# Treasures of the deep: GW-observation of black hole-spin down at 5.5 sigma

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van Putten & Della Valle, 2022, A&A, in press

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# Contents

GW170817

Abbott et al. 2017

Ascending merger chirp in GWs

- Double neutron star merger GW170917-GRB170817A
- Ascending-Descending chirp in gravitational radiation

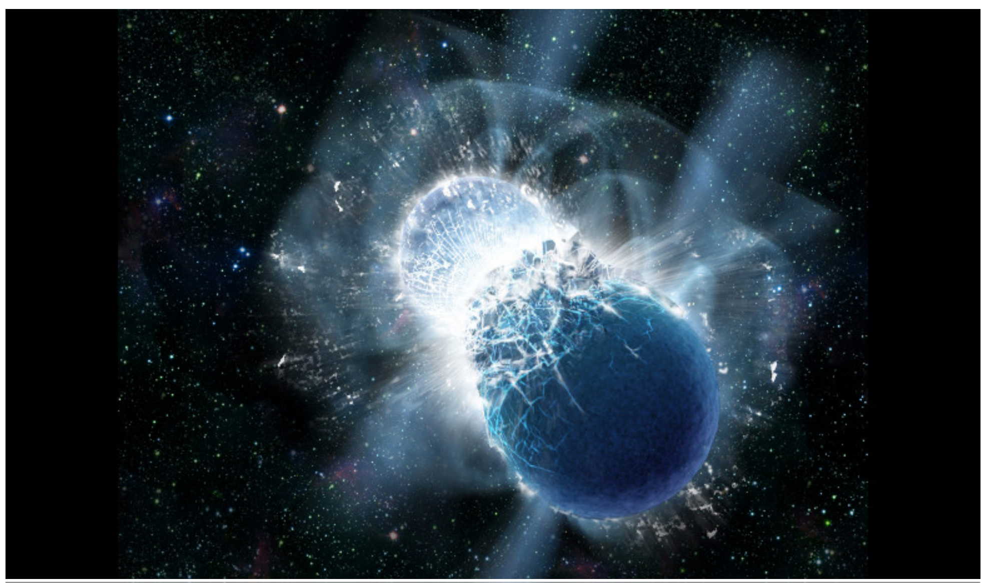
  Event timing on GW170817 sequence
  PFA and consistency in EM-GW timing

- Conclusions
- Outlook

  Astrophysics
  HPC at the horizon

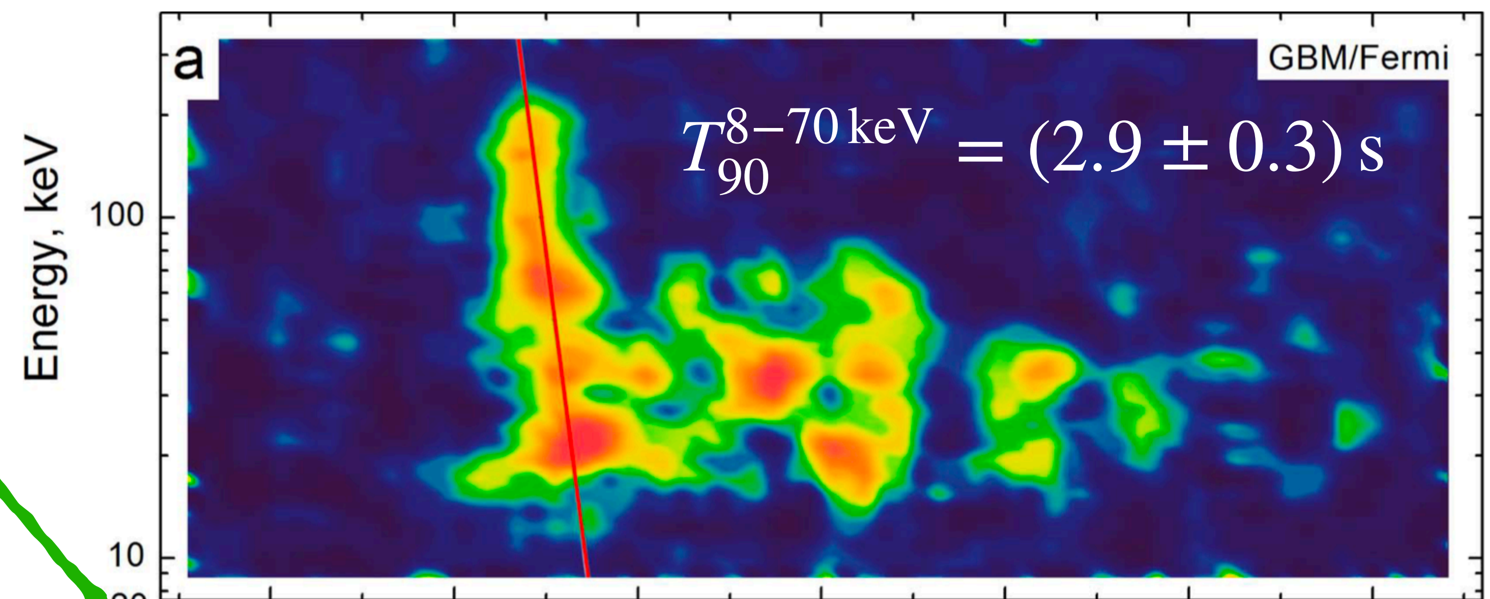
# GW170817-GRB170817A

GW170817



Abbott et al. 2017

GRB170817A




(Pozanenko et al. 2018)

$$t_{gap} = 1.7\ \mathrm{s}$$

# Central challenge

GW170817

Abbott et al. 2017

SN1987A

NS or BH?

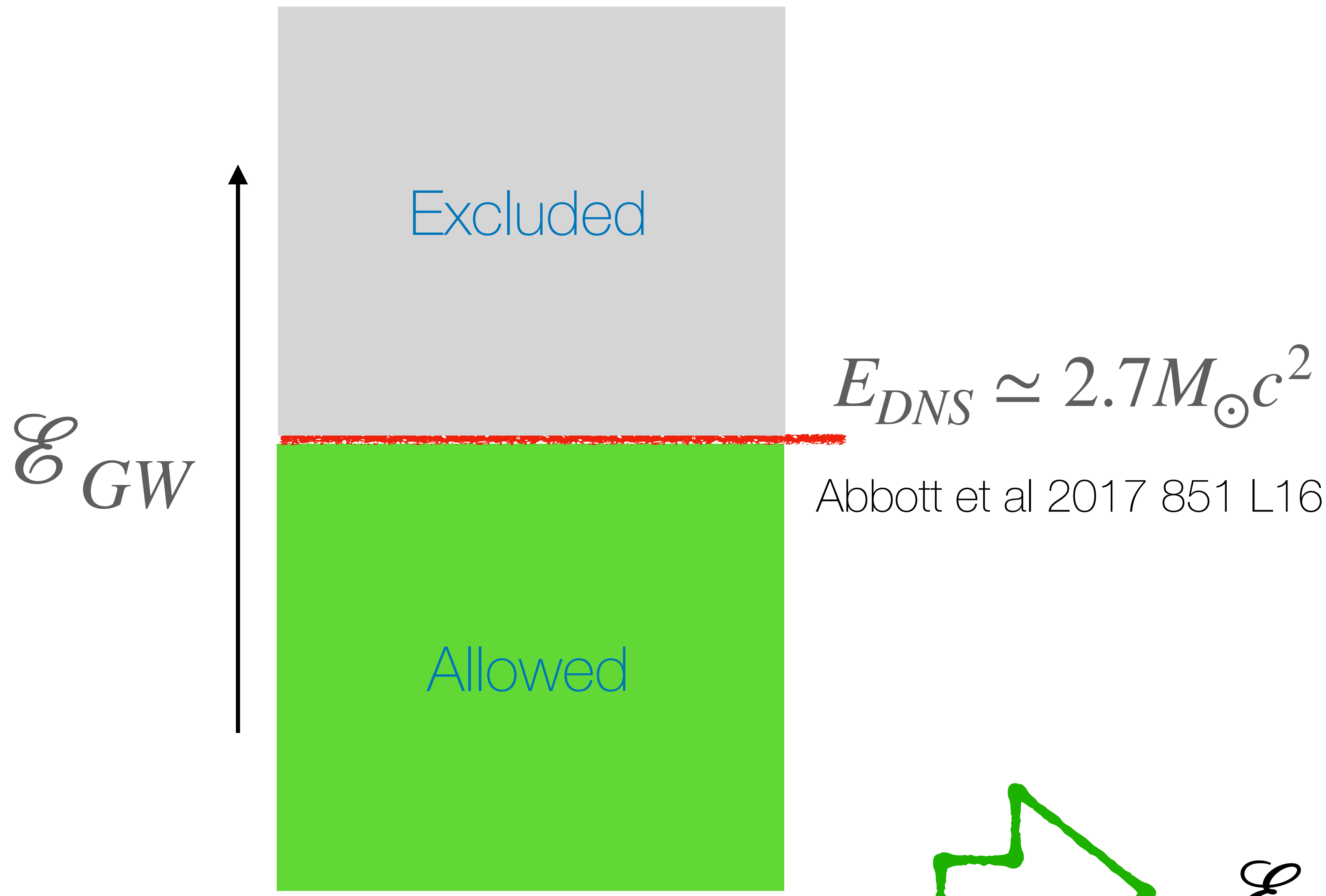
Central engine GRB170817A?

Remnant SN1987A?

Absent a pulsar, what sets a BH apart from a NS central engine?

# Multi-messenger radiation channels

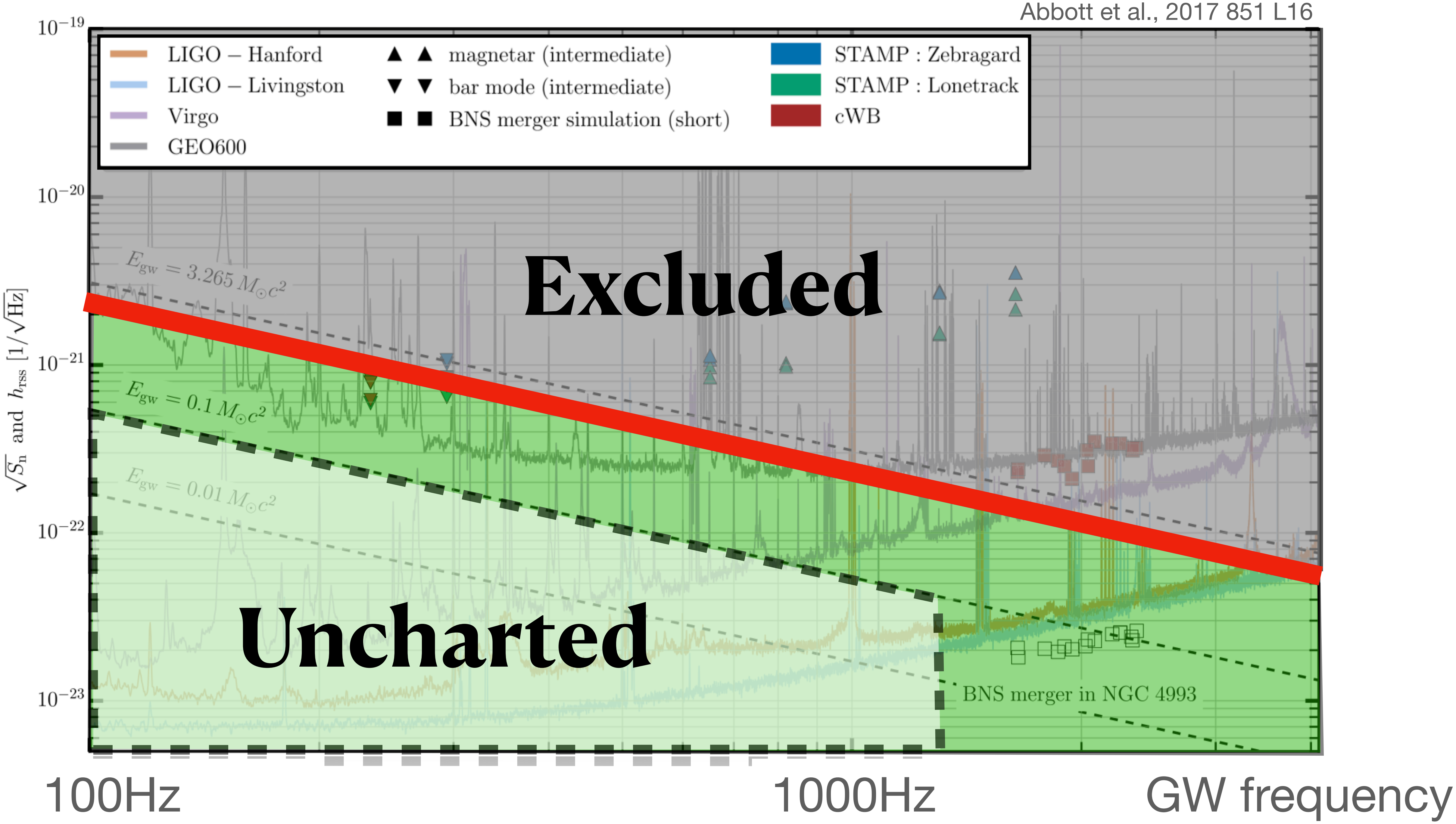
$i = \mathrm{EM}, \nu, \mathrm{GW}, \text{mass ejecta:}\ \ \mathscr{E}_i \leq \sum \mathscr{E}_k \leq E_{DNS} - E_{remnant} \leq E_{DNS}$



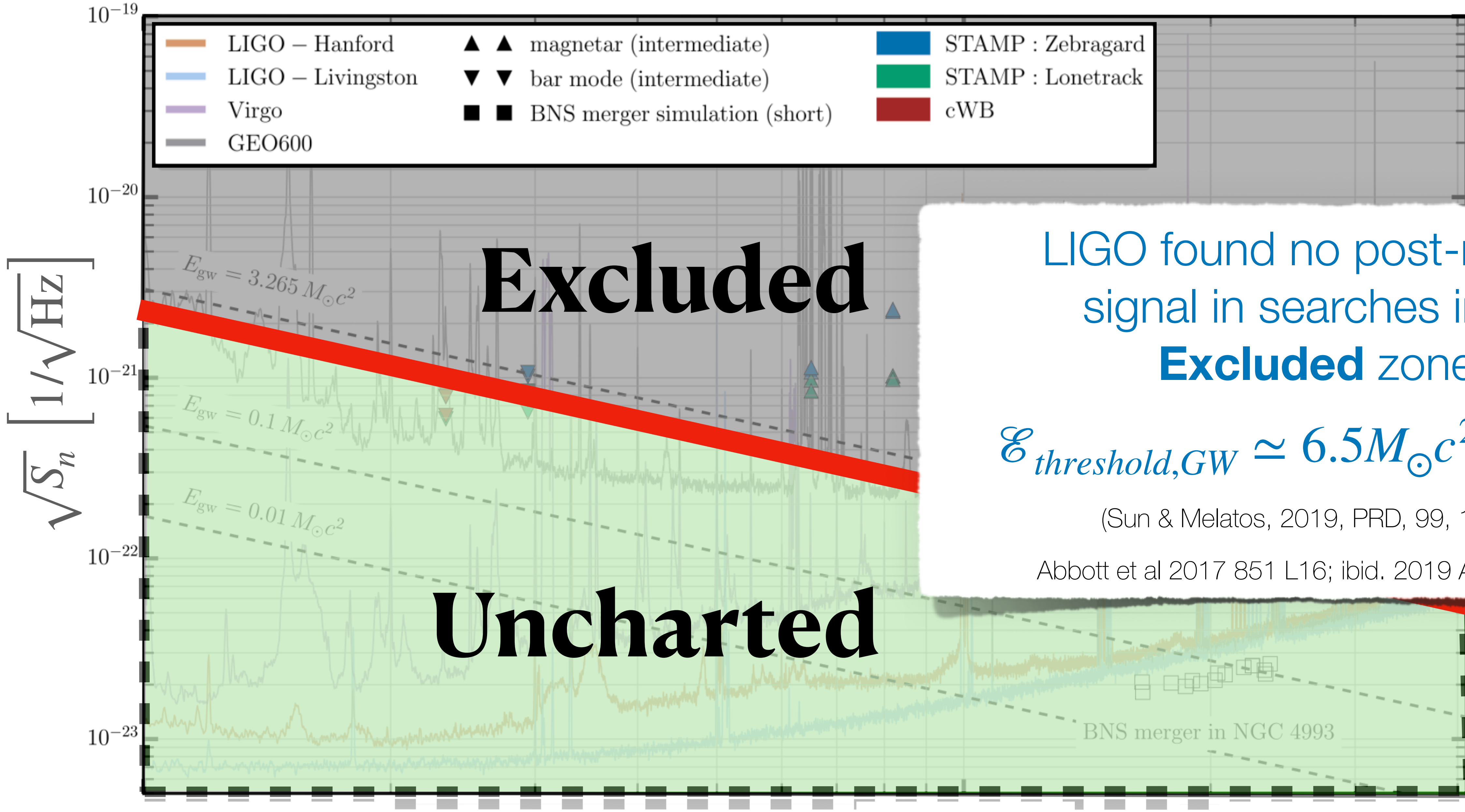

$$\mathscr{E}_{GW} \leq E_{DNS}$$

# ... search domains

Abbott et al., 2017 851 L16



# … LIGO searches for long-lived remnants




100Hz 1000Hz GW frequency

LIGO found no post-merger signal in searches in the **Excluded** zone:

$$\mathcal{E}_{threshold,GW} \simeq 6.5 M_\odot c^2 \gg E_{DNS}$$

(Sun & Melatos, 2019, PRD, 99, 123003

Abbott et al 2017 851 L16; ibid. 2019 ApJ 875 160)

