High-frequency broadband H1-detector response to a M4.1 earthquake in LIGO O2

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JGW-P1910462-v1 (2019)

KAGRA f2f
Toyama
Aug 23 2019

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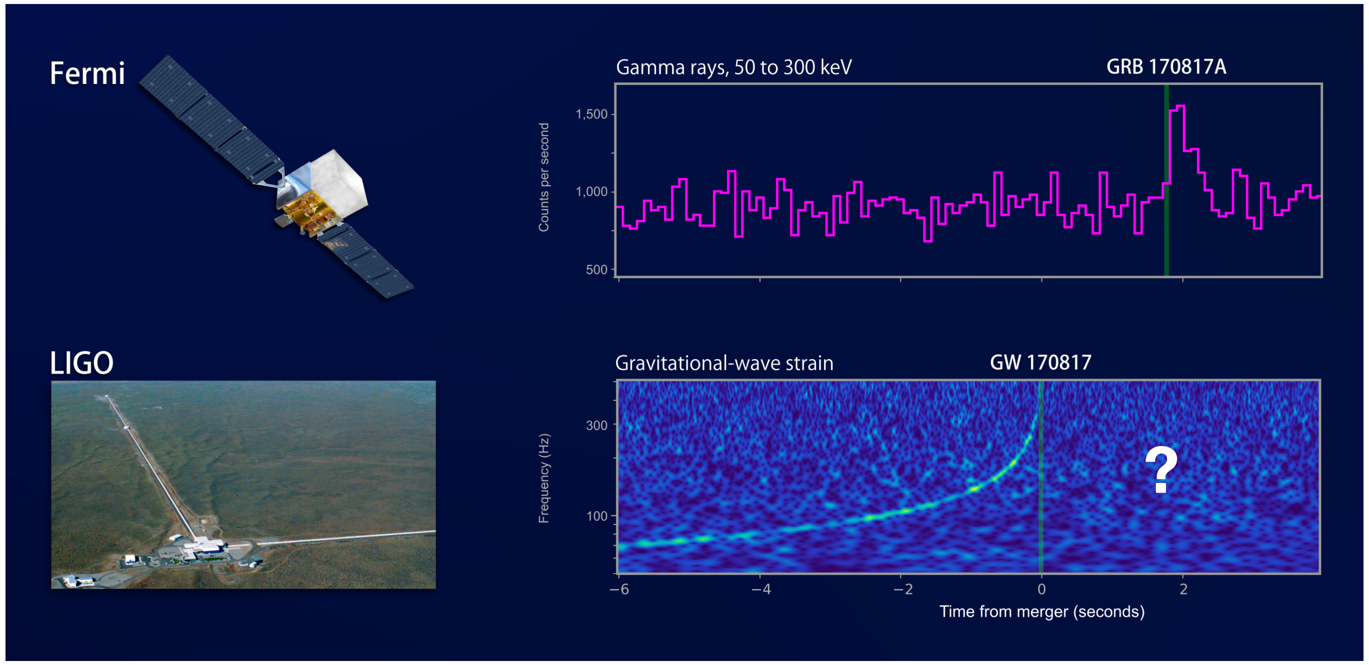
Signals from the abyss

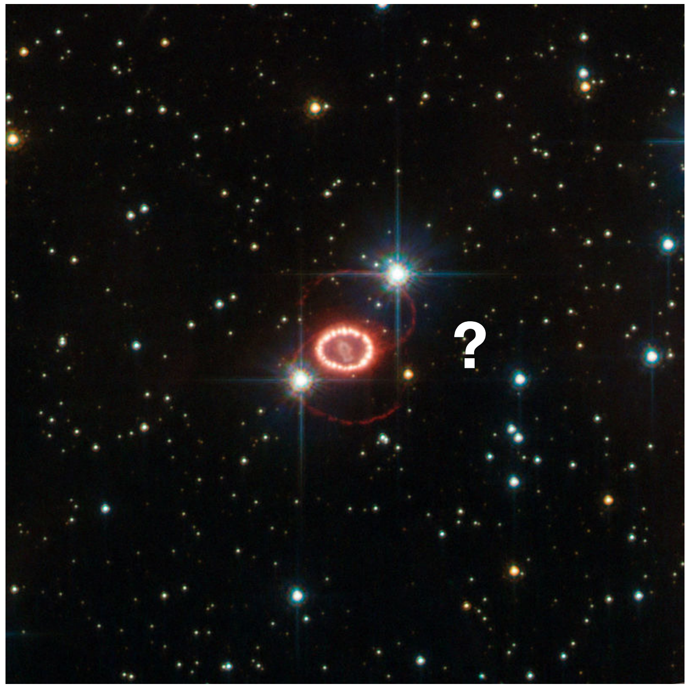
Potentially most prominent GW-emissions derive from angular momentum-rich sources:

Mergers



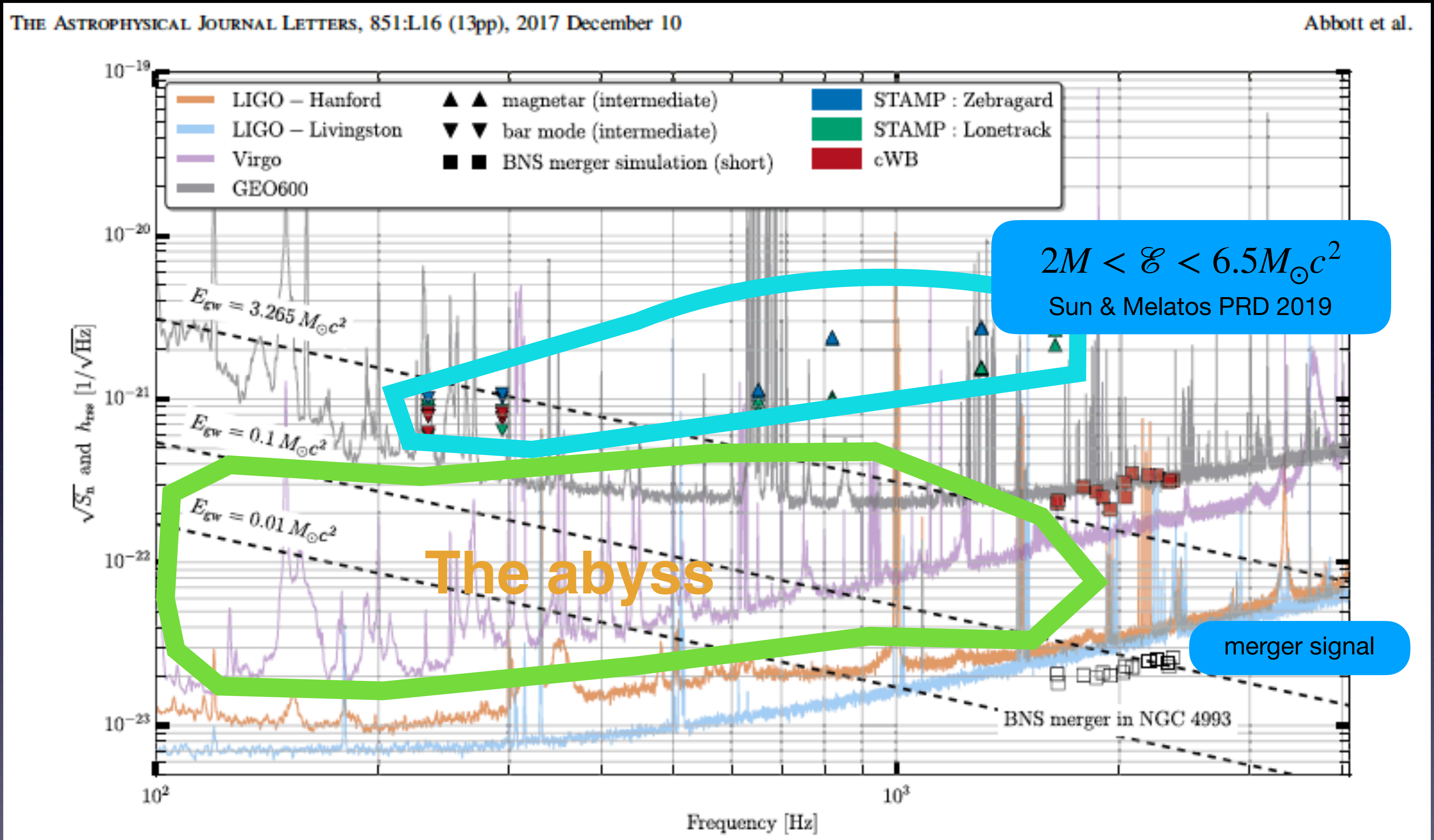
Similar outcome: rotating NS, BH

Core-collapse supernovae?



