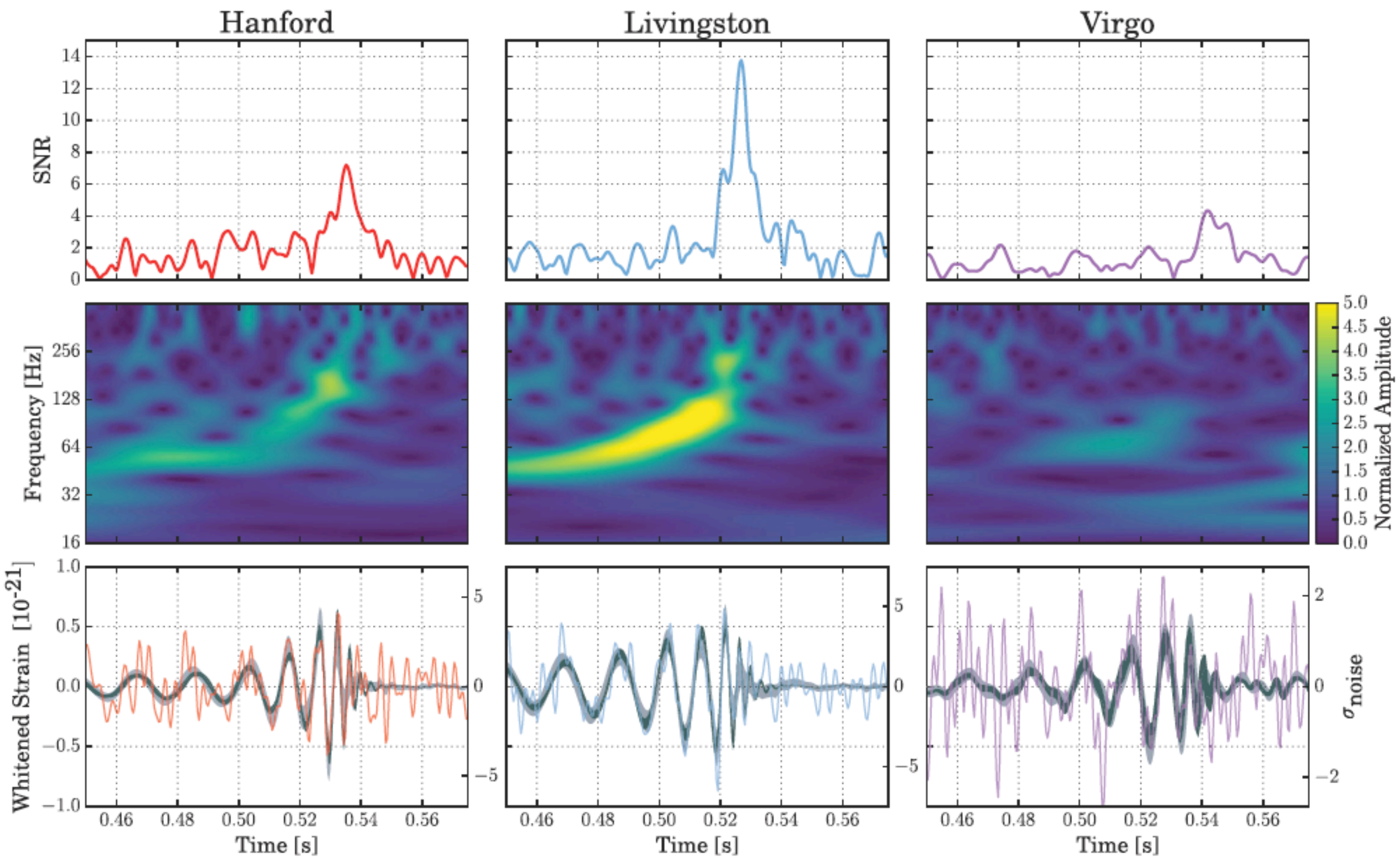
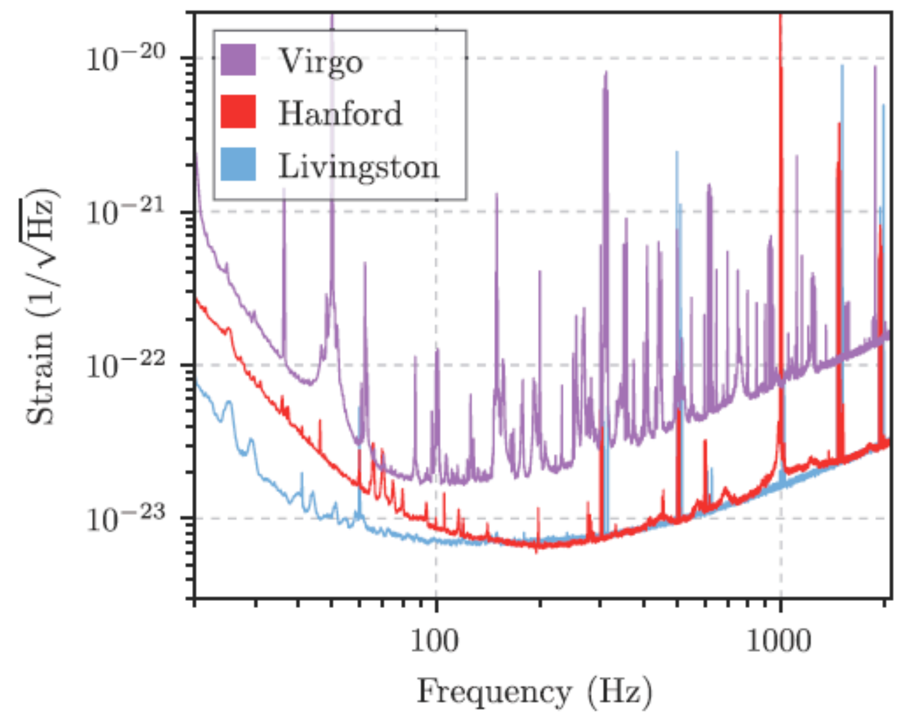
GRAVITATIONAL WAVES FROM COALESCING NEUTRON STARS: THE ROLE OF THE EQUATION OF STATE

Alessandro Nagar
Centro Fermi, INFN, Sezione di Torino & IHES
[alessandro.nagar@to.infn.it]

The IHES/INFN effective-one-body (EOB) code: https://eob.ihes.fr

JOINT LIGO-VIRGO DETECTION





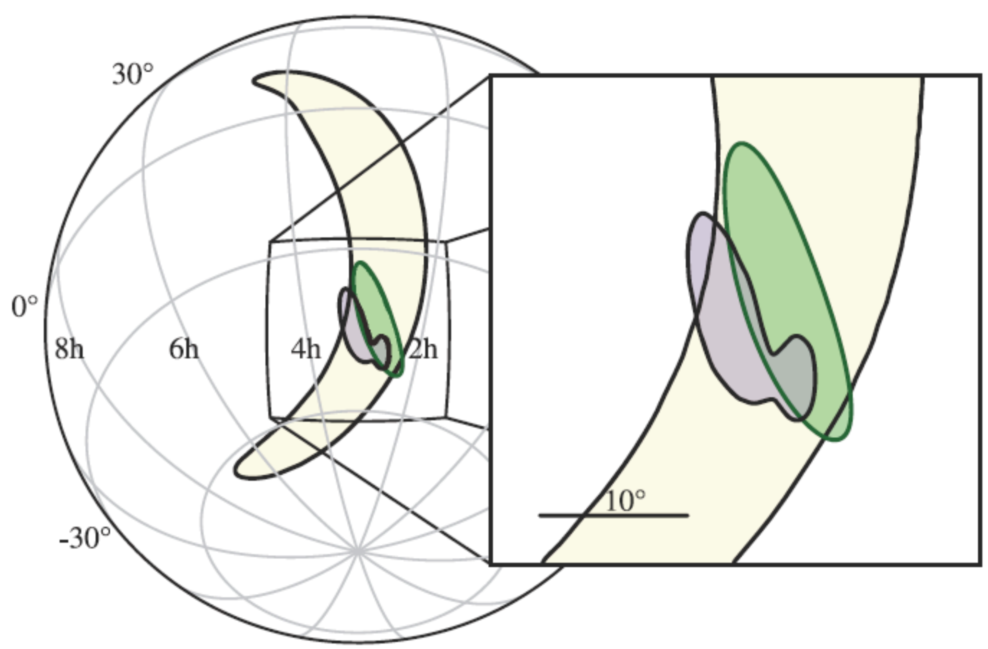


TABLE I. Source parameters for GW170814: median values with 90% credible intervals. We quote source-frame masses; to convert to the detector frame, multiply by $(1+z)$ [126,127]. The redshift assumes a flat cosmology with Hubble parameter $H_0 = 67.9\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and matter density parameter $\Omega_m = 0.3065$ [128].

Primary black hole mass m_1	$30.5^{+5.7}_{-3.0} M_\odot$
Secondary black hole mass m_2	$25.3^{+2.8}_{-4.2} M_\odot$
Chirp mass $\mathcal{M}$	$24.1^{+1.4}_{-1.1} M_\odot$
Total mass M	$55.9^{+3.4}_{-2.7} M_\odot$
Final black hole mass M_f	$53.2^{+3.2}_{-2.5} M_\odot$
Radiated energy E_{rad}	$2.7^{+0.4}_{-0.3} M_\odot\ c^2$
Peak luminosity ℓ_{peak}	$3.7^{+0.5}_{-0.5} \times 10^{56}\ \mathrm{erg\ s^{-1}}$
Effective inspiral spin parameter χ_{eff}	$0.06^{+0.12}_{-0.12}$
Final black hole spin a_f	$0.70^{+0.07}_{-0.05}$
Luminosity distance D_L	540^{+130}_{-210} Mpc
Source redshift z	$0.11^{+0.03}_{-0.04}$

THE THEORY...

Is needed to compute waveform templates for characterizing the source (GWs were detected...but WHAT was detected?)

Theory is needed to study the 2-body problem in General Relativity (dynamics & gravitational wave emission)

Theory: SYNERGY between

Analytical and Numerical General Relativity

(AR/NR)

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

HOW TO MEASURE: MATCHED FILTERING!

To extract/do parameter estimation of the GW signal from detector's output (lost in broadband noise $S_n(f)$)

$$\langle output | h_{\rm template} \rangle = \int \frac{df}{S_n(f)} o(f) h^*_{\rm template}(f)$$

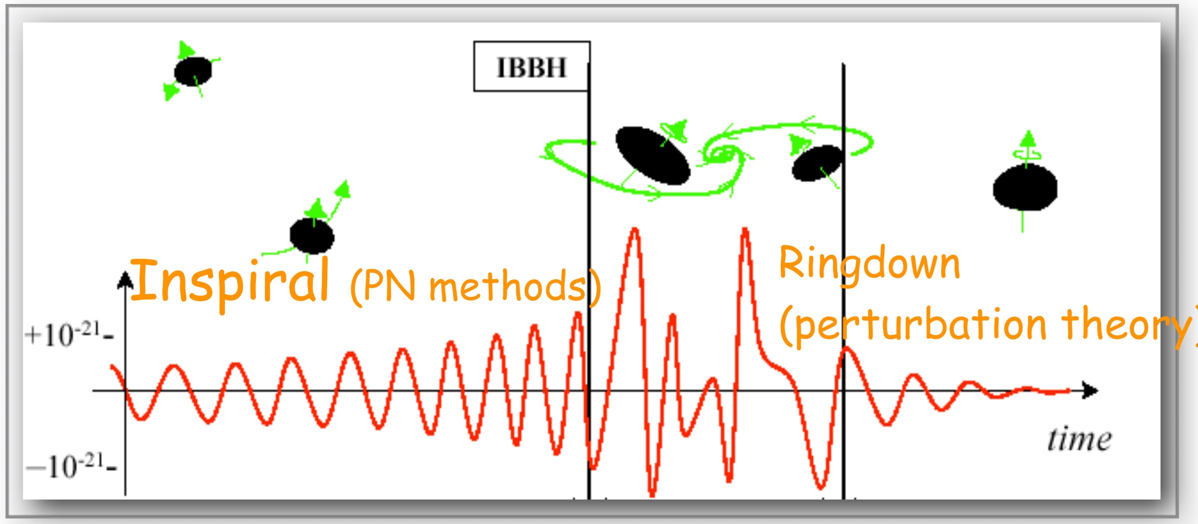
Detector's output

Template of expected GW signal

Need waveform templates!

