The Multimessenger Picture of Binary Neutron Star Mergers

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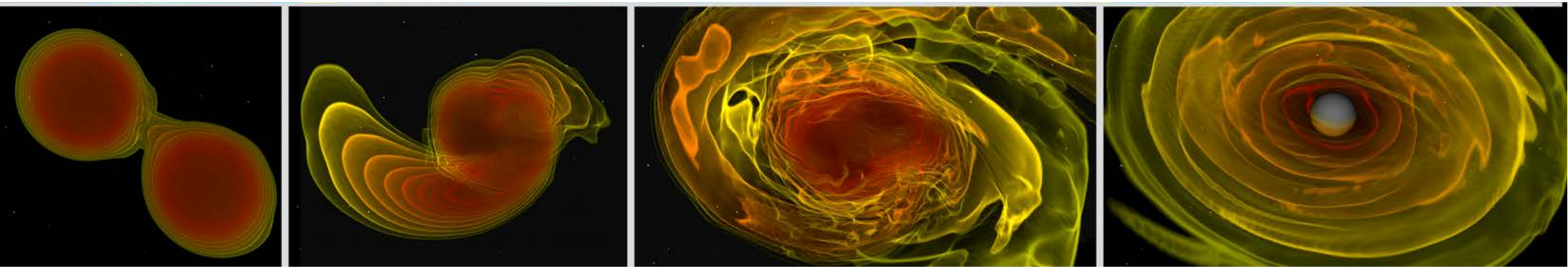


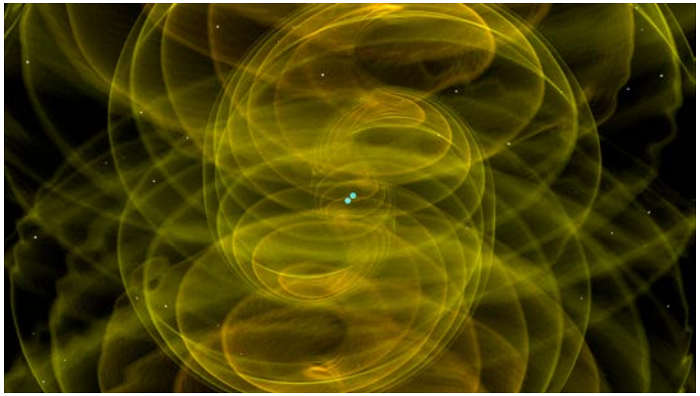
GRK-workshop: *Models of Gravity* Bremen 19th of February 2018

