LIGO-Virgo efforts to study the post-merger remnant of the GW170817 event

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for the

LIGO Scientific Collaboration

and Virgo Collaboration

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Lecce, Italy, 2018-06-04

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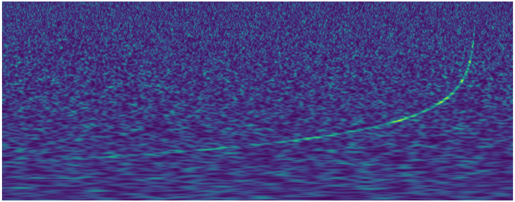
704094 GRANITE



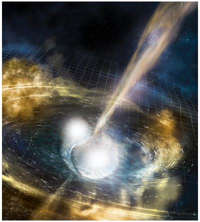
$\Longrightarrow$? ? ?

LIGO-G1800351-v5

❶ GW170817

first golden multi-messenger source

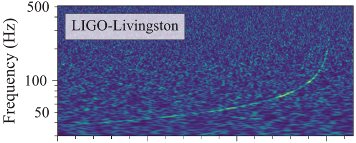
- binary neutron star (BNS) merger observed in GWs, γ-rays, X-rays, optical, IR, radio [1, 2]
- nuclear EoS constraints [1, 3, 4]
- H_0 standard siren measurement [5]
- tests of GR: speed of gravity etc [6]

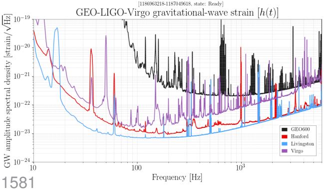


[NSF/LIGO/SSU/A.Simonnet]

from GW side:

- all information from *inspiral only*
- 'visible' chirp vanishes above $\sim$400 Hz due to rising detector noise
- close to Earth: $d = 40^{+8}_{-14}$ Mpc [1] (host NGC 4993 at $\sim$40 Mpc [2])



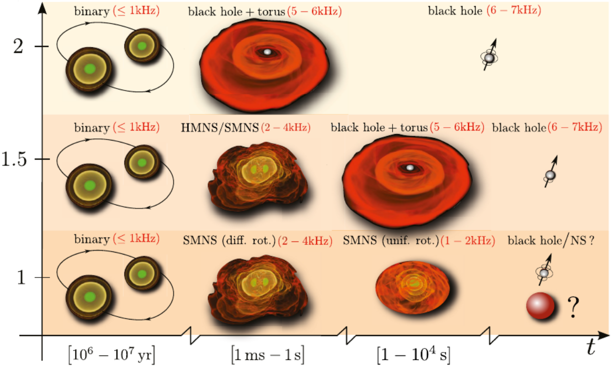


[1] Abbott et al. (LVC), *PRD* **119**,14 (2017)
[2] Abbott et al. (LVC+MMA), *APJL* **848**:L12 (2017)
[3] Abbott et al. (LVC), *arXiv*:1805.11579 [4] Abbott et al. (LVC), *arXiv*:1805.11581
[5] Abbott et al. (LVC), *Nature* **551**,85-88 (2017) [6] Abbott et al. (LVC), *APJL* **848**:L13 (2017)

❶ GW170817 and BNS remnants

remnant scenarios

1. prompt collapse to BH
2. hypermassive NS (∼ms, differential rotation)
3. supramassive NS ($\lesssim 10^4$ s, rigid rotation)
4. stable NS $(M < M_{\mathrm{TOV}})$



[Baiotti & Rezzolla 2017]
[Rep. Prog. Phys. 80]

- post-merger GWs can be smoking gun for remnant identity
- yield improved EoS constraints [see e.g. [7] Bauswein et al. (2017)]

❷ short-duration remnant searches

- prompt collapse to BH ⇒ GWs $\gtrsim 5\,\mathrm{kHz}$
  ⇒ no chance of detection with LIGO-Virgo
- circumstantial evidence for hypermassive (HMNS) case:
  - inspiral results on progenitor (e.g. total system mass: $M = 2.74^{+0.04}_{-0.01}\,M_\odot$)
    ⇒ remnant mass posteriors: main support in HMNS range [6]
  - kilonova lightcurve modelling: additional energy injection? [8, 9]
  - LIGO-Fermi 1.7 s delay . . . ?
- supramassive or stable NS unlikely, but not ruled out

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Search for Post-merger Gravitational Waves from the Remnant of the Binary Neutron Star Merger GW170817

LIGO Scientific Collaboration and Virgo Collaboration
(See the end matter for the full list of authors.)

