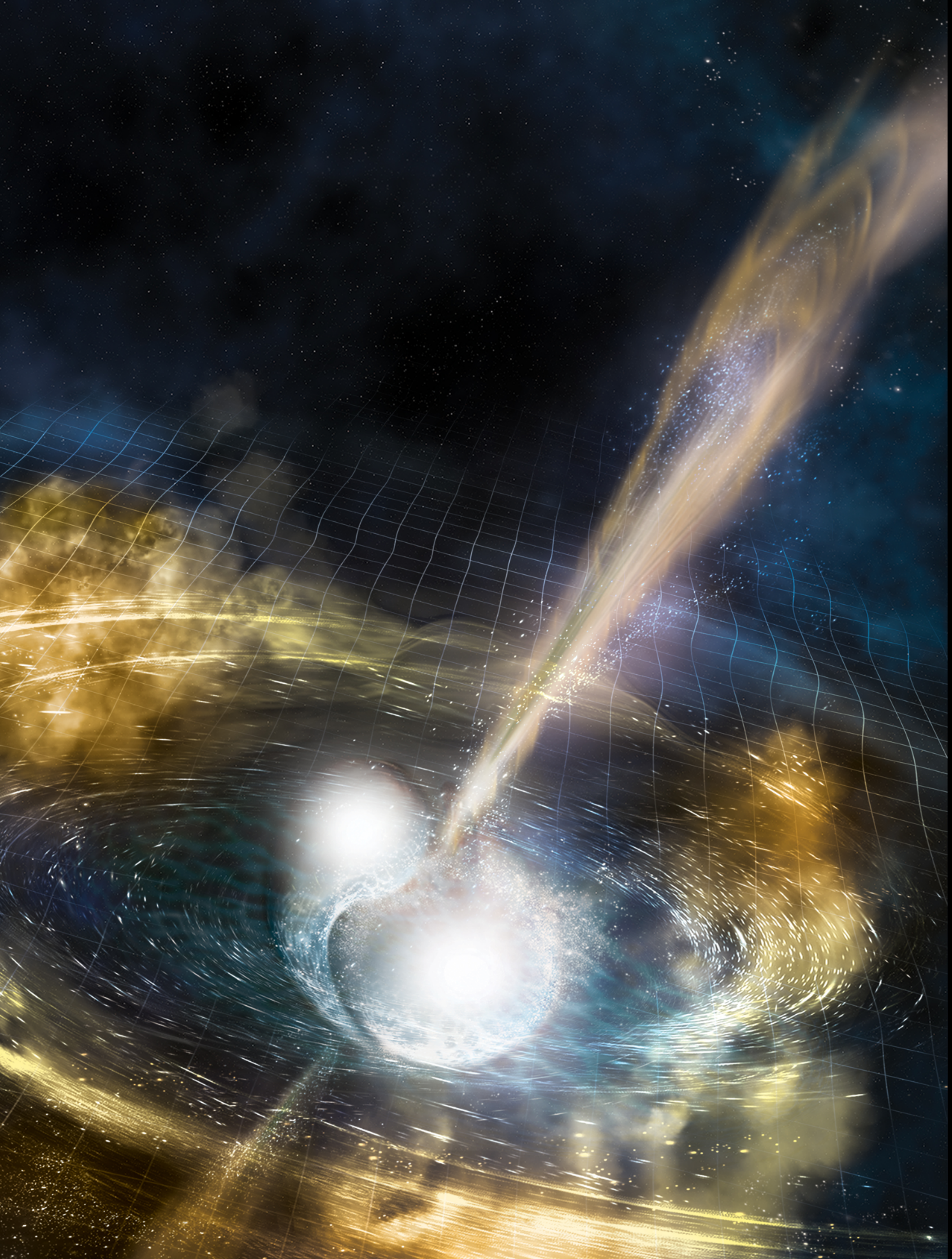
NSF/LIGO/Sonoma State University/Aurore Simonnet



