

# Multi-messenger Extended Emission from the Compact Remnant of GW170817

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# OUTLINE

GW170817 with Extended Emission ('GW170817EE')

Model-independent detection by butterfly filtering

Calorimetry on EE by signal injection

EE from black hole spin-down

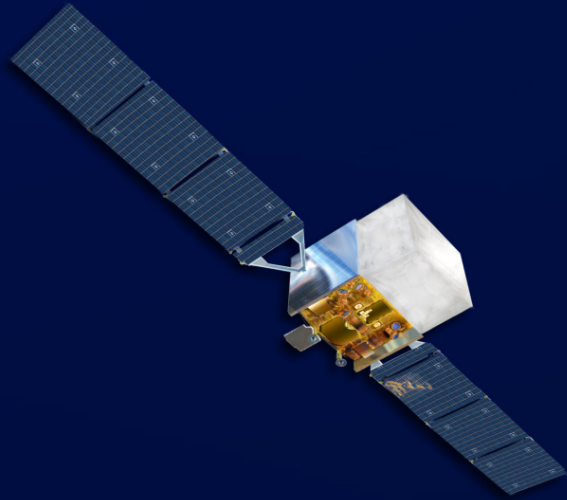
Multi-messenger EE

Conclusion and outlook

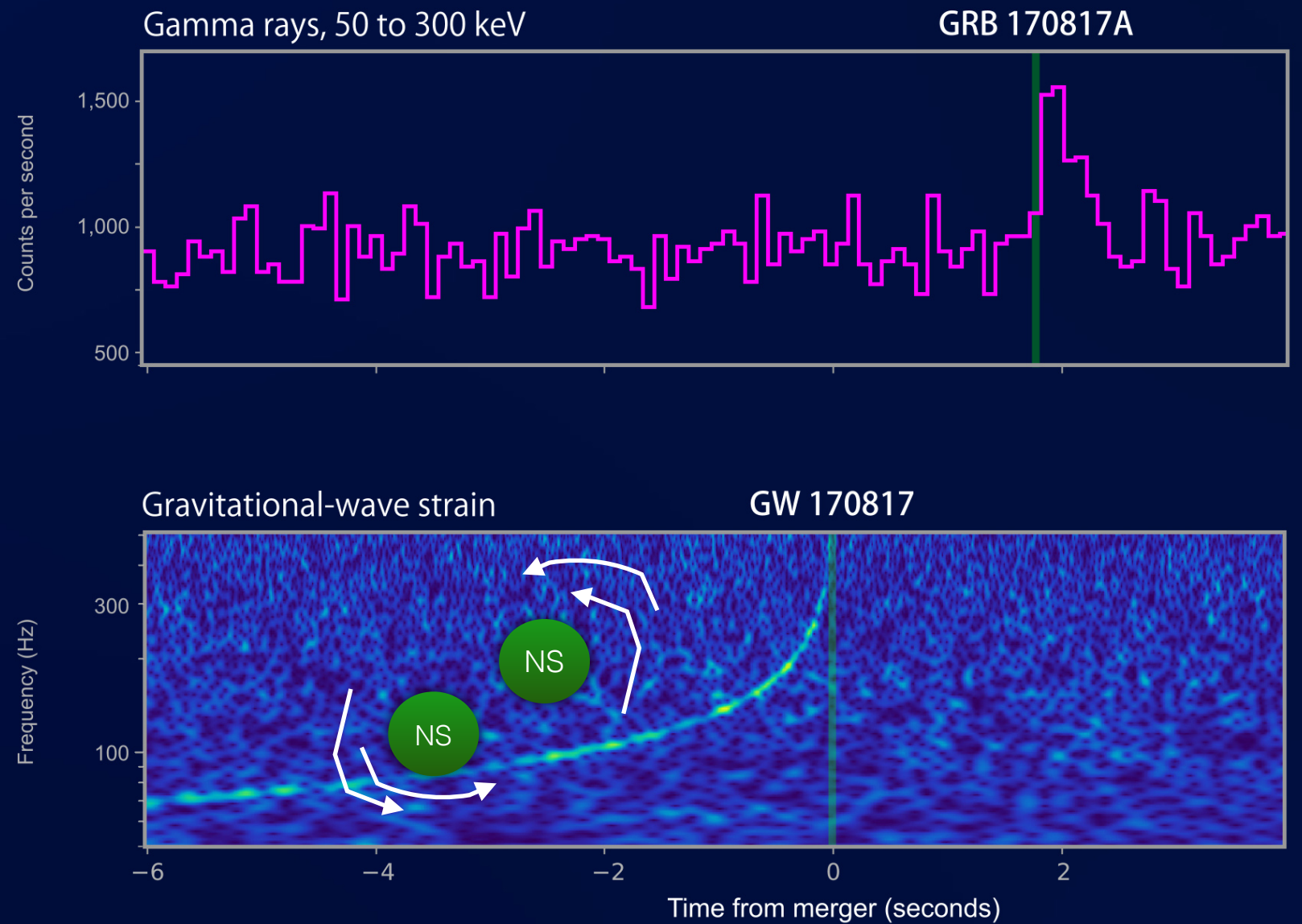


# A multi-messenger window to the Universe

Fermi



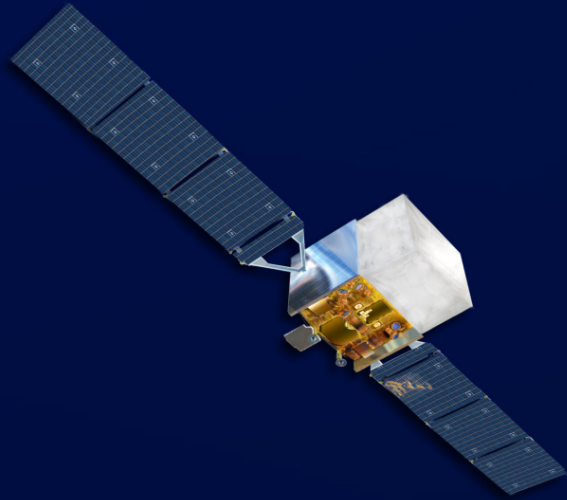
LIGO





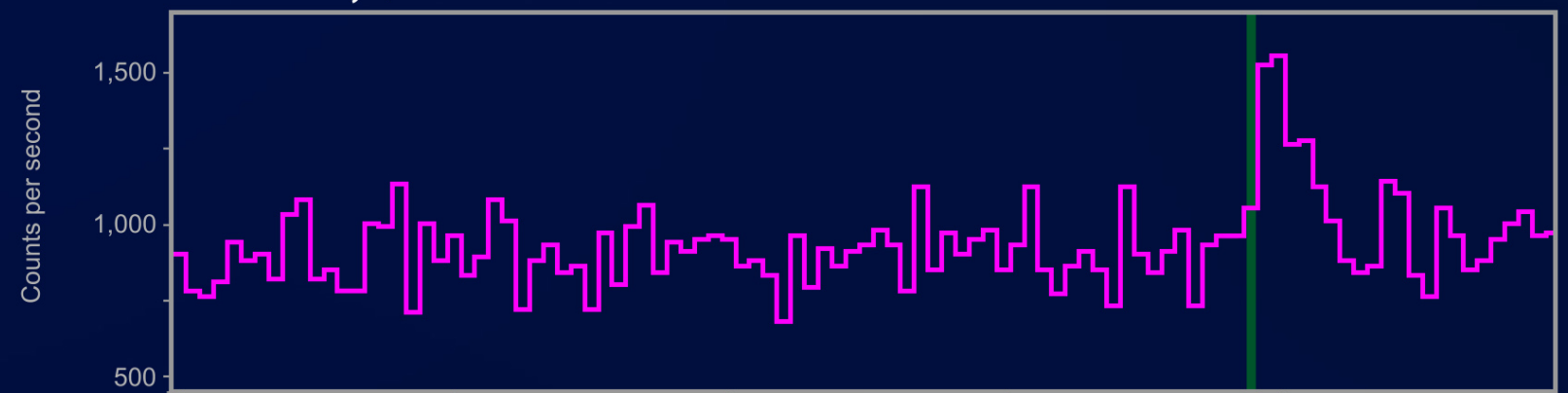
# GW170817: *what happened?*

Fermi



Gamma rays, 50 to 300 keV

GRB 170817A

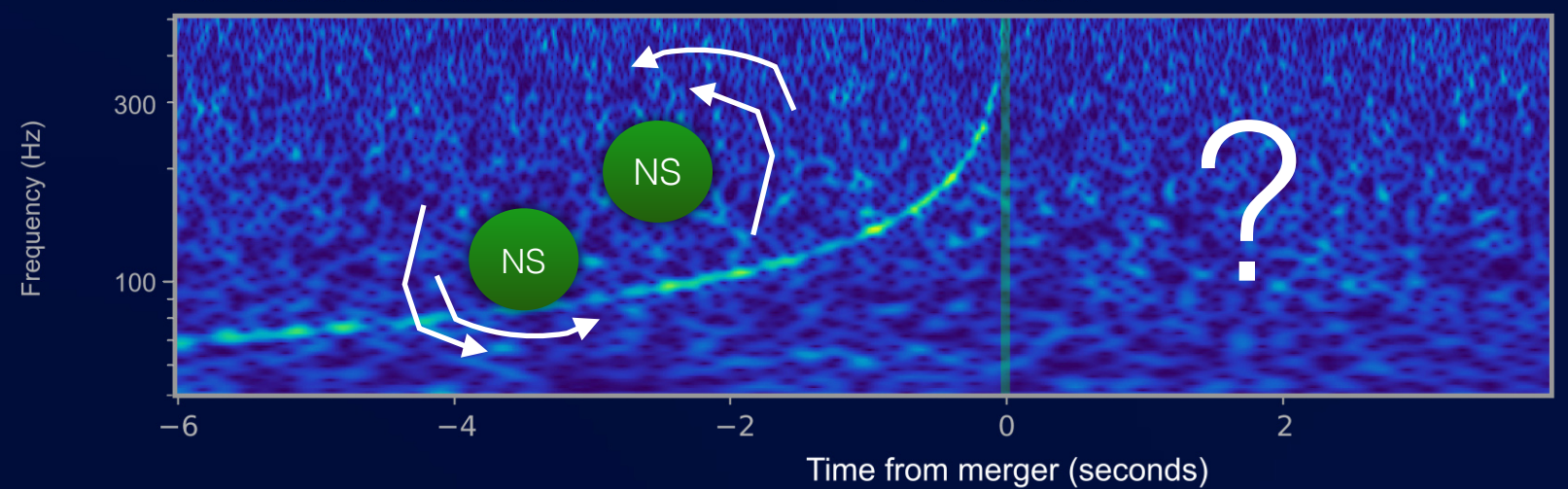


LIGO



Gravitational-wave strain

GW 170817

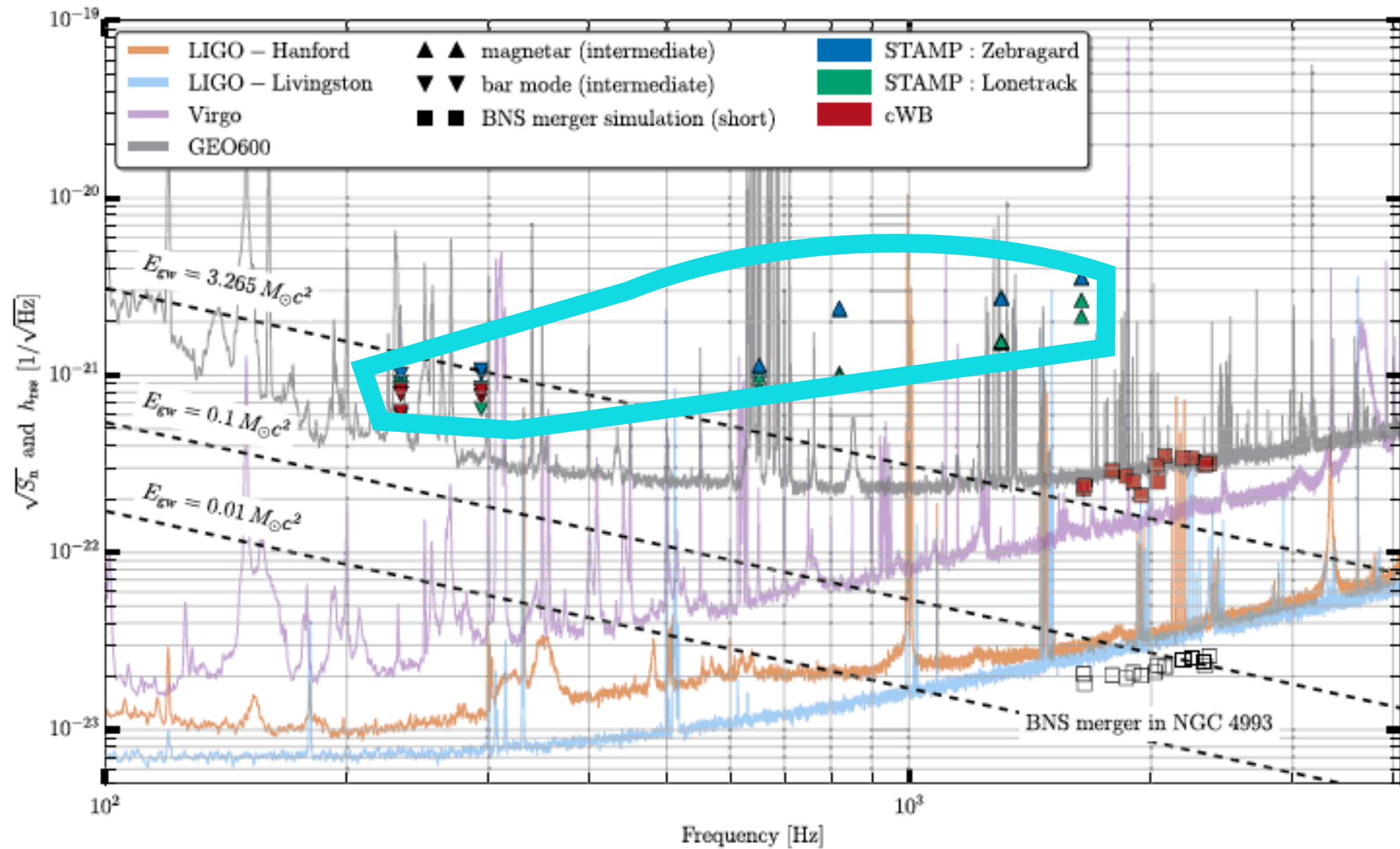




# LIGO post-merger search (2017)

THE ASTROPHYSICAL JOURNAL LETTERS, 851:L16 (13pp), 2017 December 10

Abbott et al.



