Searching for Gravitational Waves from Long Gamma-Ray Bursts

Benjamin Mannix, Genevieve Connolly

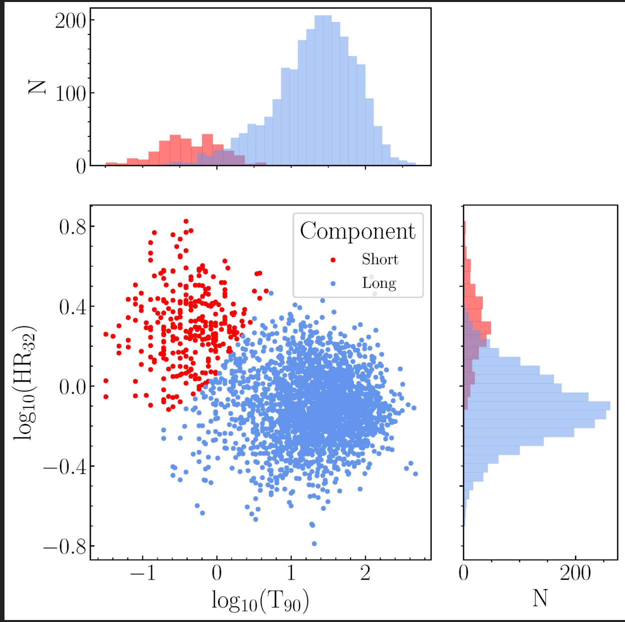
GWANW 2025

UNIVERSITY OF OREGON

LIGO

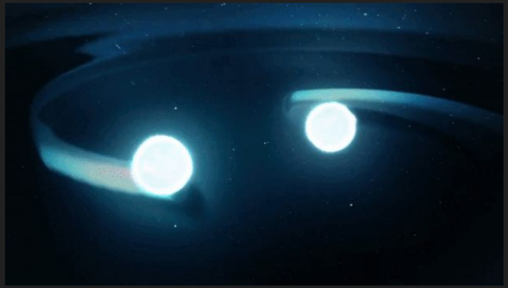
Gamma-Ray Bursts (GRB)

- Detect about 1/day
- Some of the most energetic events in the universe
- Two populations in T_{90} and spectral hardness
  - Suggests two types of sources
- Used as triggers for targeted gravitational wave searches

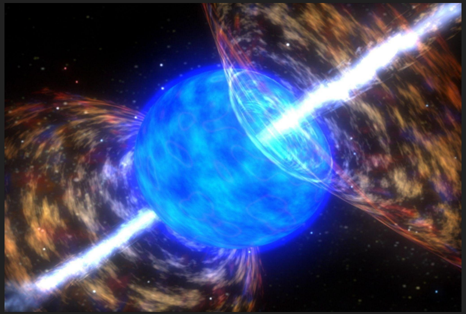


[Salmon, L. et al. Galaxies 10. issn: 2075-4434 (2022)]

Binary Neutron Star Merger



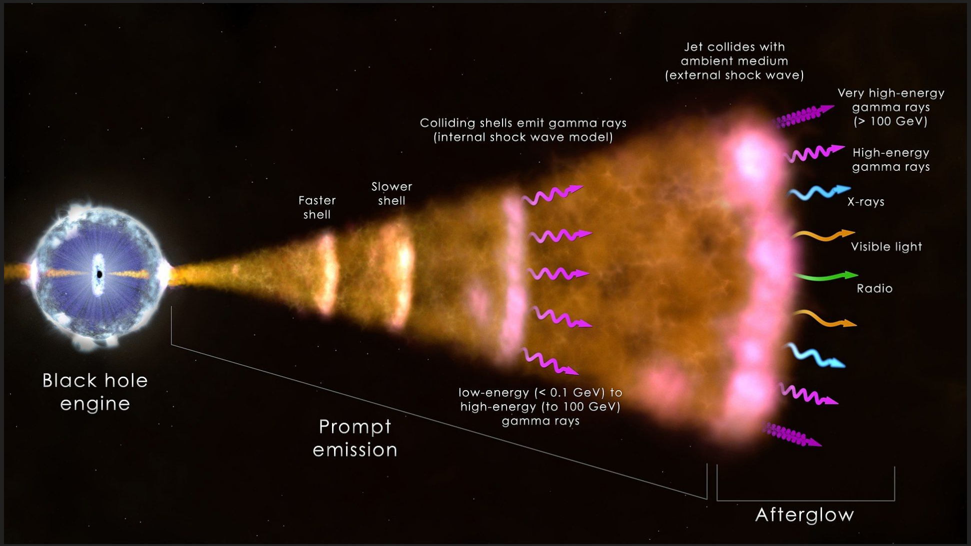
Collapsar



[NASA Goddard/CI Lab]

