Search for Gravitational Waves associated with Fast Radio Bursts detected by CHIME/FRB

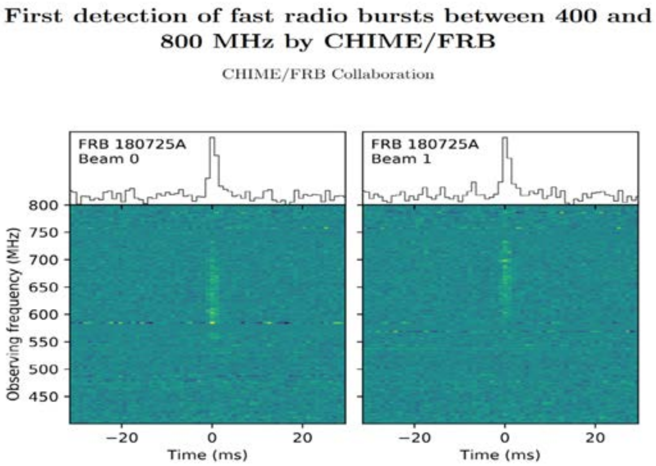
Eric Howell on behalf of the LIGO-Virgo-KAGRA and CHIME/FRB Collaborations

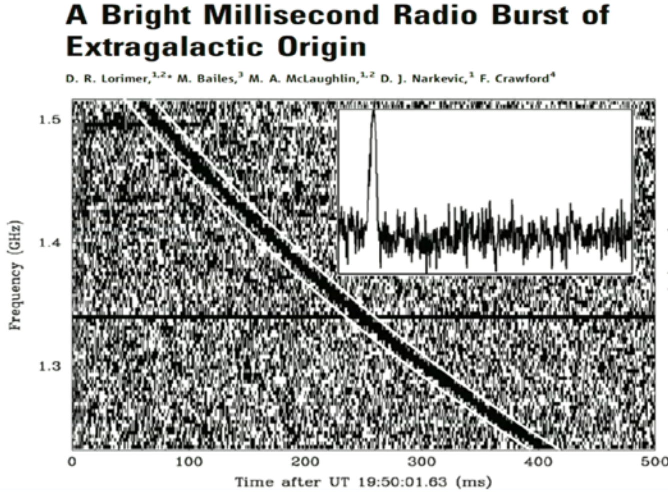
Talk outline

- Fast Radio Bursts – CHIME/FRB project, motivation, gravitational wave counterparts
- The gravitational wave analysis and data preparation
- The main results
- Looking ahead to future gravitational wave observation runs

Fast Radio Bursts (FRBs)

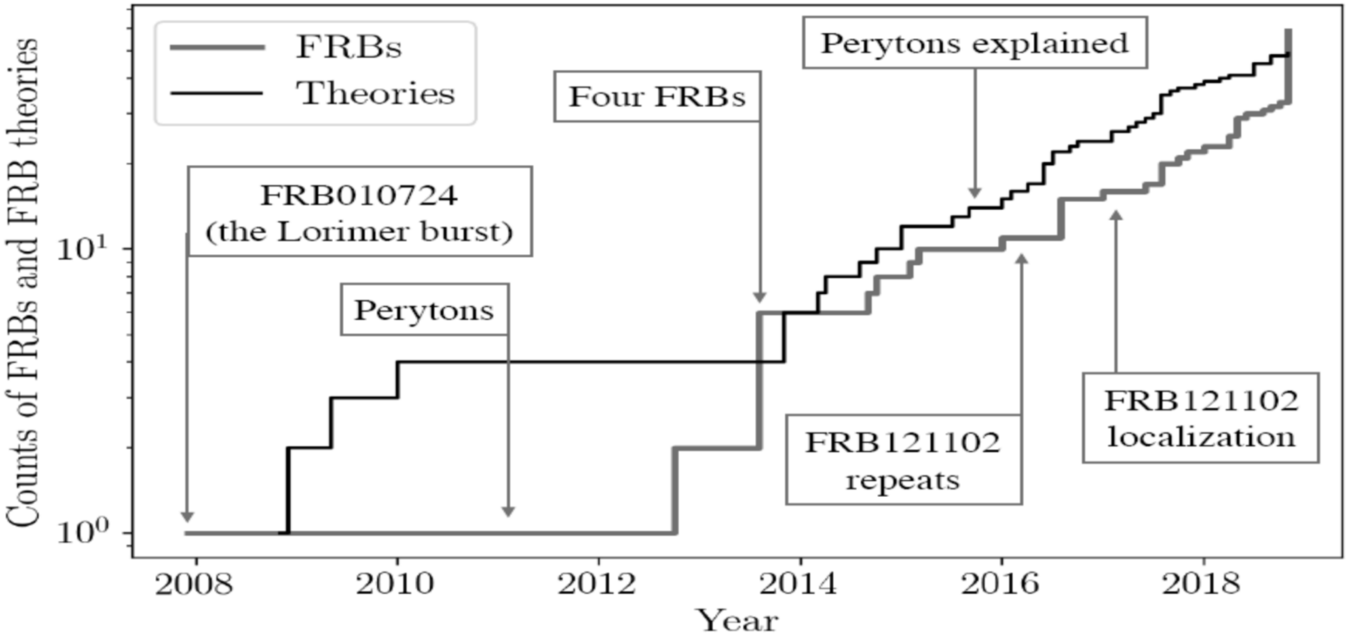
- Bright short duration radio pulses (ms) – span a large range of radio frequency
- Some FRBs have been seen to repeat
- Telescopes: Parkes, Arecibo and Green Bank Telescope, Molongolo, ASKAP preceeded CHIME (536 in first CHIME/FRB catalogue)
- Volumetric rate ~ 10^4 Gpc^{-3} yr^{-1} above 10^{42} erg s^{-1} (Luo et al 2020)





Lorimer et al. (2007)

What are FRBs



From Ravi 2019 (FRB2019, Amsterdam)

Over 50 proposed mechanisms (Platts, Weltman, Walters, Tendulkar, et al. 2018)
https://frbtheorycat.org/

