Observation of delayed black hole formation in GW170817

A multilevel analysis by heterogeneous computing

Maurice H.P.M. van Putten

Department of Physics and Astronomy
Sejong University
Seoul, South Korea

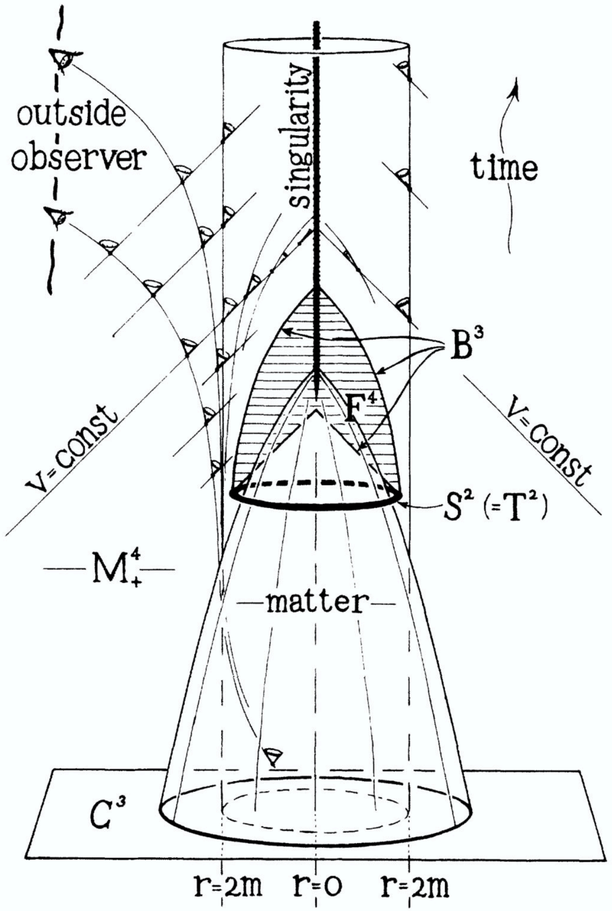
Reference
Van Putten, M.H.P.M. & Della Valle, M., 2021, under review
van Putten, M.H.P.M., Levinson, A., Frontera, Guidorzi, Amati, L. & Della Valle, M., 2019, EPJP, 134, 537

AI&ML for fundamental science Nov 15-17 2021

Outline

- Gravitational collapse to NS or BH
- GW-calorimetry applied to GRB170817A
- Rejuvenation in collapse with angular momentum
- Parameter estimation and PFA's
- Summary and conclusions

Gravitational collapse



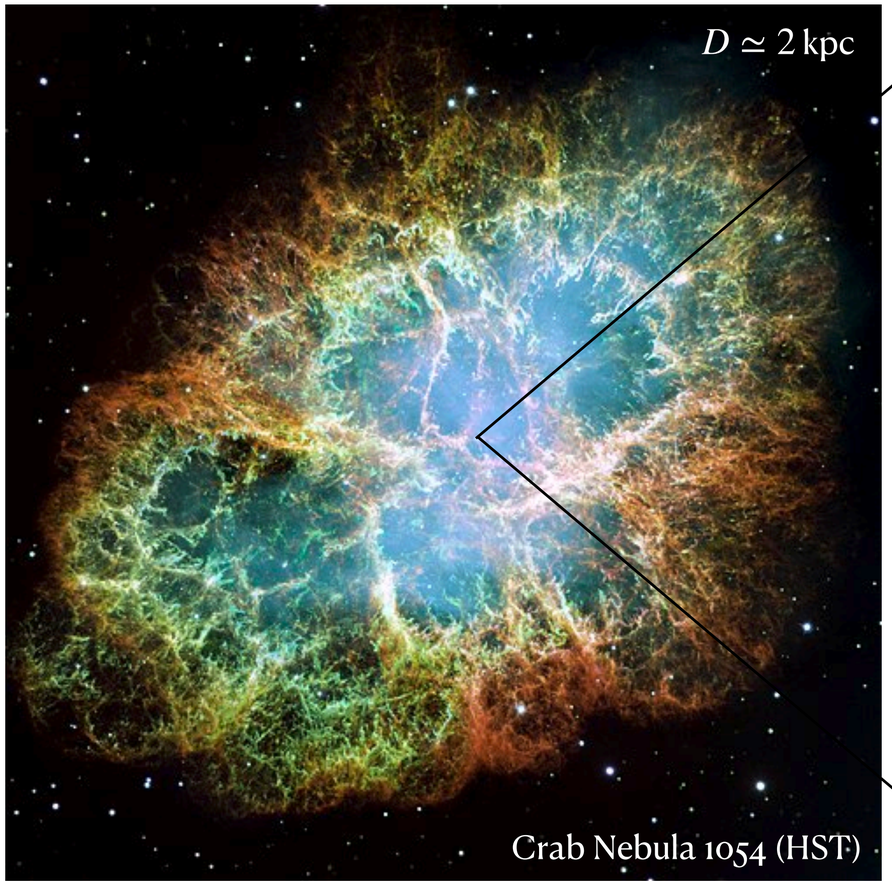
Roger Penrose
Reinhard Genzel
Andrea Ghez

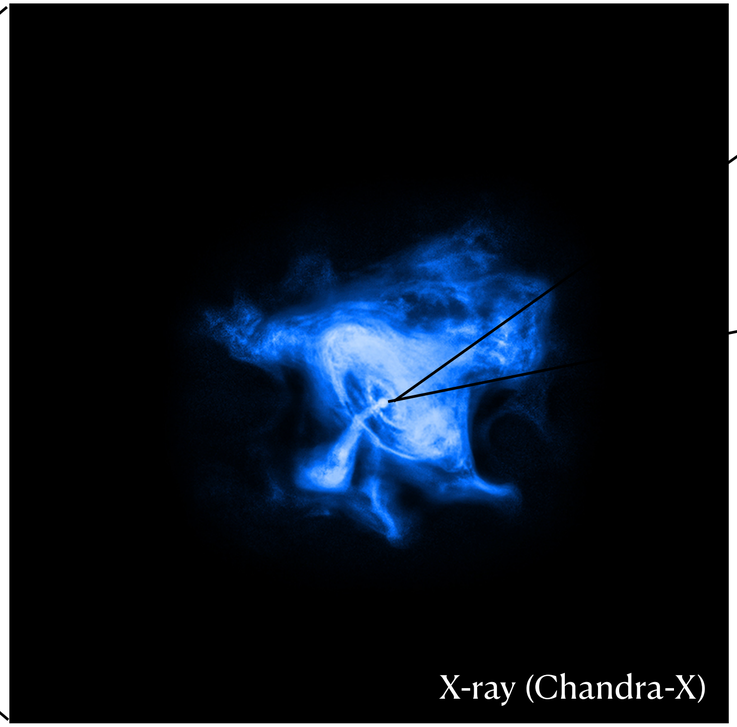
2020 Nobel Prize in Physics

Formation of "*Trapped surfaces*" from which no light shall escape: black holes of John Michel (1793) and Pierre Laplace (1795) introduce the correct radius of *Schwarzschild black holes*

