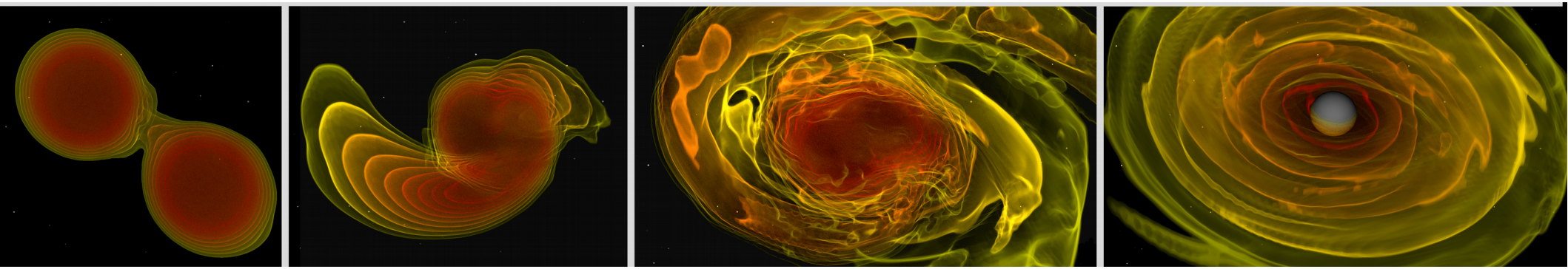
The Multimessenger Picture of Binary Neutron Star Mergers

