SEARCHING FOR AND MEASURING GRAVITATIONAL WAVES

OPPORTUNITIES AND CHALLENGES

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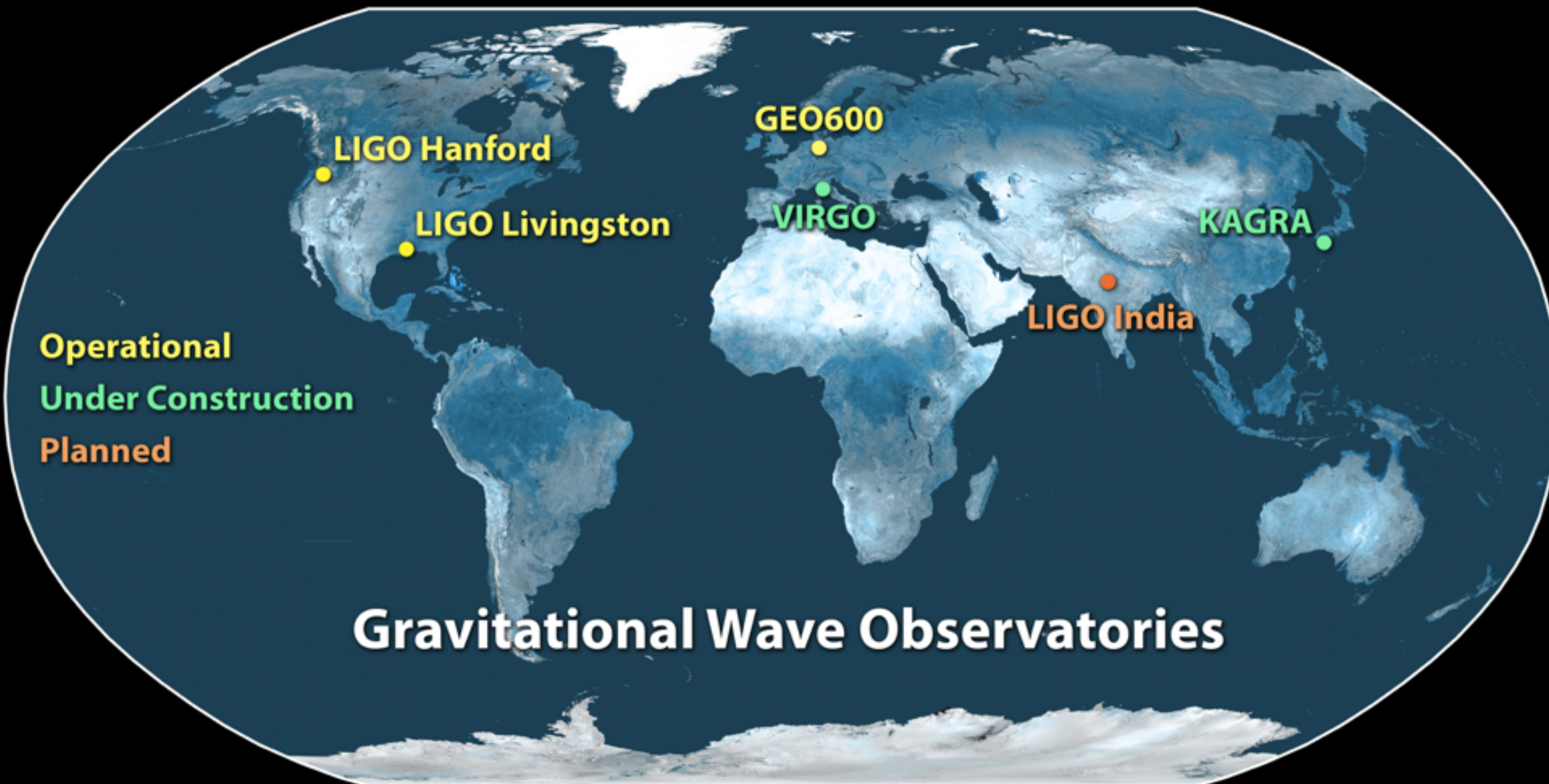
on behalf of the LIGO Scientific Collaboration and Virgo Collaboration

OVERVIEW

- LIGO has taken about 165 days worth of data over two observing runs
    - made five discoveries of
- LIGO and Virgo jointly took data during 1-25 August 2017
    - a network of three (or more) detectors is essential for full reconstruction of the incident gravitational wave
        - LIGO and Virgo have data sharing agreements
        - they make each others data available within seconds of data taking
    - LIGO and Virgo jointly detected GW170814 and GW170817
- ~~GW170814 another binary black hole merger~~
    - ~~detected in triple coincidence, localized to a factor of 30 better than LIGO alone, 3 detectors give polarization~~
- GW170817 - first observation of a binary neutron star merger
    - beginning of multi-messenger astronomy with gravitational waves

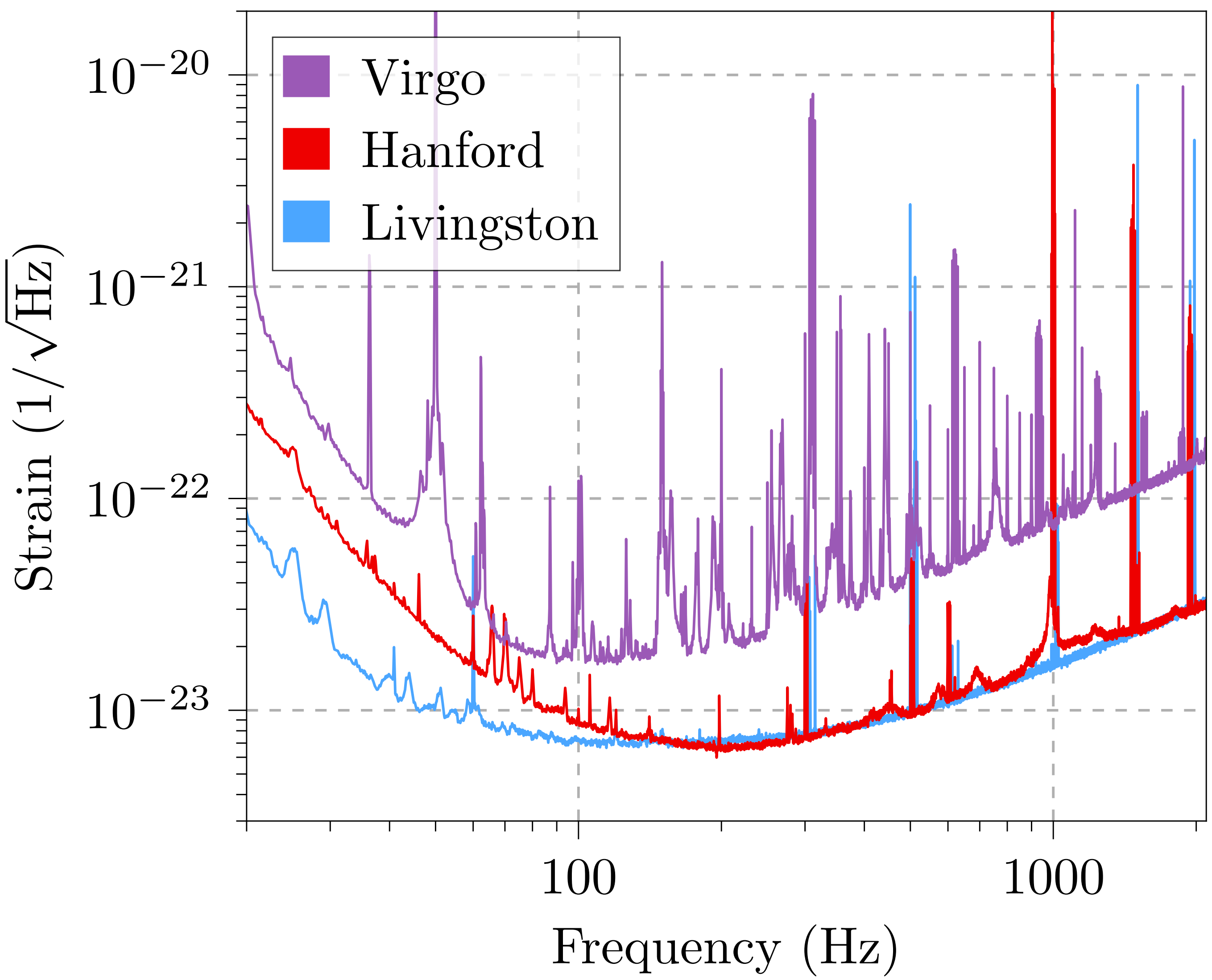
AND THEN THERE WERE THREE …

GW INTERFEROMETER NETWORK



Credit: LVC/EPO

SENSITIVITY AND DISTANCE REACH TO BINARY NEUTRON STARS



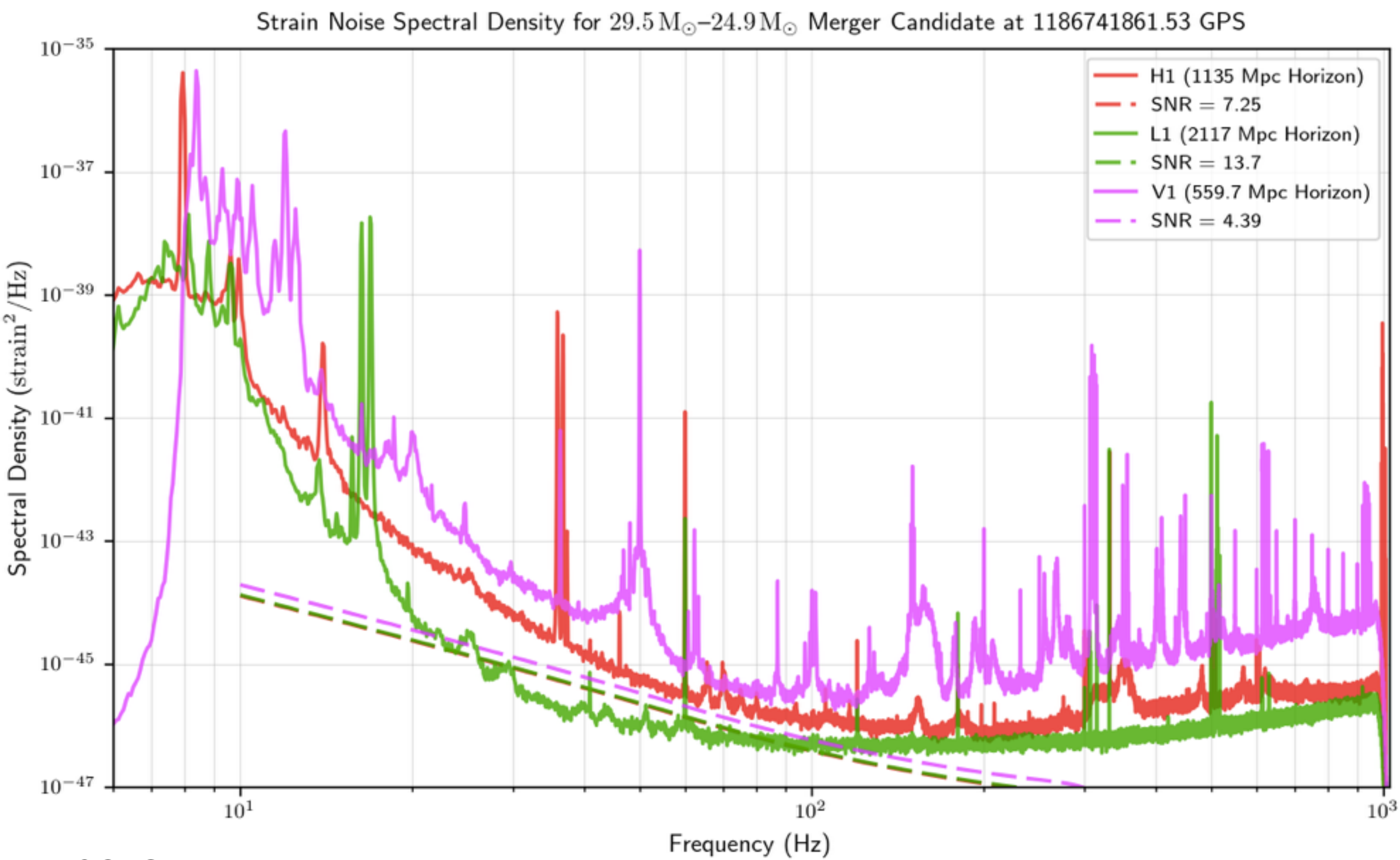
- **horizon distance** of a detector: distance at which a face-on, over-head binary would produce a signal to noise ratio of 8
- **distance reach** of a detector: a factor 2.33 smaller than horizon distance

Detector	Range	Horizon
LIGO Livingston	100 Mpc	230 Mpc
LIGO Hanford	50 Mpc	115 Mpc
Virgo	27 Mpc	63 Mpc

Phys Rev Lett. 119 141101 (2017)

TWO WEEKS INTO THE RUN ...

GSTLAL REPORTS A CANDIDATE

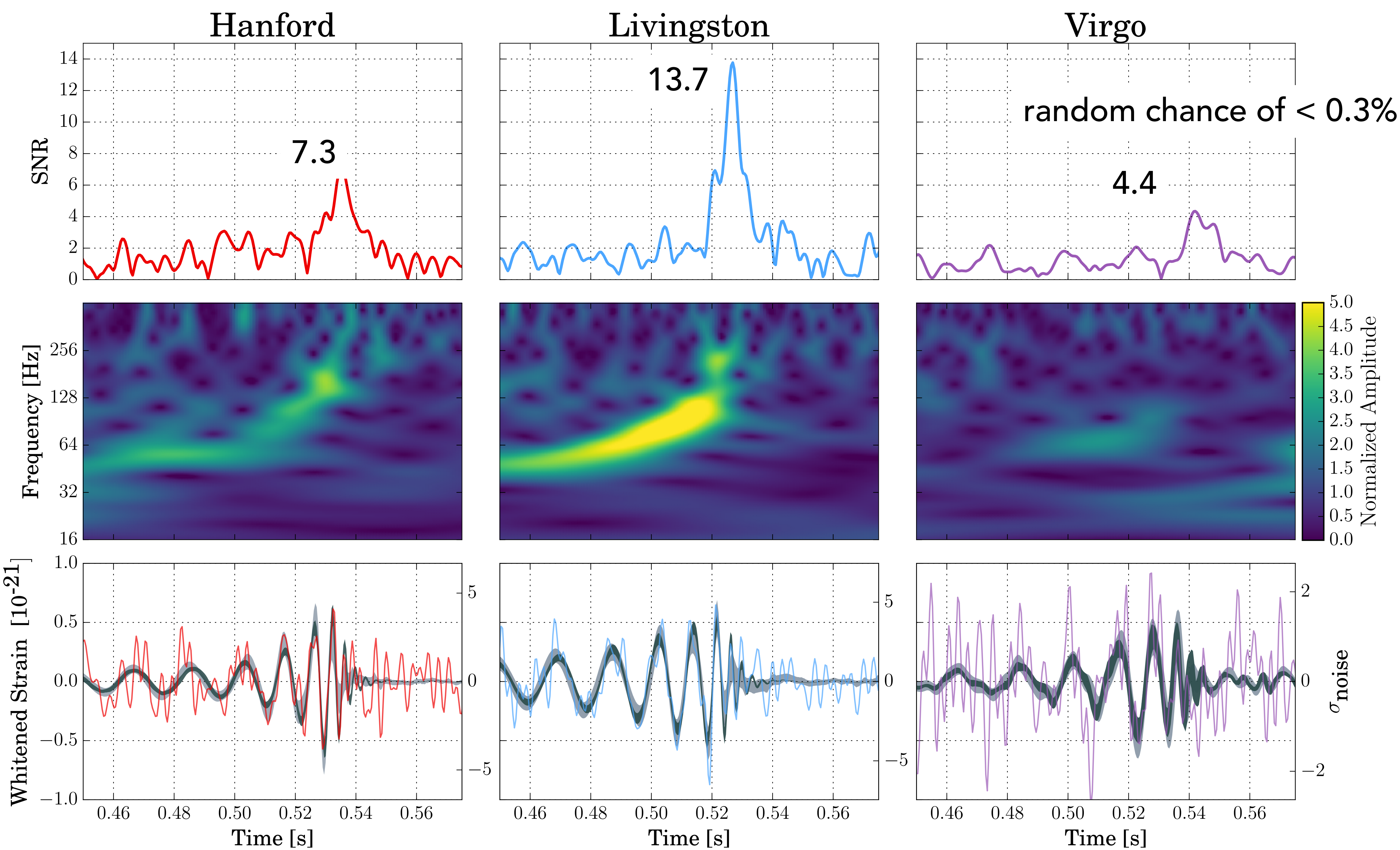


LSC: GraceDB page

GW170814: DETECTION

THREE DETECTOR SIGNAL MODEL IS PREFERRED WITH BAYES FACTOR OF 1600

Signal arrived on August 14, 2017 10:30:43 UTC at Livingston, 8 ms later at Hanford, 14 ms later at Virgo; false alarm rate < 1 in 140,000 years



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THREE DAYS AFTER GW170814 ...

GW170817: AUGUST 17, 2017, 12:41:04 UTC FIRST OBSERVATION OF A NEUTRON STAR INSPIRAL

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

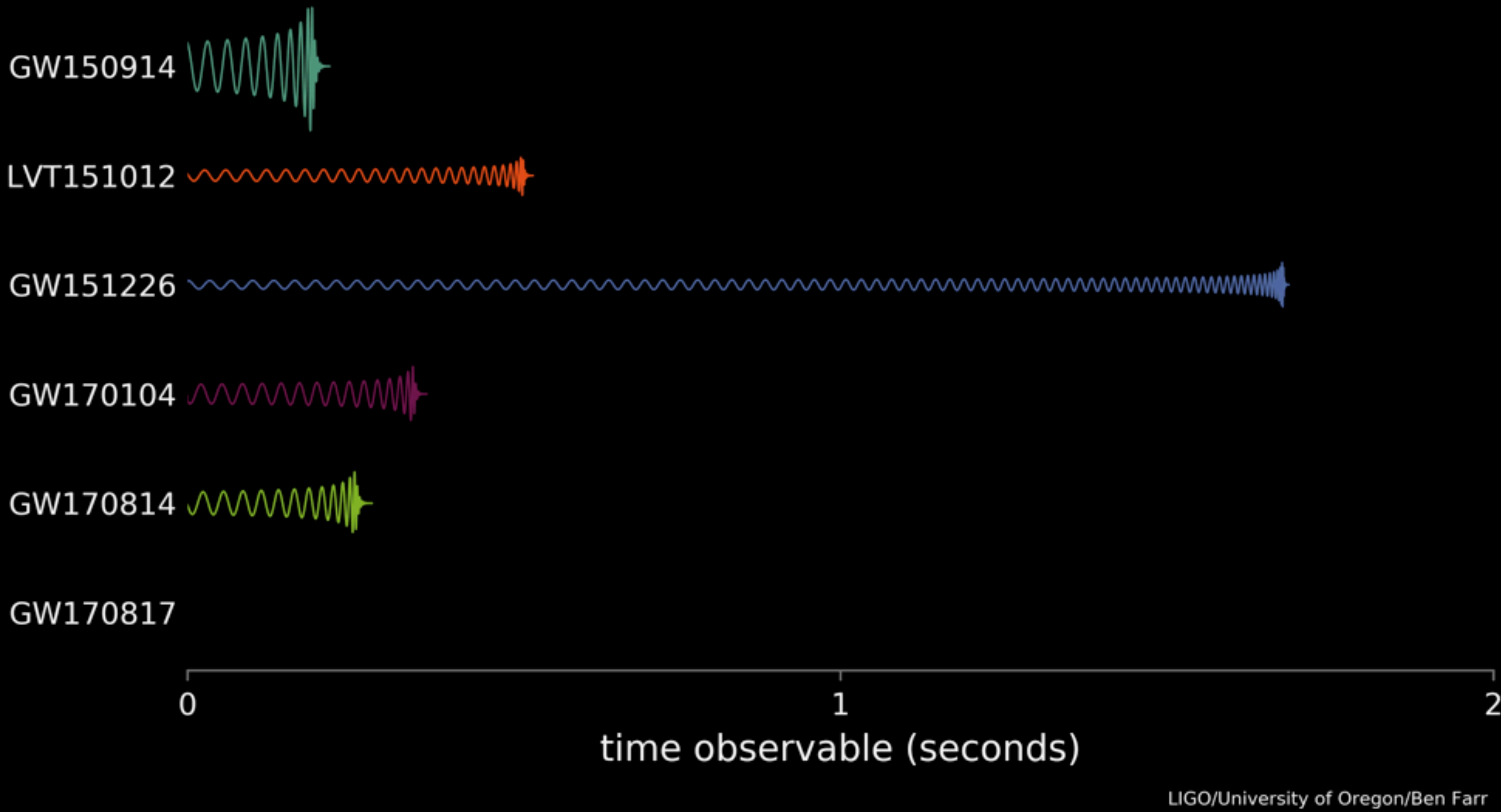
GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)

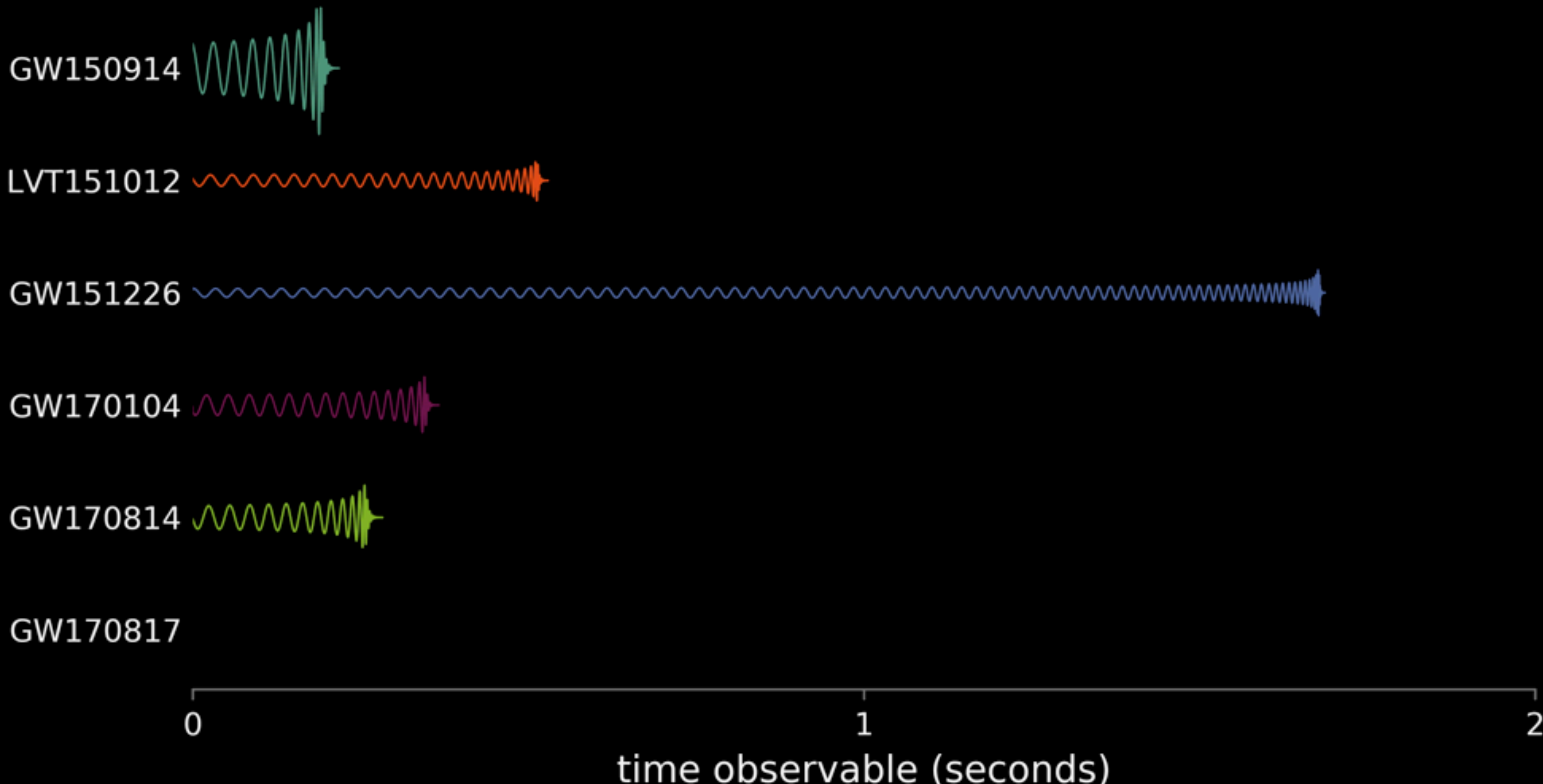
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

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.

SIGNAL LASTED FOR SEVERAL MINUTES IN BAND



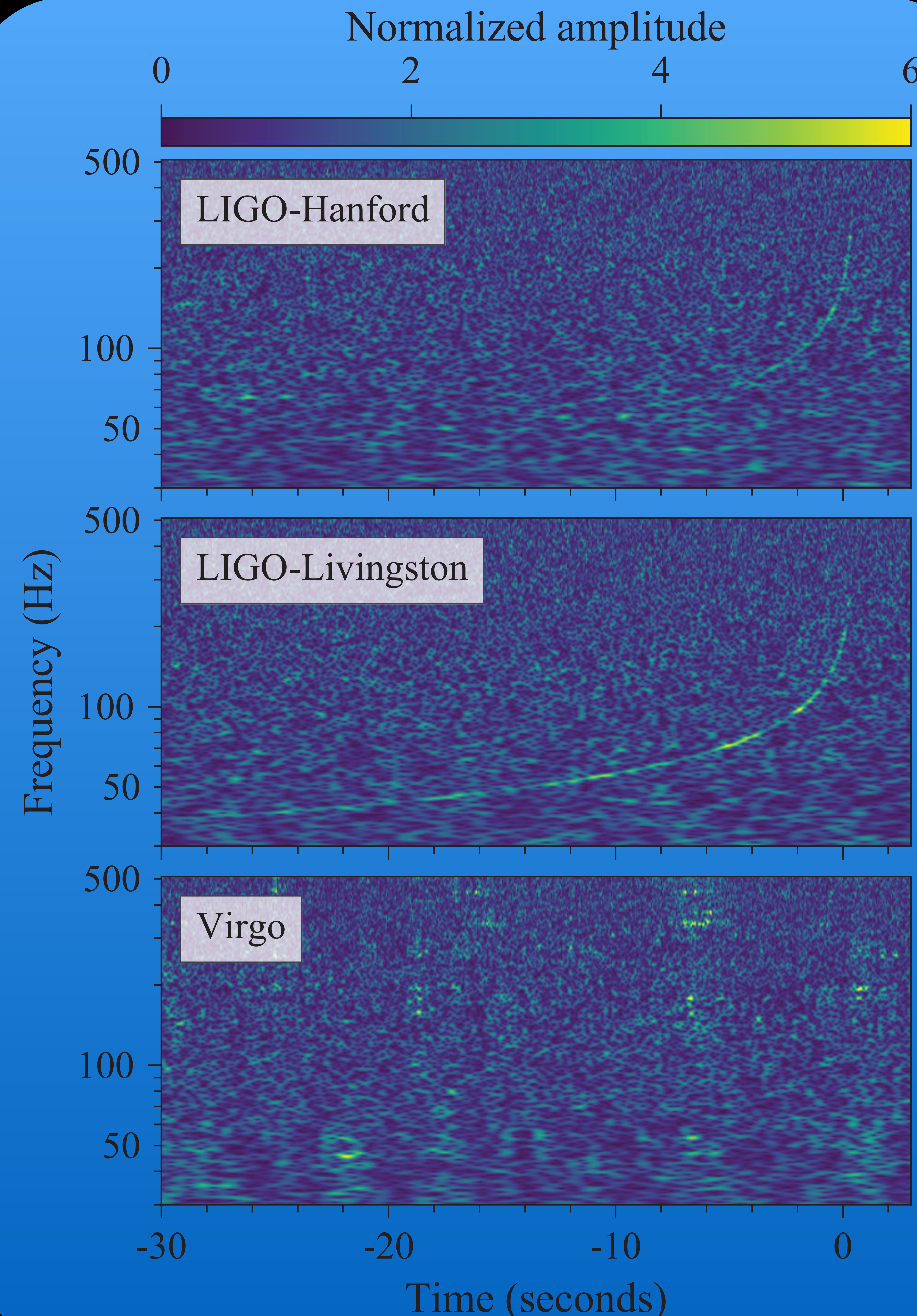
SIGNAL LASTED FOR SEVERAL MINUTES IN BAND



LIGO/University of Oregon/Ben Farr

TIME FREQUENCY PLOT OF GW170817

- Signal-to-noise ratio of 32.4
  - loudest yet
- False alarm rate of 1 in 10^6 yrs
  - most significant of all



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DETECTION: STATEMENT OF THE PROBLEM

- detector output consists of:
  - only background noise: $x(t) = n(t)$
  - noise + some interesting signal: $x(t) = h(t) + n(t)$
  - given a detector output which of the two possibilities is more likely given that the noise background is Gaussian and stationary
- formulate the problem as Bayes' theorem:

$$P(h|x) = \frac{P(x|h)P(h)}{P(x)}$$

- posterior prob. = likelihood x prior / evidence

- denominator is: $P(x) = P(x|h)P(h) + P(x|\overline{h})P(\overline{h})$
- define likelihood ratio:

$$\Lambda = \frac{P(x|h)}{P(x|n)}$$

- if signals are rare then

$$P(h) \ll 1 \text{ and } P(\overline{h}) = 1 - P(h) \simeq 1$$

- in that case the posterior prob. of a signal given data is:

$$P(h|x) = \frac{\Lambda P(h)}{1 + \Lambda P(h)}$$

- for confident detection

$$\Lambda \gg 1/P(h)$$

- rarer the signal larger should be the likelihood for a given confidence: for 5-sigma detection $P(h|x) \simeq 0.999\,999$

one in a million

COMPUTING THE LIKELIHOOD RATIO

- noise is a Gaussian random process, so at any instant t_k

$$P(n_k) = \frac{1}{\sqrt{2\pi}\sigma_k} e^{-n_k^2/2\sigma_k^2}$$

- it is more convenient to deal with Fourier domain quantities N_k (similarly, X_k and H_k):

$$P(N_k) = \frac{1}{\sqrt{2\pi}S_k} e^{-N_k^2/2S_k^2}$$

- so the probability of getting a sequence $P(\{N_k\})$

$$P(\{N_k\}) = \prod_k \frac{1}{\sqrt{2\pi}S_k} e^{-N_k^2/2S_k^2} \propto e^{-\frac{1}{2}\langle n,n\rangle}$$