Black hole formation is a robust prediction of general relativity

Supernova remnants



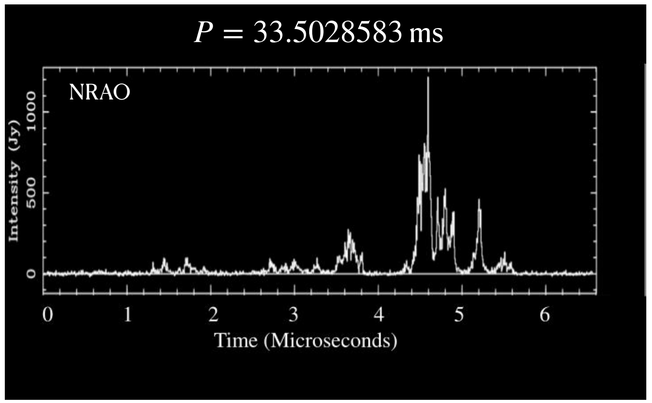


$R \simeq 10\,\mathrm{km}$

Rotating magnetized neutron star

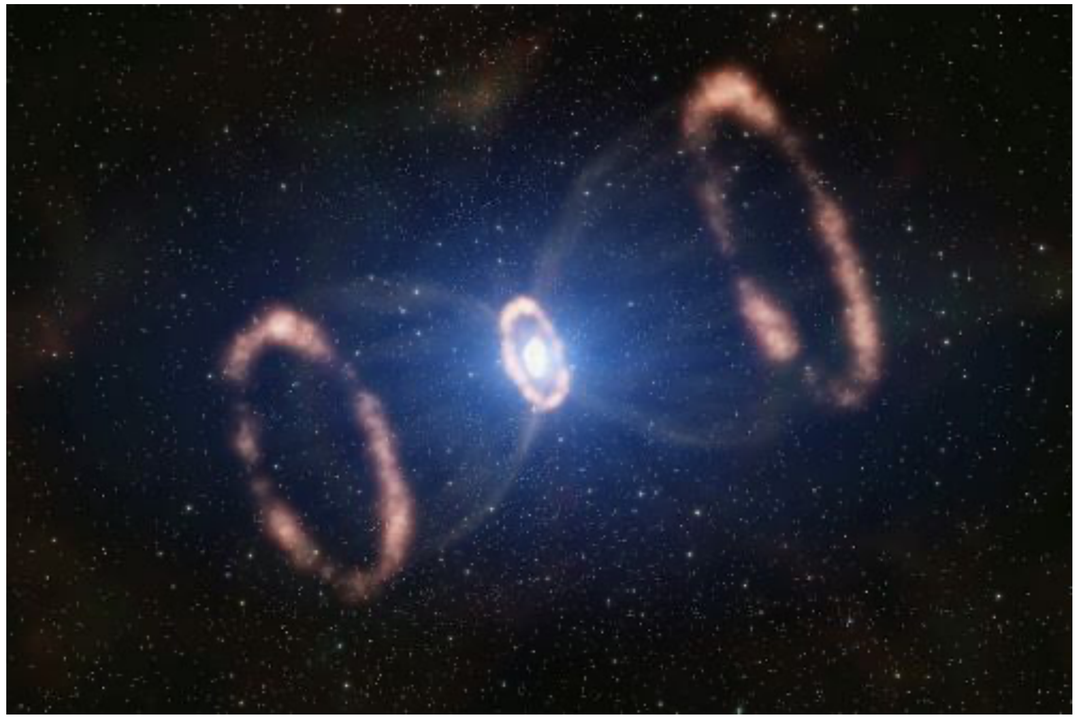
$M \simeq 1.4 M_\odot$

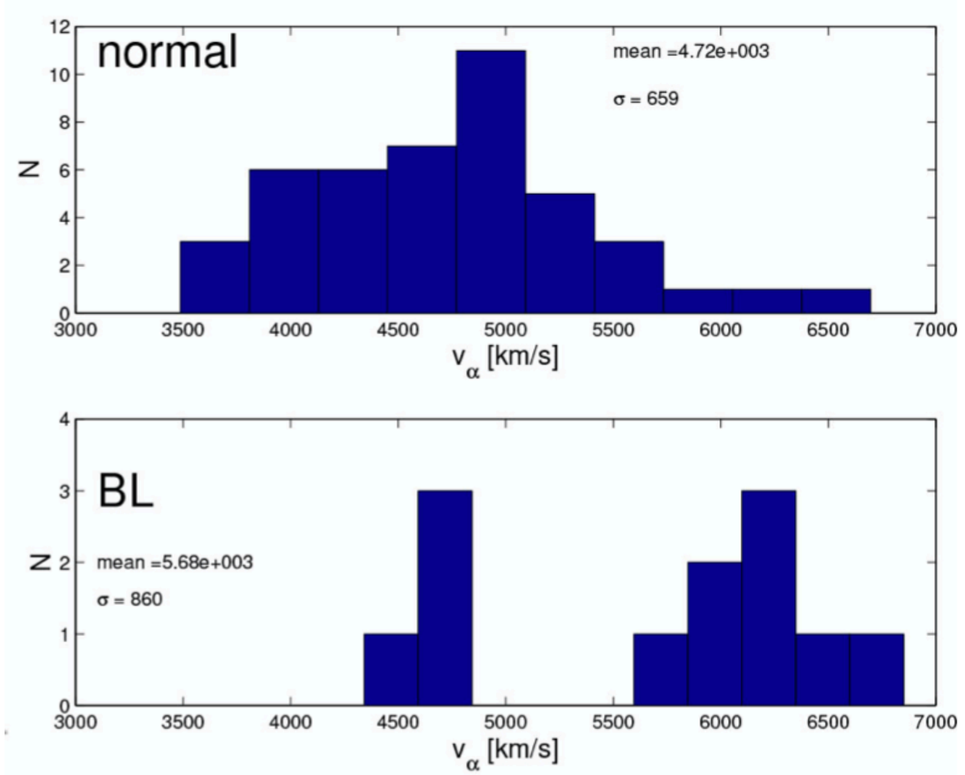
$$\Omega = \frac{2\pi}{P}$$



(J, μ) misaligned

Core-Collapse Supernovae





Maurer, Mazzali, Deng et al. 2010
van Putten, Della Valle & Levinson, 2011

Diverse population: factories of neutron stars and stellar mass black holes

… *stirred*

"Ideally, vodka martinis should be stirred, not shaken"

Angular momentum-rich gravitational collapse to *rotating* black holes

BMJ

BMJ 2013;347:f7255 doi: 10.1136/bmj.f7255 (Published 12 December 2013)

RESEARCH

CHRISTMAS 2013: RESEARCH

Were James Bond's drinks shaken because of alcohol induced tremor?

Graham Johnson *ST5 emergency medicine*[1], Indra Neil Guha *clinical associate professor of hepatology*[2], Patrick Davies *consultant paediatric intensive care*[3]

NS versus BH

CC-SNe likely powered by magnetic winds from an **angular momentum-rich central engine.**

Bisnovatyi-kogan 1970

A rapidly spinning magnetar or black hole

E_{gw} limited by central energy reservoir E_J

NS

$E_J \lesssim$ few $\% Mc^2$

Pulsars when (J, μ) misaligned

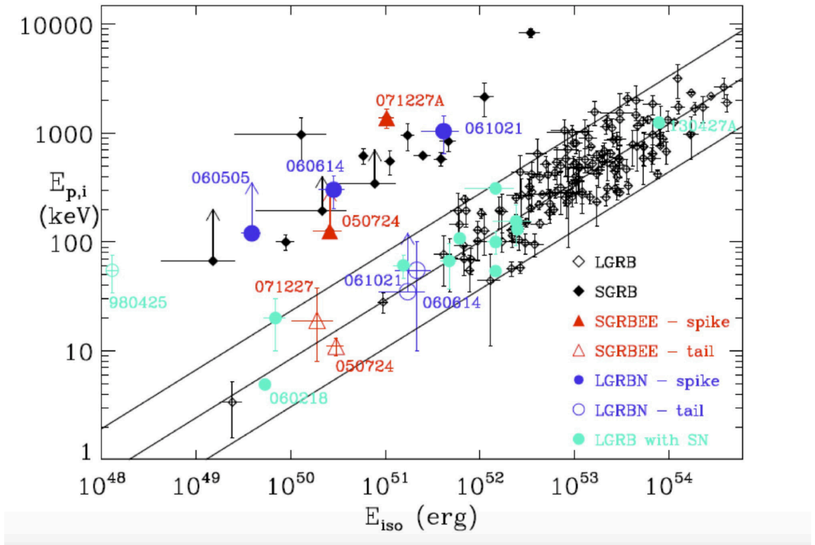
BH

$E_J \lesssim 30\% Mc^2$

Do *not* make pulsars,
(J, μ) aligned (Carter's theorem)

BH is potentially *far* more powerful than NS

LGRBs from rotating BHs?

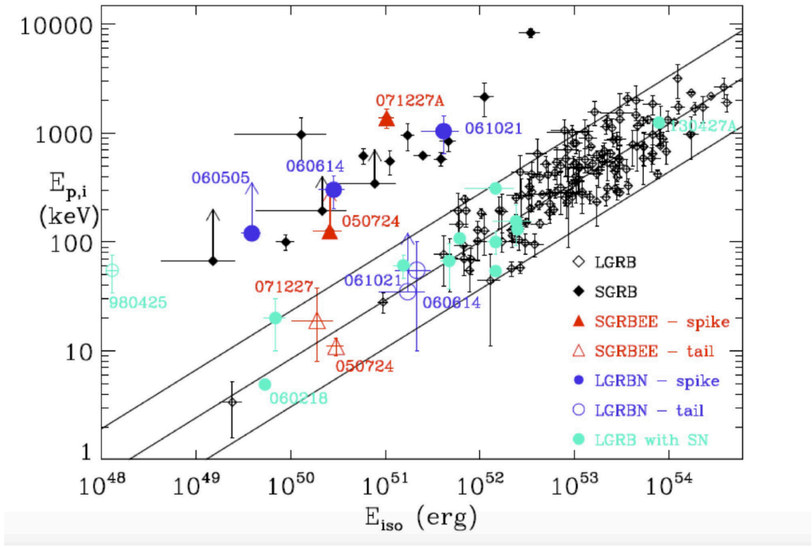


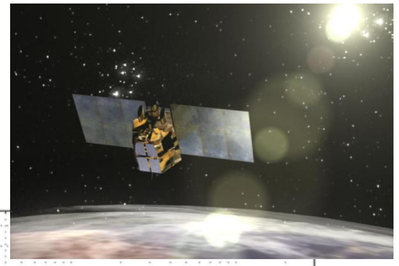
Amati relation LGRBs - SGRBEEs

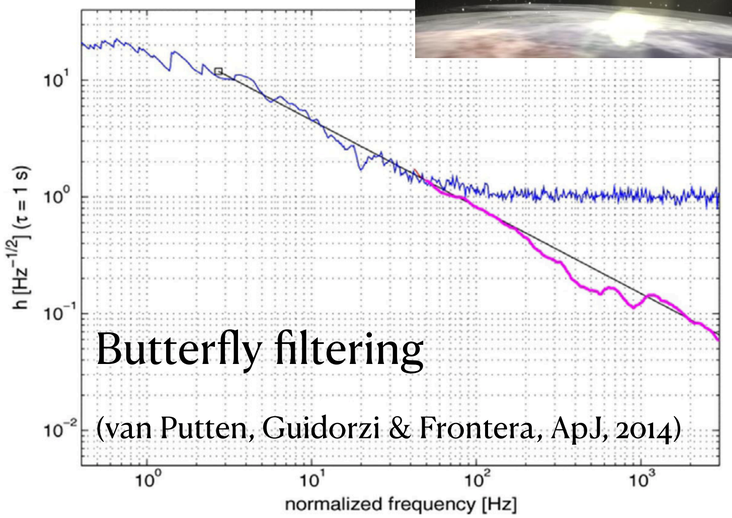
- SGRB(-EE)'s from mergers
- T90 of EE's tens of seconds >> accretion time

Duration T90: consistent with τ BH spin

LGRBs from rotating BHs?







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Broadband Komogorov spectrum of bright GRBs from *BeppoSAX*: *no* peak expected from proto-neutron stars

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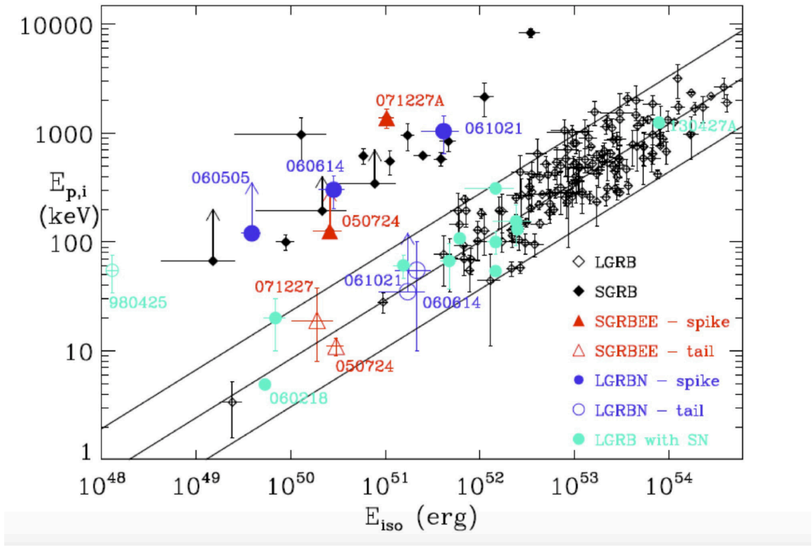

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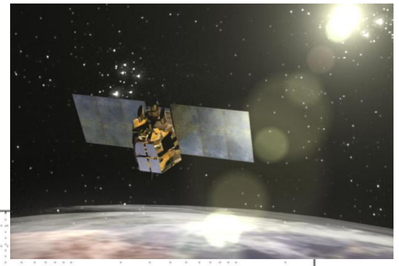
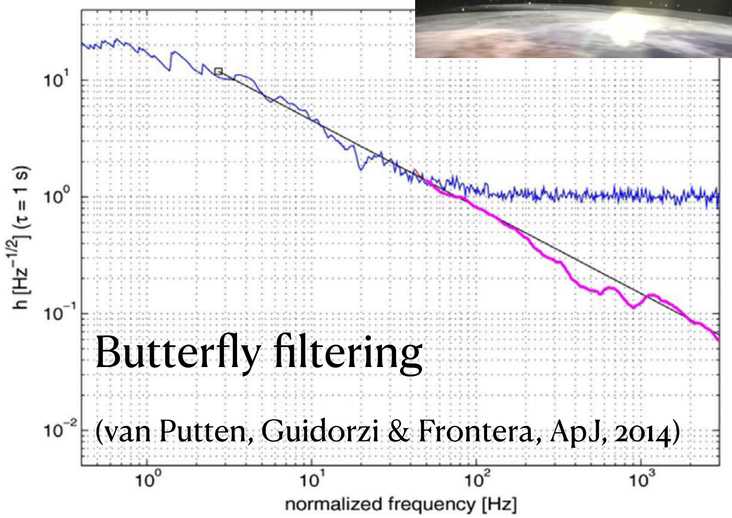
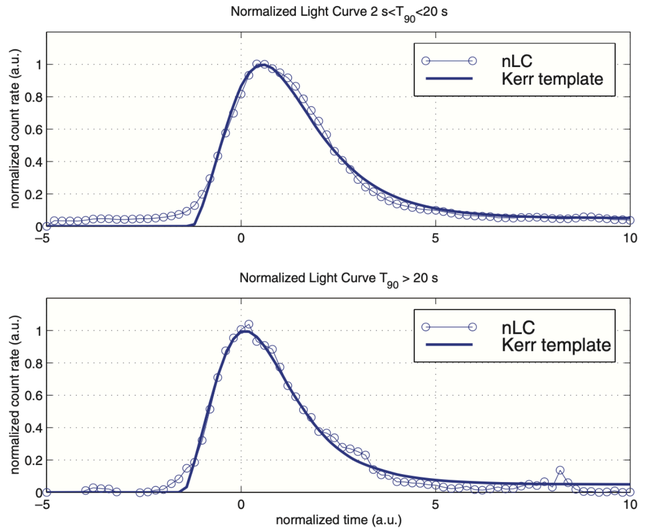