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model-agnostic search for signals $\lesssim$ 1s and $\lesssim$ 1000s

[6] Abbott et al. (LVC), *APJL* **848**:L13 (2017) [8] Kasen et al., *Nature* **551**,80 (2017) [9] Granot et al., *APJL* **850**:L24 (2017)

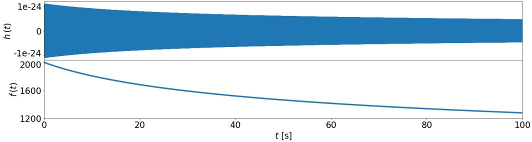
❷ short-duration remnant searches

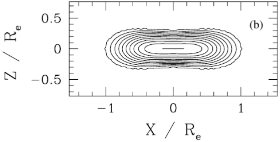
signal models considered in Abbott et al. (LVC), *APJL* **851**:L16 (2017)

- Used for sensitivity estimates, *not* assumed in search!
- high-freq modes: first few–dozens ms after merger, modelled by numerical relativity [see [10] for many refs]

[T. Dietrich et al., Albert Einstein Institute]

- secular bar modes: $\sim$ hundreds of s [11]
- long-duration power-law spindown [12] (dominated by magnetic field or GWs)





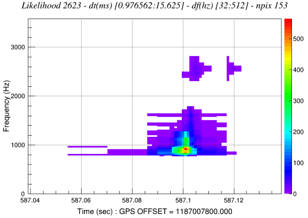
[Shibata&Karino 2004]

[10] Abbott et al. (LVC), *APJL* **851**:L16 (2017) [11] Corsi & Mészáros, *APJ* **702**,1171 (2009)
[12] Lasky et al., LIGO-T1700408

❷ short-duration remnant searches

cWB analysis

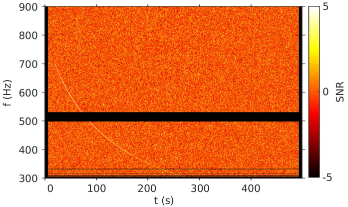
- unmodelled search for 'bursts' of excess strain power [13]
- HL data in 1–4 kHz for $\lesssim$ 1s search
- HLV data in 24–2048 Hz for $\lesssim$ 1000s search



[C. Lazzaro, CWB team] (SIMULATION!)

STAMP analysis

- 'stochastic' search, clustering power in time-freq plane [14]
- HL data, 24–2000 Hz and 2000–4000 Hz bands
- full 8.5 days of O2 data after merger split into 500 s maps
- $\Rightarrow$ in principle could find long signals in multiple chunks, but not optimal



[S. Banagiri, STAMP team] (SIMULATION!)

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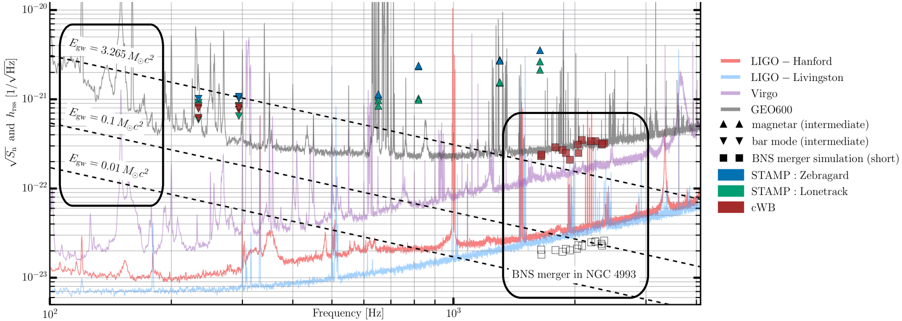
[13] Klimenko et al., *PRD* **93**,042004 (2016); [14] Thrane et al., *PRD* **83**,083004 (2011)

HL: Hanford+Livingston (LIGO), HLV: LIGO+Virgo

❷ short-duration remnant searches

- result: no detections [10]
- injecting example waveforms at GW170817 distance: typically $\sim$ factor 10 (in strain) away from detectability



