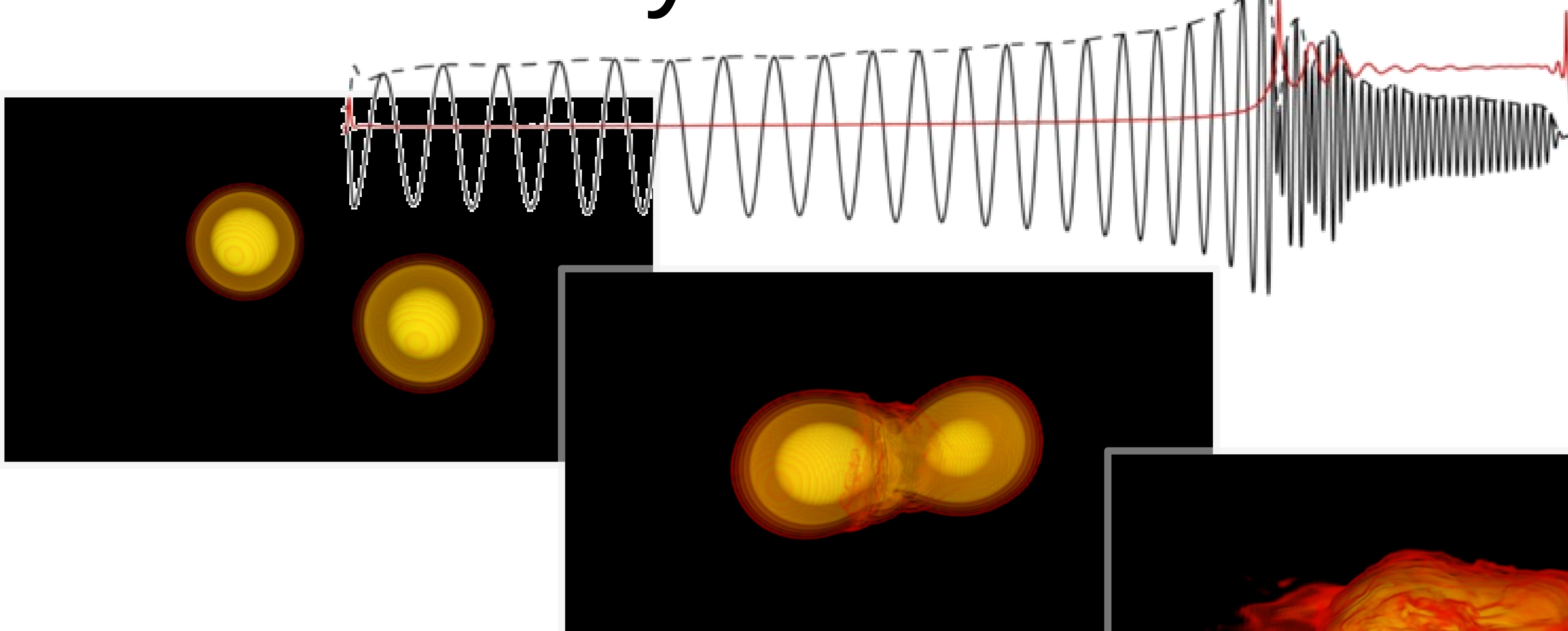
UNIVERSITÀ DI PARMA

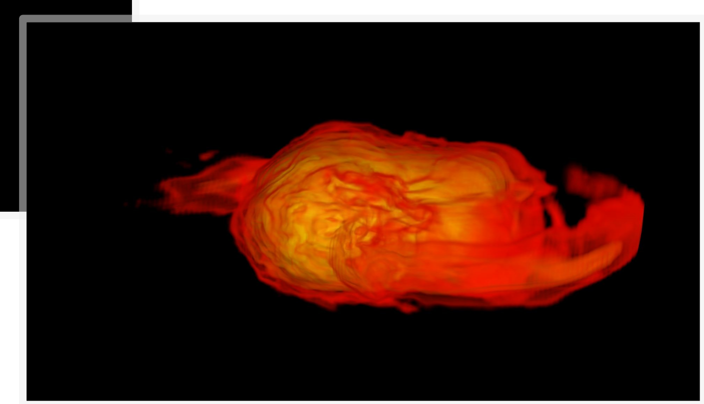
INFN Istituto Nazionale di Fisica Nucleare

VIRGO

LIGO

Modeling gravitational-waves from binary neutron stars





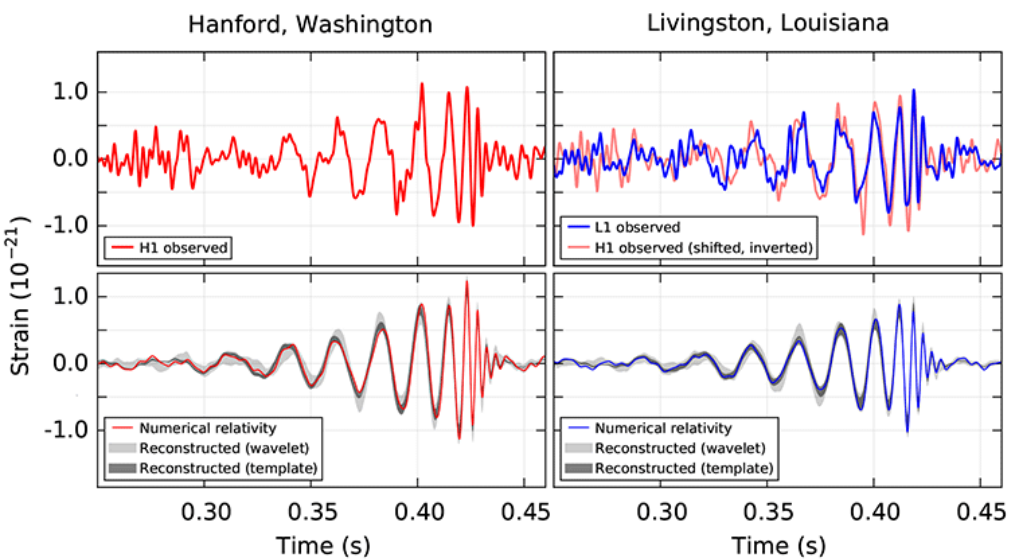
S.Bernuzzi SM&FT 2017

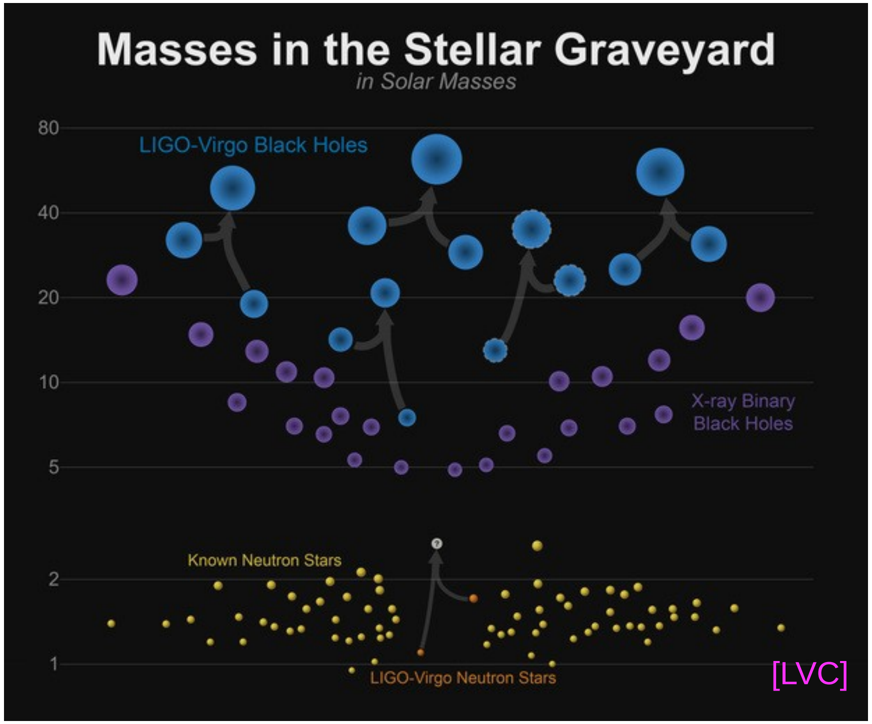
Bari, Dec 14th

Note: [LVC] = Plots/figures from LIGO&Virgo collaboration

GW150914 : GW astronomy has started

September, 14th 2015, 09:50:45 UT



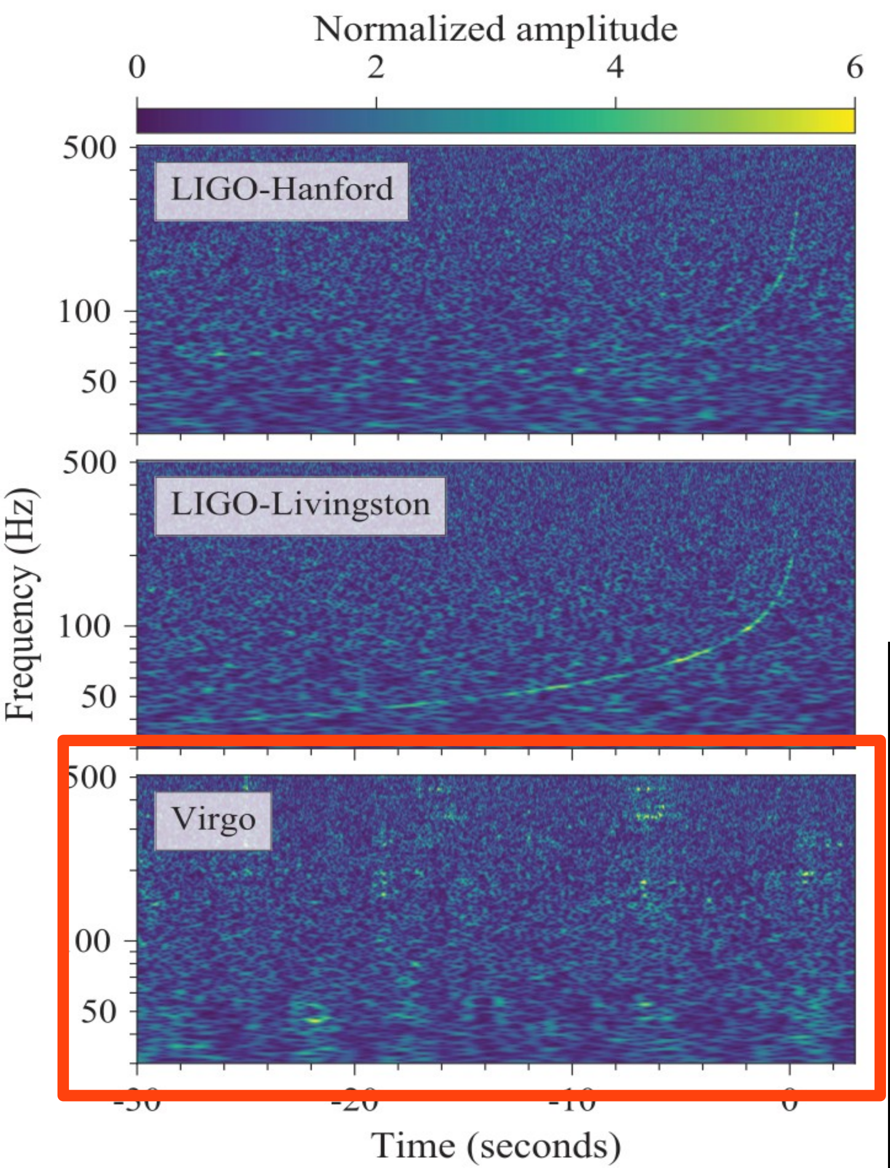


- 1st GW detected on Earth
- 1st GW from BHs
- 1st BBH merger
- Massive stellar-mass BBH population
- Test of GR in strong/dynamical regime
- *5 BBH events since 2015*

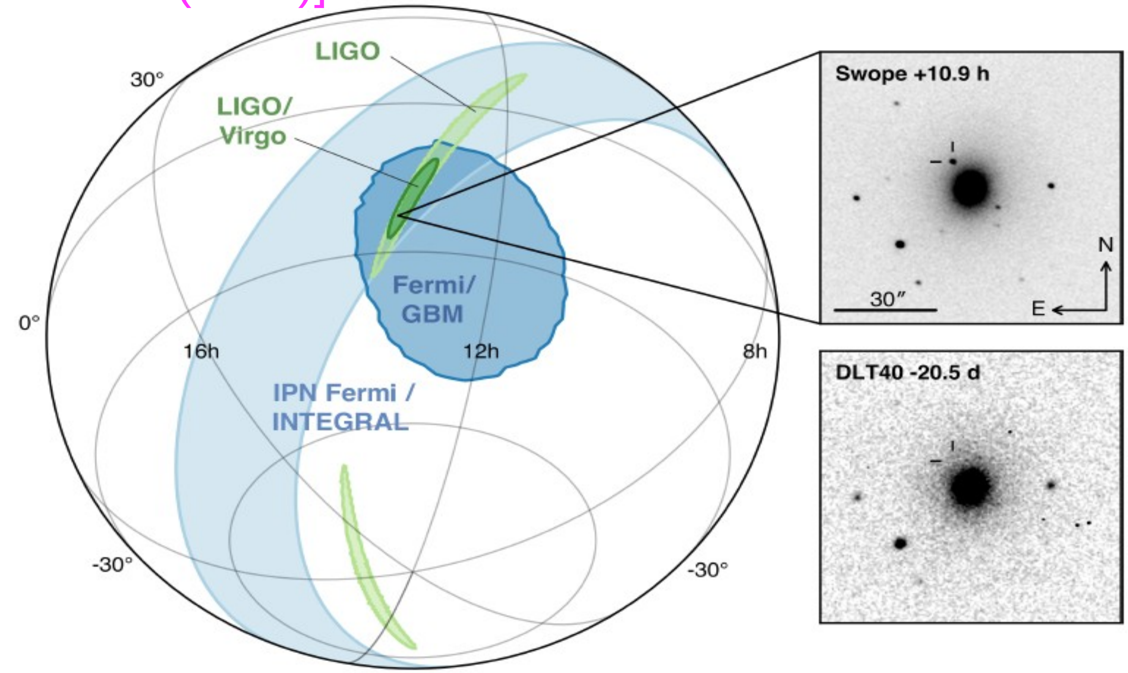
["Observation of Gravitational Waves from a Binary Black Hole Merger"
LIGO&Virgo collab. Phys. Rev. Lett. 116, 061102 (2016)]

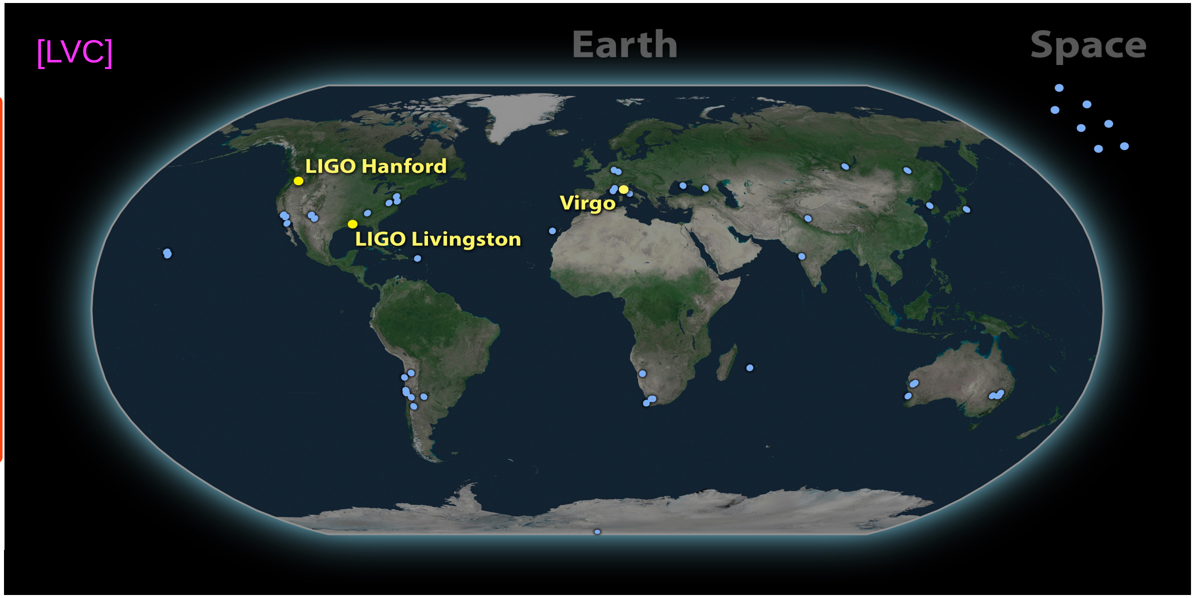
GW170817 : Multimessenger astronomy !

["GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral" LIGO&Virgo collab. Phys. Rev. Lett. 119, 161101 (2017)]



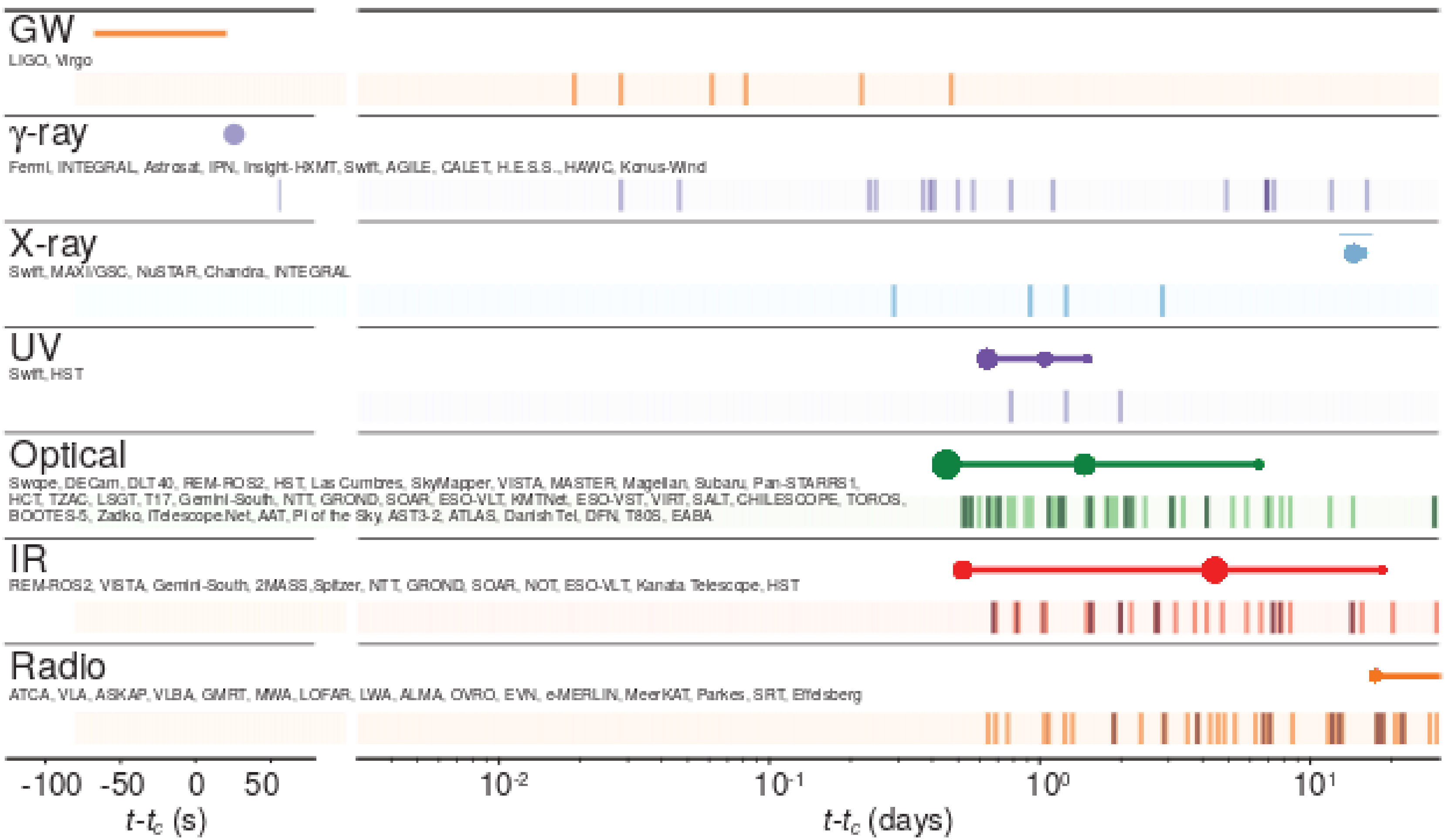
August, 17th 2017, 12:41:01 UTC





GW170817: Gravitational-waves & light from (likely) binary neutron star inspiral

[“Multi-Messenger Observations of a Binary Neutron Star Merger”
LIGO&Virgo Collab. +50 teams of electromagnetic and neutrino astronomers
Published in Astrophys. J. Lett. 848, L12 (2017)]



GW170817: Gravitational-waves & light from (likely) binary neutron star inspiral (cont.)