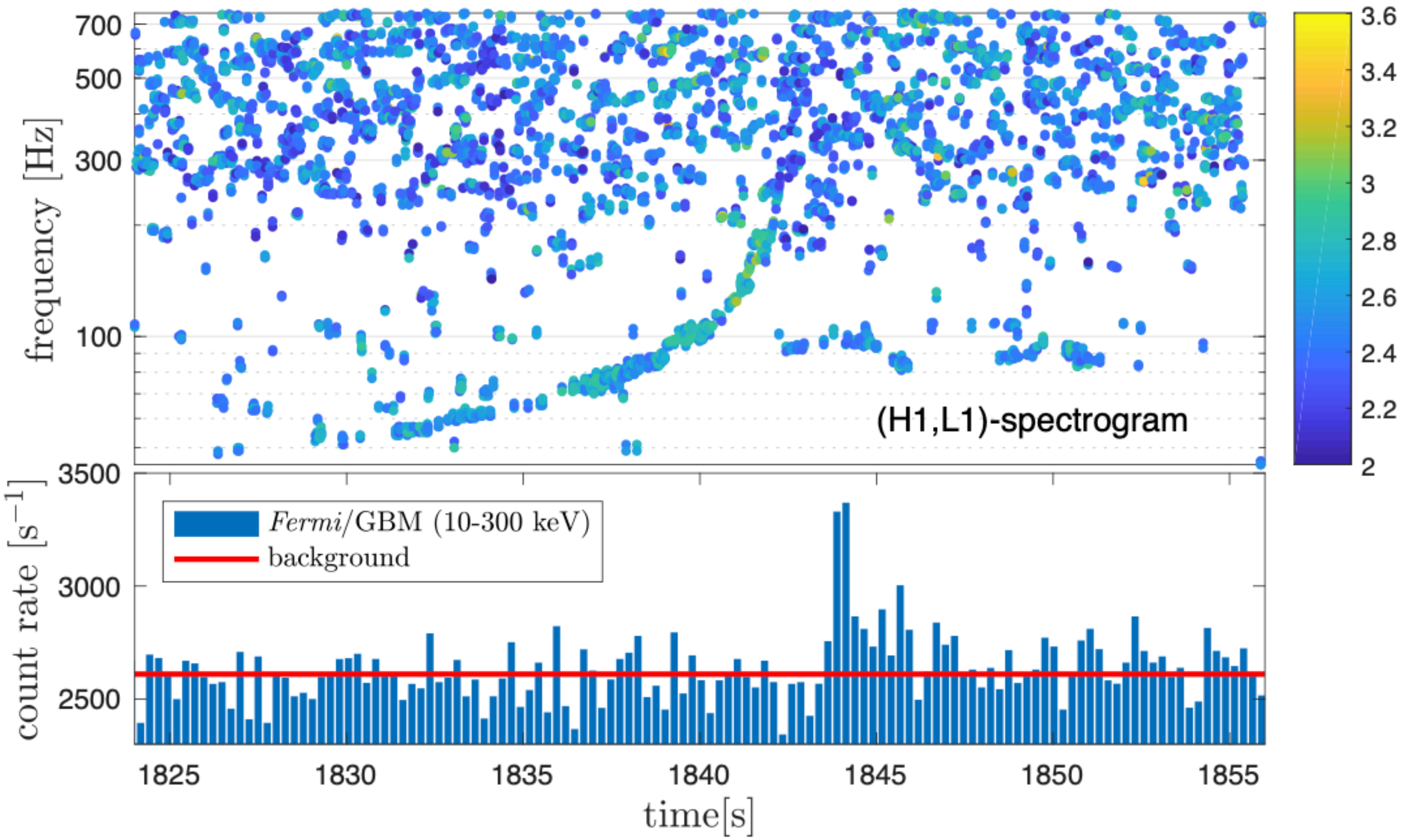
# Time-symmetric data-analysis

Matched filtering over **time-symmetric** templates:
*butterfly matched filtering*:

$$\frac{\text{Sensitivity descending branches}}{\text{Sensitivity ascending branches}} \equiv 1$$

Equal sensitivity to gravitational radiation from spin-up in binaries and spin-down of compact objects

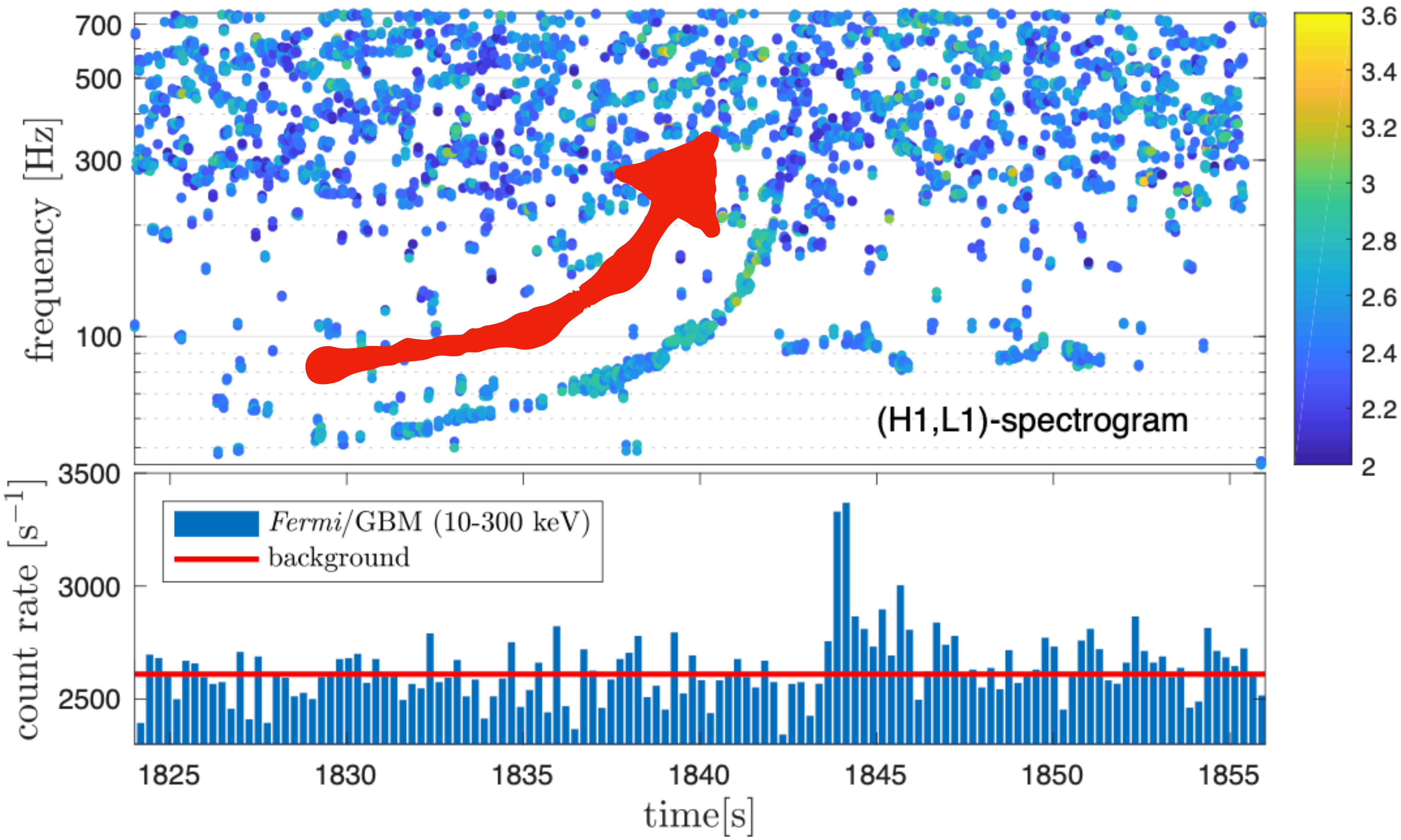
# Ascending-descending chirp




van Putten & Della Valle 2019 MNRAS 482 L46

*"A seconds-long post-merger signal candidate was reported by van Putten & Della Valle (2018), with an estimated GW energy lower than the sensitivity estimates of Abbott et al. (2017g)."* (Abbott et al 2019 ApJ 875 160)

# Ascending-descending chirp

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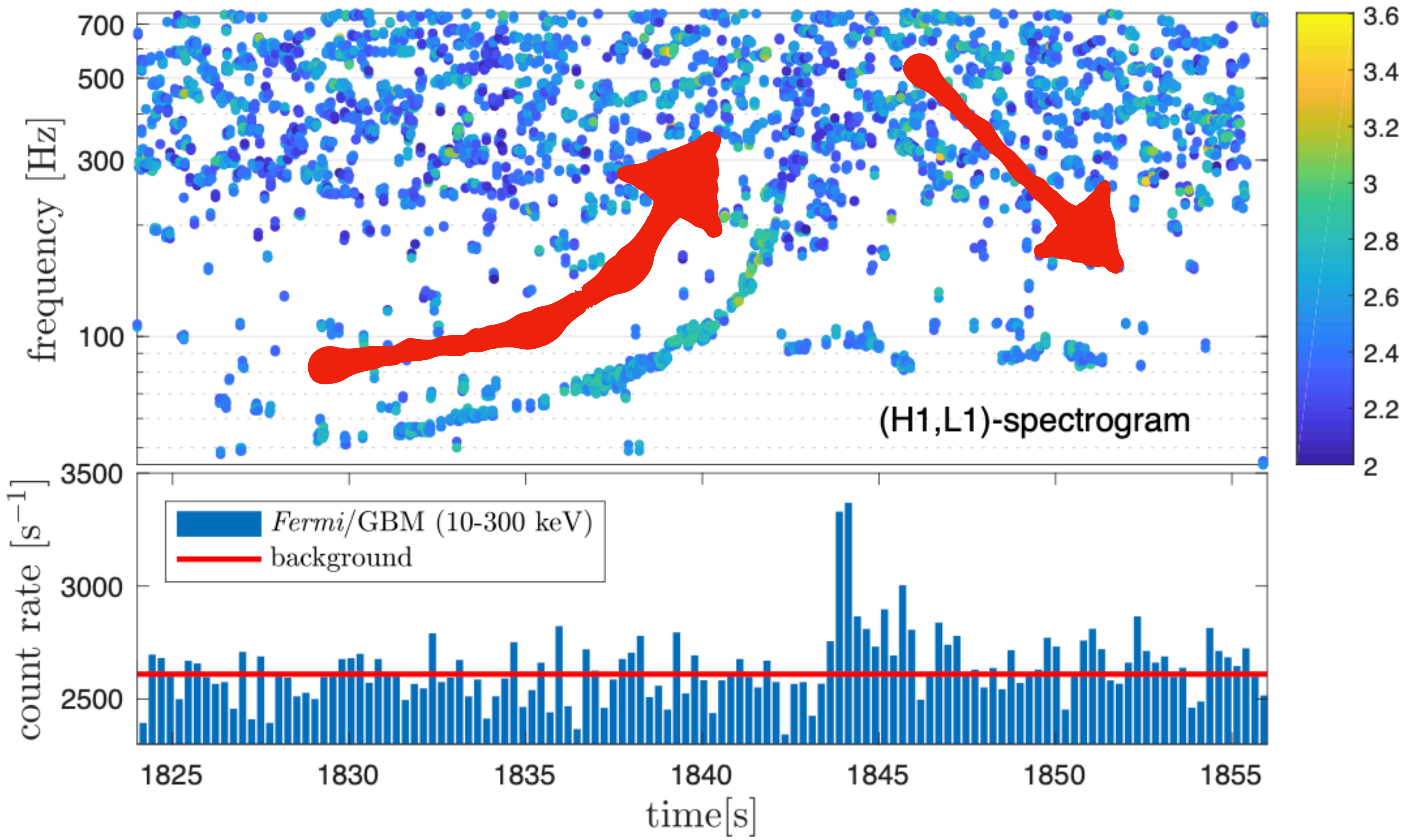


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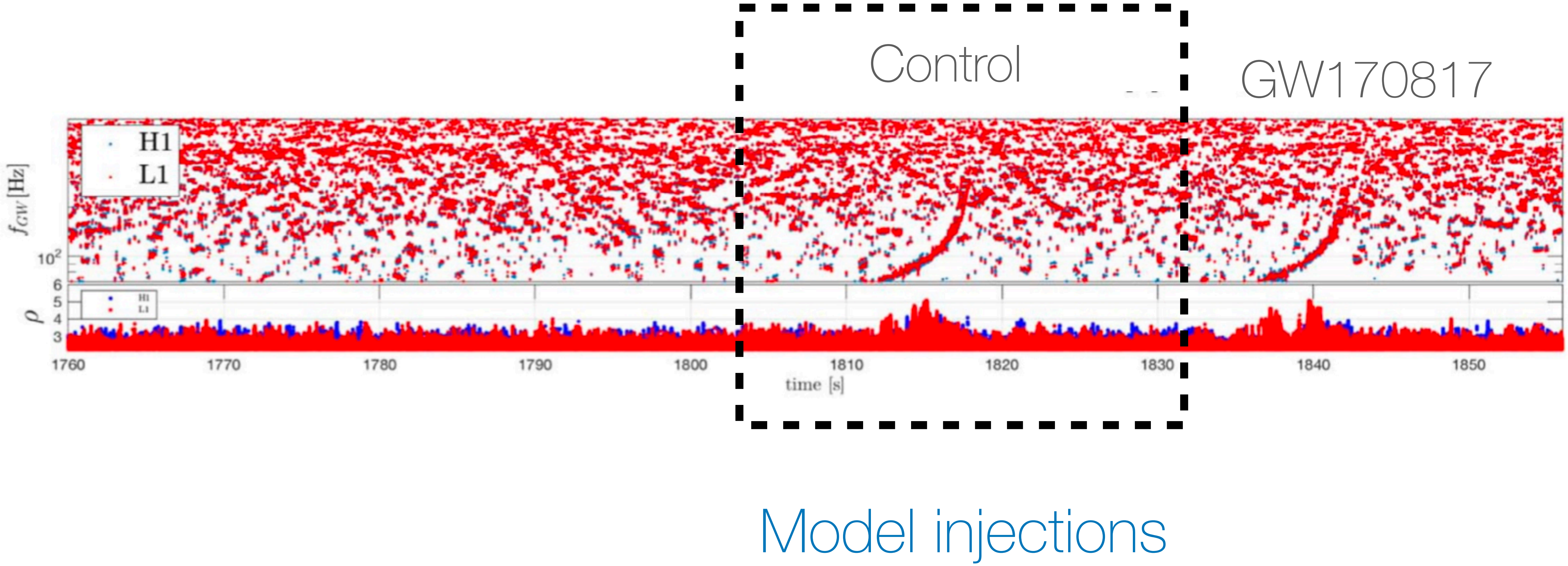
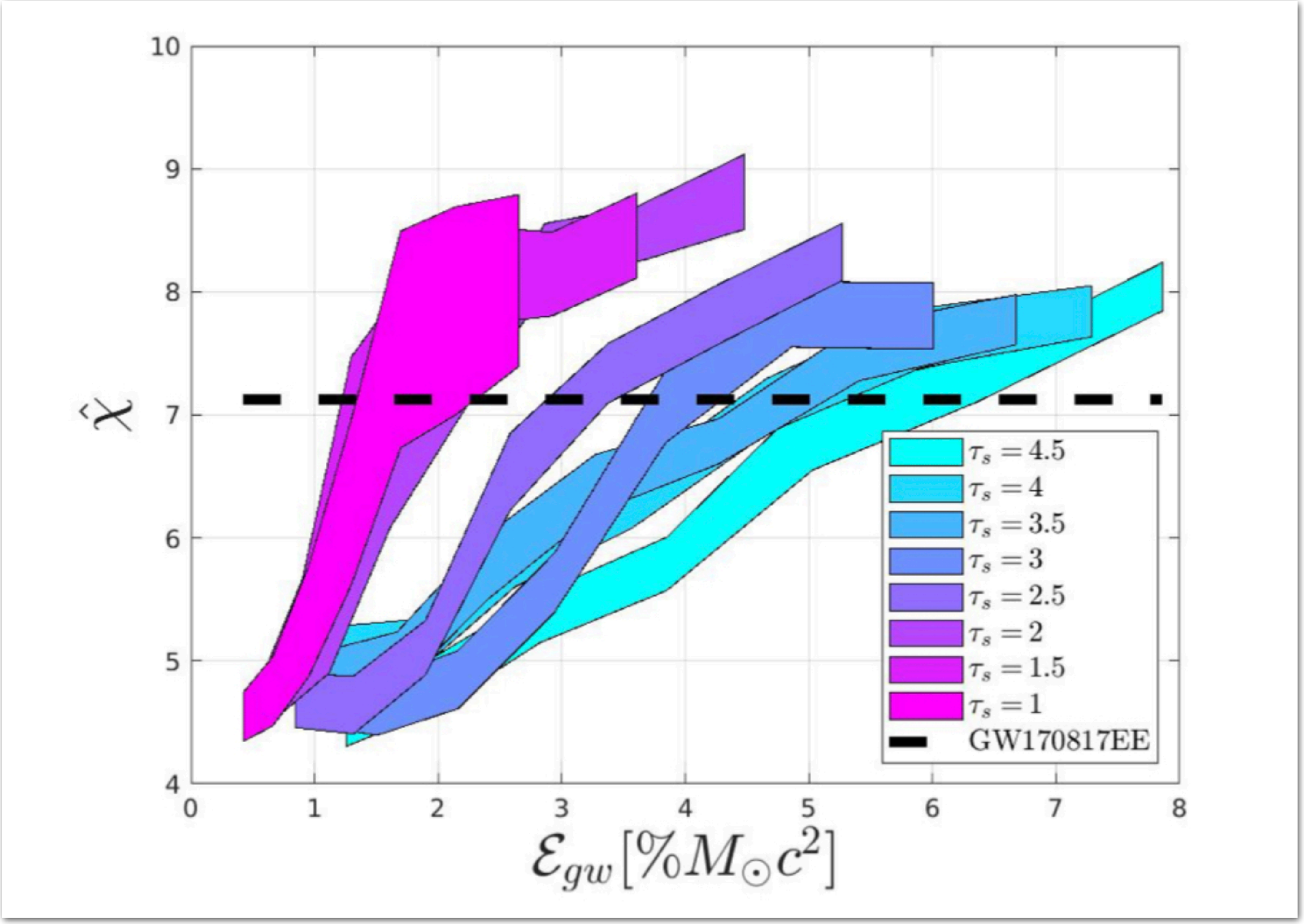
# Calibration by software injections