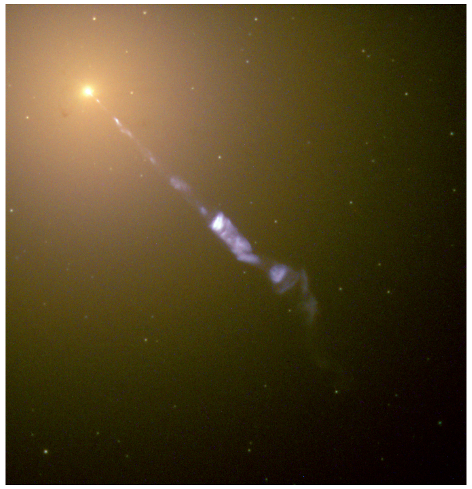
van Putten, Levinson, Frontera, Guidorzi, Amati & Della Valle, 2019, '*Prospects for multi-messenger extended emission from core-collapse supernovae in the Local Universe*,' to appear

Searching the unknown

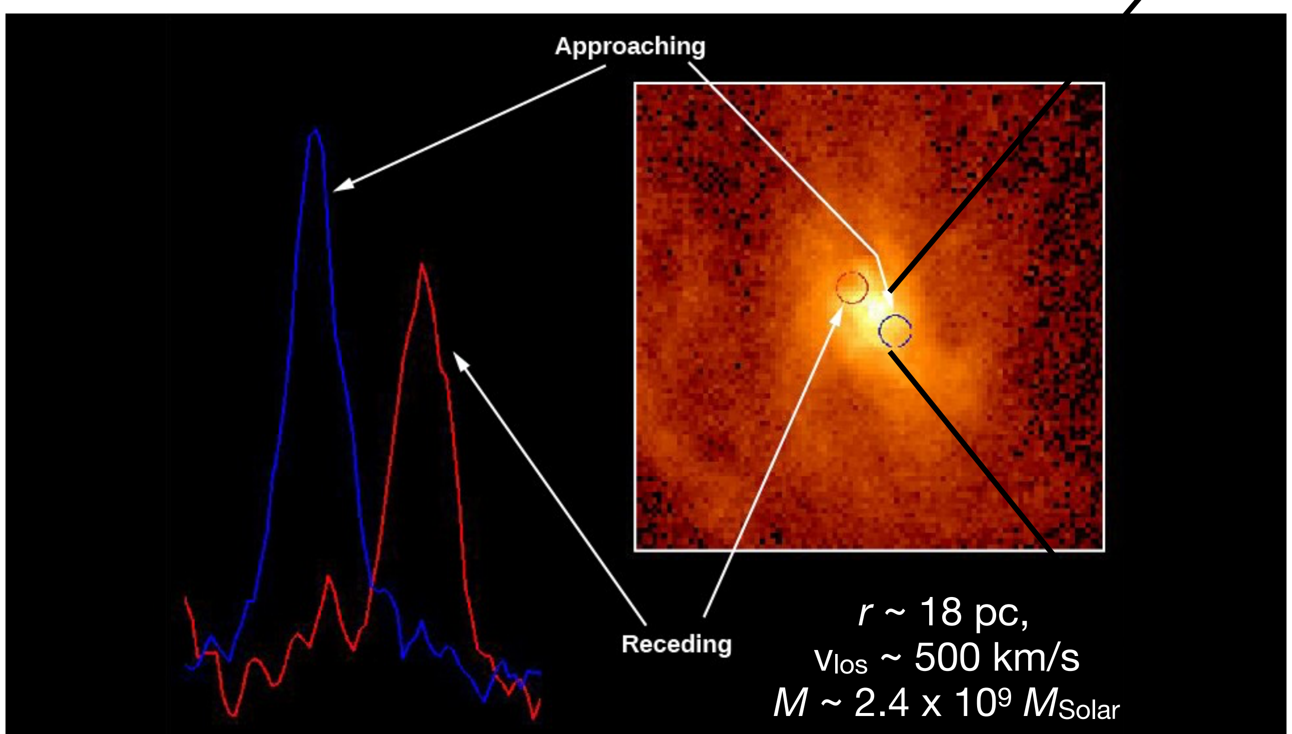


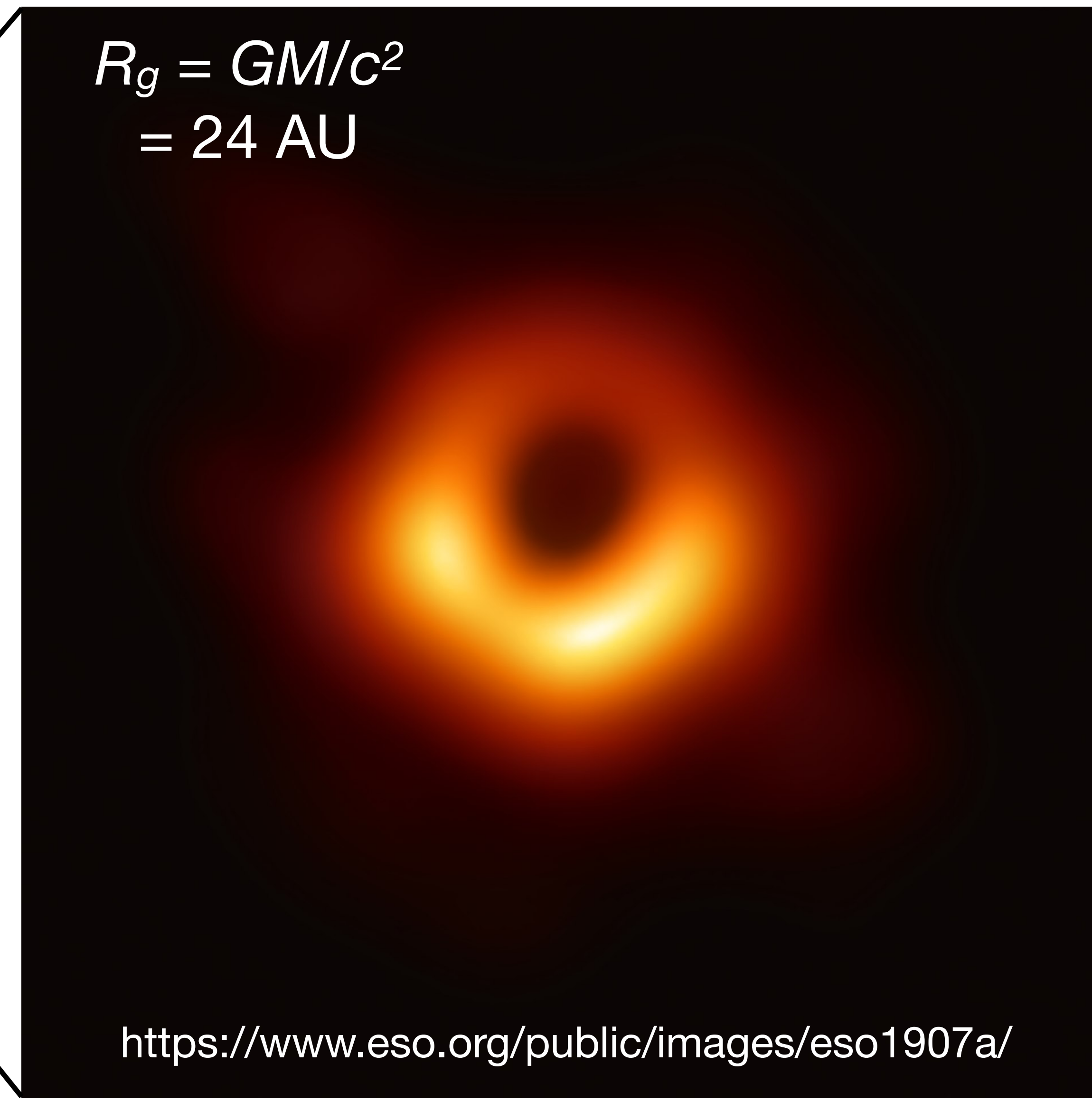
$$h_{50\%} \sim 10^{-23} - 10^{-22}$$

Rotating BH in M87: Event Horizon Telescope (2019)