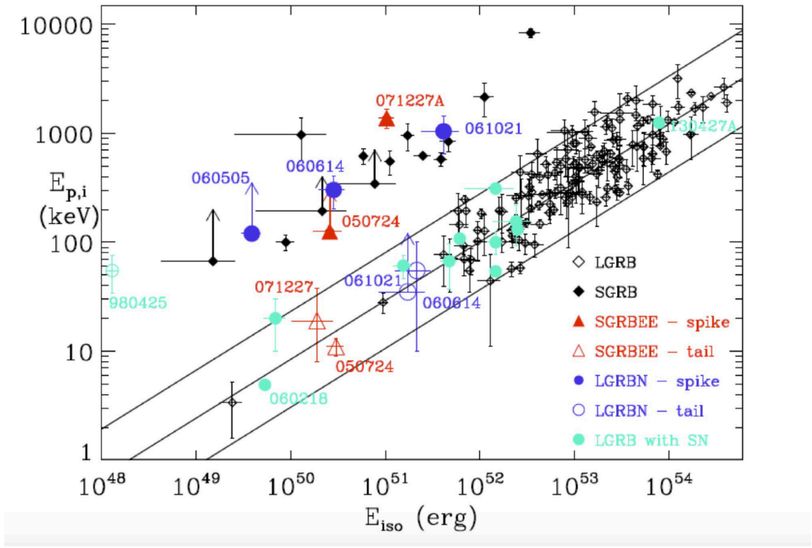
Broadband Komogorov spectrum of bright GRBs from *BeppoSAX*: *no* peak expected from proto-neutron stars



(van Putten & Gupta 2009)

nLC of BATSE 4B catalogue: consistent with BH spin-down

LGRBs from rotating BHs?



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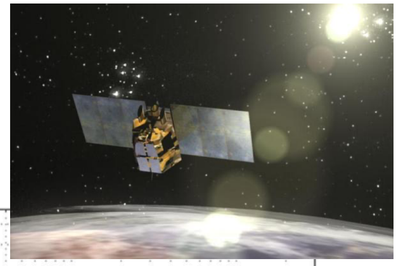
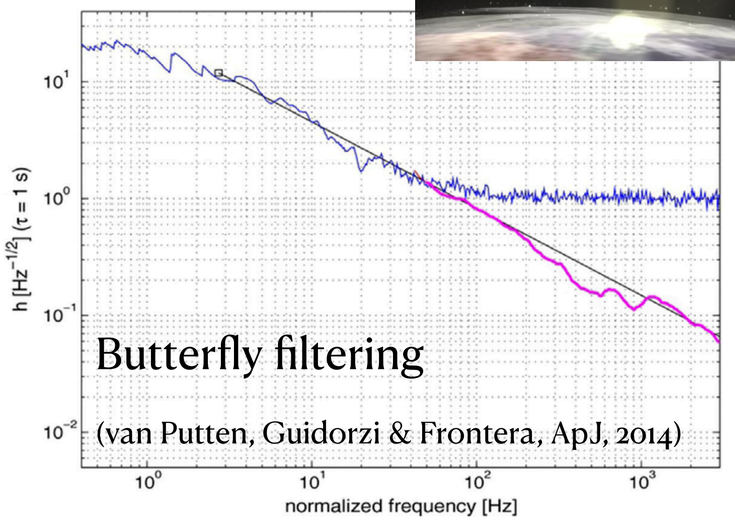
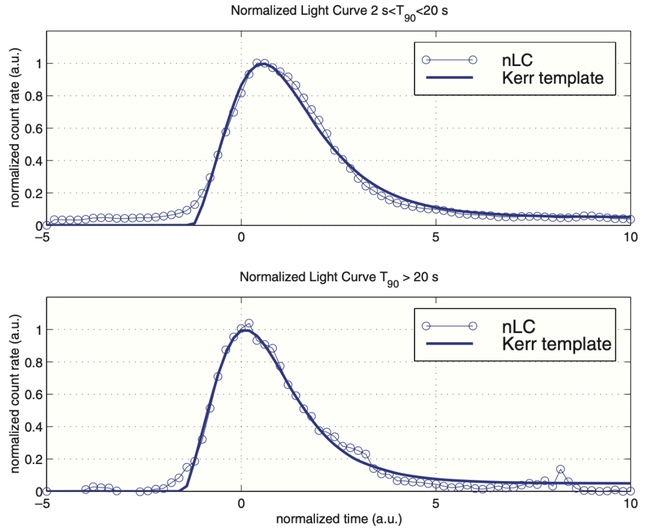




Broadband Komogorov spectrum of bright GRBs from *BeppoSAX*: *no* peak expected from proto-neutron stars

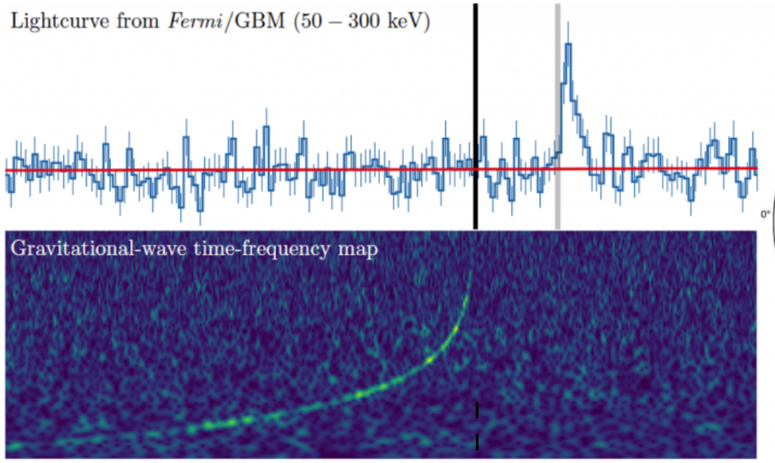


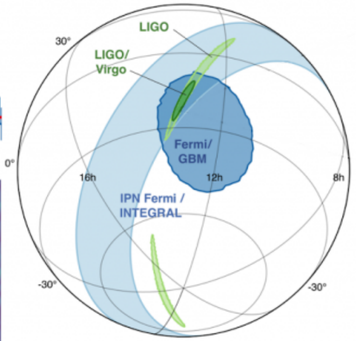
(van Putten & Gupta 2009)

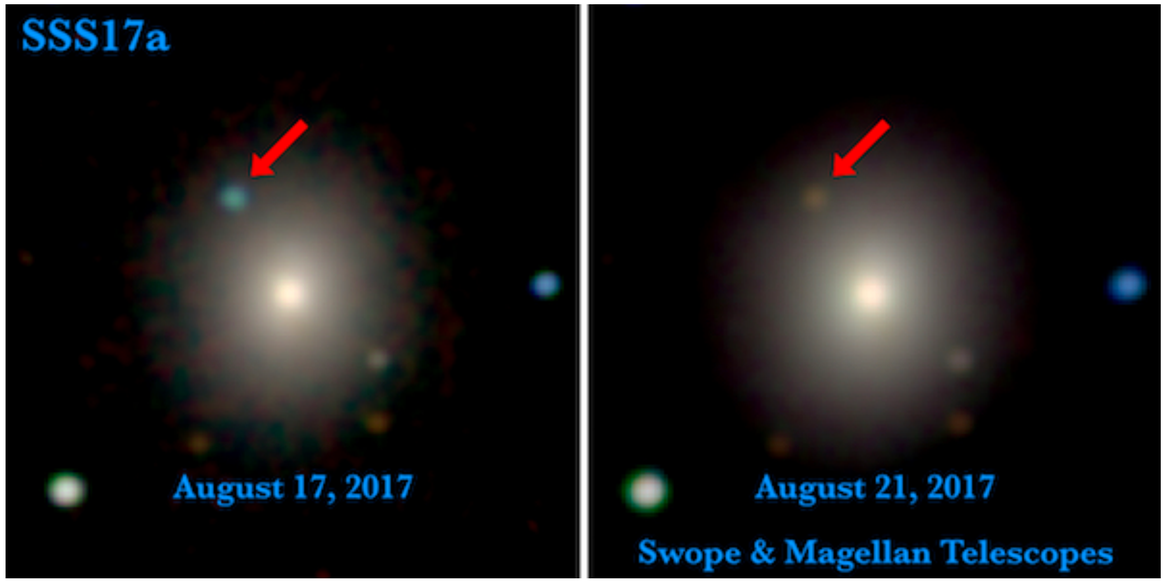
nLC of BATSE 4B catalogue: consistent with BH spin-down

True calorimetry in EM, ν and GWs?

GW170817-GRB170817A

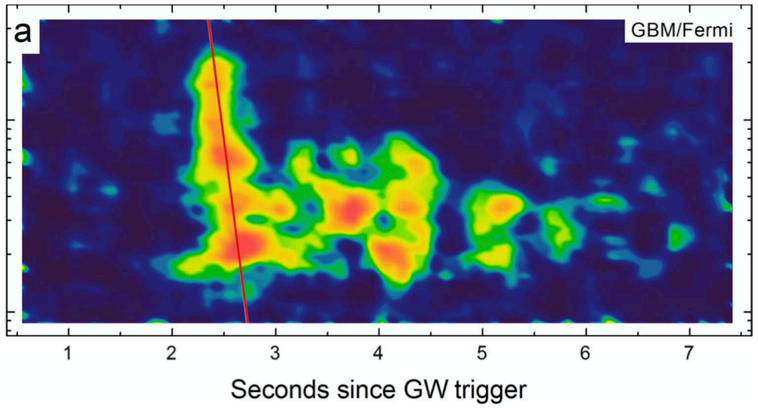






300 Earth masses of gold (at $D = 40$ Mpc in NGC 4993)

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



Pozanenko et al. 2018

Merger time t_m

NS or BH central engine?

