Exploiting Neutron Star mergers with a network of advanced gravitational-wave detectors

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GRASS 2018

Padova 01-02/03

The last LIGO-Virgo science run provided an unprecedented result.

Selected for a Viewpoint in *Physics*
PRL **119**, 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

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

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 $\deg^2$ (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

DOI: 10.1103/PhysRevLett.119.161101

The joint gravitational and electromagnetic observations provide insight into astrophysics, dense matter, gravitation and cosmology.

GW170817 sets an upper limit for BNS mergers at 1540^{+3200}_{-1220} Gpc^{-3}yr^{-1} and the masses (low spin priors) are in the range **1.17-1.60 M_{sun}**.

This observation is coincident in time and location with **GRB170817A** and optical transient **SSS17A** from galaxy NGC4993.

Emissions across all EM spectrum (UV, X-rays, Radio)

At **44 Mpc**, this is the closest GW event observed so far.

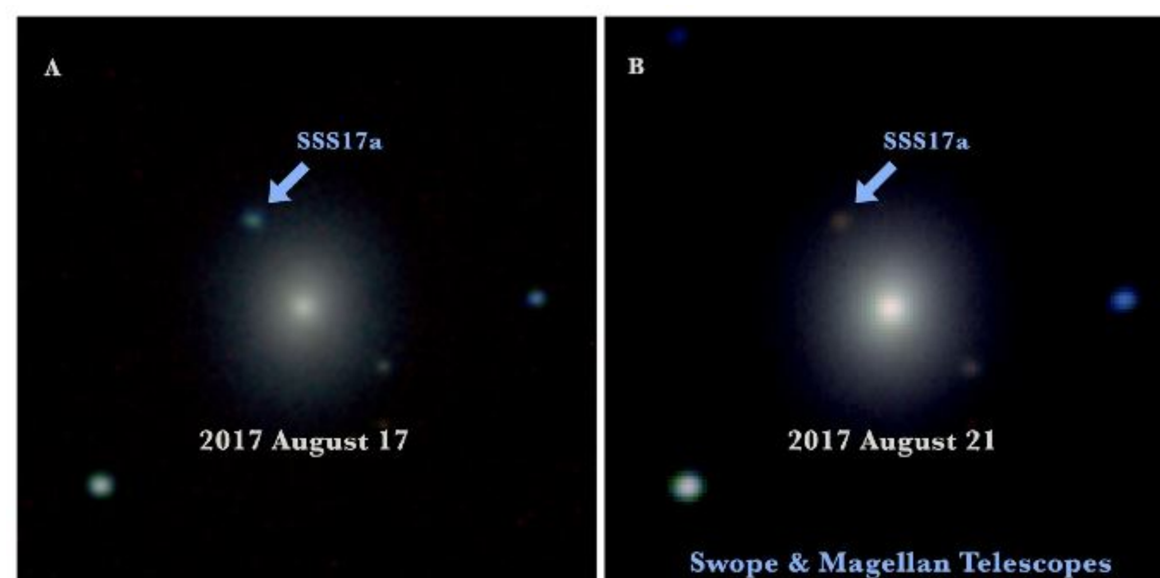


Image credits: Ryan Foley and 1M2H team

APJ 848-2 (2017)

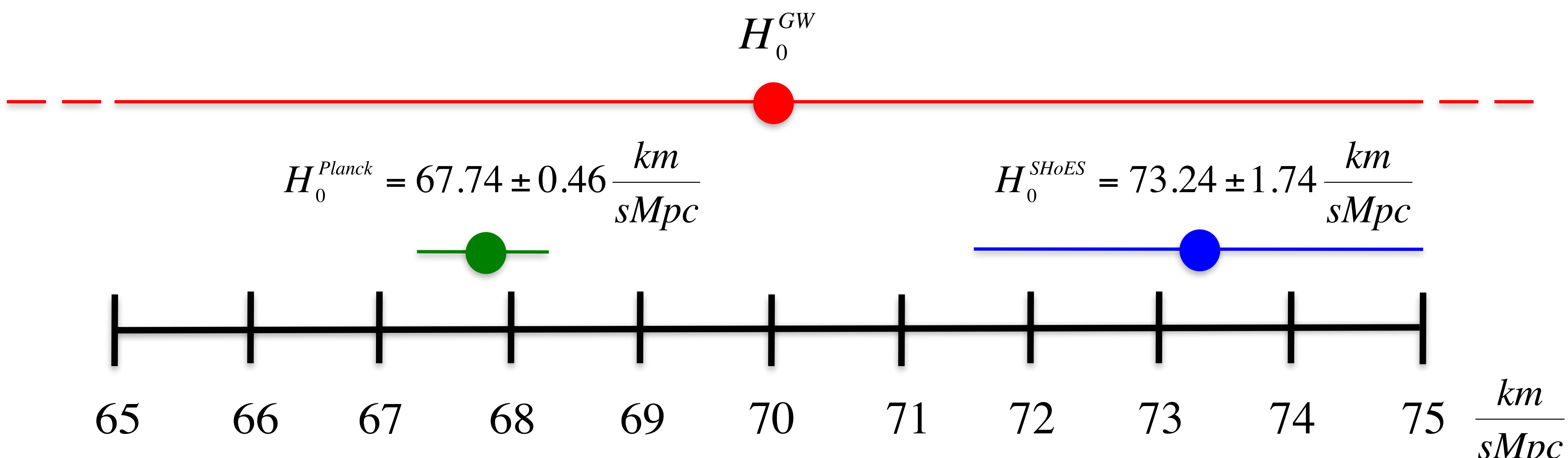
Using EM counterparts, BNS mergers can be used as **standard sirens** for the measurement of H_0. Nature 24471 (2017)