Tim Dietrich
Max Planck Institute for Gravitational Physics

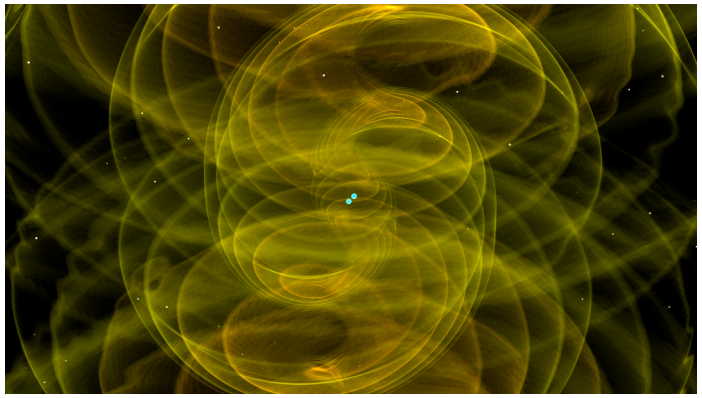


Multimessenger Picture

Gravitational Waves

-inspiral signal: chirp

-postmerger signal

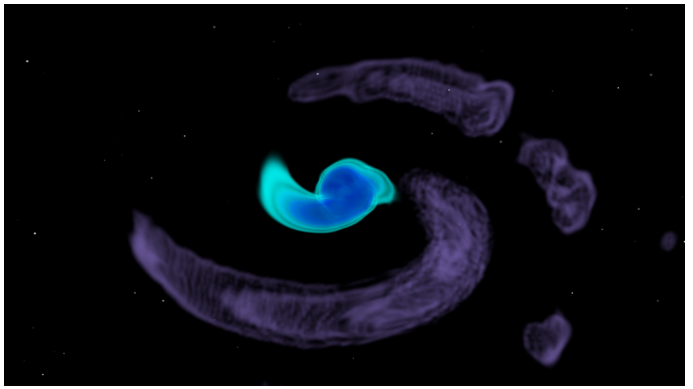


Electromagnetic Waves

-short GRB

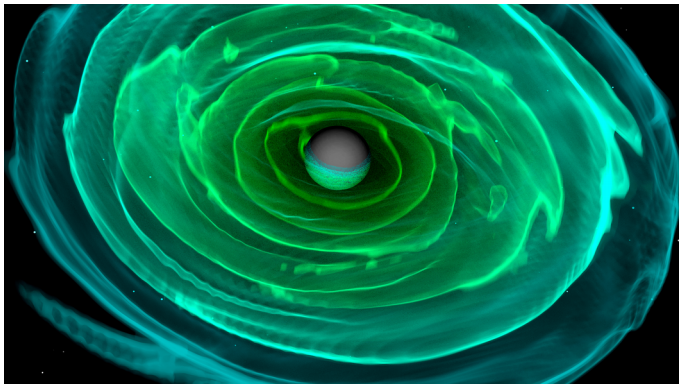
-kilo/macronovae

-radio flares

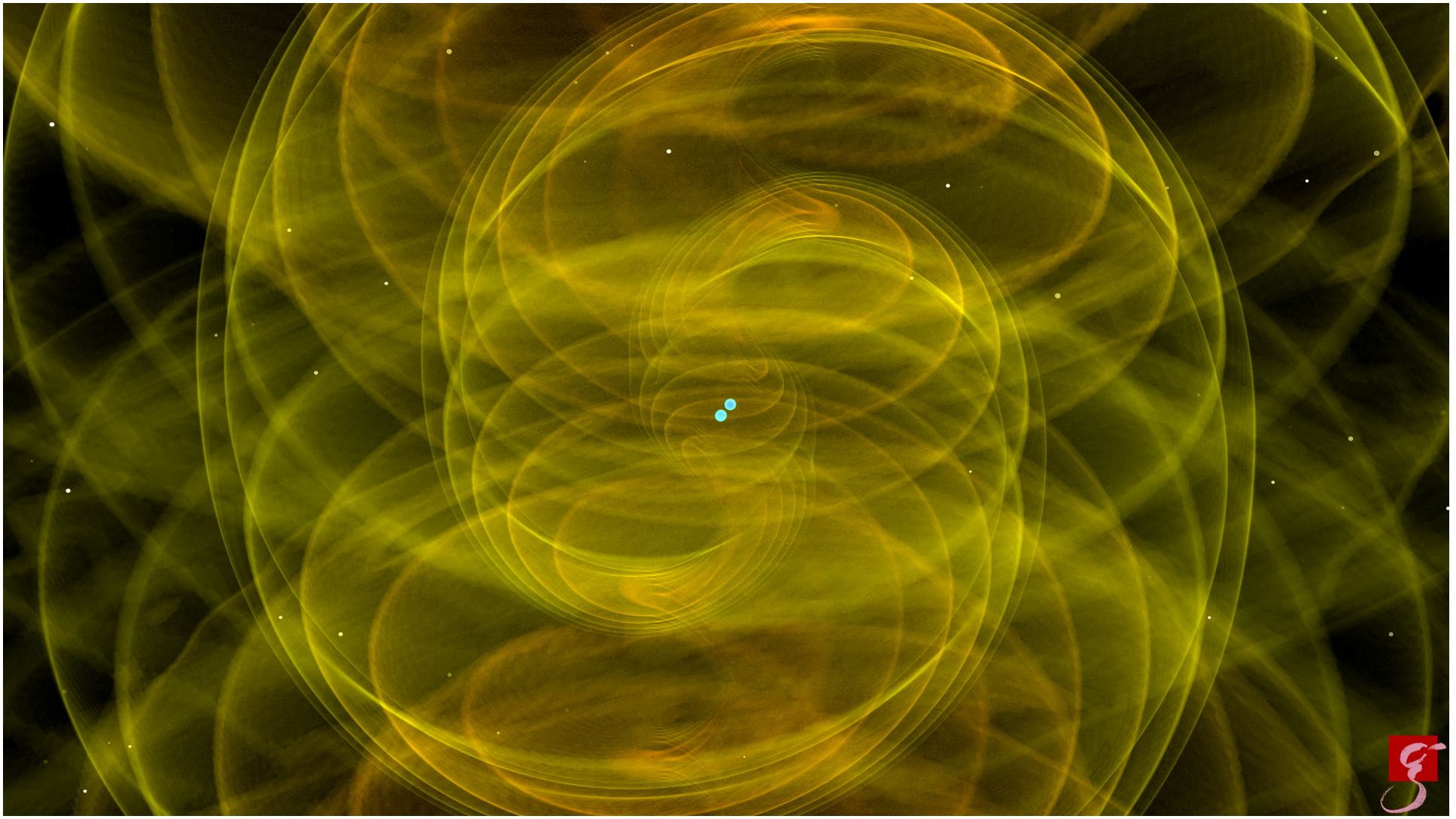


Neutrinos

-high neutrino luminosity



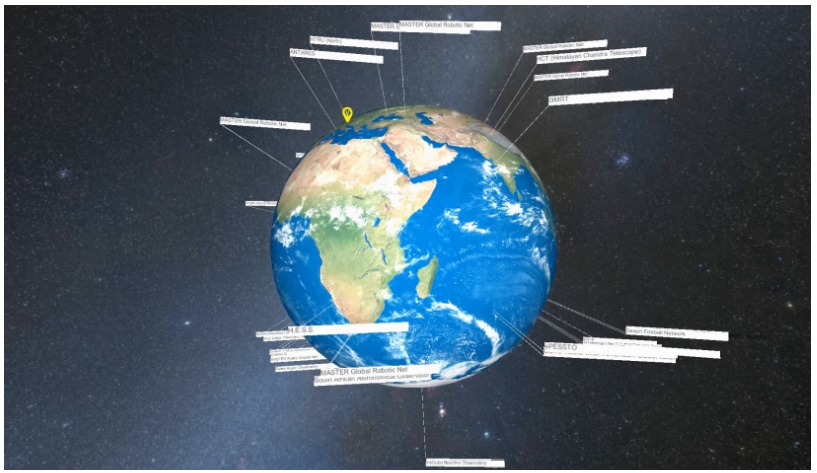
The BNS merger



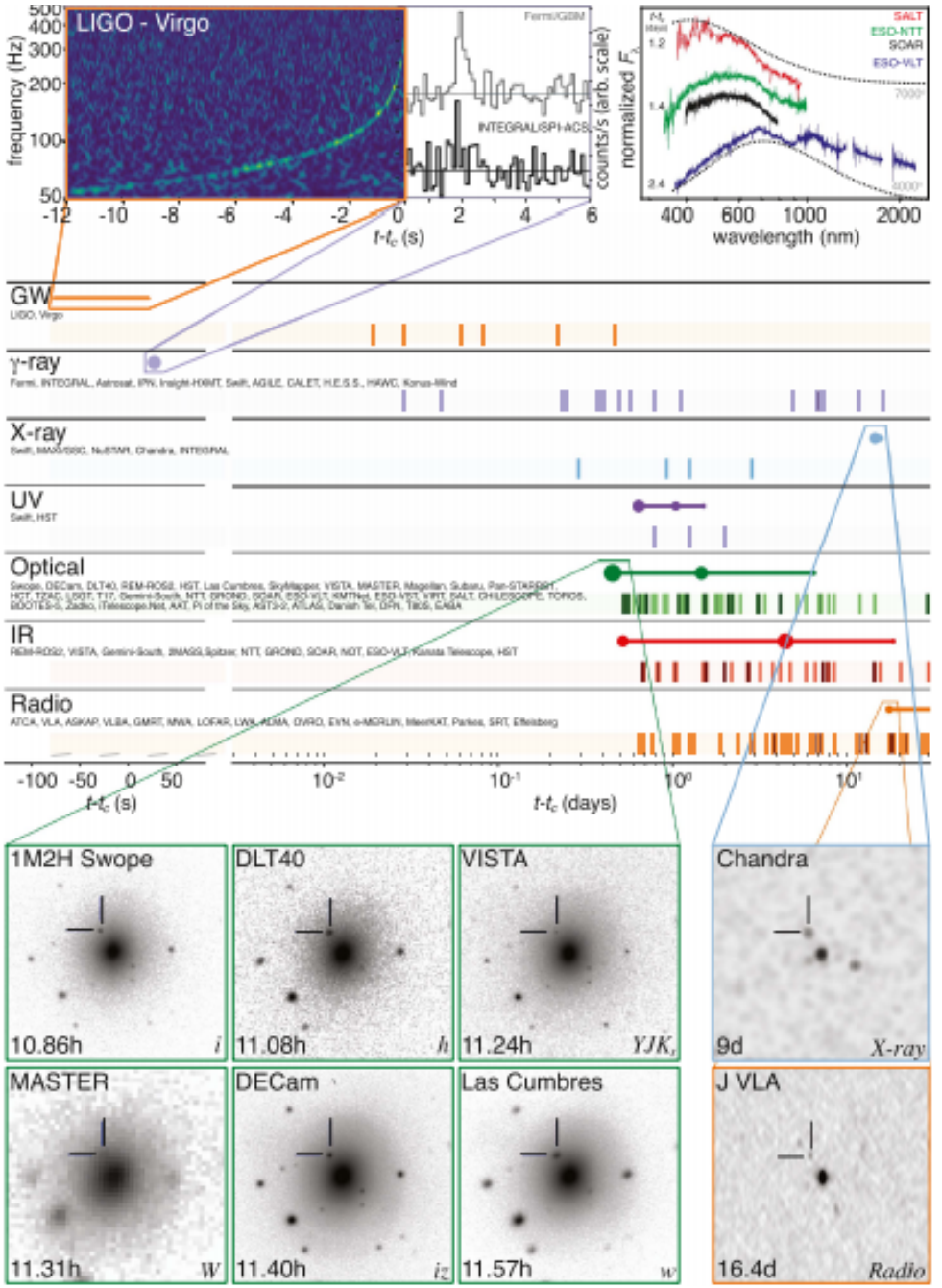
https://www.youtube.com/watch?v=V6cm-0bwJ98

GW170817

https://www.youtube.com/watch?v=xeh-bpEHMzQ



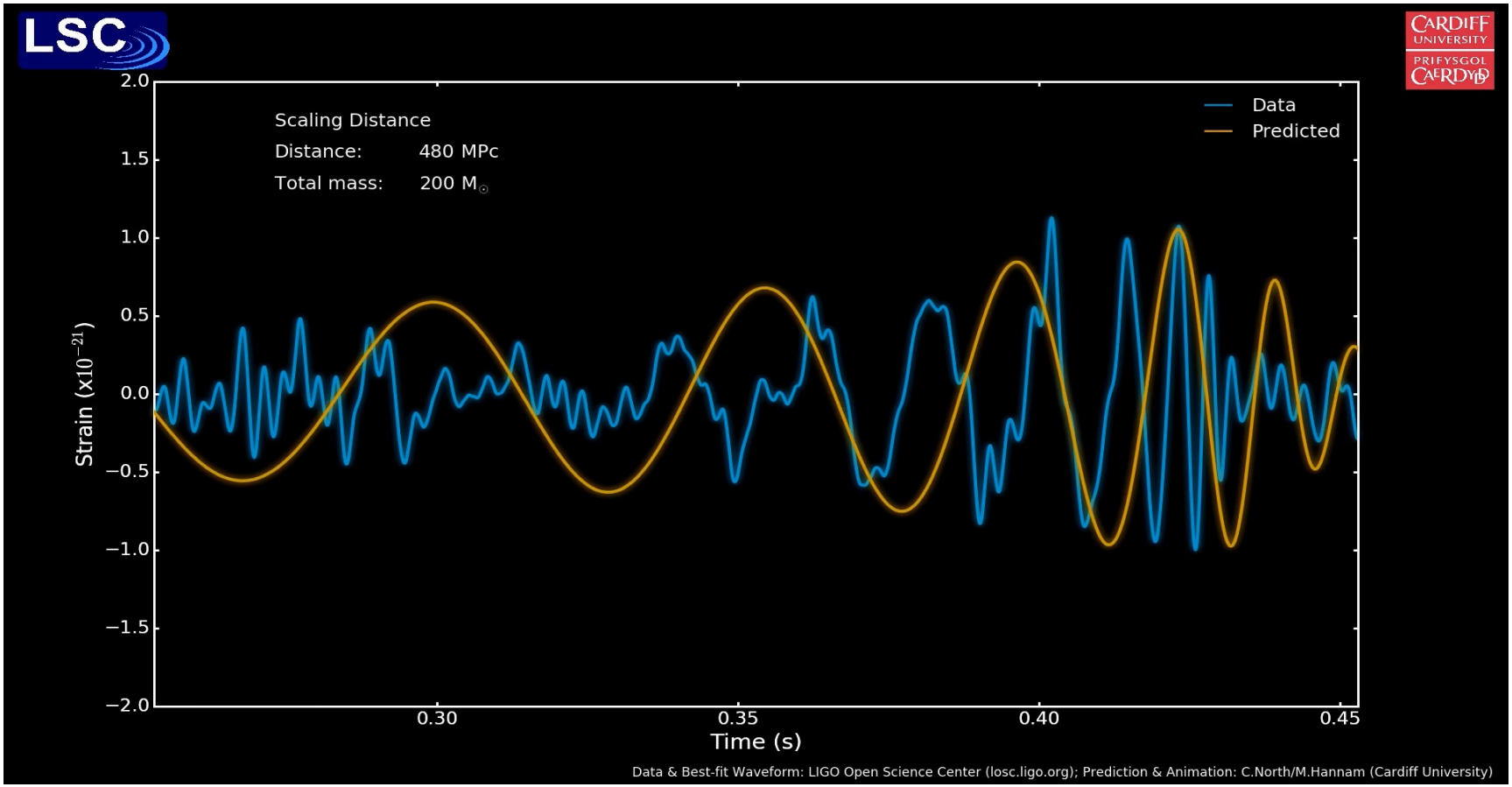
(c) Mark Myers, Swinburne University of Technology



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

Gravitational Waves

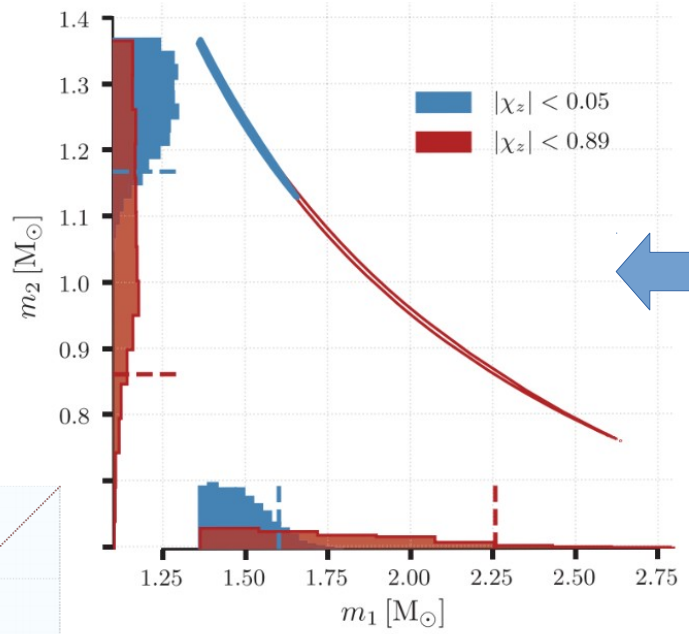
- compare signal with a large number of templates

