A multimessenger GW-GRB study of the sGRB population

PhD Candidate: Matteo Pracchia

Thesis Director: Frédérique Marion, Co-advisor: Michał Wąs

LAPP, Annecy, 17/03/2023

UNIVERSITÉ SAVOIE MONT BLANC

LAPP Laboratoire d'Annecy-le-Vieux de Physique des Particules

LIGO VIRGO KAGRA

Overview

- Part One: basic concepts
  - Gravitational waves (GW)
  - Gamma-Ray Bursts (GRBs)
  - The joint detection of 17th August 2017
- Part Two: Gravitational waves data analysis
  - The search for compact binary coalescence (CBC) events
  - CBC population properties
  - GW followup analysis of GRBs
- Part Three: A multimessenger GW-GRB study of the sGRB population
  - What can GRB 170817A tell us about the short GRB population?
  - How many joint detections can we expect during next observing runs?

Part One: basic concepts

Gravitational Waves

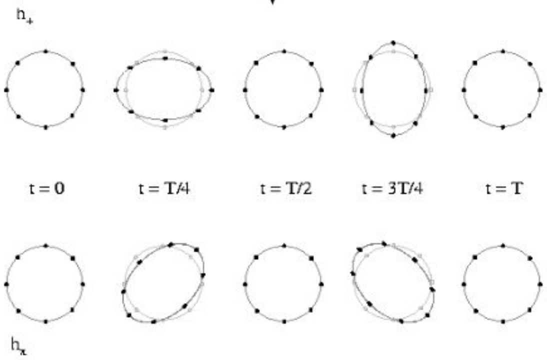
- Ripples in spacetime generated by accelerating masses
- Behavior and propagation described by General relativity
- Extremely feeble phenomena

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

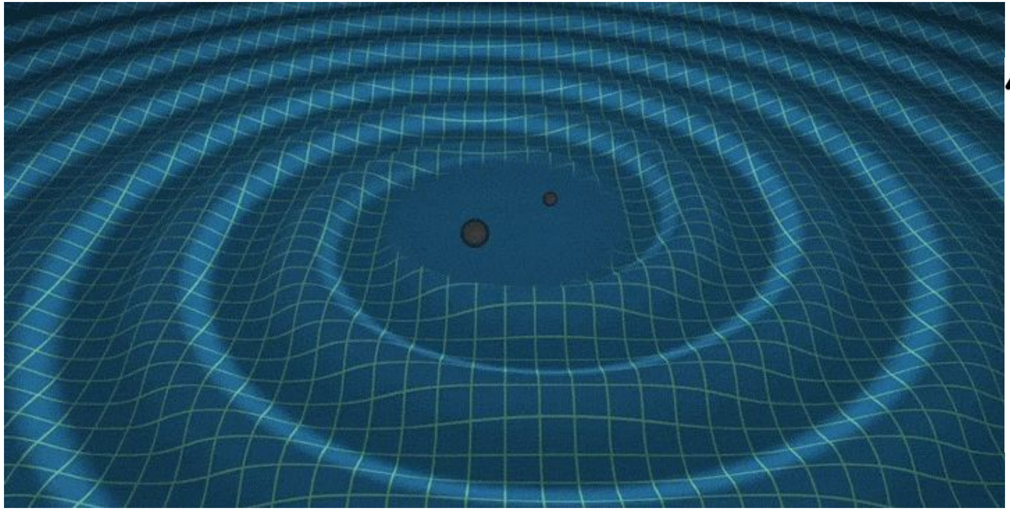
$$\downarrow$$

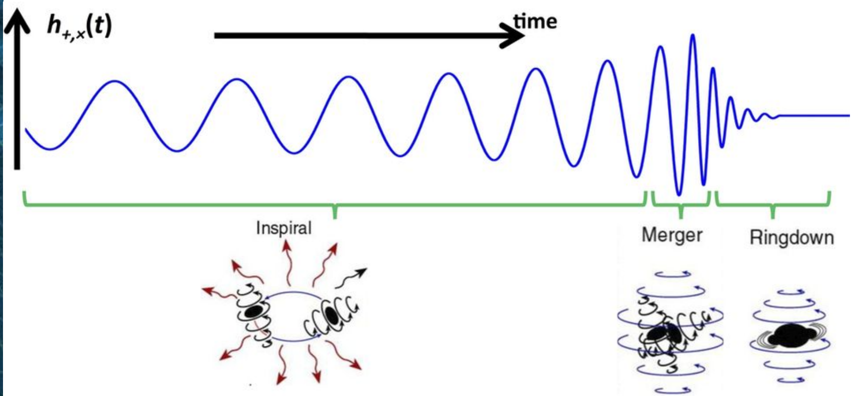
$$\Box_F \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} \delta T_{\mu\nu}$$

$$\downarrow$$



Gravitational Waves



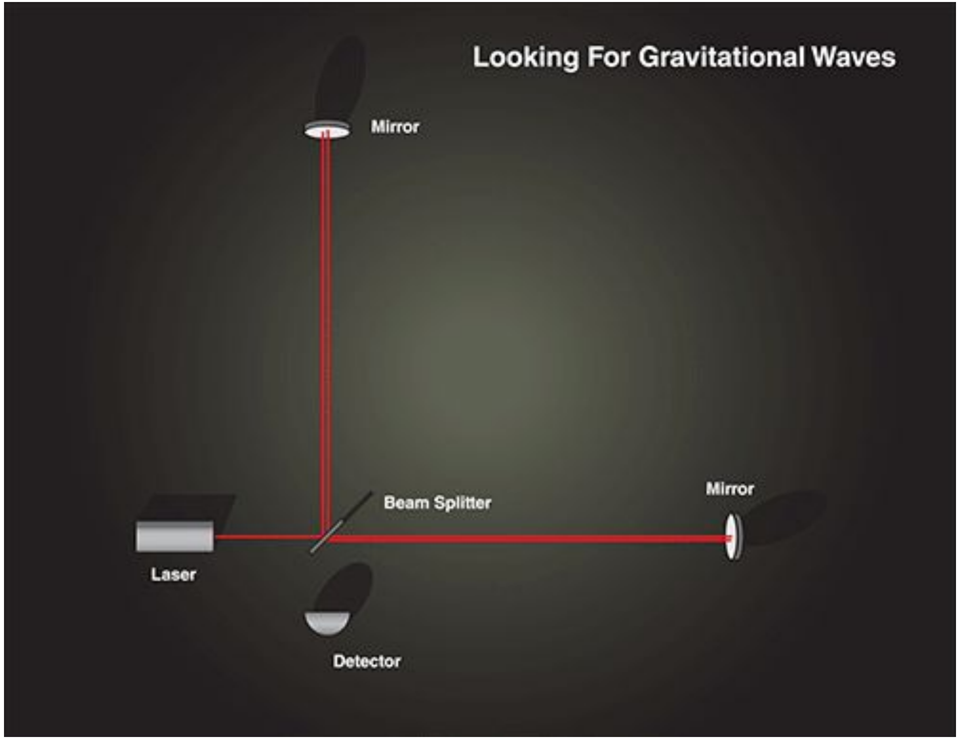


- Compact binary coalescences (CBCs): a good GW source
  - Binary neutron stars (BNS), Neutron star/black hole systems (NSBH), binary black holes (BBH)

Interferometers (IFOs)

$$\Delta L(t) = h(t)L$$

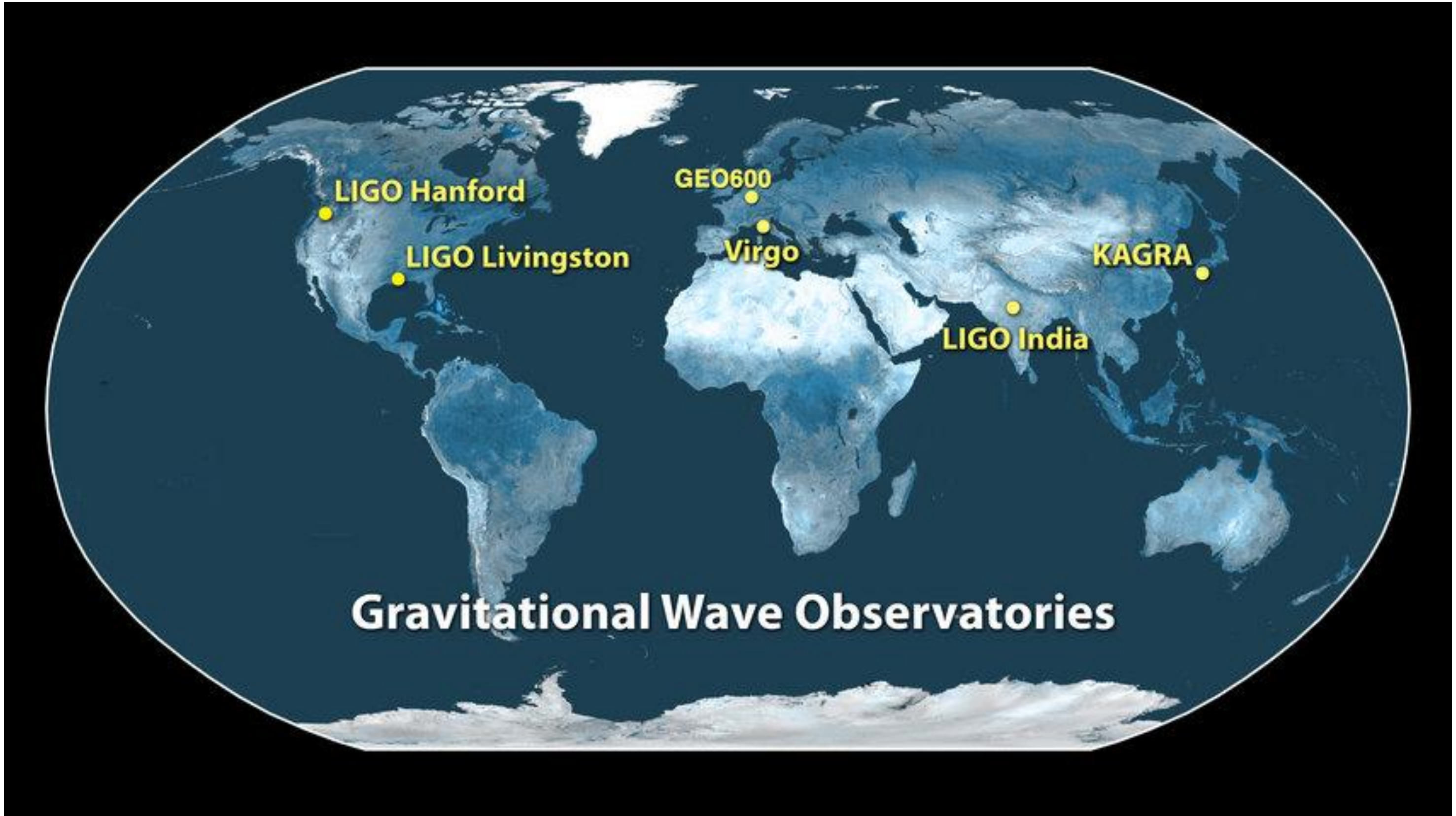
- $L \sim 3\text{-}4$ km, $h \sim 10^{-21}\text{-}10^{-22}$
- Devices to improve sensitivity
- $\Delta L \sim 10^{-18}\text{-}10^{-19}$ m
- Less than one millionth the size of an atom



Credit: NASA

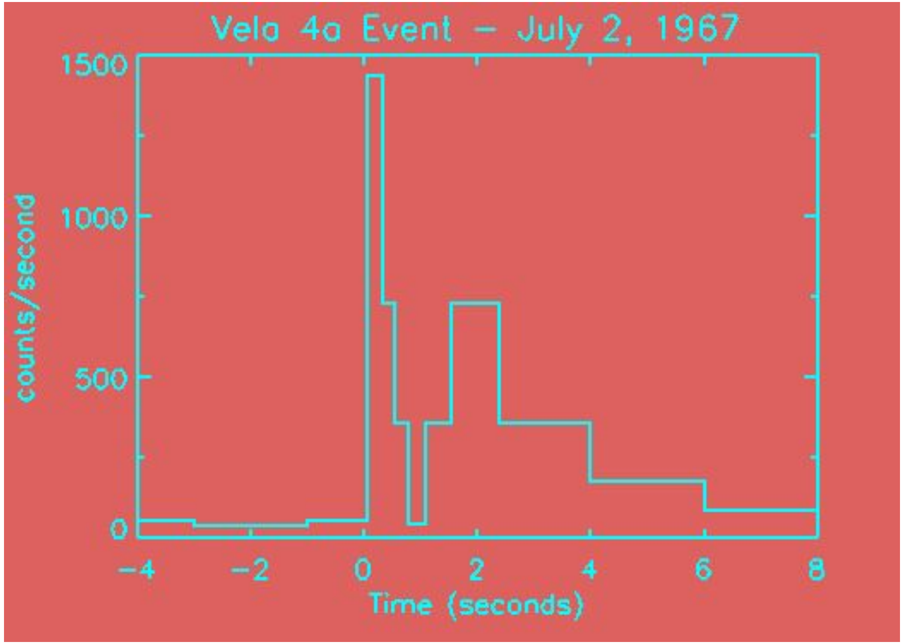
IGWN

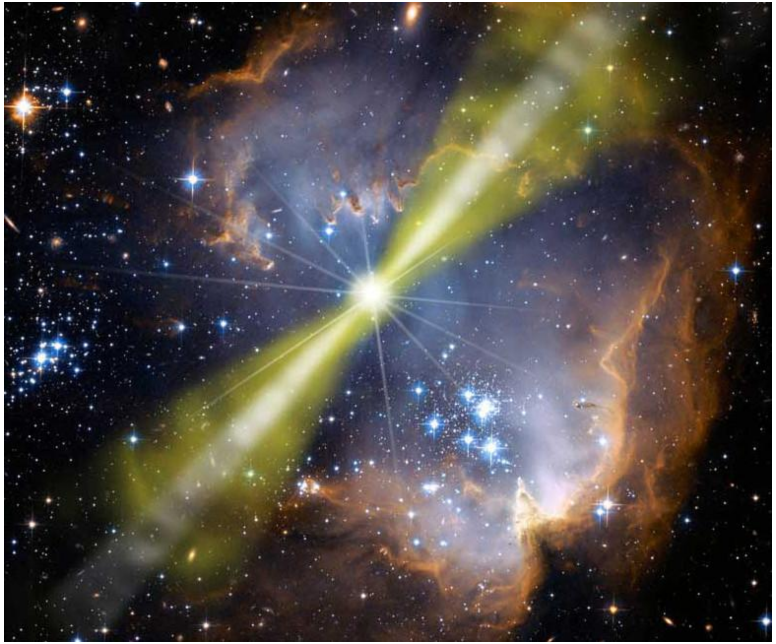
International Gravitational-Wave observatory Network



Gamma-ray bursts

- Highly variable high energy flashes of light of astronomical origin
- Discovered at the end of the 60’s by Vela spy satellites

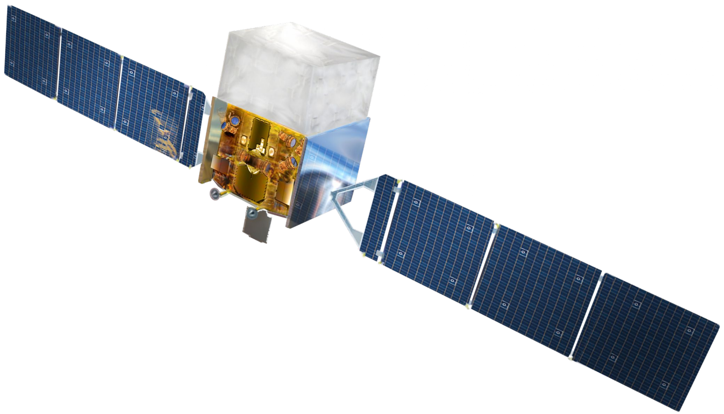




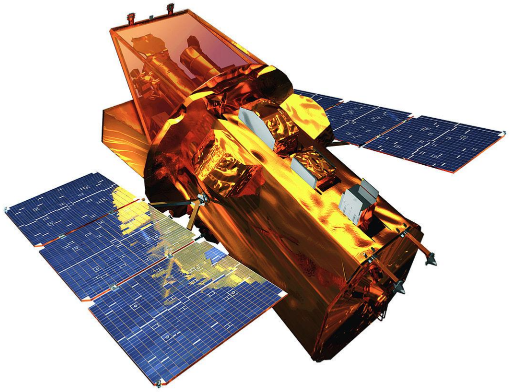
Credit: NASA

GRB detectors

- Instruments are commonly placed on spacecrafts
  - Gamma-rays highly interactive with Earth's atmosphere
- Different detectors, different energy bands