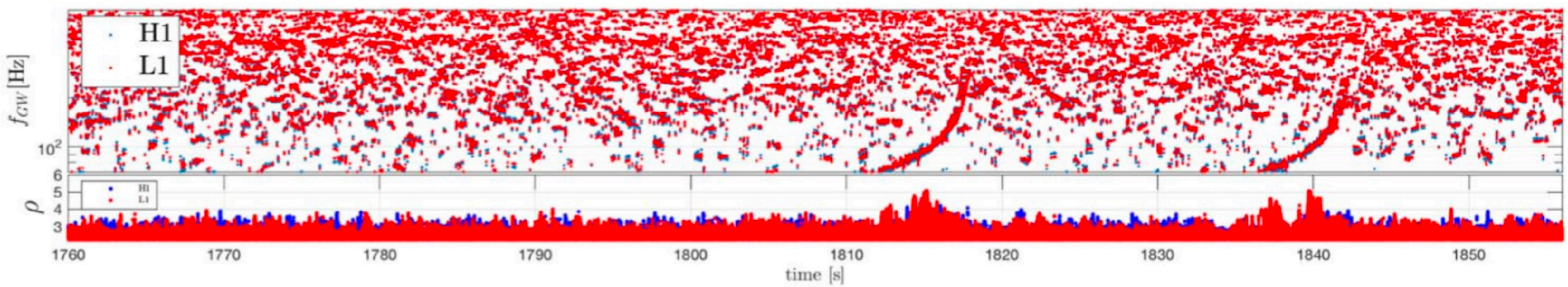
# Response curves descending chirp

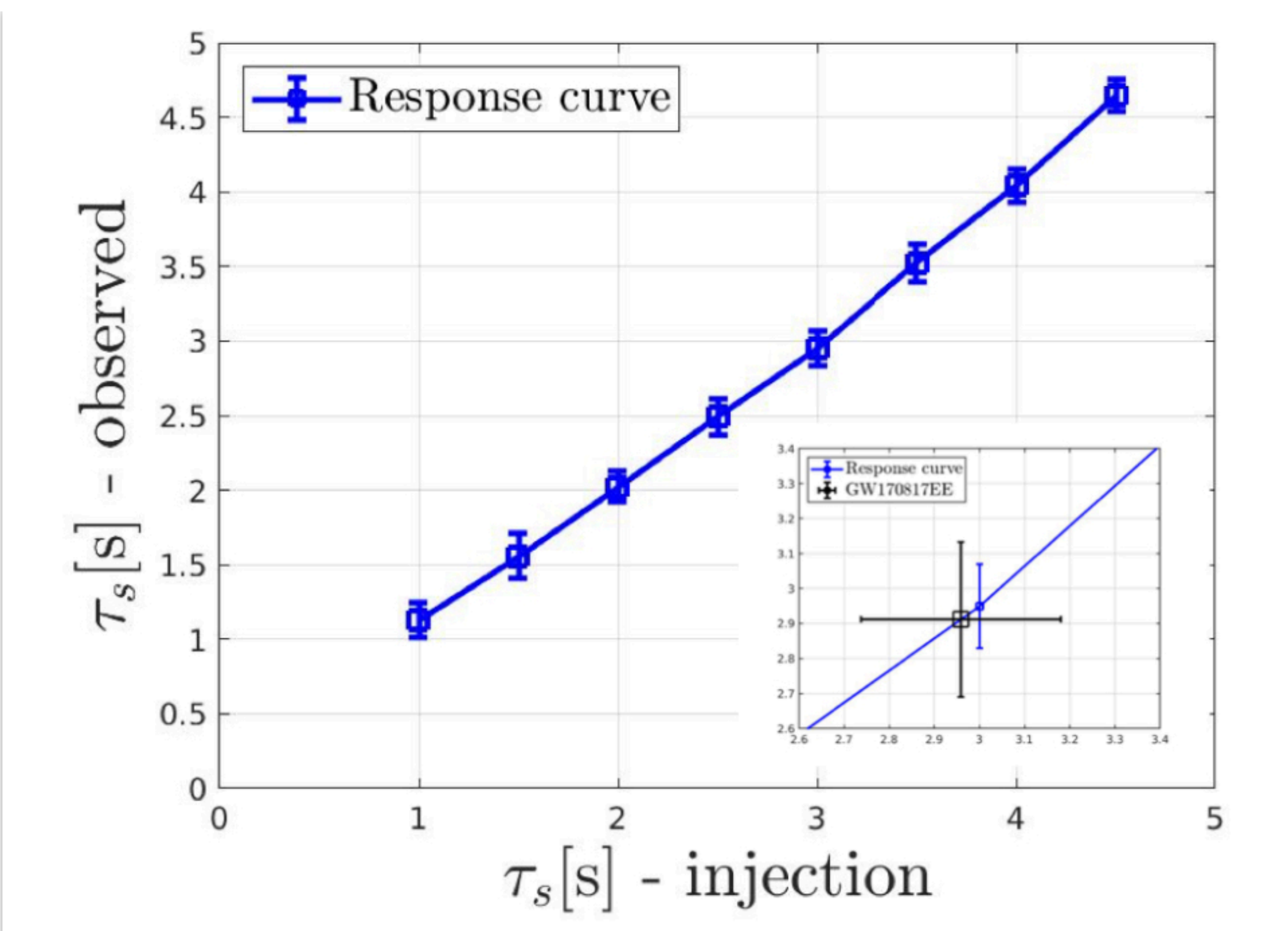


# GW-calorimetry (I)

*Matching*

Control GW170817




$$\mathscr{E}_{GW} = \left(3.5 \pm 1\right) \% \, M_\odot c^2$$

$$\tau_s = (3.0 \pm 0.1)\,\mathrm{s}$$

cf. $T_{90}^{8-70\,\mathrm{keV}} = (2.9 \pm 0.3)\,\mathrm{s}$

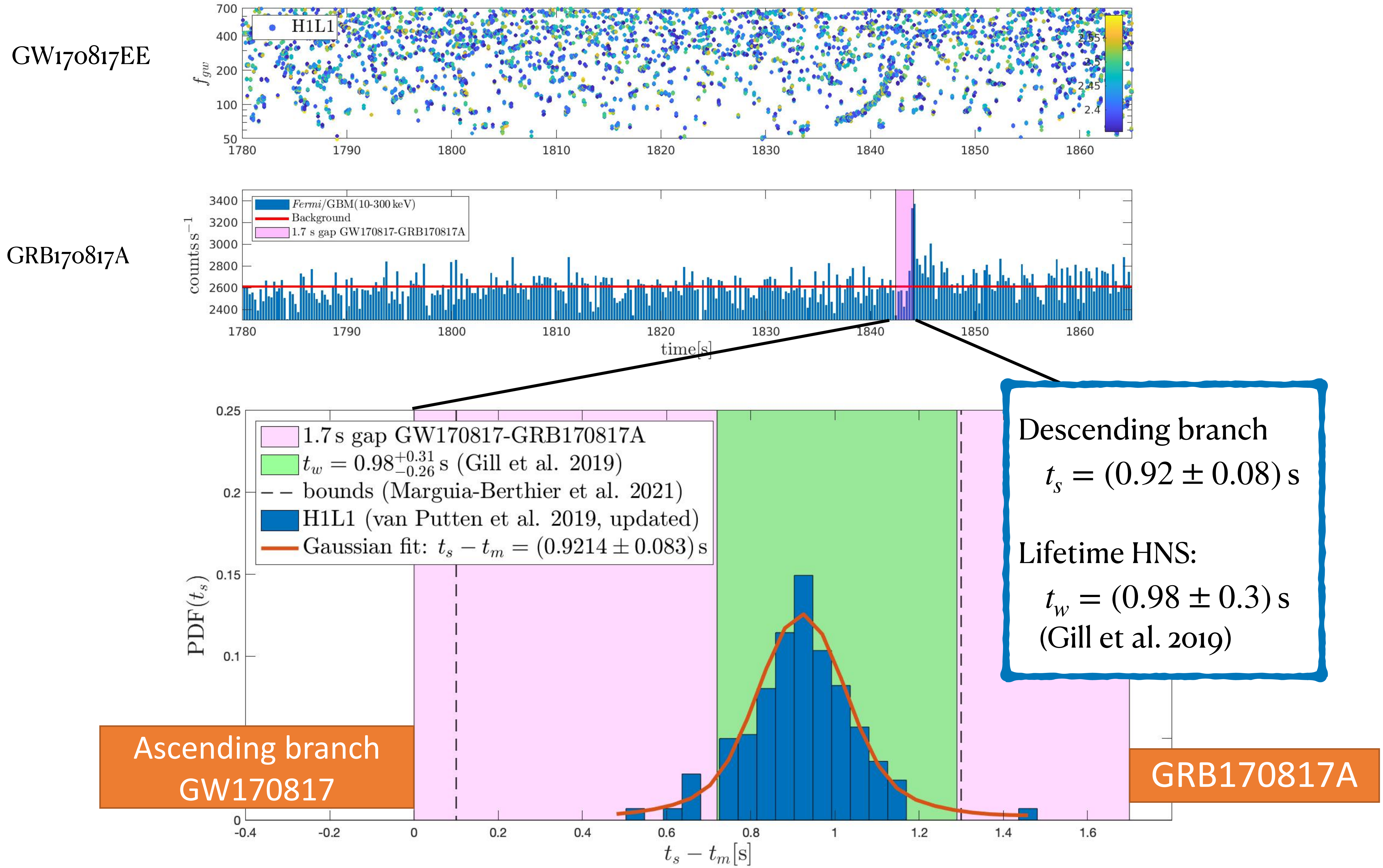
GRB170817A

# Event sequence of two branches

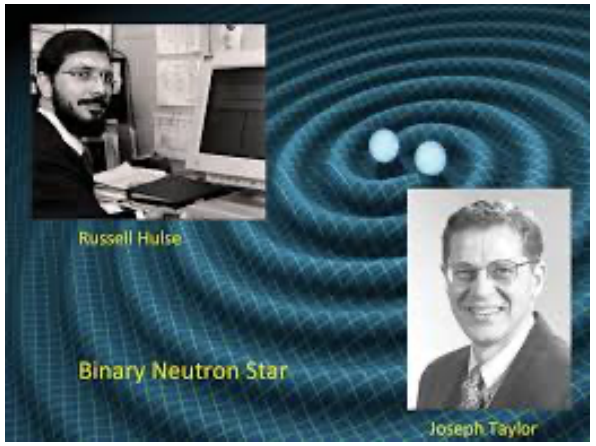
- Descending branch marks central engine GRB170817A: $t_s < t_{GRB}$
- Produced post-merger following ascending branch: $t_s > t_m$

$$t_m < t_s < t_{GRB}$$

# PDF start-time descending branch



# GW-calorimetry (II)



Nobel Prize 1993

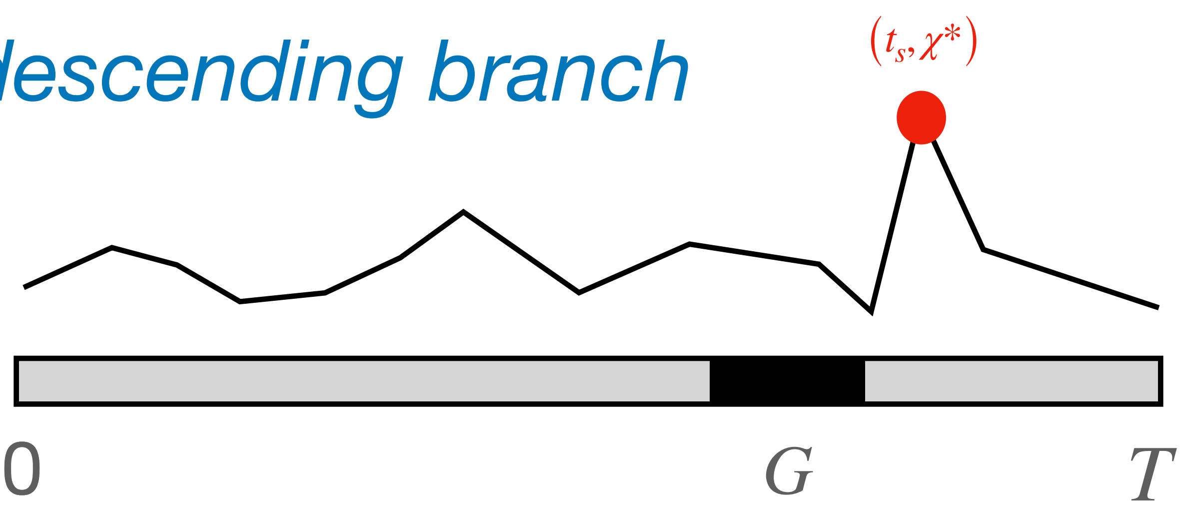
- $\mathscr{E}_{GW} \simeq 3.5\,\%\, M_{\odot}c^2$ in descending chirp
- $f_{gw} \lesssim 700$ Hz: $f_{spin} = \frac{1}{2} f_{gw} \lesssim 350$ Hz by quadrupole GW-emission

$$E_J^- \simeq \frac{\pi}{5} f_{gw}^2 M R^2 \lesssim 1.6 \times 10^{52} \left( \frac{M}{2.5 M_{\odot}} \right) \left( \frac{R}{18\text{km}} \right)^2 \text{erg} \ll \mathscr{E}_{GW}$$

HNS is energetically excluded by a factor $\gtrsim 4$

# Discrete event timing

*Correlation H1-L1 in descending branch*

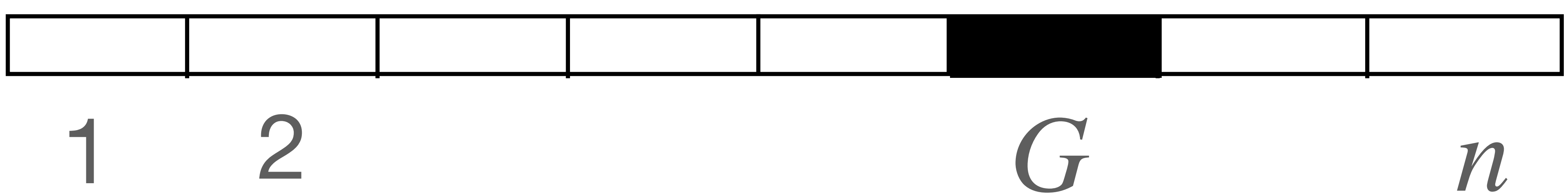



Max $\chi(t)$ over $[0,T]$: $\chi^* = \chi(t_s)$

Cell $G = [t_m, t_{GRB}]$

$$\#\,\text{cells}\; n = \frac{T}{|G|} = \frac{T}{t_g}$$

*Discrete event timing*

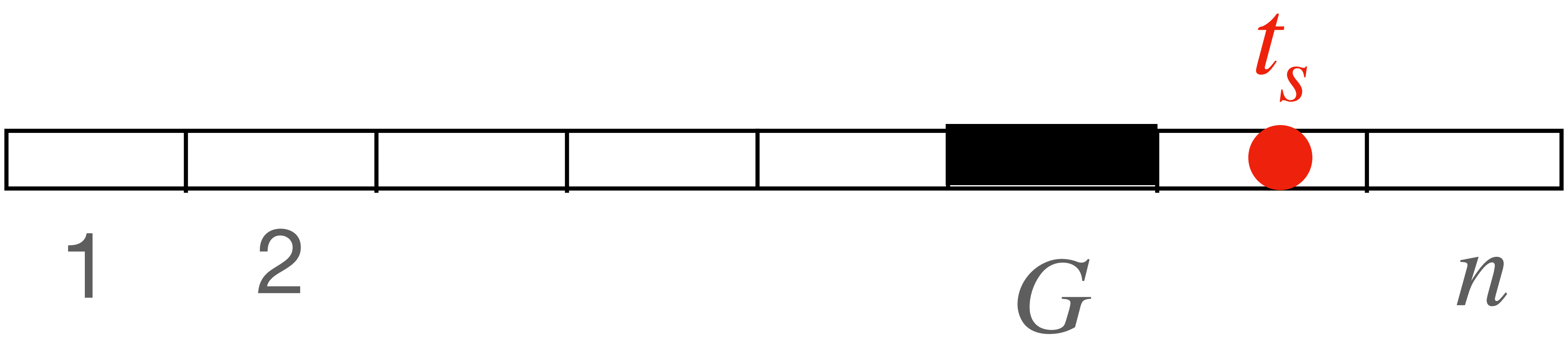



Causality satisfied if $t_s \epsilon G$

# PFA from null-hypothesis

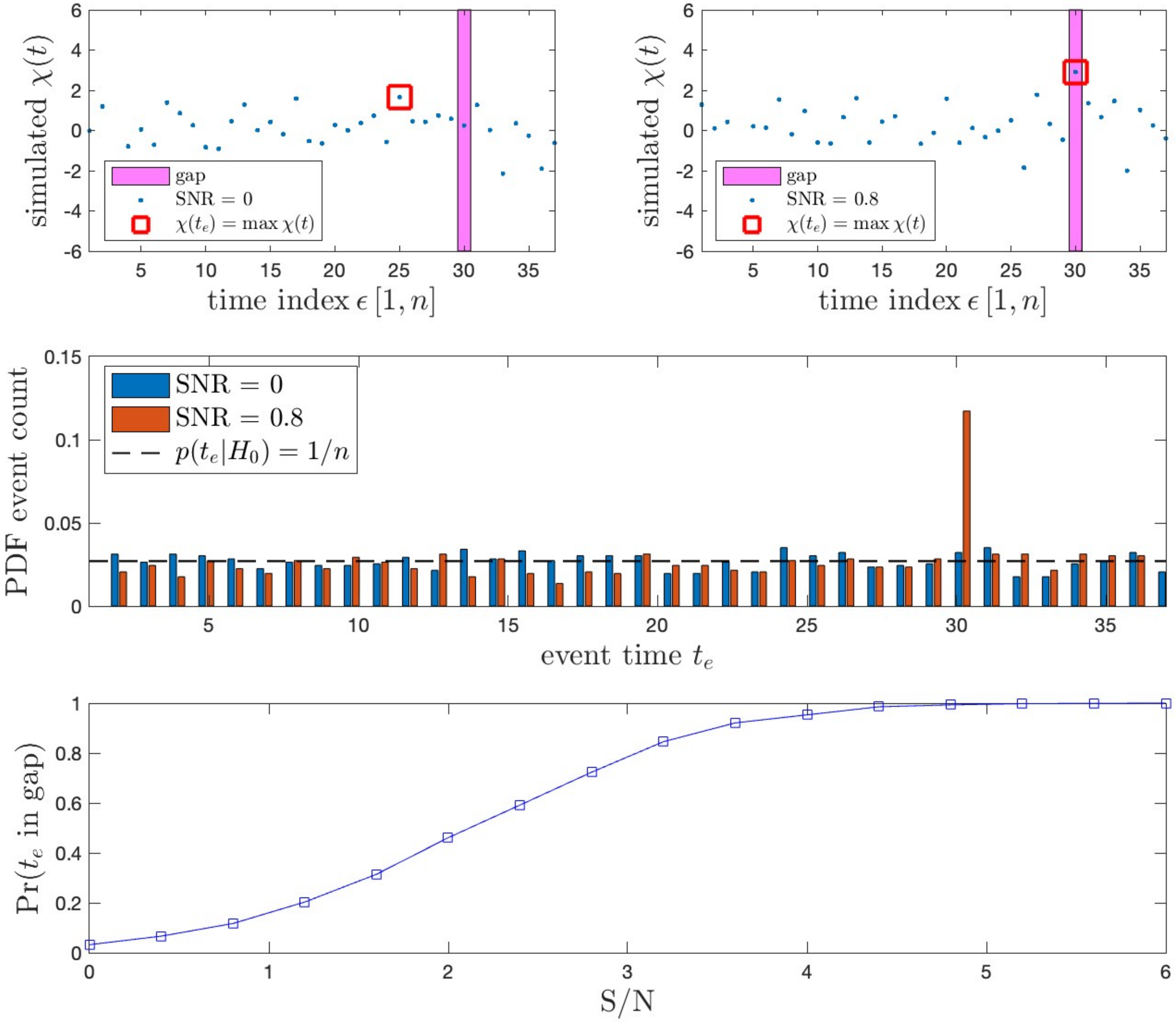

Blaise Pascal (1640)

