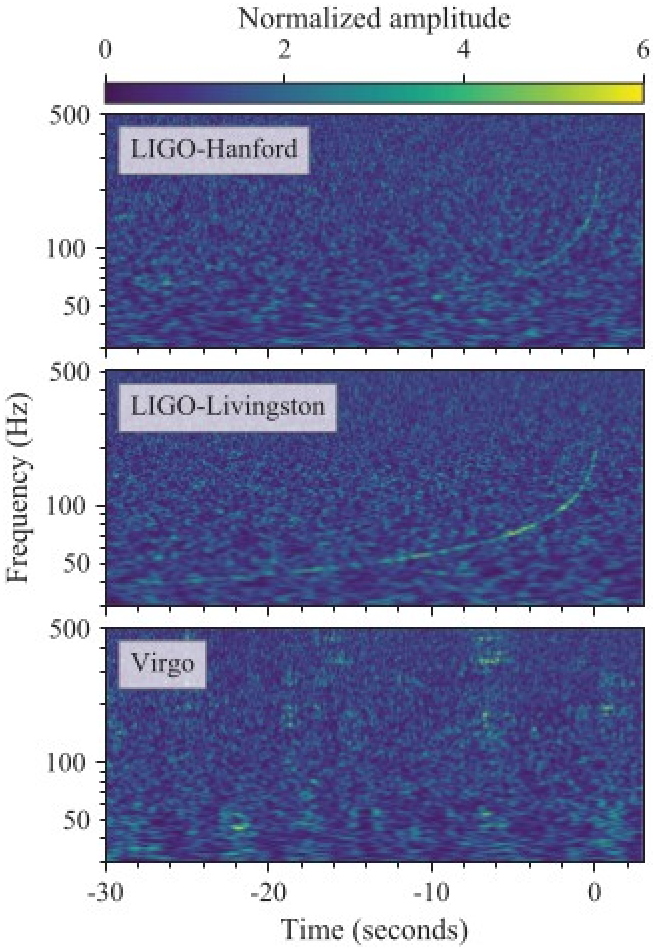
More than you ever wanted to know about GW170817
16 ApJL, 1 PRL, 1 Nature, 3 Science
… and many more in the pipeline apparently!

http://www.ligo.org/detections/GW170817.php

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

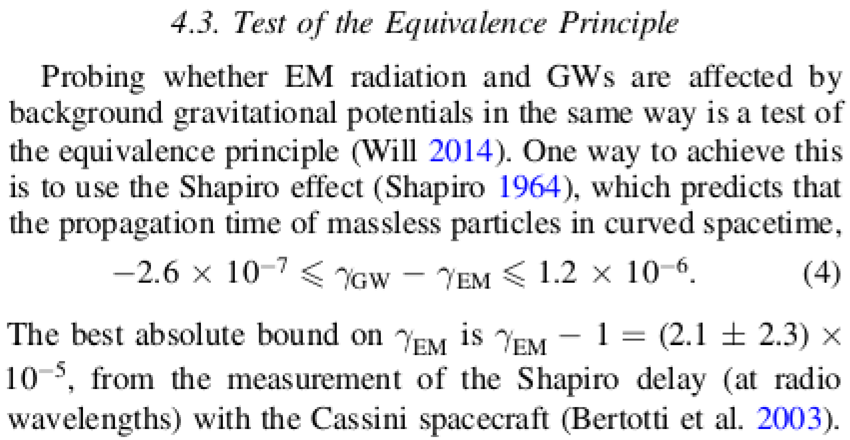


→ local coalescence rate of BNS~ 500-5000 Gpc^{-3} yr^{-1}

Journal Club
20/10/2017

Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A

We use the observed time delay of (+1.74 +/- 0.05) s between GRB 170817A and GW 170817 to: (i) constrain the difference between the speed of gravity and the speed of light to be between -3 10^{-15} and +7 10^{-16} times the speed of light, (ii) place new bounds on the violation of Lorentz invariance.



4.3. Test of the Equivalence Principle

Probing whether EM radiation and GWs are affected by background gravitational potentials in the same way is a test of the equivalence principle (Will 2014). One way to achieve this is to use the Shapiro effect (Shapiro 1964), which predicts that the propagation time of massless particles in curved spacetime,

$$-2.6 \times 10^{-7} \leqslant \gamma_{\rm GW} - \gamma_{\rm EM} \leqslant 1.2 \times 10^{-6}. \qquad (4)$$

The best absolute bound on $\gamma_{\rm EM}$ is $\gamma_{\rm EM} - 1 = (2.1 \pm 2.3) \times 10^{-5}$, from the measurement of the Shapiro delay (at radio wavelengths) with the Cassini spacecraft (Bertotti et al. 2003).