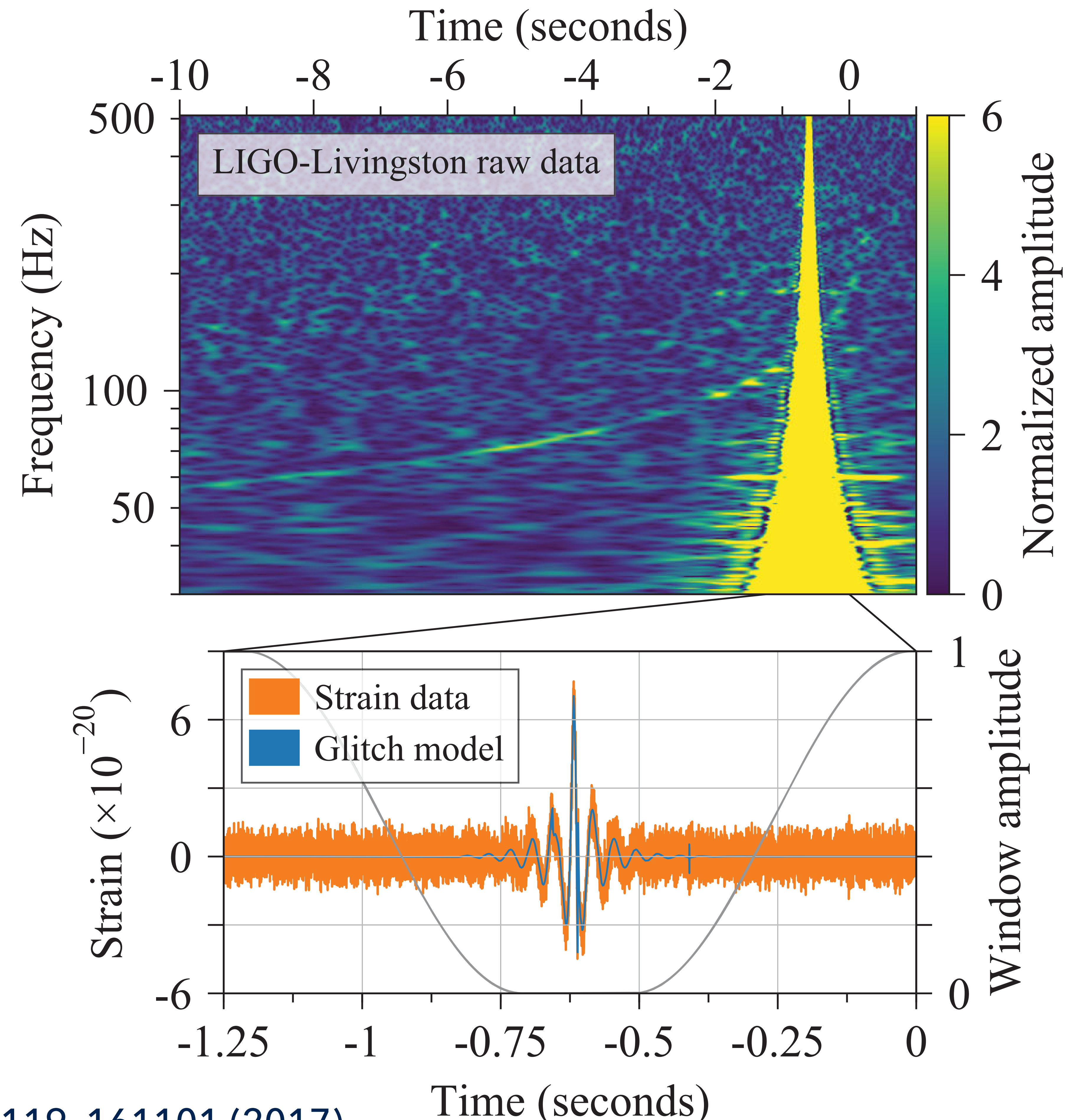
$$< a, b >= \sum |N_k|^2/S_k^2$$

- if signal is absent n=x, if signal is present n=x-h:

$$\Lambda = \frac{P(x|h)}{P(x|n)} = \frac{e^{-\frac{1}{2}\langle x-h,x-h\rangle}}{e^{-\frac{1}{2}\langle x,x\rangle}} = e^{\langle x,h\rangle - \frac{1}{2}\langle h,h\rangle}$$

DIFFICULTIES ...

- the likelihood ratio is computationally very expensive:
  - <x, h> would need to be computed at 10's of millions of points in the parameter space (parameters **μ**) before giving up - signal
  - a scheme would be needed to compute P(x|n) - background
- noise is not Gaussian or stationary
  - nothing much can be done about non-stationarity: detector behavior is assumed to be stable over periods ~ days
  - non-Gaussian and non-stationary data is rejected
    - glitch rejection, signal consistency checks, coincidence and coherent analysis, etc.



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A GEOMETRICAL FORMULATION OF DATA ANALYSIS: SIGNAL MANIFOLD

- detector outputs can be thought of as vectors
  - the set of all detector outputs forms a vector space
- signals are also vectors that live in this vector space
  - space of signals forms a manifold: signal parameters (e.g. masses and spins of black holes) are coordinates that determine the dimension of the manifold
- the scalar product $\langle a,b \rangle$ can be used to induce a metric on the manifold: $g_{\alpha\beta} = \langle h_\alpha, h_\beta \rangle$, where $h_\alpha = \delta h / \delta \mu_\alpha$
  - the signal space now acquires a shape

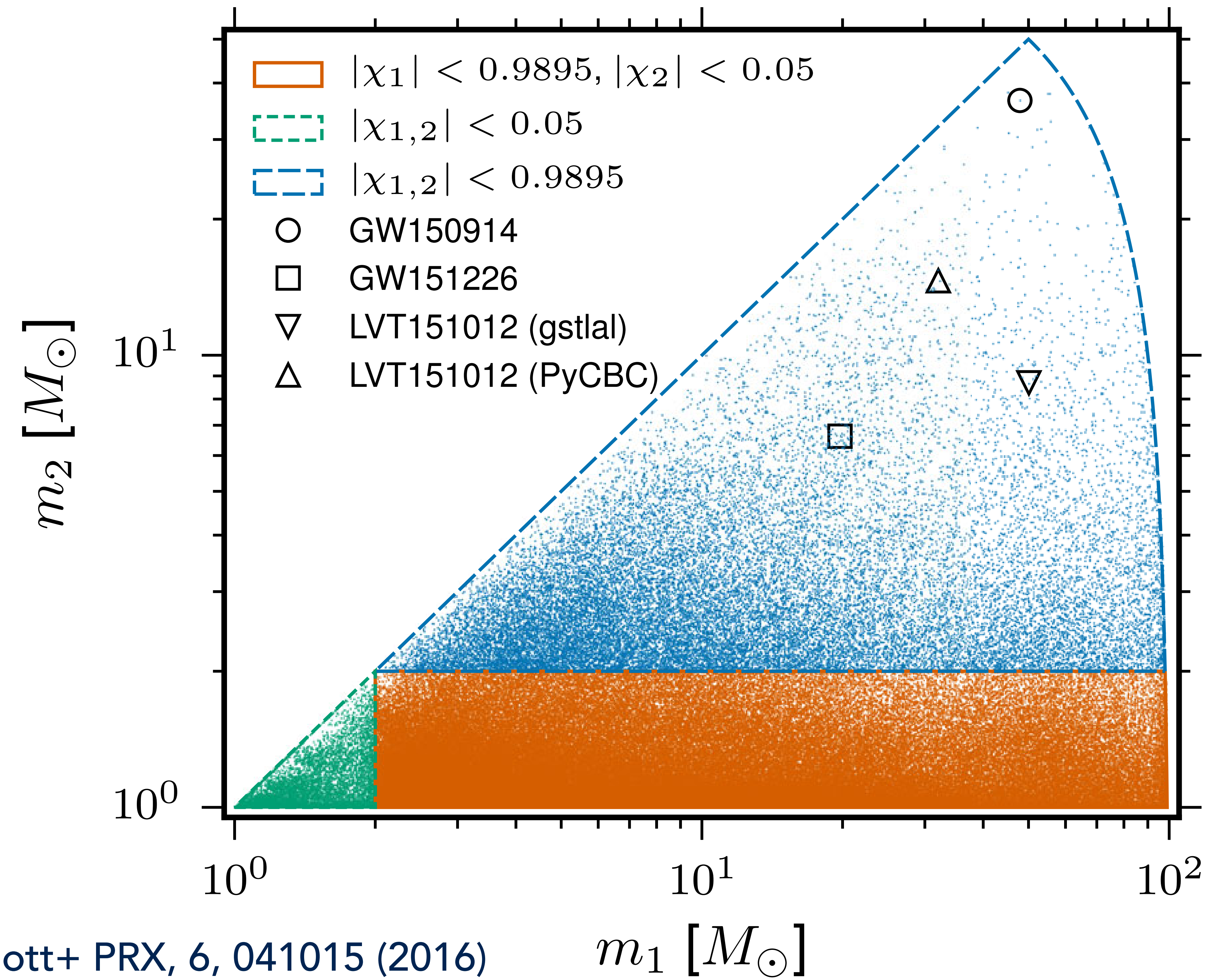
TEMPLATE BANKS FOR COMPUTING $\langle x, h(\mu) \rangle$

- volume of the parameter space is: $V = \int \sqrt{g}\, \mathrm{d}^n \mu$
- if each template covers a volume V then the number of templates is:

$$N = \frac{1}{\Delta V} \int \sqrt{g}\, \mathrm{d}^n \mu$$

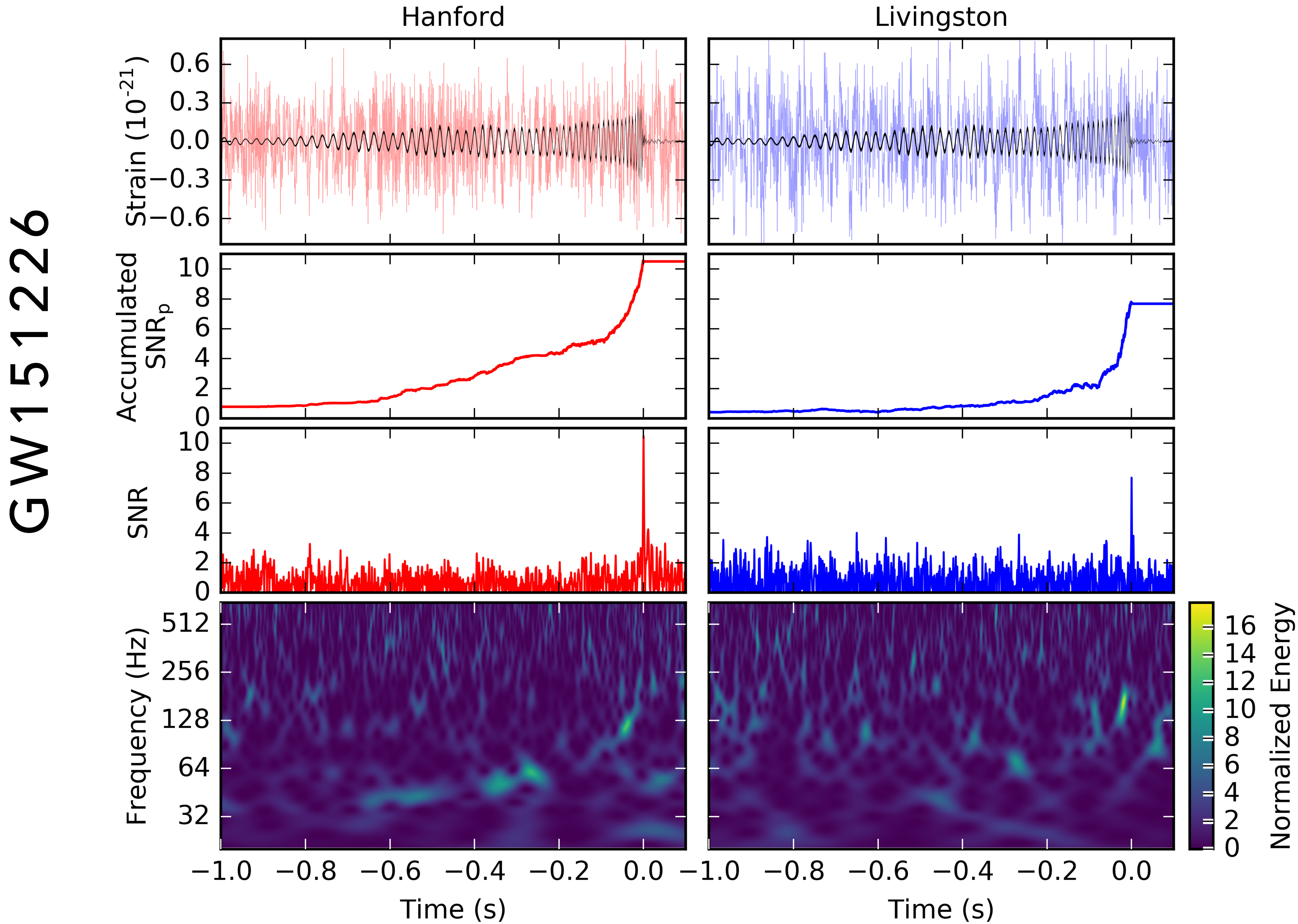
- but how to choose templates … template placement problem, a hard problem with only sub-optimal solutions
  - a uniform grid, say, in the space of masses and spins, or something more fancy?
  - a hexagonal lattice, stochastic method, …
- O1 search deployed 250,000 templates for compact binary coalescence searches, O2 about 500,000 templates

MATCHED FILTER SEARCH FOR SIGNALS OF KNOWN SHAPE



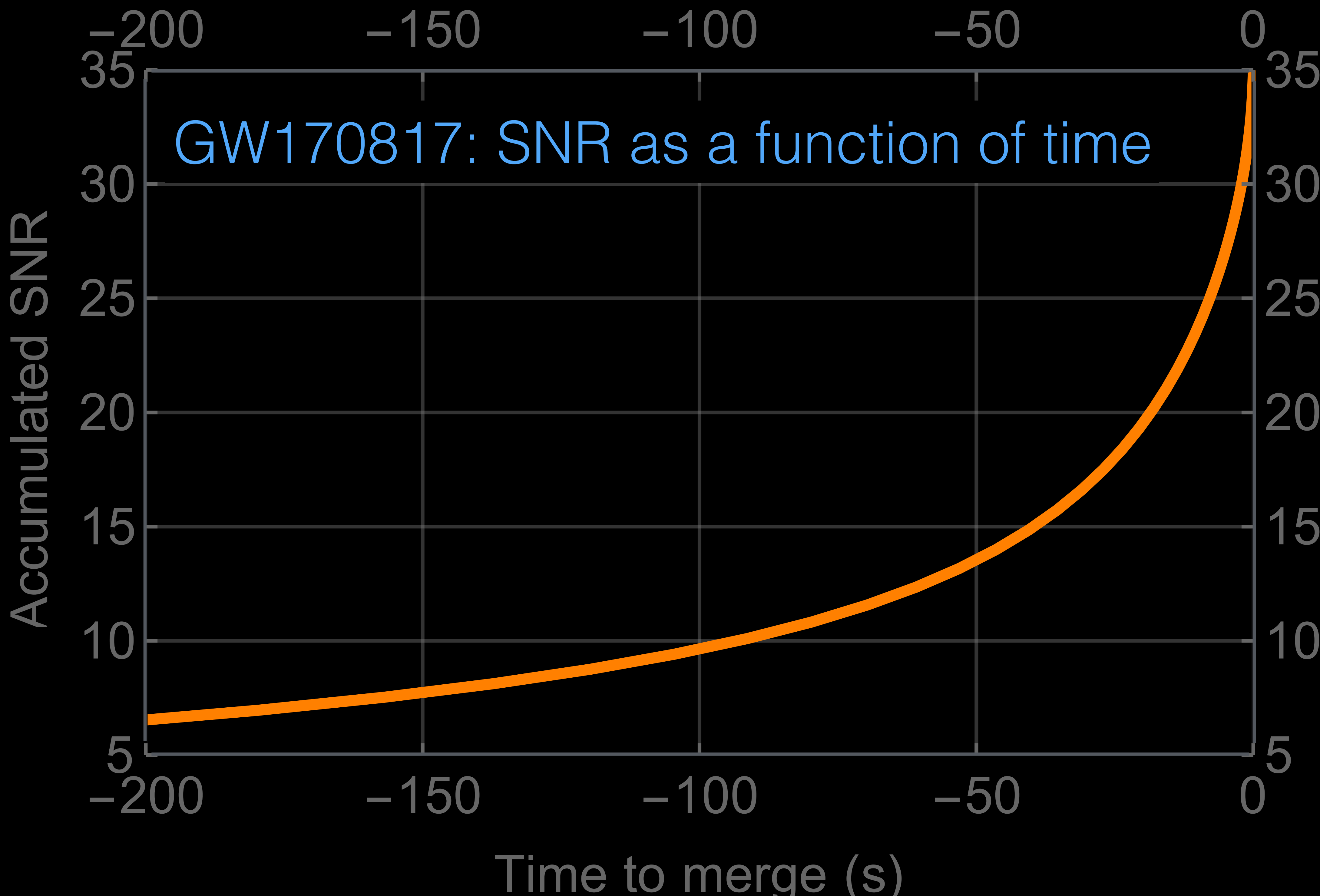
Abbott+ PRX, 6, 041015 (2016)

Matched filtering and waveform models were critical for detection and signal reconstruction



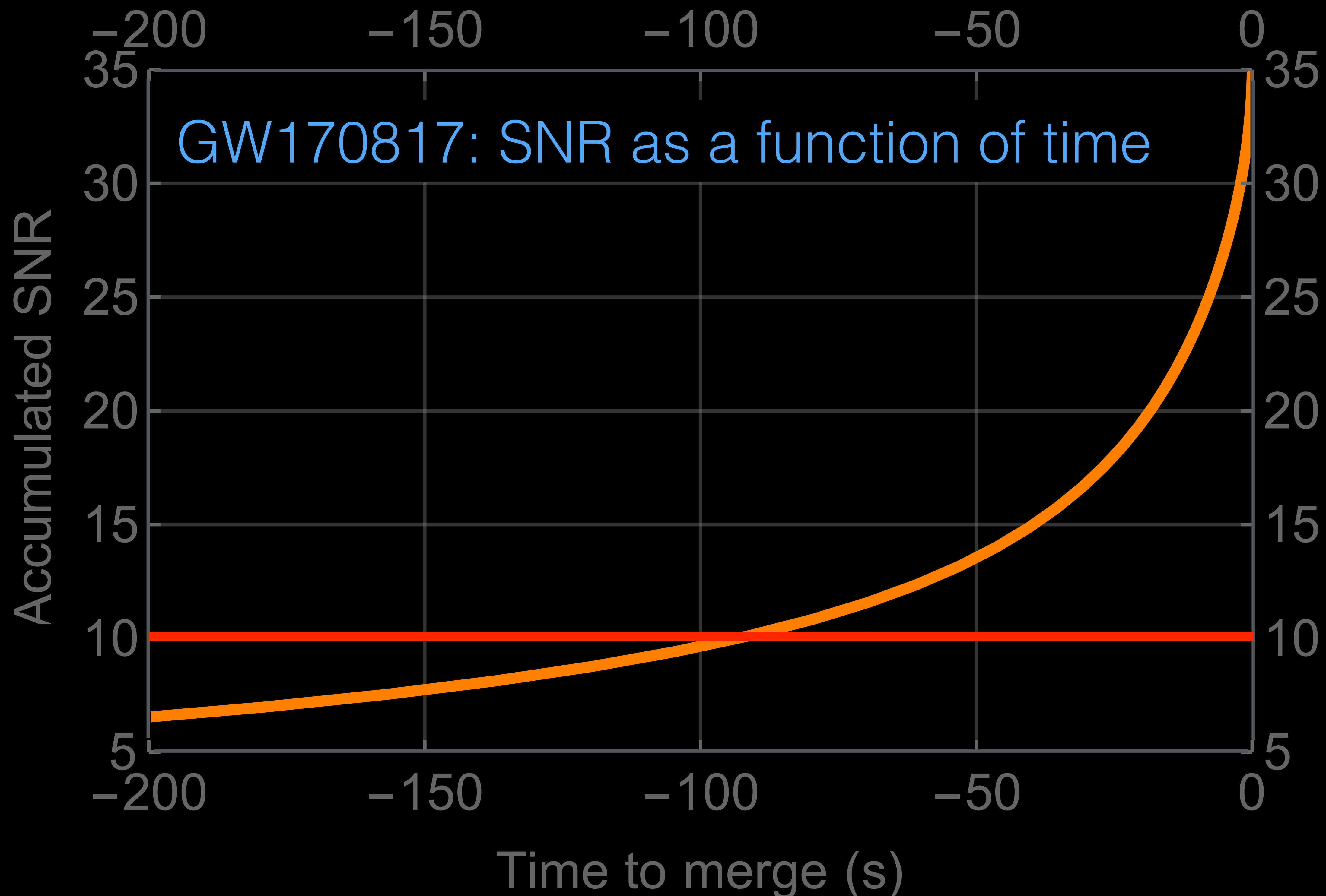
A Gravitational-Wave Early-Warning System

HOW QUICKLY CAN WE ISSUE AN ALERT FOR A GW170817-LIKE EVENT



Single detector SNR

HOW QUICKLY CAN WE ISSUE AN ALERT FOR A GW170817-LIKE EVENT



Single detector SNR

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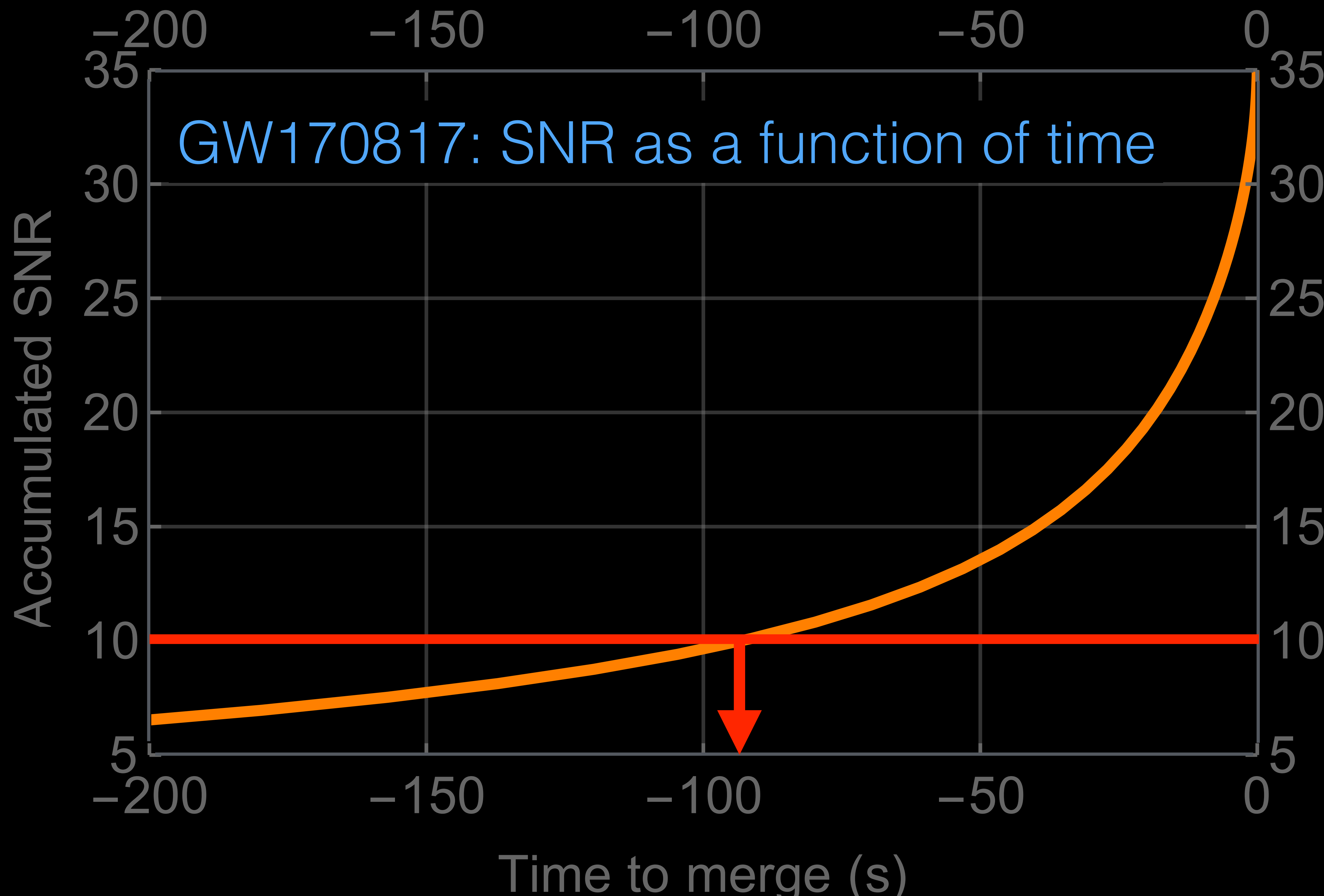
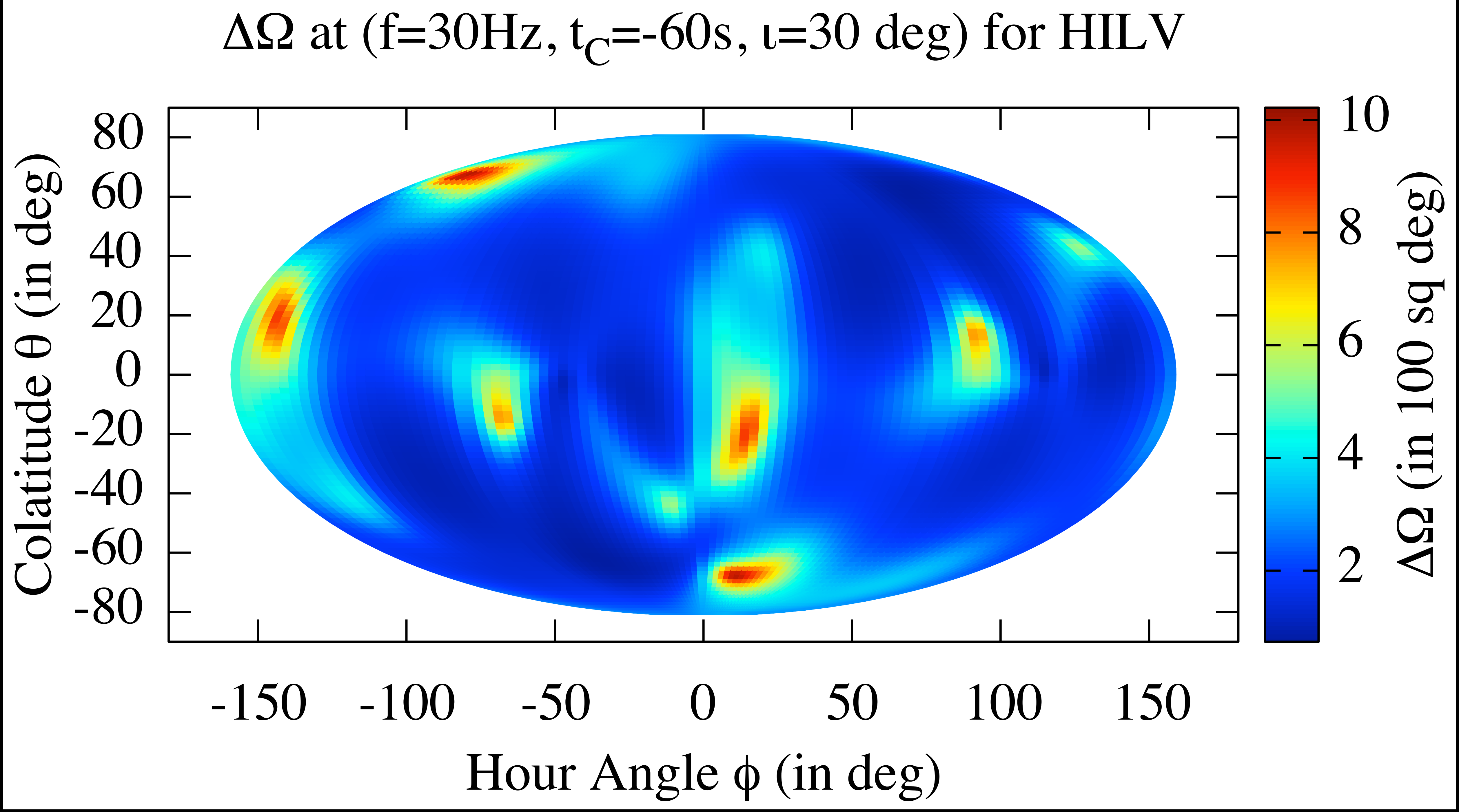


