GW170817B - The first direct detection of gravitational waves associated with a GRB

Maurice H.P.M. van Putten

van Putten & Della Valle, **2023**, A&A 669 A36
van Putten, Della Valle & Levinson, **2019**, ApJ, 876, L2
van Putten & Della Valle, **2019**, MNRAS, 482, L46
van Putten **2023** Universe, 9 279
Abchouyeh, van Putten & Amati, **2023**, ApJ, 952 157

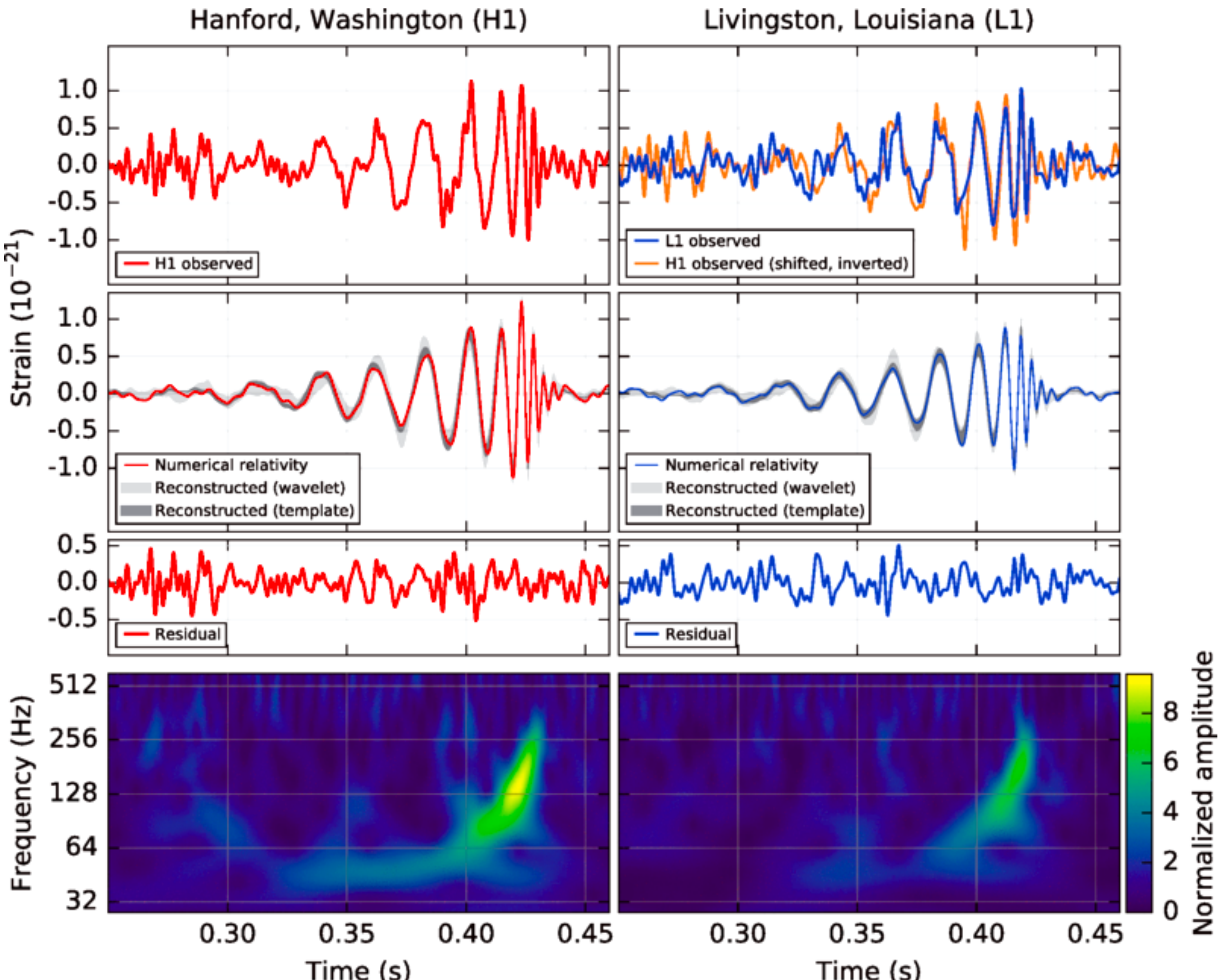
JGW-G2315437 (2023)

32nd Texas Symposium on Relativistic Astrophysics
GW Astrophysics: from LIGO to PTA
December 12 2023

CONTENTS

INTRODUCTION

The first chirp GW150914

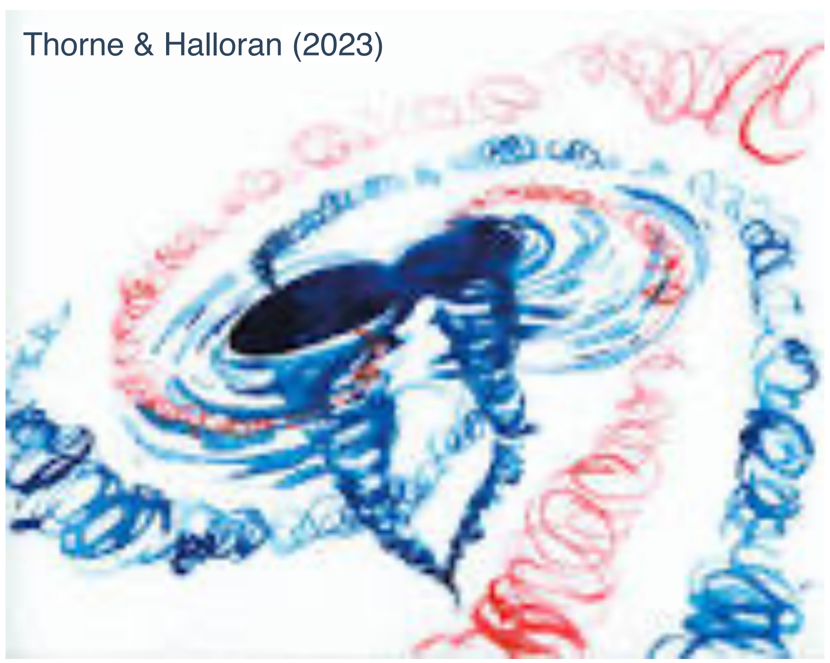


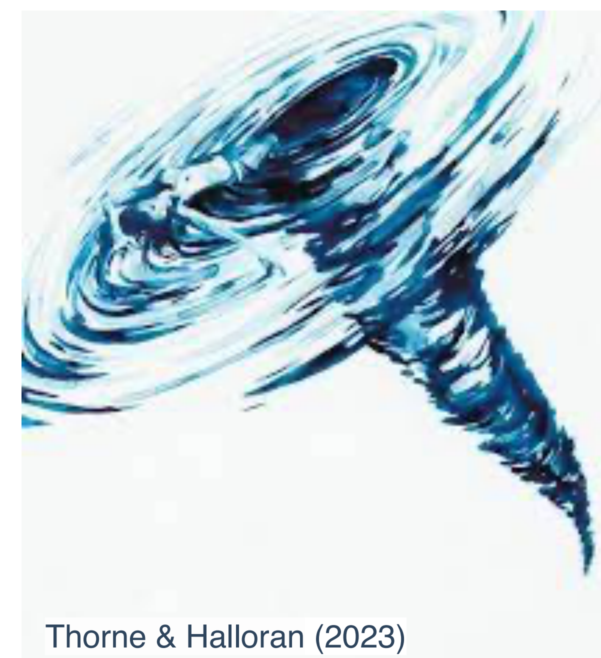
PRL2016

Unit of gravitational-wave luminosity

$$\boxed{L_0} = \frac{c^5}{G} = 3.6 \times 10^{59}\,\mathrm{erg\,s^{-1}} = 200{,}000\,M_\odot c^2\,\mathrm{s}^{-1}$$

Kerr Black Hole (1963)

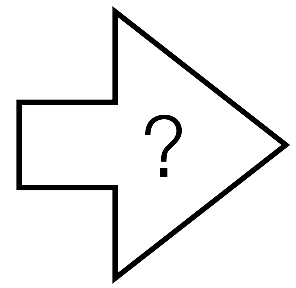




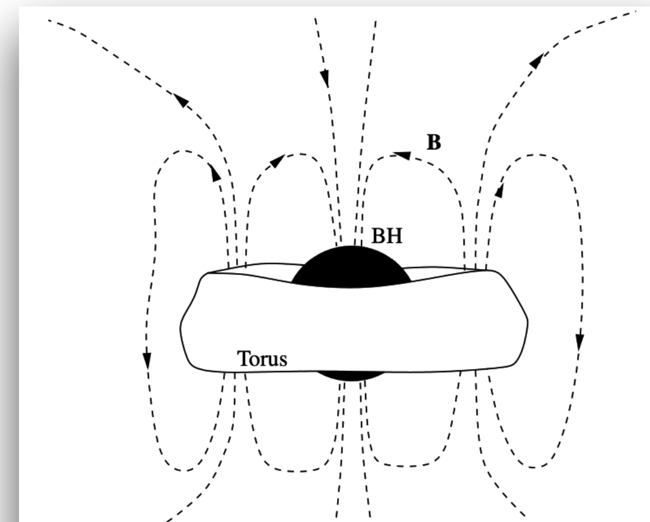
GW150914: Peak luminosity $\hat{L}_{\mathrm{GW}} \simeq 0.1\,\%\,\boxed{L_0}$