Gravitational radiation

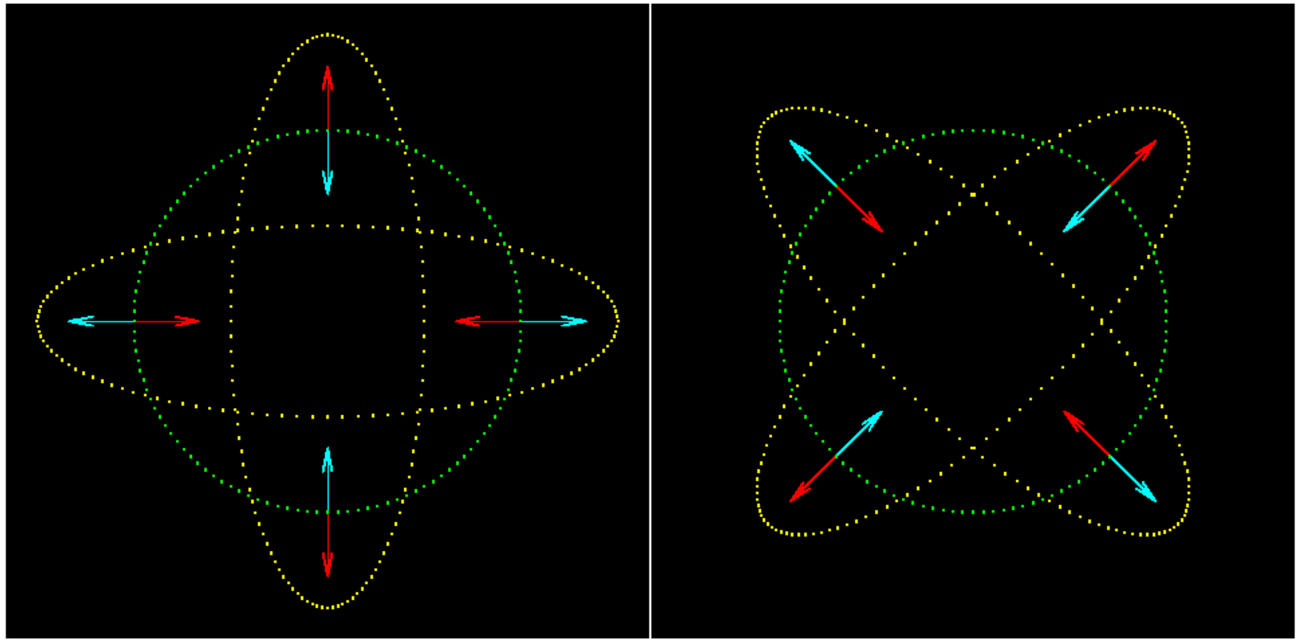
Fundamental constant of luminosity

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

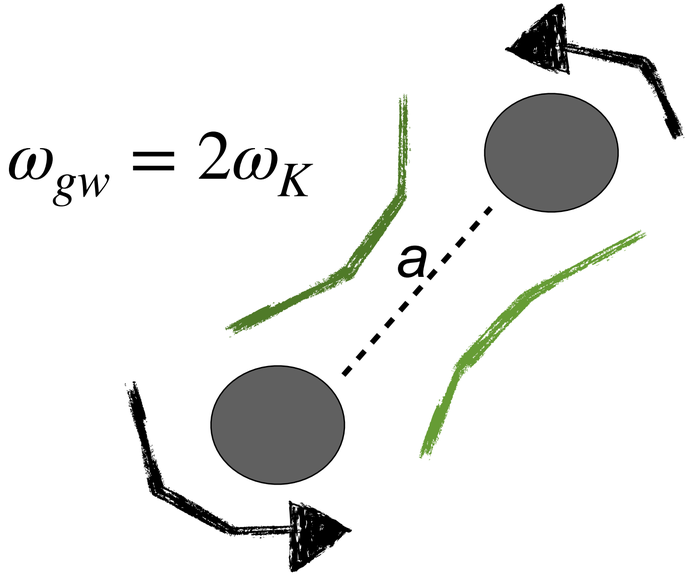
.. hypothetically from a black hole exploding in a light-crossing time scale $t_c = R_g/c$

ESO/M. Kornmesser

Gravitational radiation



http://carina.astro.cf.ac.uk/groups/relativity/research/part4.html

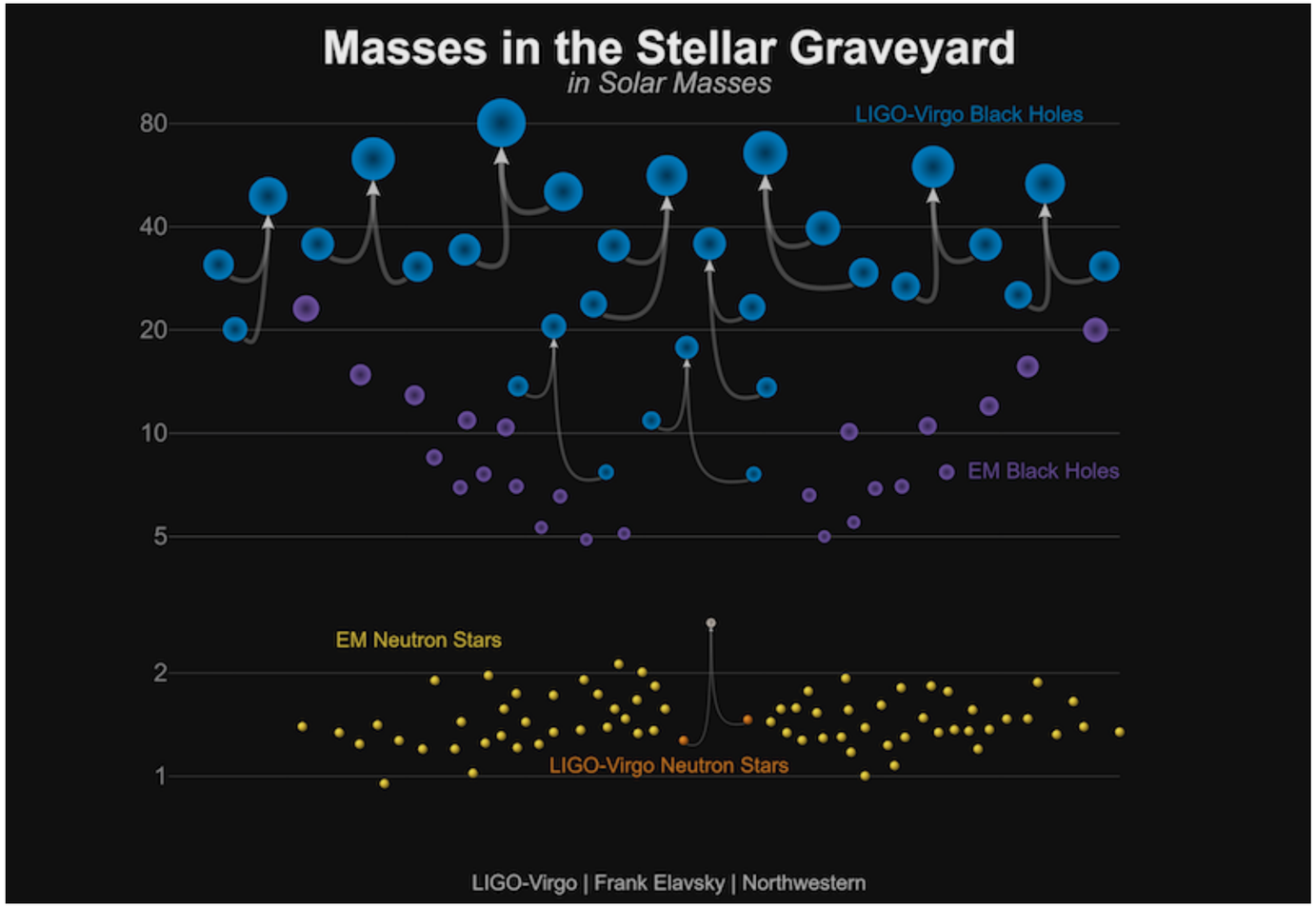


Chirp mass $\mathscr{M} \simeq 2^{\frac{1}{5}} R_g$

$$L_{gw} = \frac{32}{5} \left(\mathscr{M}\Omega_K\right)^{\frac{10}{3}} L_0$$

Observable = “tiny quadrupole perturbation” x L_0

LIGO catalogue of mergers

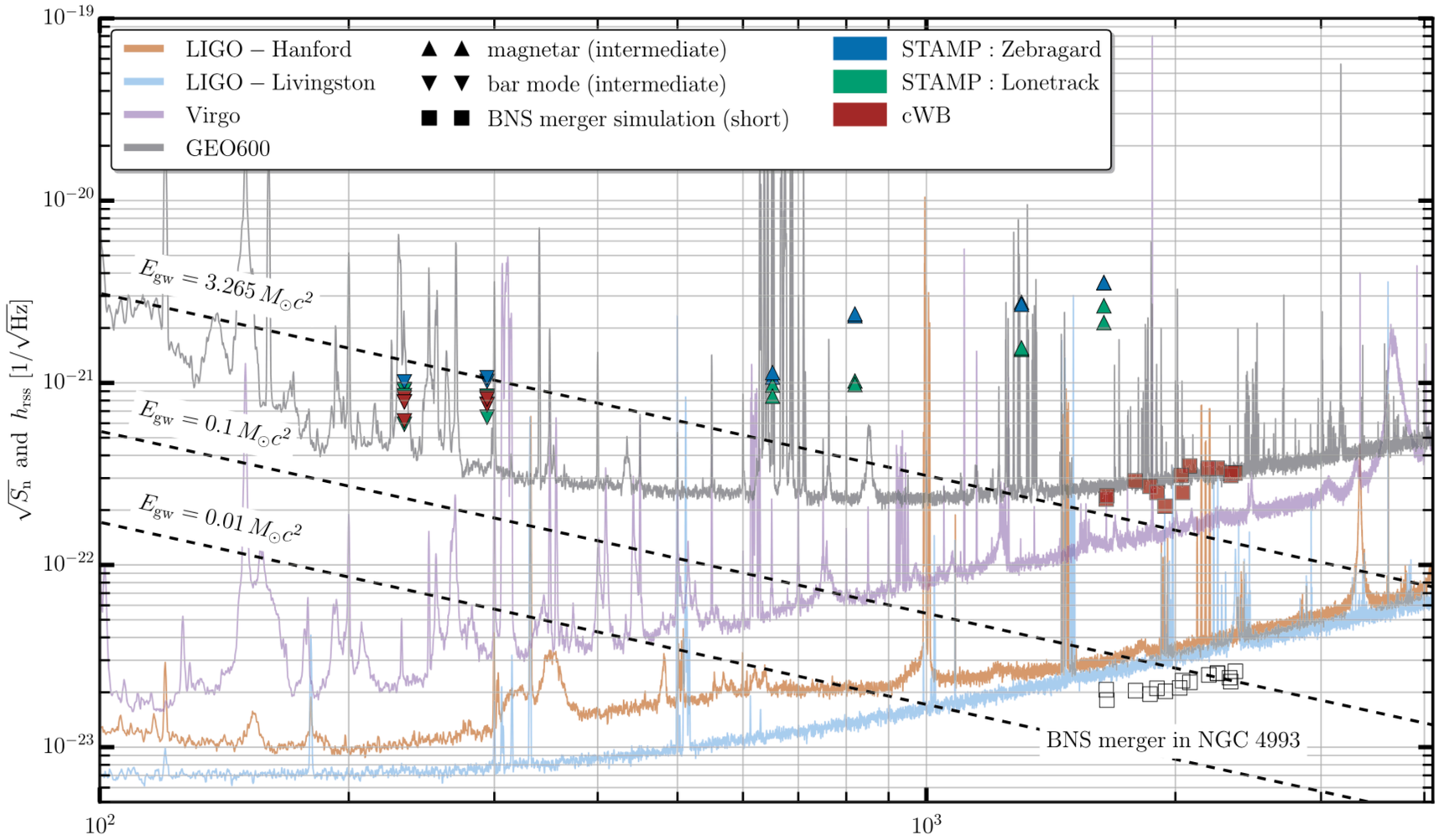


Credit: Visualization: LIGO -Virgo / Frank Elavsky, Aaron Geller / Northwestern

Some astronomical properties

Hye-Jin Park, Shin-Jeong Kim, Shinna Kim, van Putten, 2021, in prep.