$$d_{NGC\,4993} = 41.1 \pm 5.8\, Mpc$$

$$d_{GW} = 43.8^{+2.9}_{-6.9}\, Mpc$$

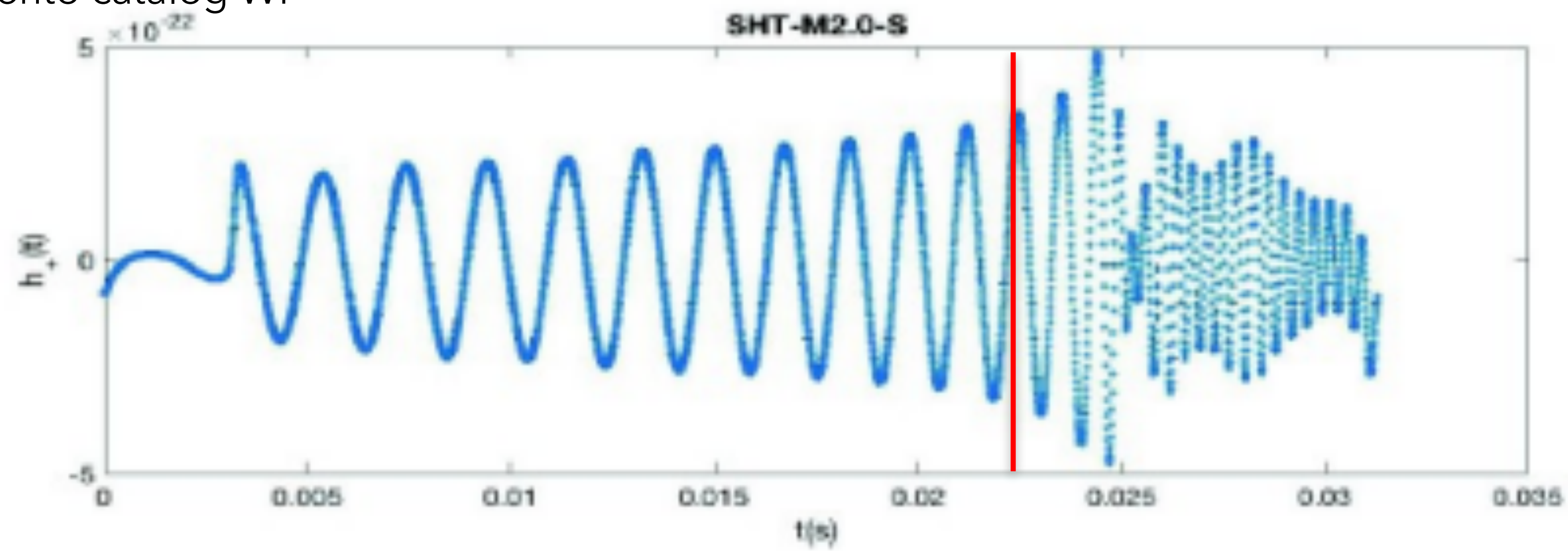
$$v_H = 3017 \pm 166 \frac{km}{s}$$

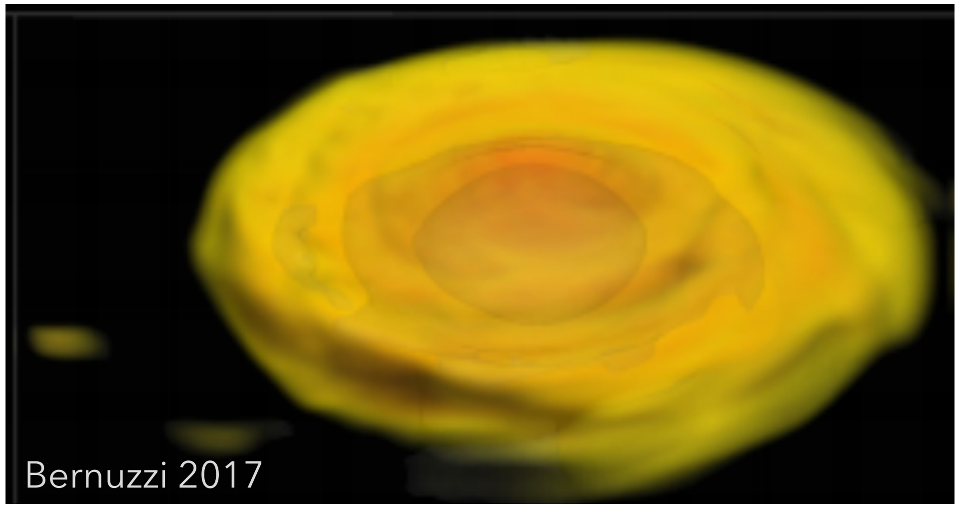
$$H_0^{GW} = \frac{v_H}{d} = 70^{+12}_{-8} \frac{km}{sMpc}$$