# THE ROBUSTNESS OF THE ASSOCIATION OF GW170817 AND GRB 170817A

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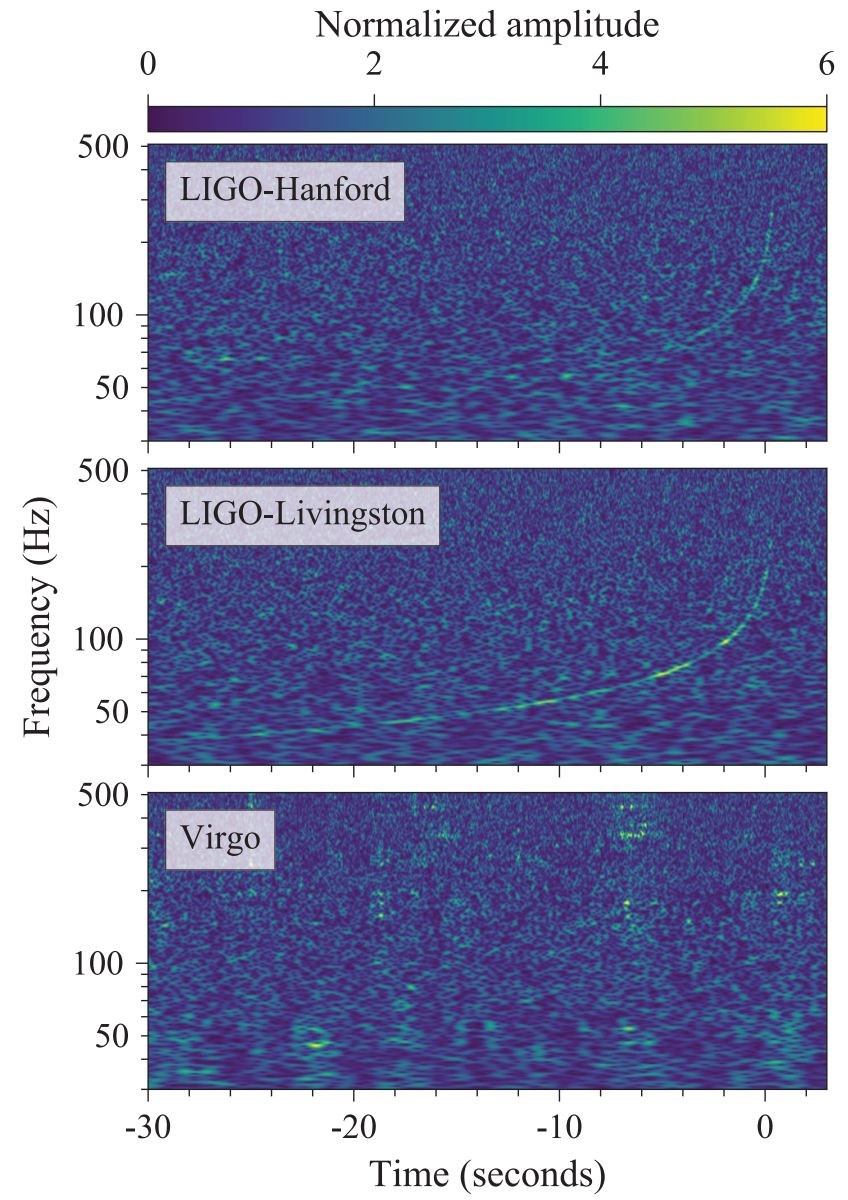
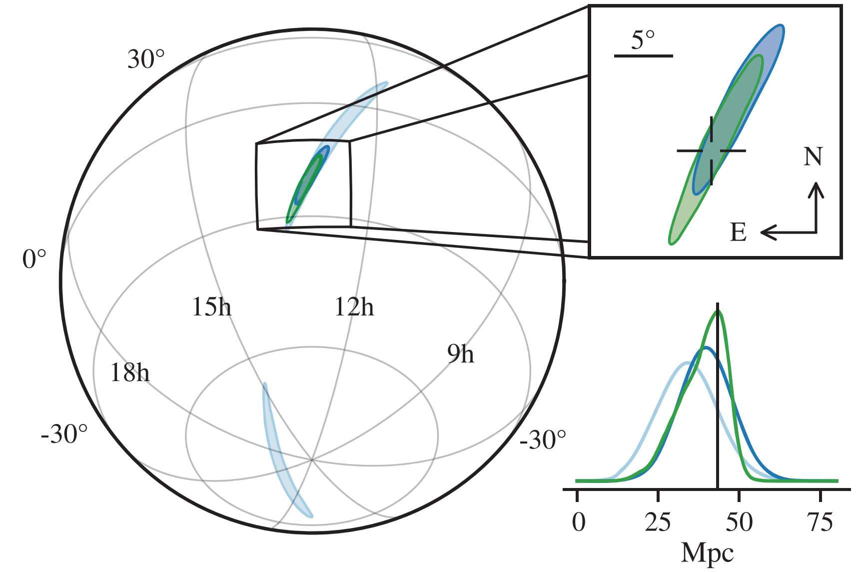
MG 16 – July 5, 2021