- Stationary noise gives a uniform prior on $t_s$
- Absent a real signal (by chance alone) $t_s$ is uniformly distributed over observation interval $[0,T]$




$$\Pr_0 \equiv \Pr\left(t_s \epsilon\, G \,\middle|\, H_0\right) = \frac{1}{n}$$

# PFA at finite S/N




$$\Pr \equiv \Pr\left(t_s\, \epsilon\, G \,\middle|\, H_1\right) \geq \Pr_0 = \frac{1}{n}$$

# Event timing - twice

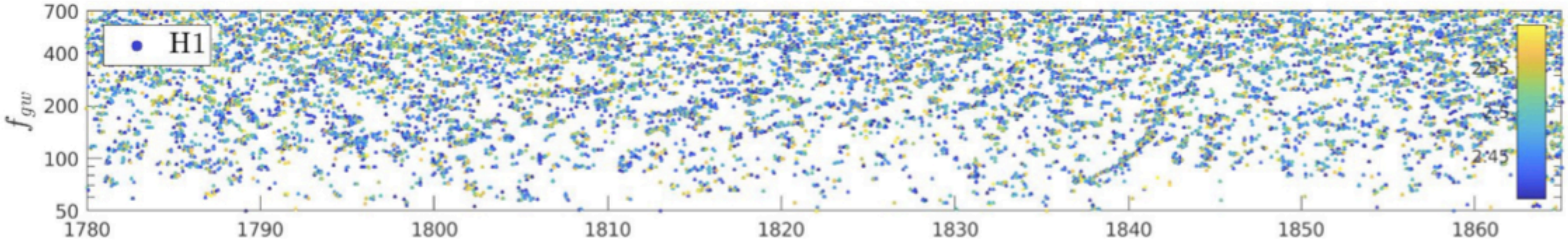
Mean $t_s$ in merged (H1,L1)-spectrograms

Consistency in H1,L1 from difference of $t_{s,\mathrm{H1}}$ and $t_{s,\mathrm{L1}}$

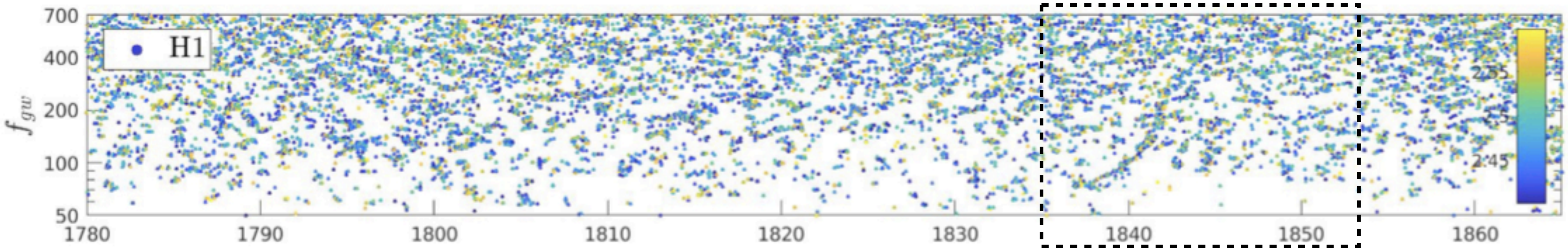
$$\begin{pmatrix} \text{Mean in (H1,L1)} \\ \text{Difference in H1,L1} \end{pmatrix} = \begin{pmatrix} 1/\sqrt{2} & 0 \\ 0 & \sqrt{2} \end{pmatrix} \mathscr{R}_{\frac{\pi}{4}} \begin{pmatrix} \mathrm{t}_{\mathrm{s,H1}} \\ \mathrm{t}_{\mathrm{s,L1}} \end{pmatrix}$$

Statistically independent timing observables ← $\mathscr{R}$ is unitary — Statistically independent under the (independent) null-hypothesis of uniform priors on H1 and L1