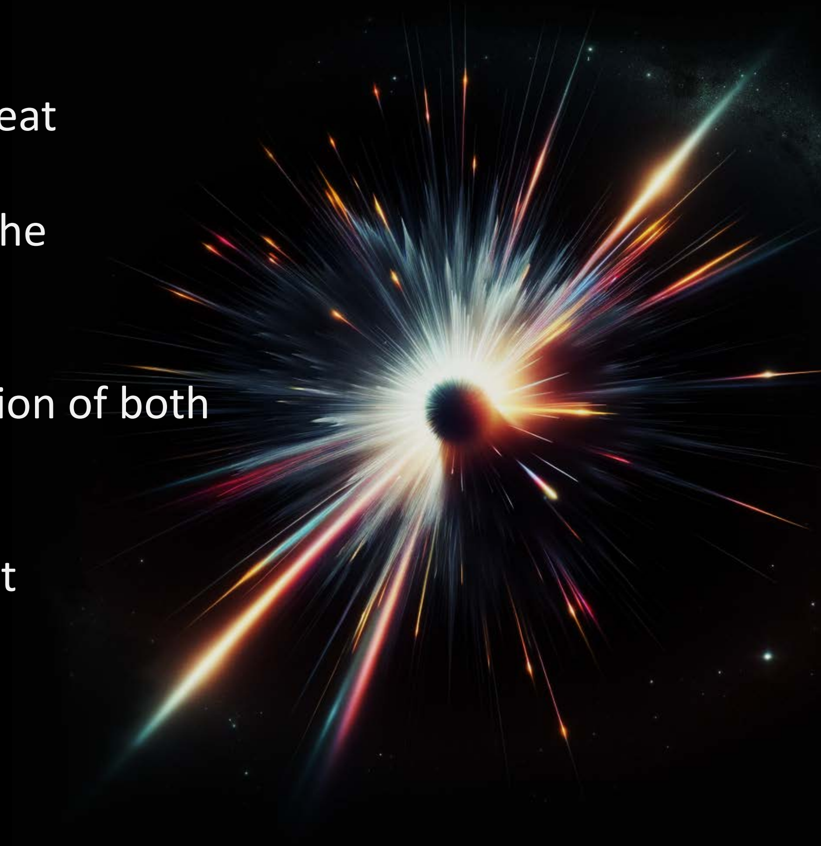
What are FRBs?

- Neutron stars collapsing to black holes, ejecting "magnetic hair" (Falcke & Rezzolla '14; Zhang '14)
- Merger of charged black holes (Zhang '16; Liu et al. '16; Liebling & Panenzuela '16)
- Magnetospheric activity during neutron star mergers (Totani '13)
- Unipolar inductor in neutron star mergers (Hansen & Lyutikov '01; Piro '12; Wang et al. '16)
- White dwarf mergers (Kashiyama et al. '13)
- Pulses from young neutron stars (Cordes & Wasserman '15; Connor et al. '15; Lyutikov et al. '16; Popov & Pshirkov '16; Kashiyama & Murase '17)
- (Young) Magnetars (Popov et al. '07; Kulkarni et al. '14; Lyubarsky '14; Katz '15; Pen & Connor ' 15; Lu & Kumar '16; Metger et al. ' 17; Beloborodov '17; Margarlit & Metzger '18)
- Schwinger instability in young magnetars (Lieu '17)
- Sparks from cosmic strings (Vachaspati '08; Yu et al. '14)
- Evaporating primordial black holes (Rees '77; Keane et al. '12)
- White holes (Barrau et al. '14)
- Flaring stars (Loeb et al. '13; Maoz et al. '15)
- Axion stars (Tkachev '15; Iwazaki '15)
- Asteroids/comets falling onto neutron stars (Geng & Huang ' 15; Dai et al. '16)
- Quark novae (Chand et al. '15)
- Dark matter-induced collapse of neutron stars (Fuller & Ott '15)
- Higgs portals to pulsar collapse (Bramante & Elahi '15)
- Planets interacting with a pulsar wind (Mottez & Zarka '15)
- Black hole superradiance (Conlon & Herdeiro '17)
- Extragalactic light sails (Lingam & Loeb '17)
- Neutron star-white dwarf binaries (Gu et al. '16)
- Clumpy jets from accreting black holes (Yi et al. '19)
- Black hole interacting with an AGN (Das Gupta & Saini '17; Waxman '17)
- Wandering AGN beam (Katz '17)
- Black hole laser powered by axion superradiant instabilities(Rosa & Kephart '18)
- Starquakes and lightning of pulsars (Wang et al. '18; Song et al. 2017)

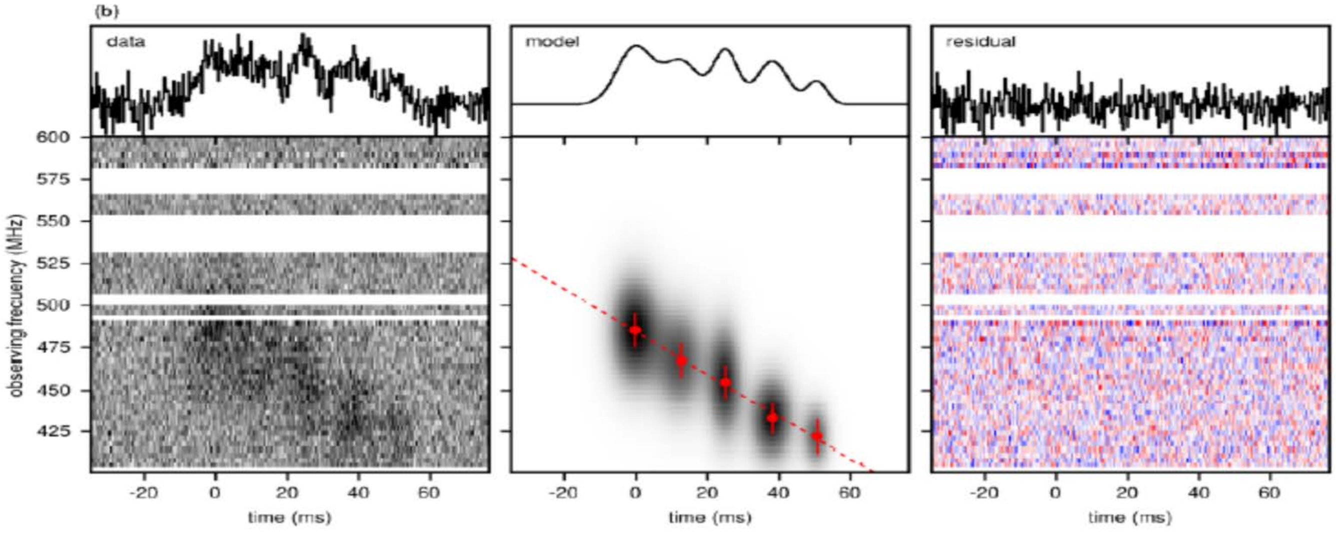
The sources of FRBs and the emission mechanisms are still unknown

FRBs and the Galactic magnetar SGR 1935+2154

- Out of around 700 FRBs 5% have been seen to repeat
- In April 2020, a repeating FRB was detected from the Galactic magnetar SGR 1935+2154.
- The event was notable for the simultaneous emission of both radio and X-ray bursts.
- The first direct evidence supporting the theory that **magnetars can produce FRBs**.