Single detector SNR

SKY RESOLUTION BEFORE MERGER OF A GW170817-LIKE EVENT



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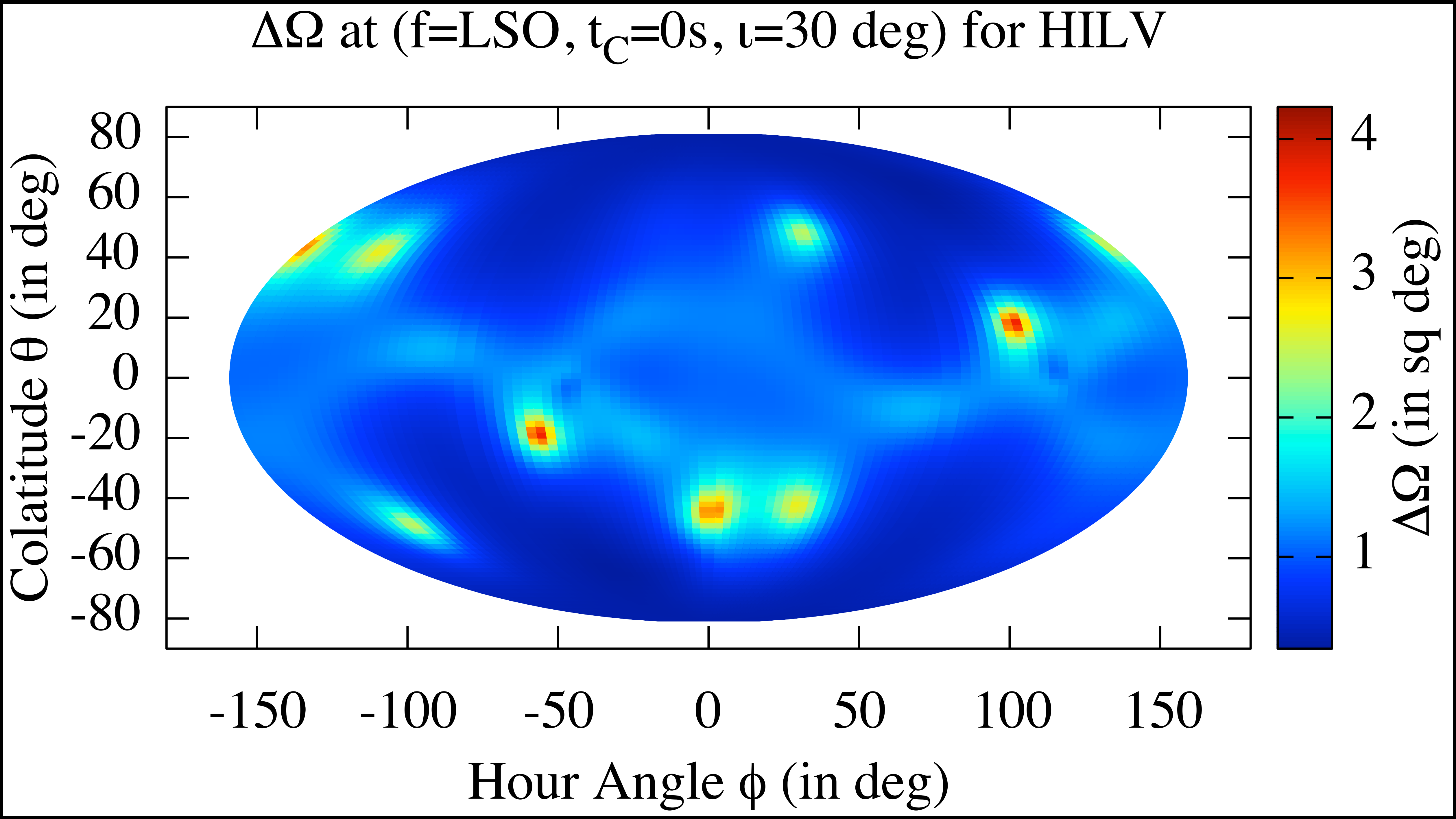
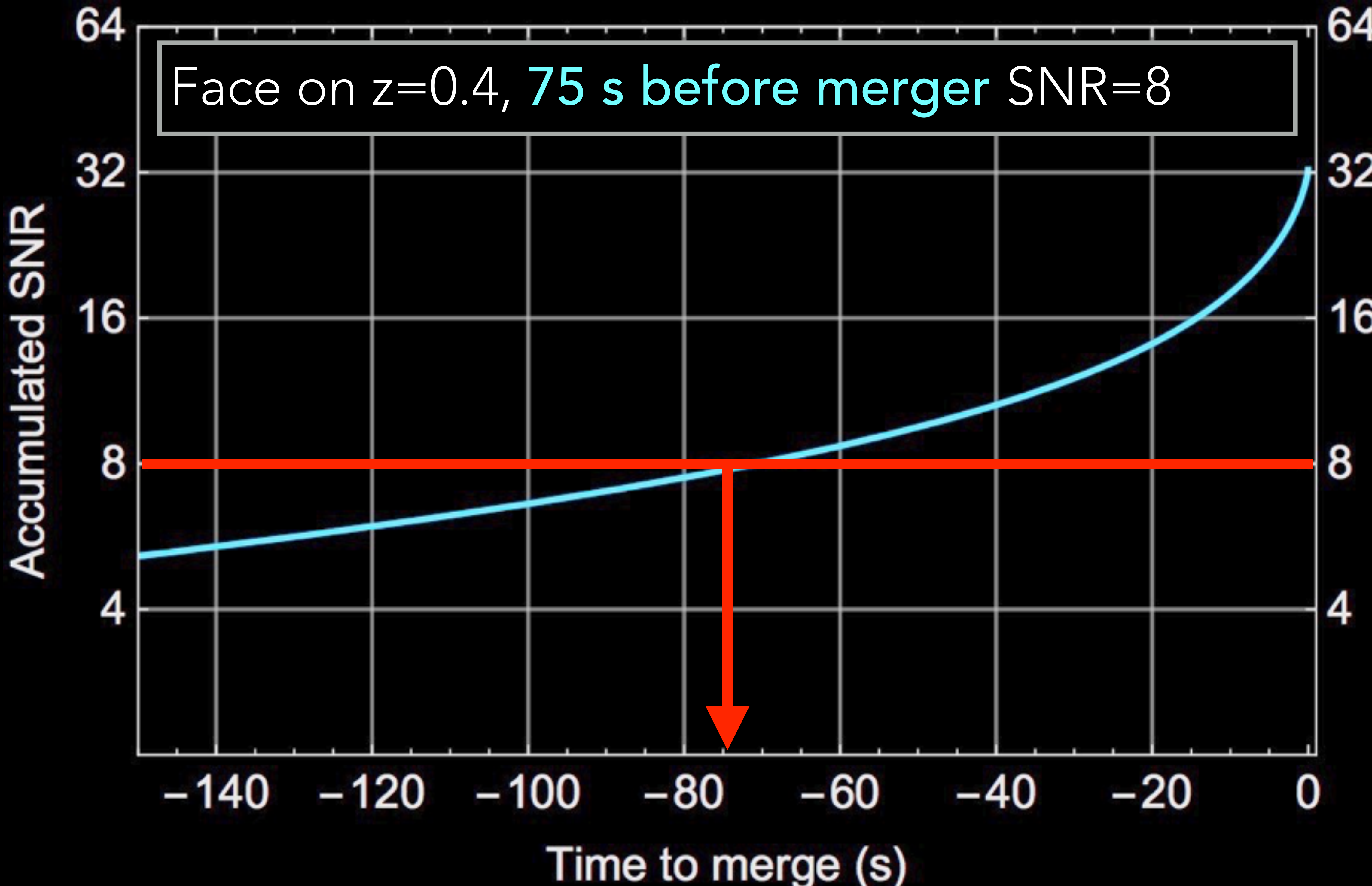


EARLY WARNING IN THE ERA OF NEXT GENERATION OF DETECTORS



Single detector SNR

measuring source parameters

MEASURING SOURCE PARAMETERS

- Bayesian analysis is used to infer the posterior probability density of parameters $\mu = \{\mu_1, \mu_2, \ldots, \mu_n\}$ given the data x:

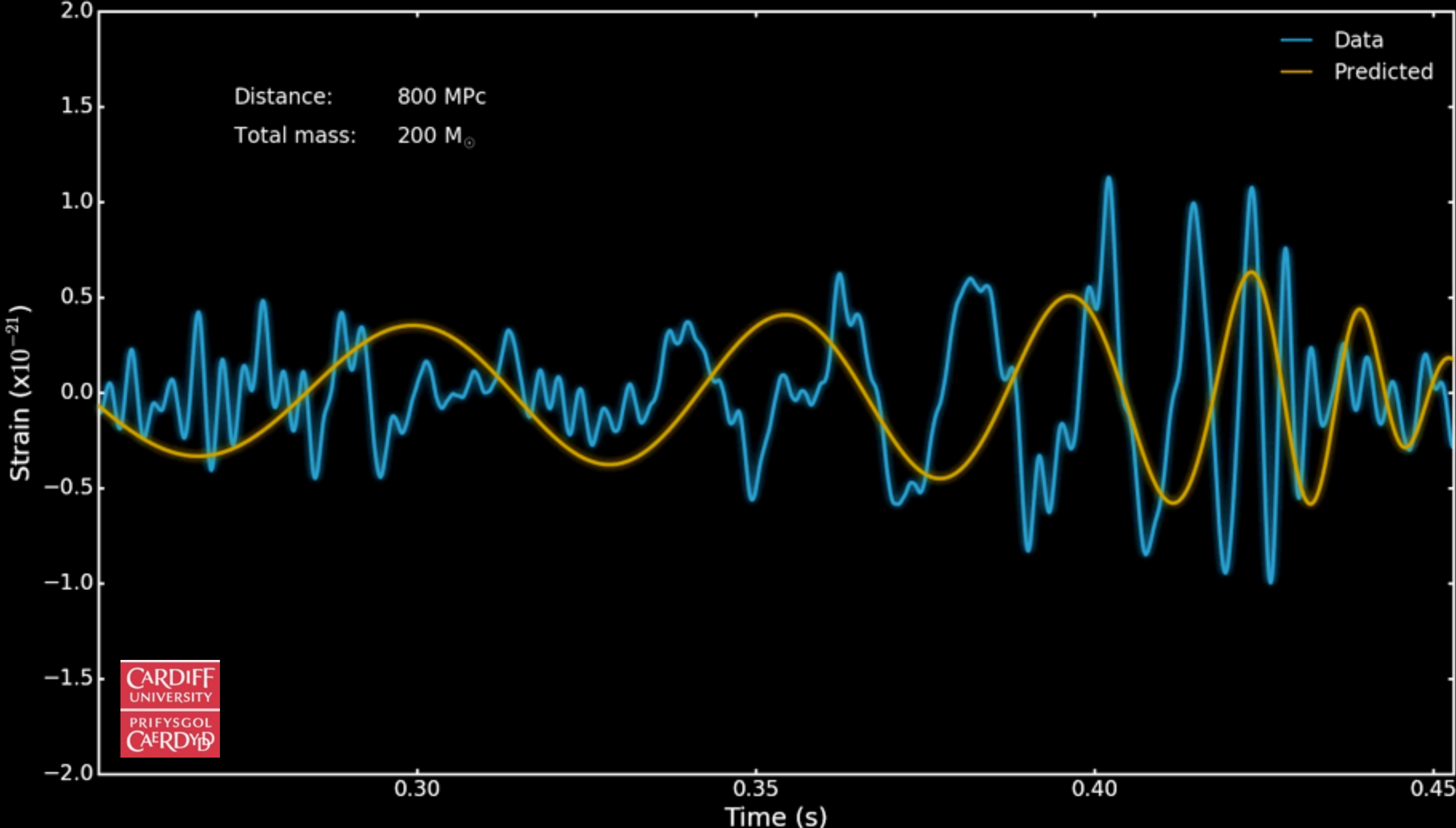
$$P(h(\mu)|x) = \frac{P(x|h(\mu))P(h)}{P(x)}$$

- in the case of binary black holes signal parameters are component masses (m_1, m_2) and spins $(\mathbf{S}_1, \mathbf{S}_2)$, ~~eccentricity e,~~ sky position (θ, ϕ), distance D, binary orientation angles (ι, δ), time of and phase at coalescence (t_c, ϕ_c); PSD, calibration, etc.

- likelihood $P(x|h(\mu))$ is very expensive as it requires computing the overlap of millions of waveforms with the data and different signal models

  - impossible to compute without fast, analytic waveform models

PARAMETER ESTIMATION USING WAVEFORMS PREDICTED BY GR



Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff Univers

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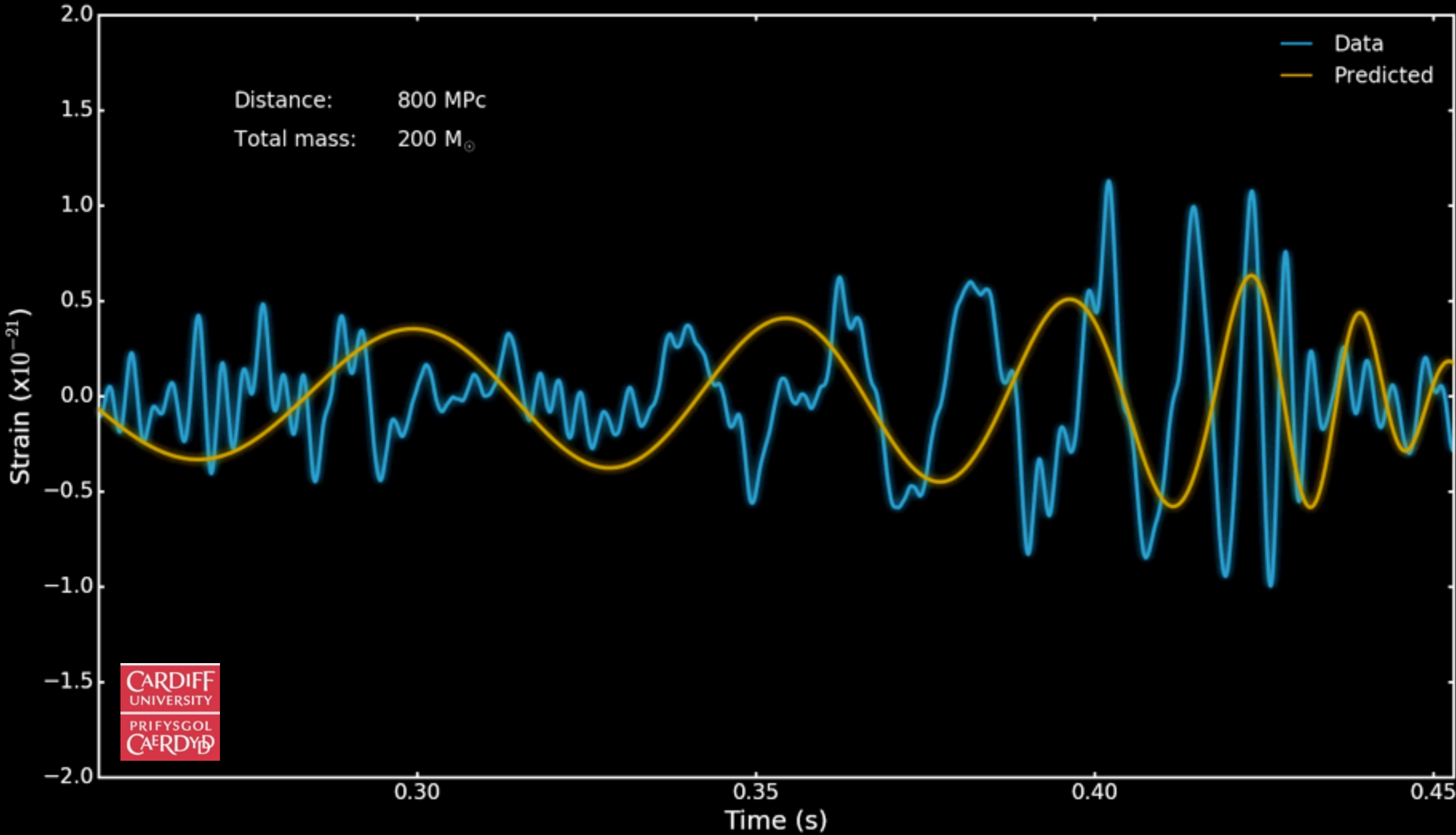
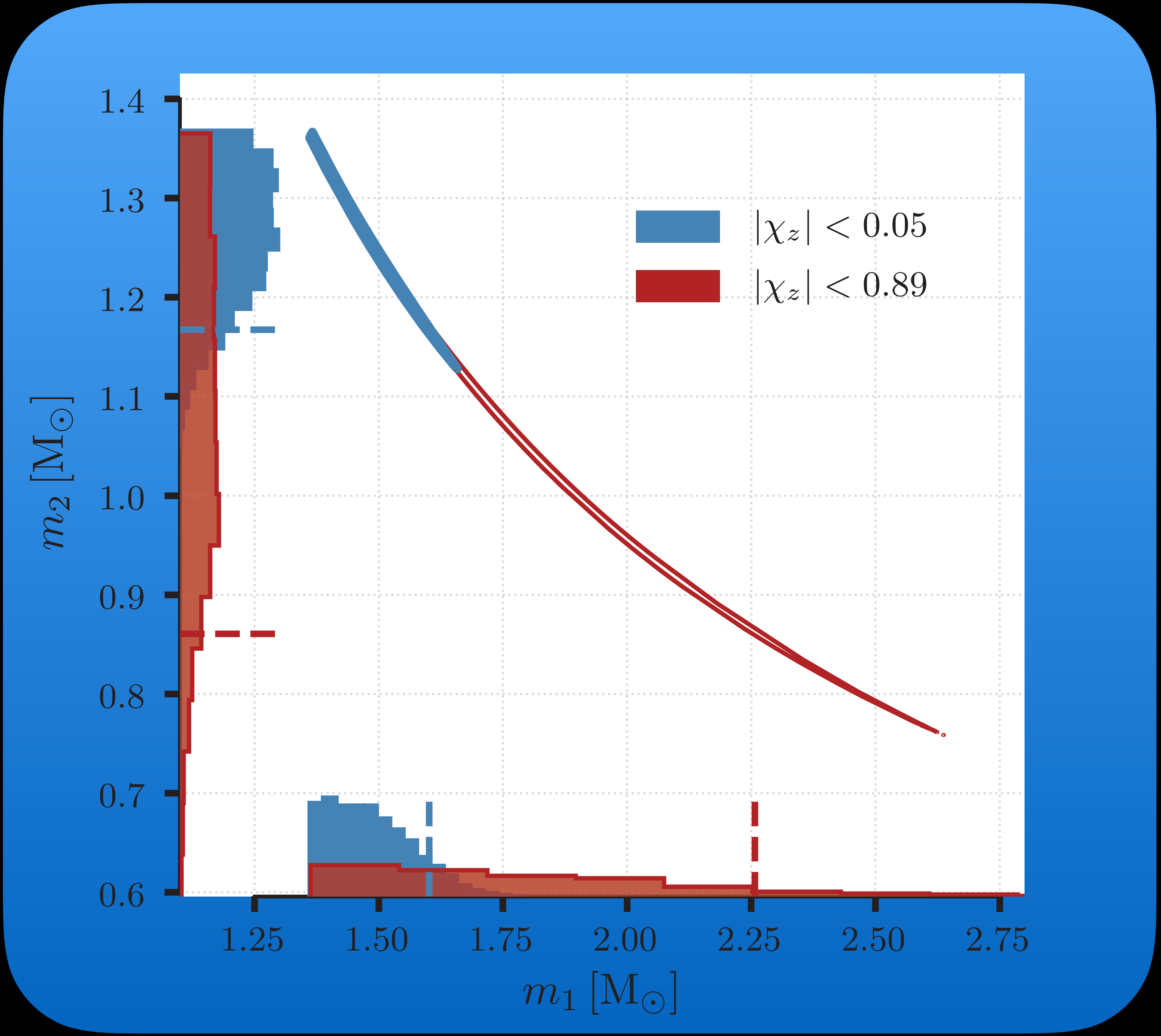


Data & Best-fit Waveform: LIGO Open Science Center (losc.ligo.org); Prediction & Animation: C.North/M.Hannam (Cardiff Univers

COMPONENT MASSES



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PROPERTIES OF GW170817: LOW NEUTRON STAR SPIN

	Low-spin priors ($\|\chi\| \leq 0.05$)
Primary mass m_1	1.36–$1.60\ M_\odot$
Secondary mass m_2	1.17–$1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.7–1.0
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 55°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800

Phys Rev Lett. 119, 161101 (2017)

PROPERTIES OF GW170817: HIGH NEUTRON STAR SPIN

	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	1.36–2.26 $M_\odot$
Secondary mass m_2	0.86–1.36 $M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	0.4–1.0
Total mass $m_{\rm tot}$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc
Viewing angle Θ	$\leq 56°$
Using NGC 4993 location	$\leq 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 1400

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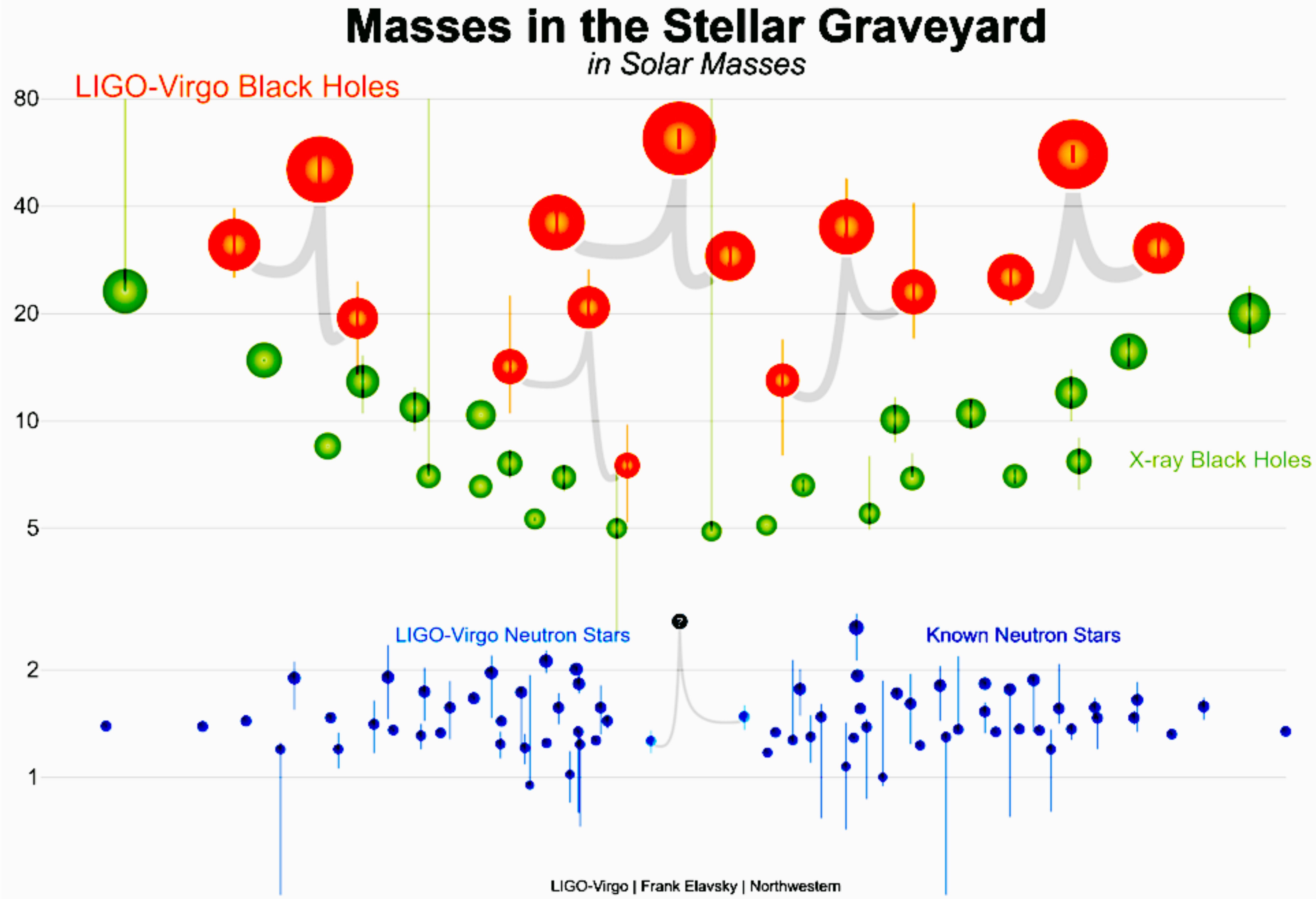
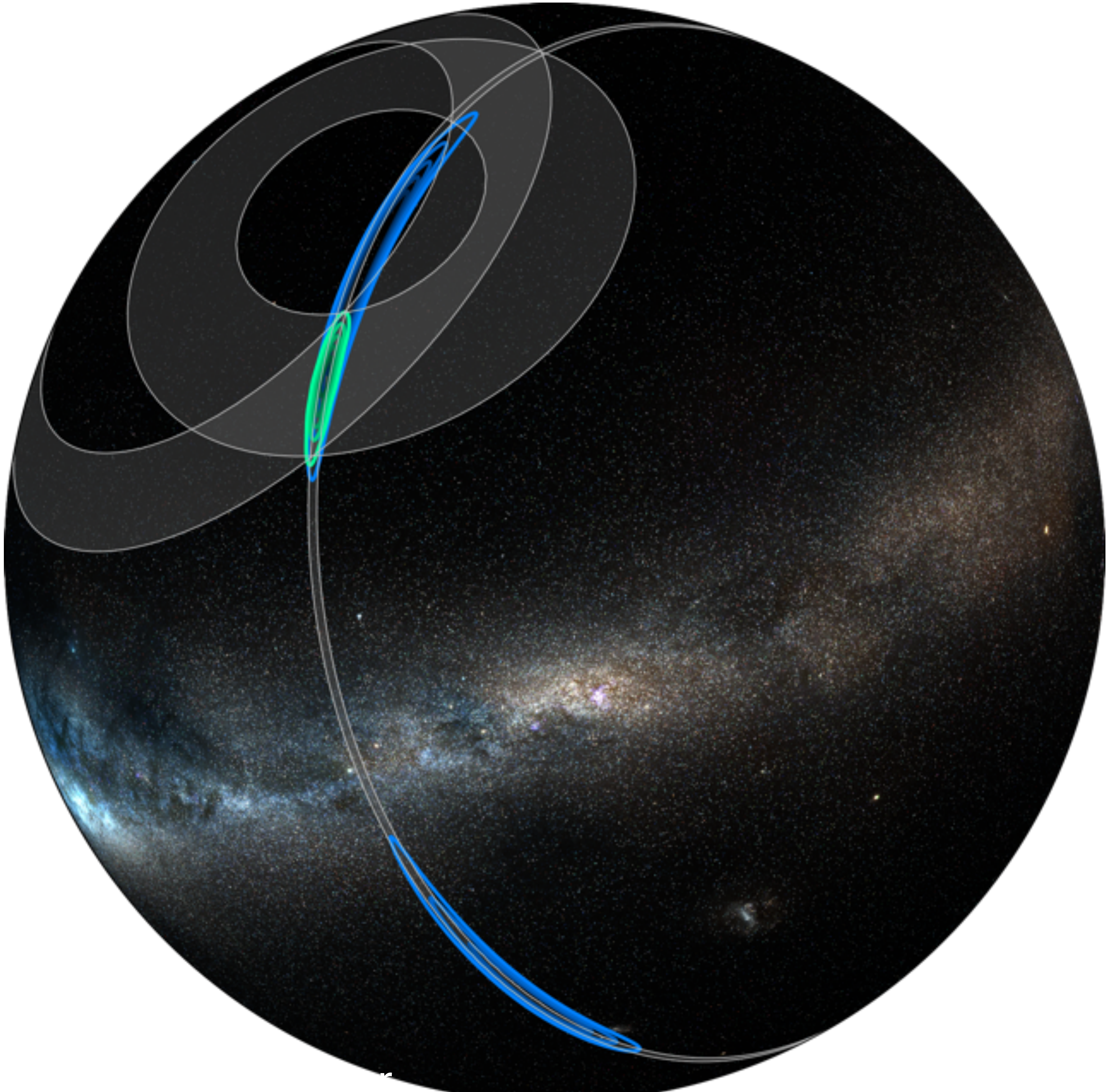
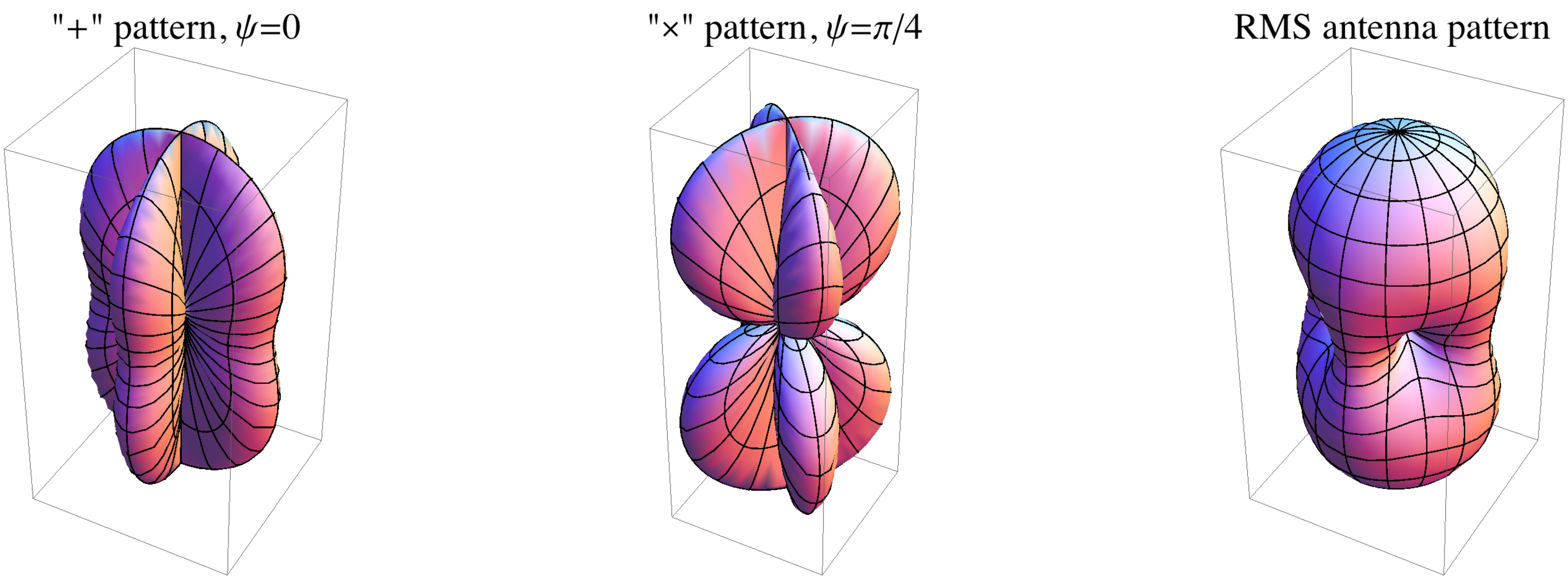