# Event timing H1, L1

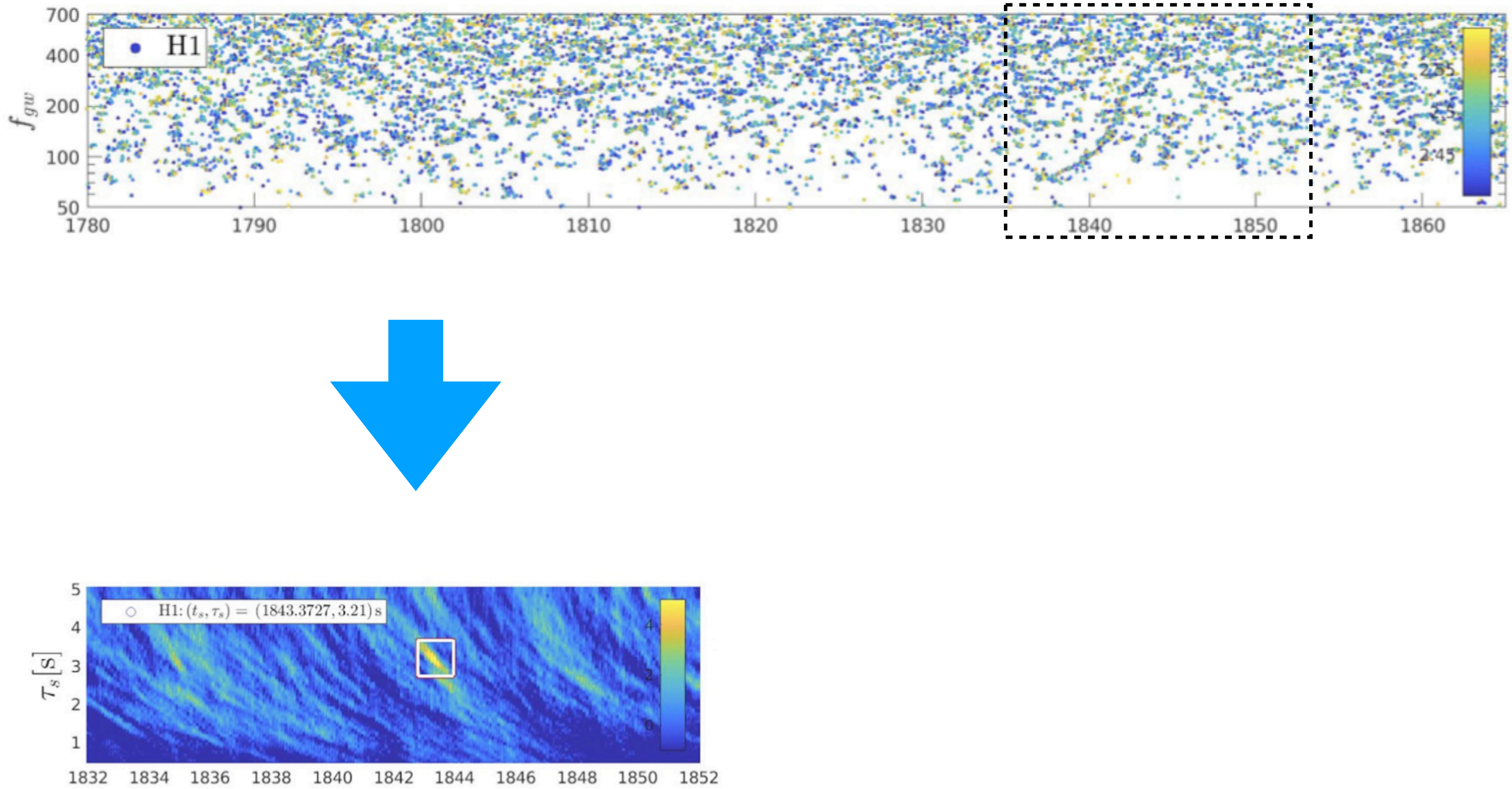


# Event timing H1, L1

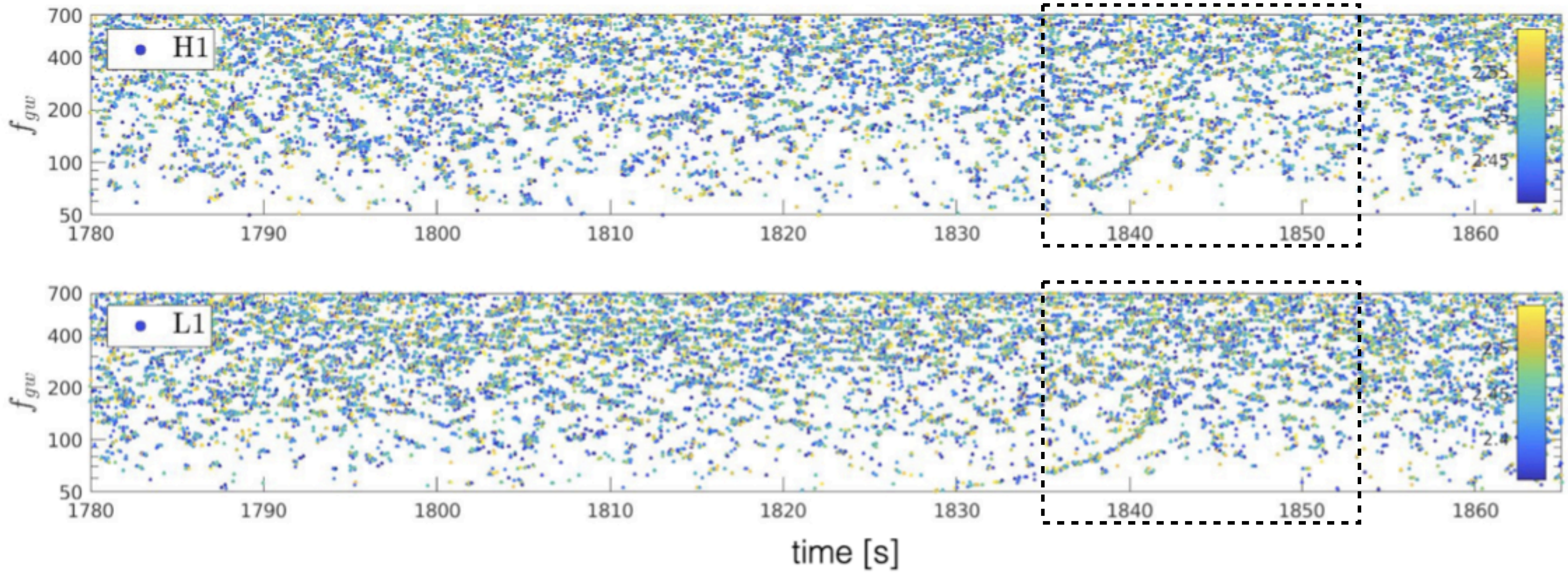


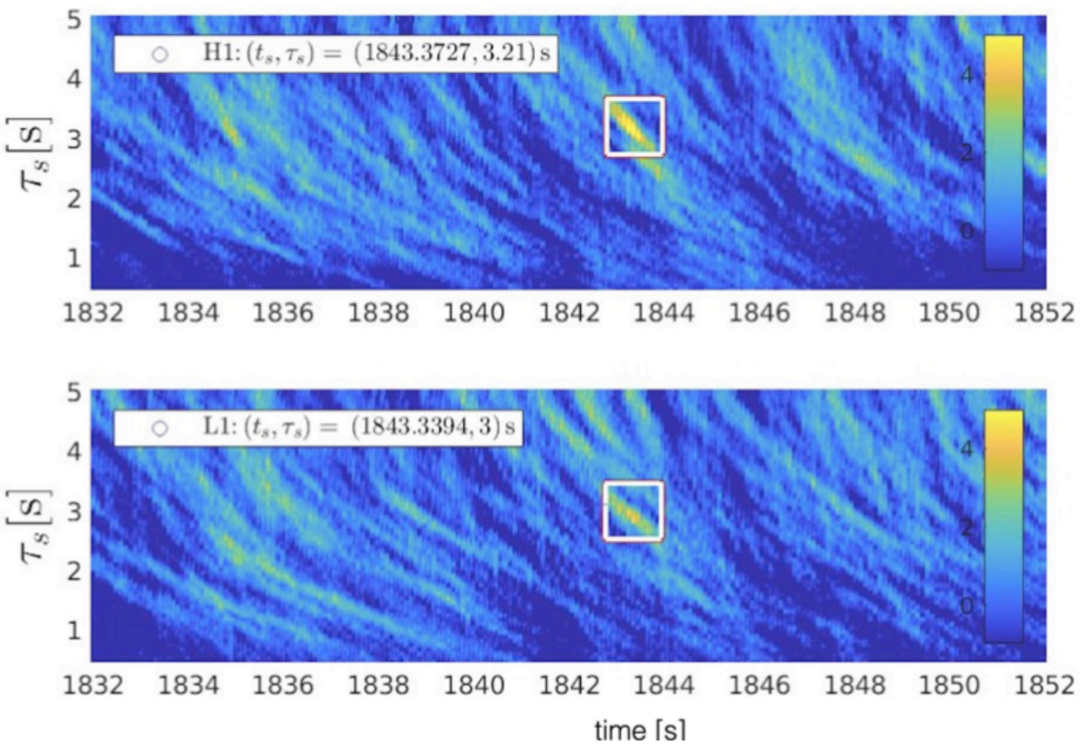

Parameter estimation - event timing

# Event timing H1, L1

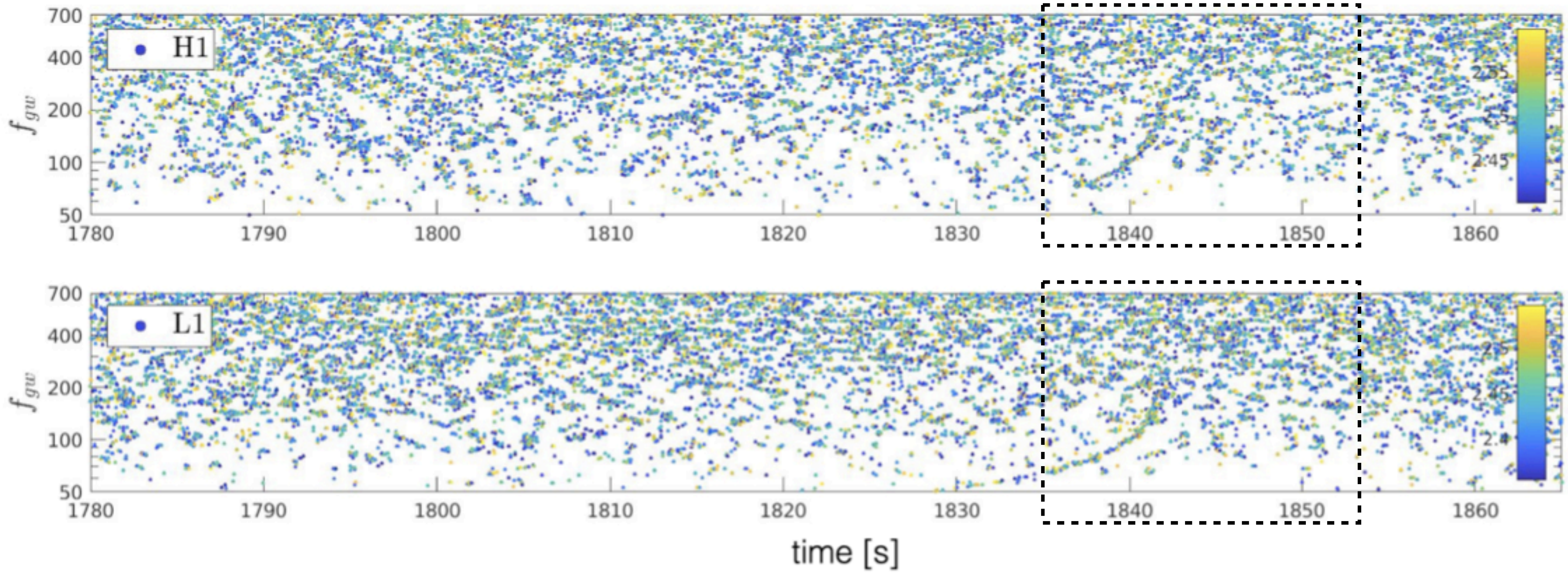


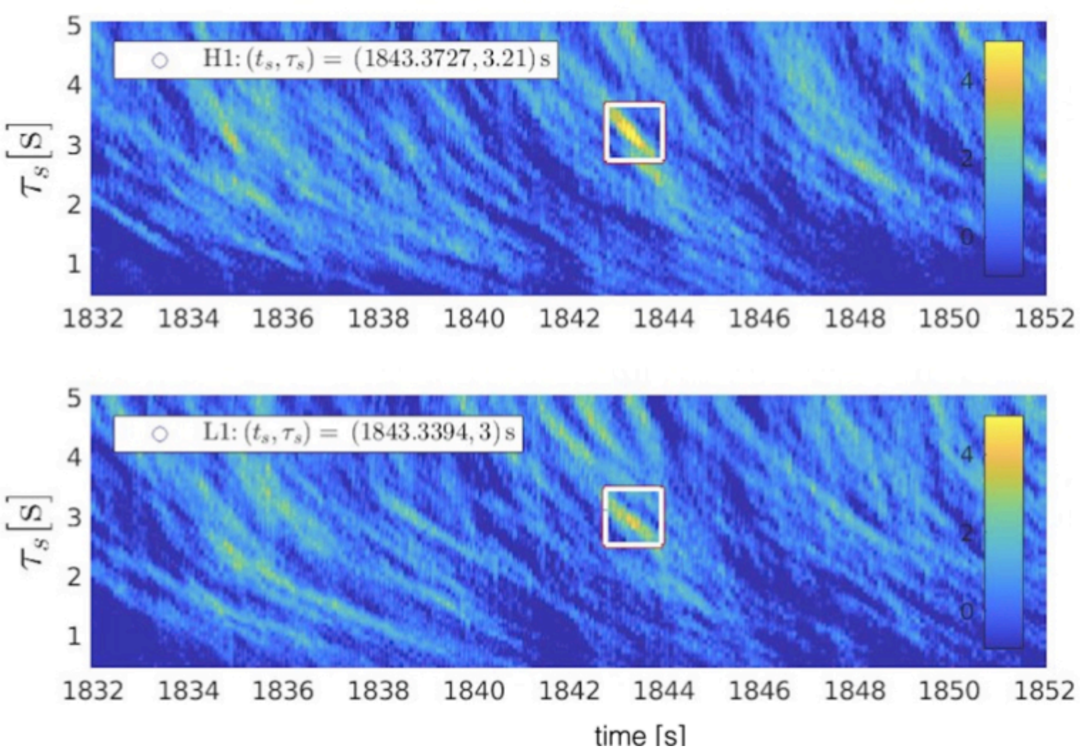
# Event timing H1, L1



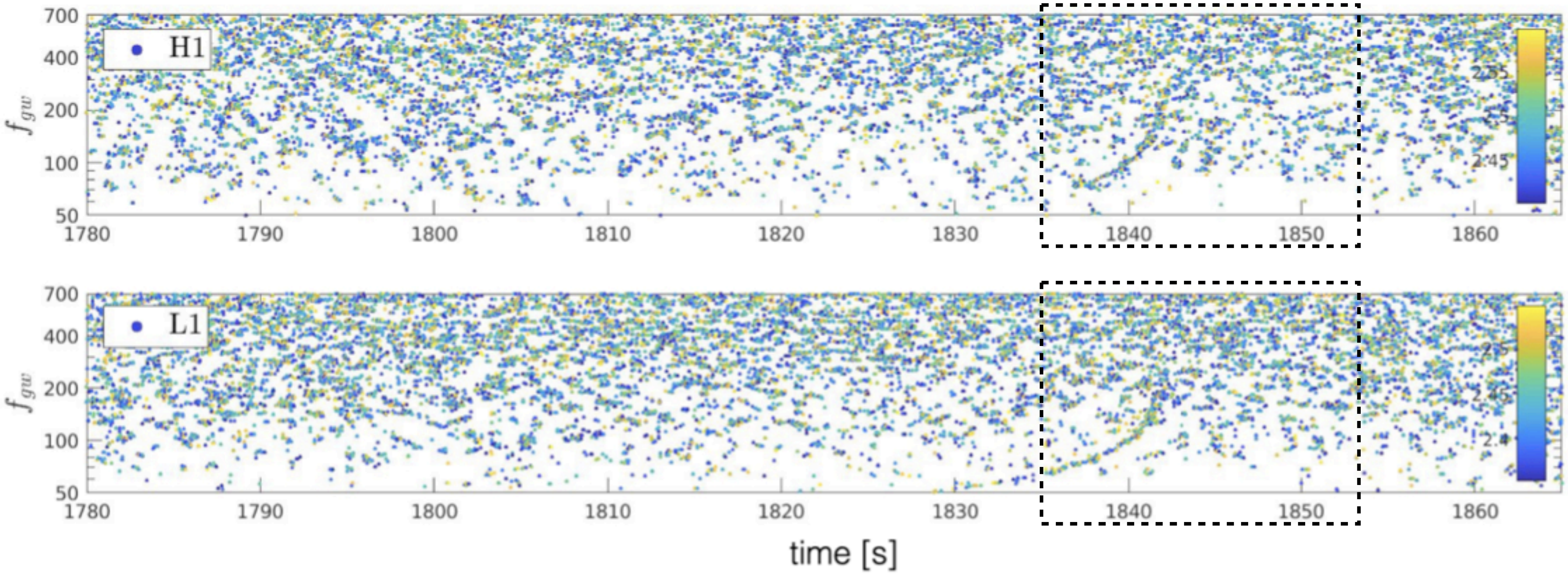
# Event timing H1, L1

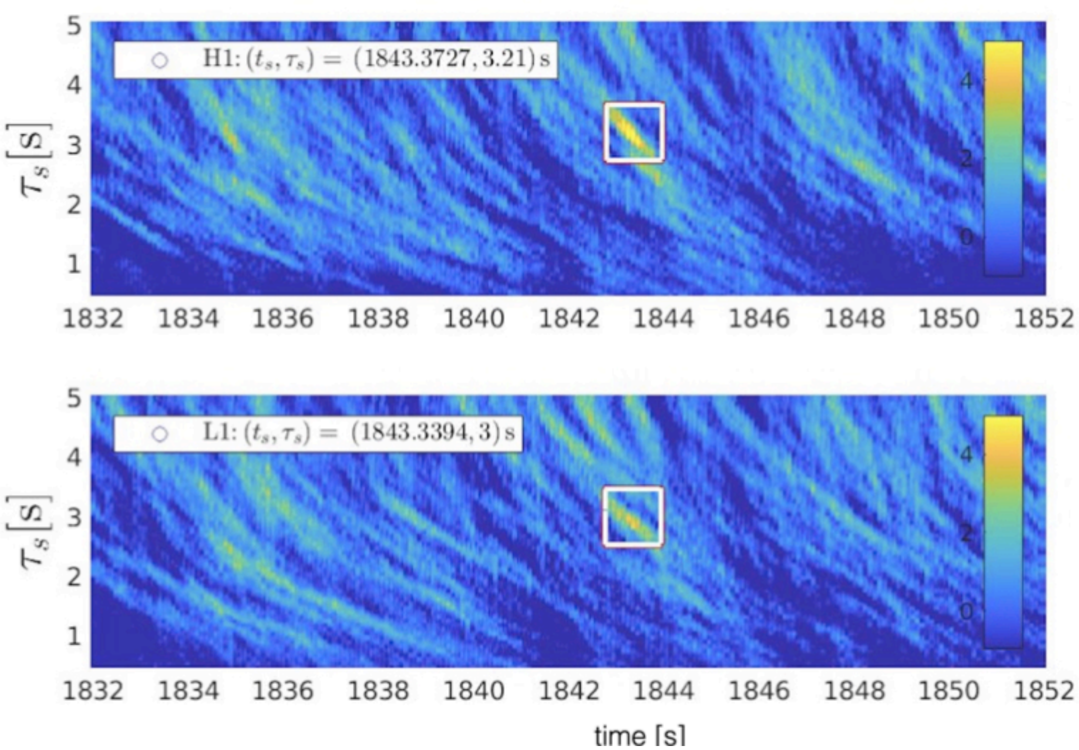


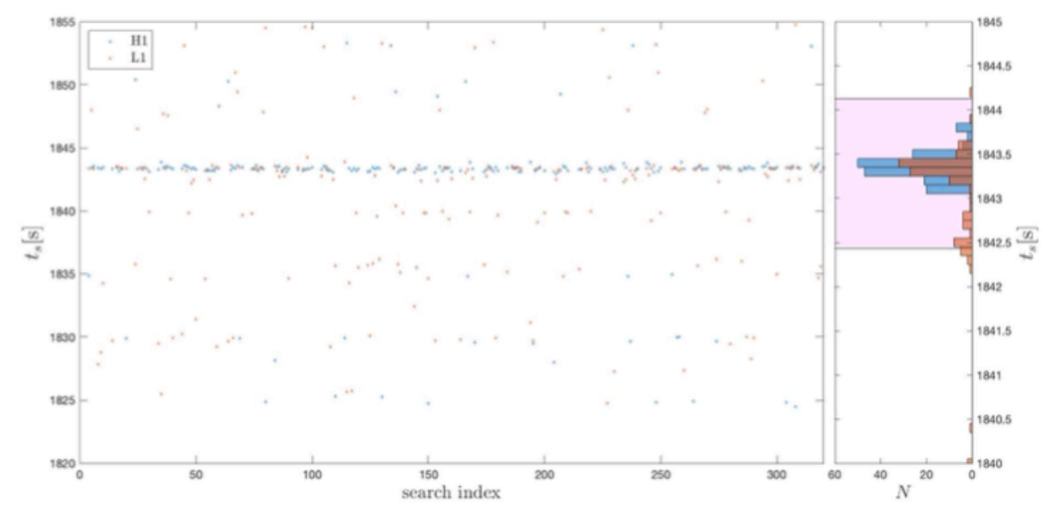




Extract PDF event timing in H1, L1 (320 samples each)