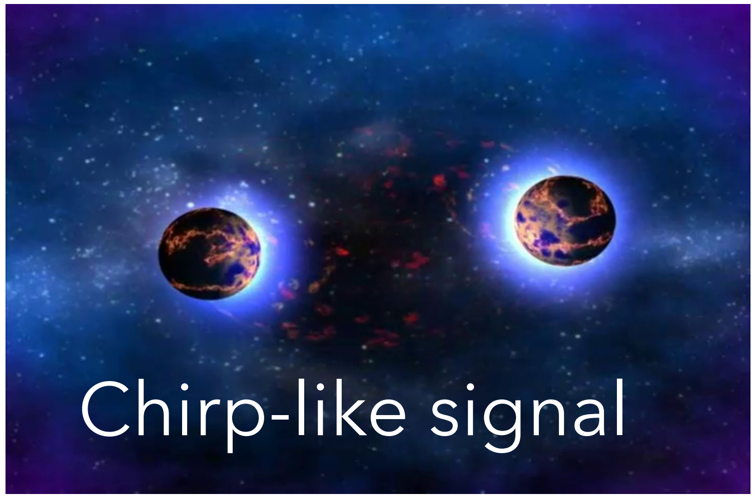


The fate of a Binary Neutron Star

Trento catalog WF



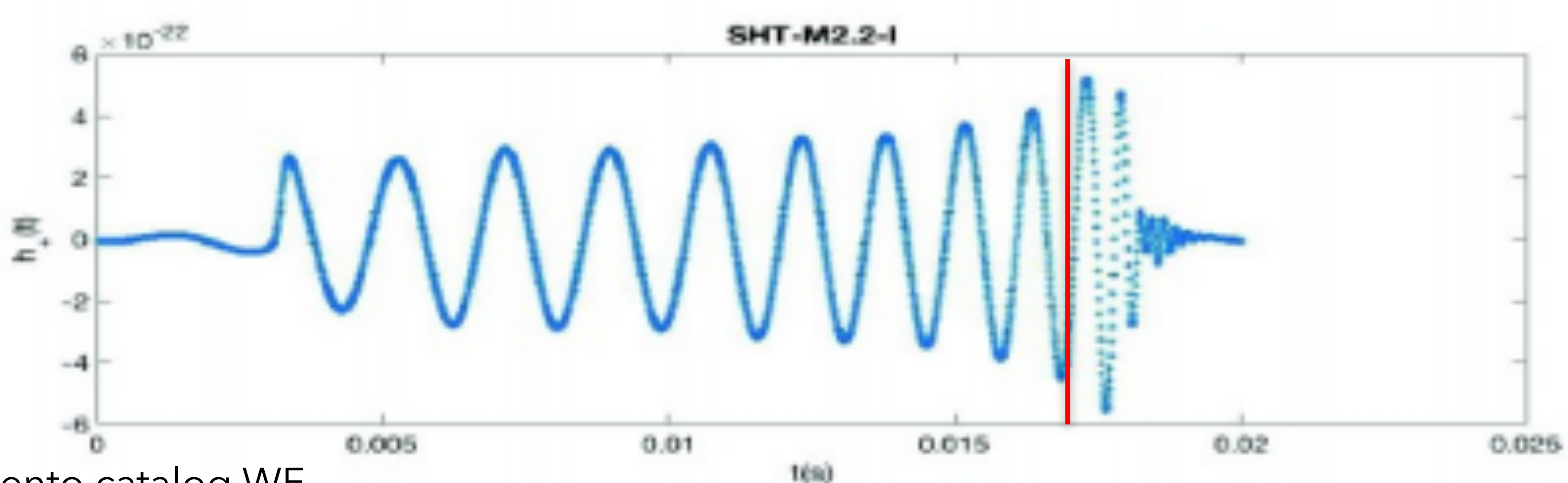




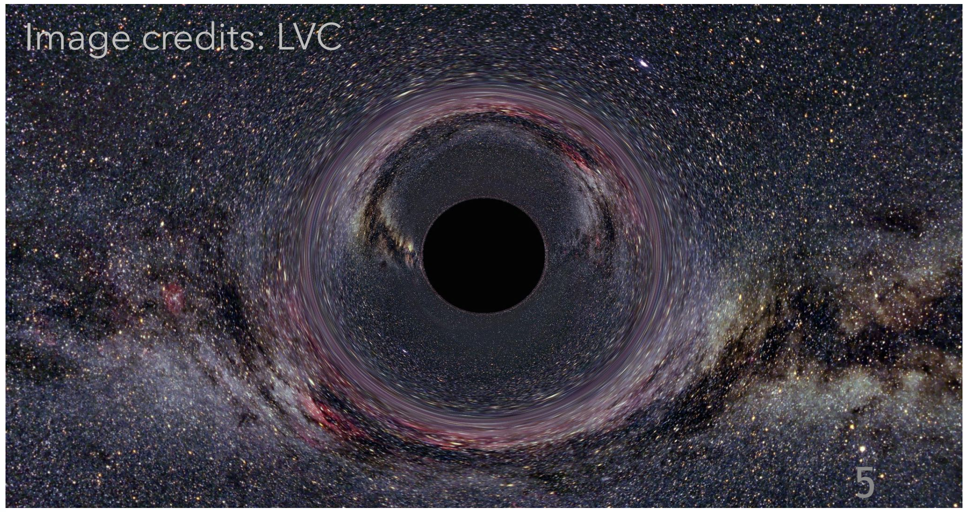
Delayed collapse:
(2 - 4 kHz)

- Supramassive NS (10 - 100 s)
- Hypermassive NS (10 - 100 ms)
- Stable NS (100 - 10^5 s)

Prompt collapse to BH (6 - 7 kHz)