Fermi (GBM, LAT)

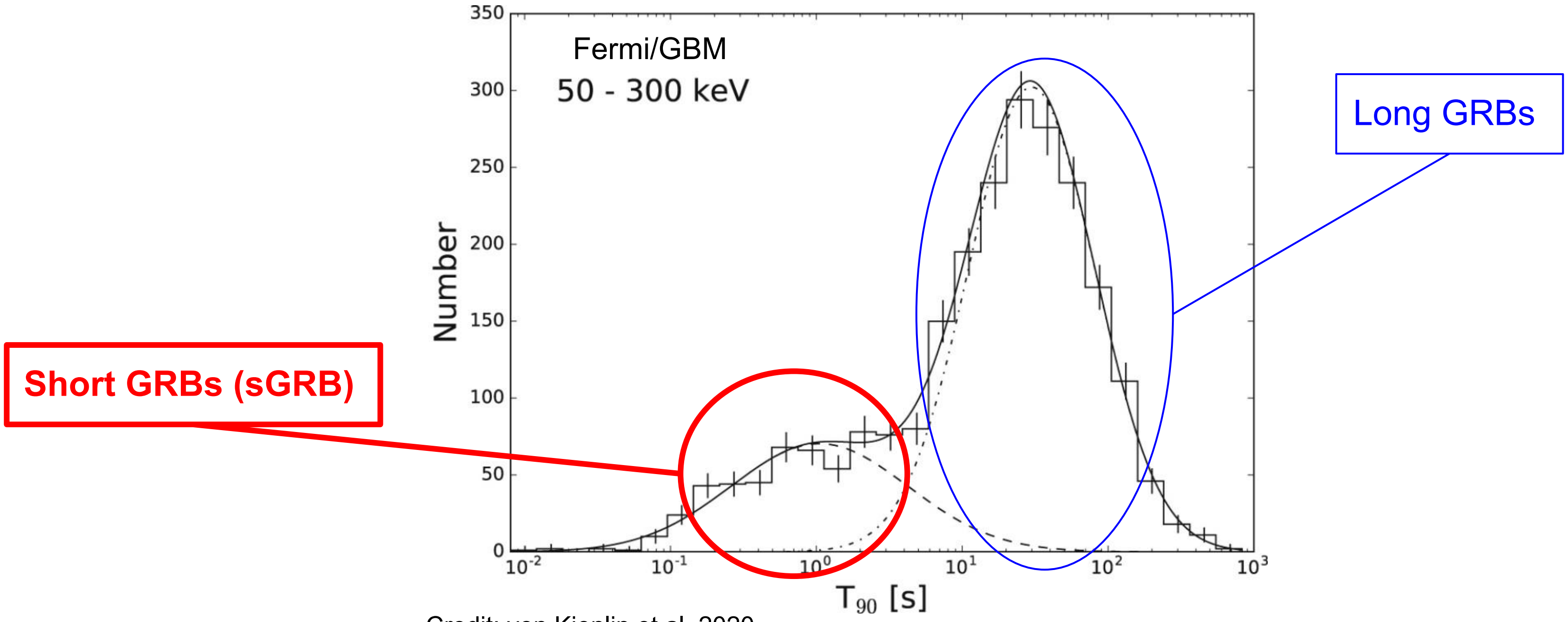


Swift (BAT)

CGRO (BATSE)

T_{90} and GRB classification

- T_{90}: time in which 90% of photons of a GRB event are detected
  - Depends on detector‘s sensitivity and energy band



Credit: von Kienlin et al. 2020

GRB photon spectrum

- Photon emission: ~ keV to ~ MeV
- Band function: empirical law fitting spectra GRBs

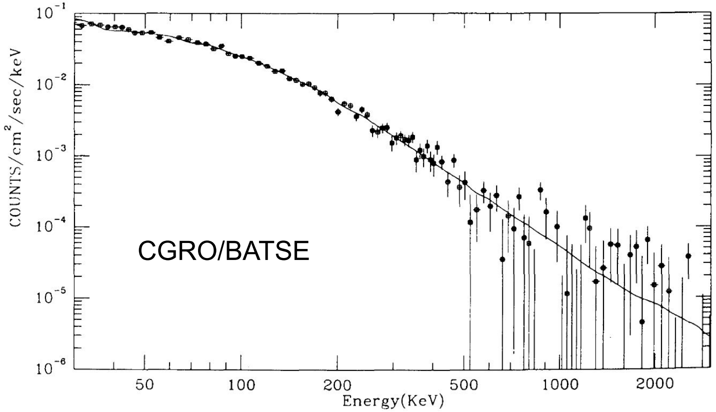
$$N(E) = \begin{cases} A\left(\frac{E}{100\ \mathrm{keV}}\right)^{\alpha_\mathrm{B}} e^{-\frac{E}{E_0}}, & E < (\alpha_\mathrm{B} - \beta_\mathrm{B})E_0 \\ A\left[\frac{(\alpha_\mathrm{B}-\beta_\mathrm{B})E_0}{100\ \mathrm{keV}}\right]^{\alpha_\mathrm{B}-\beta_\mathrm{B}} e^{\beta_\mathrm{B}-\alpha_\mathrm{B}} \left(\frac{E}{100\ \mathrm{keV}}\right)^{\beta_\mathrm{B}}, & E \geq (\alpha_\mathrm{B} - \beta_\mathrm{B})E_0 \end{cases}$$

Fermi/GBM short GRBs typical values

$$\alpha_\mathrm{B} \sim -0.5$$

$$\beta_\mathrm{B} \sim -2.25$$

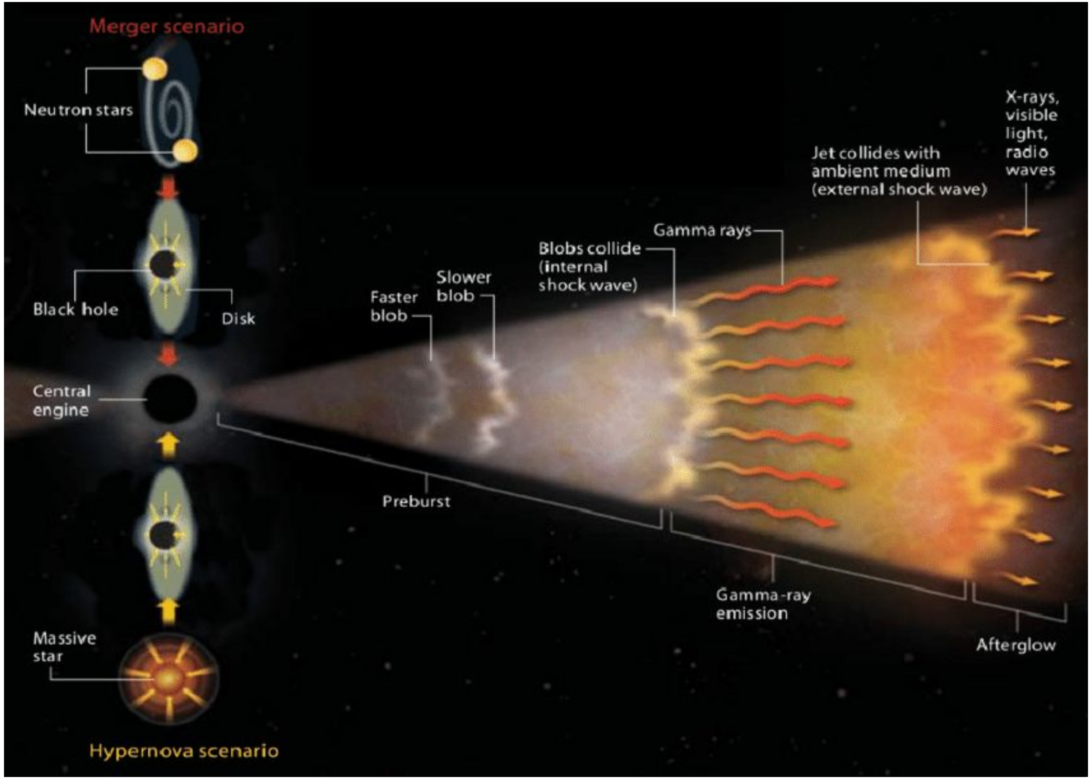
$$E_\mathrm{peak} = (2 + \alpha_\mathrm{B})E_0 \sim 800\ \mathrm{keV}$$



Credit: Band et al. 1993

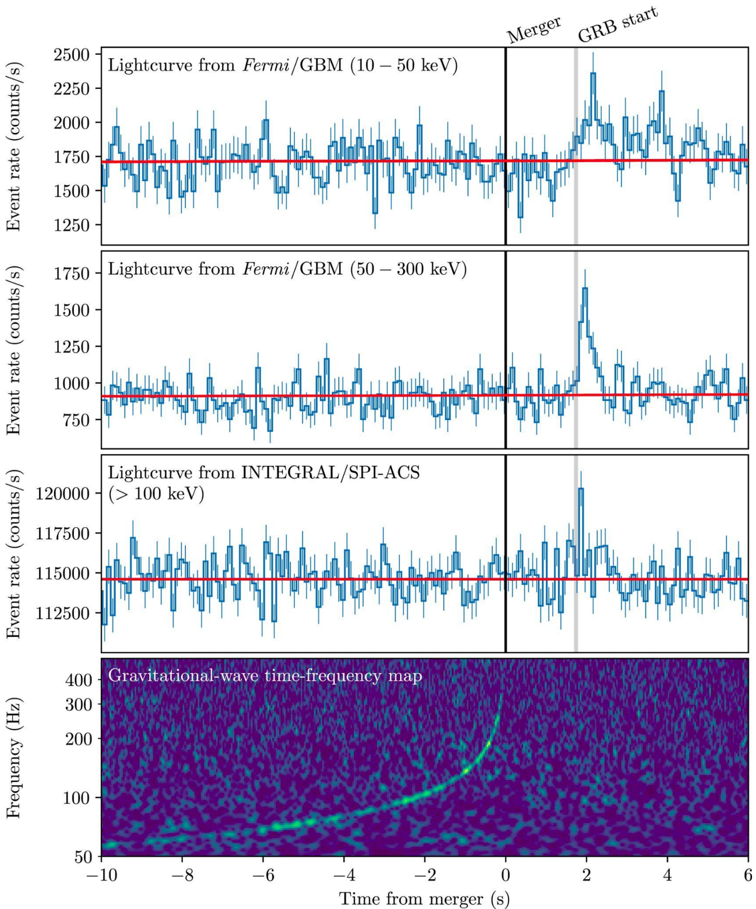
Gamma-ray bursts emission

- Highly relativistic emission
  - Collimated into a jet
- Main emission event (prompt)
- Multiband afterglow emission



Credits: NASA

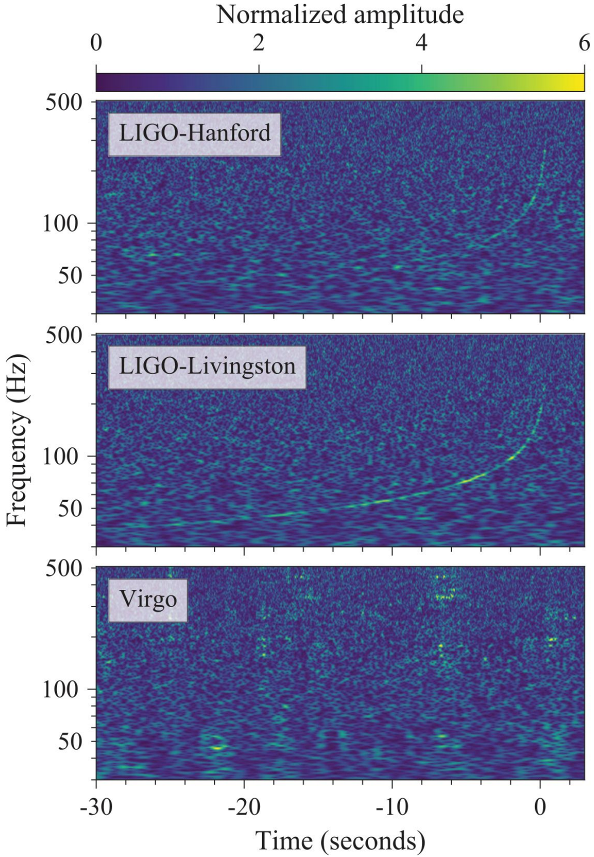
The joint detection of 17/08/17



- Unambiguous joint detection of a BNS merger GW signal and a sGRB
  - GRB 170817A detected ~1.74 ± 0.05 s after GW170817 merger
  - Same GRB detected by Fermi/GBM and Integral/SPI-ACS
  - Joint detection confirmed through observations of the afterglow

GW170817

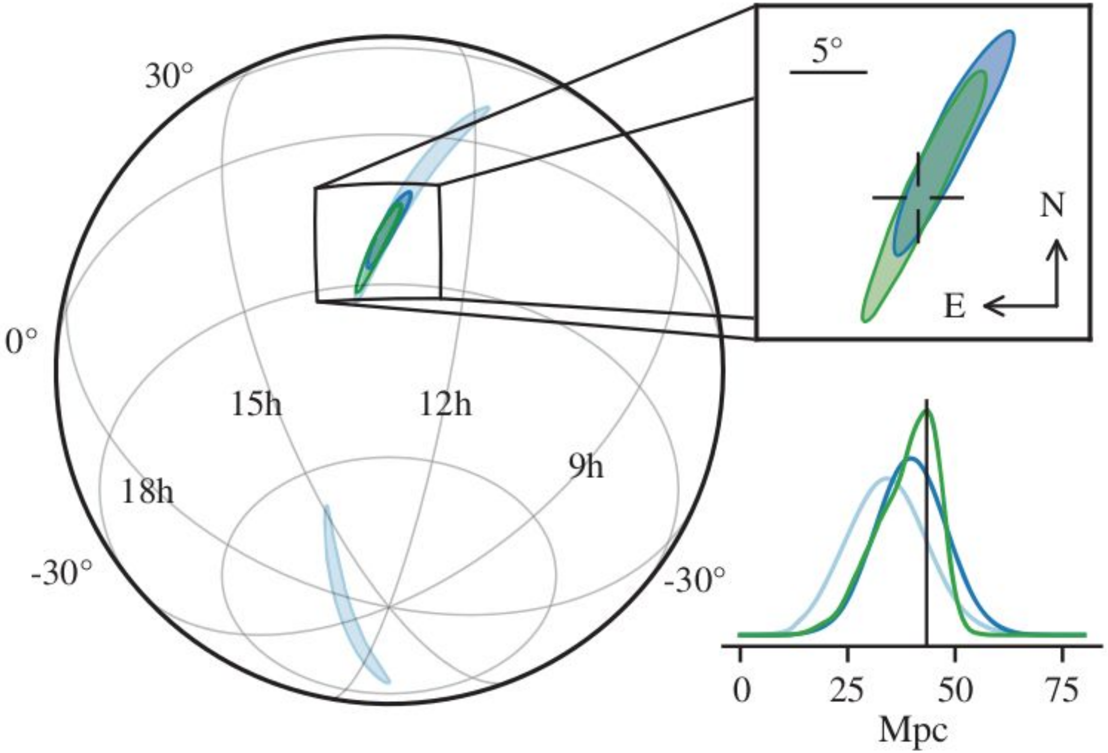
- $1.36\ M_\odot < m_1 < 1.60\ M_\odot$, $1.17\ M_\odot < m_2 < 1.36\ M_\odot$
  - First GW detected from a BNS
- Three IFOs detection
  - Lack of signal from Virgo detector