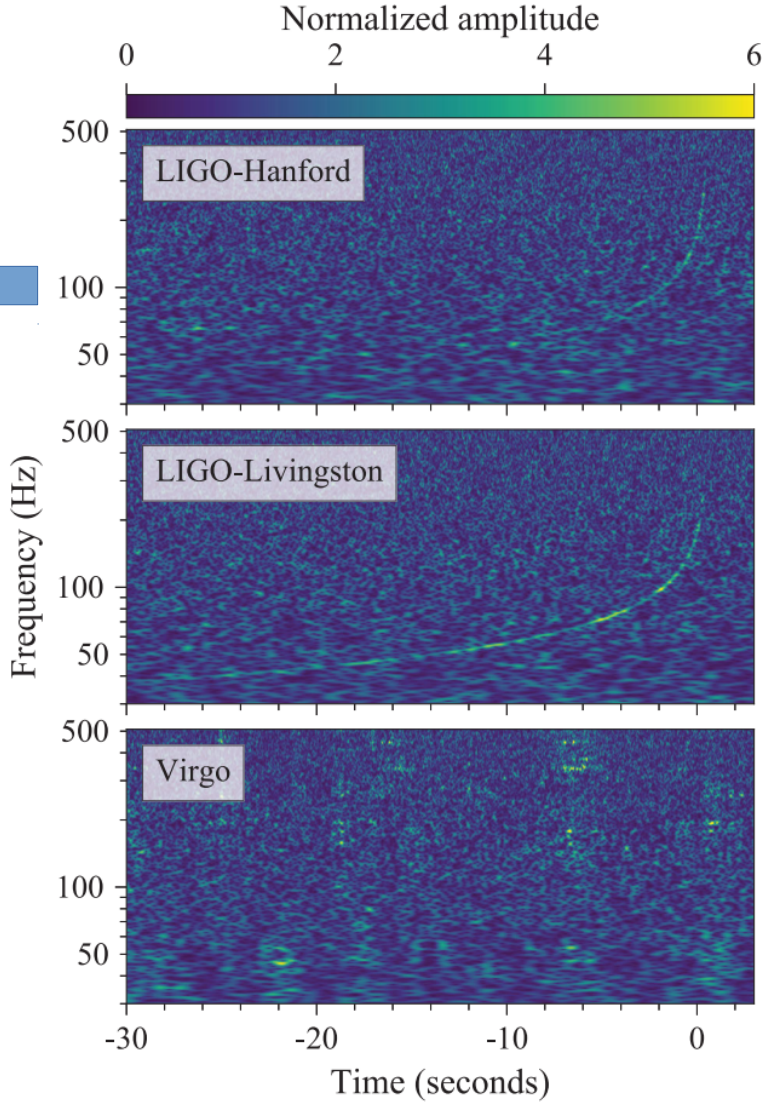


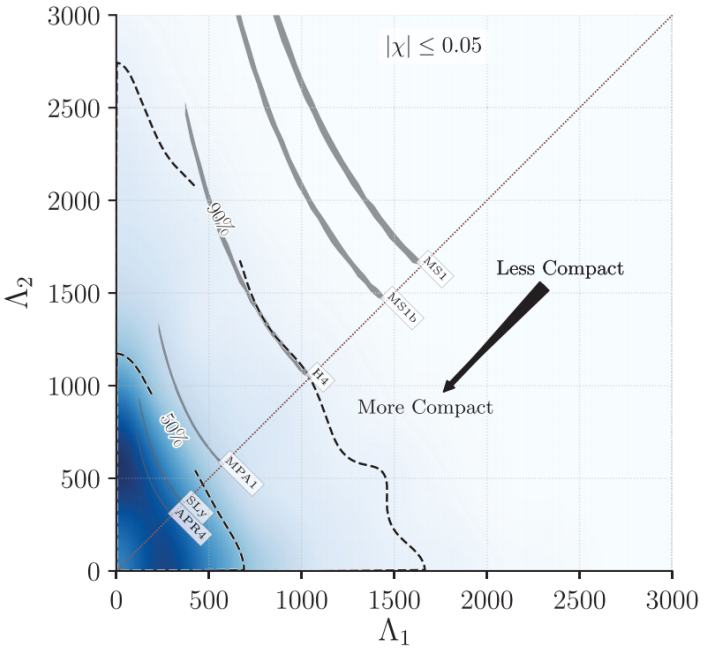
Gravitational Waves

- Chirp signal during the inspiral

Determine the mass







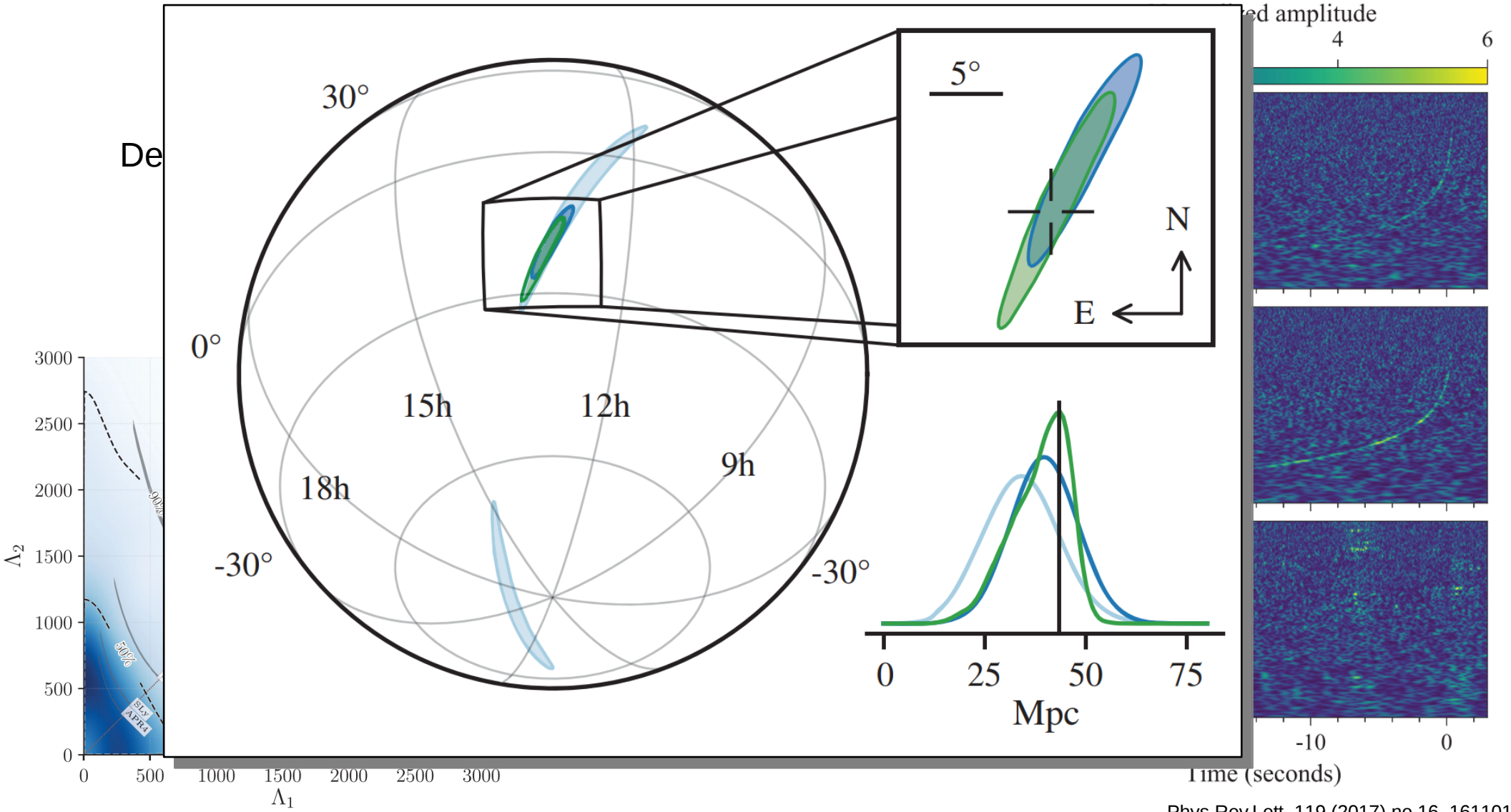
Determine the EOS

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

Gravitational Waves

- Chirp signal during the inspiral

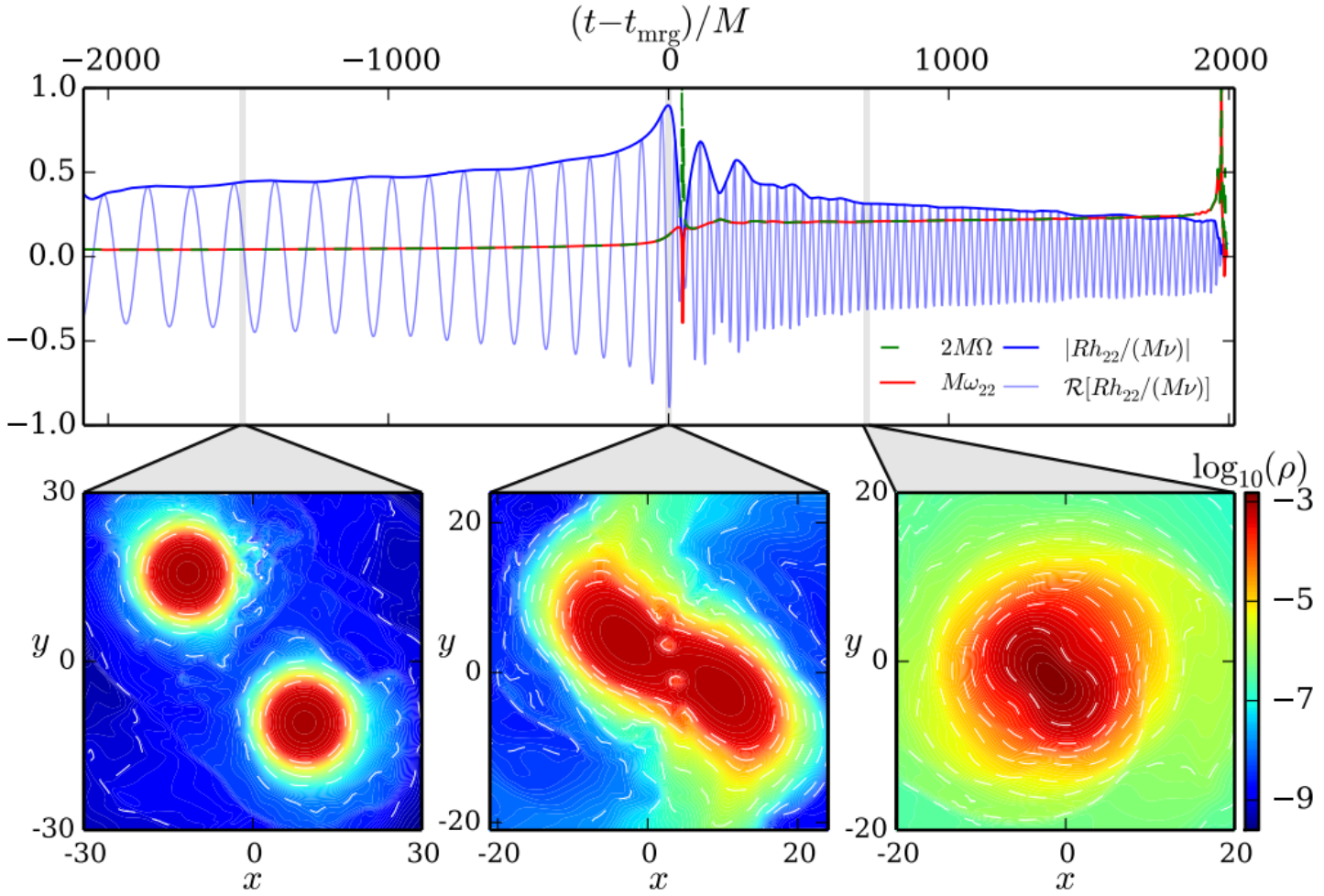
28 sq-deg



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

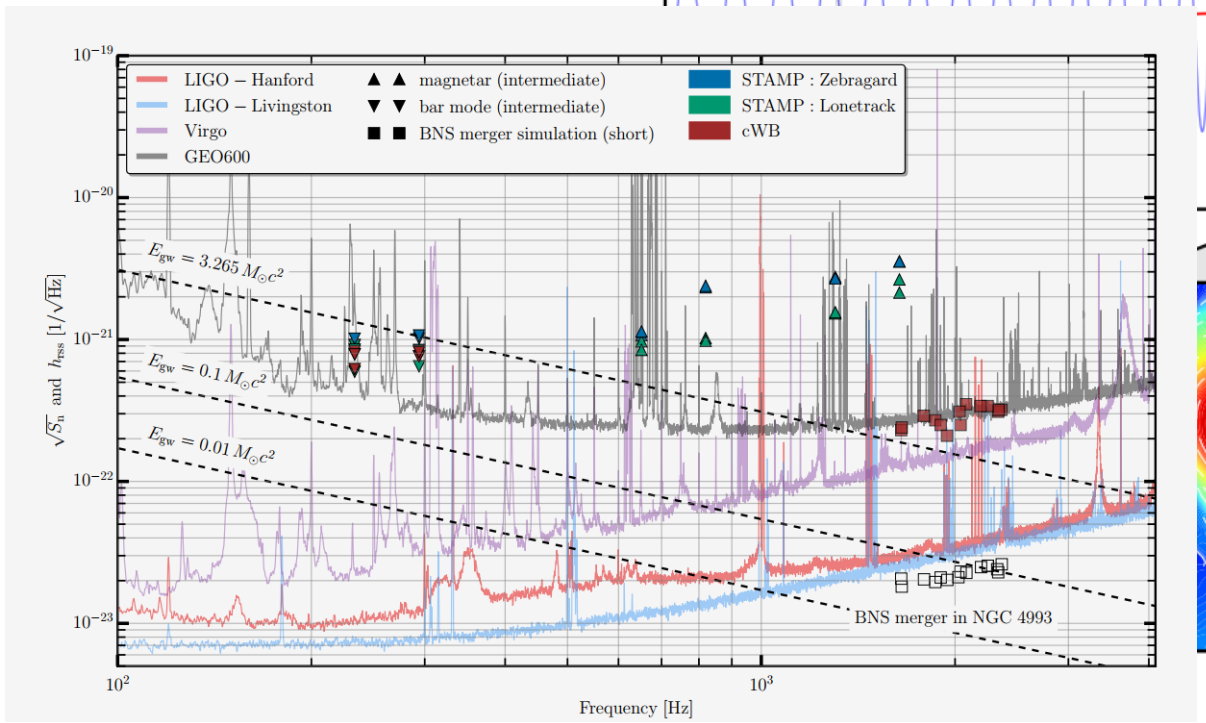
Gravitational Waves

- postmerger signal at higher frequencies with low chances of detection



Gravitational Waves