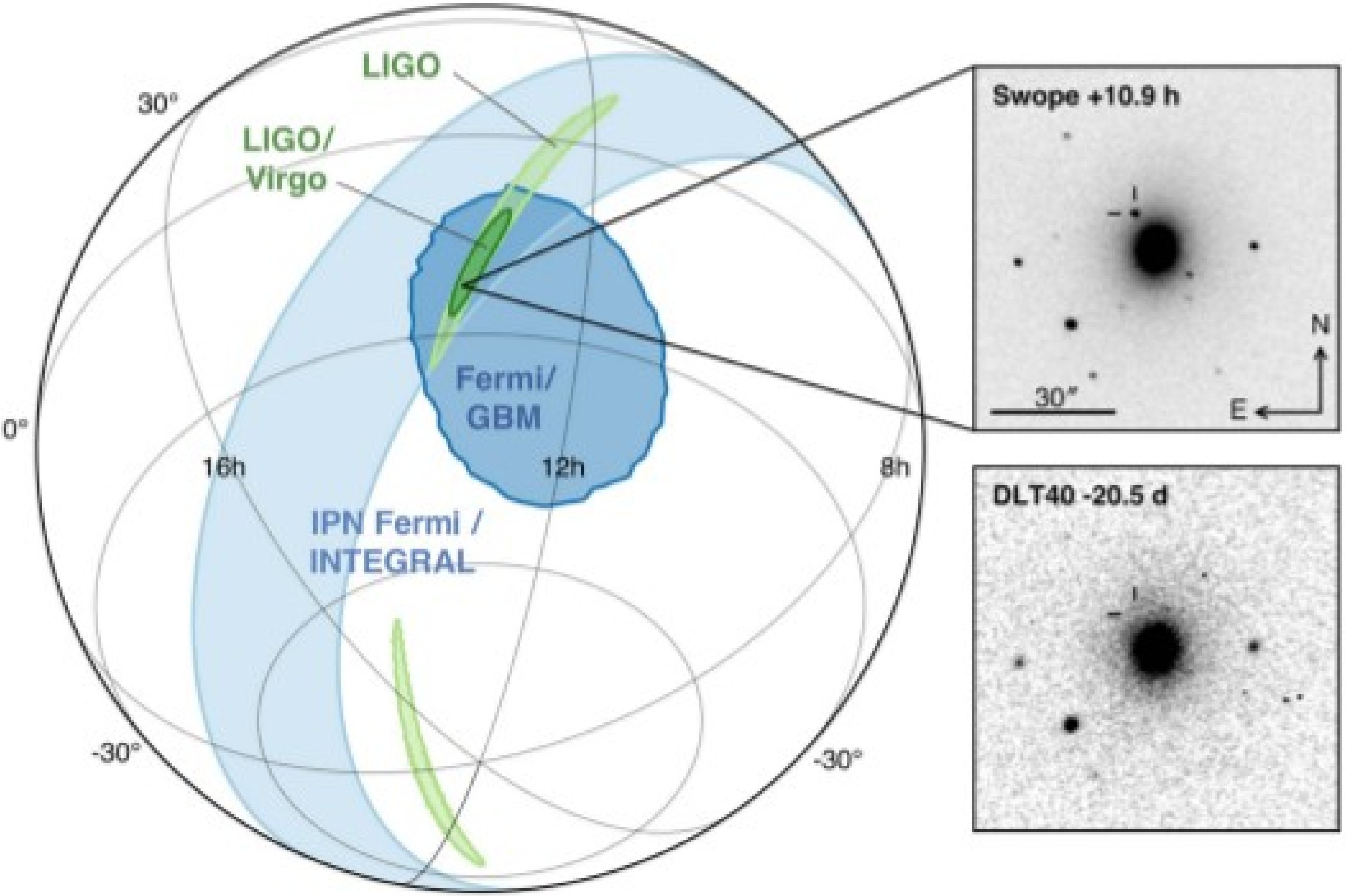
Strong constraints on cosmological gravity from GW170817 and GRB 170817A.

We show that this measurement allows us to place stringent constraints on general scalar-tensor and vector-tensor theories, while allowing us to place an independent bound on the graviton mass in bimetric theories of gravity. These constraints severely reduce the viable range of cosmological models that have been proposed as alternatives to general relativistic cosmology.

Alerts for GW170817 (17/10/2017) via GCN (Gamma-ray Coordinates Network)

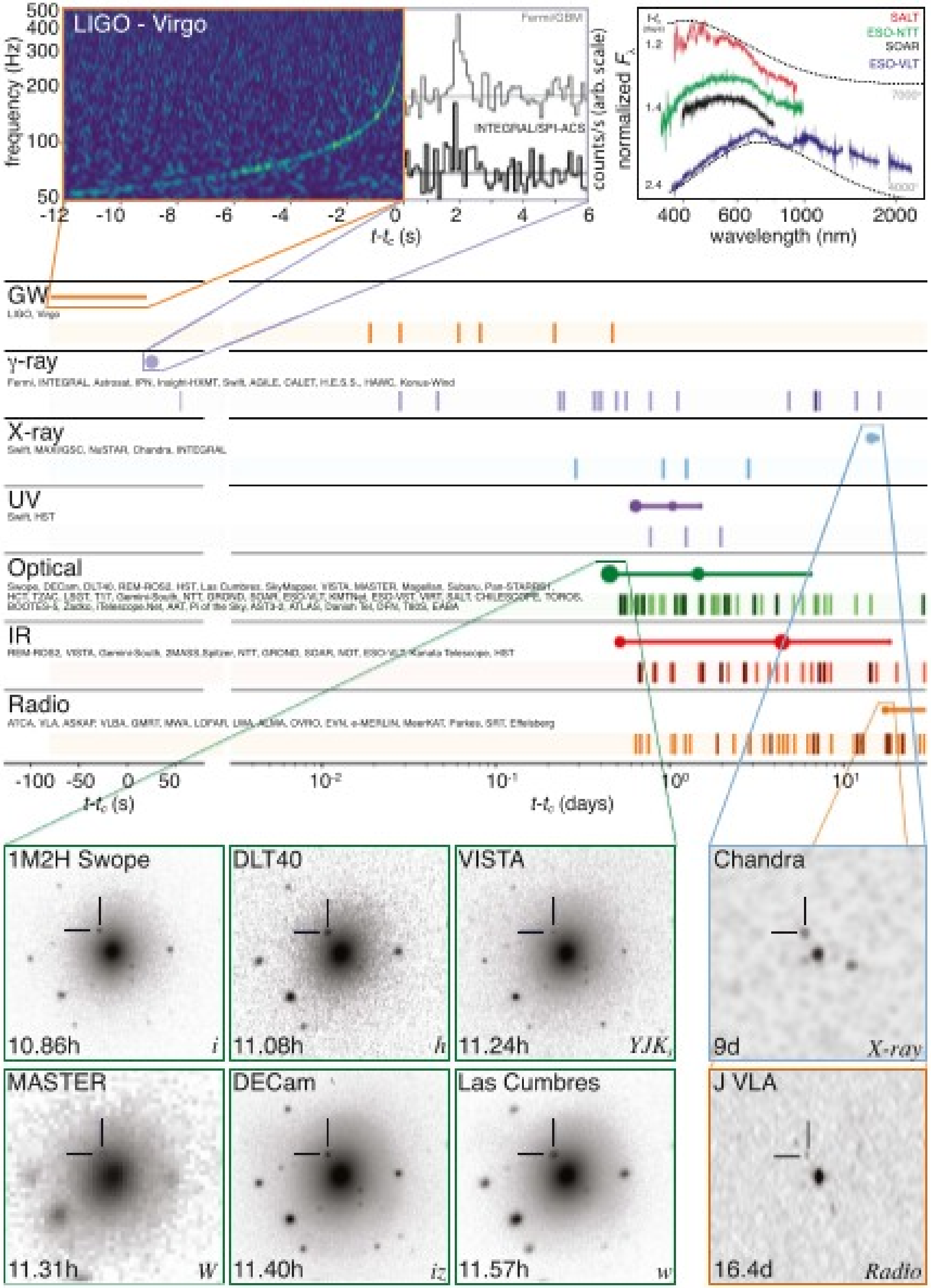
- LIGO: GCN sent 40 mn after trigger
- *Fermi*-GBM and *INTEGRAL*-SPI(ACS): GCN for GRB coincident with event within 2s
- ALV (Advances LIGO/VIRGO): GCN for localisation 4h after trigger