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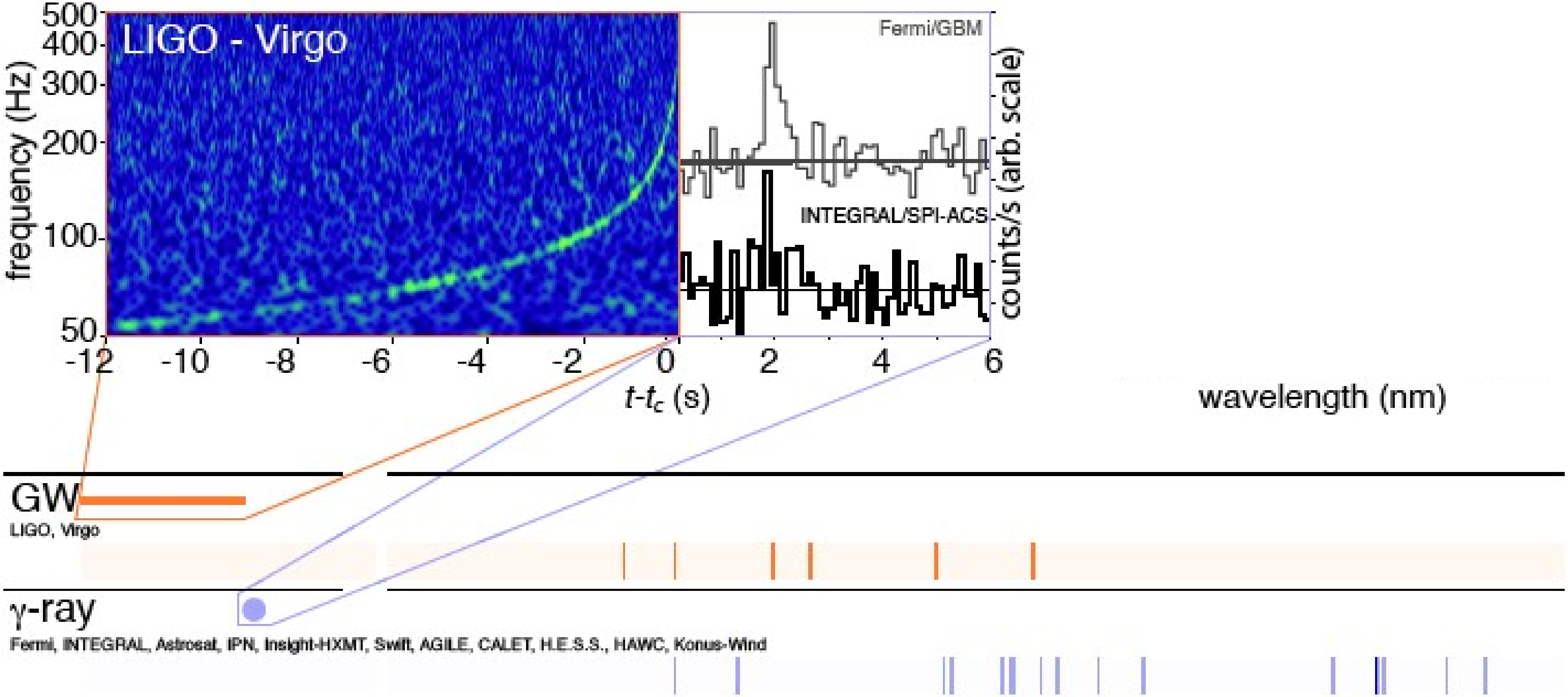
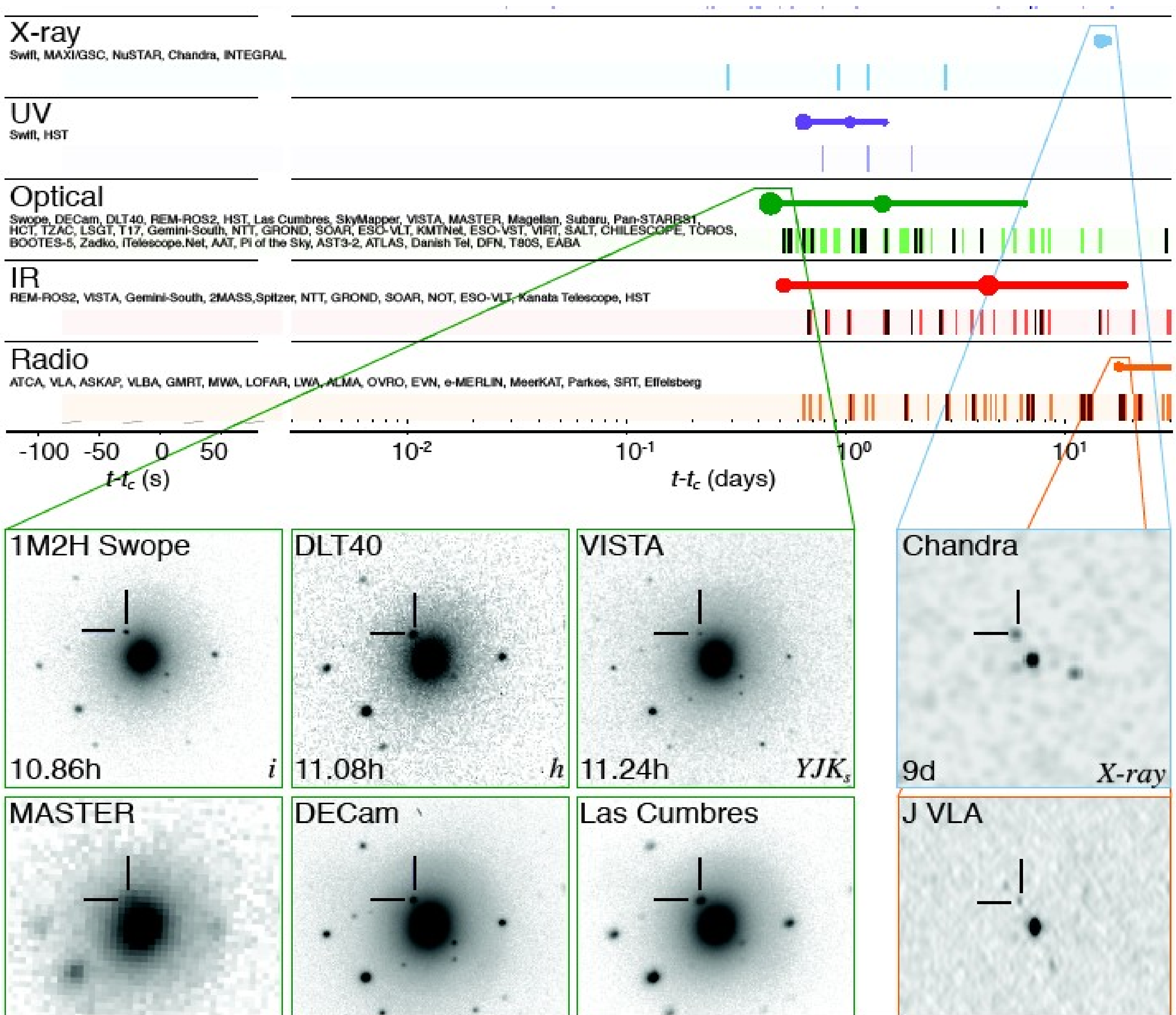


GW170817: Gravitational-waves & light from (likely) binary neutron star inspiral (cont.)



What did we learn from GW170817 ?

- GW → masses

  Source is most likely a binary neutron star system (BNS)

- GW → tidal parameters

  Constraints on NS matter

- GW+sGRB

  Connection between BNS and sGRB

- UV/O/IR→ Kilonova

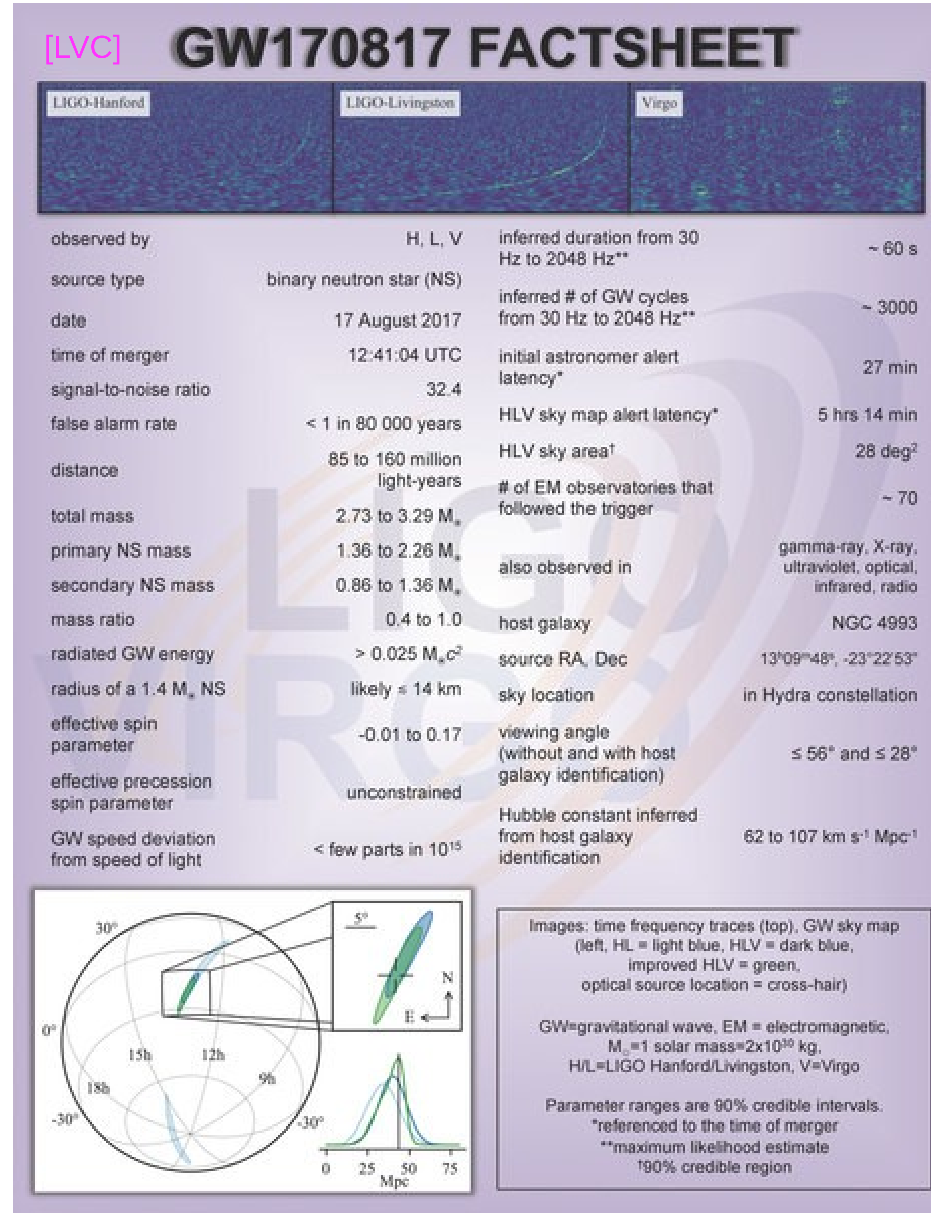
  Radioactive decay of r-process nuclei

  Main channel of formation of heavy elements

  Matter ejecta from BNS mergers are sites for r-process nucleosinthesis (ID from GW)

- EM+GW → Hubble constant

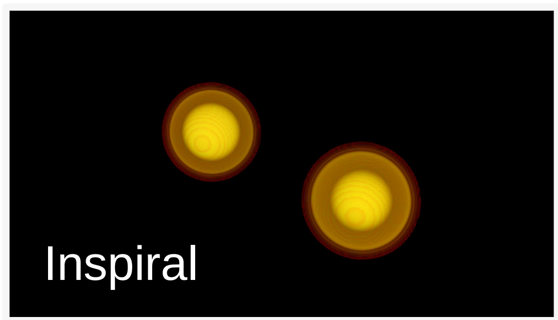
  Cosmography, independent measure



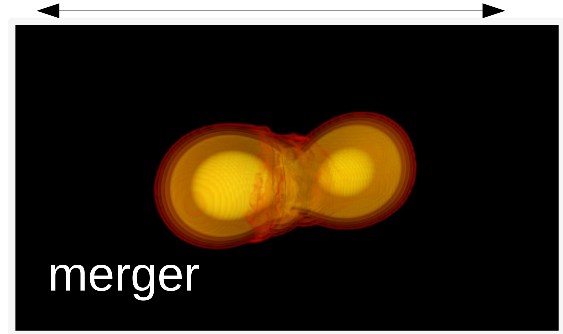
GWs: Tiny signatures of extreme events

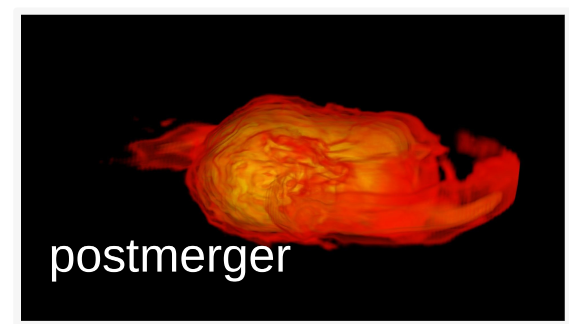
Collision of neutron stars [Mass~1.4 Msun, Radius~10 km]:

d ~ 150 km



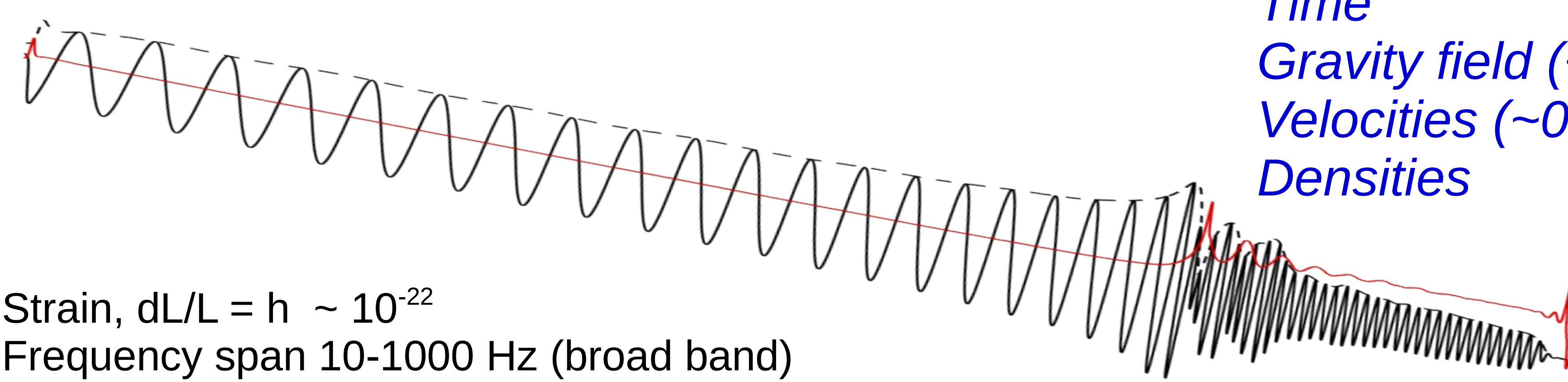
d ~ 50 km





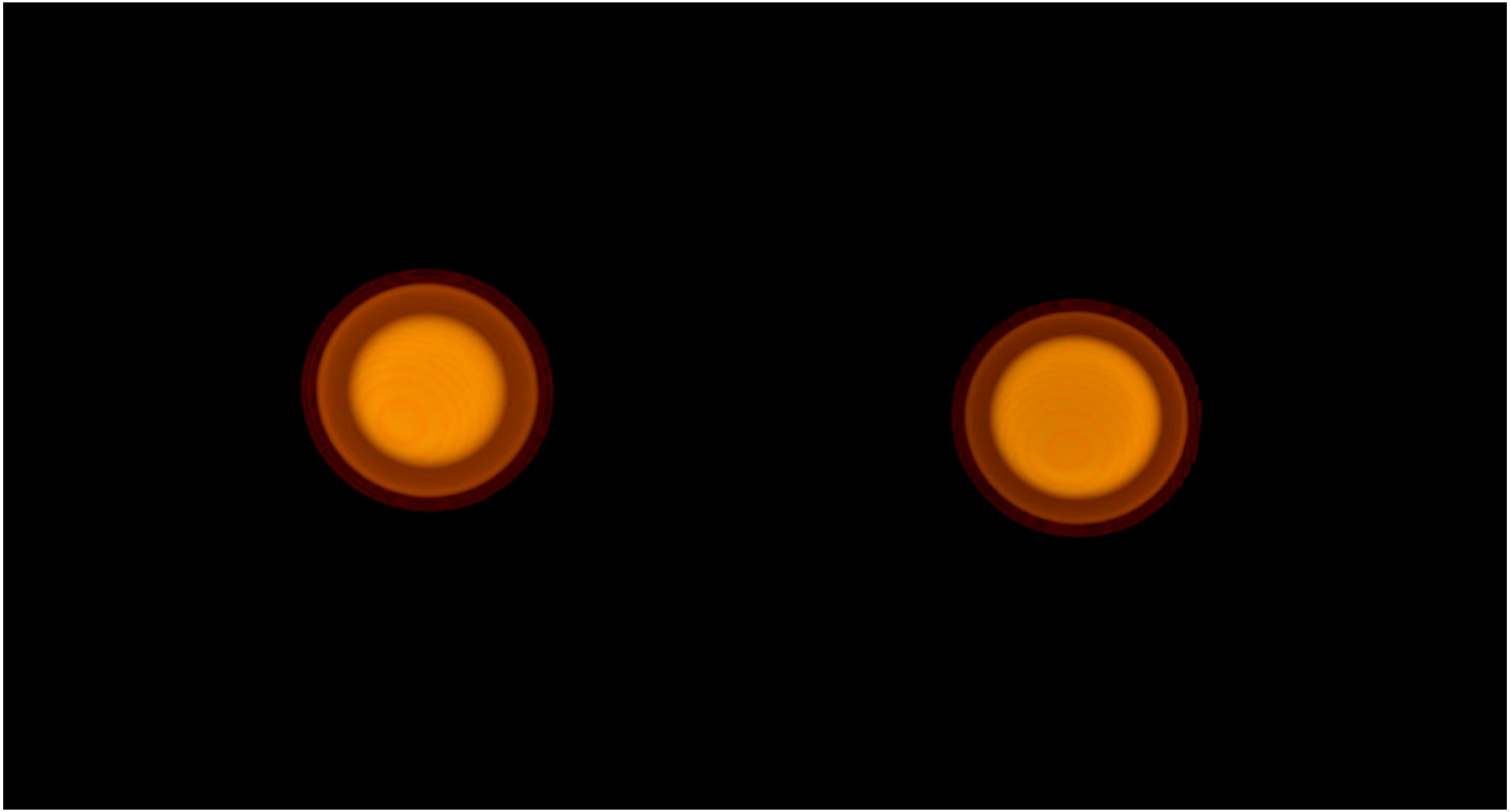
D~200 Mpc (“far away”) from the source:

Time
Gravity field (~M/d)
Velocities (~0.1 c)
Densities



Strain, $dL/L = h \sim 10^{-22}$
Frequency span 10-1000 Hz (broad band)

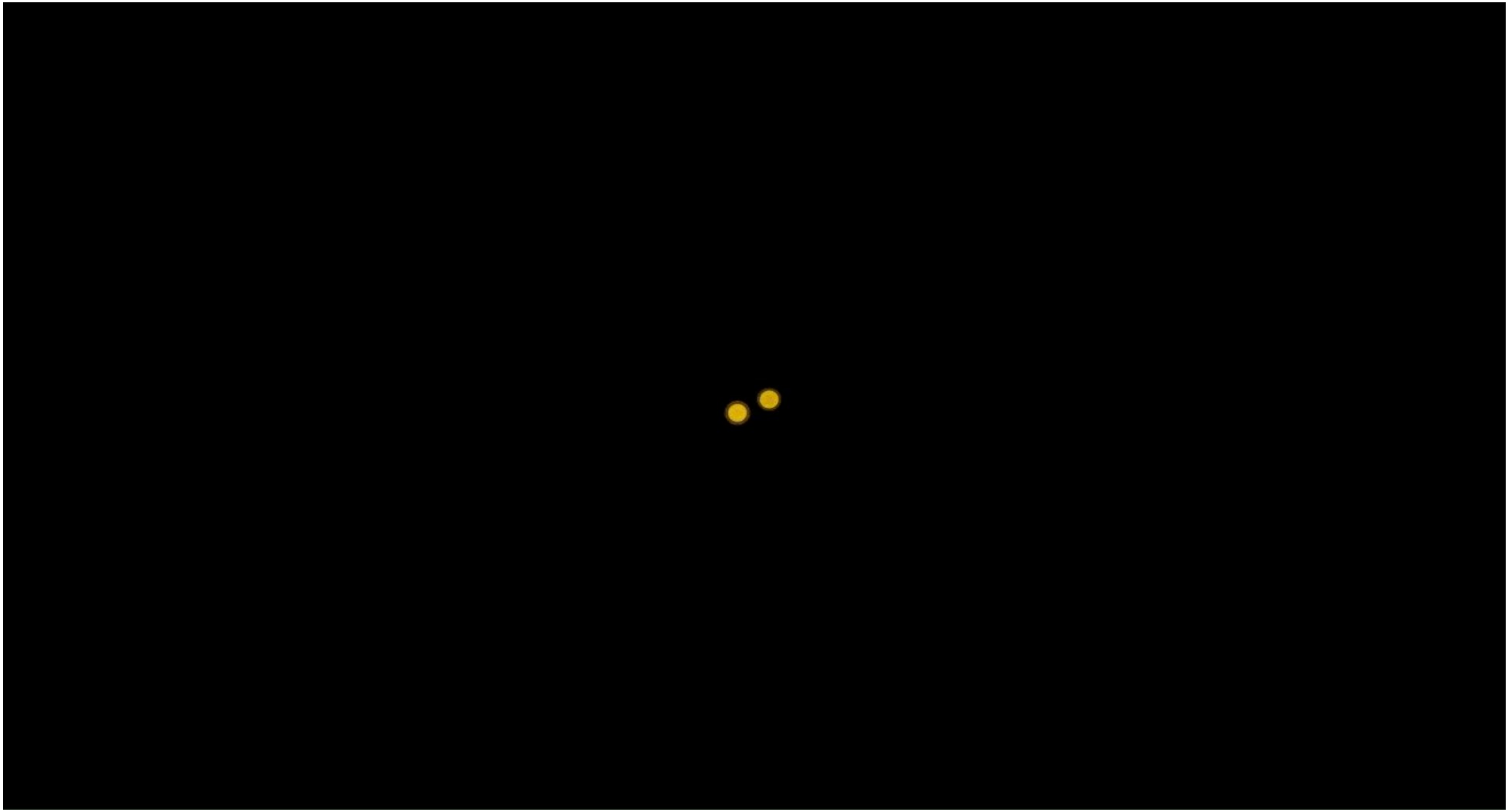
First numerical relativity simulation of neutron star merger with precessing spins: the double pulsar case



Viz by T.Dietrich

Baryon mass density

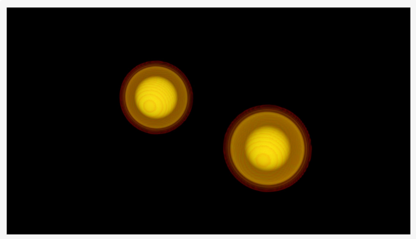
First numerical relativity simulation of neutron star merger with precessing spins: the double pulsar case