Multimessenger Picture

Gravitational Waves

-inspiral signal: chirp

-postmerger signal

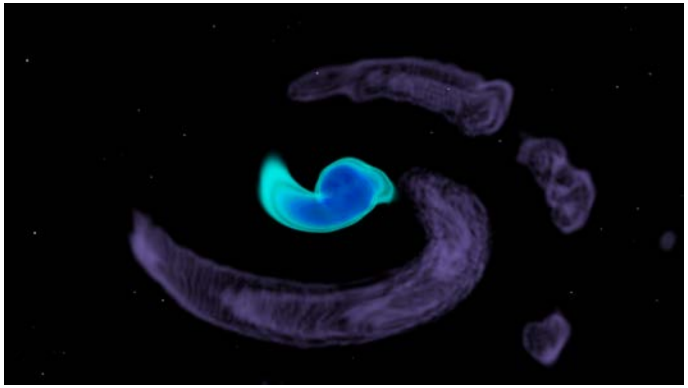


Electromagnetic Waves

-short GRB

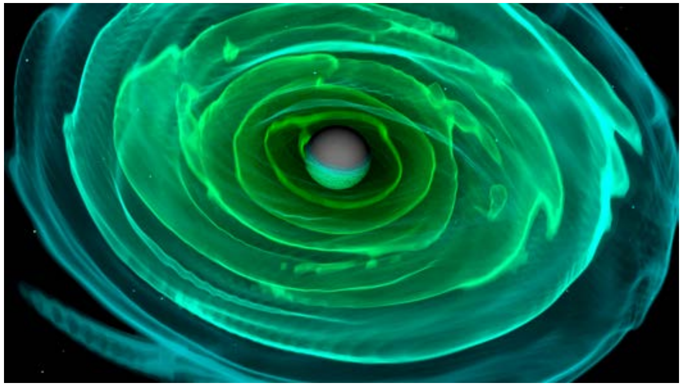
-kilo/macronovae

-radio flares

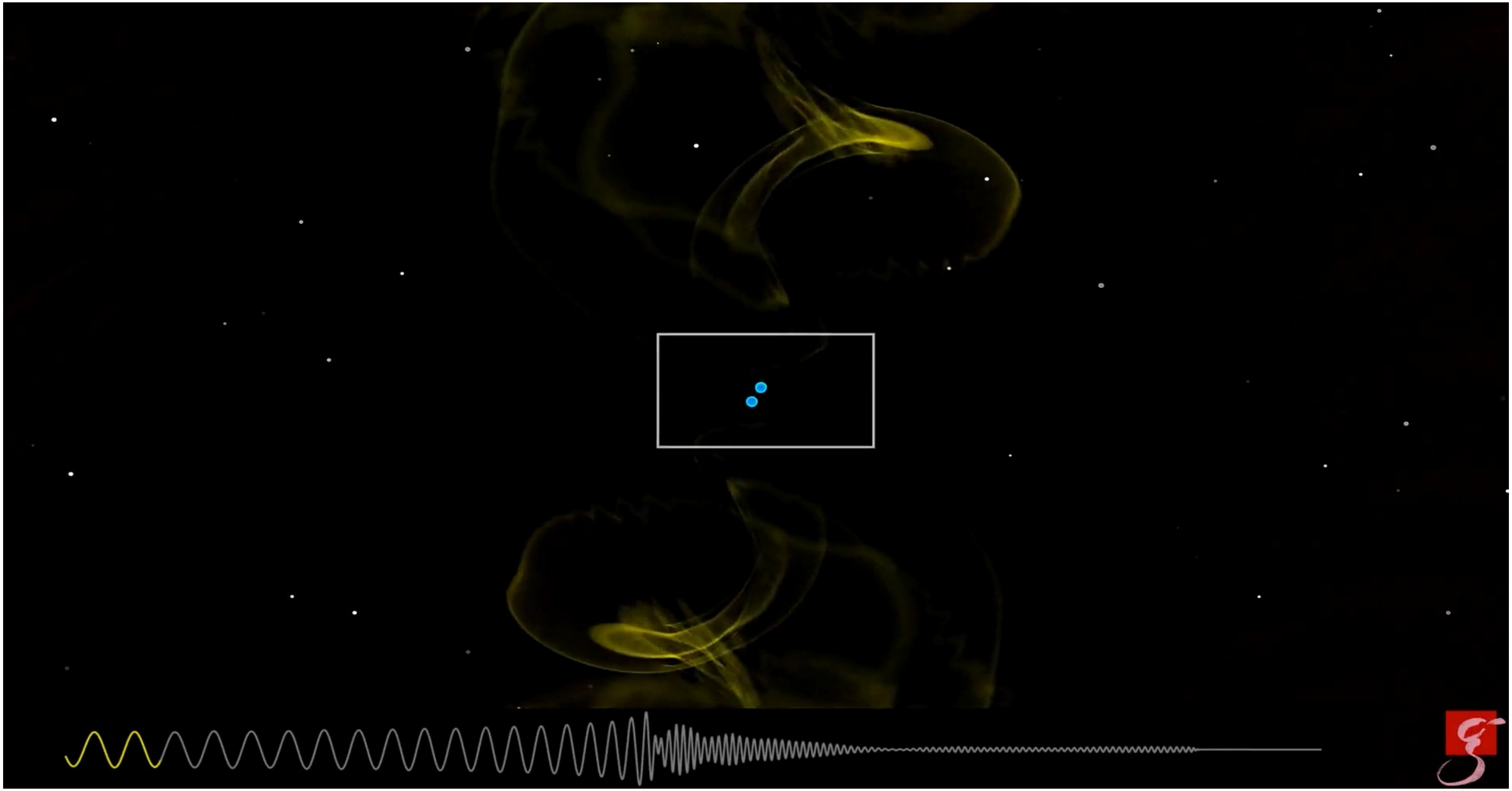


Neutrinos

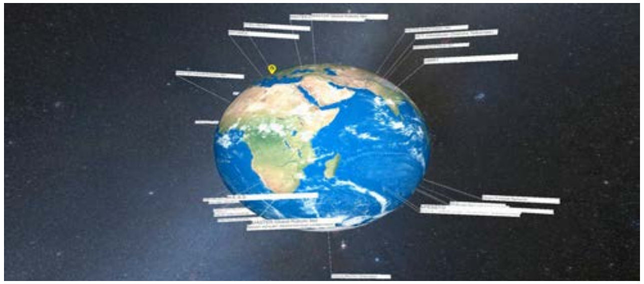
-high neutrino luminosity



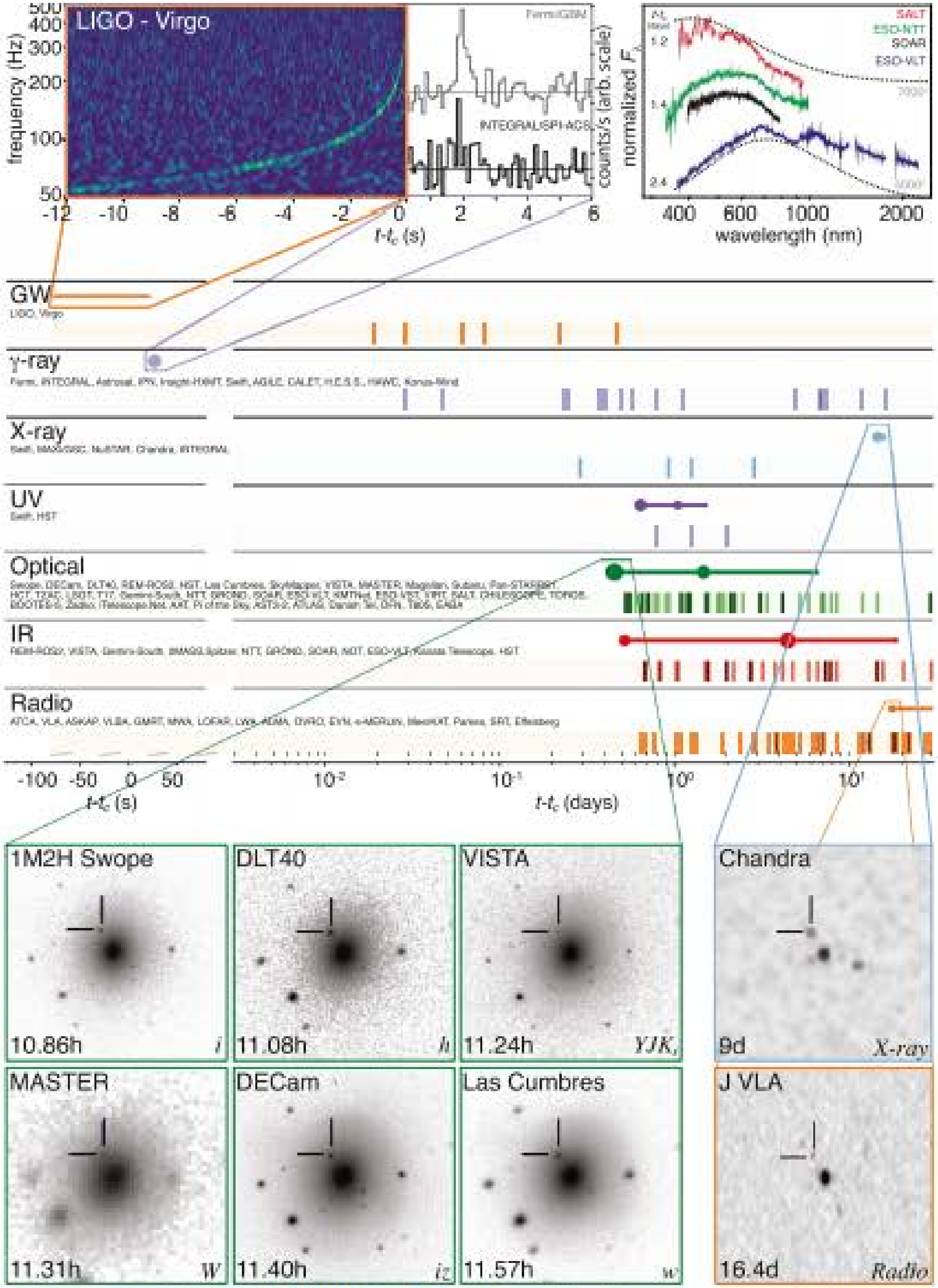
The BNS merger



GW170817

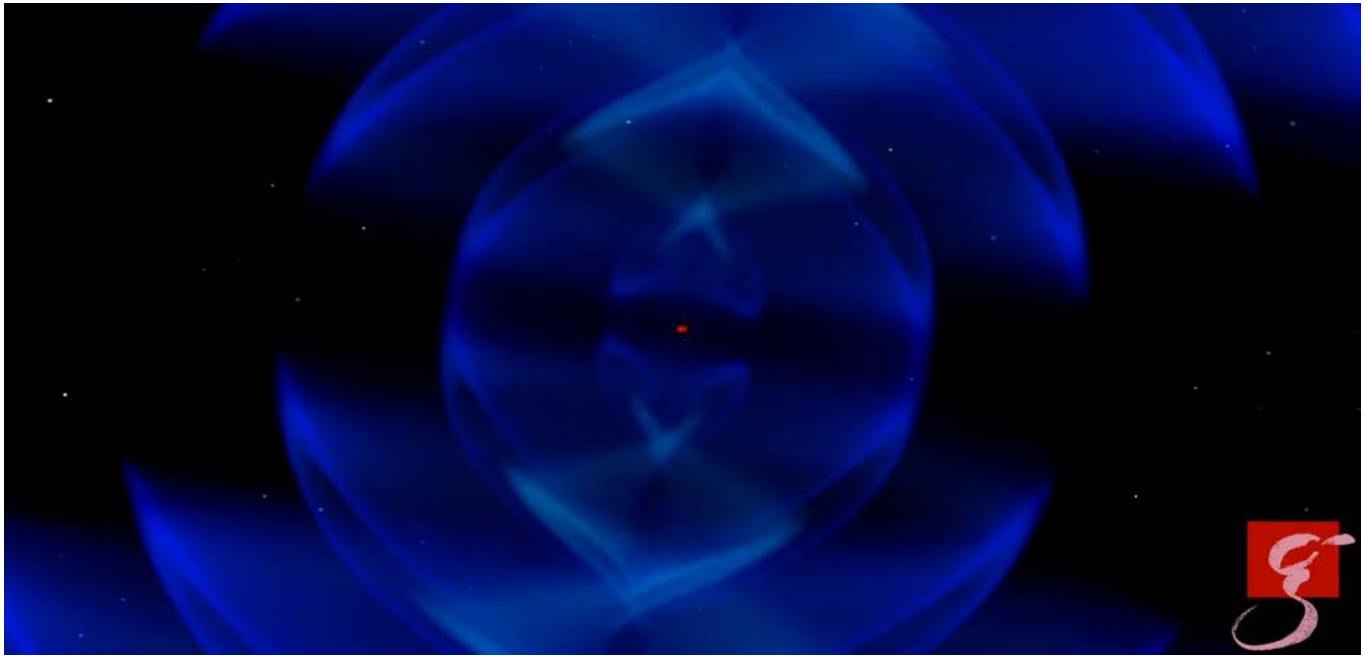


(c) Mark Myers, Swinburne University of Technology



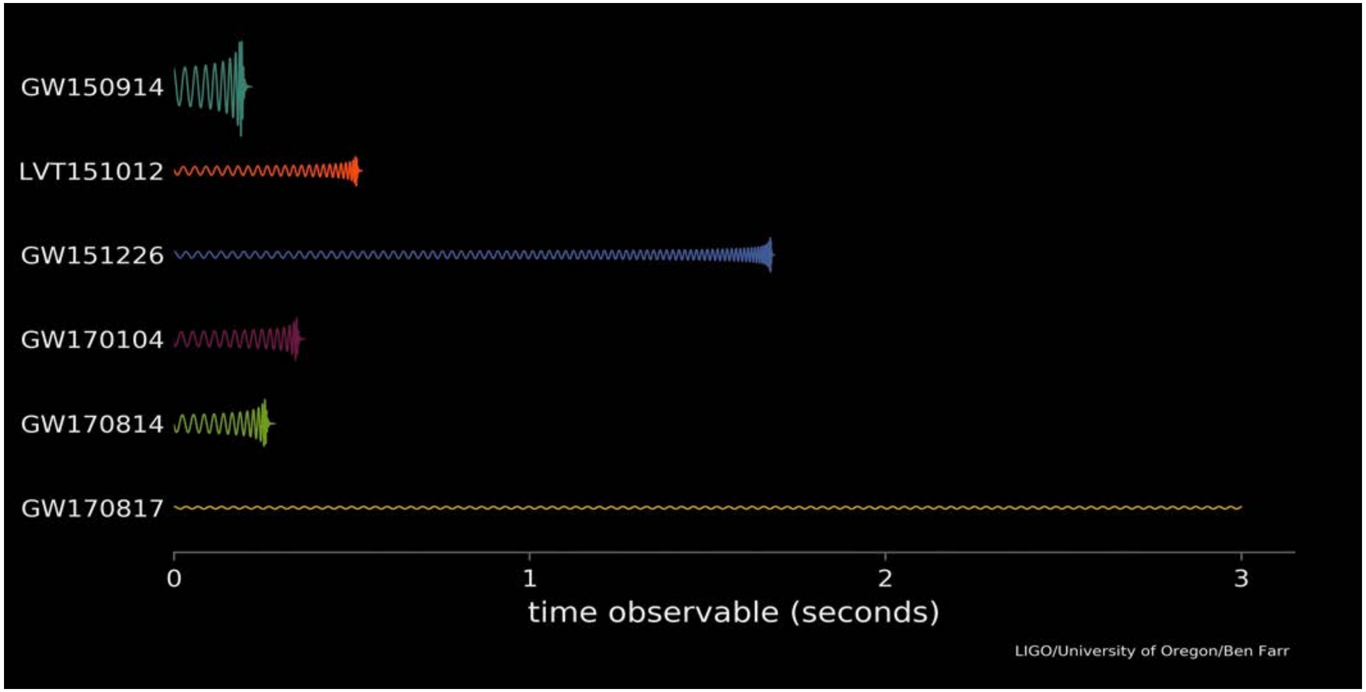
Astrophys.J. 848 (2017) no.2, L12

Gravitational Waves



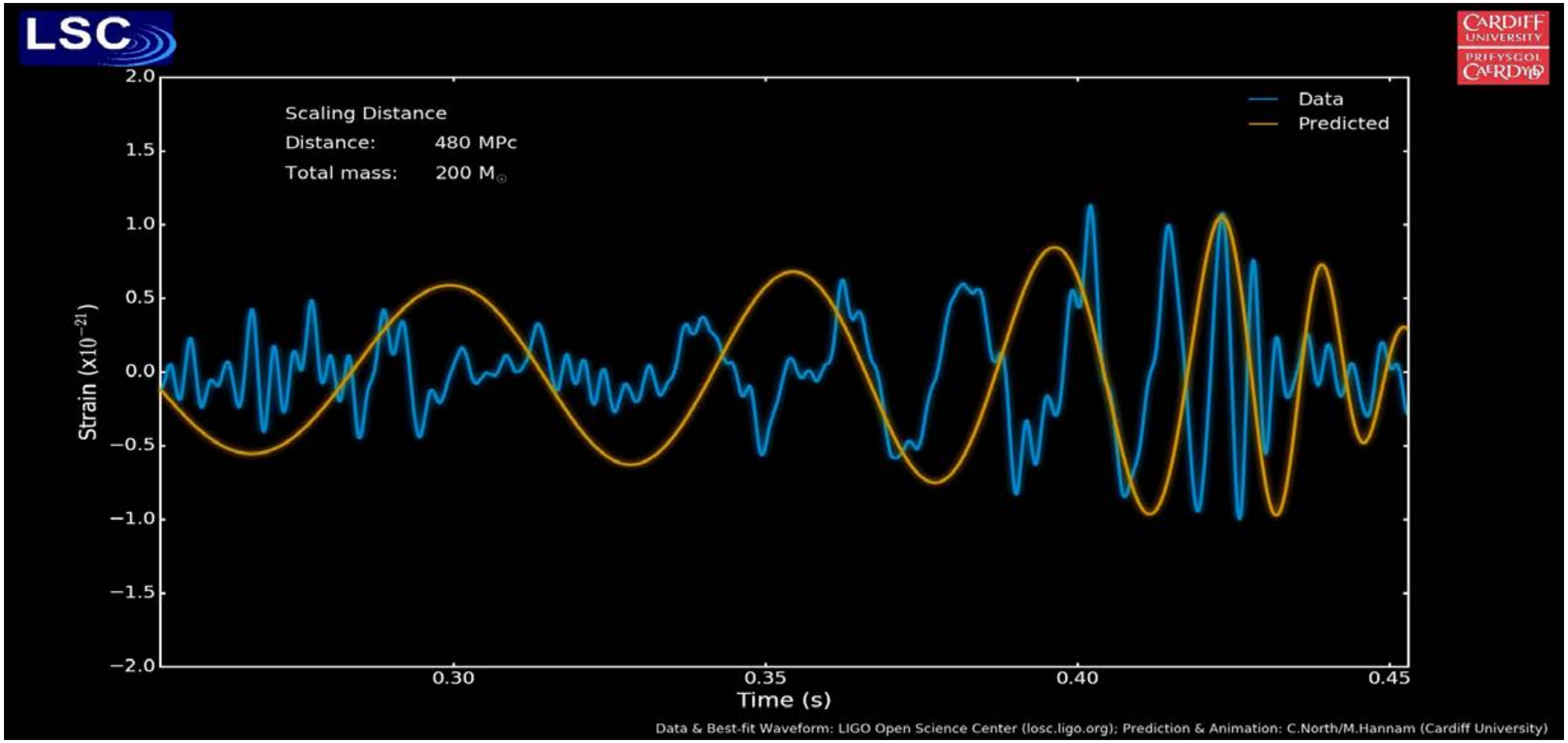
Gravitational Waves

LIGO detected several hundred of orbits for GW170817



Gravitational Waves

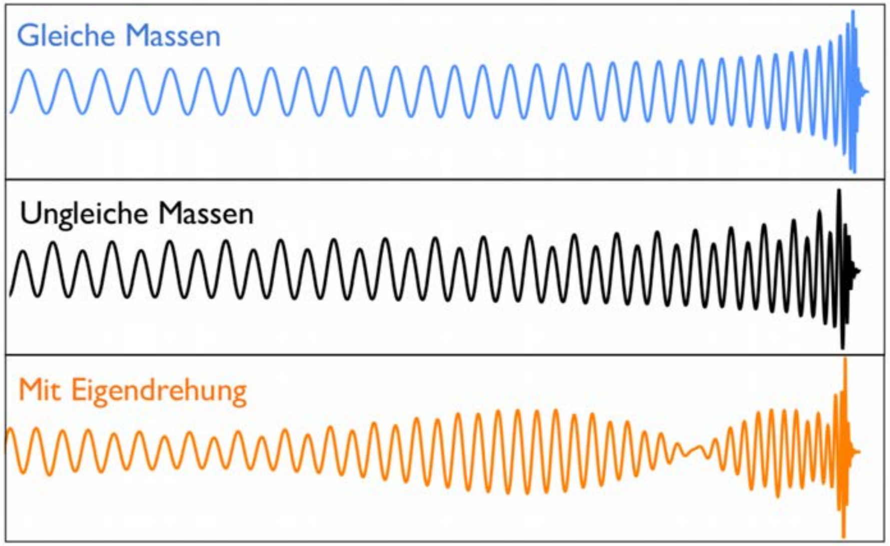
- compare signal with a large number of templates



(c) M.Hannam, C. North

Waveform models

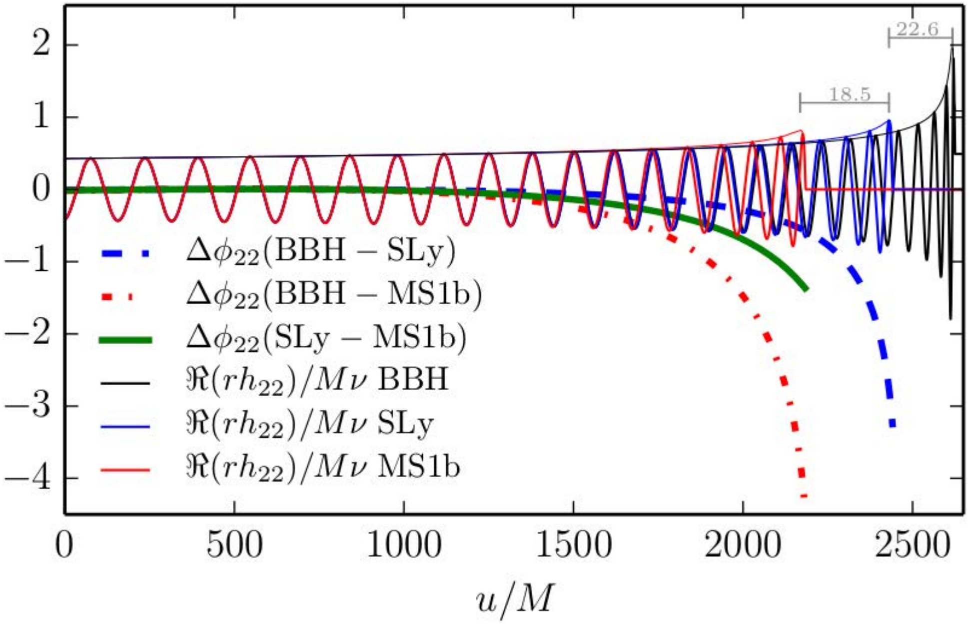
- How do we know what to search for?



A. Taraccini, T. Hinderer

Intrinsic parameters for BHs and NSs
– masses
– spins
– eccentricity

Additionally for NSs
– internal composition



Dietrich et al.

Observational parameters:
– inclination
– distance
– polarization

Waveform models

Time domain

Frequency domain

Post-Newtonian models

+ fast to compute
- inaccurate near merger

Effective one body formalism

+ agree well with most NR data
- slow to compute

→ surrogate model to allow fast evaluation

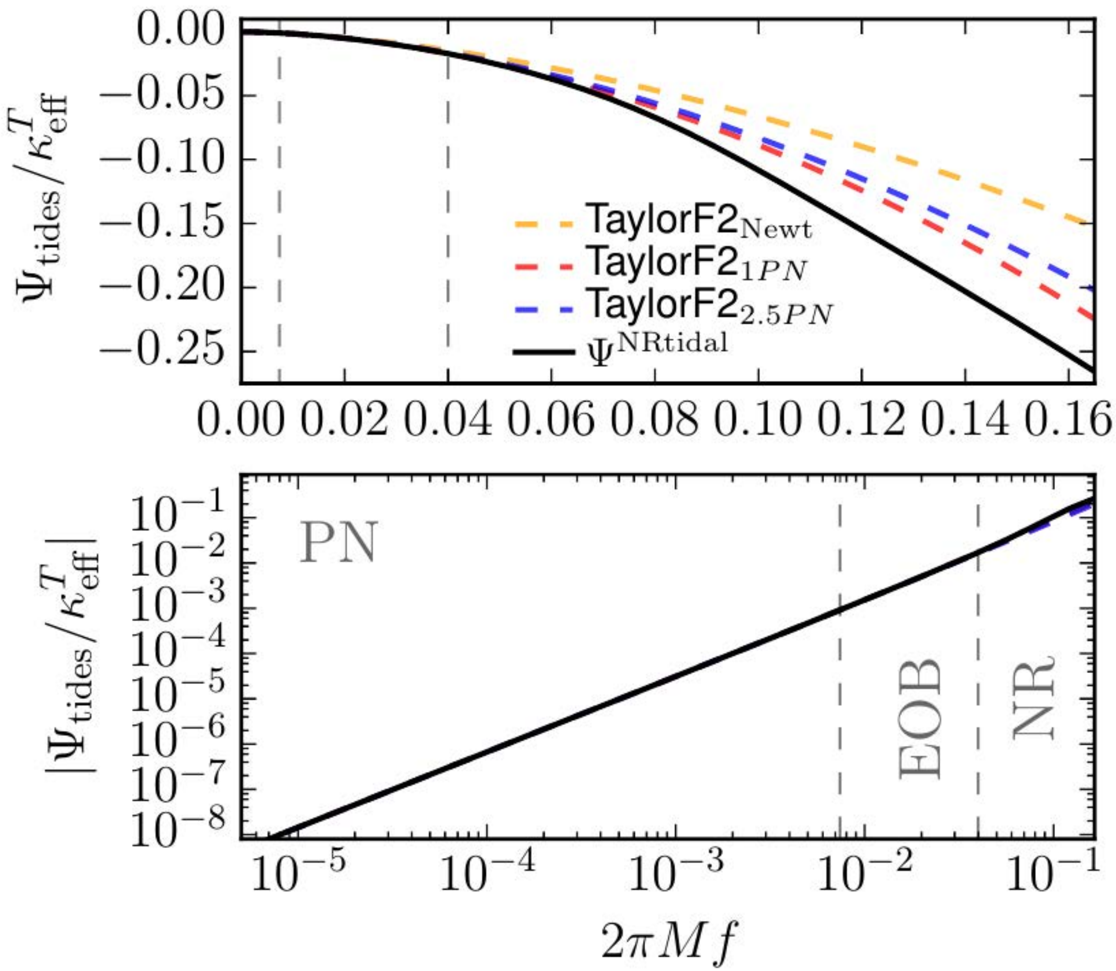
NR simulations

+ solve full Einstein equations
+ addition of microphysics possible
+ predictions for the postmerger
- only the last orbits can be evolved
- SUPER slow

Phenomenological tides

+ combination of PN/EOB/NR
+ accurate until merger
- just a fit

Phenomenological Tides



Combination of PN/EOB/NR knowledge

$$\Psi^{\rm NRtidal} = -\kappa^T_{\rm eff}\frac{\tilde{c}_{\rm Newt}}{X_A X_B} x^{5/2} \times \frac{1+\tilde{n}_1 x + \tilde{n}_{3/2} x^{3/2} + \tilde{n}_2 x^2 + \tilde{n}_{5/2} x^{5/2}}{1+\tilde{d}_1 x + \tilde{d}_{3/2} x^{3/2}}$$

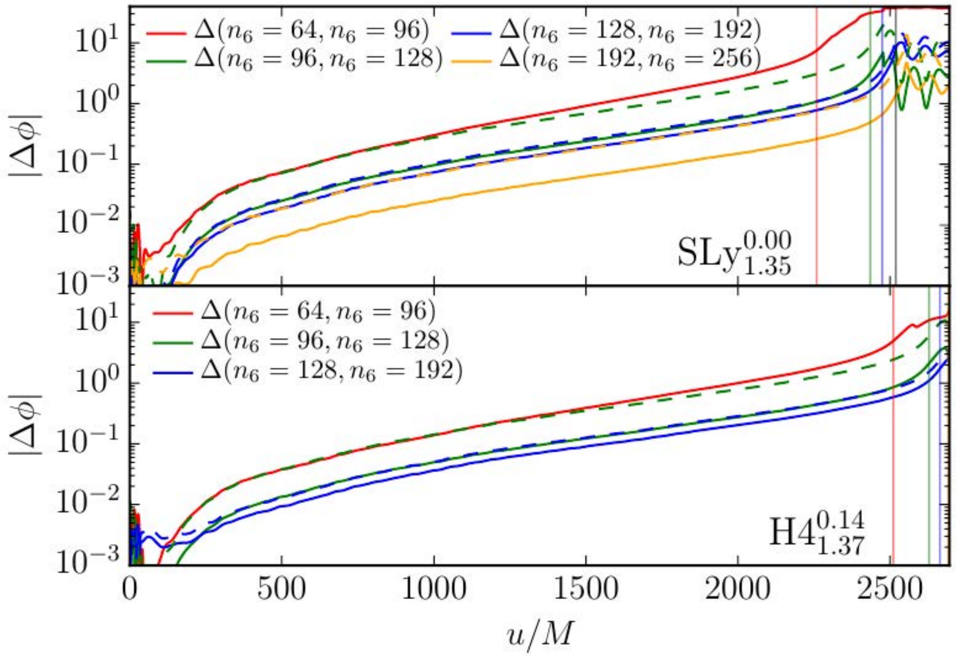
Effective tidal coupling constant:

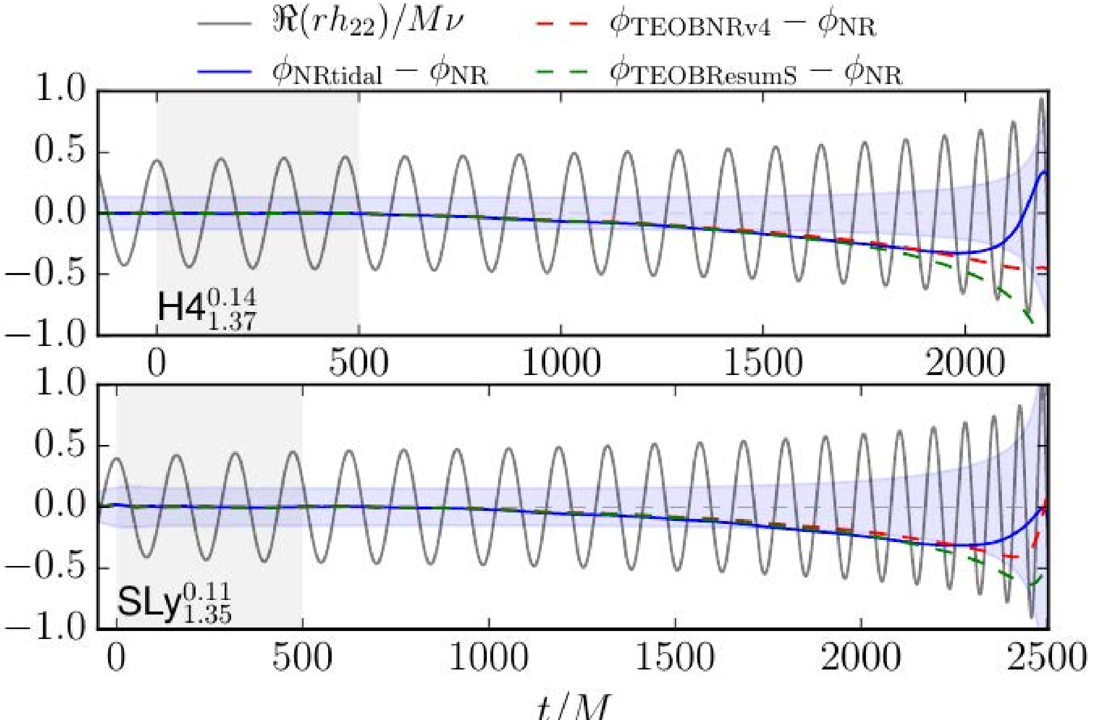
$$\kappa^T_{\rm eff} = \frac{2}{13}\left[\left(1+12\frac{X_B}{X_A}\right)\left(\frac{X_A}{C_A}\right)^5 k_2^A + (A \leftrightarrow B)\right]$$

Advances in Numerical Relativity

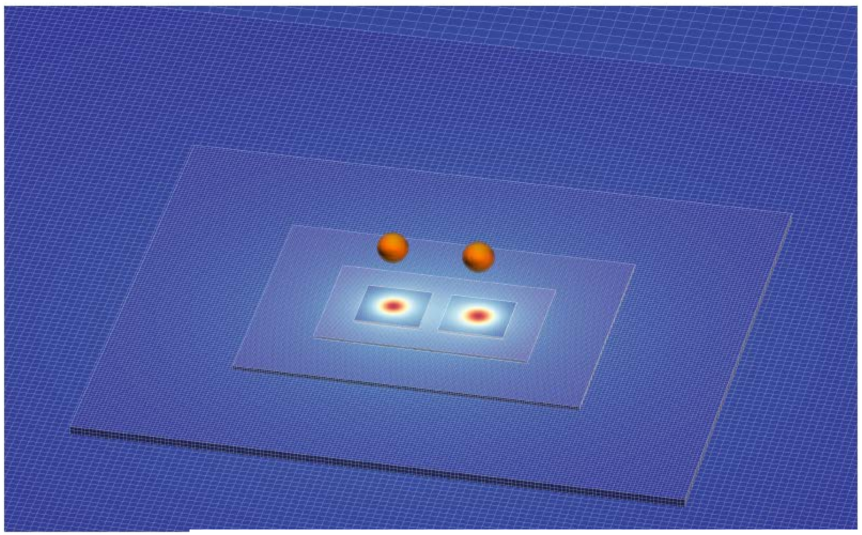
Phys.Rev. D96 (2017) no.12, 121501

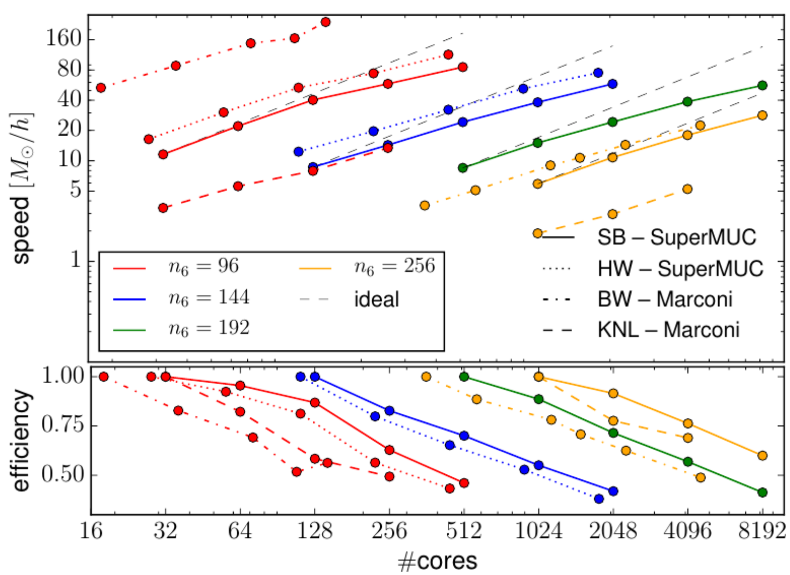
increasing accuracy of simulations





Advances in Numerical Relativity



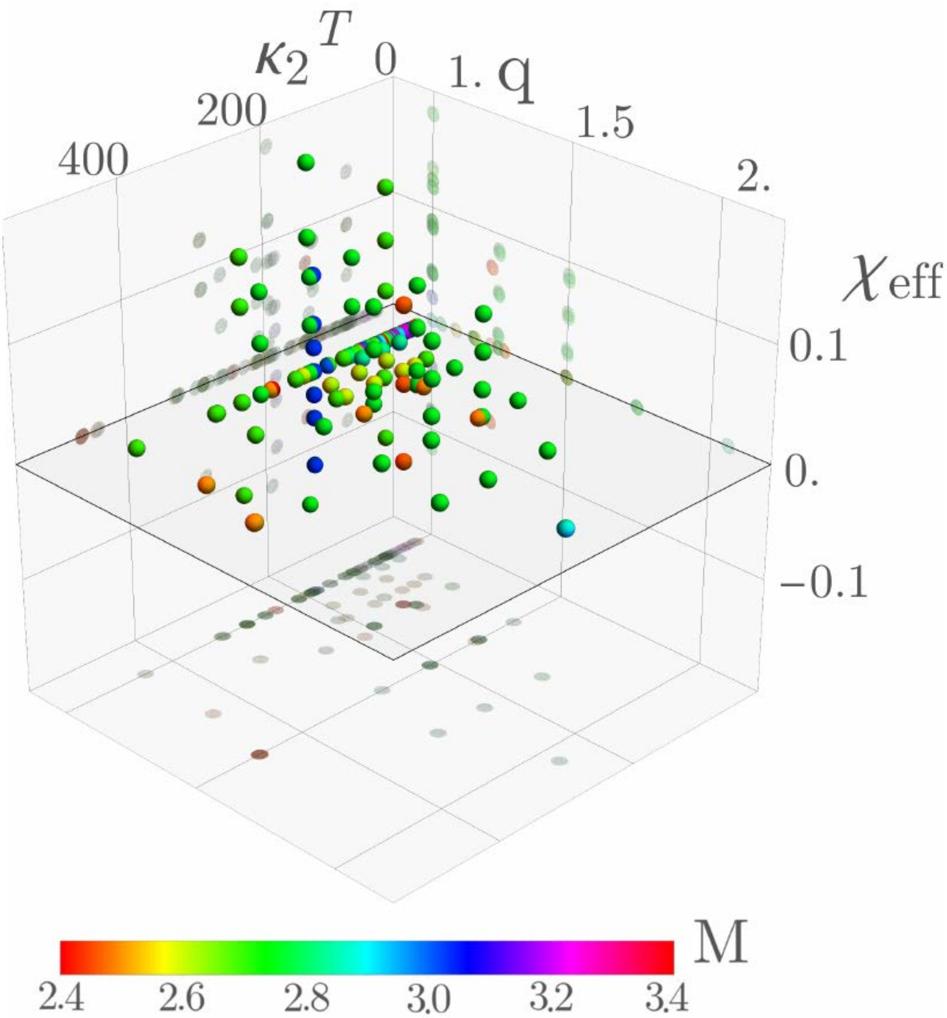


$$
\begin{aligned}
\partial_t \chi &= \frac{2}{3}\chi[\alpha(\hat{K}+2\Theta) - D_i\beta^i] \\
\partial_t \tilde{\gamma}_{ij} &= -2\alpha\tilde{A}_{ij} + \beta^k\tilde{\gamma}_{ij,k} + \tilde{\gamma}_{ik}\beta^k_{,j} - \frac{2}{3}\tilde{\gamma}_{ij}\beta^k_{,k} \\
\partial_t \hat{K} &= -D^iD_i\alpha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