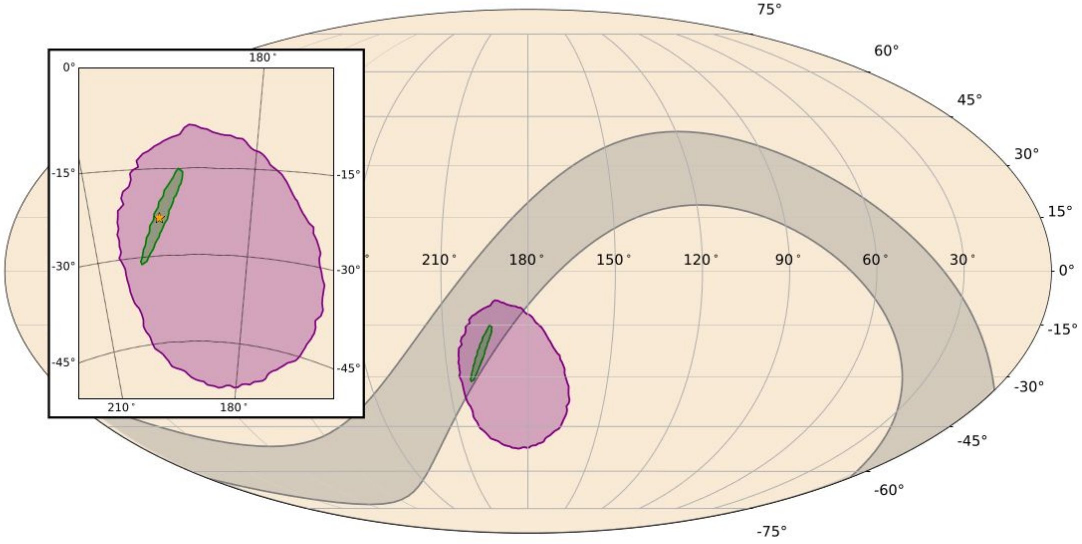
GW170817

$$D_L = 40^{+8}_{-14}\ \mathrm{Mpc}$$

- Compatible with galaxy NGC 4993: z = 0.009783
- Binary inclination $\sim 151^{+15}_{-11}\ \mathrm{deg}$
- Kilonova AT2017 gfo
  - EM transient in UV, Optical & NIR

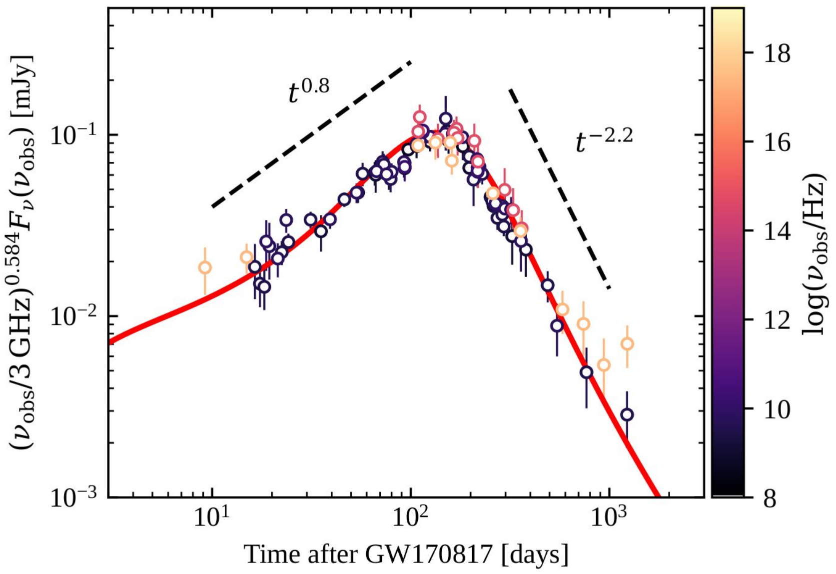


GRB 170817A



- Poor Fermi/GBM localization because low flux and South Atlantic anomaly
- Position compatible with GW170817 & NGC 4993

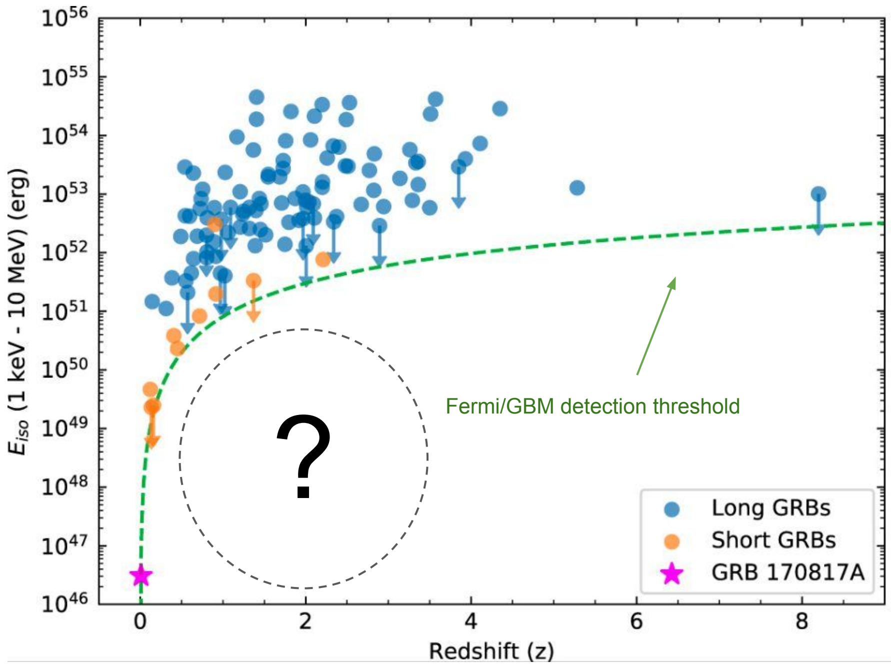
GRB 170817A afterglow

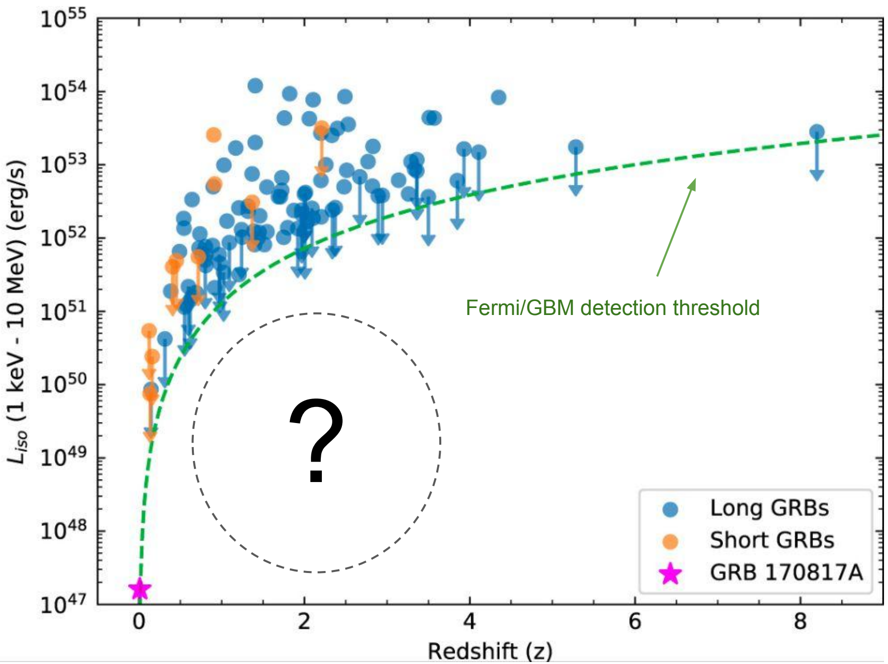


Credit: Salafia & Ghirlanda 2022

- Peak around t_{peak} ~ 155 d
  - Clue of off-axis observation
- Viewing angle from jet axis estimated: Θ~15°-30°

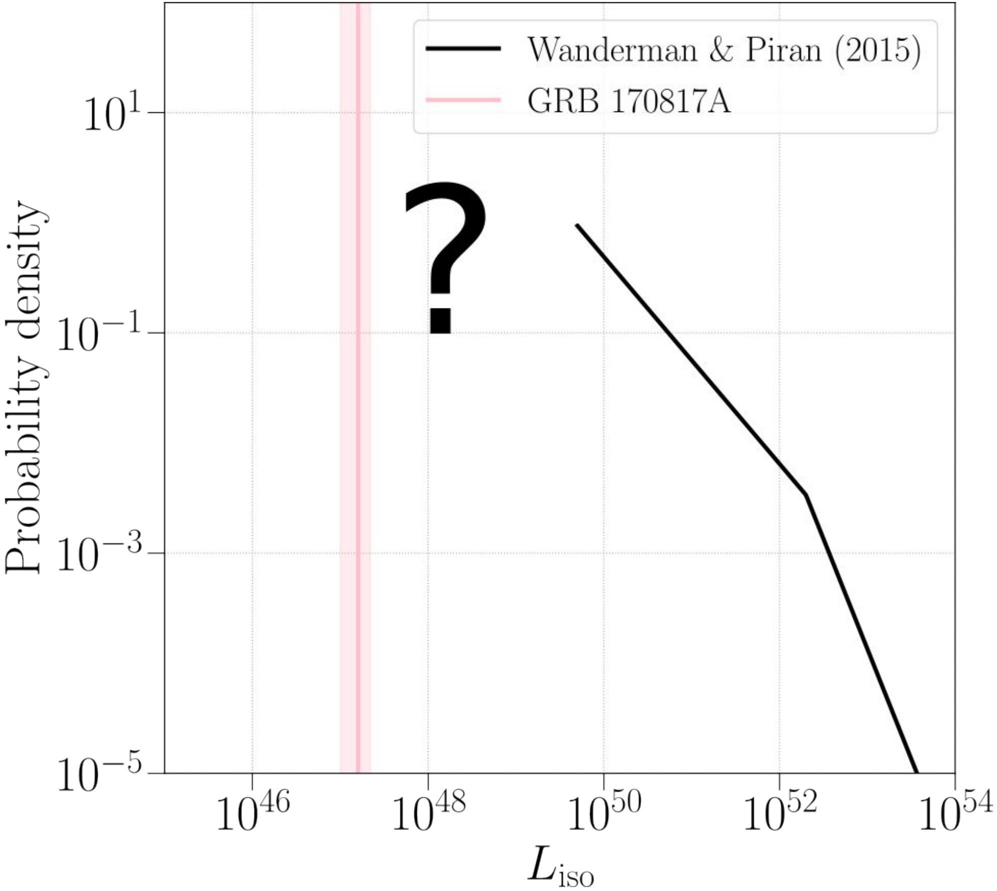
GRB 170817A energetics





- Several possible scenarios
  - Most likely a structured jet seen off-axis
- Is there an undetected part of the sGRB population?

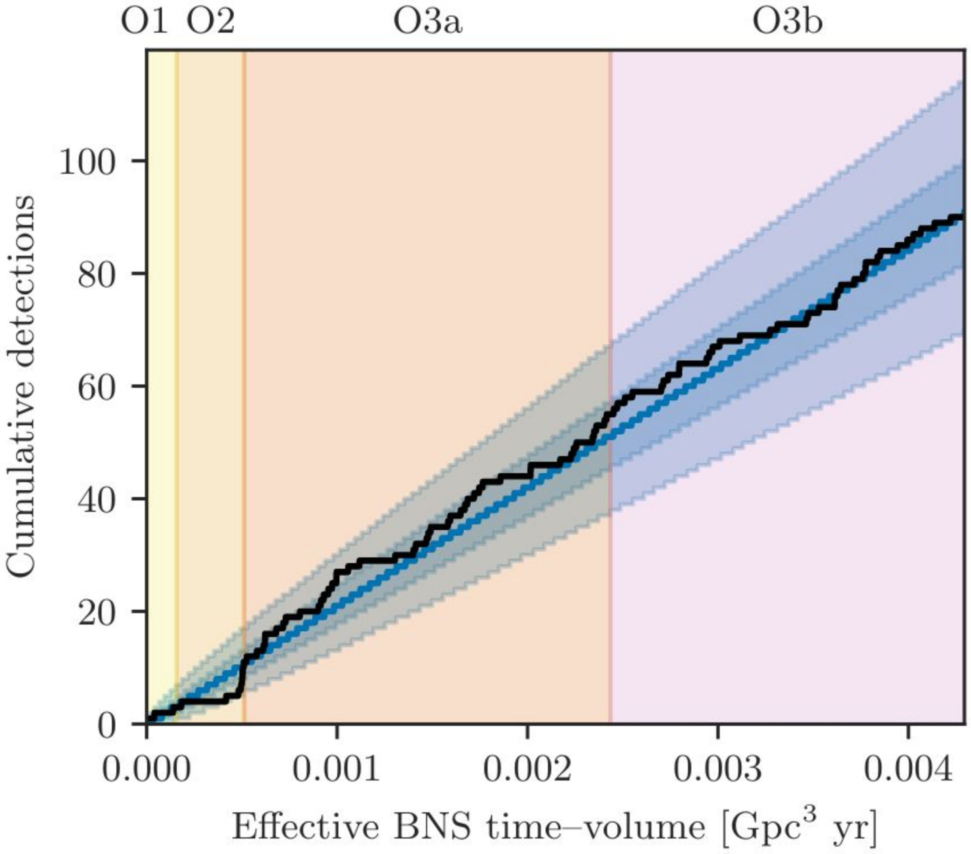
Population model: luminosity function



- How is the luminosity probability distributed?
- What can we learn from GRB 170817A?
- Can we exploit GW analysis results?

Part Two: GW data analysis

The search for CBC events



- 91 CBC candidate events
  - Mostly BBH, 2 BNS and 2 NSBH
- Two latencies of search
  - Online (~ minutes long)
  - Offline (~ weeks long)

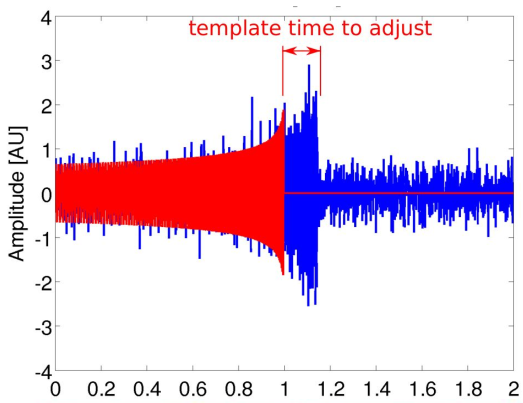
CBC and BNS rates

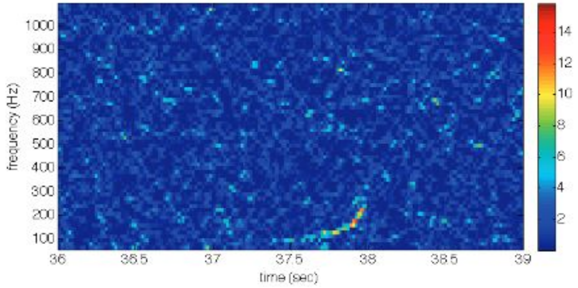
- BNS local rate density from GWTC-2 analysis
  - Uniform NS mass distribution from 1 to 2.5 $M_\odot$
  - $R_{\mathrm{BNS}} = 320^{+490}_{-240}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- BNS local rate density from GWTC-3 analysis
  - Joint mass distribution for all CBC sources

	Local rate density $[\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}]$			
Model	BNS	NSBH	BBH	Full
PDB	44^{+96}_{-34}	73^{+67}_{-37}	22^{+8}_{-6}	150^{+170}_{-71}
MS	660^{+1040}_{-530}	49^{+91}_{-38}	37^{+24}_{-13}	770^{+1030}_{-530}
BGP	98.0^{+260}_{-85}	32^{+62}_{-24}	33^{+16}_{-10}	180^{+270}_{-110}
Merged	$10 - 1700$	$7.8 - 140$	$16 - 61$	$72 - 1800$