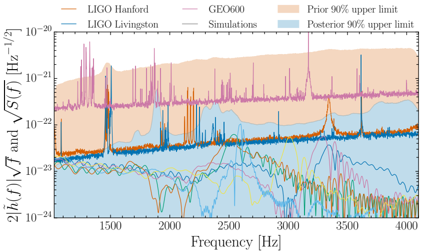
- e.g. for high-freq NR simulations, close to but not quite excluding whole system energy into post-merger GWs ($E_{\rm gw} = 3.265 M_\odot c^2$)
- current and future upgrades to LIGO+Virgo will improve overall sensitivity, and especially at high frequencies

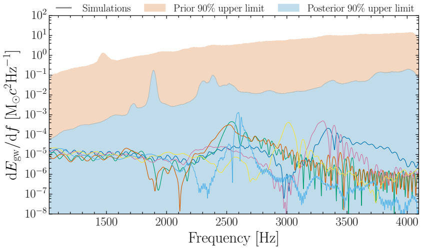
[10] Abbott et al. (LVC), *APJL* **851**:L16 (2017)

❷ short-duration remnant searches

BayesWave

- new LVC paper: "Properties of the binary neutron star merger GW170817" [3]
- no significant short-duration post-merger detection candidates from [10]
- fully Bayesian upper limits on $h(f)$ and $E_{\rm gw}(f)$ using wavelets [15, 16]
- 1 s of 1–4 kHz LIGO+GEO600 data (GEO still has decent high-f sensitivity!)
- Bayes factor ≈ 257 in favor of Gaussian noise over coherent GW signal
- strain ULs 3–10x over NR expectation at $d = 40$ Mpc (10–100x in $E_{\rm gw}$)



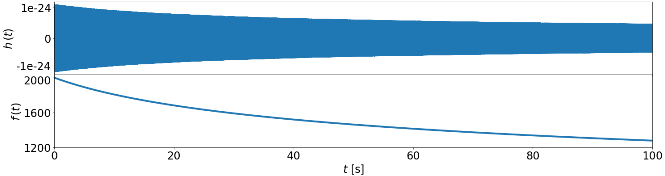


[3] Abbott et al. (LVC), *arXiv:*1805.11579 [10] Abbott et al. (LVC), *APJL* **851**:L16 (2017)
[15] Cornish & Littenberg, *CQG* **32**,135012 (2015) [16] Chatziioannou et al., *PRD* **96**,124035 (2017)

❸ long-duration remnant searches

- for signal durations $\gg 1000\,\mathrm{s}$:
  different data analysis methods can yield better sensitivity
- available LIGO data from GW170817 coalescence
  to end of O2 observing run: 8.5 days
- signal model: power-law spindown ('ms magnetar' [10, 12])

$$f_{\mathrm{gw}}(t) = f_0 \left(1 + \frac{t}{\tau}\right)^{\frac{1}{1-n}}$$



- braking index: spindown dominated by . . .
  - $n = 3$: magnetic field dipole braking
  - $n = 5$: GWs from mass quadrupole ('mountains')
  - $n = 7$: GWs from r-mode unstable oscillations

[10] Abbott et al. (LVC), *APJL* **851**:L16 (2017) [12] Lasky et al., dcc.ligo.org/T1700408

❸ long-duration remnant searches

What are the odds for a long-lived NS remnant?

- inspiral mass posteriors prefer hypermassive NS [6, 10] (collapse after ms–s) but don't exclude long-lived NS
- some circumstantial EM evidence for hypermassive NS (ejecta composition, lightcurve modeling) [8, 9]

arguments for long-lived remnant NS?

- Yu&Dai, 1711.01898: *"A long-lived remnant neutron star after GW 170817 inferred from its associated kilonova"*
- Ai et al., 1802.00571: *"The allowed parameter space of a long-lived neutron star as the merger remnant of GW170817"*
- Matsumoto et al., 1802.07732: *"Is the macronova in GW170817 powered by the central engine?"*
- Li et al., 1804.06597: *"What powered AT2017gfo associated with GW170817?"*
- Geng et al., 1803.07219: *"Brightening X-ray/Optical/Radio Emission of GW170817/SGRB 170817A: Results of an Electron-Positron Wind from the Central Engine?"*

summary

- long-lived NS with low $B(\lesssim 10^{12}\,\mathrm{G})$ could help lightcurve fitting
- problems making that low-B scenario work
- $\Rightarrow$ not the most likely scenario, but not excluded, so worth testing!