- postmerger signal at higher frequencies with low chances of detection



arXiv:1710.09320

no postmerger signal for GW170817 detected

Neutrinos

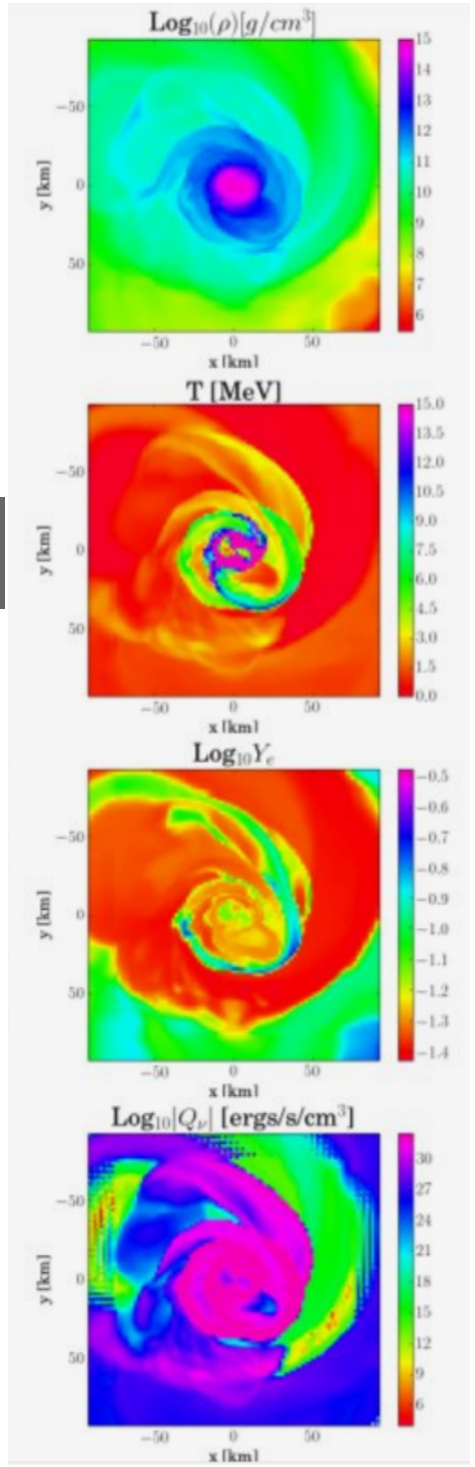
- heating during the NS merger
  virial temperature

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

  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

Lehner et al, arXiv:1603.00501

GW170817 @ 40Mpc

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

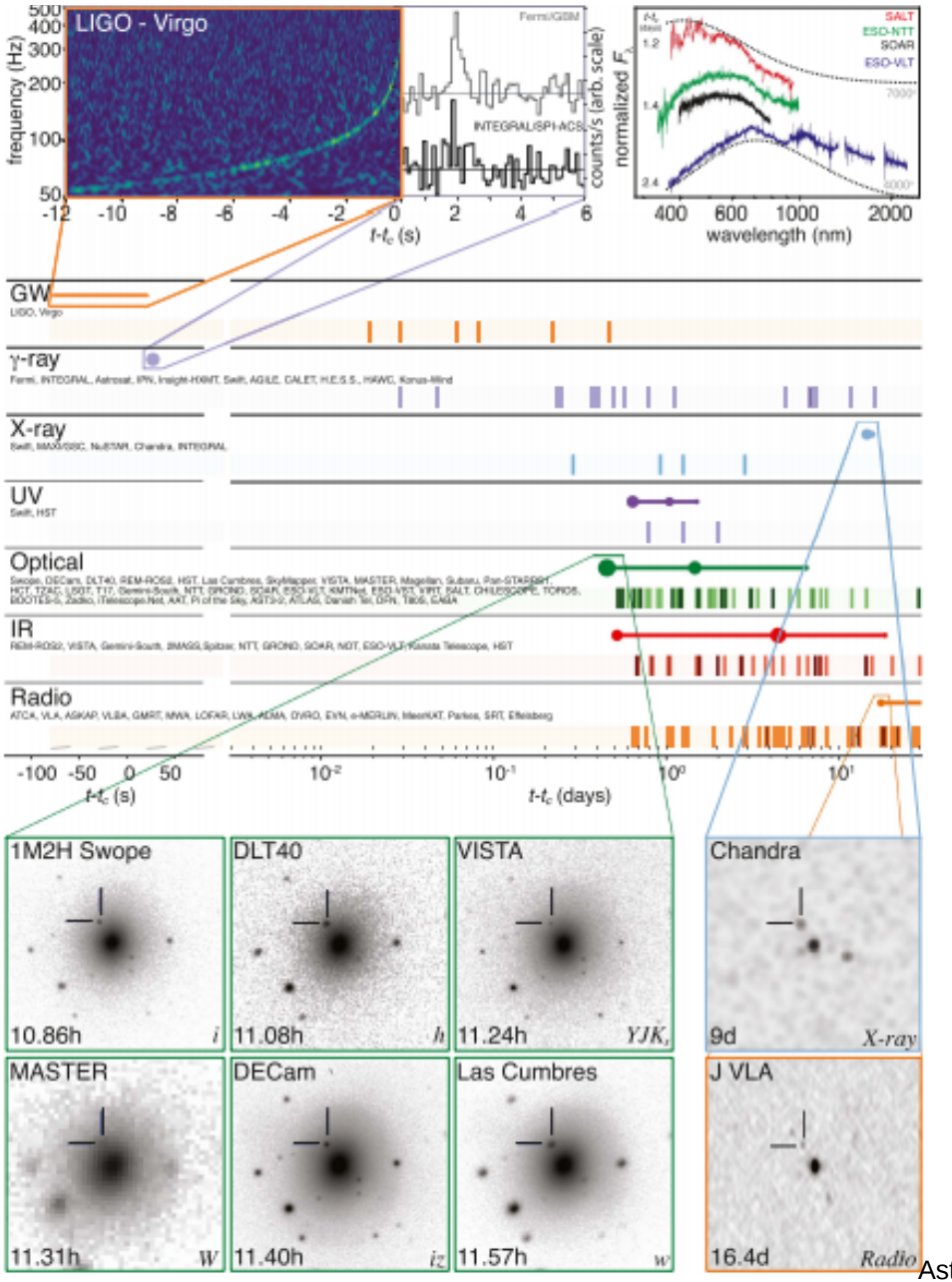
ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration,
and LIGO Scientific Collaboration and Virgo Collaboration
(See the end matter for the full list of authors.)