# Event timing H1, L1

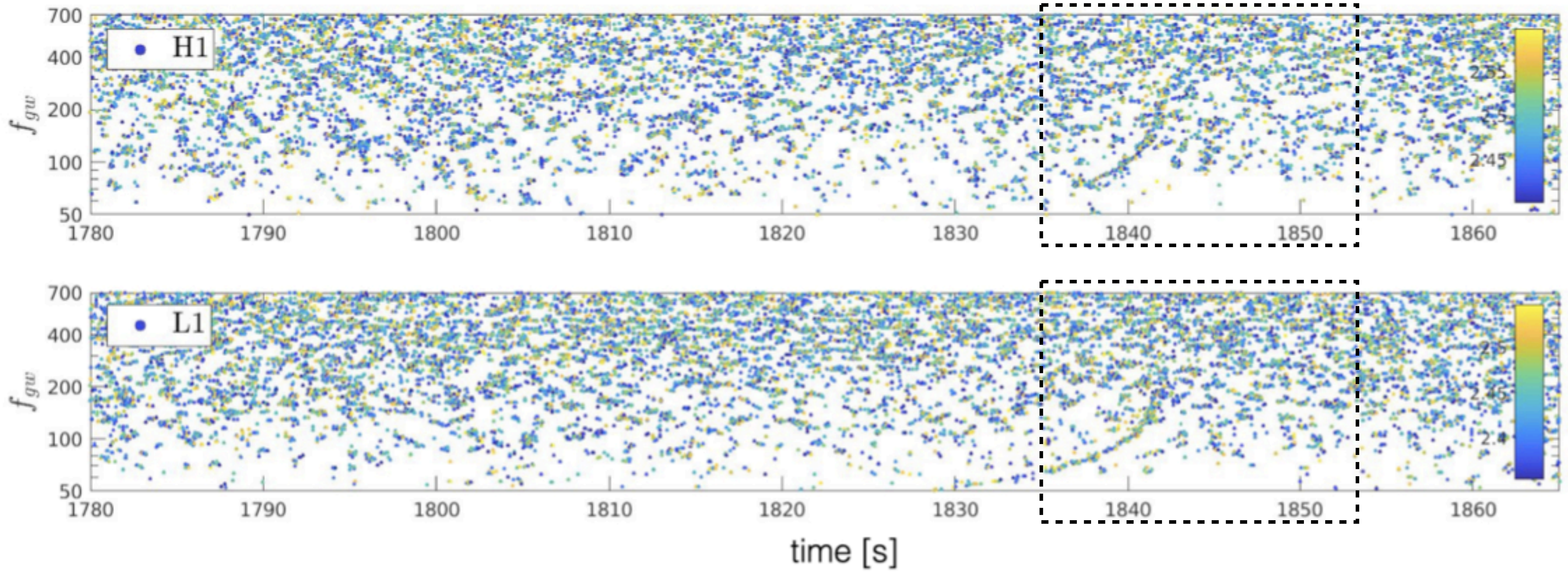


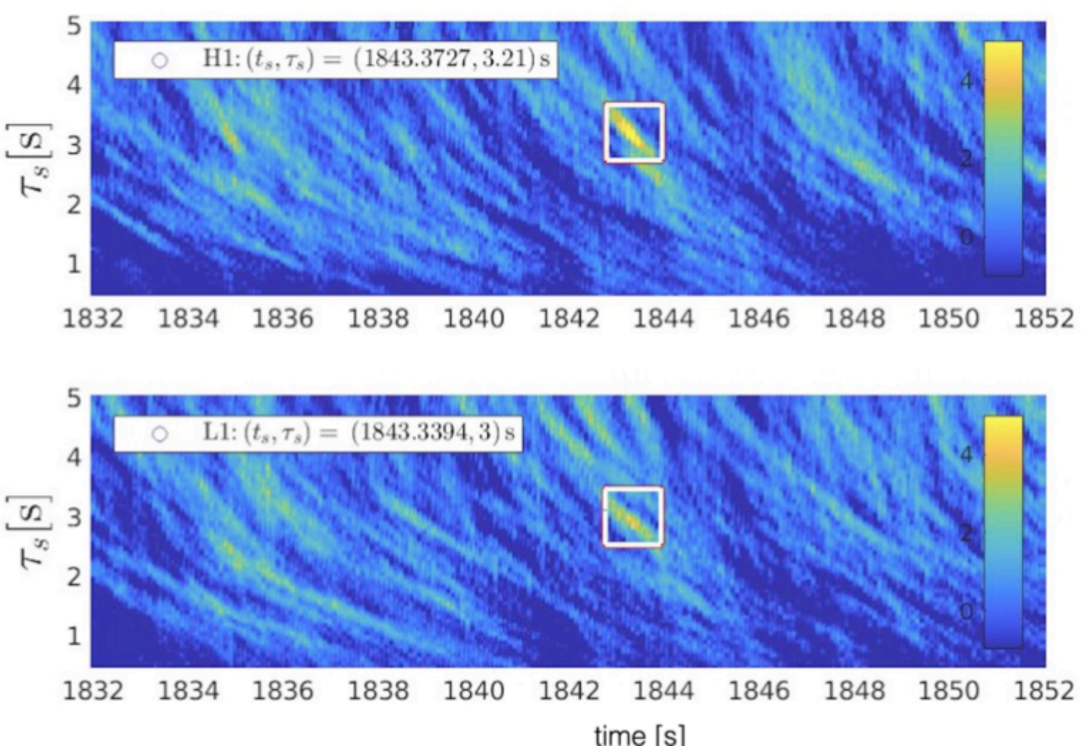



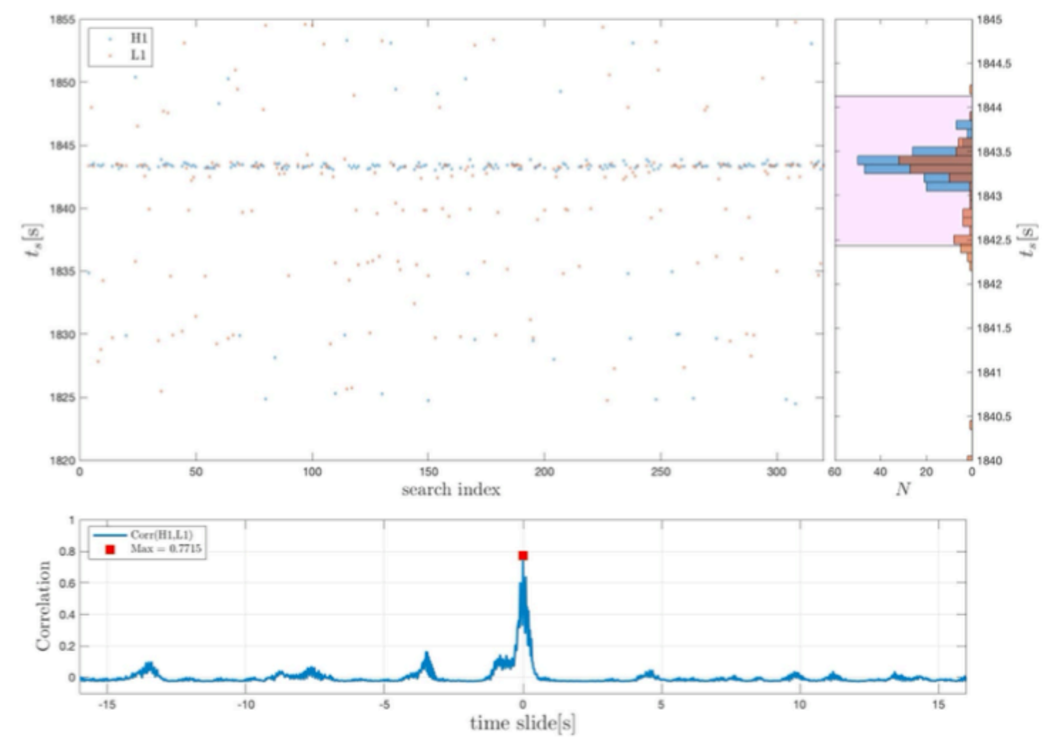




PDFs H1 and L1.
Now cross-correlate …

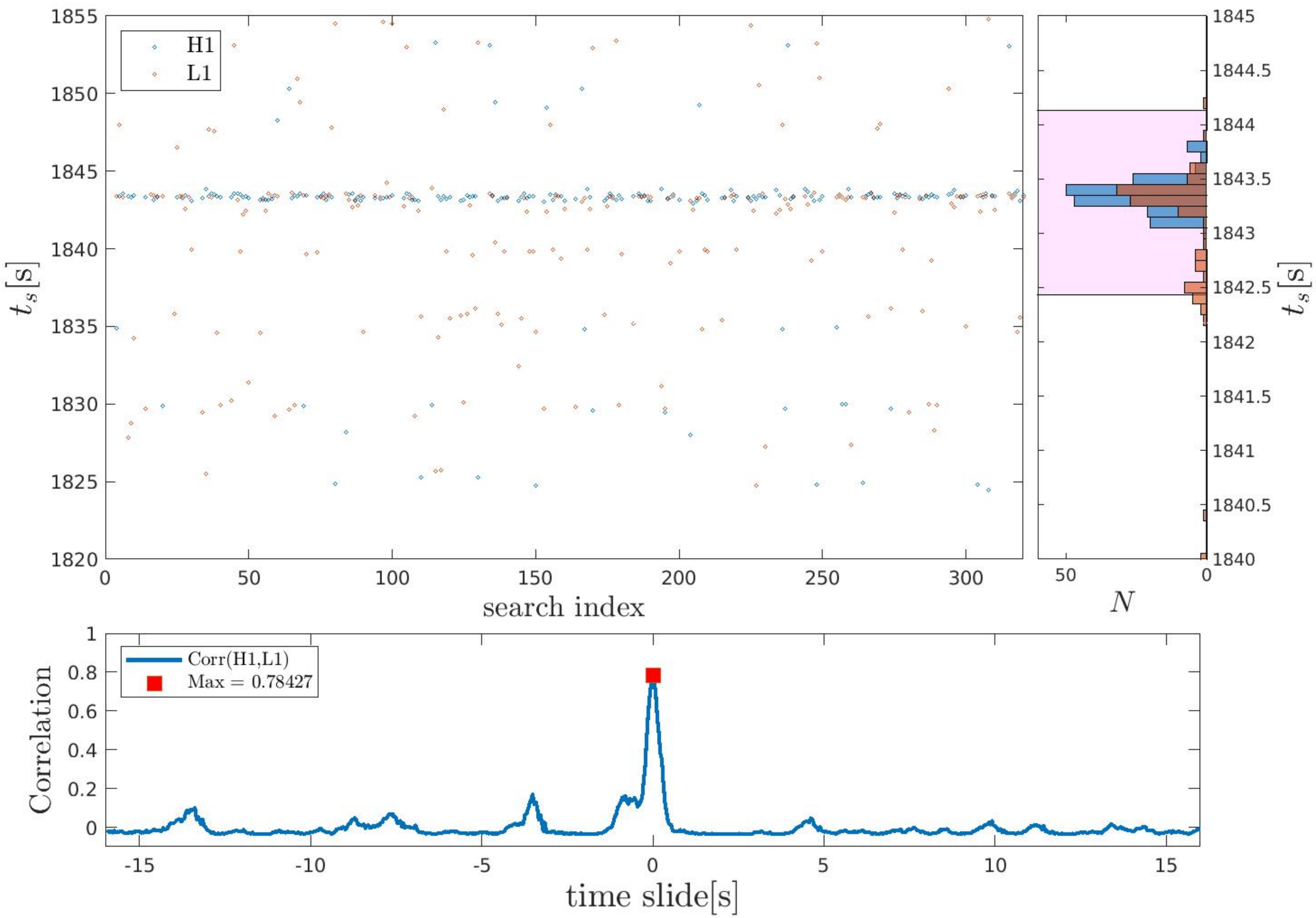
# Event timing H1, L1



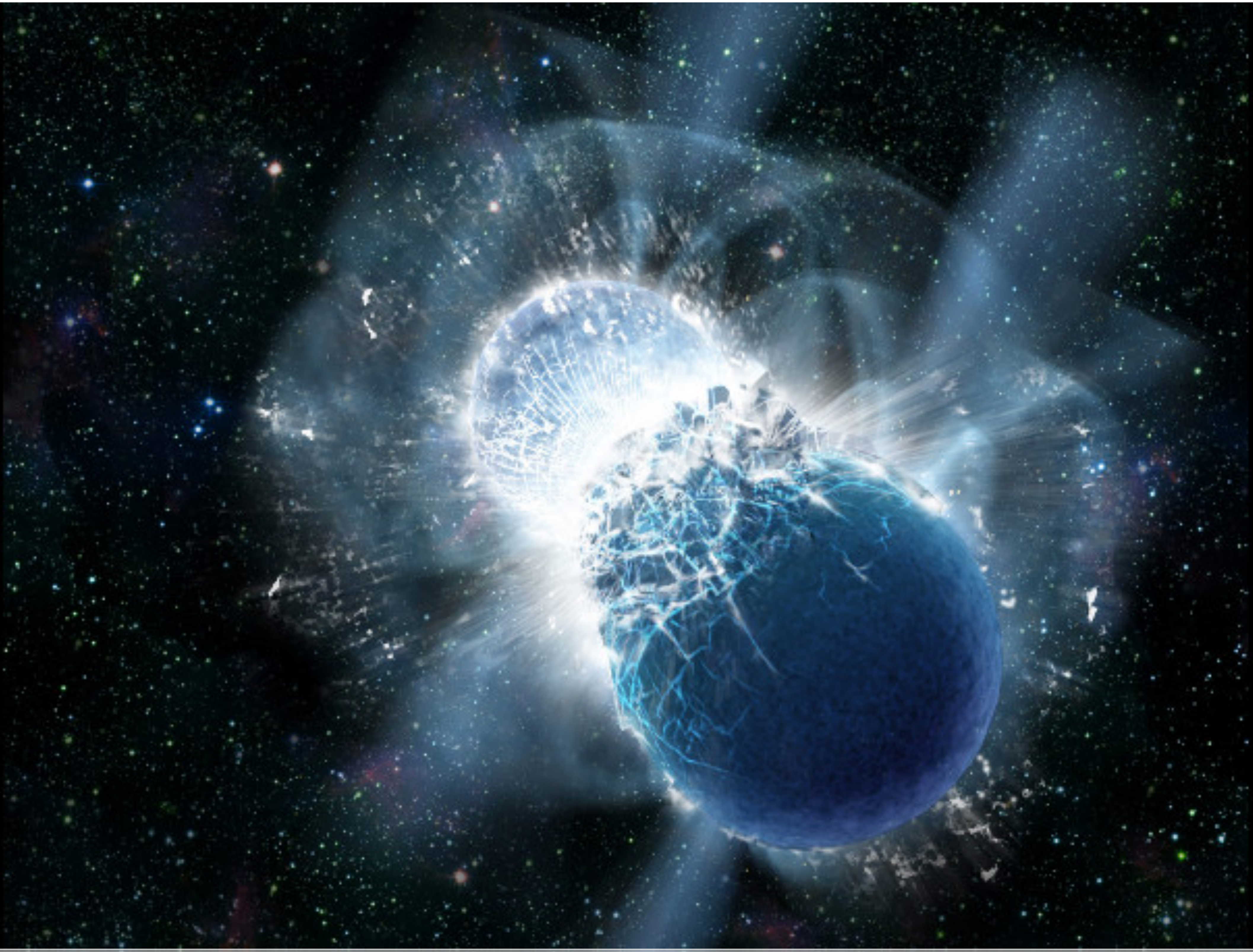



# Event timing difference in H1 and L1



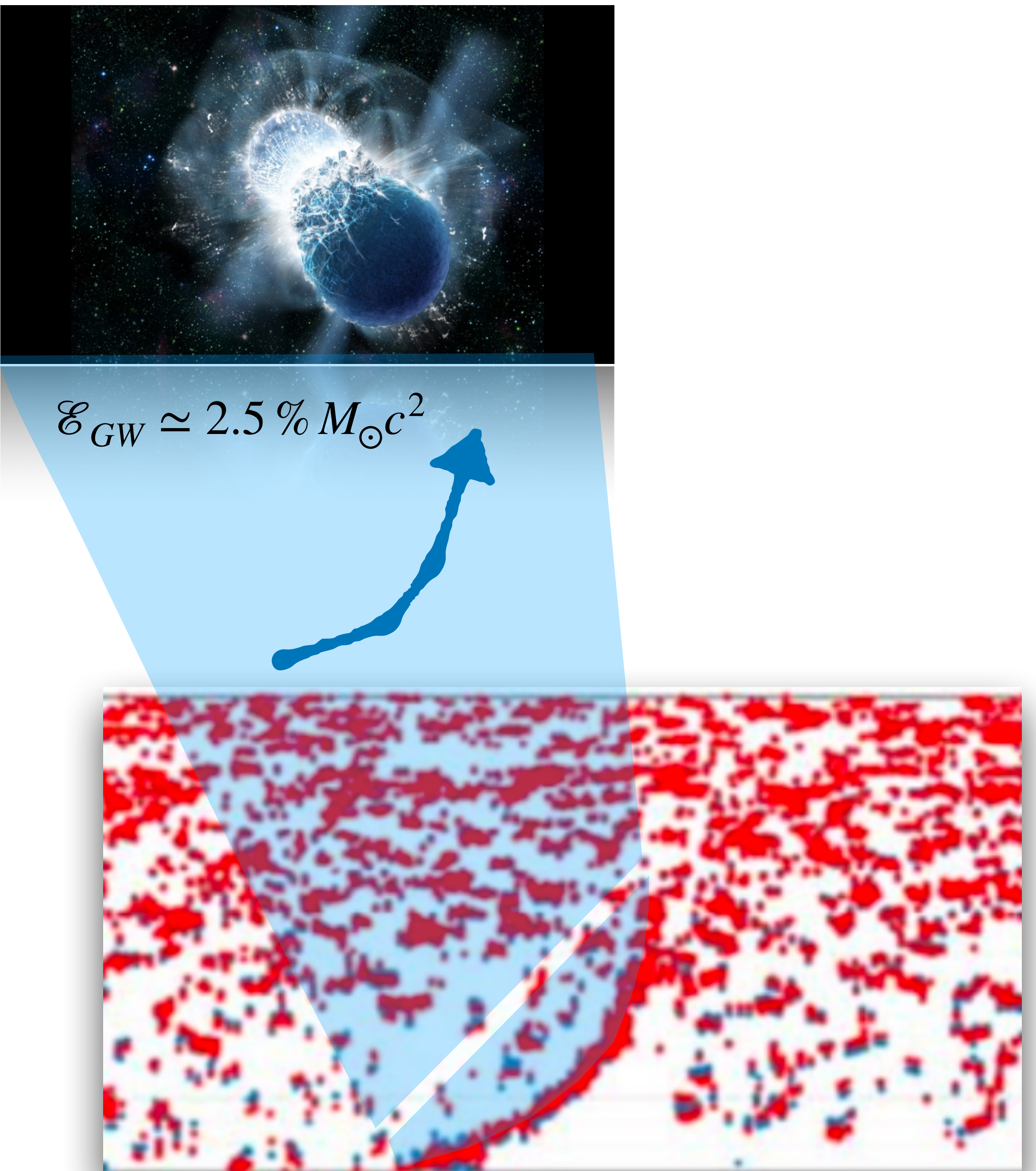

$$\mathrm{Pr}_0 = \frac{4\delta t_{res}}{T} \qquad (\delta_{res} \simeq 25\ \mathrm{ms})$$

# GW170817 sequence



# GW170817 sequence

DNS merger




van Putten Della Valle & Levinson ApJL (2019)

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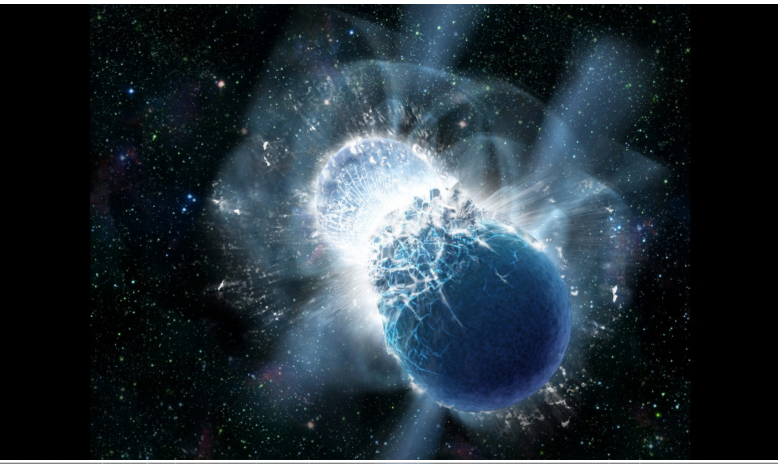
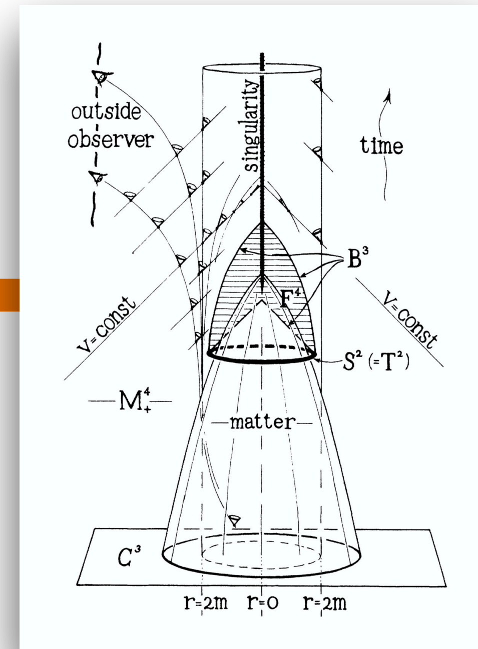


Gravitational collapse

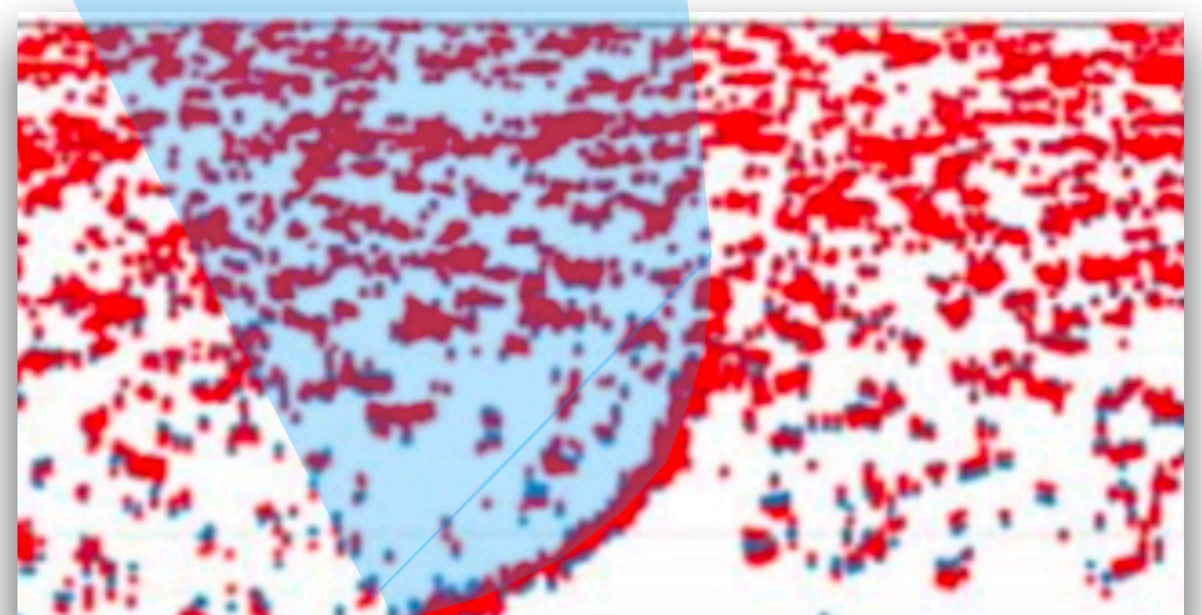



$E_J^-$

HNS

0.9s

$\mathcal{E}_{GW} \simeq 2.5\,\%\,M_\odot c^2$



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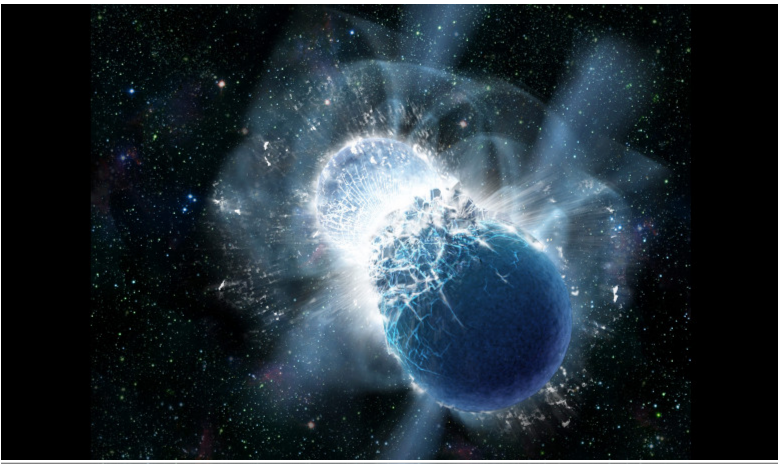