Collapsars

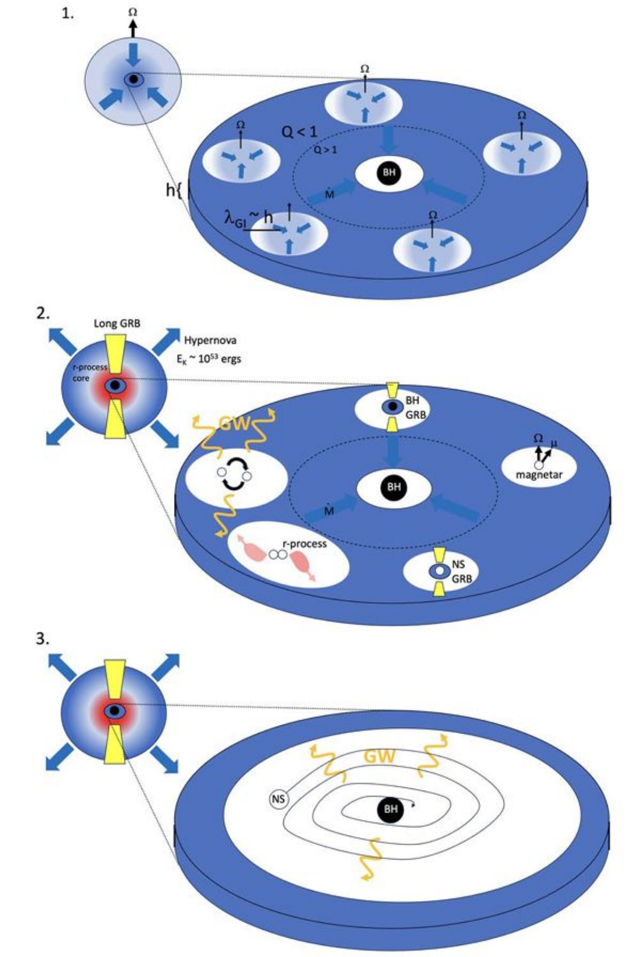
- Believed to be massive, rapidly rotating stars
- When star's life ends, likely supernova and emits gamma ray burst along rotational axis while core collapses to compact object (neutron star or black hole)
- Jet powered by mass accreting on to central engine and being launched



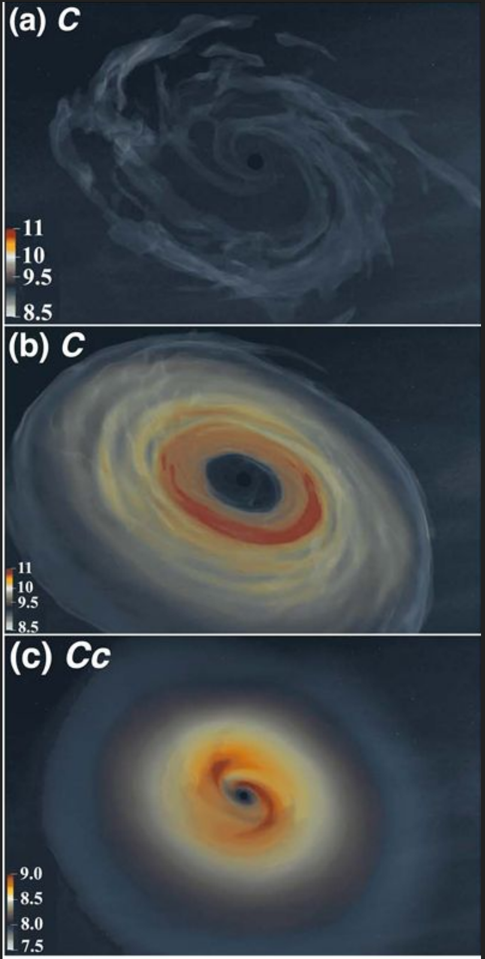
[NASA/Goddard Space Flight Center/ICRAR]

Gravitational Waves From Collapsars

- Gravitational instabilities and cooling create over densities or clumps in accretion disks
- Under the right conditions, compact objects may form in collapsar disks