GW followup search of GRBs

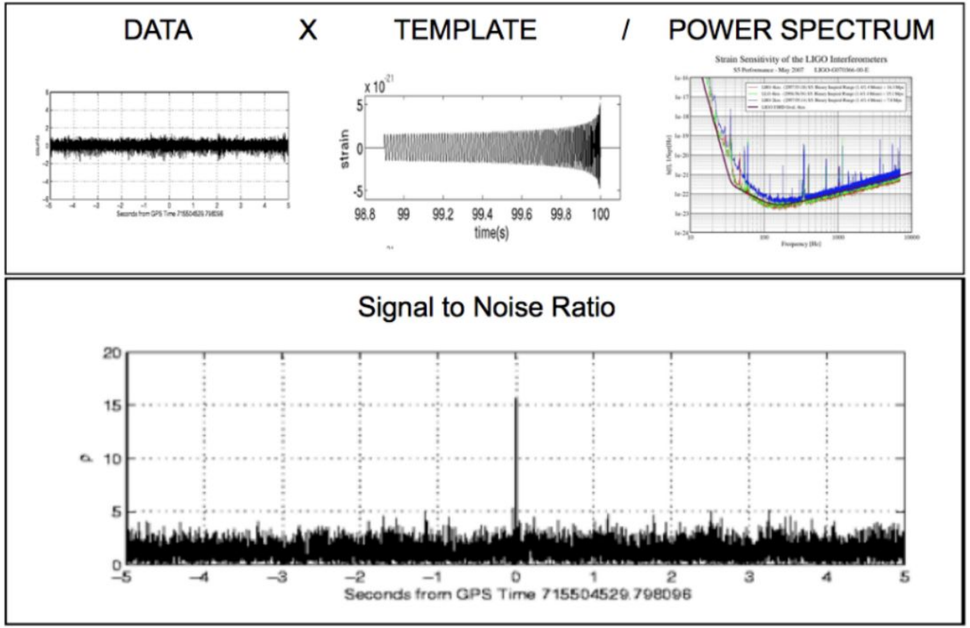
- Search for possibly subthreshold GW around the GRB trigger time and GRB sky position
- Two kinds of searches
  - Modeled search (PyGRB): matched filter analysis
    - Search for CBC signals
  - Unmodeled search (X-pipeline): coherent analysis
    - Search for generic signals





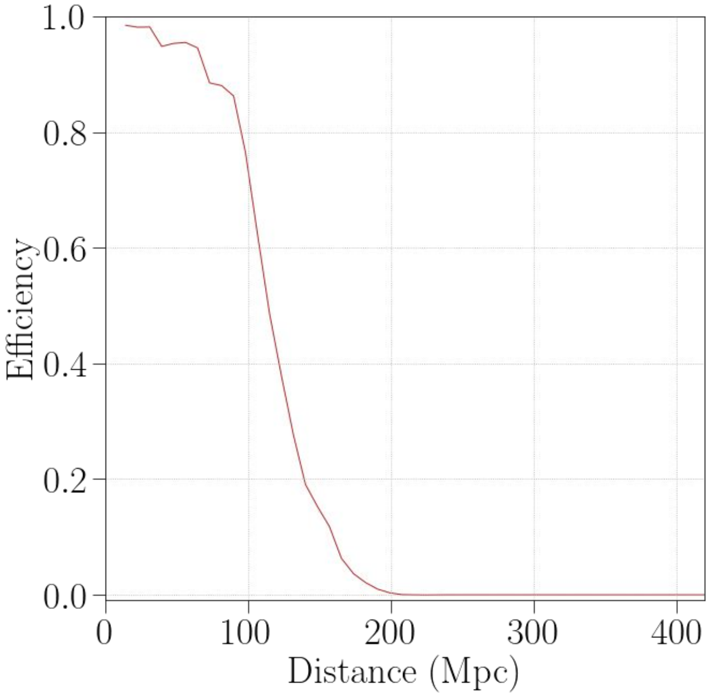
PyGRB

- Pipeline contained within PyCBC
- 30-1000 Hz frequency band
- On-source window: [-5, +1] s
- Coherent matched filtering
    - BNS and NSBH waveforms with 0° and 180° degrees of inclination
    - Potential signals ranked through their signal-to-noise ratio



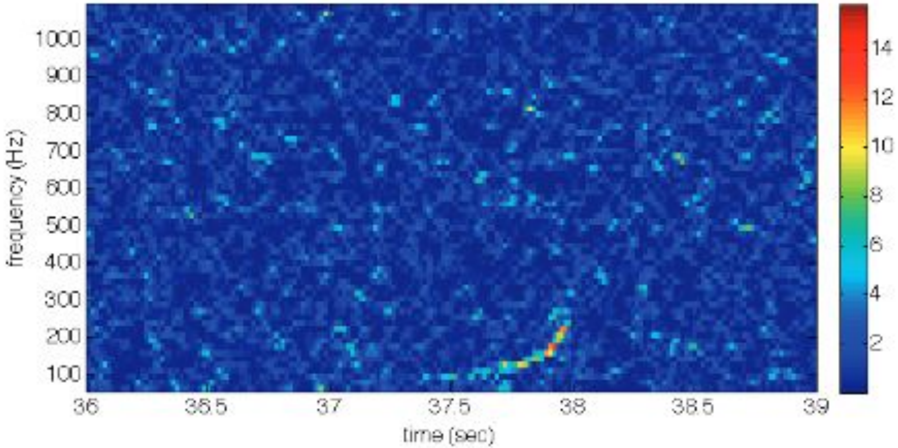
PyGRB

- Background characterization
  - ~90 minutes around GRB trigger, 6 s off-source trials
- Potential signals in on-source window compared to background
  - Statistical significance as false alarm probability (FAP)
- Sensitivity of searches determined by injecting signals into off-source data
- Efficiency as percentage of injections recovered



X-Pipeline

- Search for coherent excess energy
- On source window: [-600, max{+60, T_{90}}]
- 20-500 Hz frequency band
- Off-source trials of 660 s
- Sensitivity determined through injections
    - Long waveforms (BNS, NSBH, ADI)
    - Short waveforms (CSG)
- Autogating (from O3b)



Credits: Sutton et al. 2009

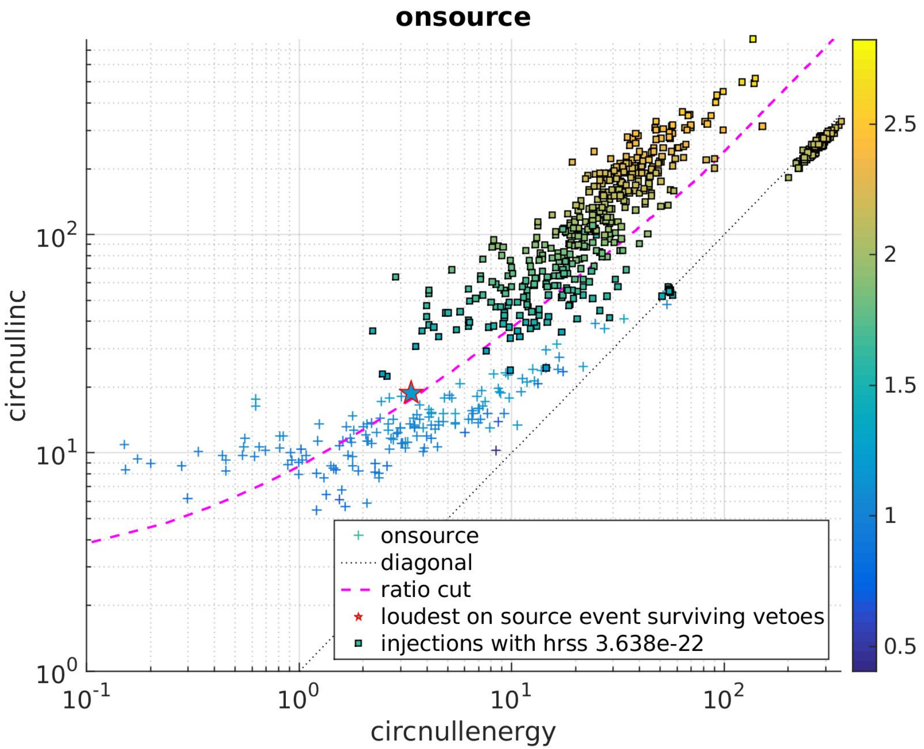
An O3b X-Pipeline focus

- 89 GRBs analyzed, 3 discarded
  - No significant events found
- 5 GRBs personally analyzed
  - GRB 191221802, GRB 191225309, GRB 191225735, GRB 200101861 and GRB 200120962
    - 2 IFOs analysis

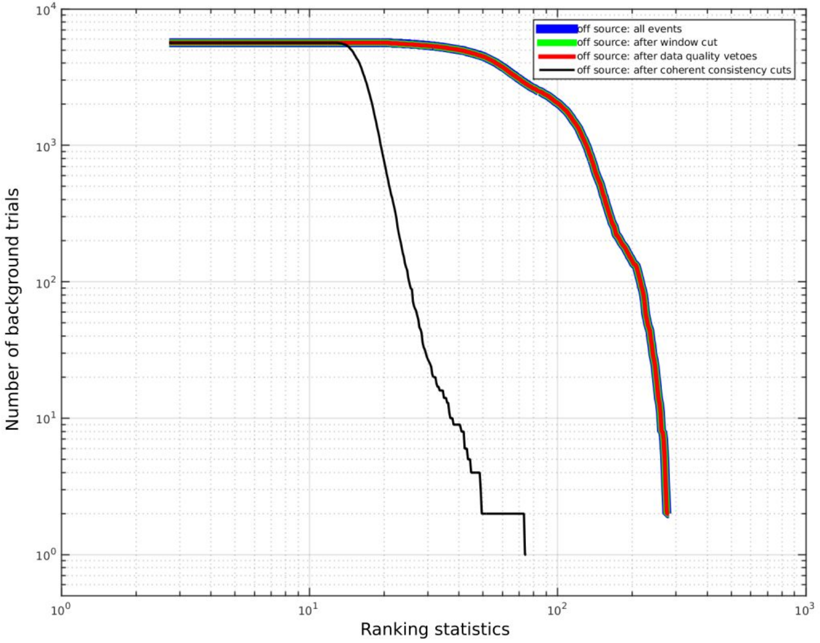
GRB	191221802	191225309	191225735	200101861	200120962
IFOs	HV	LV	HL	LV	HV
p-value	*discarded*	0.219	0.346	0.571	0.029

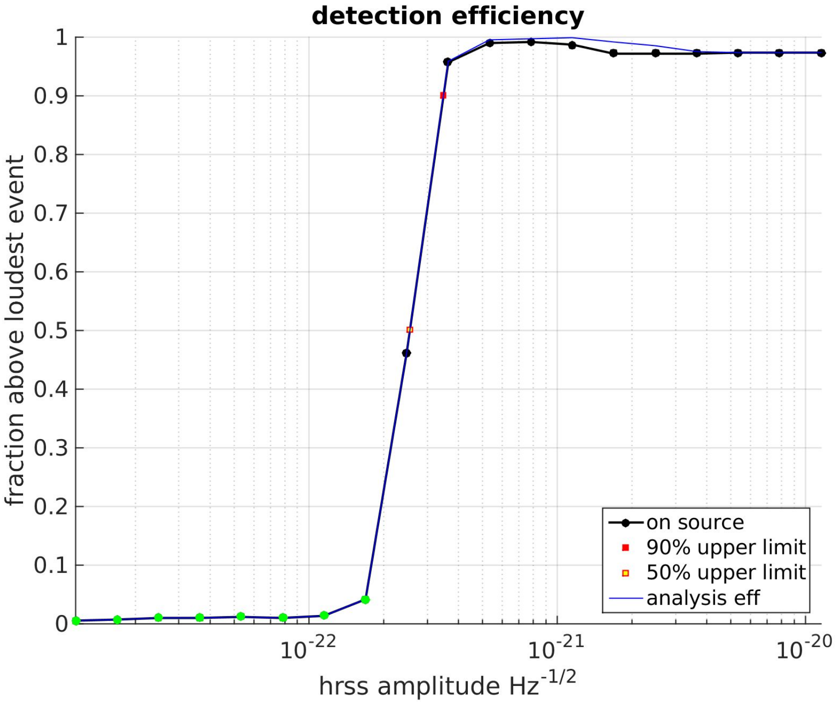
An O3b X-Pipeline focus

- Example: GRB 200101861
- On-source events partly cut away from coherent consistency cuts
  - Glitches
  - Events having common features with background



An O3b X-Pipeline focus





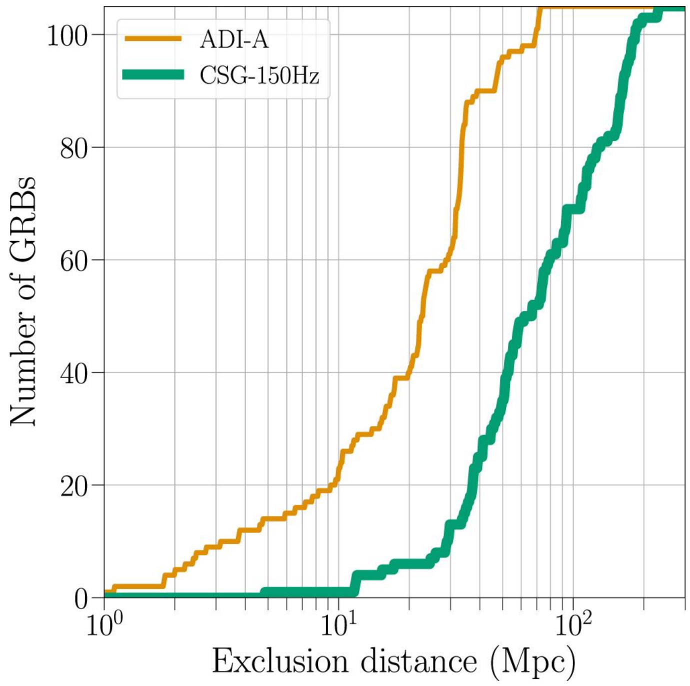
- Loudest off-source events
- Coherent consistency cuts make drop drastically ranking statistics

- Dip in the curve: vetoed injections

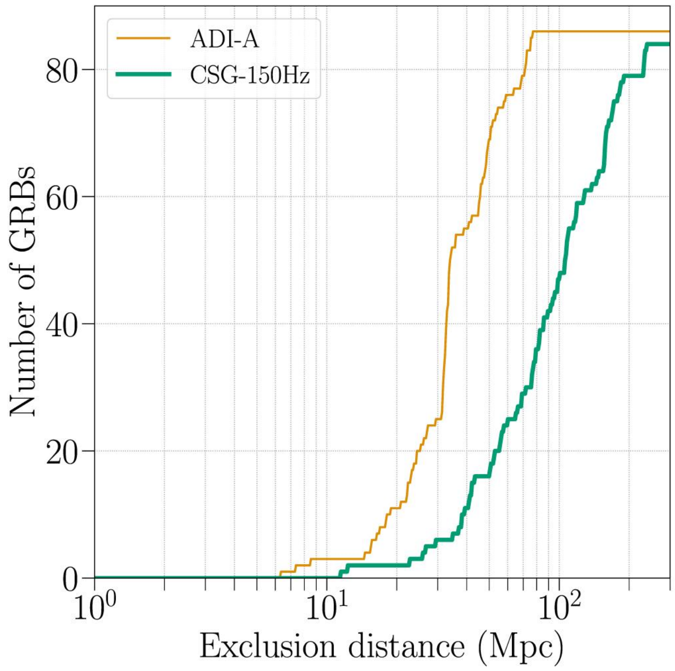
O3 X-Pipeline results

- 191 GRBs successfully analyzed through X-Pipeline

O3a



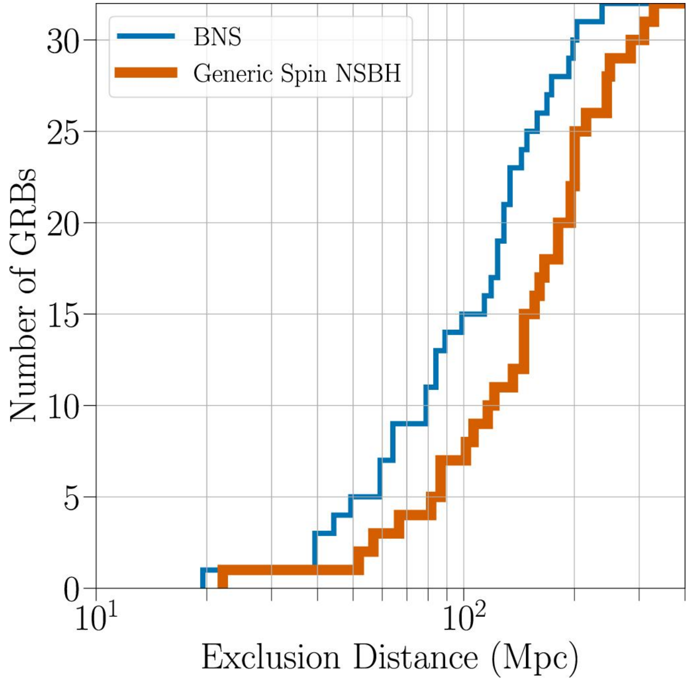
O3b



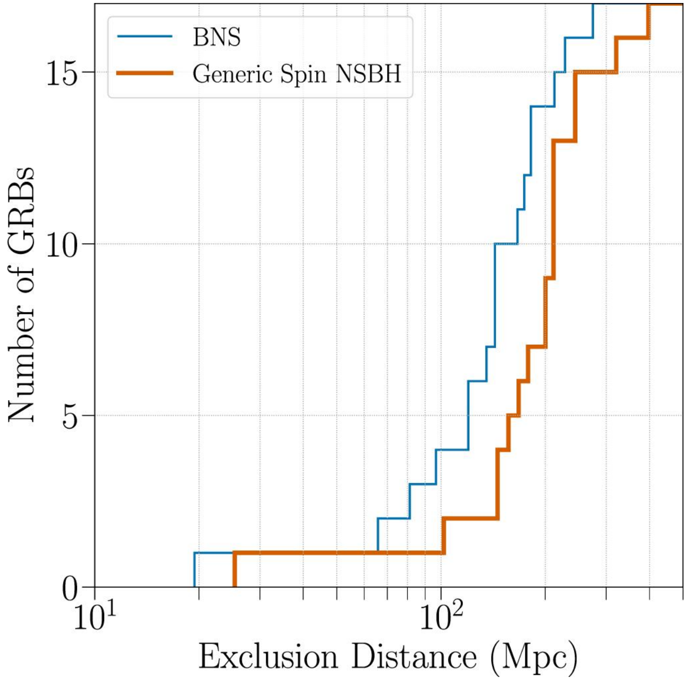
O3 PyGRB results

- 49 GRBs successfully analyzed through PyGRB
- BNS median values 119 & 149 Mpc for O3a & O3b (NSBH 160 & 207 Mpc)