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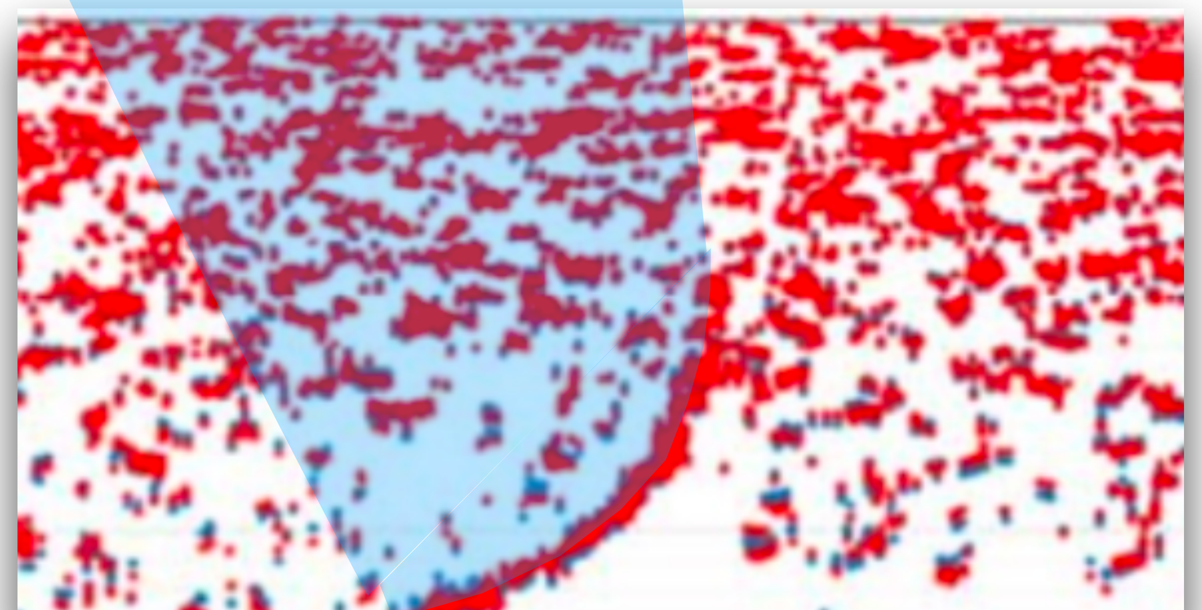

van Putten Della Valle & Levinson ApJL (2019)

$E_J^-$

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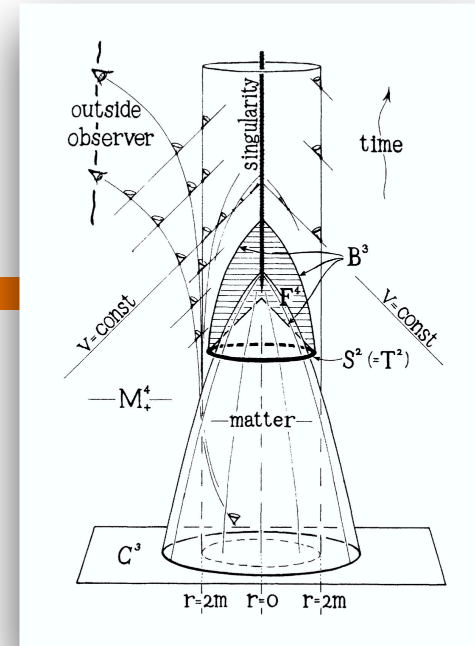
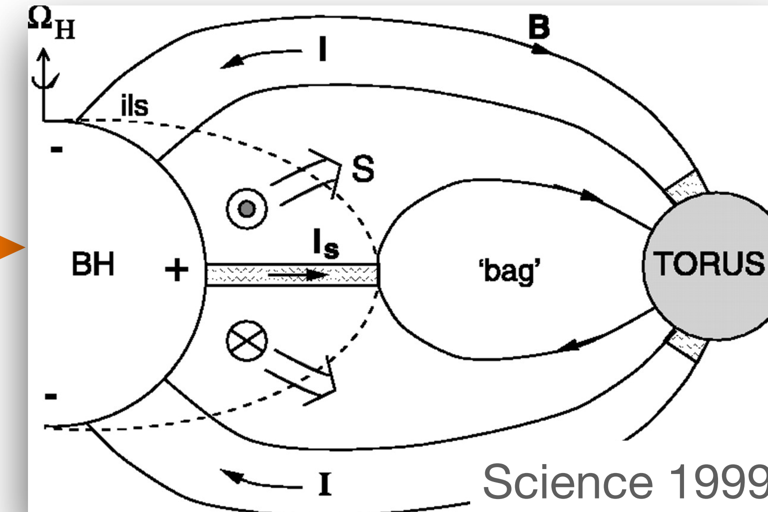



$E_J^+ \gtrsim$ few $E_J^-$

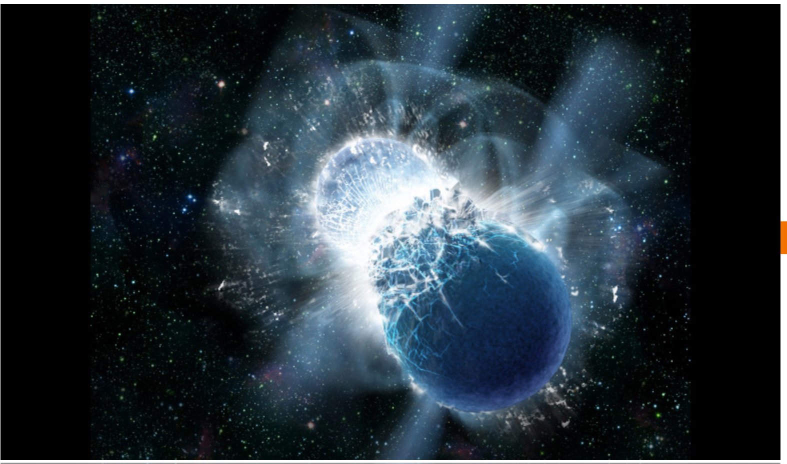


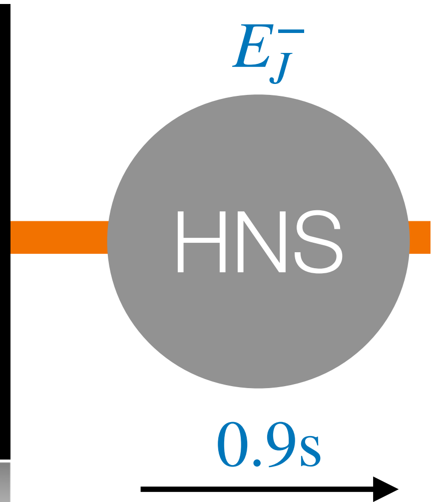

$L_H$ *mostly onto torus*

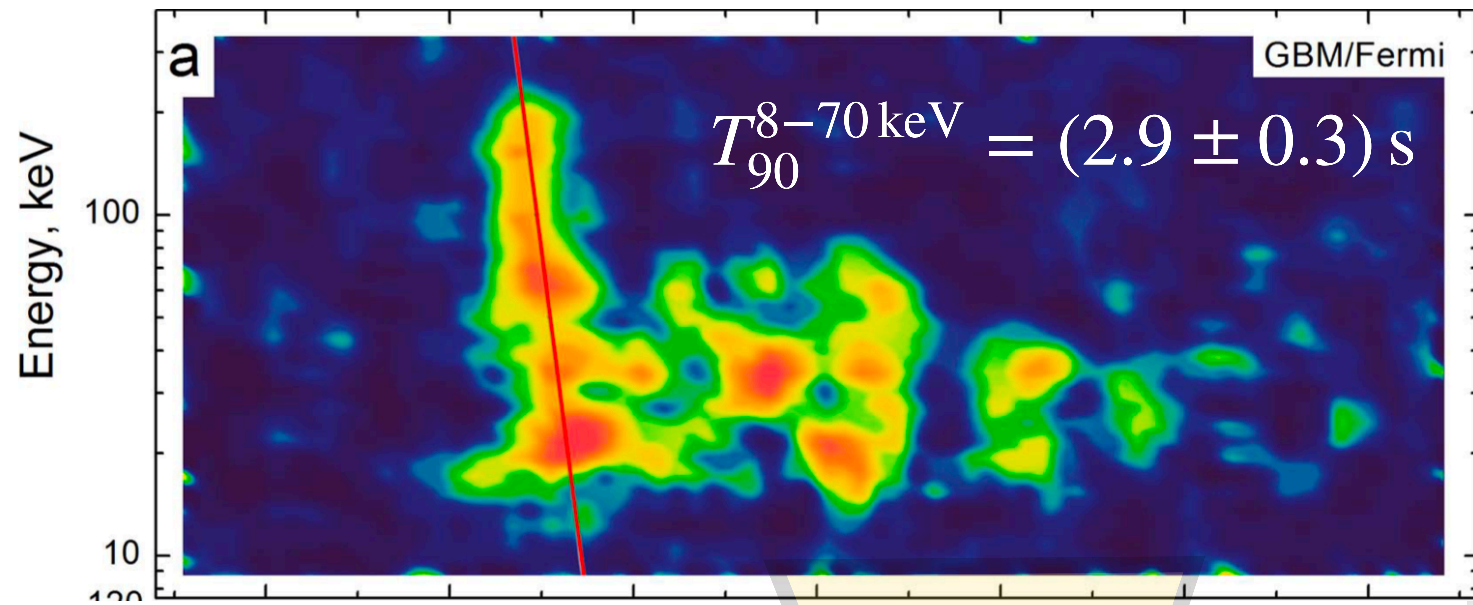
# GW170817 sequence

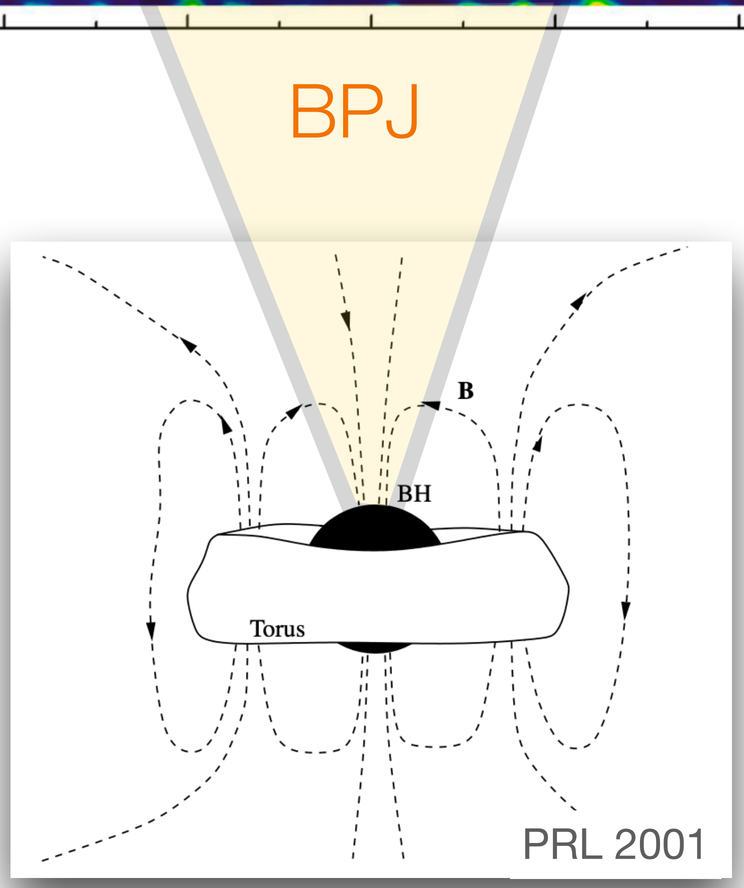
GRB170817A

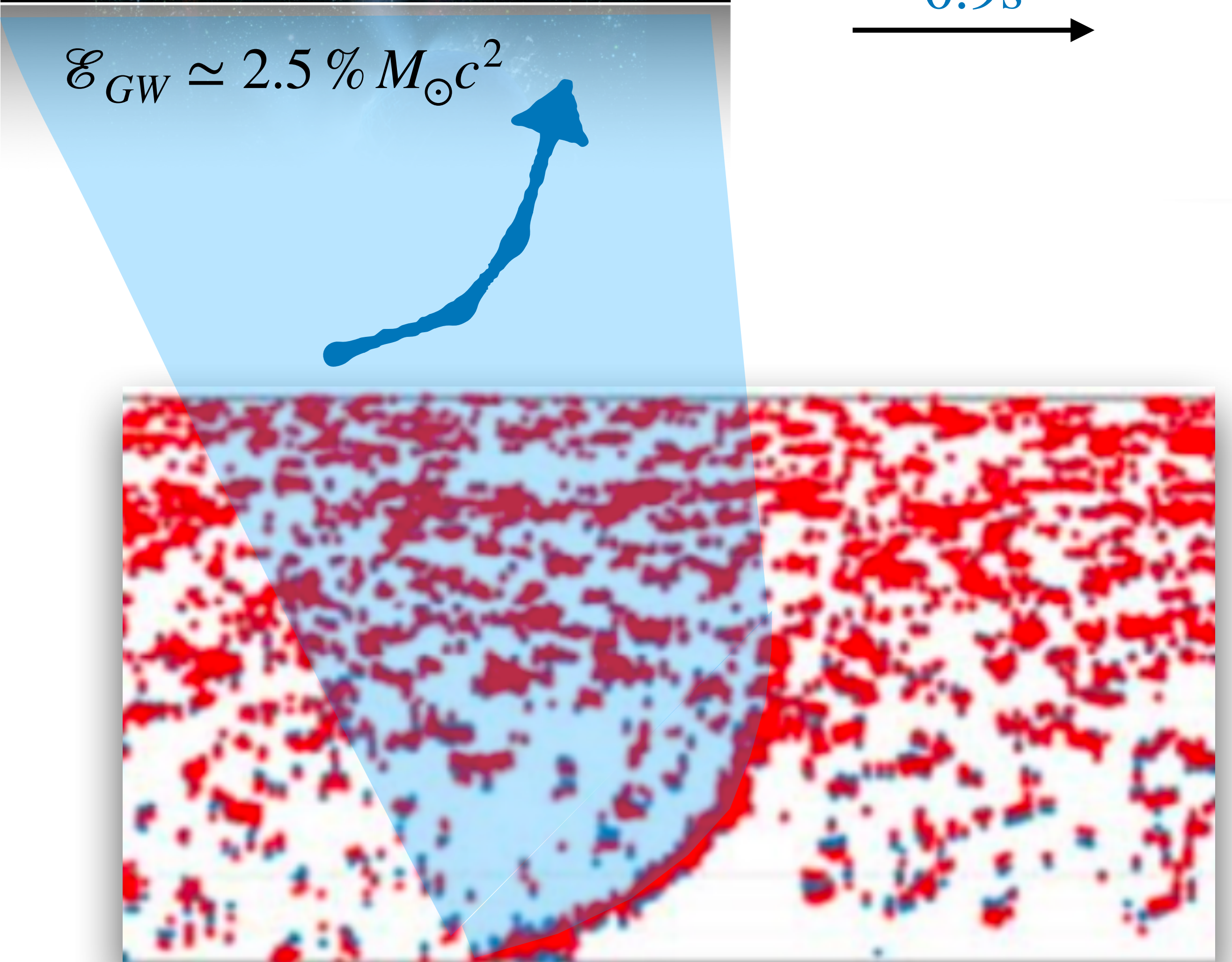
DNS merger





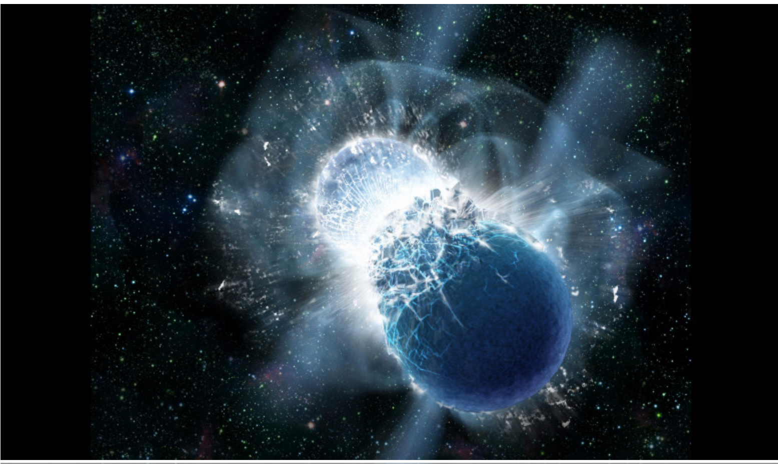




van Putten Della Valle & Levinson ApJL (2019)