Masses in the Stellar Graveyard
in Solar Masses
LIGO-Virgo Black Holes
80
40
20
10
5
2
1
X-ray Black Holes
LIGO-Virgo Neutron Stars
Known Neutron Stars
?
LIGO-Virgo | Frank Elavsky | Northwestern

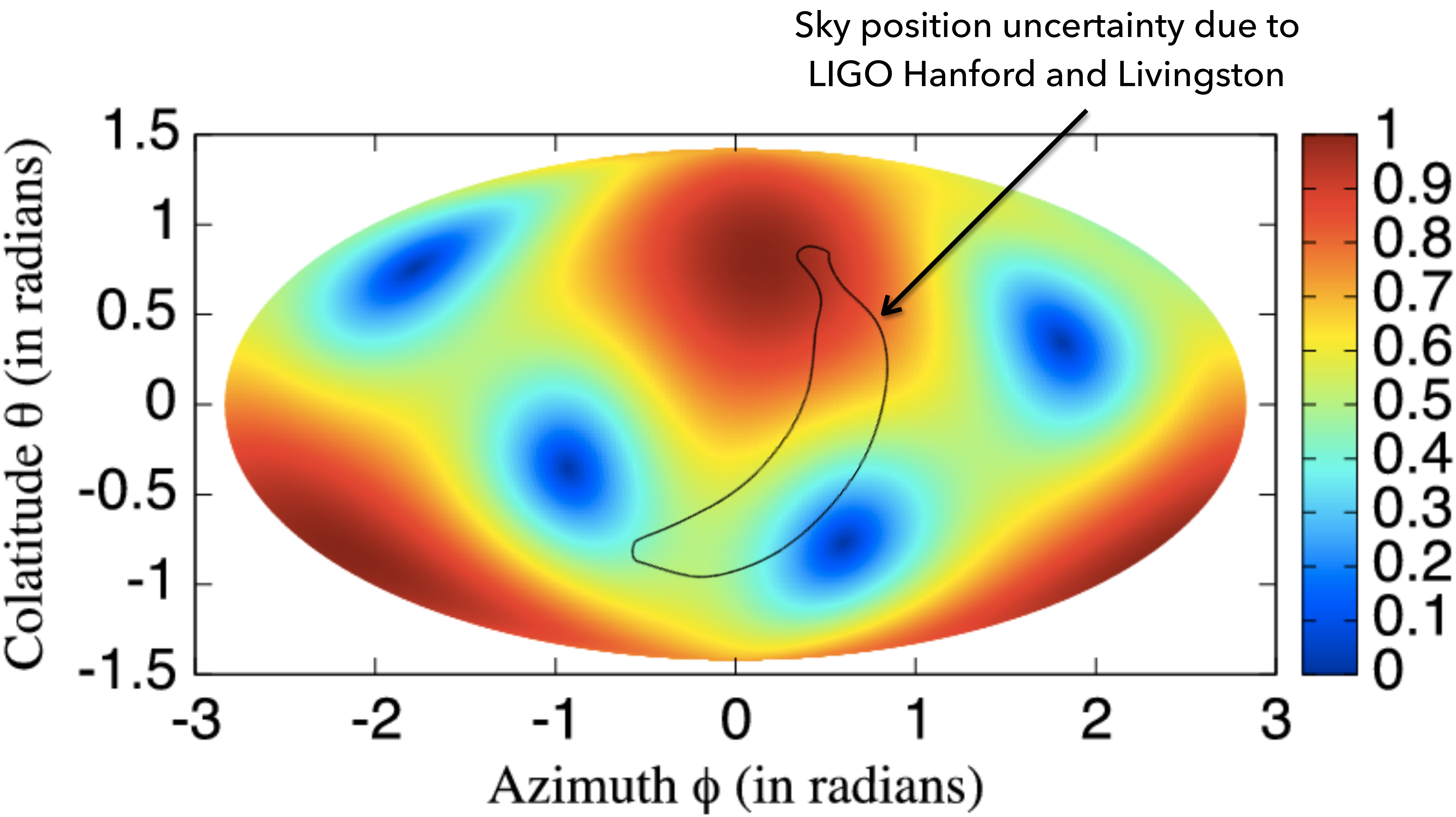
HOW DO WE LOCALIZE A SOURCE?



ANTENNA PATTERN FUNCTIONS



SKY LOCALIZATION EVEN WHEN A DETECTOR DOESN'T "SEE" THE SIGNAL



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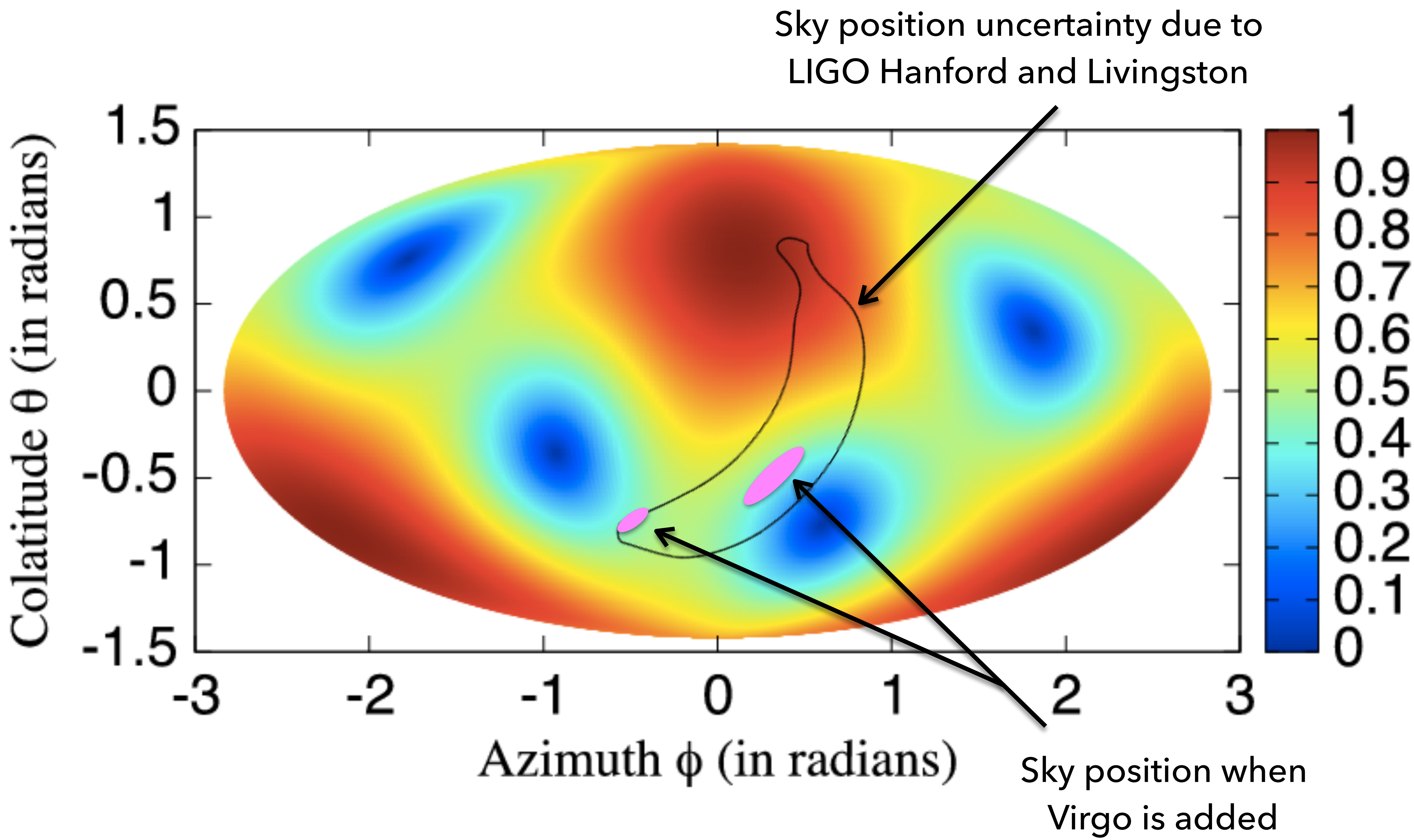
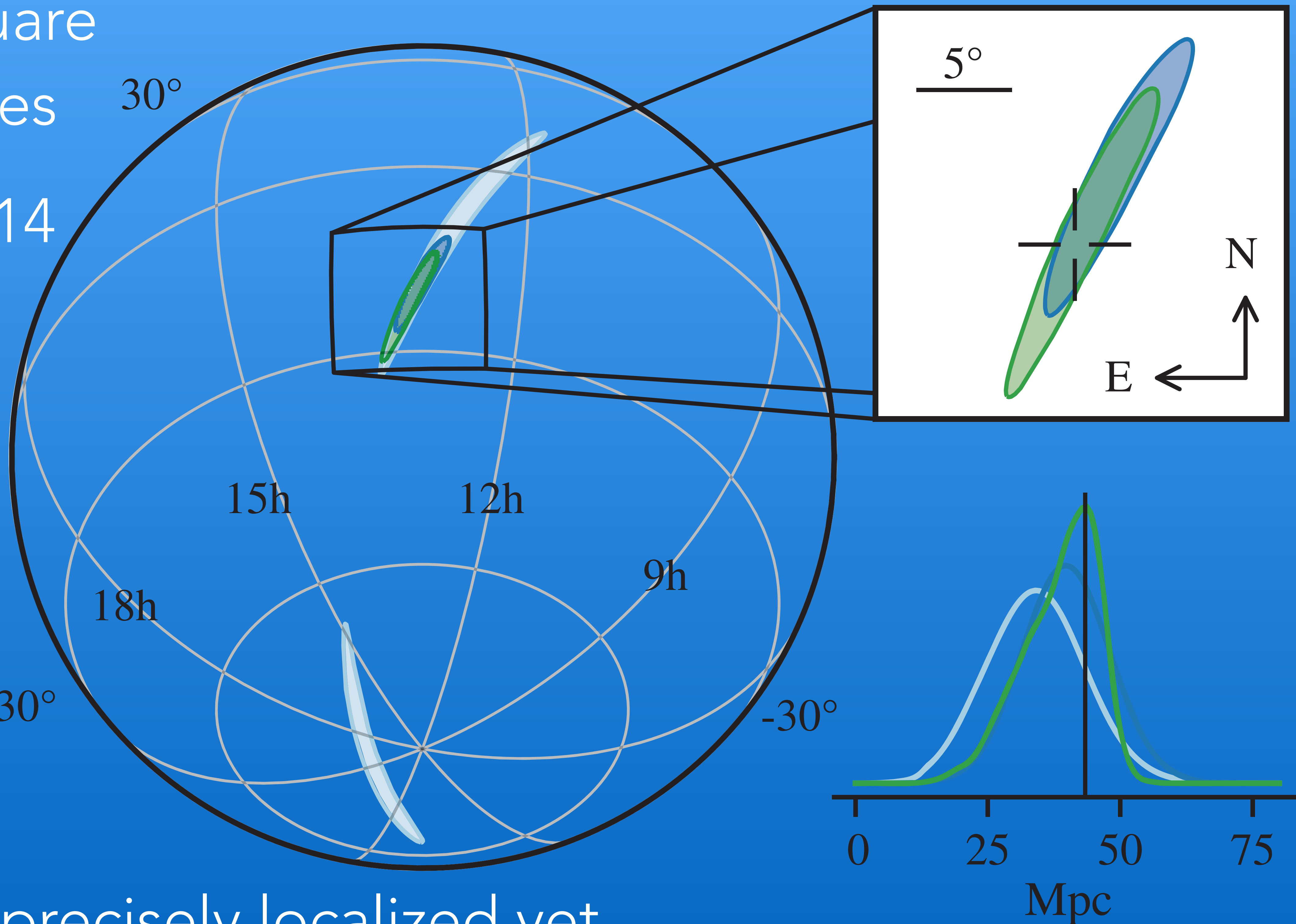


SKY POSITION AND DISTANCE

- ❖ 28 square degrees
- ❖ 40+8-14 Mpc



- ❖ most precisely localized yet

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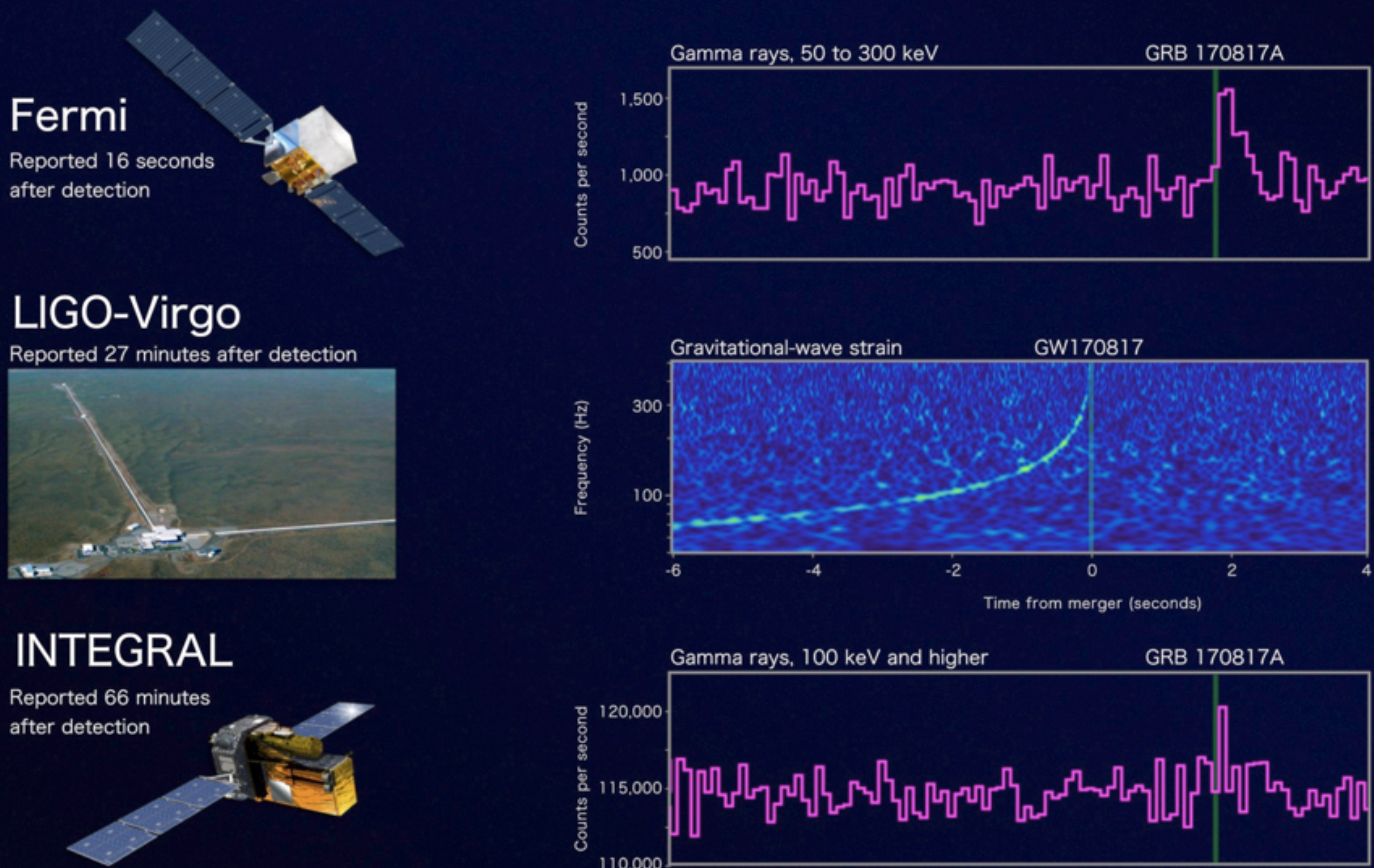
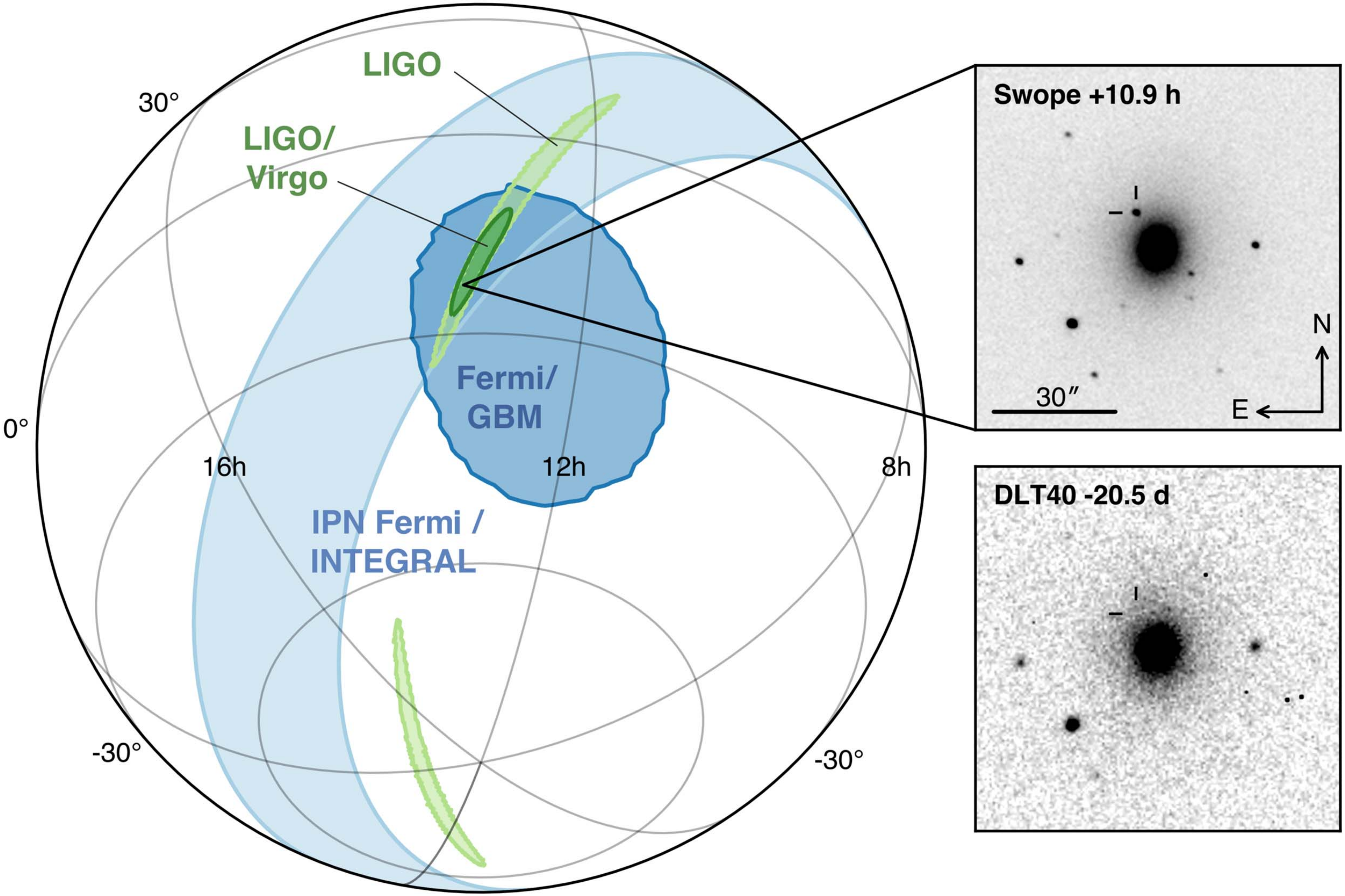
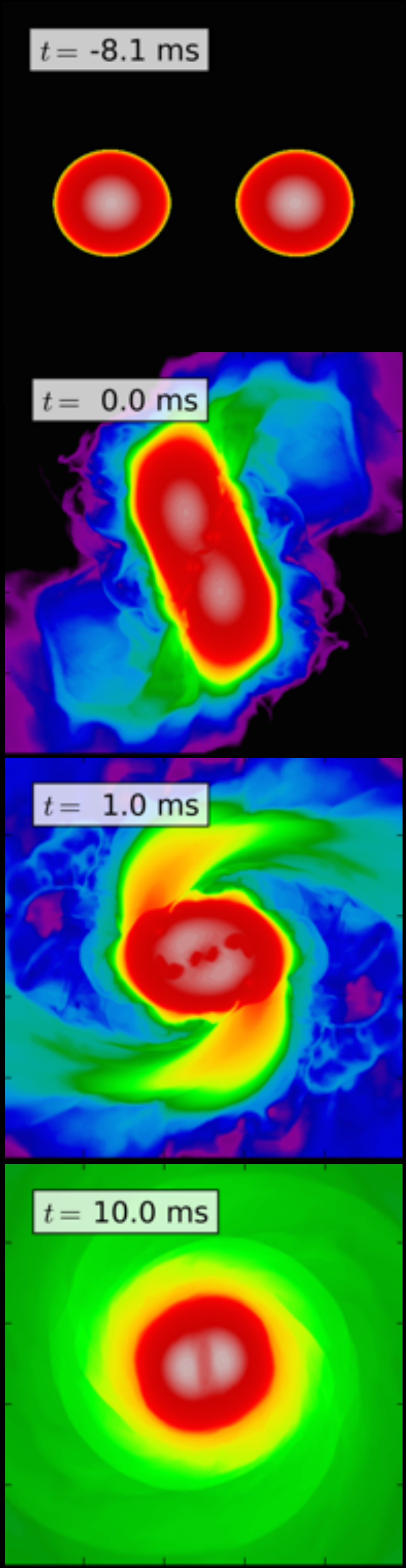
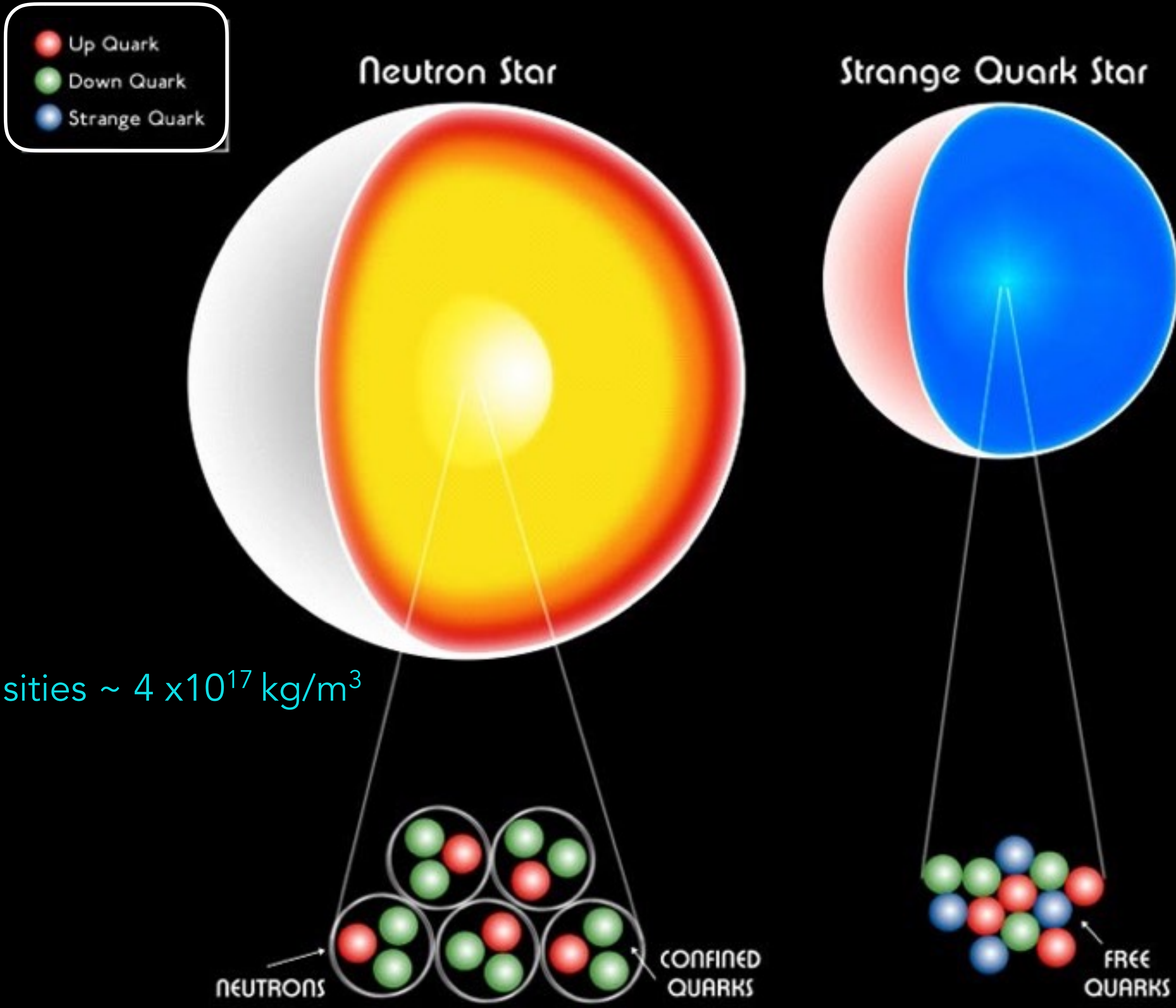
GRB IN FERMI AND INTEGRAL 1.7 S AFTER COALESCENCE




LIGO
30°
LIGO/
Virgo
Fermi/
GBM
0°
16h
12h
8h
IPN Fermi /
INTEGRAL
-30°
-30°
Swope +10.9 h
N
30″
E
DLT40 -20.5 d

EQUATION OF STATE OF DENSE NUCLEAR AND OTHER EXTREME MATTER

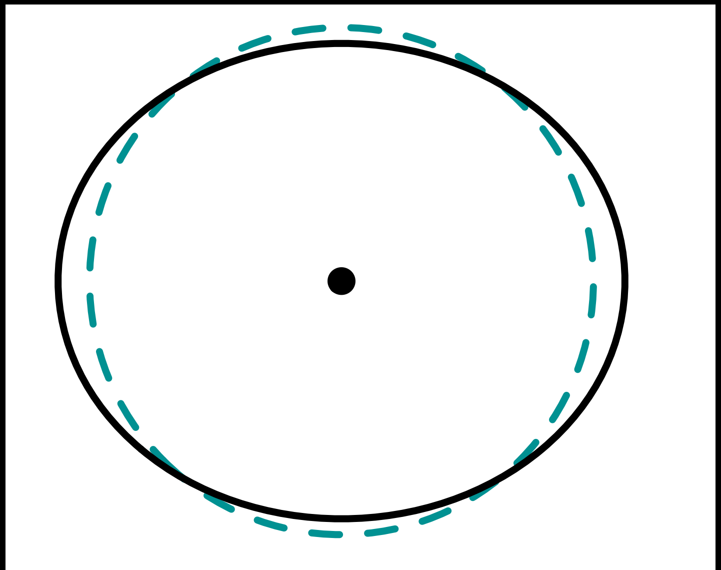




Densities ~ 4 x10^{17} kg/m^3

SIGNATURE OF EQUATION OF STATE IN BINARY NEUTRON STAR WAVEFORMS

- tidal field $\mathcal{E}$ of one companion induces a quadrupole moment Q in the other



sketch: J. Read

- in the adiabatic approximation

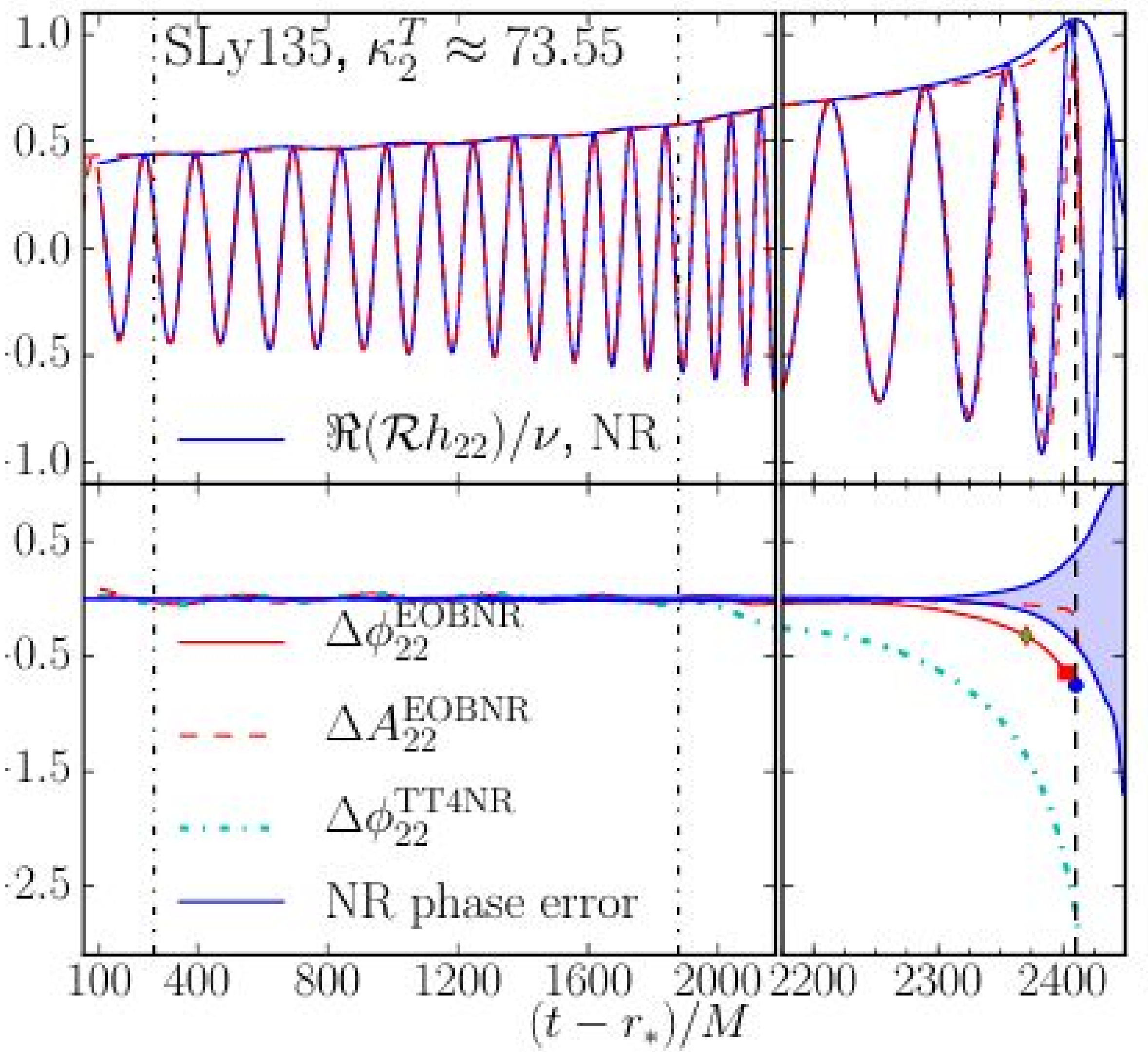
$$Q_{ij} = -\lambda(m)\, \mathcal{E}_{ij}, \qquad \lambda(m) = (2/3)\, k_2(m)\, R^5(m)$$

