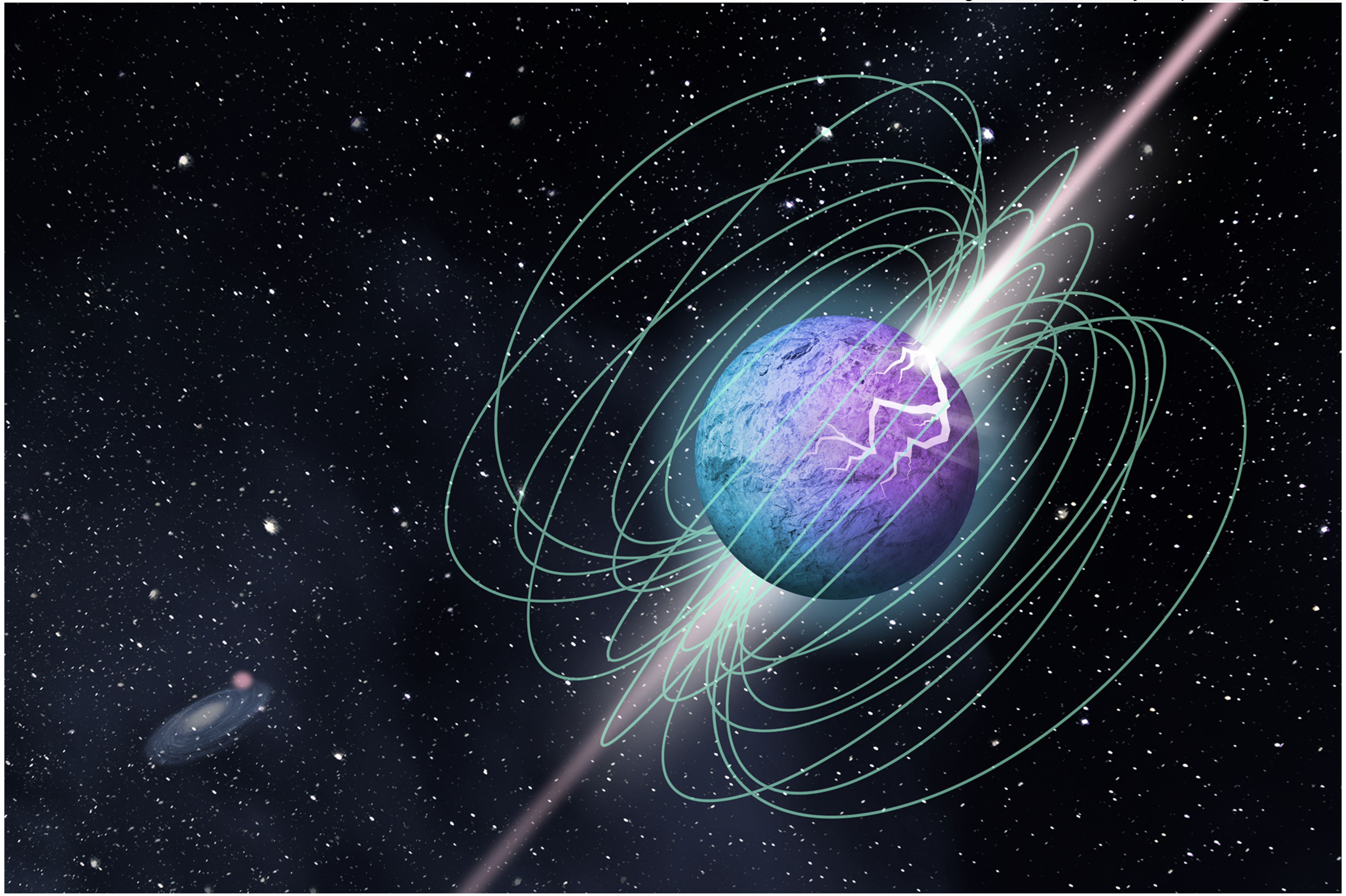
Image: McGill University Graphic Design Team