Progenitors of black hole central engines

NS/BH



Kerr BH-torus system



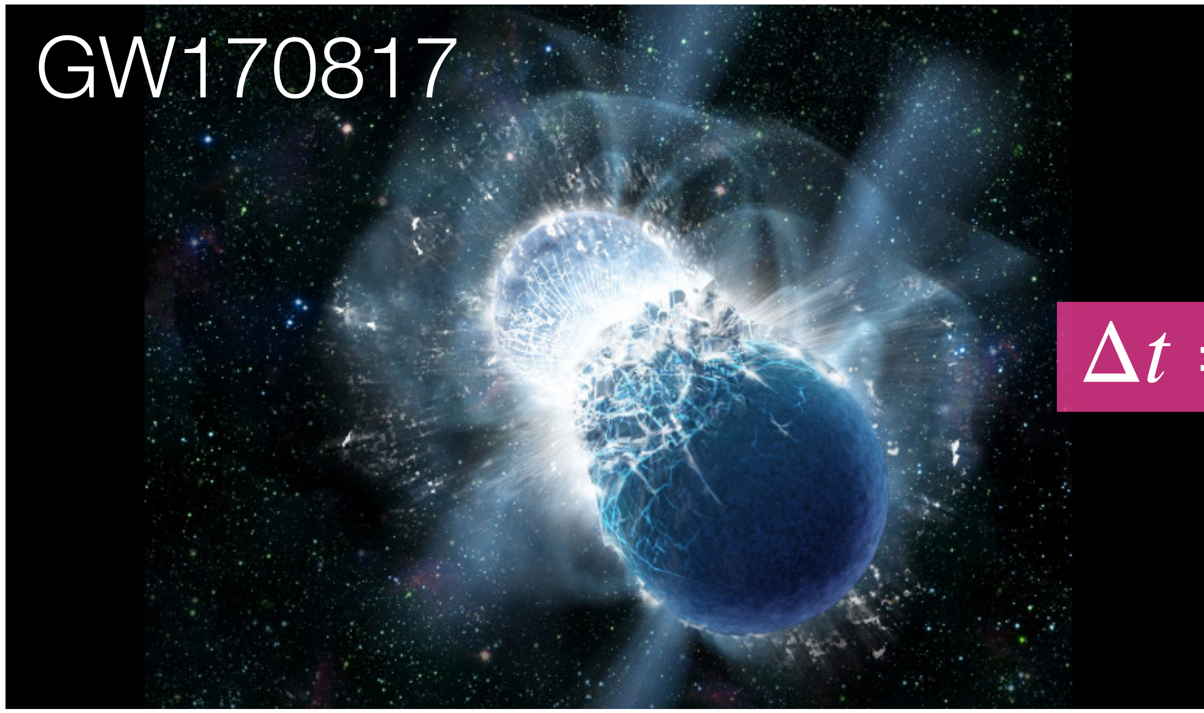
van Putten PRL 2001

Multi-messenger central engine by coupling to high-density matter

$$L_{gw} = \frac{32}{5}\left(\frac{\delta m}{M}\right)^2\left(\frac{M}{a}\right)^5 \boxed{L_0} = \mathcal{O}\left(10^{51}\right)\,\mathrm{erg\,s^{-1}}$$

van Putten PRL 2001; van Putten & Levinson 2003

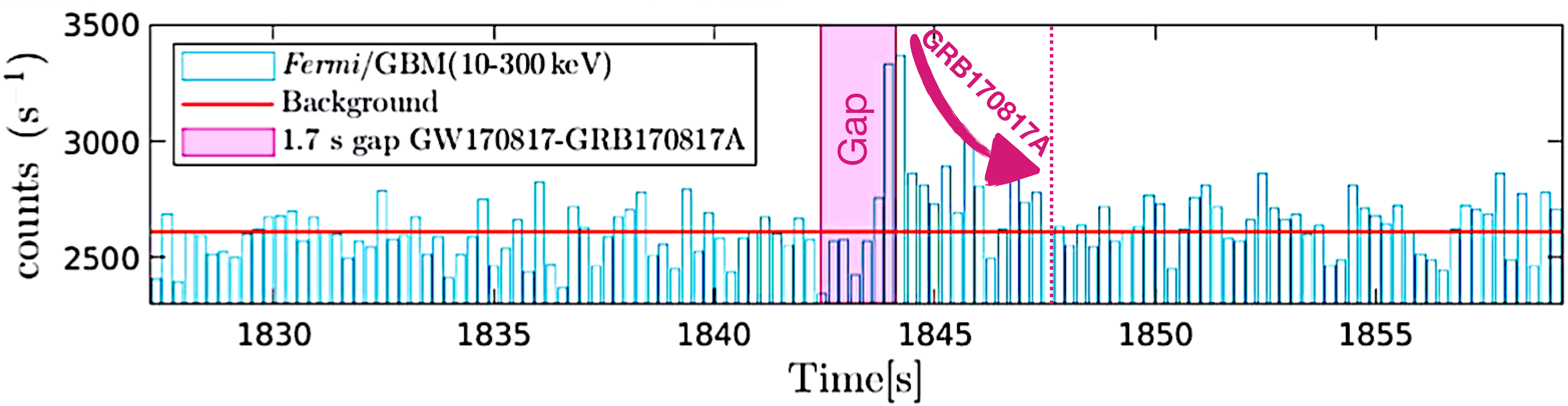
GRB170817A?



$\Delta t = 1.7$ s

“If gravitational waves are detected from one or more gamma-ray burst triggers, the waves will almost certainly reveal the physical nature of the trigger.”

Cutler & Thorne, 2002, arXiv:0204090v1



Searching for un-modeled signals

Expected detection rate:

Observational volume × Astrophysical event rate / volume

Observational volume = VT

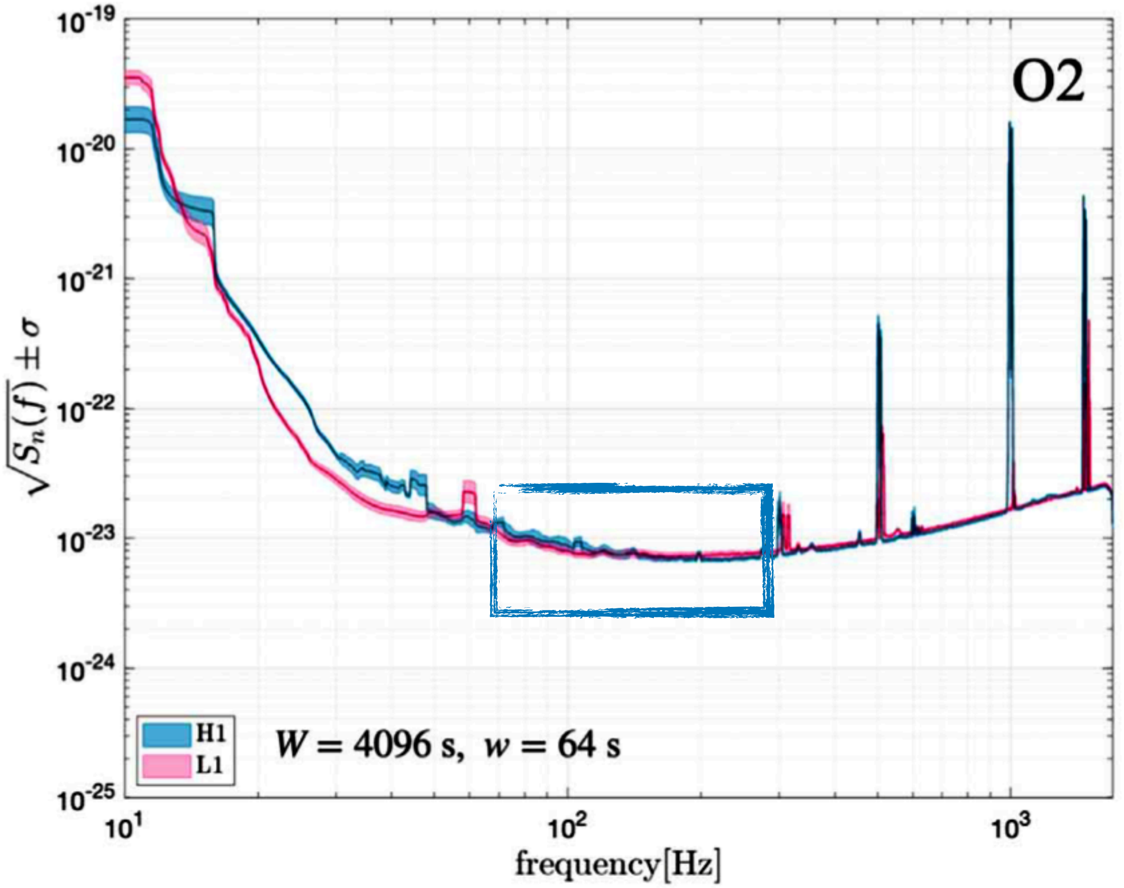
$$V = (4\pi/3) \times \text{horizon distance}^3$$