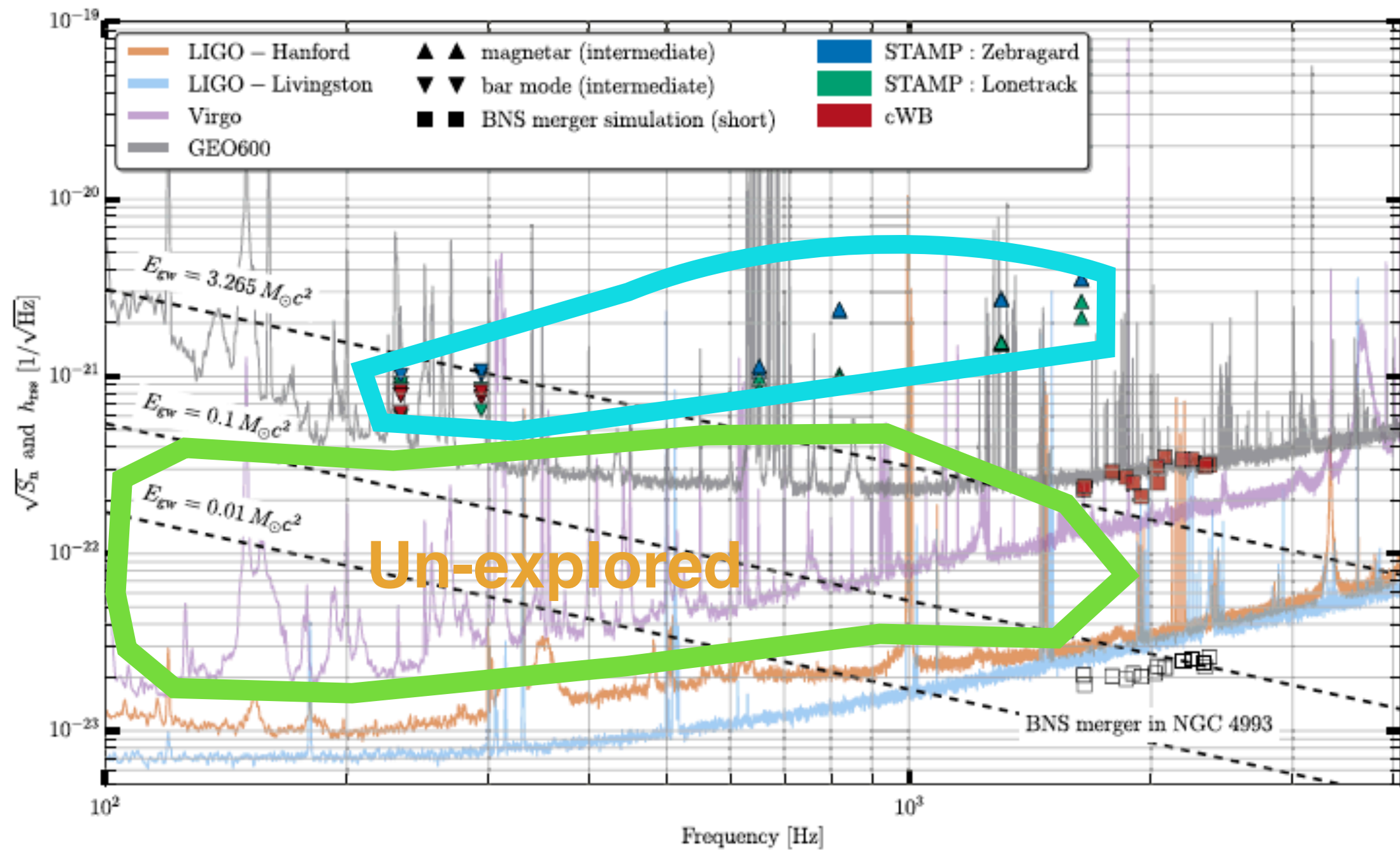
$$h_{50\%} \sim 10^{-22} - 10^{-21}$$



# LIGO post-merger search (2017)

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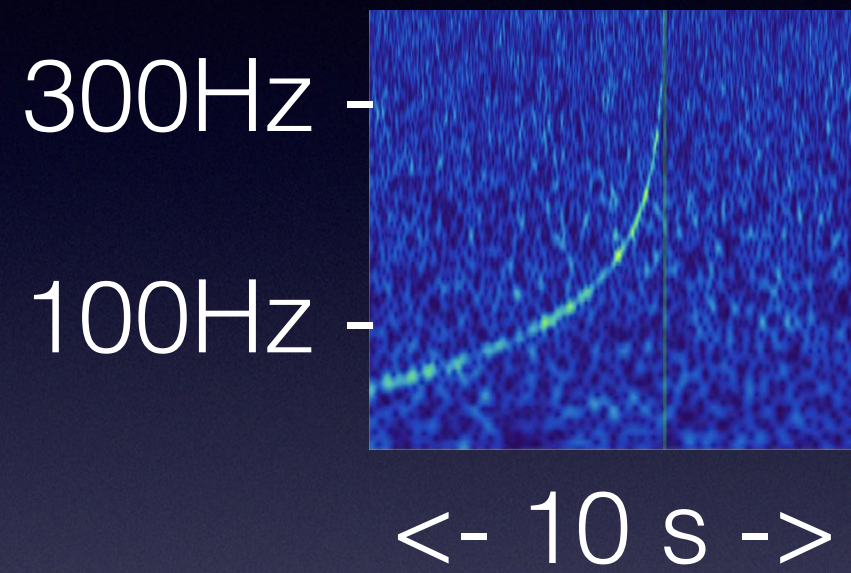
Abbott et al.



