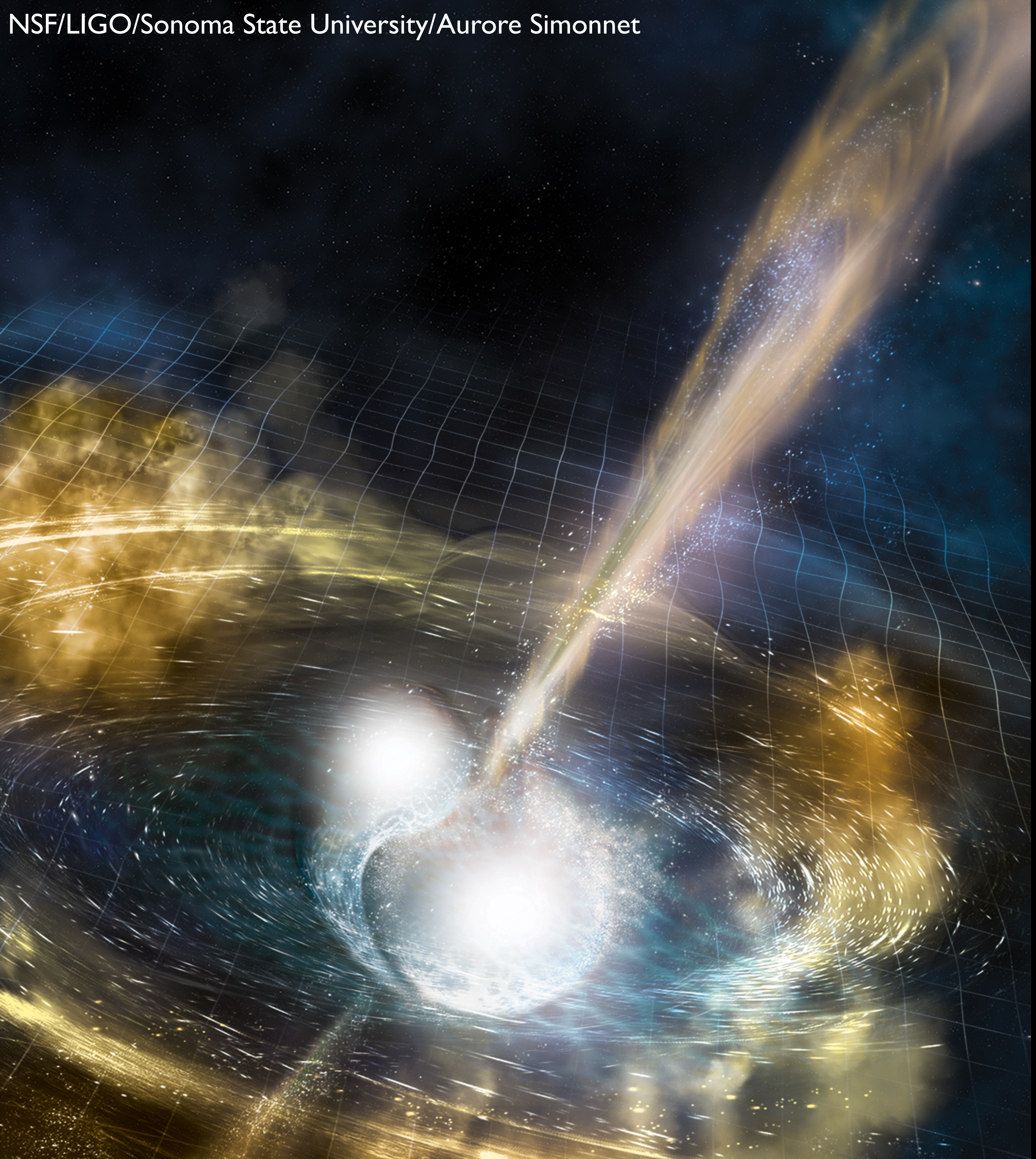


# Gravitational-Wave and Gamma-Ray Burst Joint Observations

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# Why Are We After These Joint Observations Specifcally?

1. To achieve more gravitational-wave (GW) signals

2. To detect GWs from new sources

3. Because there is still **a lot** we do not know about gamma-ray bursts (GRBs)

    - Do all binary neutron stars produce (all) short GRBs?

    - What are the details of the jet structure?

    - What are the details of the jet ignition mechanism?

