A joint GW/GRB Bayesian study for low-luminosity short GRB population

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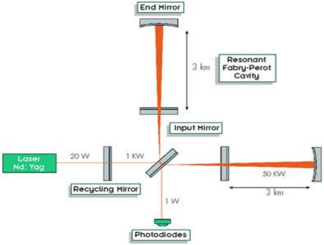
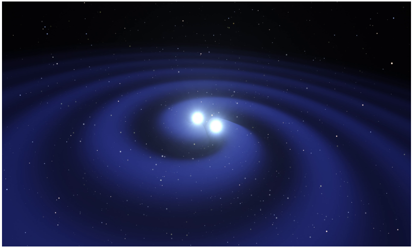
Gravitational Waves (GW)

- Perturbations of spacetime predicted by General Relativity
  - Solution found by perturbing Einstein's equations
- Observable through Michelson interferometers
  - International network
  - Observational periods (runs)

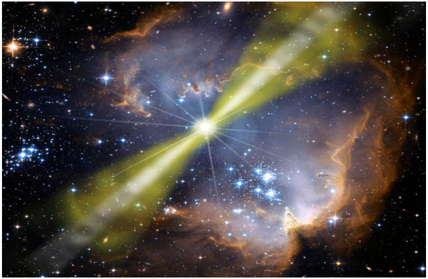


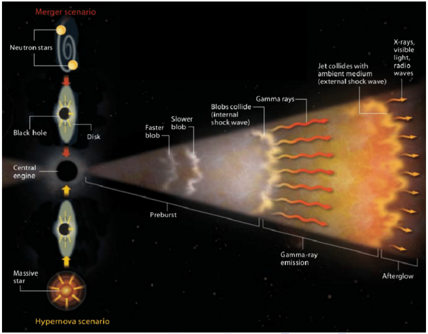


- Nowadays observed only from Compact Binary Coalescences (CBC)
  - Binary Black Holes (BBH), Binary Neutron Stars (BNS) and Neutron Star Black Hole binaries (NSBH)

Gamma-Ray Bursts (GRB)

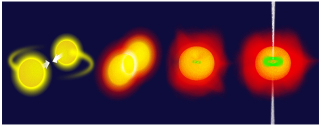
- Transient flashes of high energy light
- Generated by cataclysmic astrophysical events
  - Long GRBs (LGRB) from Core Collapse Supernovas (CCS)
  - Short GRBs (sGRB) from CBC
- Central engine produces the burst into collimated jets

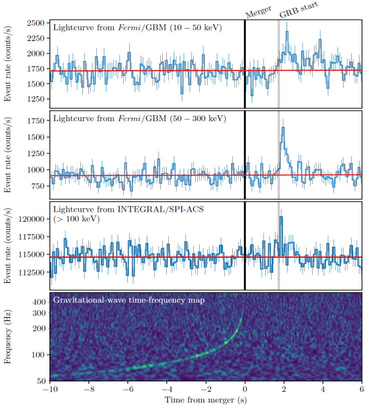




GW and GRB: multimessenger astronomy

- Multimessenger astronomy: different kinds of signals from the same event
- Search for GRB and GW signals from same source
  - sGRB from CBC (either BNS or NSBH)
  - LGRB from CCS
- Joint and unambiguous detection of GW170817 and GRB 170817A
  - BNS confirmed as possible sGRB sources
  - Confirmed by kilonova and afterglow observations





GRB 170817A: a "unique" event

- $D_L \sim 40\ \mathrm{Mpc}$, $L_{iso} \sim 10^{47}\ \mathrm{erg\ s^{-1}}$: closest and dimmest sGRB ever observed
- Needs to explore low-luminosity sGRB population

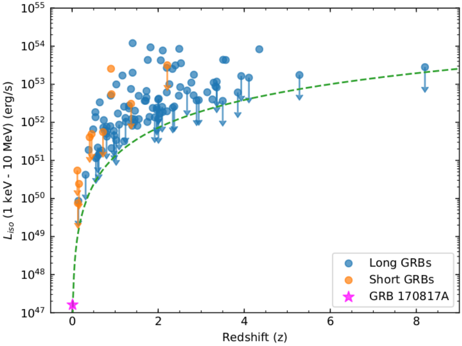


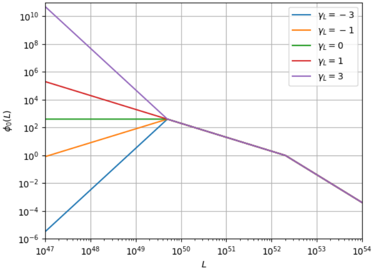
Figure: Source: B.P. Abbott *et al.* 2017 *ApJL* **848** L13