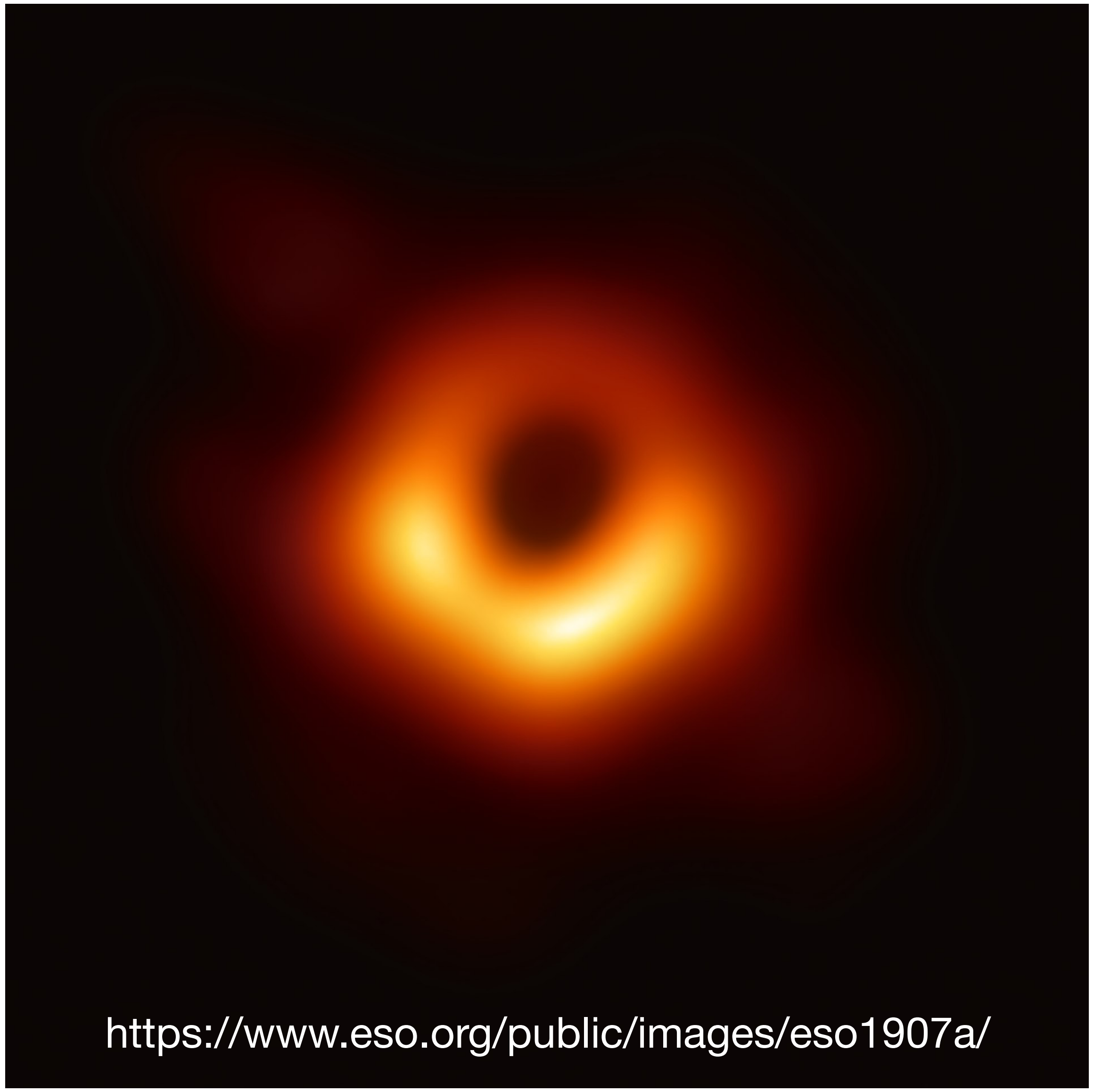
HST 1994

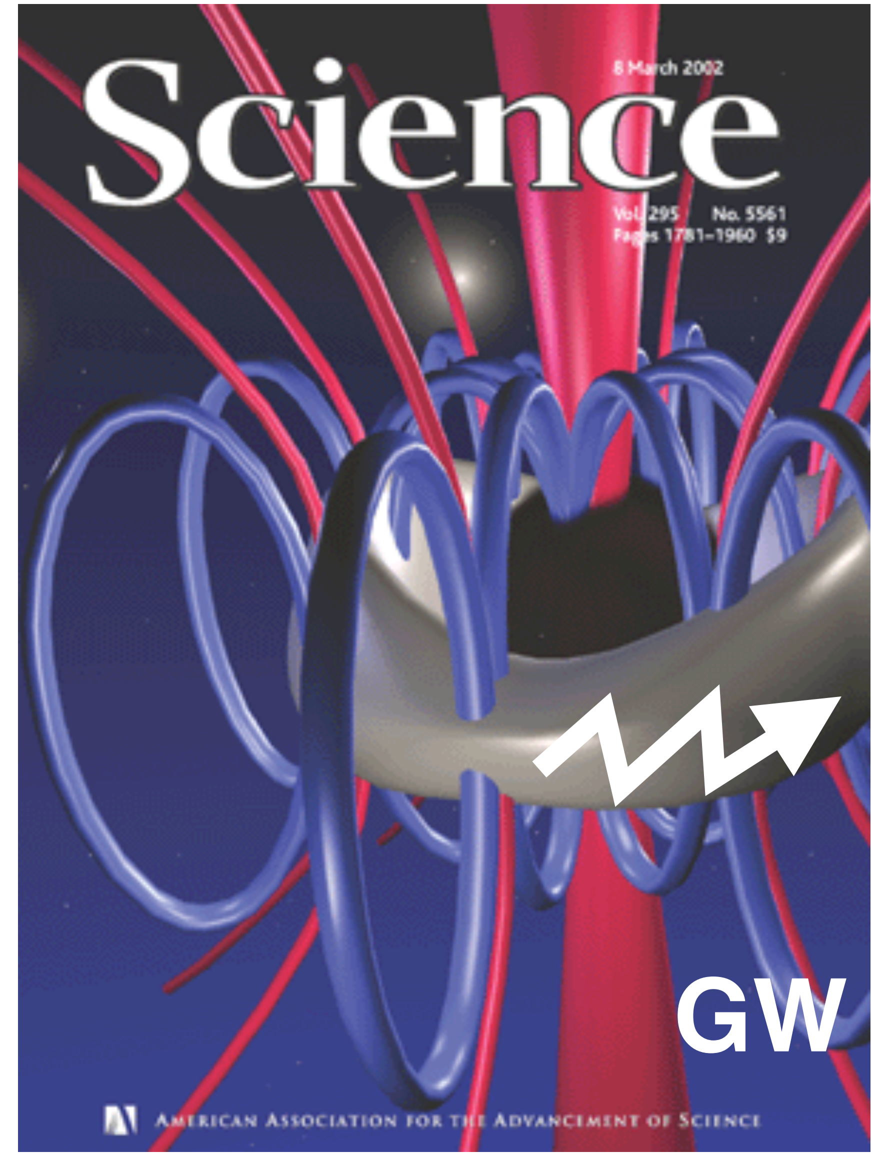




"*Our results provide strong evidence for the presence of a supermassive nuclear black hole in M87.*" Harms, Ford, Tsvetanov, hart & Dressel, ApJ, 435, L35 (1994)

Non-axisymmetric accretion disks





van Putten, & Levinson, 2002, Science, 295,1874

Duration of a GW signal: $T_{\mathrm{BH\ spin}}$

$$L_{GW} = \frac{32}{5}\left(\frac{\delta m}{M}\right)^2\left(\frac{M}{r}\right)^5 L_0 = 2\times 10^{51}\left(\frac{\delta m}{0.001M}\right)^2\left(\frac{5M}{r}\right)^5 \ \textbf{erg/s}$$

GW170817 Chirp (IMAGE)