Explore by GWs

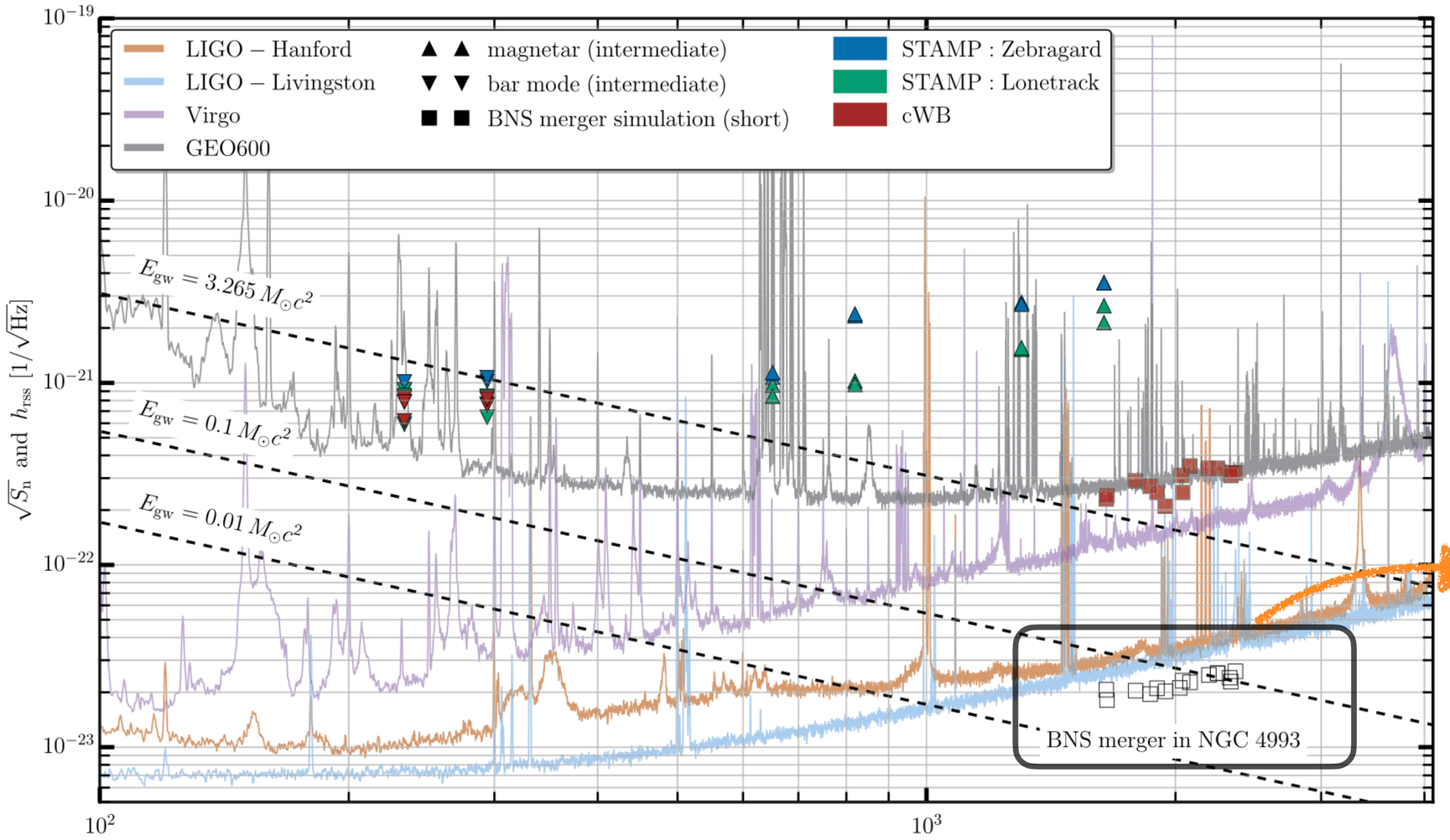


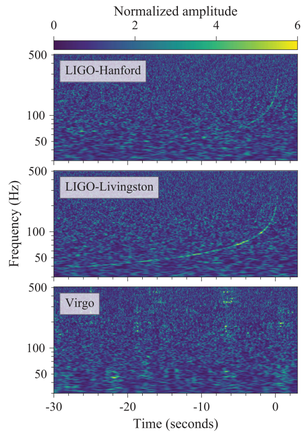
Gravitational strain

Gravitational frequency

Search scope

Gravitational strain





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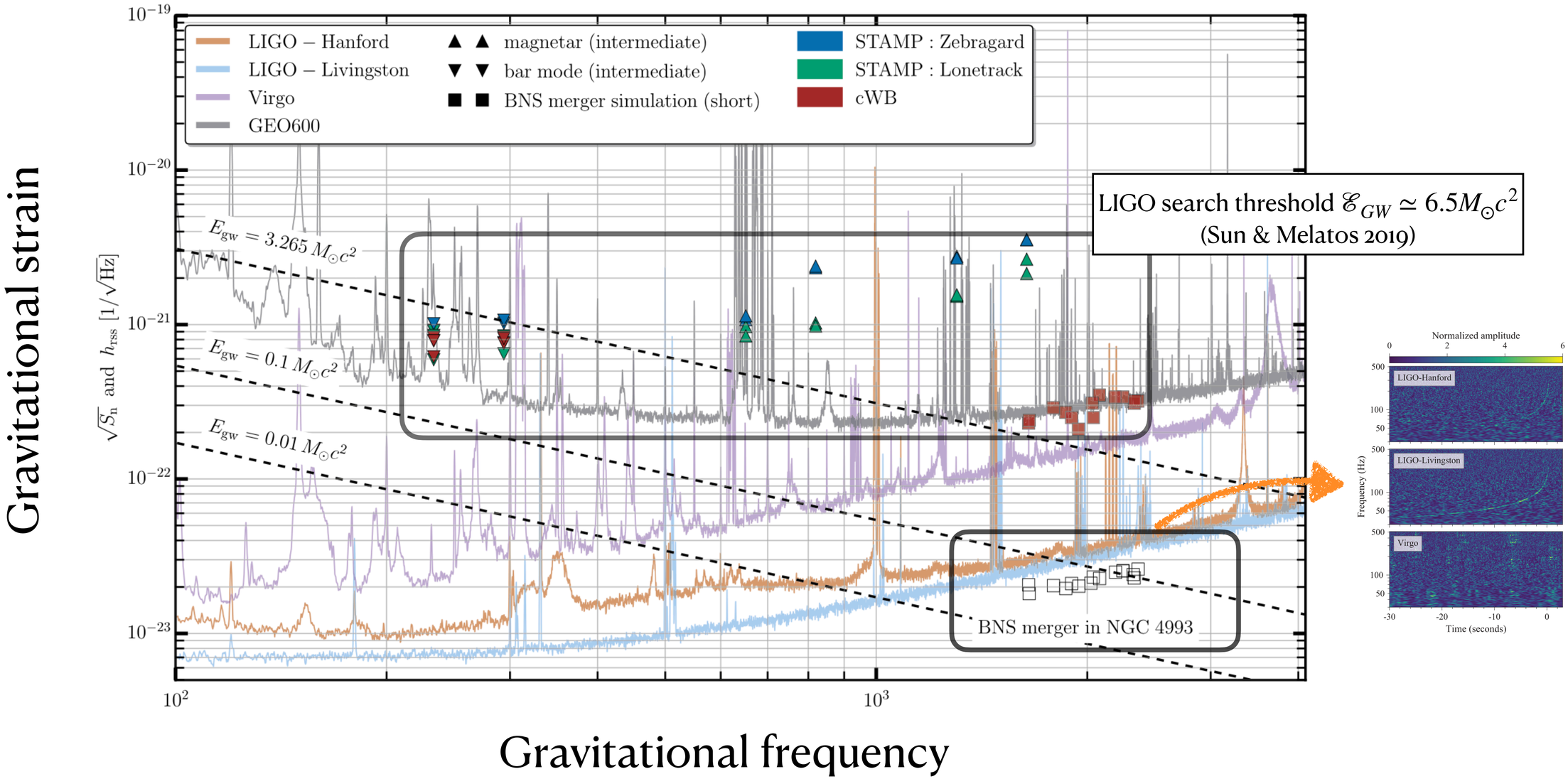