# Strategies for Joint Observations

1. As GW triggers and GRB triggers are collected **online** and independently, look for coincidences in time

2. Collect GW events **and low significance candidates**, then **offline** look for gamma-ray transients coincident with them in time and sky position

   ➡ Also enables subthreshold searches on the gamma-ray side [Fermi/GBM Team + LVC, ApJ 893, 100 (2020)]

   ➡ GW150914-GBM (extremely weak signal and poor localization) [Connaughton et al., ApJL, 826, L6 (2016)]

3. Collect GRB events, then **offline** look for GW transients coincident with them in time and sky position

   ➡ Enables deeper searches on the GW side

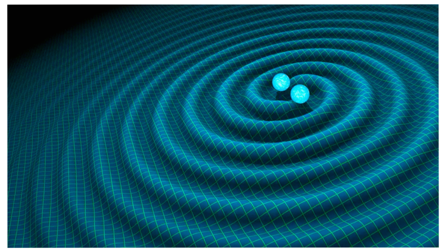
[O1: Abbott et al., ApJ 841, 89 (2017)
170817: Abbott et al., ApJL 848, L13 (2017)
O2: Abbott et al., ApJ 886, 75 (2019)
O3a: Abbott et al., ApJ 915, 86 (2021)
O3b: Abbott et al., ApJ 928, 186 (2022)
O3GK: Abbott et al., PTEP 2022, 063F01 (2022)]

# Targeting GRBs with Dedicated Gravitational-Wave Searches

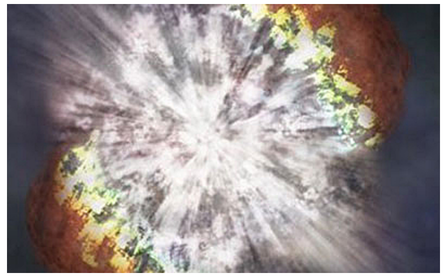
- **Goal**: determine whether GW data contains a signal consistent with the time and point/patch in the sky of an observed GRB

- Complementary searches for GW transients:

  1. compact binary coalescences (modelled)



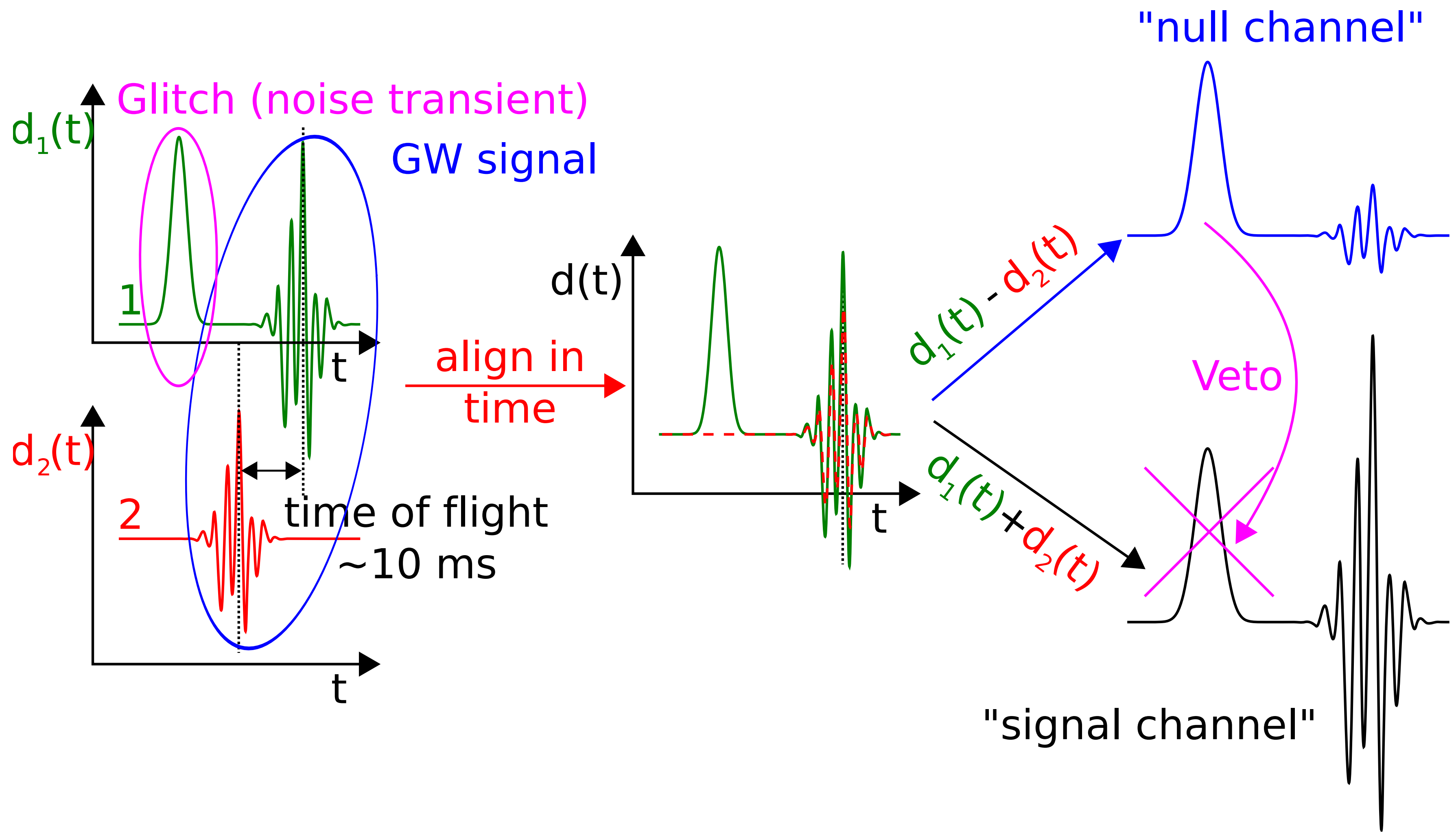
  2. transients with generic morphology (unmodelled)