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

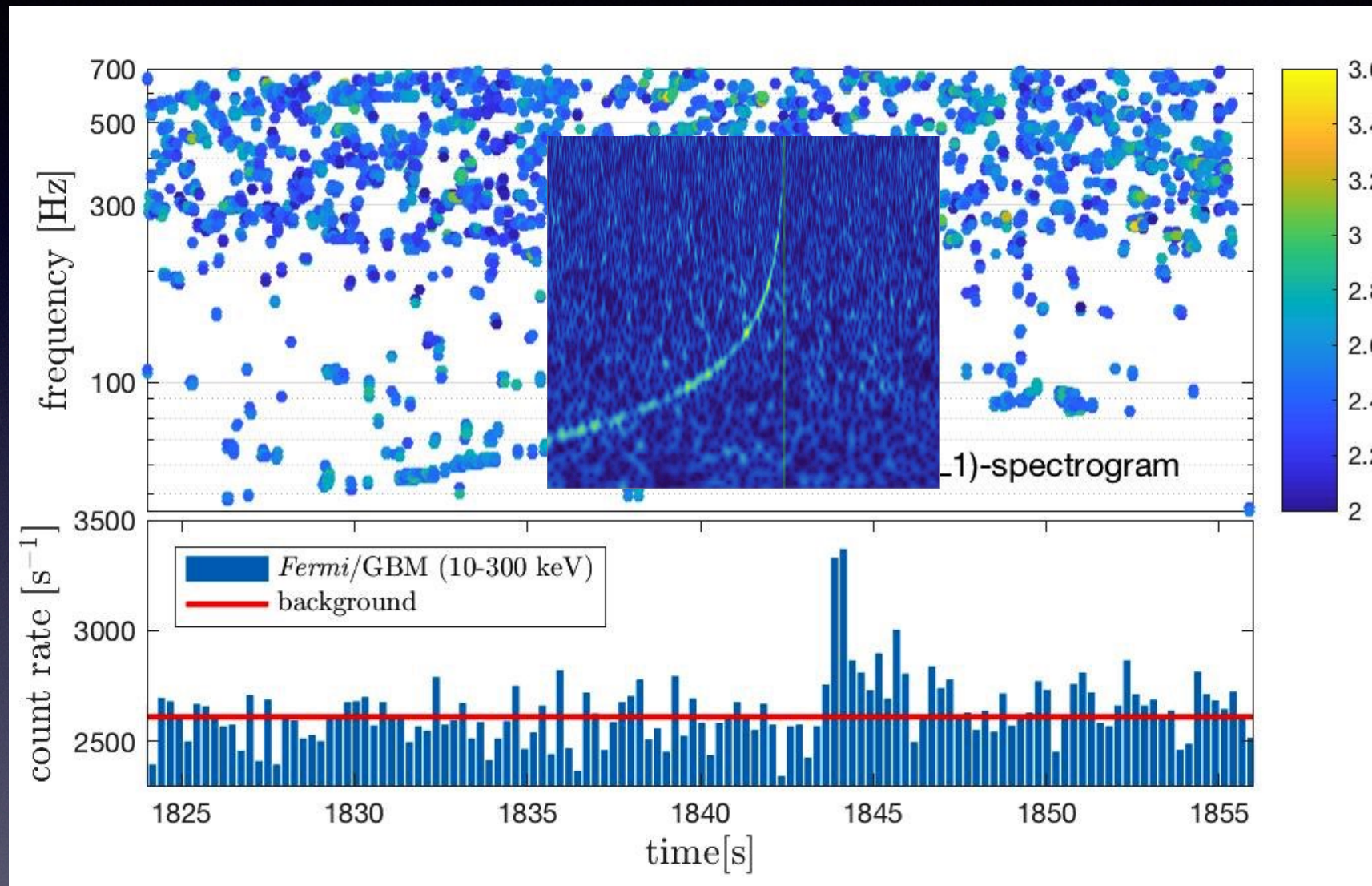


*GW170817:*





# GW170817: *Extended Emission*

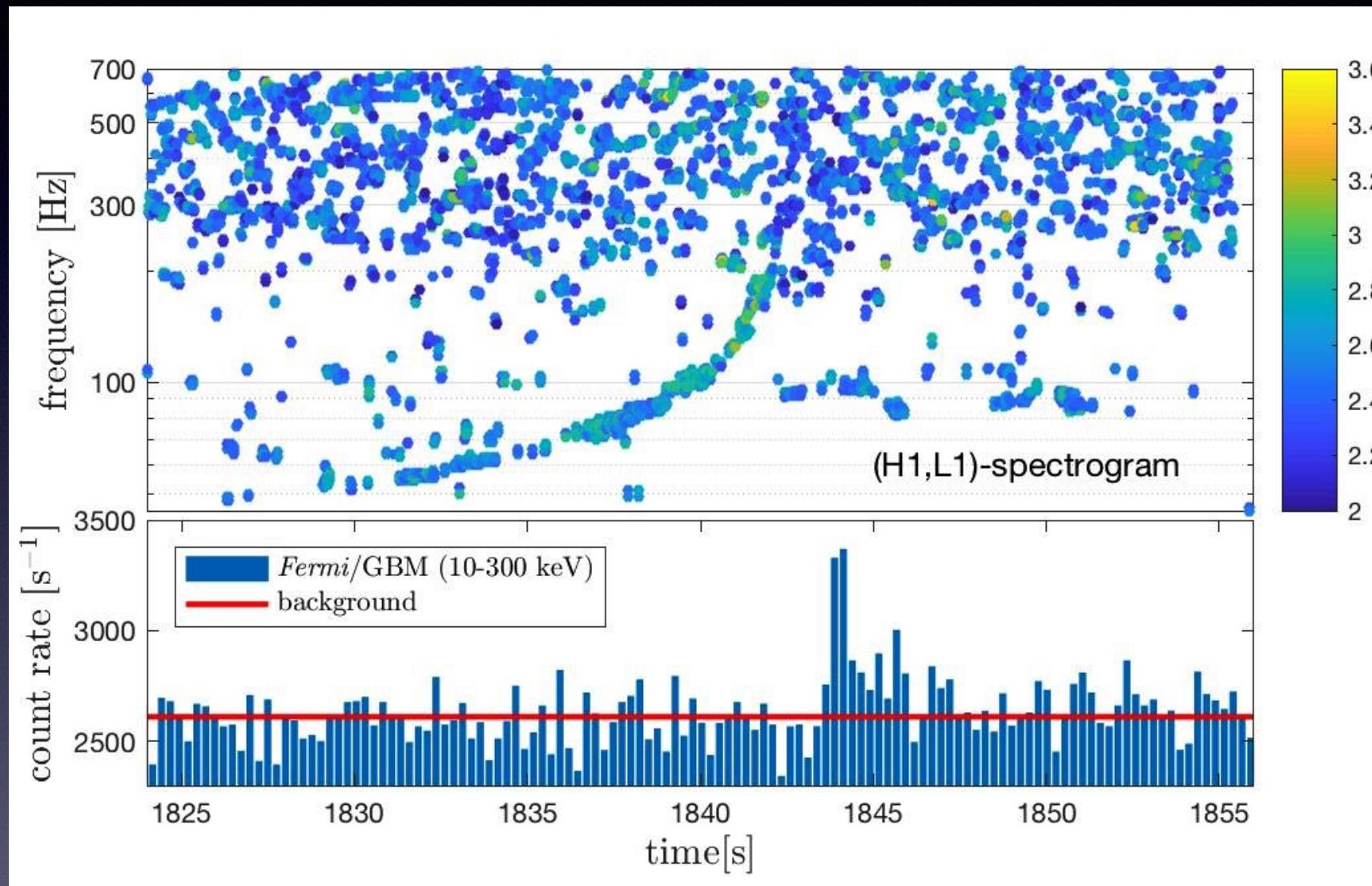


van Putten & Della Valle, 2018, MNRAS Letters, 482, L46

JGW-G1808513-v1 <https://gwdoc.icrr.u-tokyo.ac.jp/>



# GW170817: *Extended Emission*

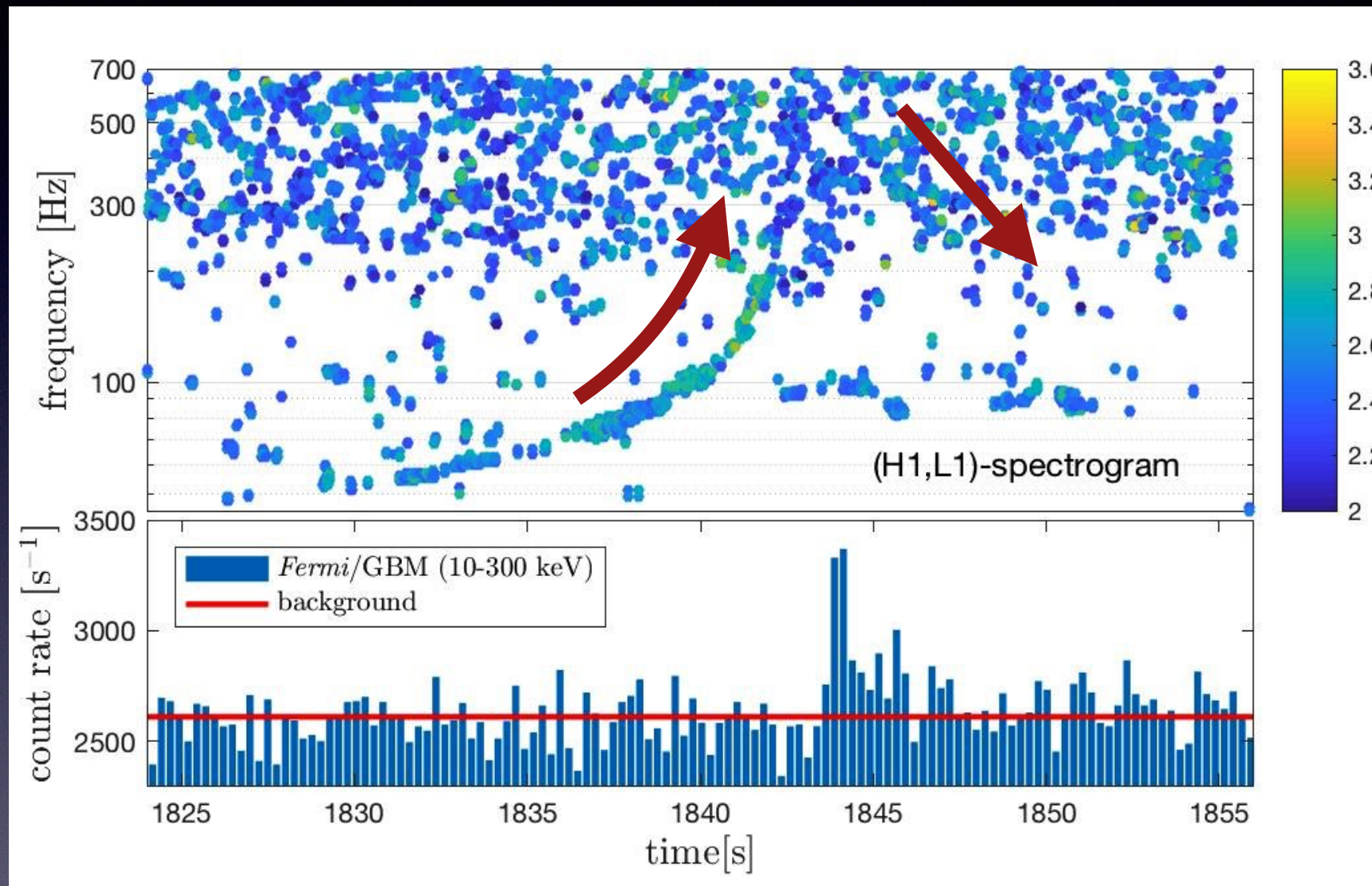


van Putten & Della Valle, 2018, MNRAS Letters, 482, L46

JGW-G1808513-v1 <https://gwdoc.icrr.u-tokyo.ac.jp/>



# GW170817: *Extended Emission*

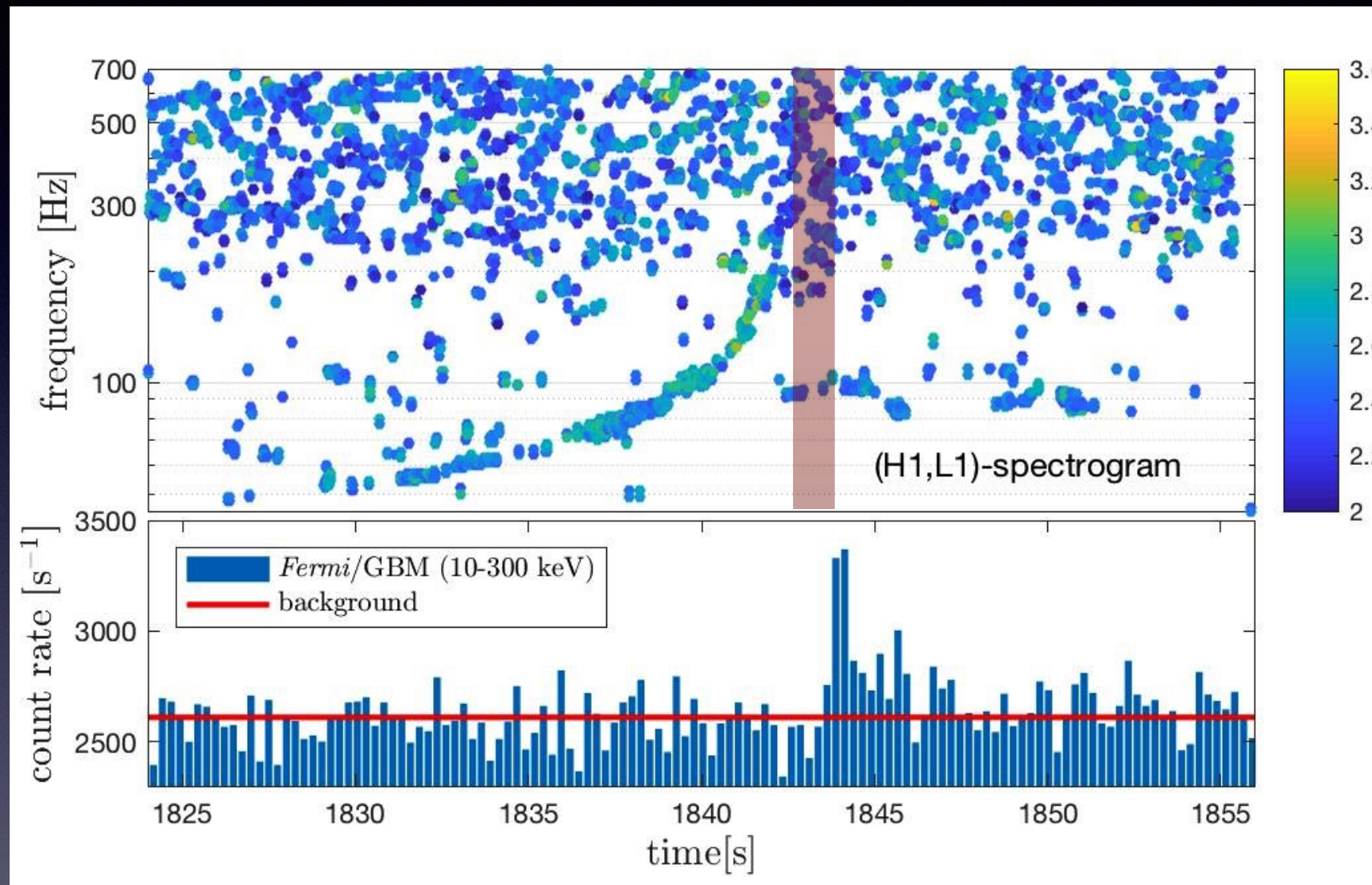


van Putten & Della Valle, 2018, MNRAS Letters, 482, L46

JGW-G1808513-v1 <https://gwdoc.icrr.u-tokyo.ac.jp/>

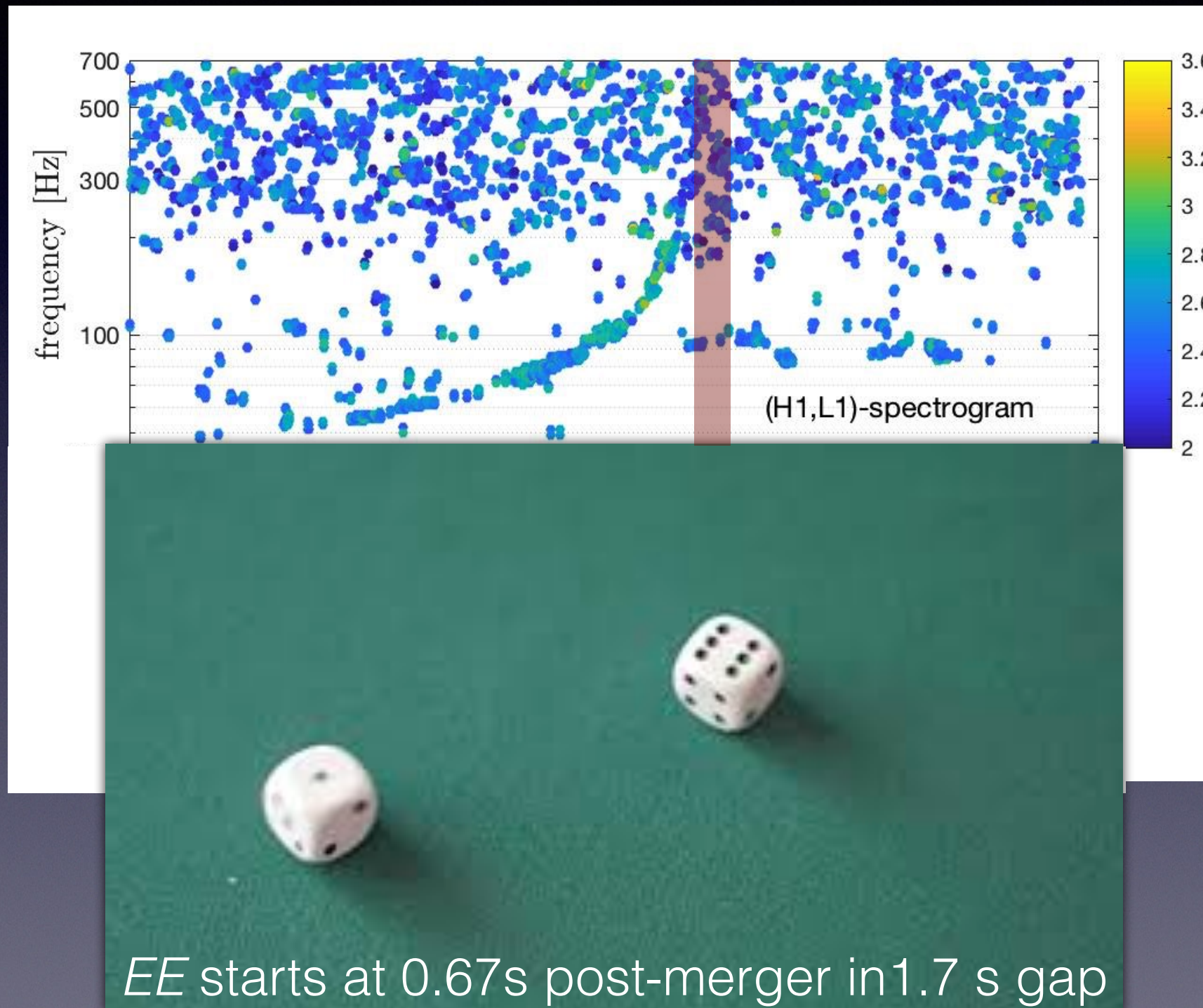


# Observational significance by timing and amplitude (statistically independent attributes)



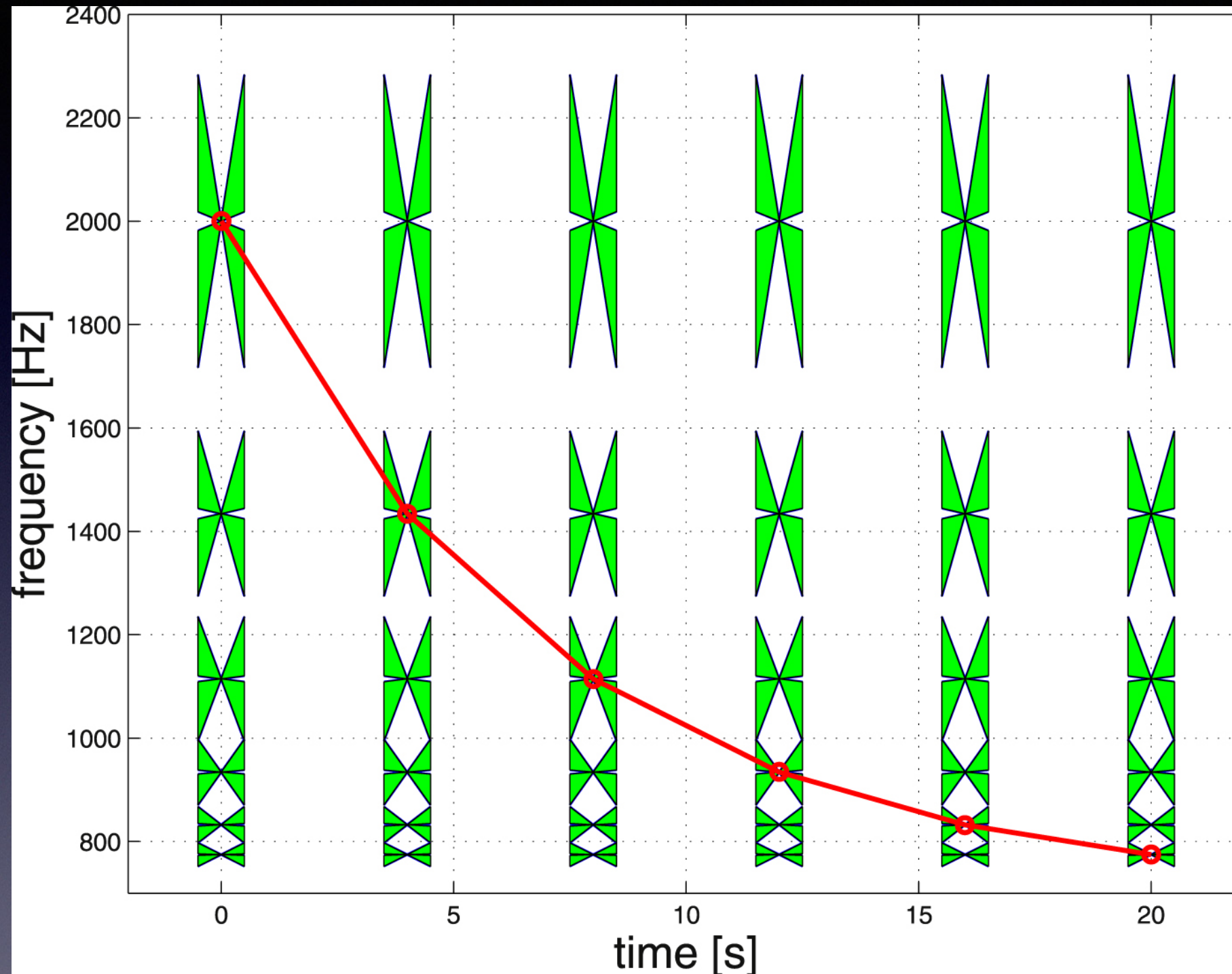


# Observational significance $4.2\sigma$ (1:40.000) by timing and amplitude (statistically independent attributes)





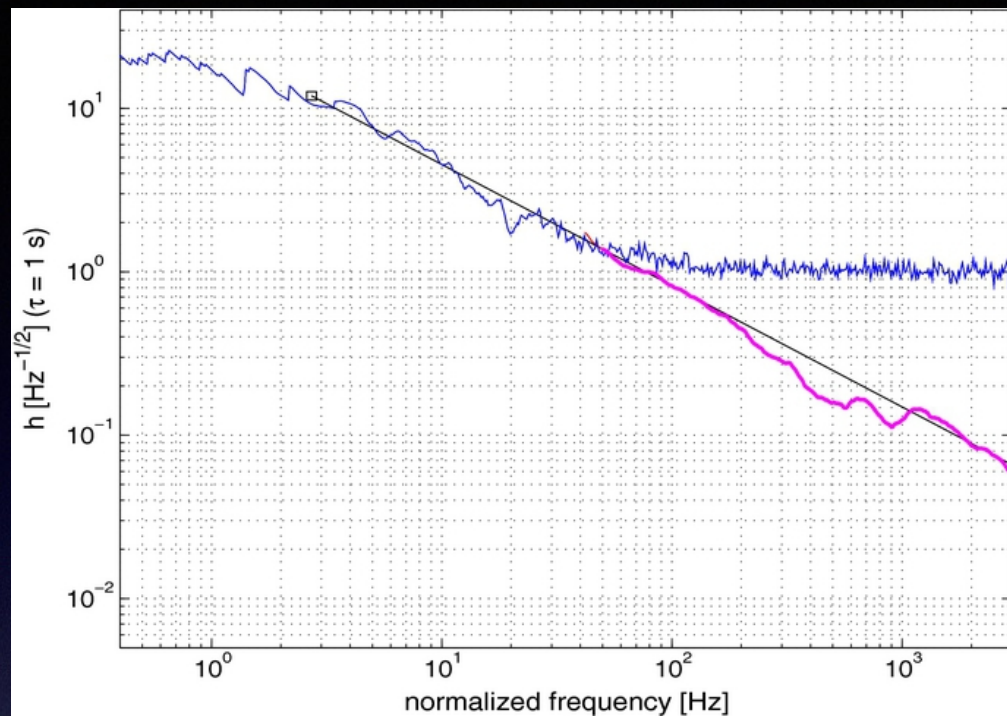
# Butterfly filtering by time-symmetric chirp-like templates



Intermediate time-scale of phase coherence  $0 < \tau < 1$  s in un-modeled searches