[B. D. Metzger *et al* 2024 *ApJL* **971** L34]

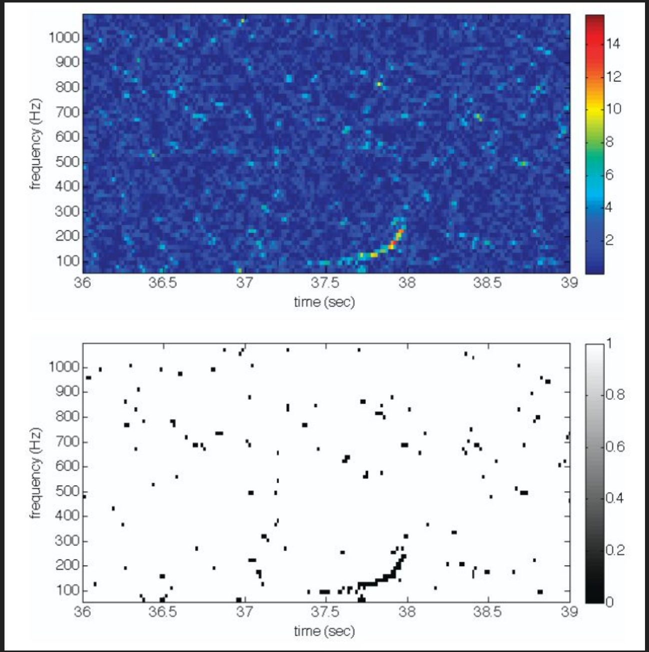


[O. Gottlieb *et al* 2024 *ApJL* **972** L4]

X-Pipeline: Targeted GW Burst Search

- Uses sky position GRB to do coherent gravitational wave search
- Searches for loudest 1% of pixels in coherent spectrogram. Calculates probability each pixel cluster is astrophysical
- Because X-pipeline is an unmodeled search, it doesn’t tell us much about the source of the gravitational waves

Black hole-neutron star signal injected and recovered using X-pipeline



[P. Sutton *et al* 2010 *New J. Phys.* **12** 053034]

In the event of a gravitational wave detection coincident with a collapsar, what can we say about the source?

Toy Model: Sub-Solar Mass Neutron Stars in Disk

The Astrophysical Journal, 658:1173 – 1176, 2007 April 1

FRAGMENTATION OF COLLAPSAR DISKS AND THE PRODUCTION OF GRAVITATIONAL WAVES

Anthony L. Piro and Eric Pfahl
Kavli Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106; piro@kitp.ucsb.edu, pfahl@kitp.ucsb.edu
Received 2006 October 23; accepted 2006 December 7

- Photodisintegration of helium can be a dominant cooling mechanism of the disk at around ~50 $R_{Schwarzschild}$
- This could potentially give rise to an overdensity collapsing into a sub-solar mass neutron star

Toy Model: Sub-Solar Mass Neutron Stars in Disk

Fragment migration: $$\frac{dr}{dt} = -r\Big(\frac{1}{t_{GW}} + \frac{1}{t_\nu}\Big)$$

GW timescale:

$$t_{GW} = \frac{5}{64\Omega}\Big(\frac{GM_{chirp}\Omega}{c^3}\Big)^{-5/3}$$

Accretion disk timescale:

$$t_\nu \approx \frac{1}{\alpha\eta^2\Omega}$$

Ω - angular frequency

M_{chirp} - chirp mass

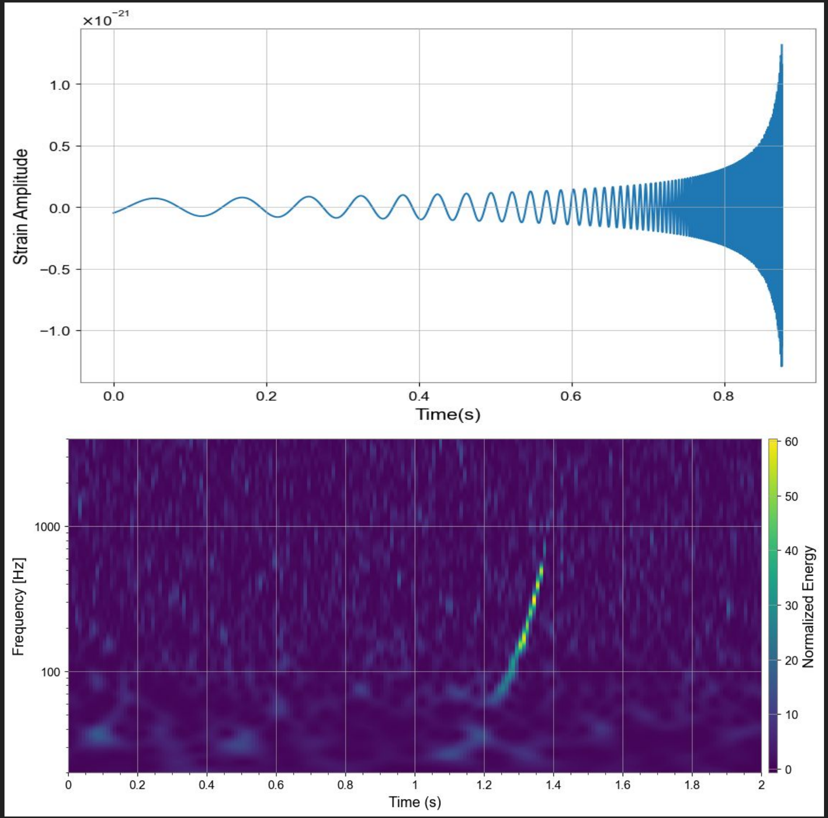
$(m_1m_2)^{3/5}/(m_1+m_2)^{1/5}$

α - viscosity parameter

η = H / r or thickness of torus accretion disk

Example Waveform

- 10 $M_{\odot}$ black hole, 0.5 $M_{\odot}$ fragment, 20 kpc away, η = 0.6
- Start fragment at 50 $R_{Schwarzschild}$
- Track evolution until it reaches Roche lobe radius (fragment is tidally disrupted)
- Calculate gravitational wave emission