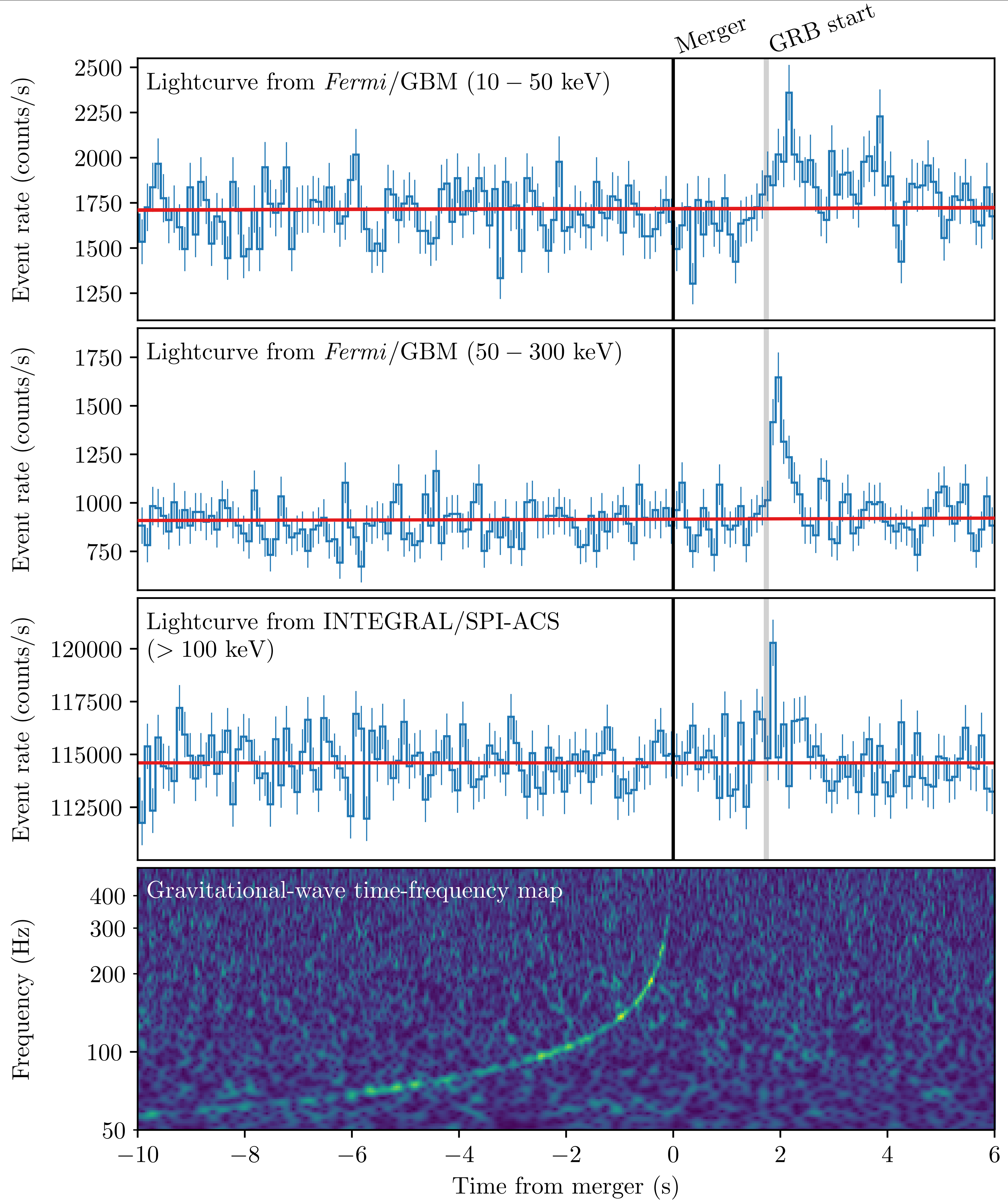

# GW170817

- Observed by the LIGO-Virgo Collaboration in low-latency and confirmed offline by all-sky, coincident searches [Cannon+ 2012; Messick+ 2017; Usman+ 2016; Nitz+ 2017]

- SNR=32.4 and false-alarm-rate < 1 in 80,000 years [LVC, PRL **119**, 161101 (2017); LVC, PRX **9**, 011001 (2019)]