- $\lambda(m)$ is tidal deformability, $k_2(m)$ is the Love number and R is the NS radius

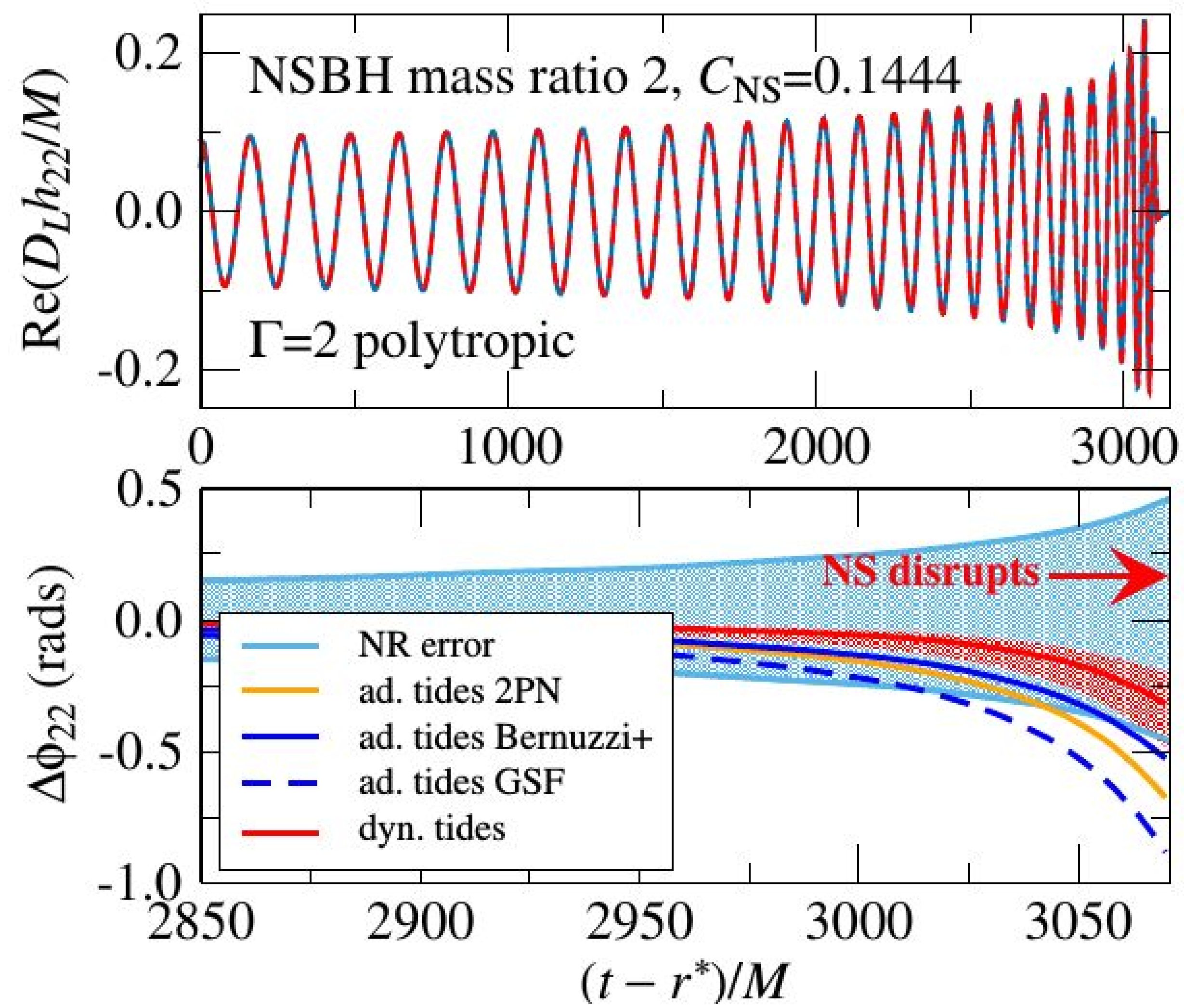
$$\Lambda \equiv G\lambda(Gm_{\rm NS}/c^2)^{-5}$$

$$\Lambda \in [300, 600]$$

ACCURATE WAVEFORM MODELS IS KEY TO MEASURING NEUTRON STAR RADIUS

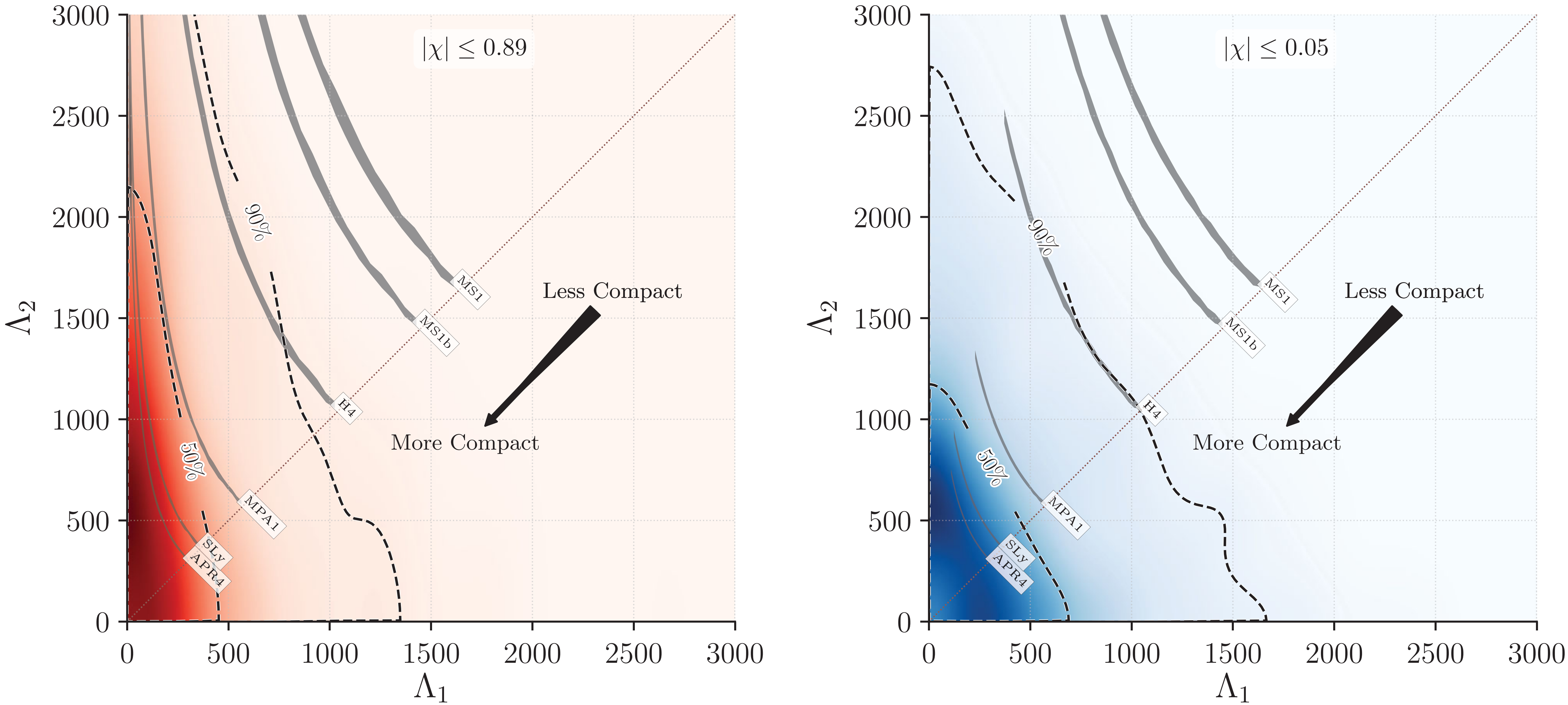


[Bernuzzi+, PRL **115**, 091101 (2015)]



[Hinderer+, PRL **116**, 181101 (2016)]

TIDAL DEFORMABILITY OF NEUTRON STARS



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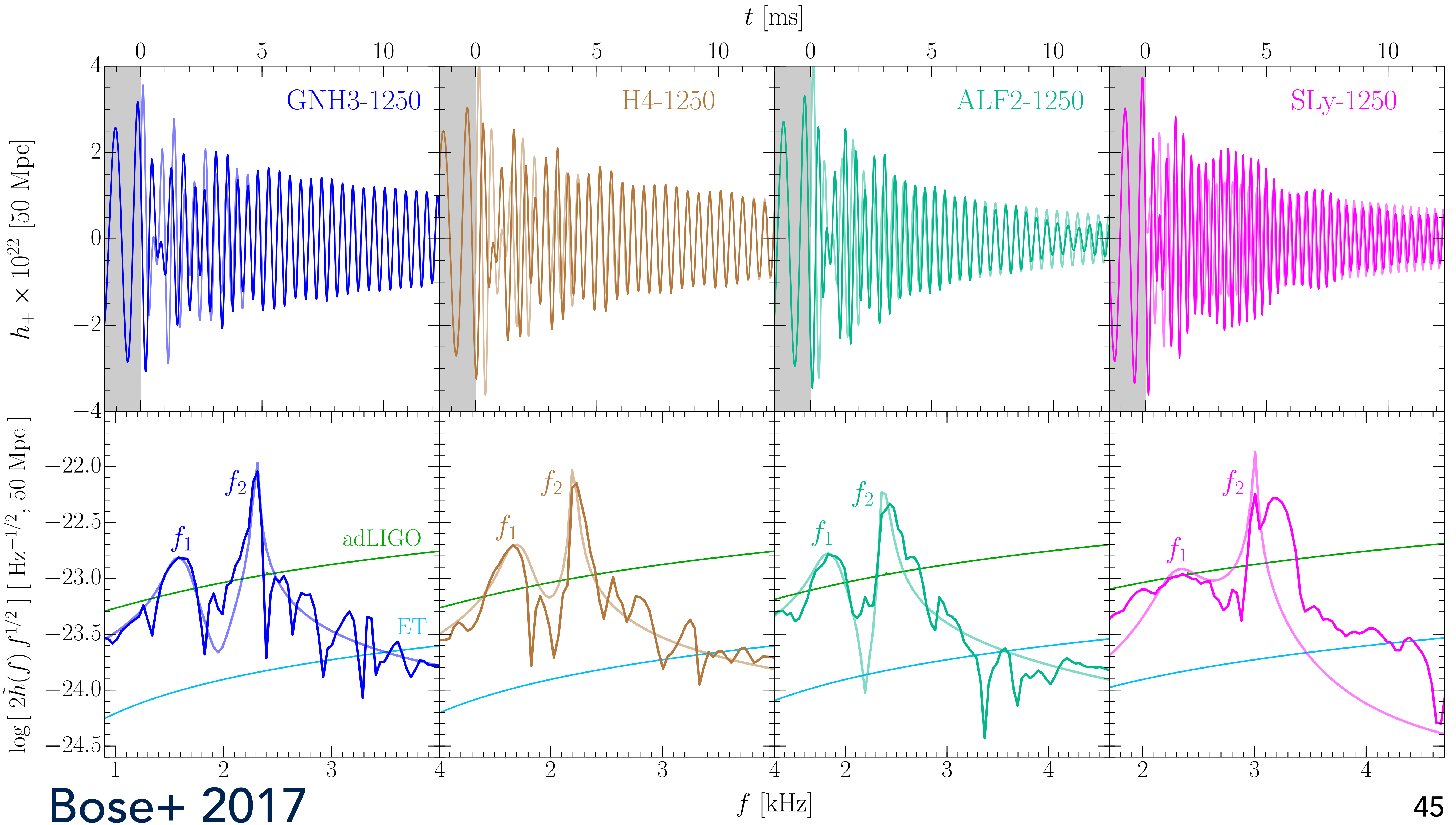
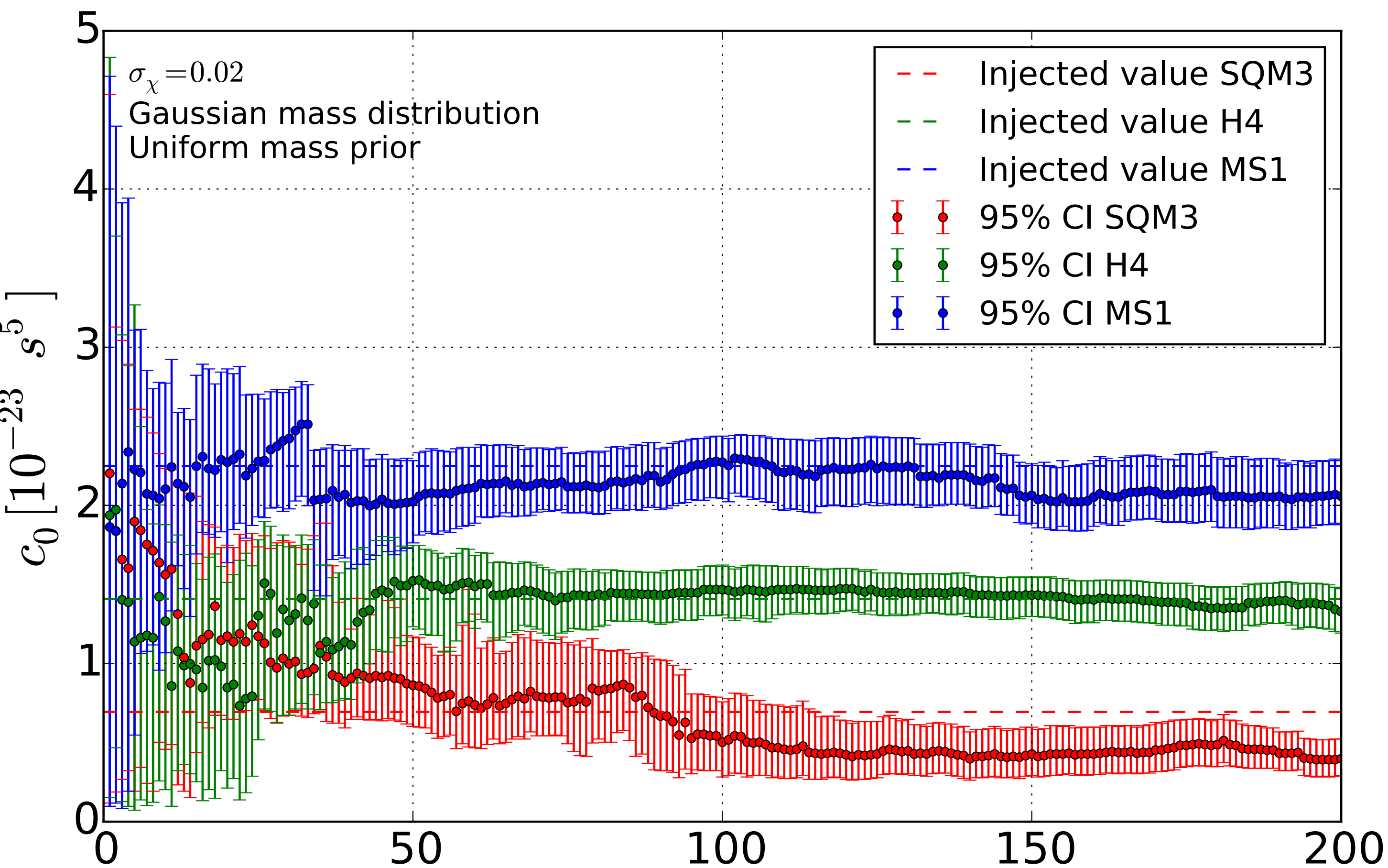
BINARY NEUTRON STAR WAVEFORMS

$$h(t) = \alpha \exp(-t/\tau_1)\left[\sin(2\pi f_1 t) + \sin(2\pi(f_1 - f_{1\epsilon})t) + \sin(2\pi(f_1 + f_{1\epsilon})t)\right] + \exp(-t/\tau_2)\sin(2\pi f_2 t + 2\pi\gamma_2 t^2 + \pi\beta_2).$$



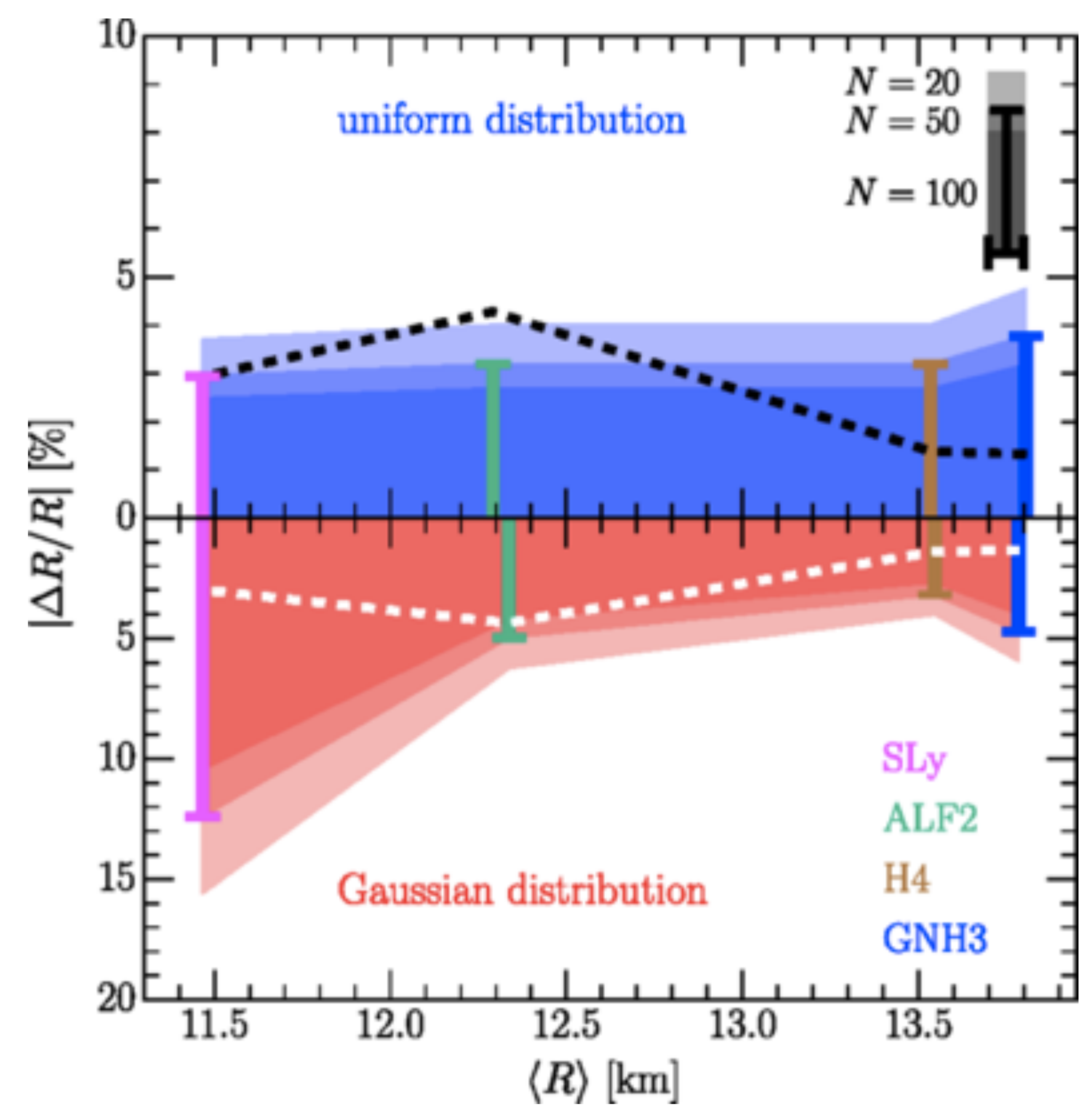
Bose+ 2017

Equation of state from inspiral part of the waveform

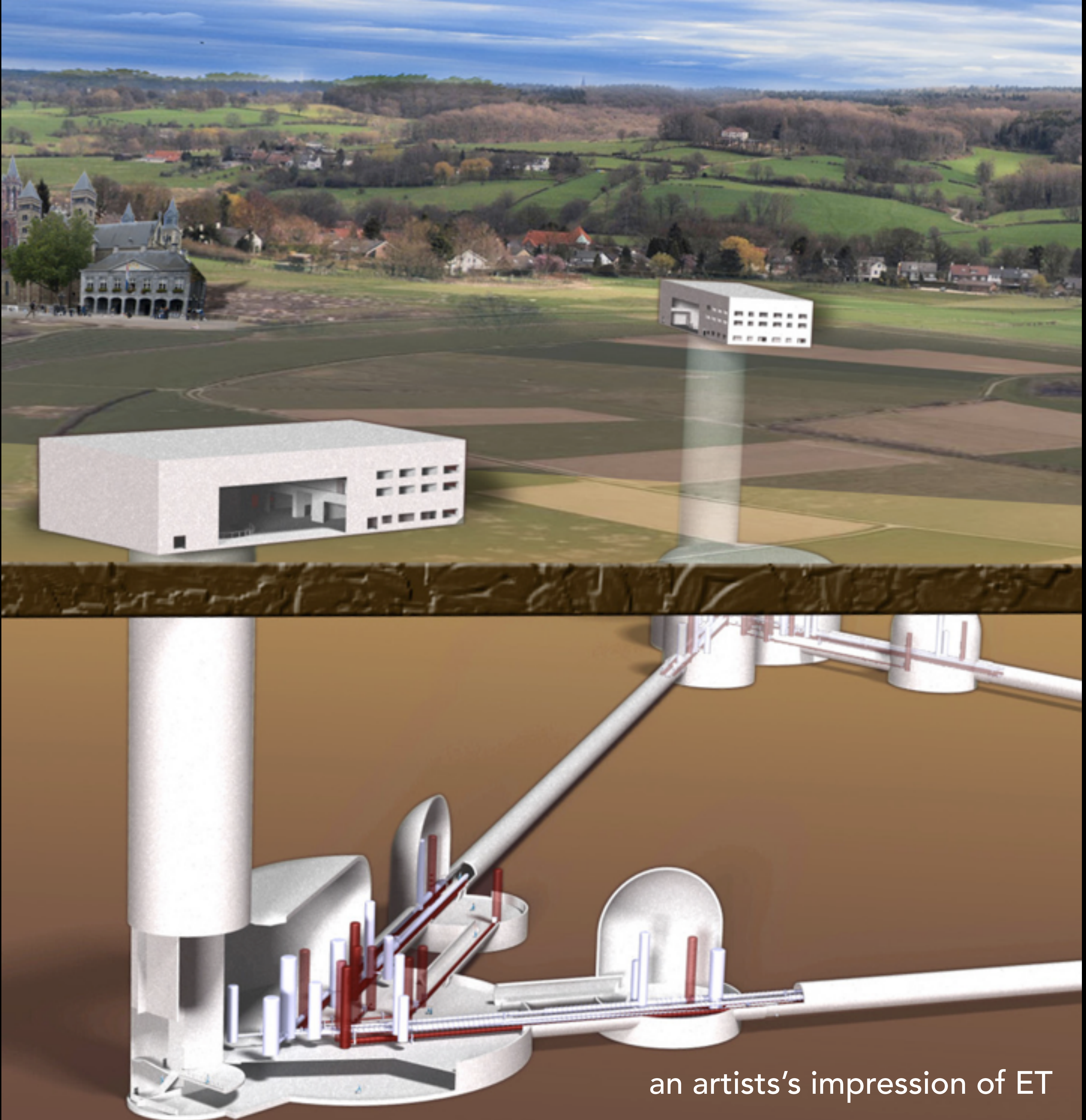


Agathos+, 2015

radius and tidal deformability from the post-merger signal



Bose+, 2017



VOYAGER:
x 3 improvement in aLIGO strain sensitivity

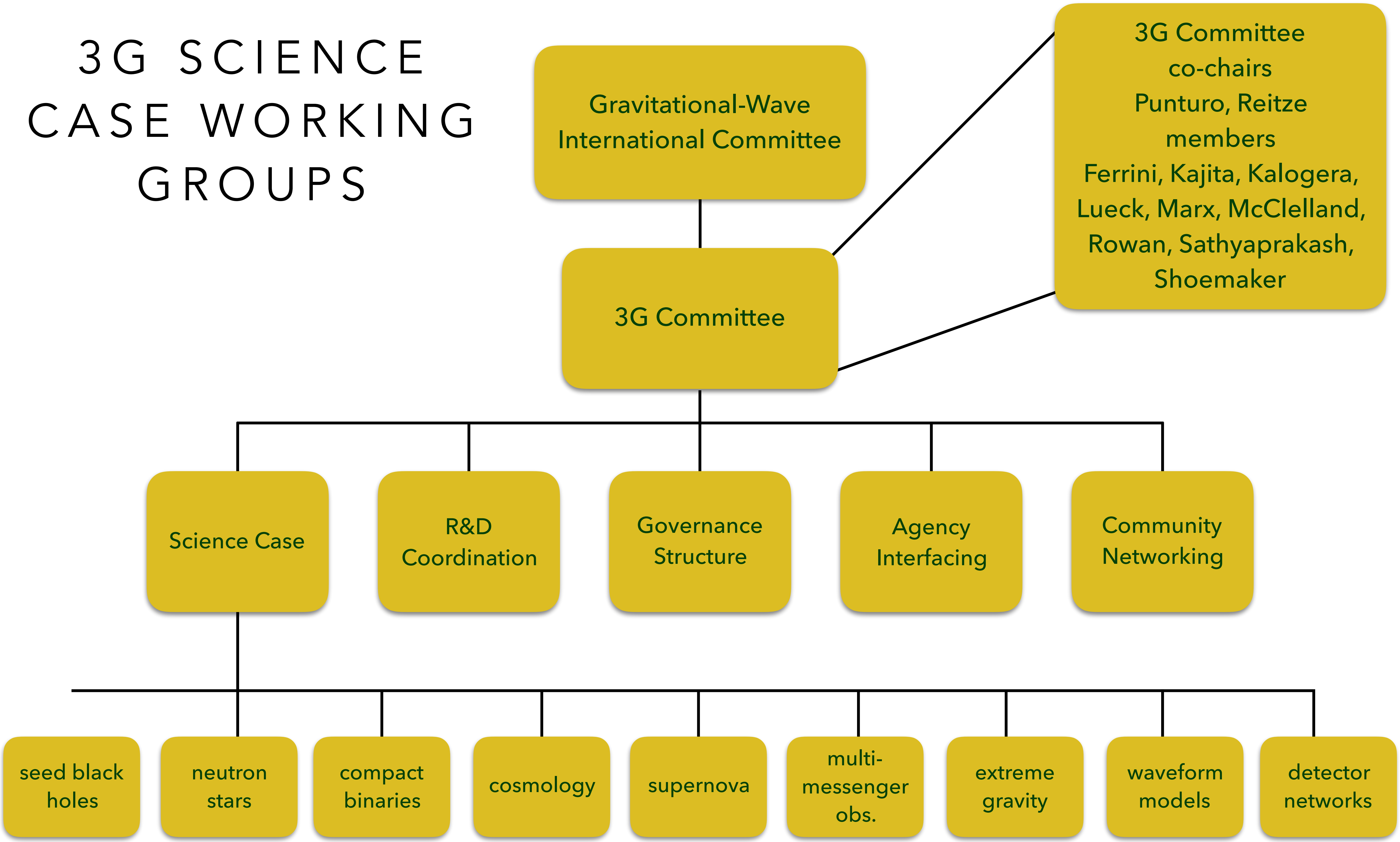
EINSTEIN TELESCOPE:
Triangular, 10 km arm length, underground, cryogenic detectors

COSMIC EXPLORER:
40 km arm length, cryogenic, overground interferometer

NEXT GENERATION OF GW DETECTORS

- to fully exploit the GW window we will need new facilities
- GWIC formed a subcommittee to develop a vision for the next generation of ground-based detectors
- one of the charges to the GWIC subcommittee is:
  - *"commission a study of ground-based gravitational wave science from the global scientific community, investigating potential science vs. architecture vs. network configuration vs. cost trade-offs, …"*
  - GWIC subcommittee has constituted five 3G subcommittees:
    - (1) Science Case Team (3G-SCT), (2) R&D Coordination, (3) Governance, (4) Agency Interfacing, (5) Community Networking
- the Science Case will be developed by an international consortium of scientists under the leadership of the 3G-SCT (18 members)

3G SCIENCE CASE WORKING GROUPS



for membership of committees see:
https://gwic.ligo.org/3Gsubcomm/

WHAT CAN GW ASTRONOMY TELL US?