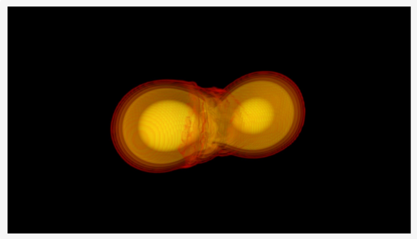


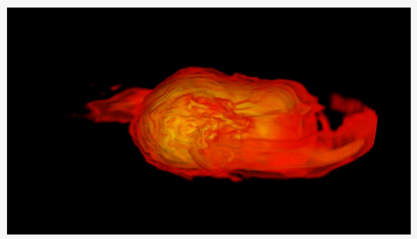
Viz by T.Dietrich

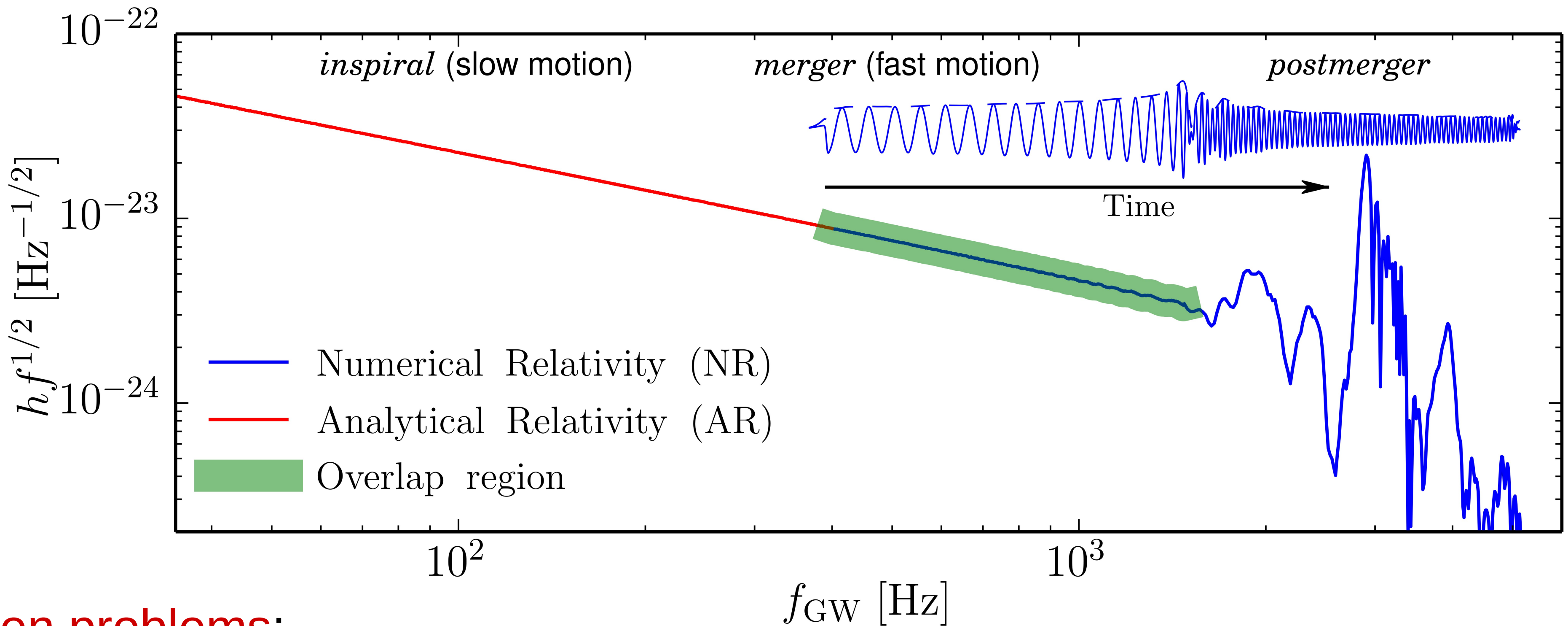
Weyl curvature scalar

The GW spectrum of binary neutron stars







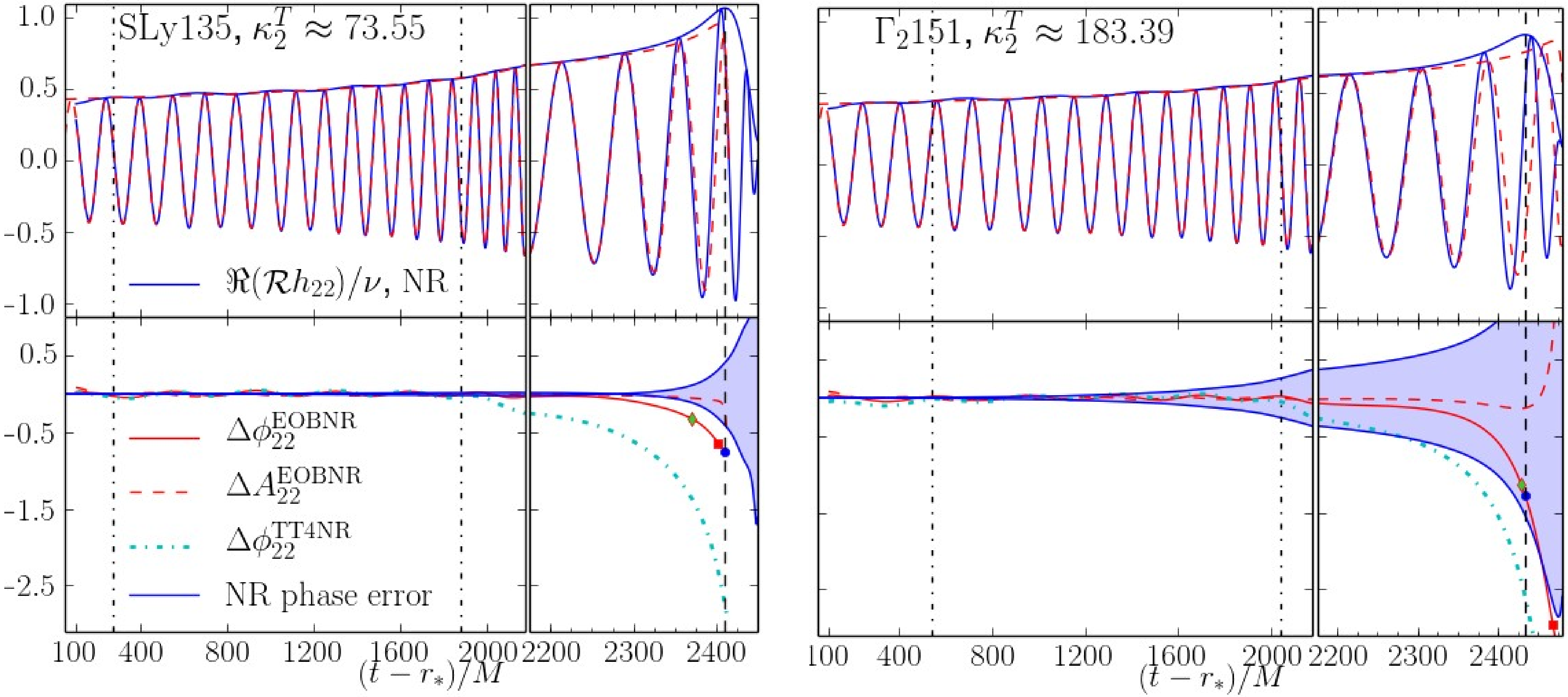


Open problems:

- Faithful and **complete waveform model** (*inspiral+merger+postmerger*)
- Coverage of the **parameter space** (mass, spins, EOS, …)
- Precise prediction of the merger remnant (e.g. collapse, black hole)

First waveform model for inspiral → merger

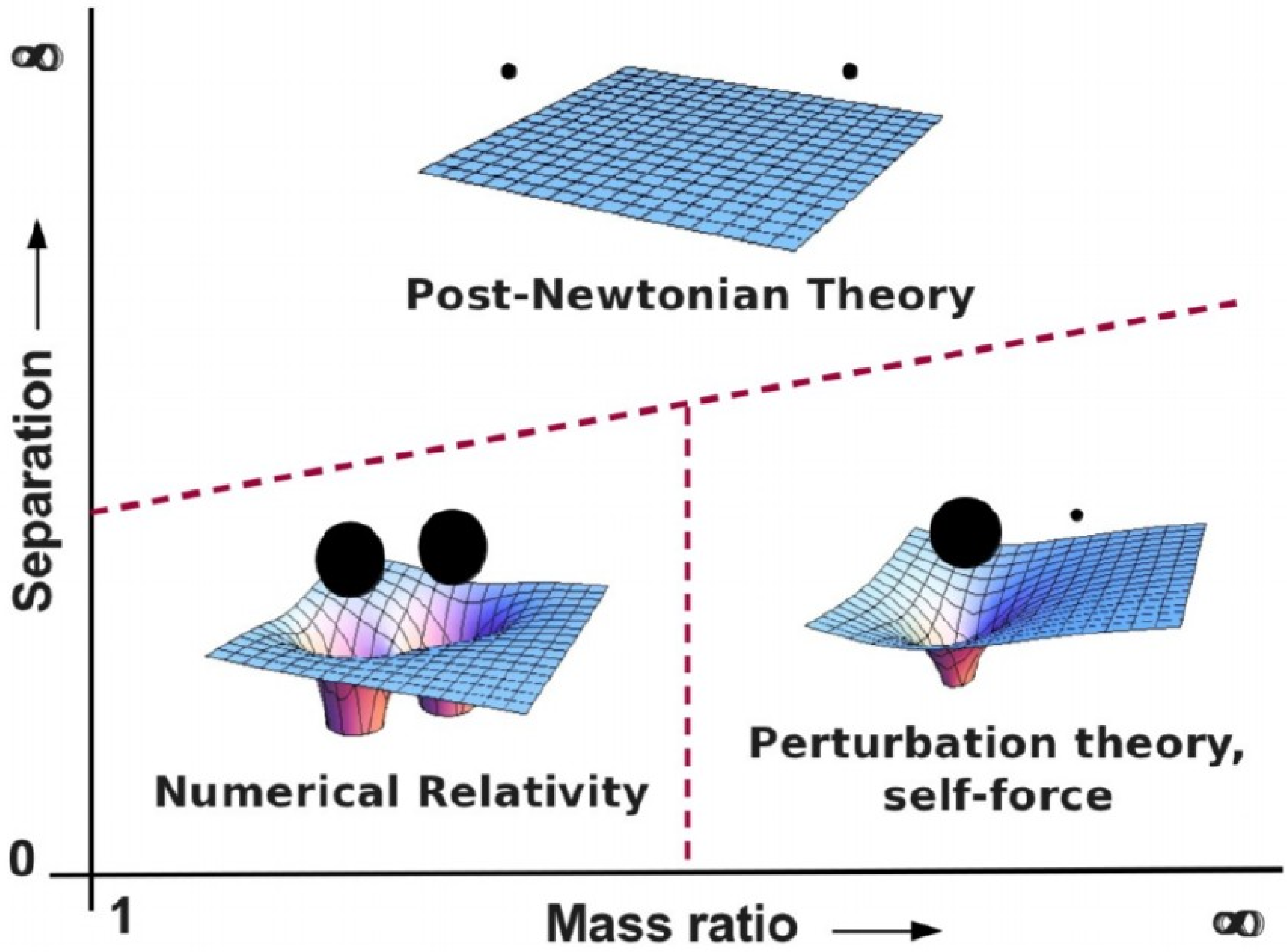
[SB,Nagar,Dietrich,Damour PRL 114 (2015)]



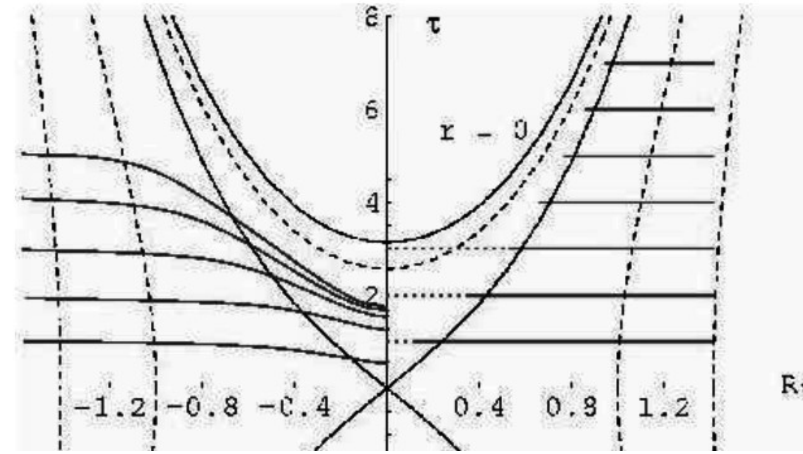
- Effective-one-body model with tides, GSF Resummed approach [Bini+ 2014]
- Valid from low frequencies to merger, PREDICT the merger waveform
- Accuracy: uncertainties of the numerical data (improve simulations!)

See [Hinderer+ PRL 116 (2016)] for an alternative approach

Methods for the GR 2-body problem



$$
\begin{aligned}
\partial_t \tilde{\Gamma}^i =& -2\,\tilde{A}^{ij}\,\partial_j\alpha + 2\,\alpha\left[\tilde{\Gamma}^i{}_{jk}\,\tilde{A}^{jk} - \frac{3}{2}\,\tilde{A}^{ij}\,\partial_j\ln(\chi)\right.\\
&\left. - \frac{1}{3}\,\tilde{\gamma}^{ij}\,\partial_j(2\,\hat{K} + \Theta) - 8\,\pi\,\tilde{\gamma}^{ij}\,S_j\right] + \tilde{\gamma}^{jk}\,\partial_j\partial_k\beta^i\\
&+ \frac{1}{3}\,\tilde{\gamma}^{ij}\partial_j\partial_k\beta^k + \beta^j\,\partial_j\tilde{\Gamma}^i - (\tilde{\Gamma}_{\rm d})^j\,\partial_j\beta^i\\
&+ \frac{2}{3}\,(\tilde{\Gamma}_{\rm d})^i\,\partial_j\beta^j - 2\,\alpha\,\kappa_1\left[\tilde{\Gamma}^i - (\tilde{\Gamma}_{\rm d})^i\right],\\
\partial_t\Theta =& \frac{1}{2}\,\alpha\left[R - \tilde{A}_{ij}\,\tilde{A}^{ij} + \frac{2}{3}\,(\hat{K} + 2\,\Theta)^2\right]\\
&- \alpha\left[8\,\pi\,\rho + \kappa_1\,(2 + \kappa_2)\,\Theta\right] + \beta^i\partial_i\Theta\,,
\end{aligned}
$$



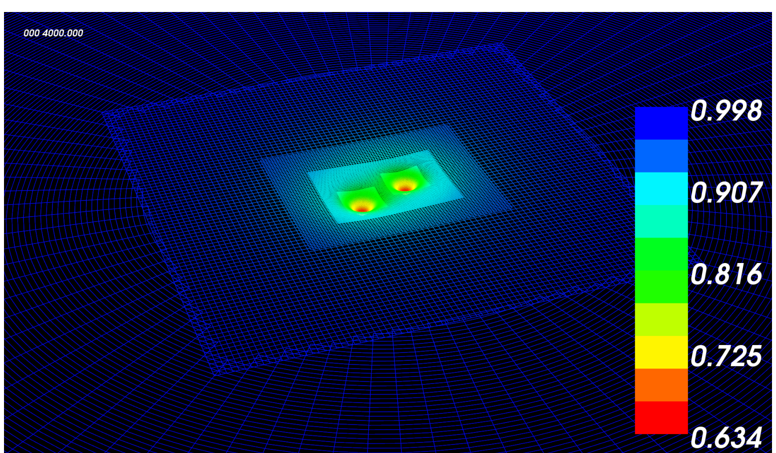
GR Formulation and Cauchy problem
+ GR hydrodynamics

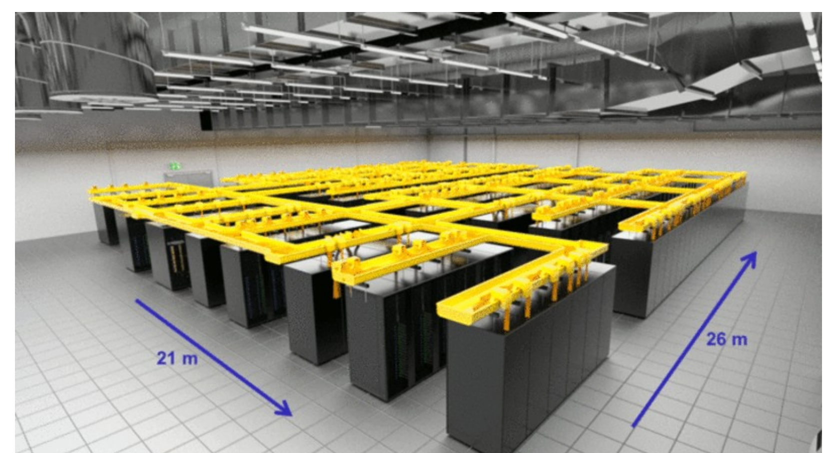
Coordinates and Singularities

Numerical relativity in a nutshell

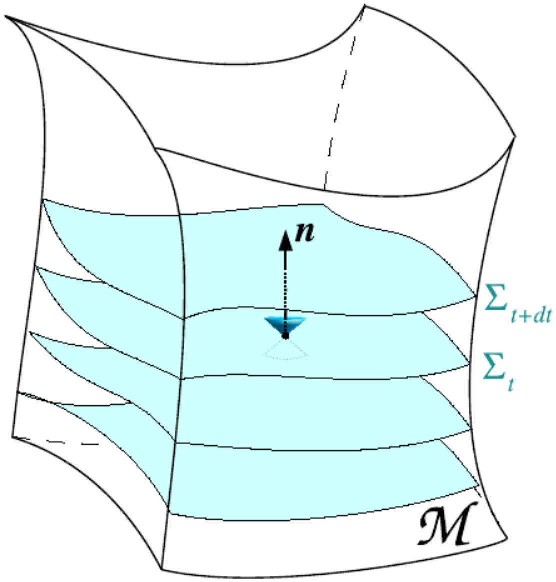
Numerical methods for PDEs on adaptive grids

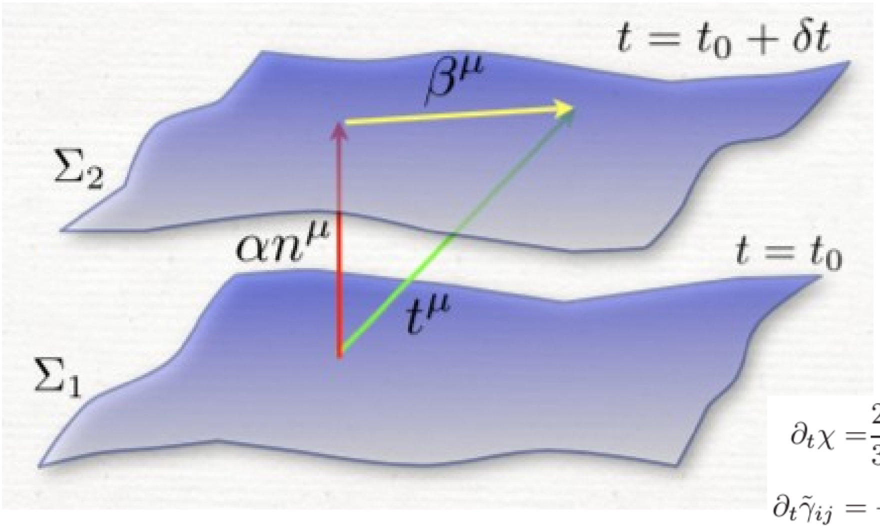
High-performance-computing (HPC)