Trento catalog WF



What can GWs tell us? - Neutron Stars

Inspiral

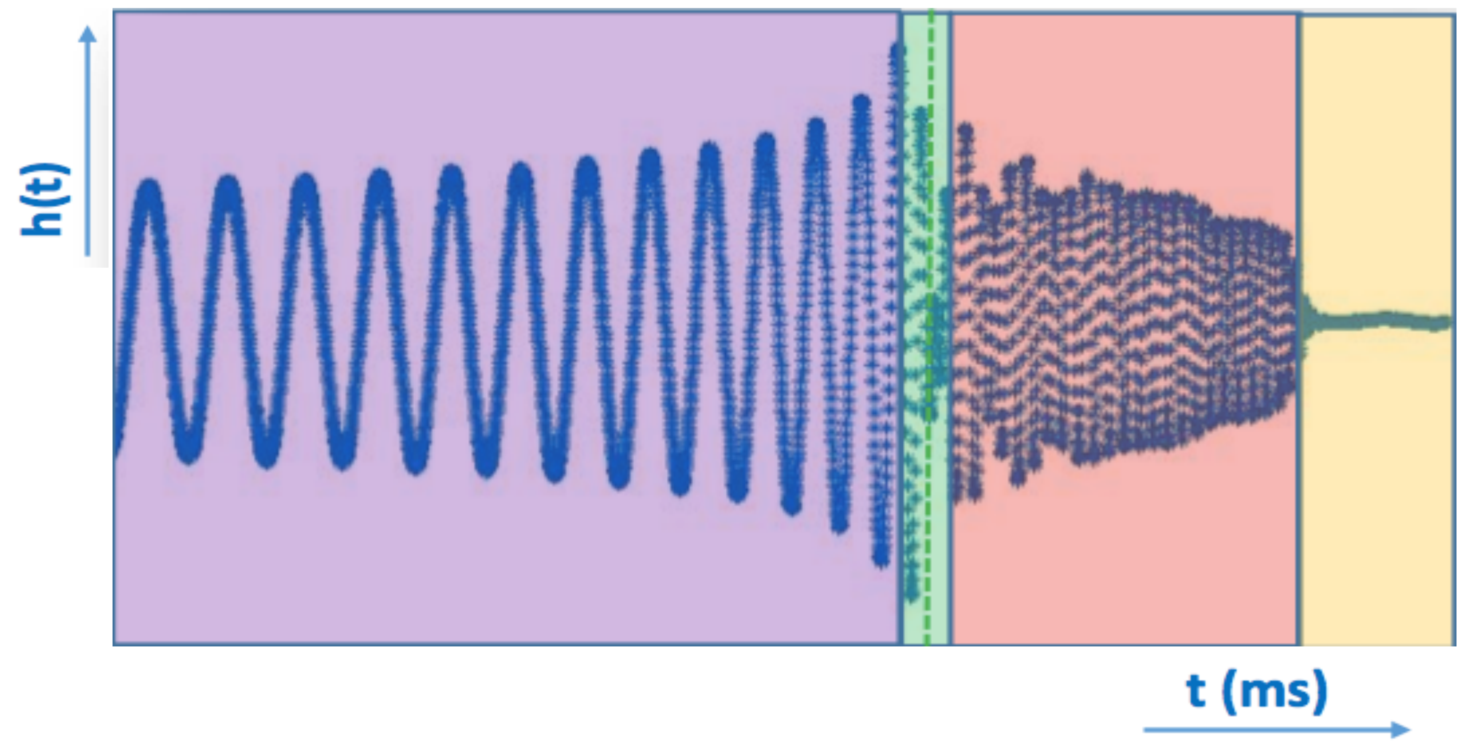
Phase evolution

Tidal deformability

Constraints on EOS stiffness

Merger

Collision and merger of the two NSs



Post-merger

Frequency peaks in PM

Compactness, radius, ecc…

Ringdown

Final mass and spin

What can GWs tell us? - Neutron Stars

Inspiral

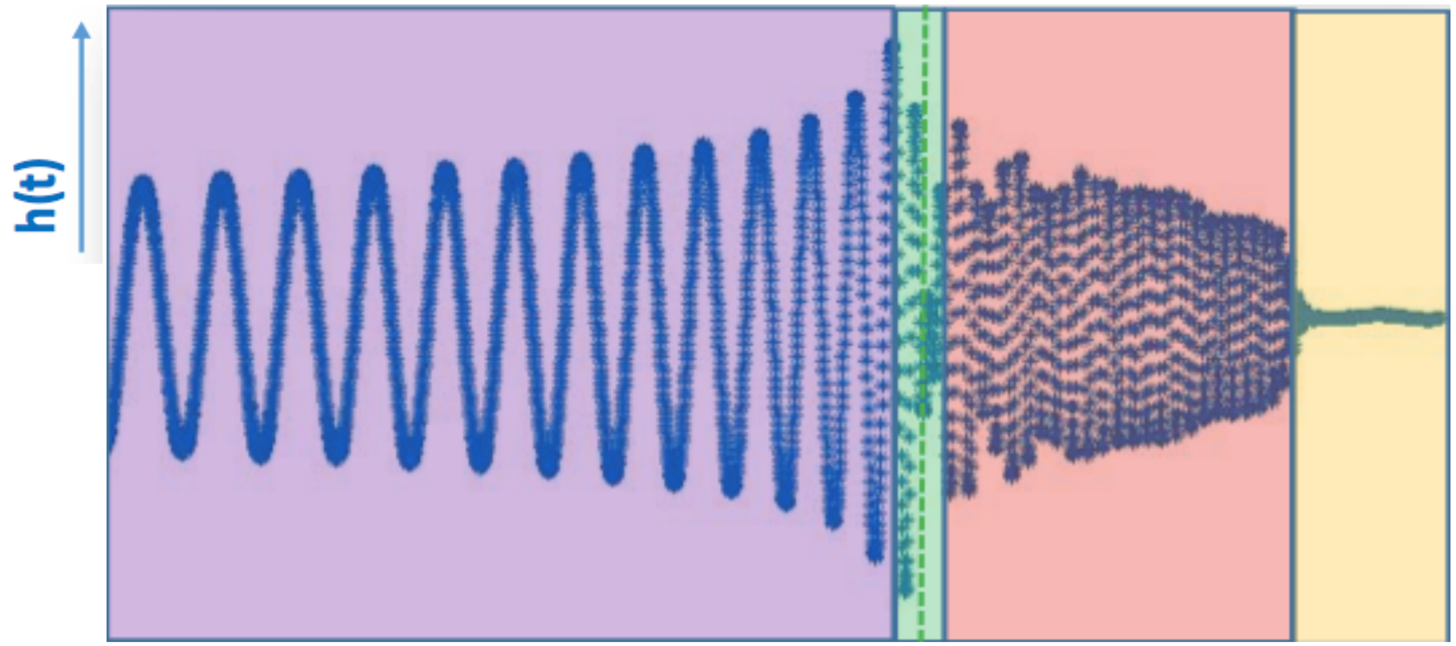
Phase evolution

↓

Tidal deformability

↓

Constraints on EOS stiffness



The phase evolution is driven mainly by the tidal deformability

$$\simeq k_2 \left(\frac{R}{r}\right)^5$$

If NS are spinning there is another EOS-dependent effect scaling as

$$\simeq \frac{QS^2}{r^2}$$

Harry & Hinderer - arXiv:1801.09972v1

What can GWs tell us? - Neutron Stars