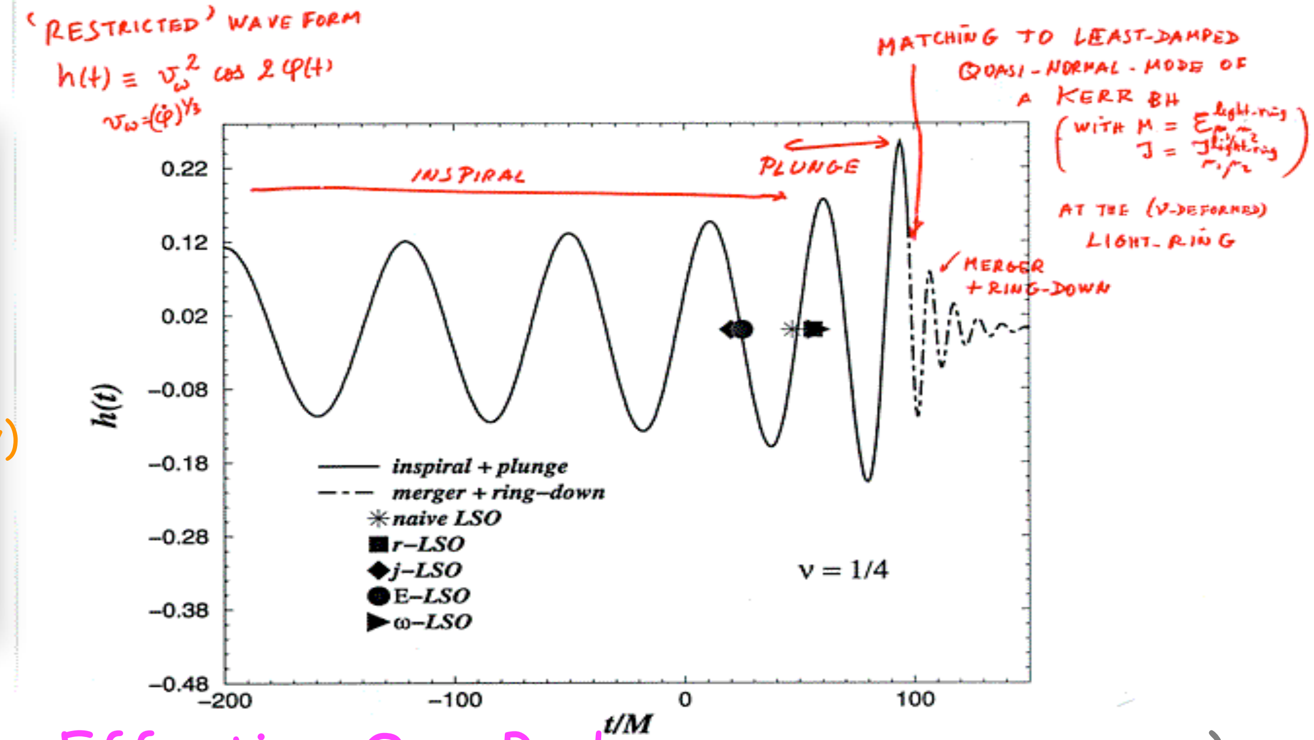
TEMPLATES FOR GWS FROM BBH COALESCENCE

Brady, Craighton & Thorne, 1998



Inspiral (PN methods)

Ringdown (perturbation theory)



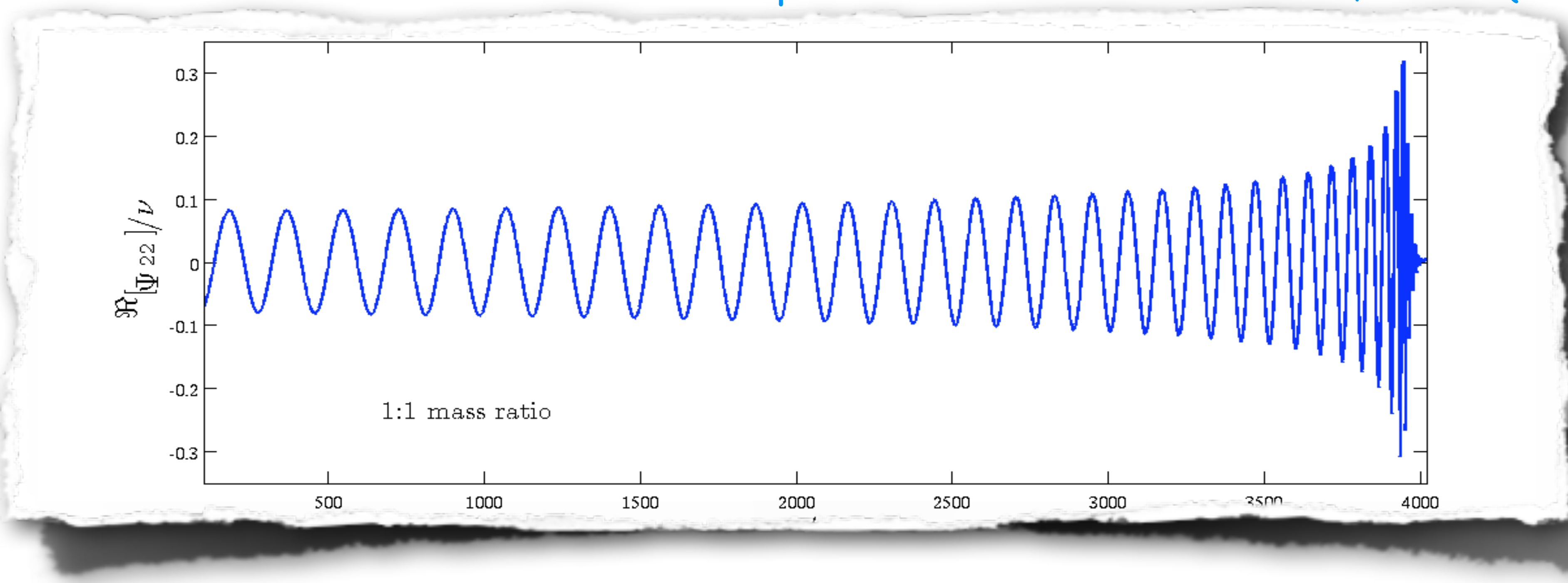
Merger:
Numerical Relativity

Effective-One-Body (Buonanno & Damour (2000))

PN-resummation (Damour, Iyer, Sathyaprakash (1998))

Numerical Relativity: >= 2005 (F. Pretorius, Campanelli et al., Baker et al.)

Most accurate data: Caltech-Cornell spectral code: M. Scheel et al., 2008 (SXS collaboration)



Spectral code

Extrapolation (radius & resolution)

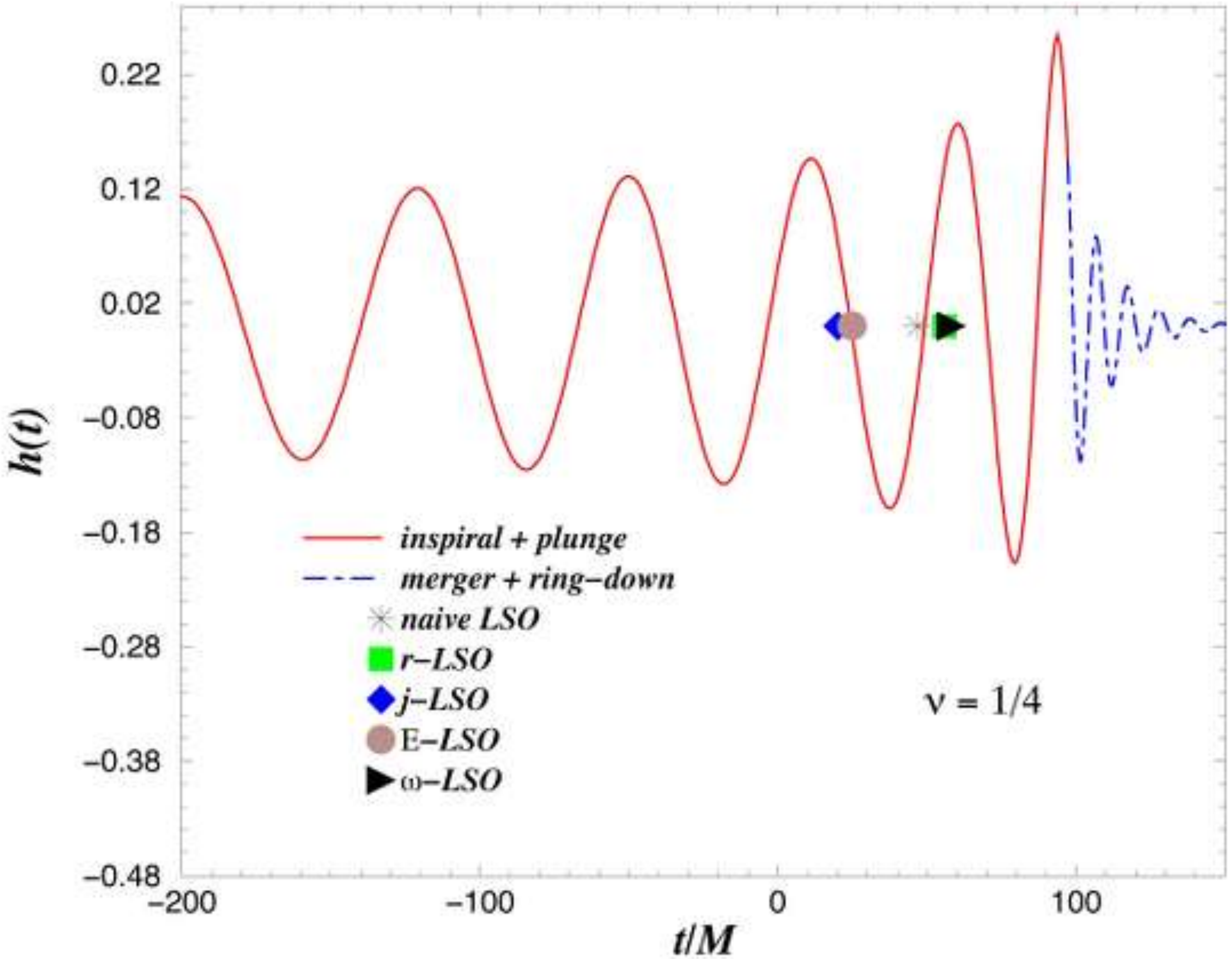
Phase error:

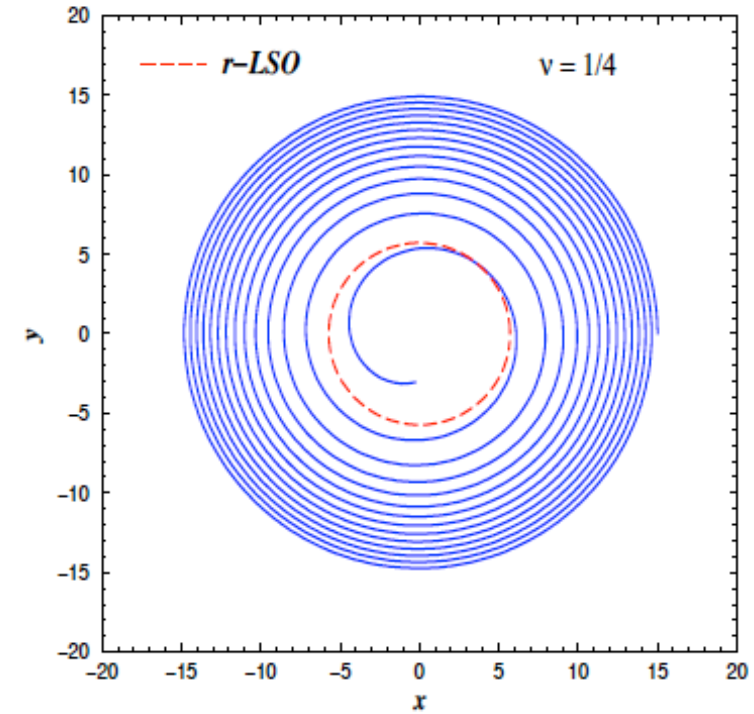
< 0.02 rad (inspiral)

<0.1 rad (ringdown)

EFFECTIVE ONE BODY (EOB): 2000

Numerical Relativity was not working (yet...)
EOB formalism was predictive, qualitatively and semi-quantitatively correct (10%)





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

A. Buonanno & T. Damour, PRD 59 (1999) 084006
A. Buonanno & T. Damour, PRD 62 (2000) 064015

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

> 2005: Developing EOB & interfacing with NR
2 groups did (and are doing) it

- A.Buonanno+ (AEI)
- T.Damour & AN + (>2005)

$$\boxed{h_+ - i h_\times = \frac{1}{r}\sum_{\ell m} h_{\ell m}\, {}_{-2}Y_{\ell m}(\theta,\phi)}$$

ANALYTYCAL WAVEFORM MODELS

BBHs

(i) Effective-one-body (EOB) models for Inspiral-Merger-Ringdown (IMR):

AEI: NR-calibrated: ~~SEOBNRv2~~, SEOBNRv3 (P), SEOBNRv4 (LVC)

IHES/INFN: NR-informed; TEOBResumS (Matlab & c++; LAL-ification in progress) [UniTo]

(ii) IMRPhenomenological models (UIB & Cardiff)

IMRPhenomD (LVC)

IMRPhenomP (Pv2) (LVC)

(iii) **Postmerger-ringdown:** Damour& AN 2014, Del Pozzo & AN, PRD 95 (2017) 124034 [UniTo&UniPi]

BNSs: Tidal effects

T-EOB-AEI (including NS oscillations)

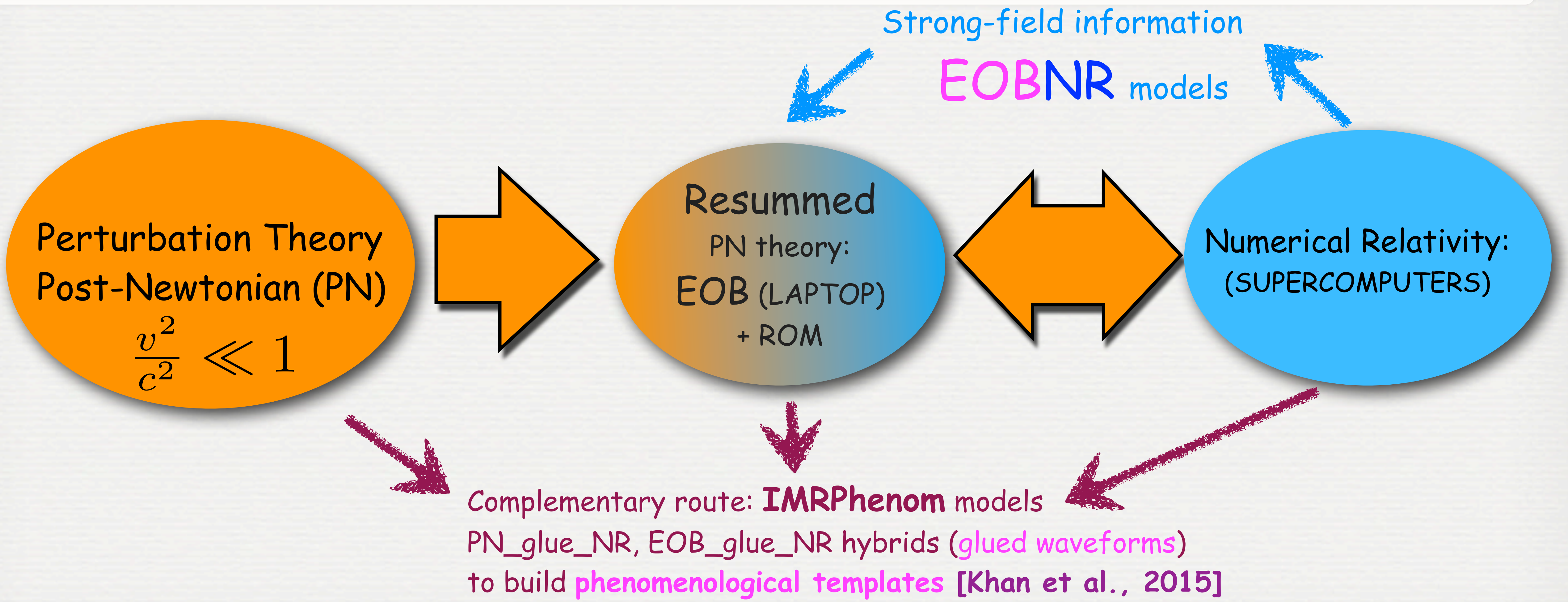
TEOBResumS (no NS oscillations, including GSFs & spin. Matlab & c++; LAL-inprogress)