The second repeater FRB 180814



- Sub-pulse structure downward frequency drift observed in repeater
- Pulses arrive at slightly later times at lower radio frequencies
- This was also observed in FRB121102 suggesting similarity in the emission mechanisms
- From processes within a magnetar magnetosphere ? Higher-frequency radio waves are emitted from regions closer to the neutron star's surface ?

Multi-Component FRB: FRB 20191221A

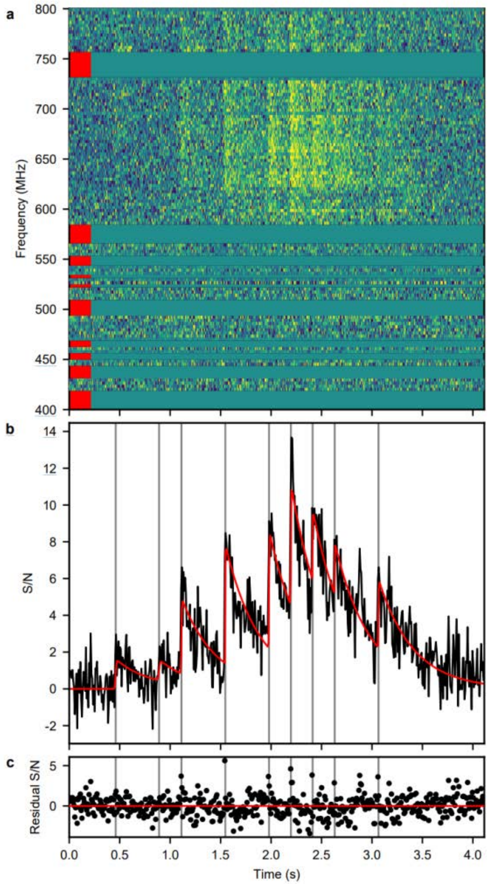
CHIME detected FRB 20191221A has a long duration (~3 seconds) and multiple components (at least 9), making it an outlier among FRBs.

Periodicity Detected: A periodic separation of 216.8 milliseconds between the burst components has been identified with high significance

- The periodic nature of the emission in FRB 20191221A is consistent with the rotation period of known NSs
- Some other FRBs have some evidenced periodicity, but significance is not strong enough to confirm it (FRBs 20210206A and 20210213A)

Extragalactic Source Confirmation: The FRB's dispersion measure significantly exceeds the maximum expected from the Milky Way, confirming its extragalactic nature.

Implications for FRB Progenitors: The dispersion measure suggests it is extragalactic – this supports the case for NS origins of extragalactic bursts.



Physical models for Fast Radio Bursts

Rapid Energy Release: FRBs emit massive amounts of energy within milliseconds over narrow Bandwidths - necessitating a coherent emission process.

Brightness Temperatures: The extraordinarily high observed brightness temperatures imply a **coherent mechanism** - incoherent processes (e.g., thermal emission) are too inefficient to produce intense energy bursts at radio frequencies.

Coherent Emission: Particles accelerated in sync along electromagnetic fields, producing radiation with a unified phase and high intensity.

Astrophysical Models for FRBs: Must account for mechanisms that cause particle bunching, where particles emit radiation in a coherent phase.

Why search for Gravitational Waves ?

For non-repeating FRBs, several origins are postulated. Many are difficult to test. GW data offers an opportunity to test FRB models related to compact binary coalescence as well as other sources.

Magnetic Reconnection (Wang et al., 2013):
Toroidal magnetic field is induced around the NS's magnetic field lines. Toroidal field strength builds up to rival the poloidal field of the magnetospheres, resulting in magnetic reconnection.

Magnetic Braking (Totani,2013):
Merger of two differentially rotating NSs into a uniformly rotating hypermassive NS that spins down and magnetic braking generates coherent radiation.

Changing Magnetic Flux (Dokuchaev and Eroshenko, 2017):
Interaction of magnetospheres during the NSs close encounters, leading to FRB-like emissions.

BH Battery (Mingarelli et al., 2015):
NS-BH merger, the NSs magnetic field lines wrap around the BHs event horizon.
Charged particles in the NS magnetosphere are propelled along magnetic field lines by the BH.

BH Battery: FRBs from NSBH mergers

During a NS-BH merger, the NSs magnetic field lines wrap around the BHs event horizon.

We get a process analogous to a battery in a circuit:

- The NS acts as an external resistor
- The NS magnetic field lines function like wires
- The plasma in the magnetosphere provides the current
- The BH serves as the power source

Charged particles in the NS magnetosphere are propelled along magnetic field lines by the BH generating an FRB-like emission (Mingarelli et al., 2015)

The CHIME Instrument

Prior to 2018, only around 70 FRBs had been catalogued, the majority by Australian telescopes: Parkes (27 FRBs) and ASKAP (28 FRBs)

British Columbia, Canada - Four 20m x 100m cylindrical reflectors – 4 x 256 antennas

- large collecting area with broad frequency coverage (400-800 MHz)
- **large instantaneous field-of-view (200 square degrees)**
- **Resolution of order 10s of arc mins**
- Real-time FRB detection backend for de-dispersion, event detection and recording
- **CHIME/FRB detected 800 FRBs during O3 (April 2019 – March 2020) – large sample from a homogenious survey**

- Fast Radio Bursts – CHIME/FRB project, motivation and gravitational wave counterparts
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GW searches for transient radio sources

First search was led by Brennan Hughey: B. P. Abbott et al., PRD 93, 122008 (2016)

- **14 Parkes FRBs** were considered
- GW data was available for 6 FRBs during GEO 600 Astrowatch and iVirgo (VSR4-2011)
- Used **X-PIPELINE** to conduct coherent search +/- 2 min around FRB
- **No GW coincidences** – but study provided a useful framework for future searches using greater GW sensitivities

Ryan Fisher led CBC searches around 3 FRB triggers recorded during O1/O2 double detector time

Targeted Searches

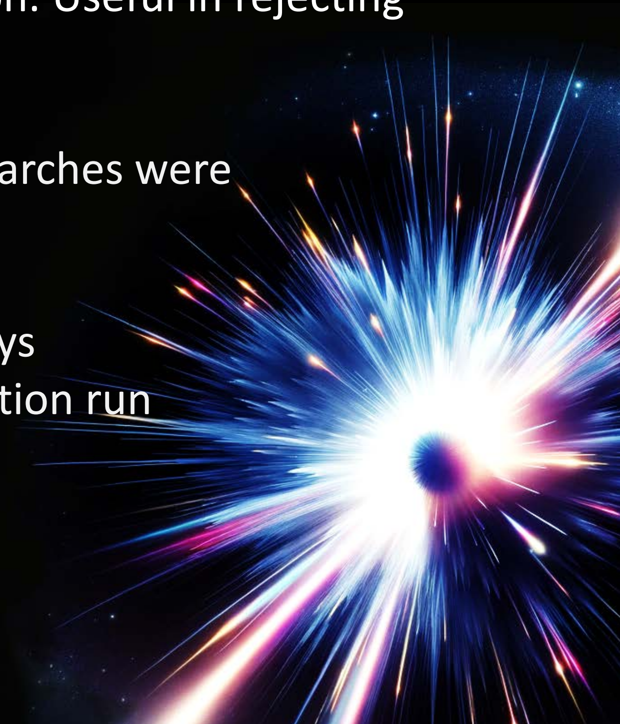
- Perform a GW search around the temporal and spatial coordinates of known FRBs.