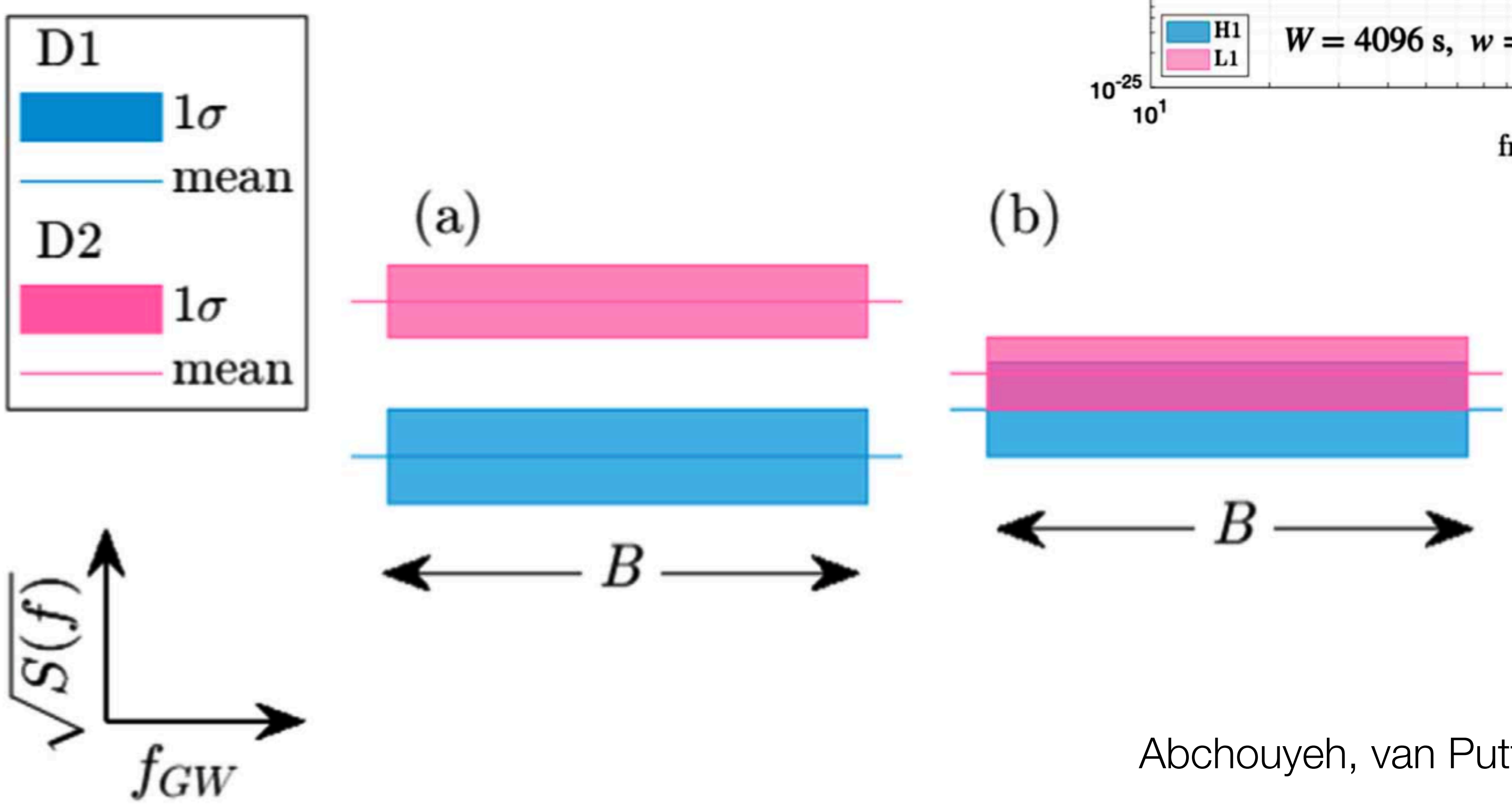
$$T = T_{obs} \times \text{detector yield } (y)$$

LIGO-Virgo-KAGRA

Detector yield with two or more detectors

Detector pair at nominal performance over
$B = 100 - 250\,\mathrm{Hz}$

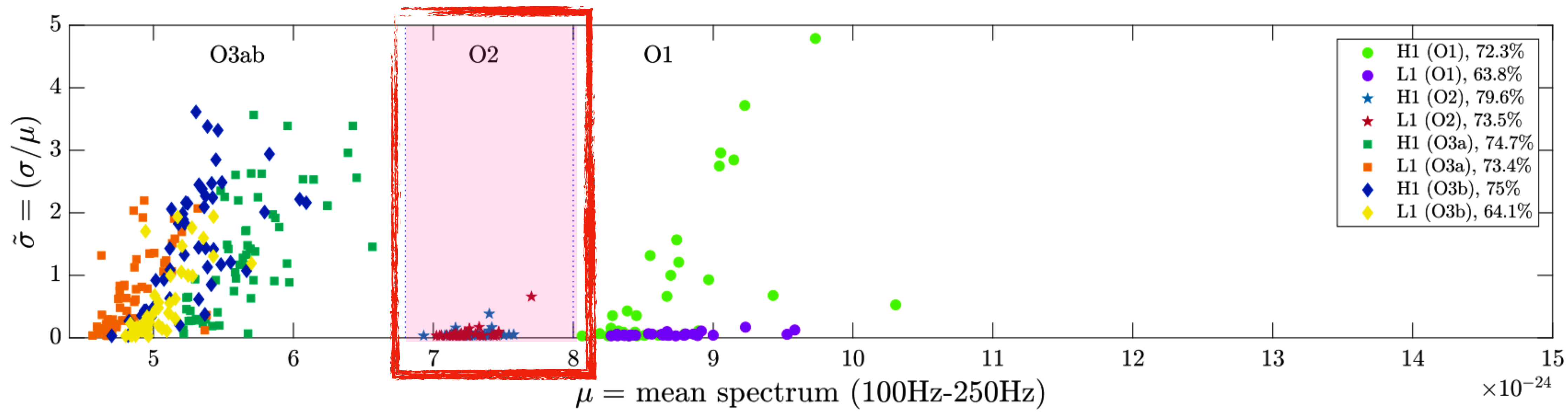




Abchouyeh, van Putten & Amati 2023 ApJ 952 157

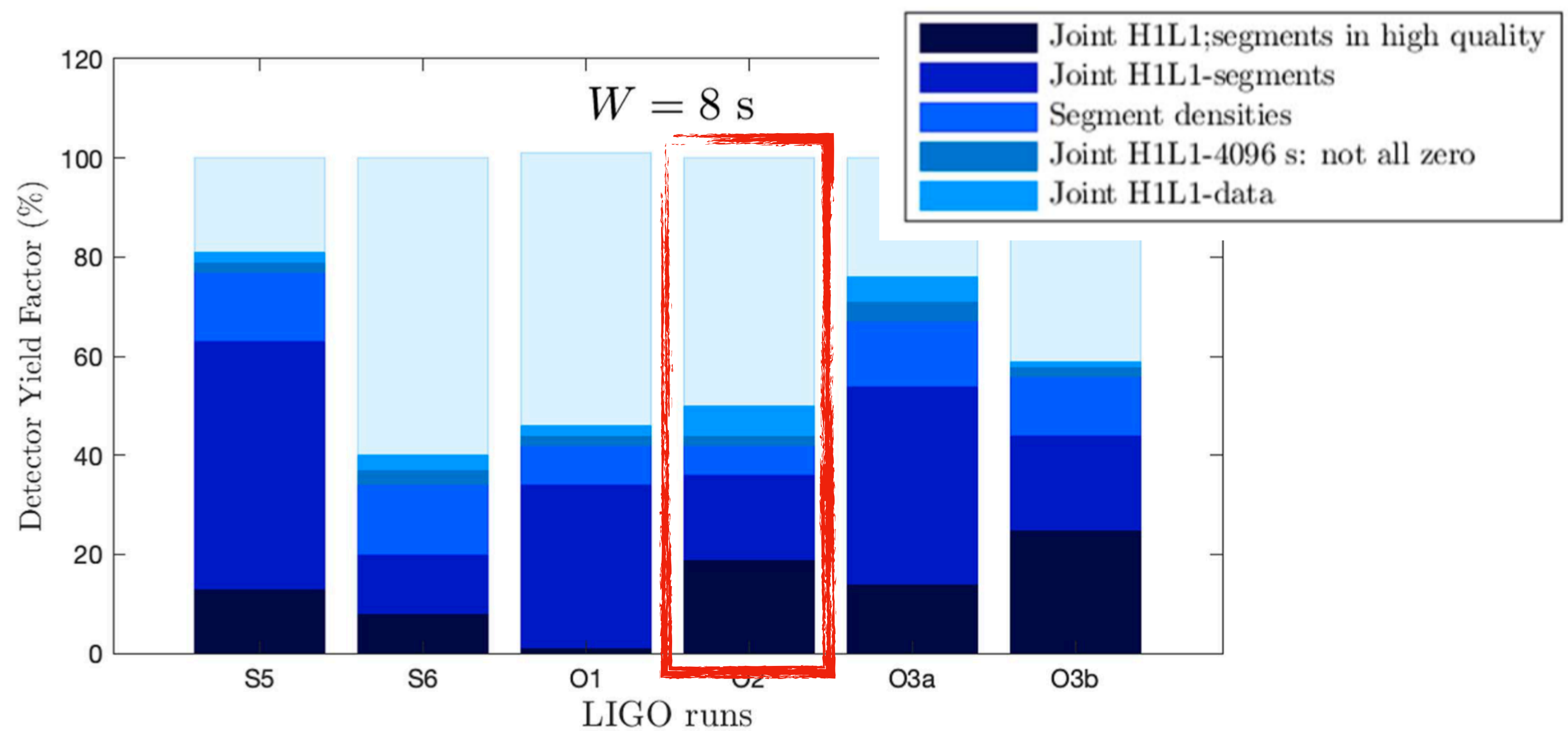
… for long-duration bursts

O2 was an exceptionally stable run for long-duration bursts



LH-detector yield y:

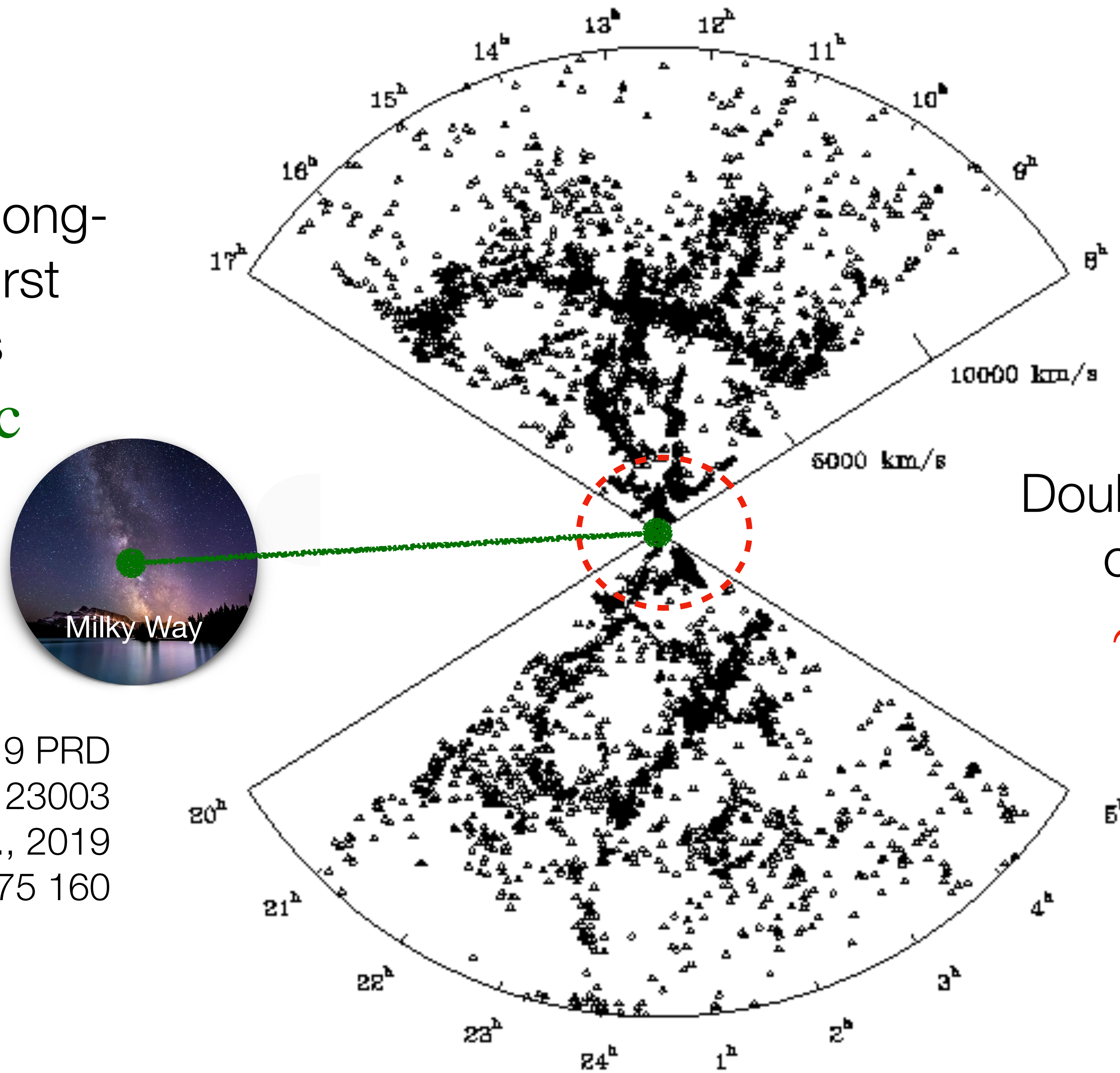
$$W = 8\,\mathrm{s}$$
$$B = 100 - 250\,\mathrm{Hz}$$



LVK horizon distances

Un-modeled long-duration burst searches

$\sim 1\,\mathrm{Mpc}$



Double neutron star coalescence

$\sim 100\,\mathrm{Mpc}$

Sun & Melatos 2019 PRD 99 123003

Abbott, B.P., et al., 2019 ApJ 875 160

Geller and Huchra 1989, Science 246, 897

… software versus hardware limited

LVK search horizon distances:

$$\text{un-modeled-to-CBC} = \frac{\text{galactic}}{\text{extragalactic}} < \frac{1}{40} \quad \text{(GW170817)}$$

Wait for third generation of detectors?

Abbott, B.P., et al., 2019
ApJ 875 160

Maybe not…

DATA ANALYS PROCEDURE

New procedure

Equal horizon distances:

un-modeled-to-CBC = 1

ascending-to-descending GW-chirps = 1

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

Butterfly Matched Filtering

Time-sliced FFT has sensitivity limited by time-frequency uncertainty relation $\tau\delta f = 1,\ \tau \simeq 1/\sqrt{\dot{f}}$:

Sensitivity scales with $\sqrt{N} \lesssim f^{\frac{1}{2}} \left|\dot{f}\right|^{-1/4}$

Butterfly MF over bank of time-symmetric chirp-like templates:

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

- Time-symmetric sensitivity to un-modeled signals on par with CBC
- gain = $\sqrt{\frac{N_n}{N_{FFT}}} \simeq \left(\frac{(n+2)!}{2}\Delta N^{\frac{n}{2}}\right)^{\frac{1}{2(n+2)}} \simeq 2.2\ (n=1)$
- Gain $= \sqrt{2}$ gain $\simeq 3.11$ for merged (H1,L1)-spectrograms

van Putten 2023 Universe 9 279

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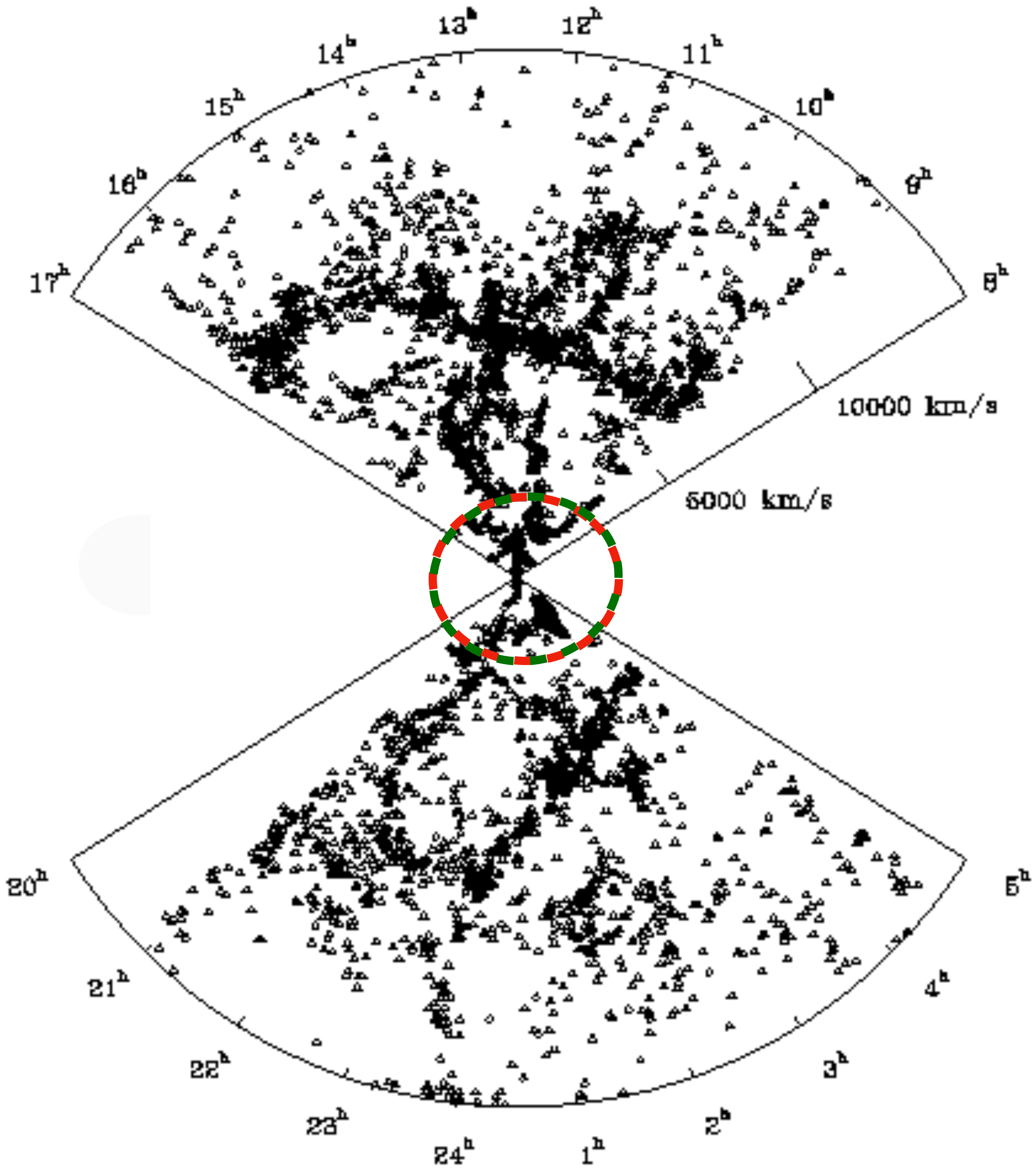
- Gain $= \sqrt{2}$ gain $\simeq 3.11$ for merged (H1,L1)-spectrograms

x2 is equivalent to a decade of improvement in detector sensitivity.