Received 2017 October 15; revised 2017 November 9; accepted 2017 November 10; published 2017 November 29

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

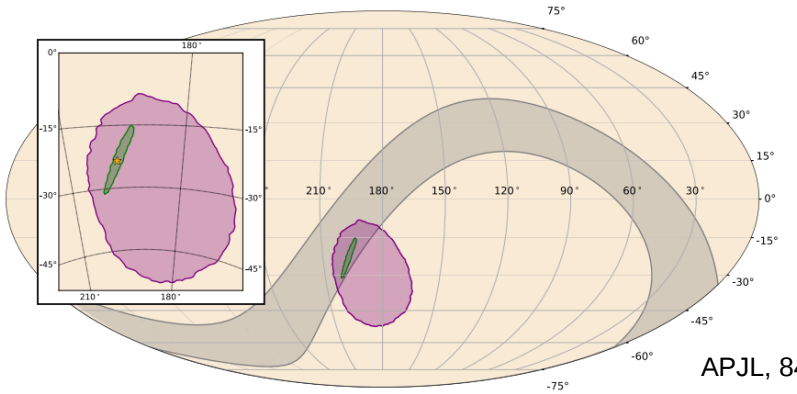


Timeline video:
https://www.youtube.com/watch?v=xBvz5ilc8rE

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

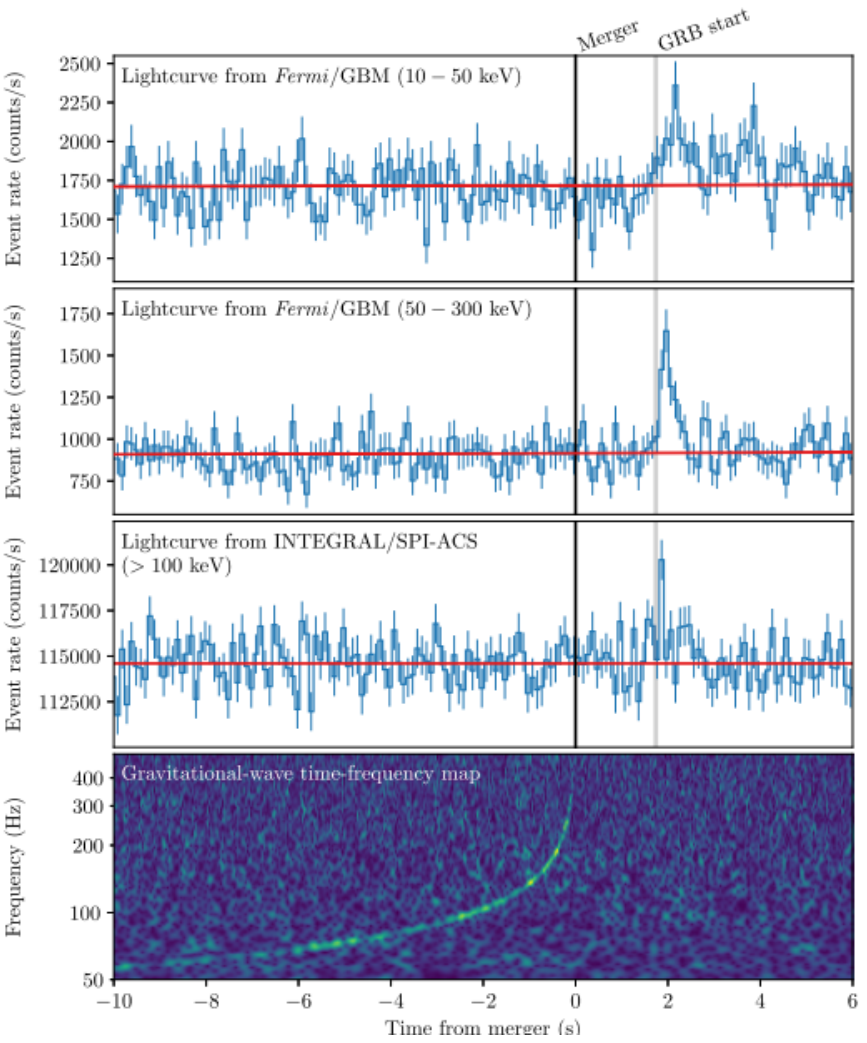
EM Signals – sGRBs

GRB170817A



APJL, 848:L13

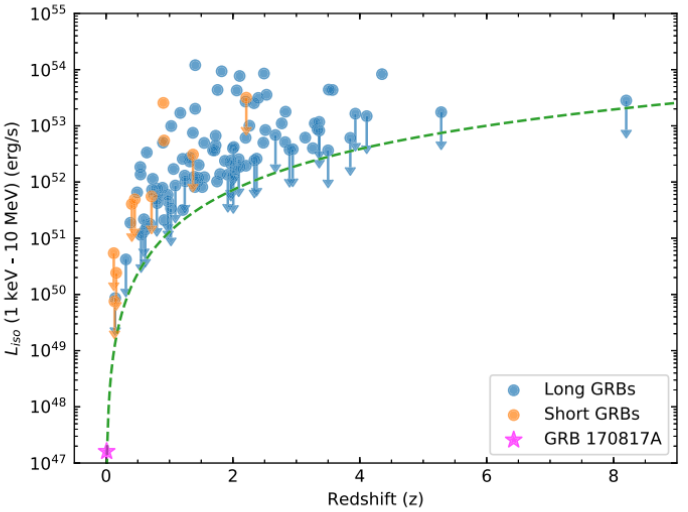
– GRB detection 1.7s after the merger
  → constrain speed of gravity
  → test equivalence principle
  → Lorentz invariants violation test
– time coincidence (4.4 sigma)
– spatial coincidence (5.2 sigma)
– two components:
  – main emission: peak
  – tail emission consistent with blackbody radiation