- We use a coherent analysis using data from multiple GW detectors. This is more costly or an all-sky search but reasonable if we have a known position. Useful in rejecting background noise “glitches”.

- In LIGO/Virgo observation run O3a, the ranges of targeted searches were 1.4-1.8 times the average O3a LIGO ranges

- A targeted search could reveal sources missed in all-sky surveys
  - interesting candidates would initiate a full parameter estimation run

- The selection of an optimal time window is crucial – want to maximise signal detection while still minimizing noise



O3a Search Overview

The CHIME/FRB data consisted of 338 bursts observed within the O3a LVC observing run (1 April 2019 – 1 Oct 2019) – we used the closest ~10 % of this sample

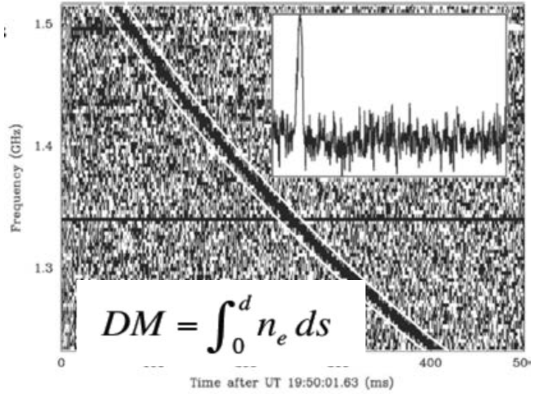
It was a targeted search - so searched for gravitational waves using the sky-position and de-dispersed event time of each FRB

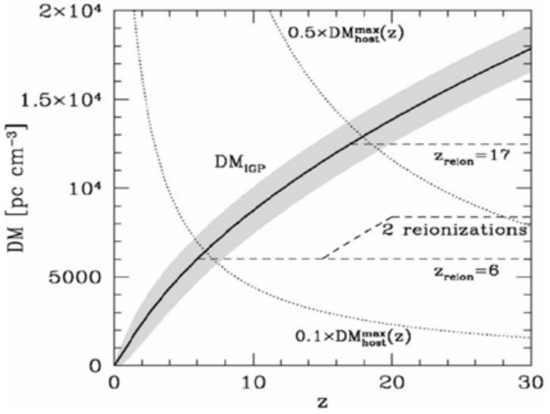
Modelled search (pyGRB) for known source types (neutron star mergers NS-NS, neutron star – black hole NS-BH) – non-repeaters

Un-modelled search (X-Pipeline) – various morphologies (burst like signals) – repeaters and non-repeaters

Dispersion as a distance indicator

Delay between high and low frequency signal components from interactions with free electrons along the light path through the IGM - **Dispersion measure (DM)** -





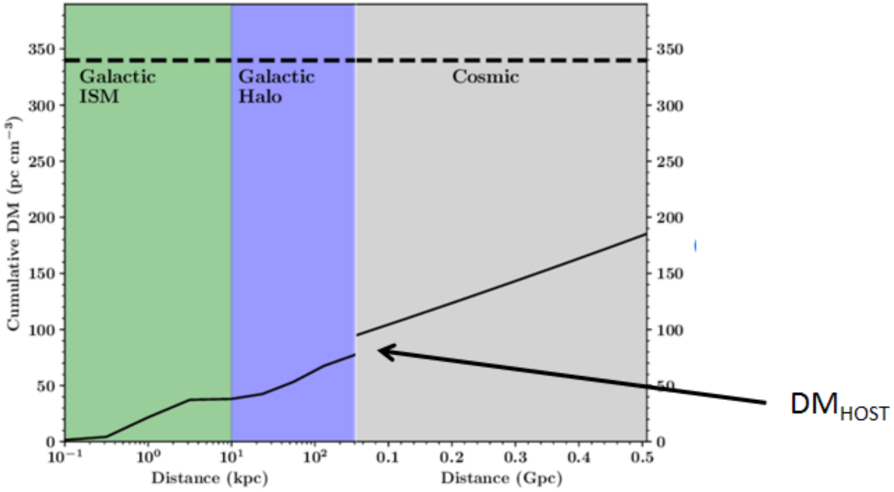
Inoue 2004

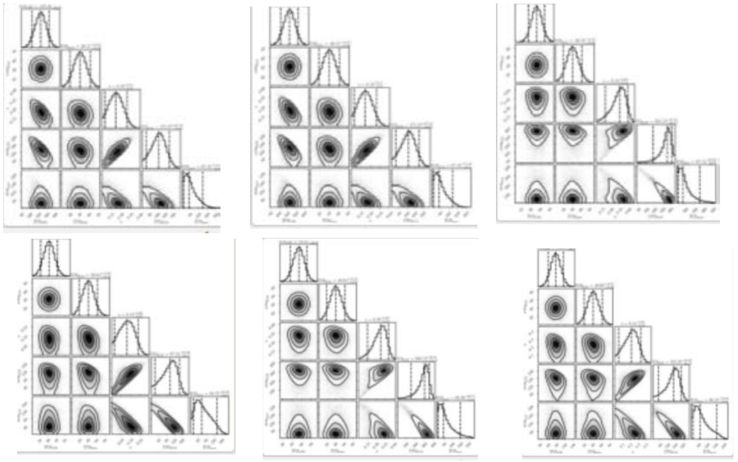
- DM_{IGM} measure of column density of free electrons through the intergalactic plasma
- DM_{IGM} used to estimate the maximum redshift through the Macquart Relation (Macquart et al. 2020) –a maximum distance for each FRB through Bayesian inference

Dispersion as a distance indicator

Must account for DM contributions from the Milky way DM_{MW}, its halo DM_{HALO} and the host galaxy DM_{HOST} – run inference on full FRB sample