TTaylorF2 [UniTo & UniPr]

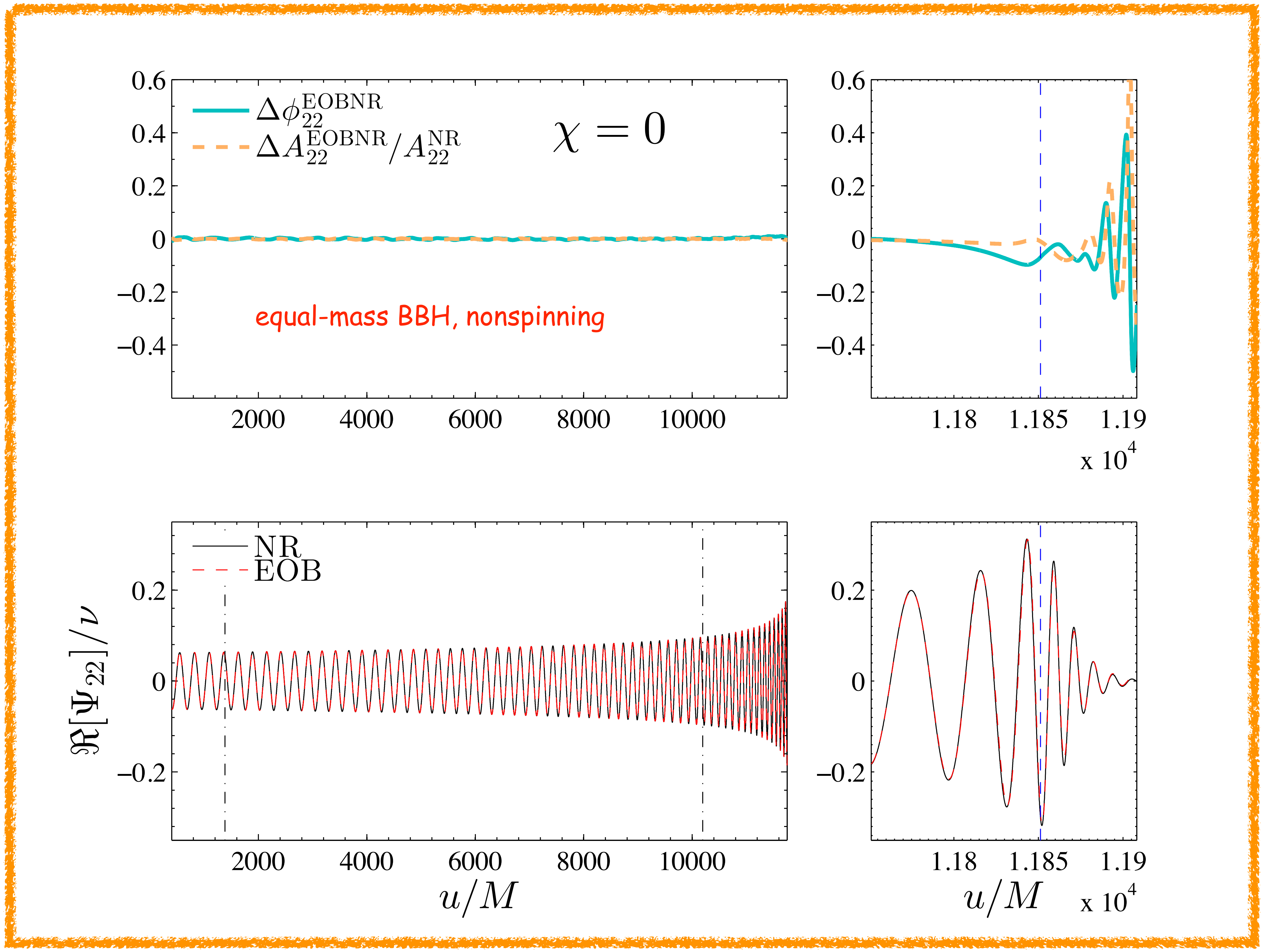
NRTides [Unipr, Bernuzzi+2017]

IMPORTANCE OF AN ANALYTICAL FORMALISM

- **Theoretical**: physical understanding of the coalescence process, especially in complicated situations (e.g., precessing spins).
- **Practical**: need hundreds of thousands of accurate GWs templates for detection and data analysis. Need analytical templates: $h\left(m_1, m_2, \vec{S}_1, \vec{S}_2\right)$
- **Solution**: synergy between analytical & numerical relativity



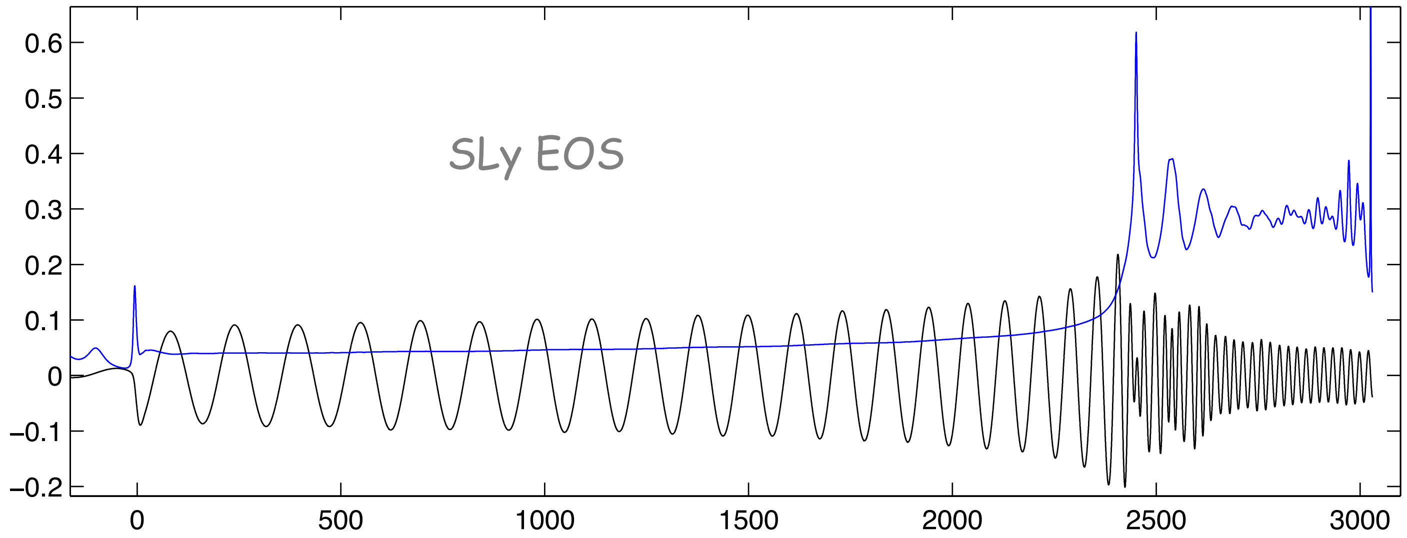
RESULTS: EOBNR/NR WAVEFORMS (NO SPIN)



Nagar, Damour, Reisswig & Pollney, PRD 93 (2016), 04404

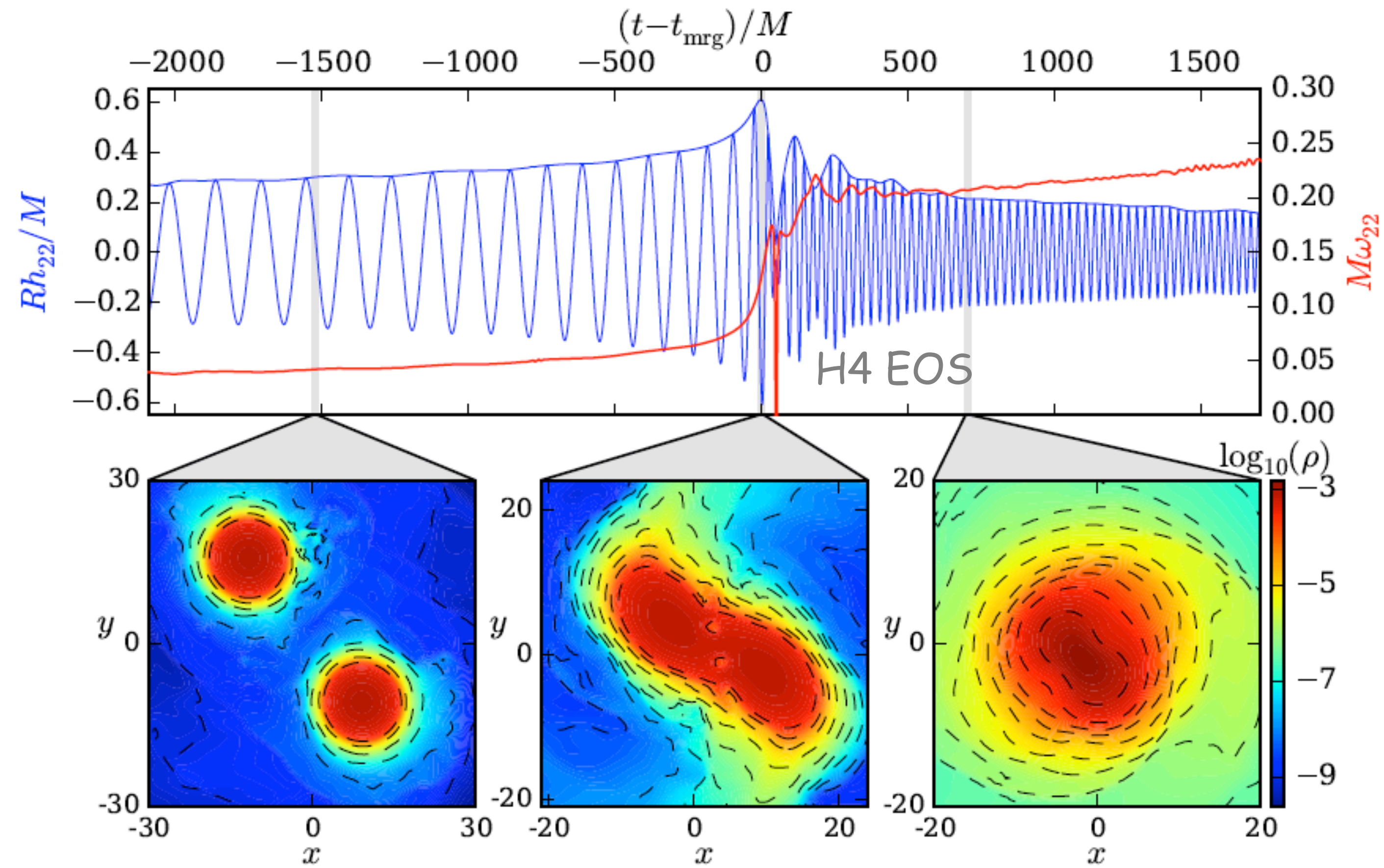
TEOBResumS: equal-mass, no spin

BINARY NEUTRON STARS (BNS)



$$q = 1 \qquad M = 2.7 M_{\odot}$$

- Tidal effects
- Love numbers (tidal "polarization" constants)
- EOS dependence & "universality"
- EOB/NR for BNS



See:

Damour&Nagar, PRD 2009
Damour&Nagar, PRD 2010
Damour,Nagar et al., PRL 2011
Bini,Damour&Faye, PRD2012
Bini&Damour, PRD 2014
Bernuzzi, Nagar, et al, PRL 2014
Bernuzzi, Nagar, Dietrich, PRL 2015
Bernuzzi, Nagar, Dietrich & Damour,PRL, 2015
Dietrich, Bernuzzi & Tichy, 2017

ANALYTICALLY: MOTION AND GW IN GR

Hamiltonian: conservative part of the dynamics

Radiation reaction: mechanical energy/angular momentum goes away in GWs and backreacts on the system.

The (closed) orbit CIRCULARIZES and SHRiNks with time

Waveform

General Relativity is NONLINEAR!

Post-Newtonian (PN) approximation: expansion in $\frac{v^2}{c^2}$

POST-NEWTONIAN HAMILTONIAN (C.O.M)

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

where

$$\widehat{H}_{\mathrm{N}}(\mathbf{q},\mathbf{p}) = \frac{\mathbf{p}^2}{2} - \frac{1}{q}, \tag{4.28a}$$

Newton (0PN)

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

(1PN, 1938) - [Einstein-Infeld-Hoffman]

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

(2PN, 1982/83) - [Damour-Deruelle]

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

(3PN, 2000) - [Damour, Jaranowski,Schaefer]

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

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

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

FLUX & WAVEFORM (3.5PN)

$$\frac{dE}{dt} = -\mathcal{L}$$

balance equation

Mechanical loss GW luminosity

$$\mathcal{L} = \underbrace{\frac{32c^5}{5G}\nu^2 x^5}_{\text{Newtonian quadrupole}}\Bigg\{1 + \left(-\frac{1247}{336} - \frac{35}{12}\nu\right)x + 4\pi x^{3/2} + \left(-\frac{44711}{9072} + \frac{9271}{504}\nu + \frac{65}{18}\nu^2\right)x^2$$
$$+ \left(-\frac{8191}{672} - \frac{583}{24}\nu\right)\pi x^{5/2}$$
$$+ \left[\frac{6643739519}{69854400} + \frac{16}{3}\pi^2 - \frac{1712}{105}C - \frac{856}{105}\ln(16\,x)\right.$$
$$\left. + \left(-\frac{134543}{7776} + \frac{41}{48}\pi^2\right)\nu - \frac{94403}{3024}\nu^2 - \frac{775}{324}\nu^3\right]x^3$$
$$+ \left(-\frac{16285}{504} + \frac{214745}{1728}\nu + \frac{193385}{3024}\nu^2\right)\pi x^{7/2} + \mathcal{O}\left(\frac{1}{c^8}\right)\Bigg\}.$$

