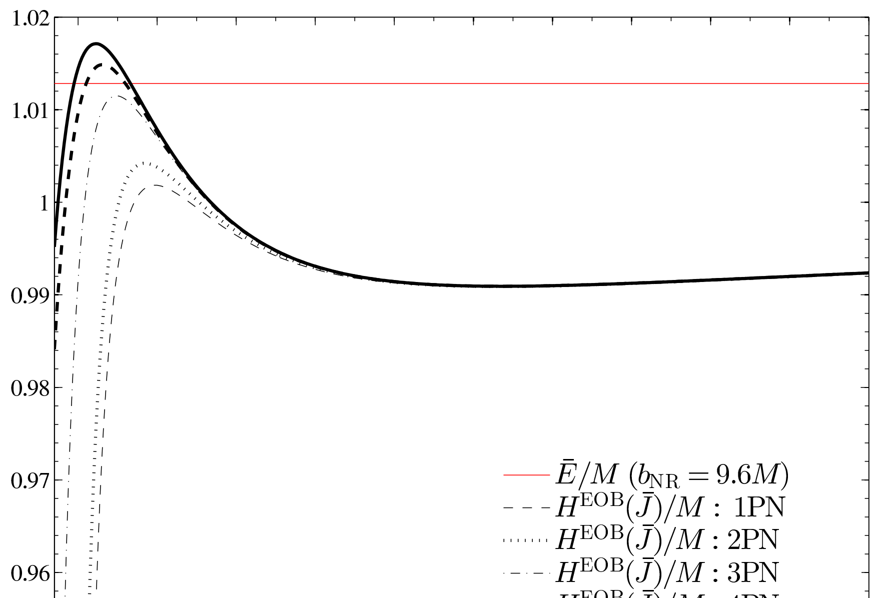


STRONG-FIELD SCATTERING OF TWO BLACK HOLES

(Damour, Guercilena, Hinder, Hopper, Nagar, Rezzolla 2014)







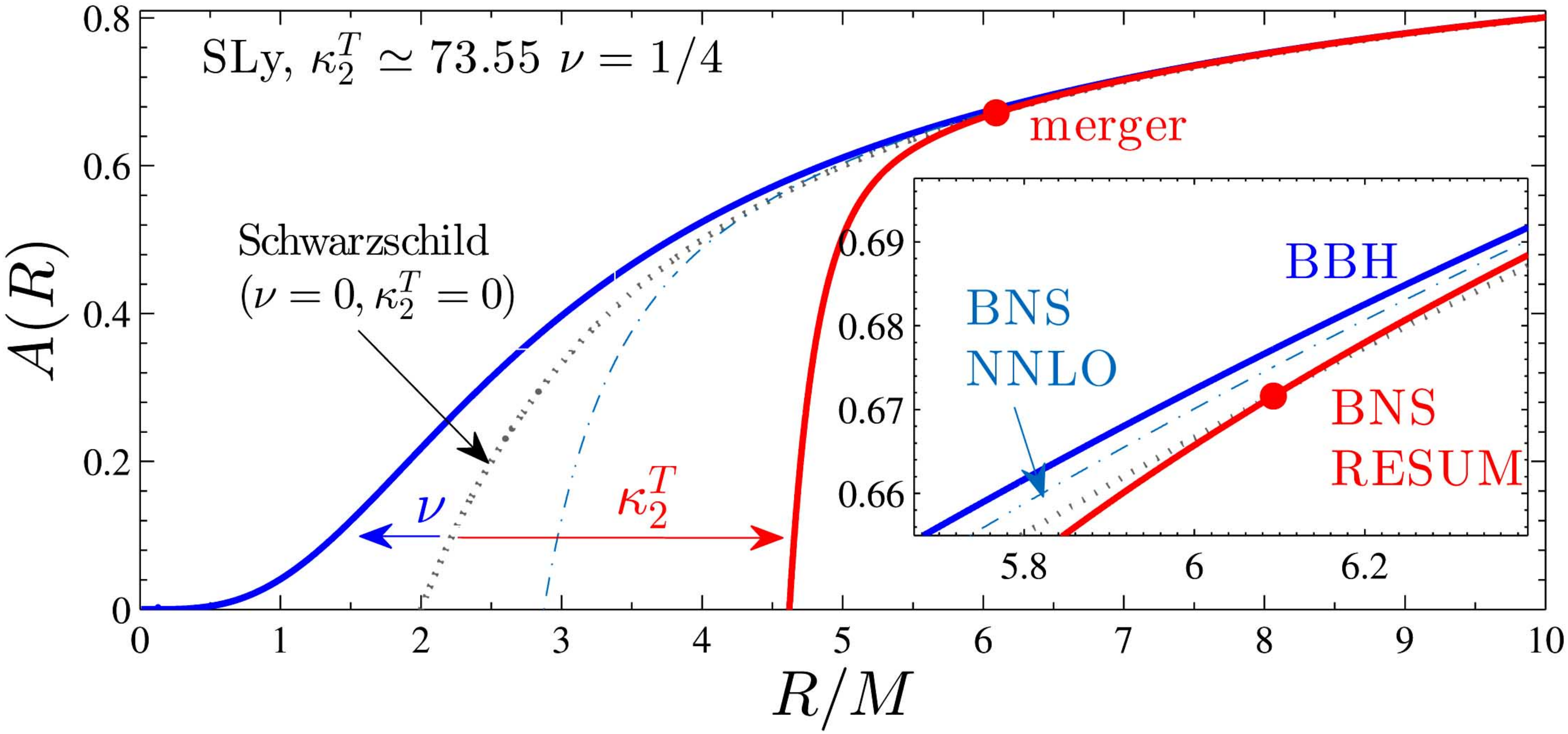
(PERSONALLY-BIASSED) FUTURE PROSPECTS IN: EOB THEORY + FUNDAMENTAL PHYSICS

PROBING THE NUCLEAR EOS FROM LATE INSPIRAL TIDAL EFFECTS IN NSNS OR BHNS

Tidal extension of EOB (TEOB) [Damour-Nagar 09]

$$\begin{aligned} A(r) &= A_r^0 + A^{\text{tidal}}(r) \\ A^{\text{tidal}}(r) &= -\kappa_2^T u^6 \left(1 + \bar{\alpha}_1 u + \bar{\alpha}_2 u^2 + \dots\right) + \dots \end{aligned}$$