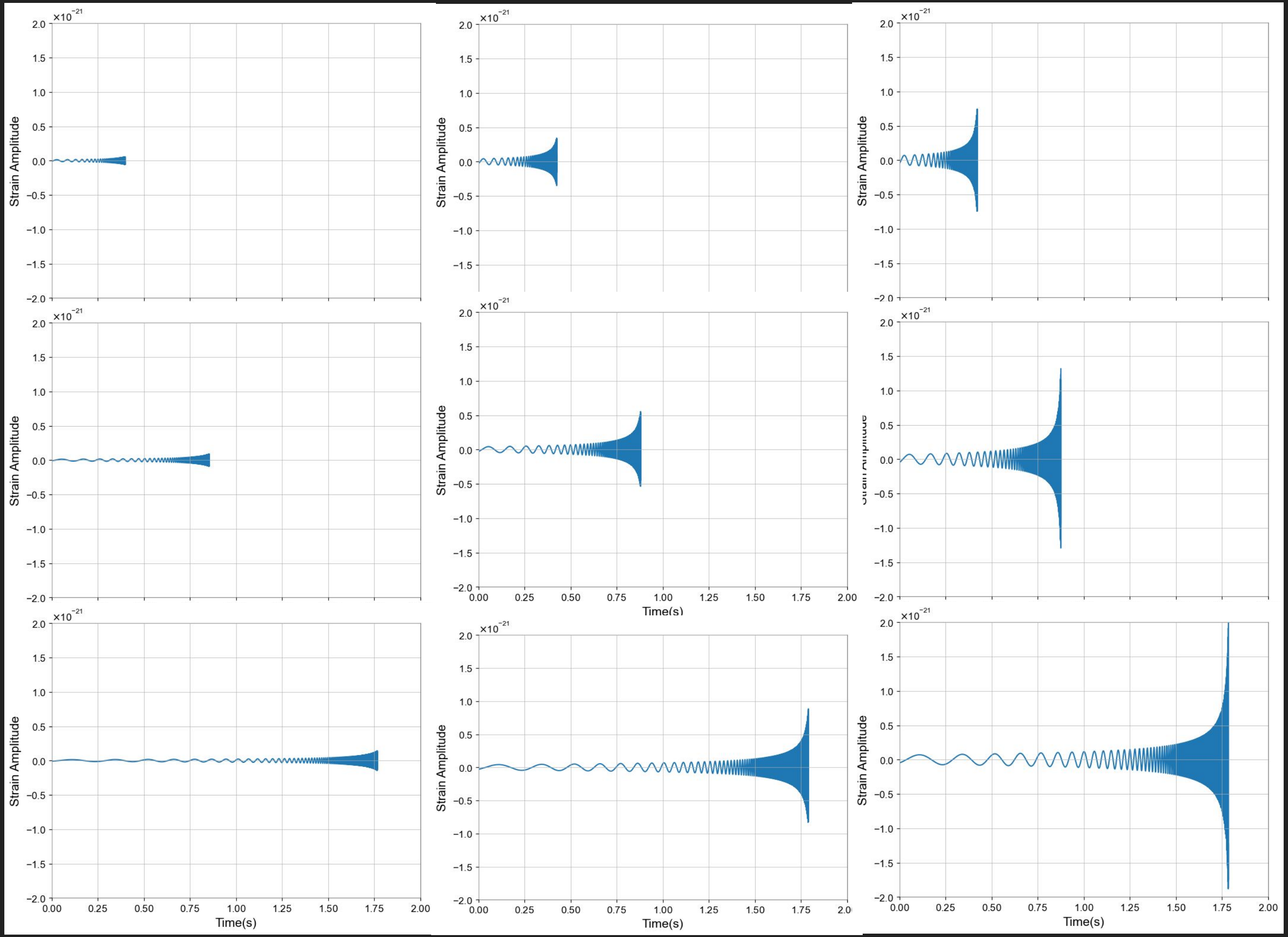


	$m_f = 0.1\ M_\odot$	$m_f = 0.3\ M_\odot$	$m_f = 0.5\ M_\odot$

$M_{BH} = 5\ M_\odot$

$M_{BH} = 10\ M_\odot$

$M_{BH} = 20\ M_\odot$



Next Steps

- Inject example waveforms into X-pipeline to measure sensitivity
- Feed the model into parameter estimation tool (Bilby)
- Assume normal CBC parameters in vacuum and see if Bilby fits a solution
- In the case of marginal GW detection, can we still put estimates on the source?

Examining the Toy Model

Pros

- Simple model which makes testing parameter estimation easier
- GW amplitude is in a realistically detectable scenarios

Cons

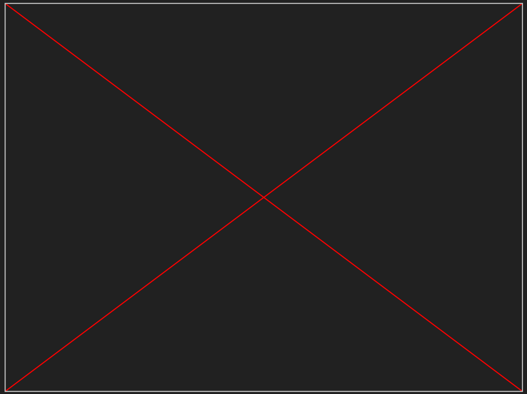
- Forming neutron degenerate objects in disks requires fine tuning cooling
- Realistically, a GW signal will not be this clean

Realistic Model: Cooled Disk Instability

In LIGO's Sight? Vigorous Coherent Gravitational Waves from Cooled Collapsar Disks

Ore Gottlieb,[1,2] Amir Levinson,[3] and Yuri Levin[2,1,4]

- Supernova, BNS or BHNS → central black hole + accretion disk
- Neutrino cooling in disk increases its density, leading to Rossby wave instability
- Cooled disk characteristic ratio: 0.1 ≲ H/R ≳ 3, but most GW emission occurs in the innermost region
- Richardson number measures instability, $R_i \lesssim 0.25$ → RWI $$R_i = g\left(\frac{1}{\gamma}\frac{d\ln p}{dr} - \frac{d\ln\rho}{dr}\right)\left(r\frac{d\Omega}{dr}\right)^{-2}$$
- Characteristic strain is independent of BH mass ($M_{BH} \sim R_d$), but depends on M_d →disk thickness, circularization radius of the gas, the envelope mass $$h_c \approx 7\times10^{-23}\epsilon\frac{10\,\mathrm{Mpc}}{D}\frac{M_{\rm BH}}{10\,M_\odot}\frac{M_d}{0.1\,M_\odot}\frac{100\,\mathrm{km}}{R_d}$$