Newtonian quadrupole

$$h^{22} = -8\sqrt{\frac{\pi}{5}}\frac{G\nu m}{c^2 R}e^{-2i\phi}x\Bigg\{1 - x\left(\frac{107}{42} - \frac{55}{42}\nu\right) + x^{3/2}\left[2\pi + 6i\ln\left(\frac{x}{x_0}\right)\right] - x^2\left(\frac{2173}{1512} + \frac{1069}{216}\nu - \frac{2047}{1512}\nu^2\right)$$
$$- x^{5/2}\left[\left(\frac{107}{21} - \frac{34}{21}\nu\right)\pi + 24i\nu + \left(\frac{107i}{7} - \frac{34i}{7}\nu\right)\ln\left(\frac{x}{x_0}\right)\right]$$
$$+ x^3\left[\frac{27\,027\,409}{646\,800} - \frac{856}{105}\gamma_E + \frac{2}{3}\pi^2 - \frac{1712}{105}\ln 2 - \frac{428}{105}\ln x\right.$$
$$\left. - 18\left[\ln\left(\frac{x}{x_0}\right)\right]^2 - \left(\frac{278\,185}{33\,264} - \frac{41}{96}\pi^2\right)\nu - \frac{20\,261}{2772}\nu^2 + \frac{114\,635}{99\,792}\nu^3 + \frac{428i}{105}\pi + 12i\pi\ln\left(\frac{x}{x_0}\right)\right] + O(\epsilon^{7/2})\Bigg\},$$

$$C = \gamma_E = 0.5772156649...$$

$$x = (M\Omega)^{2/3} \sim v^2/c^2$$

EFFECTIVE-ONE-BODY (EOB)

approach to the general relativistic two-body problem

(Buonanno-Damour 99, 00, Damour-Jaranowski-Schäfer 00, Damour 01, Damour-Nagar 07, Damour-Iyer-Nagar 08)

key ideas:

(1) Replace two-body dynamics (m_1, m_2) by dynamics of a particle $(\mu \equiv m_1 m_2/(m_1+m_2))$ in an effective metric $g^{\text{eff}}_{\mu\nu}(u)$, with

$$u \equiv GM/c^2 R\,, \quad M \equiv m_1 + m_2$$

(2) Systematically use RESUMMATION of PN expressions (both $g^{\text{eff}}_{\mu\nu}$ and $\mathcal{F}_{RR}$) based on various physical requirements

(3) Require continuous deformation w.r.t. $\nu \equiv \mu/M \equiv m_1 m_2/(m_1+m_2)^2$ in the interval $0 \leq \nu \leq \frac{1}{4}$

STRUCTURE OF THE EOB FORMALISM

PN dynamics
(DD81,D82,DJS01,IF03,BDIF04)

PN rad losses
WW76, BDIWW95, BDEFI05

PN waveform
BD89, B95&05,ABIQ04,

BH perturbations
RW57, Z70, Z72

Resummed (BD99)

Resummed (DIS98)

Resummed (DN07,DIN08)

QNMs spectrum
$\sigma_N = \alpha_N + i\omega_N$

EOB Hamiltonian
$H_{\rm EOB}$

EOB Rad. Reac. force
$\hat{\mathcal{F}}_\varphi$

Factorized waveform

$$h_{\ell m} = h^{(N,\epsilon)}_{\ell m}\hat{h}^{(\epsilon)}_{\ell m}$$
$$\hat{h}^{(\epsilon)}_{\ell m} = \hat{S}^{(\epsilon)}_{eff} T_{\ell m} e^{i\delta_{\ell m}} \rho^{\ell}_{\ell m}$$

Matching at merger time

$$\frac{dr}{dt} = \left(\frac{A}{B}\right)^{1/2} \frac{\partial \hat{H}_{\rm EOB}}{\partial p_{r_*}},$$
$$\frac{dp_{r_*}}{dt} = -\left(\frac{A}{B}\right)^{1/2} \frac{\partial \hat{H}_{\rm EOB}}{\partial r},$$
$$\Omega \equiv \frac{d\varphi}{dt} = \frac{\partial \hat{H}_{\rm EOB}}{\partial p_\varphi},$$
$$\frac{dp_\varphi}{dt} = \hat{\mathcal{F}}_\varphi\,.$$

BNS: tides
(Love numbers)

$$h^{\rm ringdown}_{\ell m}(t) = \sum_N C^+_N e^{-\sigma^+_N (t-t_m)}$$

Phenomenological fit to NR postmerger phase

EOB waveform

$$h^{\rm EOB}_{\ell m} = \theta(t_m - t) h^{\rm insplunge}_{\ell m}(t) + \theta(t - t_m) h^{\rm ringdown}_{\ell m}(t)$$

EXPLICIT FORM OF THE EOB HAMILTONIAN

EOB Hamiltonian

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

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

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

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

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

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

Simple effective Hamiltonian:

$$\hat{H}_{\rm eff} \equiv \sqrt{p_{r_*}^2 + A(r)\left(1 + \frac{p_\varphi^2}{r^2} + z_3 \frac{p_{r_*}^4}{r^2}\right)} \qquad p_{r_*} = \left(\frac{A}{B}\right)^{1/2} p_r$$

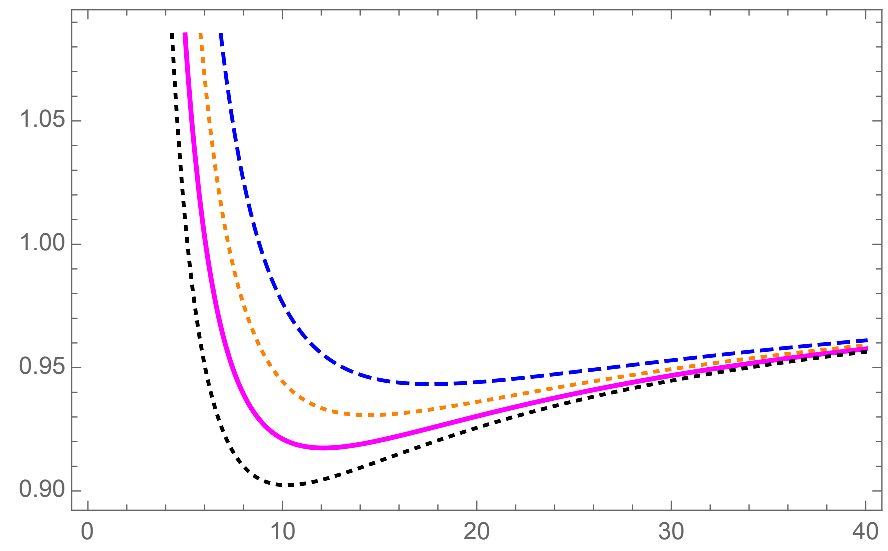
Crucial EOB radial potential

Contribution at 3PN

EFFECTIVE POTENTIALS

Newtonian gravity (any mass ratio):
circular orbits are always stable. No plunge.

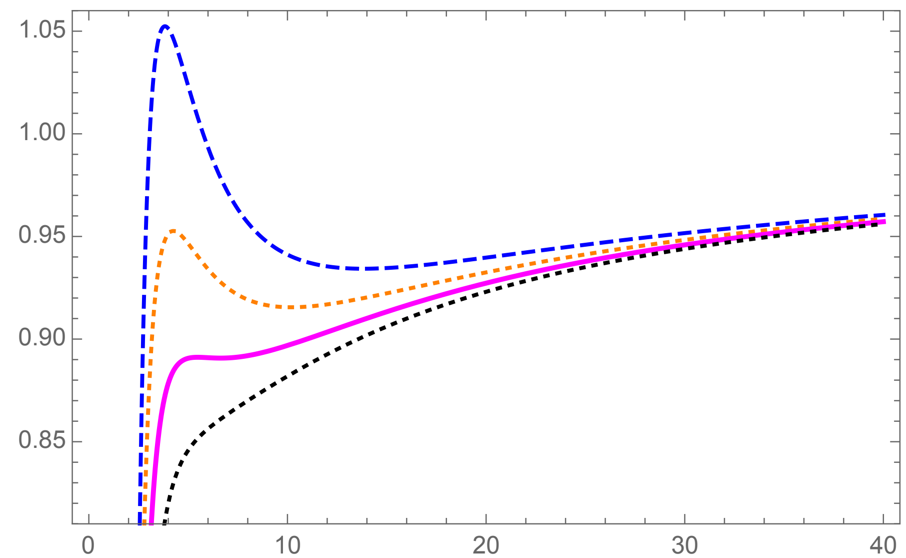
$$W^{\rm eff}_{\rm Newt} = 1 - \frac{2}{r} + \frac{p_\varphi^2}{r^2}$$



Test-body on Schwarzschild black hole:

last stable orbit (LSO) at **r=6M**; plunge

$$W^{\rm eff}_{\rm Schwarzschild} = \left(1 - \frac{2}{r}\right)\left(1 + \frac{p_\varphi^2}{r^2}\right)$$



EOB, Black-hole binary, any mass ratio:

last stable orbit (LSO) at **r<6M** plunge

$$W^{\rm eff}_{\rm EOB} = A(r;\nu)\left(1 + \frac{p_\varphi^2}{r^2}\right)$$

ν -deformation of the Schwarzschild case!

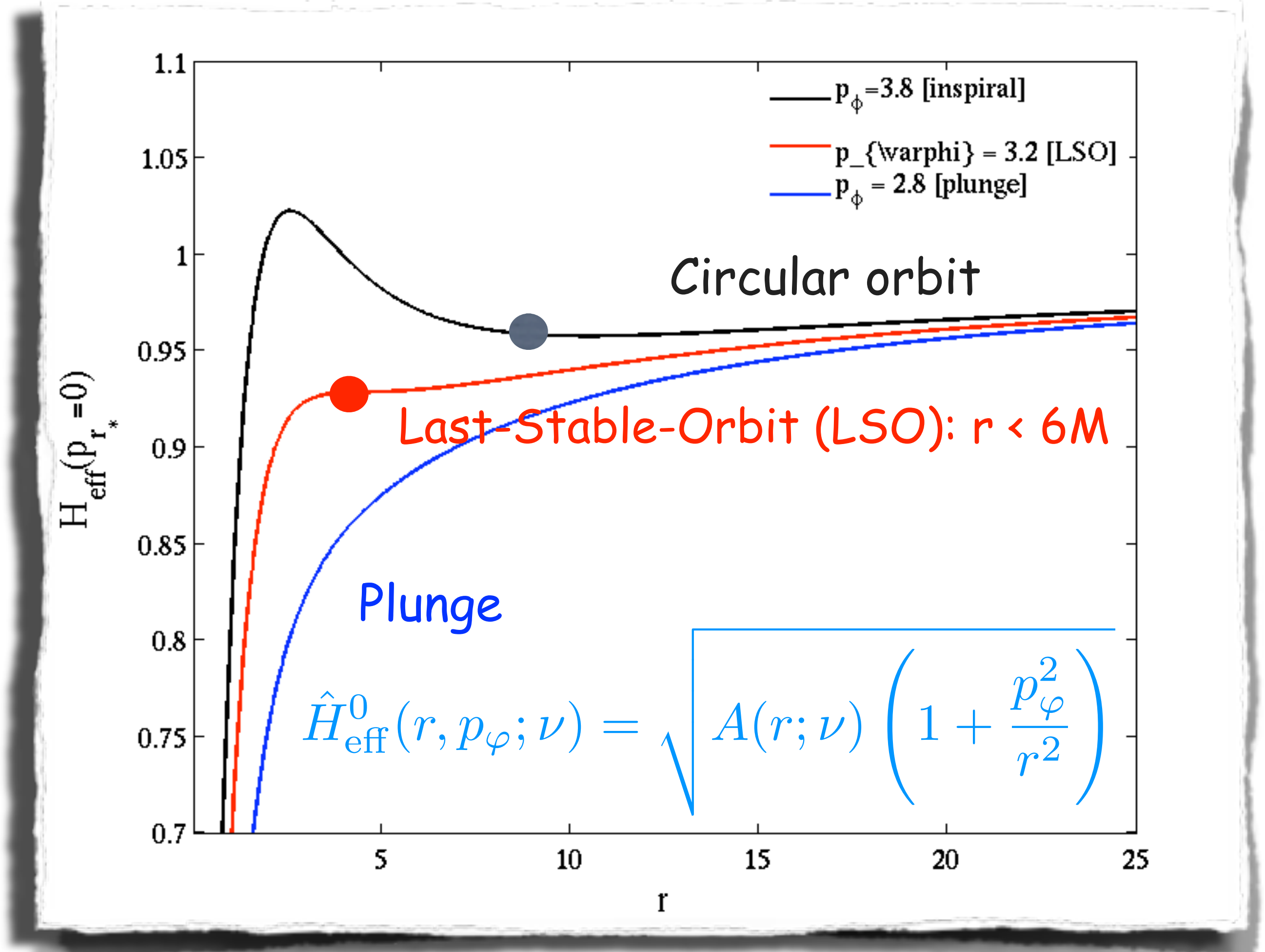
HAMILTON'S EQUATIONS & RADIATION REACTION

$$\dot{r} = \left(\frac{A}{B}\right)^{1/2} \frac{\partial \hat{H}_{\rm EOB}}{\partial p_{r_*}}$$

$$\dot{\varphi} = \frac{\partial \hat{H}_{\rm EOB}}{\partial p_{\varphi}} \equiv \Omega$$

$$\dot{p}_{r_*} = -\left(\frac{A}{B}\right)^{1/2} \frac{\partial \hat{H}_{\rm EOB}}{\partial r} + \hat{\mathcal{F}}_{r_*}$$

$$\dot{p}_{\varphi} = \hat{\mathcal{F}}_{\varphi}$$



- The system must radiate angular momentum
- How?Use PN-based (Taylor-expanded) radiation reaction force (ang-mom flux)
- Need flux resummation

$$\hat{\mathcal{F}}_{\varphi}^{\rm Taylor} = -\frac{32}{5}\nu\Omega^5 r_\Omega^4 \hat{F}^{\rm Taylor}(v_\varphi)$$

Resummation multipole by multipole
(Damour&Nagar 2007,
Damour, Iyer & Nagar 2008,
Damour & Nagar, 2009)

Plus horizon contribution [AN&Akcay2012]

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, Bini& Damour2013, DamourJaranowski&Schaefer 2014].