TEOB[NR] A(R) potential (Bernuzzi et al. 2015)

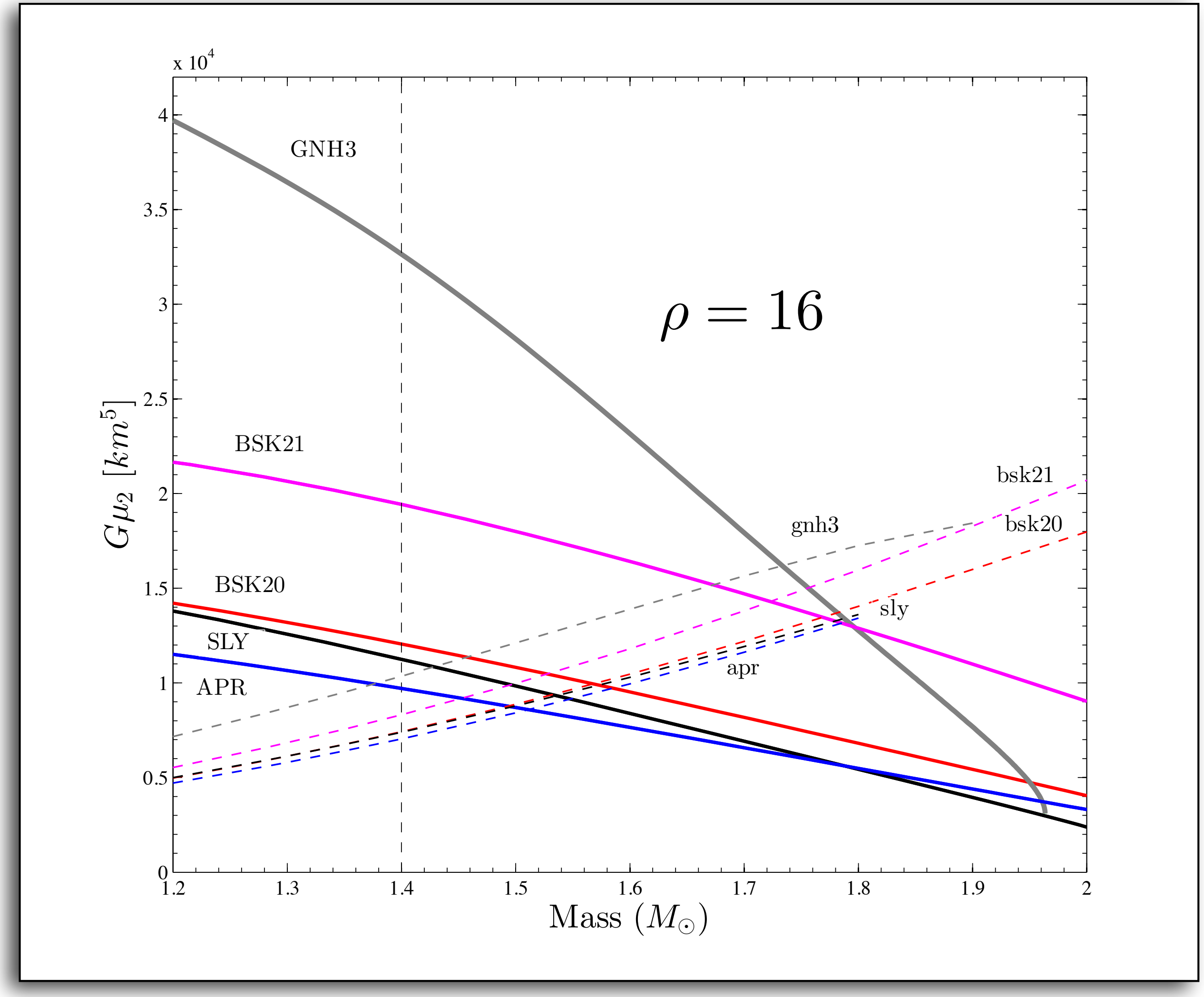


FUTURE PROSPECT 1:
PROBING THE NUCLEAR EOS FROM LATE INSPIRAL TIDAL EFFECTS IN NSNS OR BHNS

Tidal parameter:

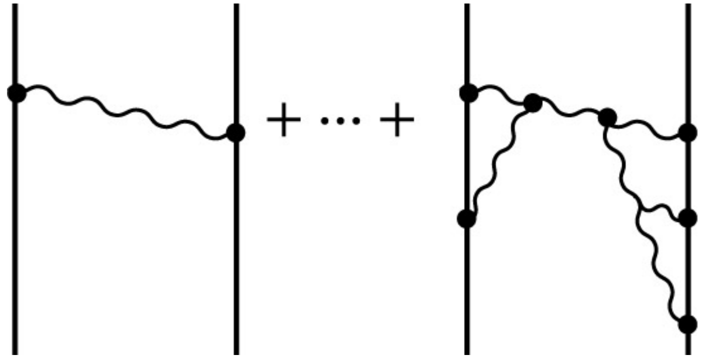
$$\kappa_2^T(\mu_2^A, \mu_2^B)$$

can be measured from data analysis of BNS late inspiral (Damour-Nagar-Villain 12; Del Pozzo et al 13; Agathos et al 15, ….)