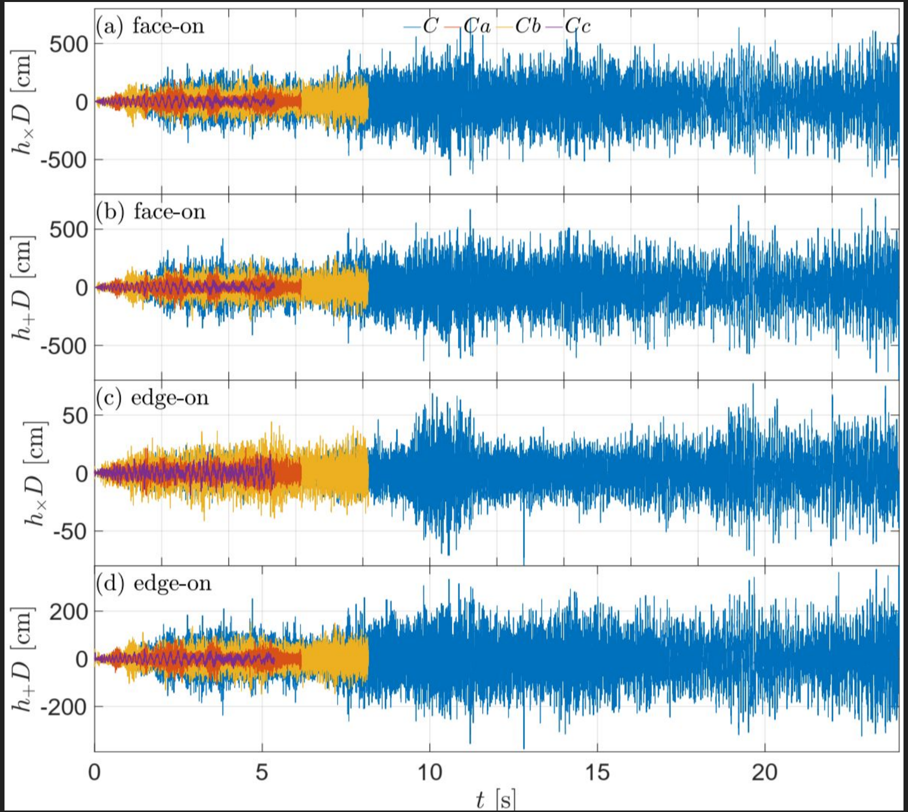
Gottlieb et al. 2024

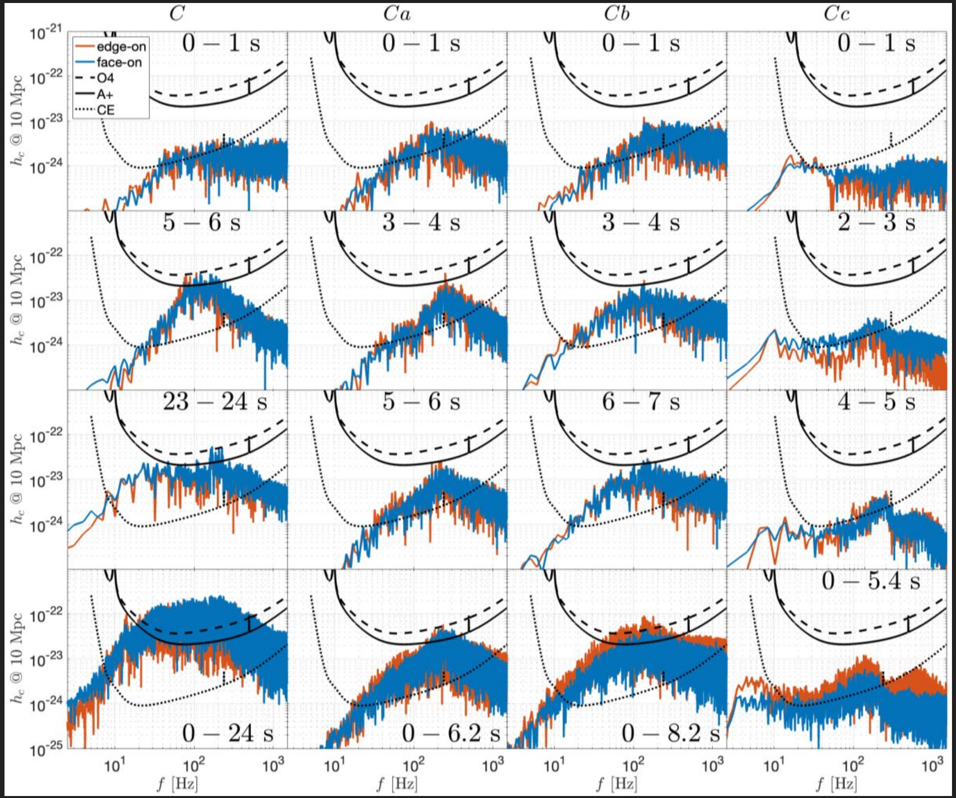
Cooled Disk Waveforms

Model	Setup	H/R	β_p	$\max(\sigma_0)$	a_{BH}	$M_{BH}\,[M_\odot]$	T_s [s]	$R_{max}\,[r_g]$	E_{GW} [erg]	ϱ (LVK)	ϱ (CE)	LVK rate [yr^{-1}]	f_{GW} [Hz]
B	BNS merger	0.1	10^4	-	0.68	2.67	0.3	10^3	2×10^{46}	0.1; 0.2	0.4; 1.4	0	500-2000
C	Collapsar	0.1	-	10^{-3}	0.8	10	24	10^5	7×10^{50}	25; 46	390; 750	$\lesssim 1$	30-300
Ca	Collapsar	0.1	-	10^{-3}	0.1	10	6.2	10^5	1.5×10^{49}	16; 33	180; 360	$\lesssim 1$	200-300
Cb	Collapsar	0.1	-	10^{-4}	0.8	10	7.4	10^5	8×10^{49}	27; 54	350; 690	$\lesssim 1$	100-200
Cc	Collapsar	0.3	-	0	0.8	10	5.4	10^5	1.5×10^{49}	5; 9	74; 130	$\lesssim 10^{-2}$	100-200

Gottlieb et al. 2024

Cooled Disk Waveforms