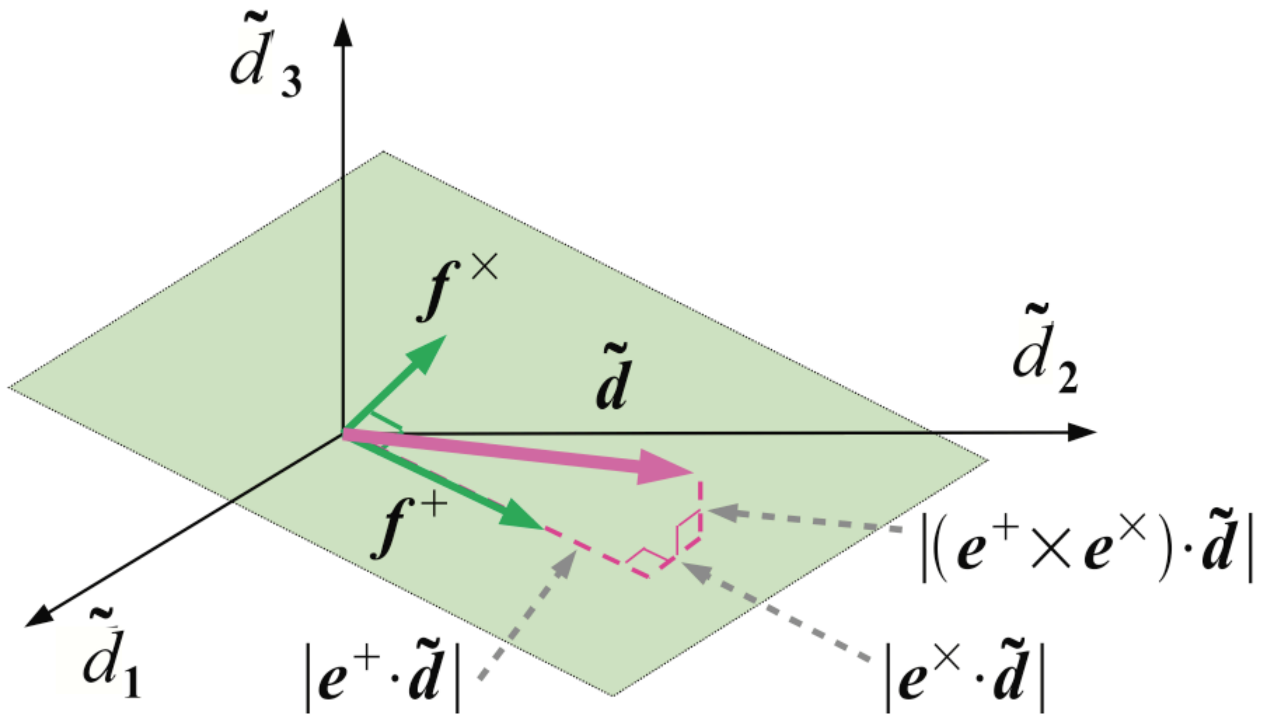


- **Advantage**: knowing time and/or sky location simplifies analysis, lowers detection thresholds, reduces background ⇒ sensitivity increase

# Targeted Coherent Searches

- **Coherent strategy**: use the known GRB sky location and relative GW detector sensitivities to appropriately time shift and weight the individual detector data streams