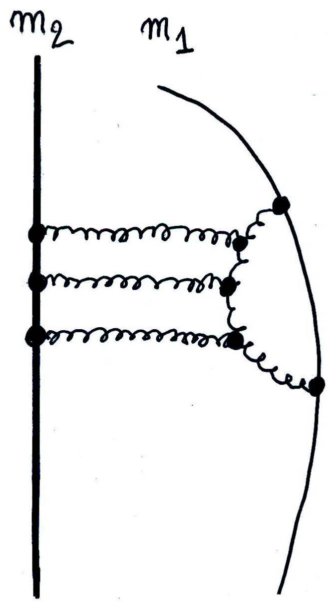


EOB AND GSF

Comparable-mass case: $m_1 \sim m_2$



Gravitational Self-Force Theory : $m_1 << m_2$



- Analytical high-PN results : Blanchet-Detweiler-LeTiec-Whiting '10, Damour '10, Blanchet et al '10, LeTiec et al '12, Bini-Damour '13-15, Kavanagh-Ottewill-Wardell '15
- (gauge-invariant) Numerical results : Detweiler '08, Barack-Sago '09, Blanchet-Detweiler-LeTiec-Whiting '10, Barack-Damour-Sago '10, Shah-Friedman-Keidl '12, Dolan et al '14, Nolan et al '15, …
- Analytical PN results from high-precision (hundreds to thousands of digits !) numerical results : Shah-Friedman-Whiting '14, Johnson-McDaniel-Shah-Whiting '15

EOB, GSF AND 4PN

4PN analytically complete + 5PN logarithmic term in the A(u) function:

[Damour 2009, Blanchet et al. 2010, Barack, Damour & Sago 2010, Le Tiec et al. 2011, Barausse et al. 2011, Akcay et al. 2012, Jaranowski&Schaefer 2013, Bini& Damour2013, DamourJaranowski&Schaefer 2014].

$$A_{5\mathrm{PN}}^{\mathrm{Taylor}} = 1 - 2u + 2\nu u^3 + \left(\frac{94}{3} - \frac{41}{32}\pi^2\right)\nu u^4 + \nu[a_5^c(\nu) + a_5^{\ln}\ln u]u^5 + \nu[a_6^c(\nu) + a_6^{\ln}\ln u]u^6$$

$$a_5^{\log} = \frac{64}{5}$$
$$a_5^c = a_{5_0}^c + \nu a_{5_1}^c$$
$$a_{5_0}^c = -\frac{4237}{60} + \frac{2275}{512}\pi^2 + \frac{256}{5}\log(2) + \frac{128}{5}\gamma$$
$$a_{5_1}^c = -\frac{221}{6} + \frac{41}{32}\pi^2$$
$$a_6^{\log} = -\frac{7004}{105} - \frac{144}{5}\nu$$

Recent GSF confirmations of ADM [Damour–Jaranowski–Schaefer 2014] 4PN dynamics

Damour-Jaranowski-Schaefer 2016 using several bridges (EOB, periastron precession, First Law BBH Dynamics [LeTiec-Blanchet-Whiting 2012], order-reduction) and recent GSF results [vandeMeent-Shah2015; Bini-Damour-Geralico2016; Hopper-Kavanagh-Ottewill2016; Akcay-vandeMeent2016; vandeMeent2016;…

$$\rho_4^{c,\mathrm{DJS}} = \frac{58265}{1536}\pi^2 - \frac{215729}{180} + \frac{5024}{15}\gamma_{\mathrm{E}} + \frac{1184}{15}\ln 2 + \frac{2916}{5}\ln 3.$$

$= 64.6405647571193\ldots\ldots$

$$\rho_4^{c,\mathrm{num}[35]} = 64.640566(2), \qquad \delta^{\mathrm{B^3FM}}\rho_4^c = \frac{44026}{315} \approx 139.7650794.$$

FUTURE PROSPECTS 2

GSF + EOB for LISA

GSF community working on 2SF approximation, i.e.

$$A(u) = 1 - 2u + \nu a_1(u) + \nu^2 a_2(u) + O(\nu^3)$$

Fundamental physics challenges:

understand remarkable cancellations in EOB A(u;nu)

use recent mathematical understanding of high-loop Feynman amplitudes
(Broadhurst-Kreimer, Bloch-Esnault-Kreimer-Deligne, Brown, Bloch-Vanhove, ….)

GSF : ANALYTICAL HIGH-PN RESULTS

Bini-Damour 15

$$
\begin{aligned}
a_{10}^{c} = {} & \frac{18605478842060273}{7079830758000}\ln(2) - \frac{1619008}{405}\zeta(3) - \frac{21339873214728097}{1011404394000}\gamma \\
& + \frac{27101981341}{100663296}\pi^6 - \frac{6236861670873}{125565440}\ln(3) + \frac{360126}{49}\ln(2)\ln(3) + \frac{180063}{49}\ln(3)^2 \\
& - \frac{121494974752}{9823275}\ln(2)^2 - \frac{24229836023352153}{549755813888}\pi^4 + \frac{1115369140625}{124540416}\ln(5) + \frac{96889}{2779} \\
& + \frac{75437014370623318623299}{18690753201120000} - \frac{60648244288}{9823275}\ln(2)\gamma + \frac{200706848}{280665}\gamma^2 \\
& + \frac{11980569677139}{2306867200}\pi^2 + \frac{360126}{49}\gamma\ln(3), \\
a_{10}^{\ln} = {} & -\frac{21275143333512097}{2022808788000} + \frac{200706848}{280665}\gamma - \frac{30324122144}{9823275}\ln(2) + \frac{180063}{49}\ln(3), \\
a_{10}^{\ln^2} = {} & \frac{50176712}{280665}, \\
a_{10.5}^{c} = {} & -\frac{185665618769828101}{24473489040000}\pi + \frac{377443508}{77175}\ln(2)\pi + \frac{2414166668}{1157625}\pi\gamma - \frac{5846788}{11025}\pi^3 - \frac{24}{} \\
a_{10.5}^{\ln} = {} & \frac{1207083334}{1157625}\pi.
\end{aligned}
$$