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

1PN 2PN 3PN 4PN 5PN

$$\left.\begin{aligned} a_5^{\log} &= \frac{64}{5} \\ a_5^c &= a_{5_0}^c + \nu a_{5_1}^c \\ a_{5_0}^c &= -\frac{4237}{60} + \frac{2275}{512}\pi^2 + \frac{256}{5}\log(2) + \frac{128}{5}\gamma \\ a_{5_1}^c &= -\frac{221}{6} + \frac{41}{32}\pi^2 \end{aligned}\right\}$$

4PN fully known ANALYTICALLY!

$$a_6^{\log} = -\frac{7004}{105} - \frac{144}{5}\nu$$

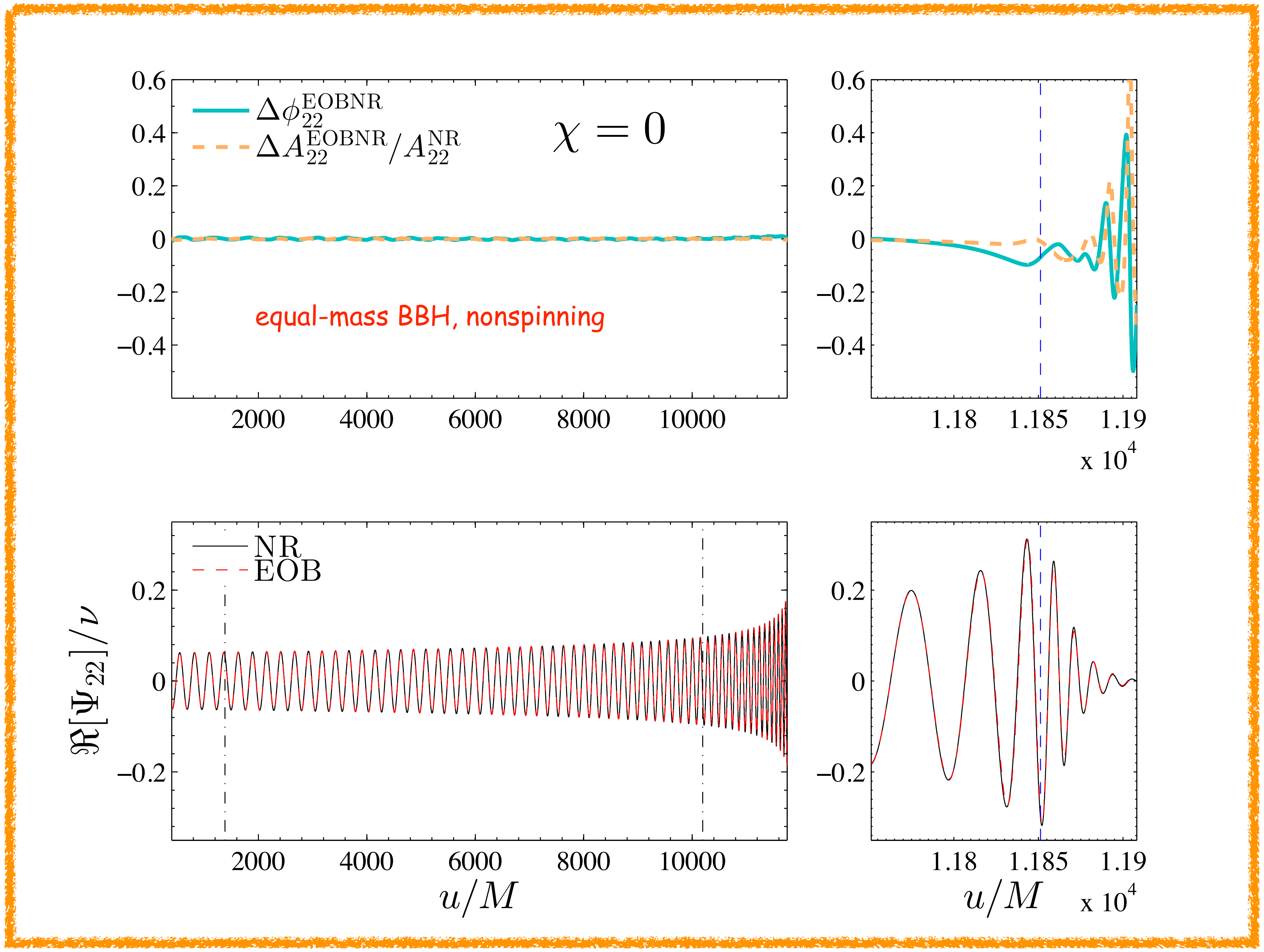
5PN logarithmic term (analytically known)

NEED ONE "effective" 5PN parameter from NR waveform data: $a_6^c(\nu)$

State-of-the-art EOB potential (5PN-resummed):

$$A(u;\nu,a_6^c) = P^1_5[A^{\rm Taylor}_{\rm 5PN}(u;\nu,a_6^c)]$$

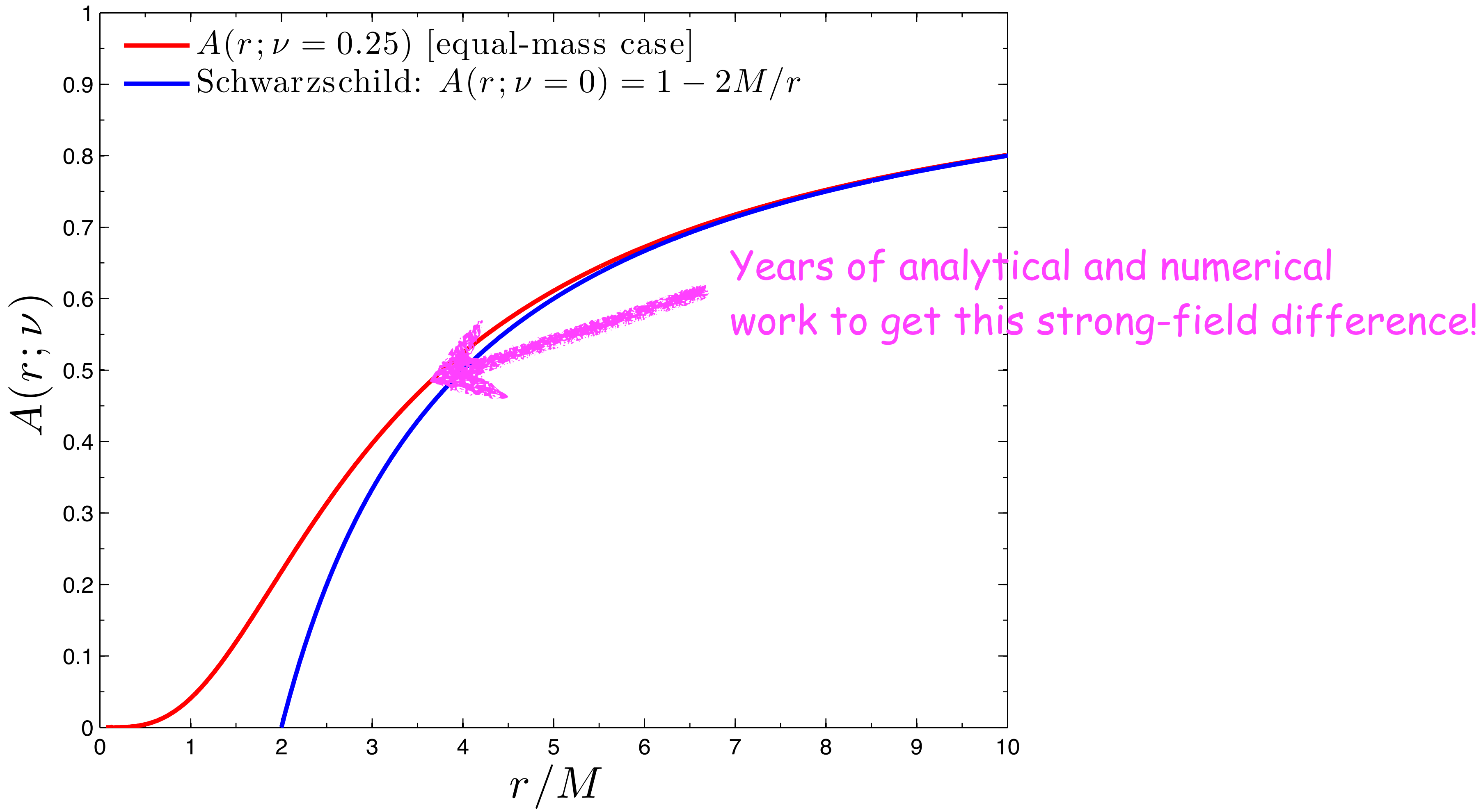
RESULTS: EOBNR/NR WAVEFORMS (NO SPIN)



Nagar, Damour, Reisswig & Pollney, PRD 93 (2016), 04404

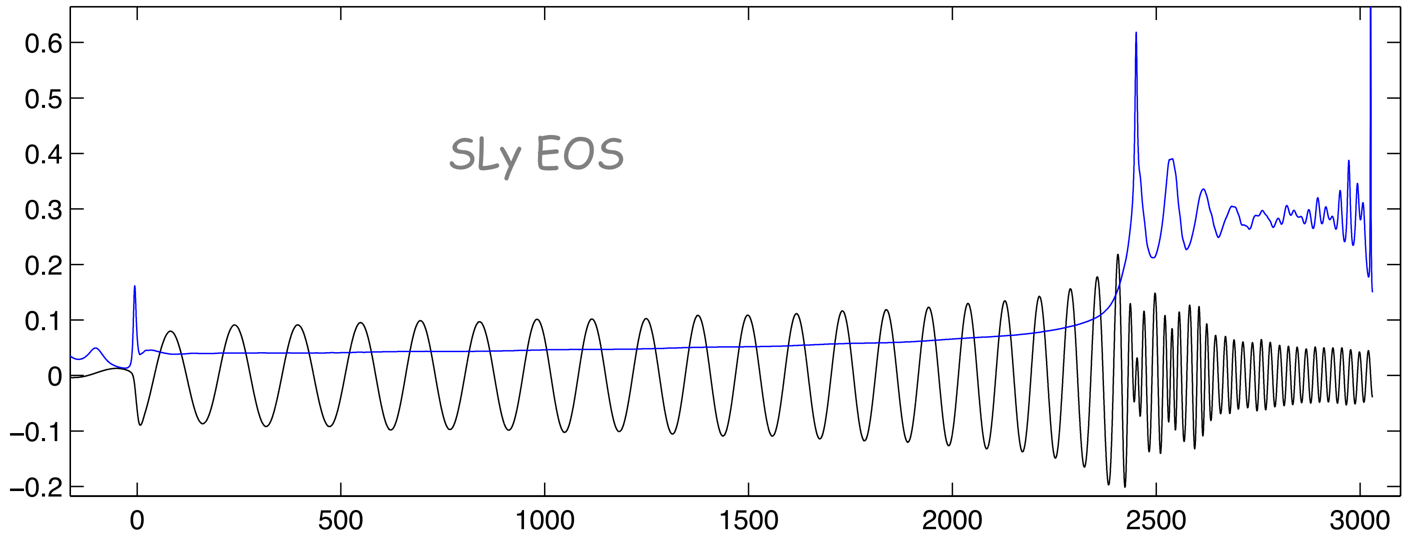
TEOBResumS: equal-mass, no spin

THE EOB[NR] POTENTIAL



From EOB/NR-fitting: $a_6^c(\nu) = 3097.3\nu^2 - 1330.6\nu + 81.3804$

BINARY NEUTRON STARS (BNS)



$$q = 1 \qquad M = 2.7 M_\odot$$

- Tidal effects
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- EOB/NR for BNS

See:

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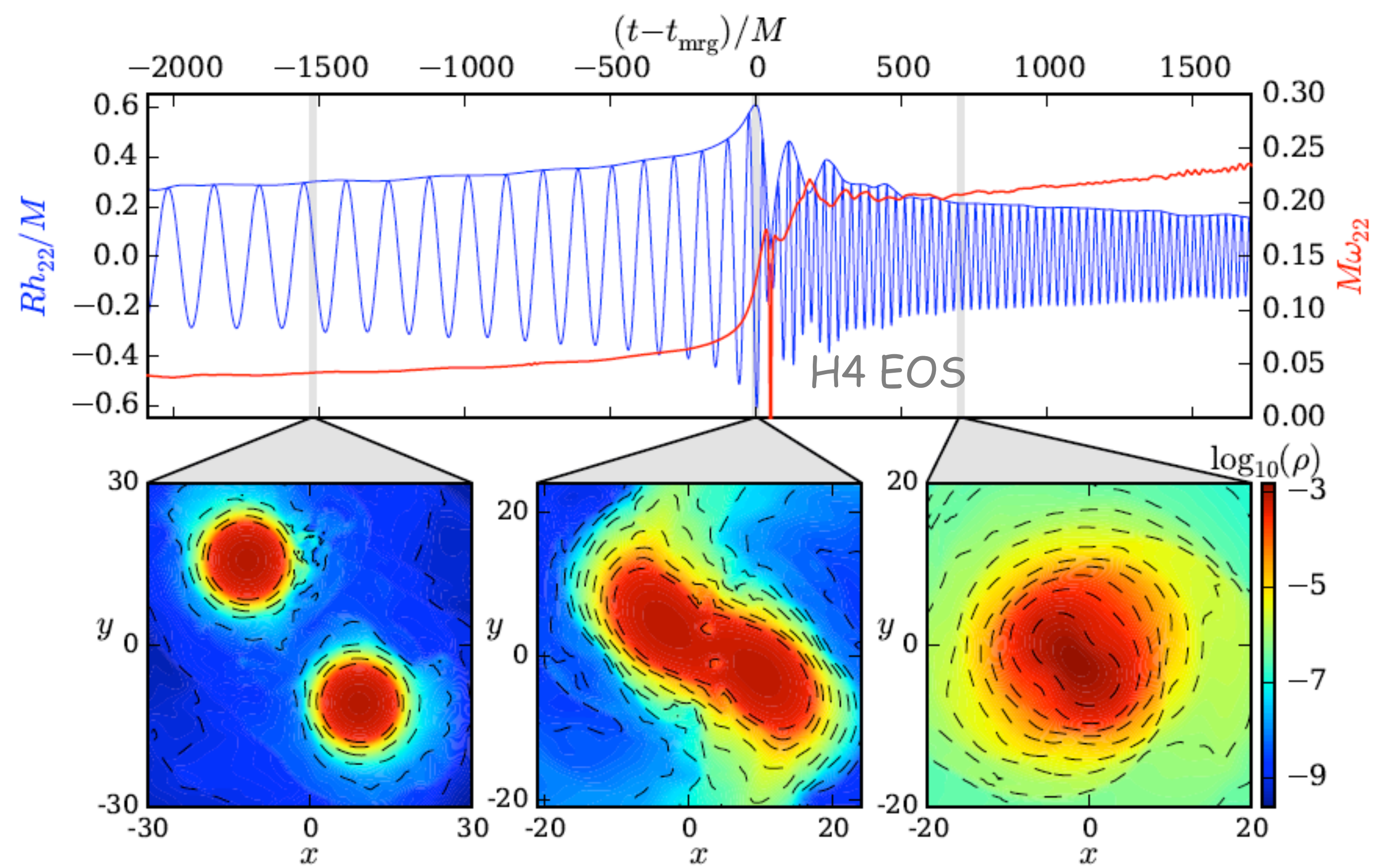
Bernuzzi, Nagar, et al, PRL 2014
Bernuzzi, Nagar, Dietrich, PRL 2015
Bernuzzi, Nagar, Dietrich & Damour,PRL, 2015



BNS: ANALYTICAL NEEDS

- Study the response of each neutron star to the tidal field of the companion [theory of relativistic Love numbers (i.e. tidal polarizability coefficients) + tidal corrections to dynamics (beyond Newtonian accuracy)]
- Incorporate the corresponding tidal effects within a theoretical framework able to describe the gravitational wave signal emitted by inspiralling compact binaries (up to merger): EOB-resummed description of dynamics and waveforms
- Compare/check analytical models against NR simulations; possibly, inform, when needed, the EOB model with high-order tidal information extracted from NR
- Assess the measurability of tidal effects within the signal seen by interferometric detectors
- Construct surrogate models (e.g. ROMs) for fast template evaluation [Lackey et al. 2016]

A BIT OF HISTORY...