Numerical relativity: Cauchy problem in GR



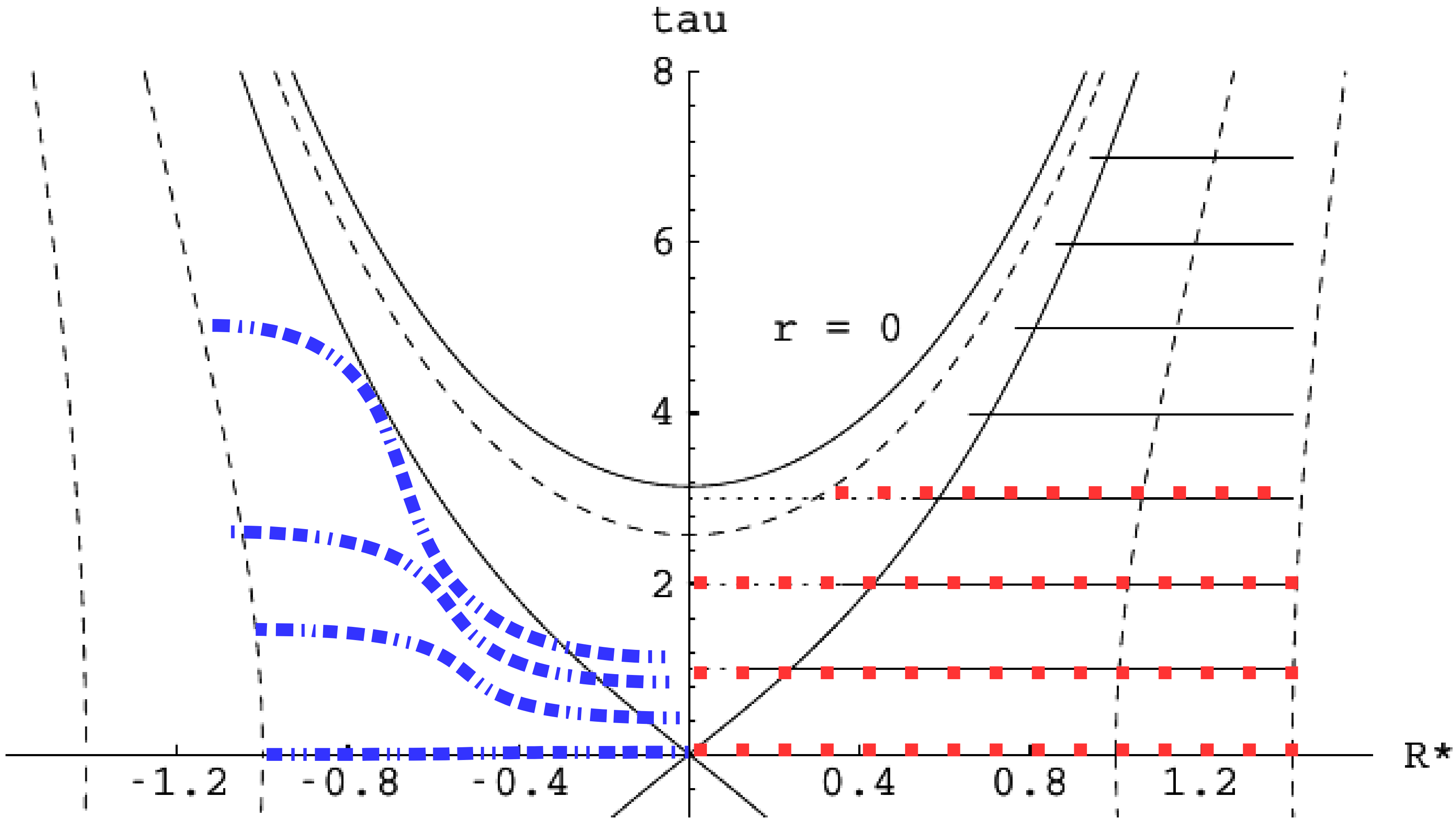


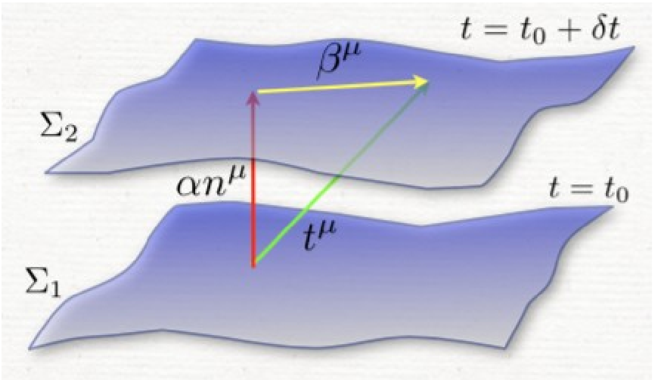
$$
\begin{aligned}
\partial_t \chi =& \frac{2}{3}\chi[\alpha(\hat{K} + 2\Theta) - D_i\beta^i],\\
\partial_t \tilde{\gamma}_{ij} =& -2\alpha\tilde{A}_{ij} + \beta^k\tilde{\gamma}_{ij,k} + 2\tilde{\gamma}_{k(i}\beta^k_{,j)} - \frac{2}{3}\tilde{\gamma}_{ij}\beta^k_{,k}\ ,\\
\partial_t \hat{K} =& -D^iD_i\alpha + \alpha[\tilde{A}_{ij}\tilde{A}^{ij} + \frac{1}{3}(\hat{K} + 2\Theta)^2]\\
& + 4\pi\alpha[S + \rho_{\mathrm{ADM}}] + \alpha\kappa_1(1-\kappa_2)\Theta + \beta^i\hat{K}_{,i}\\
\partial_t \tilde{A}_{ij} =& \chi[-D_iD_j\alpha + \alpha(R_{ij} - 8\pi S_{ij})]^{\mathrm{tf}}\\
& + \alpha[(\hat{K} + 2\Theta)\tilde{A}_{ij} - 2\tilde{A}^k{}_i\tilde{A}_{kj}]\\
& + \beta^k\tilde{A}_{ij,k} + 2\tilde{A}_{k(i}\beta^k_{,j)} - \frac{2}{3}\tilde{A}_{ij}\beta^k{}_{,k}\\
\partial_t \tilde{\Gamma}^i =& -2\tilde{A}^{ij}\alpha_{,j} + 2\alpha[\tilde{\Gamma}^i_{jk}\tilde{A}^{jk} - \frac{3}{2}\tilde{A}^{ij}\ln(\chi)_{,j}\\
& - \frac{1}{3}\tilde{\gamma}^{ij}(2\hat{K} + \Theta)_{,j} - 8\pi\tilde{\gamma}^{ij}S_j] + \tilde{\gamma}^{jk}\beta^i_{,jk}\\
& + \frac{1}{3}\tilde{\gamma}^{ij}\beta^k_{,kj} + \beta^j\tilde{\Gamma}^i_{,j} - \tilde{\Gamma}_{\mathrm{d}}{}^j\beta^i_{,j} + \frac{2}{3}\tilde{\Gamma}_{\mathrm{d}}{}^i\beta^j_{,j}\\
& - 2\alpha\kappa_1(\tilde{\Gamma}^i - \tilde{\Gamma}_{\mathrm{d}}{}^i),\\
\partial_t \Theta =& \alpha[\frac{1}{2}R - \frac{1}{2}\tilde{A}_{ij}\tilde{A}^{ij} + \frac{1}{3}(\hat{K} + 2\Theta)^2\\
& - 8\pi\rho_{\mathrm{ADM}} - \kappa_1(2 + \kappa_2)\Theta] + \mathcal{L}_\beta\Theta.
\end{aligned}
$$

- 3+1 formulation (hyperboloidal slices?)
- Initial data (Lichnerowic, York, ...)
- Evolution schemes (GHG; ADM →BSSN, Z4c)
- Well posedness (Choquet-Bruhat; Friedrich; …. Gundlach&Martin-Garcia) [*need gauge fix*]

[SB, Hilditch arXiv:0912.2920]

Numerical relativity: singularities & crash tests

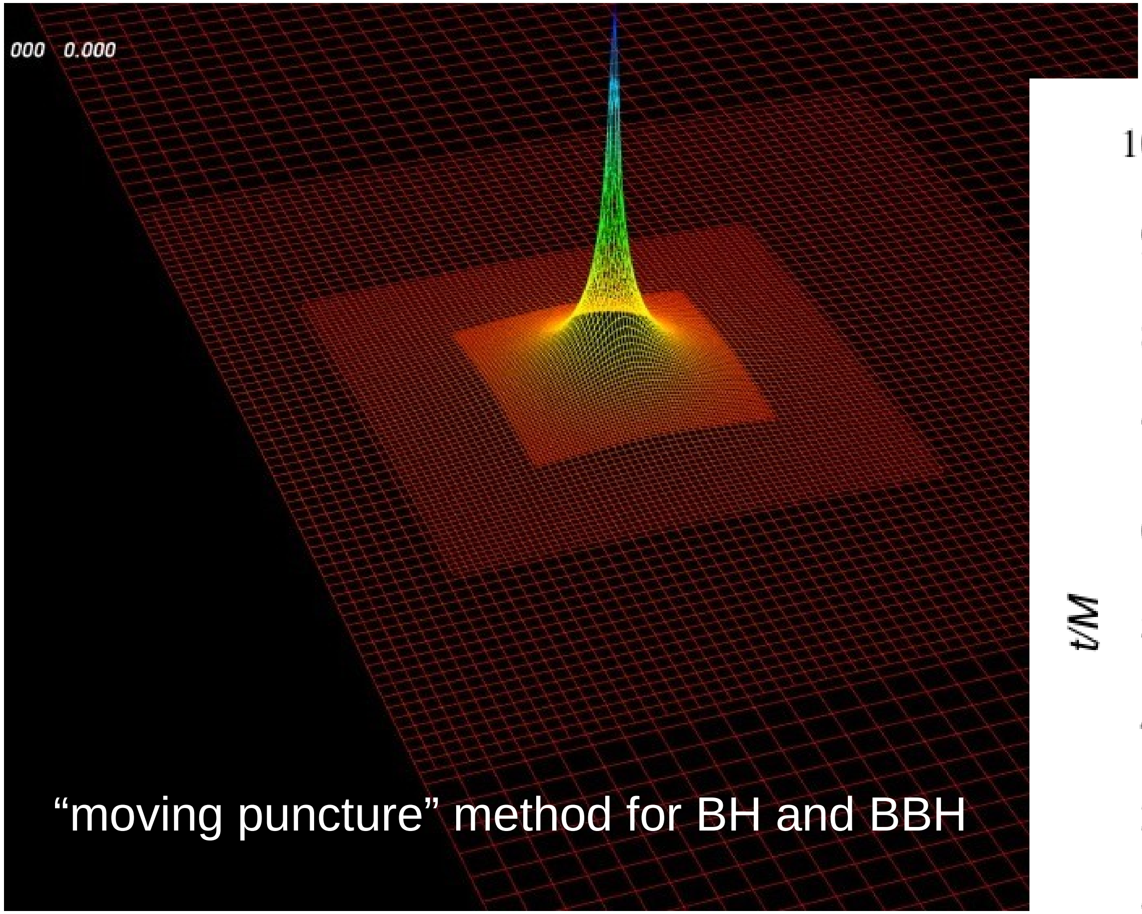




- Crash at tau=pi (geodesic slicing)
- Lapse collapse, slice stretching (1+log, shift=0)

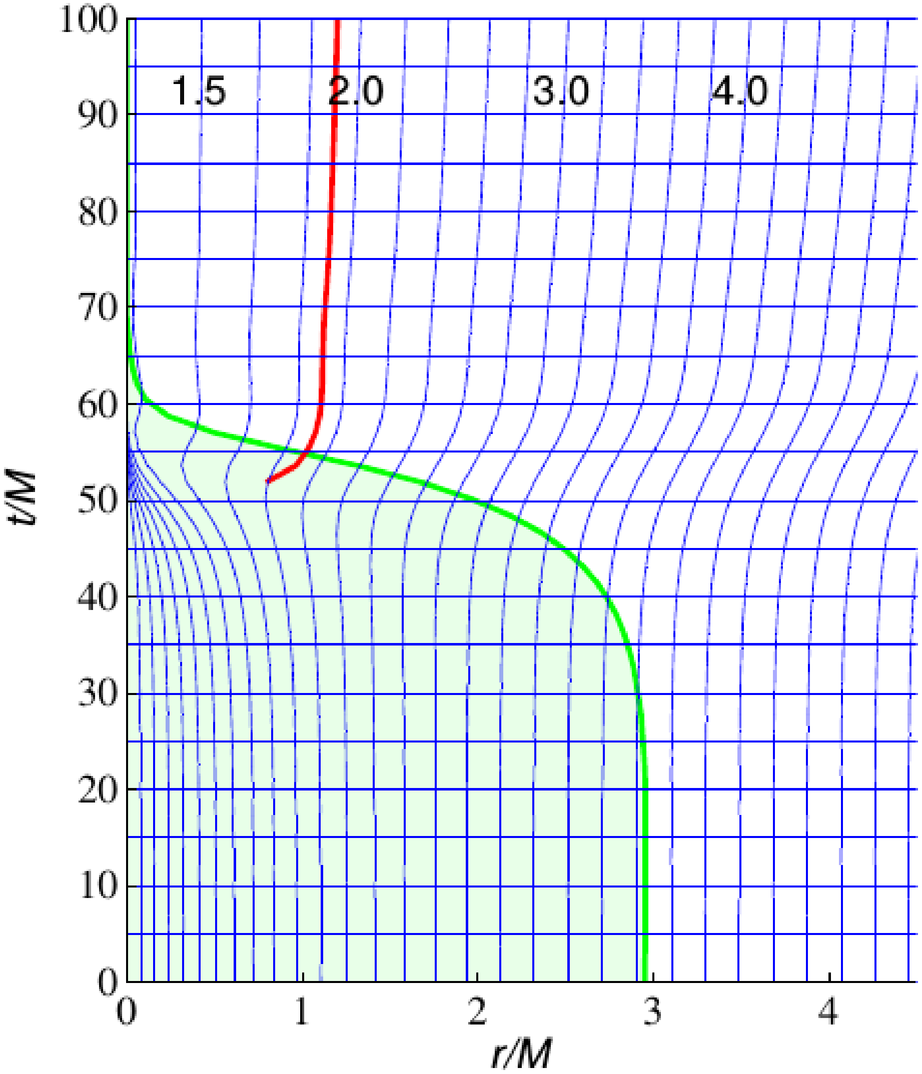
e.g. [Bruegmann arXiv:9912009]

Numerical relativity: singularities & coordinates



[Brandt&Bruegmann, arXiv:gr-qc/9703066,
Baker+ arXiv:gr-qc/0511103,
Campanelli+ arXiv:gr-qc/0511048]

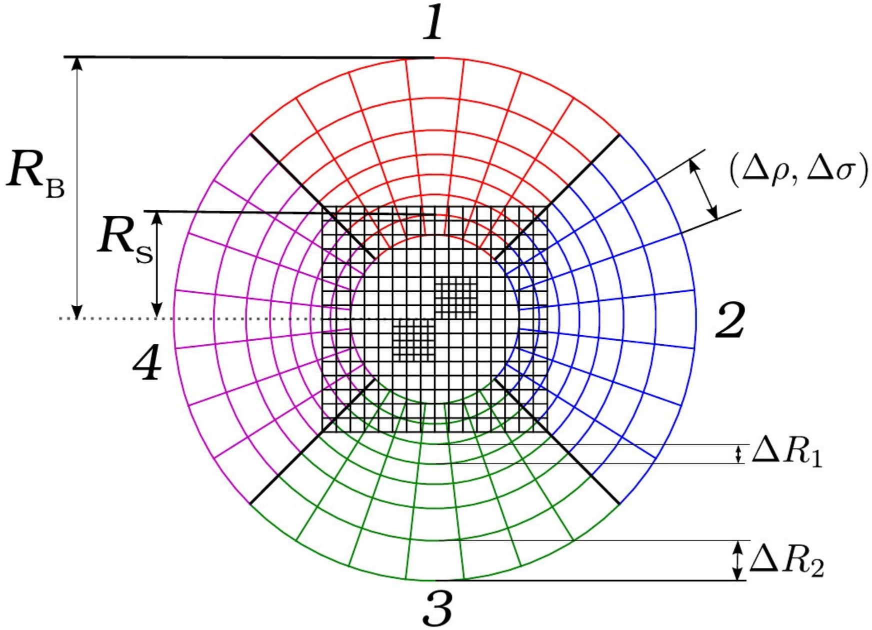
Gravitational collapse to BH

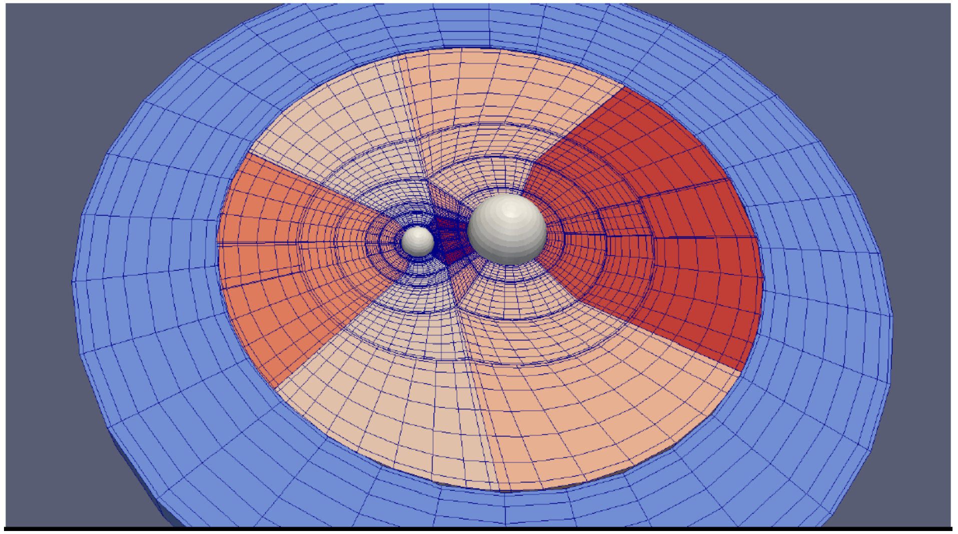


[Thierfelder, SB, Hilditch, Bruegmann, Rezzolla
arXiv:1012.3703]

Numerical relativity: numerical methods (some)

Adaptive mesh refinement (AMR) → resolve multiple scales





Grid based, AMR Berger-Oliger

Method of line w\ Runge-Kutta (Subcycling)

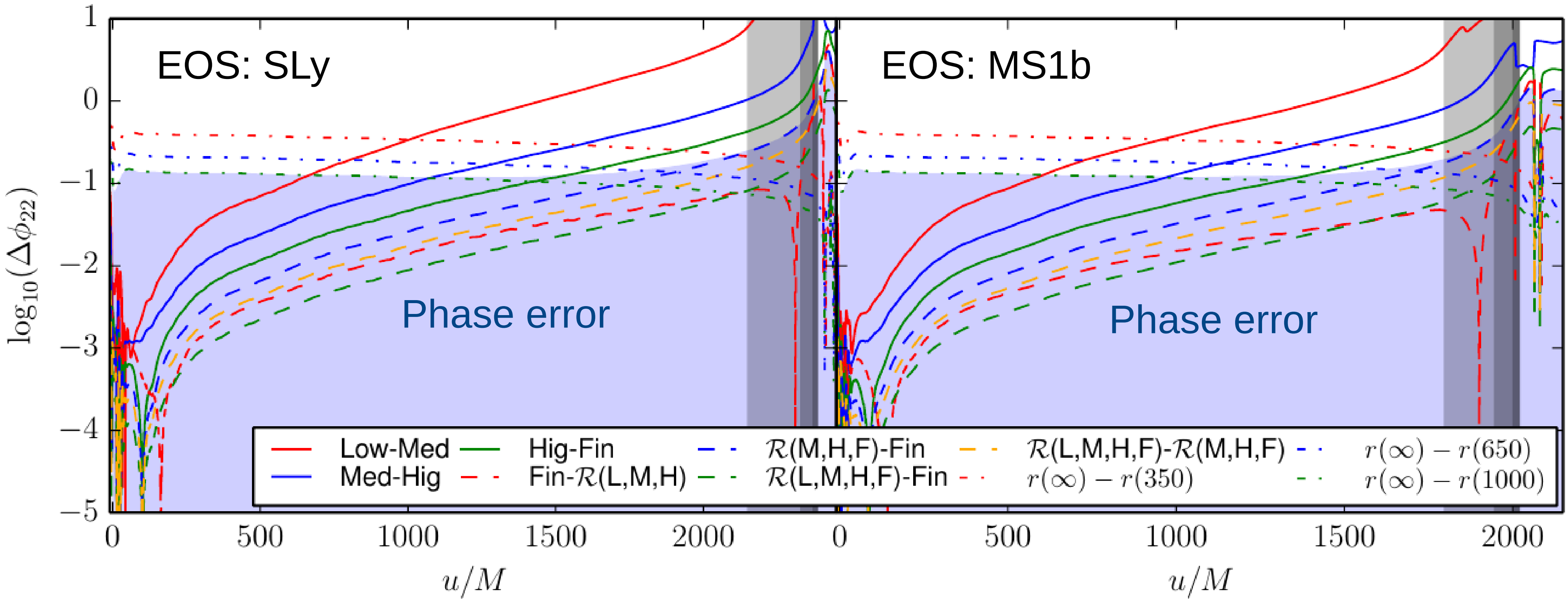
Finite differencing and finite volumes

Numerical relativity specs

- R.H.S. complexity (derivatives and contractions)
  → stencil ("horizontal") + pointwise ("vertical") ops
- High-order operators (large 3D stencils > 5 pts/direction)
  → communication overhead for distributed computations
- Memory: >~ O(100) 3D grid function per time level

Improved NR GW with high-order WENO schemes

[SB,Dietrich PRD94 064062 (2016)]

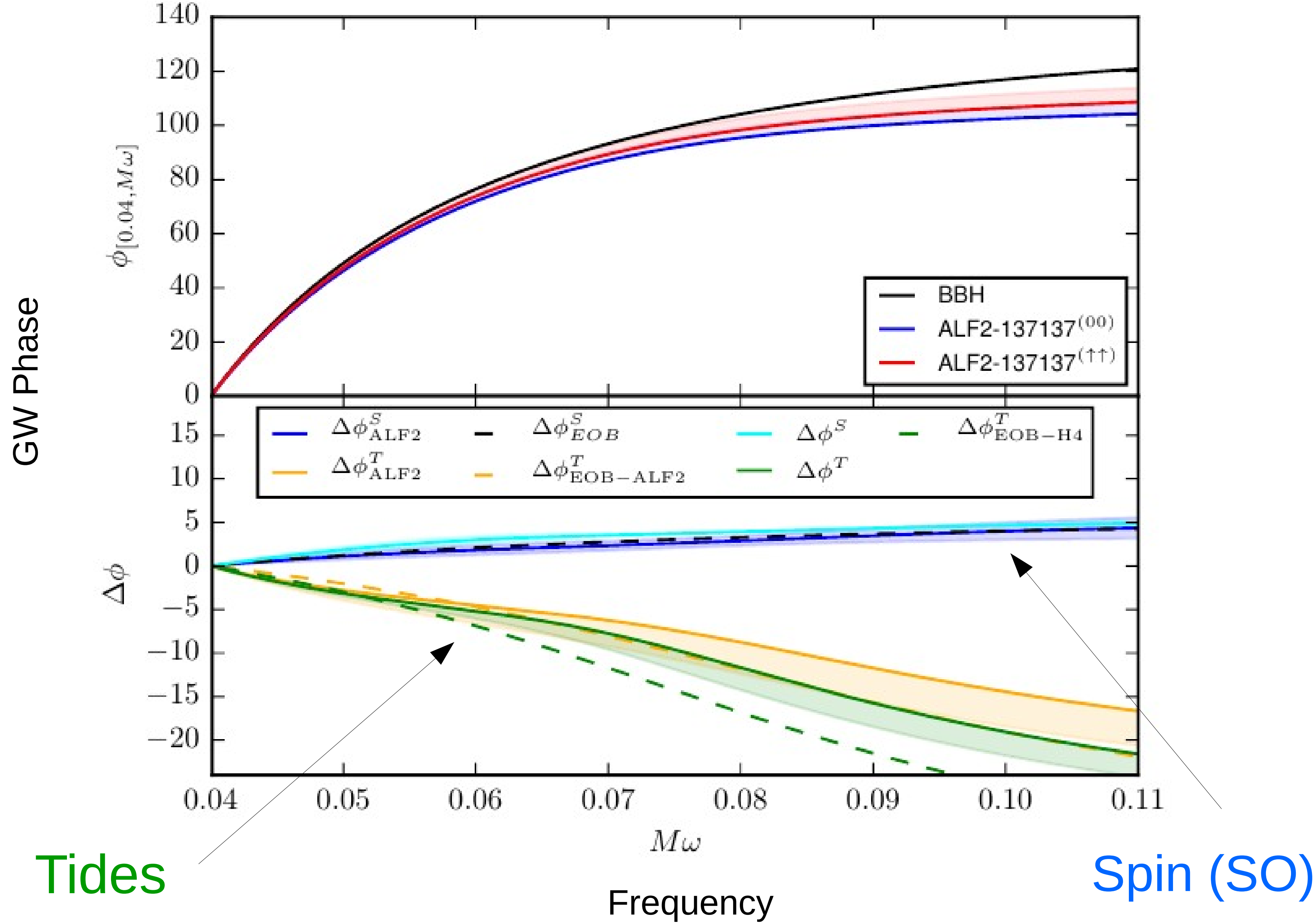


- Robust convergence assessment (although not 5th order)
- Large resolution span (64^3 -192^3), no alignment
- Error budget: significant improvement wrt FV schemes