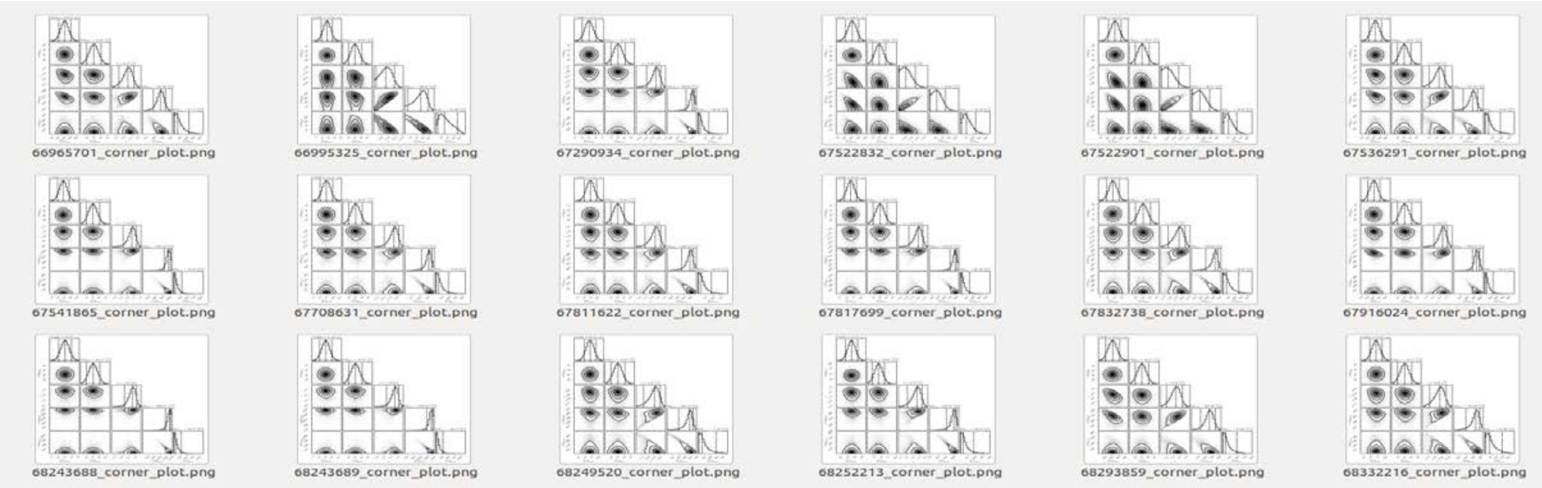
Approximate z_{MAX} from DM_{IGM} : $DM_{TOTAL} = DM_{IGM} + DM_{MW} + DM_{HALO} + DM_{HOST}/(1 + z)$





Framework follows Bhardwaj et al. 2021 & Macquart et al. 2020

The input data sample



An MCMC was performed on OzStar for the 360 FRBs (to obtain distance posteriors)

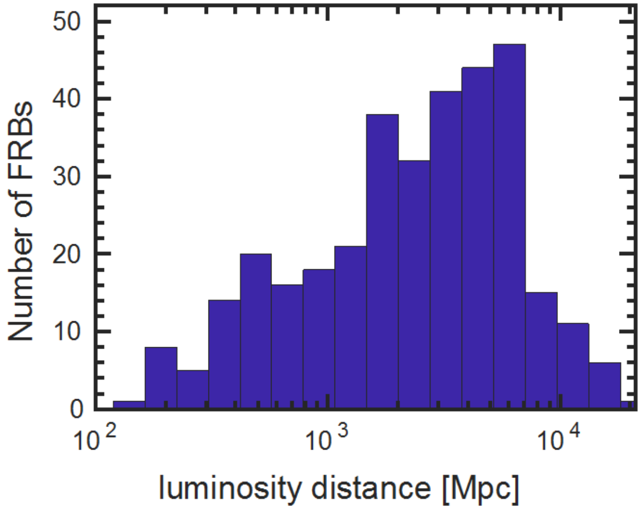
Large uncertainties in the estimates – choice of priors for various DM components

Sample has been sent to CHIME to identify known pulsars, RRATs and repeaters

The CHIME/FRB Analysis Sample

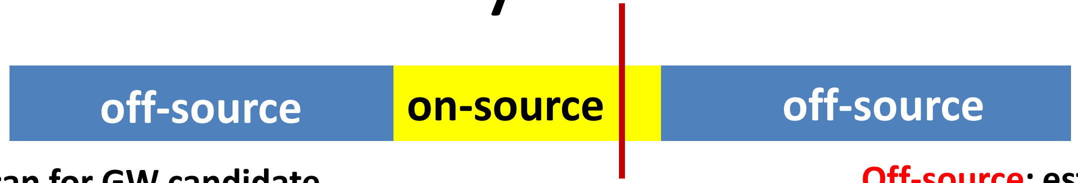
- Redshift posteriors converted to luminosity distance using flat-Λ cosmology
- Given LVK network has a relatively smaller range than the observed FRB distances, only the closer FRB events were considered
- Final total events analyzed:
  - 40 FRBs followed up by unmodelled search
    - Including 11 Repeater events
  - 22 FRBs followed up by modelled search (no repeaters)
  - Closest non-repeater was FRB20190425A at

  [13 – 386] Mpc - median value of 133 Mpc



The distribution of inferred median distances for the CHIME/FRB data sample

O3a analysis overview



On-source: Scan for GW candidate

Off-source: estimate noise background

FRB TIME

Modelled - compact binary coalescence search - matched filtering (template bank)

PyGBC ran on all **non-repeaters** with GW data that passes quality checks with a time window of **[-10s, + 2s]** “on source” - relative to the de-dispersed FRB arrival time

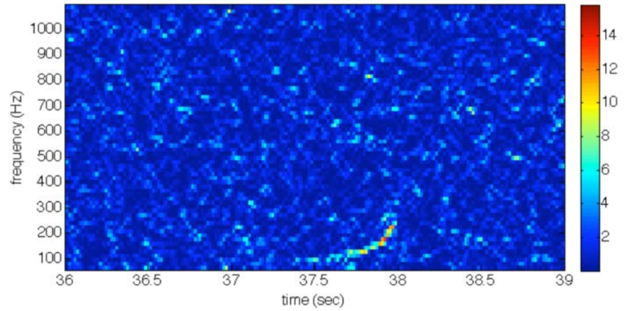
Unmodelled search – time-frequency mapping– un-modelled signal