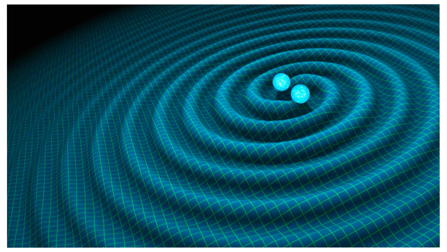


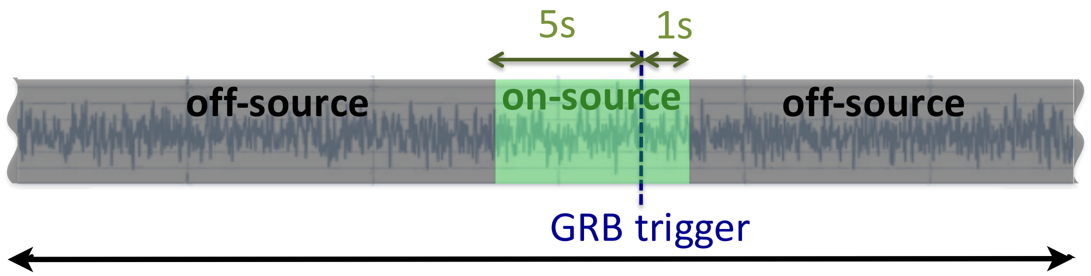




[Credit: M.Was, P.Sutton]

# Targeted Coherent Searches

Modelled



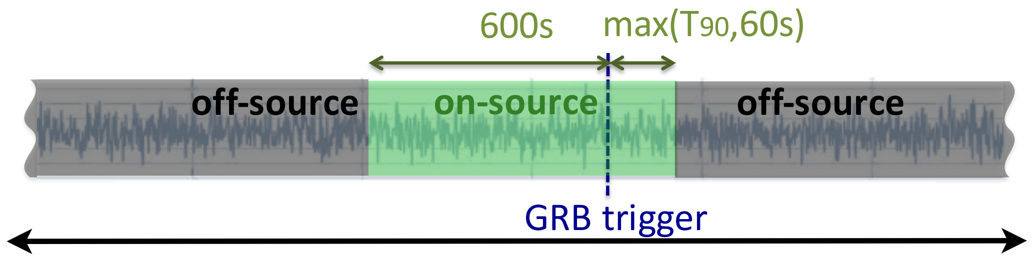



~0.5h

30 Hz – 1000Hz

[Harry, Fairhurst, PRD 83, 084002 (2011); Williamson et al., PRD 90, 122004 (2014)]

Unmodelled




~3h

16 Hz – 500Hz

[Sutton *et al.*, New J. Phys., 12, 053034 (2010); Was *et al.*, PRD 86, 022003 (2012)]

Short GRBs: $T_{90} + \delta T_{90} < 2$ s

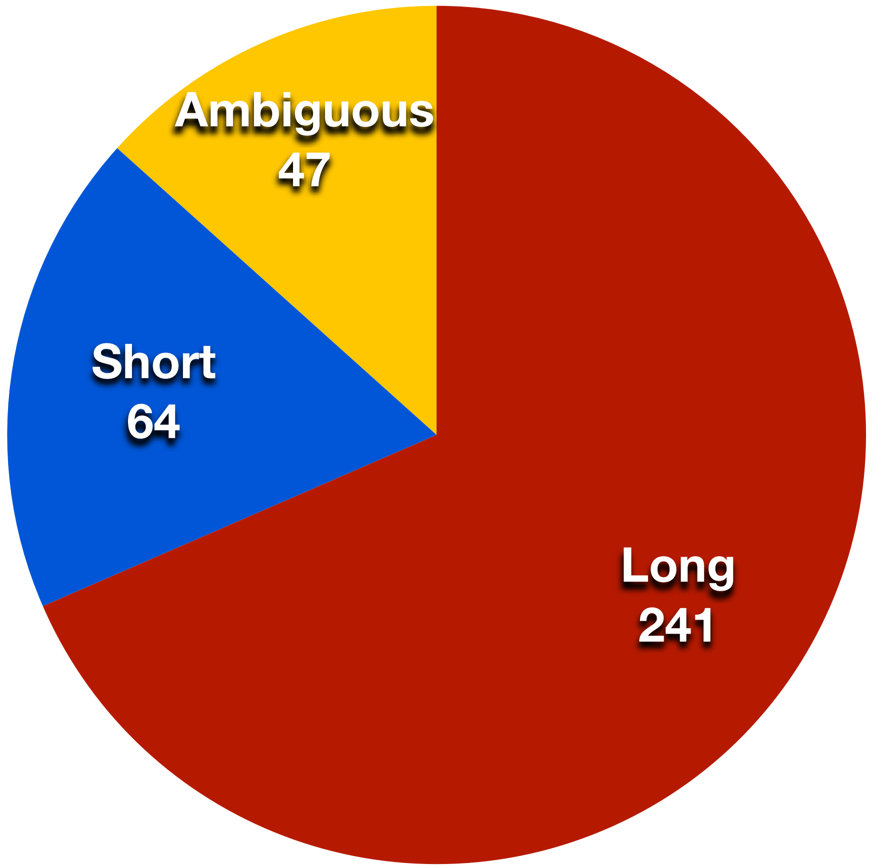
Long GRBs: $T_{90} - \delta T_{90} > 4$ s