Advances in Numerical Relativity

Coverage of large region of BNS parameter space

- – spinning systems
- – high mass ratio systems
- – precessing systems
- – eccentric systems



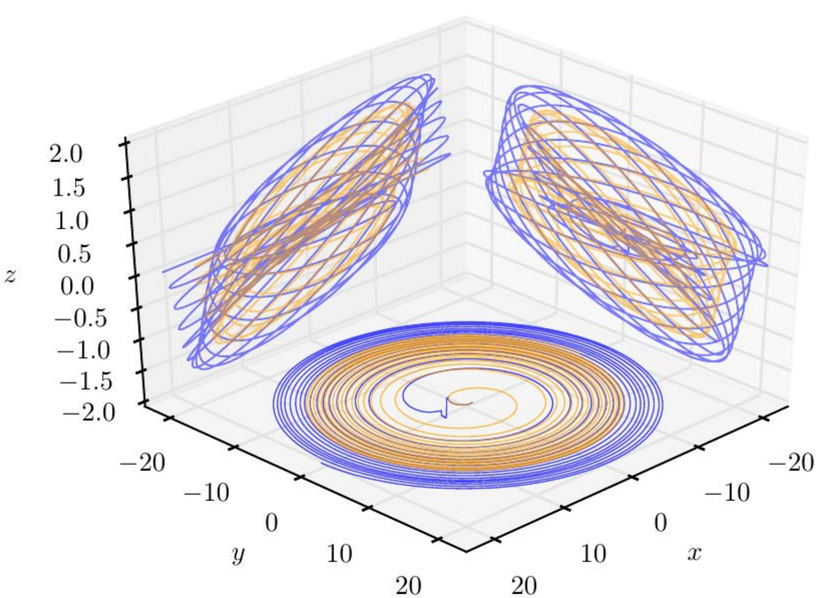
Inclusion of microphysics

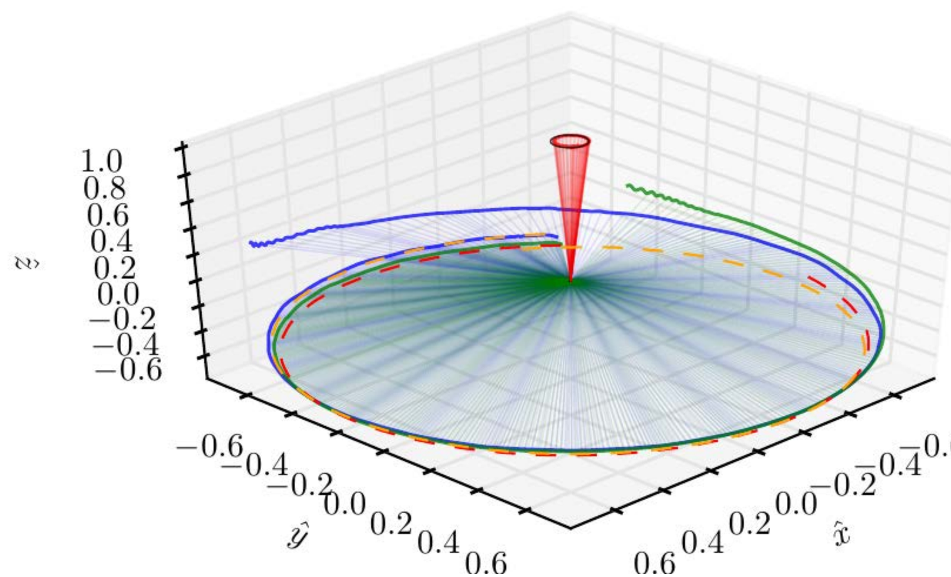
- – neutrino schemes
- – magnetic fields (ideal/resistive MHD)
- – viscous hydrodynamics

Advances in Numerical Relativity

Phys.Rev. D89 (2014) no.10, 104021 , Phys.Rev. D95 (2017) no.4, Phys.Rev. D96 (2017) no.12, 121501 , 044045, arXiv:1712.02992

- Precessing and Spinning configurations
  - spin effects even in late inspiral as important as tidal effects
  - spin effects effect the postmerger evolution

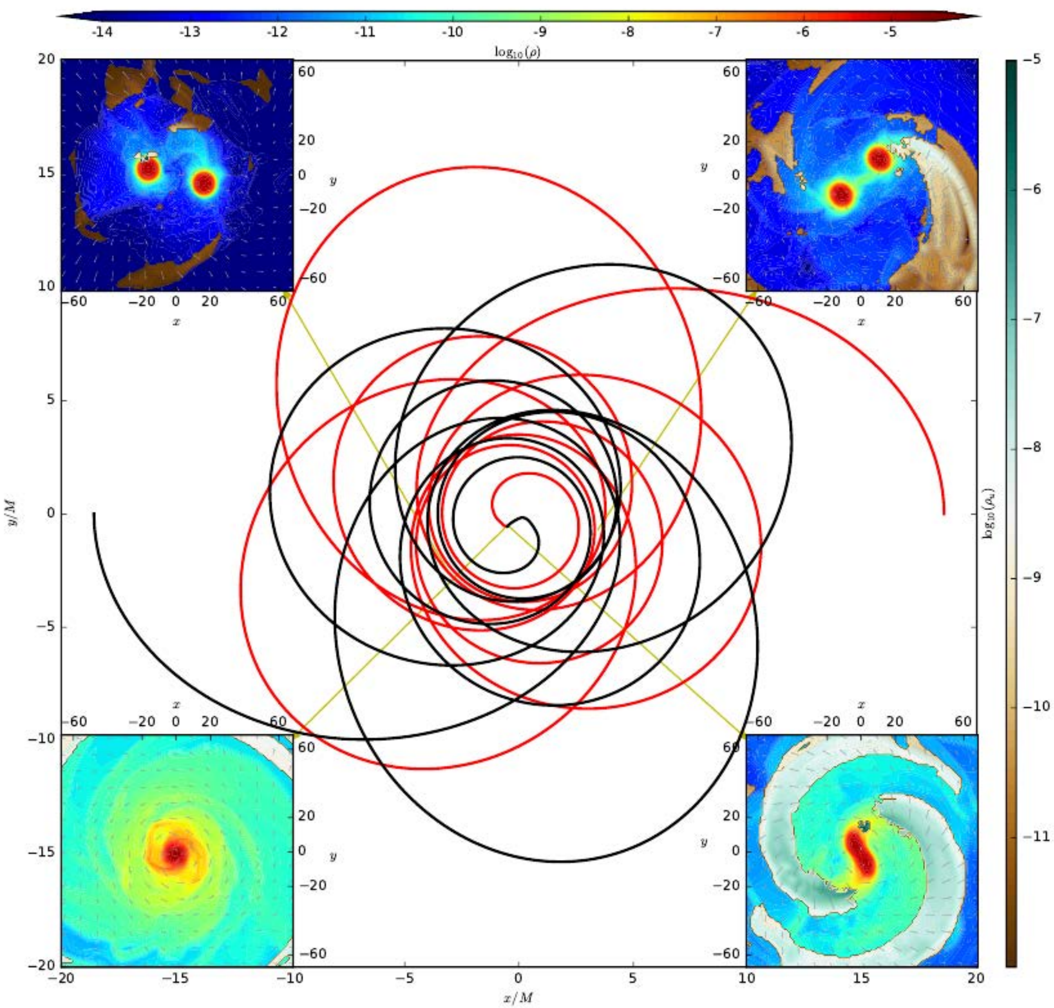


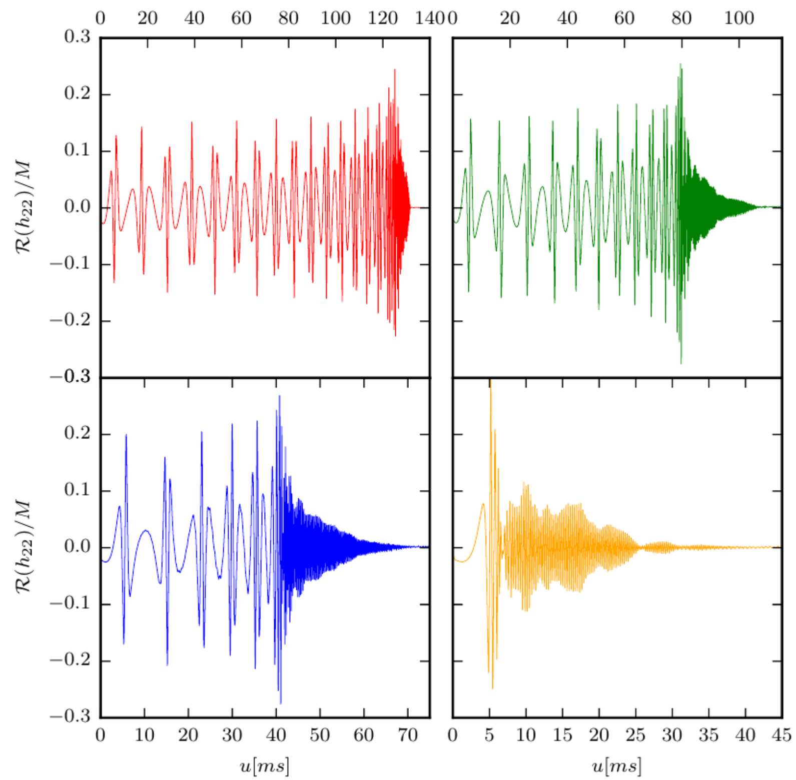


Advances in Numerical Relativity

- Eccentric systems

– f-mode induces oscillations due to close encounters





Advances in Numerical Relativity

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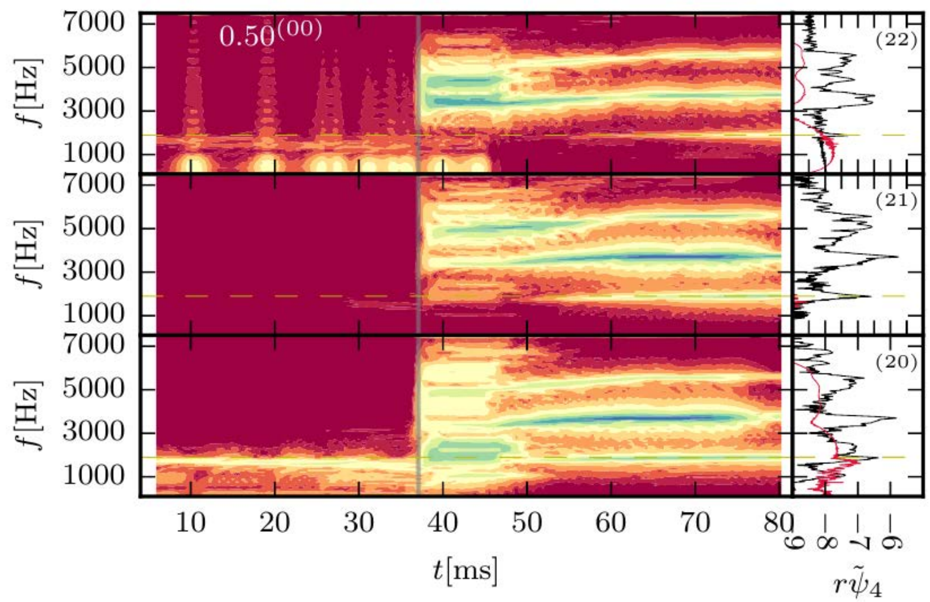
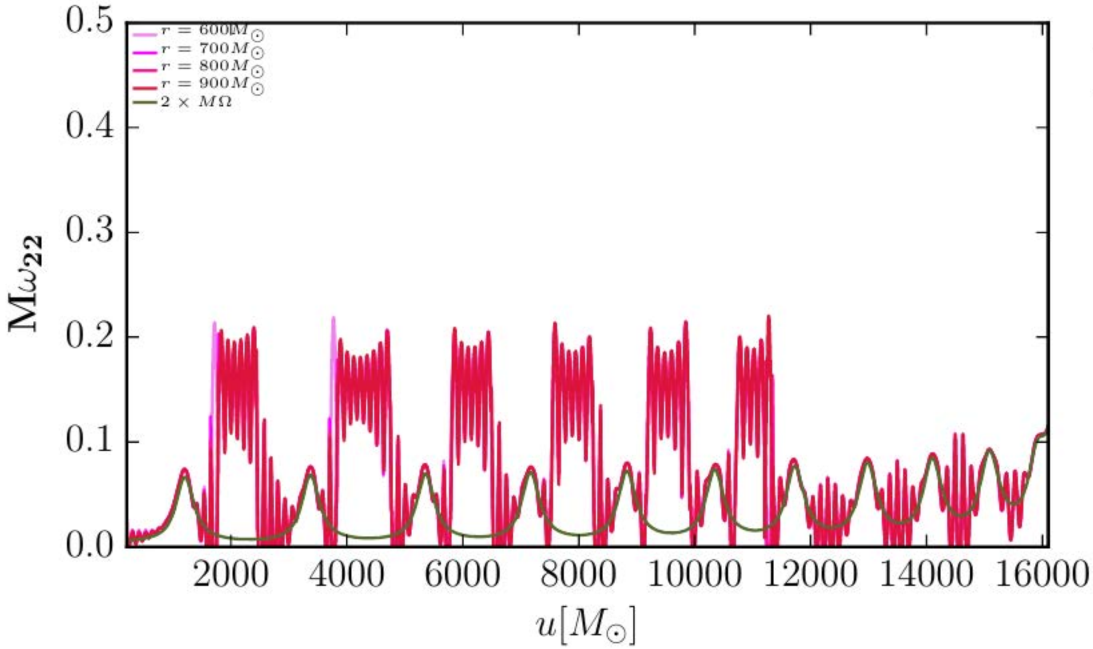
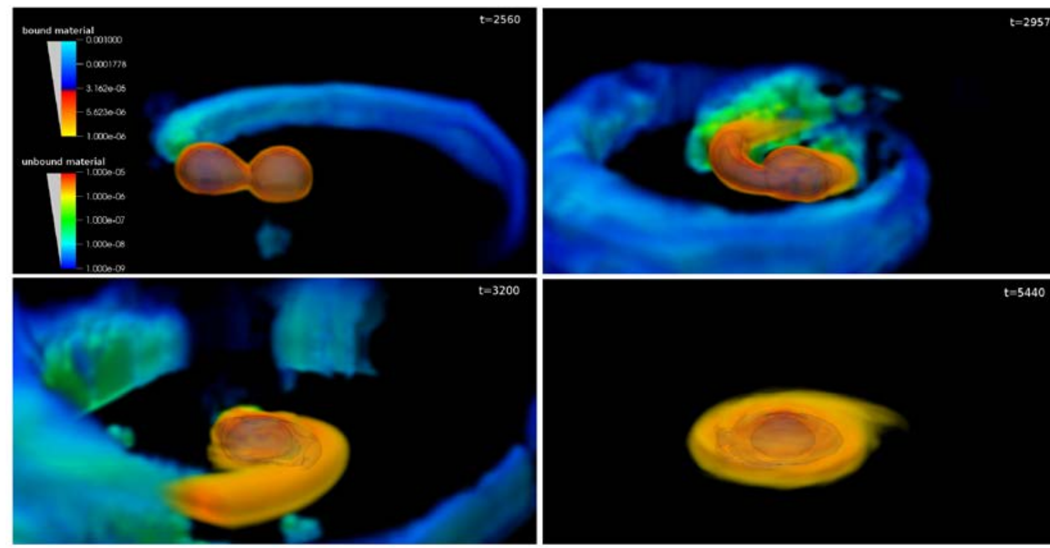