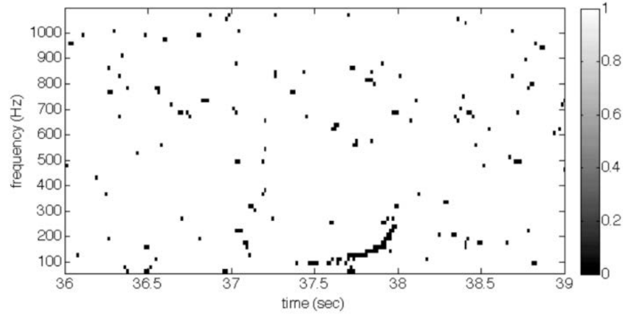
X-pipeline ran on all FRBs with 2 or more IFOs active and with good data within a time window **[-600s, + 120s]** – search for **non-repeaters** (to 2kHz) and **repeaters** (to 4khz)

- The search sensitivity determined by comparing the most significant event in the on-source to the off-source (background)

X-Pipeline Analysis overview

- **Unmodelled** search for generic transients **X-Pipeline** (Sutton et al. 2010; Was et al. 2012)
- Search window: [-600 s, +60 s] around de-dispersed FRB time of detection
- Searches for coherent, **excess power** in multiple detectors, without requiring a waveform match
- 32 Hz – 2000 Hz - Broadband search up to 2 kHz - in order to cover NS quasinormal mode emission (specifically f-mode)
- A threshold is applied to the excess power in the time-frequency plane so that a fixed percentage (e.g., 1%) of the pixels with the highest value are marked as black pixels
- A clustering algorithm is then applied to identify candidates and given a ranking statistic based on energy
- Candidates then undergo a series of veto checks





Effective range or exclusion distance

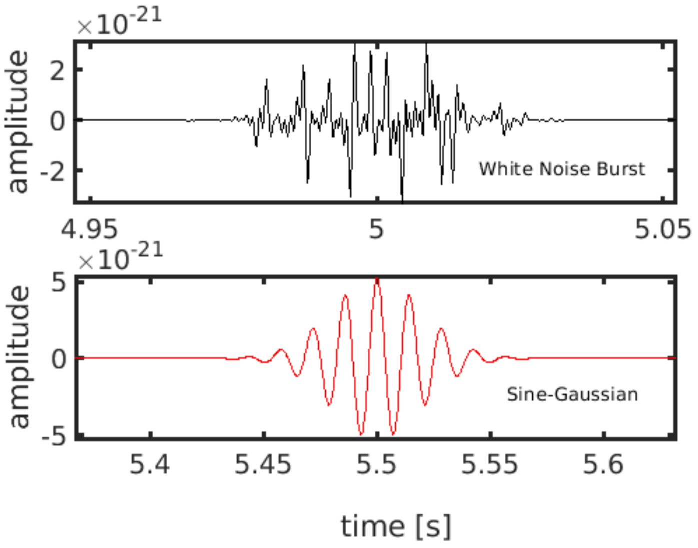
90% confidence lower bounds on the distance upper limits

Sensitivity range D_{90} or exclusion distance is determined using a wide range of injected waveform models

PyCBC – BNS, NSBH (aligned and generic spins)

X-pipeline - Sine-Gaussian, White Noise Burst, ringdown and others used in the GRB search)

D_{90} is the distance at which 90% of the injected signals injected into the **off-source** data are recovered with a ranking statistic greater than the loudest **on-source** event



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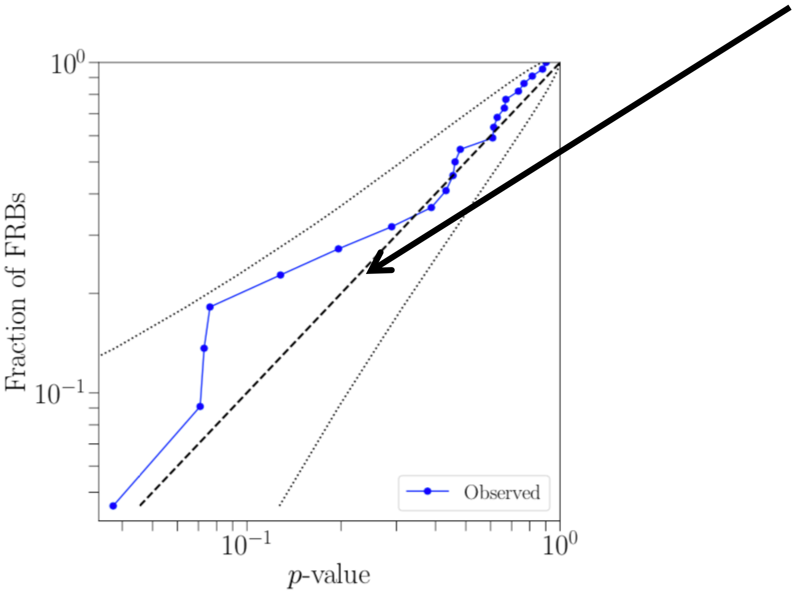
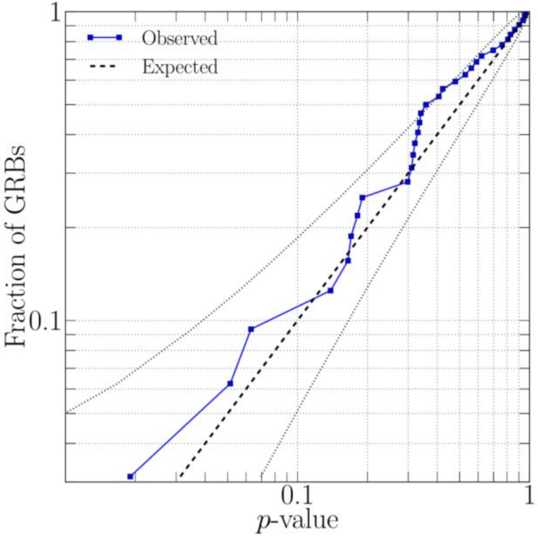
P-Value cumulative Distributions