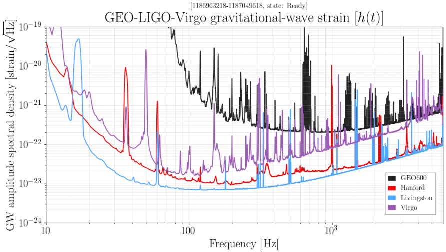
[6] Abbott et al. (LVC), *APJL* **848**:L13 (2017) [10] Abbott et al. (LVC), *APJL* **851**:L16 (2017)
[8] Kasen et al., *Nature* **551**,80 (2017) [9] Granot et al., *APJL* **850**:L24 (2017)

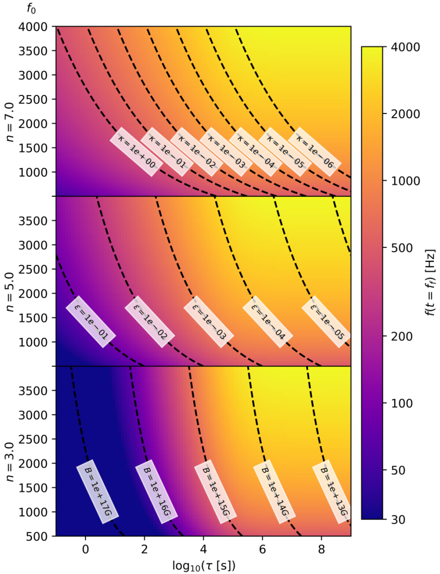
❸ long-duration remnant searches

power-law spindown

$$f_{\mathrm{GW}}(t) = f_0\left(1+\frac{t}{\tau}\right)^{\frac{1}{1-n}}$$ [12]

- for f_0 in $1000 - 4000\,\mathrm{Hz}$, reasonable B-fields and ϵ yield spindowns into sensitive range
- most SNR from high f, though
- $d=40\,\mathrm{Mpc}$: need $\epsilon \gtrsim 0.01$, high τ

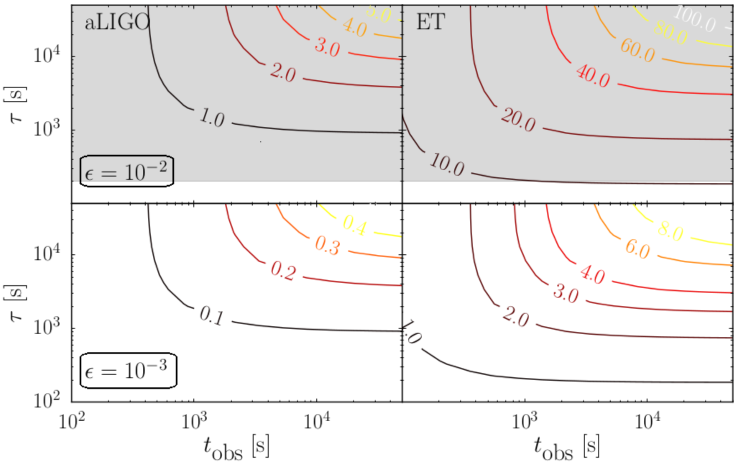




[12] Lasky et al., dcc.ligo.org/T1700408 [17] Zhang & Meszaros, *APJ* **552**,L35 (2001)
[18] Ho & Lai, *APJ* **543**,386-394 (2000)

❸ long-duration remnant searches

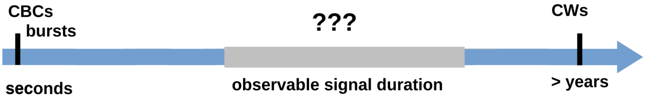
single-detector optimal matched-filter SNRs at $d = 40\,\mathrm{Mpc}$



[Sarin et al., *arXiv:*1805.01481]

❸ long-duration remnant searches

long post-merger GWs: between traditional analysis regimes



- some unmodelled pipelines easy to modify
- better sensitivity possible when *assuming* power-law spindown

recent development on unmodelled pipelines:

- STAMP-VLT (stochastic search, S. Banagiri @Minnesota [19])
- hidden-Markov Viterbi tracking (L. Sun @Melbourne [21])