Kavanagh et al 15

$$
\begin{aligned}
c_{15} = {} & -\tfrac{2069543450583769619340376724}{325477442086506084375}\zeta(3) + \tfrac{6519502629824500793 6}{22370298575625}\gamma\zeta(3) - \tfrac{5049442304}{25725}\gamma^2\zeta(3) + \tfrac{1262360576}{15435}\pi^2\zeta(3) \\
& + \tfrac{171722752}{441}\zeta(3)^2 + \tfrac{1613866959570176}{496621125}\zeta(5) - \tfrac{343445504}{441}\gamma\zeta(5) - \tfrac{146997248}{105}\zeta(7) + \tfrac{56314978304}{385875}\zeta(3)\log^2(2) \\
& - \tfrac{106445664}{343}\zeta(3)\log^2(3) + \tfrac{151670998244849797696}{22370298575625}\zeta(3)\log(2) - \tfrac{190336581632}{1157625}\gamma\zeta(3)\log(2) \\
& + \tfrac{28863591064624341}{4909804900}\zeta(3)\log(3) - \tfrac{212891328}{343}\gamma\zeta(3)\log(3) - \tfrac{212891328}{343}\zeta(3)\log(2)\log(3) - \tfrac{77186767578125}{19876428}\zeta(3)\log \\
& - \tfrac{2039263232}{3675}\zeta(5)\log(2) - \tfrac{49128768}{49}\zeta(5)\log(3) + \tfrac{298267427515018397019736592175289419501391539444290849}{6587612222544653226142468405031917319531250} \\
& - \tfrac{680766176845363776831328694806032908750 1419}{704310948124803722562607729544062500}\gamma + \tfrac{1598346944412603247831006289829388}{526171715038677033591890625}\gamma^2 - \tfrac{1007647146215971027644}{335890033113009375} \\
& + \tfrac{461219496448}{72930375}\gamma^4 - \tfrac{28338275082077591587855063450276303790065762907243197}{999703155845143418115744045792755712000000}\pi^2 + \tfrac{25191178655399275691104}{67178006622601875}\gamma\pi^2 \\
& - \tfrac{230609748224}{14586075}\gamma^2\pi^2 + \tfrac{105480323357757226894713787760391180776248036241}{304245354831316028025099055320268800000}\pi^4 + \tfrac{1262360576}{385875}\gamma\pi^4 \\
& - \tfrac{6208472839612966972691457131143}{266930151354100246118400}\pi^6 + \tfrac{3573178781920929118281329}{151996487423754240}\pi^8 - \tfrac{10136323685888}{72930375}\log^4(2) + \tfrac{38438712}{2401}\log^4(3) \\
& - \tfrac{1778960861264826796478 72}{549638236003106 25}\log^3(2) - \tfrac{89686013106176}{364651875}\gamma\log^3(2) + \tfrac{153754848}{2401}\log^3(2)\log(3) \\
& - \tfrac{131463845322790269123}{245735735245000}\log^3(3) + \tfrac{153754848}{2401}\gamma\log^3(3) + \tfrac{153754848}{2401}\log(2)\log^3(3) + \tfrac{11933074267578125}{51161925672}\log^3(5) \\
& + \tfrac{3878258674166628974595420635200204}{189421817413923732093080625}\log^2(2) - \tfrac{3440856379914601692151168}{1007670099339028125}\gamma\log^2(2) - \tfrac{16582891400192}{121550625}\gamma^2\log^2(2) \\
& + \tfrac{4145722850048}{72930375}\pi^2\log^2(2) - \tfrac{523697163373483905609}{245735735245000}\log^2(2)\log(3) + \tfrac{461264544}{2401}\gamma\log^2(2)\log(3) \\
& + \tfrac{45454535766189065888302299261759}{6569728226789883034880000}\log^2(3) - \tfrac{394391535968370807369}{245735735245000}\gamma\log^2(3) + \tfrac{230632272}{2401}\gamma^2\log^2(3) \\
& - \tfrac{96096780}{2401}\pi^2\log^2(3) - \tfrac{437493411770075173449}{245735735245000}\log(2)\log^2(3) + \tfrac{461264544}{2401}\gamma\log(2)\log^2(3) \\
& + \tfrac{230632272}{2401}\log^2(2)\log^2(3) + \tfrac{11933074267578125}{17053975224}\log^2(2)\log(5) - \tfrac{2505842696993145943705498046875}{402136320895332222431232}\log^2(5) \\
& + \tfrac{11933074267578125}{17053975224}\gamma\log^2(5) + \tfrac{11933074267578125}{17053975224}\log(2)\log^2(5) + \tfrac{47929508316470415142010251}{56464635170211840000}\log^2(7) \\
& - \tfrac{181636067216895220421537747685253699734494659}{6338798533123233503063469565896562500}\log(2) + \tfrac{742036621552191085437995316530101 36}{4735545435348093302327015625}\gamma\log(2) \\
& - \tfrac{1482169326522492515499392}{1007670099339028125}\gamma^2\log(2) - \tfrac{4905667647488}{364651875}\gamma^3\log(2) + \tfrac{371228115490667668451168}{604602059603416875}\pi^2\log(2) \\
& + \tfrac{1226416911872}{72930375}\gamma\pi^2\log(2) + \tfrac{23792072704}{17364375}\pi^4\log(2) - \tfrac{4141158375397180302387095124935855747727}{1082666315962744888801986560000000}\log(3) \\
& + \tfrac{9459358001131575454332055276239}{691550339662092951040000}\gamma\log(3) - \tfrac{394391535968370807369}{245735735245000}\gamma^2\log(3) + \tfrac{153754848}{2401}\gamma^3\log(3) \\
& + \tfrac{131463845322790269123}{196588588196000}\pi^2\log(3) - \tfrac{192193560}{2401}\gamma\pi^2\log(3) + \tfrac{8870472}{1715}\pi^4\log(3) \\
& + \tfrac{21441150106021138984596292714 8381}{13139456453579766069760000}\log(2)\log(3) - \tfrac{437493411770075173449}{122867867622500}\gamma\log(2)\log(3) \\
& + \tfrac{461264544}{2401}\gamma^2\log(2)\log(3) - \tfrac{192193560}{2401}\pi^2\log(2)\log(3) + \tfrac{978612948501709853277095576118865234375}{17942749191956127021132384903168}\log(5) \\
& - \tfrac{2505842696993145943705498046875}{201068160447666111215616}\gamma\log(5) + \tfrac{11933074267578125}{17053975224}\gamma^2\log(5) - \tfrac{59665371337890625}{204647702688}\pi^2\log(5) \\
& - \tfrac{2505842696993145943705498046875}{201068160447666111215616}\log(2)\log(5) + \tfrac{11933074267578125}{8526987612}\gamma\log(2)\log(5) \\
& - \tfrac{5858006173792308915665113013914648081}{32391919320751280297779200000 0}\log(7) + \tfrac{47929508316470415142010251}{28232317585105920000}\gamma\log(7) \\
& + \tfrac{47929508316470415142010251}{28232317585105920000}\log(2)\log(7) + \tfrac{740024994425816010121 1}{656763448320000 00}\log(11),
\end{aligned}
$$