Gravitational strain

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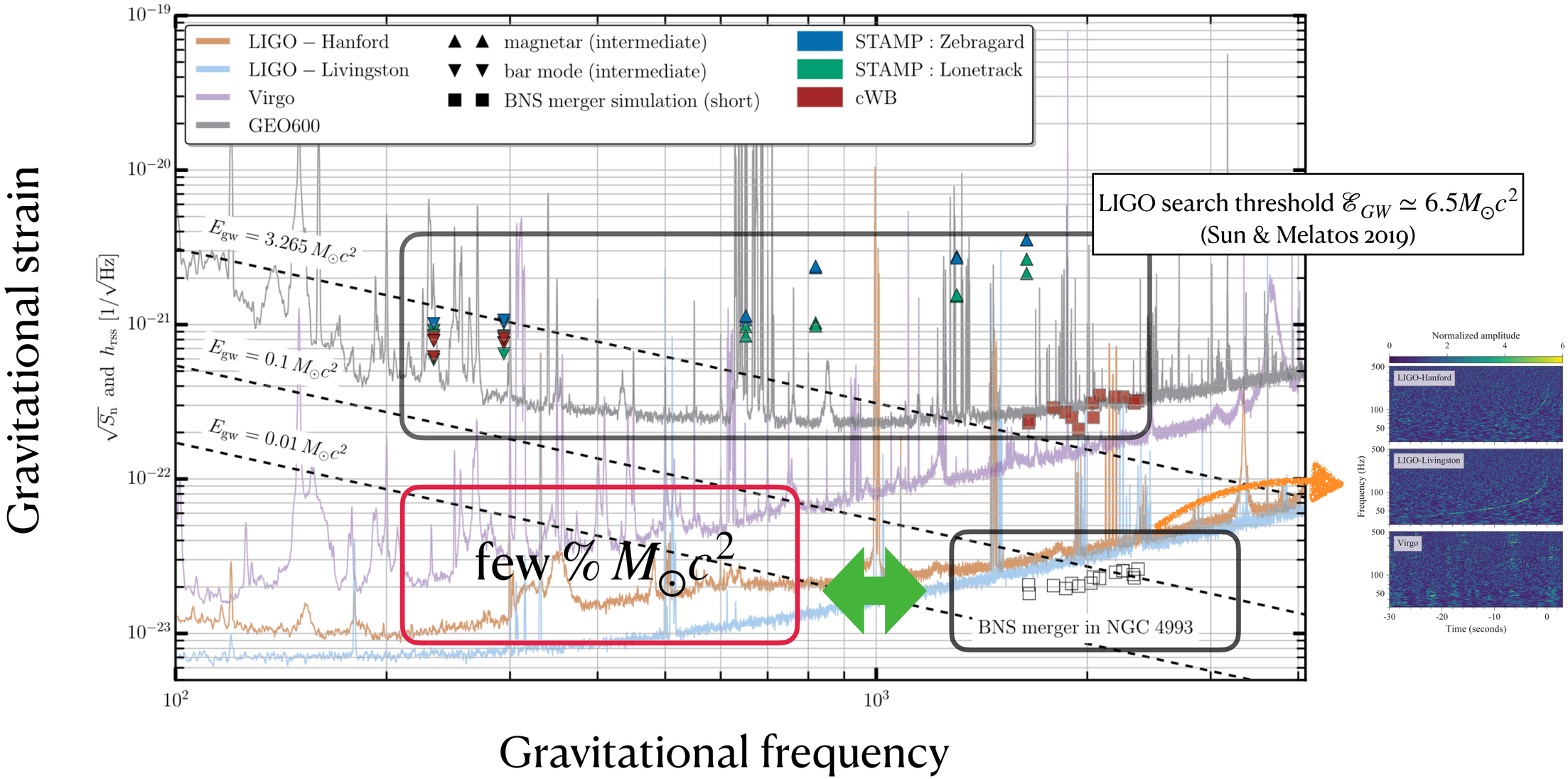
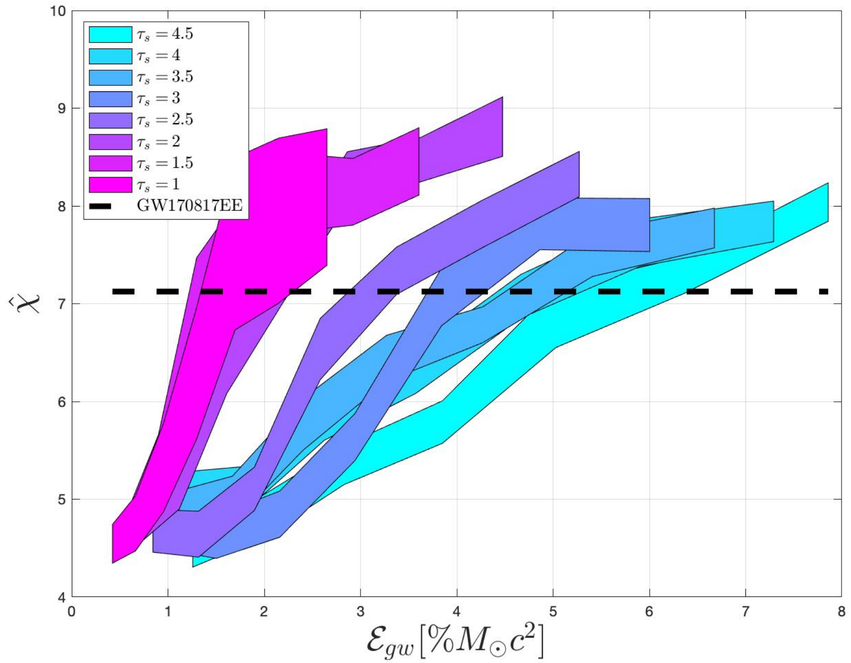
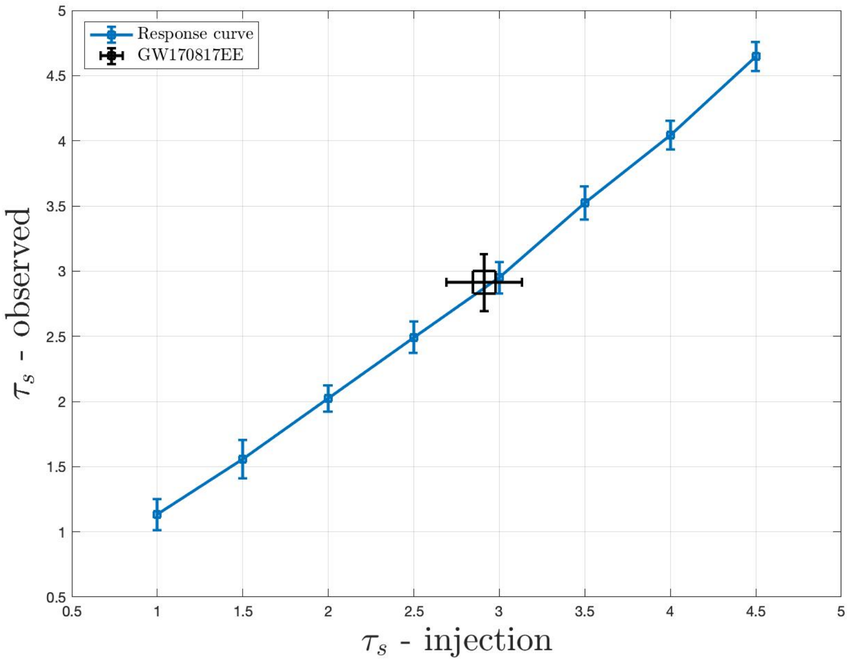


Gravitational strain

Gravitational frequency

Butterfly filtering response curves





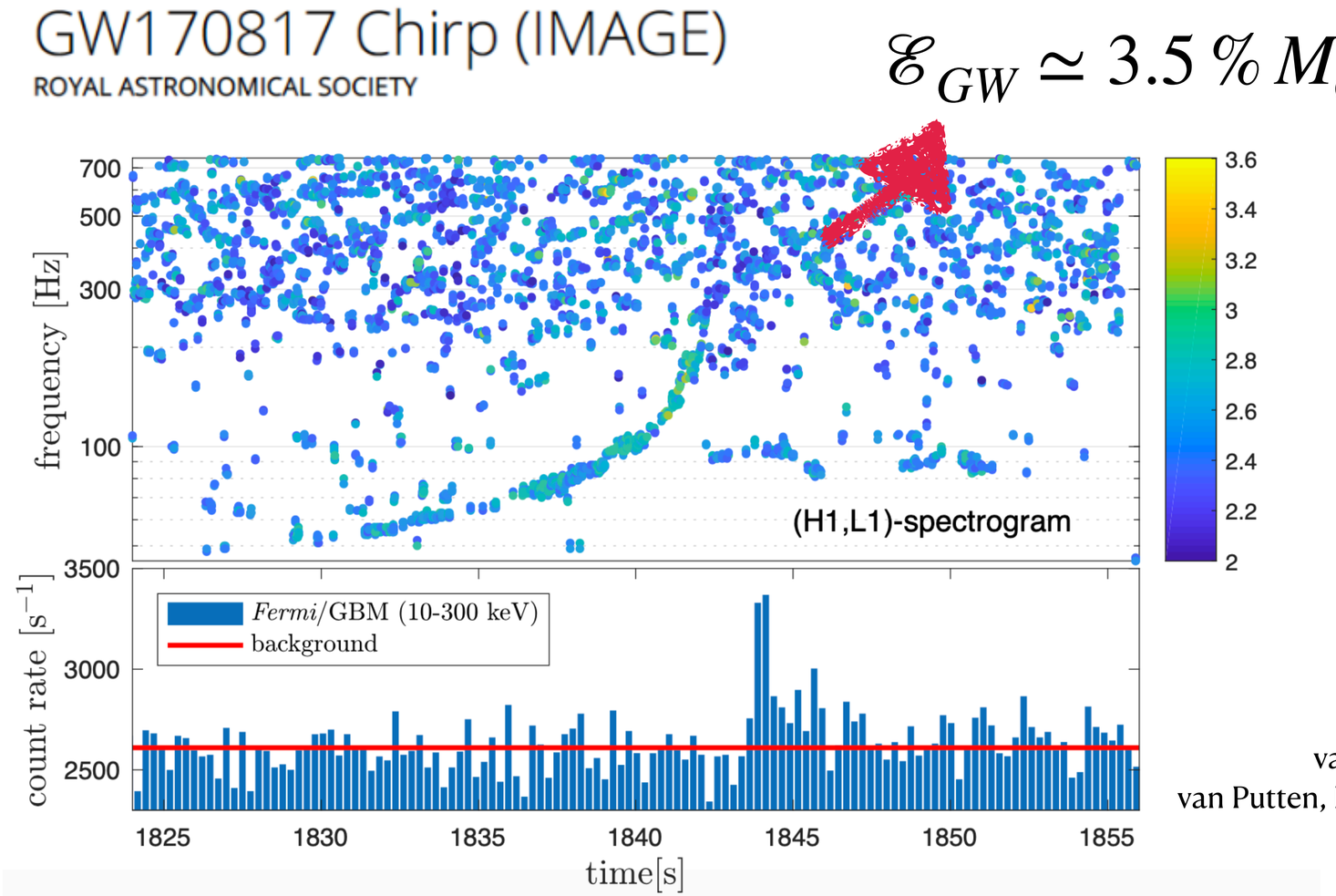
Search threshold $\mathscr{E}_{GW} \simeq 1\,\%\,M_\odot c^2$

Relative sensitiviy $= \dfrac{\text{merger}}{\text{post-merger}} \sim 1$

Movie in *.mp4 https://zenodo.org/record/4390382

$$\text{Relative sensitiviy} = \frac{\text{un-modeled search}}{\text{modeled search}} \sim 1$$

GW-calorimetry



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

van Putten & Della Valle 2019
van Putten, Della Valle & Levinson 2019

$\mathscr{E}_{GW}$ indicates NS or BH?

From NS?

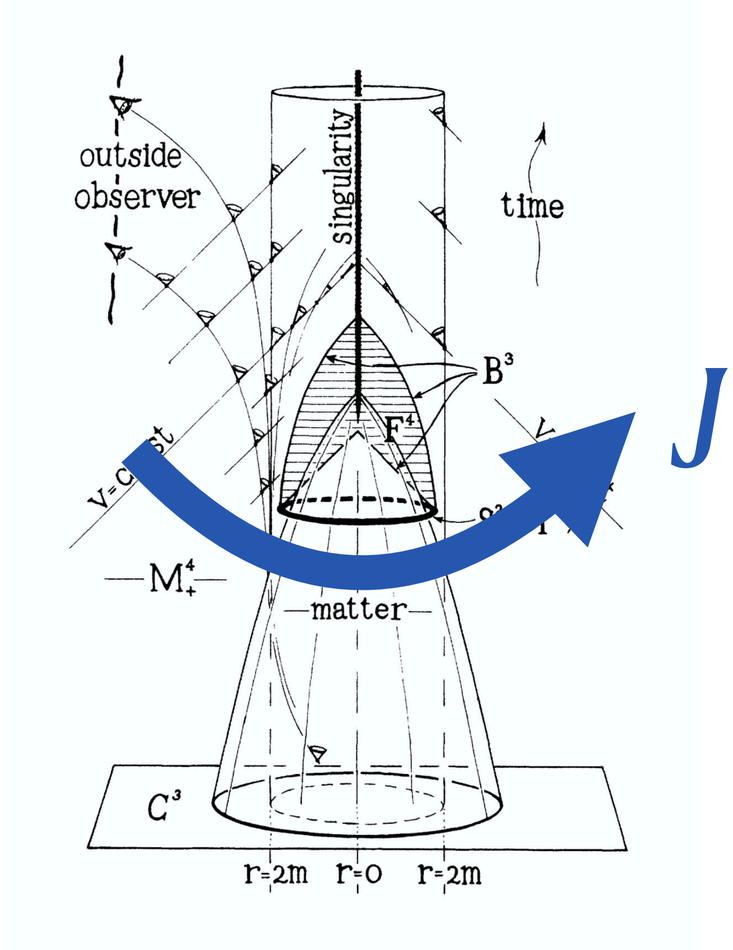
$\mathscr{E}_{GW} \simeq 3.5\,\% M_\odot c^2$ post-merger descending chirp