Joint GW/GRB population study: Luminosity Function

- Multimessenger astronomy (GW+GRB) to explore low luminosity population
  - Statistical population study of sGRB joint with GW analysis
- Simple model to describe sGRB luminosity (L) from Wanderman & Piran (2015)
  - Luminosity probability distribution as a broken power function $\phi_0(L)$
  - Adding low luminosity branch

$$\phi_0(L) \equiv \frac{\mathrm{d}P}{\mathrm{d}\log L} = \begin{cases} \left(\frac{L}{L_{**}}\right)^{-\gamma_L}\left(\frac{L_{**}}{L_*}\right)^{-\alpha_L}, & L_0 \leq L < L_{**} \\ \left(\frac{L}{L_*}\right)^{-\alpha_L}, & L_{**} \leq L < L_* \\ \left(\frac{L}{L_*}\right)^{-\beta_L}, & L \geq L_* \end{cases}$$

$$P(\gamma_L, L_0|x) = \frac{\mathfrak{L}(x|\gamma_L, L_0)\Pi(\gamma_L, L_0)}{\int_{\gamma_L^{min}}^{\gamma_L^{max}}\int_{L_0^{min}}^{L_0^{max}} \mathfrak{L}(x|\gamma_L, L_0)\Pi(\gamma_L, L_0)\mathrm{d}\gamma_L \mathrm{d}L_0}$$



Joint GW/GRB population study: Luminosity Function

- α_L, β_L and L_* constrained by sGRB observations at mid-high luminosities
  - L_{**} lower cutoff of original distribution
- Goal: put a constrain on γ_L and L_0 through Bayesian analysis
  - Prior Probability Distribution Function (PDF) and Likelihood to build a posterior PDF
  - Constraints on γ_L and L_0 found through credible intervals

$$\phi_0(L) \equiv \frac{\mathrm{d}P}{\mathrm{d}\log L} = \begin{cases} \left(\frac{L}{L_{**}}\right)^{-\gamma_L}\left(\frac{L_{**}}{L_*}\right)^{-\alpha_L}, & L_0 \le L < L_{**} \\ \left(\frac{L}{L_*}\right)^{-\alpha_L}, & L_{**} \le L < L_* \\ \left(\frac{L}{L_*}\right)^{-\beta_L}, & L \ge L_* \end{cases}$$

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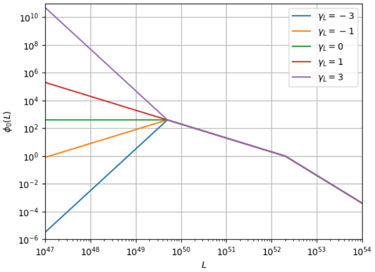


Joint GW/GRB population study: Bayesian analysis

- Extension of analysis done for O2 LIGO/Virgo GRB followup paper
- Estimation of local sGRB rate and joint GW–GRB detection rate
- Local observed rate ($z \ll 1$) strongly depending on γ_L
- Results will be published soon in LVK O3b GRB followup paper

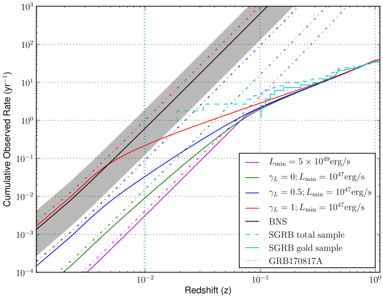
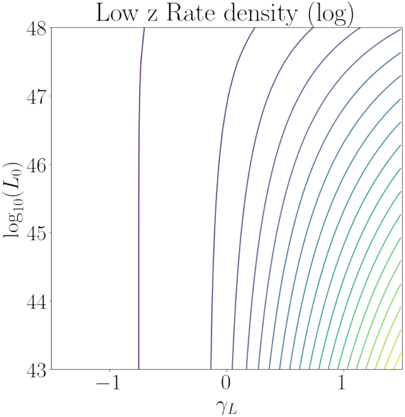
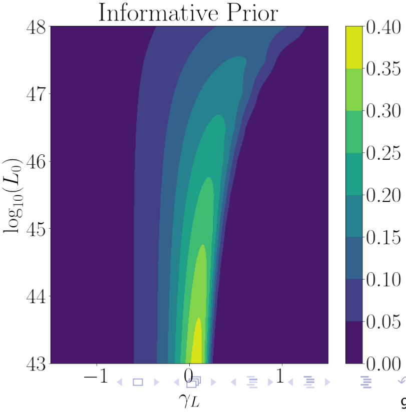


Figure: Source: B.P. Abbott *et al.* 2019 *ApJ* **886** 75

Prior PDF $\Pi(\gamma_L, L_0)$

- Observed sGRB rate redshift distribution
  - Luminosity function for determining subtreshold fraction of sGRBs
- Prior computing
  - Uninformative assumption: logarithm of local observed rate density probability constant over γ_L and L_0
  - Prior rescaled by assumption that all sGRBs are due to BNS





Likelihood $\mathfrak{L}(x|\gamma_L, L_0)$

- Likelihood as probability of seeing what observed during first three observational runs
  - Using efficiency curves from modeled GW search corresponding to short GRBs
  - One single joint detection during O2, no joint detections during O1 and O3
  - O2 joint detection has to occur at same redshift as GW170817 and luminosity as GRB 170817A
- Posterior PDF: results to be published!