van Putten 2023 Universe 9 279

BMF extragalactic horizon distance



DNS and un-modeled long-duration burst searches

$\sim$ 100 Mpc

Validated by detailed benchmarking

van Putten & Della Valle **2023** A&A 669 A36

Abchouyeh, van Putten & Amati **2023** ApJ 952 157

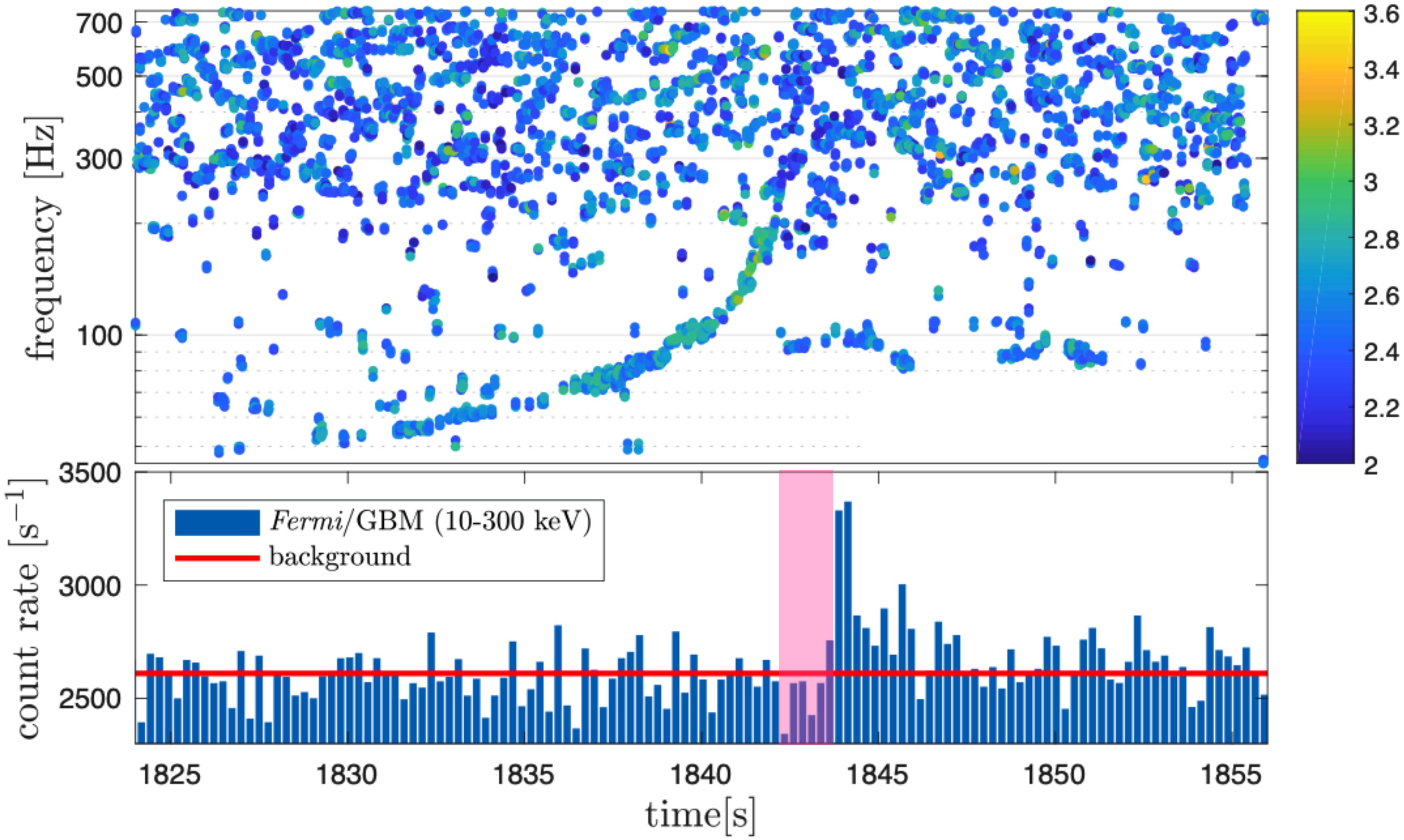
van Putten **2023** Universe 9 279

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

:hra 1989, Science 246, 897

FINDINGS

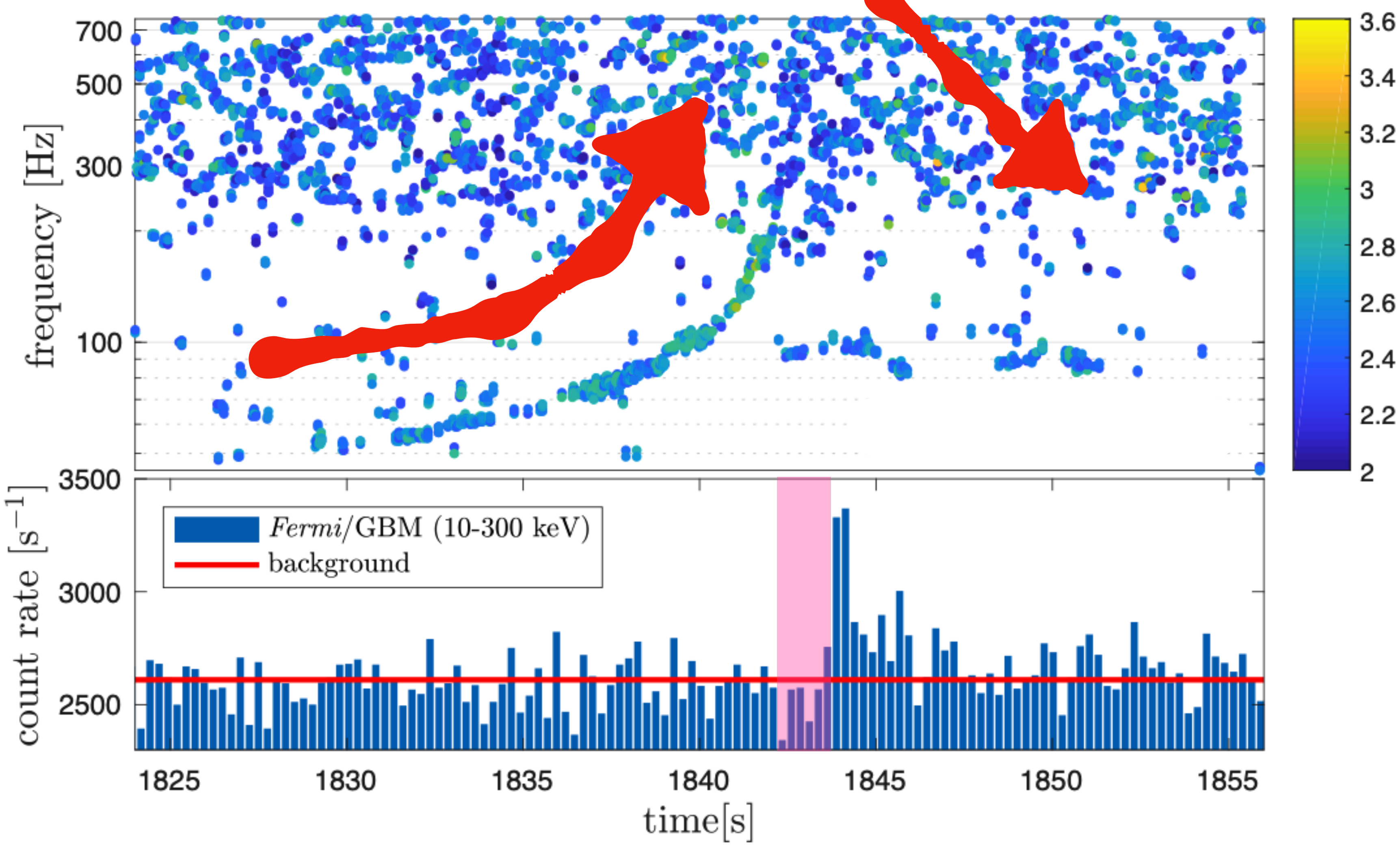
GW170817



van Putten & Della Valle 2019 MNRAS 482 L46

GW170817 - GW170817B

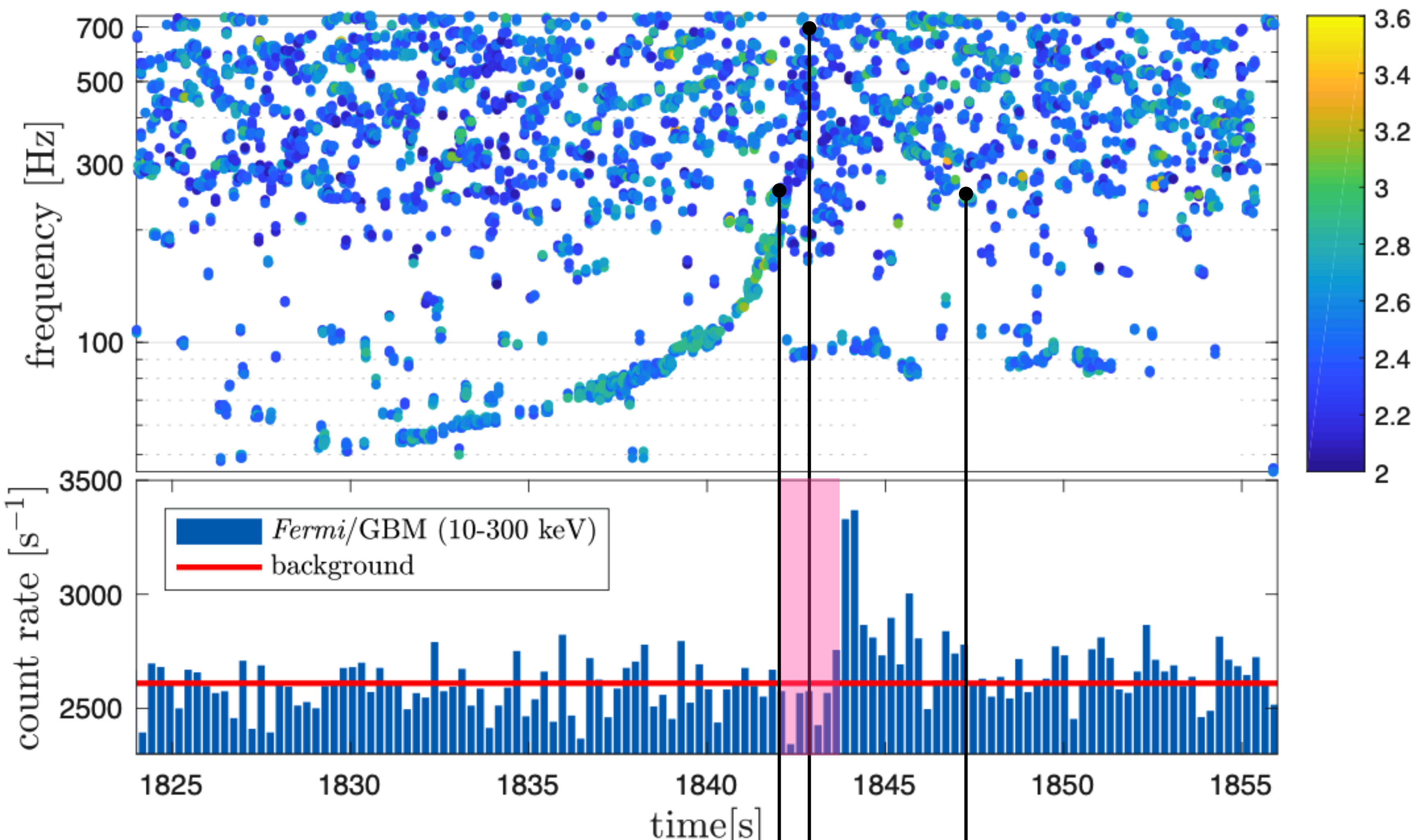
$$G_1 - C_4^{\#} \qquad F_5 - G_3^{\#}$$