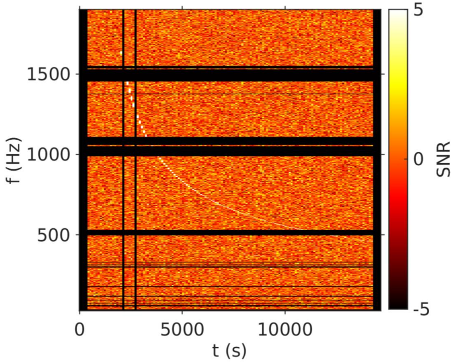
recent development on modelled pipelines:

- SkyHough [22] variant (M. Oliver & A. Sintes @Mallorca)
- FrequencyHough [23] variant (A. Miller, C. Palomba et al. @Rome)

[19] Thrane, Mandic, Christensen, *PRD* **91**,104021 (2015) [21] Sun et al., *PRD* **97**,043013 (2018)
[22] Krishnan et al., *PRD* **70**,082001 (2004) [23] Palomba et al., *CQG* **22**,1255 (2005)

❸ STAMP-VLT

- unmodelled search
- different configuration of same algorithm as in previous search [10]
- clustering power in time-freq plane [14, 19]
- candidates selected with Bézier curves
- data split into 15 000 s maps (500 s in [10])



[S. Banagiri, STAMP team]

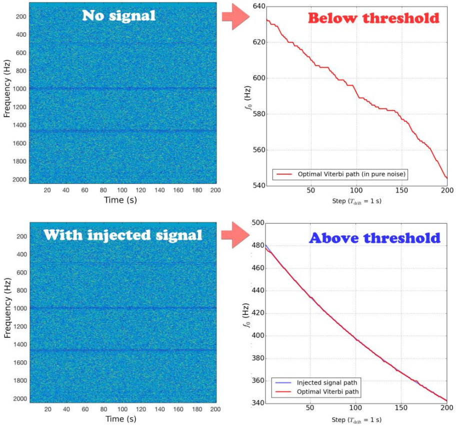
(simulated signal; dark bands: vetoed contaminations)

- two separate bands: 30–1900 Hz and 2000-4000 Hz
- 100 s × 1 Hz and 50 s × 1 Hz resolution

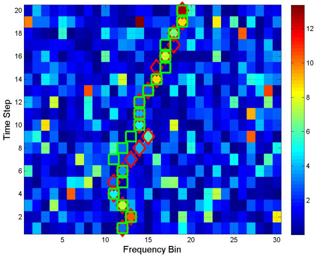
[10] Abbott et al. (LVC), *APJL* **851**:L16 (2017) [14] Thrane et al., *PRD* **83**,083004 (2011)
[19] Thrane, Mandic, Christensen, *PRD* **91**,104021 (2015)

❸ Hidden Markov Model

- unmodelled search
- allows for signal drift from bin to bin in time-frequency plane [21, 24]



[L. Sun]



[L. Sun]

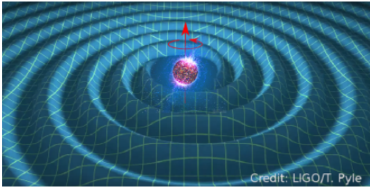
- previously used for Sco X-1 binary [20] and supernova remnants [21]
- GW170817 post-merger: analysing 10 000 s of data

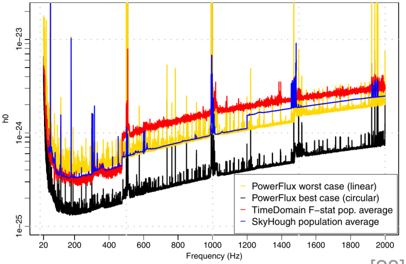
[20] Abbott et al. (LVC), *PRD* **95**,122003 (2017) [21] Sun et al., *PRD* **97**,043013 (2018)
[24] Suvorova et al., *PRD* **93**,123009 (2016)

❸ CW-like modelled searches

Continuous Waves

- spinning NSs with non-axisymmetric deformations emit GWs
- weak ($h_0 \lesssim 10^{-25}$!), long duration, slow evolution
- computationally challenging
- several search methods routinely applied to LIGO+Virgo (e.g. [25, 26, 27, 28])





[28]