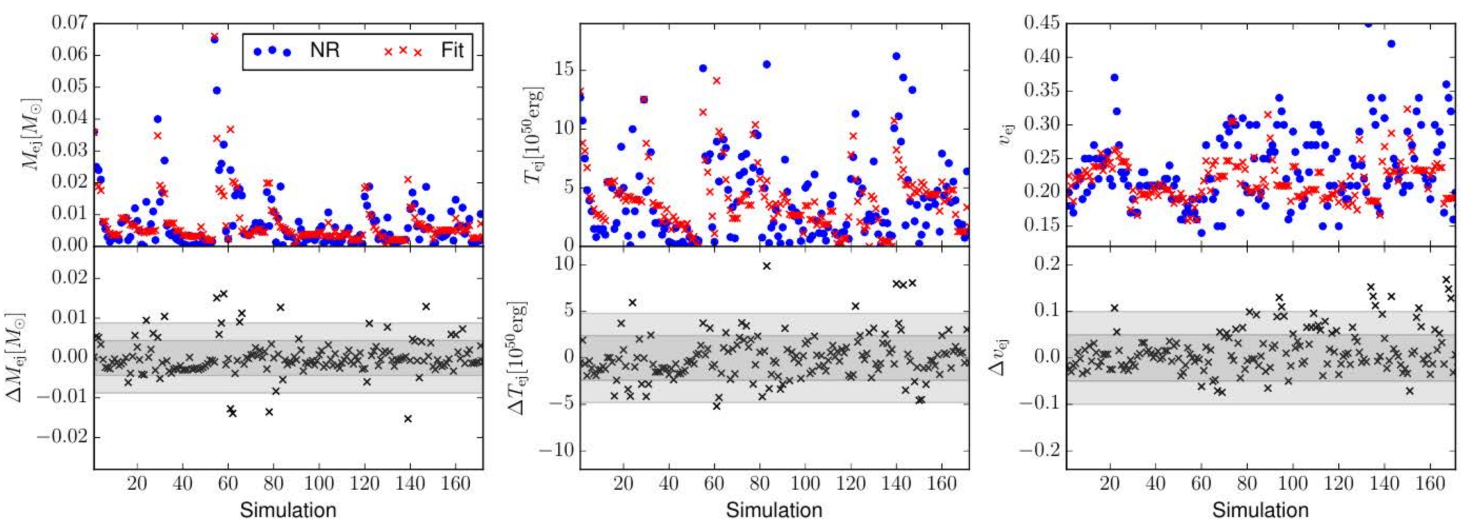


Advances in Numerical Relativity

Class.Quant.Grav. 34 (2017) no.10, 105014

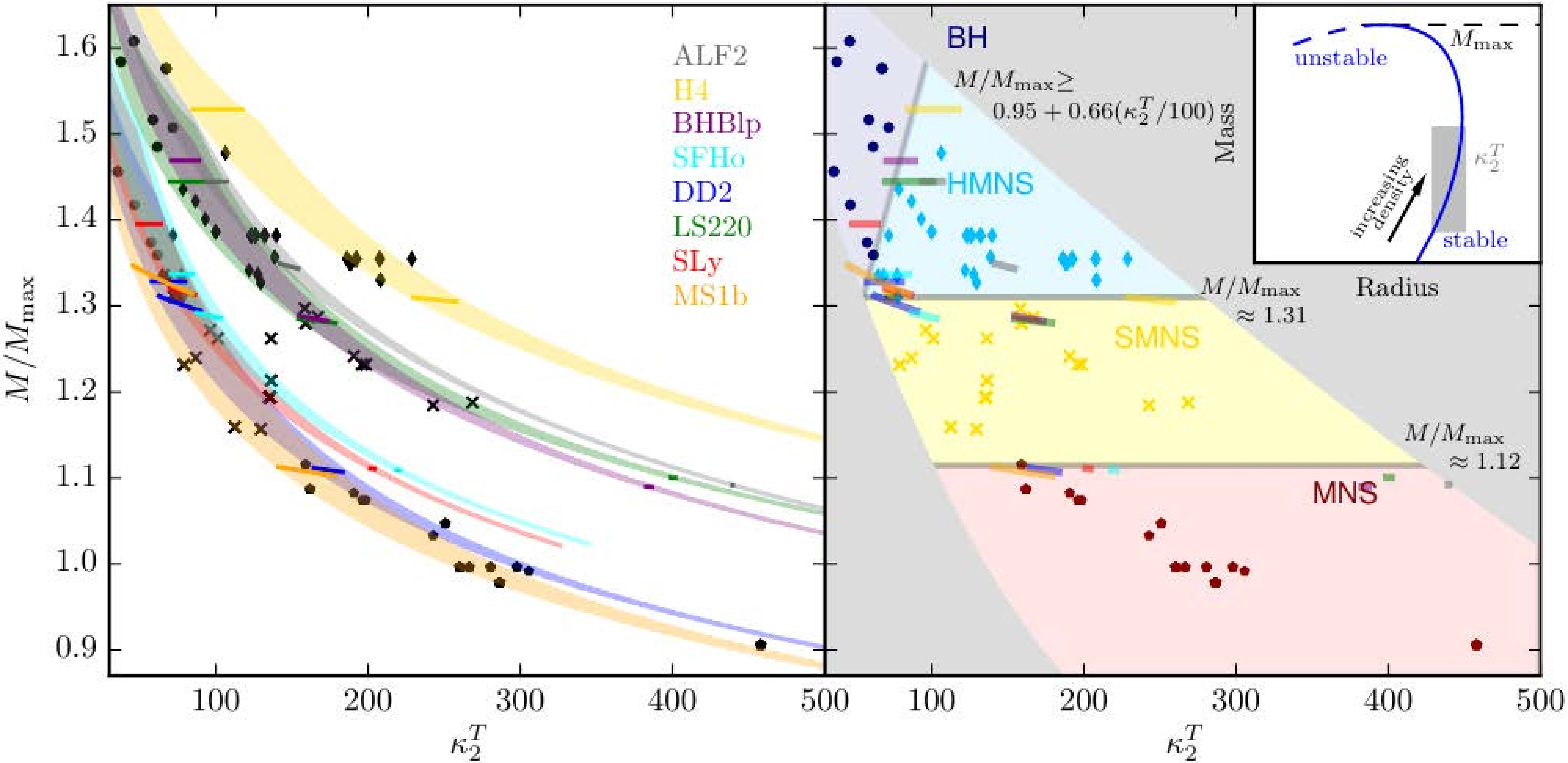
- Predictions about ejecta mass and compositions
  - dynamical ejecta:
    - tidal tail
    - shock heating
  - disk winds
    - neutrino driven winds
    - magnetic winds
    - secular