See also [SB+ arXiv:1205.3403] [Radice+ arxiv:1306.6052]

Spins & tides during merger: phasing

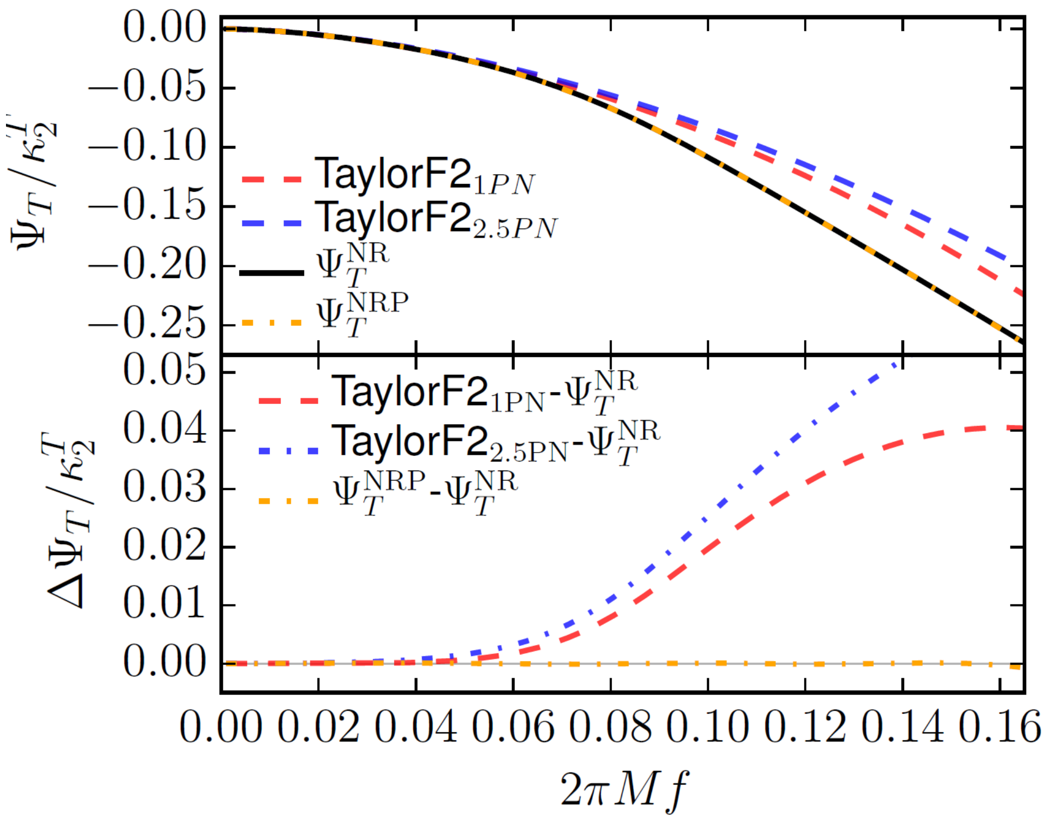
[Dietrich, SB, Ujevic, Tichy PRD 95 (2017)]

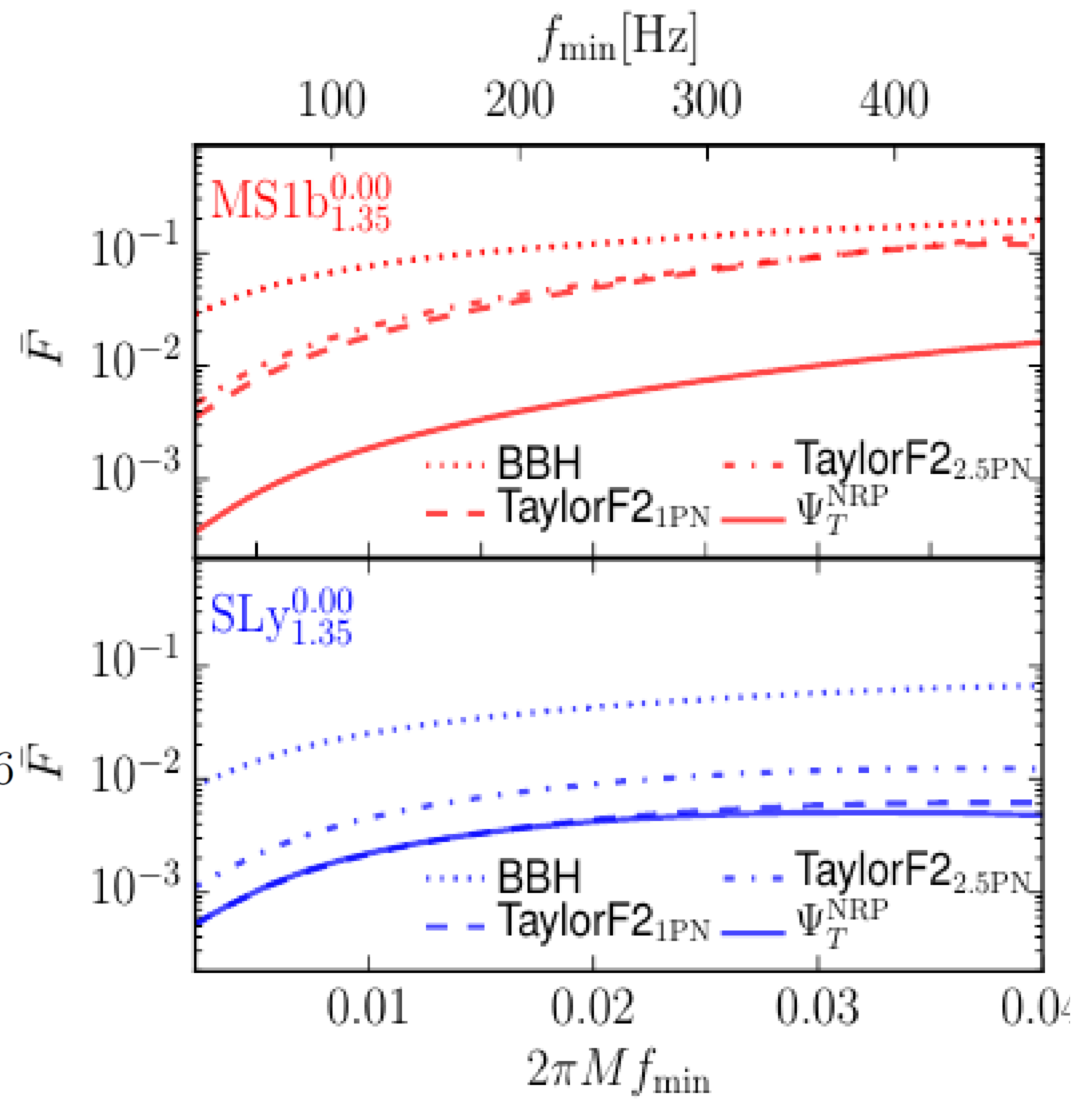


Closed-form tidal approximants from NR

[Dietrich, SB, Tichy arXiv:1706.02969]

First NR-based tidal approximant
Fast, flexible, accurate



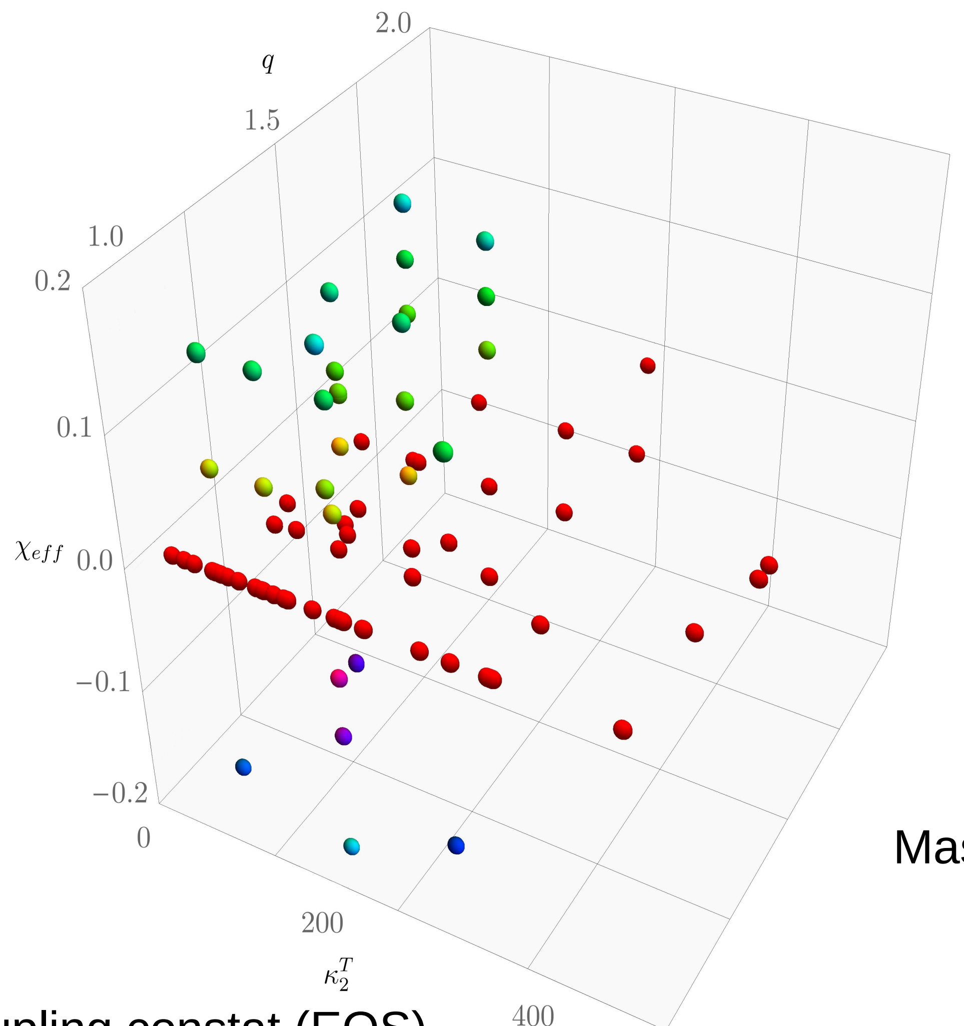


Used for GW170817 analysis!

Exploring the BNS parameter space

Largest exploration of parameter space in strong-field regime available to date

Effective Spin



Mass ratio

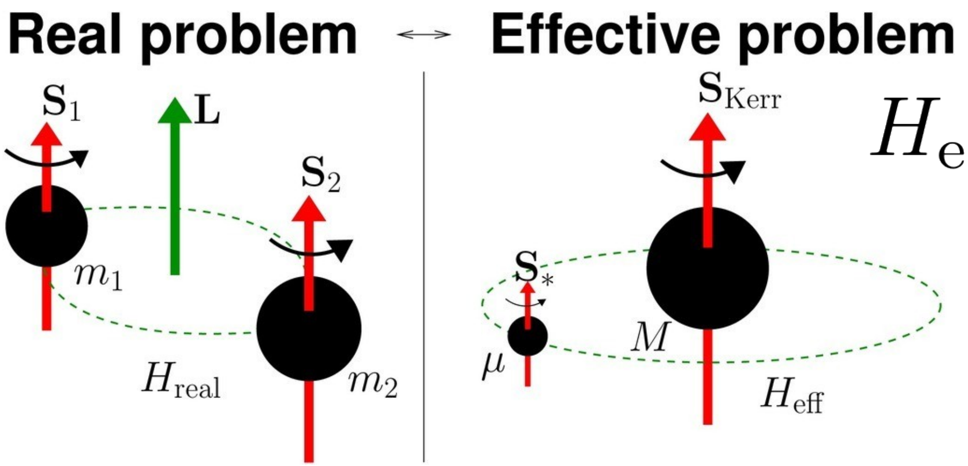
Tidal coupling constat (EOS)

- 130 BNS
- 330 dataset (multiple resolutions)
- >= 10 orbits + post merger
- Variation of M, q, EOS, spins
- Variation of input physics

More data:
[Bernuzzi+ PRL (2015), Dietrich+ PRD91 (2015), SB+ PRD94 (2016), Radice+ PRD94 (2016), SB&Dietrich PRD94 (2016), Dietrich+ PRD95 024029 (2017), Radice+ ApJL 842 (2017), ….]

Effective-One-Body

[Buonanno&Damour PRD 1999,2000]



Credit: A.Taracchini/AEI

$$H_{\rm eff} \sim \mu\sqrt{A(u)(1+p_\phi^2 u^2) + p_{r*}^2}$$

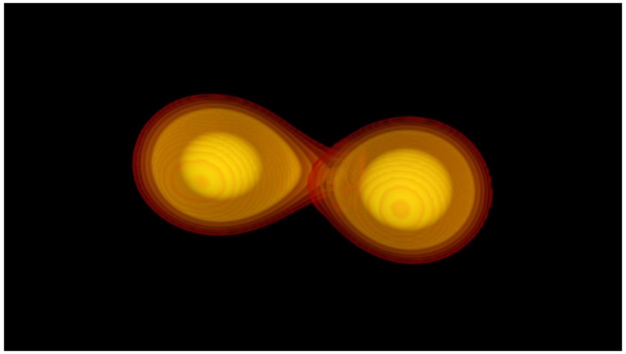
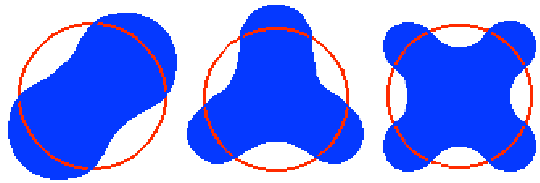
$$A(u;\nu;\kappa_2^T) = A^0(u;\nu) + A^T(u;\nu;\kappa_2^T)$$

$$A^0(u;\nu) = 1 - 2u + \nu(...$$

- Includes test-mass limit (i.e. particle on Schwarzschild)
- Includes post-Newtonian and self-force results
- Uses resummation techniques → predictive strong-field regime
- Includes tidal interactions (→ BNS) [Damour&Nagar PRD 2010]
- Flexible framework, can include NR results (“NR-informed”)
- Most accurate framework to describe compact binary waveforms

See e.g. [Taracchini+ PRD 2014][SB+ PRL 2015][Nagar+ PRD 2015][Hinderer+ 2016]

Relativistic Tides

[Hinderer arXiv:0711.2420,
Damour&Nagar arXiv:0906.0096,
Binnington&Poisson arXiv:0906.1366]

$$\lambda_2 \propto \frac{Q_{ij}}{\partial_{ij}\Phi_{ext}}$$

$$\kappa_2^T = 2\left[\frac{X_A}{X_B}\left(\frac{X_A}{C_A}\right)^5 k_2^A + \frac{X_B}{X_A}\left(\frac{X_B}{C_B}\right)^5 k_2^B\right]$$

[Damour&Nagar arXiv:0911.5041]

Tidal contribution to (post-) Newtonian dynamics and waveform:

Hamiltonian (Newtonian limit):

$$H_{\mathrm{EOB}} \approx Mc^2 + \frac{\mu}{2}\left(\mathbf{p}^2 + A(r) - 1\right)$$

$$A(r) = 1 - 2/r - \kappa_2^T(\lambda_2)/r^6$$

Tides are attractive and "act" at small separations

Tidal coupling constant

Waveform:

$$h \sim A f^{-7/6} e^{-i\Psi(f)} \approx A f^{-7/6} e^{-i\Psi_{PP}(f)} + i39/4\kappa_2^T x(f)^{5/2}$$

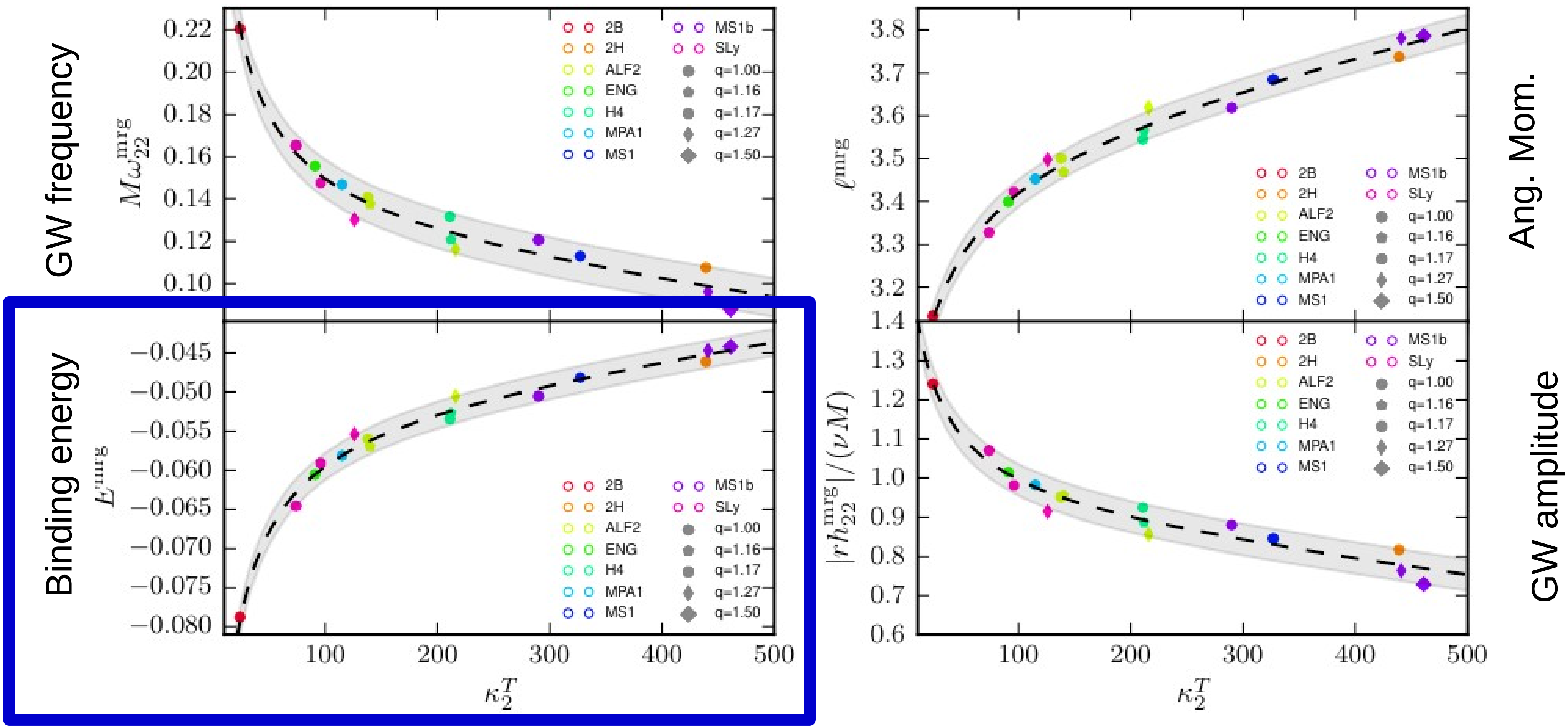
Key point: No other binary parameter (mass, radii, etc) enter separately the formalism

One parameter to characterize merger dynamics

[SB,Nagar,Balmelli,Dietrich,Ujevic PRL 112 (2014)]

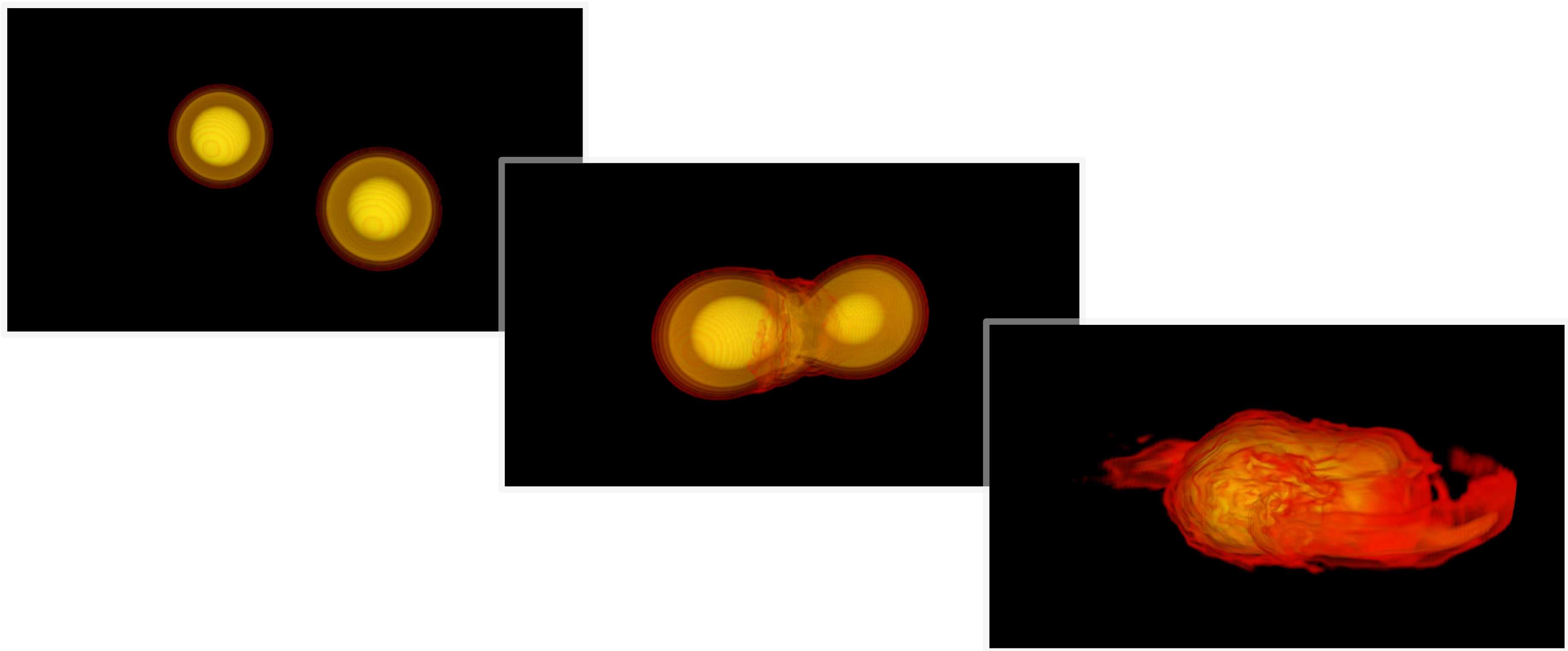
Predict energy emitted in GW for all binaries, range 1-2% M
(all possible EOS, masses, mas-ratios)