- fundamental physics
  - equation of state of ultra dense matter, dark energy EoS
  - gravastars, wormholes, …, testing non-BH paradigms?
- astrophysics
  - formation and evolution of compact binaries, GRB engines, supernovae
- cosmology
  - primordial and astronomical GW backgrounds
  - primordial origin of black hole binaries
  - standard siren cosmography

LIGO-LIVINGSTON OBSERVATORY

Credit: LIGO Livingston

LIGO-HANFORD OBSERVATORY

Credit: LIGO Hanford

VIRGO AT CASCINA, ITALY

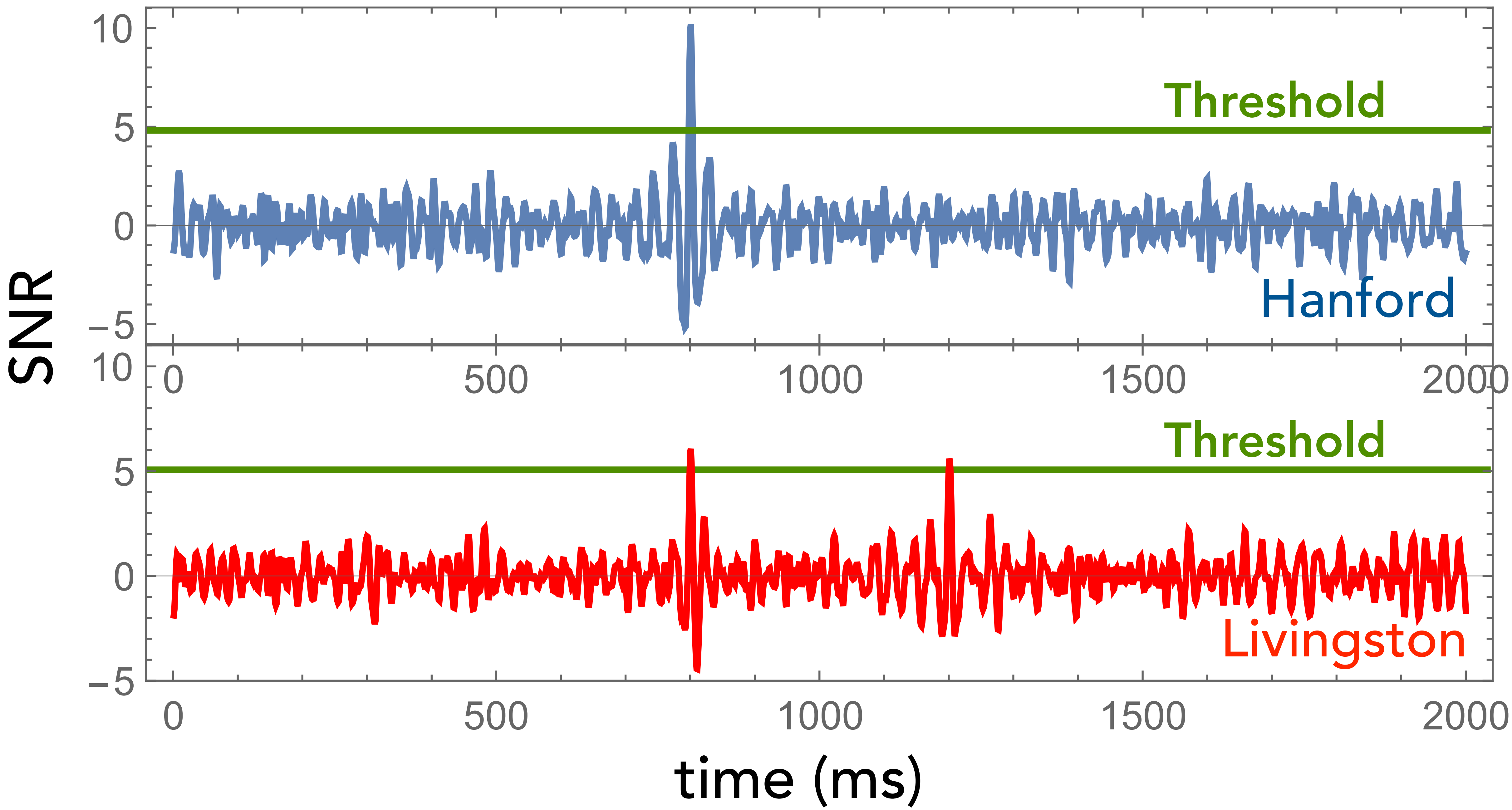
Credit: Virgo

HOW DO WE MEASURE THE BACKGROUND?

- two independent methods are used to measure the background
  - method of time-shifts with coincident triggers
  - method of likelihood with single detector triggers
- time-shift method
  - change the time stamp of triggers from one detector relative to the other by more than the light travel time between the detectors and then look for coincidence
- likelihood method
  - compute the probability density function of non-coincident triggers as a function of their likelihood for each detector; deduce the likelihood of chance coincidence from the distributions

COINCIDENT DETECTION

- coincidence detection: look for triggers coincident within light-travel time in a network of detectors



COINCIDENT DETECTION

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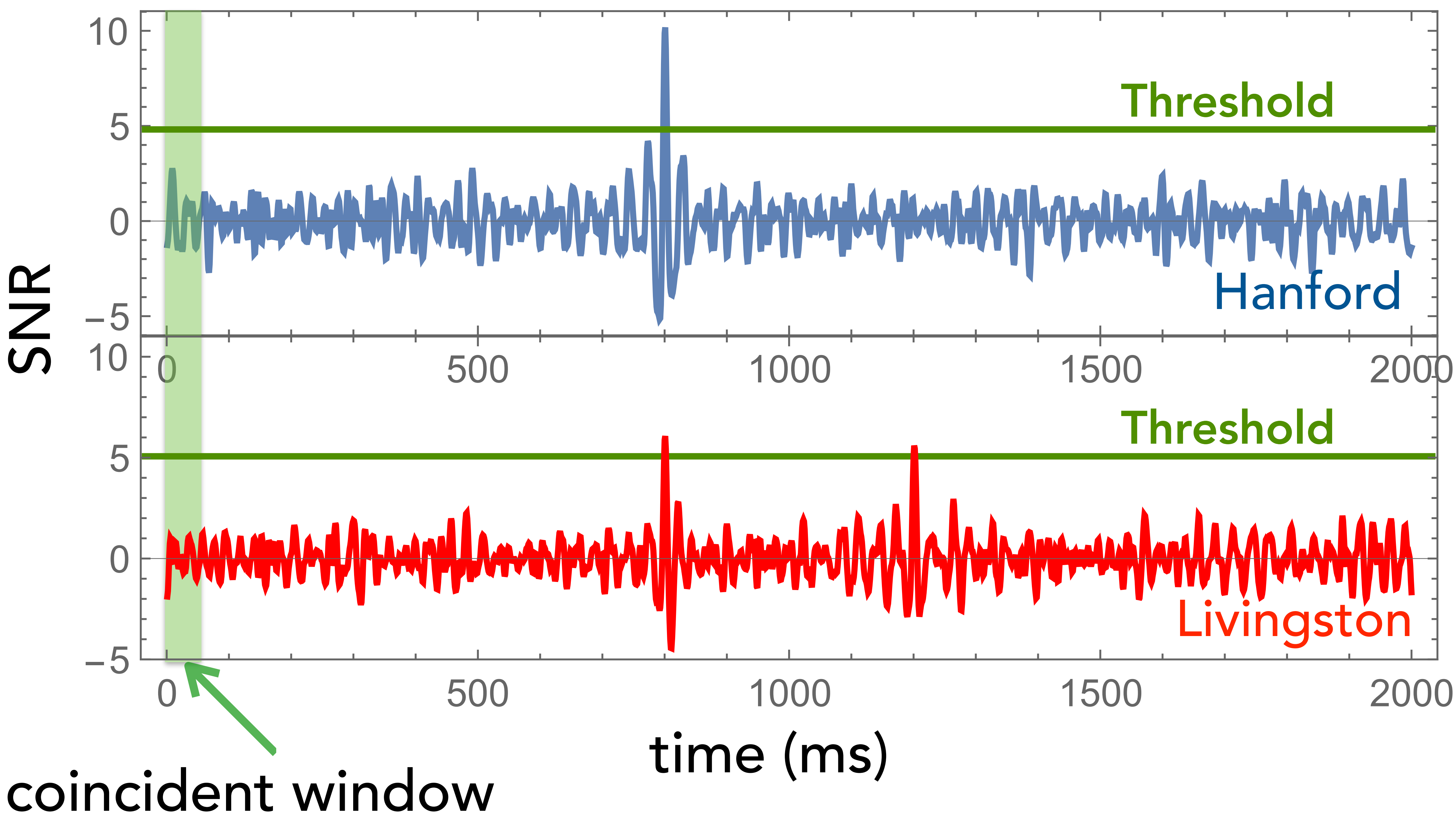

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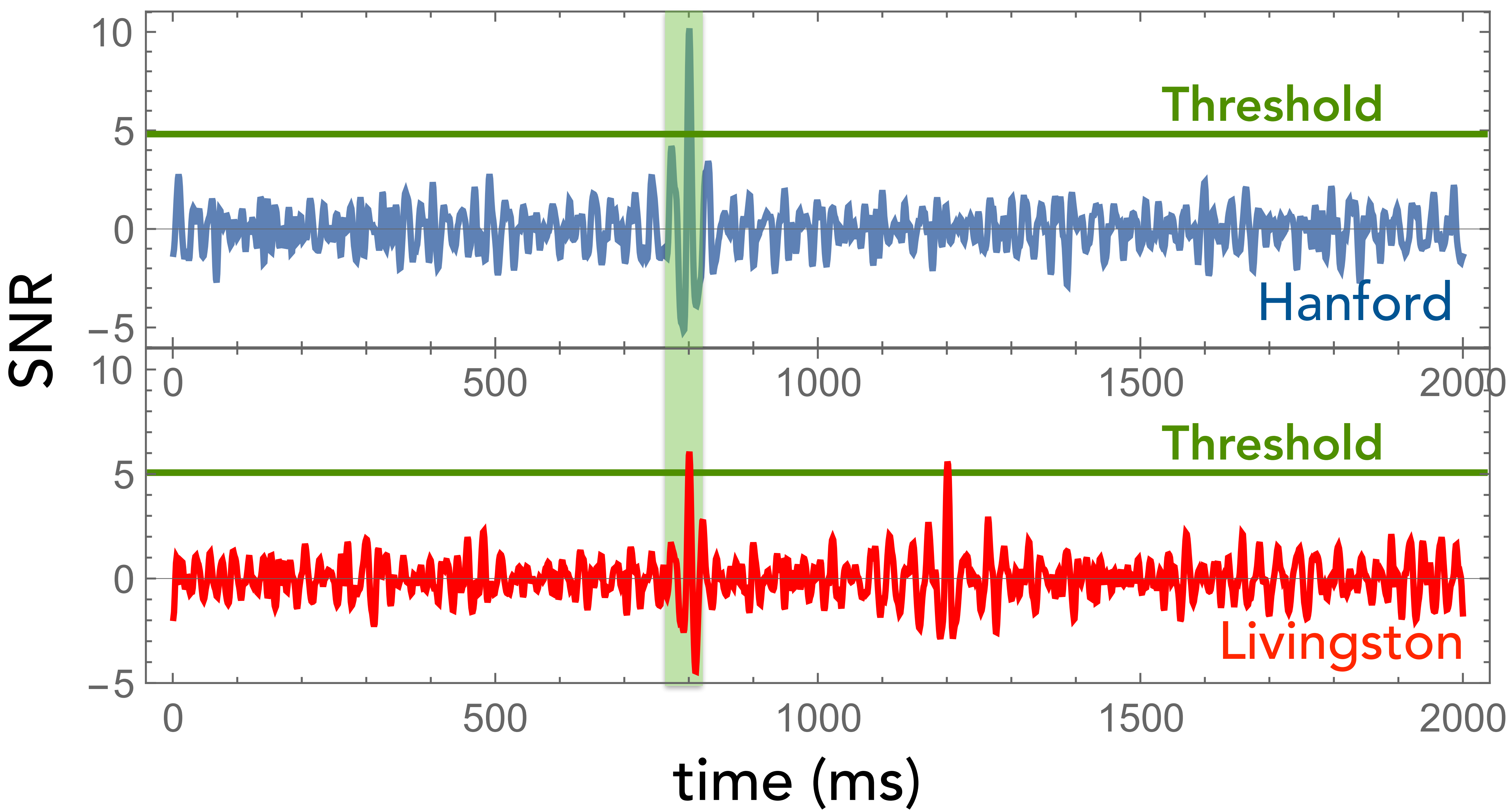

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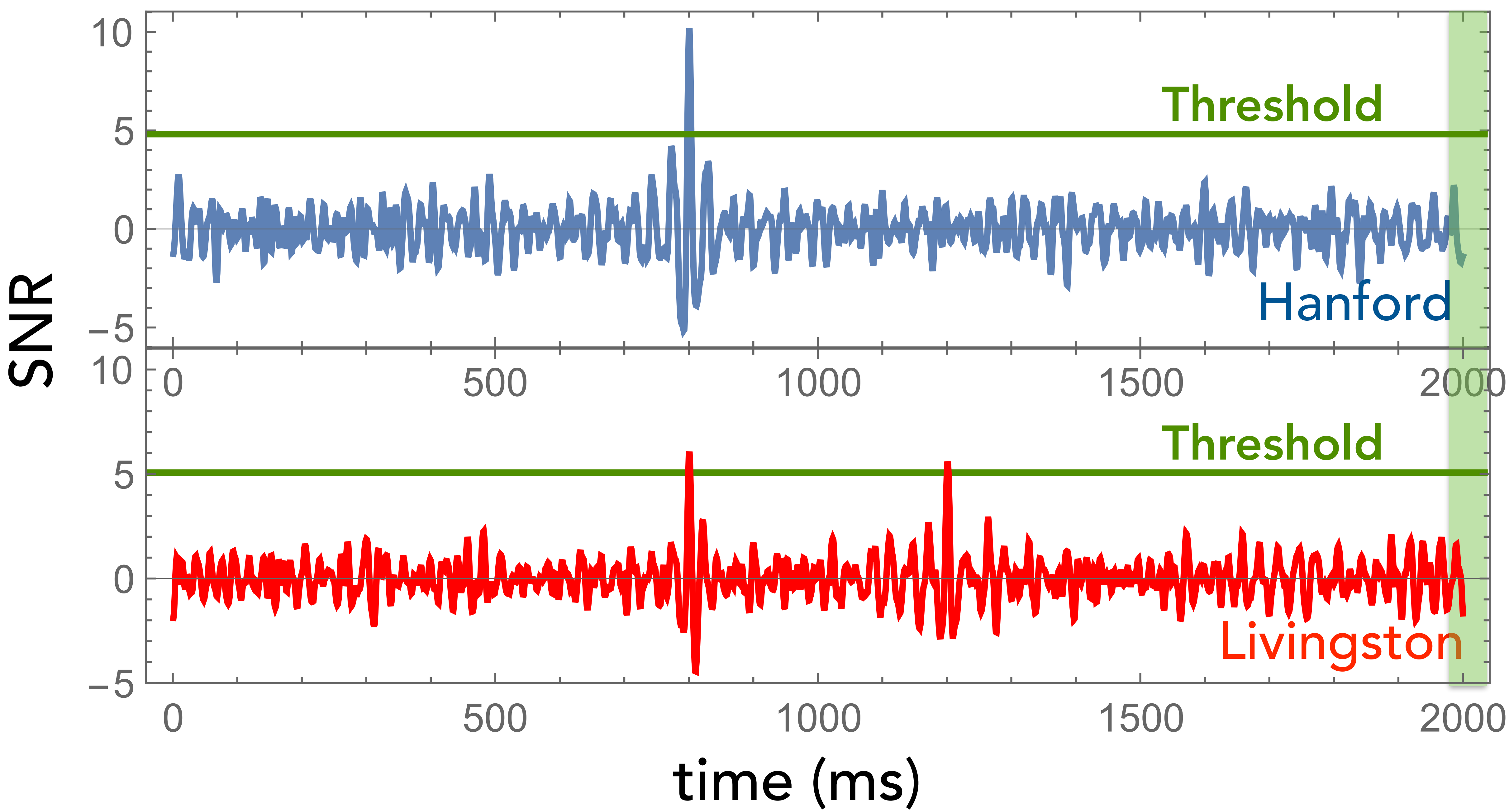

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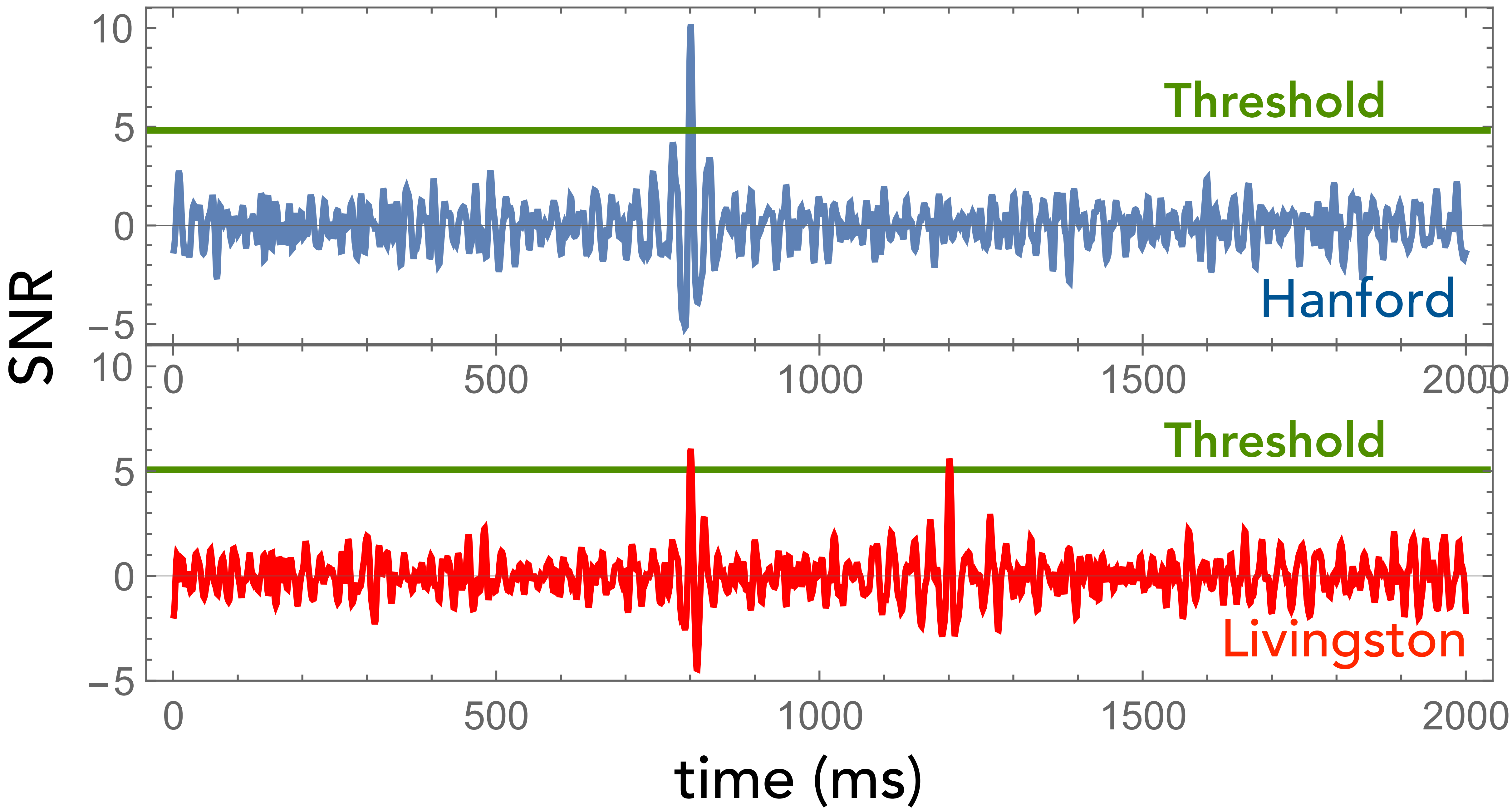
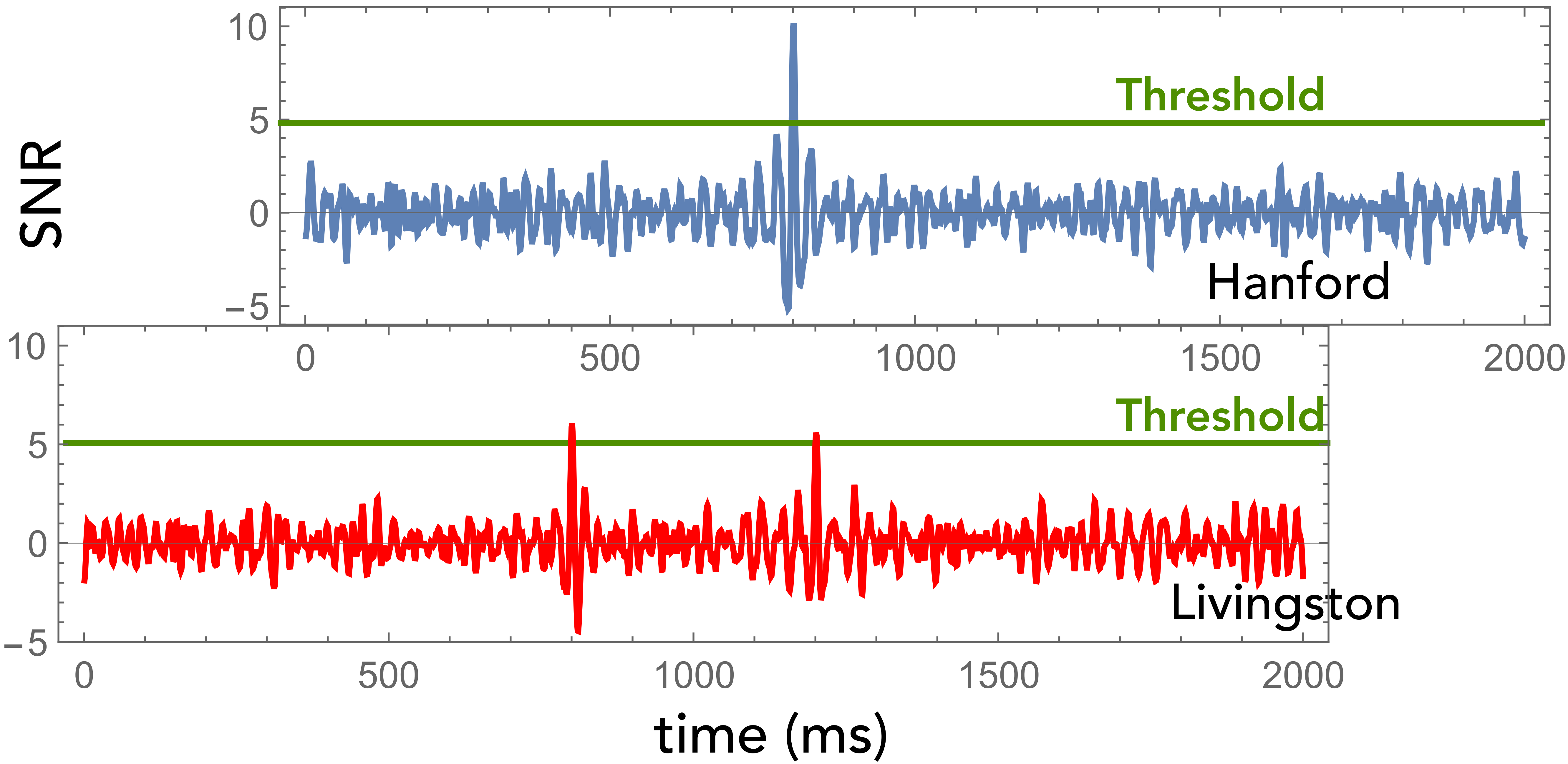


TIME-SHIFT METHOD FOR BACKGROUND ESTIMATION

- shift one of the data sets with respect to the other and then look for coincidence - any coincidence now is a false alarm



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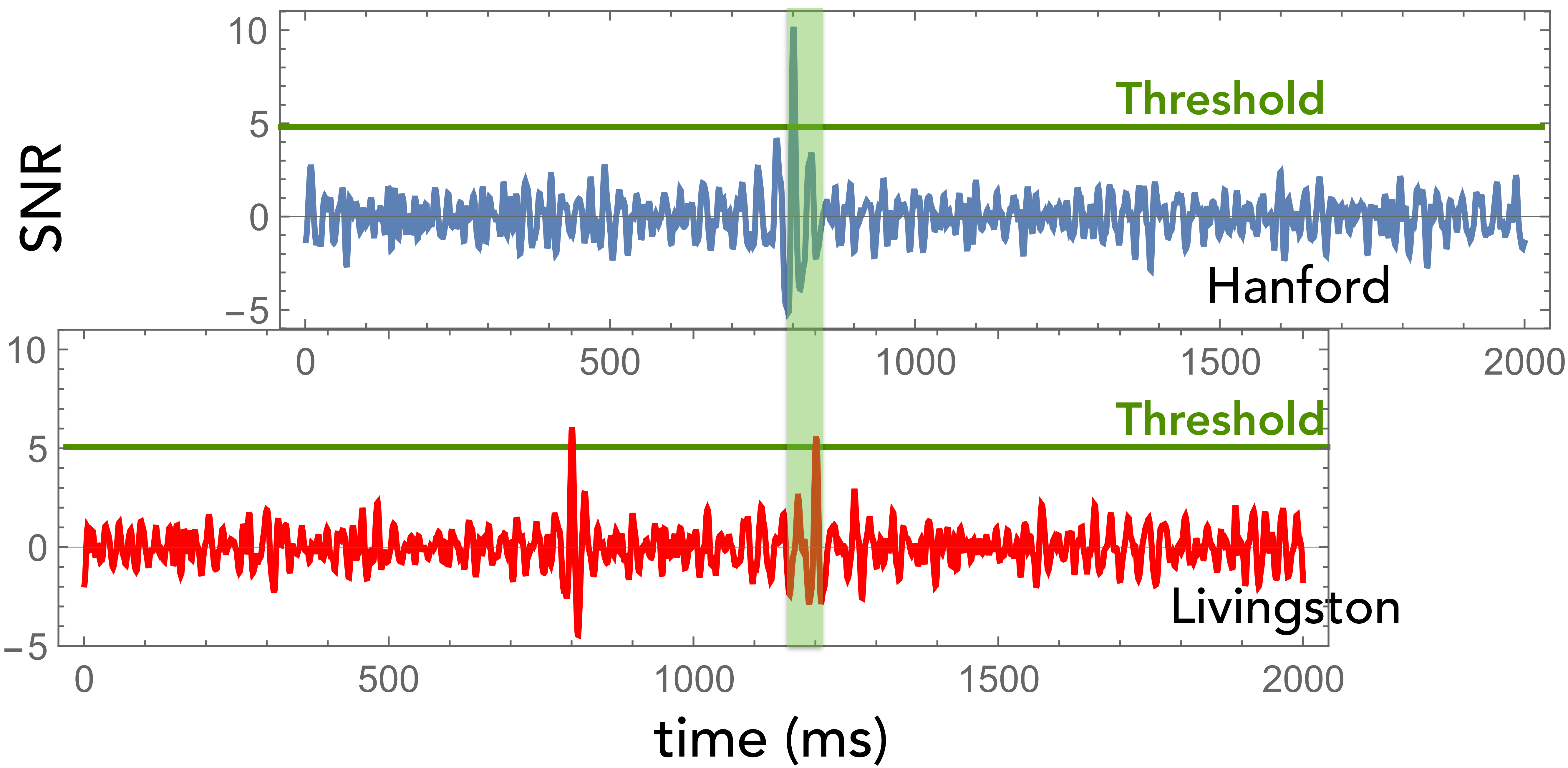
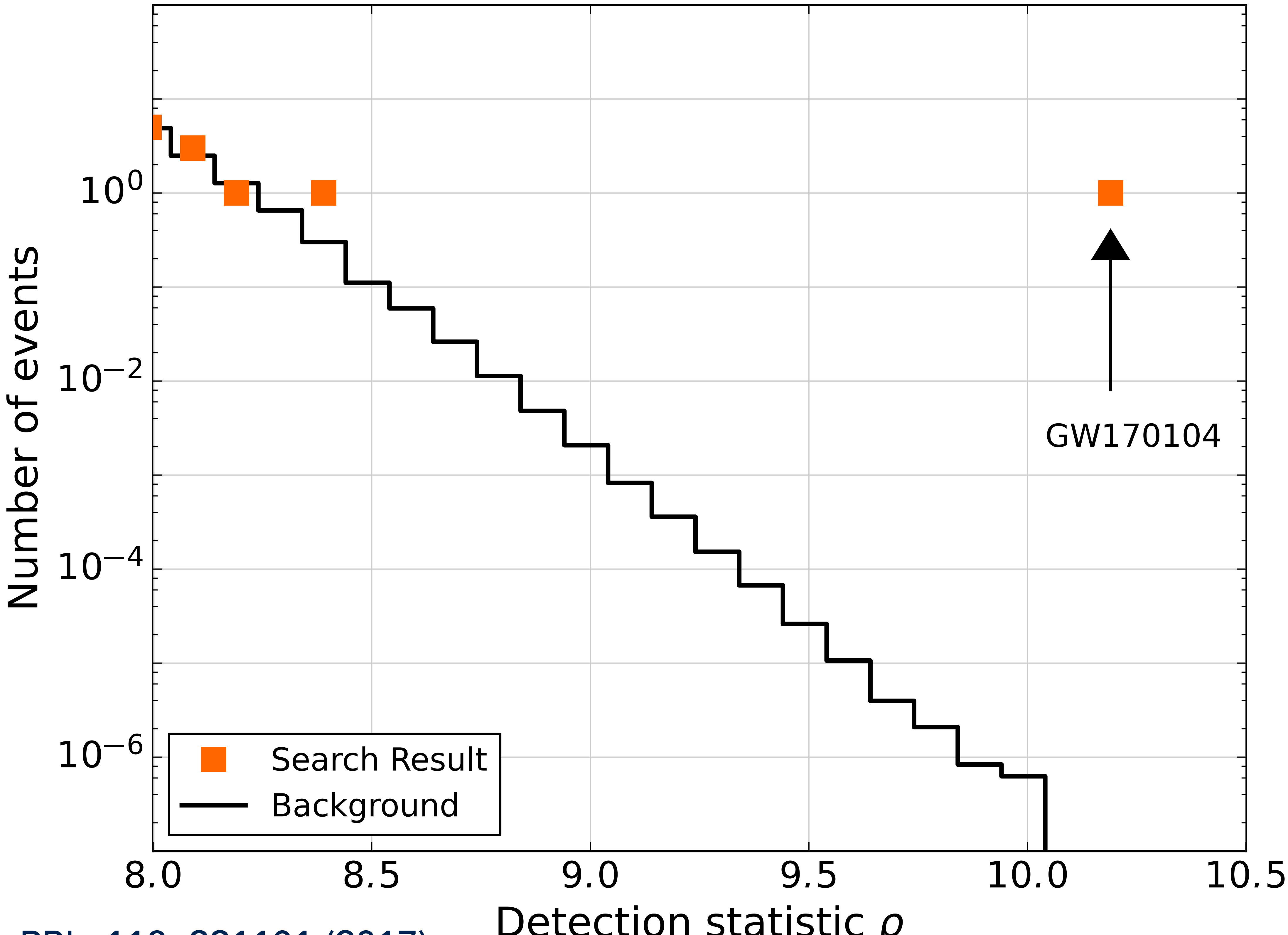
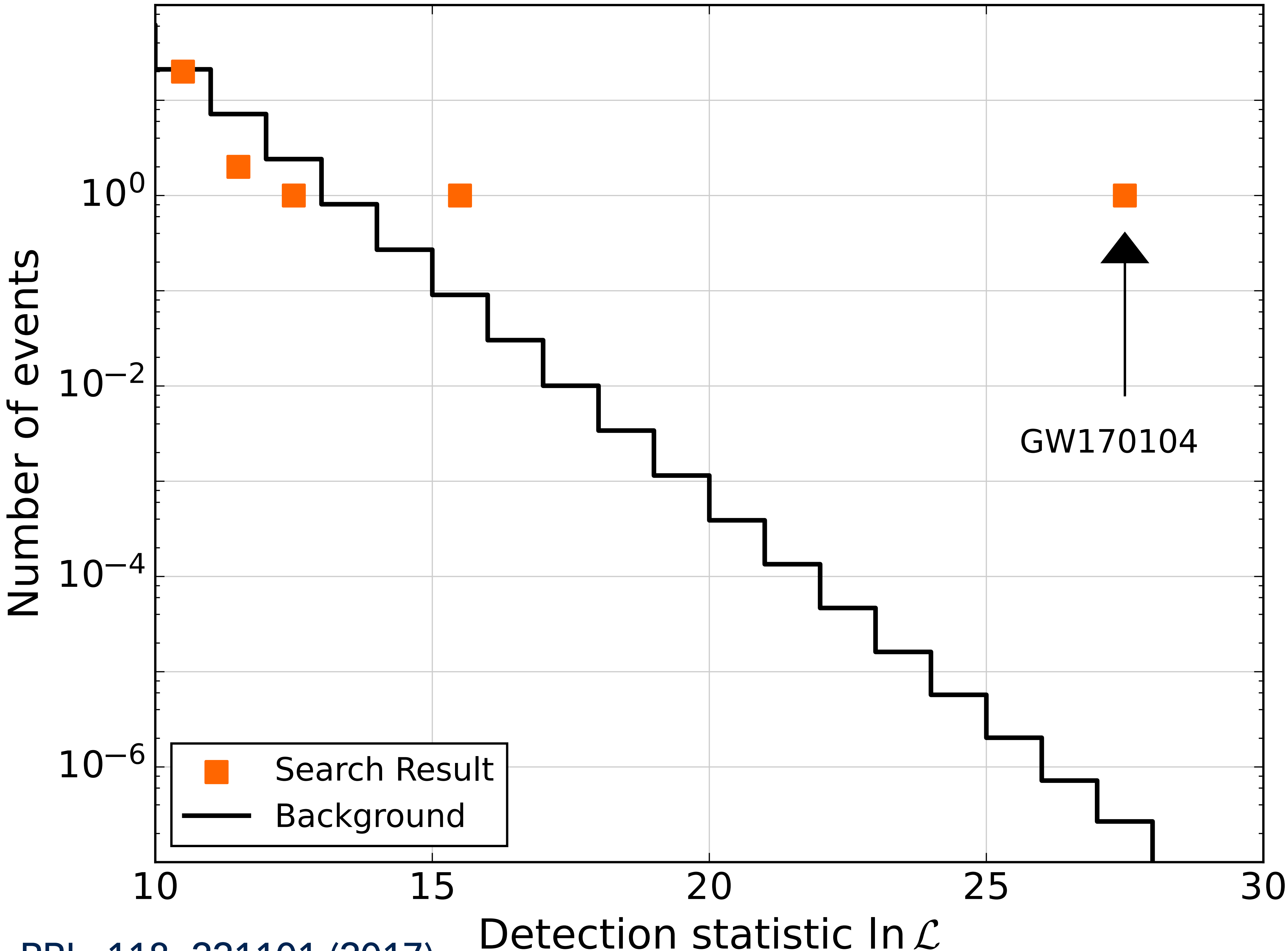