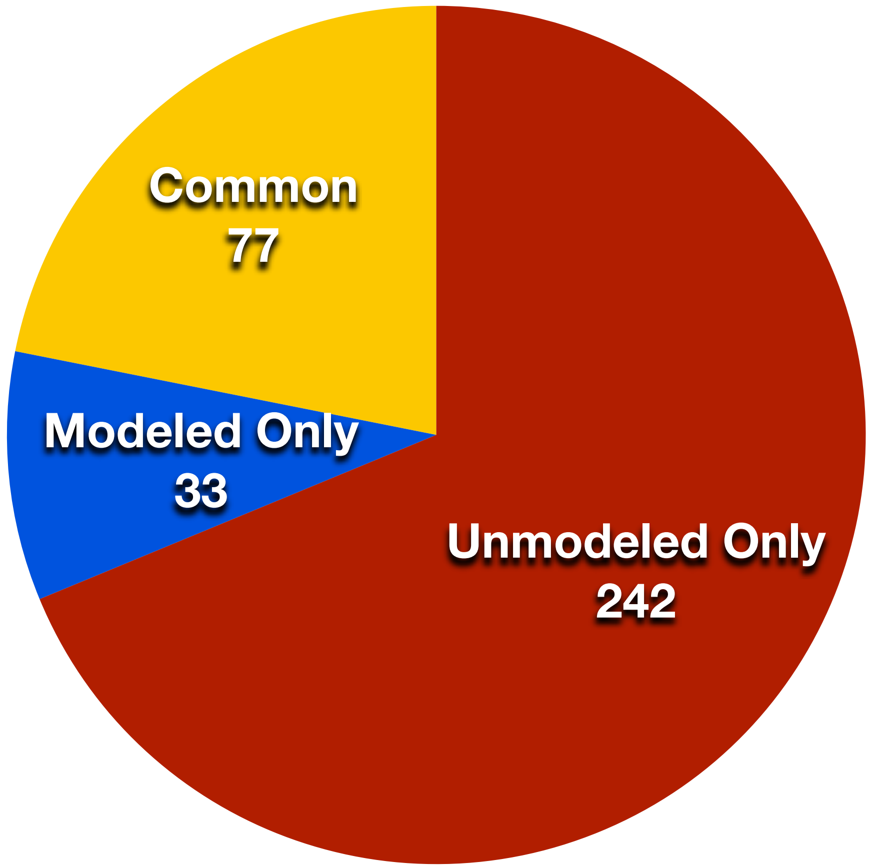
The rest are labelled ambiguous

- Store loudest trigger in the **on-source**
- Calculate its significance using the **off-source**, the playground for noise characterization