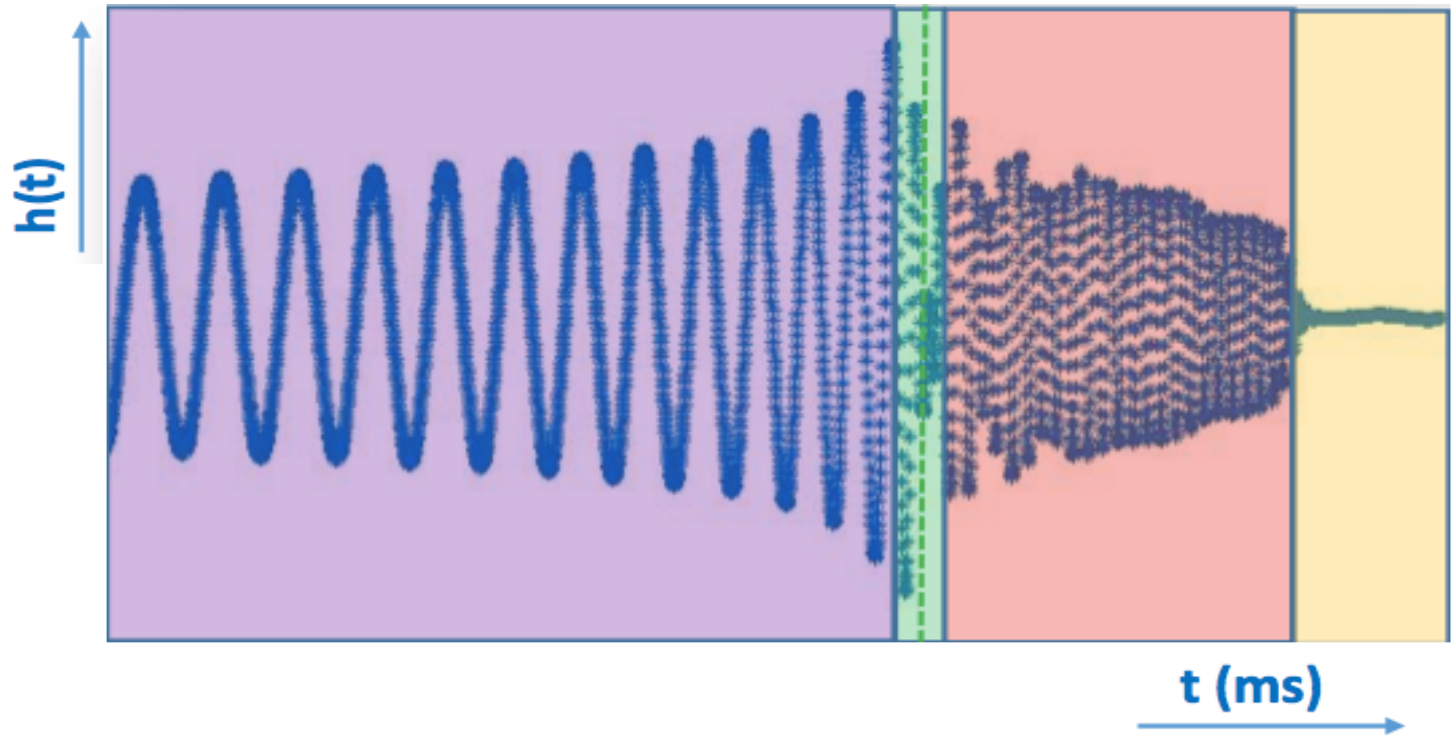
The Post-Merger spectrum will present at least 3 strong peaks.

$$f_1, f_2, f_3$$

$$f_2 \simeq \frac{(f_1 + f_3)}{2}$$

Mode couplings may give rise to a fourth peak dubbed:

$$f_{2-0}$$



Post-merger

Frequency peaks in PM

↓

Compactness, radius, ecc…

Rezzolla & Takami
PRD 93 - 124051 (2016)

Takami, Rezzolla, Baiotti
PRD 91 - 064001 (2015)

Drawbacks

- BNS mergers are extremely difficult to model
- Wide parameter space
- Possible unexpected and un-modeled physics

Inadequate templates can lead to a potential loss of signal and/or information (e.g. most models take into account low-spinning BNS only).

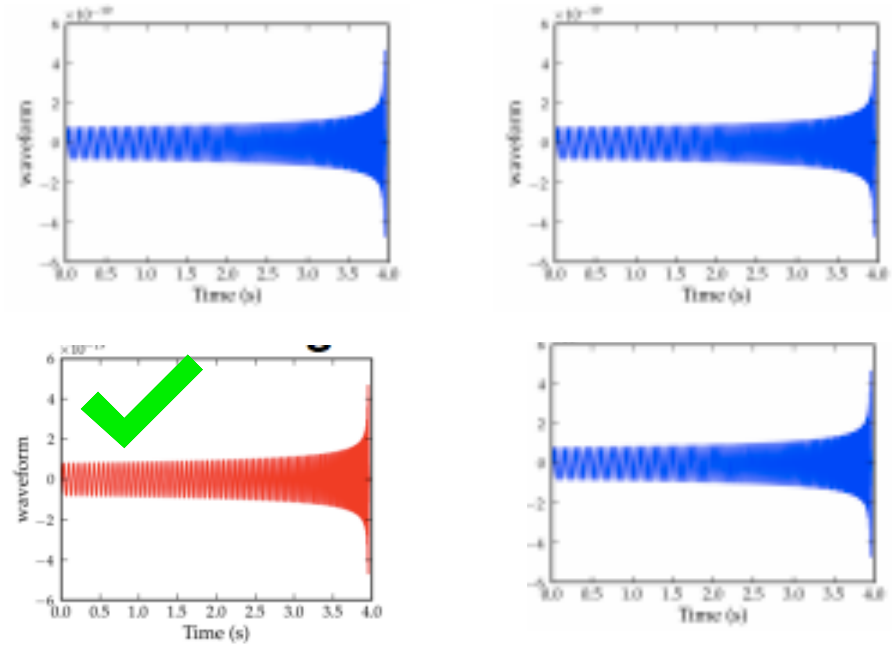
↓

Procedures not relying on models are needed.