# Applications

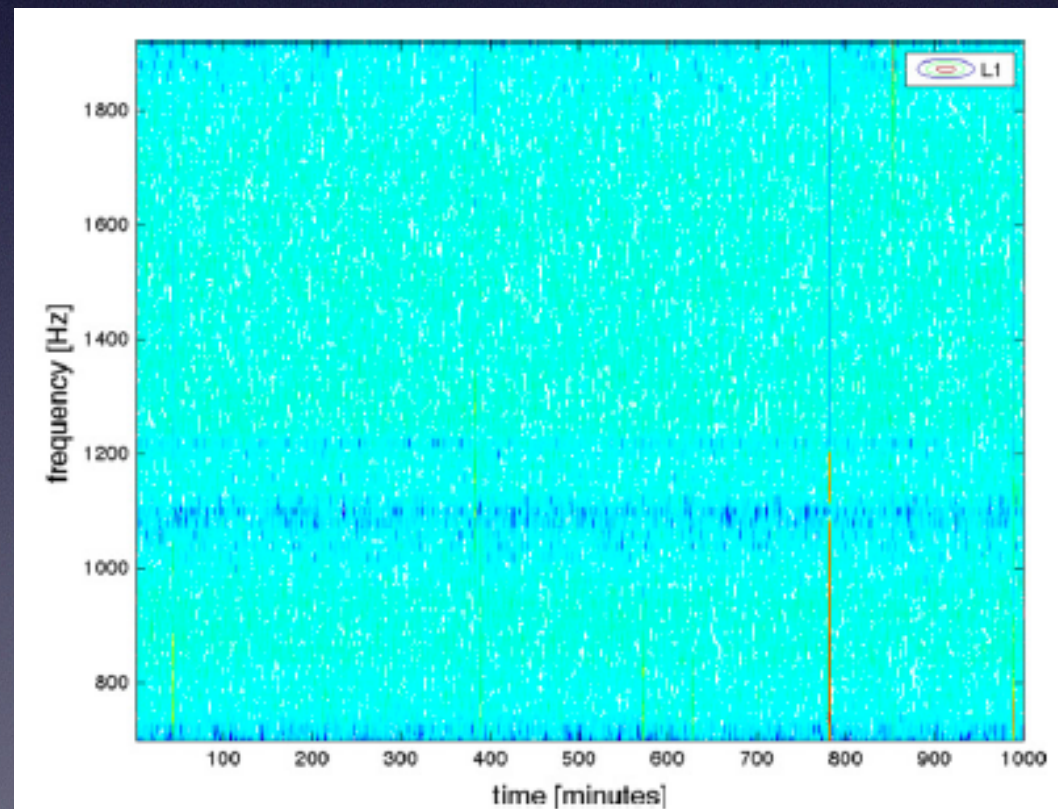
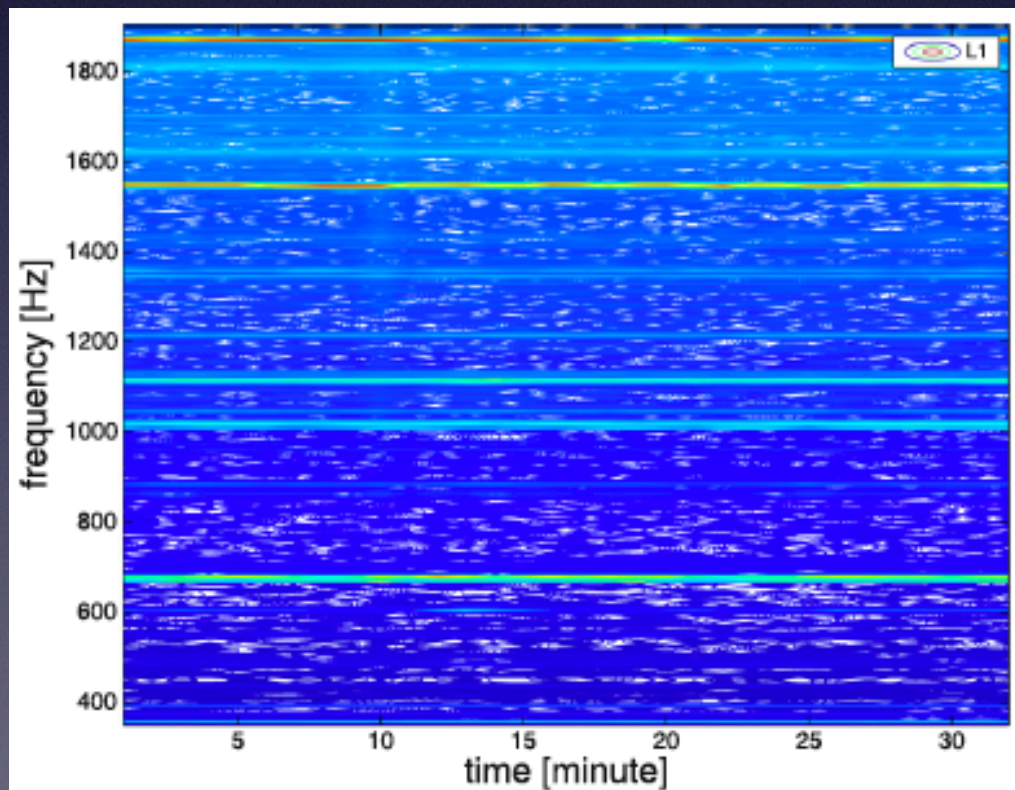


Kolmogorov spectrum BeppoSAX light curves of long GRBs

van Putten, Guidorzi & Frontera, 2014, ApJ, 786, 146

8.64 million templates ( $\tau=1\text{s}$ )

16k templates ( $\tau=1\text{s}$ )

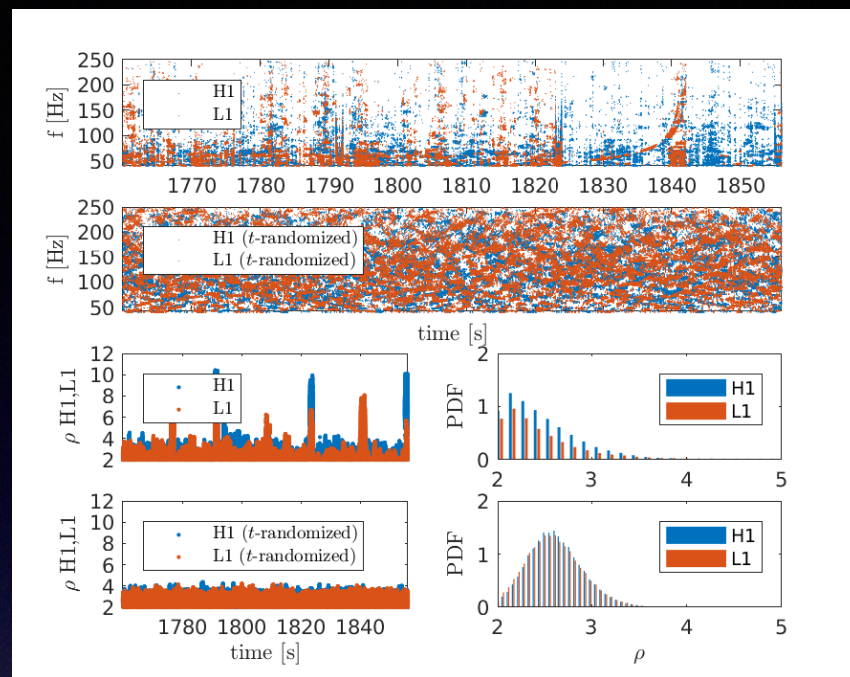


Line-suppression in LIGO S6 (van Putten, 2016, ApJ, 819, 169)

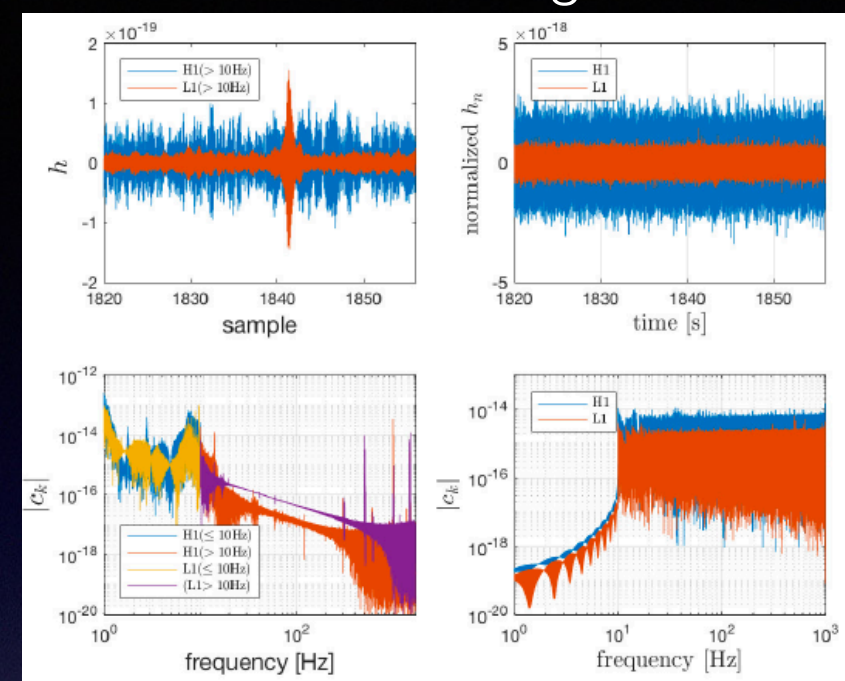


# Whitening LIGO O2

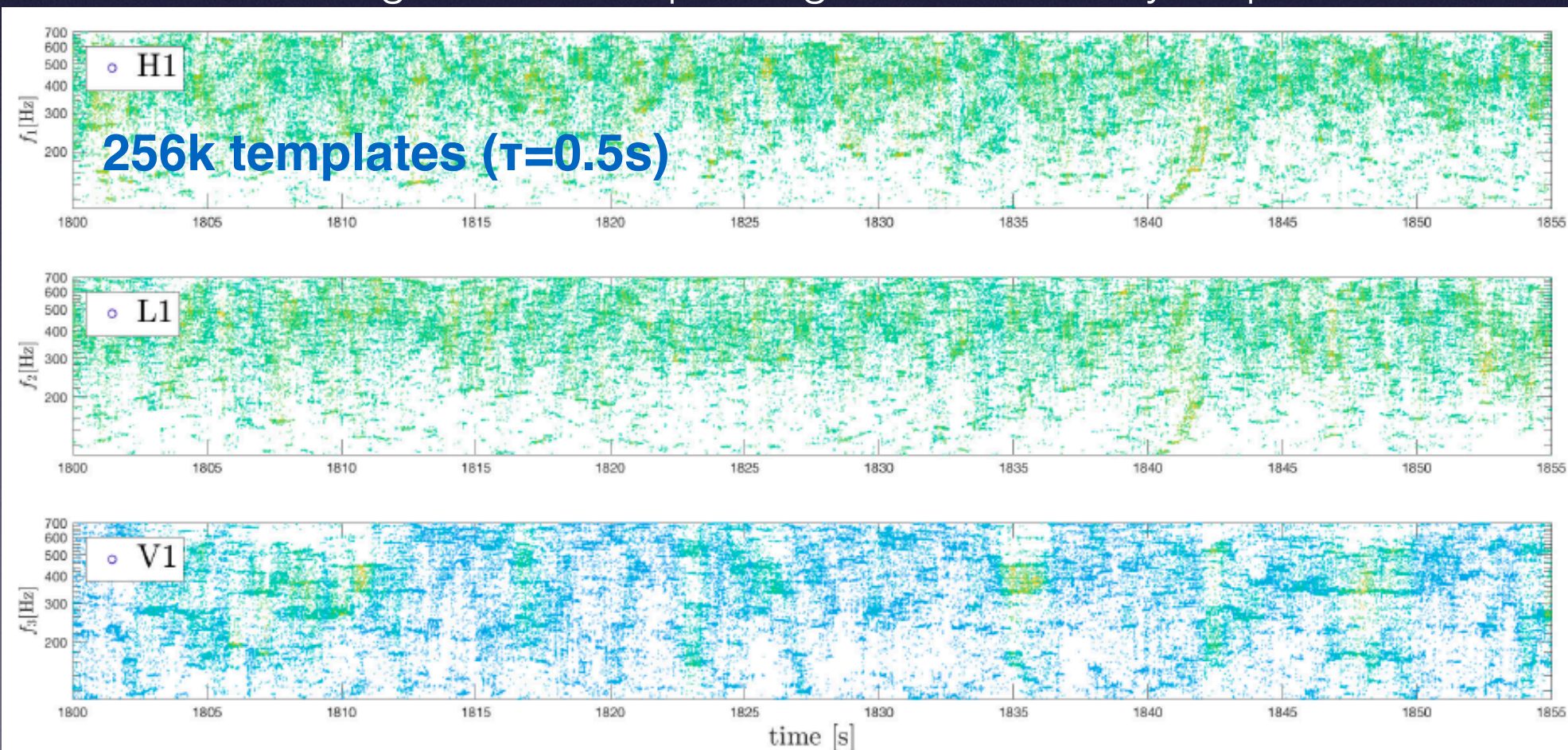
Un-whitened



Whitening

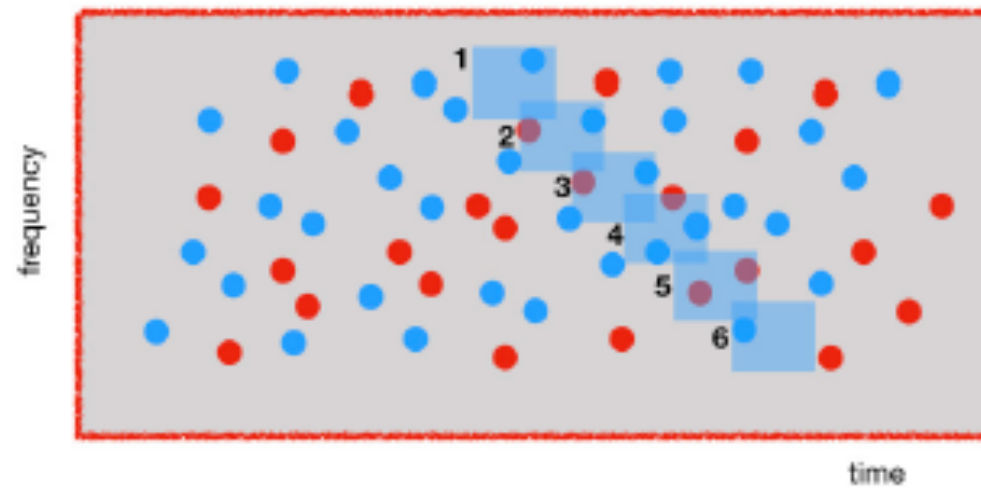
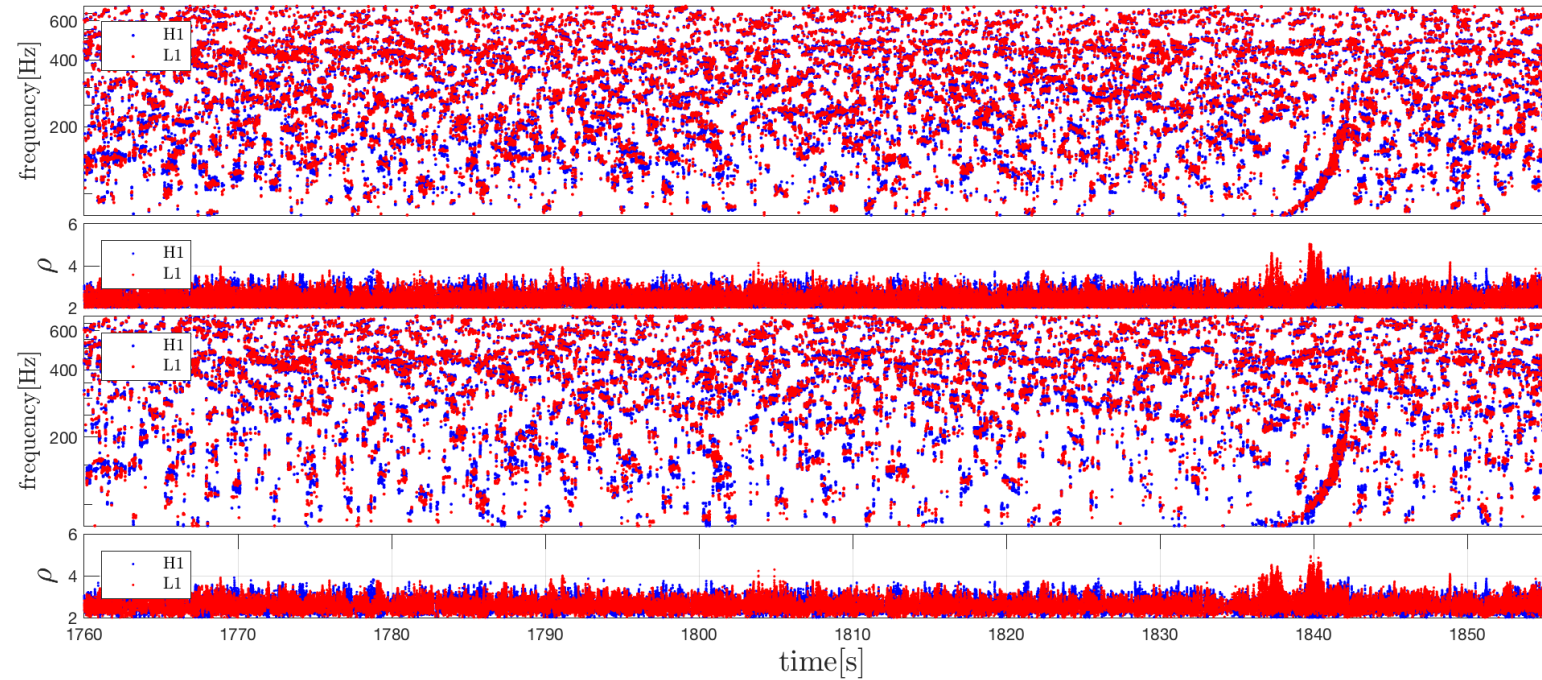