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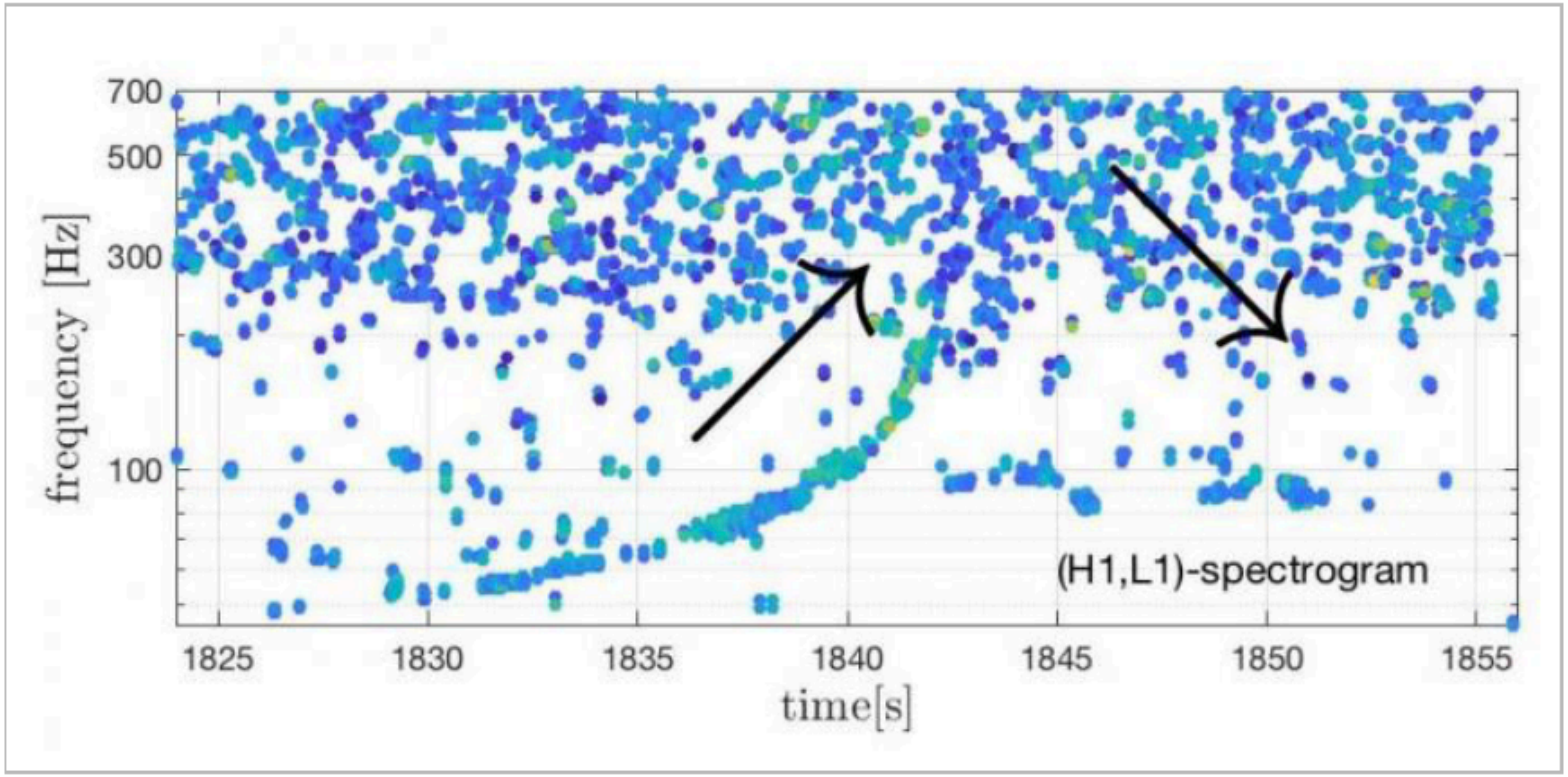

Nov 14 2018 Van Putten & Della Valle, 2019, MNRAS, 482, L46

Spin down of a compact remnant: HNS or BH?

GW170817 Chirp (IMAGE)

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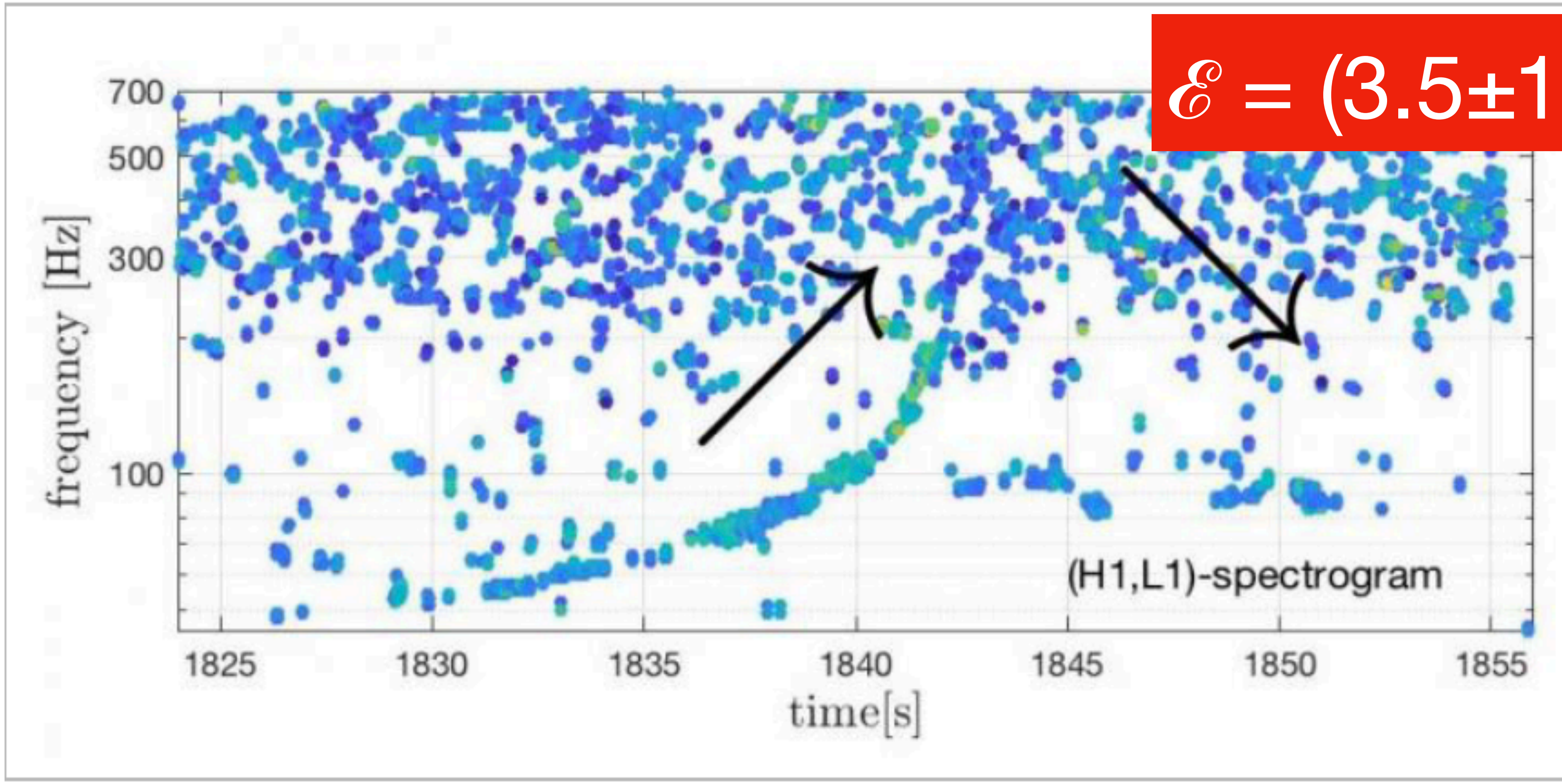


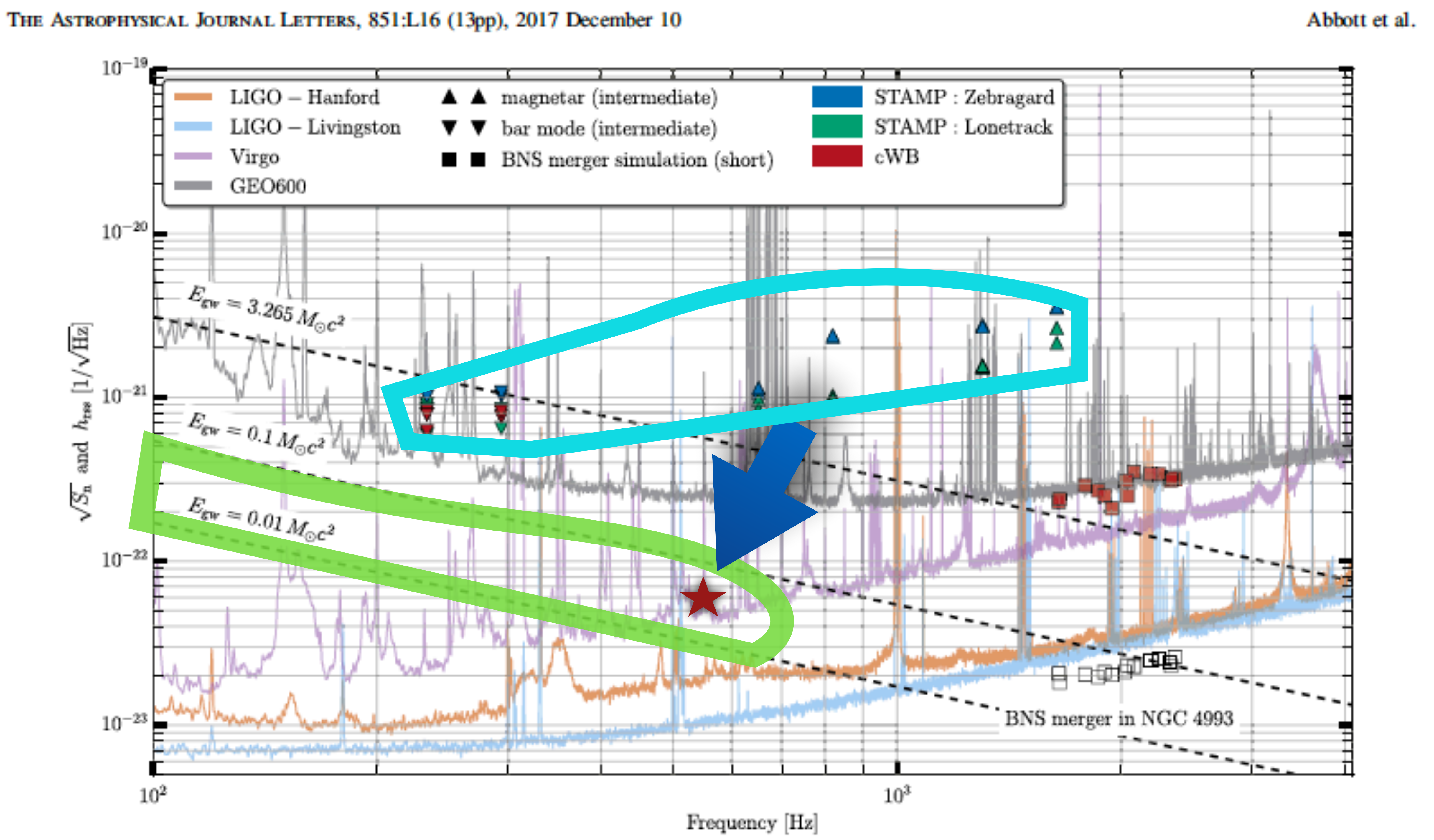
$\mathscr{E} = (3.5 \pm 1)\% M_\odot c^2$