van Putten & Della Valle 2019 MNRAS 482 L46

… high-resolution event timing

$\mathcal{E}_{GW} \simeq 3.5\ \%\ M_\odot c^2$ exceeds E_J^{HMNS} by 4x



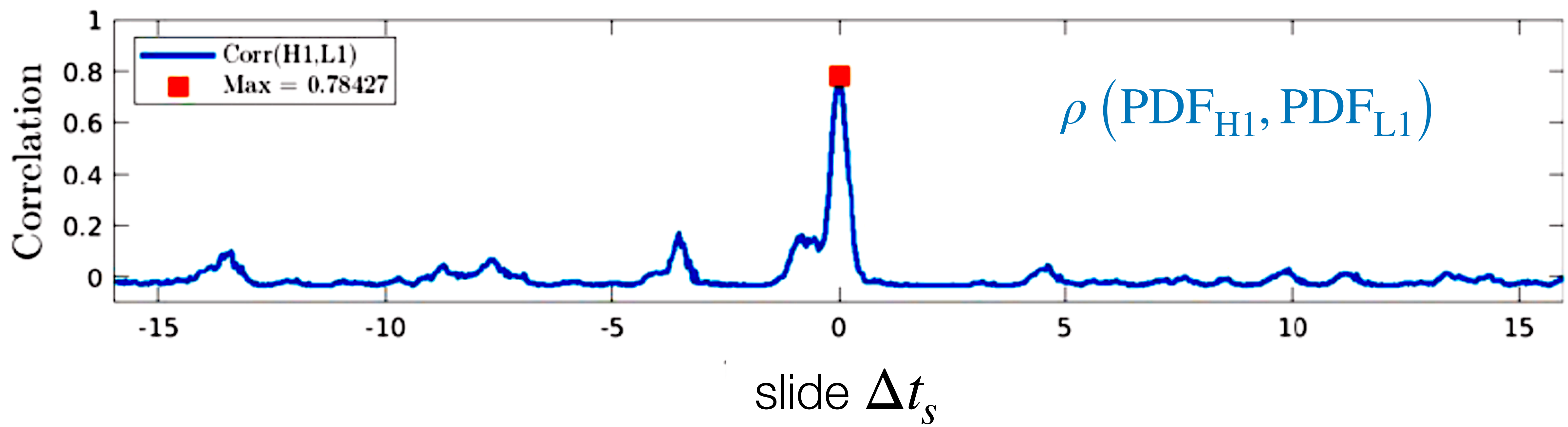
van Putten & Della Valle
2019 MNRAS 482 L46

$t_{delay} = 0.92$s 3.7s $T_{GW170817B} = 3.7$ **s**

PFA from high-resolution event timing

Unitary transformation (H1,L1):

$$\begin{pmatrix} \text{Causality } \bar{t}_s \,\epsilon \text{ gap} \\ \text{Consistency by } \Delta t_s \end{pmatrix} \sim \mathscr{R}_{\frac{\pi}{4}} \begin{pmatrix} t_{s,\mathrm{H1}} \\ t_{s,\mathrm{L1}} \end{pmatrix}$$



$$\mathrm{PFA} = \mathrm{PFA}_1 \times \mathrm{PFA}_2 \lesssim \frac{1.7}{2048} \times \frac{0.1}{2048} = 4.1 \times 10^{-8}$$