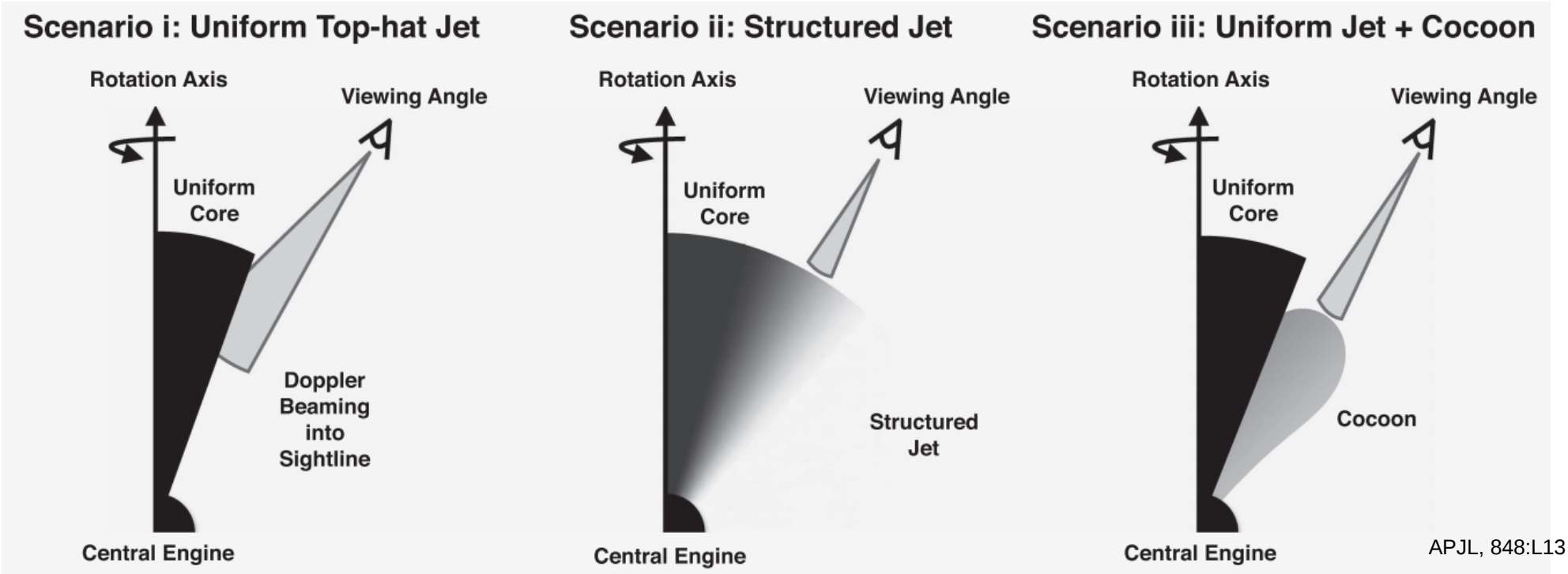


APJL, 848:L13

EM Signals – sGRBs

- low luminosity
- different possible scenarios

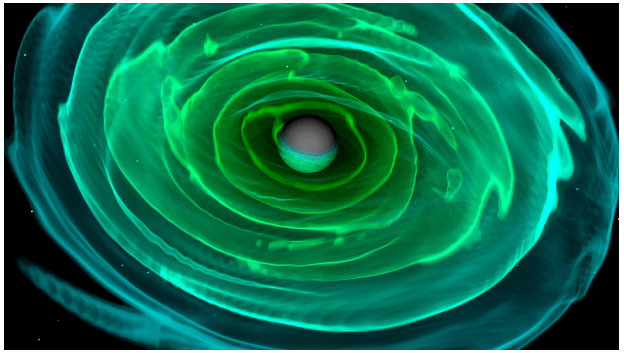


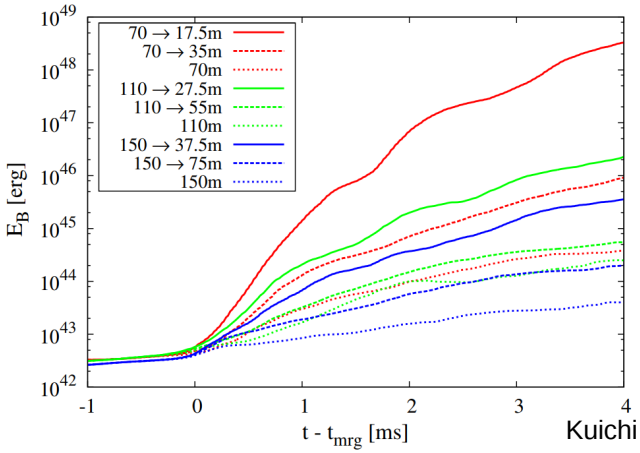


APJL, 848:L13

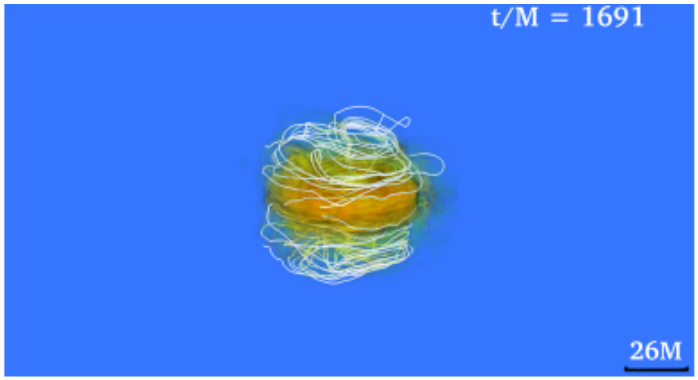
EM Signals – sGRBs

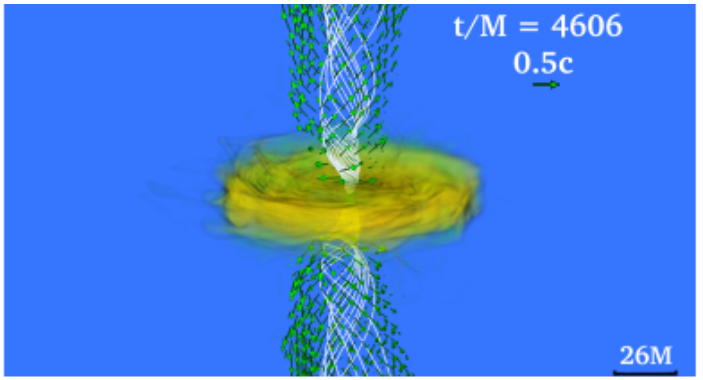
- BH + disk system
  - Neutrino & anti-neutrino annihilation
  - Magnetic field amplification and jet formation