1983-Damour. Relativistic generalization of Love numbers

1989-1991-Damour-Soffel-Xu: magnetic&electric tidal polarization constants (tidal polarizabiility)

2007-Hinderer. First Love number computation in GR

2008-Hinderer& Flanagan. Polytropes. Inspiral only - not promising

2009-TD&AN - Binnington&Poisson - multipolar Love numbers

2009- Hinderer. Love numbers for realistic EOS. Measurability inspiral only - not promising

2009- TD&AN - Tidal Effective One Body model (TEOB). Up to merger (contact). 1PN dynamical effects

2010- Vines, Hinderer & Flanagan. 1PN effects in waveforms

2010 - EOB/NR comparisons [Baiotti, Damour, Nagar+]. **TaylorT4 ruled out.** Strong tides close to merger?

2011 - 2PN tidal terms [Bini, Damour & Faye]

2012 - Damour, Nagar & Villain. EOB. Strong indications for measurability of Love numbers up to merger.

2012 - Bernuzzi, Nagar et al.: high order reconstruction - E(j) correct. Disentangle tides & noise. Strong tides?

2013 - Del Pozzo+; Agathos+. TaylorF2 up to merger. Bayesian analysis. Measurability of Love numbers.

2014 - Bini& Damour: GSF-informed tidal potential

2015 - Bernuzzi, Nagar, Dietrich&Damour - EOB-GSF/NR compatibility up to merger. Several EOS.

2015 - Hotokezaka et al. Similar analysis confirming BNDD. **Negligible eccentricity.**

2015 - Hinderer +: inclusion of f-mode oscillations in EOB model. BHNS relevancy. H4 EOS.

2016 - Hotokezaka+; EOB-NR hybrids & new assessment of LN measurability; several EOS; PN finally ruled out

2016 - Lackey, Bernuzzi+: ROM of BNDD model

2017 - Dietrich-Hinderer: comparisons between TEOB: high level of consistency

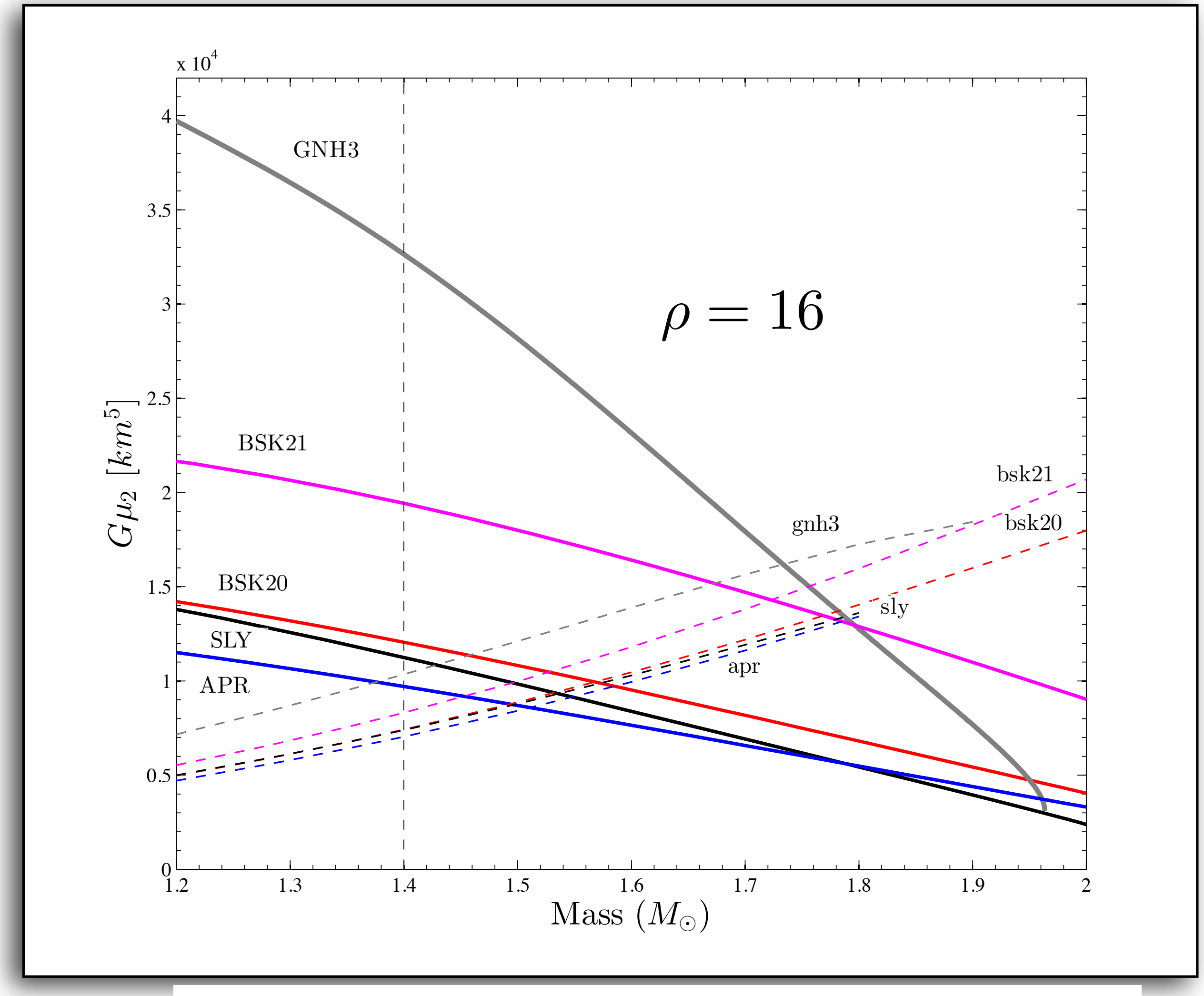
2017 - Bernuzzi-Dietrich-Tichy: NR-based, closed form tidal approximants

MEASURING LOVE NUMBERS

<2012. Inspiral only; not very promising [Hinderer et al. + 2008]

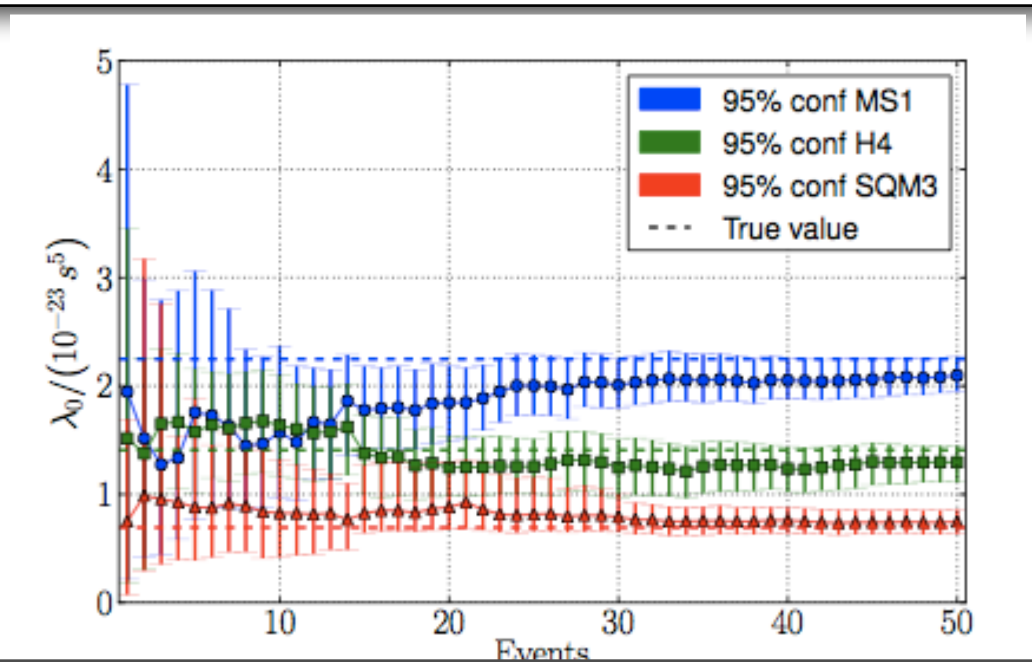
RESULT (Damour ,Nagar, Villain 2012)

Tidal polarizability parameters *can actually be measured* by adv LIGO with a reasonable SNR=16



Use EOB controlled, accurate, description of the phasing up to BNS merger!

Confirmed by Bayesian analysis:
Del Pozzo+ 2013 Agathos+2015



TIDAL EFFECTS IN EOB FORMALISM

Tidal extension of EOB formalism: nonminimal worldline couplings

$$\Delta S_{\text{nonminimal}} = \sum_A \frac{1}{4}\mu_2^A \int ds_A \left(u^\mu u^\nu R_{\mu\alpha\nu\beta}\right)^2 + \dots$$

Damour&Esposito-Farèse96, Goldberger&Rothstein06, TD&AN09

Relativistic Love number

Modifications of the EOB effective metric...

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

And tidal modifications of GW waveform & radiation reaction

Need analytical theory for computing $\mu_2,\ \kappa_2^T,\ \bar{\alpha}_1 \dots$

(?)Need accurate NR simulations to check/inform the higher-order PN tidal contributions, that may be quite important during the late inspiral up to merger

LOVE NUMBERS IN GENERAL RELATIVITY

Relativistic star in an external gravito-electric & gravito-magnetic (multipolar) tidal field

The star acquires induced gravito-electric and gravito-magnetic multipole moments

Linear tidal polarization

Induced multipole moments

$$M_L^{(A)} = \mu_\ell^A G_L^{(A)}$$
$$S_L^{(A)} = \sigma_\ell^A H_L^{(A)}$$

External multipolar field

$$G\mu_\ell = [length]^{2\ell+1}$$
$$G\sigma_\ell = [length]^{2\ell+1}$$

$$2k_\ell \equiv (2\ell-1)!!\frac{G\mu_\ell}{R^{2\ell+1}}$$

$$j_\ell \equiv (2\ell-1)!!\frac{4(\ell+2)}{\ell-1}\frac{G\sigma_\ell}{R^{2\ell+1}}$$

Dimensionless relativistic "second" Love numbers

Actual calculation based on star perturbation theory: Love numbers are obtained as boundary conditions (matching interior to exterior perturbations)

RELATIVISTIC LOVE NUMBERS (POLYTROPIC EOS)

"rest-mass polytrope" (solid lines)

$$p = K\mu^\gamma$$

$$e = \mu + \frac{p}{\gamma - 1}$$

"energy polytrope" (dashed lines)