→ 4 telescopes independently discover optical counterpart (~0.5 d)



Multi-messenger Observations of a Binary Neutron Star Merger

(50 collaborations, 999 laboratories, >2000 authors)


LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12
-10
-8
-6
-4
-2
0
2
4
6
$t-t_c$ (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
SALT
ESO-NTT
SOAR
ESO-VLT
1.2
1.4
2.4
7000°
4000°
400
600
1000
2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, Pi of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS, Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100
-50
0
50
$t-t_c$ (s)
10^{-2}
10^{-1}
10^{0}
10^{1}
$t-t_c$ (days)
1M2H Swope
10.86h
i
DLT40
11.08h
r
VISTA
11.24h
YJK_s
Chandra
9d
X-ray
MASTER
11.31h
W
DECam
11.40h
iz
Las Cumbres
11.57h
w
J VLA
16.4d
Radio

The Distance to NGC 4993: The Host Galaxy of the Gravitational-wave Event GW170817

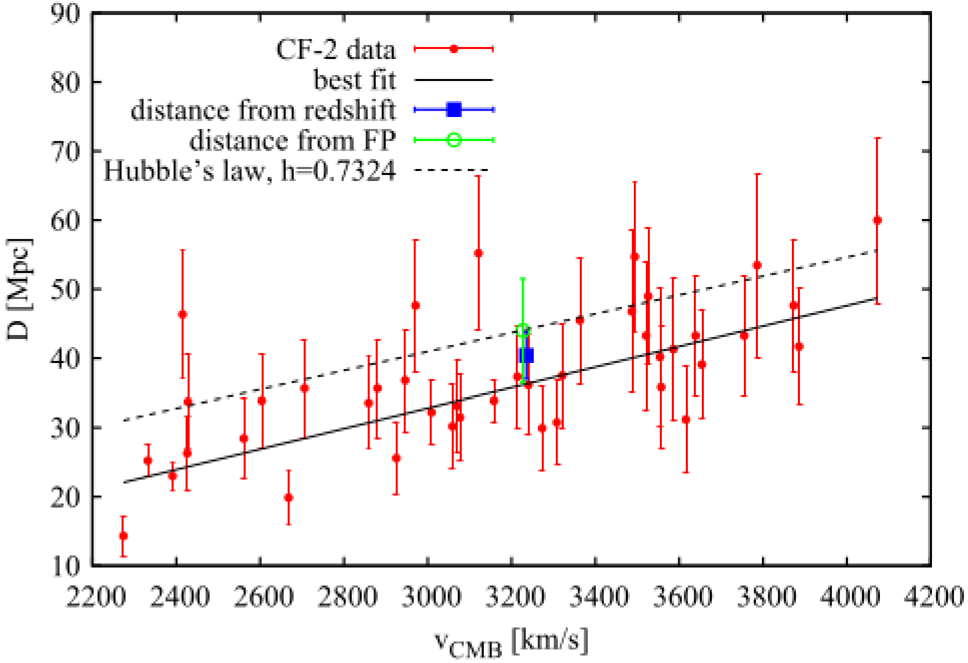


Figure 5. Distance vs. recession velocity in the CMB frame for Cosmicflows-2 galaxies. The best-fitting relation is consistent with the distance derived for NGC 4993 from the redshift and FP methods within the errors.

Distance Estimates to NGC 4993

Method	Distance (Mpc)
Redshift	40.4 ± 3.4
Fundamental Plane	44.0 ± 7.5
Combined Electromagnetic (z+FP)	41.0 ± 3.1
Gravitational Waves	$43.8^{+2.9}_{-6.9}$

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Discovery of the Optical Counterpart Using the Dark Energy Camera

Dark Energy Camera (DECam) = Blanco 4m telescope

→ signal observed (*i, z* bands) 11.4 h post-merger at z=0.0098 (OK with LIGO d=40+/-8Mpc)
→ transient associated with NGC 4993 (chance coincidence rejected @99.5%CL)
→ luminosity range expected for kilonova (1000 times brighter than a nova)