O3a



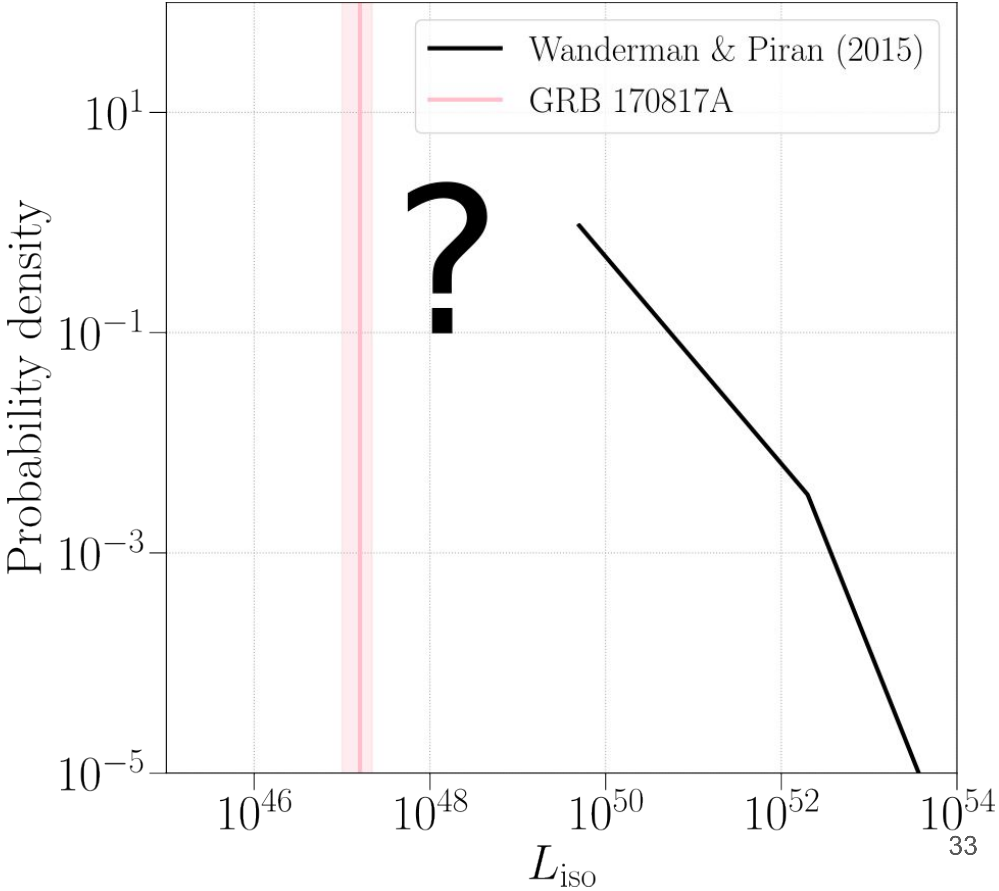
O3b



Part Three: A multimessenger GW-GRB study of the sGRB population

Population model: luminosity function

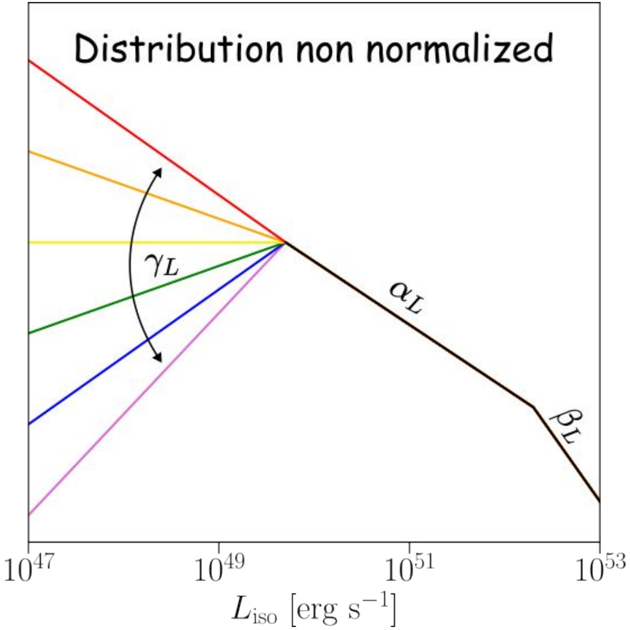
- How is the luminosity probability distributed?
- What can we learn from GRB 170817A?
- Can we exploit GW analysis results?



Population model: luminosity function

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

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



- α_L, β_L, L_* and L_{**} constrained through mid-high luminosity observations
- γ_L and L_0 to be constrained through Bayesian analysis
- Exploiting PyGRB efficiency curves & BNS local rate density distribution

Mid-high luminosity parameters

Wanderman & Piran (2015)

$$\phi_0^{\mathrm{WP15}}(L_{\mathrm{iso}}) \equiv \frac{\mathrm{d}P}{\mathrm{d}\ln(L_{\mathrm{iso}})} \propto \begin{cases} \left(\frac{L_{\mathrm{iso}}}{L_*}\right)^{-\alpha_L}, & L_{\mathrm{iso}} \leq L_* \ , \\ \left(\frac{L_{\mathrm{iso}}}{L_*}\right)^{-\beta_L}, & L_{\mathrm{iso}} > L_* \end{cases}$$

- Short GRBs samples from Fermi/GBM, Swift/BAT and CGRO/BATSE
- BNS as main progenitors of short GRBs
- α_L, β_L, L_* constrained through maximum likelihood method
  - α_L~0.94, β_L~2, L_*~2x10^{52} erg s^{-1}
  - Low luminosity cutoff: L_{**}=5x10^{49} erg s^{-1}

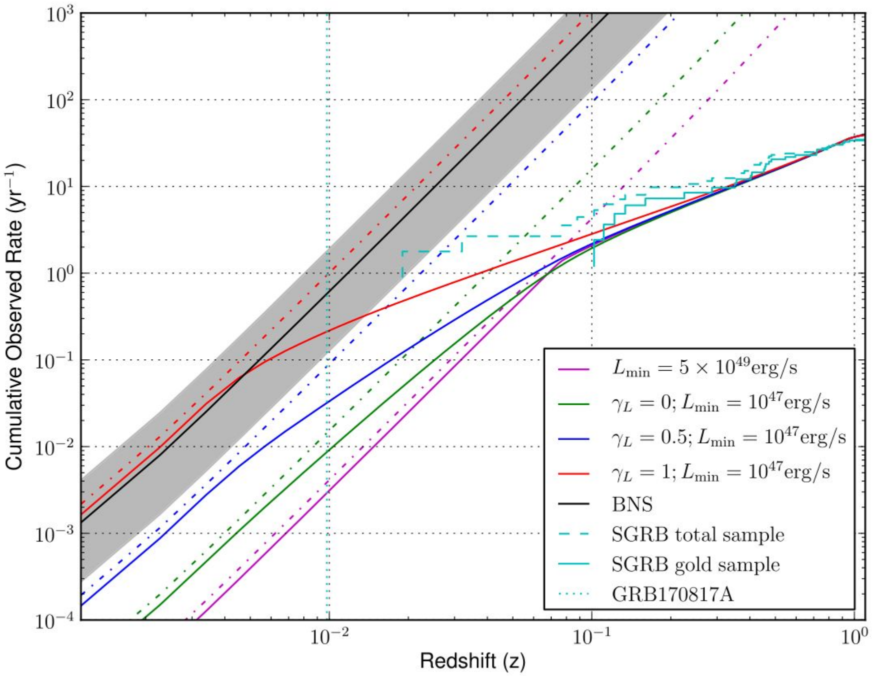
$$\rho_{\mathrm{sGRB}}(z) \propto \begin{cases} e^{\frac{z-0.9}{0.39}}, & z \leq 0.9 \\ e^{-\frac{z-0.9}{0.26}}, & z > 0.9 \end{cases}$$

$$\rho_0^{\mathrm{WP15}} \equiv \rho_{\mathrm{sGRB}}(z=0) \simeq 4.1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

$$R_{\mathrm{BNS}} = 320^{+490}_{-240}\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$$

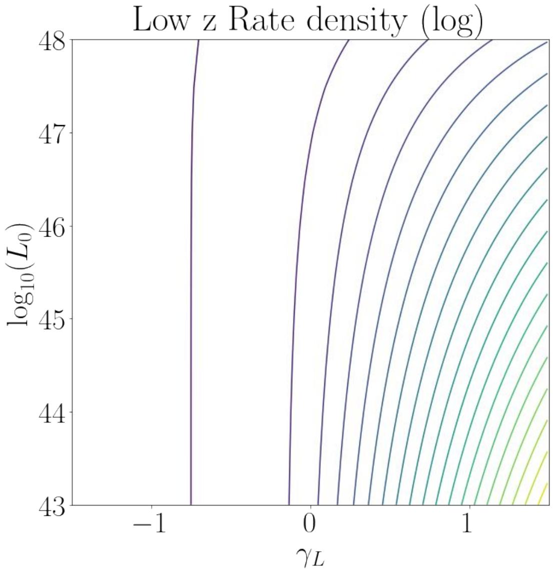
Population model: luminosity function

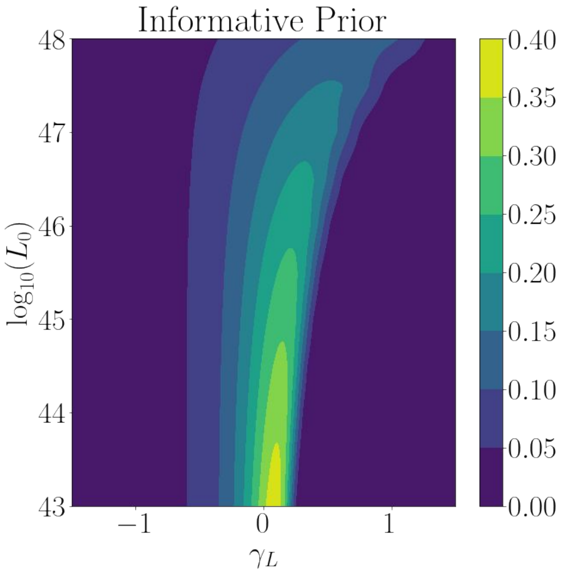
- Extension of analysis described in O2 IGWN GRB followup paper
  - Rewrote entirely to Python3
  - Broader γ_L parameter space
  - Added L_0 parameter
  - Added BNS rate information
  - Complete set of O1 to O3 PyGRB efficiency curves



Prior PDF

- Observed sGRB rate distribution vs *z*
- Logarithm of local observed rate density probability constant over γ_L and L_0
- BNS as main progenitors for short GRBs
    - BNS local rate density distribution from GW observations





Likelihood

PyGRB efficiency curve for a given sGRB *i*

$$P_i^{\rm det}(\gamma_L, L_0) = \int_0^{\infty} \phi_0(L, \gamma_L, L_0)\mathcal{N}_{\tilde{L}}(L)\,\mathrm{d}\ln L \int_0^{\infty} \eta_i(z)\frac{\mathrm{d}P_{\rm obs}^{\rm GRB}}{\mathrm{d}z}\delta(z - \tilde{z})\mathrm{d}z$$

Lognormal distribution for GRB 170817A luminosity

$$P_i^{\neg\rm det}(\gamma_L, L_0) = 1 - \int_0^{\infty} \eta_i(z)\frac{\mathrm{d}P_{\rm obs}^{\rm GRB}}{\mathrm{d}z}\mathrm{d}z$$

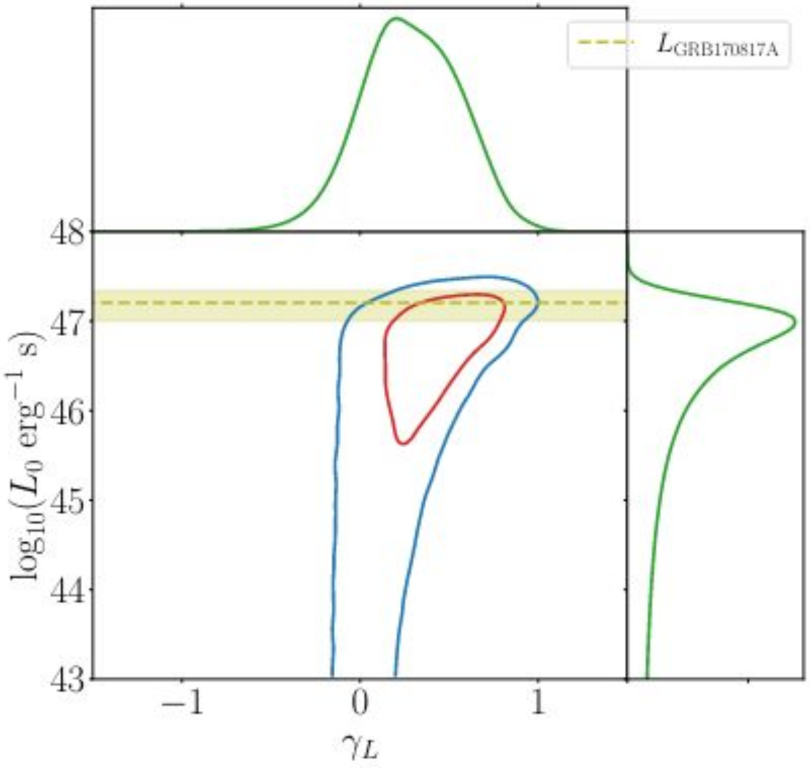
Dirac delta distribution for NGC 4993 redshift

$$\mathfrak{L}(\gamma_L, L_0) = \sum_i^{N_{\rm GRB}} \left(P_i^{\rm det}(\gamma_L, L_0) \prod_{j \neq i} P_j^{\neg\rm det}(\gamma_L, L_0) \right)$$