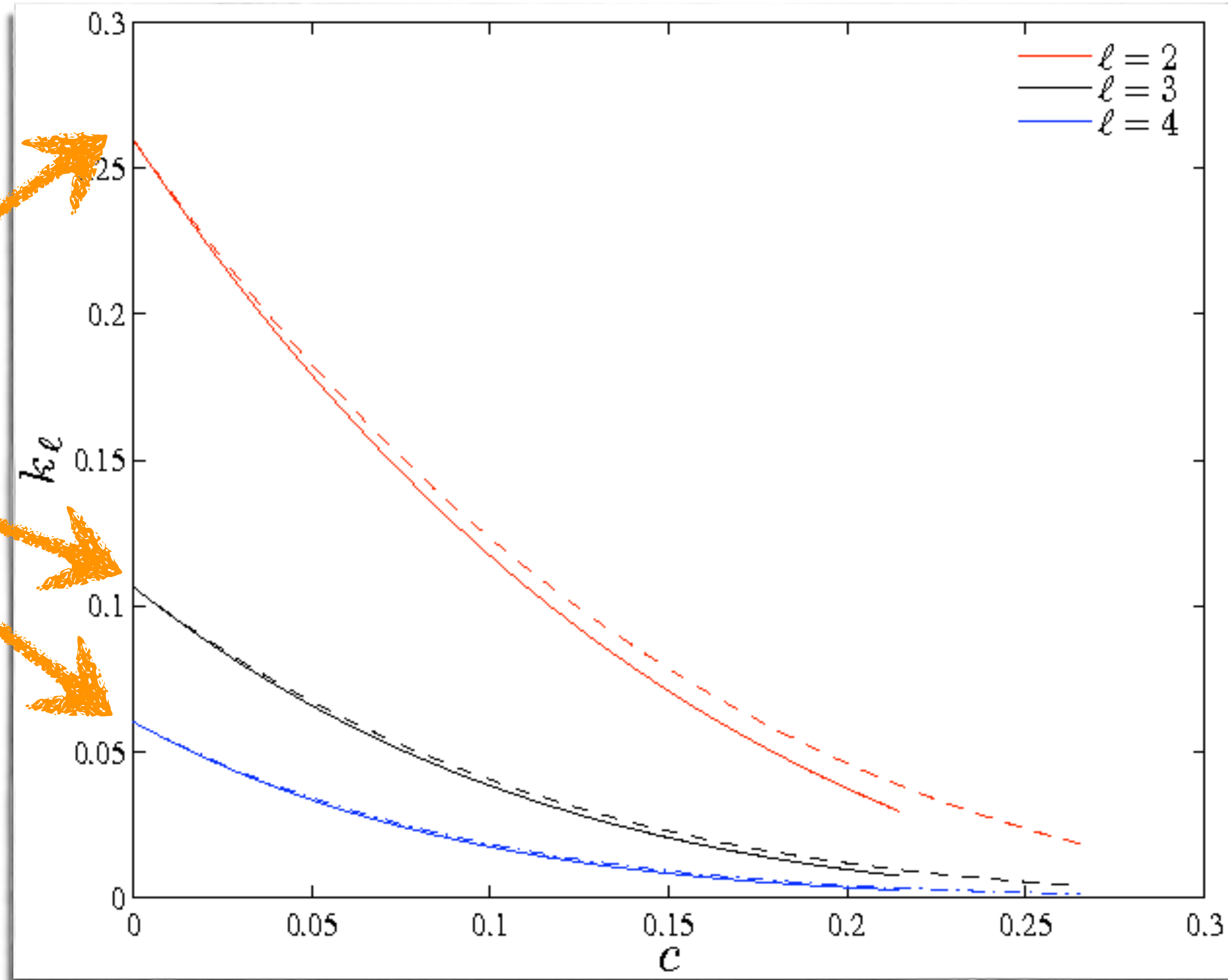
$$p = Ke^\gamma$$

Tidal polarization parameters

$$M_L^{(A)} = \mu_\ell^A G_L^{(A)}$$

$$2k_\ell \equiv (2\ell - 1)!! \frac{G\mu_\ell}{R^{2\ell+1}}$$

Newtonian values

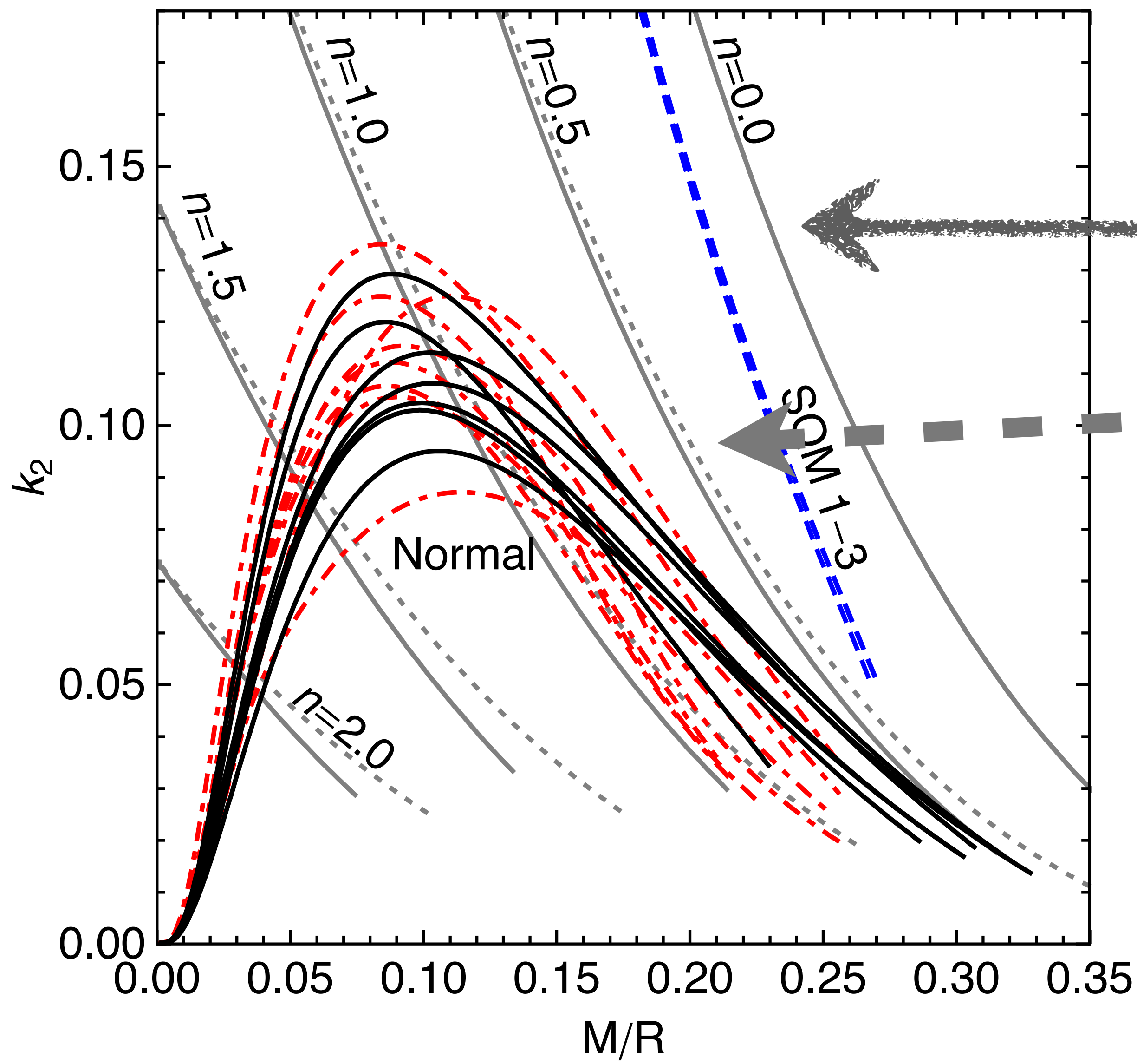


Newtonian values

Relativistic values

RELATIVISTIC LOVE NUMBERS: (REALISTIC EOS)

DN 2009 (SLy & FPS)
Hinderer et al. 2010 (several tabulated EOS)



Polytropic EOS

$$p = K\rho^{1+1/n}$$

$$p = K\epsilon^{1+1/n}$$

TIDAL INTERACTION POTENTIAL

Central tidal "coupling constant":

$$\kappa_\ell^T \equiv 2\left[\frac{1}{q}\left(\frac{X_A}{C_A}\right)^{2\ell+1} k_\ell^A + q\left(\frac{X_B}{C_B}\right)^{2\ell+1} k_\ell^B\right]$$

$$M_A = M_B \quad \ell = 2 \quad k_2^A = k_2^B \;\Rightarrow\; \kappa_2^T = \frac{1}{8}\frac{k_2}{\mathcal{C}^5}$$

$X_{A,B} \equiv M_{A,B}/M$

Function of: masses, compactnesses and relativistic Love numbers

$\kappa_2^T \sim 100$

In the dynamics:

$$A(u) = A^0(u) + A^{\rm tidal}$$

$$A^{\rm tidal} = \sum_{\ell\geq 2} -\kappa_\ell^T u^{2\ell+2} \hat{A}_\ell^{\rm tidal}(u)$$

"Newtonian" (LO) part + PN corrections (NLO, NNLO, ...)

NLO & NNLO tidal PN corrections known analytically

[Bini, Damour& Faye 2011]

$$\hat{A}_2^{\rm tidal} = 1 + \frac{5}{4}u + \frac{85}{14}u^2$$

THREE RESULTS

1. Numerical-relativity matches effective-one-body (EOB) analytical-relativity waveforms and dynamics essentially up to merger. Method to compute GW templates for LIGO/Virgo to measure EOS out of tidal effects
S. Bernuzzi, A. Nagar, T. Dietrich & T. Damour, PRL 114 (2015), 161103
"Modeling the Dynamics of Tidally Interacting Binary Neutron Stars up to Merger"
[checked by Hotokezaka et al., PRD 91 (2015) 6, 064060, notably with reduced eccentricity]

2. Quasi-universality in BNS merger (binding energy, angular momentum, GW frequency vs tidal coupling constant): explained using EOB theory
S. Bernuzzi, A. Nagar, S. Balmelli, T. Dietrich & M. Ujevic, PRL 112 (2014), 201101
"Quasiuniversal properties of neutron star mergers"

3. Quasi-universality of post-merger Mf_2 frequency vs tidal coupling constant
S. Bernuzzi, A. Nagar & T. Dietrich, arXiv:1504.01764
"Towards a description of the complete gravitational wave spectrum of neutron star mergers"
Unifying description of inspiral, merger and post-merger phases

RESUMMED TIDAL INTERACTION

Bini&Damour (2015) resummed expression for $\hat{A}_{\ell}^{\mathrm{tidal}}$

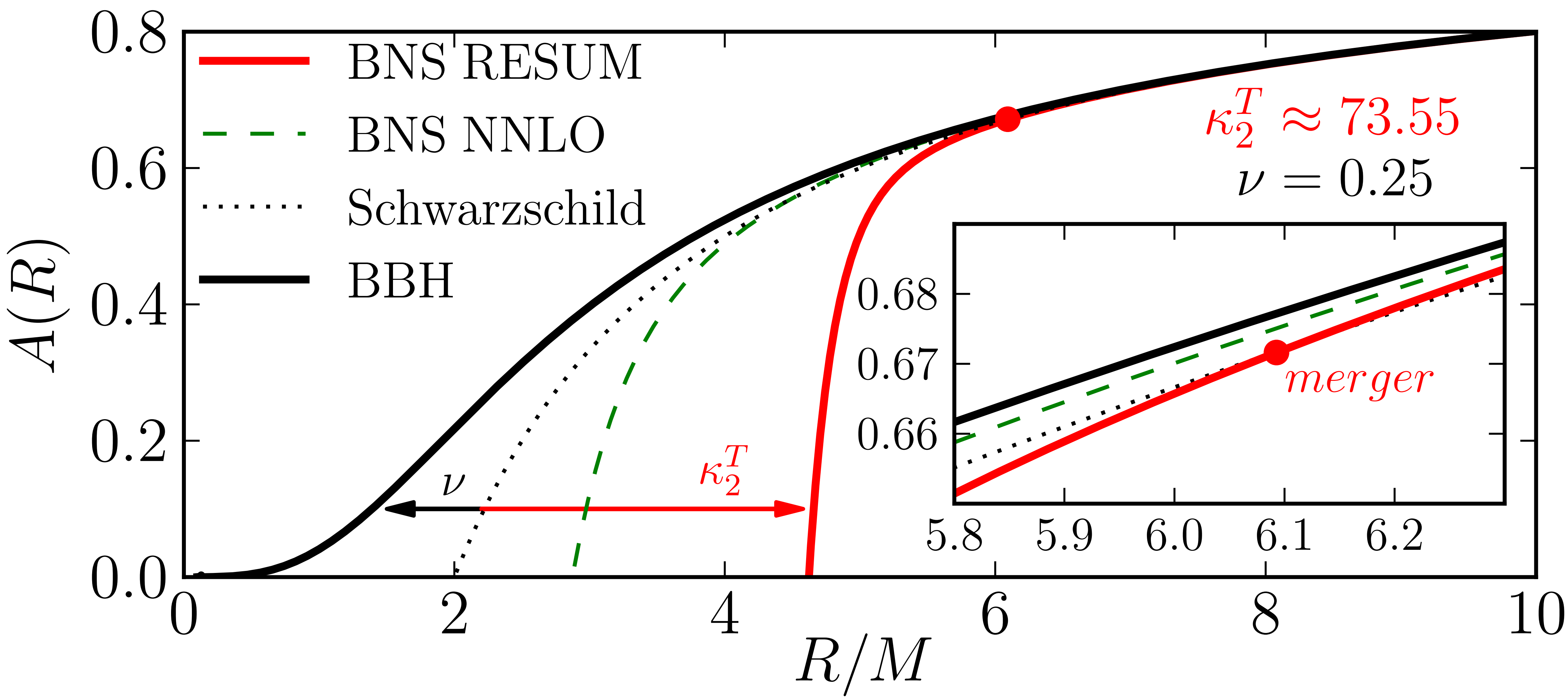
Presence of a pole: potential strongly attractive @ mrg

$$A_T^{(+)}(u;\nu) \equiv -\sum_{\ell=2}^{4}\left[\kappa_A^{(\ell)} u^{2\ell+2}\hat{A}_A^{(\ell^+)} + (A \leftrightarrow B)\right]$$

$$\hat{A}_A^{(2^+)}(u) = 1 + \frac{3u^2}{1-r_{\mathrm{LR}}u} + \frac{X_A\tilde{A}_1^{(2^+)1\mathrm{SF}}}{(1-r_{\mathrm{LR}}u)^{7/2}} + \frac{X_A^2\tilde{A}_2^{(2^+)2\mathrm{SF}}}{(1-r_{\mathrm{LR}}u)^p}$$

$p = 4$

Because of analytic considerations (BD 2015)



EOB (orbital) interaction potential

$$A(u) = A^0(u) + A^{\mathrm{tidal}}$$

$$A^{\mathrm{tidal}} = \sum_{\ell\geq 2} -\kappa_\ell^T u^{2\ell+2} \hat{A}_\ell^{\mathrm{tidal}}(u)$$ "Newtonian" (LO) part x PN corrections (NLO, NNLO, ...)

pointmass part

$$A_0 = 1 - 2u + 2\nu u^3 + \left(\frac{94}{3} - \frac{41}{32}\right)\nu u^4 + \nu[a_5^c(\nu) + a_5^{\ln}\ln u]u^5 + \nu[a_6^c(\nu) + a_6^{\ln} u]u^6$$