Single detector spectrograms of butterfly output





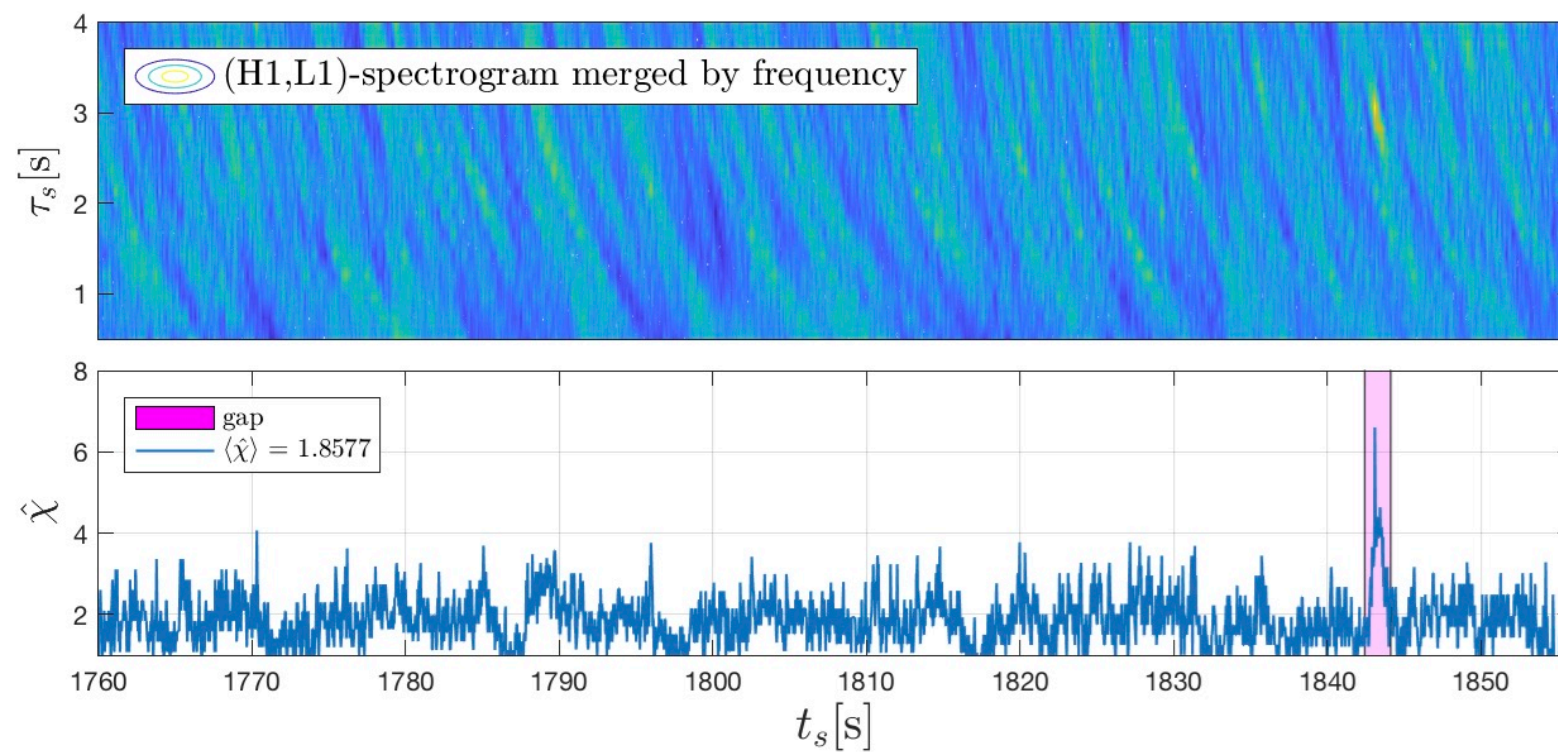
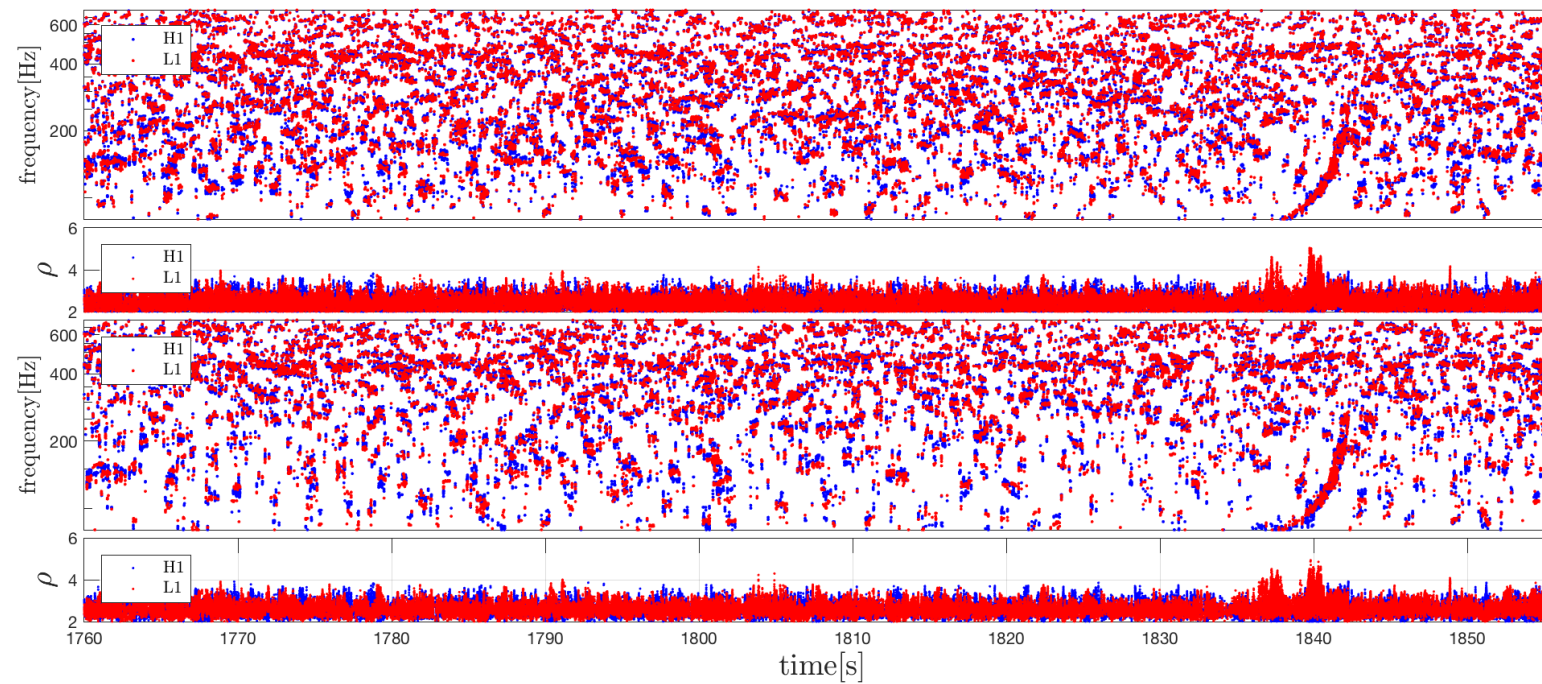
# Edge detection by $\chi$ -image analysis on H1&L1



**Figure A6.** Schematic illustration of edge detection by  $c = \sum_{i=1}^8 c_i = 0 + 1 + 1 + 1 + 0 + 0 = 3$ , counting the number of coincident hits in a merged spectrogram along a strip, here descending, discretized by cells of width  $\delta f$  and  $\delta t$  in frequency and time.

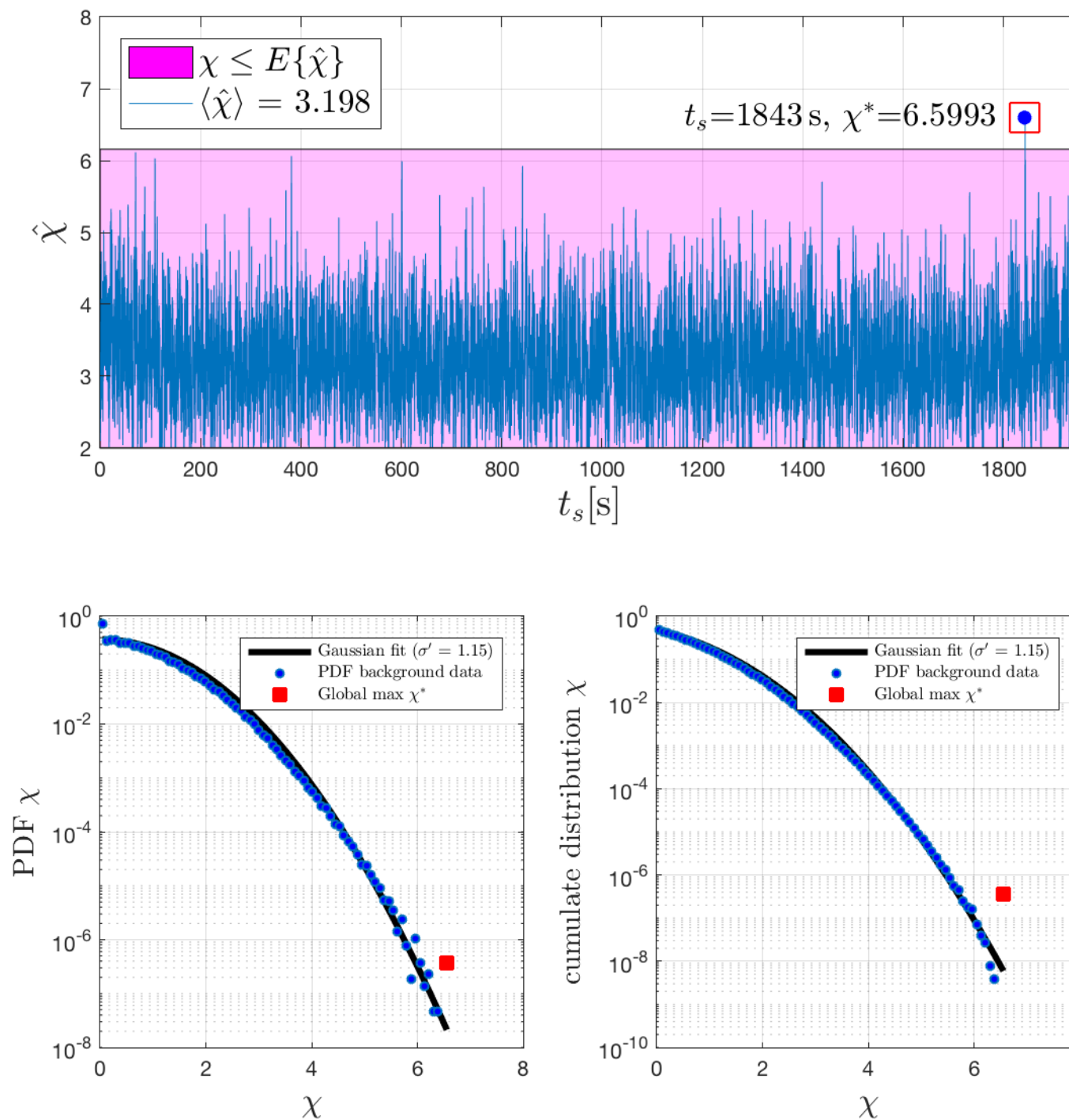


# $\chi$ -image analysis: peak





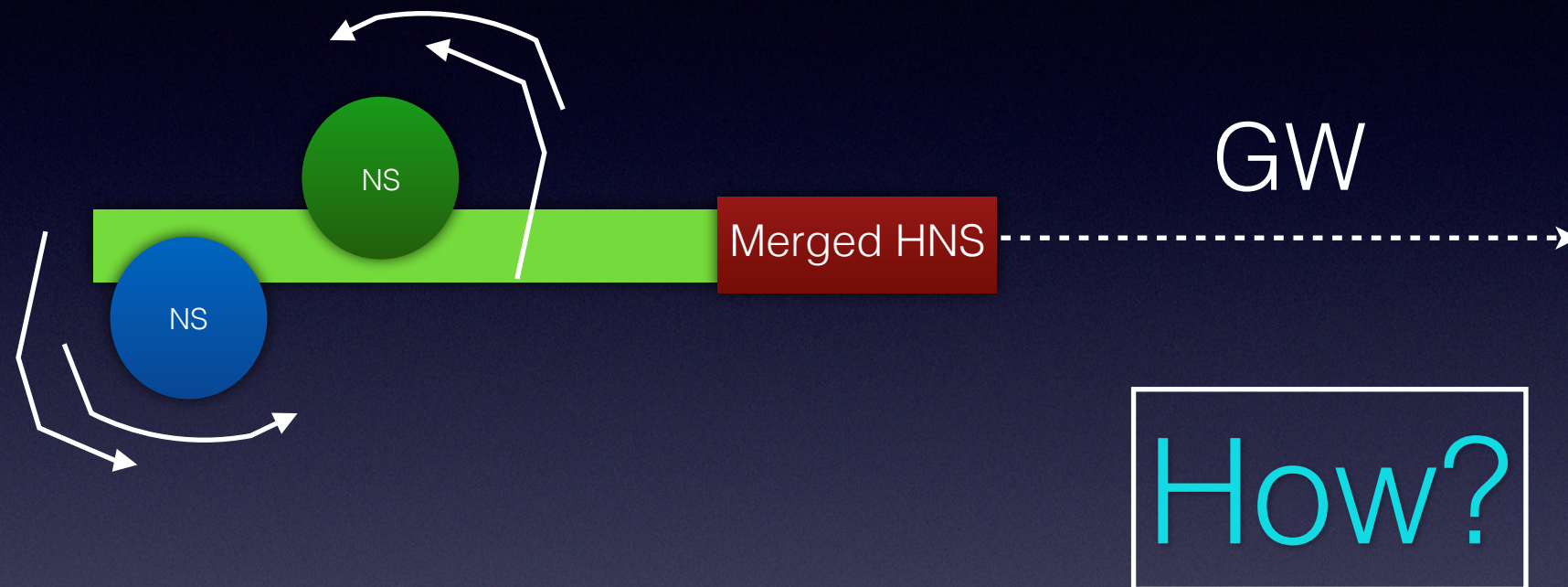
# $\chi$ -Image analysis: peak and background statistics



256 million scan parameters



*EE* - a descending chirp - radiates  $J$  HNS out to infinity.