van Putten, Della Valle & Levinson, 2019, ApJ, 876, L2

"Too much for [E_J of] HNS":

Kerr BH spin-down following delayed collapse of a HNS in the immediate aftermath of the merger

Shifting the Window



$$h \sim few \times 10^{-23}$$

Counter-parts from nearby CC-SNe?

All-sky blind searches

AMD Radeon GPU-CPU nodes
- 4 GPU with DDR6 or HBM per CPU
  - 4096 stream processors/GPU
  - 128 GB RAM

Performance:
- 32 teraflop per node

Cluster networking:
- Dynamical load balancing over VPGEONET

Peak performance: 0.3 petaflop (150,000 stream processors)

van Putten, 2019, XBEGE User Guide v1.0 JGW-T1909860-v1

Same choice of hardware:

AMD
CRAY
OAK RIDGE National Laboratory
U.S. DEPARTMENT OF ENERGY

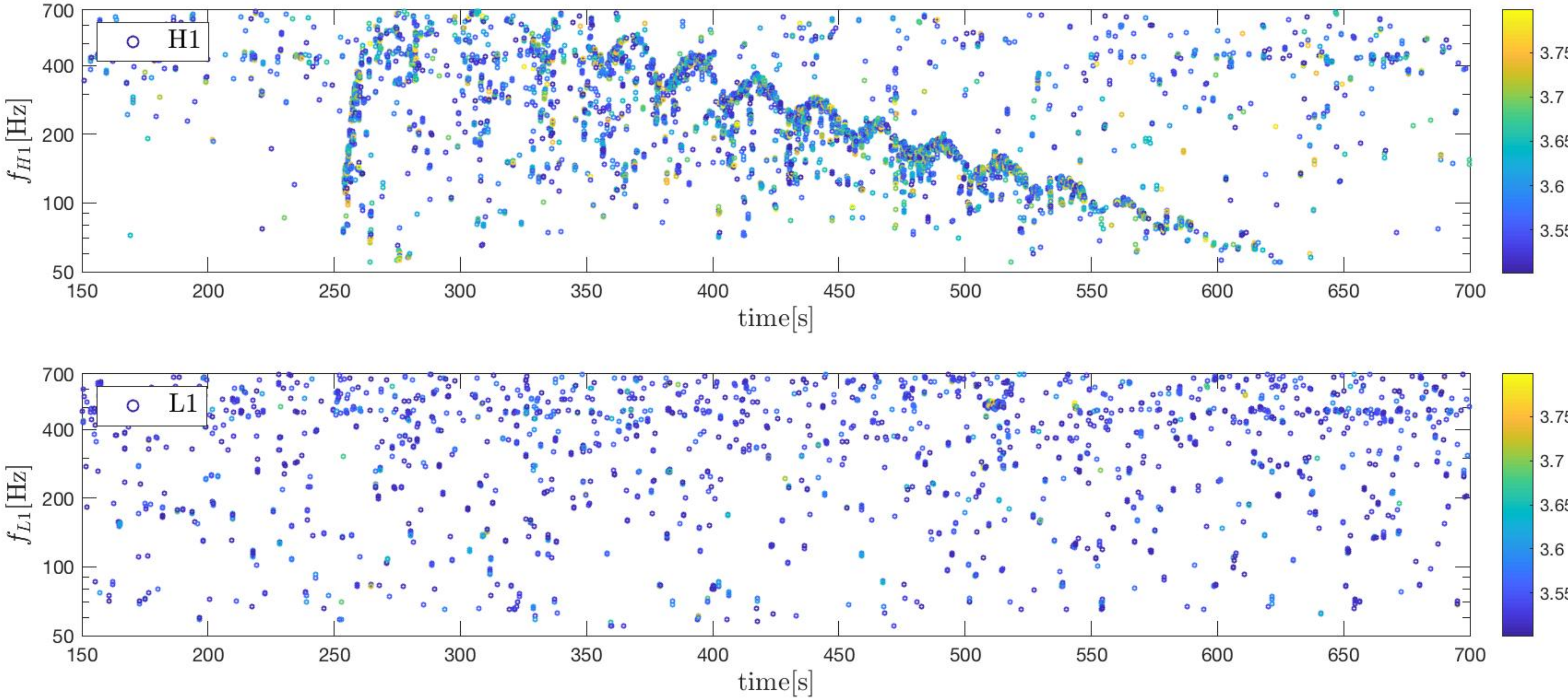
SANTA CLARA, Calif. 05/07/2019

World's Fastest Supercomputer at Oak Ridge National Laboratory

AMD innovations to be used in the Frontier system include:

- Radeon GPU with High Bandwidth Memory (HBM)
- Four AMD GPUs to one CPU per node