1PN 2PN 3PN 4PN

5PN term "informed" by NR

$$a_6^c(\nu) = 3097.3\nu^2 - 1330.6\nu + 81.3804$$

$$A^{\mathrm{resum}}(u;\nu, a_6^c) = P_5^1[A_0(u;\nu, a_6^c)]$$

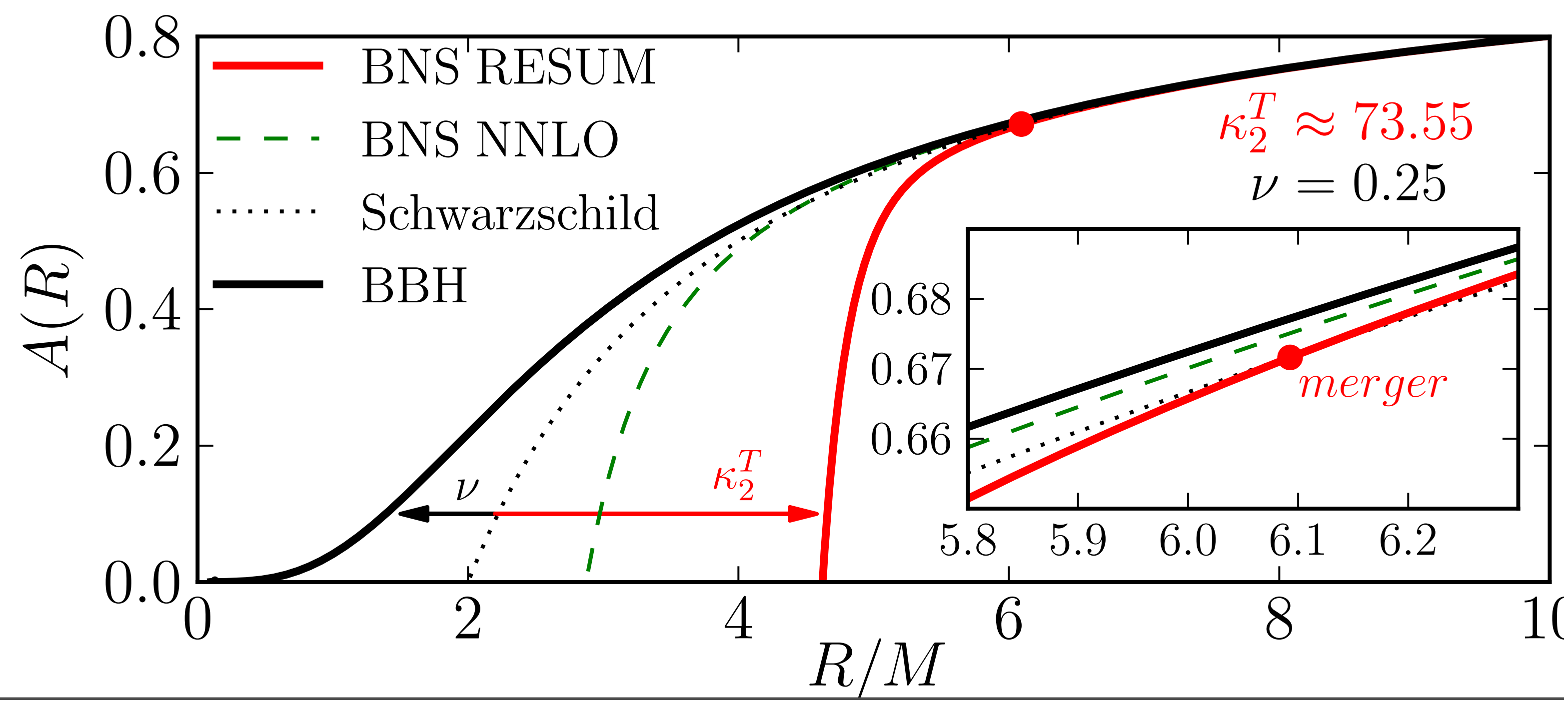
tidal part

$$A_T^{(+)}(u;\nu) \equiv -\sum_{\ell=2}^{4}\left[\kappa_A^{(\ell)} u^{2\ell+2} \hat{A}_A^{(\ell^+)} + (A \leftrightarrow B)\right]$$

$$\kappa_A^{(\ell)} = 2\frac{X_B}{X_A}\left(\frac{X_A}{C_A}\right)^{2\ell+1} k_\ell^A$$

Love numbers

$$X_{A,B} \equiv m_{A,B}/M$$



WAVEFORM

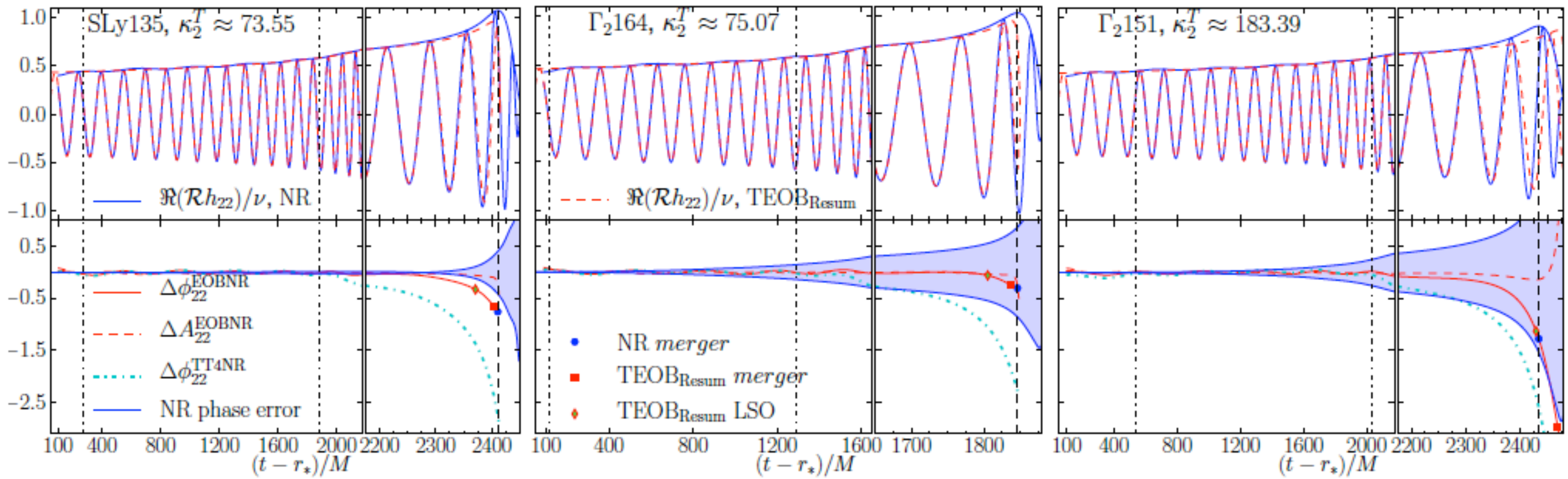


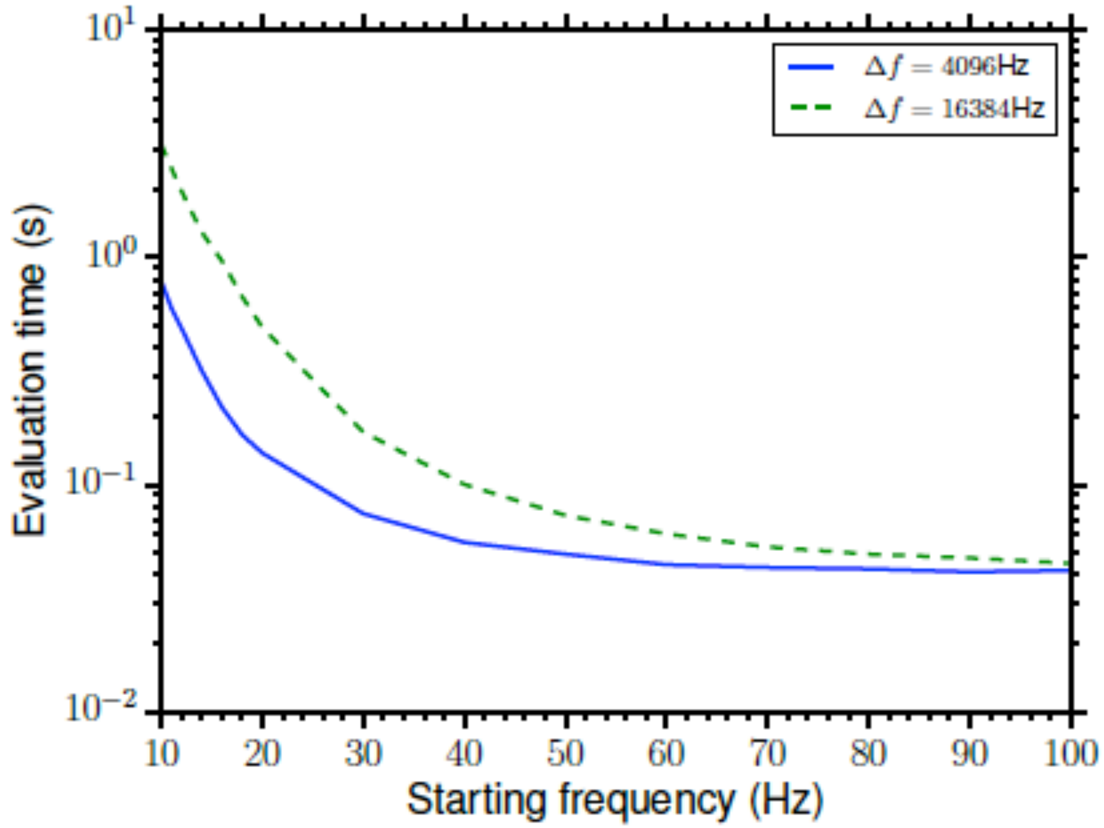
FIG. 3: Phasing and amplitude comparison (versus NR retarded time) between TEOB$_{\rm Resum}$, NR and the phasing of TT4 for three representative models. Waves are aligned on a time window (vertical dot-dashed lines) corresponding to $I_\omega \approx (0.04, 0.06)$. The markers in the bottom panels indicate: the crossing of the TEOB$_{\rm Resum}$ LSO radius; NR (also with a dashed vertical line) and EOB merger moments.

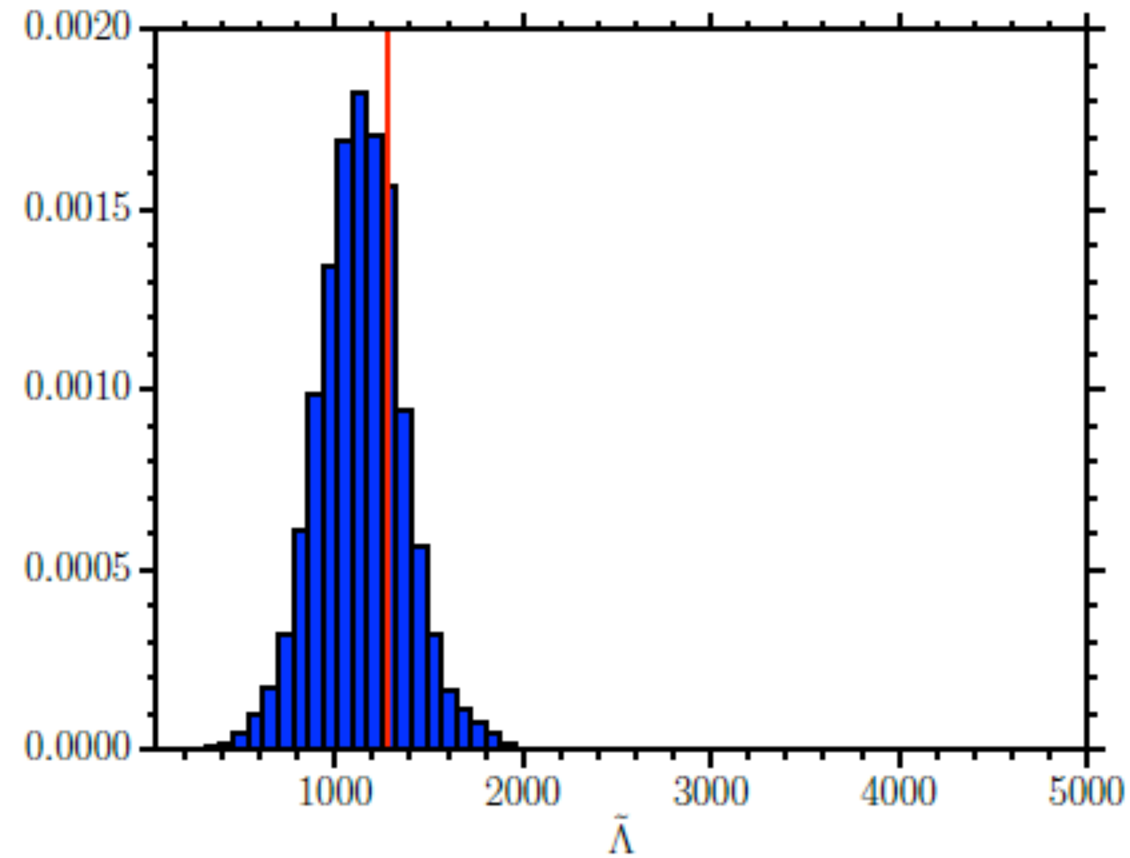
Name	EOS	κ_2^T	$r_{\rm LR}$	$\mathcal{C}_{A,B}$	$M_{A,B}[M_\odot]$	$M^0_{\rm ADM}[M_\odot]$	$\mathcal{J}^0_{\rm ADM}[M_\odot^2]$	$\Delta\phi^{\rm TT4}_{\rm NRmrg}$	$\Delta\phi^{\rm TEOBNNLO}_{\rm NRmrg}$	$\Delta\phi^{\rm TEOBResum}_{\rm NRmrg}$	$\delta\phi^{\rm NR}_{\rm NRmrg}$
2B135	2B	23.9121	3.253	0.2049	1.34997	2.67762	7.66256	−1.25	−0.19	$+0.57^a$	±4.20
SLy135	SLy	73.5450	3.701	0.17381	1.35000	2.67760	7.65780	−2.75	−1.79	−0.75	±0.40
$\Gamma_2 164$	$\Gamma = 2$	75.0671	3.728	0.15999	1.64388	3.25902	11.11313	−2.29	−1.36	−0.31	±0.90
$\Gamma_2 151$	$\Gamma = 2$	183.3911	4.160	0.13999	1.51484	3.00497	9.71561	−2.60	−1.92	−1.27	±1.20
H4135	H4	210.5866	4.211	0.14710	1.35003	2.67768	7.66315	−3.02	−2.43	−1.88	±1.04
MS1b135	MS1b	289.8034	4.381	0.14218	1.35001	2.67769	7.66517	−3.25	−2.84	−2.45	±3.01

S. Bernuzzi, A. Nagar, T. Dietrich & T. Damour, PRL 114 (2015), 161103

Implementation: ROM of TEOBResumS

Surrogate model for TEOB_ihes: Lackey,Bernuzzi,Galley,Meidan&Van Den Broeck 2016
Maximum error: 0.043 radians in phase
Implemented in LAL TEOBResum_ROM





T(S)EOB_ihes models are available as stand-alone matlab codes and as c++ codes (LAL-ification in progress with Nikhef group)

SUMMARY

1. Italian-driven (INFN Torino and Parma U) effort of having NR-informed, EOB-based waveform models for DA purposes. BBH & BNS. Spin aligned. Higher modes.

2. TEOBResumS: spin-aligned waveform model for BBH and NS. It can be used for measuring the EOS through the measure of the tidal polarizability constants.

3. Compatibility (within NR errors) between such EOBNR model and state-of-the art NR data over mass ratio and spin

4. BNS waveforms are very mature, and different avatars exists that can be used for DA purposes to measure the EOS