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

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Gravitational Waves (GW)

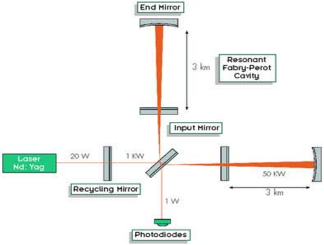
- Perturbations of spacetime predicted by General Relativity
  - Solution found by perturbing Einstein's equations
- Observable through Michelson interferometers
  - Nowadays observed only from compact binary coalescences

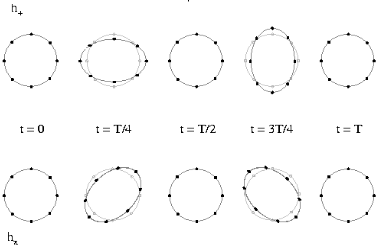
$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\downarrow$$

$$\Box_F \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} \delta T_{\mu\nu}$$

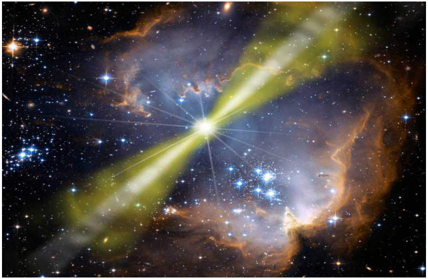
$$\downarrow$$

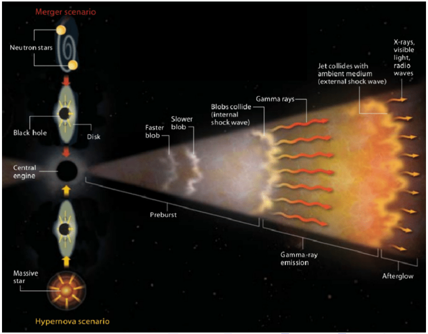




Gamma-Ray Bursts (GRB)

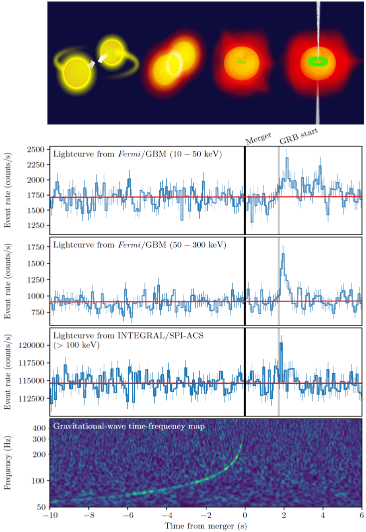
- Transient flashes of high energy light
- Generated by cataclysmic astrophysical events
  - Long GRBs (LGRB) from core collapse supernovas
  - Short GRBs (sGRB) from compact object coalescences
- Central engine produces the burst into collimated jets





GW and GRB: multimessenger astronomy

- Multimessenger astronomy: different kinds of signals from the same event
- Joint and unambiguous detection of GW170817 and GRB 170817A
  - Binary neutron star systems (BNS) as short GRB (sGRB) sources
  - Confirmed by kilonova afterglow observations



GRB 170817A: an unique event

- $D_L \sim 40$ Mpc, $L_{\rm iso} \sim 10^{47}$ erg s^{-1}: closest and dimmest sGRB ever observed
  - Off-axis observation
- Needs to explore low-luminosity sGRB population
  - I.e. fraction of sGRB population potentially observable off axis

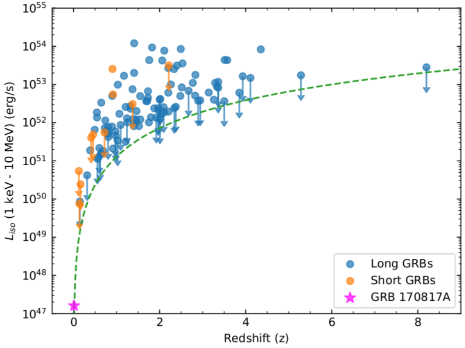
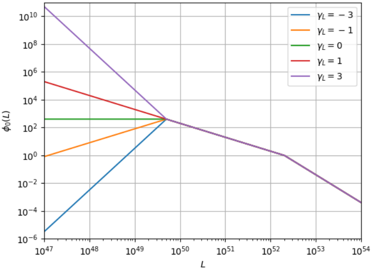


Figure: Source: B.P. Abbott *et al* 2017 *ApJL* **848** 2 L13

Joint GW/GRB population study: Luminosity Function

- Multimessenger astronomy (GW+GRB) to explore low luminosity population
  - Statistical sGRB population study exploiting with GW analysis results