7-minute long descending chirp in H1 in LIGO O2

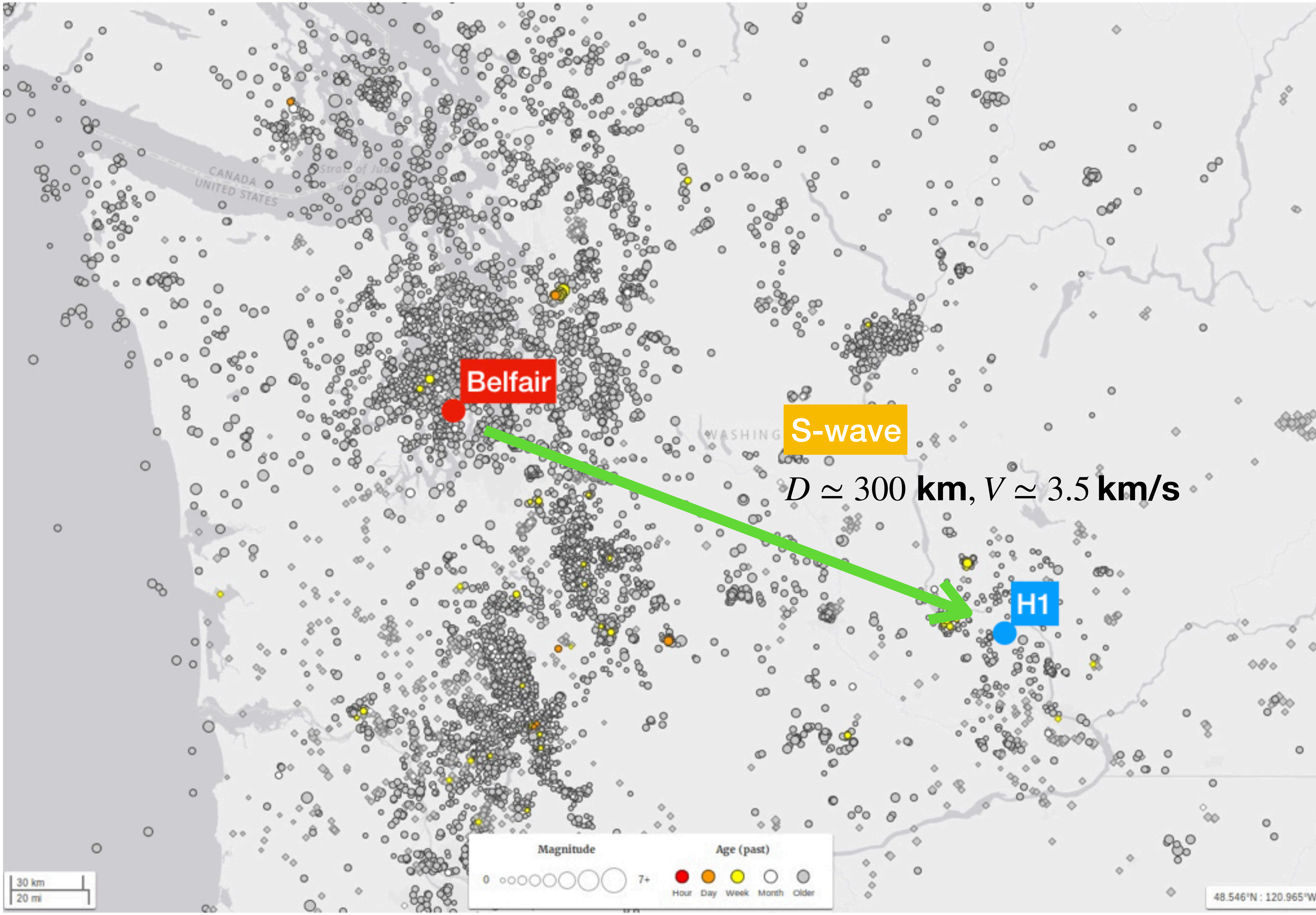


van Putten, 2019, JGW-P1910462-v1

Descending chirp modulated by quasi-periodic oscillation of 40 mHz

In H1 but not L1: local excitation near Hanford, WA, …

M4.1 earthquake 80 s prior in nearby Belfair



Induced earthquakes in Groningen (NL)

On the origin of exponential growth... 863

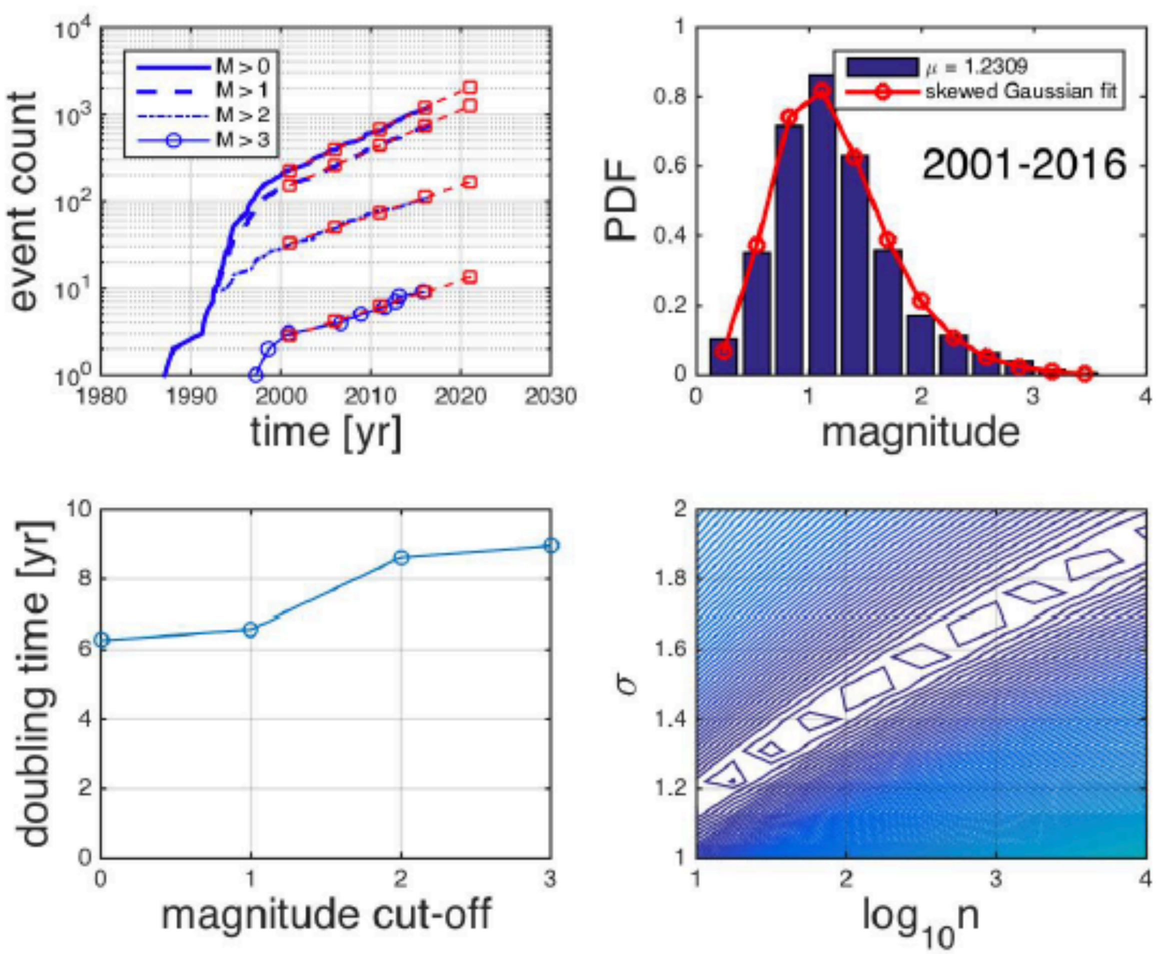


Fig. 1 (Left panels.) Exponential growth in event counts in Groningen that extrapolate to one M > 0 event per day in 2025. (Right panels.) The distribution of magnitudes is skewed, here modeled by that of maxima of event clusters of size n, drawn from a normal distribution with dispersion σ. A contour plot of residual least square (L_2) errors (bottom right) shows best-fit parameters $n \simeq 2250$, $\sigma \simeq 1.7$ (white strip)

PDF of maxima of a cluster of *n* earthquakes with STD σ (and mean zero)

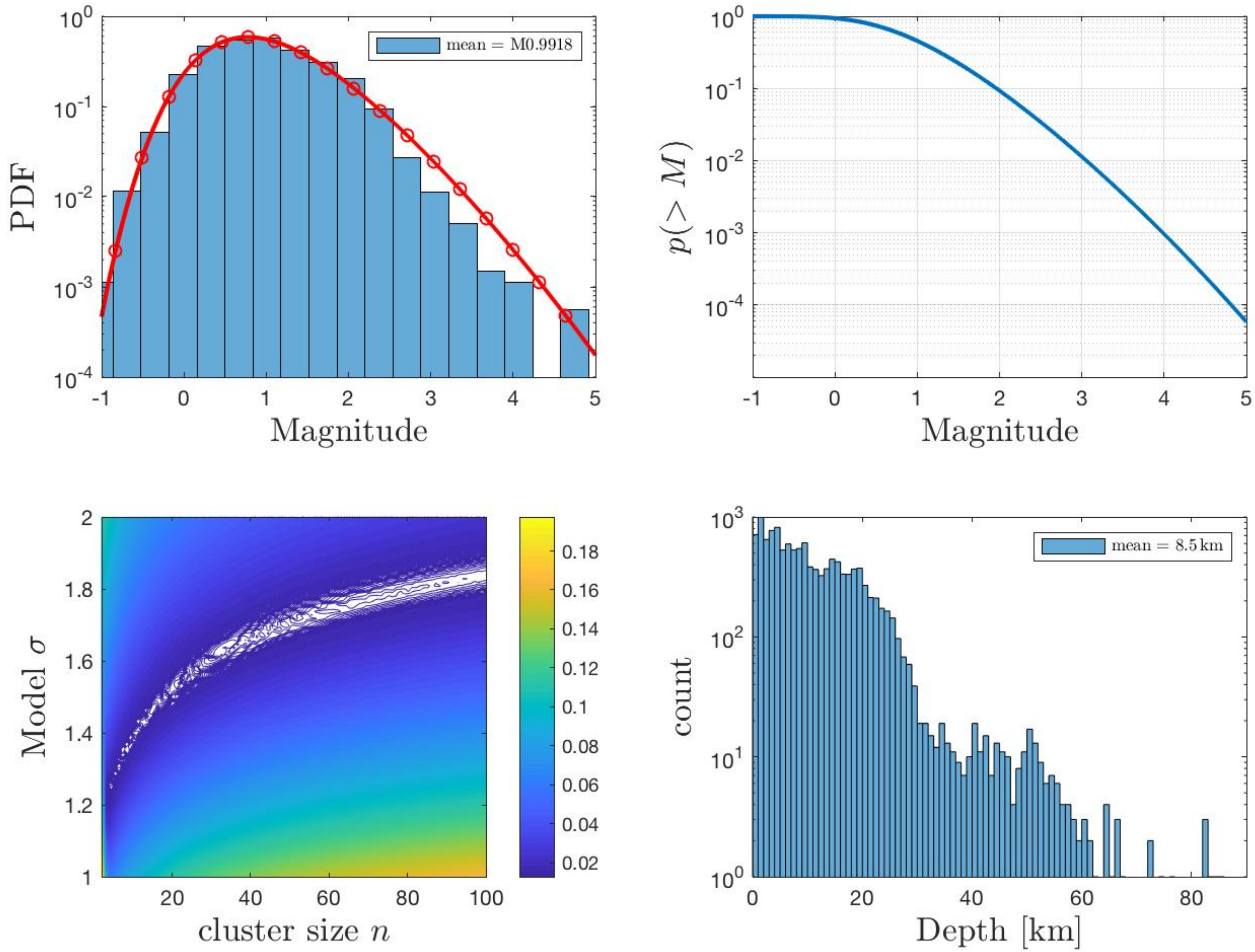
$$p(x) = \frac{n}{\sigma}\sqrt{\frac{2}{\pi}}\,\mathbf{erf}(y)^{n-1}e^{-y^2}$$

$$y = \frac{x}{\sqrt{2}\sigma}$$

van Putten, M.H.P.M., van Putten, A.F.P., & van Putten, M.J.A.M., 2016, Earthquakes and Structures, 11, 861