SIGNIFICANCE OF GW170104: TIME-SHIFT METHOD



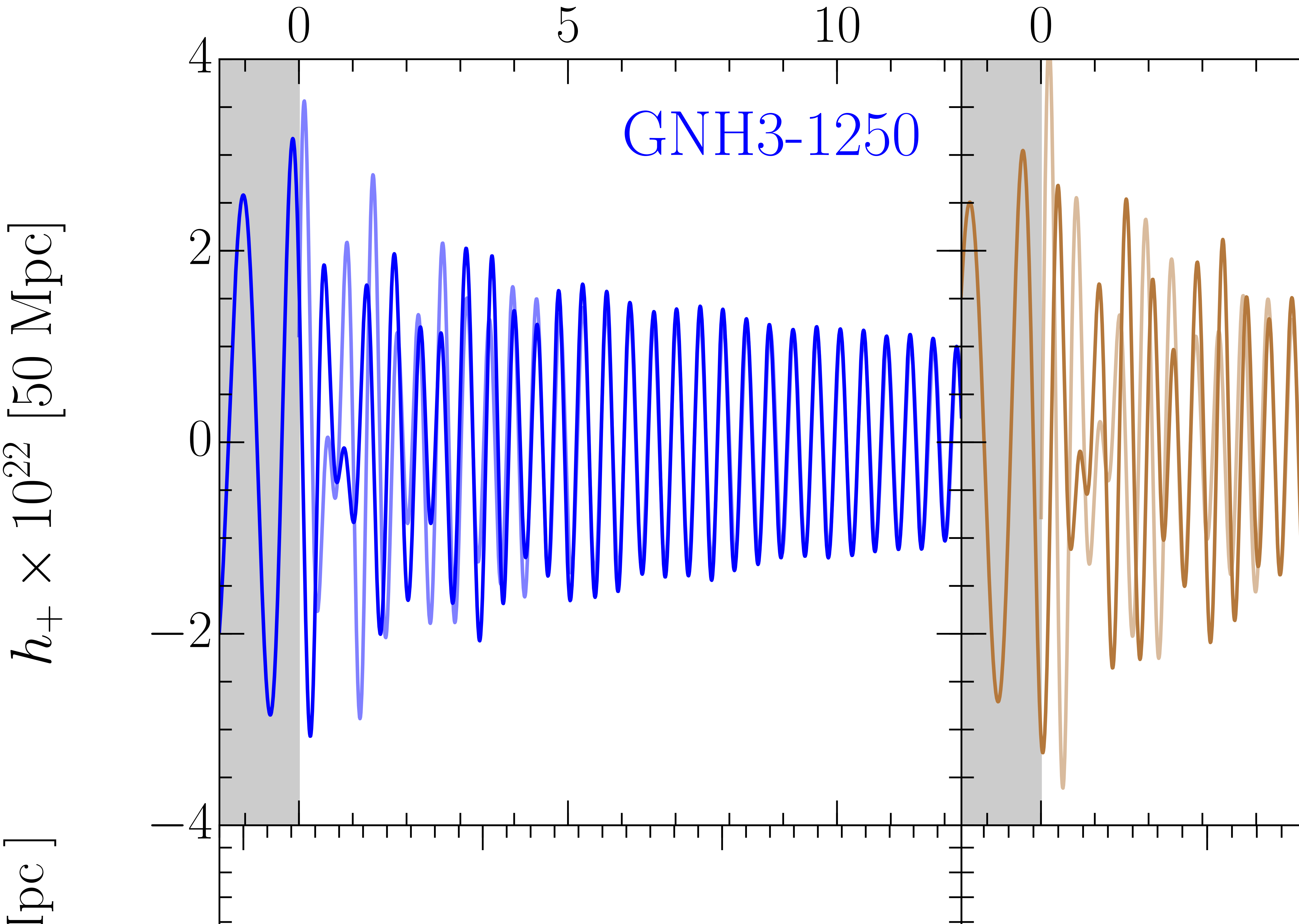
Abbott+ PRL, 118, 221101 (2017)

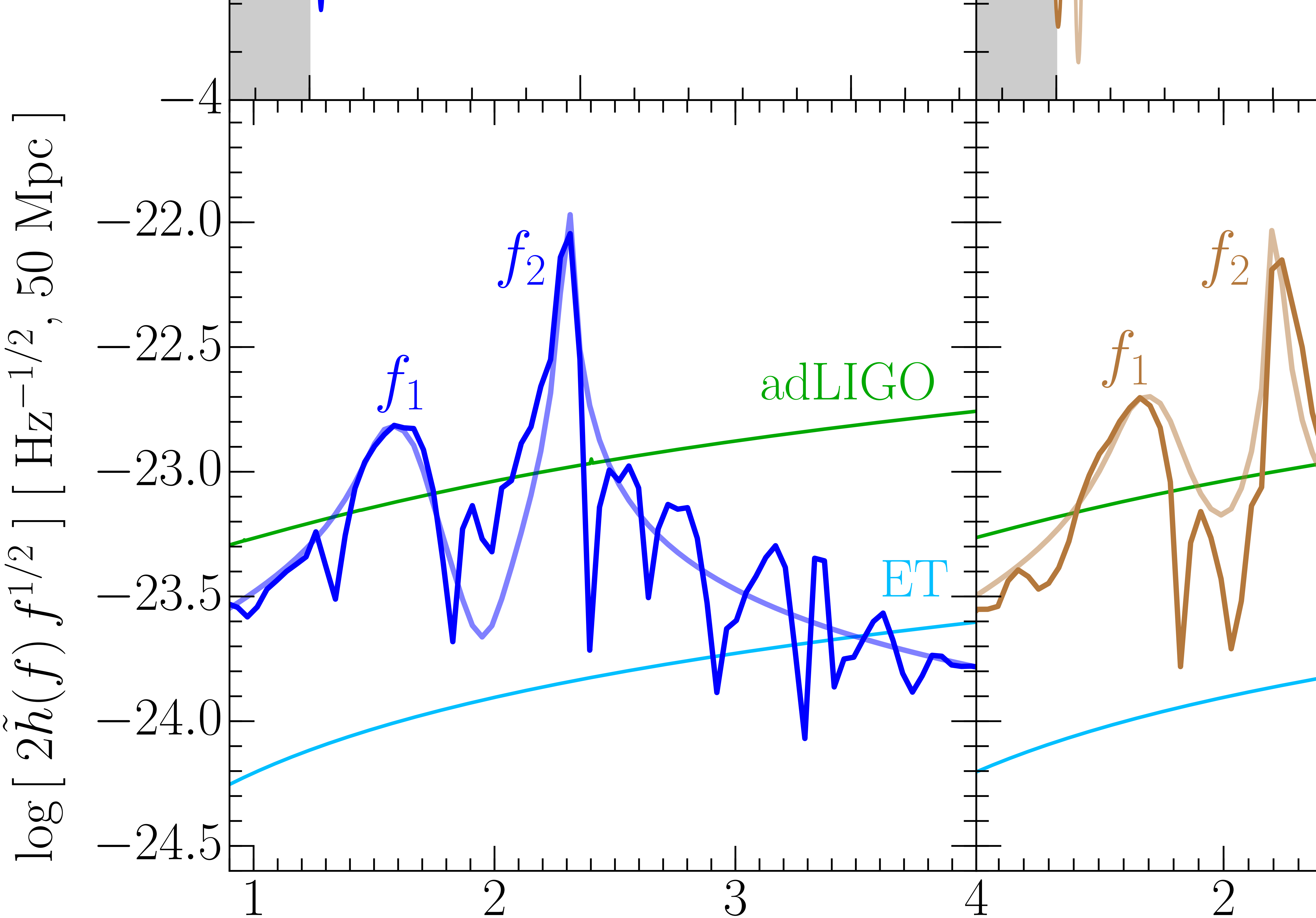
SIGNIFICANCE OF GW170104: LIKELIHOOD METHOD



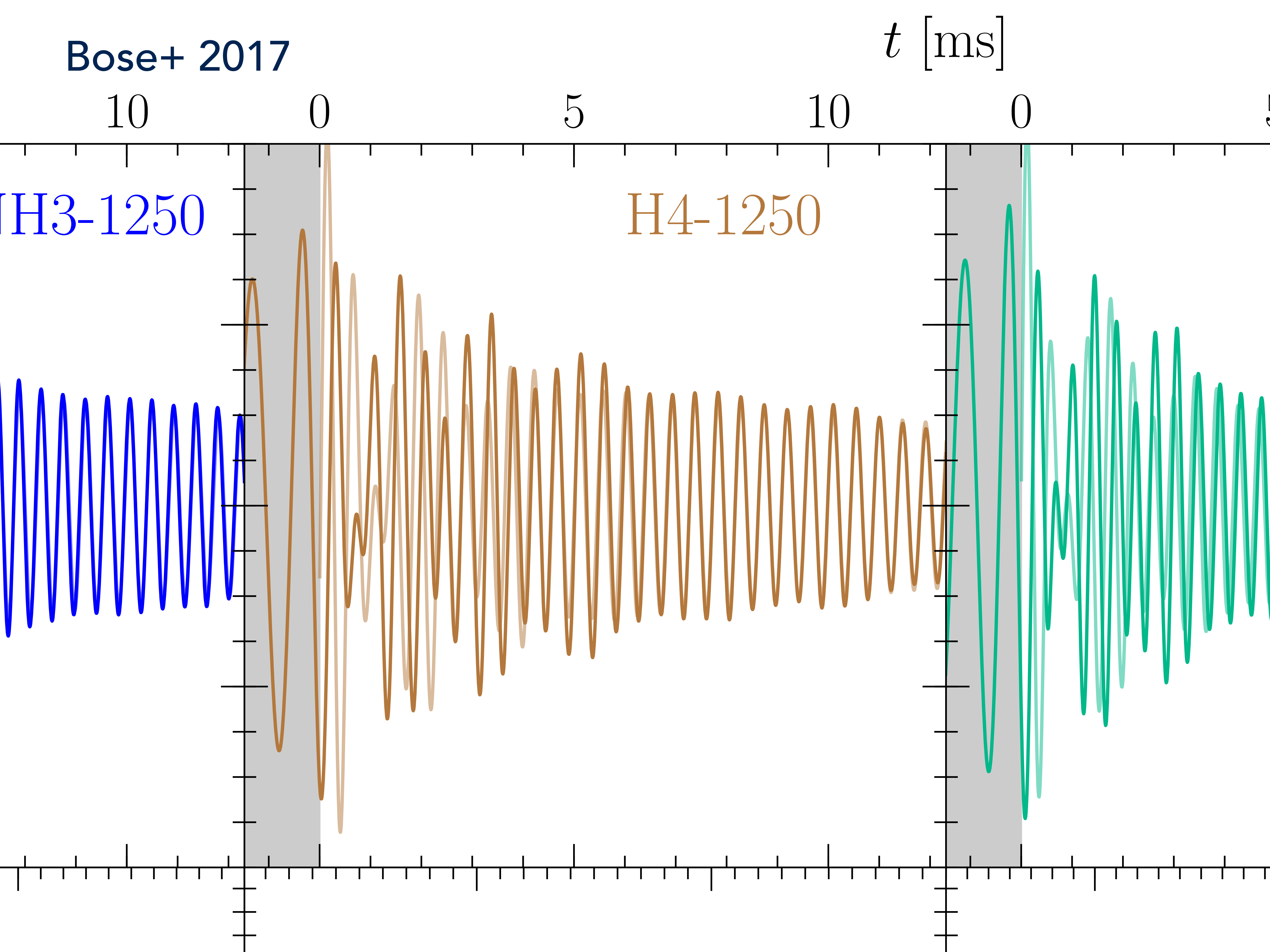
Abbott+ PRL, 118, 221101 (2017)

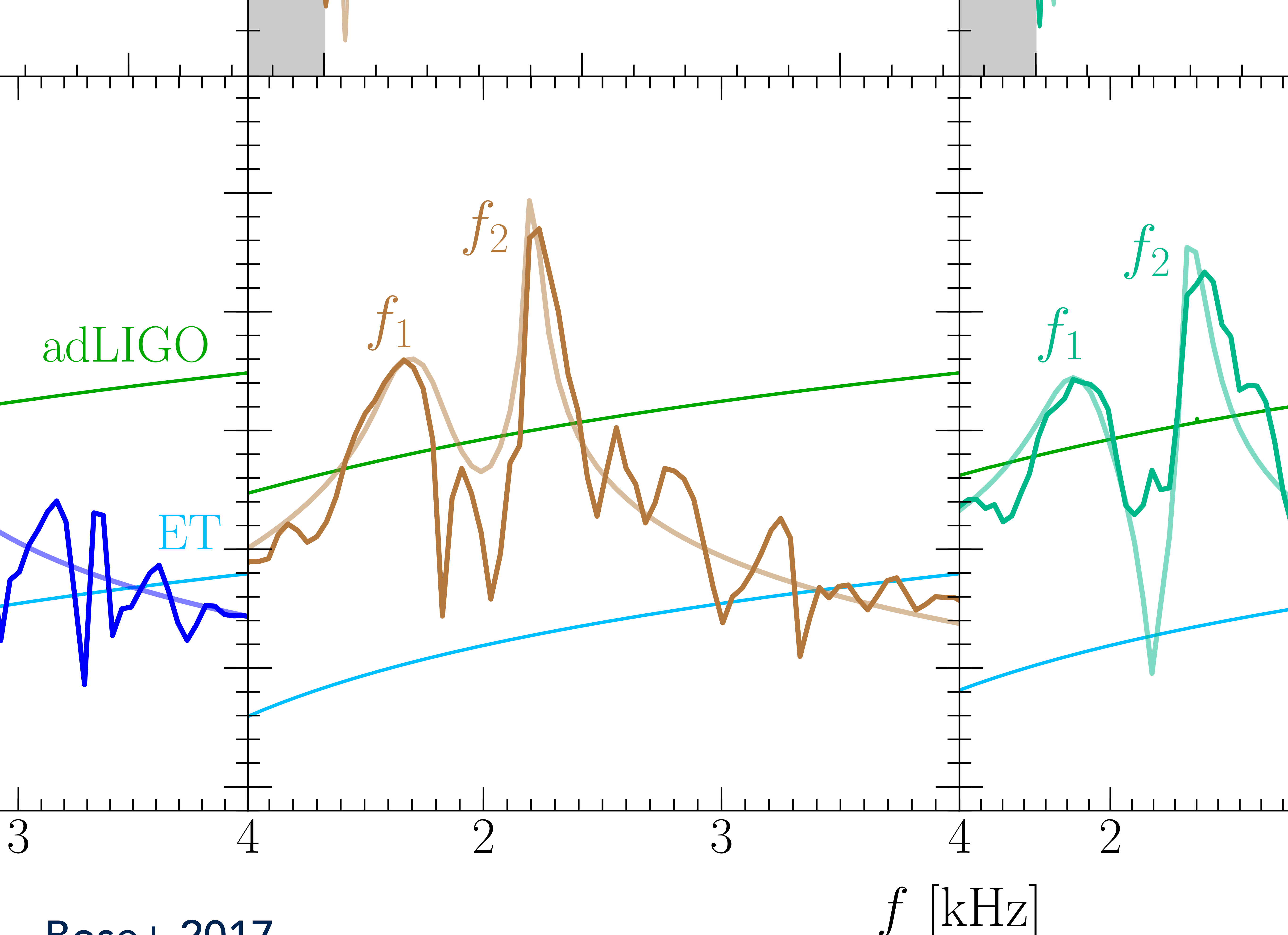
Bose+ 2017



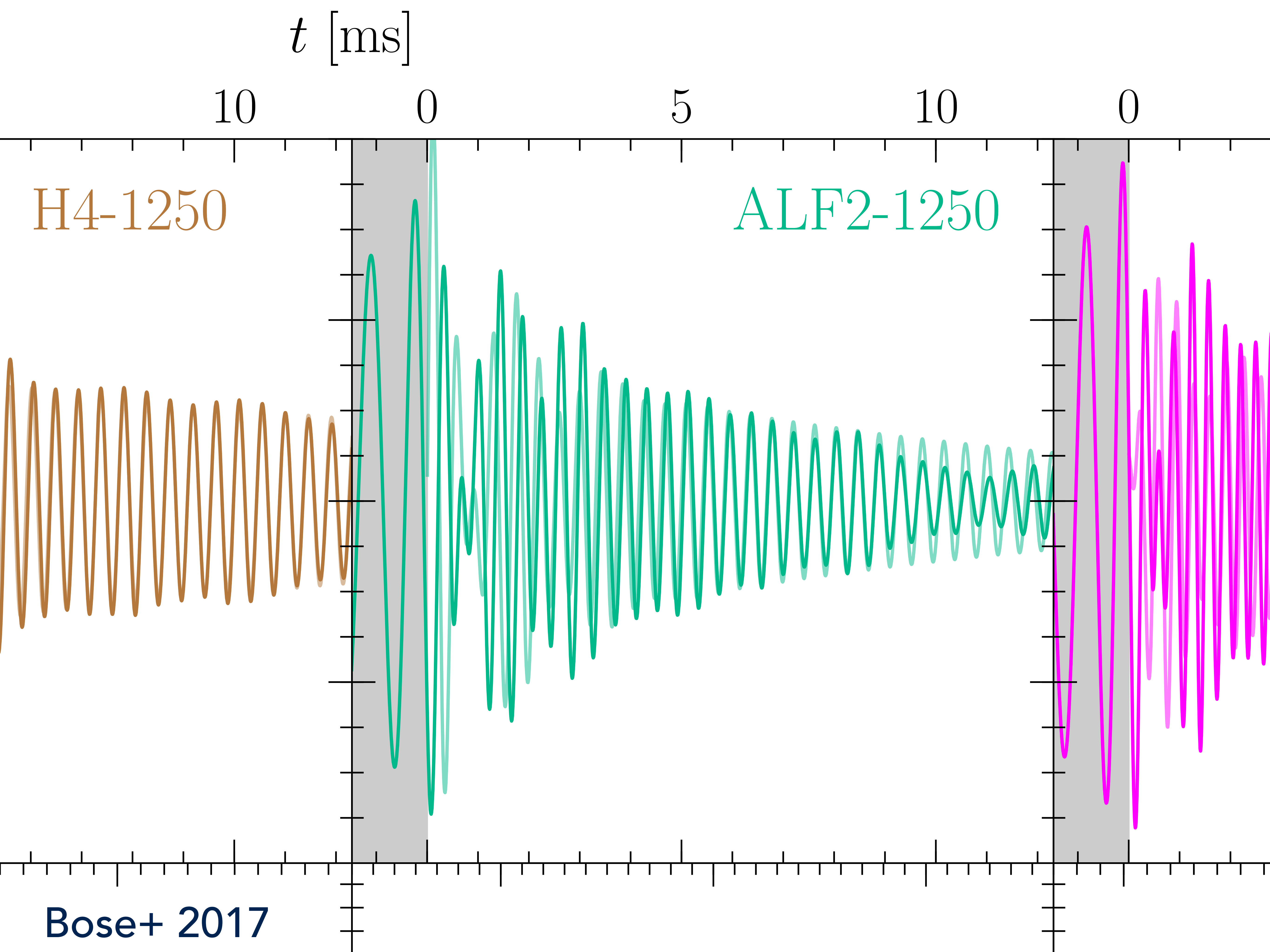

f_2
f_1
adLIGO
ET
f_1
f_2
−4
−22.0
−22.5
−23.0
−23.5
−24.0
−24.5
1
2
3
4
2
$\log[\,2\tilde{h}(f)\,f^{1/2}\,]\ [\ \mathrm{Hz}^{-1/2},\ 50\ \mathrm{Mpc}\ ]$