YAHOO!  
NEWS

<https://news.yahoo.com/epic-crash-neutron-stars-creates-174436470.html>

## Epic Crash of Neutron Stars Creates 'Hypermassive Magnetar'

Mike Wall, Nov. 16 2018



# Calorimetry on Extended Emission

$$\mathcal{E} = \int_0^T L_{GW}(t) dt, \quad L_{GW} = \left( [h/C_h] f_{GW} \right)^2$$

Observed-to-true strain  $C_h$

van Putten & Levinson, 2002, Science, 295, 1874; ibid. 2003 ApJ 584 937  
van Putten Della Valle & Levinson, 2019, under review

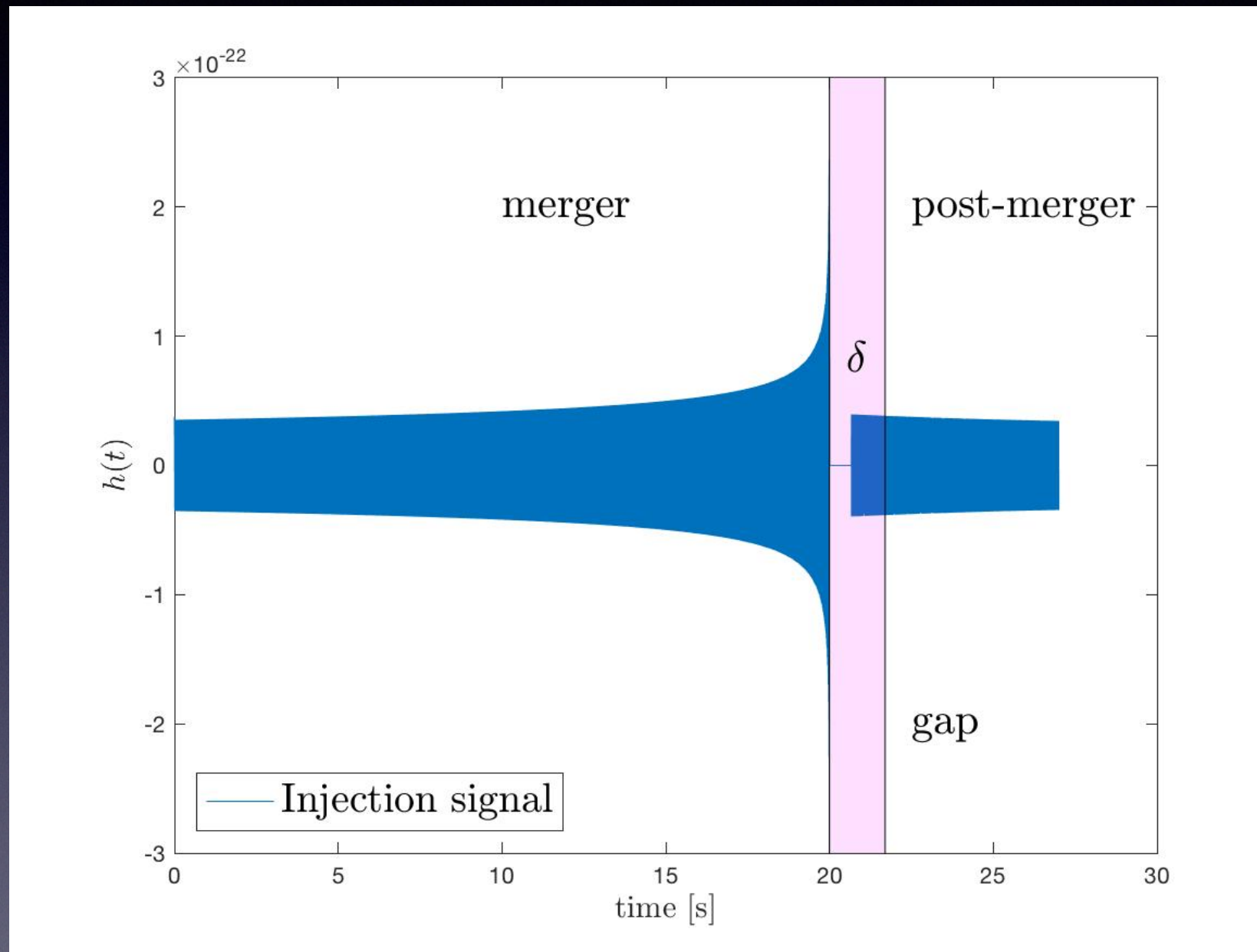


# Calorimetry by Injection Experiment

(work at AEI, Hannover)

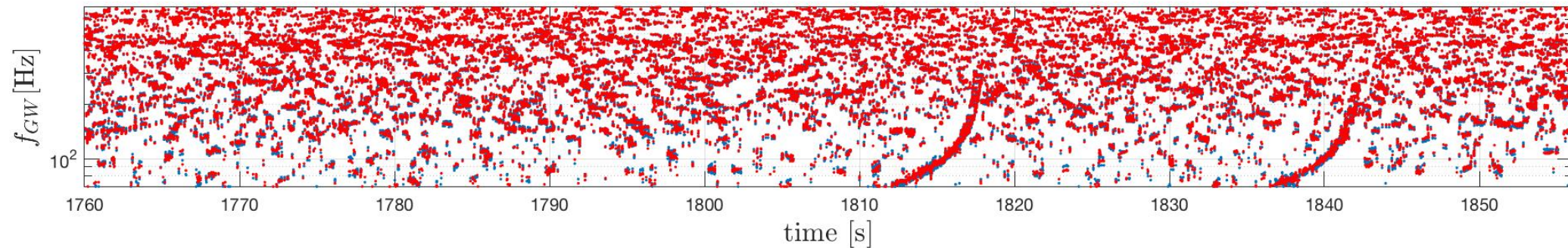
GW170817

$$\mathcal{E} \simeq ? \% M_{\odot} c^2$$





*(H1,L1)-spectrogram merged by frequency coincidences*



*Injection*

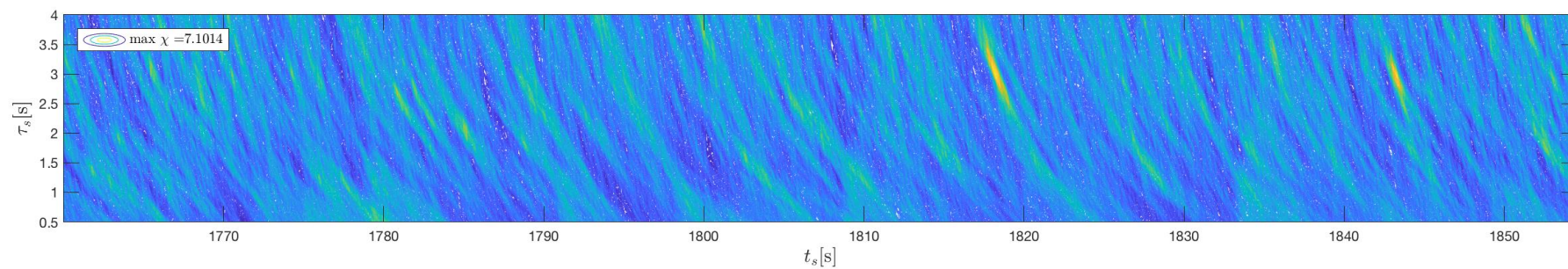
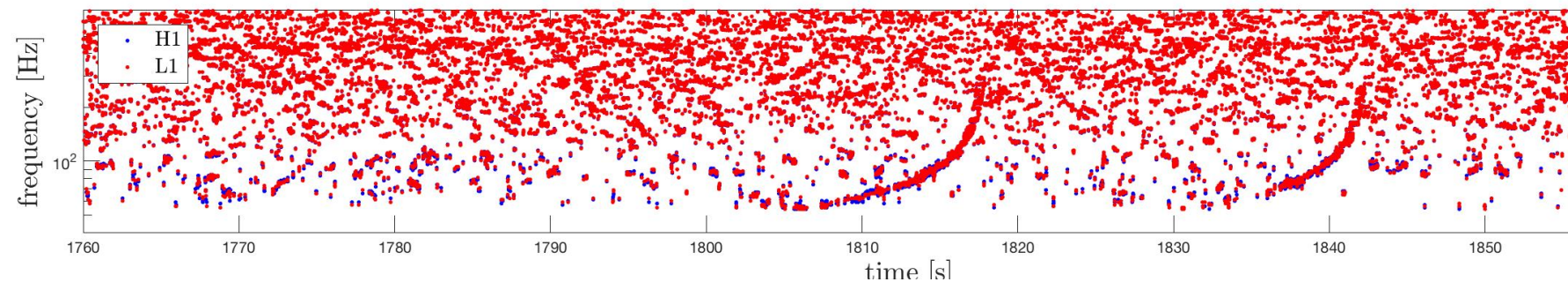
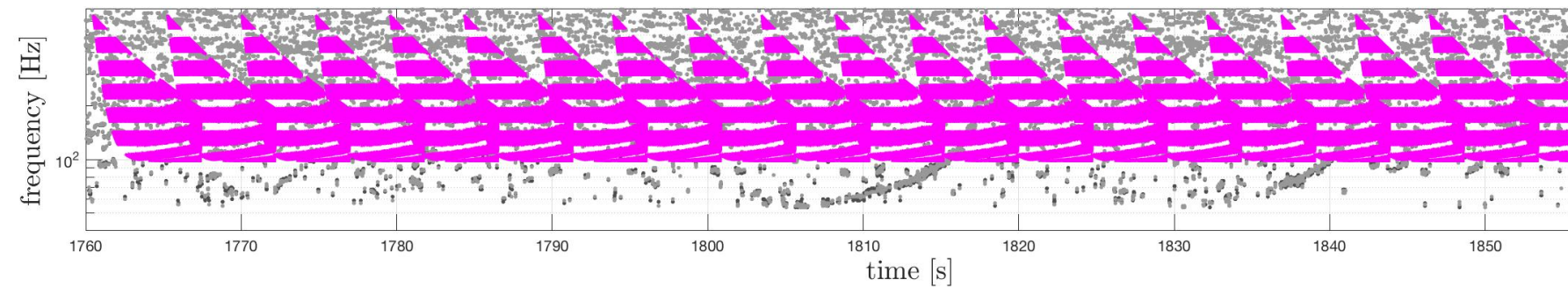
GW170817EE

*Calibration step: match ascending branches: true-to-observed strain  $C_h \sim 0.7$*

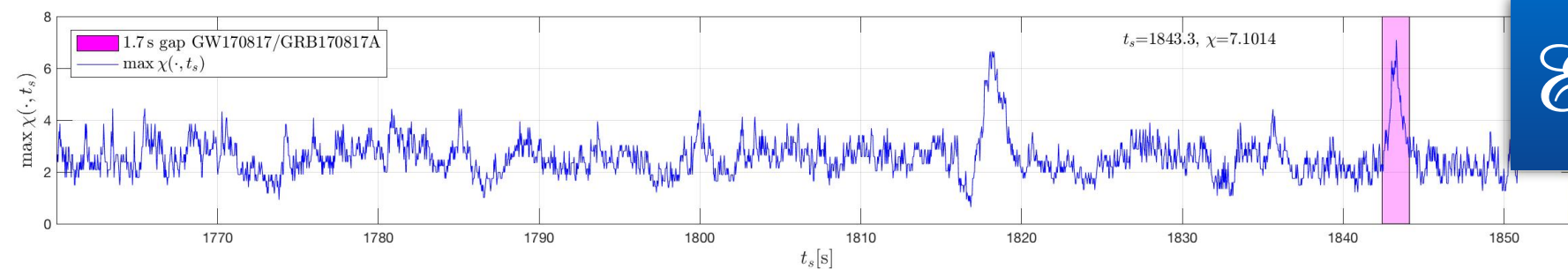


# $\chi$ -image analysis: matching peaks

*Scan over exponential features*



$\uparrow$   $\tau$



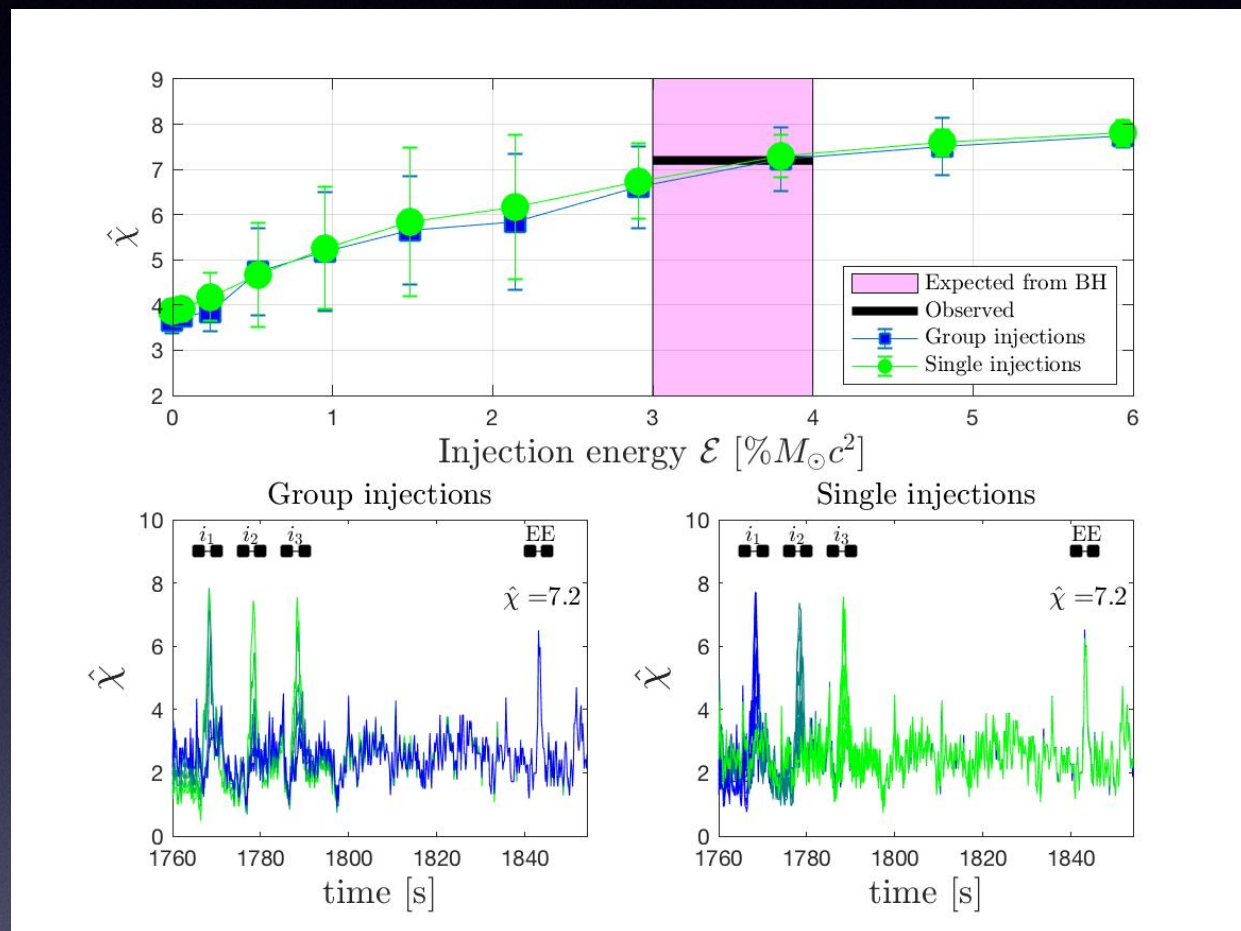
$$\mathcal{E} \simeq 3 \% M_{\odot} c^2$$