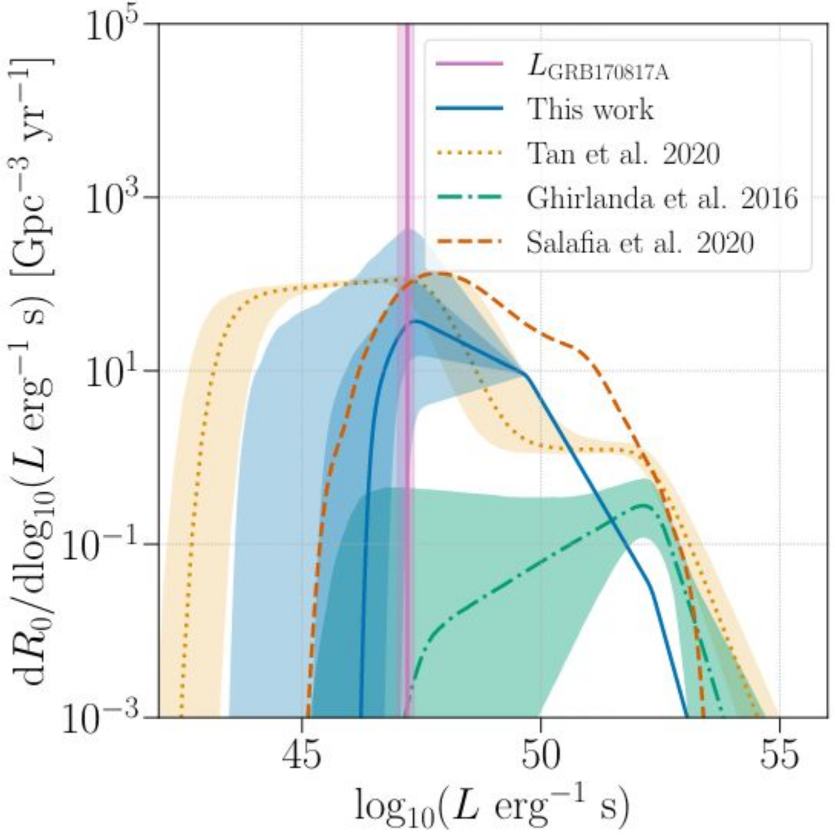
- Likelihood: probability of detecting one GW transient associated to short GRBs detected during IGWN observing runs
  - Joint detection: same redshift as NGC 4993 and same measured luminosity as GRB 170817A
  - PyGRB GW efficiency curves

Posterior PDF

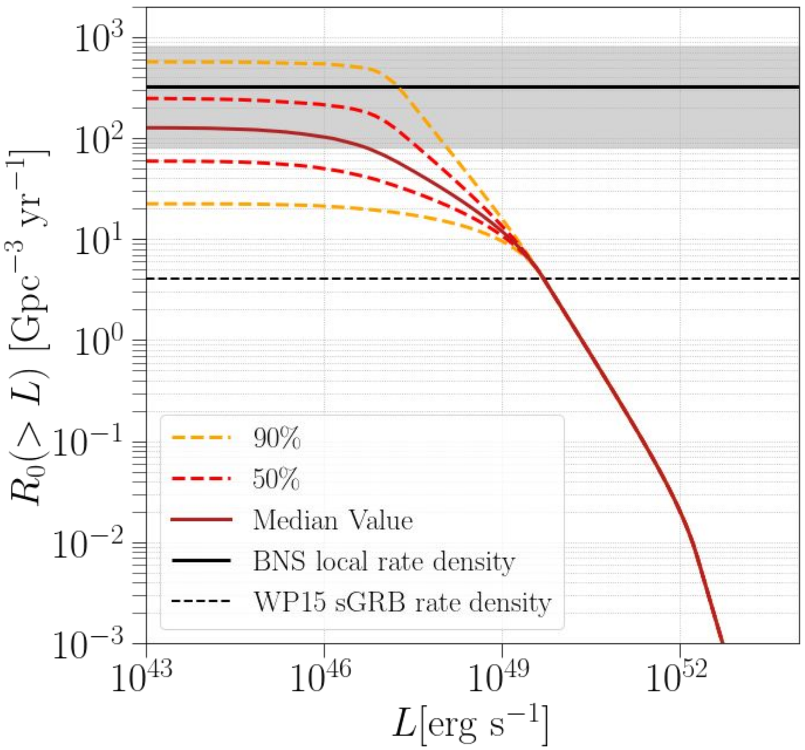
- L_0 compatible with luminosity measured for GRB 170817A
- No information about lower luminosity events
- From marginalized posterior $\gamma_L = 0.28 \pm 0.45$



Local rate density vs luminosity

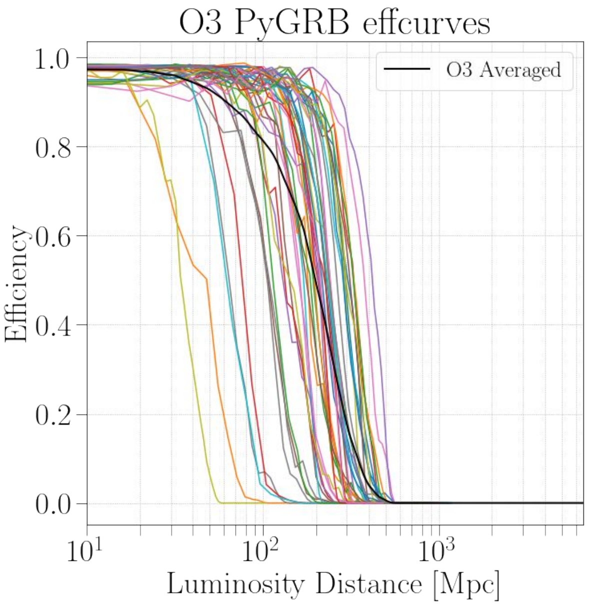


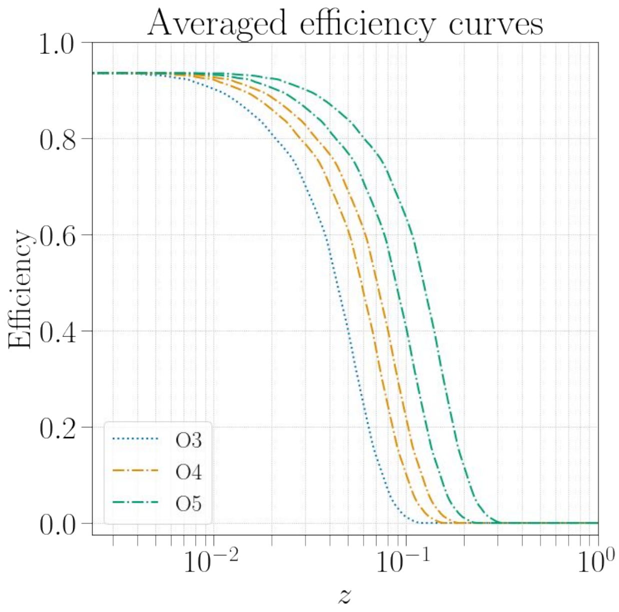
Local rate density vs luminosity



$$R_0^{\rm tot} = 124^{+433}_{-101}\ {\rm Gpc}^{-3}\ {\rm yr}^{-1}$$

GW network efficiency curves





- O3 PyGRB GW efficiency curves averaged
- Rescaled to O4 and O5 BNS ranges
- "No IFOs" duty cycle

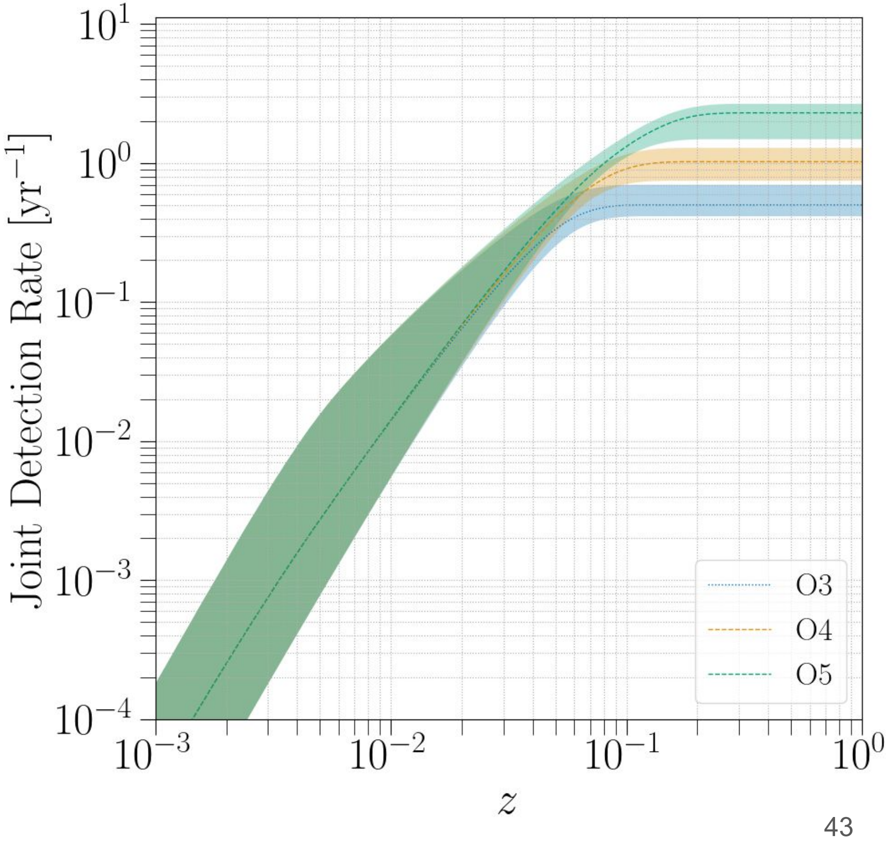
$$\Upsilon = \sqrt{\frac{\sum_i r^2_{\mathrm{O4},i}}{\sum_j r^2_{\mathrm{O3},j}}} \qquad \eta^{\mathrm{GW}}_{\mathrm{O4}}(d_{\mathrm{L}}) = \eta^{\mathrm{GW}}_{\mathrm{O3}}(d_{\mathrm{L}}\Upsilon^{-1})$$

GW-GRB joint detection rates

- Observed GRB rate + GW efficiency curves

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

- Normalized through Fermi/GBM observed rate (39.5 yr $^{-1}$)
- Uncertainty from parameters and BNS ranges estimates

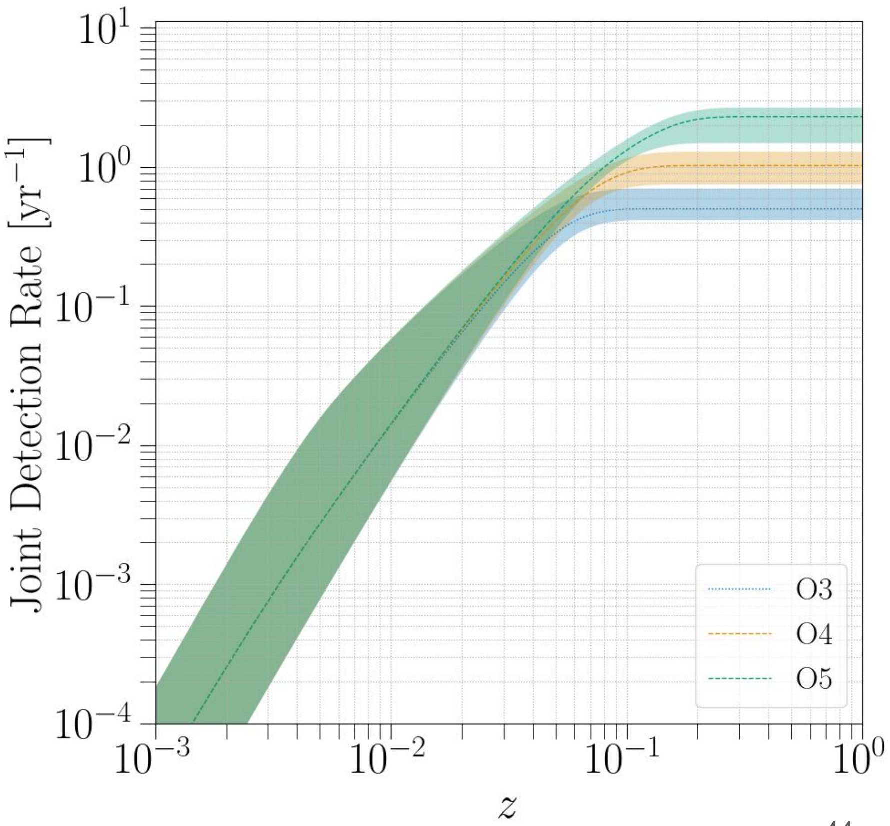


GW-GRB joint detection rates

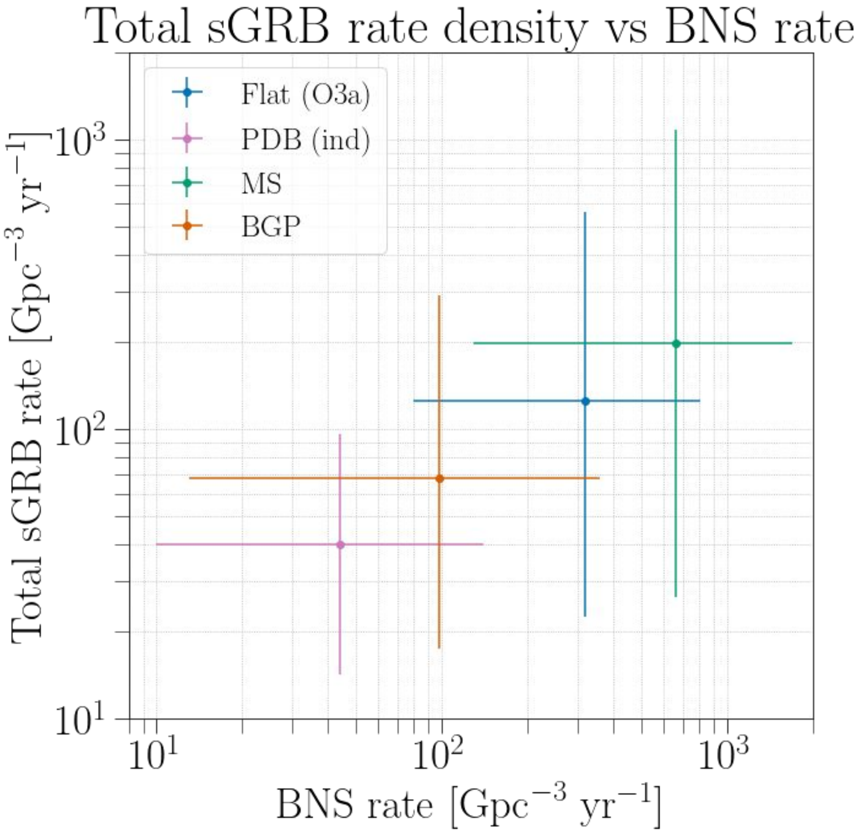
$$R^{\mathrm{O4}}_{\mathrm{GW-GRB}} = 1.02^{+0.26}_{-0.28}\ \mathrm{yr}^{-1}$$
$$R^{\mathrm{O5}}_{\mathrm{GW-GRB}} = 2.31^{+0.36}_{-0.82}\ \mathrm{yr}^{-1}$$

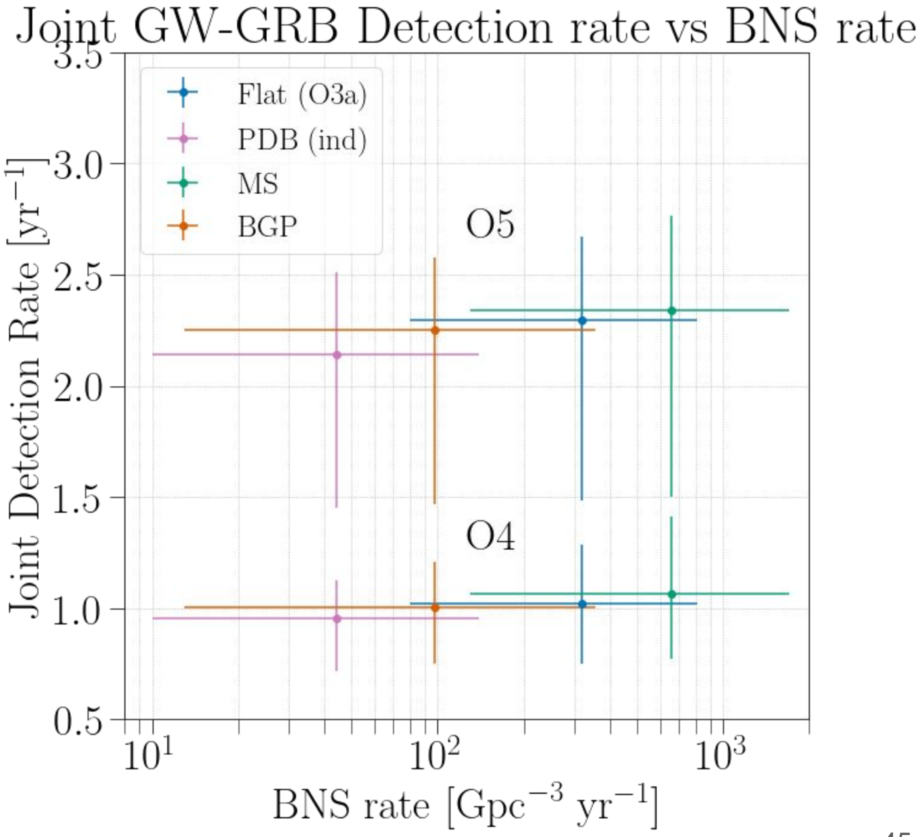
- ~ 78 % probability of having at least one joint detection in O4
  - ~ 99 % in O5
- Without low-luminosity GRB population:

$$\tilde{R}^{\mathrm{O4}}_{\mathrm{GW-GRB}} = 0.63 \pm 0.13\ \mathrm{yr}^{-1}$$
$$\tilde{R}^{\mathrm{O5}}_{\mathrm{GW-GRB}} = 1.63 \pm 0.45\ \mathrm{yr}^{-1}$$