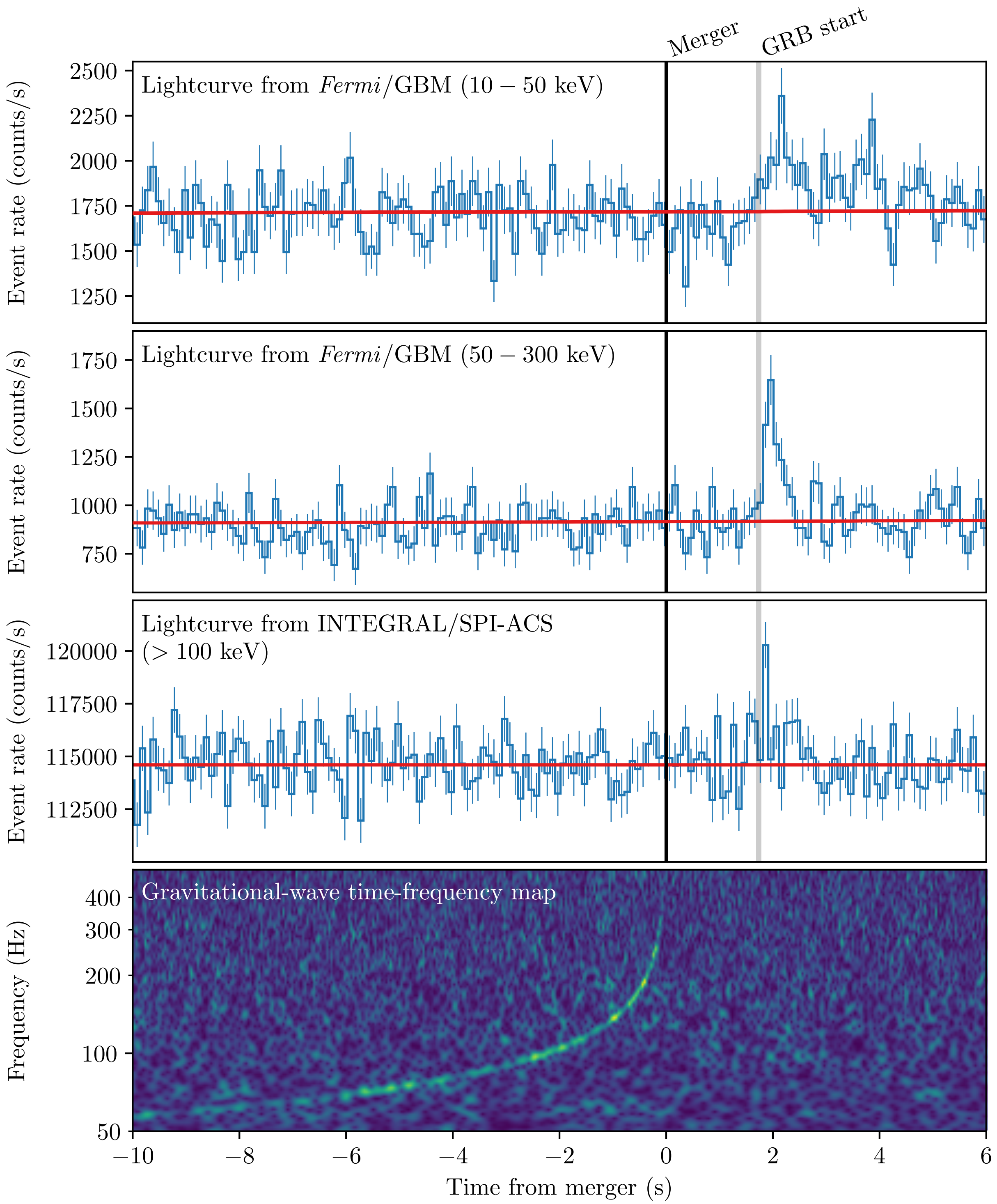
# Sample of GRBs Followed Up During the Observing Runs

1. O1 (12 September 2015 – 19 January 2016): 41 Fermi, Swift and IPN GRBs followed up
2. O2 (30 November 2016 – 25 August 2017): 111 Fermi, Swift and IPN GRBs followed up
3. O3a (1 April 2019 – 1 October 2019): 111 Fermi and Swift GRBs followed up
4. O3b (1 November 2019 – 27 March 2020): 89 Fermi and Swift GRBs followed up



# GW170817 and GRB 170817A




- 1 firm joint observation
- Odds that GRB 170817A and GW170817 have a common origin vs distinct origins are $\gtrsim 10^6$
- Remember: this was the loudest GW ever recorded, it is an uncommon event
- No evidence of GWs associated with any of the 351 GRBs

[Abbott et al., ApJL 848, L13 (2017)]

# Latest Exclusion Distances

Median 90% Exclusion Distances ($D_{90}$) for the Both the Modeled and Generic Transient Searches during O3b

| Modeled Search (Short GRBs) | BNS | NSBH Generic Spins | NSBH Aligned Spins |
|---|---|---|---|
| $D_{90}$ (Mpc) | 149 | 207 | 257 |

| Generic Transient Search (All GRBs) | CSG 70 Hz | CSG 100 Hz | CSG 150 Hz | CSG 300 Hz |
|---|---|---|---|---|
| $D_{90}$ (Mpc) | 166 | 126 | 92 | 42 |

| Generic Transient Search (All GRBs) | ADI A | ADI B | ADI C | ADI D | ADI E |
|---|---|---|---|---|---|
| $D_{90}$ (Mpc) | 34 | 140 | 54 | 22 | 52 |

- GRB 200228A is the record holder for the modelled search with 282 Mpc, 399 Mpc, 528 Mpc

[Abbott et al., ApJ 928, 186 (2022)]

# Population Studies

$$\phi_0(L_{\rm iso}) \equiv \frac{dP}{d\log(L_{\rm iso})} = \begin{cases} \left(\frac{L_{\rm iso}}{L_{**}}\right)^{-\gamma_L}\left(\frac{L_{**}}{L_*}\right)^{-\alpha_L}, & L_0 \leqslant L_{\rm iso} \leqslant L_{**} \\ \left(\frac{L_{\rm iso}}{L_*}\right)^{-\alpha_L}, & L_{**} < L_{\rm iso} \leqslant L_* \,, \\ \left(\frac{L_{\rm iso}}{L_*}\right)^{-\beta_L}, & L_{\rm iso} > L_* \end{cases}$$