Bose+ 2017

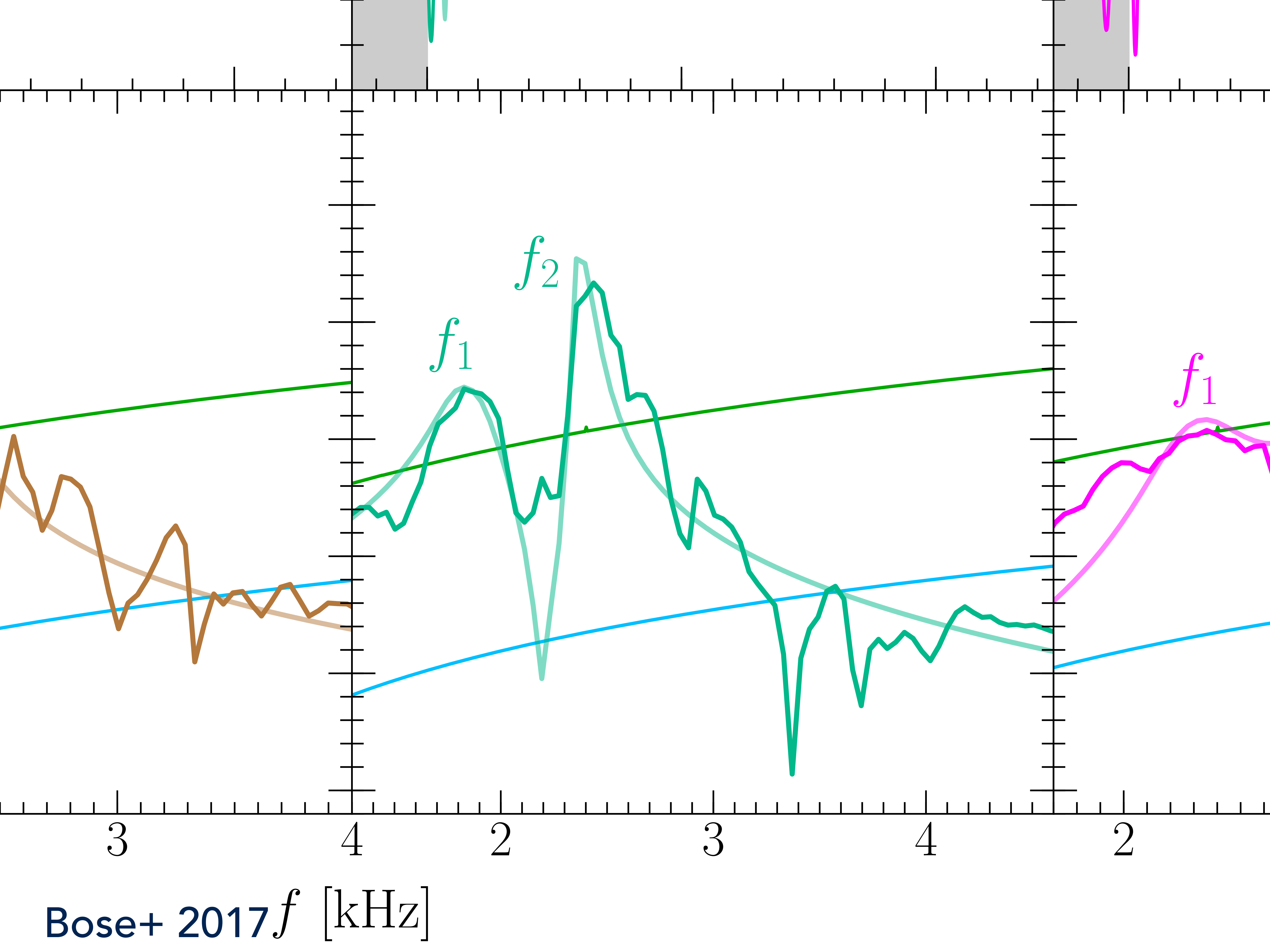

Bose+ 2017
t [ms]
10
0
5
10
0
MH3-1250
H4-1250

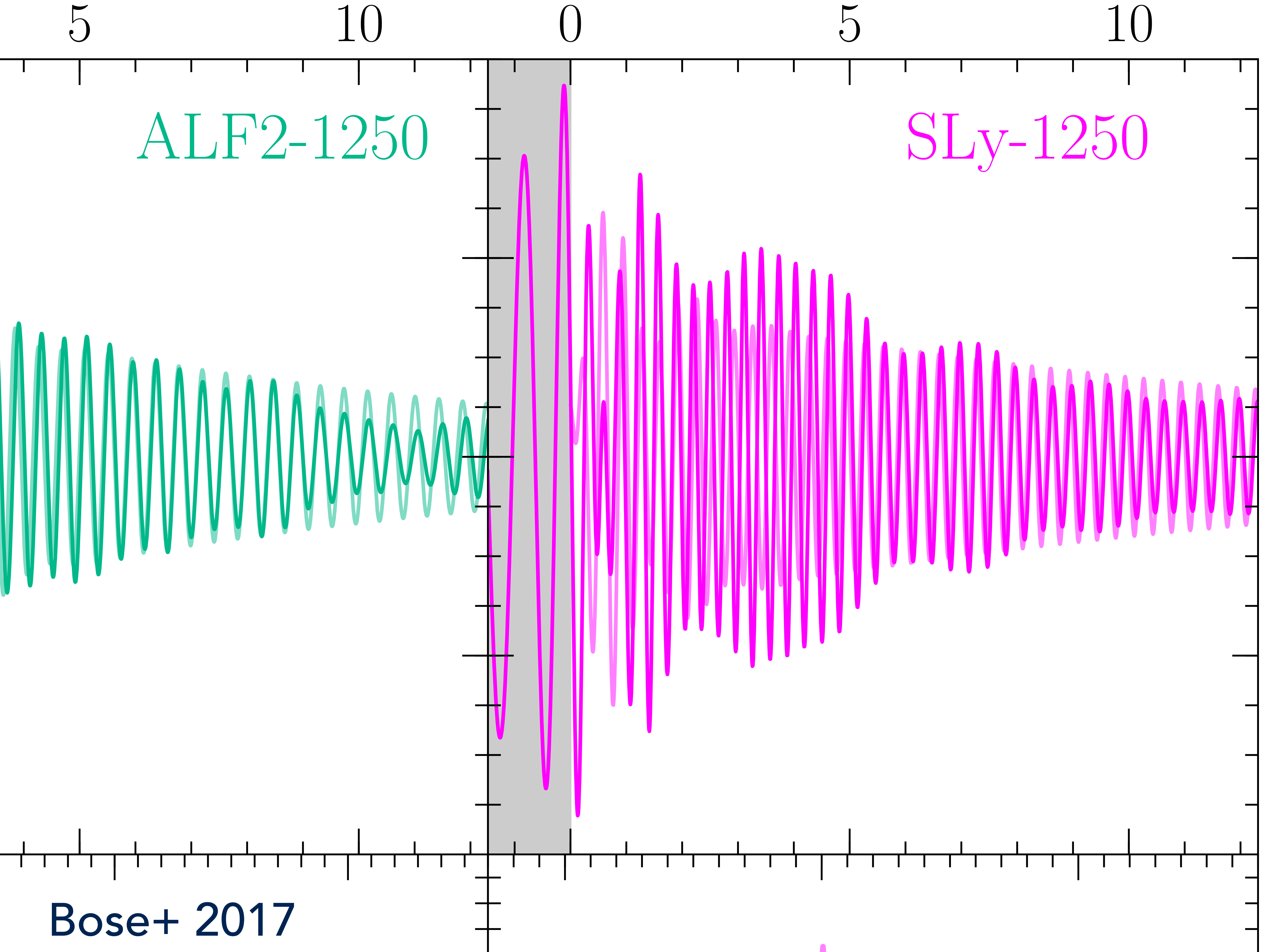


Bose+ 2017

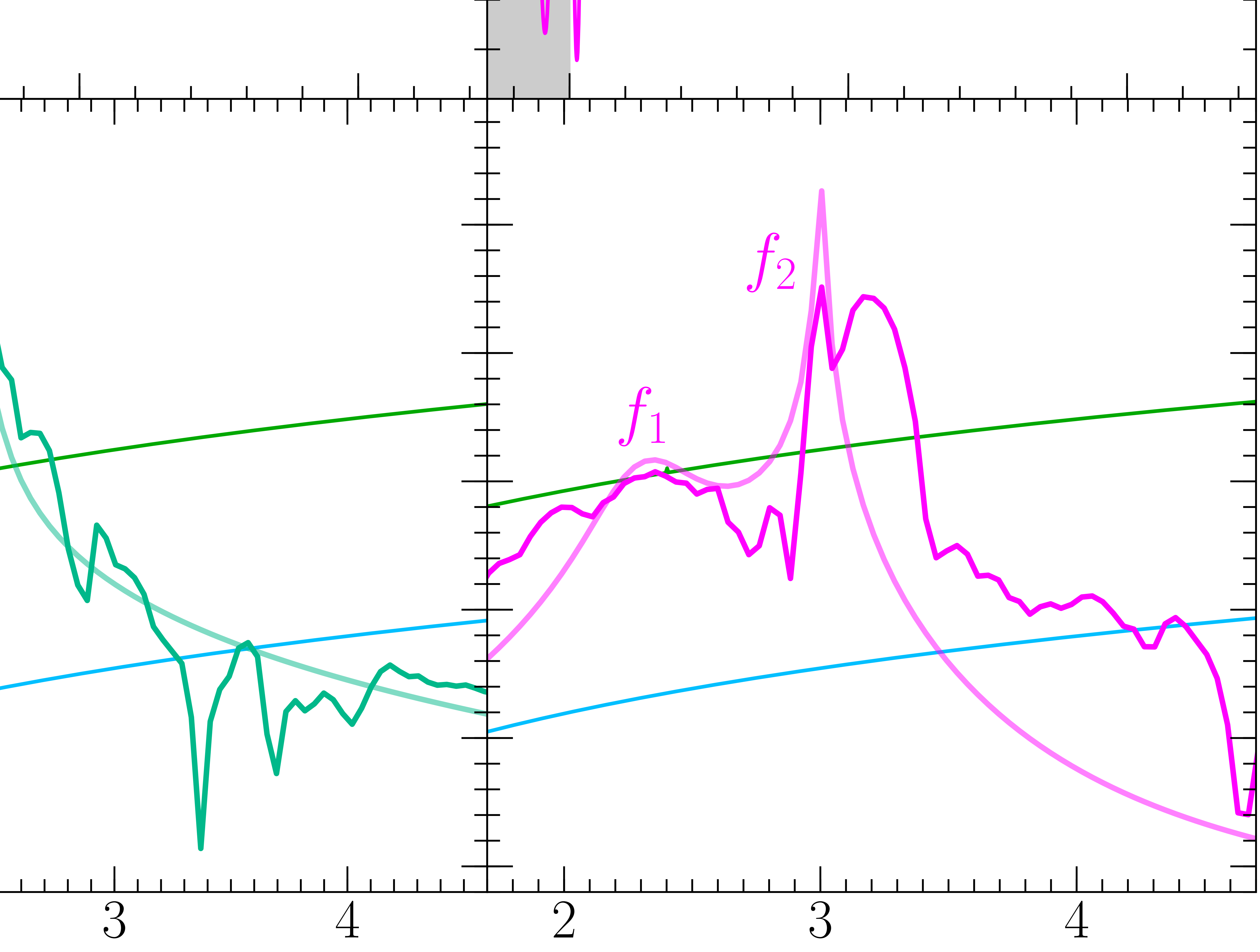


t [ms]
10
0
5
10
0
H4-1250
ALF2-1250
Bose+ 2017


f_2
f_1
f_1
3
4
2
3
4
2
Bose+ 2017
f [kHz]

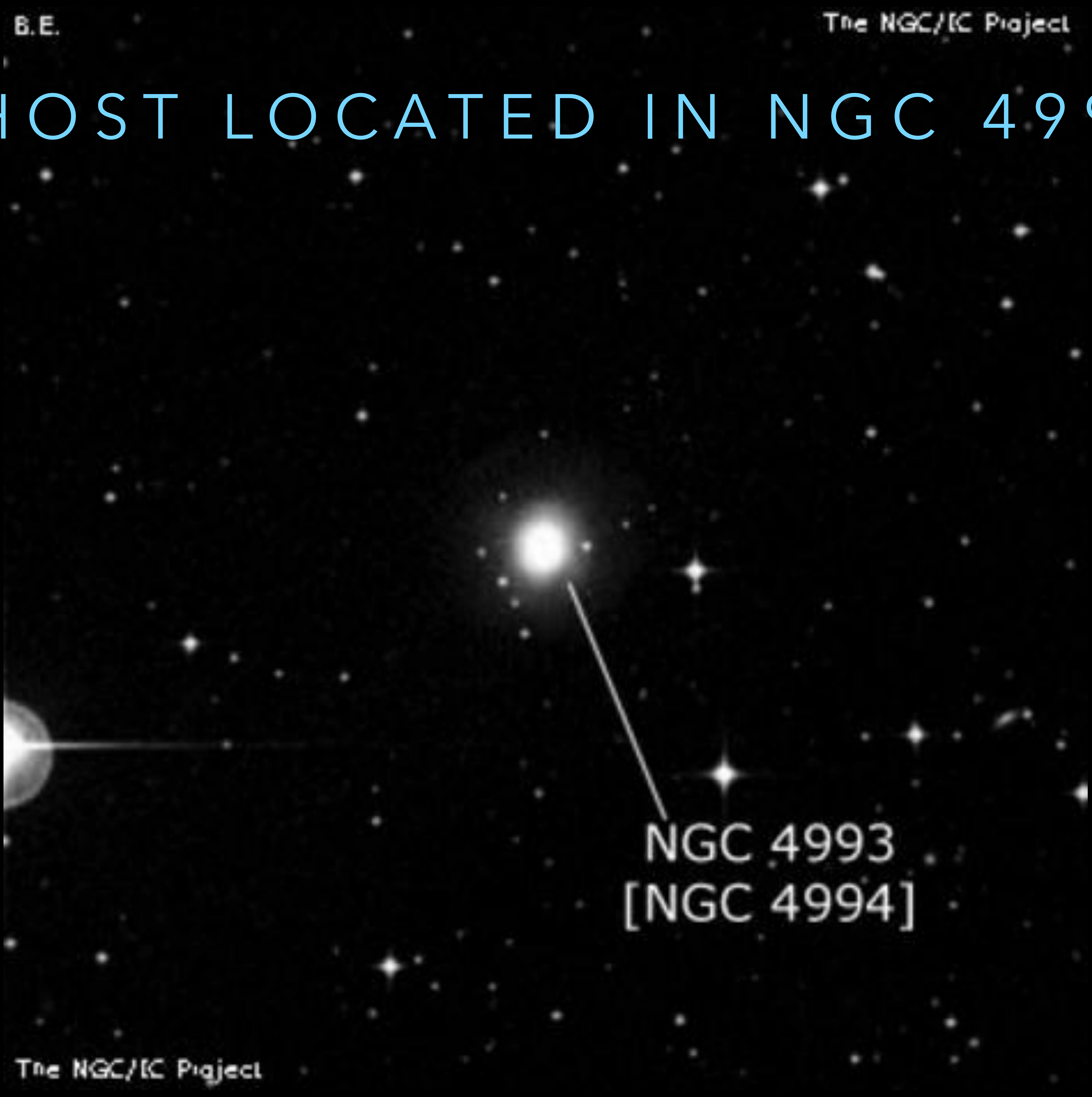


Bose+ 2017

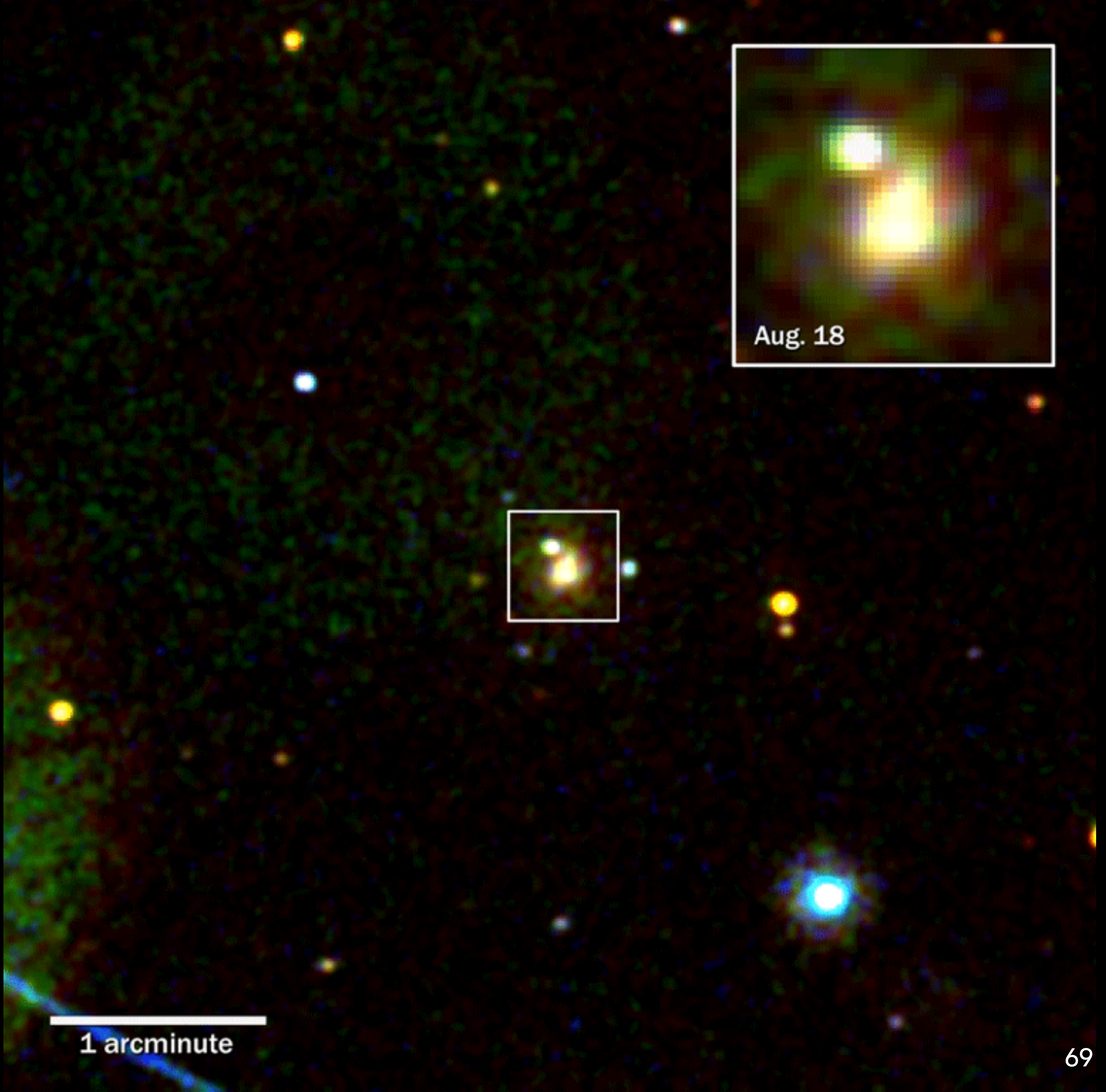


Bose+ 2017

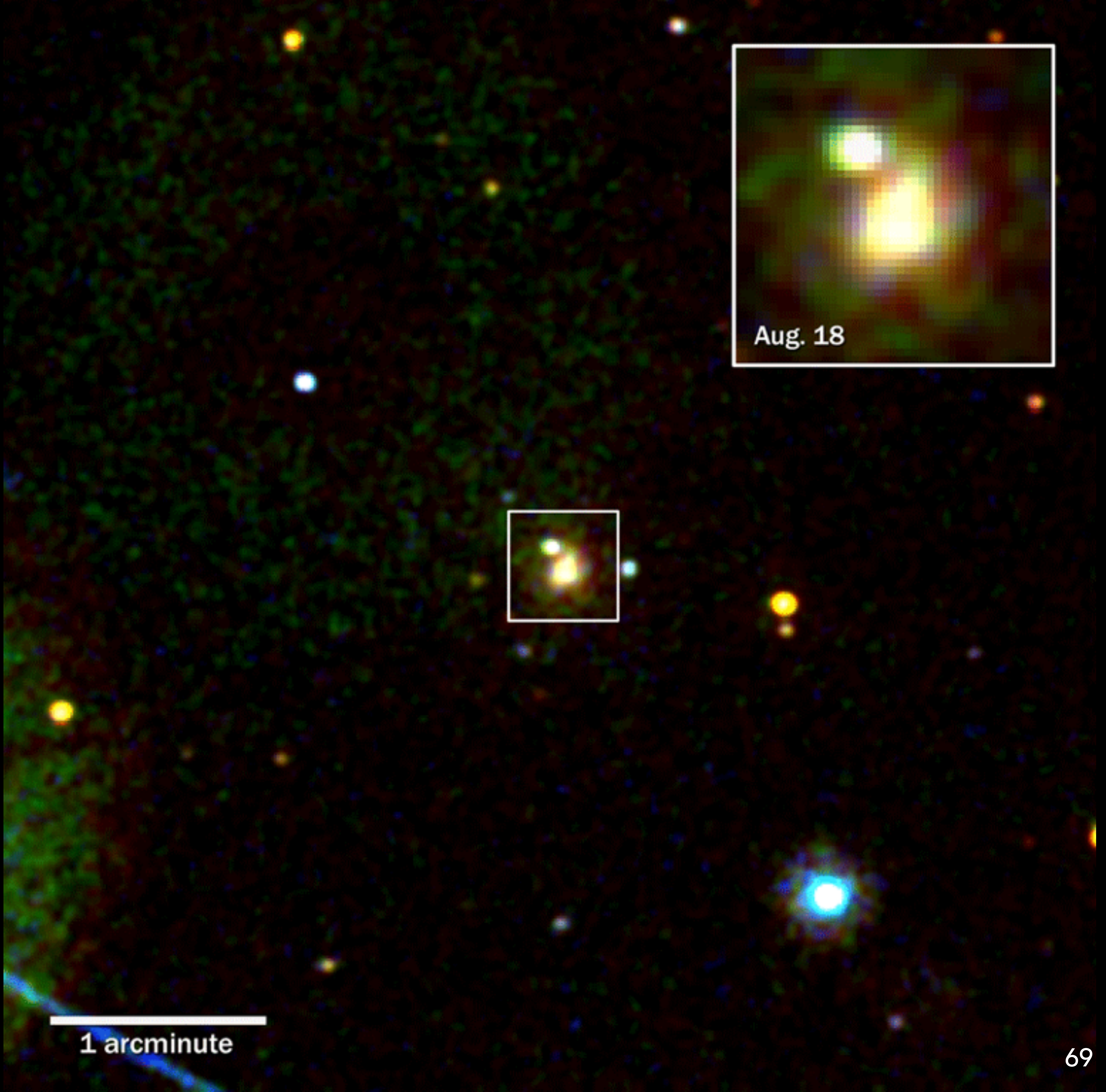
HOST LOCATED IN NGC 4993

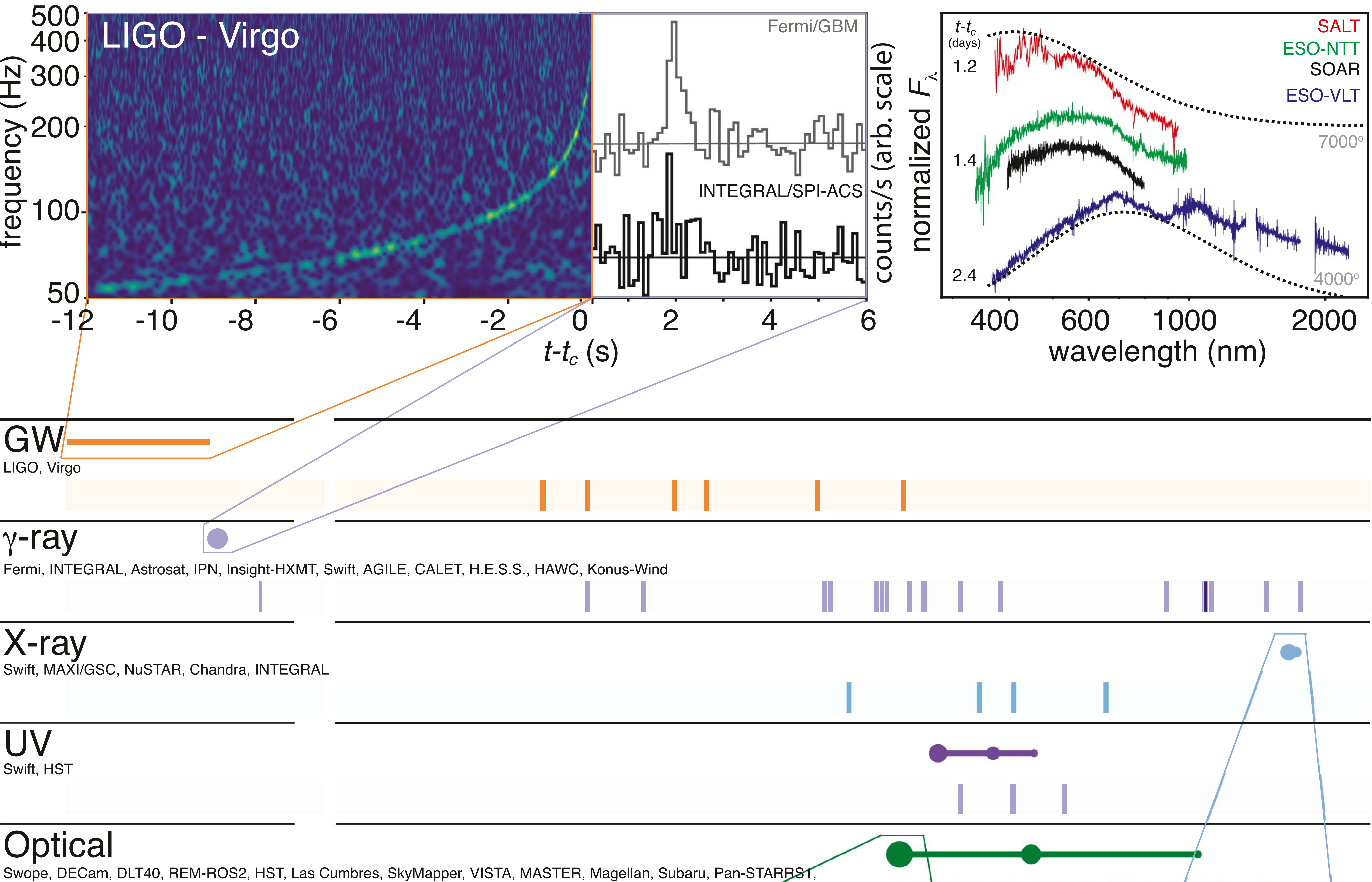


UV: CREDIT NASA AND SWIFT

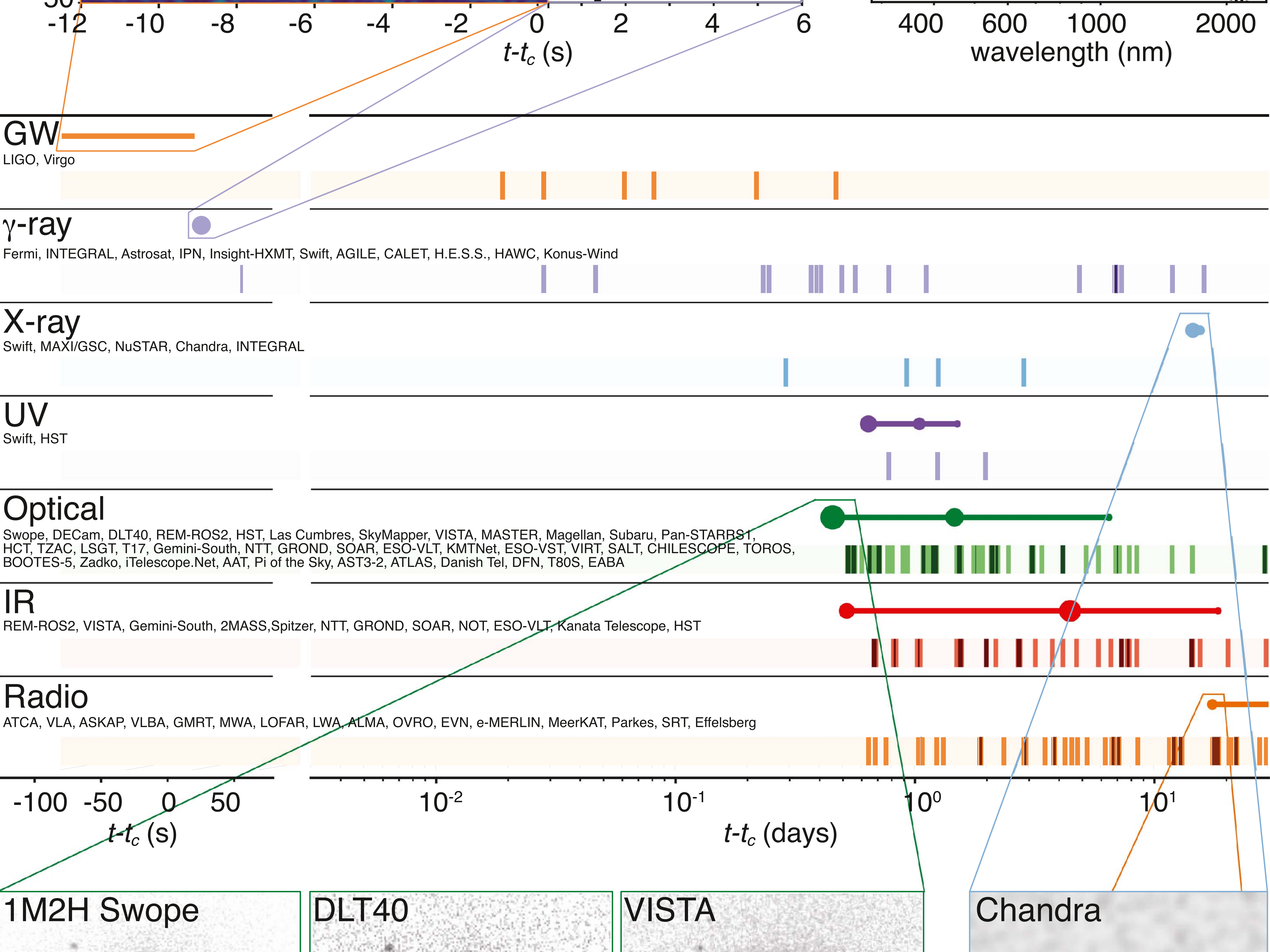


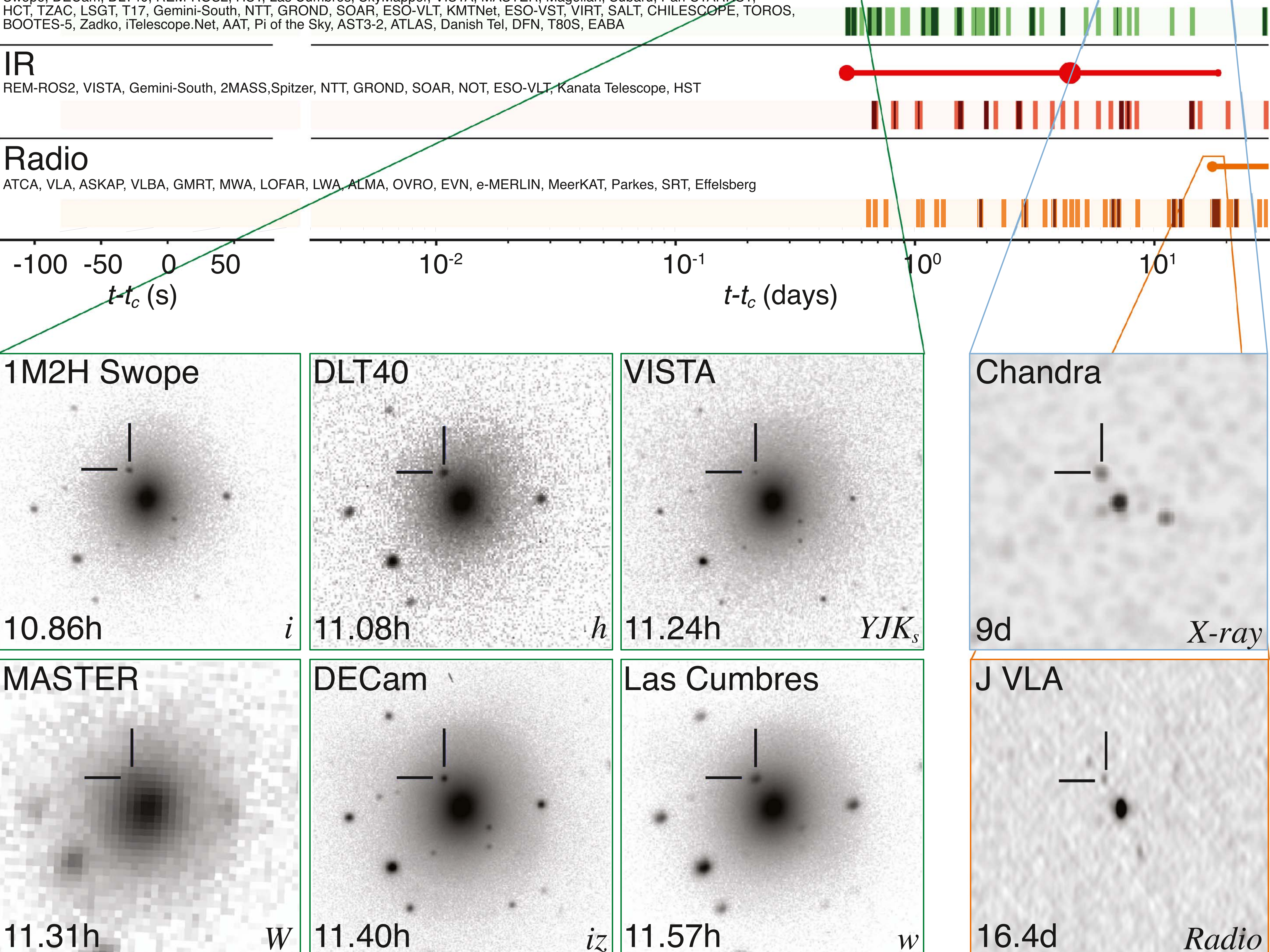
UV: CREDIT NASA AND SWIFT





LIGO - Virgo
Fermi/GBM
INTEGRAL/SPI-ACS
frequency (Hz)
counts/s (arb. scale)
t-tc (s)
t-tc (days)
SALT
ESO-NTT
SOAR
ESO-VLT
1.2
1.4
2.4
7000°
4000°
normalized Fλ
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,


-12 -10 -8 -6 -4 -2 0 2 4 6
t-tc (s)
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-tc (s)
10-2 10-1 100 101
t-tc (days)
1M2H Swope
DLT40
VISTA
Chandra


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,
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IR
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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
h
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