$$t_s \simeq 0.67 \text{ s}$$



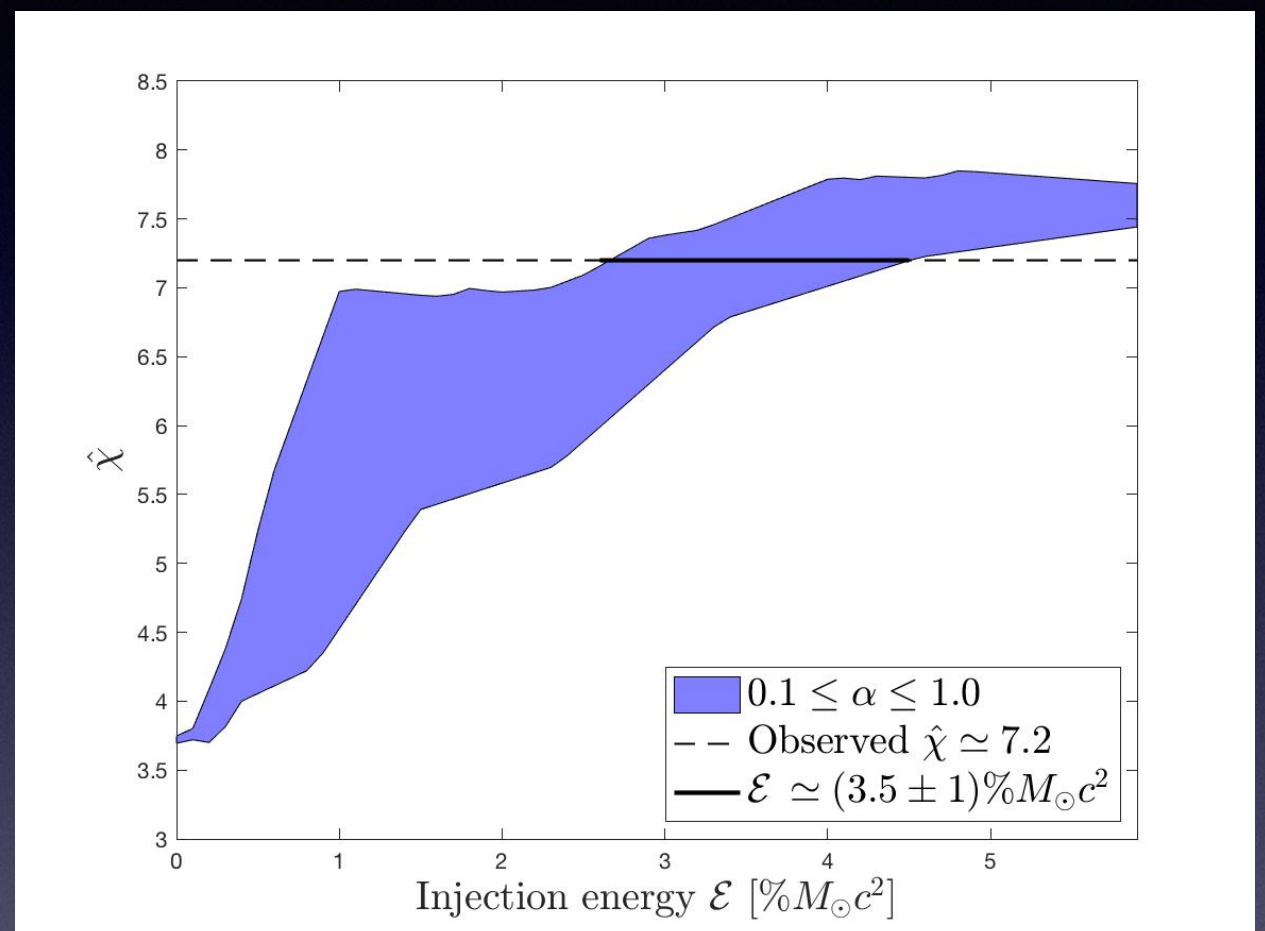
# Response curve $\chi(E)$

## Single and group injections



No interference between injections

## Response function



$$h(f) \sim f^{\alpha} \quad (0.1 \leq \alpha \leq 1)$$

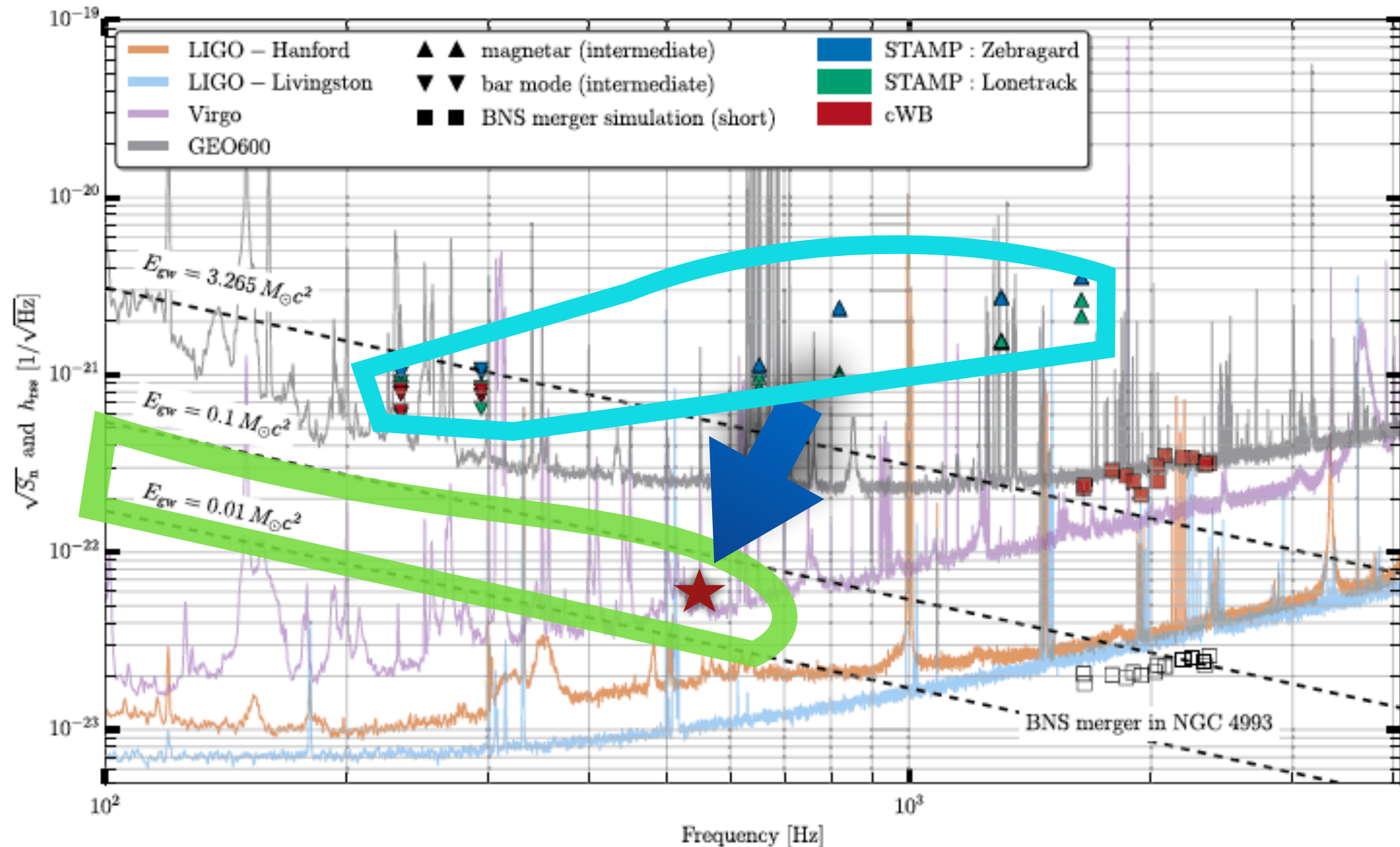
van Putten Della Valle & Levinson, 2019, under review



# Shifting the Window...

THE ASTROPHYSICAL JOURNAL LETTERS, 851:L16 (13pp), 2017 December 10

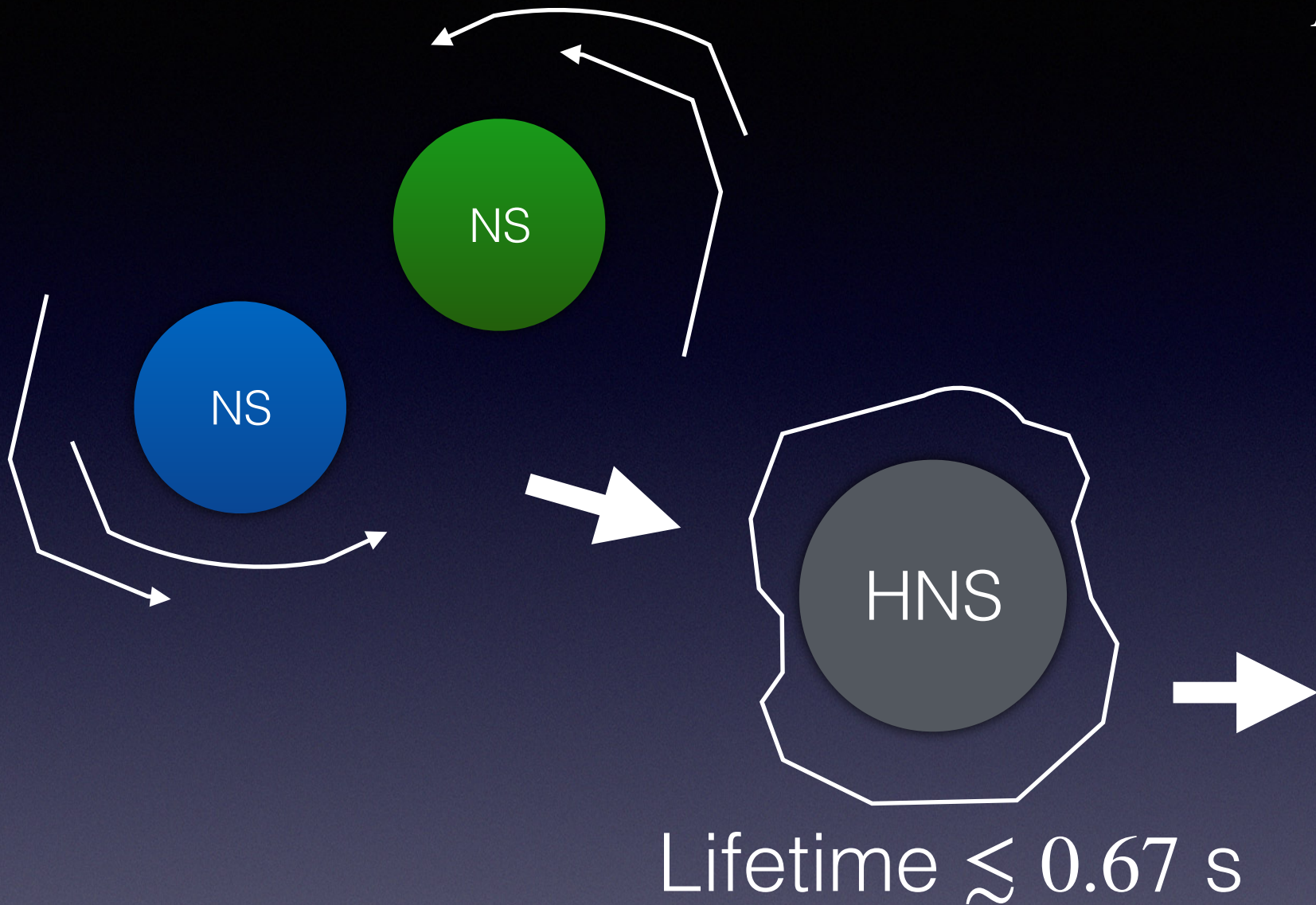
Abbott et al.



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

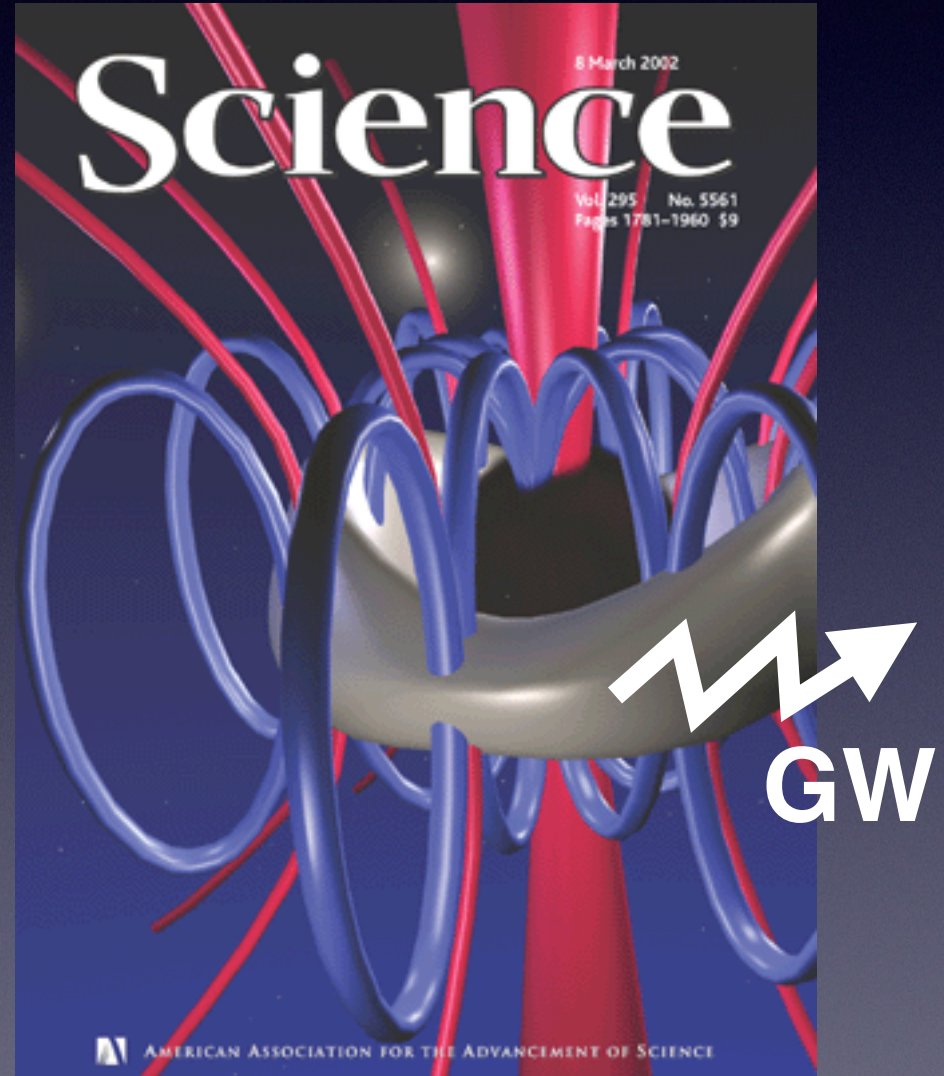


# Core-collapse greatly enhances $E_J$



$$E_J \lesssim 1M_{\odot}c^2$$

(  $\sim 3M_{\odot}$  Kerr BH)