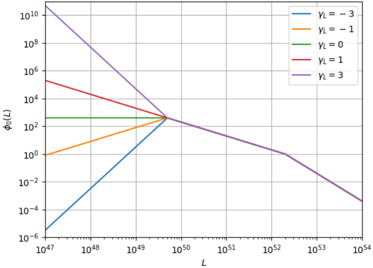
$$\phi_0(L_{\rm iso}) \equiv \frac{{\rm d}P}{{\rm d}\ln L_{\rm iso}} = \begin{cases} \left(\frac{L_{\rm iso}}{L_{**}}\right)^{-\gamma_L}\left(\frac{L_{**}}{L_*}\right)^{-\alpha_L}, & L_0 \le L_{\rm iso} < L_{**} \\ \left(\frac{L_{\rm iso}}{L_*}\right)^{-\alpha_L}, & L_{**} \le L_{\rm iso} < L_* \\ \left(\frac{L_{\rm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



Joint GW/GRB population study: Luminosity Function

- Broken power law to describe sGRB luminosity distribution $\phi_0(L_{\rm iso}) = \mathrm{d}P/\mathrm{d}\ln(L_{\rm iso})$
  - α_L, β_L, L_* and L_{**} fixed in Wanderman & Piran (2015)
  - Added low luminosity branch

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



Joint GW/GRB population study: Bayesian analysis

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

- Goal: put a constrain on γ_L and L_0 through Bayesian analysis
  - Constraints on γ_L and L_0 found through confidence intervals
- Extension of analysis done for O2 LIGO/Virgo GRB followup paper

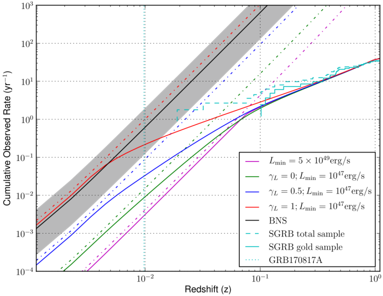


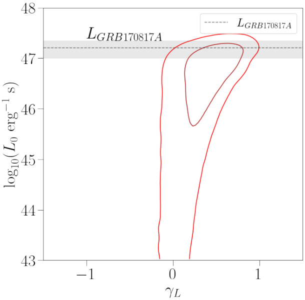
Figure: Source: B.P. Abbott *et al* 2019 *ApJ* **886** 75

- Local rate ($z \ll 1$) strongly depending on γ_L

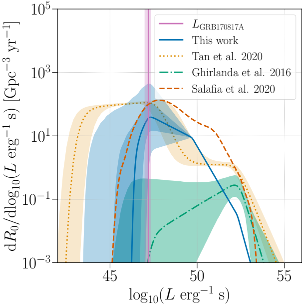
Prior PDF $\Pi(\gamma_L, L_0)$ & Likelihood $\mathfrak{L}(x|\gamma_L, L_0)$

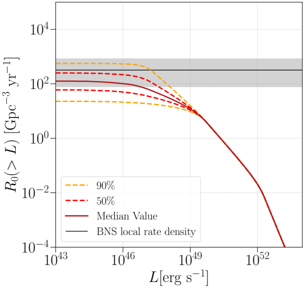
- Observed sGRB rate redshift distribution
  - Short GRB redshift distribution
  - GRB energy spectrum modeled through Band function
  - Luminosity function
  - Properties of *Fermi*/*GBM* detector
- Prior computing
  - Uninformative assumption: logarithm of local observed rate density probability constant over γ_L and $\ln(L_0)$
  - Informative assumption: BNS rate as upper limit for sGRB rate
- Likelihood as probability of seeing what observed during LIGO/Virgo runs
  - One 170817-like joint detection during three LIGO/Virgo runs
  - Exploited results of modeled GW follow-up of GRBs (PyGRB)

Results



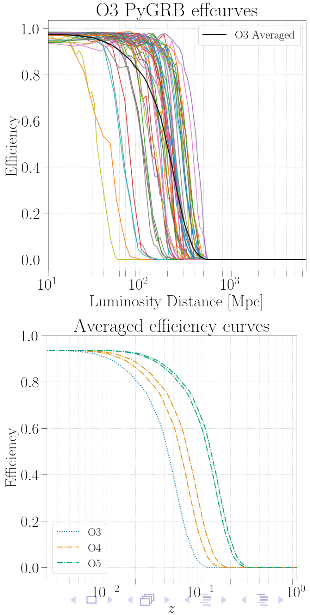
- From marginalized posterior over L_0: $\gamma_L = 0.28 \pm 0.45$
- Luminosity function peaks around $L \sim L_{\mathrm{GRB170817A}}$
- sGRB local rate density compatible with BNS local rate density