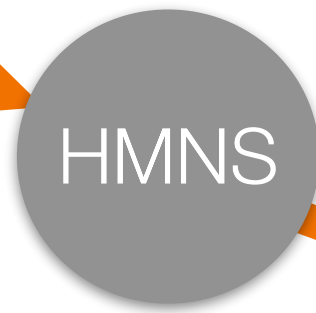
Z-score 5.5

DNS to HMNS

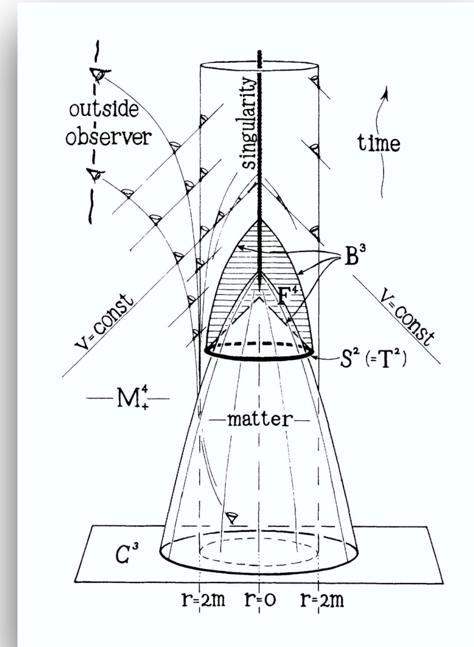
HMNS

→ kilonova AT2017gfo

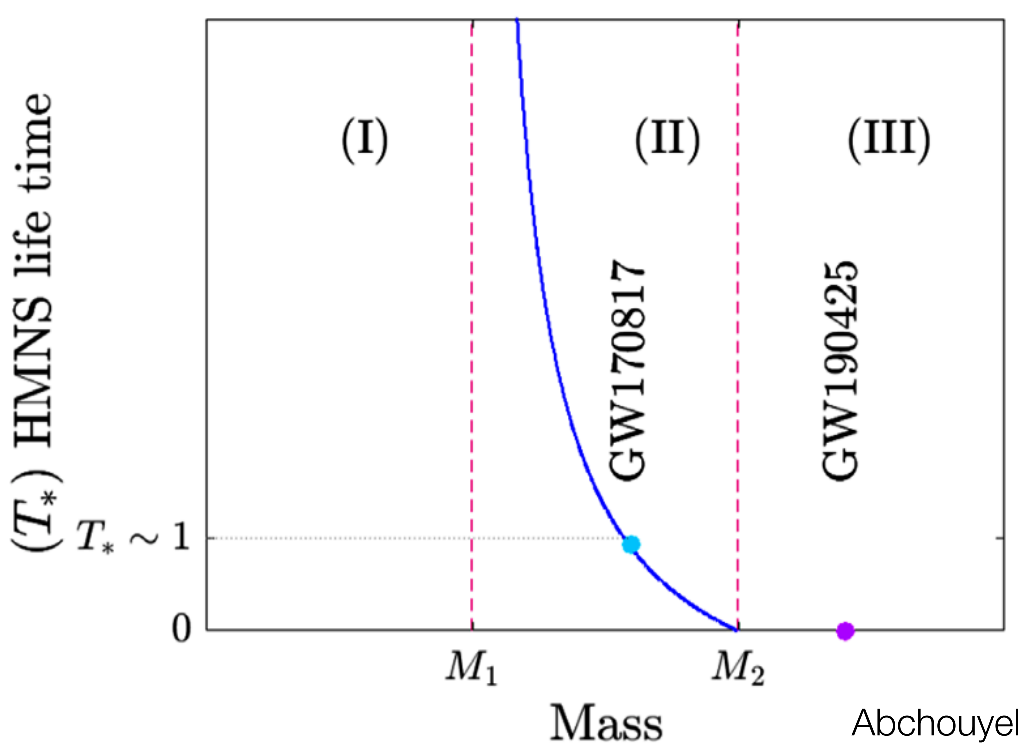
Collapse to a Kerr black hole



(0.92 ± 0.08) s

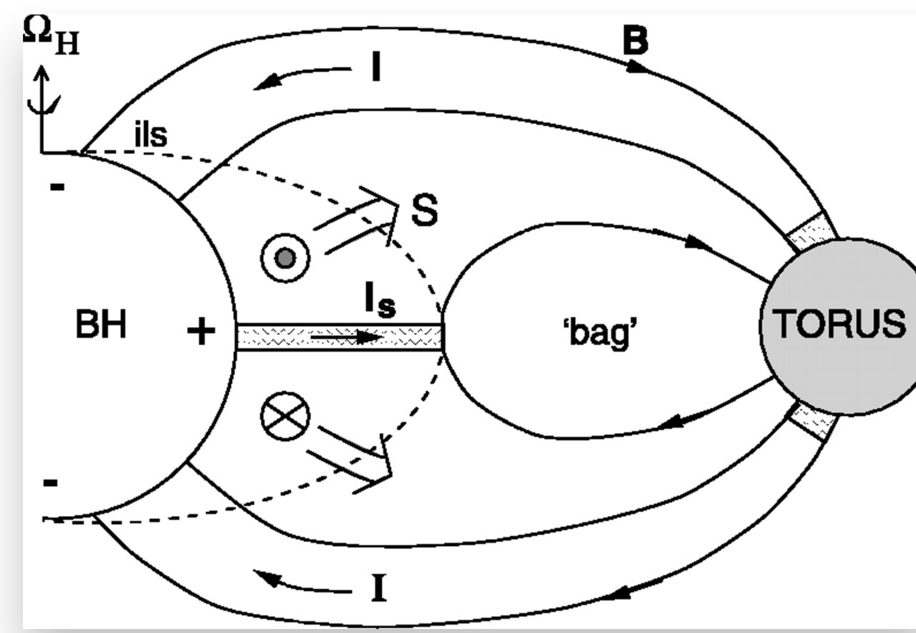


R. Penrose



Abchouyeh, van Putten, Amati, 2023, ApJ, 952, 157

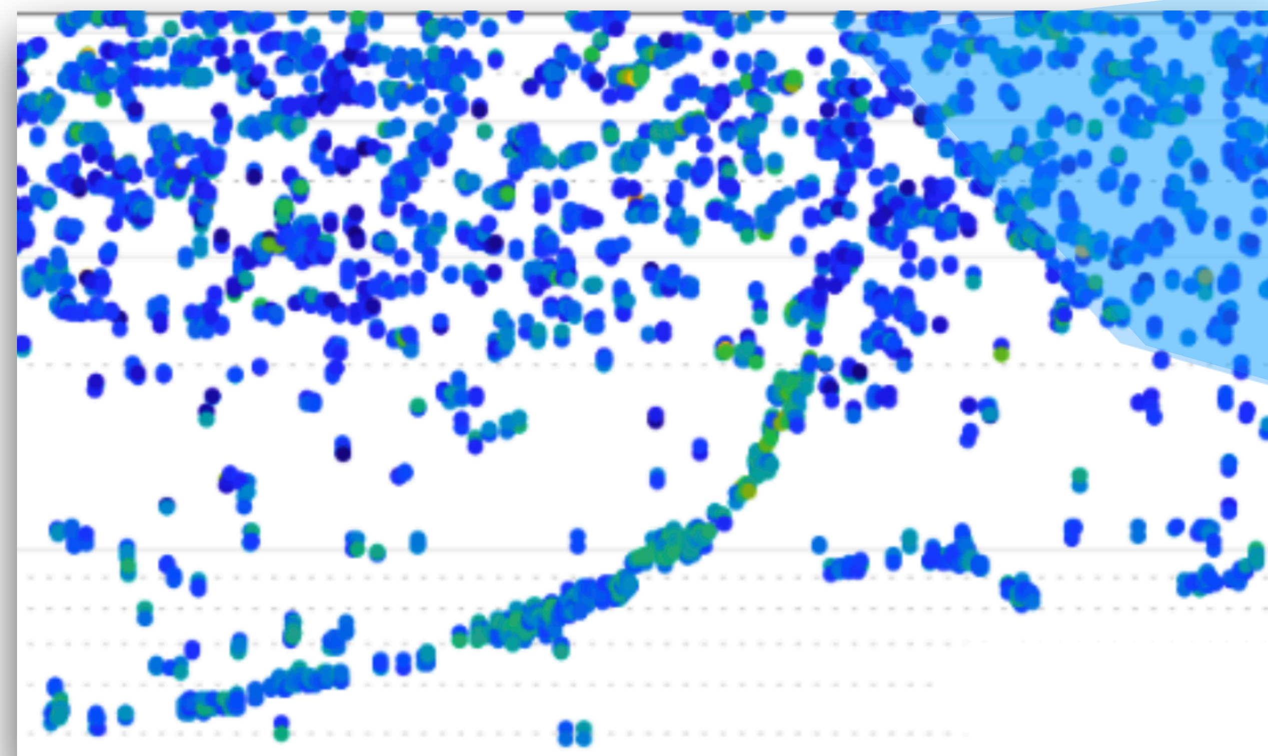
Rejuvenation in E_J



van Putten, 1999, Science, 284, 115

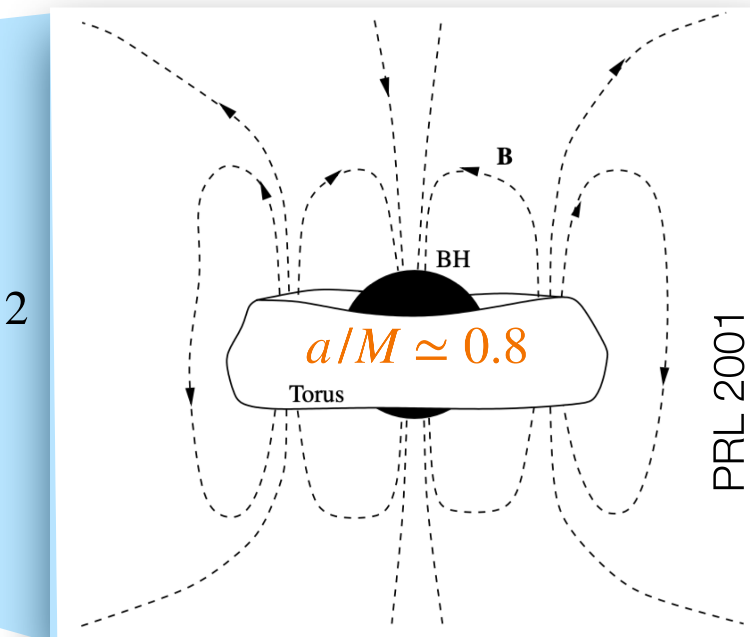
GW170817B

$$F_5 - G_3^{\#}$$



van Putten & Della Valle (2019)

$$\mathscr{E}_{GW} \simeq 3.5\,\%\,M_{\odot}c^2$$

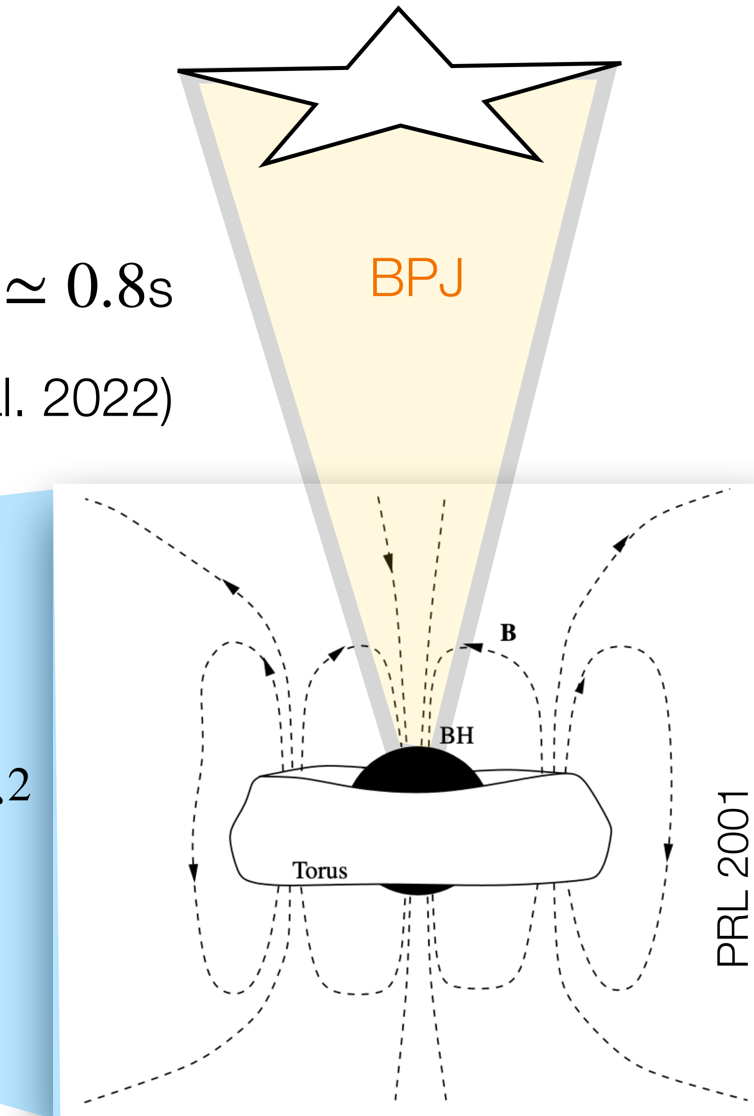


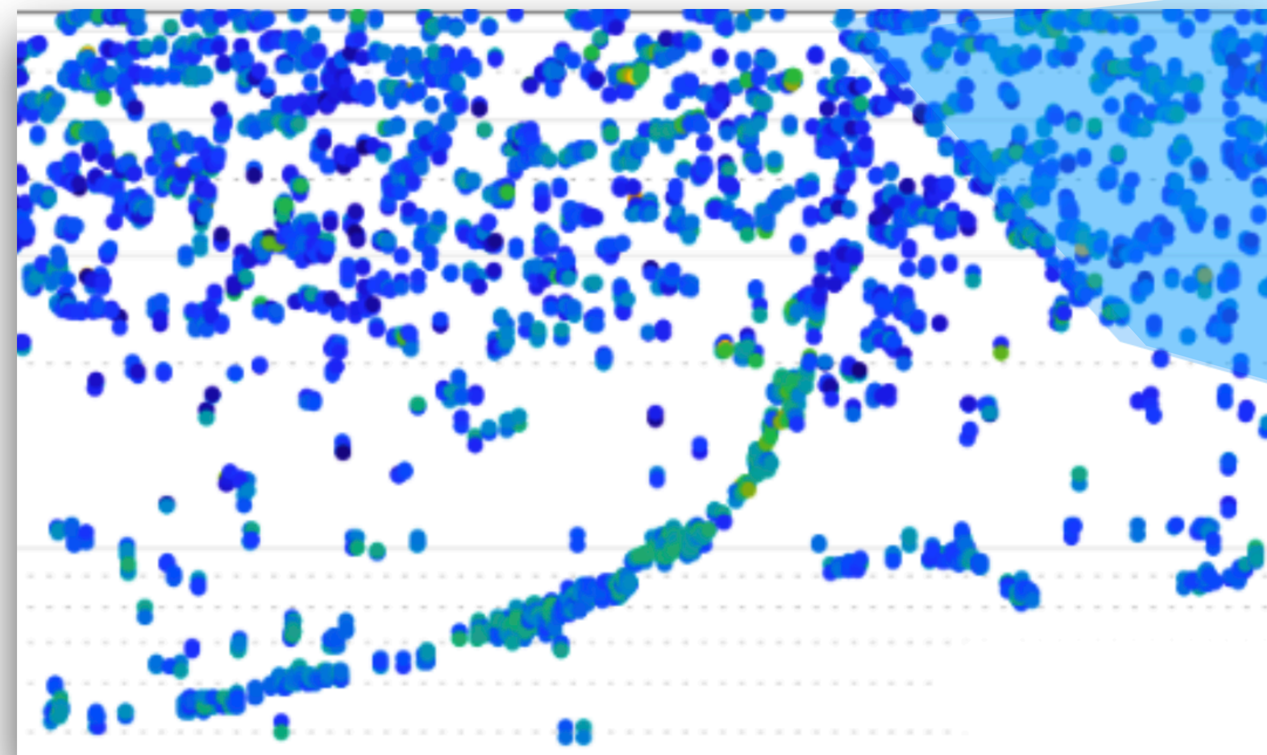
Radiative cooling mostly in GW-emission (PTP 2012)