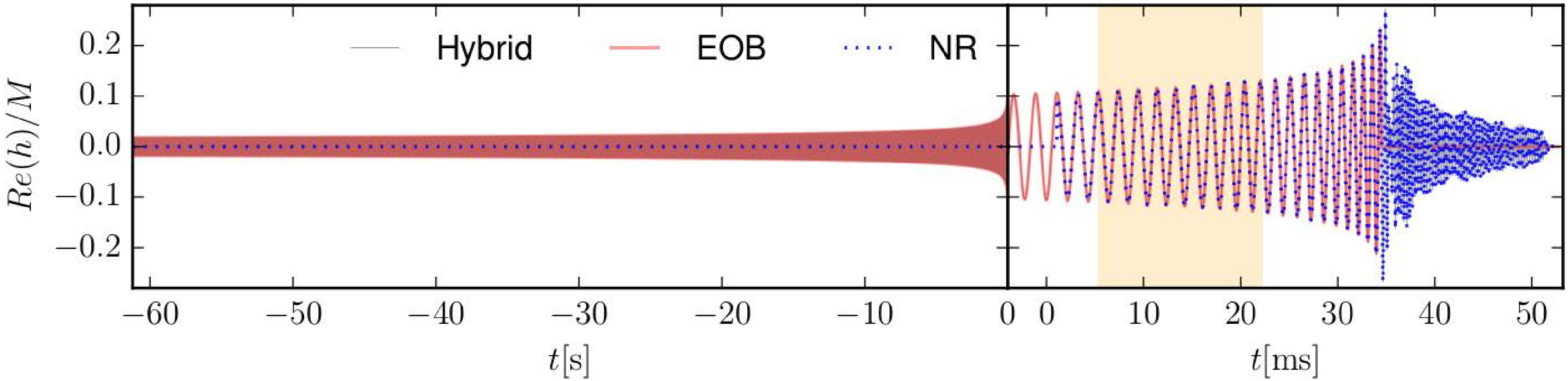


Advances in Numerical Relativity

Predicting merger outcome



Testing Waveform models

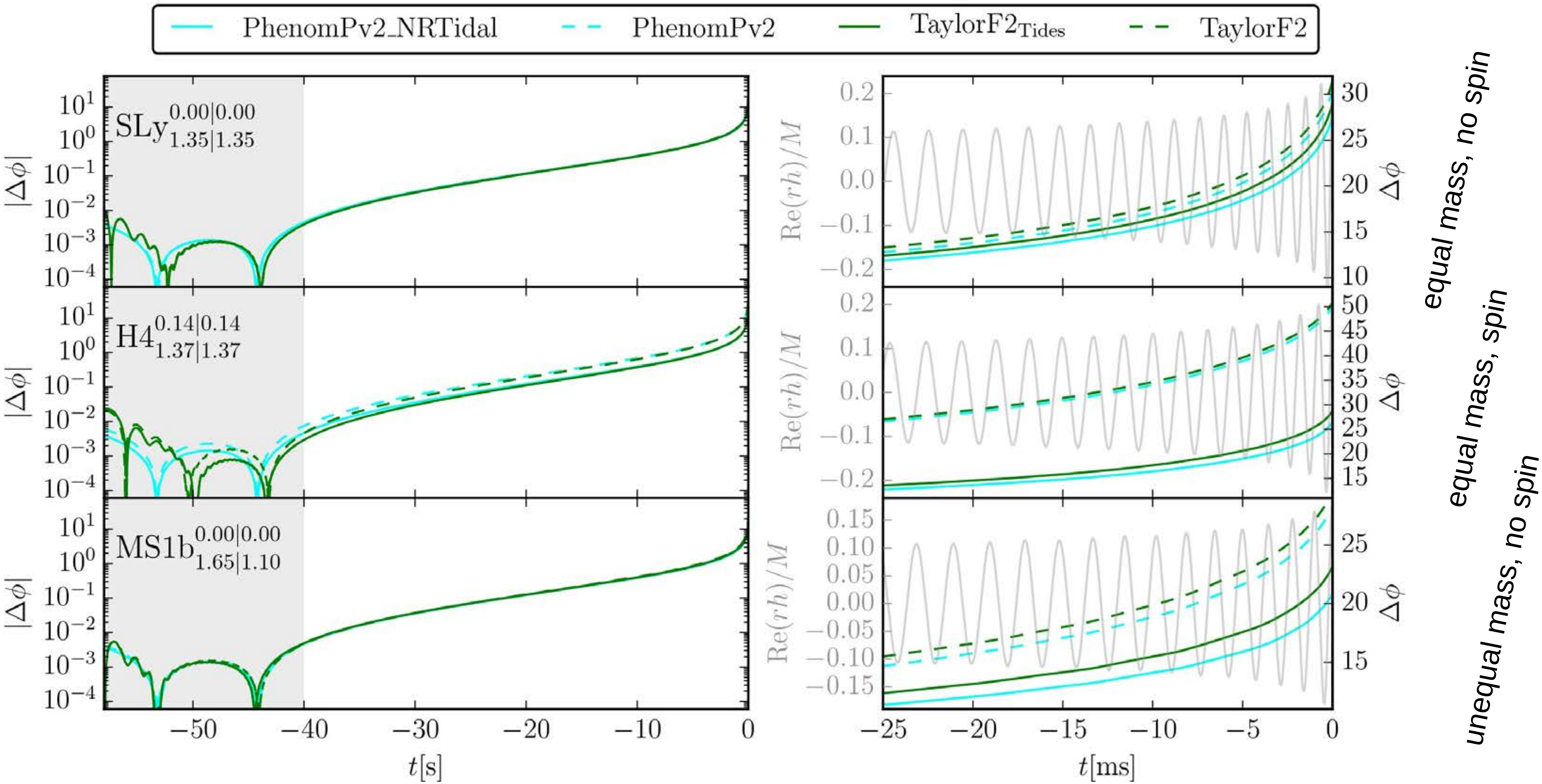


Combination of

semi-analytical tidal effective-one-body and **numerical relativity**

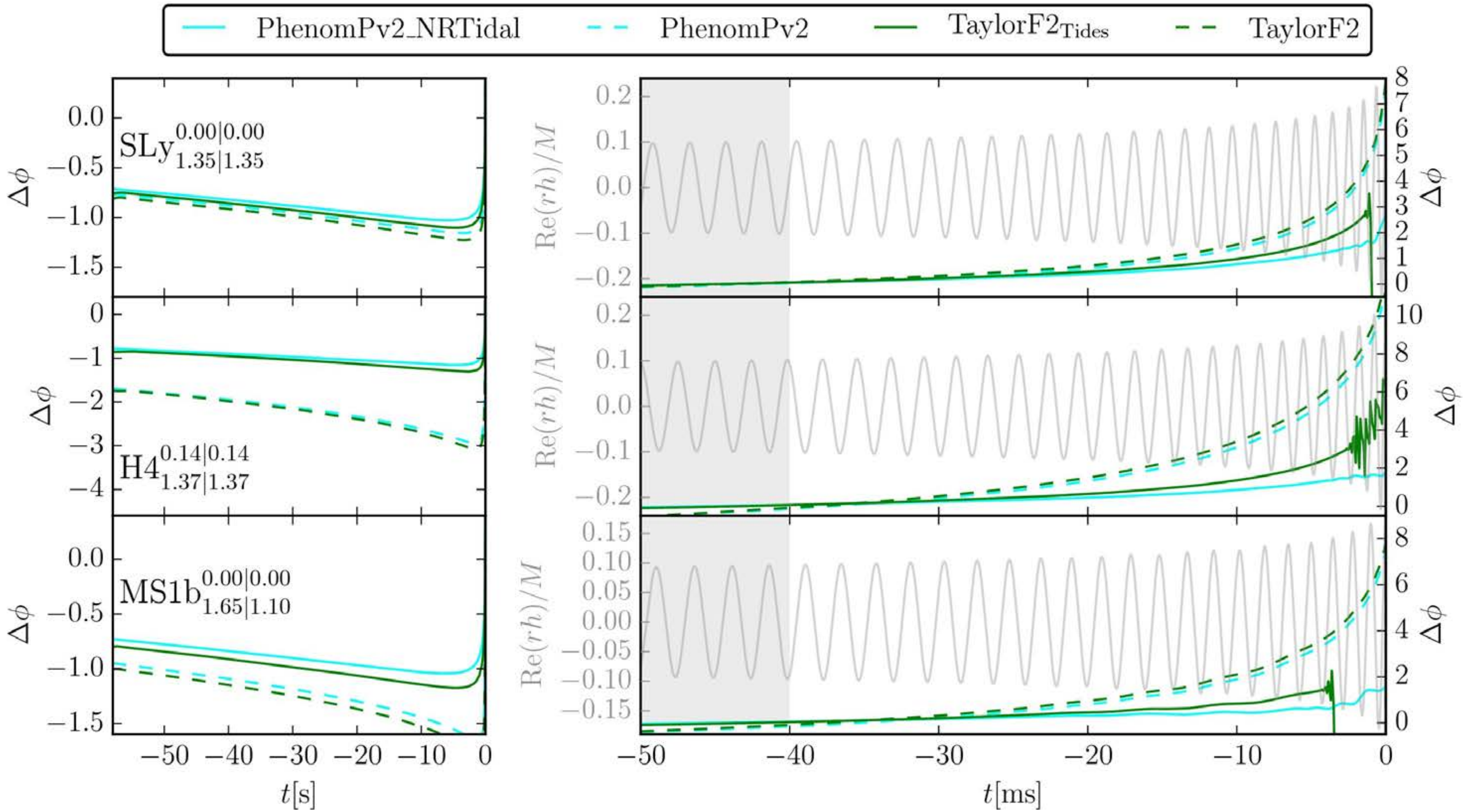
Testing Waveform models

LIGO most sensitive to phase evolution – early alignment



Testing Waveform models

LIGO most sensitive to phase evolution – alignment in late inspiral

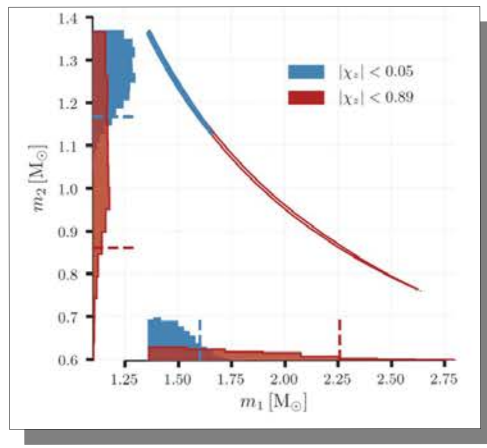


Gravitational Waves

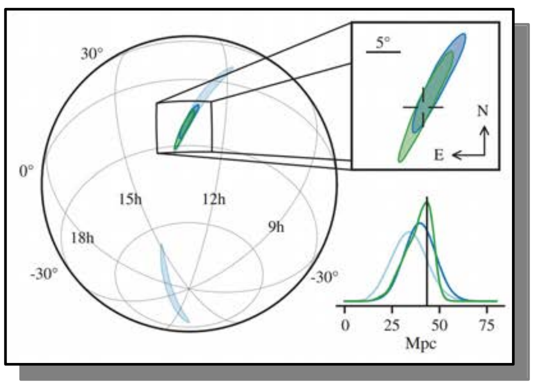
- Chirp signal during the inspiral

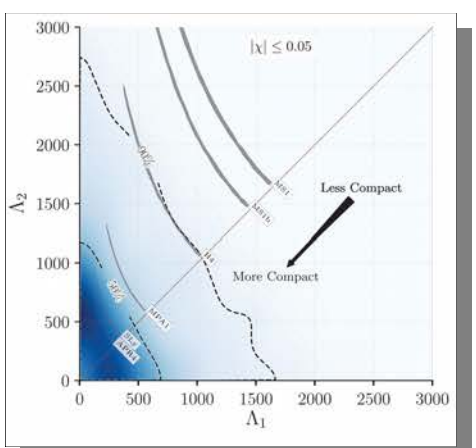
28 sq-deg

Determine the mass

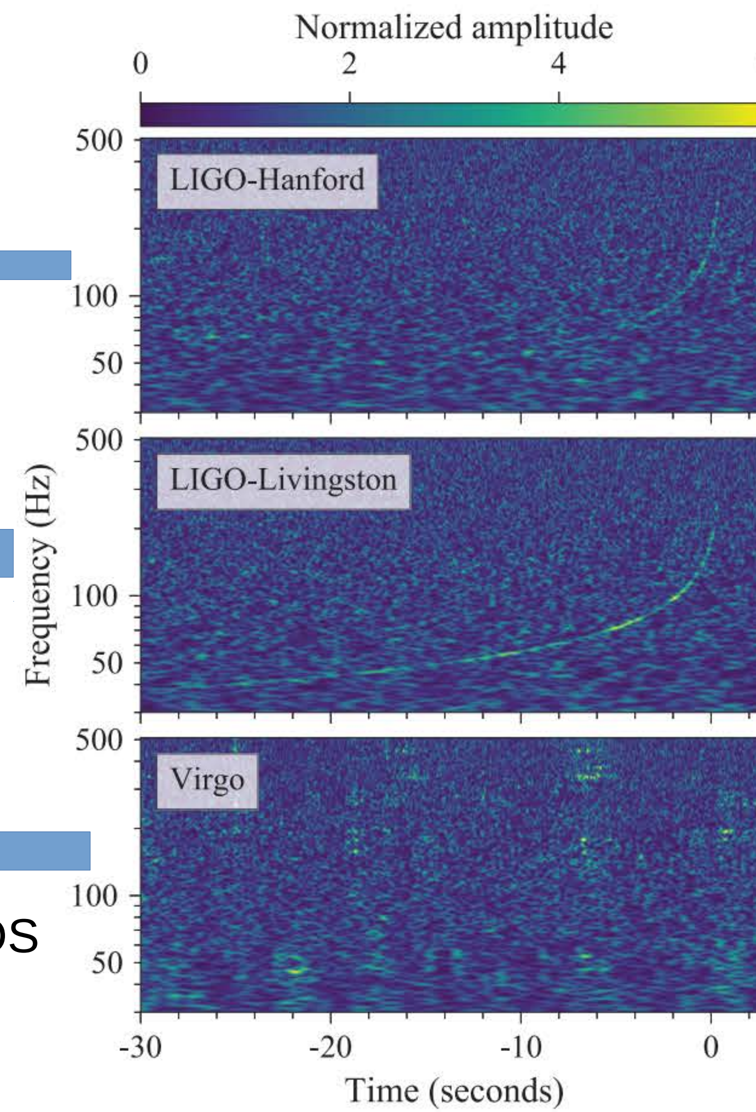


Sky localization





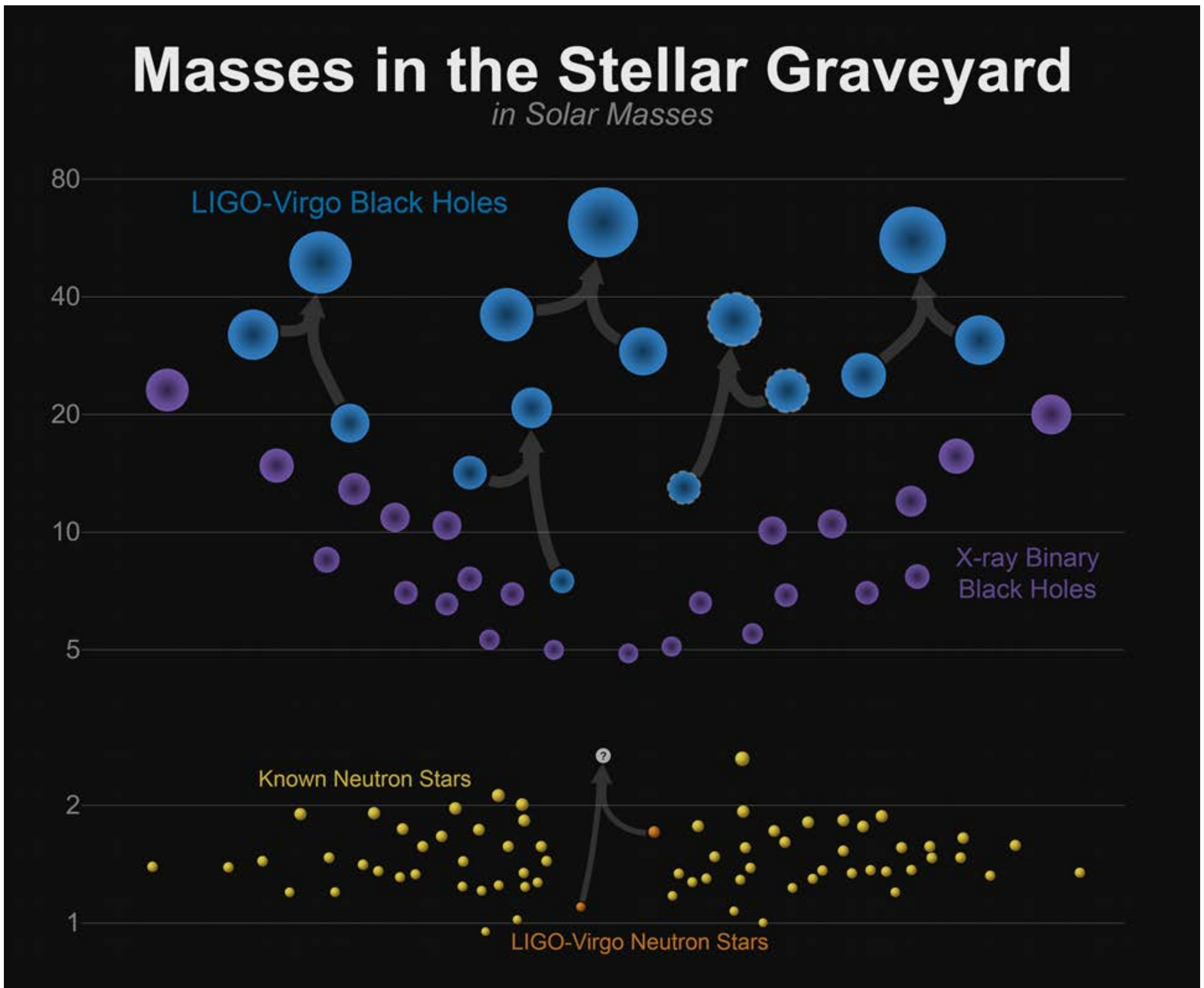
Determine the EOS

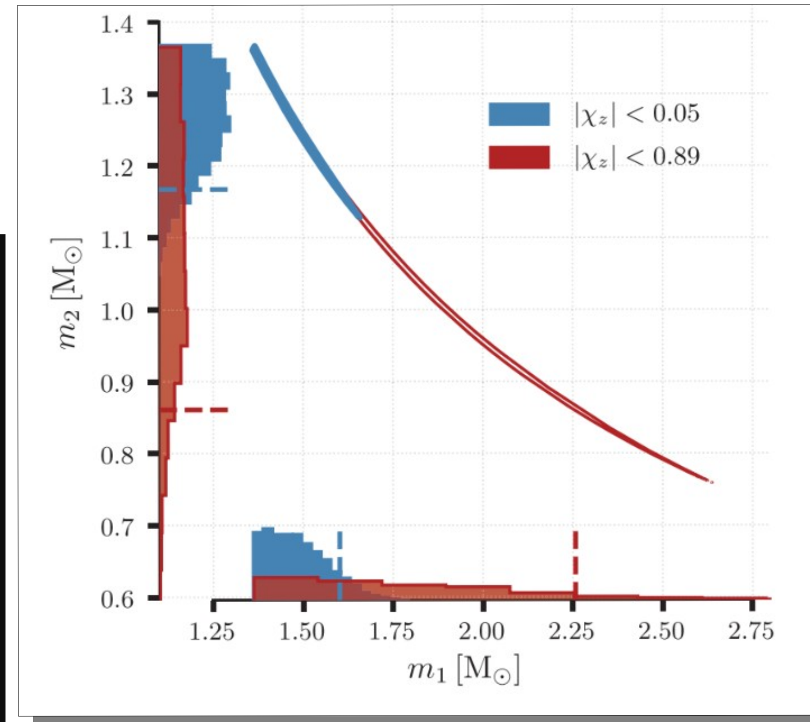


Phys.Rev.Lett. 119 (2017) no.16, 161101

Gravitational Waves: Parameter Estimation

- Mass Constraints



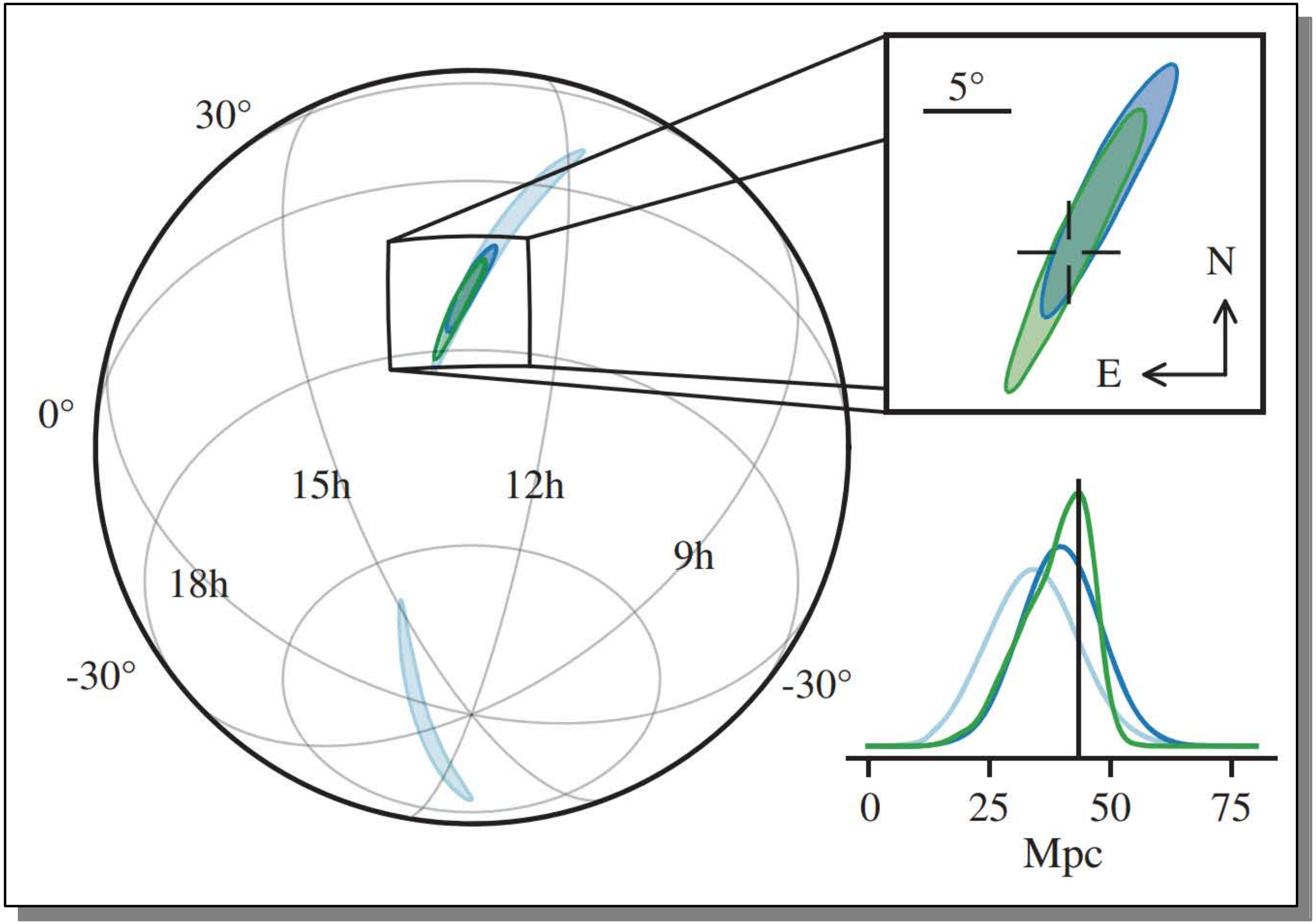


Phys.Rev.Lett. 119 (2017) no.16, 161101

LIGO-Virgo/Frank Elavsky

Gravitational Waves: Parameter Estimation

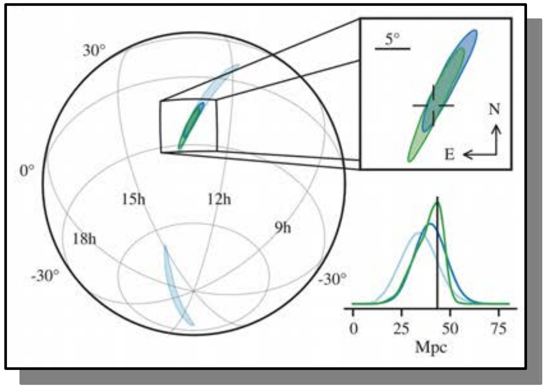
- Sky localization

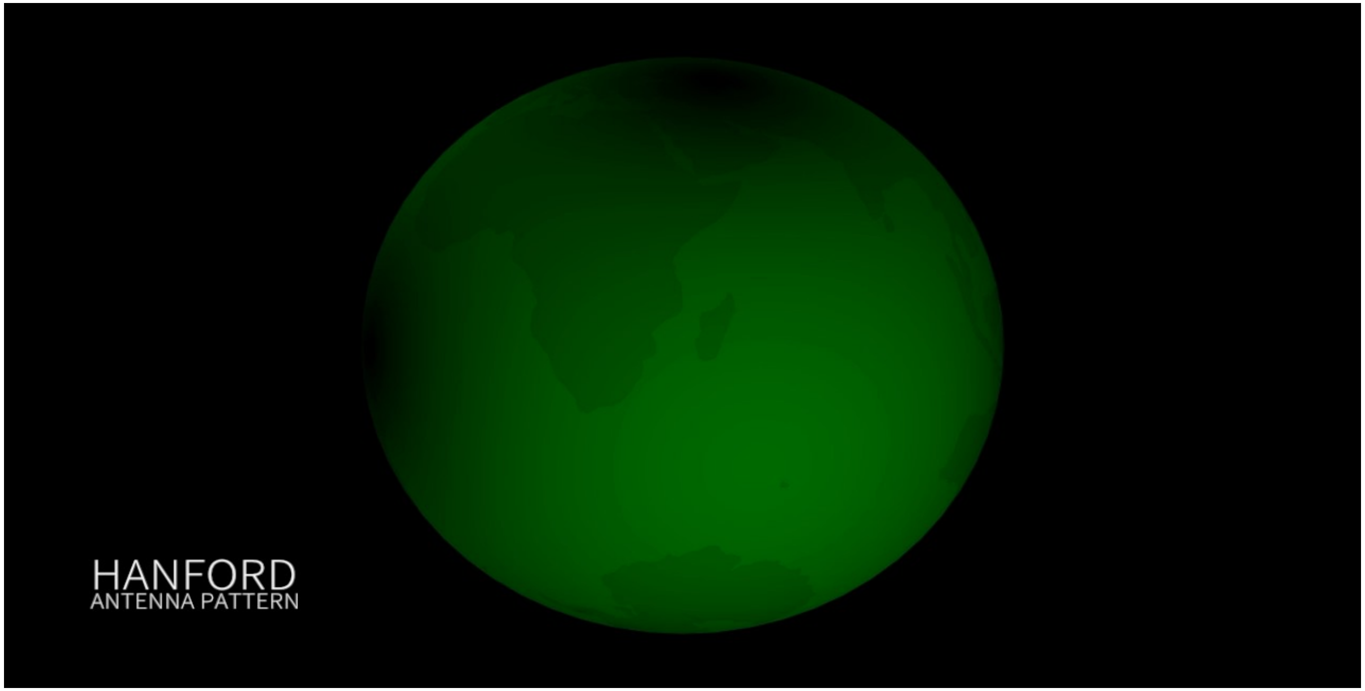


Phys.Rev.Lett. 119 (2017) no.16, 161101

Gravitational Waves: Parameter Estimation

- Sky localization

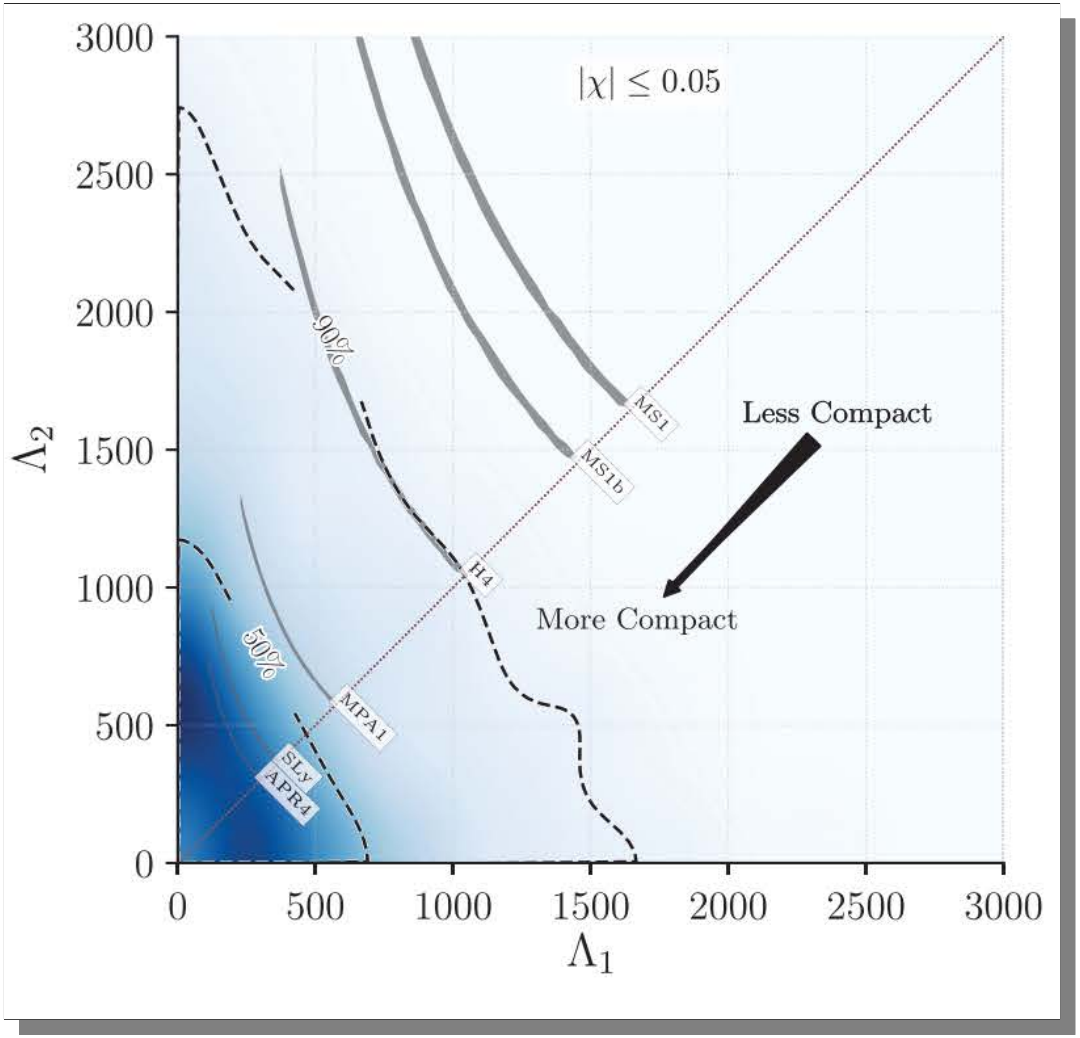




Leo Singer

Gravitational Waves: Parameter Estimation

- Determine the Equation of State

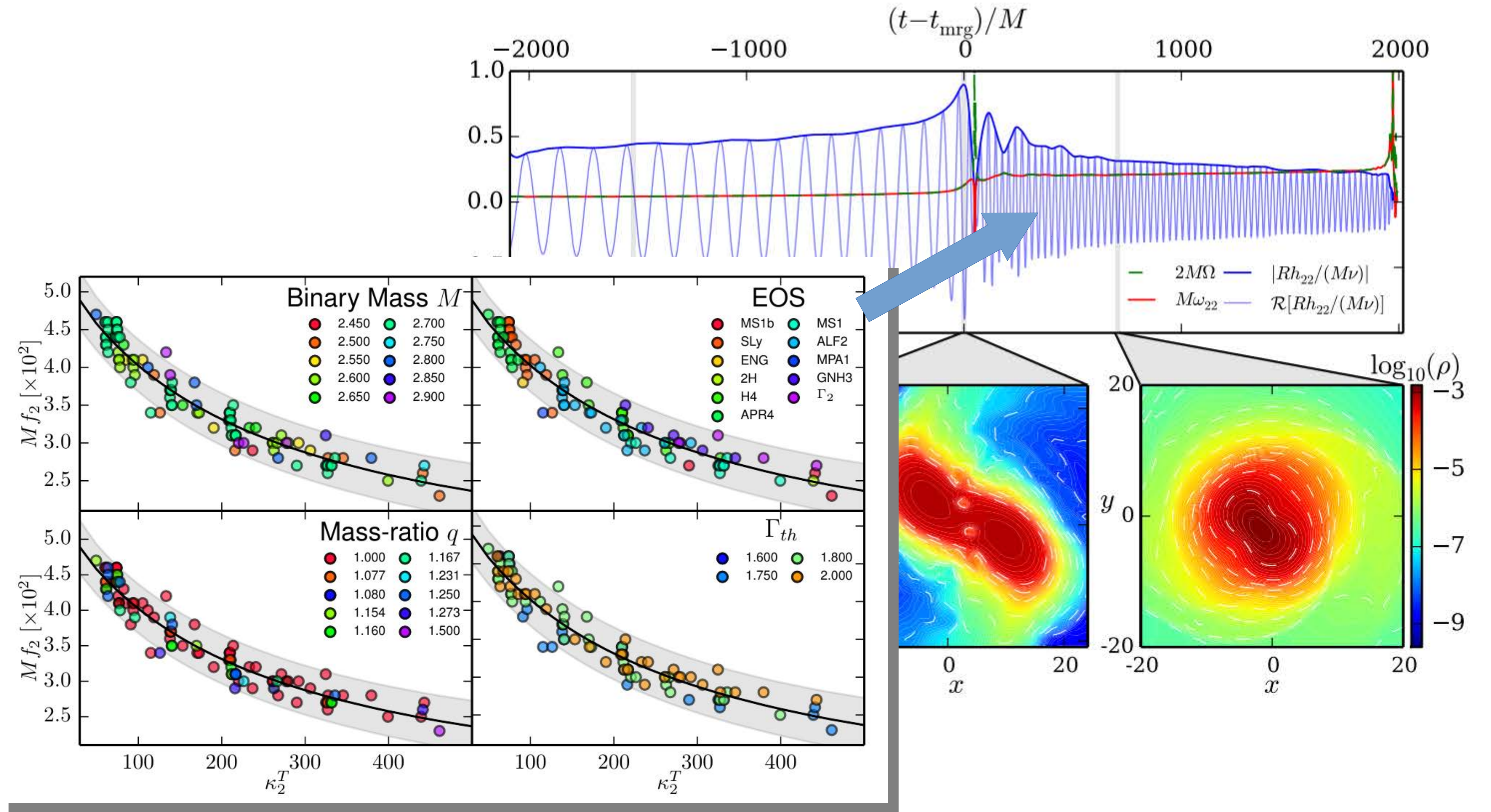


GW observations
favor Nss with smaller radii

Phys.Rev.Lett. 119 (2017) no.16, 161101

Gravitational Waves: Postmerger

- postmerger signal at higher frequencies with low chances of detection



Gravitational Waves: Postmerger

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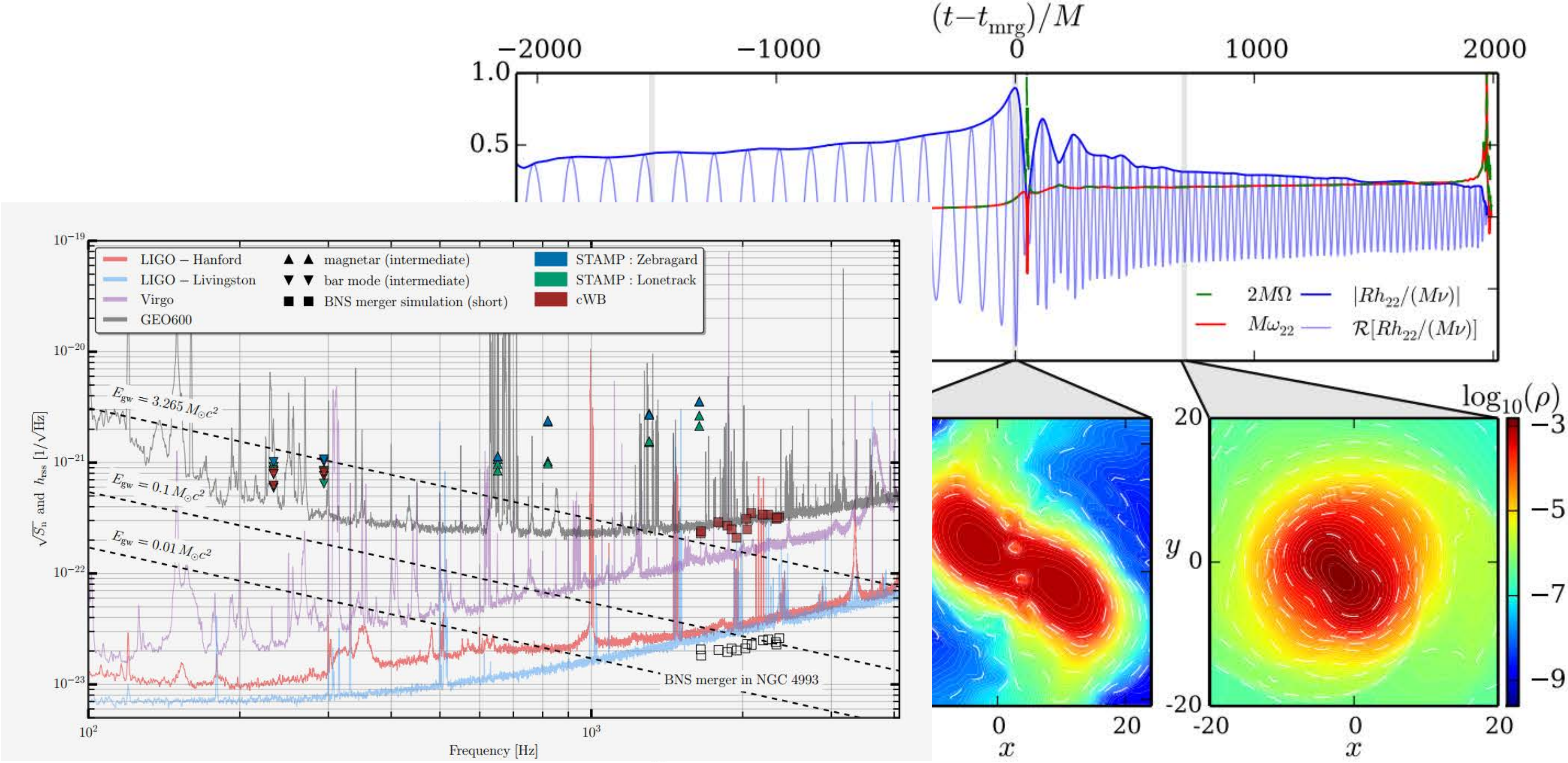
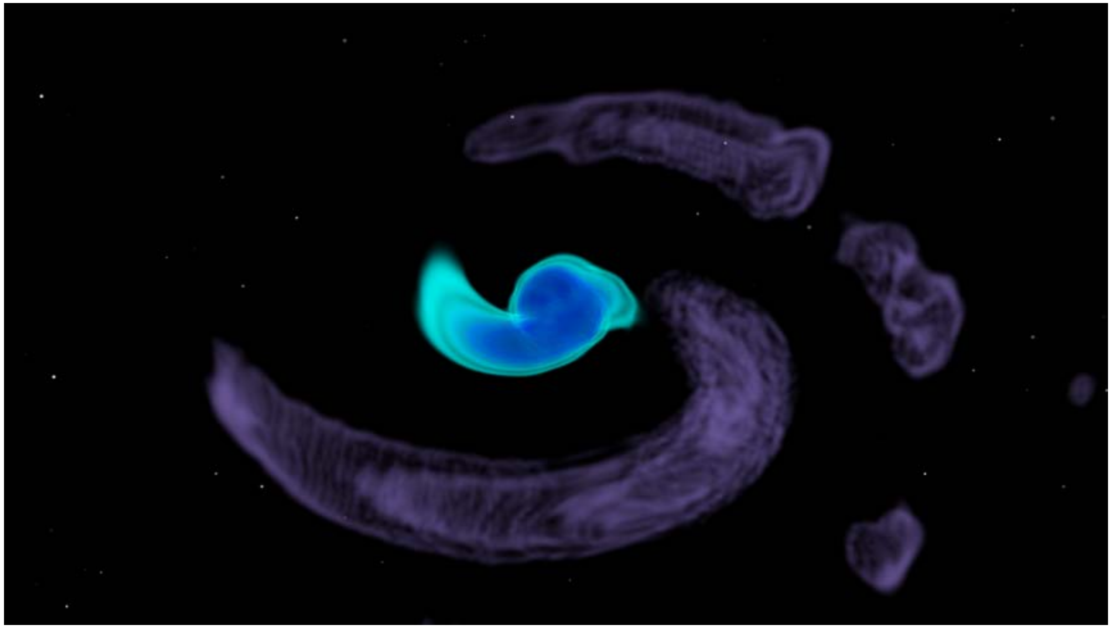


arXiv:1710.09320

no postmerger signal for GW170817 detected

Neutrinos



Neutrinos

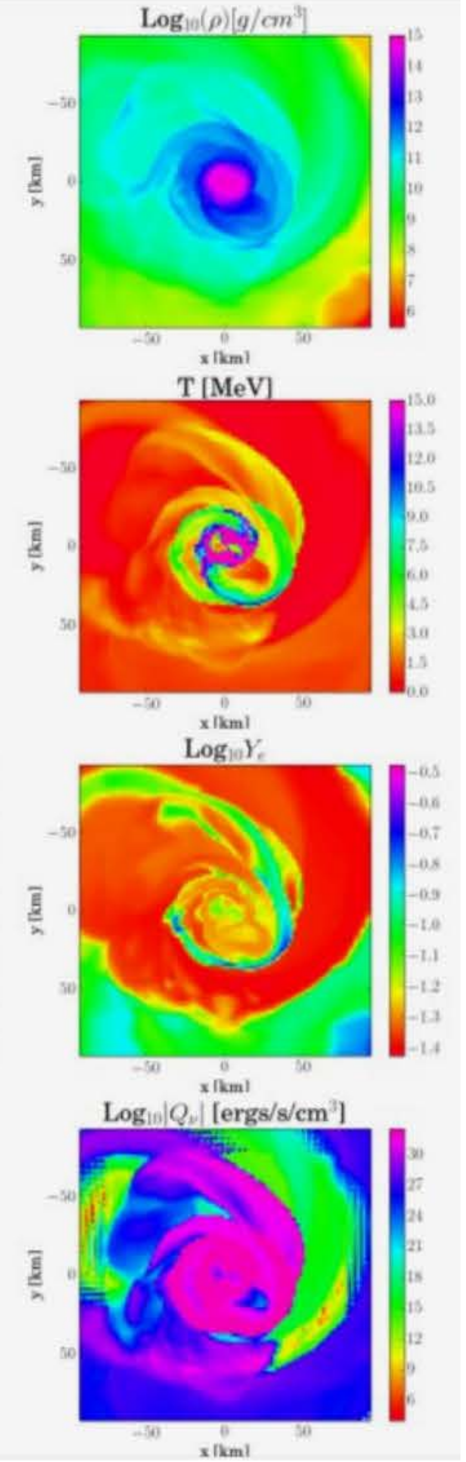
- heating during the NS merger
  virial temperature

$$T_{\rm vir} \sim 25\ {\rm MeV}\ (M/2.5\ {\rm M}_\odot)\ (100\ {\rm km}/R)$$

Electron- positron production

$$n + e^+ \rightarrow p + \bar{\nu}_e$$

- Also production of heavy leptons etc.



Lehner et al., arXiv:1603.00501

Neutrinos

- Detection of neutrinos very unlikely