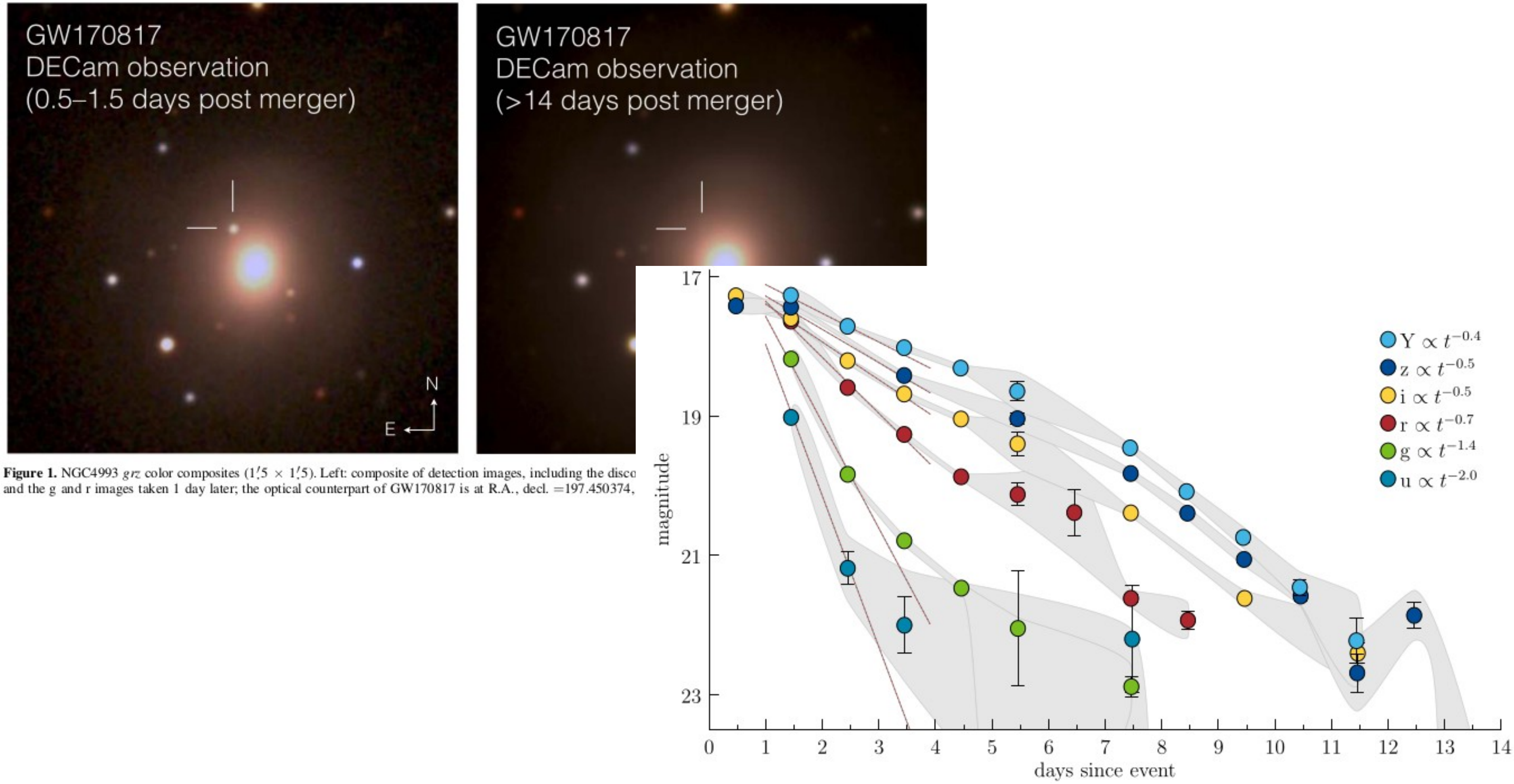
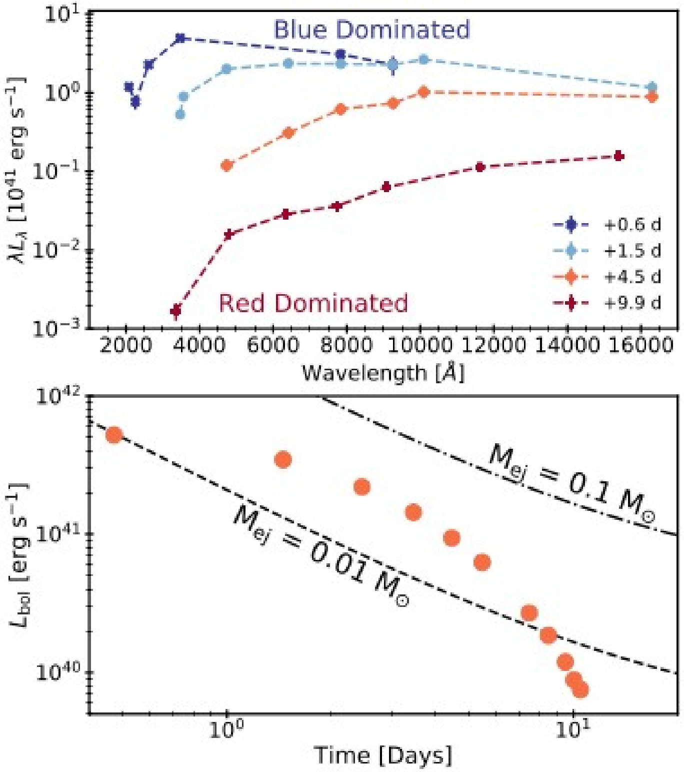


Figure 1. NGC4993 *grz* color composites (1′.5 × 1′.5). Left: composite of detection images, including the disco
and the g and r images taken 1 day later; the optical counterpart of GW170817 is at R.A., decl. =197.450374,

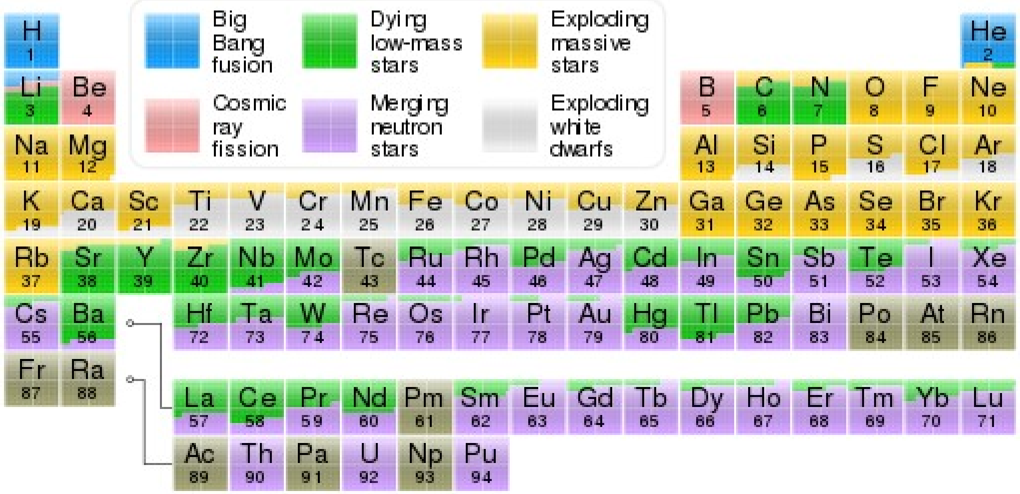
The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. II. UV, Optical, and Near-infrared Light Curves and Comparison to Kilonova Models