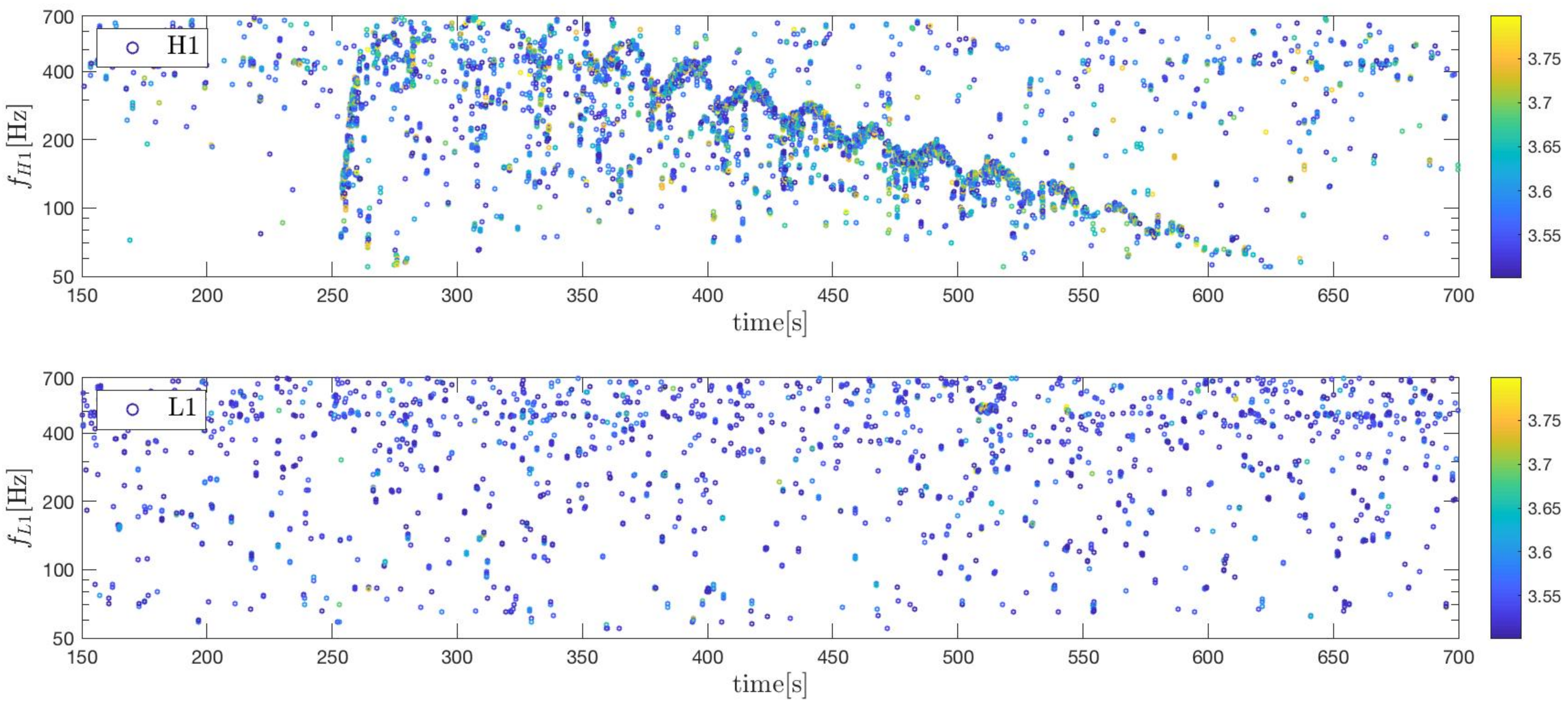
van Putten, M.H.P.M., Guidorzi, C. & Frontera, F., 2014, ApJ, 786, 146

Estimated rate of >M4 events about Hanford, WA



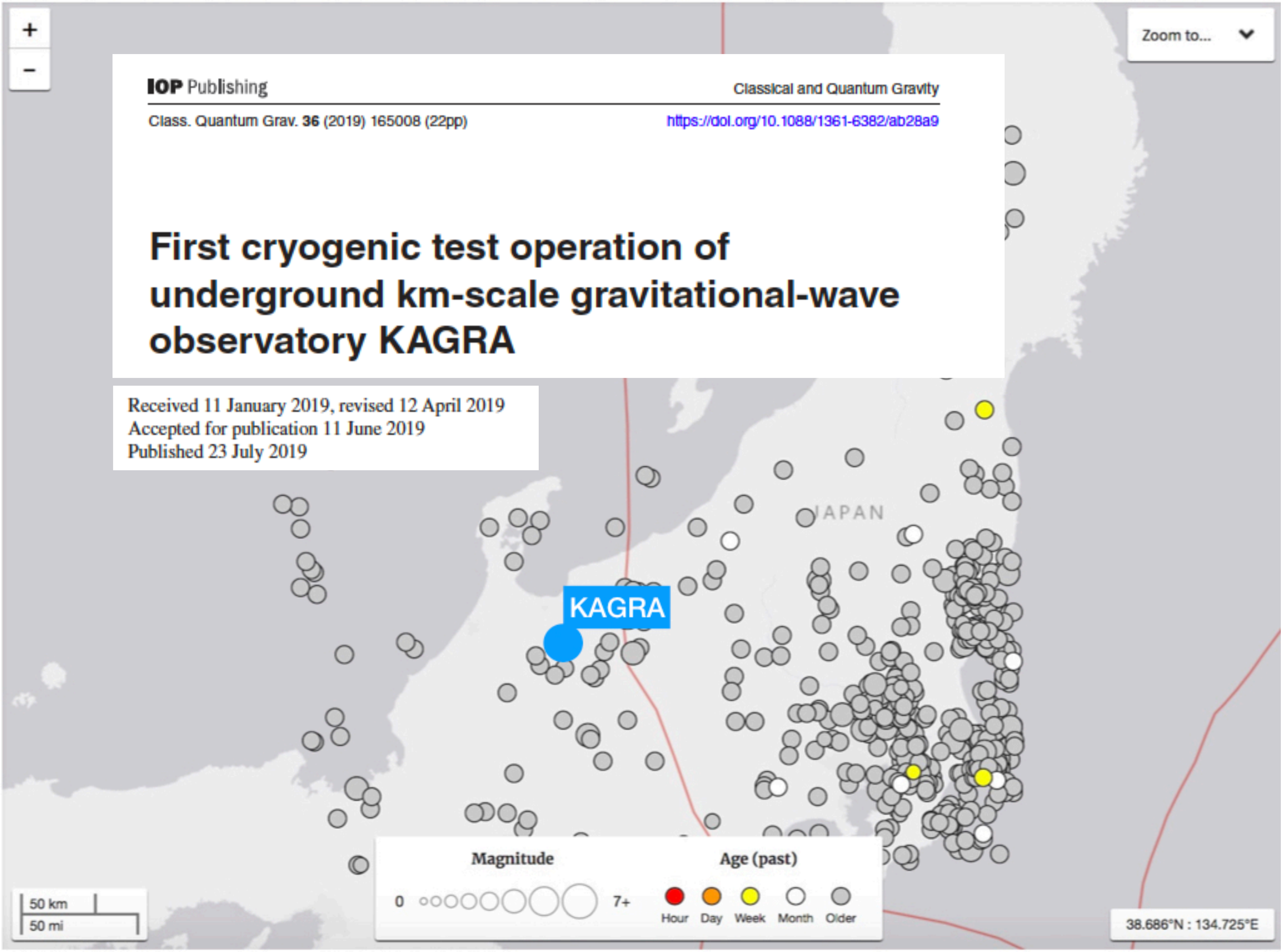
1 per four months of observation time: same as H1&L1 in LIGO O2

EQ170223



High-frequency broadband H1-detector response to a M4.1 earthquake in Belfair on 2017-02-23 (5 am UTC)