Expected distribution under a no-signal hypothesis and 90% confidence bands



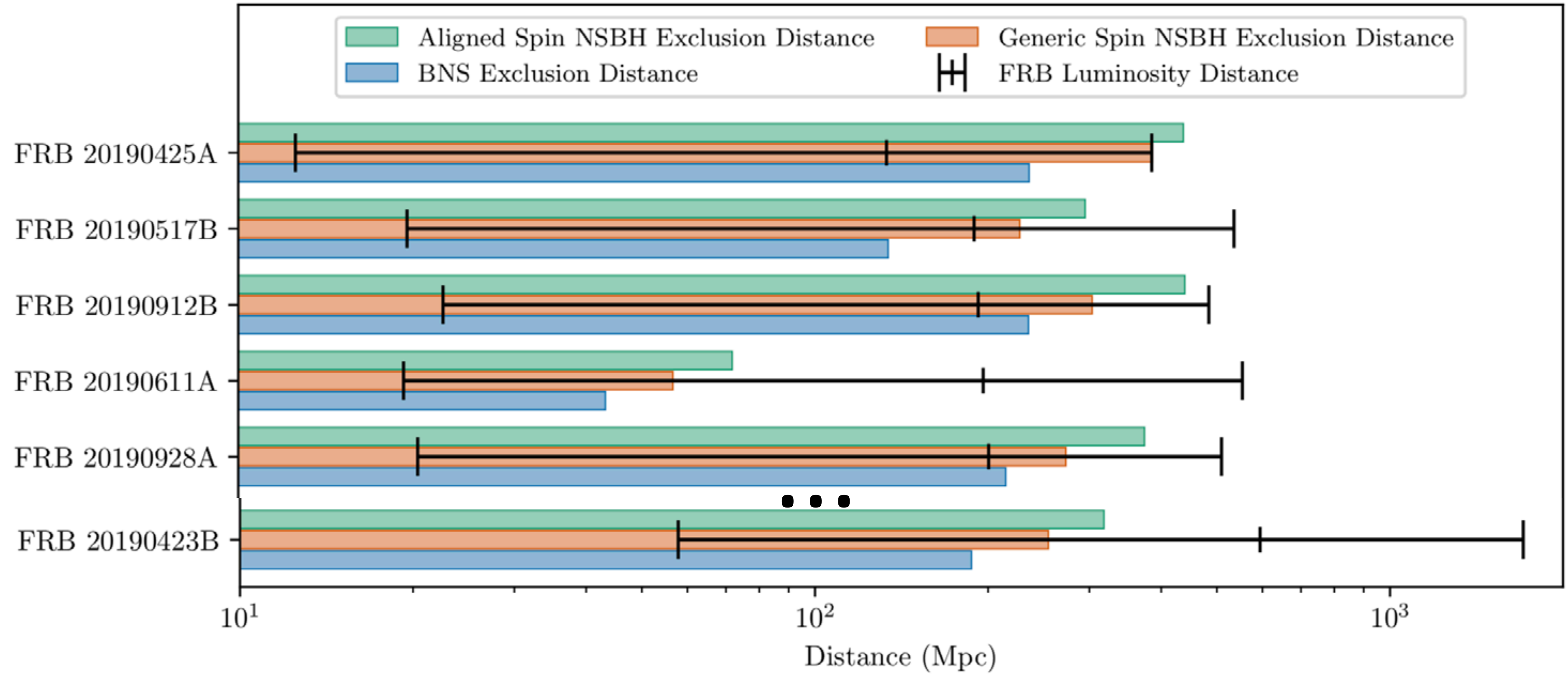
Modelled/PyGRB



Unmodelled/X-Pipeline

P-value (False Alarm Probability) determined by counting the fraction of off-source trials with an event loader than the one observed

Modeled searches: Exclusion distances VS inferred distances



Lower limits on the 90% confidence level exclusion distances for GW against the 90% credible intervals (whisker plots) on the luminosity distance posterior for each FRB

Unmodeled searches: O3 constraints on GW energy

- Energy upper limits based on lower bounds on the D_L for each FRB and sensitive range of the un-modelled search
- **Binding energy of a NS ~ 10^{53} ergs**

- For **closest non-repeating FRB**, 20190425A, found 2.5×10^{50} ergs for the 70 Hz SG-A model, 7.9×10^{54} ergs for the 1995 Hz SG-H model

- **Closest repeater**, FRB 20190825A, find 5.83×10^{55} erg to 5.98×10^{55} erg

FRB	D_L [Mpc]	SG A	SG B	SG G	SG H
FRB 20190410A	60.1	1.5×10^{52}	2.8×10^{52}	3.0×10^{56}	1.1×10^{57}
FRB 20190419B	24.8	2.6×10^{51}	4.3×10^{51}	5.0×10^{55}	1.5×10^{58}
FRB 20190423B	57.8	5.9×10^{52}	8.9×10^{52}	3.4×10^{57}	1.1×10^{58}
FRB 20190425A	12.6	2.5×10^{50}	3.5×10^{50}	1.6×10^{54}	7.9×10^{54}
FRB 20190517C	44.3	5.8×10^{51}	8.8×10^{51}	9.8×10^{55}	3.5×10^{56}
FRB 20190518D	62.0	9.5×10^{51}	1.3×10^{52}	3.6×10^{55}	2.0×10^{56}
FRB 20190531B	37.2	3.2×10^{51}	3.4×10^{51}	8.1×10^{54}	3.1×10^{55}
FRB 20190601C	198.7	8.6×10^{52}	1.1×10^{53}	4.8×10^{56}	1.5×10^{57}
FRB 20190604G	97.1	1.1×10^{53}	3.2×10^{53}	3.2×10^{57}	1.2×10^{58}
FRB 20190605C	68.2	3.0×10^{52}	2.8×10^{52}	5.2×10^{56}	1.6×10^{57}
FRB 20190606B	168.6	1.7×10^{53}	1.3×10^{53}	3.6×10^{56}	1.4×10^{57}
FRB 20190612B	64.9	8.2×10^{51}	8.5×10^{51}	3.7×10^{55}	3.6×10^{56}

Optimistic models such as Corsi & Owen (2011) predict 10^{48}-10^{49} erg in GW energy at around 1-2 kHz.

Other studies predict a much lower energy conversion to GW energy $10^{28} – 10^{38}$ erg (Levin & van Hoven 2011, Zink et al. 2012)