Gottlieb et al. 2024

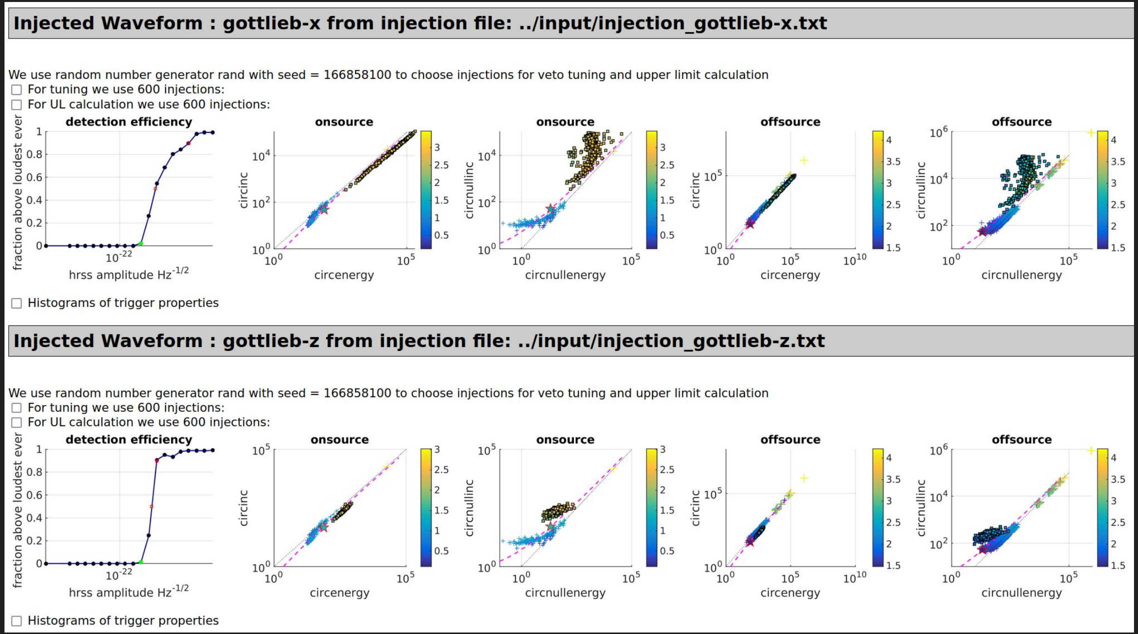
GRB-GW Searches

- On-source window: starts 600 s before the GRB trigger time and ends at 60 s after trigger time, or T_{90} after if T_{90} > 60 s
- Jet propagates in stellar envelope before breakout
- Collapsar disk lifetime: ~100 s
- GW could arrive several minutes before LGRB
- Collapsar rates: $\mathscr{R}_{\mathrm{lGRB}} \sim 1\,\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ $\mathscr{R}_{\mathrm{Collapsar}} \approx 100\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$
- With SNR 20: “LVK O4 holds the potential to detect GWs emanating from accretion disks up to distances of a few dozen Mpc”
- LVK event rate: $\sim 10^{-2}\, \varrho_{20}^{-3}\, \mathrm{yr}^{-1}$