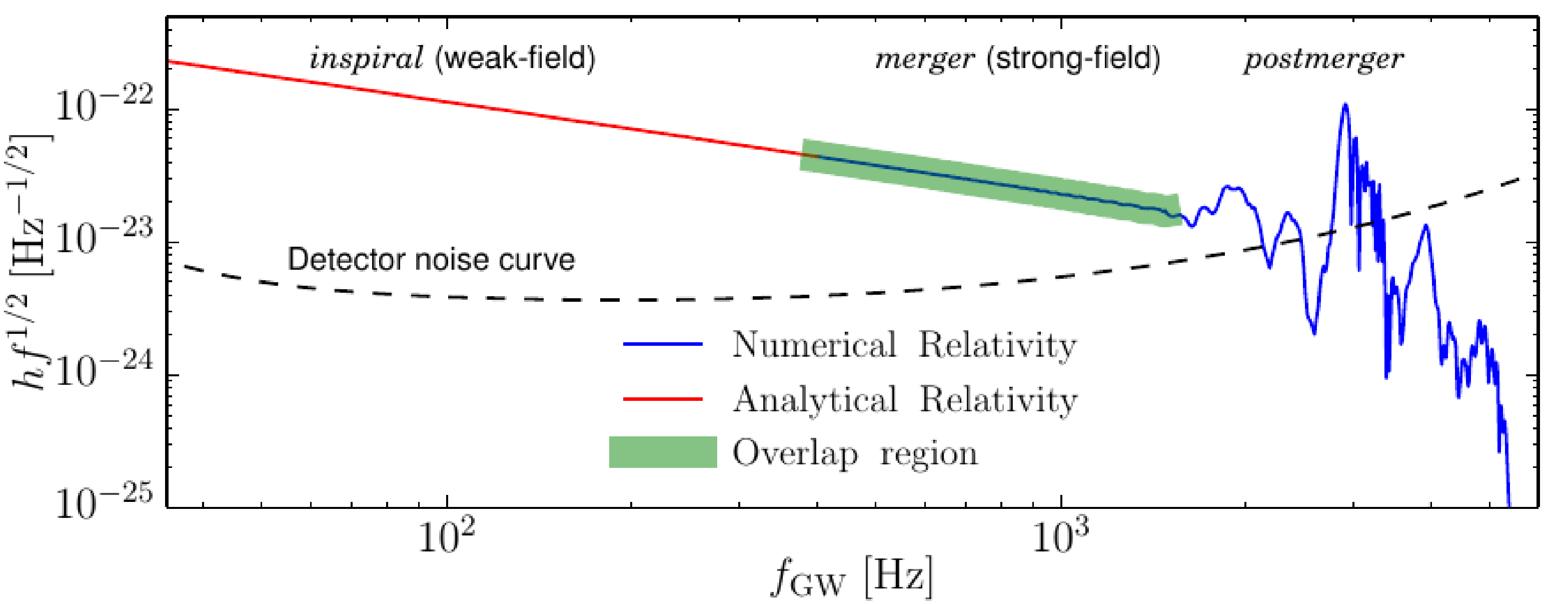
Predict energy emitted for given binary by specifying solely the kappa value



Tidal polarizability coef. (l=2)

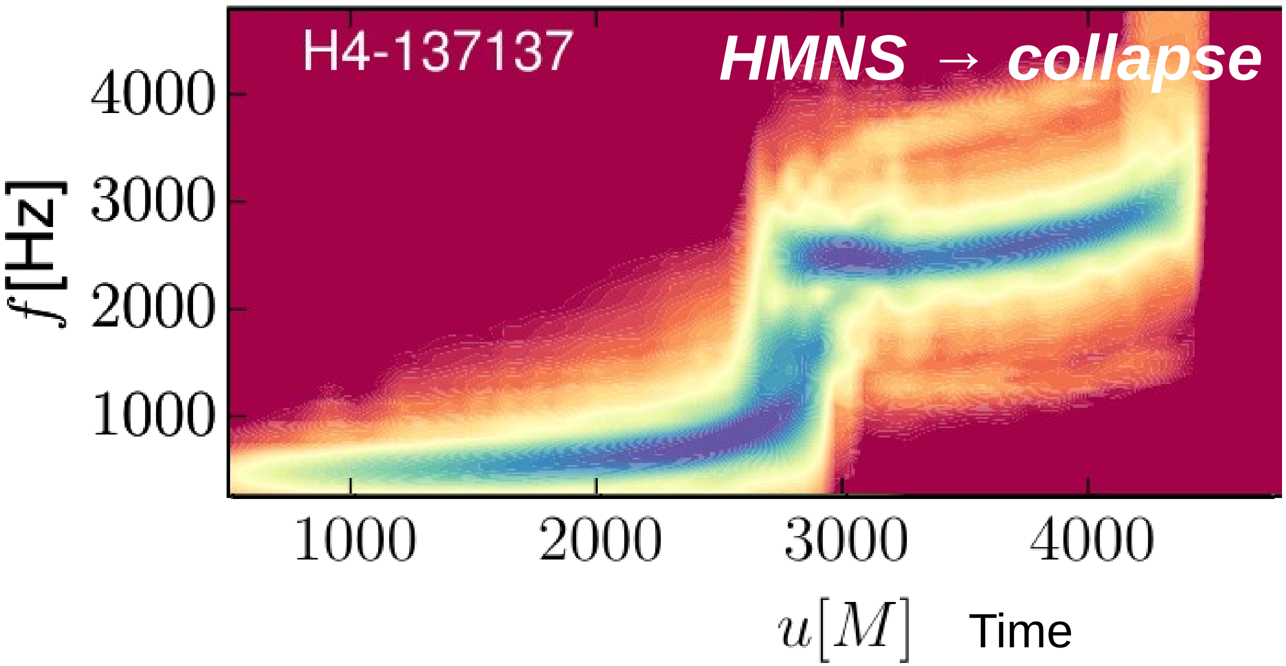
Inspiral - merger → postmerger

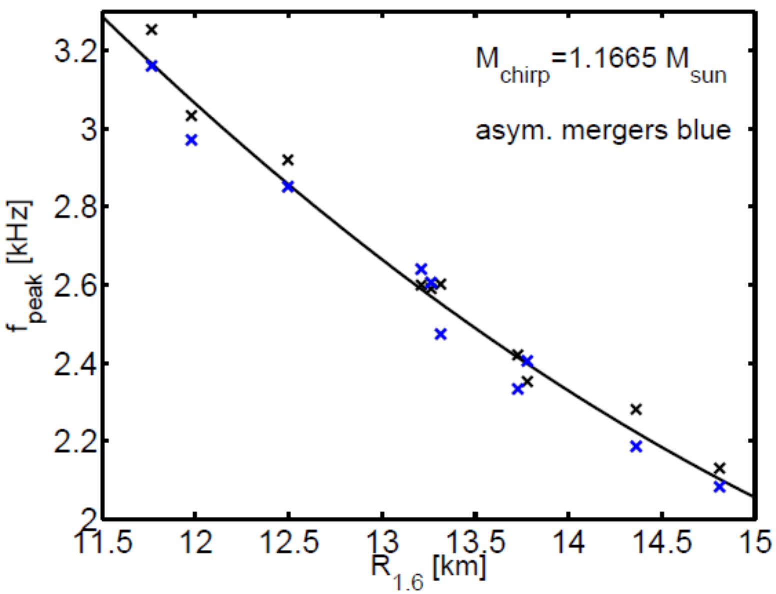




Postmerger models spectrum

[Bauswein+ arxiv:1006.3315]



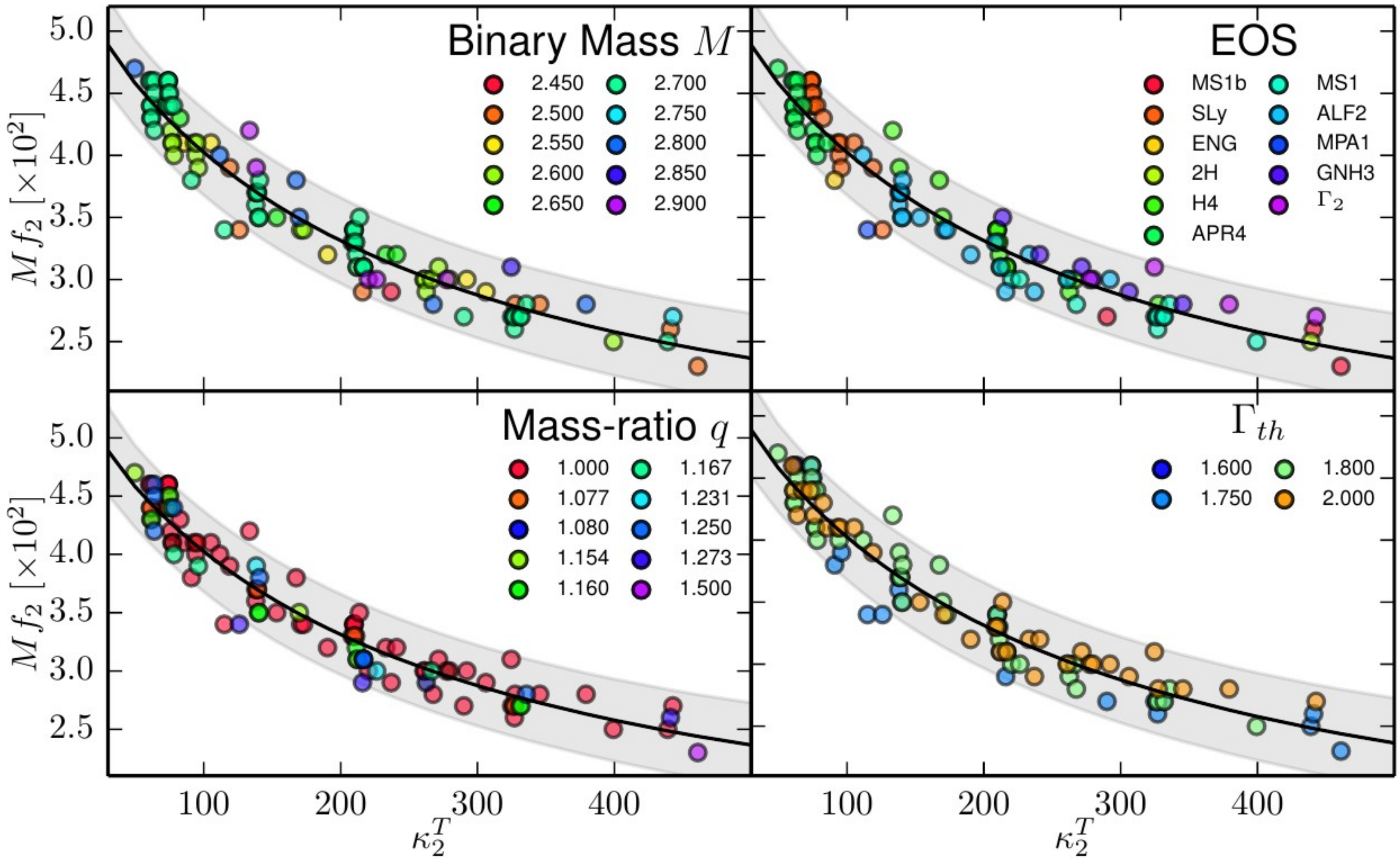


- Various models associate f_2 to isolated equil. star properties
- Possibility to extract “EOS-related info” (R_x,M_{max},...)
- Conceptually indepedent on inspiral-merger models

[Bauswein+ arXiv:1106.1616, Hotokezaka+ arXiv:1307.5888, Takami+ arXiv:1403.5672, Clark+ arXiv:1509.08522, ...]

Peak frequency correlates to tidal parameter

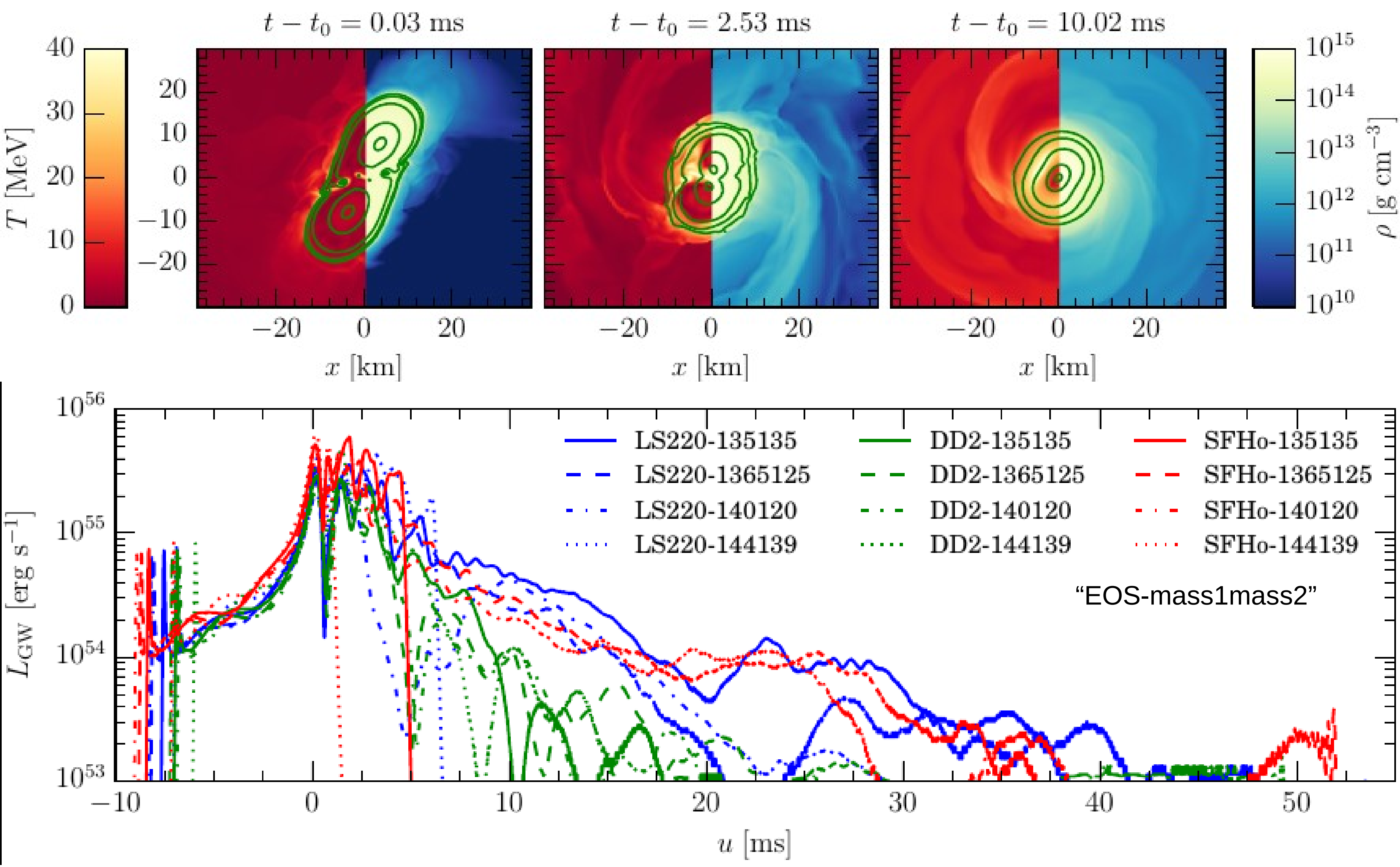
[SB, Dietrich, Nagar PRL 115 (2015)]



- Large NR dataset (~100, 3 codes) [+ Hotokezaka+ arXiv:1307.5888, Takami+ arXiv:1403.5672]
- Postmerger frequencies essentially determined by *merger* physics
- Conceptually “compatible” with inspiral-merger → Unified model !

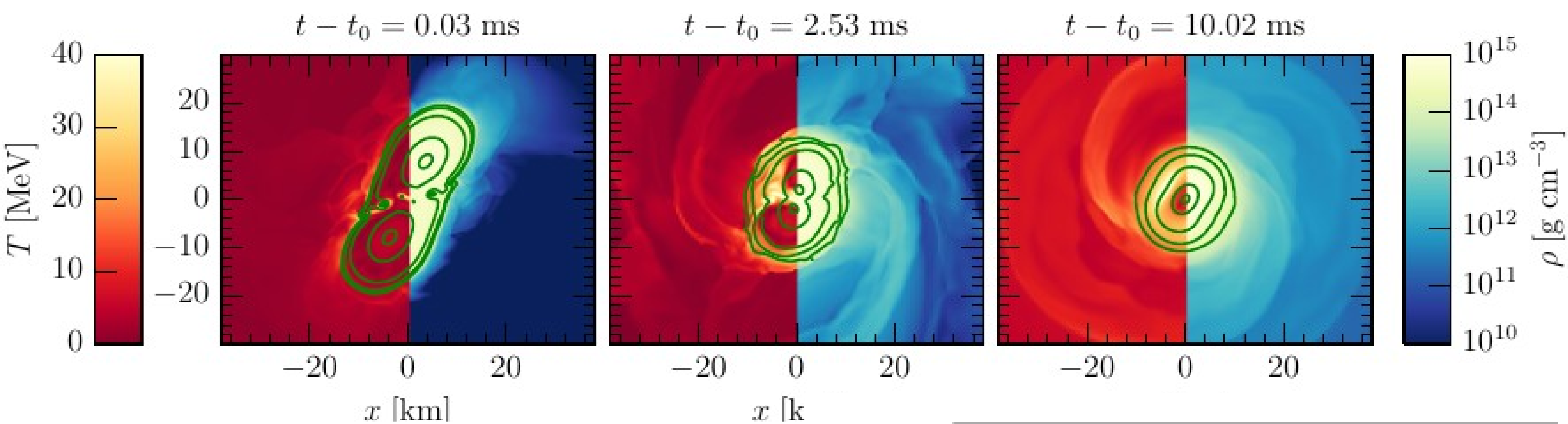
Remnant HMNS is the loudest GW phase

[SB, Radice, Ott, Roberts, Moesta, Galeazzi PRD94 024023 (2016)]

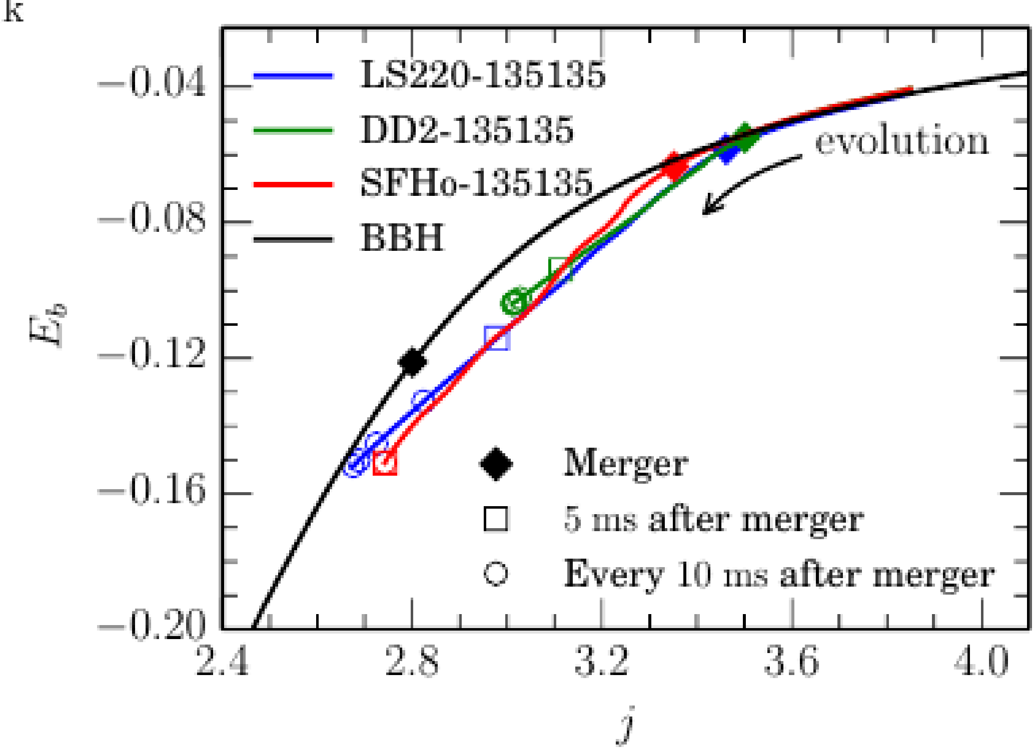


Remnant HMNS is the loudest GW phase

[SB, Radice, Ott, Roberts, Moesta, Galeazzi PRD94 024023 (2016)]



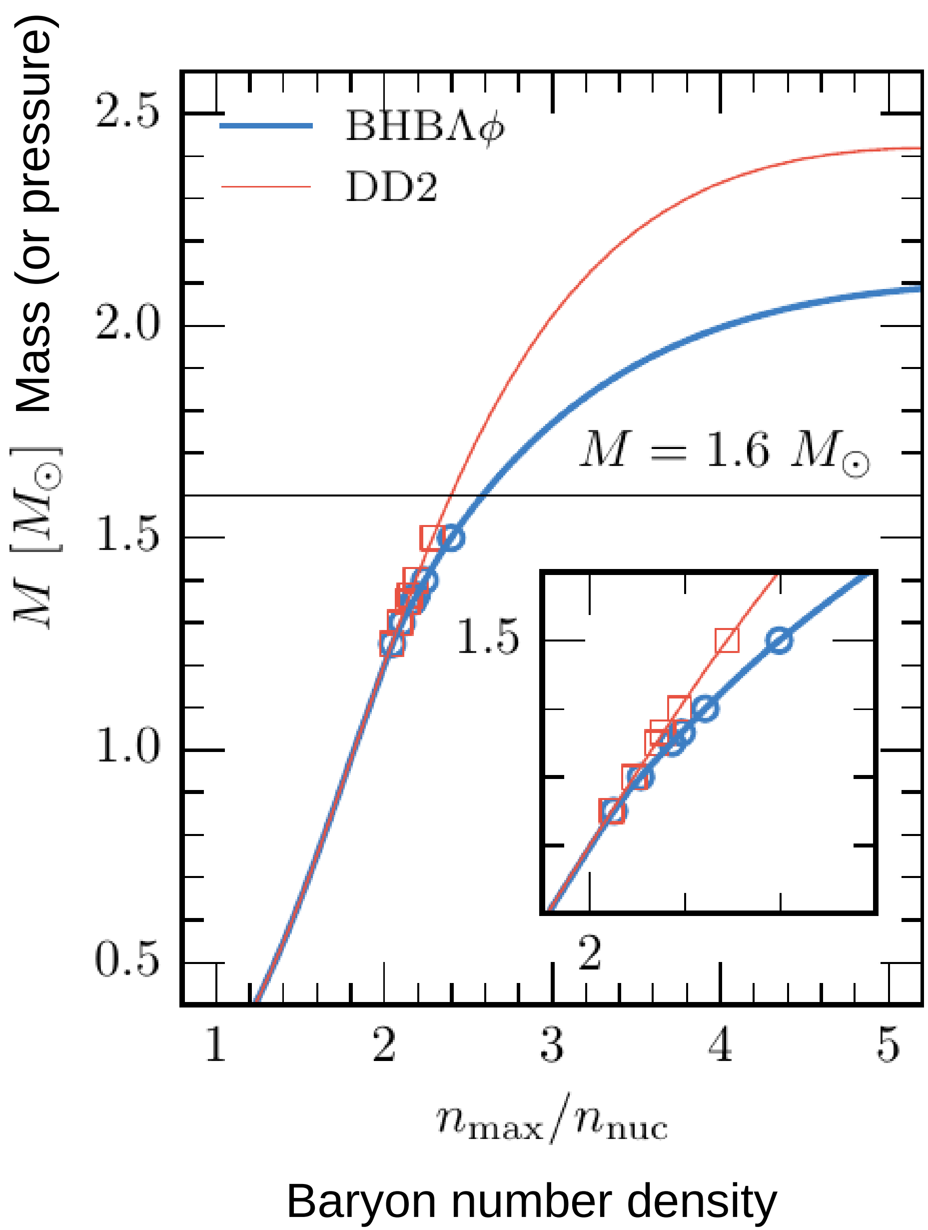
- Emission is FAST: $\tau_{GW} \sim 20$ ms
- Emission is LOUD: E(HMNS) ~ 2x E(merger)
- Note: explain the $f_2(\kappa_2)$ correlation



Simulations w/ microphysics & neutrinos largest-to-date campaign

Merger remnant reaches extreme densities

Can GW observations inform us about EOS changes at those densities?