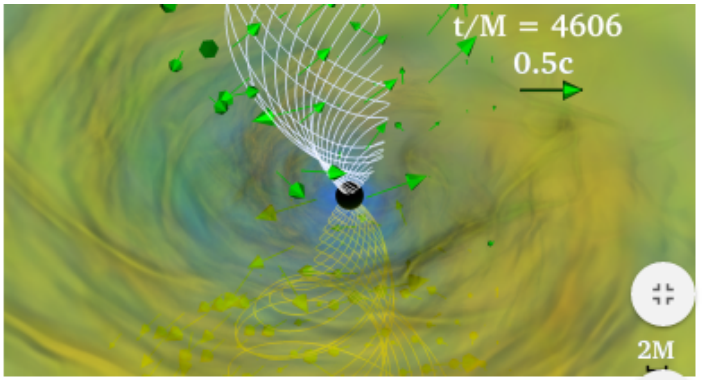




Kuichi et al., PRD92, 124034



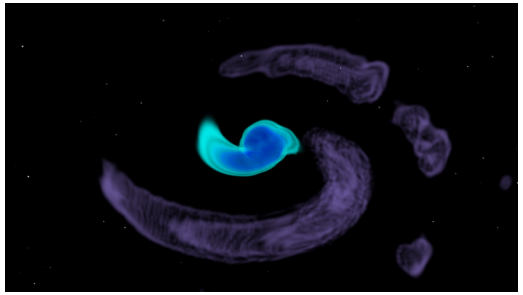




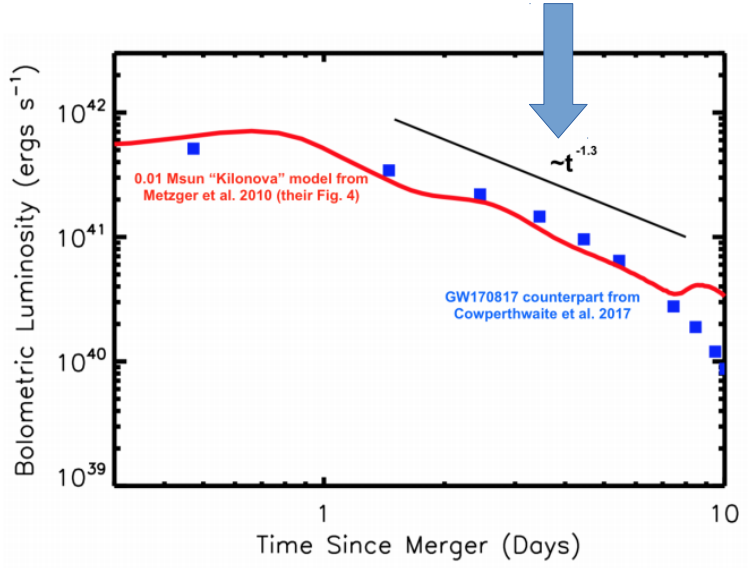
Ruiz et al., APJ. 824 (2016), L6

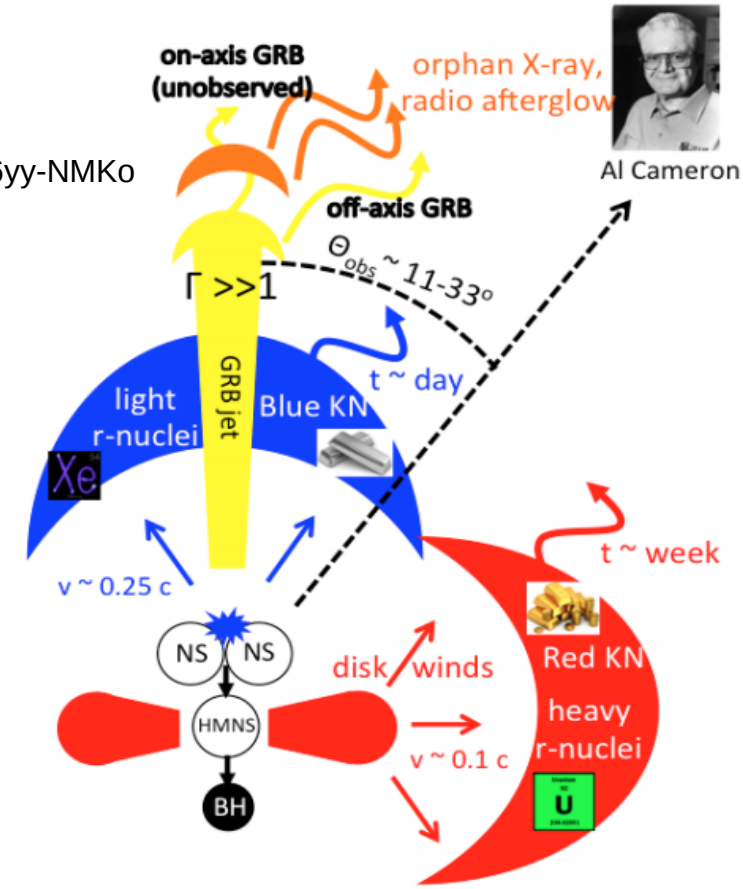
EM Signals – Kilonova

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



https://www.youtube.com/watch?v=LHK6yy-NMKo





Al Cameron

Metzger, arxiv:1710.05931

EM Signals

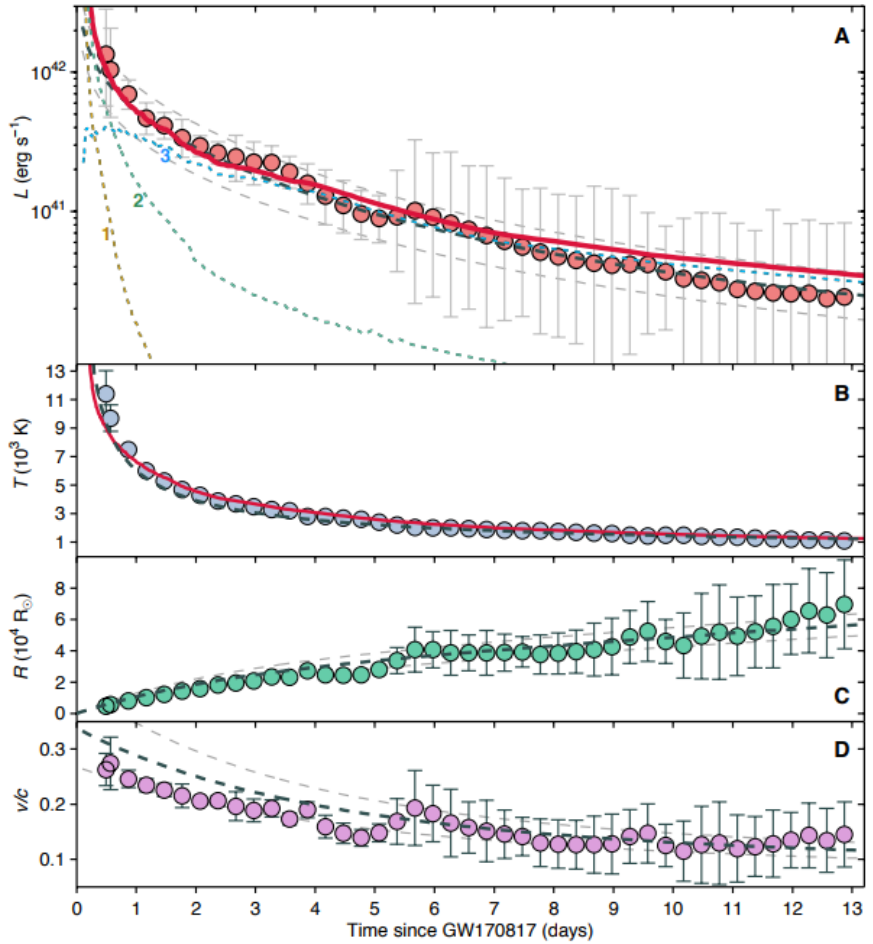
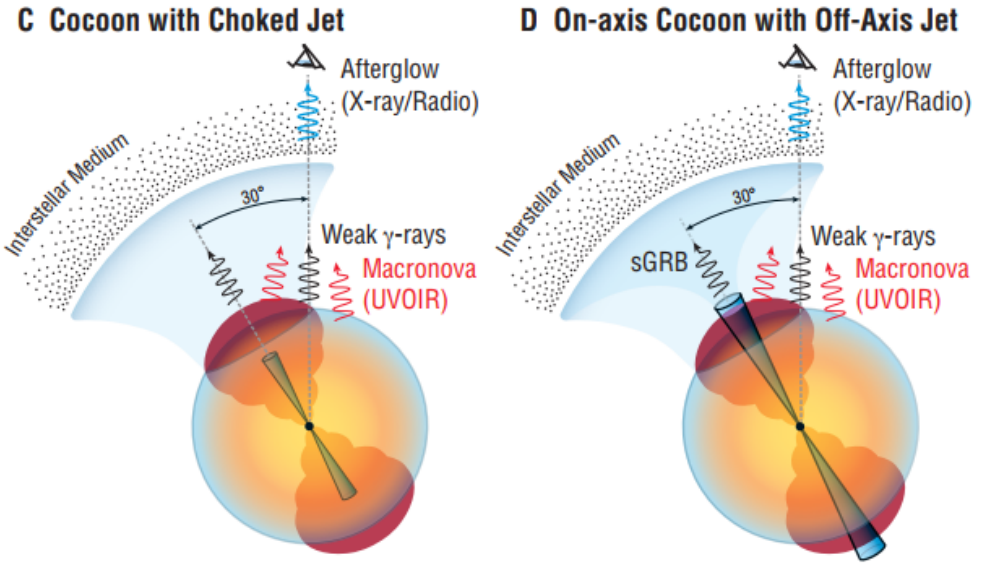


Figure 2: The evolution of EM170817 derived from the observed spectral energy distribution. (A) Bolometric luminosity. (B) Blackbody temperature. (C) Photospheric radius. (D) Inferred expansion velocity. Individual points represent blackbody fits performed at discrete epochs to which the observed photometry 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 (>0.4c; green dashed line labeled 2), and slow macronova (<0.4c; blue dashed line labeled 3).

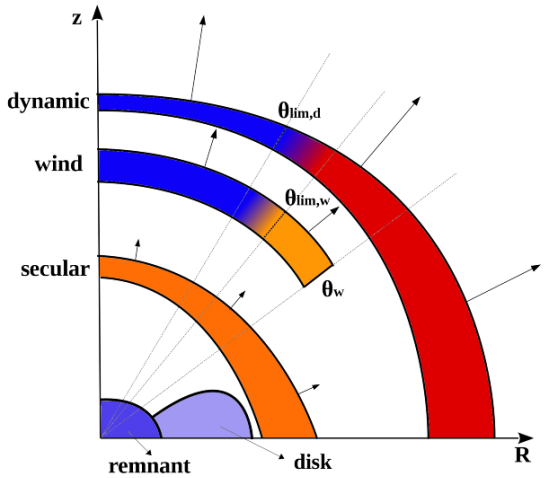
lluminating Gravitational Waves: A Concordant Picture of Photons from a Neutron Star Merger

Kasliwal et al., Science 16 Oct 2017



EM Signals – Kilonova

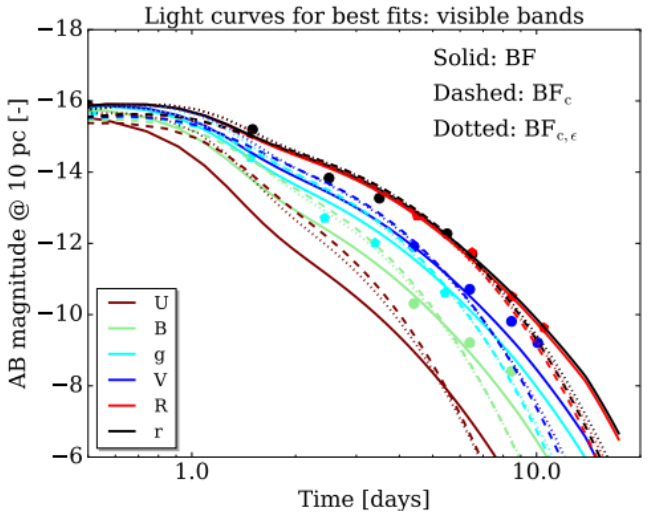
- possible models:

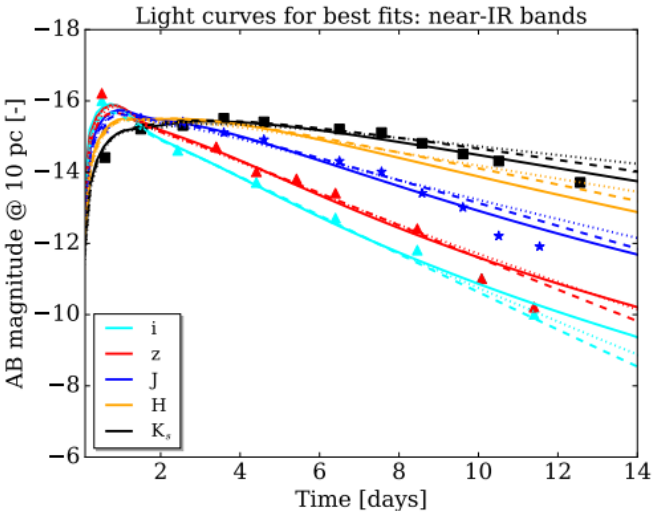


AT2017gfo: an anisotropic and three-component kilonova counterpart of GW170817

Perego et al, APJ 850 (2017) L37

- three components evolved by semi-analytical model





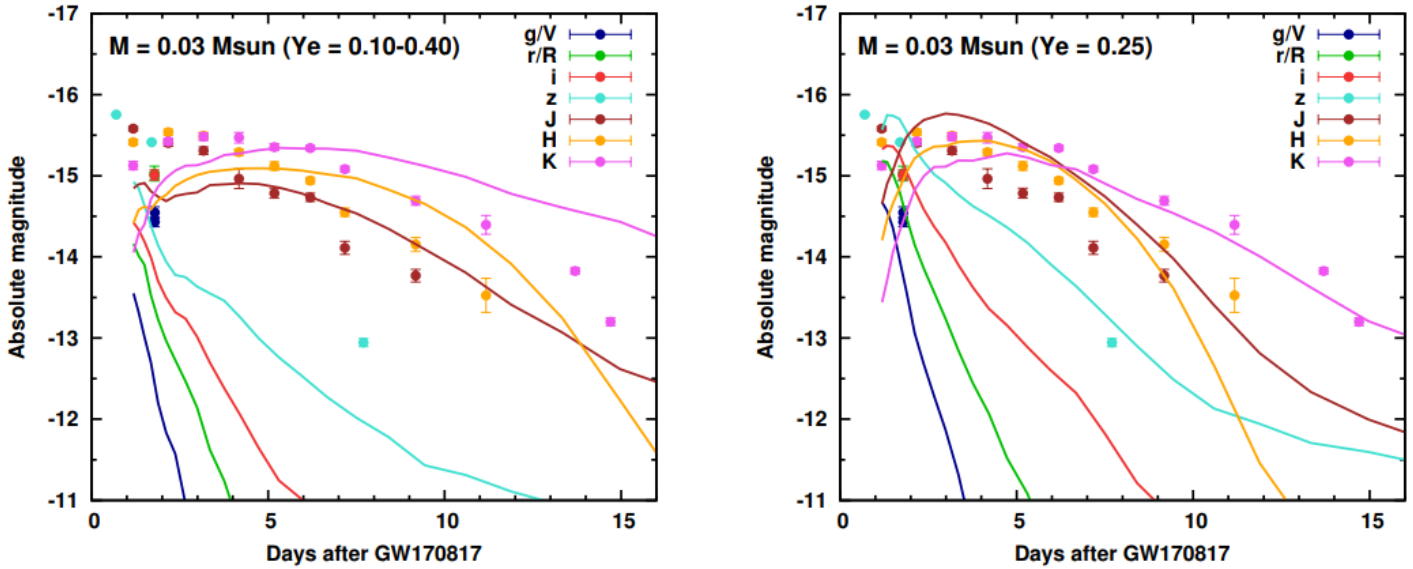
EM Signals – Kilonova

- possible models:

Kilonova from post-merger ejecta as an optical and near-infrared counterpart of GW170817

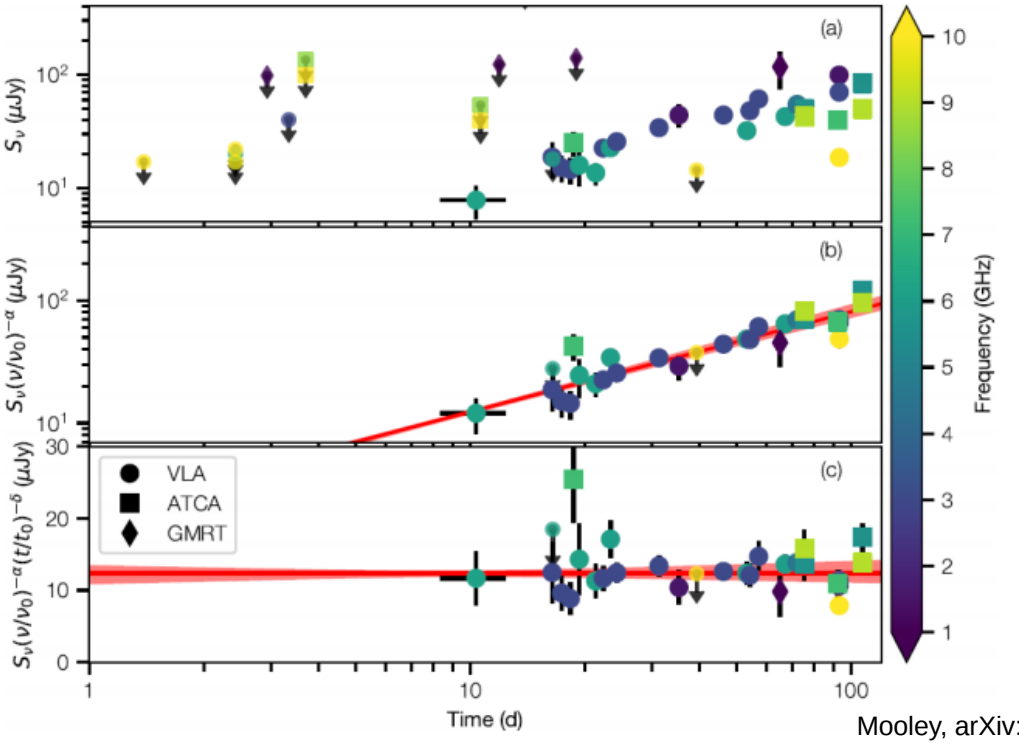
Tanaka et al., Publ.Astron.Soc.Jap.

  - radiative transfer Monte-Carlo simulation

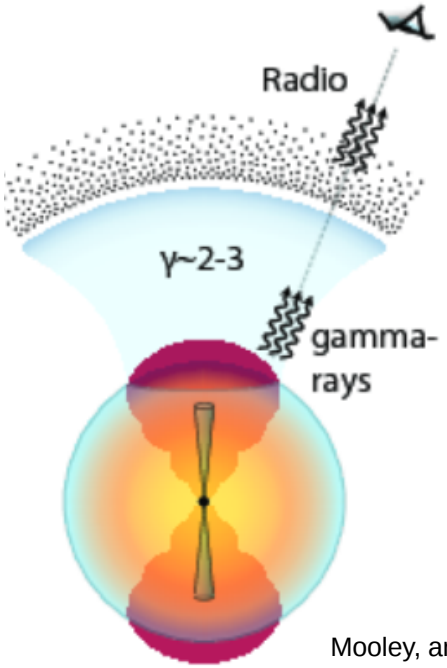


EM Signals – radio signals

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

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

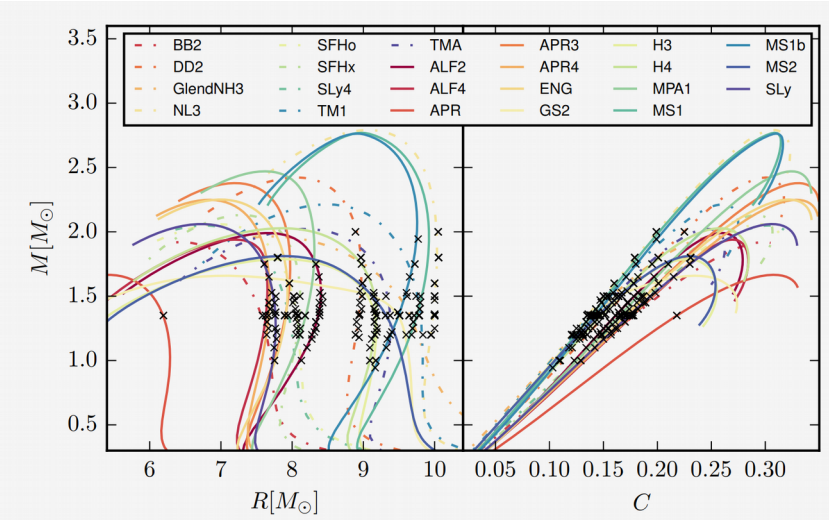
Nakar E and Piran T 2011 Nature 478 82–84

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

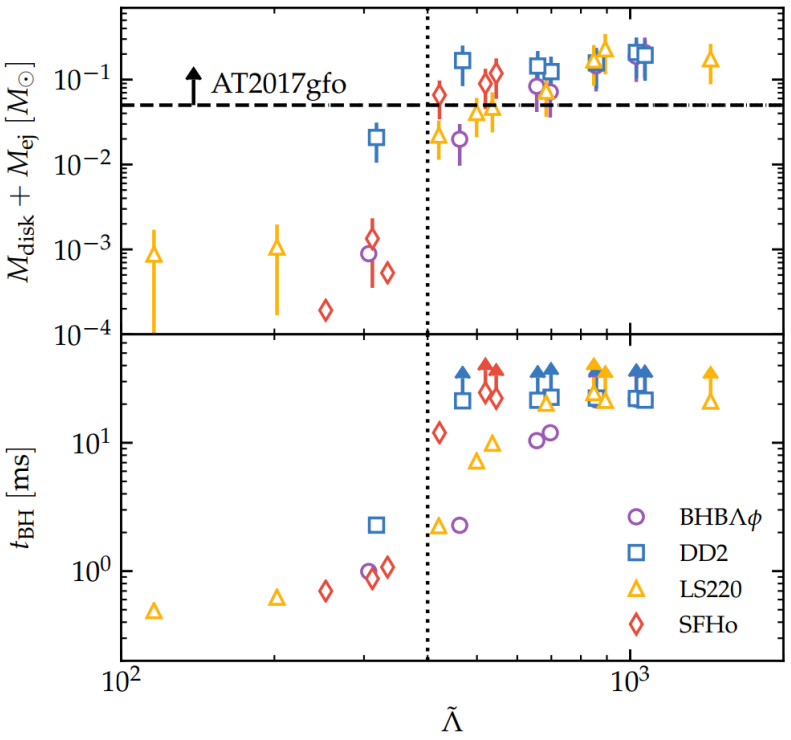
$$M_{\rm max}^{\rm sph} \lesssim 2.16 M_\odot$$

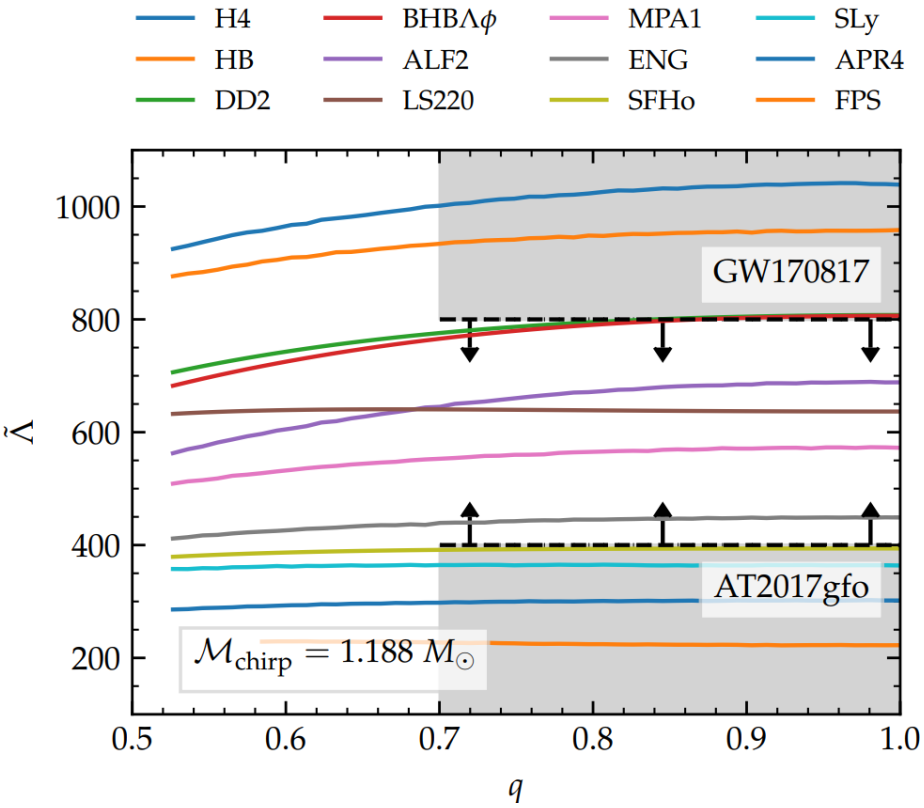
  - Shibata et al., arxiv:1710.07579

$$2.15\text{–}2.25 M_\odot$$

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