@10kpc

EoS	q	t [ms]	$\langle E_{\bar{\nu}_e} \rangle$ [MeV]	$\langle E_{\nu_e} \rangle$ [MeV]	$L_{\bar{\nu}_e}$ [10^{53} erg/s]	R_ν [#/ms]
NL3	1.0	3.4	18.5 (22.4)	15.2 (18.3)	0.7	18
NL3	0.85	3.0	15.6 (18.7)	12.6 (15.1)	0.8	18
DD2	1.0	3.3	18.3 (22.1)	14.6 (17.4)	1.1	28
DD2	0.85	2.8	18.1 (21.7)	15.1 (18.0)	1.0	25
DD2	0.76	2.4	19.7 (23.9)	14.8 (17.9)	1.3	36
SFHo	1.0	3.5	24.6 (29.7)	23.5 (28.3)	3.5	121
SFHo	0.85	3.9	17.8 (21.3)	15.3 (17.9)	2.0	50

emission for 10ms up to 2s
< 5000 neutrinos

Lehner et al, arXiv:1603.00501

GW170817 @ 40Mpc

< 0.0003 neutrinos

The Astrophysical Journal Letters, 850:L35 (18pp), 2017 December 1
https://doi.org/10.3847/2041-8213/aa9aed

CrossMark

Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration,
and LIGO Scientific Collaboration and Virgo Collaboration
(See the end matter for the full list of authors.)

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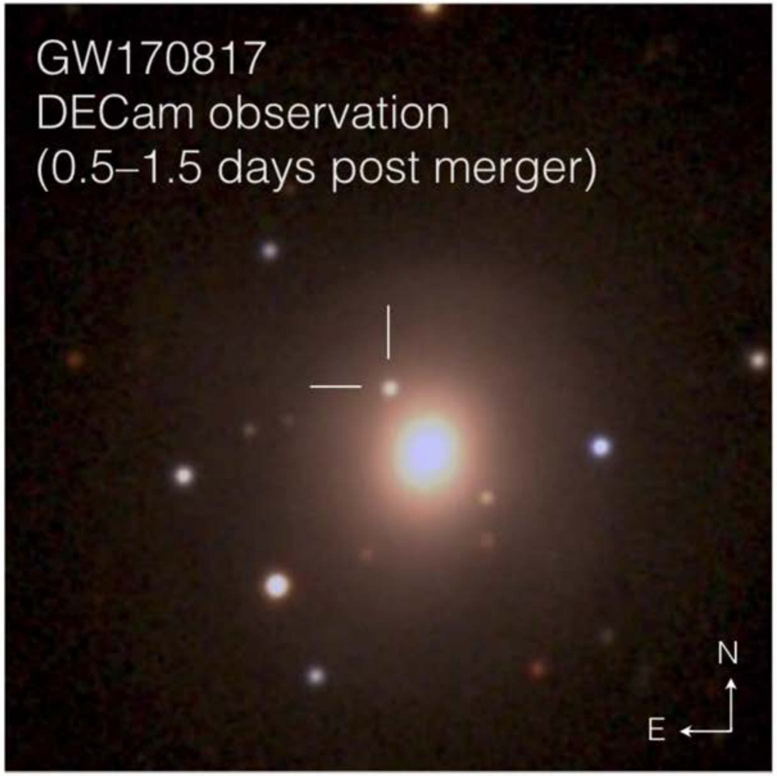
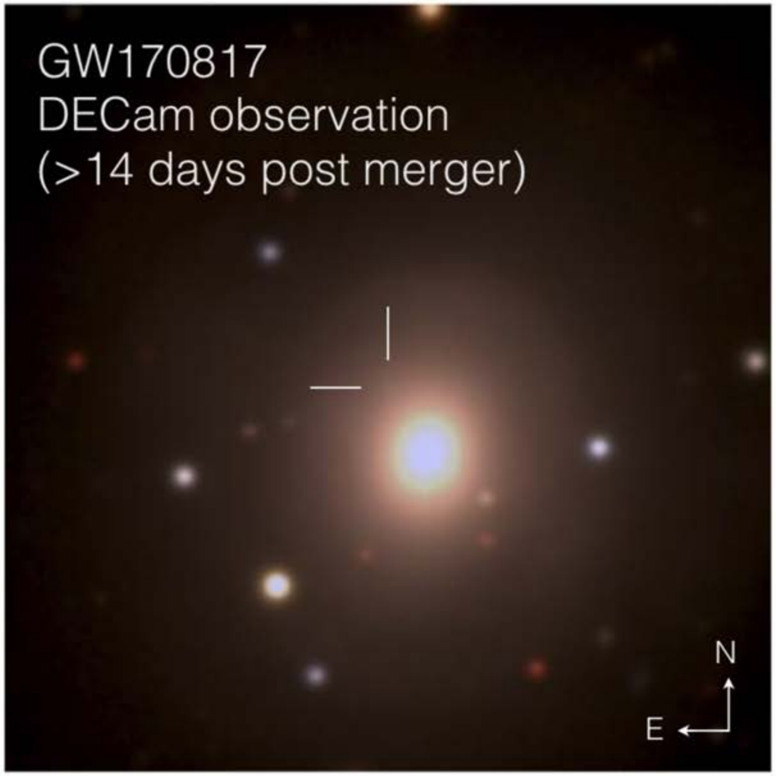
Abstract

The Advanced LIGO and Advanced Virgo observatories recently discovered gravitational waves from a binary neutron star inspiral. A short gamma-ray burst (GRB) that followed the merger of this binary was also recorded by the *Fermi* Gamma-ray Burst Monitor (*Fermi*-GBM), and the Anti-Coincidence Shield for the Spectrometer for the *International Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*), indicating particle acceleration by the source. The precise location of the event was determined by optical detections of emission following the merger. We searched for high-energy neutrinos from the merger in the GeV–EeV energy range using the ANTARES, IceCube, and Pierre Auger Observatories. No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger, but found no evidence of emission. We used these results to probe dissipation

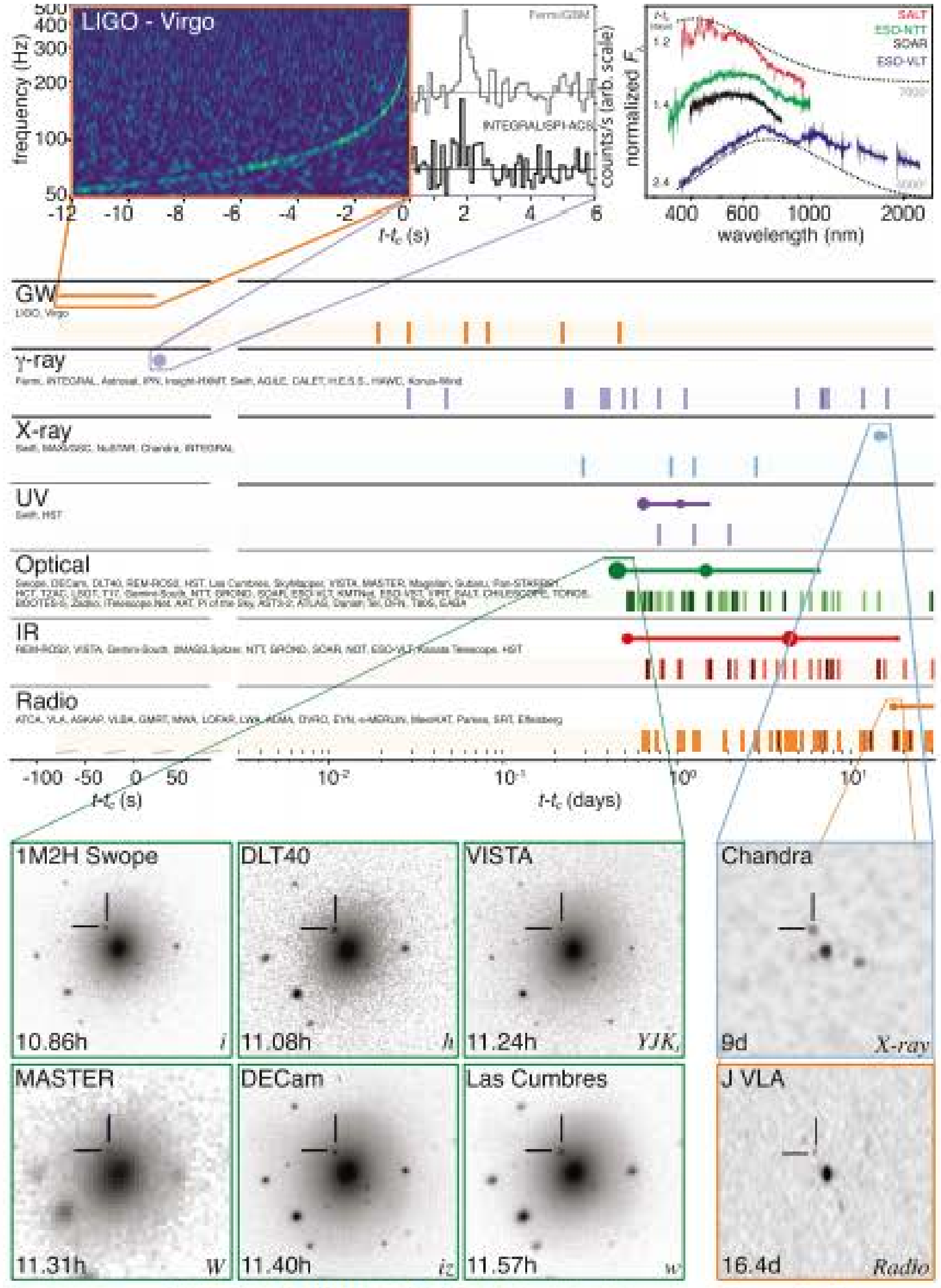
EM signals


GW170817
DECam observation
(0.5–1.5 days post merger)
N
E


GW170817
DECam observation
(>14 days post merger)
N
E

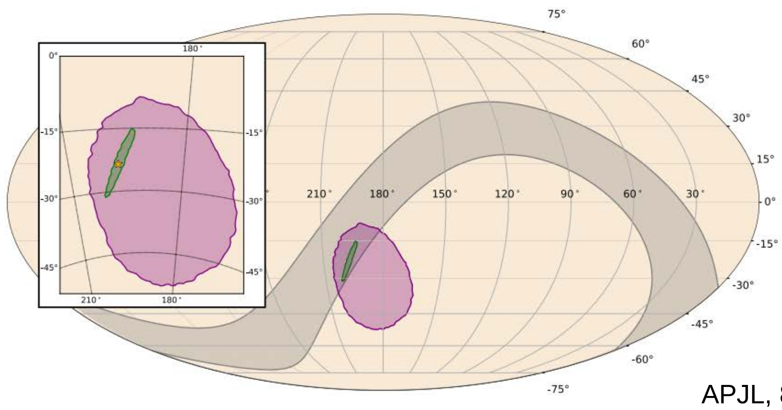
EM Signals

Timeline



EM Signals – sGRBs

GRB170817A

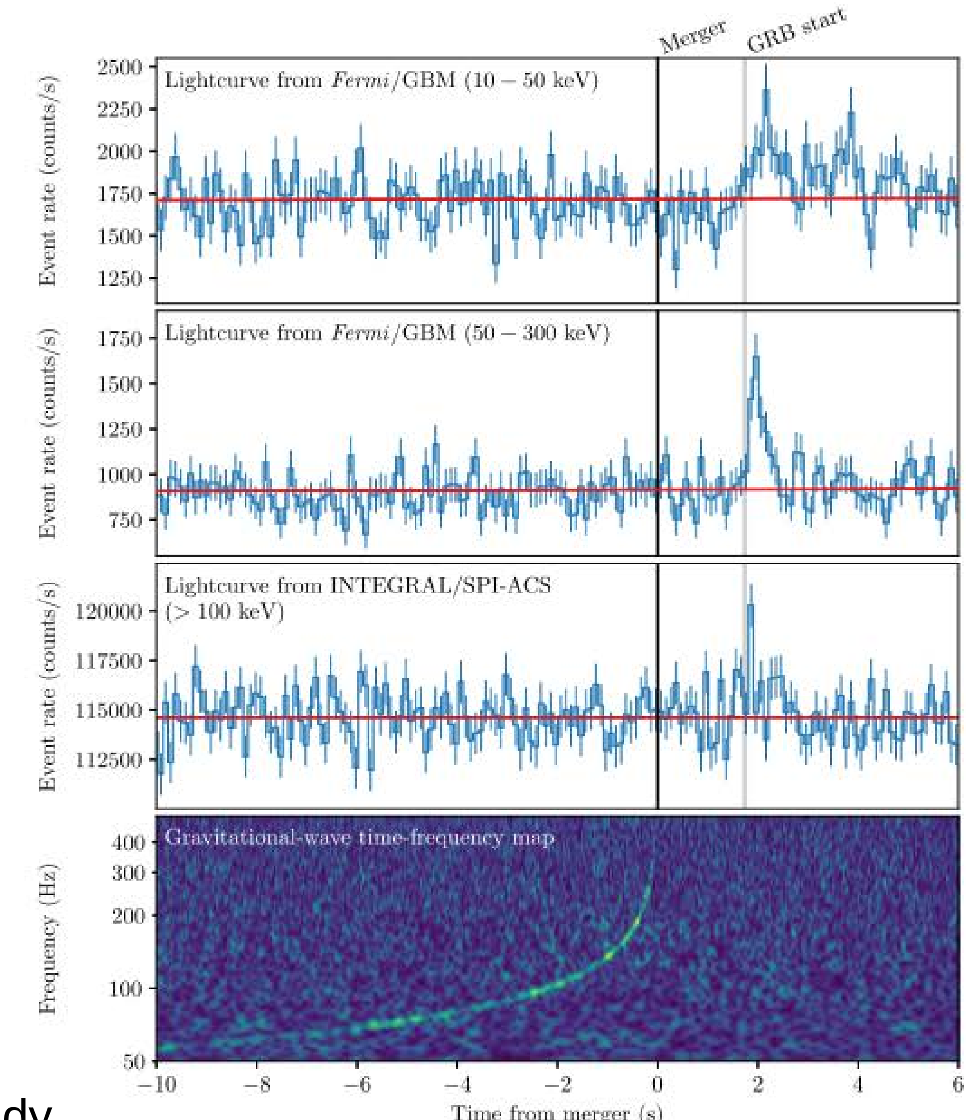


APJL, 848:L13

- GRB detection 1.7s after the merger
  - → constrain speed of gravity

$$-3 \times 10^{-15} \leqslant \frac{\Delta v}{v_{\rm EM}} \leqslant +7 \times 10^{-16}$$