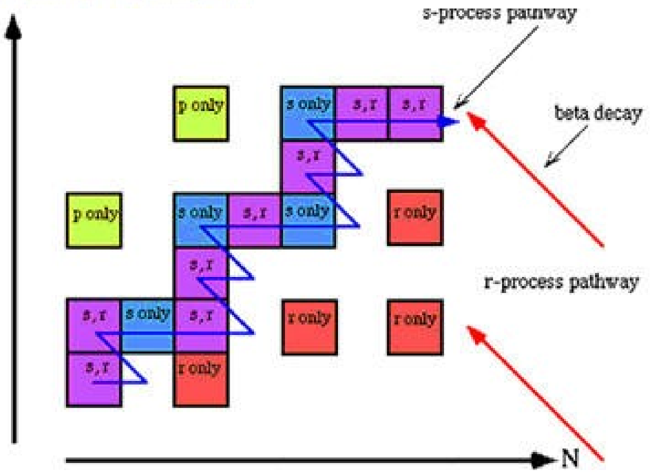
DECam (optical), Gemini-South/FLAMINGOS-2 (NIR), HST (UV)

→ Evidence of r-process-powered kilonova (blue=Lanthanide-poor, red=Lanthanide-rich)
→ Pure SN (^{56}Ni), pure Lanthanide-rich or poor scenarios failed to capture light-cure evolution
→ 2 component model (shock-heated polar region from collision + post-merger accretion disk outflow) ?



SEDs at four representative epochs (assuming isotropic emission). The transition from a blue dominated spectrum at early times to a spectrum dominated by a red component at late times is clearly visible. Bottom: Bolometric light curve spanning *ugrizYH*. Expected values for *r*-process heating from Metzger et al. (2010) are shown for comparison, indicating that the observed emission requires few × $10^{-2}\ M_\odot$ of *r*-process ejecta. Error bars are given at the 1σ level in all panels, but may be smaller than the points.





The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. III. Optical and UV Spectra of a Blue Kilonova from Fast Polar Ejecta

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. IV. Detection of Near-infrared Signatures of *r*-process Nucleosynthesis with Gemini-South

III. Early emission ~ ‘blue KN’: ~0.3 Msol ejecta @ 0.3c, lanthanide frac. $<10^{-4}$ => light r-process (A<140)
IV. Late (>2.5 d) ~ ‘red KN’: 0.04 Msol ejecta @ 0.1c, lanthanide frac.$\sim 10^{-2}$ => heavy r-process elements
→ Consistent with NS merger (r<12km), favours NS as major contributors to r-process nucleosynthesis

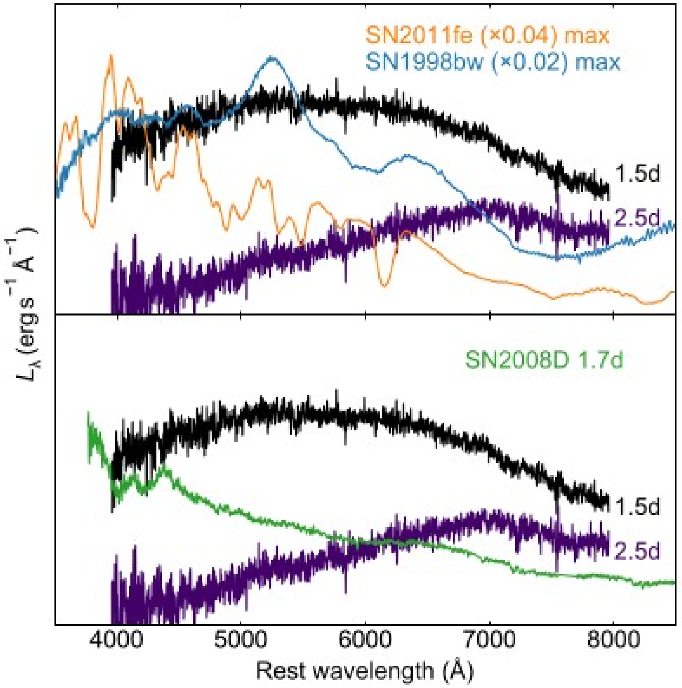
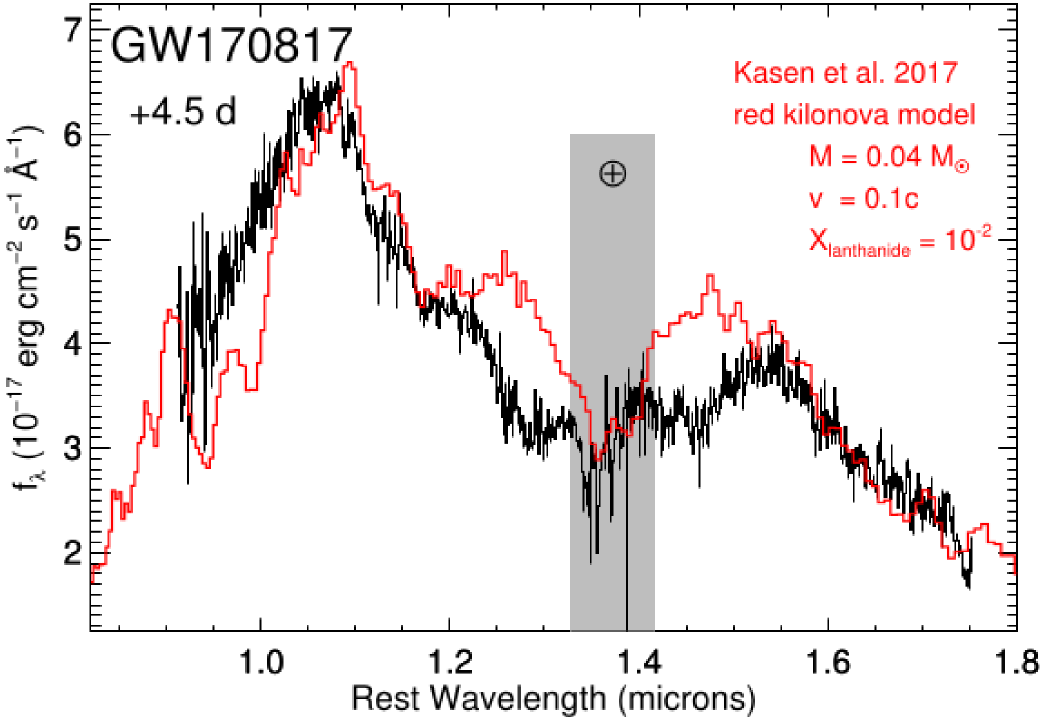


Figure 3. Comparison of our optical spectra of GW170817 to supernova spectra. Top: supernovae at maximum light. The supernova opacity is dominated by iron group elements, with a velocity of $\sim 10^4$ km s^{-1}. The GW170817 spectra do not show obvious resolved line features like the supernovae. Bottom: supernova shortly after explosion. Despite the comparable age of the ejecta from the BNS merger, the spectra are much redder than a supernova. Together, this suggests: (i) a composition with many more blended lines at blue/UV wavelengths, and (ii) significantly faster expansion velocities.