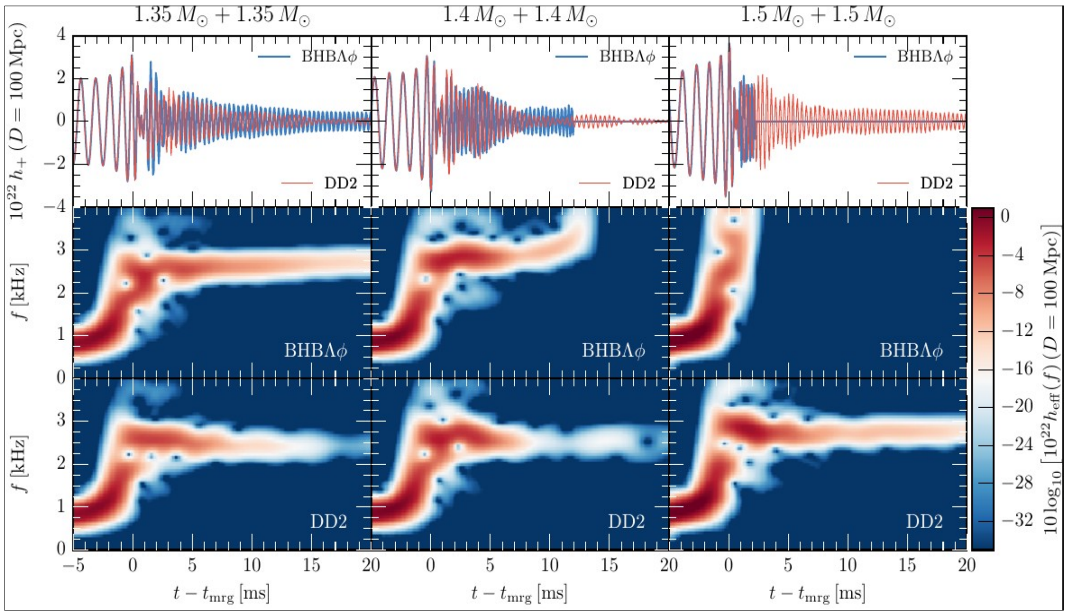
- Baryon number density **n ~ 3-5 n$_{nuc}$**
- Extra DOF/phase transitions?
- Specific model: Λ-hyperons

  [Banik+ arxiv:1404.6173]

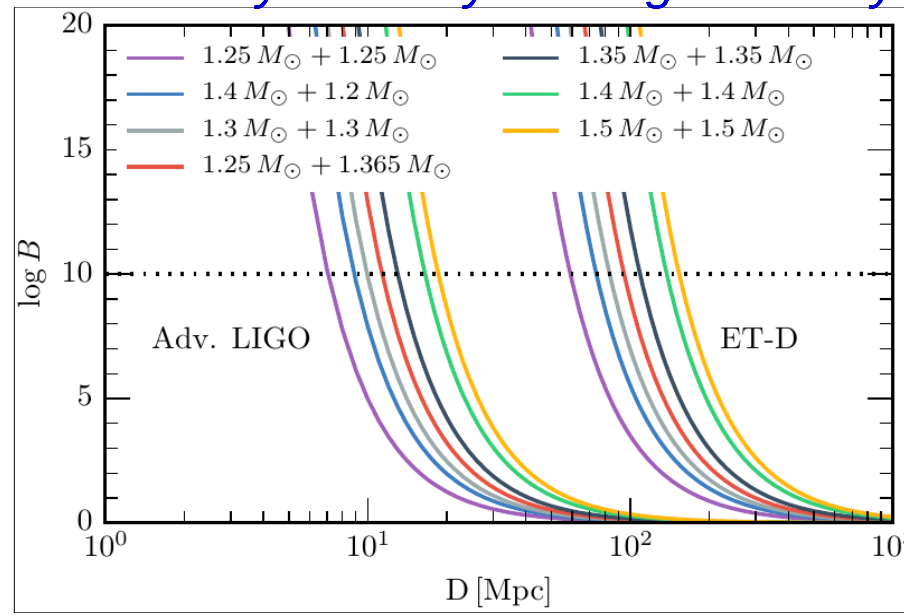
  Microphysical EOS compatibile with astro and nuclear phys constraints
- In general: “softness” effects

GWs could probe such “softness effects”

[Radice, SB, Del Pozzo, Ott, Roberts ApJL (2017)]



Data-analysis study: distinguishablity



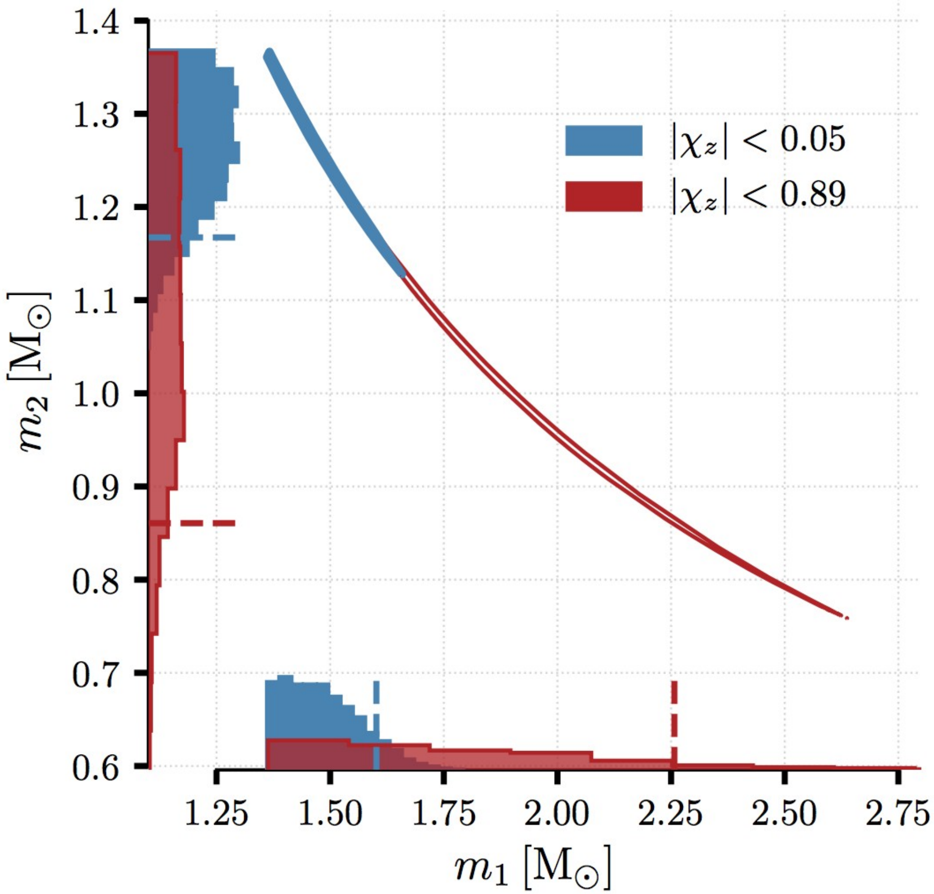
log(Bayes factor) vs. Source distance

- Postmerger GW morfology contains unique info
- Detailed and generic models are necessary for DA studies
- High-freq. GW challenging to detect (→ Einstein telescope)

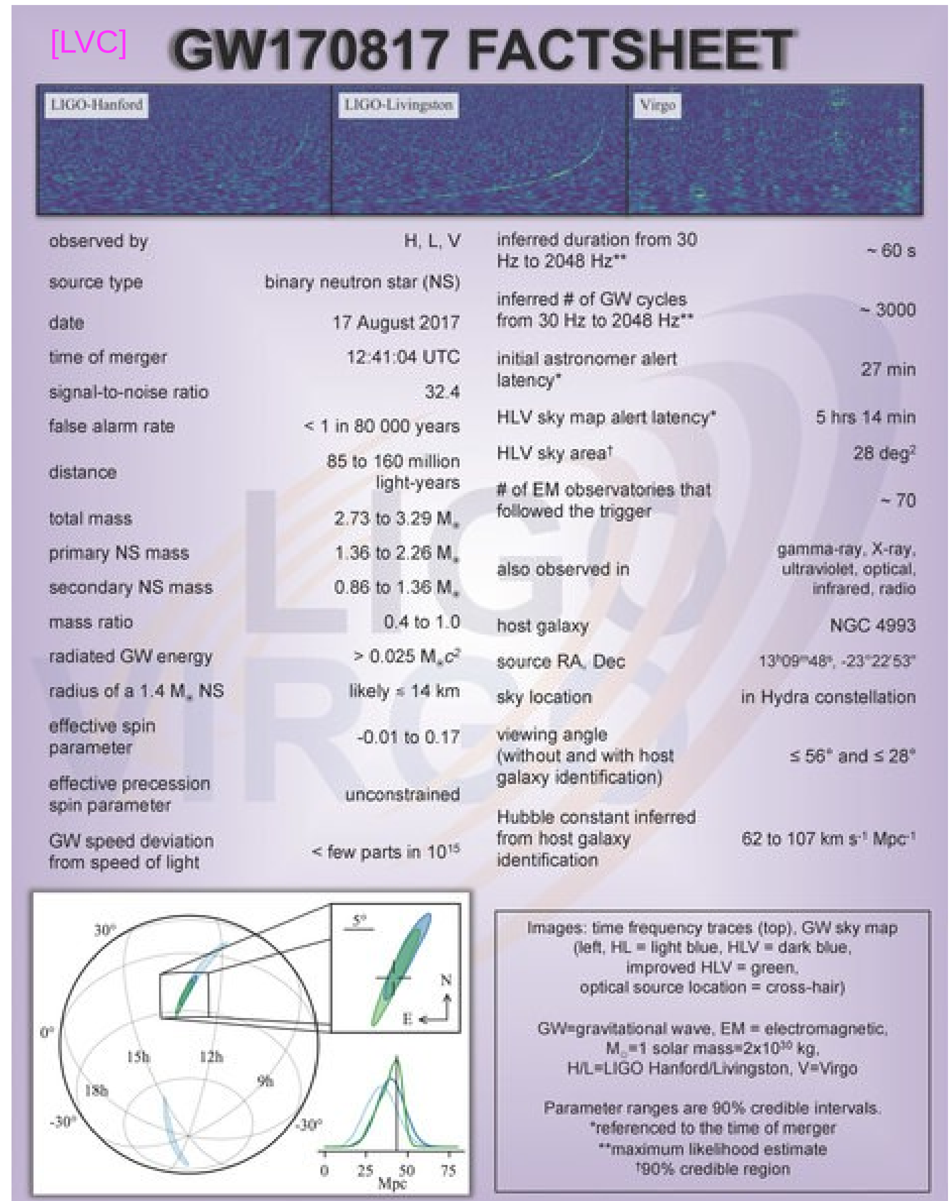
GW170817: A binary neutron star system

[LIGO&Virgo collab. Phys. Rev. Lett. 119, 161101 (2017)]

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$



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



observed by	H, L, V	inferred duration from 30 Hz to 2048 Hz**	~ 60 s
source type	binary neutron star (NS)	inferred # of GW cycles from 30 Hz to 2048 Hz**	~ 3000
date	17 August 2017	initial astronomer alert latency*	27 min
time of merger	12:41:04 UTC	HLV sky map alert latency*	5 hrs 14 min
signal-to-noise ratio	32.4	HLV sky area†	28 deg^2
false alarm rate	< 1 in 80 000 years	# of EM observatories that followed the trigger	~ 70
distance	85 to 160 million light-years	also observed in	gamma-ray, X-ray, ultraviolet, optical, infrared, radio
total mass	2.73 to 3.29 $M_\odot$	host galaxy	NGC 4993
primary NS mass	1.36 to 2.26 $M_\odot$	source RA, Dec	$13^h09^m48^s$, $-23°22'53''$
secondary NS mass	0.86 to 1.36 $M_\odot$	sky location	in Hydra constellation
mass ratio	0.4 to 1.0	viewing angle (without and with host galaxy identification)	≤ 56° and ≤ 28°
radiated GW energy	> 0.025 $M_\odot c^2$	Hubble constant inferred from host galaxy identification	62 to 107 km s^{-1} Mpc^{-1}
radius of a 1.4 $M_\odot$ NS	likely ≲ 14 km		
effective spin parameter	-0.01 to 0.17		
effective precession spin parameter	unconstrained		
GW speed deviation from speed of light	< few parts in 10^{15}		

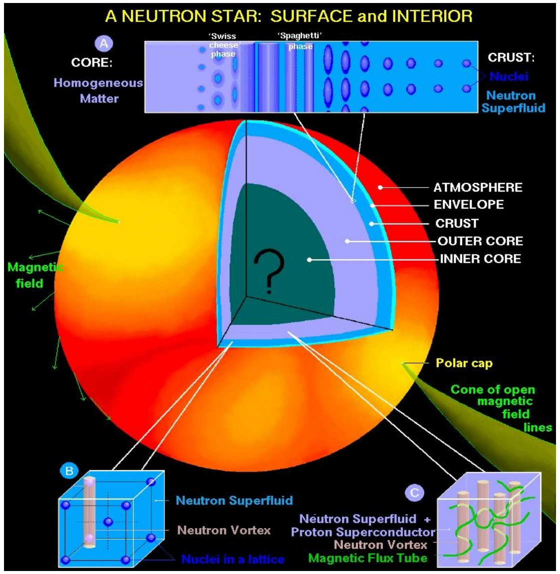
Images: time frequency traces (top), GW sky map (left, HL = light blue, HLV = dark blue, improved HLV = green, optical source location = cross-hair)

GW=gravitational wave, EM = electromagnetic, $M_\odot$=1 solar mass=2×10^{30} kg, H/L=LIGO Hanford/Livingston, V=Virgo

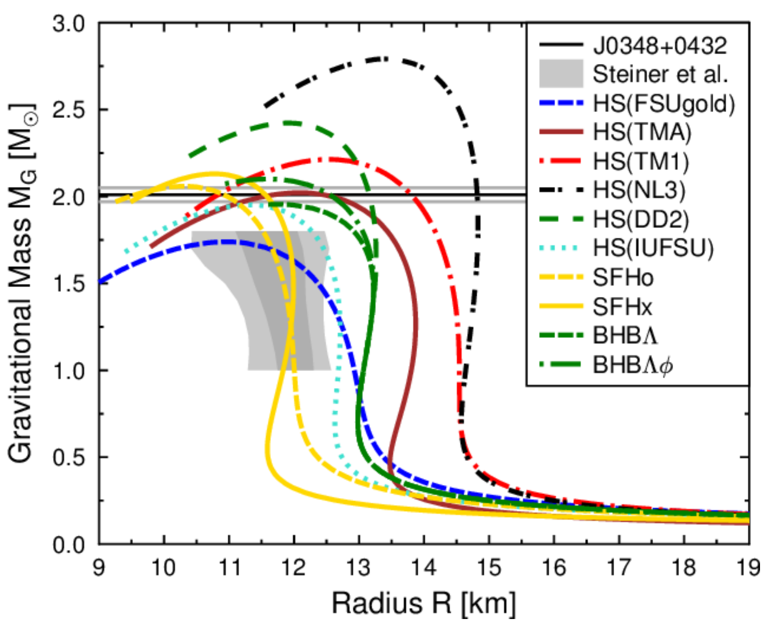
Parameter ranges are 90% credible intervals.
*referenced to the time of merger
**maximum likelihood estimate
†90% credible region

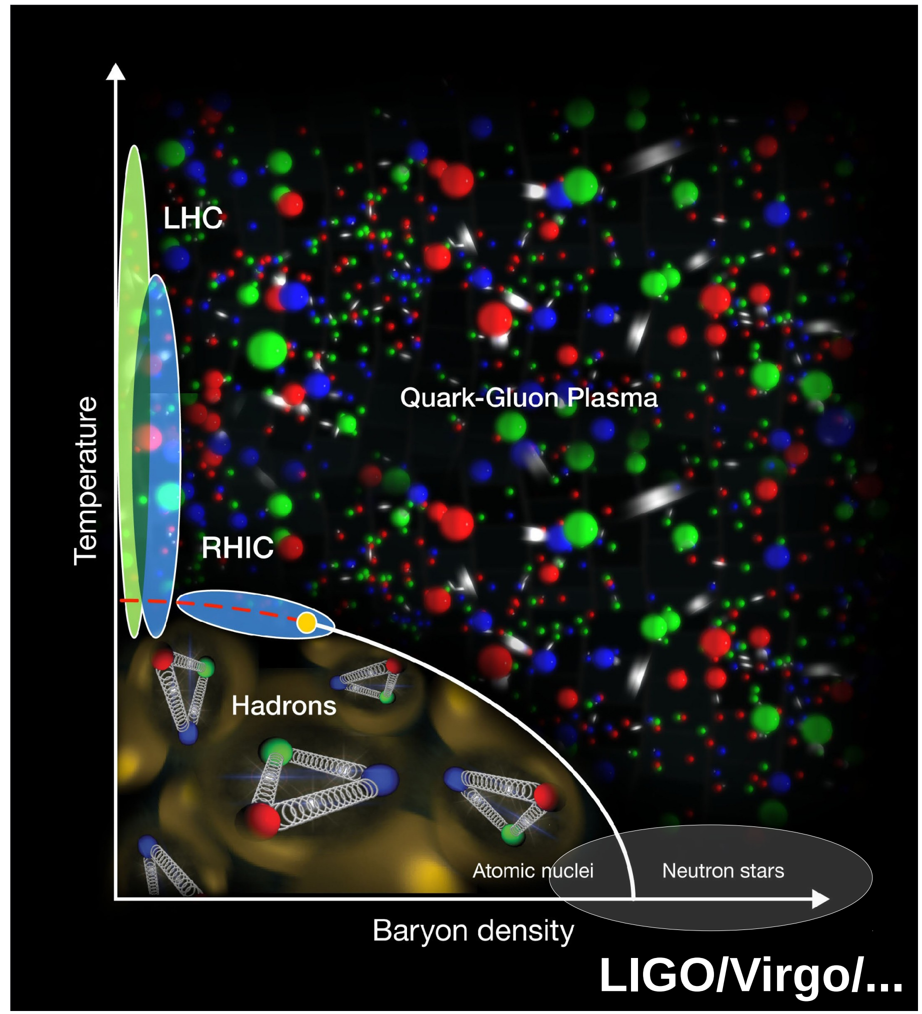
Fundamental physics

Constraining the Equation of State of matter at supranuclear densities



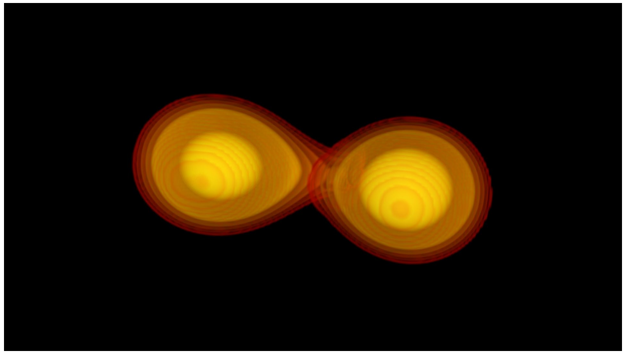
Different EOS → different star's structure