- First GW inspiral signal consistent with a binary neutron star source

- 28 deg$^2$ sky localization at 90% probability

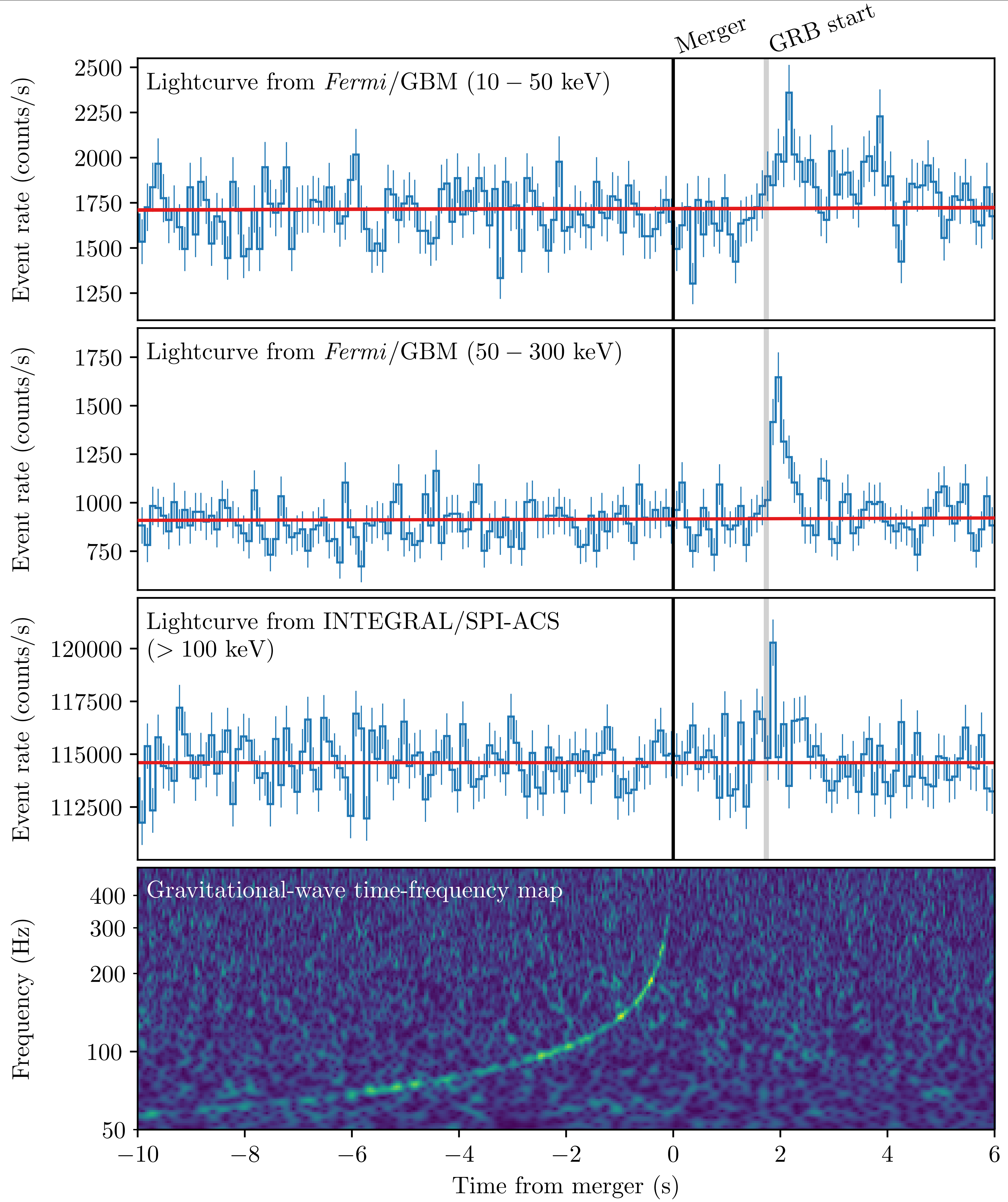



[LVC & *Fermi* GBM & INTEGRAL, ApJL **848**, L13 (2017)]

# GRB 170817A

- Signal exceeds 5σ in 3 of the 12 NaI detectors of Fermi GBM
- ~0.5 s standard triggering pulse + subsequent softer, weaker, few seconds long emission
- $T_{90}$ = (2.0 ± 0.5) s, fluence = (1.4 ± 0.3) × $10^{-7}$ erg cm$^{-2}$
- The duration distribution (alone and with the spectral hardness one) shows that it is 3 times more likely to be a short than a long GRB
- 1100 deg$^2$ 90% credible region
- $T_{GRB}$ - $T_{GW}$ = (1.74 ± 0.05) s

[Goldstein+ 2017]