LIGO/Virgo Data Analysis: transients

TEMPLATE SEARCHES

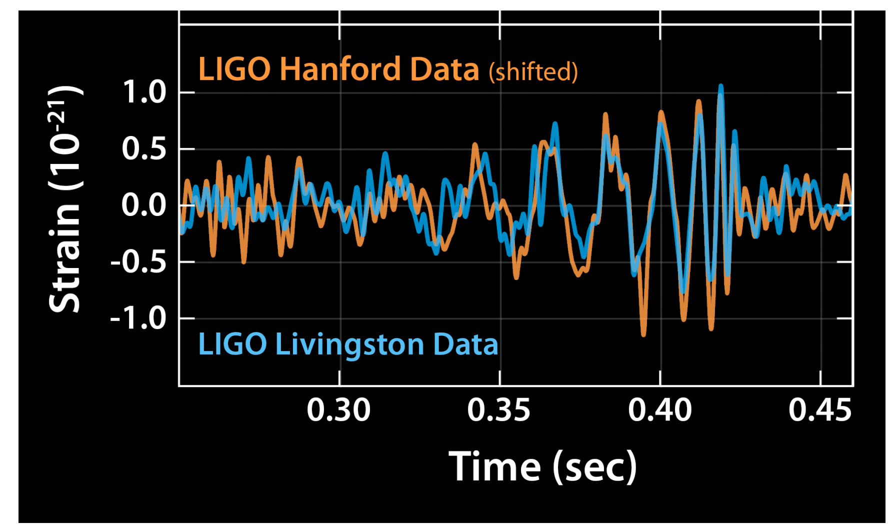
Find template that fits data best (matched filtering)



- Confident detection and PE
- Need exact source model, may fail if models don't match Nature

BURST SEARCHES

Minimal or no assumptions on source waveform and parameters



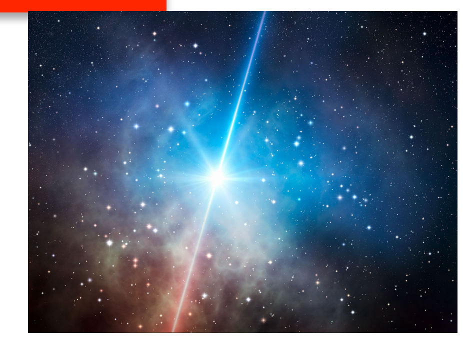
- Can search for un-modeled and unexpected sources
- Limited parameter estimation

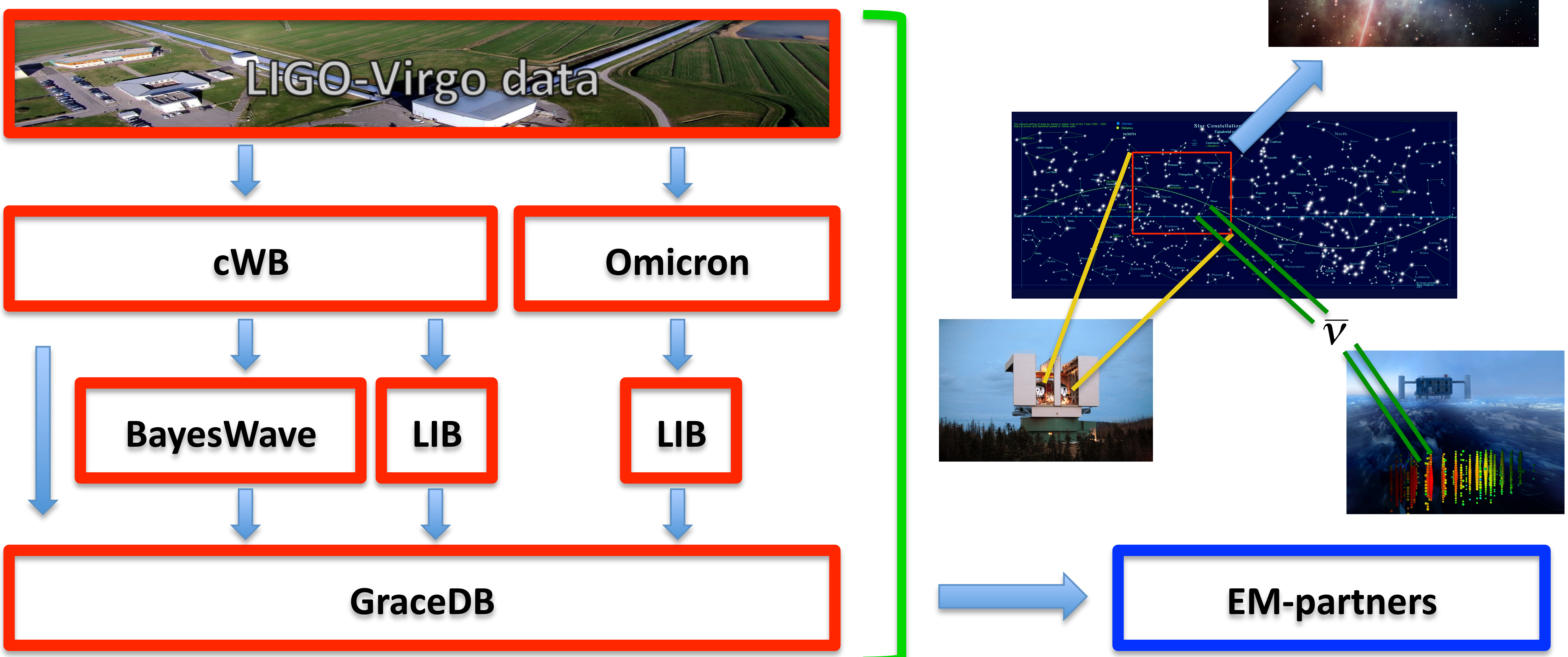
Both suitable for low latency analysis.