Searching for Gravitational Waves from Magnetar Bursts

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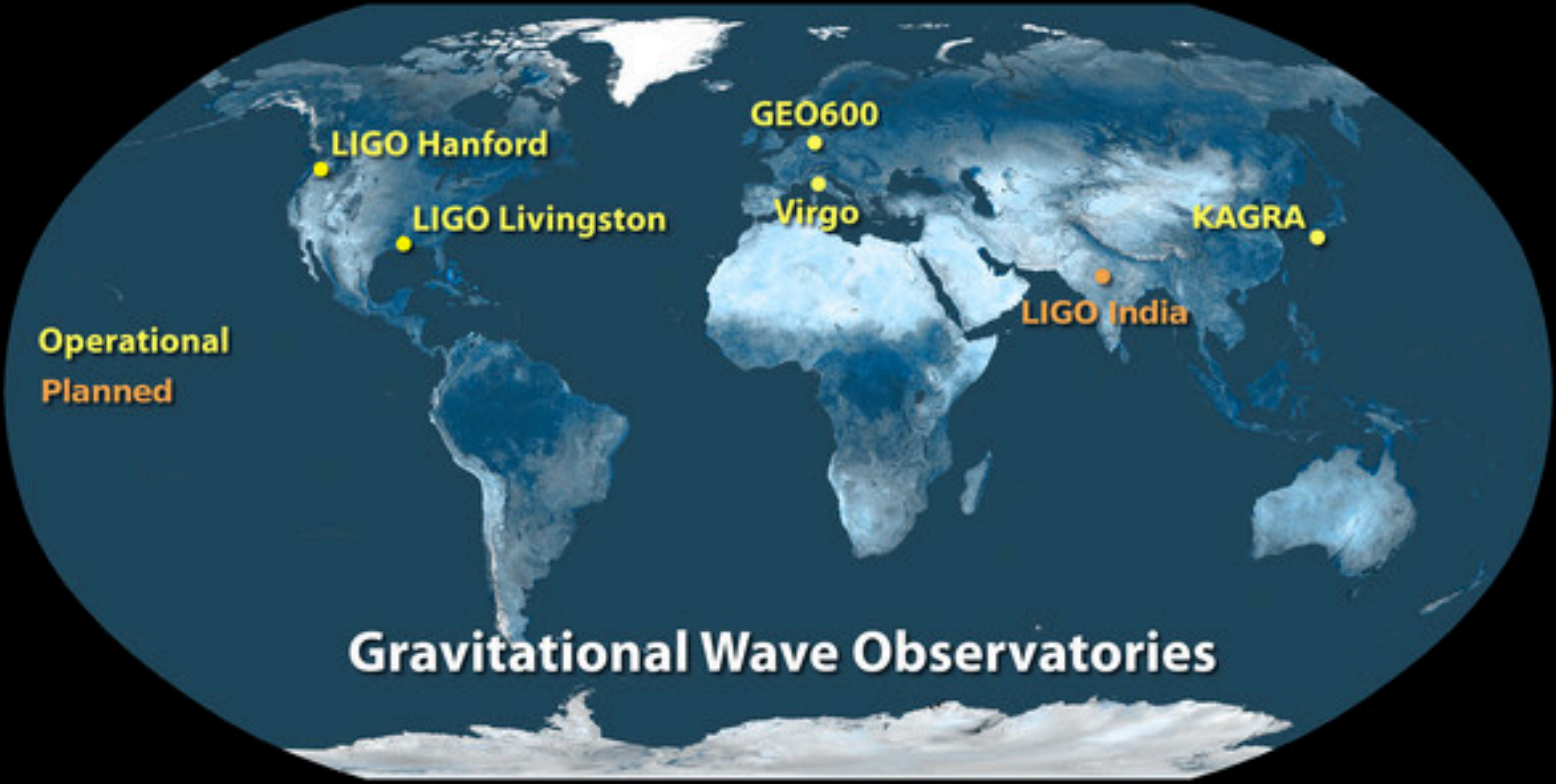
Overview

1. Interferometric Gravitational Wave Detectors and GW Detections
2. Magnetars
3. Search Methodology
4. Results of Past Searches
5. Future Search Outlook