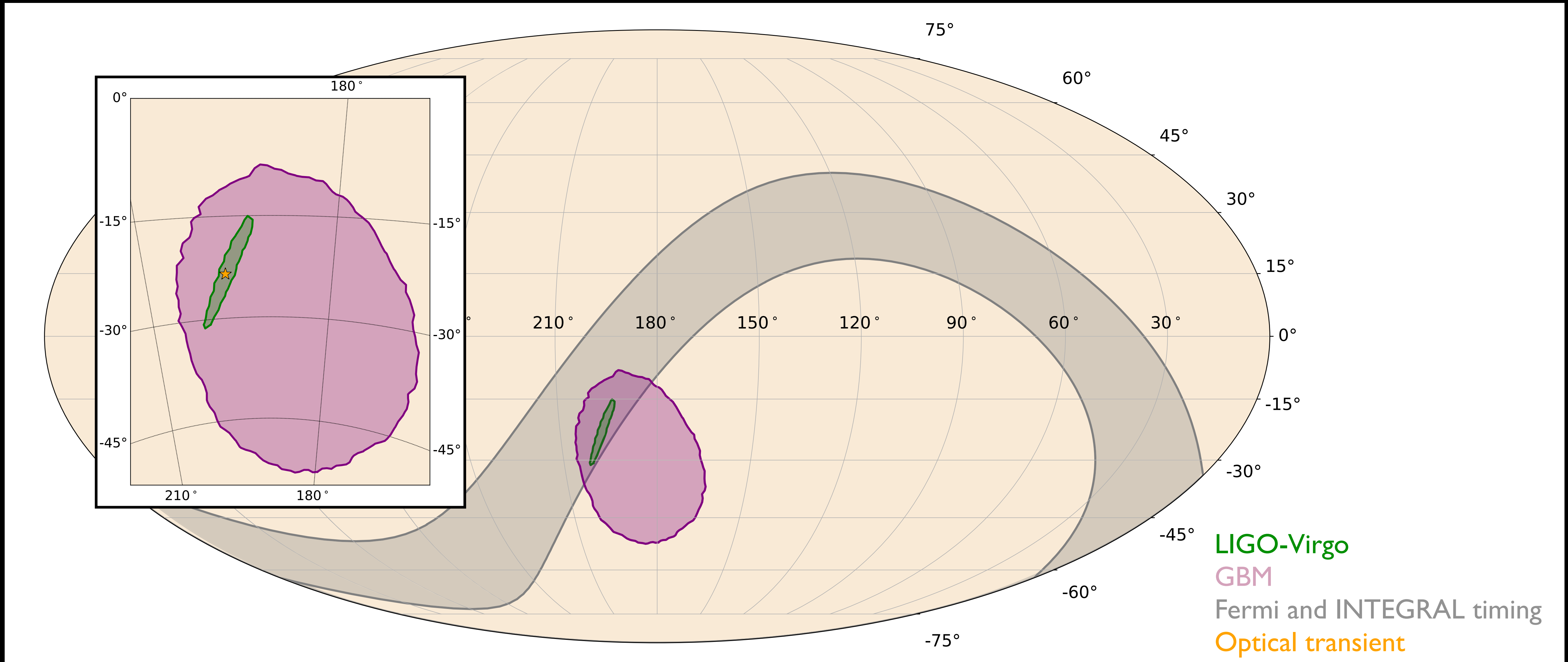

[LVC & *Fermi* GBM & INTEGRAL, ApJL **848**, L13 (2017)]

# GRB 170817A

- SPI-ACS finds a single excess at $T_{GW}$ + 1.88 s with SNR = 4.6 at 100ms temporal resolution
- Fluence = (1.4 ± 0.4) x $10^{-7}$ erg $cm^{-2}$
- Temporal association of 4.2σ between the GBM observation of GRB 170817A and the event observed by SPI-ACS
- SPI-ACS alone would not have reported this event, but it would have reported it while searching around GW170817, with an independent association significance of 3.2σ

[Savchenko+ 2017]

# Is it the Same Event?




[LVC & *Fermi* GBM & INTEGRAL, ApJL **848**, L13 (2017)]

[LVC, ApJL **848**, L12 (2017)]

$$T_{GRB} - T_{GW} = (1.74 \pm 0.05)\ \mathrm{s}$$

# Temporal Agreement

- **Null hypothesis** that the short GRB and GW are independent Poisson processes: how **unlikely** is it to observe them so close in time?

Either side of the GW time

GBM short GRB rate until then

$$P_{\text{Temporal}} = 2\ (1.74\ \text{s})\ (351/3324\ \text{days} / 0.85) = 5.0 \times 10^{-6}$$

Time delay

GBM is disabled 15% of the time (South Atalantic Anomaly transit)

- **A 4.4σ Gaussian-equivalent significance**

# Spatial Agreement

- **Null hypothesis** that the two observations are independent events: how **unlikely** is it to observe them with this spatial agreement?

HEALPix indices

$$\mathcal{S} = \sum_{i=1}^{N_{\rm pix}} P_{GRB,i} P_{GW,i}$$

Posterior probabilities of the two maps

Compare to a background generated by randomly shifting and rotating 10 times 164 GBM posteriors (localized with the same methodology)

- $P_{\rm Spatial} = 0.01$ or **2.3σ Gaussian-equivalent significance**

# Null Hypothesis Testing

- The two *p*-values are independent, so the probability that GW170817 and GRB 170817A occurred this close in time and with this level of location agreement **by chance** (i.e., assuming the null hypothesis) is

$$P_{\text{Temporal}} \times P_{\text{Spatial}} = \underbrace{(5.0 \times 10^{-6})}_{\text{Dominates}} \times 0.01 = 5.0 \times 10^{-8}$$

- A **5.3σ Gaussian-equivalent significance**

# Beyond Null Hypothesis Testing

- Calculate the **odds** between the common (*C*) source hypothesis and the hypothesis of two distinct signals (*SS*) given the two data sets:

Prior odds

Bayes factor

$$\mathcal{O}_{C/SS} \equiv \frac{\pi(\mathcal{H}^C)}{\pi(\mathcal{H}^{SS})} \mathcal{B}_{C/SS} = \frac{\pi(\mathcal{H}^C)}{\pi(\mathcal{H}^{SS})} \frac{P(D_{\mathrm{GW}}, D_{\mathrm{GRB}}|\mathcal{H}^C)}{P(D_{\mathrm{GW}}, D_{\mathrm{GRB}}|\mathcal{H}^{SS})}$$

$$= \frac{\pi(\mathcal{H}^C)}{\pi(\mathcal{H}^{SS})} \frac{P(D_{\mathrm{GW}}|\mathcal{H}^C) P(D_{\mathrm{GRB}}|\mathcal{H}^C)}{P(D_{\mathrm{GW}}|\mathcal{H}^S) P(D_{\mathrm{GRB}}|\mathcal{H}^S)} \mathcal{I}_\theta(D_{\mathrm{GW}}, D_{\mathrm{GRB}})$$

Posterior overlap integral

$$\int_{\Theta^S} \frac{P(\theta|D_{\mathrm{GW}}, \mathcal{H}^C) P(\theta|D_{\mathrm{GRB}}, \mathcal{H}^C)}{P(\theta|\mathcal{H}^C)} d\theta$$

[Ashton+, ApJ **860**, 6 (2018)]

# Beyond Null Hypothesis Testing

- Restrict to directional and temporal parameters only
- Assume all-sky observatories with isotropic and stationary sensitivities

$$\mathcal{O}_{C/SS} = \frac{\pi(\mathcal{H}^{C})}{\pi(\mathcal{H}^{SS})} \mathcal{I}_{\mathbf{\Omega},t_c}(D_{\mathrm{GW}}, D_{\mathrm{GRB}})$$

- Assuming the coalescence time is determined exactly from the GW data and that the priors on the direction and coalescence time factor

$$\mathcal{I}_{\mathbf{\Omega},t_c} = \mathcal{I}_{\mathbf{\Omega}} \mathcal{I}_{t_c}$$

[Ashton+, ApJ **860**, 6 (2018)]

# Beyond Null Hypothesis Testing

- $\mathcal{I}_{t_c}$ vanishes unless $t_{GW}$ - 1s ≤ $t_{GRB}$ ≤ $t_{GW}$ + 5s, in which case $\mathcal{I}_{t_c} = \frac{T}{\Delta t}$ where $T$ is the co-observing time and $\Delta t$ = 6s

- $\mathcal{I}_{\Omega}$ = 32.4 from the localization posteriors (it increases to 37.5 when using uniform posteriors over the 28 deg$^2$ and 1100 deg$^2$ areas)

$$\frac{\pi(\mathcal{H}^C)}{\pi(\mathcal{H}^{SS})} = \frac{\text{Poisson}(1; R_{GW,GRB}T)}{\text{Poisson}(1; R_{GW}T)\text{Poisson}(1; R_{GRB}T)} \simeq \frac{R_{GW,GRB}}{R_{GW}R_{GRB}T} \simeq \frac{1}{R_{GBM}T}$$

- With a rate of 0.124/day, $\mathcal{O}_{C/SS}(D_{GW}, D_{GRB}) \gtrsim 10^6$

[Ashton+, ApJ **860**, 6 (2018)]

# Conclusions

- GW170817: false-alarm-rate < 1 in 80,000 years $m_1 \in (1.36, 1.90) M_\odot$ $m_2 \in (1.00, 1.36) M_\odot$

- GRB 170817A: a short GRB witnessed by two observatories

- GW170817 and GRB 170817A are robustly associated

1. A Frequentist *p*-value approach finds that the GW and GRB data are inconsistent with the **null hypothesis**: agreement by chance has a **5.3σ Gaussian-equivalent significance**

2. A Bayesian approach shows that the **common source model** is **enormously favoured ($\gtrsim 10^6$)** over a model that describes GW170817 and GRB 170817A as unrelated signals