Earthquakes around KAGRA, Japan



IOP Publishing

Classical and Quantum Gravity

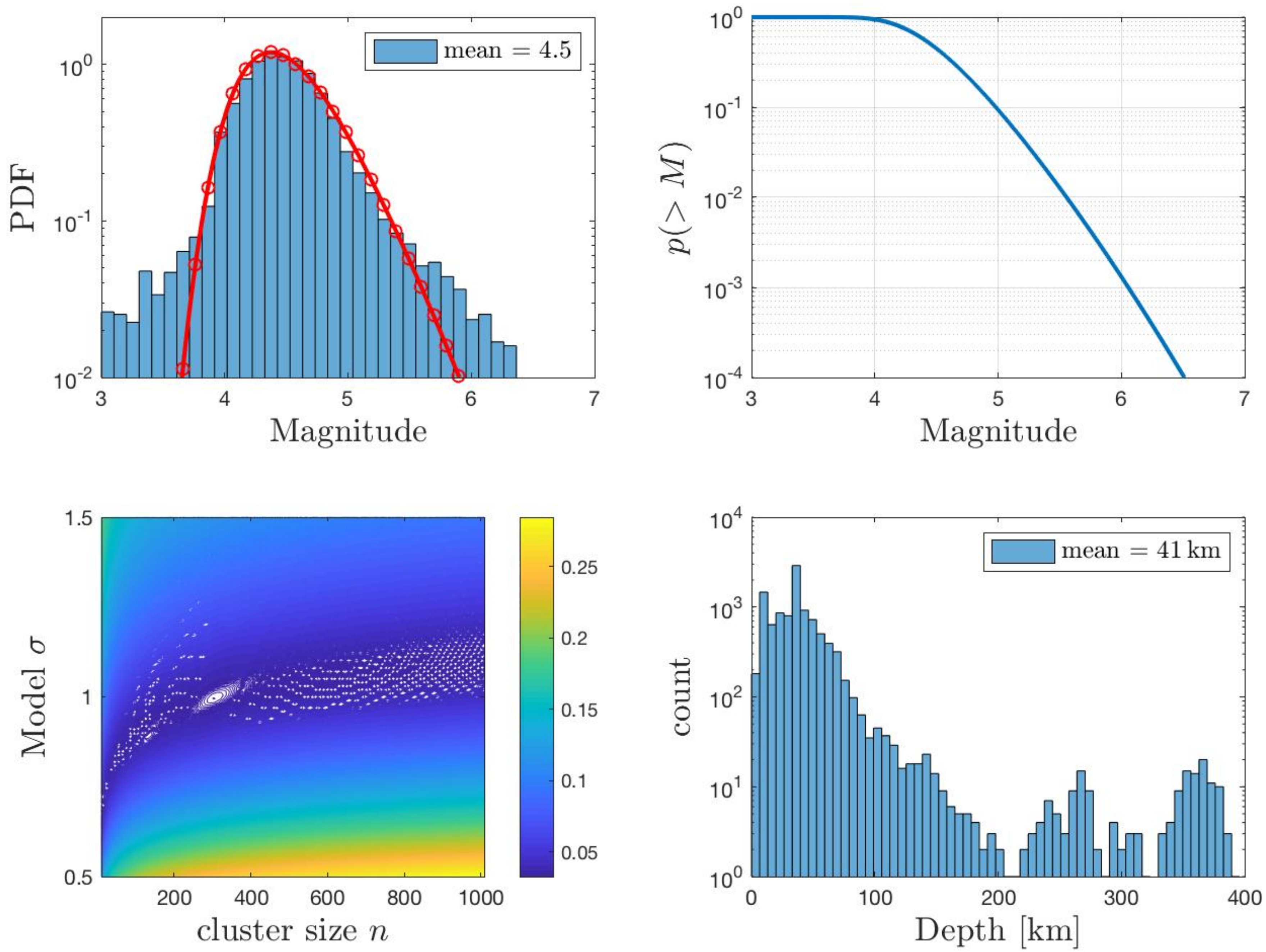
Class. Quantum Grav. **36** (2019) 165008 (22pp)

https://doi.org/10.1088/1361-6382/ab28a9

First cryogenic test operation of underground km-scale gravitational-wave observatory KAGRA

Received 11 January 2019, revised 12 April 2019
Accepted for publication 11 June 2019
Published 23 July 2019

Earthquakes around KAGRA, Japan



Far more severe: mean magnitude of about M4.5

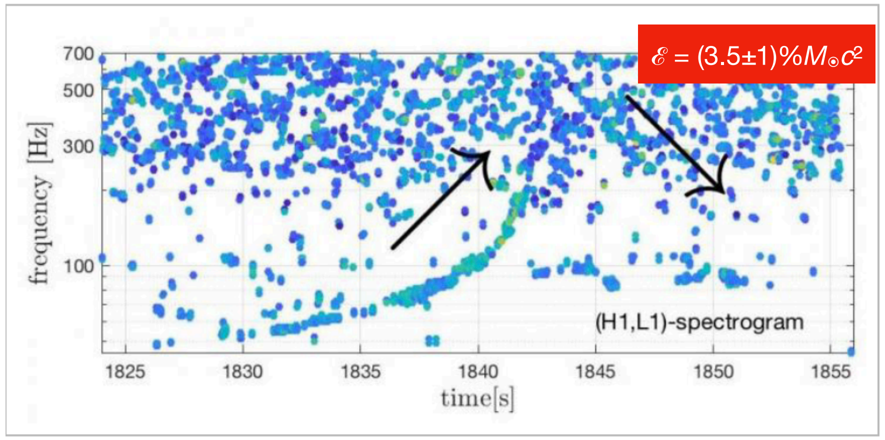
Underground, KAGRA will have better seismic isolation agains surface waves?

Conclusions and outlook

GW170817:

- Calorimetric evidence of a Kerr BH post-merger to GW170817
- Counterparts from nearby core-collapse supernovae? All-sky blind search, novel HPC challenge

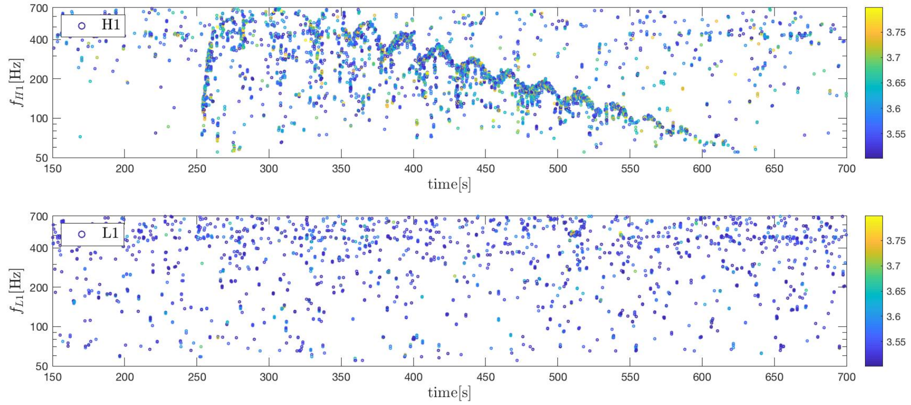
GW170817 Chirp (IMAGE)
ROYAL ASTRONOMICAL SOCIETY



H1-Earthquake:

- Complex 7-minute descending chirp H1 with mHz modulation, seismic isolation response overall to a M4.1 earthquake in Belfair 80 s prior
- Map out the H1-seismic isolation response as function of M and direction over next few years
- Similar seismic isolation response function of KAGRA?

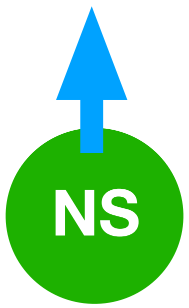
EQ170223

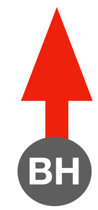


Extra Slide

Spin-energy NS and BH

$$E_J \simeq \frac{1}{5}MR^2\Omega^2 = \frac{GM^2}{5R}\left(\frac{\nu_s}{\nu_{\max}}\right)^2 \simeq \frac{1}{5}Mc^2\left(\frac{R_g}{R}\right)\left(\frac{\nu_s}{\nu_{\max}}\right)^2$$





$$E_J \lesssim 2\,\%\, M_\odot c^2 \left(\frac{\nu_s}{\nu_{\max}}\right)^2 \left(\frac{M}{1.5M_\odot}\right)$$

$$E_J \lesssim 20\,\%\, Mc^2 \left(\frac{\nu_s}{\nu_{\max}}\right)^2$$

Exact solution of Roy P. Kerr (1963)

$$E_J \le 29\,\%\, Mc^2$$

Spin-energy of a stellar mass black hole readily exceeds that of a neutron star by an order of magnitude or more