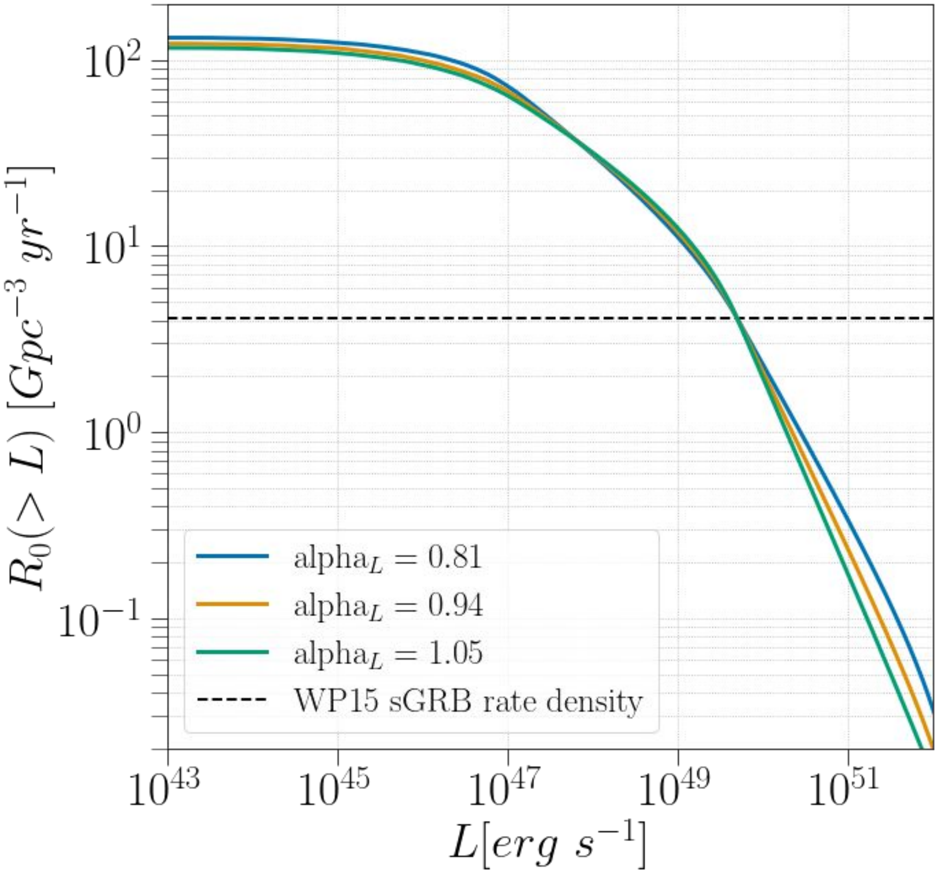


Dependence on NS mass distribution



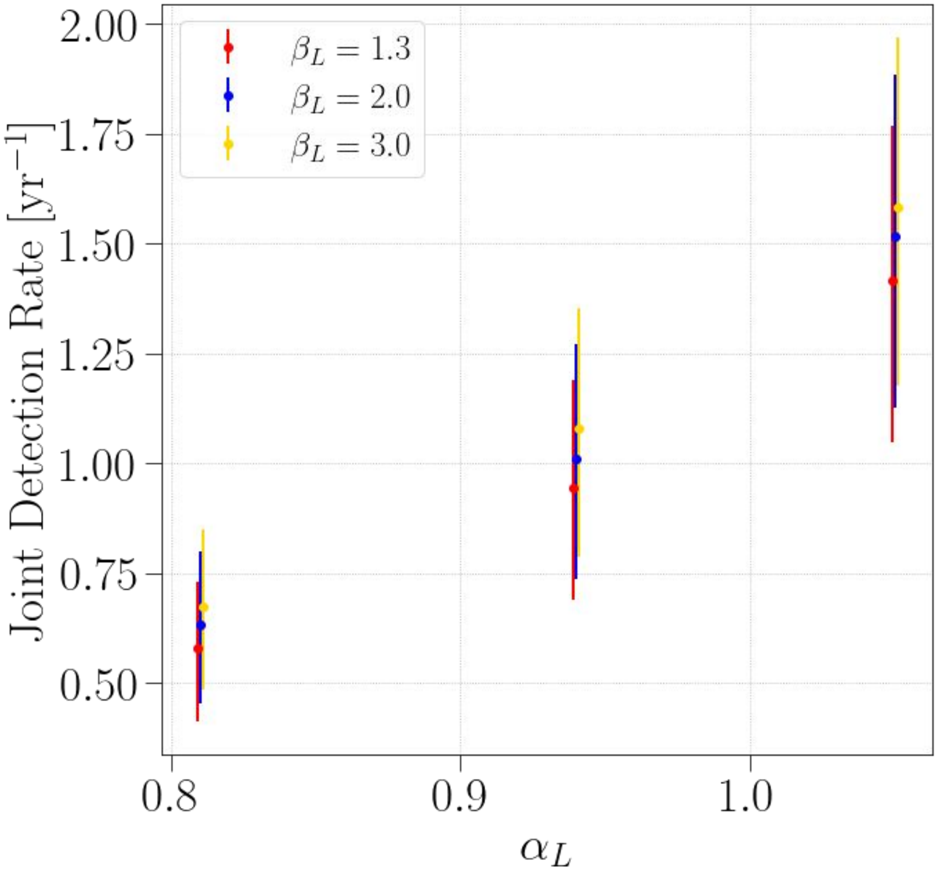


Dependence on WP15 parameters



- Analysis run with different values of α_L, β_L and L_*
  - GWTC-2 BNS local rate density
  - $R_0^{\mathrm{sGRB}}(L > L_{**}) = 4.1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

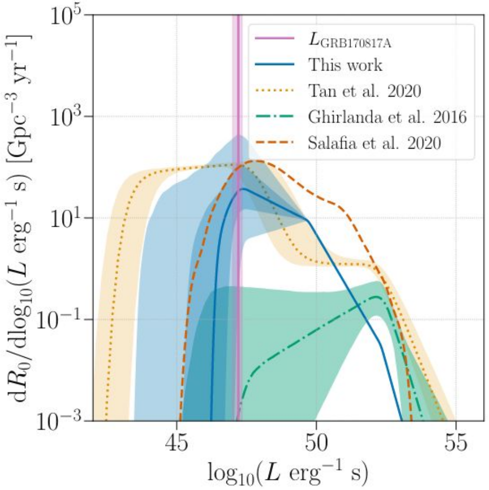
Dependence on WP15 parameters

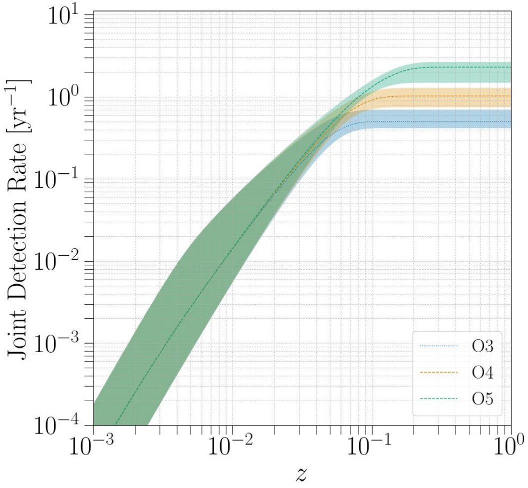


- Analysis run with different values of α_L, β_L and L_*
    - GWTC-2 BNS local rate density
    - $R_0^{\mathrm{sGRB}}(L > L_{**}) = 4.1\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$

Conclusions

- Big part of short GRB population undetected
  - Luminosity distribution peaks around GRB 170817A value
- Joint GW-GRB detection rate
  - Likely to have at least one joint detection during next observing runs





Future developments

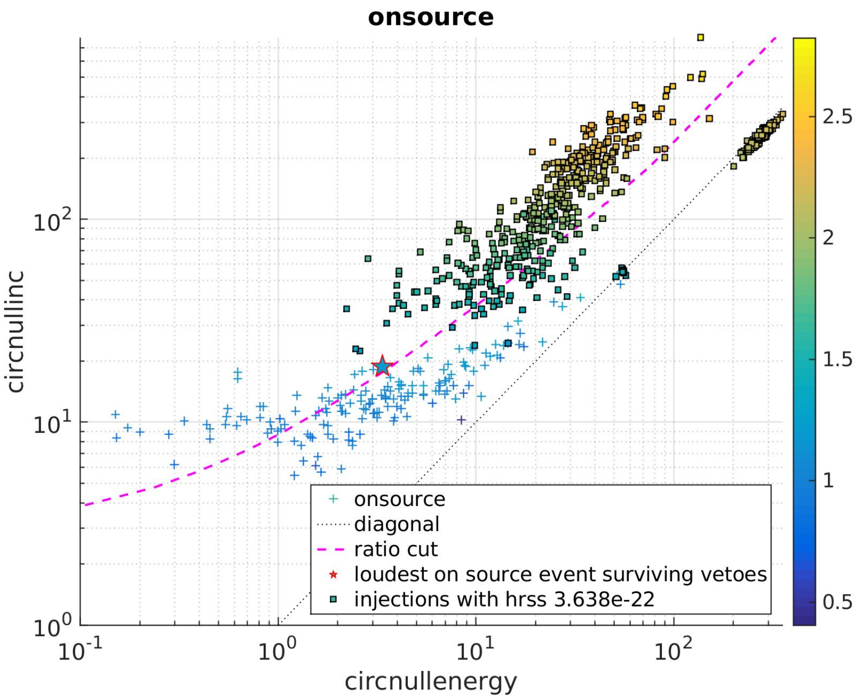
- Future developments
  - Analysis with future O4 data
  - Similar analysis of full sGRB population
    - Data from GRB catalogues
    - Spectral peak energy dependent on L_{iso}
  - Dependence of L_{iso} on viewing angle

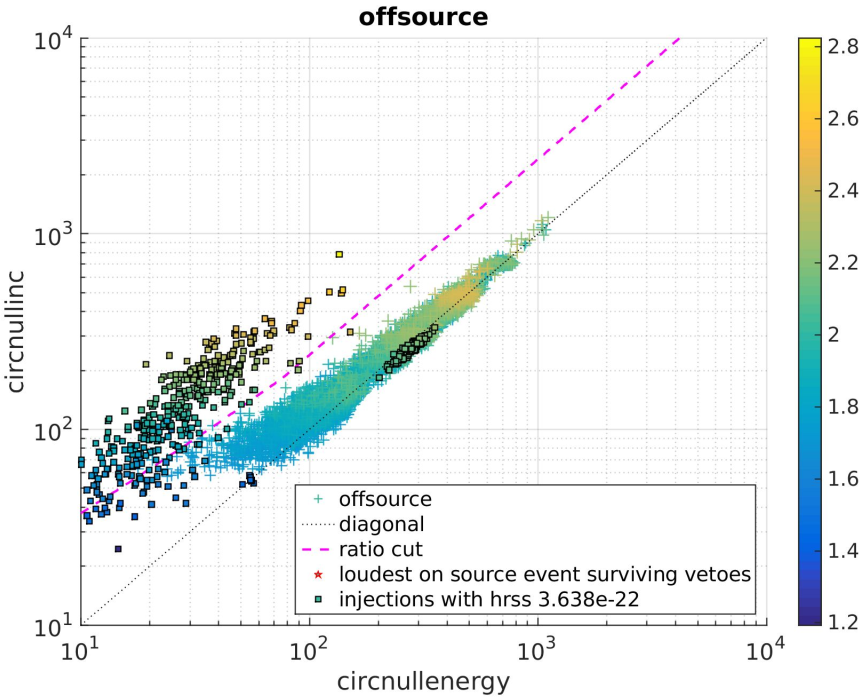
The End

(thank you for the attention)