\+ **The Emergence of a Lanthanide-rich Kilonova Following the Merger of Two Neutron Stars**

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. V. Rising X-Ray Emission from an Off-axis Jet

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VI. Radio Constraints on a Relativistic Jet and Predictions for Late-time Emission from the Kilonova Ejecta

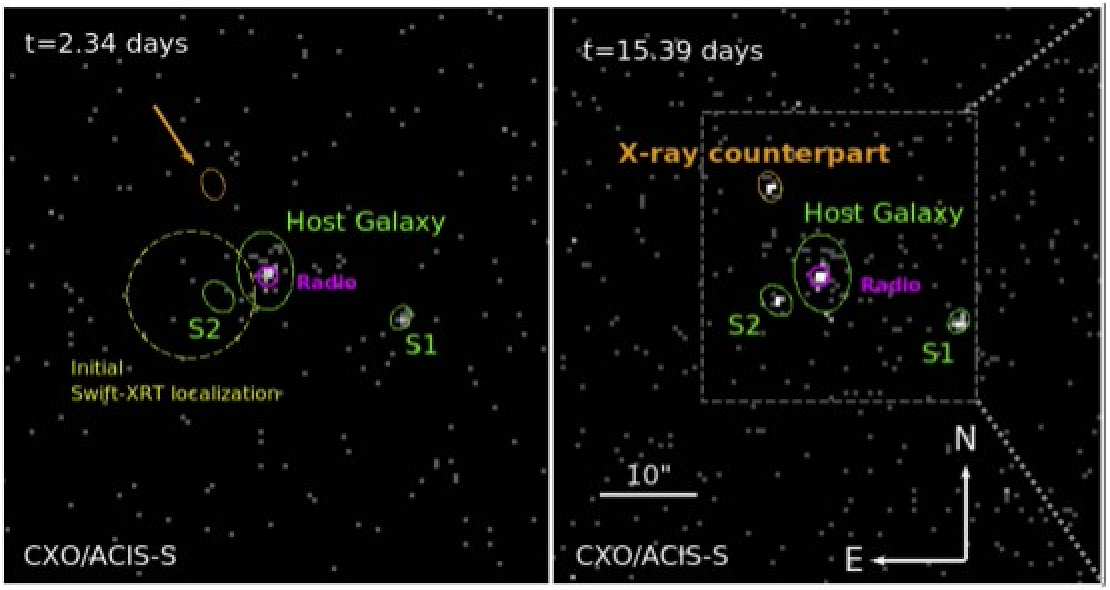
X-ray (Swift, Chandra), radio (VLA, ALMA)

Non-thermal X-ray radiation and radio expected if system launch relativistic jets (postulated for short GRB)

→ no signal 2d after event, rise and then peak at t>15d (need to observe at d~100)

→ consistent afterglow short GRB with relativistic jet (10^{49}-10^{50} erg) off-axis in 10^{-4}-10^{-2} cm^{-3}

→ prediction of emergence of late-time radio emission (deceleration) on timescale 5-10 yrs



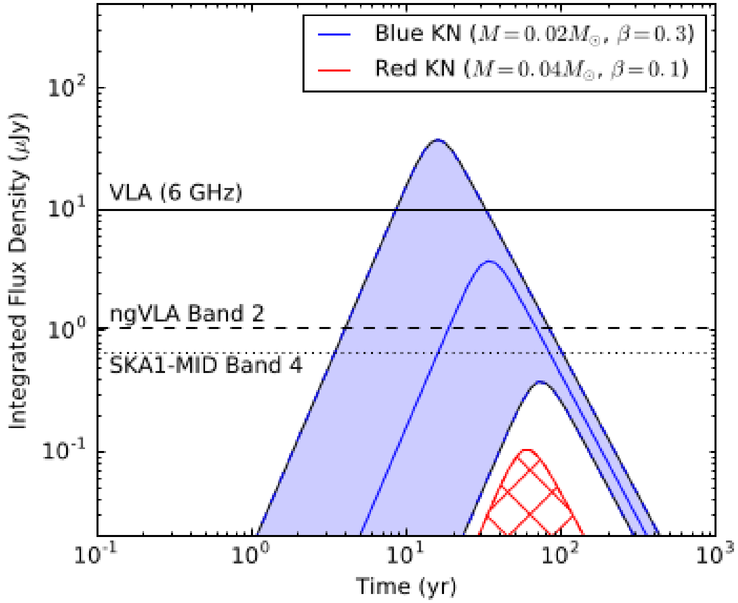


Figure 4. Radio emission predicted from decelerated KN ejecta for the two component model described in Cowperthwaite et al. (2017), assuming the density range allowed by our VLA observations, $n = 10^{-4}$–10^{-2} cm^{-3}. The

+ A Deep *Chandra* X-Ray Study of Neutron Star Coalescence GW170817
+ *Swift* and *NuSTAR* observations of GW170817: Detection of a blue kilonova

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VII. Properties of the Host Galaxy and Constraints on the Merger Timescale

The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VIII. A Comparison to Cosmological Short-duration Gamma-Ray Bursts

Archival HST data of NGC4993 + X-ray to radio photometry (2MASS, WISE,VLA...)