GW-GRB Joint detection rate

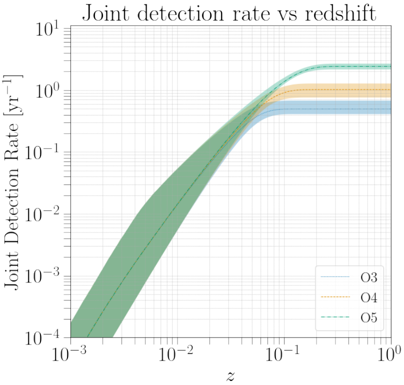
- LIGO/Virgo network GW efficiency curve
  - O3 PyGRB efficiency curves averaged
  - Rescaled to O4 and O5 BNS ranges
  - "No IFOs" duty cycle



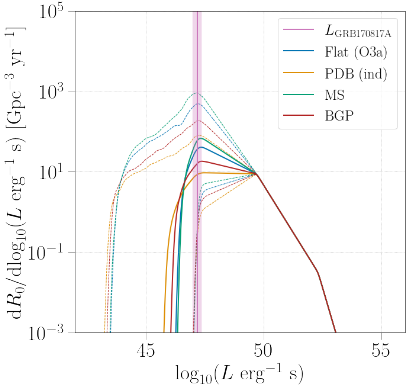
GW-GRB Joint detection rate

$$R_{\rm GW-GRB}(<z) = R_0^{\rm GBM} \frac{\int_0^z \frac{{\rm d}P_{\rm GRB}}{{\rm d}z'} \eta_{\rm O4}^{\rm GW}(d_{\rm L}(z')){\rm d}z'}{\int_0^{z_{\rm max}} \frac{{\rm d}P_{\rm GRB}}{{\rm d}z'}{\rm d}z'}$$

- Normalized through *Fermi/GBM* observed rate ($R_0^{\rm GBM} = 39.5\ {\rm yr}^{-1}$)
- Dependence on (γ_L, L_0) highlights dependence on low luminosity part of the population



Dependence on NS mass distribution

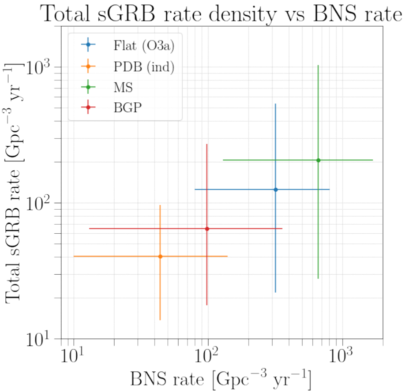


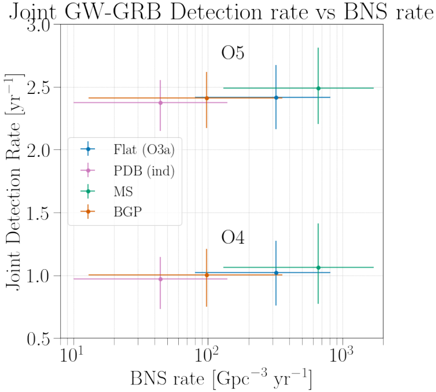
- Different NS mass distributions bring to different BNS rates
  - From O3a population analysis uniform NS mass distribution between 1 and 2.5 $M_\odot$
  - In O3b population analysis considered various distributions of masses and spins

Comparing results from different NS mass distributions				
	Flat (O3a)	PDB (ind)	MS	BGP
BNS rate $[\mathrm{Gpc}^{-3}\ \mathrm{s}]$	320^{+490}_{-240}	44^{+96}_{-34}	660^{+1040}_{-530}	98^{+260}_{-85}
γ_L	0.28 ± 0.45	$0.01^{+0.38}_{-0.37}$	$0.39^{+0.48}_{-0.51}$	$0.14^{+0.43}_{-0.40}$
sGRB Rate $[\mathrm{Gpc}^{-3}\ \mathrm{s}]$	128^{+445}_{-107}	41^{+95}_{-27}	206^{+824}_{-178}	65^{+207}_{-47}
O4 JDR $[\mathrm{yr}^{-1}]$	$1.03^{+0.25}_{-0.27}$	$0.97^{+0.18}_{-0.24}$	$1.07^{+0.32}_{-0.29}$	$1.00^{+0.21}_{-0.25}$
O5 JDR $[\mathrm{yr}^{-1}]$	2.42 ± 0.26	$2.37^{+0.18}_{-0.22}$	$2.49^{+0.32}_{-0.28}$	$2.41^{+0.21}_{-0.24}$

Dependence on NS mass distribution

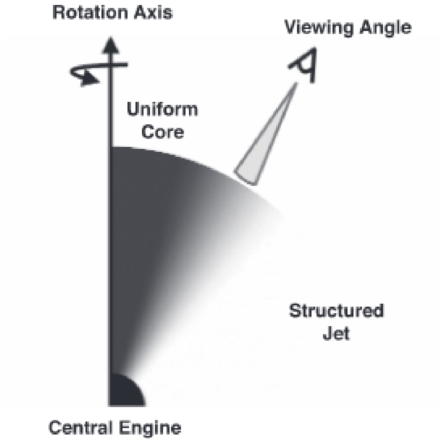
- sGRB rates averagely lower when considering lower BNS rates





What's next?