FUTURE PROSPECT 3:
GW BURSTS FROM COSMIC STRINGS IN LIGO/... AND LISA

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Gravitational Wave Bursts from Cosmic Strings

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Cusps of cosmic strings emit strong beams of high-frequency gravitational waves (GW). As a consequence of these beams, the stochastic ensemble of gravitational waves generated by a cosmological network of oscillating loops is strongly non-Gaussian, and includes occasional sharp bursts that stand above the rms GW background. These bursts might be detectable by the planned GW detectors LIGO/VIRGO and LISA for string tensions as small as $G\mu \sim 10^{-13}$. The GW bursts discussed here might be accompanied by gamma ray bursts.

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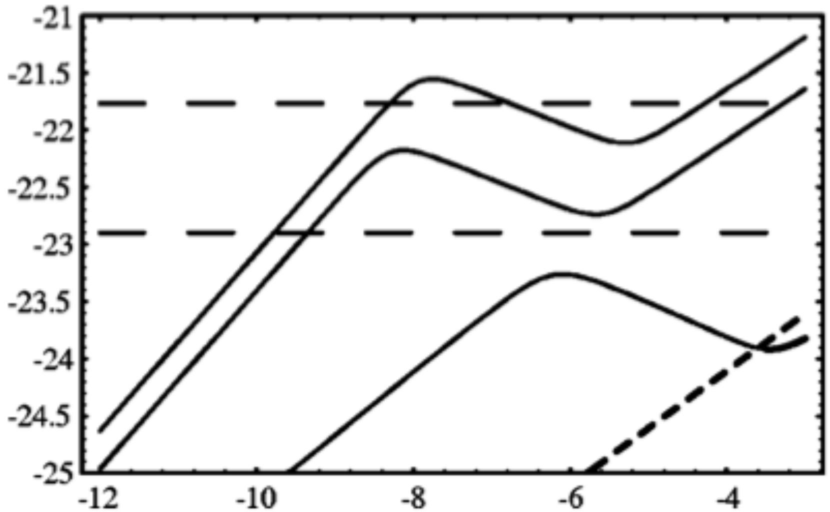
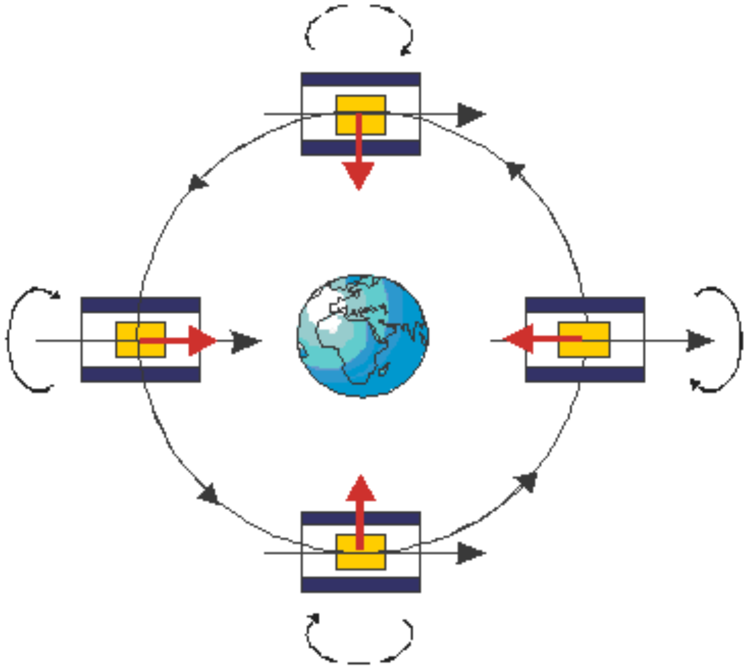


FIG. 1. Gravitational wave amplitude of bursts emitted by cosmic string cusps (upper curves) and kinks (lower curve) in the LIGO-VIRGO frequency band, as a function of the parameter $\alpha = 50G\mu$ (in a base-10 log-log plot). The upper curve assumes that the average number of cusps per loop oscillation is $c=1$. The middle curve assumes $c=0.1$. The lower curve gives the kink signal (assuming only one kink per loop). The horizontal dashed lines indicate the one sigma noise levels (after optimal filtering) of LIGO 1 (initial detector) and LIGO 2 (advanced configuration). The short-dashed line indicates the "confusion" amplitude noise of the stochastic GW background.