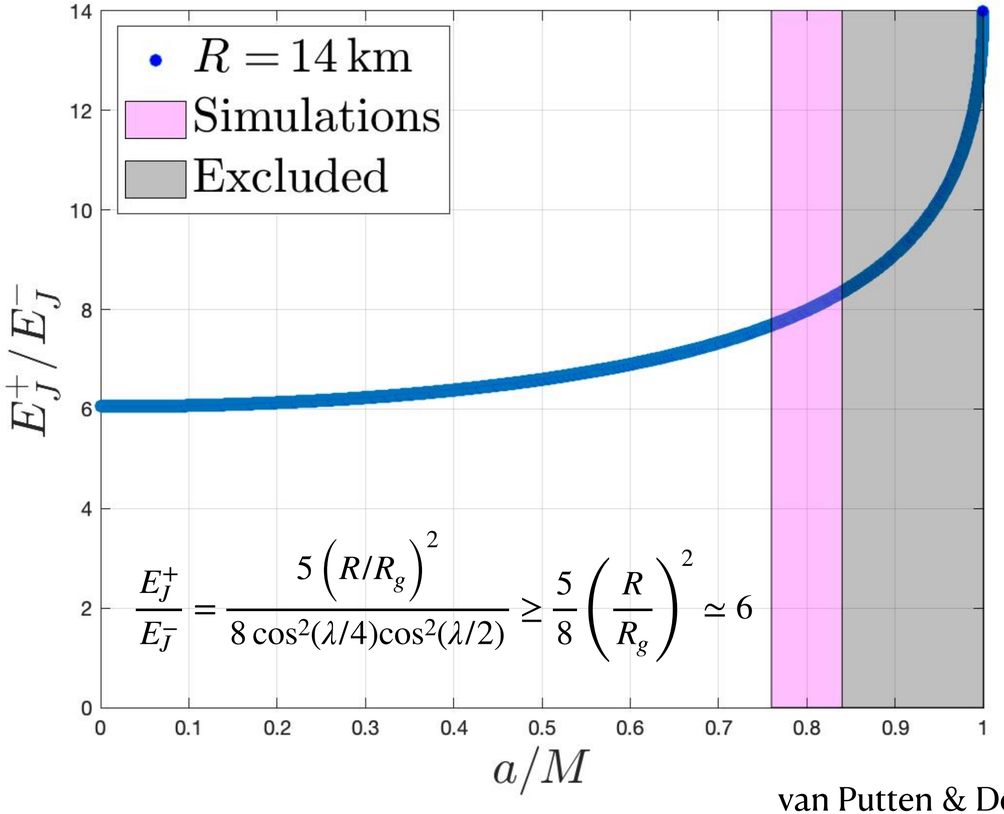
$$f_{gw} \lesssim 700\,\mathrm{Hz}\, f_{spin} = \frac{1}{2} f_{gw} \lesssim 350\,\mathrm{Hz}$$

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

HNS is energetically ruled out by a factor of at least 4

Rejuvenation in *stirred* collapse

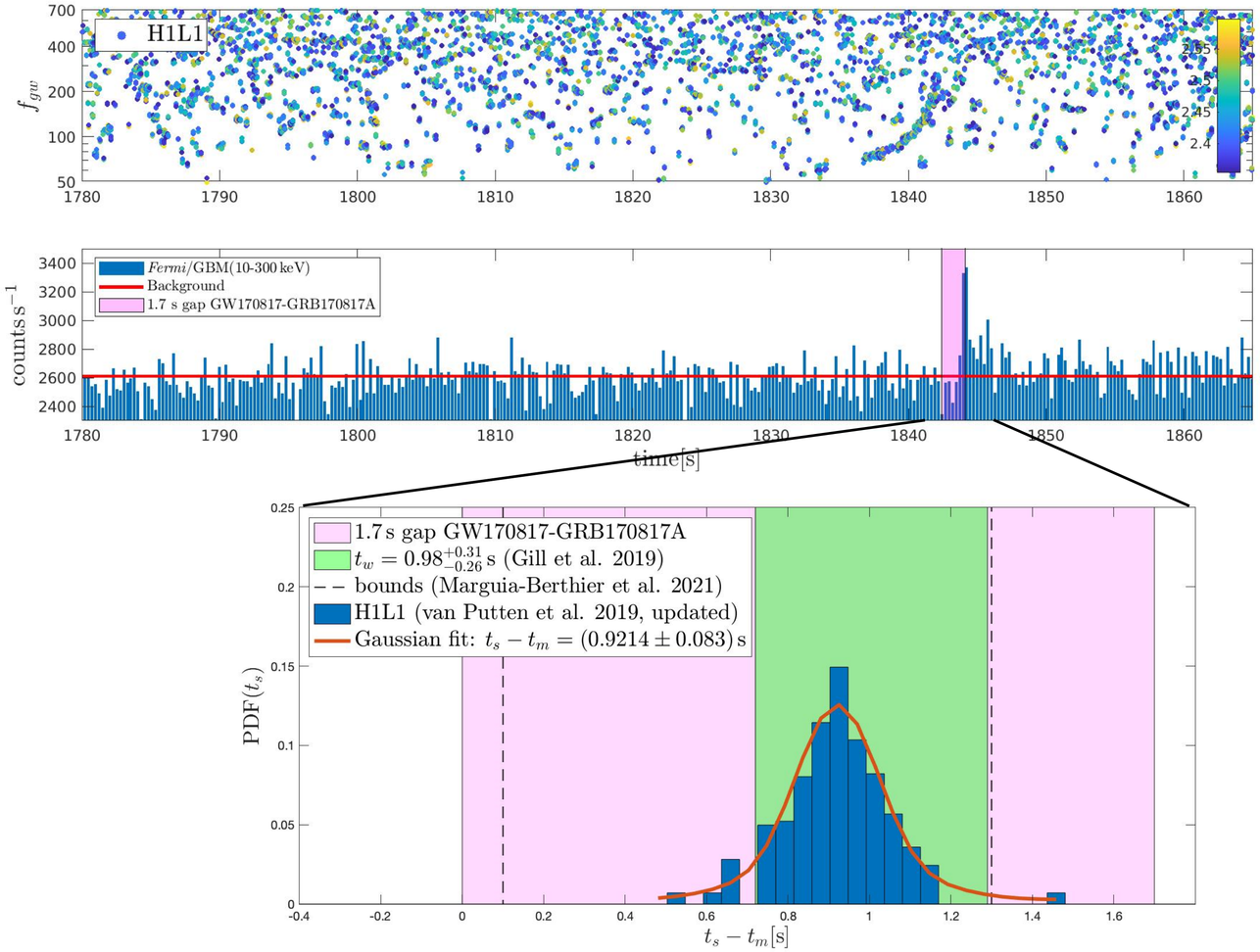




van Putten & Della Valle, under review

HNS defines (M, J), E_J^- ➡ BH with $E_J^+ \gg E_J^-$

Gravitational collapse *in the 1.7 s gap*



GW170817EE

GRB170817A

Start-time in the 1.7 gap

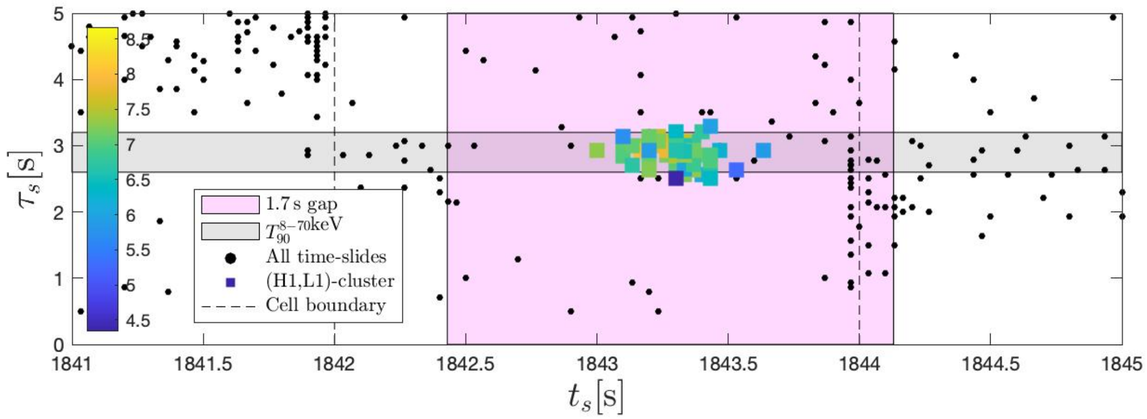
$$t_s = (0.92 \pm 0.1)\ \text{s} \simeq t_w = (0.98 \pm 0.3)\ \text{s}$$

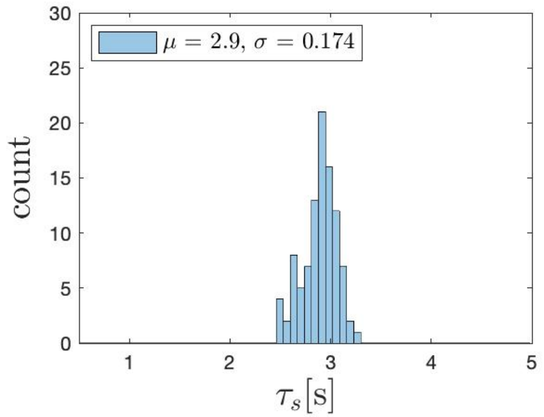
GW-data EM-data (Gill et al. 2019)