- Dependence of $L_{\rm iso}$ from observing angle θ_v
  - First model: gaussian dependence with two parameters $(L^{\rm c}_{\rm iso}, \theta_c)$
  - Possible models which include more parameters
- Predictions for next LVK runs



The end (thanks!)

Backup: LIGO/Virgo search for GW transients associated with GRBs

- X-pipeline for unmodeled GW search
  - Search for subthreshold GW transients given time and position of a GRB event
  - Coherent search among the detectors to avoid *glitches*
- No significant GW event among the analyzed GRBs

Backup: GRB isotropic peak luminosity

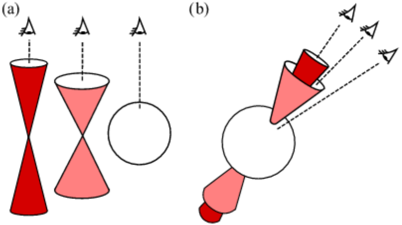


Figure 1. Sketch of the two possible scenarios described in Lipunov et al. (2001). In the first one (a) GRB jets are seen on-axis, and they differ by their semi-aperture and consequently their observed energy, with the brightest being the most collimated; in the second one (b) the jet configuration is such that the viewing angle determines which component contributes most significantly to the received energy.

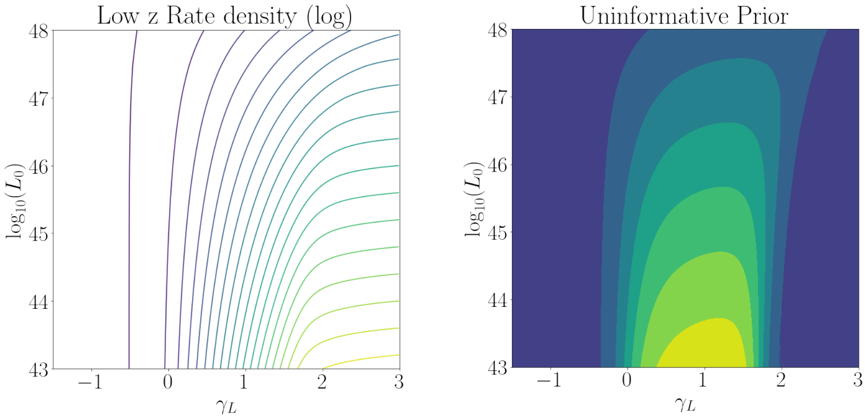
Figure: Source: O.S. Salafia *et al.* 2015 *MNRAS* **450** 4 3549–3558

$$L_{\rm iso} = 4\pi \frac{D_L^2(z)}{(1+z)} k(z) C_{\rm det} P_{64}$$

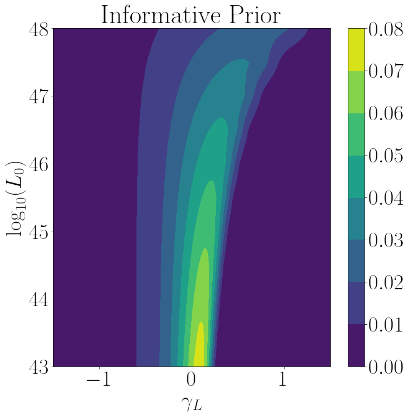
$$C_{\rm det} = \frac{\int_{10{\rm MeV}}^{1{\rm keV}} E N(E) {\rm d}E}{\int_{E^{\rm d}_{\rm min}}^{E^{\rm d}_{\rm max}} N(E) {\rm d}E}$$

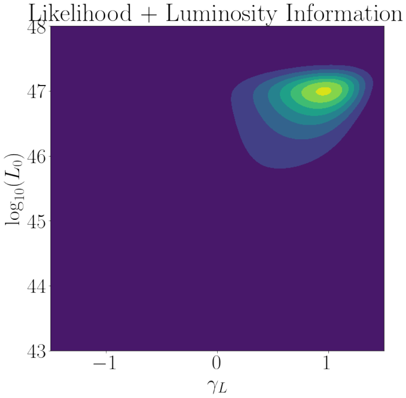
$$k(z) = \frac{\int_{E^{\rm d}_{\rm min}}^{E_{\rm max}} N(E) {\rm d}E}{\int_{(1+z)E^{\rm d}_{\rm min}}^{(1+z)E_{\rm max}} N(E) {\rm d}E}$$

Backup: iso-rate curves & uninformative prior



Backup: informative prior & likelihood





Backup: marginalized posteriors