FUTURE PROSPECT 4:
EQUIVALENCE PRINCIPLE VIOLATION

Space mission MICROSCOPE: launched April 25, 2016



Microscope will test the
universality of free fall
at the 10^-15 level

Could discover the most probable modification of GR:
an EP-violating scalar field or ``dilaton''

A CITATION TO KEEP IN MIND

«Our mistake is not the we take our theories too seriously,
but that we do not take them seriously enough »
Steven Weinberg

TESTS OF STRONG-FIELD GRAVITY

Paradox: GWs from coalescing BBH is certainly a signal coming from a relativistic (v/c =1/2) and strong-field (GM/c^2r=1/2) regime, but it is not clear if it can detect interesting violations from GR

Issue: no primary scalar hair on BH

$$L = \frac{1}{16\pi G}(R - 2(\partial\varphi)^2)$$

with two BHs phi=constant is a solution (modulo cosmological gradients)

TESTING THEORIES

Phenomenological (theory-independent) approach

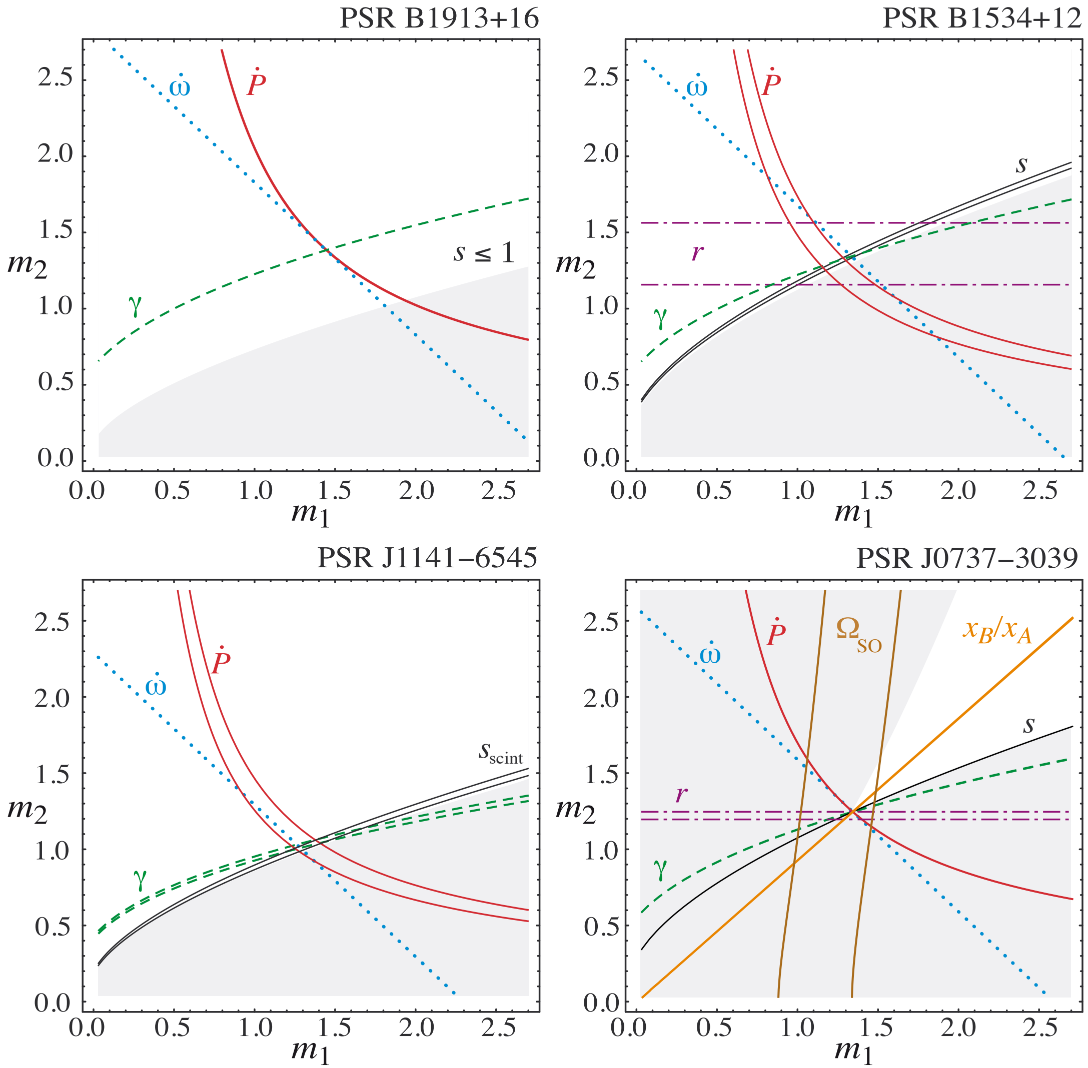
e.g. Mercury's periastron advance: $\dot{\omega}$

Comparing specific theories:
e.g. Newtonian vs Einsteinian gravity

Theory-space approach:
consider a multi-dimensional space of theories:
e.g. tensor-scalar gravity with free parameters
and/or free functions.
Problem: scarcity of sound, well-motivated alternatives to GR.
Lack of proof that currently considered alternative theories are
theoretically, and phenomenologically, sound
(Vainshtein mechanism ??; higher-derivative ghosts ??).
Use of models containing unmotivated scales

BINARY-PULSAR TESTS OF STRONG-FIELD GRAVITY

Phenomenological tests using the DD timing formula: Parametrized Post-Keplerian approach (Damour-Taylor 92)



THEORY-DEPENDENT PULSAR TESTS

1. Using a two-parameter space of tensor-scalar theories to consistently gather limits on deviations from GR
2. Thanks to spontaneous scalarization (Damour-Esposito-Farese93) one proves that pulsars probe possible large deviations GR linked to the inner strong-field of NSs
3. One can then compare the probing power of pulsar vs GW tests