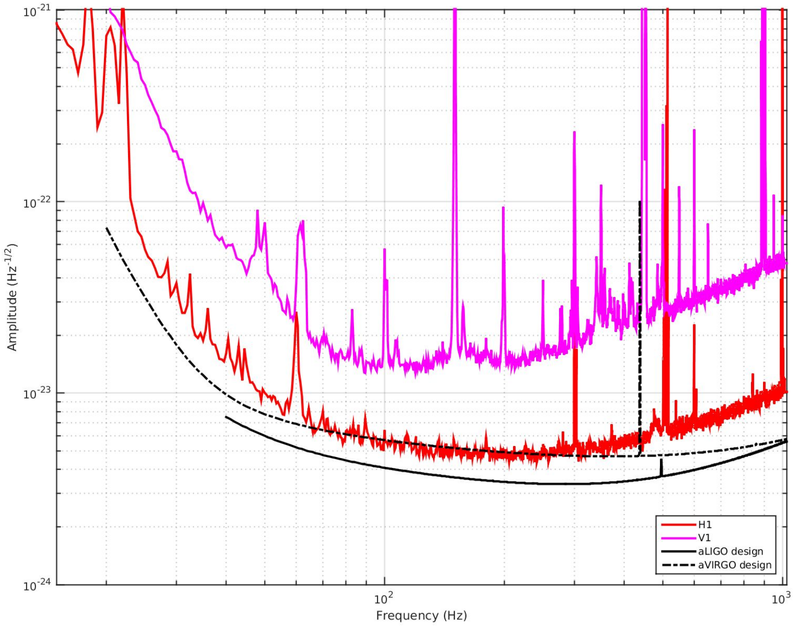
Backup

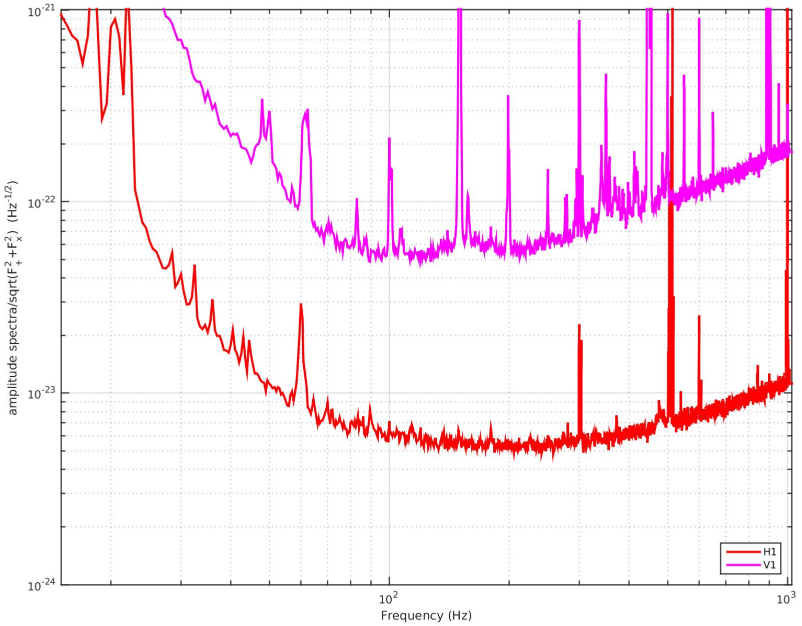
Inside X-Pipeline





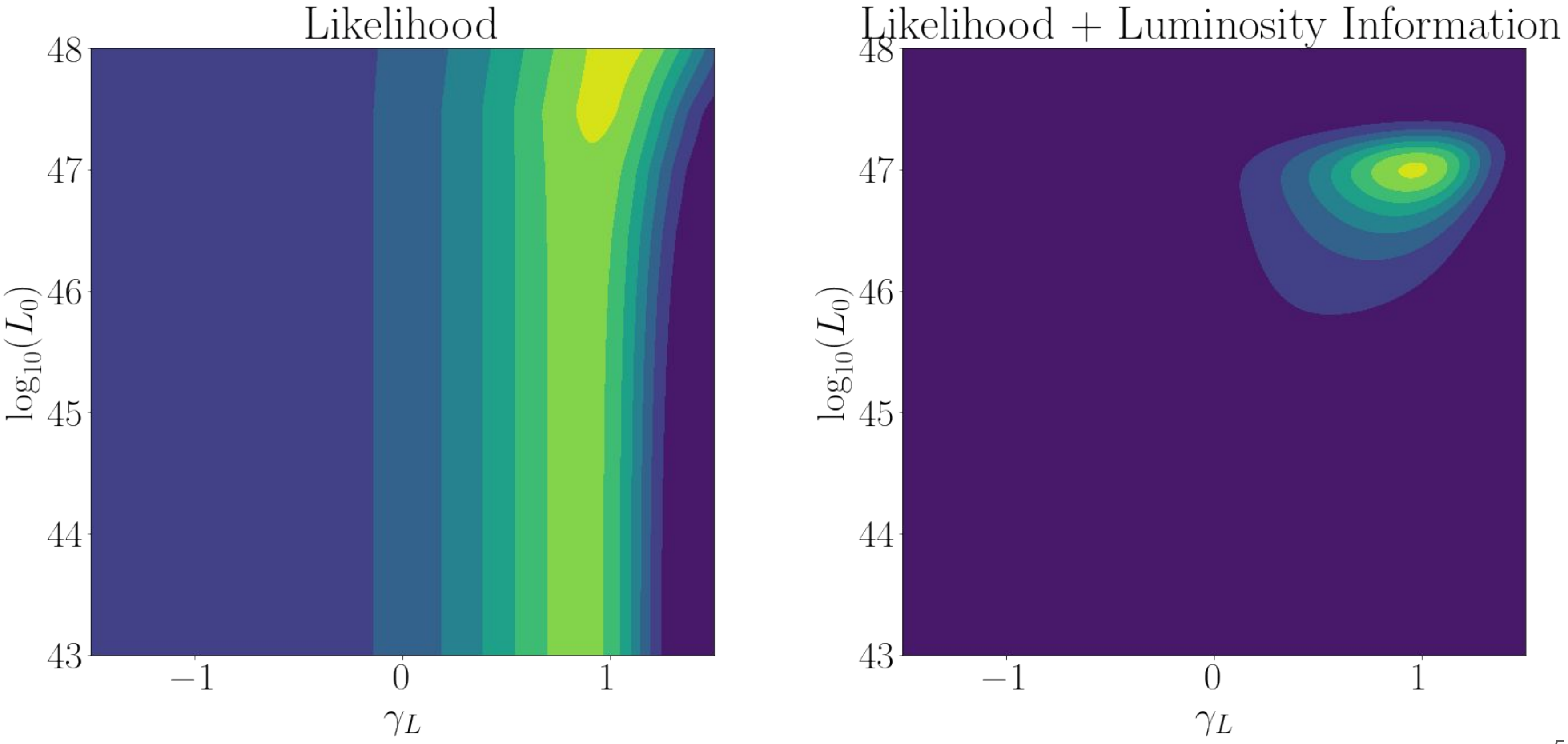
Rejected X-pipeline analysis: sensitivity



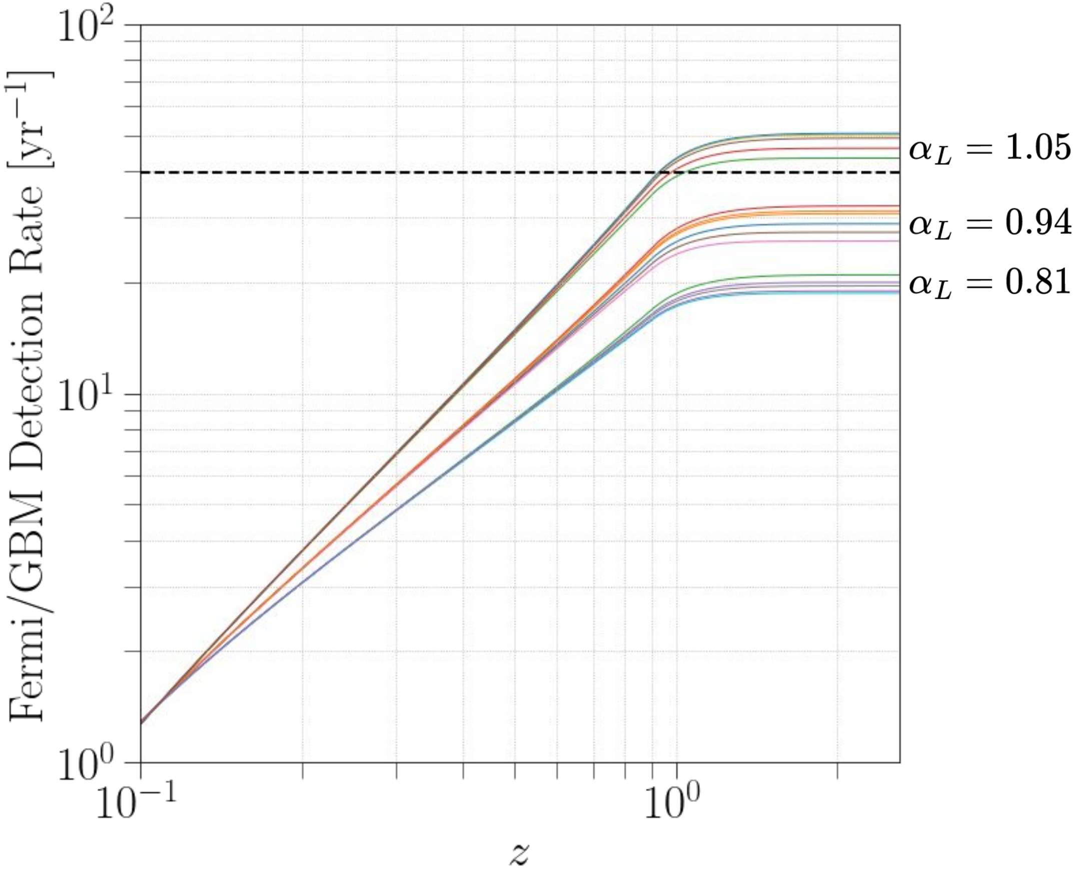


GRB 191221802

Likelihood plots



Fermi/GBM observed rate



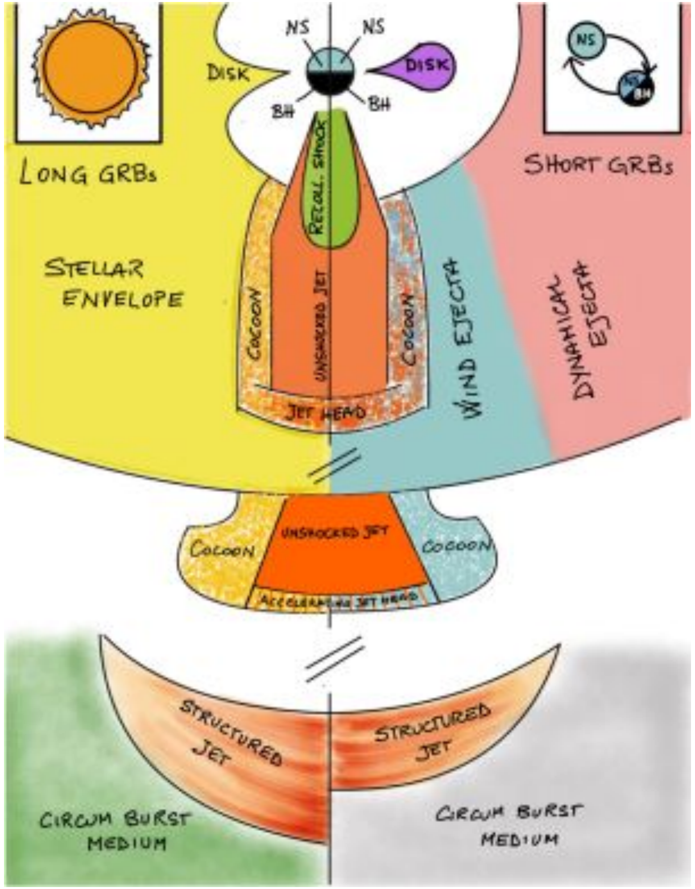
Dependence on NS mass distribution

Comparing results for different NS mass distributions				
	Flat (O3a)	PDB (ind)	MS	BGP
BNS local rate density [$\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$]	320^{+490}_{-240}	44^{+96}_{-34}	660^{+1040}_{-530}	98^{+260}_{-85}
γ_L	0.28 ± 0.45	$0.01^{+0.38}_{-0.37}$	$0.38^{+0.48}_{-0.51}$	$0.13^{+0.43}_{-0.40}$
sGRB local rate density [$\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$]	124^{+433}_{-101}	40^{+96}_{-26}	199^{+875}_{-173}	68^{+224}_{-51}
O4 joint GW–GRB detection rate [yr^{-1}]	$1.02^{+0.26}_{-0.28}$	$0.96^{+0.17}_{-0.24}$	$1.05^{+0.33}_{-0.30}$	$0.99^{+0.21}_{-0.26}$
O5 joint GW–GRB detection rate [yr^{-1}]	$2.31^{+0.36}_{-0.82}$	$2.17^{+0.34}_{-0.71}$	$2.34^{+0.43}_{-0.84}$	$2.26^{+0.32}_{-0.79}$

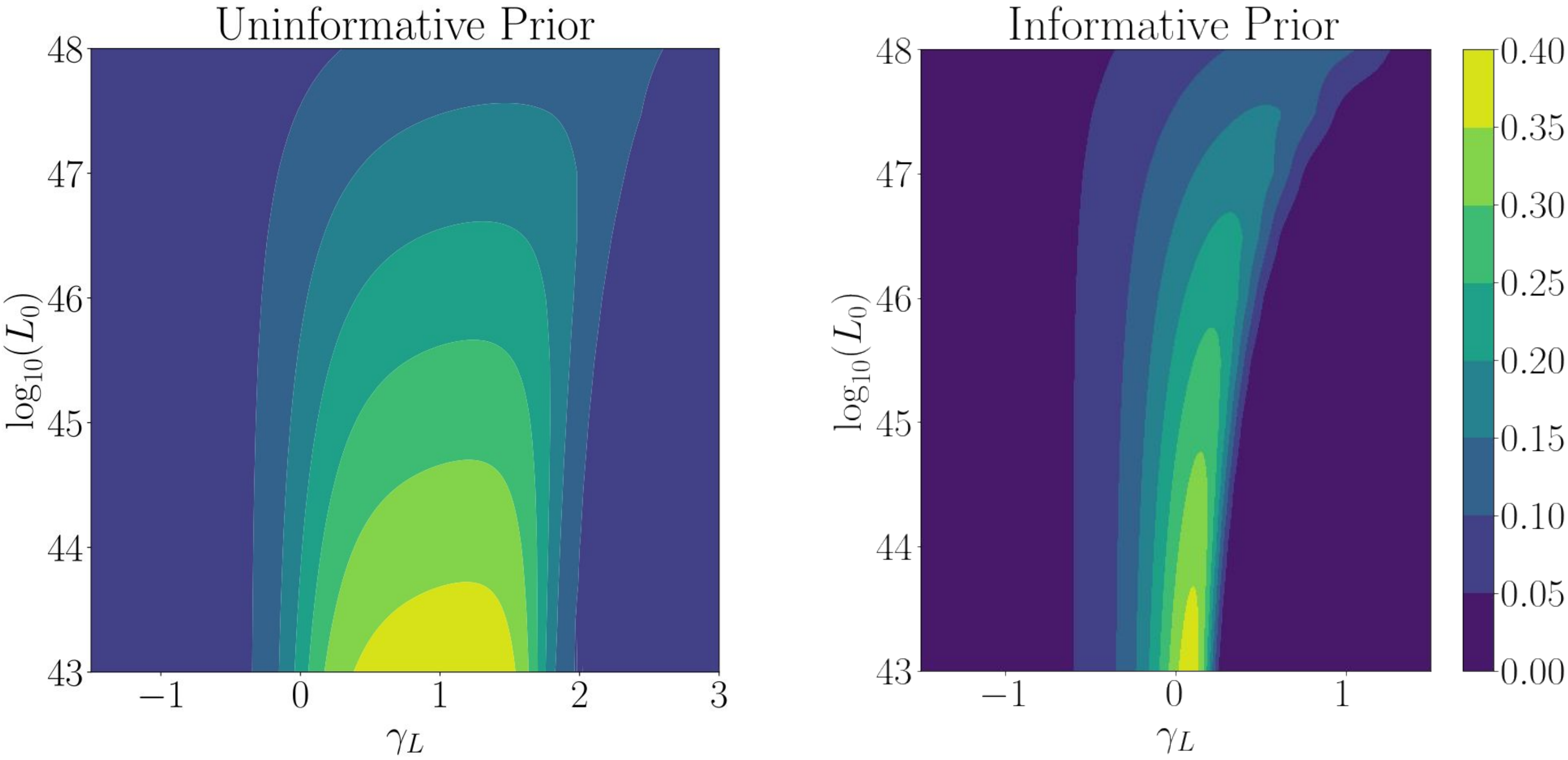
Dependence on WP15 parameters

α_L	β_L	L_* [erg s^{-1}]	γ_L	$R_0^{\rm tot}$ [Gpc^{-3} yr^{-1}]	$R_{\rm GW-GRB}^{\rm O4}$ [yr^{-1}]	$R_{\rm GW-GRB}^{\rm O5}$ [yr^{-1}]
0.81	1.3	1.6×10^{52}	$0.34^{+0.46}_{-0.47}$	133^{+490}_{-111}	$0.60^{+0.16}_{-0.17}$	$1.46^{+0.22}_{-0.57}$
0.81	2.0	3.3×10^{52}	$0.34^{+0.46}_{-0.47}$	132^{+482}_{-110}	$0.58^{+0.15}_{-0.16}$	$1.43^{+0.21}_{-0.55}$
0.81	3.0	2.0×10^{52}	$0.33^{+0.46}_{-0.47}$	130^{+482}_{-108}	$0.67^{+0.17}_{-0.19}$	$1.65^{+0.24}_{-0.64}$
0.94	1.3	3.3×10^{52}	0.28 ± 0.45	127^{+445}_{-104}	$0.92^{+0.24}_{-0.25}$	$2.06^{+0.33}_{-0.73}$
0.94	2.0	2.0×10^{52}	0.28 ± 0.45	124^{+433}_{-101}	$1.02^{+0.26}_{-0.28}$	$2.31^{+0.36}_{-0.82}$
0.94	3.0	1.6×10^{52}	0.27 ± 0.45	121^{+437}_{-99}	$1.14^{+0.29}_{-0.31}$	$2.56^{+0.40}_{-0.90}$
1.05	1.3	2.0×10^{52}	0.23 ± 0.44	116^{+402}_{-94}	$1.42^{+0.35}_{-0.37}$	$3.00^{+0.49}_{-0.98}$
1.05	2.0	1.6×10^{52}	$0.22^{+0.44}_{-0.43}$	112^{+387}_{-90}	$1.56^{+0.38}_{-0.40}$	$3.31^{+0.52}_{-1.09}$
1.05	3.0	3.3×10^{52}	$0.23^{+0.44}_{-0.43}$	115^{+391}_{-93}	$1.48^{+0.36}_{-0.38}$	$3.14^{+0.51}_{-1.03}$

GRB emission model



Prior PDF



Uninformative Prior
Informative Prior
48
47
46
45
44
43
−1
0
1
2
3
γ_L
$\log_{10}(L_0)$
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00