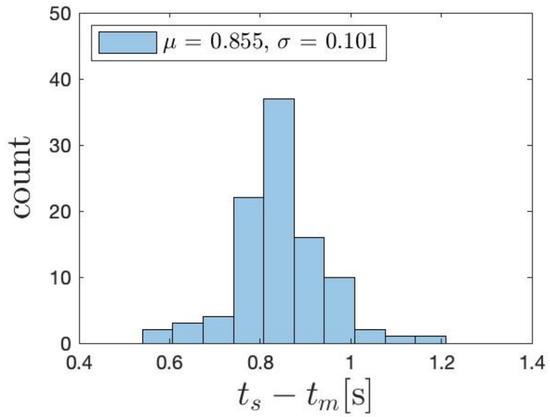
PFA: $p_1 = 1.7/2048$

van Putten & Della Valle, 2021, under review
AI&ML 2021/2

Parameter estimation







$$\tau_s \simeq T_{90}^{8-70\mathrm{keV}}$$

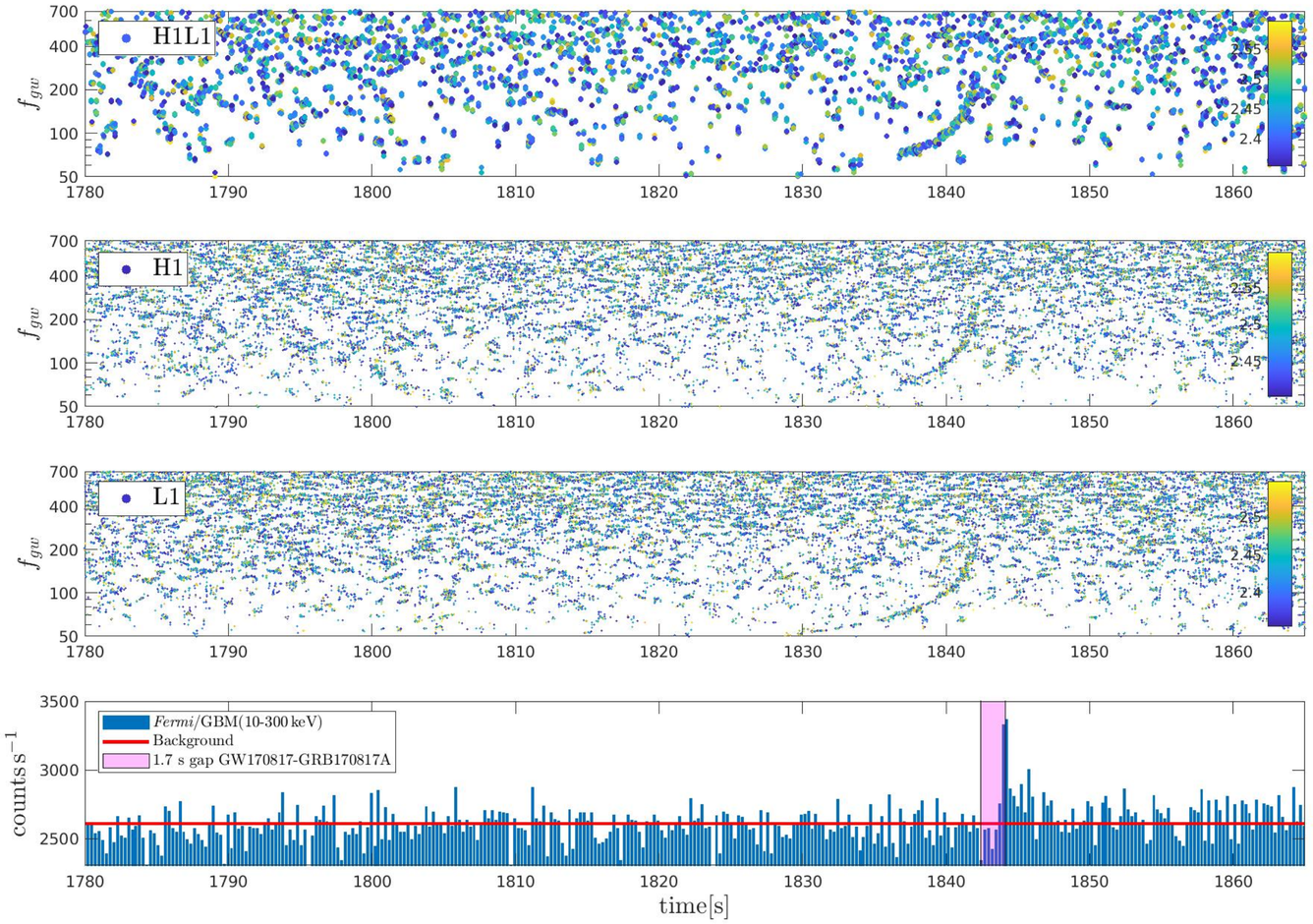
Consistency

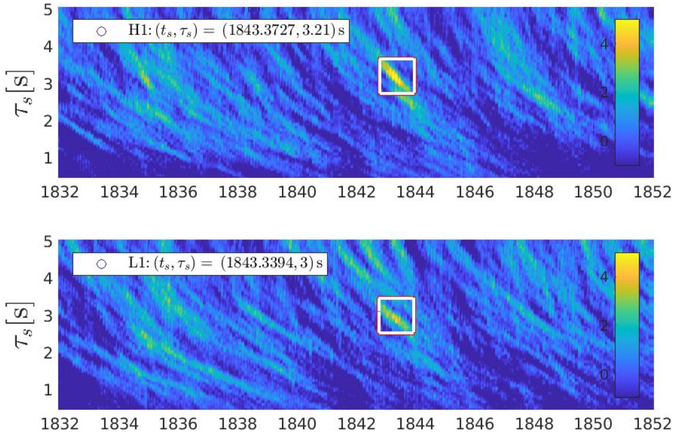
- Duration EE in GWs
- Duration GRB170817A

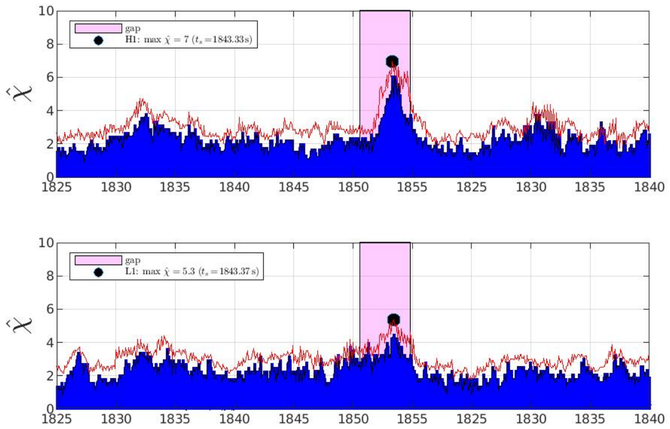
Consistency duration GRB170817A, EE in GWs and τ of BH-spin

Independent H1- and L1-analysis

$$f_{gw}(t) = (f_s - f_0)\, e^{-\frac{t - t_s}{\tau_s}} + f_0$$



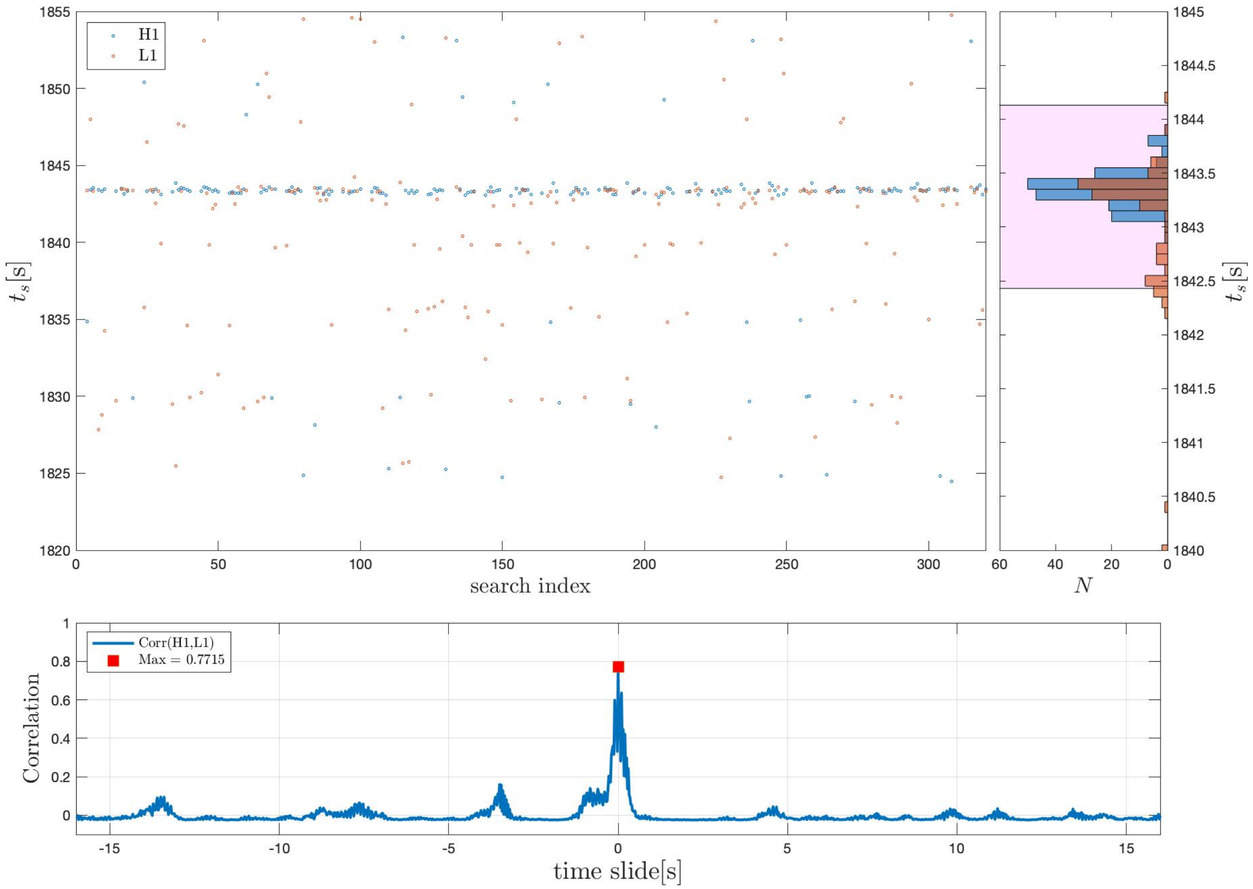




van Putten & Della Valle, 2021, under review

Same parameter estimates (t_s, τ_s) from H1 and L1 individually

Cross-correlation PDF(t_s) of H1 and L1



van Putten & Della Valle, 2021, under review

PFA: $p_2 = 4 \times 0.025/2048$

Conclusions and outlook

GW1701817: Delayed collapse to a BH by GW-calorimetry and timing (PFA = 4×10^{-8})

- **Multilevel un-modeled data-analysis**
  - Spectrograms generated butterfly MF (enhancement over intermediate time scales)
  - Parameter extraction by χ-image analysis - suitable for AI&ML?
  - PDFs generated by time-slide analysis and multiple trials (template seeds, stride in output)

Conclusions and outlook

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  - Spectrograms generated butterfly MF (enhancement over intermediate time scales)
  - Parameter extraction by χ-image analysis - suitable for AI&ML?
  - PDFs generated by time-slide analysis and multiple trials (template seeds, stride in output)
- **Implementation by heterogeneous computing**
  - Mixed C++/F90/C99 software under OpenCL (“HPC”)
  - High throughput: 6x real-time @200kHz correlations per GPU-node with HBM2 (“HTC”)
  - Dynamical load balancing over a synaptic LAN

Conclusions and outlook

GW1701817: Delayed collapse to a BH by GW-calorimetry and timing (PFA = 4×10^{-8})

- **Multilevel un-modeled data-analysis**
  - Spectrograms generated butterfly MF (enhancement over intermediate time scales)
  - Parameter extraction by χ-image analysis - suitable for AI&ML?
  - PDFs generated by time-slide analysis and multiple trials (template seeds, stride in output)
- **Implementation by heterogeneous computing**
  - Mixed C++/F90/C99 software under OpenCL ("HPC")
  - High throughput: 6x real-time @200kHz correlations per GPU-node with HBM2 ("HTC")
  - Dynamical load balancing over a synaptic LAN
- **Upcoming observations in O4 LIGO-Virgo-KAGRA in 2022**
  - Expect the un-expected from angular momentum-rich gravitational collapse (recall SN1987A)
  - Signals may include ascending and descending chirps!

"GW detection is one of the most exciting and expanding scientific frontiers impacting central questions in astronomy"

(Pathways to Discovery in A&A for the 2020s, Decadal Survey 2021, p42; https://www.nationalacademies.org/event/11-04-2021/pathways-to-discovery-in-astronomy-and-astrophysics-for-the-2020s-public-briefing)