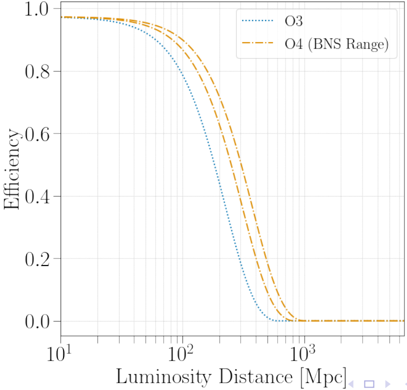
$$P_{\mathrm{O2}}(1\ \mathrm{jd}|\gamma_L, L_0) = \sum_{i=1}^{N_{\mathrm{O2}}^{\mathrm{GRB}}} \left(P_i^{\mathrm{det}}(\gamma_L, L_0) \prod_{j \neq i} P_j^{\neg\mathrm{det}}(\gamma_L, L_0) \right)$$

$$P_{\mathrm{O1+O3}}(0\ \mathrm{jd}|\gamma_L, L_0) = \prod_{i}^{N_{\mathrm{O1}}^{\mathrm{GRB}}} P_i^{\neg\mathrm{det}}(\gamma_L, L_0) \prod_{i}^{N_{\mathrm{O3}}^{\mathrm{GRB}}} P_i^{\neg\mathrm{det}}(\gamma_L, L_0)$$

$$\mathfrak{L}(x|\gamma_L, L_0) = P_{\mathrm{O2}}(1\ \mathrm{jd}|\gamma_L, L_0) P_{\mathrm{O1+O3}}(0\ \mathrm{jd}|\gamma_L, L_0)$$

O4 Joint Detection Rate

- O3 GW network efficiency curve averaged from GRB followup analysis ones
  - 49 Total GW efficiency curves
  - Duty cycle between detectors
  - Non operative IFOs
- O4 GW efficiency curve rescaled
  - BNS range estimated for O4

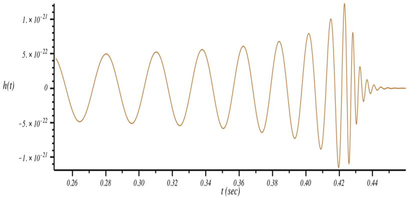


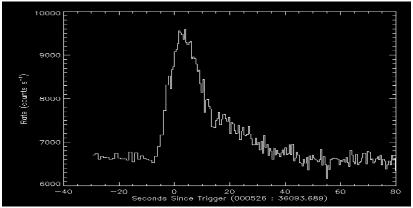
O4 Joint Detection Rate

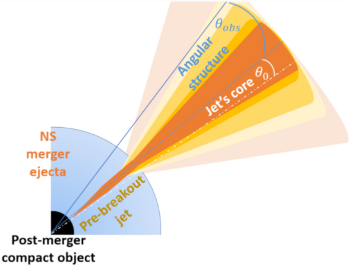
- O4 Joint detection rate computation
  - Used GW network and *Fermi/GBM* sensitivity
  - Rescaled through the *Fermi/GBM* observed sGRB rate ($\sim 40\ \mathrm{yr}^{-1}$)

$$R_{\mathrm{GW-GRB}}(< z, \gamma_L, L_0) = R_0^{\mathrm{GRB}} \frac{\int_0^z \frac{\mathrm{d}P_{\mathrm{obs}}^{\mathrm{sGRB}}}{\mathrm{d}z'} \eta_{\mathrm{O4}}^{\mathrm{GW}}(d_{\mathrm{L}}(z'))\mathrm{d}z'}{\int_0^{z_{max}} \frac{\mathrm{d}P_{\mathrm{obs}}^{\mathrm{sGRB}}}{\mathrm{d}z'}\mathrm{d}z'}$$

Future Prospects







Source: P. Beniamini *et al.* 2019 *MNRAS* **840** 11

- Results published soon!
- Introduce structured jet model
  - Quasi-universal structure
  - Distribution for jet parameters
  - Apparent vs intrinsic jet structure

The end (thanks!)