Gottlieb et al. 2024

X-Pipeline Injections

- X (edge-on): ~82 kpc
- Z (face-on): ~30 kpc



Waveform name and parameters	central frequency (Hz)	hrss_50% (Hz^{-1/2})	hrss_90% (Hz^{-1/2})	injection scale 50% UL	injection scale 90% UL	% of NaNs during tuning	amplitude SNR in H1	amplitude SNR in L1	total (root sum square) amplitude SNR
adi-a	149.778 Hz	7.92642e-23	1.13075e-22	0.0846069	0.120697	0	16.7292	16.4276	23.4464
gottlieb-x	86.3741 Hz	5.68247e-22	2.84665e-21	0.641022	3.21122	0	80.4376	81.2966	114.365
gottlieb-z	77.8068 Hz	4.73806e-22	5.97847e-22	0.537334	0.678007	0	64.8375	65.2383	91.9779

Next Steps

- Injections at other Mpc (anybody speak Matlab?)
- Investigating how characteristic strain changes with M_d , R_d , etc, more injections
- Deriving a model for Bilby
- Asking Ore Gottlieb for more simulated waveforms

Future Work: ZTF Triggers (Sam Callos)

- Zwicky Transient Facility (ZTF) catalogues supernovae (SNe)
- GWs possible from accretion disks associated with type Ib/c SNe
  - GRBs are highly beamed and don’t always hit us, so can use SNe observations to look for more GWs
- Searching for triggers within 200 Mpc
  - Many within this range
  - 30+ within 100 Mpc
  - Closest trigger at 11.5 Mpc
- Next: Use X-Pipeline to search for GWs
  - Check if supernova events are within LIGO observing time
  - Narrowing down accretion disk lifetime makes detection difficult

Ben may graduate some day. Postdocs?

Work in my PhD included:

- Detector characterization, Physical Environment Monitoring
- ~6 months as an LHO Fellow
- Software Development/Maintenance (Ligocam)
- Targeted Gravitational Wave Searches in Multimessenger Transients

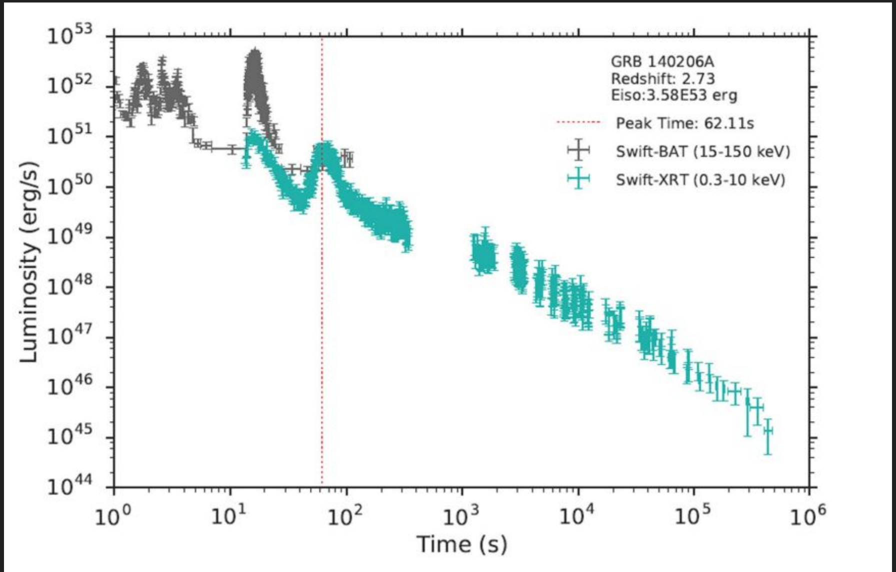
Thinking about graduation and searching for jobs in the current state of the country

Questions?

Benjamin Mannix: bmannix@uoregon.edu
Genevieve Connolly: gconnoll@uoregon.edu

X-ray flares

- Some x-ray curves showing flaring with large x-ray peaks throughout the decay. Possible explanation: accretion disk fragmentation



[Ruffini, R. et al. ApJ 852, 53. (2018)]