# GW170817 sequence

GRB170817A

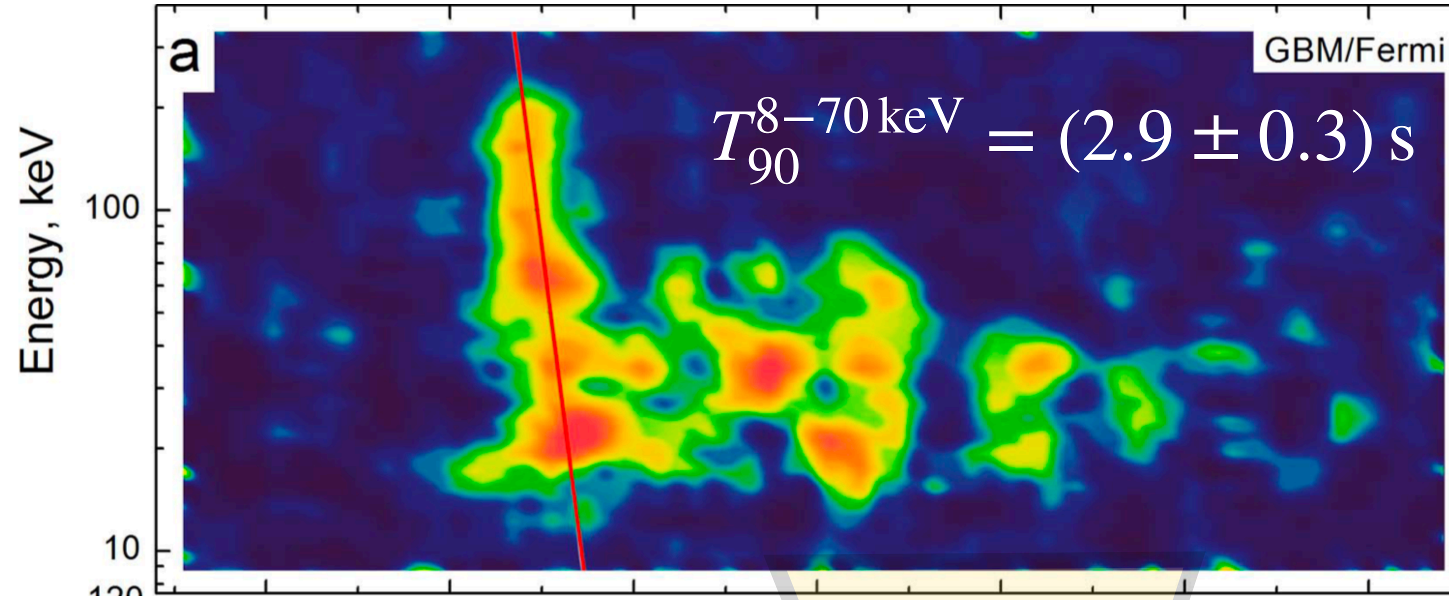
DNS merger



$E_J^-$

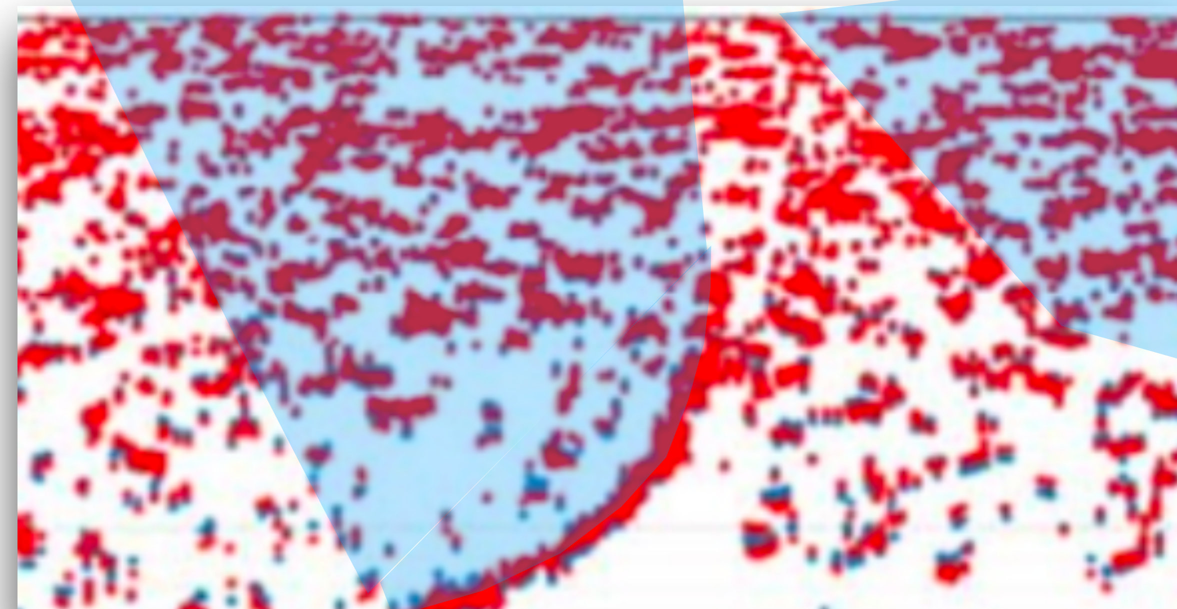
HNS

0.9s




BPJ

$\mathscr{E}_{GW} \simeq 2.5\,\%\,M_\odot c^2$



van Putten Della Valle & Levinson ApJL (2019)

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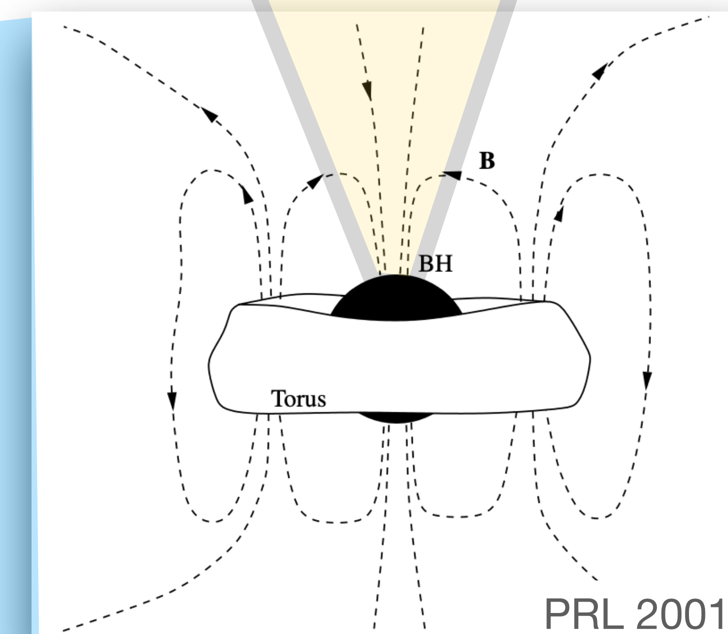
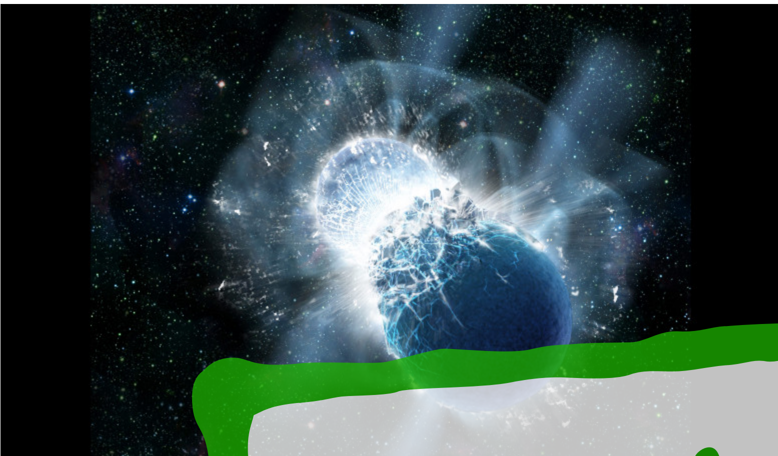



*Radiative cooling mostly in GW-emission*

# GW170817 sequence

GRB170817A

DNS merger

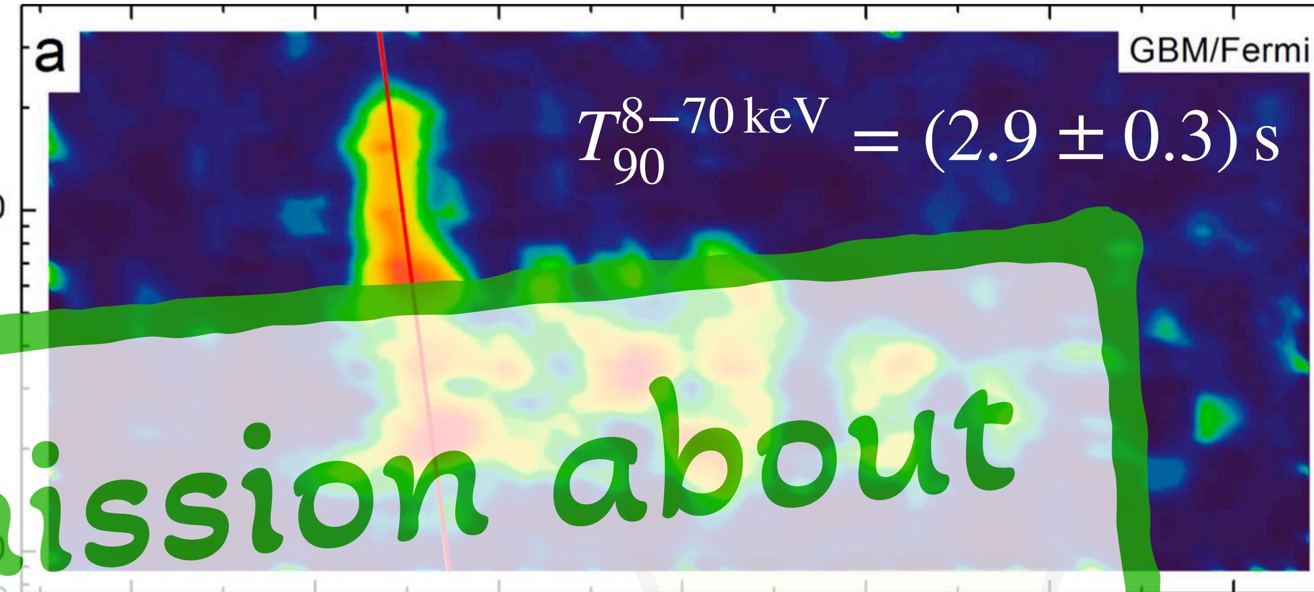


$E_J^-$

HNS

0.9 s

$\mathcal{E}_{GW} \simeq 2.5\,\% M_\odot c^2$

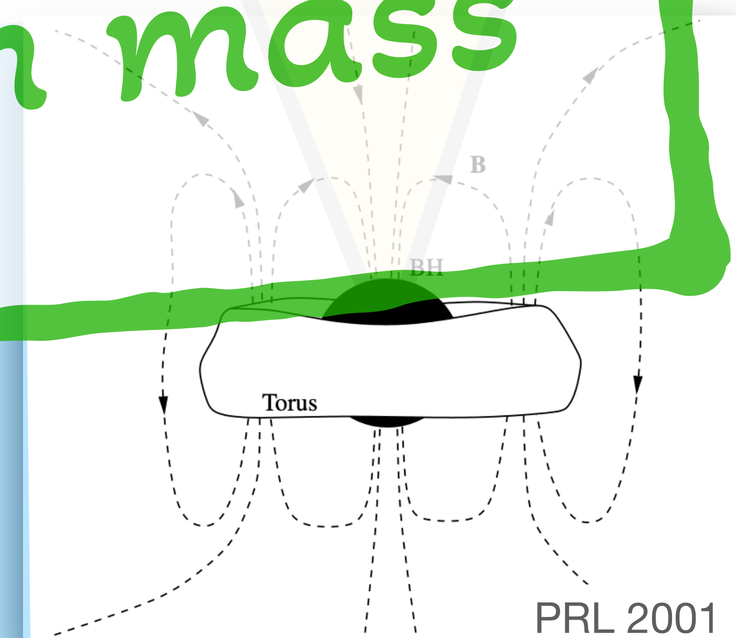



BPJ

Total GW-emission about 2% of total system mass

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

van Putten Della Valle & Levinson ApJL (2019)




*Radiative cooling mostly in GW-emission*

# Joint PFA

## Analysis of a snippet of H1L1-data of $T = 2048$ s:

Discrete event timing in merged (H1,L1)-spectrograms: $\mathrm{PFA}_1 = \frac{t_g}{T} = \frac{1.7}{2048}$

Consistency in independent analysis of H1 and L1: $\mathrm{PFA}_2 = \frac{4\delta t_{res}}{T} \simeq \frac{0.1}{2048}$

## Statistical independence of mean and difference under null-hypothesis:

$$\mathrm{PFA}_1 \times \mathrm{PFA}_2 = \frac{t_g}{T} \times \frac{0.1}{2048} = 4.1 \times 10^{-8} \quad \text{(Z-score 5.5)}$$

# Consistency EM-GW timing

| | HNS lifetime to gravitational collapse | GRB170817A duration and lifetime of central engine | Reference |
|---|---|---|---|
| EM | $t_w = (0.98 \pm 0.3)\,\mathrm{s}$ | $T_{90}^{8-70\,\mathrm{keV}} \simeq (2.9 \pm 0.3)\,\mathrm{s}$ | Gill et al. 2019<br>Pozanenko et al. 2018 |
| GW | $t_s = (0.92 \pm 0.08)\,\mathrm{s}$ | $\tau_s = (3.0 \pm 0.1)\,\mathrm{s}$ | A&A, in press |

# Conclusion

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

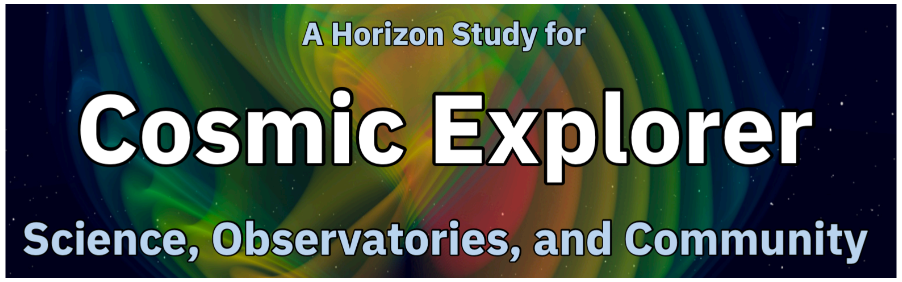
Cutler & Thorne, 2002, arXiv:0204090v1

## Central engine GRB170817A?

| | | |
|---|---|---|
| ☒ | NS | Excluded by GW-calorimetry |
| ☑ | BH | Descending branch at 5.5σ |

# Outlook?

Evans, et al., 2021, arXiv:2109.09882v2




Box 5.2: Key Science Question 2

**How does matter behave under the most extreme conditions in the universe?**

Cosmic Explorer will measure gravitational radiation from binary neutron star coalescences and provide the precise source localizations required for multimessenger astronomy, allowing us to:

- Determine the internal structure and composition of neutron stars;
- Explore new regions in the phase diagram of quantum chromodynamics;
- Map heavy element nucleosynthesis in the universe through counterpart kilonovae and distant mergers;
- Reveal the central engine for the highly relativistic jets that power short gamma-ray bursts.

# Outlook

*Expect:*

DNS events from upcoming LVK O4-5 (March 2023)
Opportunities to probe central engines to CC-SNe

*Diversity* in EM-GW afterglows to DNS, in kilonovae and GRB-GW?

*Descending branch* in GW from CC-SNe? (Run-up may be complex and include a merger, Imshennik & Ryazkshaya, 2004, Astron. Lett., 30, 14)

Stay tuned for $\mathscr{E}_{EM}\mathscr{E}_{\nu}\mathscr{E}_{GW}$ events

# HPC at the horizon

Analysis including parameter estimation: exaFLOP on a 400 teraFLOP multi-LAN heterogeneous compute platform. Work is two-fold:

- Matched filtering over a dense bank of templates (banks of size $2^{19}$)
  Correlations in Fourier-domain by FFT
  Extract tails of raw output in post-callback (predicted by Parseval sums)

- Parameter estimation by image analysis of spectrograms (in Local Memory GPUs)

Dynamical load balancing by synaptic processing: *work-items upon request by individual nodes* (sans server)

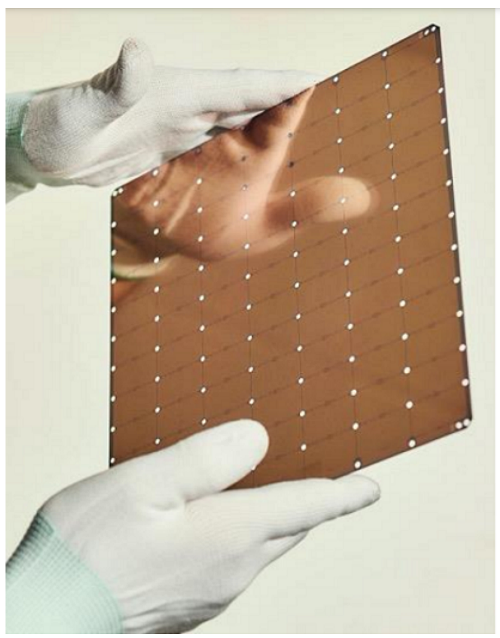
**LAN1**: O - - - - O O O O ↘ ↖

List of line-items of work
(atomic access over **NAS**)

**LAN2**: O - - - - O O O O ↗ ↙

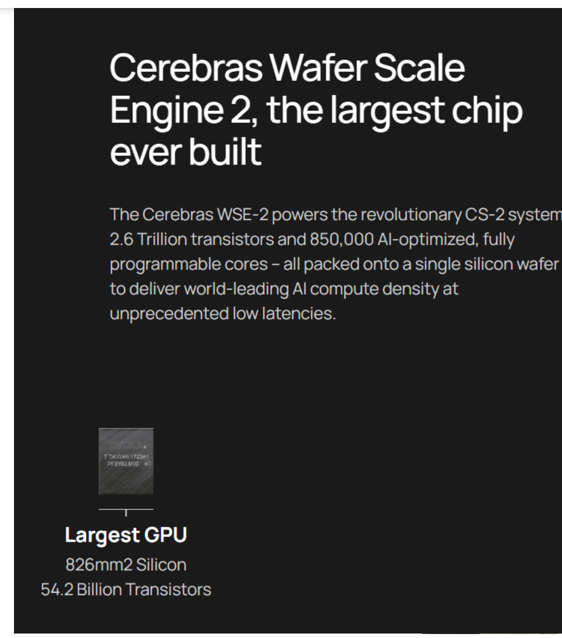
# Wafer-scale HPC

Distributed computing over a homogeneous mesh
Extremely low memory overhead to compute ratio



Cerebras Wafer-Scale Engine

| | Gen1 WSE | Gen2 WSE |
|---|---|---|
| Fabrication process | 16 nm | 7 nm |
| Silicon area | 46,225 mm$^2$ | 46,225 mm$^2$ |
| Transistors | 1.2 Trillion | 2.6 Trillion |
| AI-optimized cores | 400,000 | 850,000 |
| Memory on-chip | 18 GB | 40 GB |
| Memory bandwidth | 9 PB/s | 20 PB/s |
| Fabric bandwidth | 100 Pb/s | 220 Pb/s |





Efficient FFT-based matched filtering signal processing — work in progress :)