$$L_\star \simeq 2 \times 10^{52}\,{\rm erg\,s^{-1}}$$

$$L_{\star\star} \simeq 5 \times 10^{49}\,{\rm erg\,s^{-1}}$$

$$\alpha_L = 0.94$$

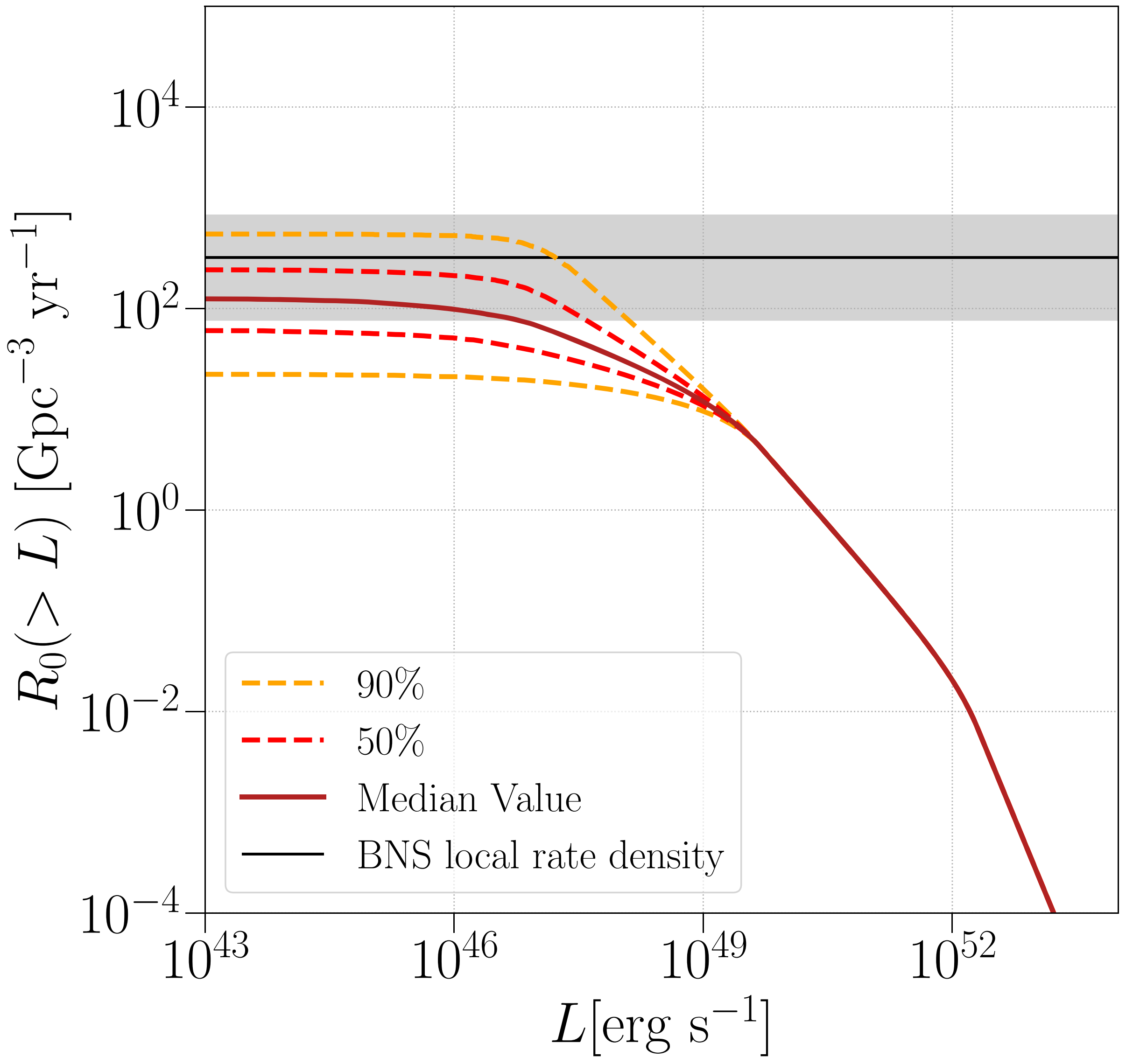
$$\beta_L = 2$$

- A Bayesian analysis constrains the parameters $\gamma_L$ and $L_0$ using the modelled search results from the O1, O2, O3a, and O3b, and the results on binary neutron star merger rate from the second GW transient catalog