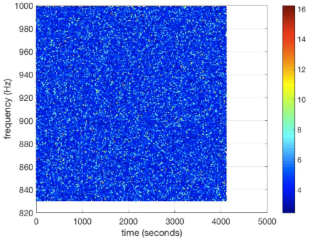
adaptation to post-merger remnant

- rapid frequency evolution
- hence limited in-band signal length
- but possibly stronger signal

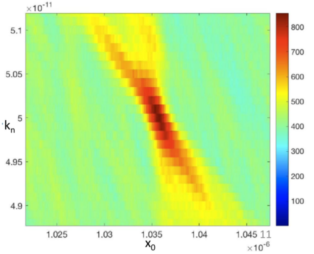
[25] Abbott et al. (LVC), *APJ* **839**,12 (2017) [26] Abbott et al. (LVC), *PRD* **96**,122004 (2017)
[27] Abbott et al. (LVC) *PRD* **96**,062002 (2017) [28] Abbott et al. (LVC), *PRD* **97**,102003 (2018)

Hough transform searches

- computationally efficient CW searches [22, 23]
- peaks in time-frequency data mapped to different space and straight lines detected with Hough transform method
- grid over model parameters (n, f_0, τ)



⇓ [A. Miller]



Discrete PowerLaw Tracker

- adapted from [22, 29] (SkyHough)
- 1–8 s long SFTs, 1 day of data

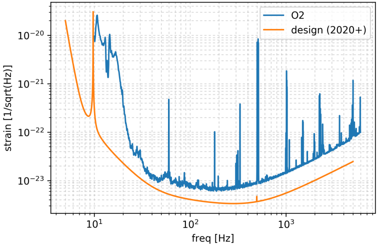
FrequencyHough post-merger

- adapted from [23, 30]
- transforming to $k_n = -\dot{f}/f^n, \quad x_0 = f_0^{1-n}$
- 2–8 s SFTs, 1 day of data

[22] Krishnan et al., *PRD* **70**,082001 (2004) [29] Aasi et al. (LVC), *CQG* **31**,085014 (2014)
[23] Palomba et al., *CQG* **22**,1255 (2005) [30] Astone et al., *PRD* **90**,042002 (2014)

4 BNS observations in future observing runs

- improved high-freq sensitivity crucial for postmerger search
- aLIGO currently being upgraded between O2 and O3
- design sensitivity: 2020+ [31]
- estimate for ms-duration signals: $\sim$ 20–40 Mpc horizon [32]
- for long-duration searches: very parameter-dependent



- GRB/X-ray observations yield encouraging constraints [33]
- successful post-merger GW detection $\Rightarrow$ strong evidence about remnant identity (long-duration signal: fully conclusive), while EM evidence often ambiguous
- remnant identity yields EoS constraints [7] complementary to inspiral (+probing *difference* of pre- and post-merger EoS!)

[31] Barsotti et al., dcc.ligo.org/T1800044 [32] Clark et al., *CQG* **33**,085003 (2016)
[33] Sarin et al., *arXiv:*1805.01481 [7] Bauswein et al., *APJL* **850**:L34 (2017)

Thanks for your attention!

Questions welcome!

Please also go see Andrew Miller's poster.

references

[1] Abbott et al. (LVC), *PRD* **119**,14 (2017)

[2] Abbott et al. (LVC+MMA), *APJL* **848**:L12 (2017)

[3] Abbott et al. (LVC), *arXiv*:1805.11579

[4] Abbott et al. (LVC), *arXiv*:1805.11581

[5] Abbott et al. (LVC), *Nature* **551**,85-88 (2017)

[6] Abbott et al. (LVC), *APJL* **848**:L13 (2017)

[7] Bauswein et al., *APJL* **850**:L34 (2017)

[8] Kasen et al., *Nature* **551**,80 (2017)

[9] Granot et al., *APJL* **850**:L24 (2017)

[10] Abbott et al. (LVC), *APJL* **851**:L16 (2017)

[11] Corsi & Mészáros, *APJ* **702**,1171 (2009)

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[17] Zhang & Meszaros, *APJ* **552**,L35 (2001)

[18] Ho & Lai, *APJ* **543**,386-394 (2000)

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[24] Suvorova et al., *PRD* **93**,123009 (2016)

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[30] Astone et al., *PRD* **90**,042002 (2014)

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[32] Clark et al., *CQG* **33**,085003 (2016)

[33] Sarin et al., *arXiv*:1805.01481

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