Low latency pipelines

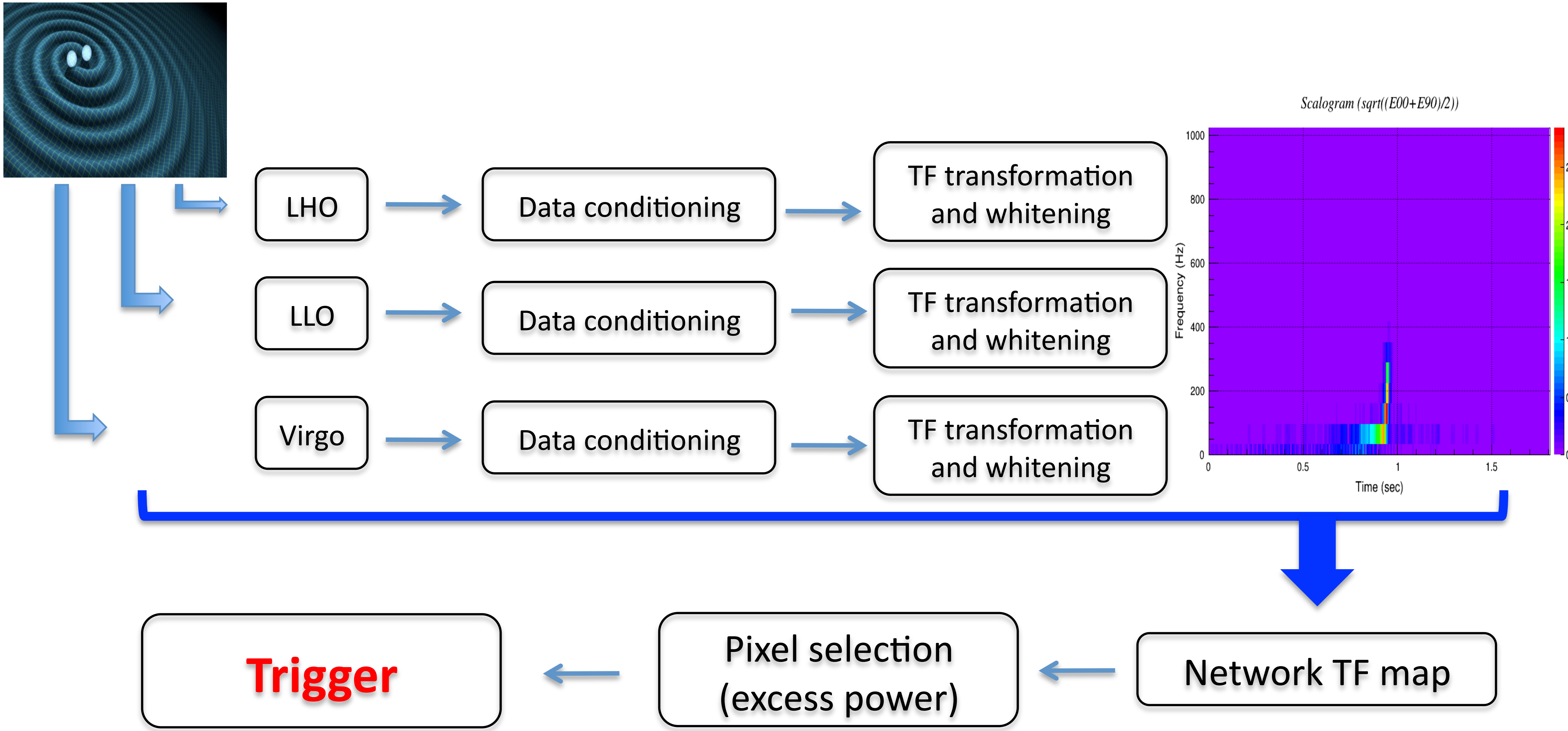
Un-modeled burst search pipelines (PRD.93.122004)

- Coherent WaveBurst (cWB – Klimenko et al. arXiv 1511.05999)
- oLIB (Omicron + LIB – Lynch et al. arXiv 1511.05955)
- cWB + BayesWave (van der Sluys et al. CQG 32(13):135012)





What is cWB?



Triggers are analyzed coherently to estimate the signal waveform and parameters using a constrained likelihood method (maximization over sky position loop)

(Klimenko et al. *PRD 72:122002, 2005*).

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GW170817
Post-Merger analysis

APJ 851 - 1 (2017)

Estimated PM energy is: $E_{GW} = 3.265 M_{\odot} c^2$

For short duration signals (<1s), cWB has a lower limit of.

$$4.8 M_{\odot} c^2$$

Best upper limit:

No constrains possible.