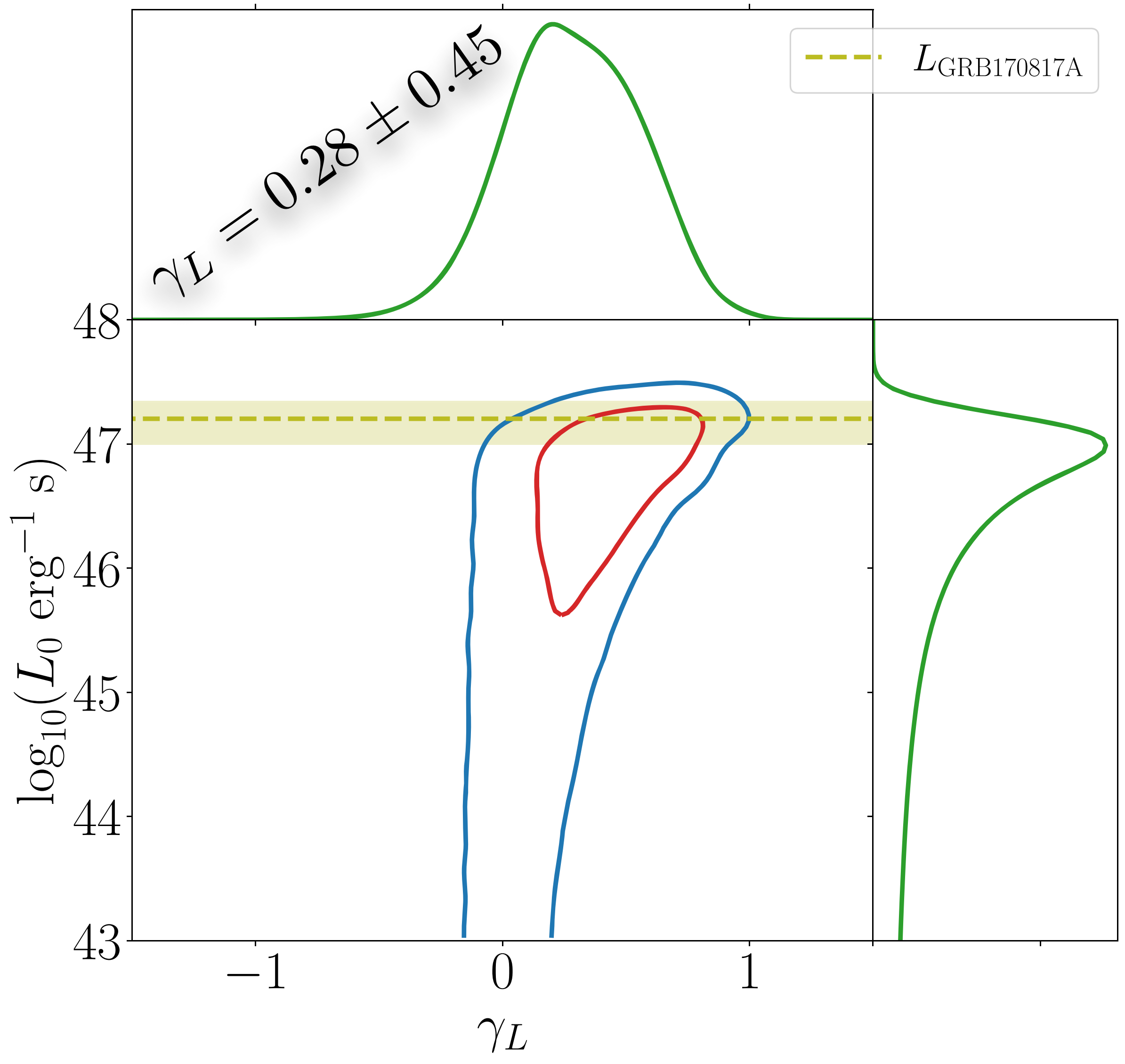
**[Wanderman & Piran, MNRAS 448, 3026 (2015); Abbott et al., ApJ 928, 186 (2022), Abbott et al., ApJL 913, L7 (2021)]**

# Population Studies

## Inverse cumulative rate




## Posterior distribution




- Estimated joint detection rate for Fermi/GBM in O4: $1.04^{+0.26}_{-0.27}$ yr$^{-1}$

[Abbott et al., ApJ 928, 186 (2022)]

# Concluding Remarks

1. GWs will allow us to probe the progenitors and dynamics of GRBs, providing answers to fundamental questions in this field

2. Several strategies and pipelines are in place aiming for joint GW+GRB observations

3. The LIGO-Virgo-KAGRA Collaboration followed up 352 GRBs, achieved 1 joint detection, and started placing constraints on the population of low-luminosity short GRBs

4. The expected detection rate in O4 is $1.04^{+0.26}_{-0.27}\ \mathrm{yr}^{-1}$

5. Fast forward to the Einstein Telescope/Cosmic Explorer Era

    - $10^5$ compact binary coalescences per year, with detection ranges at $z \gtrsim 3$
    - On-axis short GRBs become the most promising counterparts to GW signals for redshift identification
    - New gamma-ray observing facilities are mandatory