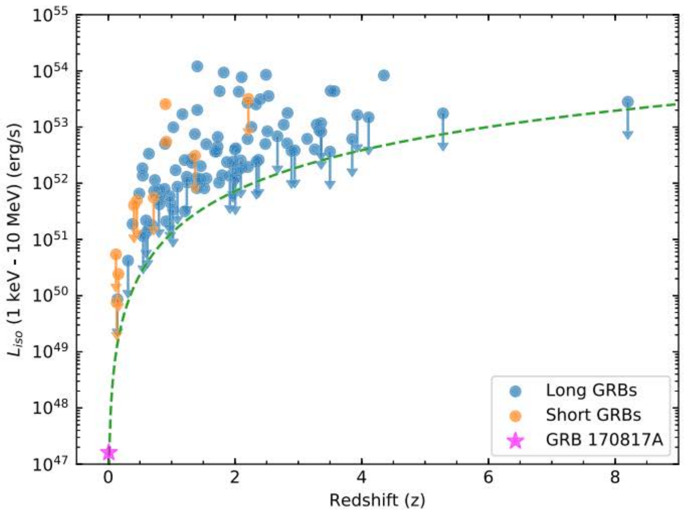
  - → test equivalence principle
  - → Lorentz invariants violation test
- time coincidence (4.4 sigma)
- spatial coincidence (5.2 sigma)
- two components:
  - main emission: peak
  - tail emission consistent with blackbody radiation

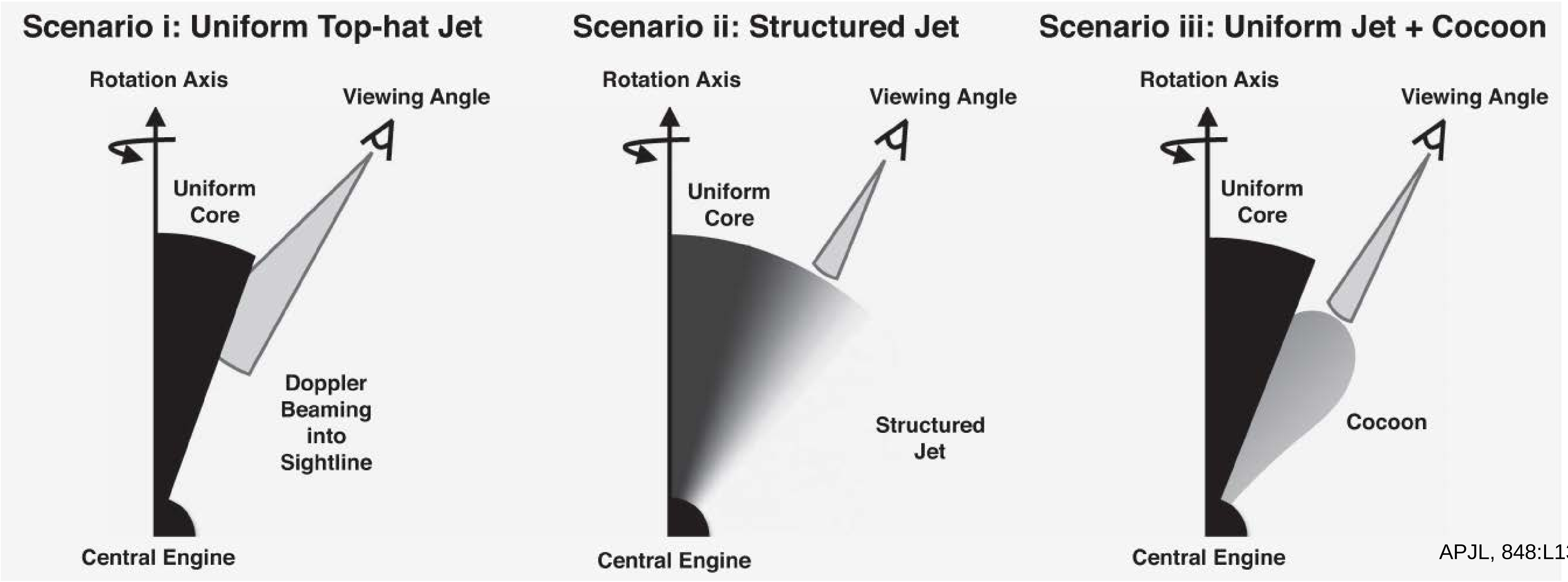


APJL, 848:L13

EM Signals – sGRBs

- low luminosity
- different possible scenarios





APJL, 848:L13

EM Signals- sGRB

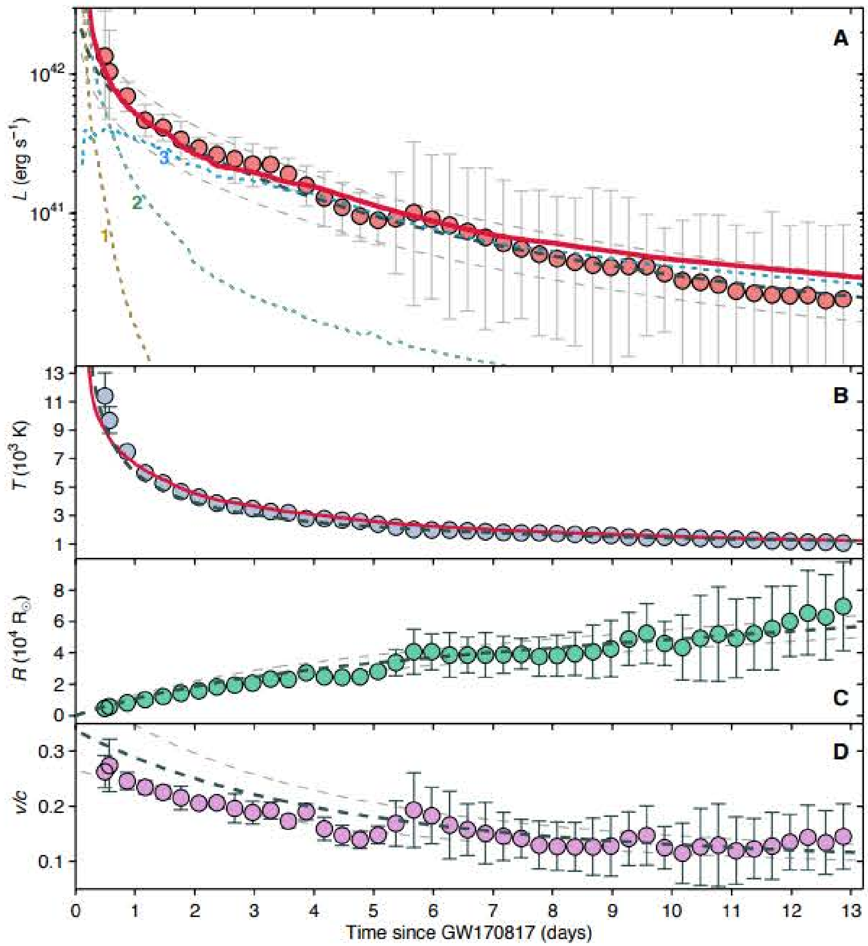
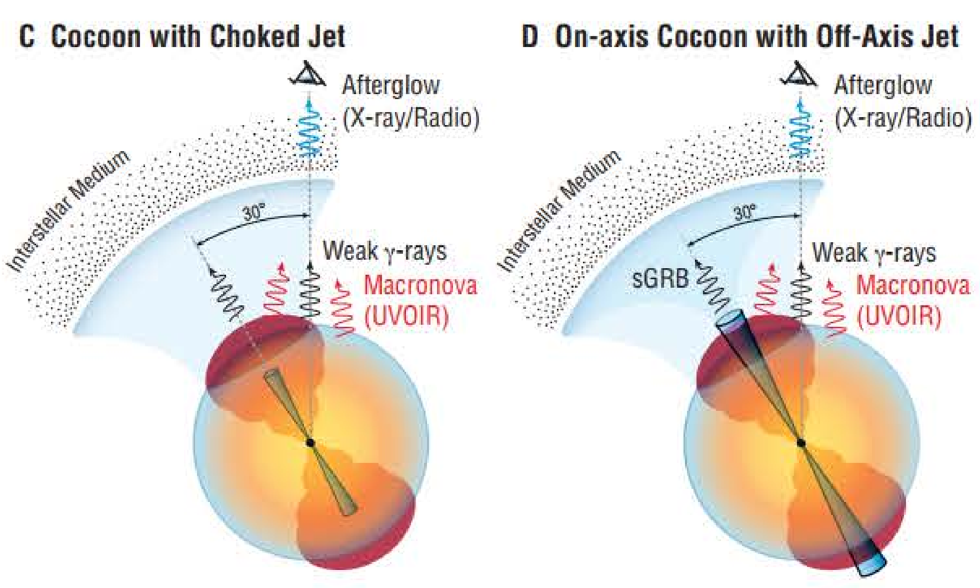


Figure 2: The evolution of EM170817 derived from the observed spectral energy distribution. (A) Bolometric luminosity. (B) Blackbody temperature. (C) Photospheric radius. (D) Inferred expansion velocity. Individual points represent blackbody fits performed at discrete epochs to which the observed photometry has been interpolated using low-order polynomial fits. Dashed lines represent an independent Markov-Chain Monte Carlo fit without directly interpolating between data points (see (*10*) for methodology and best-fit parameter values). The solid red lines (in A and B) represent the results of a hydrodynamical simulation of the cocoon model where the UVOIR emission is composed of (in A) cocoon cooling (yellow dashed line labeled 1), fast macronova (>0.4*c*; green dashed line labeled 2), and slow macronova (<0.4*c*; blue dashed line labeled 3).

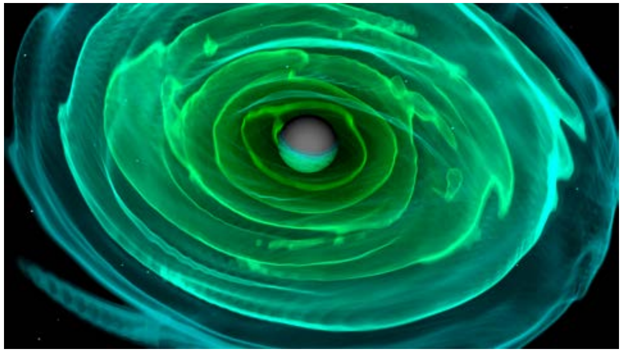
Iluminating Gravitational Waves: A Concordant Picture of Photons from a Neutron Star Merger

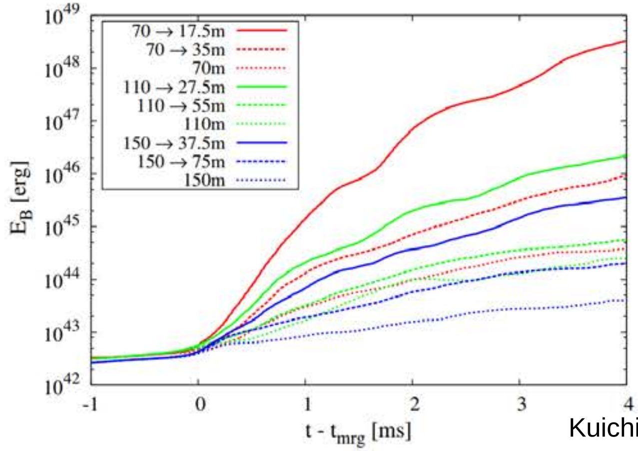
Kasliwal et al., Science 16 Oct 2017



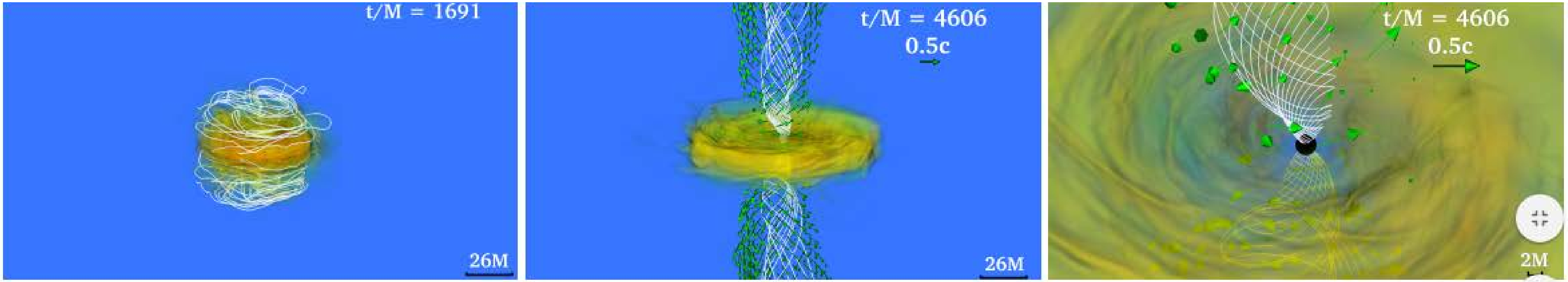
EM Signals – sGRBs

- BH + disk system
  - Neutrino & anti-neutrino annihilation
  - Magnetic field amplification and jet formation





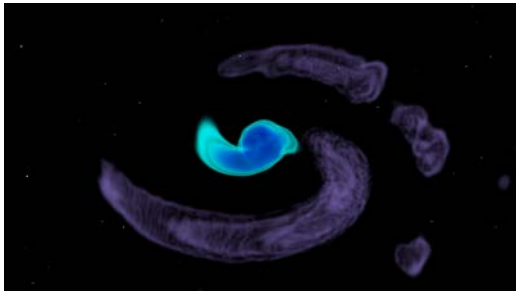
Kuichi et al., PRD92, 124034

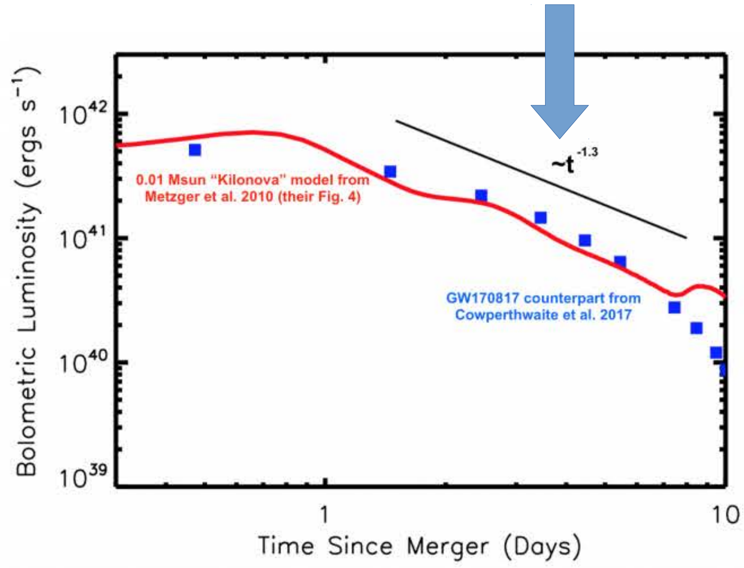


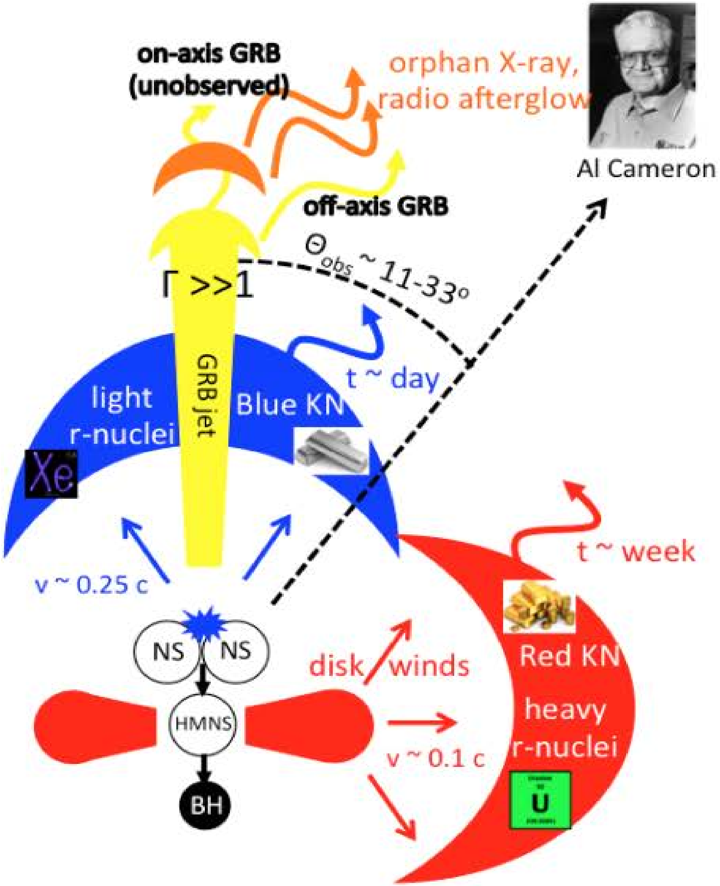
Ruiz et al., APJ. 824 (2016), L6

EM Signals – Kilonova

- pseudo-black body radiation from r-process elements
- formation of heavy elements