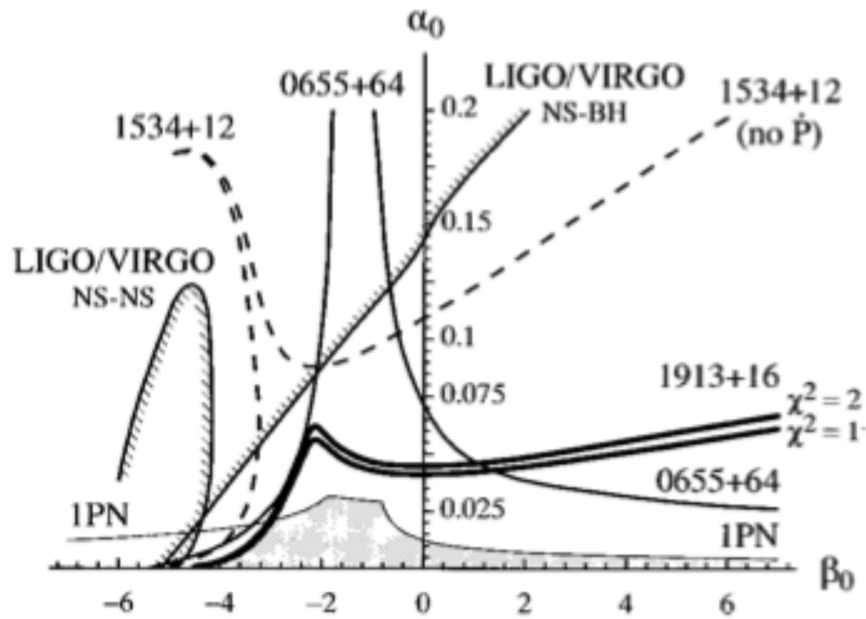
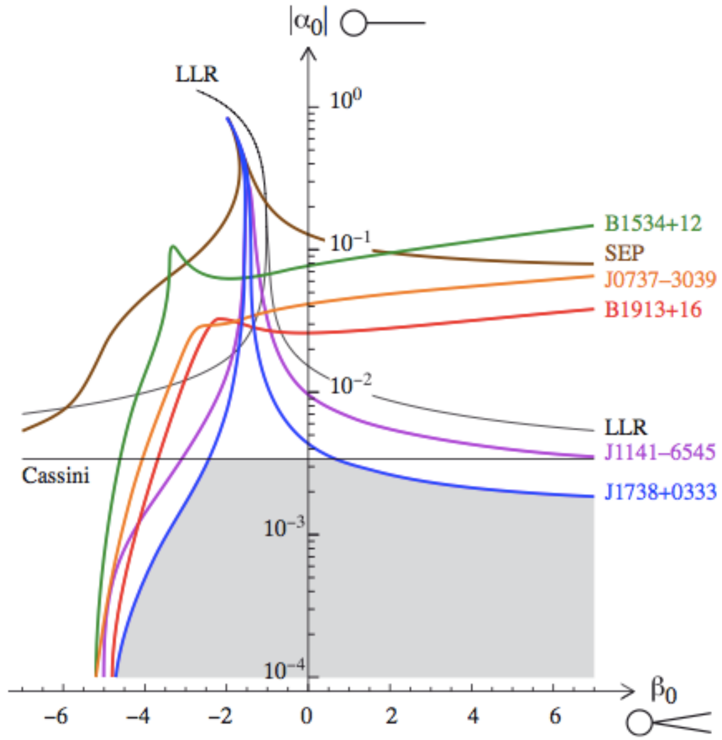


FIG. 1. Region of the (α_0, β_0) theory plane allowed by s system tests, binary-pulsar experiments, and future gravity- detections, in the case where nuclear matter is described by polytrope (2.4),(2.5). In view of the reflection symmetry

Damour-Esposito-Farese 98



Freire-Wex-Esposito-Farese et al.12

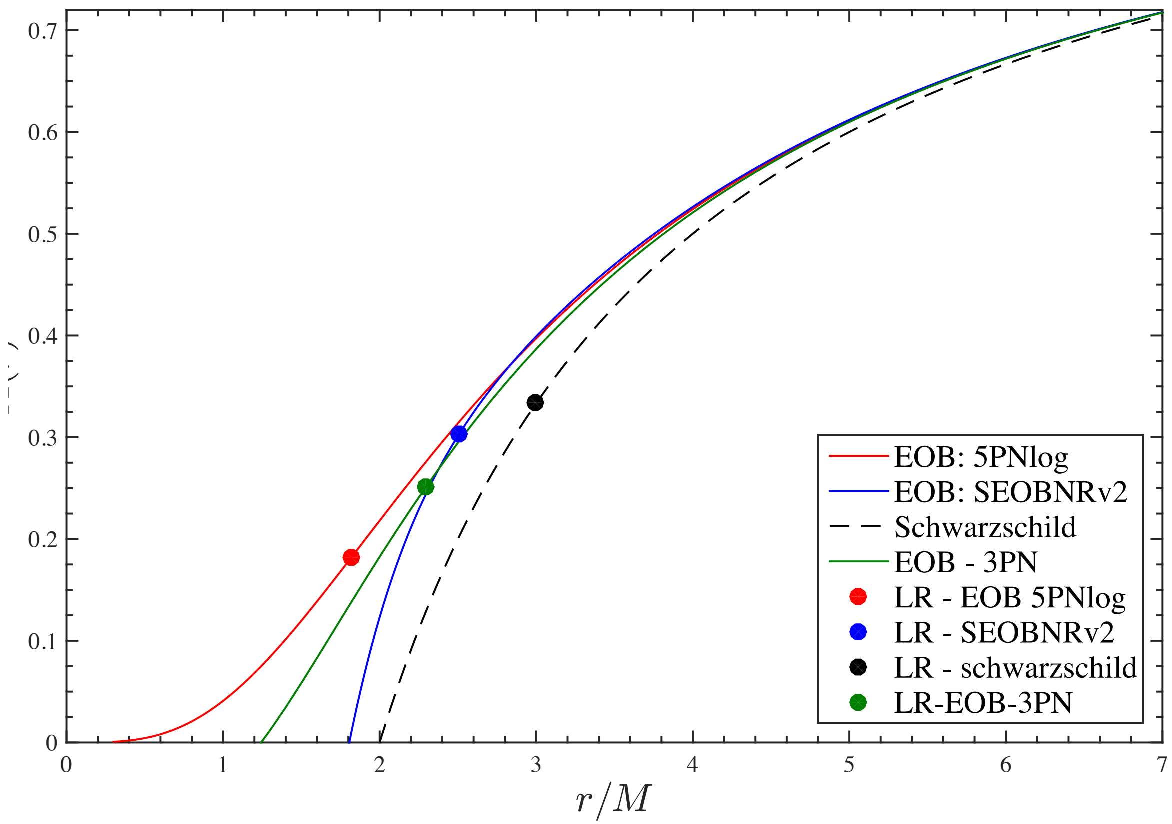
TESTING STRONG-FIELD GRAVITY IN BBH ?