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

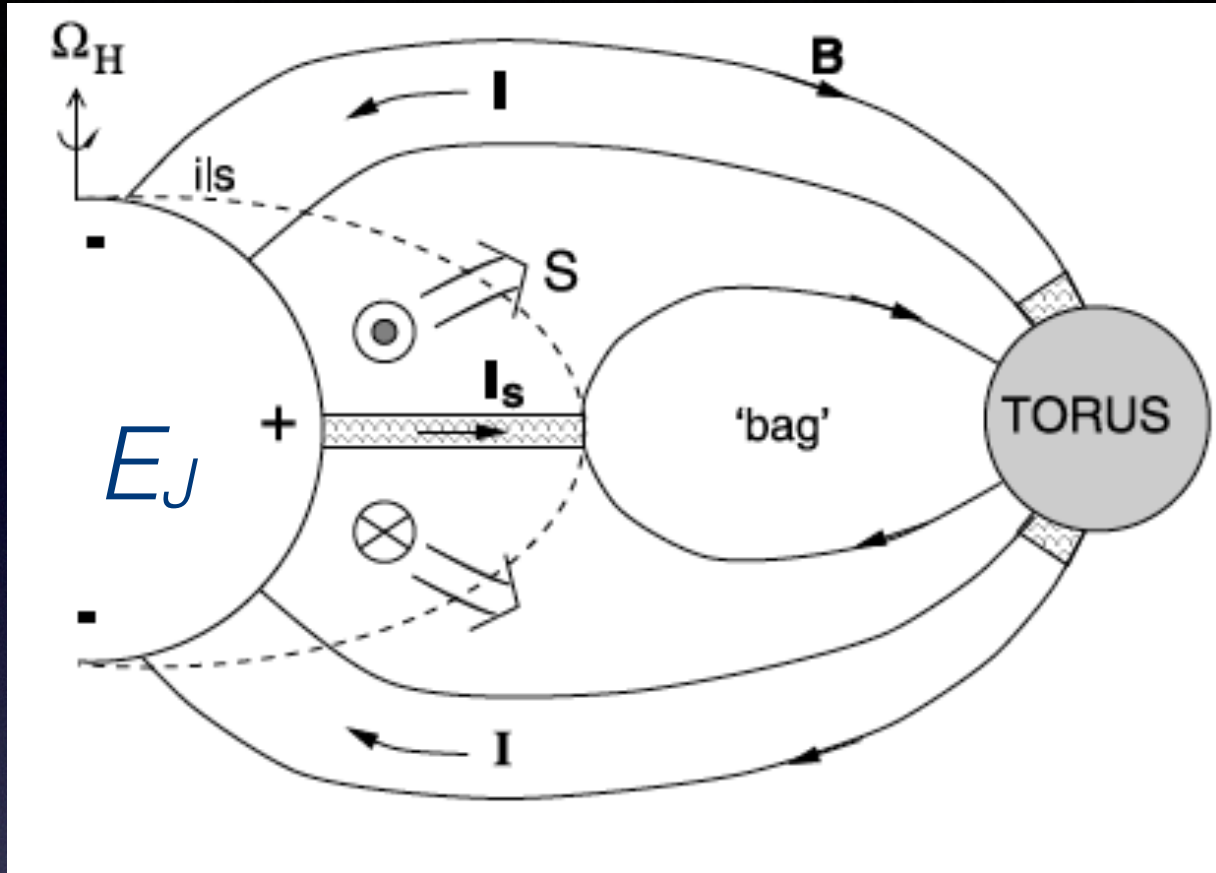
$$\text{Duration} = T_s$$

- $\text{cf. } t_c \lesssim 0.9 \text{ s}$ 
Murguia-Berthier, 2019, GWPop, Aspen
- $\text{cf. } t_c \lesssim 0.98^{+0.31}_{-0.26} \text{ s}$ 
Gill & Rezzolla, 2019, arXiv: 1901.04138



Expected output from a Kerr black hole

van Putten, 1999, Science, 285, 115



$L_H = -\dot{M}, T = -J_H$

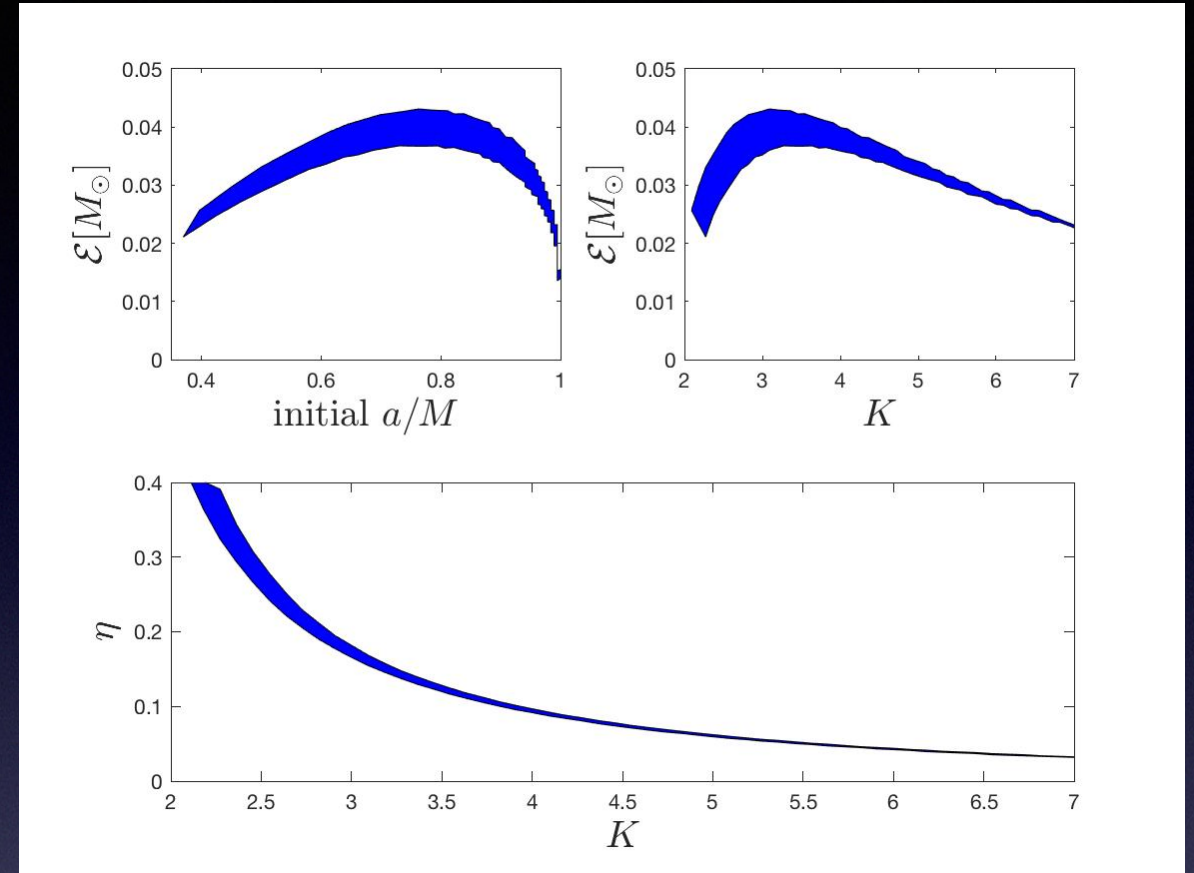
$Kr_{ISCO}$

$$\mathcal{E} \simeq 3\% M_{\odot} c^2$$

by non-axisymmetric torus of  $\sim 3R_{\text{ISCO}}$  about a low mass non-extremal BH ( $a/M \sim 0.75$ )

*Theory and injection results agree.*

van Putten, Della Valle & Levinson, 2019 (under review)



$f_{GW,i} = 650\text{Hz}$  (observed):  
 $K \simeq 3, \eta \simeq 15\%$



# *GW170817EE*: complex sequence in three Acts



$$E_J < 1 \% M_{\odot} c^2 \rightarrow E_J \simeq 0.3 M_{\odot} c^2 \rightarrow \mathcal{E} \simeq 3 \% M_{\odot} c^2$$

$J = J_{\text{HNS}}$  conserved in CC

van Putten, Della Valle & Levinson, 2019 (under review)

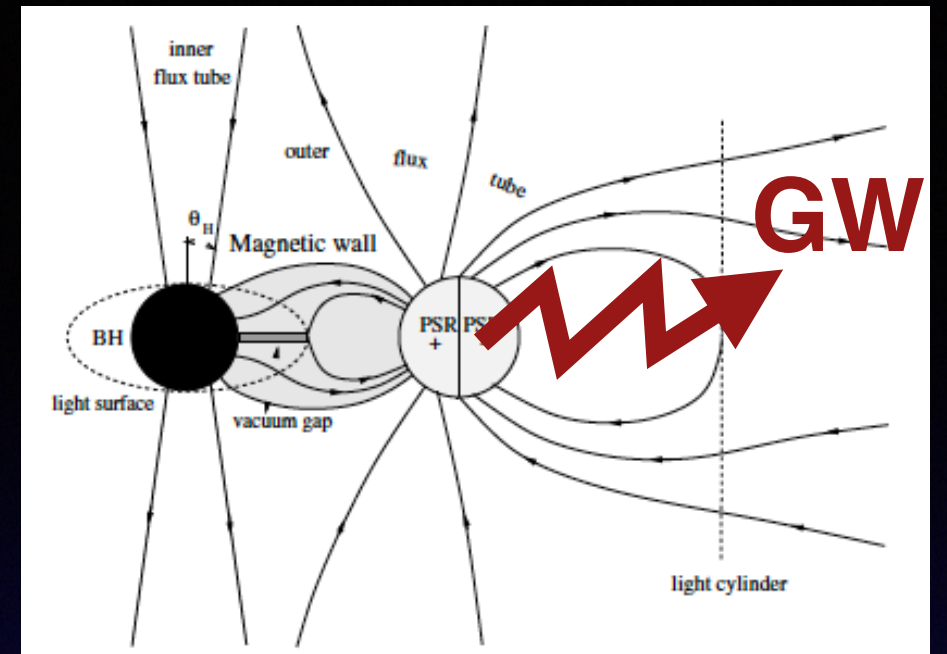


# Burst of MMEE

*Duration set by lifetime of spin:*

$$T_s \simeq 1.5\text{s} \left( \frac{\sigma}{0.1} \right)^{-1} \left( \frac{z}{6} \right)^4 \left( \frac{M}{M_\odot} \right)$$

$$z = \frac{r}{M}, \quad \sigma = \frac{M_T}{M}$$



van Putten & Levinson, 2003, ApJ, 584, 937

*GRB170817A - kilonova:*

$$E_j \simeq \frac{1}{4z^4} E_J \simeq 10^{50} \text{erg} \quad E_w \simeq \eta^2 E_J \simeq 10^{52} \text{erg}$$

Agrees with observational constraints (Mooley et al. 2019):

**kilonova**

$$E_j \simeq 10^{49-50} \text{erg} \quad E_k \simeq 4.5 \times 10^{51} \text{erg}$$

**GRB170817A**

van Putten, Della Valle & Levinson, 2019 (under review)



# Conclusion

## Calorimetric evidence of Kerr BHs

$$1\% < \mathcal{E} < 10\%, \quad h \sim \text{few} \times 10^{-23}$$

## Multi-messenger Extended Emission

$$\text{GW170817} \text{EE:} \quad \mathcal{E} \simeq 3\% M_{\odot} c^2$$

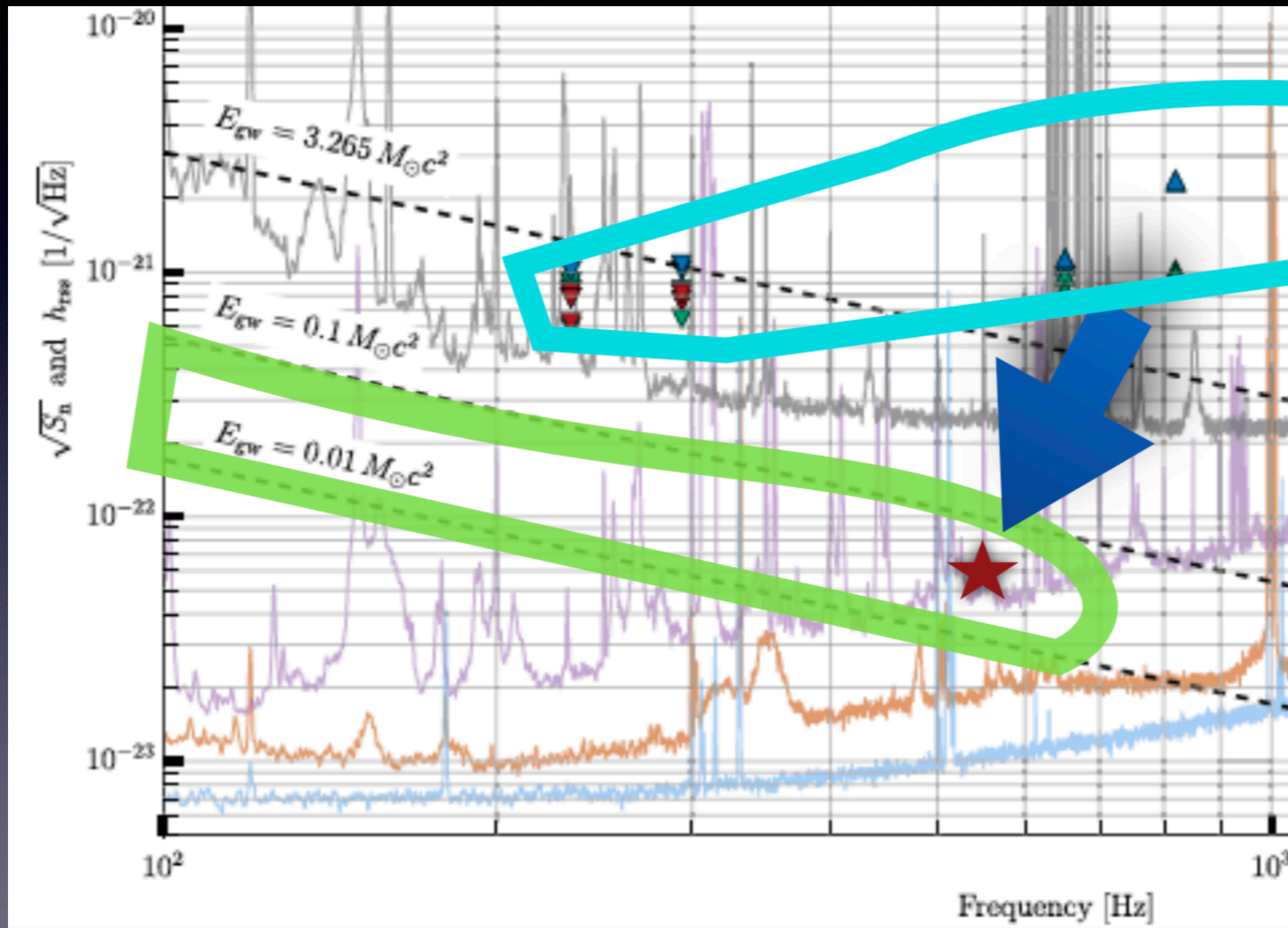
$$\text{Kilonova:} \quad 0.2\% M_{\odot} c^2$$

$$\text{GRB170817A:} \quad 0.01\% M_{\odot} c^2$$



# Shifting the Window:

New Opportunities for **EE to DNS, NS-BH and CC-SNe ...**



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