VII. Peak of SFR at >10 Gyr declined to 0.01 Msol/yr today → median merger timescale ~ 6.8-13.6 Gyr

VIII. X-ray ~3000 (50) times less than median (faintest) X-ray afterglow luminosity (~10^4 (500) less for radio)

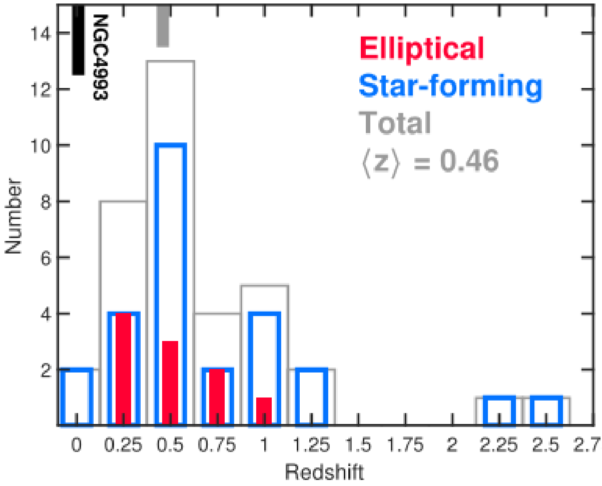
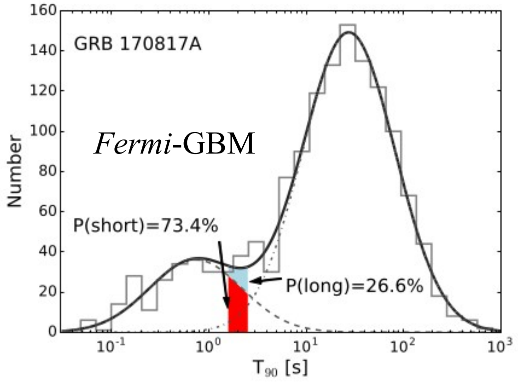
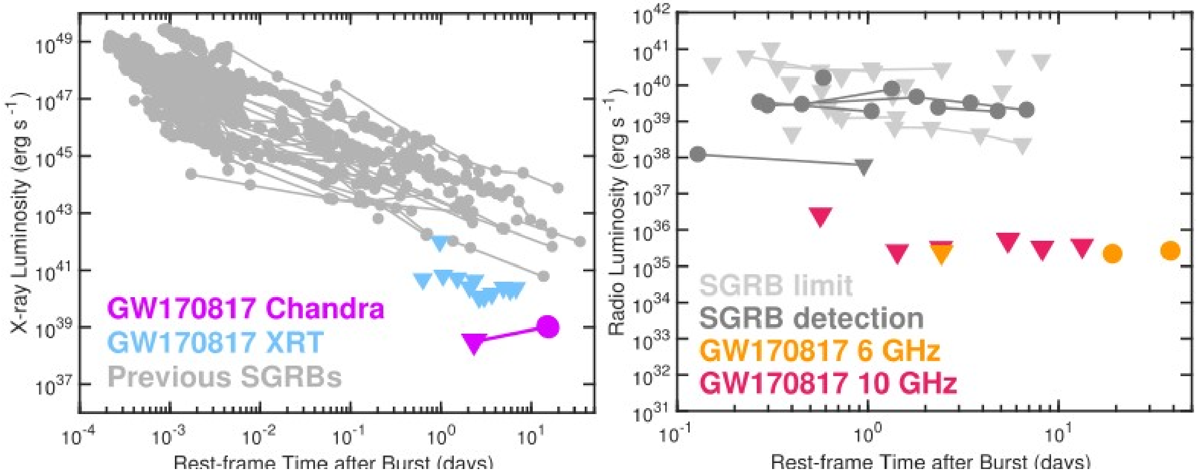


Figure 1. Redshift distribution of 36 short GRBs discovered over 2004–2017 (gray). The distributions are divided by host galaxy type: elliptical (red) and star-forming (blue) galaxies. The redshift of NGC 4993 is denoted (black line), along with the median for the short GRB population (gray line) of $\langle z \rangle \approx 0.46$.





A gravitational-wave standard siren measurement of the Hubble constant

The Hubble constant H_0 measures the mean expansion rate of the Universe. At nearby distances ($d \lesssim 50$ Mpc) it is well approximated by the expression

$$v_{\rm H} = H_0 d \qquad (1)$$

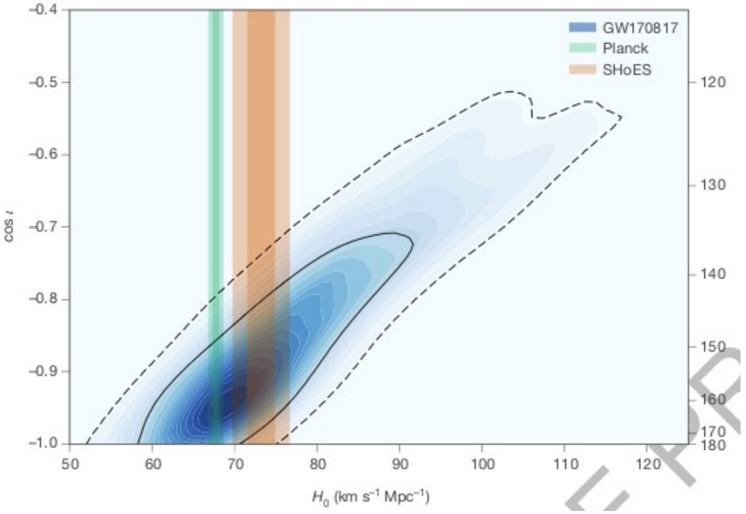
where $v_{\rm H}$ is the local 'Hubble flow' velocity of a source, and d is the distance to the source. At such distances all cosmological distance measures (such as luminosity distance and comoving distance) differ at the order of $v_{\rm H}/c$ where c is the speed of light. As $v_{\rm H}/c \approx 1\%$ for GW170817 we do not distinguish between them. We are similarly insensitive to the values of other cosmological parameters, such as Ω_m and Ω_Λ.

To obtain the Hubble flow velocity at the position of GW170817, we use the optical identification of the host galaxy NGC 4993[7]. This identification is based solely on the two-dimensional projected offset and is independent of any assumed value of H_0. The position and redshift of this galaxy allow us to estimate the appropriate value of the Hubble flow velocity. Because the source is relatively nearby the random relative motions of galaxies, known as peculiar velocities, need to be taken into account. The peculiar velocity is about 10% of the measured recessional velocity (see Methods).

To compute H_0 we need to estimate the background Hubble flow velocity at the position of NGC 4993. In the traditional electromagnetic calibration of the cosmic 'distance ladder'[19], this step is commonly carried out using secondary distance indicator information, such as the Tully–Fisher relation[24], which allows one to infer the background Hubble flow velocity in the local Universe scaled back from more distant secondary indicators calibrated in quiet Hubble flow. We do not adopt this approach here, however, in order to preserve more fully the independence of our results from the electromagnetic distance ladder. Instead we estimate the Hubble flow velocity at the position of NGC 4993 by correcting for local peculiar motions.