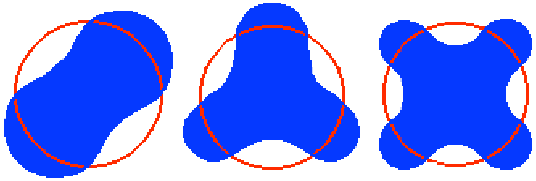




Binary neutron star mergers

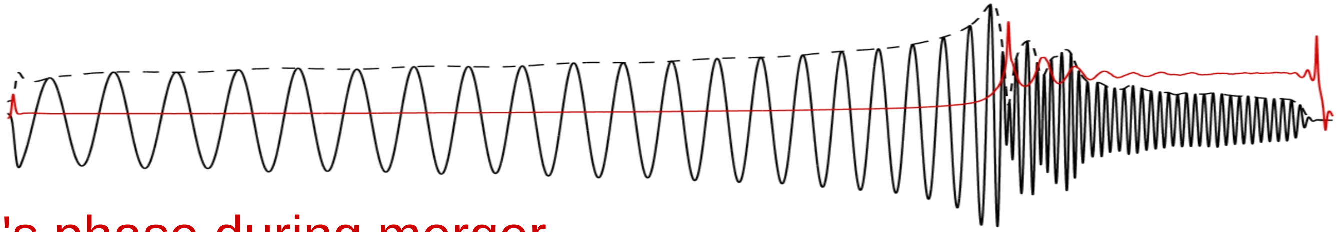
Example: observing tidal effects in GWs tells us about the neutron star matter





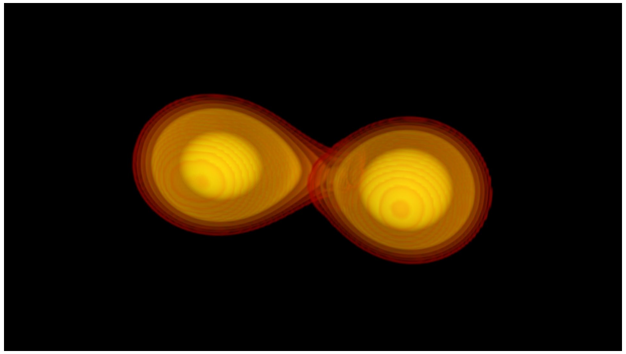
Tides depend critically on EOS

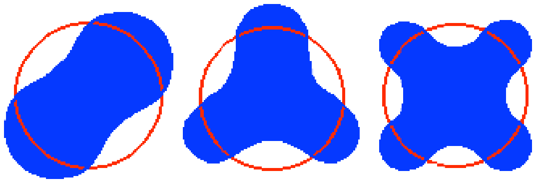
$$Q_{ij} = \lambda_2 G_{ij} \sim \lambda_2 \partial_i \partial_j \phi$$



Tides determine the wave's phase during merger

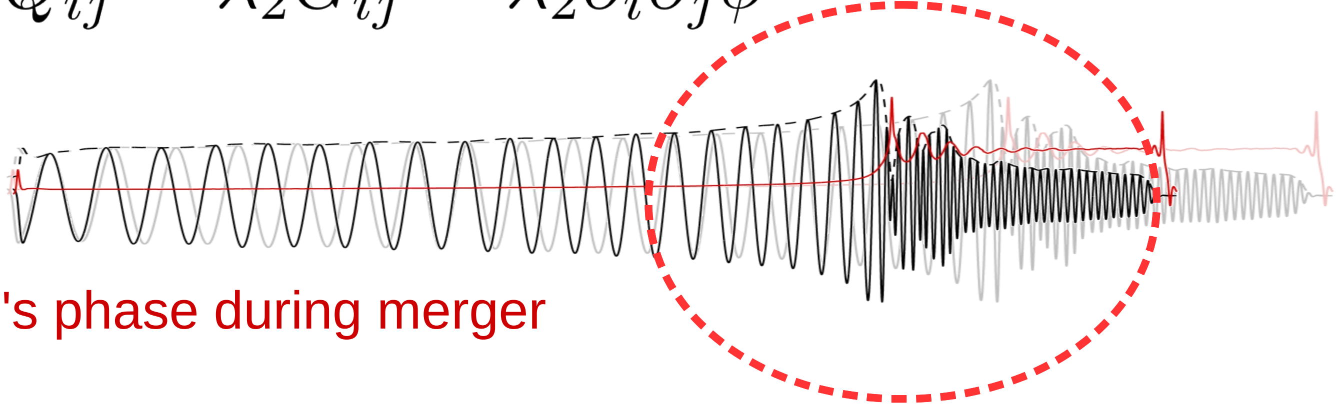
Example: observing tidal effects in GWs tells us about the neutron star matter





Tides depend crucially on EOS

$$Q_{ij} = \lambda_2 G_{ij} \sim \lambda_2 \partial_i \partial_j \phi$$



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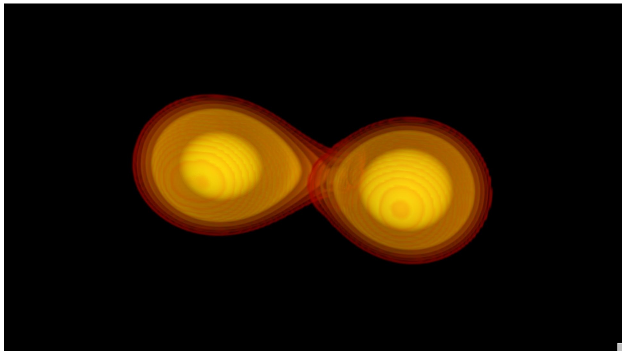

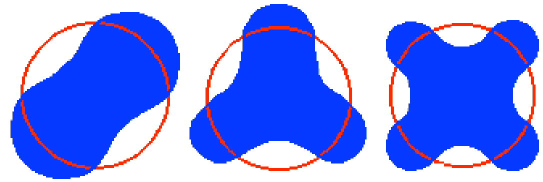

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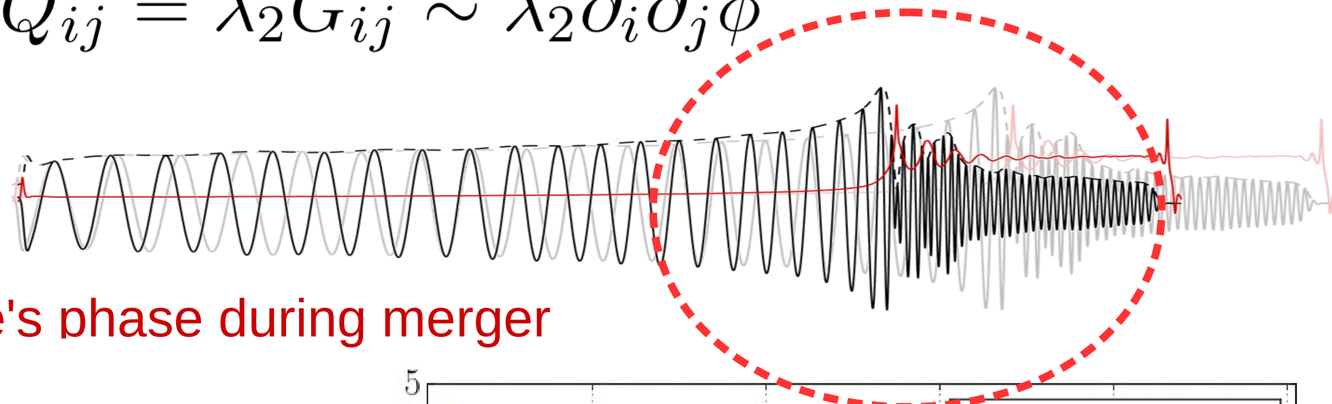

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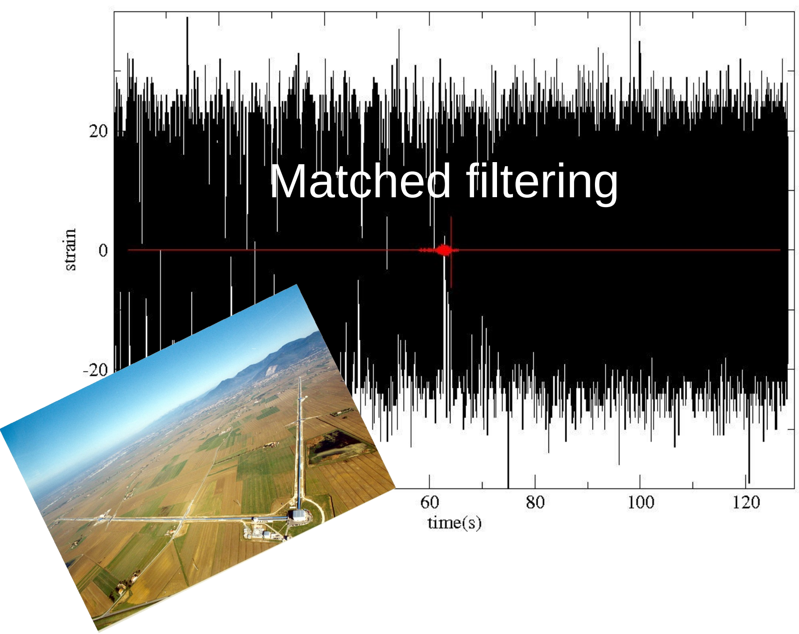
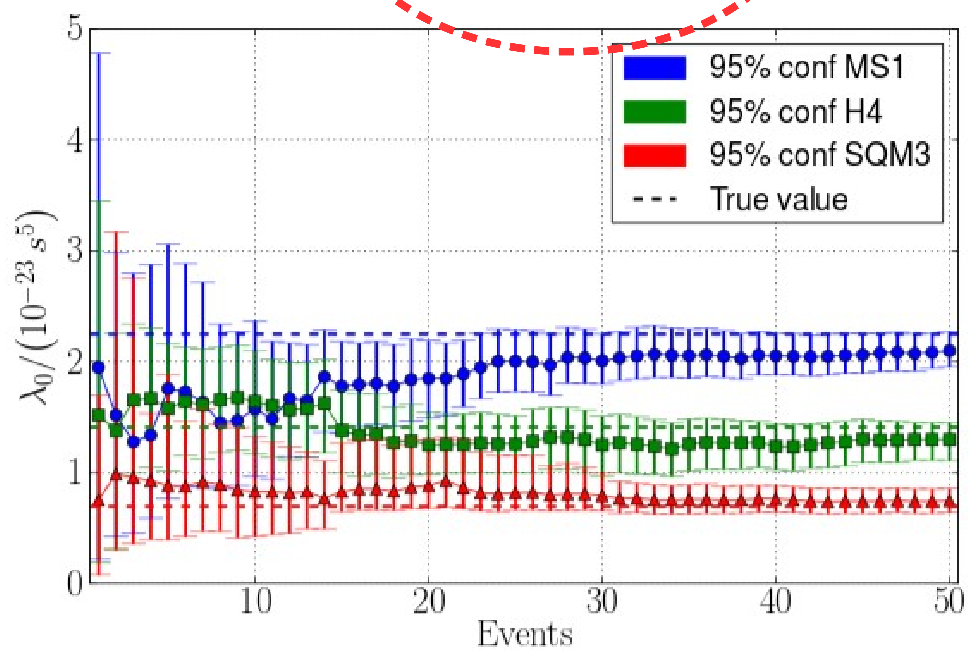
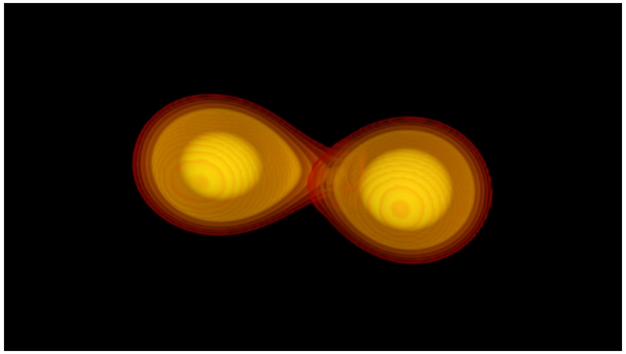
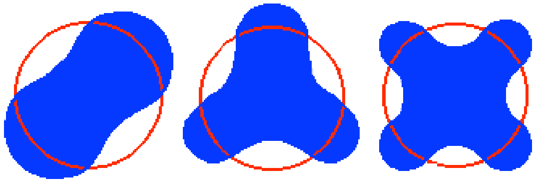


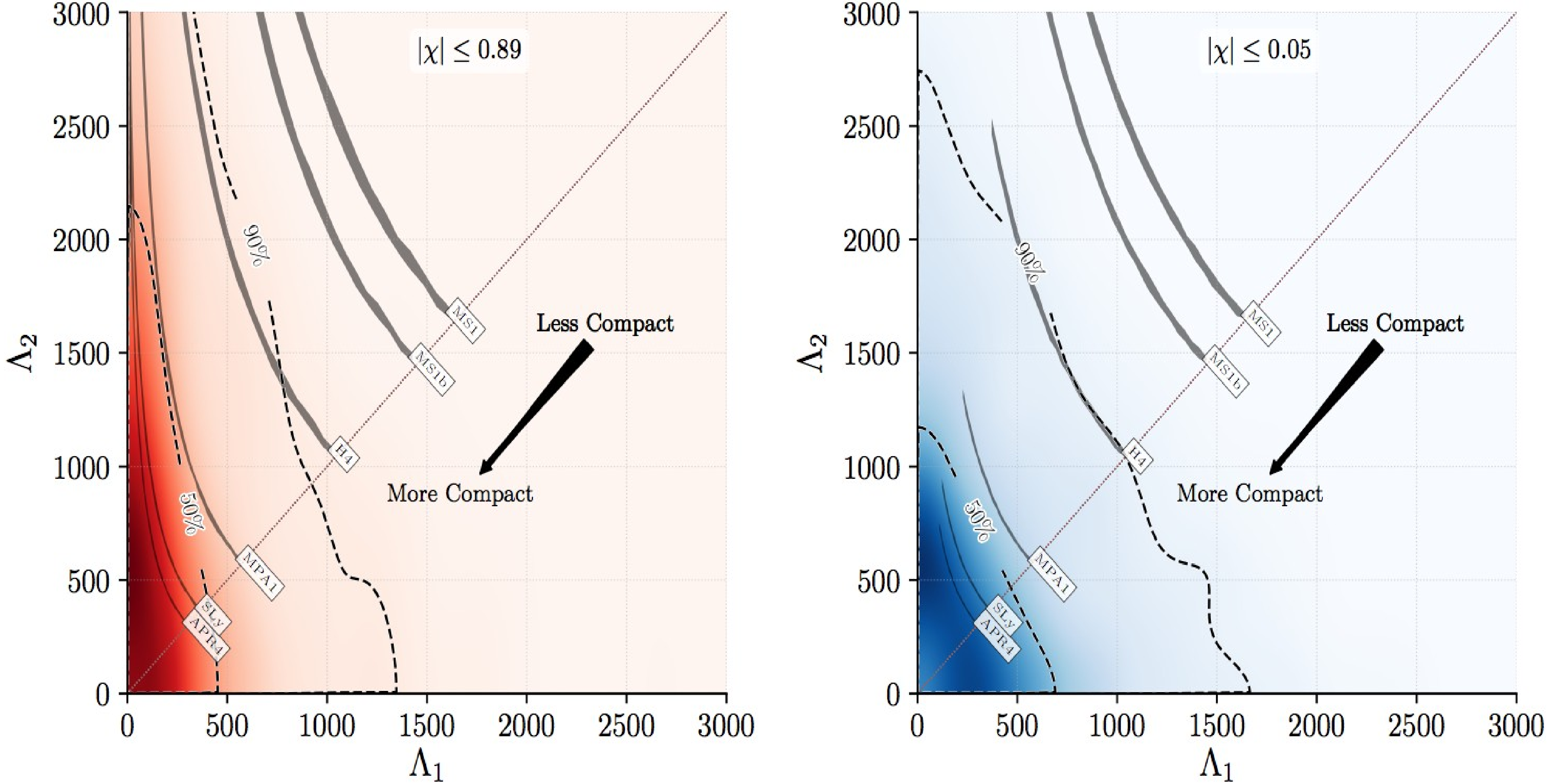


[Del Pozzo+ PRL 111 (2013)]





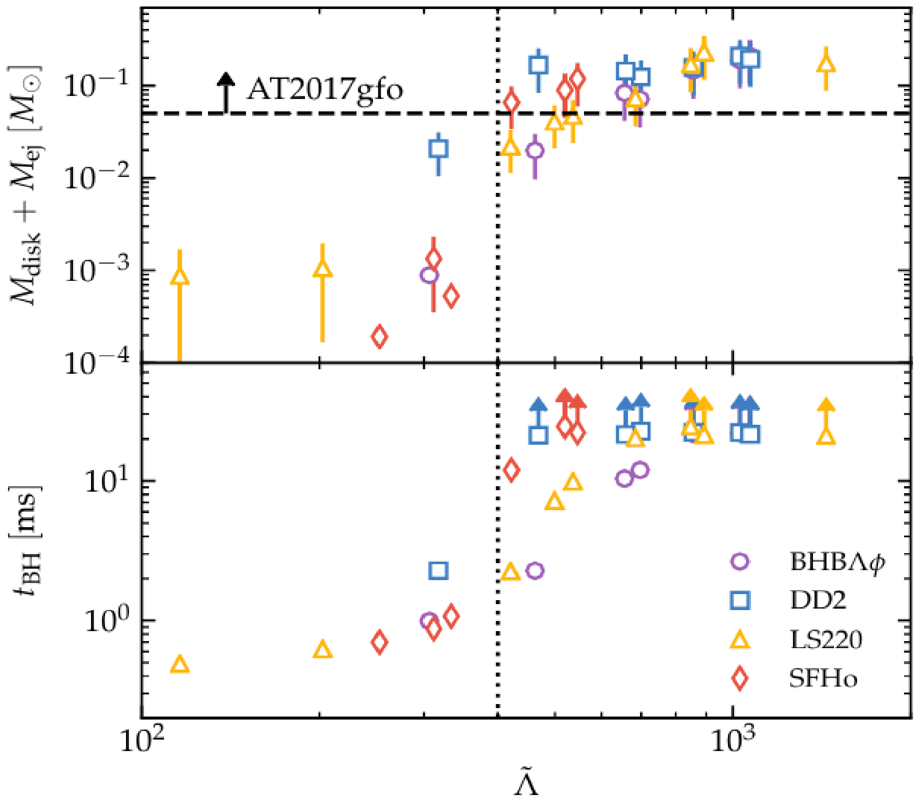
$$\lambda_2 \propto \frac{Q_{ij}}{\partial_{ij}\Phi_{ext}}$$

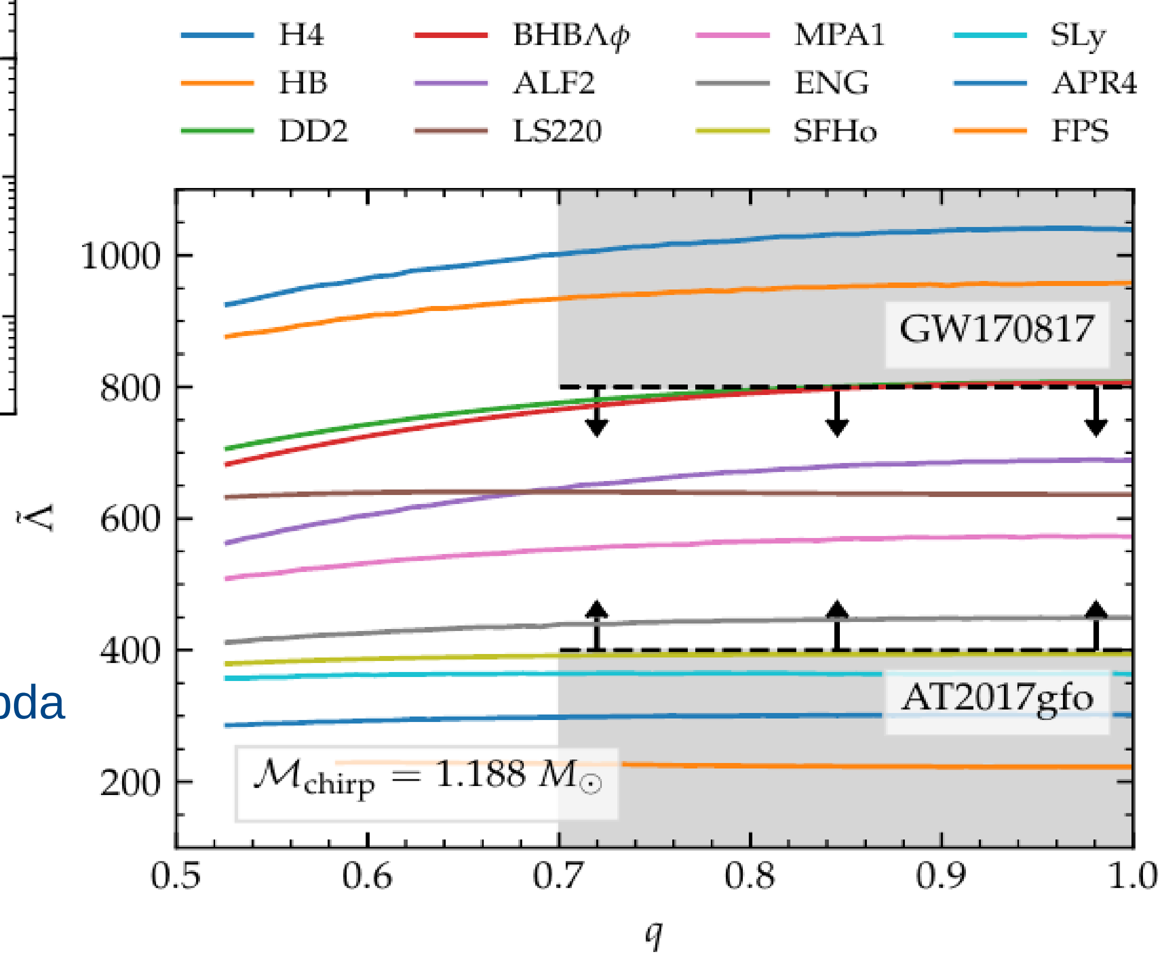


[LIGO&Virgo collab. Phys. Rev. Lett. 119, 161101 (2017)]

Joint constraint on the neutron star equation of state from multimessenger observations

[Radice, Perego, Zappa, SB arxiv:1711.03647]





- kN model → lower bound on Mdisk
- Numerical relativity → Mdisk(Lambda)
- EM+NR analysis → lower bound on Lambda
- GW analysis → upper bound on Lambda

Summary

- Binary neutron stars key sources for GW astronomy
- Unique info about extreme matter
- GW measurements <u>require</u> precise waveform models
- Building GW models: interface analytical and numerical relativity method
- Strong-field GR-dynamics crucial input for electromagnetic emission models