Courtesy Caltech/MIT/LIGO Laboratory

Courtesy Caltech/MIT/LIGO Laboratory

Image: The Virgo collaboration/CCO 1.0

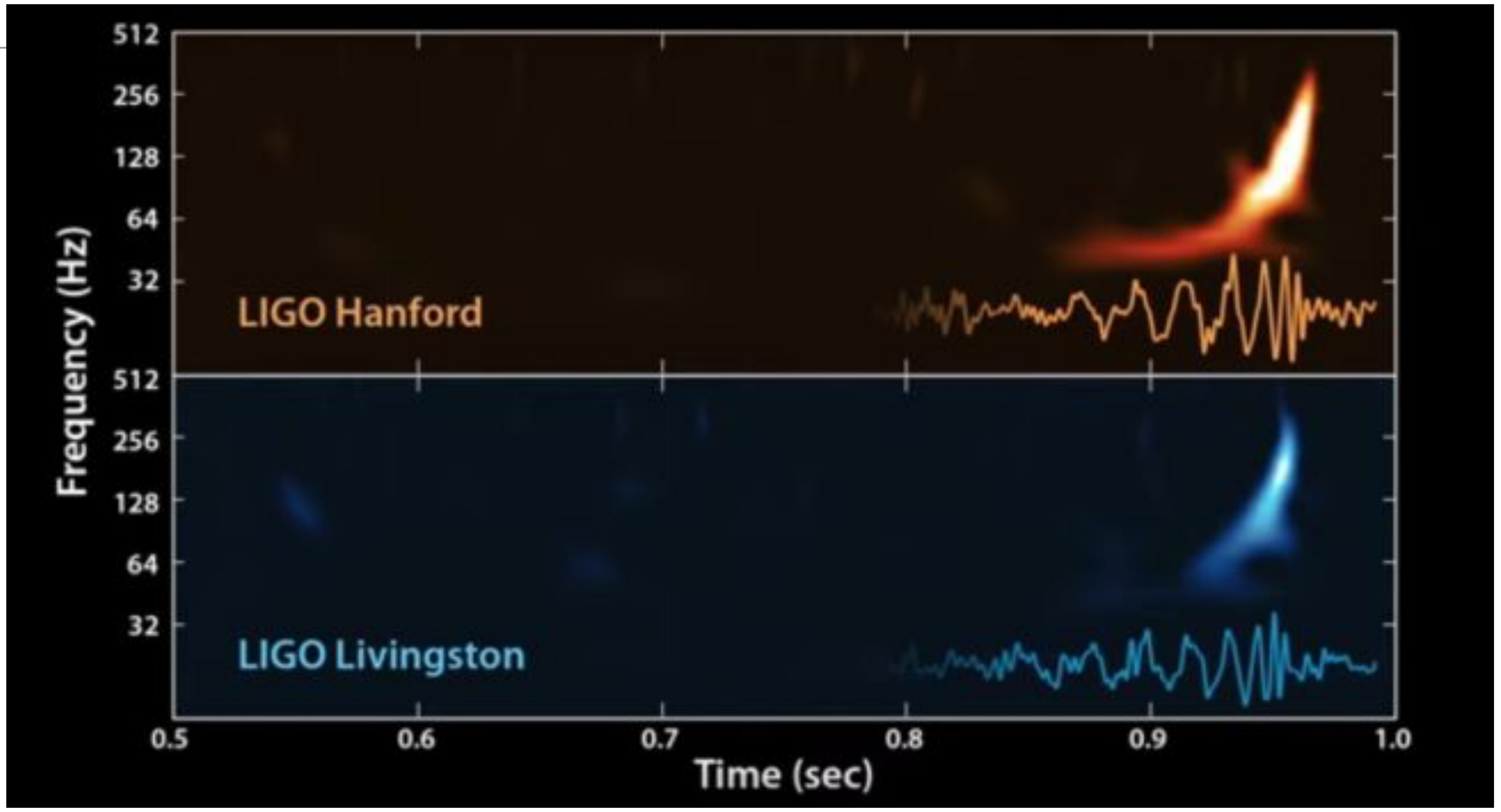


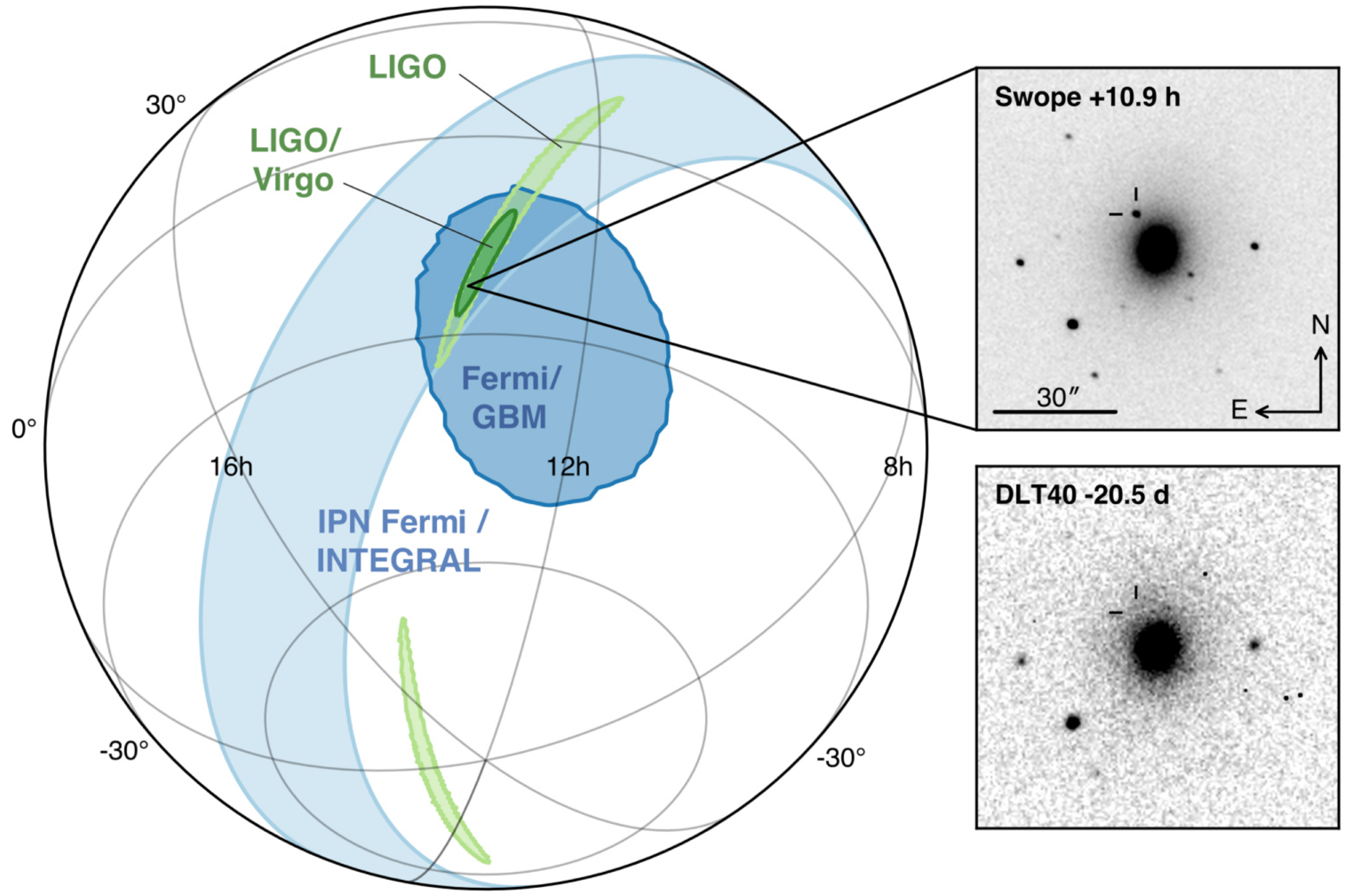
Courtesy Caltech/MIT/LIGO Laboratory

Gravitational Wave Detections

- 50 detections in O1, O2, O3a
- First direct detection GW150914, binary black hole merger
- First binary neutron star merger detected on August 17, 2017
    - Multi-messenger astronomy
- Two neutron star black hole mergers detected after O3a
    - GW200105 and GW200115