I suggest two new possibilities:
a new phenomenological one, and a new theory-dependent one

1: Parametrized EOB (PEOB) approach:

Use the analytical flexibility of EOB: flex some of the crucial EOB functions determining the complete EOB waveform (including ring down) by modifying them in the strong-field (u =O(1)) or relativistic (x=O(1)) domain

A(r)



Possibility 2: Consider BHs in simplest String-inspired gravity

Consider a 4-parameter, two-derivative deformation of BBH in GR

$$L[g_{\mu\nu}, \varphi, A_\mu) = \frac{1}{16\pi G}(R - 2(\partial\varphi)^2 - \frac{1}{4}e^{g\varphi}F_{\mu\nu}F^{\mu\nu})$$

$$g_{\mu\nu}^{\mathrm{obs}} = e^{g'\varphi}g_{\mu\nu}$$

Here, A_mu is a « graviphoton » (Scherk), that could be coupled to dark matter, or to some shadow matter. Dimensionless parameters for « electric-type charges » (assuming some type of charge separation during gravitational collapse; differently from the NS case: Q_NS=0):

$$g; g'; q_1 = \frac{Q_1}{16\pi G m_1}; q_2 = \frac{Q_2}{16\pi G m_2}$$

The scalar hair of each (isolated) BH is a function of g, and q <~ 1.
The 4 parameters will coherently and smoothly deform the dynamics, the radiation damping, the merger, the ringdown, and the observed waveform (adding a spin-0 polarization). By restricting the parameters to special sub-spaces one can explore the sensitivity of GW150914 to various consistent strong-field effects (e.g. q1 + q2=0 or not =0)

CONCLUSIONS (1)

After the incredible excitement of observing the GW signal from the coalescence of two 30 M_sun BHs, and before GW astronomy becomes a routine, continuous discovery of more of the same sources, it would be marvelous if Nature, and GWs, had more surprises in store, especially if they were related to the most fundamental aspects of physics, such as:

GW bursts from cosmological-size (fundamental) strings

Equivalence-Principle violation possibly related to the dilaton

Conceptually, one would very much like BH coalescences to open a window on new physics (quantum effects during horizon coalescence, e.g. if there is some truth in the firewall or fuzzball ideas), but it is not clear (in view of the very low-energy character of the process) if this can be the case.

GWS AND THE A. EINSTEIN INSTITUTE (1)

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6/10/92

Dear Thibault,

enclosed is the final version of our Einstein-memo which I have given to the president of the MPG. Notice one important change: Not one small <u>or</u> one large solution is proposed, but instead a "stepwise construction" of a (large) institute, with some participation of the MPG from the start <u>in any case</u>. (This resulted from further discussion within MPG and seems preferable). Many thanks for your work and advice.

Best regards,

yours, Jürgen

Telex 524629 astro d

GWS AND THE A. EINSTEIN INSTITUTE (2)

Memorandum
on the founding of an "Albert-Einstein-Institut für Gravitationsphysik"

1) Observation–oriented classical general relativity.
Relativistic celestial mechanics, gravitational waves, compact objects, approximation methods, particularly numerical methods.
2) Gravitation and quantum theory
Quantization methods, supersymmetric theories, higher-dimensional theories, string theories, lower–dimensional models, conformal field theory, semi–classical approximation theories, alternative (gauge–)theories.

3) Physical foundations and mathematical problems of classical general relativity.
Structure of solutions and spaces of solutions of the field equations, initial value problems, asymptotics, singularities, mathematical basis of approximation methods.

4) Cosmology, astro–particle physics.
Processes in the early universe, inflation, formation of galaxies and clusters, gravitational lens phenomena.

The research should mainly concentrate on *basic physics*, not on astrophysical phenomenology.

GWS AND THE A. EINSTEIN INSTITUTE (3)

One should keep in mind the impact of the mathematical and quantum-related context to the discovery of GWs, e.g.

1.the Time-Frequency transient-signal analysis fed itself on basic mathematical works by Yves Meyer, I Daubechies, S Jaffard, J L Journe, and on ideas by Kenneth Wilson

2. the NR codes fed themselves, on the one side on mathematical ideas that originated, notably, in works of Choquet-Bruhat 1952, Choquet-Bruhat-Ruggeri 1983, H. Friedrich 1985, and on the other side, on the idea of « puncture » which was invented by B. Bruegmann starting from his quantum-gravity analytical background

3. Some of the PN and EOB work stemmed out of inquiries from J. Ehlers, collaborations with B. Schmidt, and fed itself on quantum-related ideas (EOB correspondence, dim. reg.).
It might further benefit from current progress on quantum string-theory-related, amplitude calculations (a la Theisen, Schlotterer, .)…

4. Discovering BHs reinforces the challenge to understand the physics near space like (big-crunch) singularities, for which new ideas are being notably pursued at the AEI (Nicolai, Kleinschmidt,Fleig,…); deepening ideas that originated in work by J. Ehlers