$h_{rss}^{50\%} = 2.1 \times 10^{-22} Hz^{-1/2}$

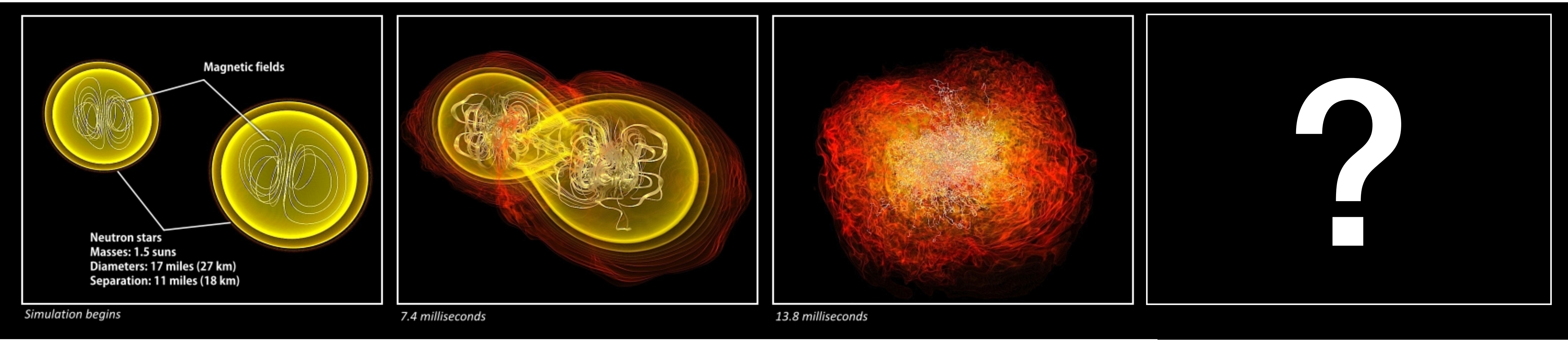
$1kHz < f_{GW} < 4kHz$

For intermediate duration signals (<500s):

Bar-mode model (cWB - STAMP): $h_{rss}^{50\%} = 5.9 \times 10^{-22} Hz^{-1/2}$ $E_{GW} = 2 M_{\odot} c^2$

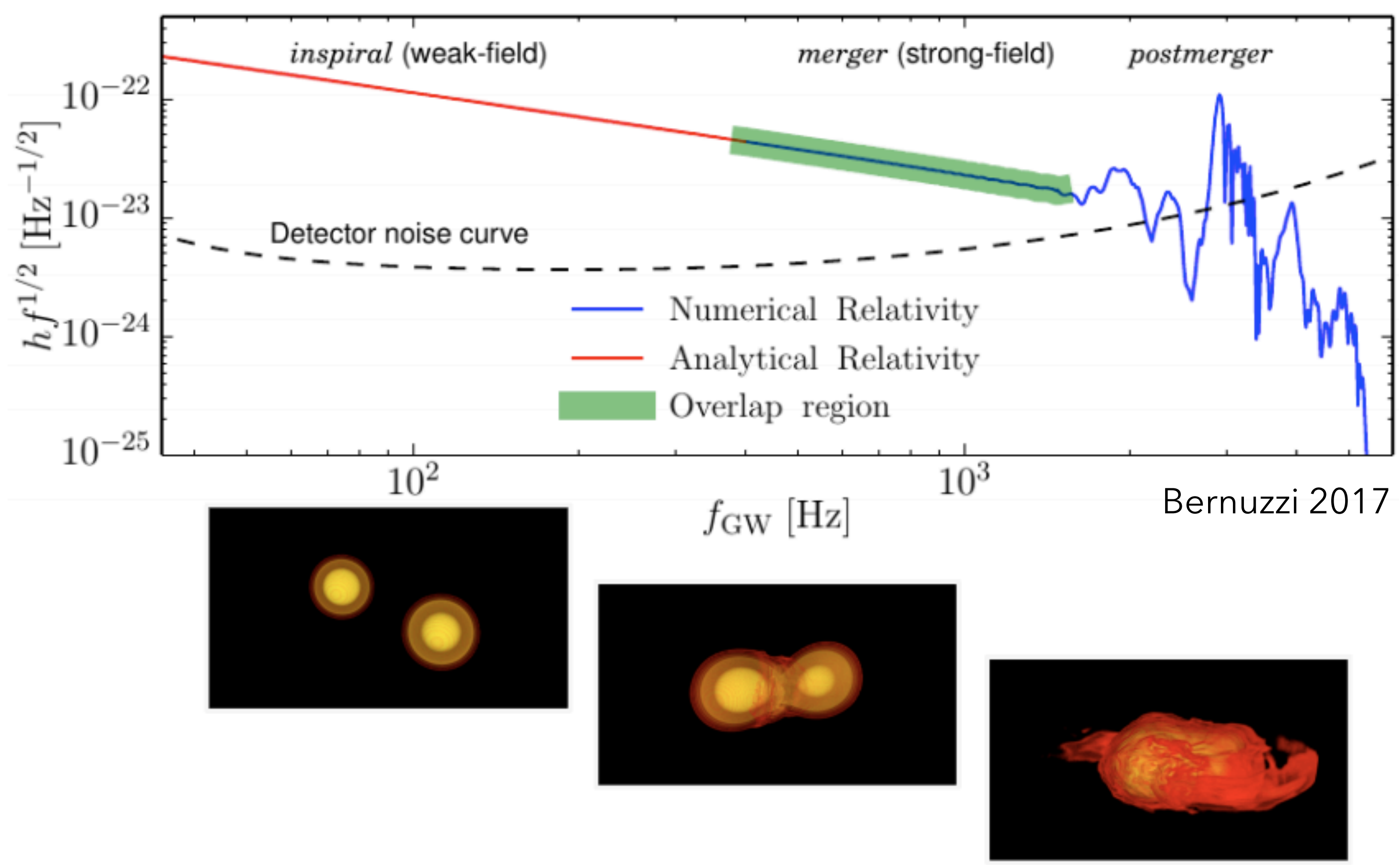
Magnetar model (STAMP) $h_{rss}^{50\%} = 8.4 \times 10^{-22} Hz^{-1/2}$ $E_{GW} = 4 M_{\odot} c^2$

Can we observe a PM signal with current sensitivities?



Sensitivity not enough yet

The post merger falls in a frequency region where the detectors are not sensitive enough or not calibrated.



Bernuzzi 2017

We can only set upper limits on the signal.

Conclusions

- At 40 Mpc even a matched-filter search would have a SNR of less than 2.
- At design sensitivity, matched filter with precisely modelled PM could detect merger remnants between 20 and 40 Mpc with a reasonable SNR.
- Theoretical uncertainties make un-modelled searches important.

The End

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