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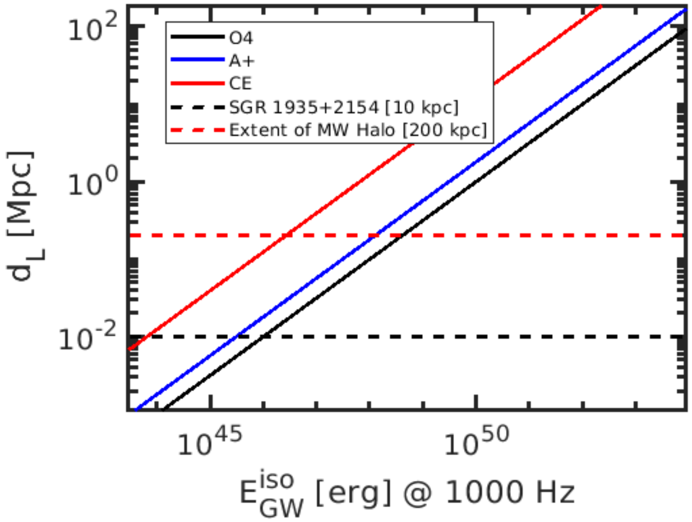
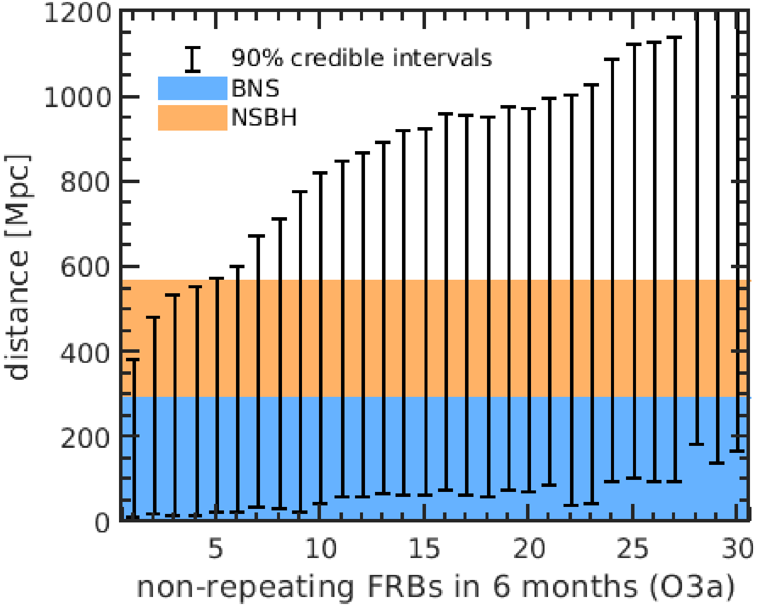
Unmodeled searches: Projected constraints on GW energy

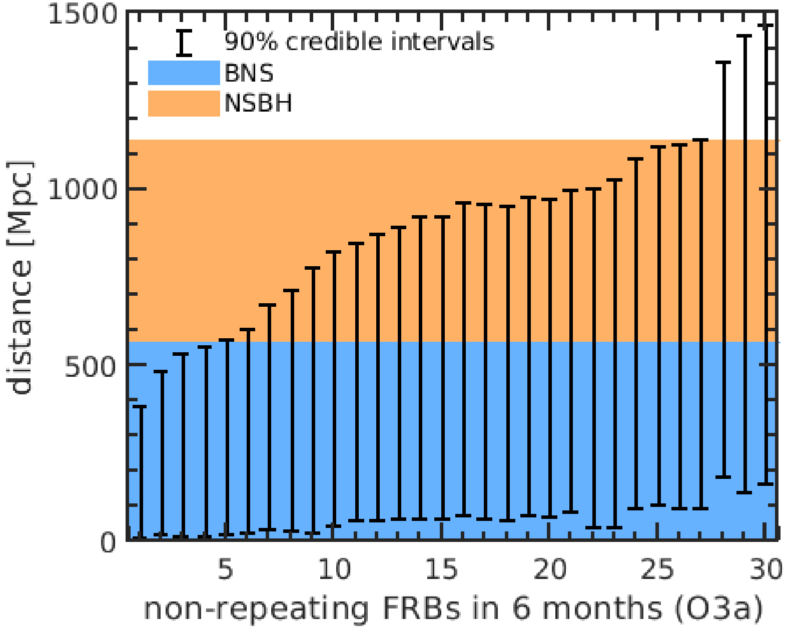


- O3a got as low as 10^{50} ergs (70 Hz) – 10^{54} ergs (2000 Hz)
- **SGR-magnetar burst (SGR 1935+2154)** in 2020 was 1-month after O3b had finished.
- The **repeater near M81 was** in the O3b data. Only H1 was taking data - X-pipeline requires 2-IFO data.

- Optimistic models such as Corsi & Owen (2011) predict 10^{48}-10^{49} ergs in GW energy at around 1-2 kHz via the NS fundemental *f*-mode. An FRB in the MW Halo during O4 will start to probe this constraint.
- Other studies predict a much lower energy conversion to GW energy 10^{28} – 10^{38} ergs (Levin & van Hoven 2011, Zink et al. 2012)

Looking ahead to O4 and O5 (2026+)





- O5 - the detection range for BNS mergers is expected to exceed the maximum distances of at least 20 FRBs
- For NSBH mergers, it will surpass the maximum distances of over 100 FRBs

CHIME –outrigger telescopes

Enabling large-scale localization is a high-priority science goal for FRBs, and one that will be addressed with the CHIME/FRB Outriggers project.

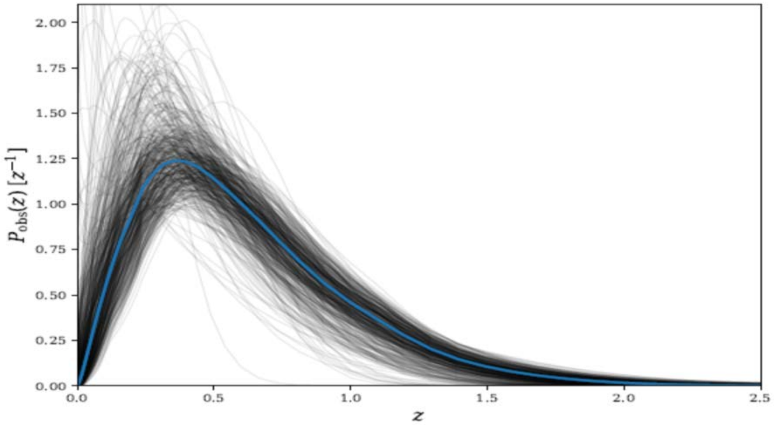
In the next few years, CHIME/FRB is deploying a set of **Outrigger telescopes which are smaller versions of CHIME**

These will be located at sufficient distances (distances ranging from 100s to several 1000s of kms from CHIME) to allow autonomous Very Large Baseline Interferometry (VLBI) on detected FRBs.

(Confirmed sites: Allenby BC, Canada, Green Bank Observatory, U

This will allow **sub-arcsecond localisations on hundreds of FRBs/year** allowing:

- host galaxy identifications
- redshift determination through optical



Predicted redshift distributions from CHIME/FRB Outriggers

Conclusions

- No significant evidence for a gravitational-wave association with any FRB in our O3a searches – starting to impose on NSBH models for FRBs
- Limits on GW energy produced by the FRB events analysed un-constraining
- O3b analysis nearly completed – paper early next year
- O4 – single paper – would expect to start constraining NSBH models
- O4 - SGR-magnetar burst (SGR 1935+2154) or M81 event ?

- **Paper (open access):** https://iopscience.iop.org/article/10.3847/1538-4357/acd770/pdf
- **Science summary:** https://www.ligo.org/science/Publication-O3aFRB/
- **Conversation article:** https://theconversation.com/a-search-for-links-between-two-of-the-universes-most-spectacular-phenomena-has-come-up-empty-for-now-180237

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