NGC 4993 is part of a collection of galaxies, ESO-508, whose center-of-mass recession velocity relative to our local CMB frame[27] is[28] $3{,}327 \pm 72$ km s^{-1}. We correct the group velocity by 310 km s^{-1} owing to the coherent bulk flow[29,30] towards The Great Attractor (see Methods for details). The standard error on our estimate of the peculiar velocity is 69 km s^{-1}, but recognizing that this value may be sensitive to details of the bulk flow motion that have been imperfectly modelled, in our subsequent analysis we adopt a more conservative estimate[30] of 150 km s^{-1} for the uncertainty on the peculiar velocity at the location of NGC 4993, and fold this into our estimate of the uncertainty on $v_{\rm H}$. From this, we obtain a Hubble velocity $v_{\rm H} = 3{,}017 \pm 166$ km s^{-1}.

This quantity, representing the local expansion rate of the Universe, sets the overall scale of the Universe and is of fundamental importance to cosmology. Our measurements do not require any form of cosmic 'distance ladder'[19]; the gravitational-wave analysis directly estimates the luminosity distance out to cosmological scales. Here we report $H_0 = 70.0^{+12.0}_{-8.0}$ kilometres per second per megaparsec, which is consistent with existing measurements[20,21], while being completely independent of them.



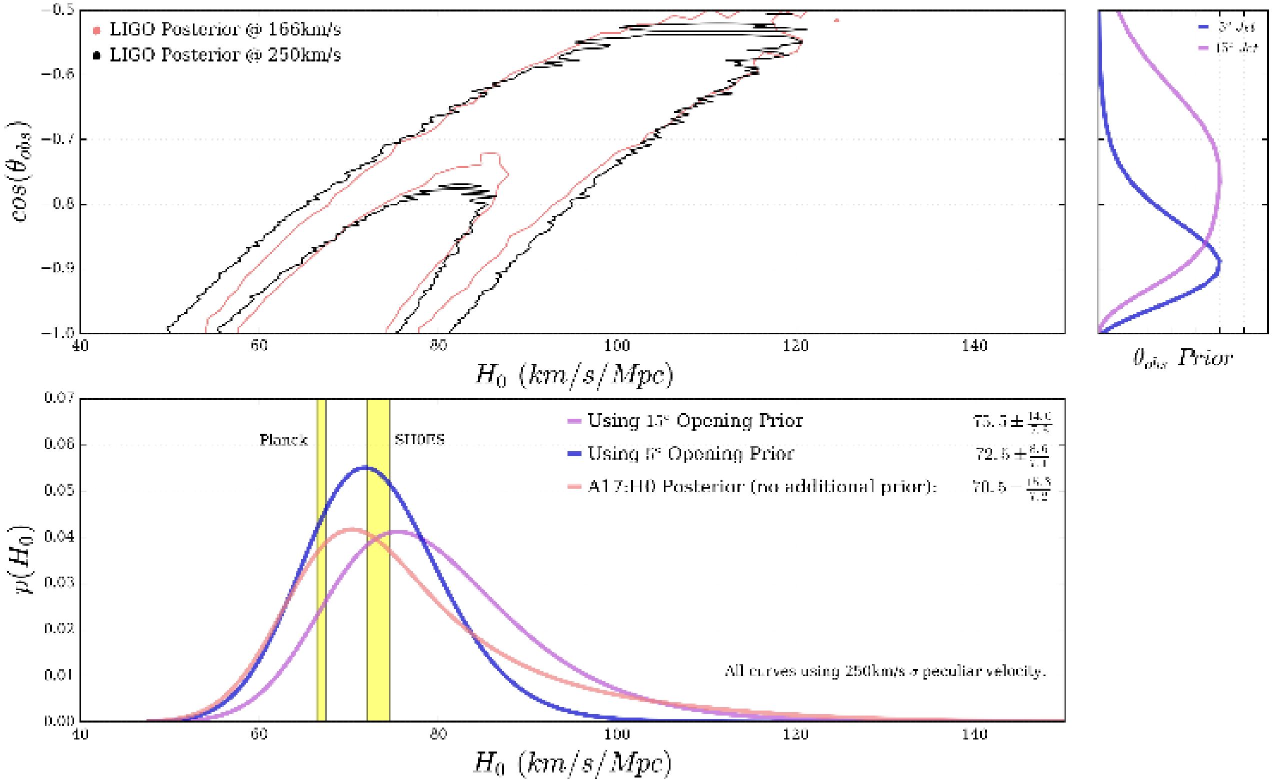


FIG. 2.— Constraints on the Hubble constant H_0 for BNS merger G298048 with and without prior on the inclination of the system. Upper: Black 1 and 2 σ contours from LIGO data server assume 166km/s peculiar velocity uncertainty. Red 1 and 2 σ contours noised to 250km/s peculiar velocity uncertainty. Right: Visual representation of the calculated priors on θ_{obs}. Lower: Marginalized constraints on H_0 for our two scenarios for which inclination priors have been calculated as well as for the noised up 250km/s LIGO contour alone.

$\frac{12.0}{8.0}$ km/s/Mpc found in A17:H0. However, for our best H_0 determination, we use a more realistic peculiar velocity uncertainty of 250 km/sec derived from N-body simulations and the empirical scatter of low-z SNe. Combining the inclination and peculiar velocity yields a best result of $H_0 = 75.5 \pm \frac{14.0}{7.3}$ km/s/Mpc for H0 from this system. We note that this is in modestly better agreement with the local distance ladder than the Planck CMB, though a significant such discrimination will require ∼ 50 such events. Further measurements of the X-ray and radio emission from GW170817 in the upcoming months will lead to tighter constraints on the jet off-axis angle.

Prospects of the local Hubble parameter measurement using gravitational waves from double neutron stars

novae. At present, the estimated DNS merger rate $(1.5^{+3.2}_{-1.2}) \times 10^{-6}\mathrm{Mpc}^{-3}\mathrm{yr}^{-1}$ has a large uncertainty. But, if it is at the high end, we could measure the local Hubble parameter H_L with the level of $\Delta H_L/H_L \sim 0.042$ (1σ level), after the third observational run (O3). This accuracy is four times better than that obtained from GW170817 alone, and we will be able to examine the Hubble tension at 2.1σ level.