GW170817B - GRB170817A

$$\Delta t_{GRB} = \left(t_{gap} - t_{delay}\right) \simeq 0.8\text{s}$$

$\Gamma \simeq 70,\ \theta \simeq 20^0$ (Mooley et al. 2022)





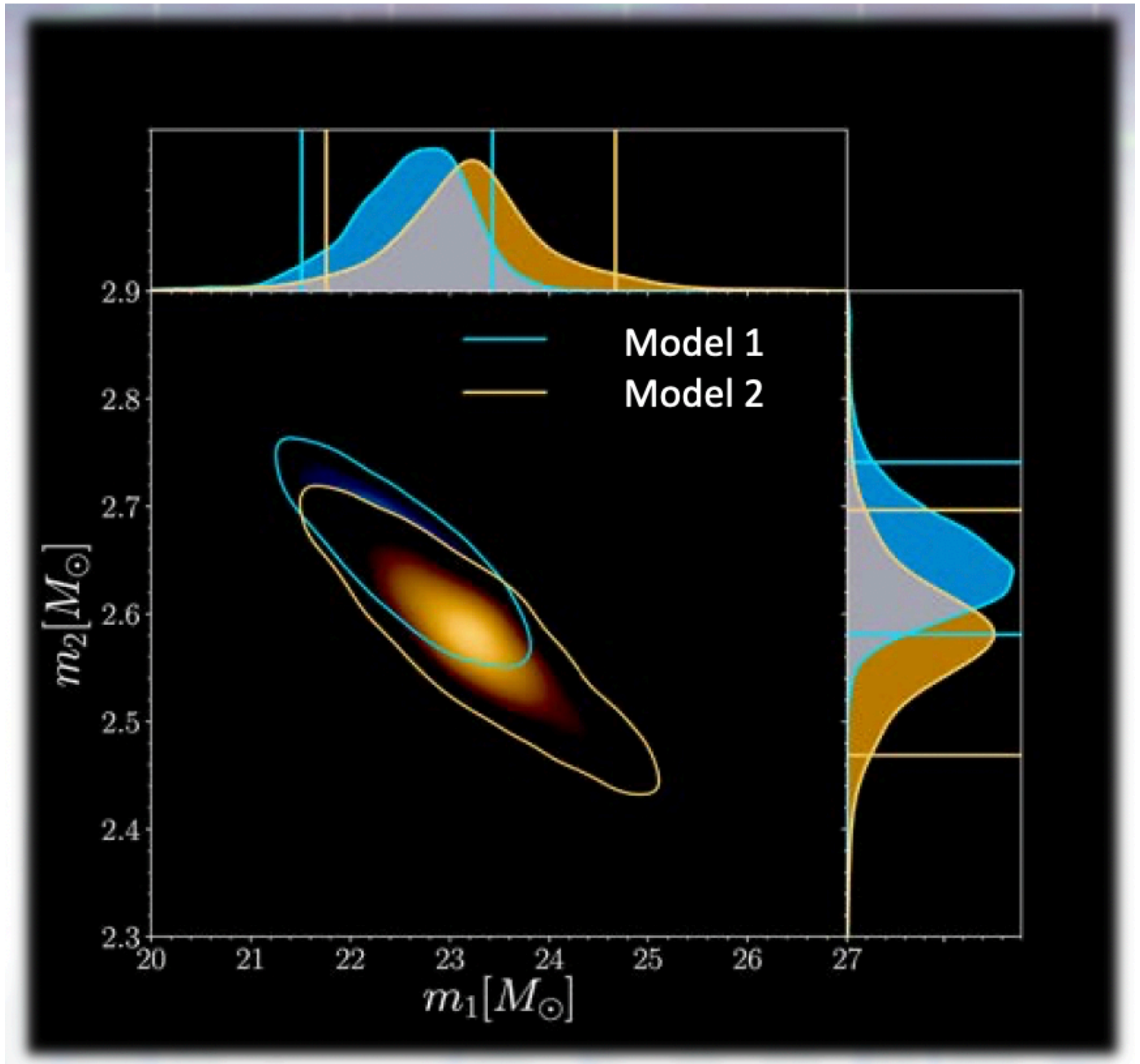
van Putten & Della Valle (2019)

$$\mathscr{E}_{GW} \simeq 3.5\,\%\,M_\odot c^2$$

Radiative cooling mostly in GW-emission (PTP 2012)

$$D \text{ radiative front to source: } \frac{c\Delta t_{GRB}}{1-\beta\cos\theta} \simeq 0.03\ \text{AU}$$

O3: GRB190814 (D = 240 Mpc)



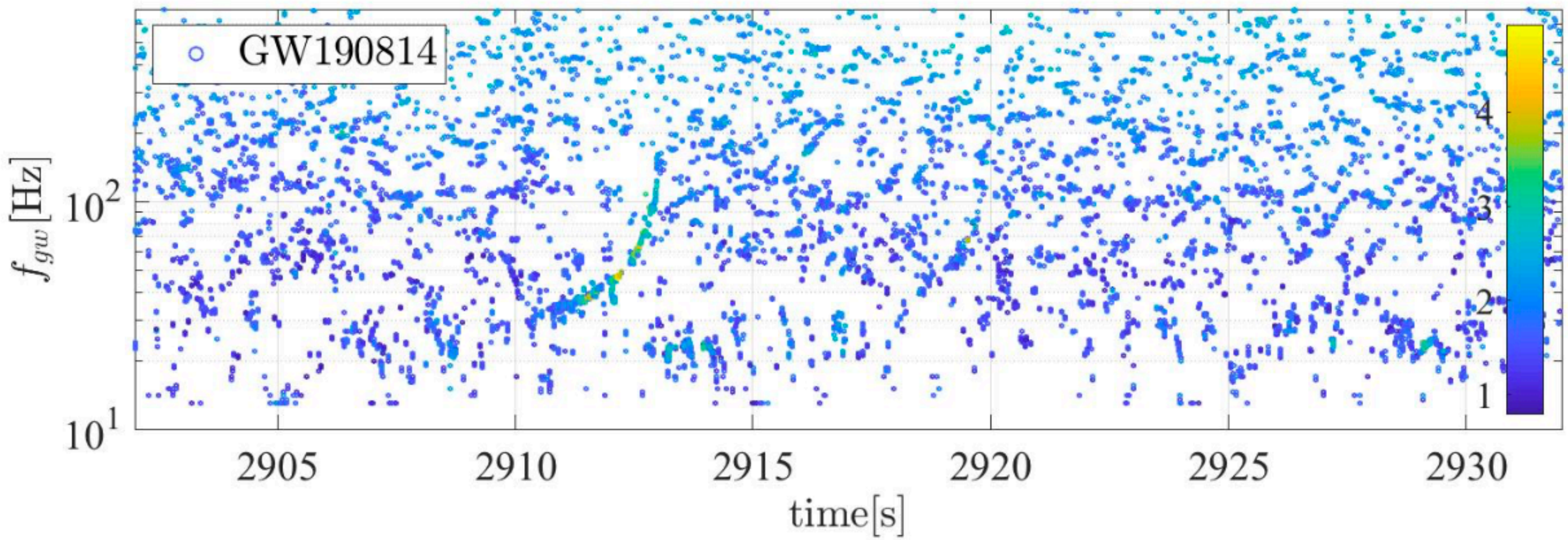
R. Ewing, R. Huxford*, D. Singh**
*The Pennsylvania State University

Unresolved

BH companion: NS/low-mass BH?

Post-merger drama?

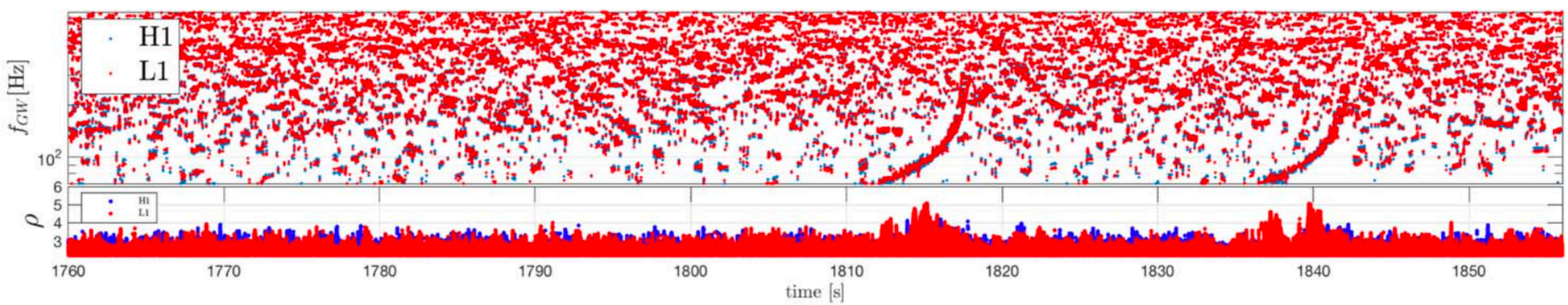
GRB190814 - *too far out for O3 detector sensitivity …*



$D \simeq 40$ Mpc (O2)

Injection

GW170817(B)



van Putten, 2020, LVC Burst Meeting; based on van Putten, Della Valle & Levinson, 2019, ApJ, 876, L2

CONCLUSIONS

Central engine GRB170817A

GRB170817A

"If gravitational waves are detected from one or more gamma-ray burst triggers, the waves will almost certainly reveal the physical nature of the trigger."

Cutler & Thorne, 2002, arXiv:0204090v1

Kerr Fest 2004 (ChristChurch)

To Roy Kerr:

Congratulations with the 60th anniversary of your Kerr solution.

In $F_5 - G_3^\#$ (GW170817B), for the first time, the Kerr solution appears as an object in Nature by its large spin-energy.

van Putten & Levinson 2002 Science 295 1874

Stay tuned for new DNS and NS-BH during O4-5