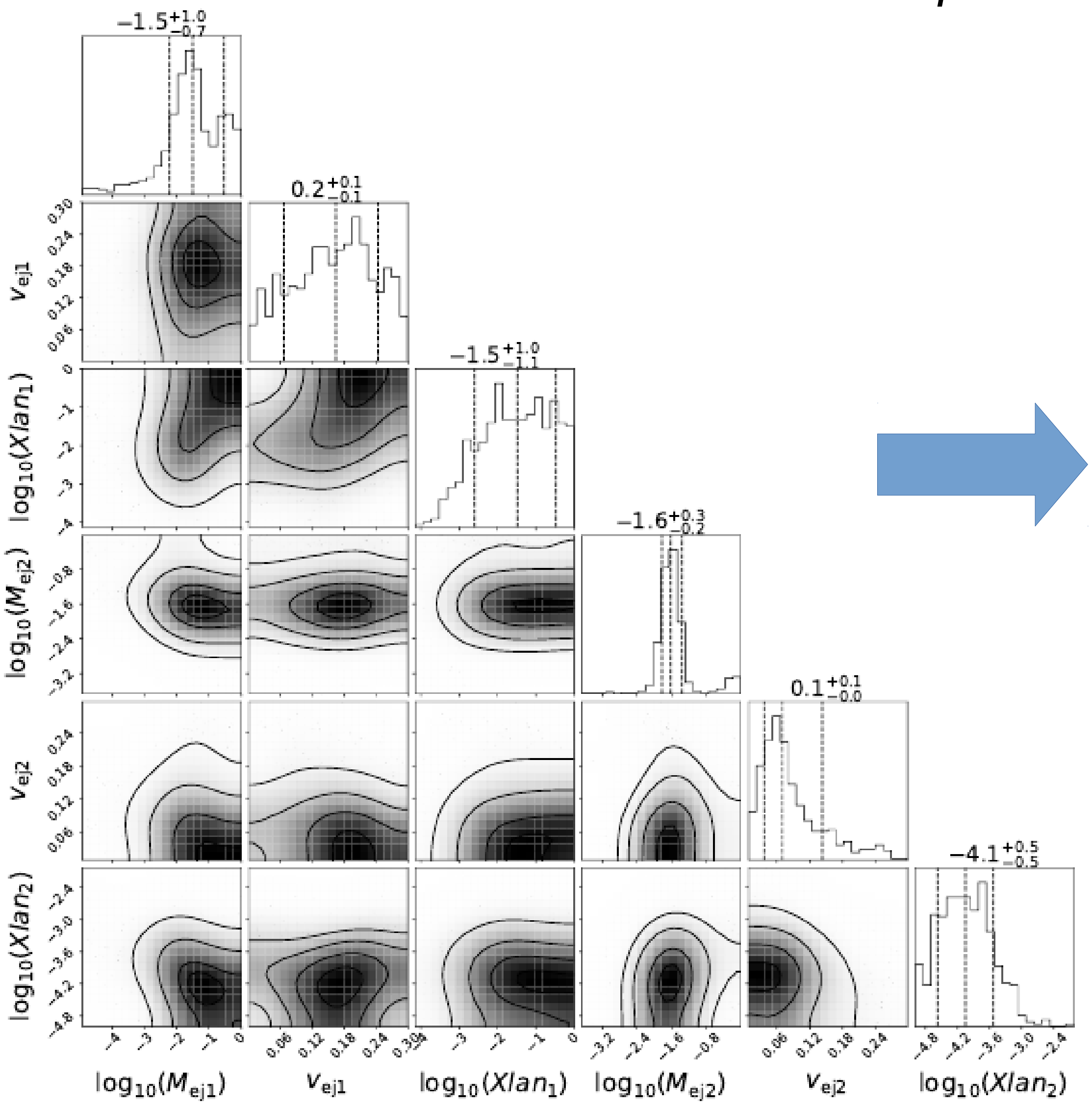


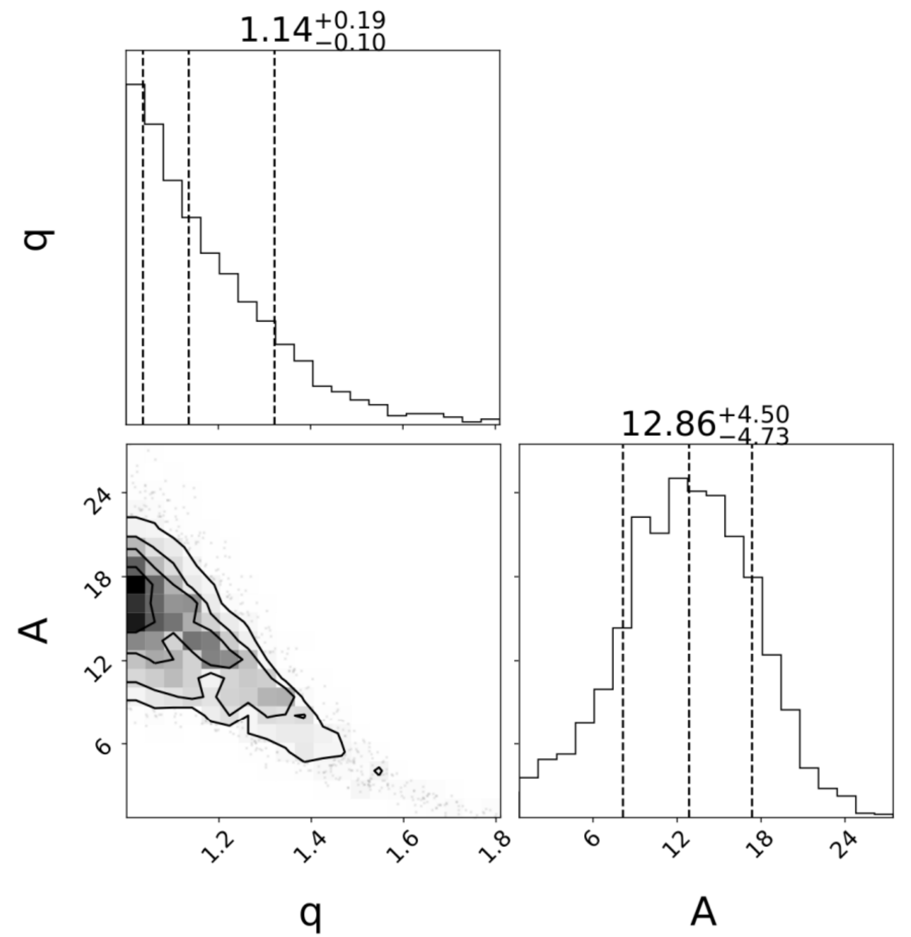
Metzger, arxiv:1710.05931

EM Signals – Kilonova

- possible models:

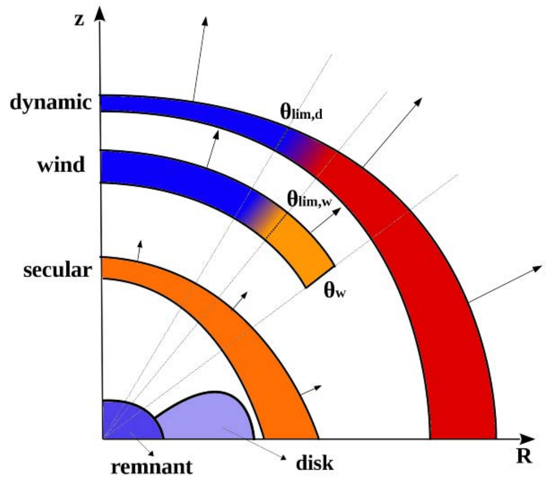
two component model





EM Signals – Kilonova

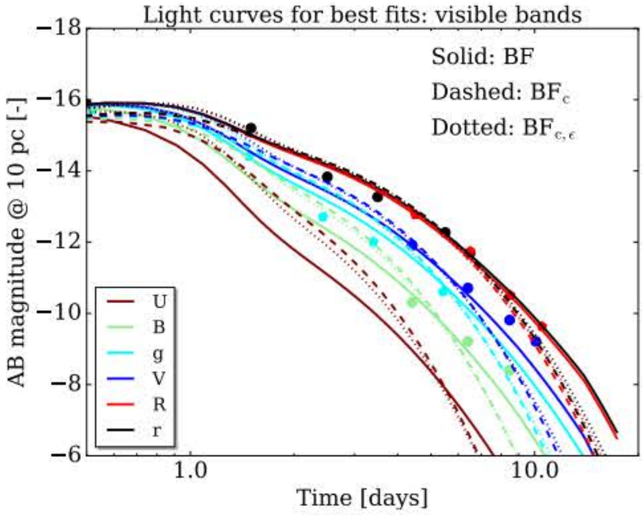
- possible models:

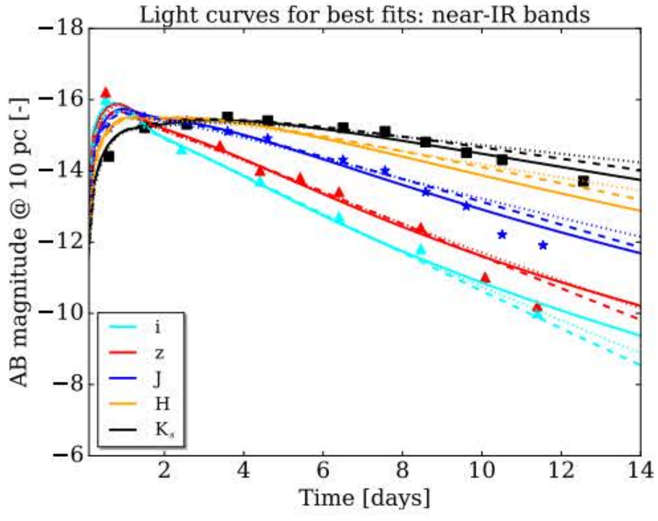


AT2017gfo: an anisotropic and three-component kilonova counterpart of GW170817

Perego et al, APJ 850 (2017) L37

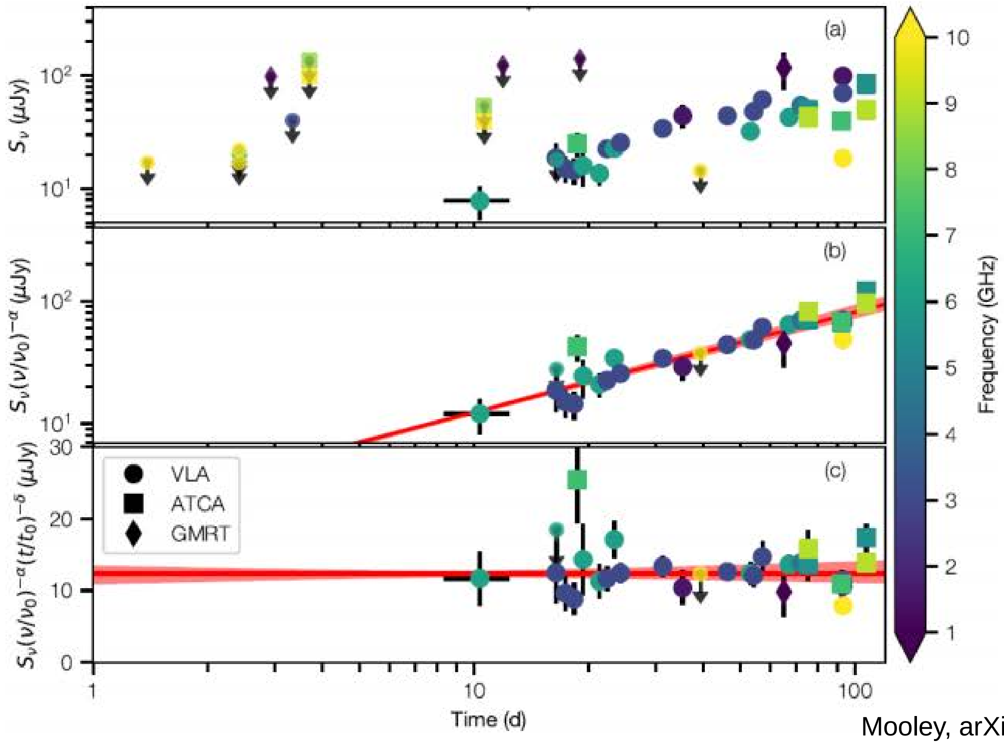
  - three components evolved by semi-analytical model



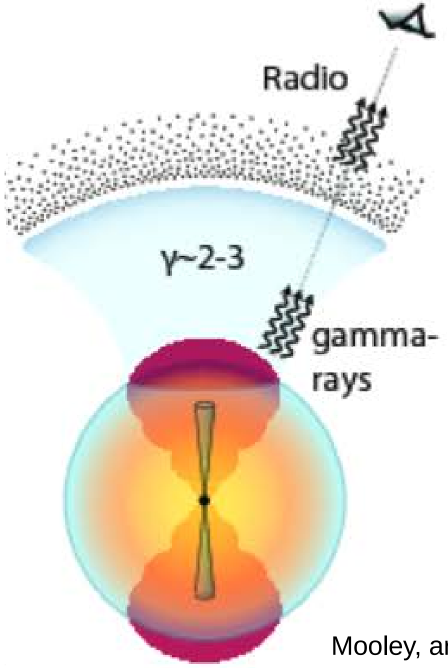


EM Signals – radio signals

ongoing radio observations support cocoon model



Mooley, arXiv:1711.11573



Mooley, arXiv:1711.11573

also: Sub-relativistic outflows with peak times of a few months up to years

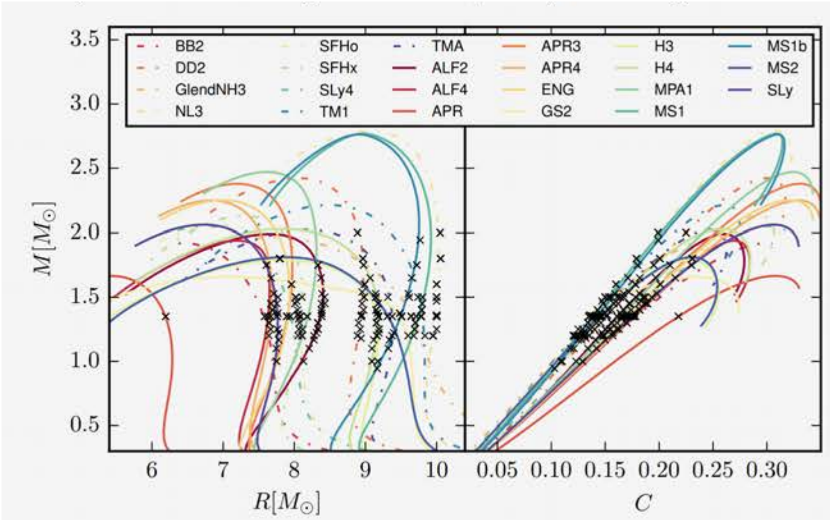
$$t_{\rm peak}^{\rm rad} = 1392 \text{ days} \times \left(\frac{T_{\rm ej}}{10^{49}\rm erg}\right)^{\frac{1}{3}} \left(\frac{n_0}{\rm cm^{-3}}\right)^{-\frac{1}{3}} \left(\frac{v_{\rm ej}}{0.1}\right)^{-\frac{5}{3}}$$

Nakar E and Piran T 2011 Nature 478 82–84

EM Signals – Applications

- Maximum mass of NSs
  - Ma et al., arXiv:1711.05565

$$M_{\rm max} < (2.19,\ 2.32) M_\odot$$



  - Rezzolla et al., arXiv: 1711.00314

$$2.01 \pm 0.04 \ \leq \ M_{\rm TOV}/M_\odot \ \lesssim \ 2.16 \pm 0.03$$

  - Ruiz et al., arxiv:1711.00473

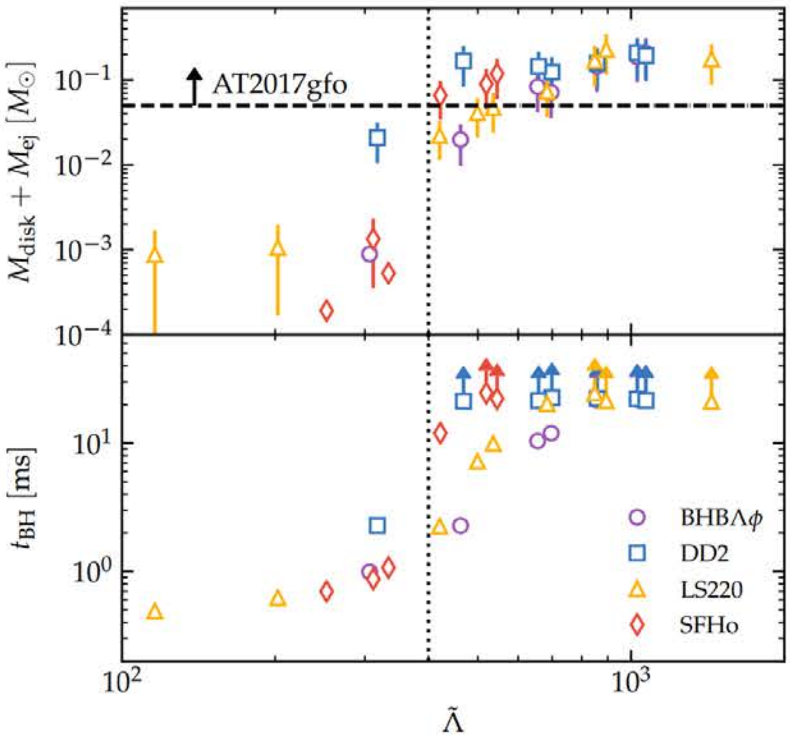
$$M^{\rm sph}_{\rm max} \lesssim 2.16 M_\odot$$

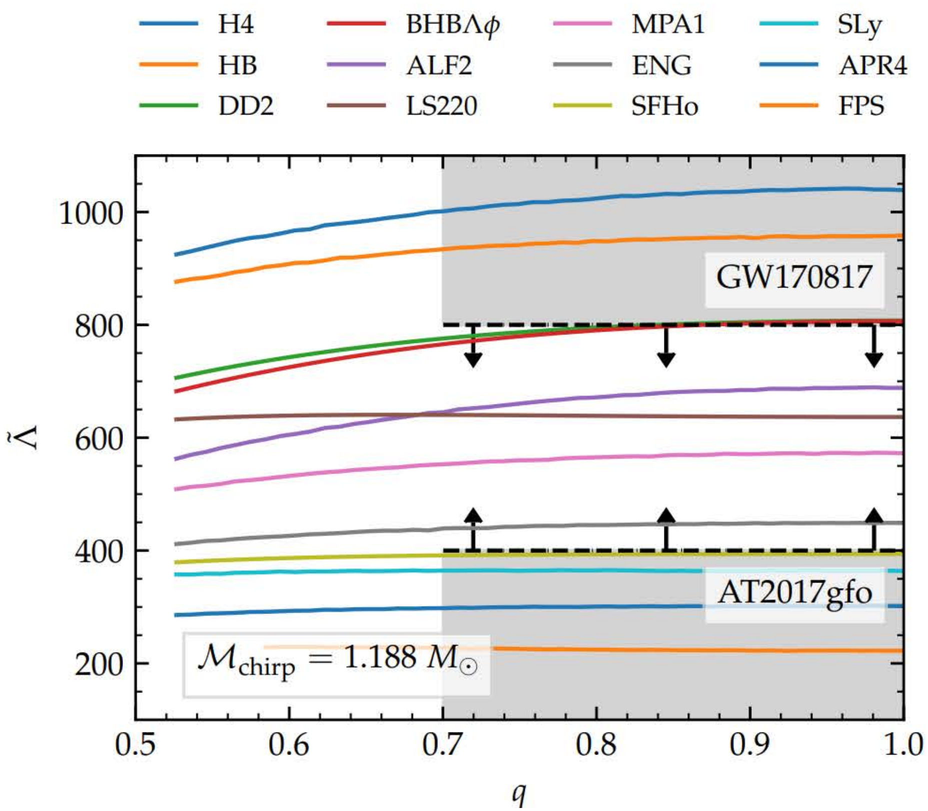
  - Shibata et al., arxiv:1710.07579

$$2.15\text{–}2.25 M_\odot$$

EM Signals – Applications

- Constraining the EOS:





Radice et al., arxiv:1711.03647

Summary

- Neutron star mergers are central engines for sGRBs and kilo/macronovae
- Neutron star mergers produce heavy elements
- MMA allows EOS and maximum mass constraints
- MMA constraints speed of gravity, Lorentz variation, equivalence principle