Credit: LIGO Scientific Collaboration

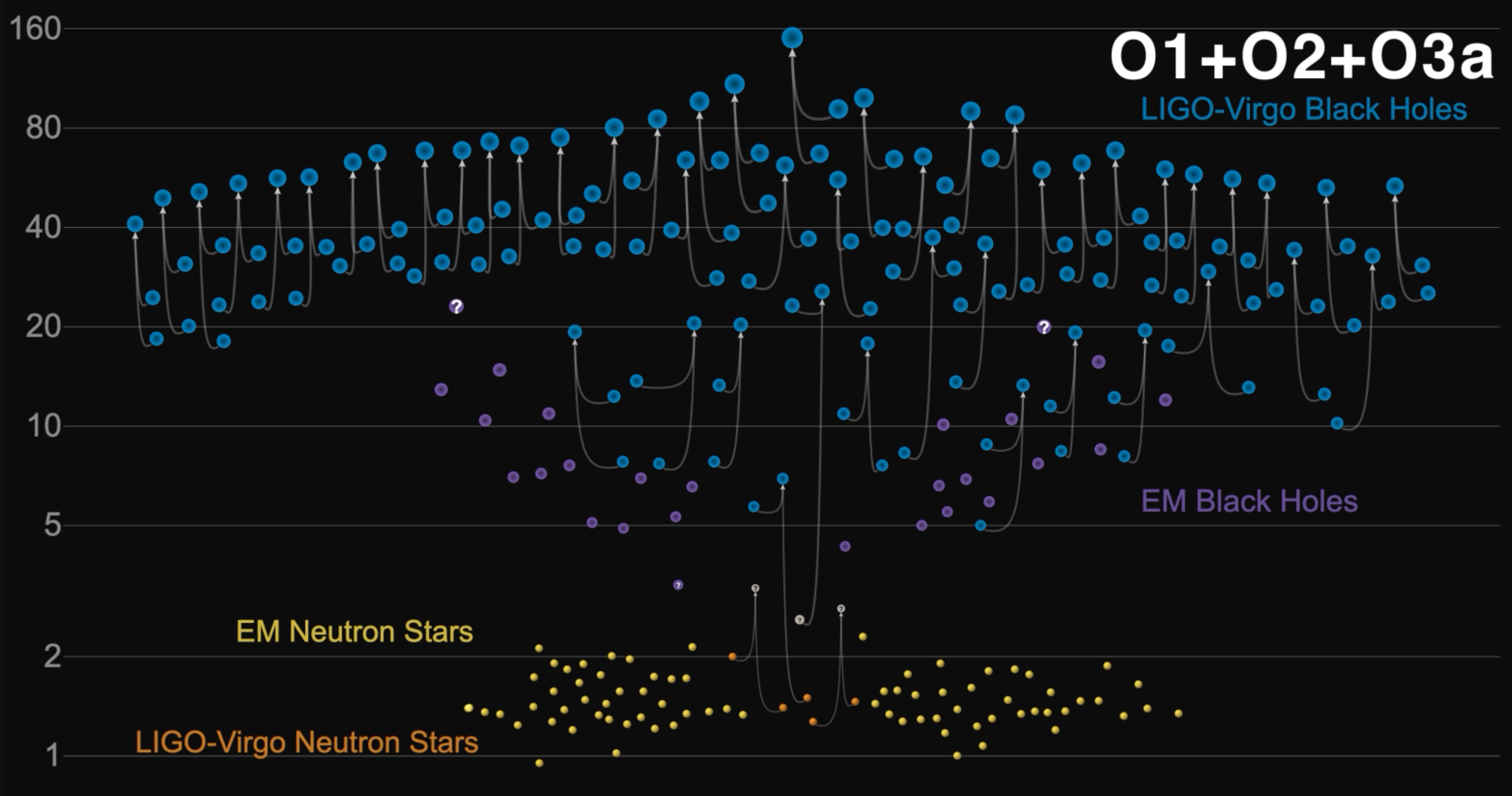




Source: B. P. Abbott et al 2017 ApJL 848 L12

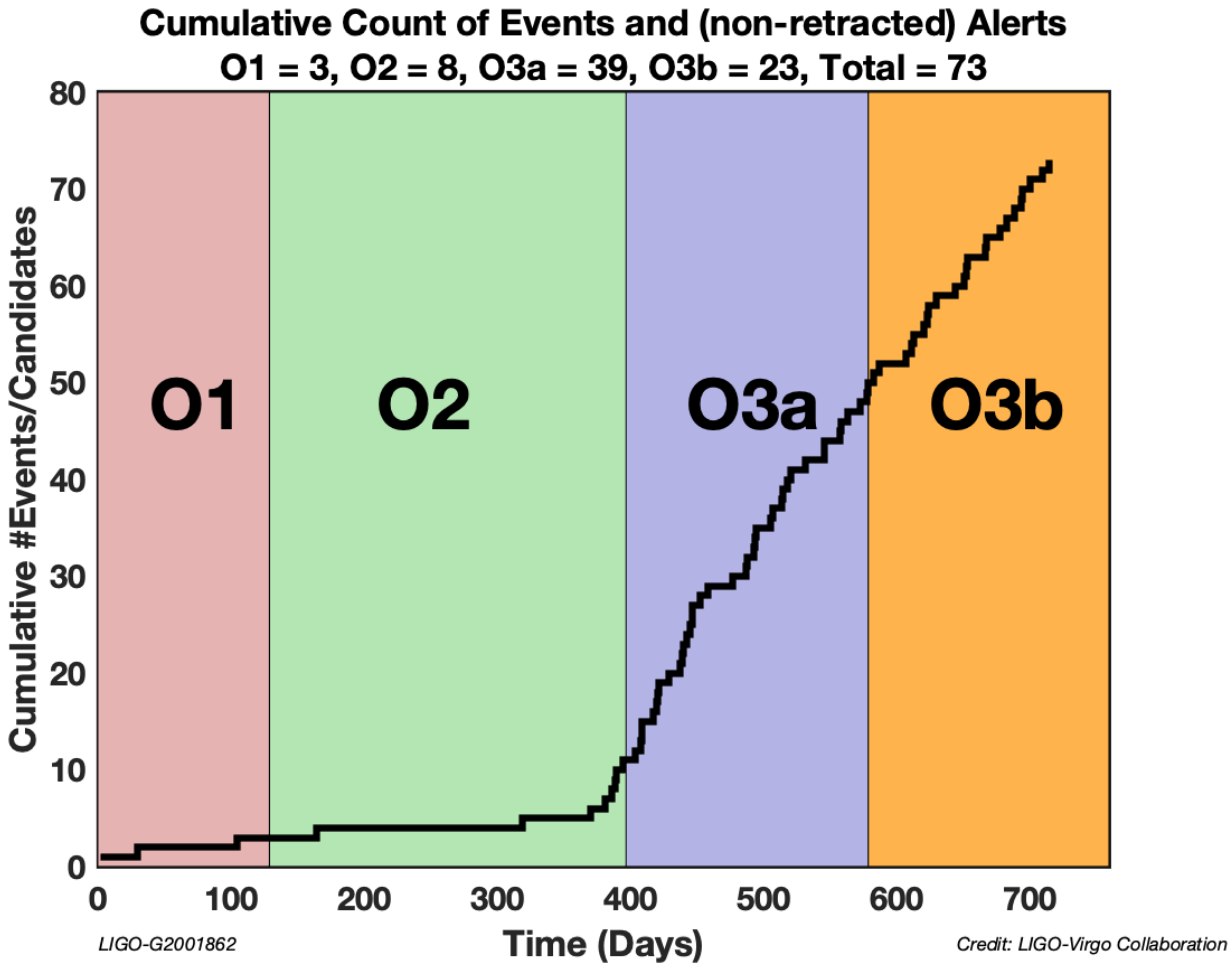
Masses in the Stellar Graveyard

in Solar Masses

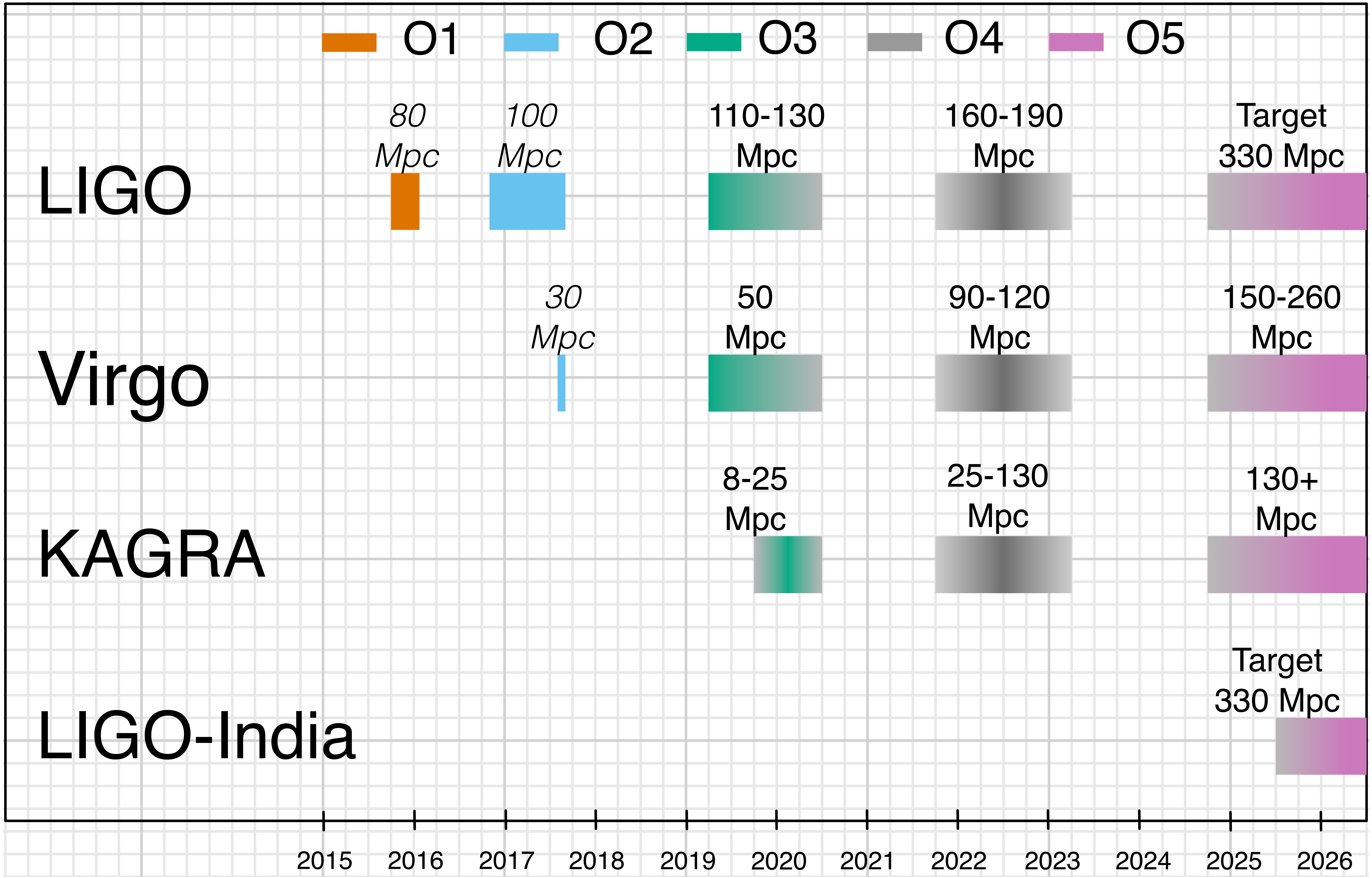


LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern

Candidate Events and Non-retracted Alerts



Observation Run Plans



Source: LVK, https://dcc.ligo.org/LIGO-P1900218/public

LSC Search Groups

- **Compact Binary Coalescence (CBC) Group** - Binary black hole (BBH), binary neutron star (BNS), and neutron star and black hole (NSBH) mergers
- **Continuous Wave Group** - Rotating neutron star
- **Stochastic Group** - Stochastic gravitational wave background
- **Burst Group** - Supernovae, cosmic strings, gamma-ray bursts (GRBs)

Magnetars - Discovery and Historical Background

1979: Discovery of soft gamma repeaters (SGRs) from bursts and giant flare (triangulated from satellites throughout solar system, most luminous extra-solar gamma ray event at the time)

- **Soft Gamma Repeaters:** Repeated bursts of soft gamma rays and hard X-rays from the same sky location

1980: First Anomalous X-ray pulsar (AXP) identified

- **Anomalous X-Ray Pulsars:** X-ray pulsars without a partner object from which to accrete material

Credit: NASA's Goddard Space Flight Center/S. Wiessinger

Magnetars: Discovery and Historical Background

- **1992: Magnetar model** put forth as an explanation for soft gamma repeaters by Duncan and Thompson (detailed more fully in 1995)

- **1996:** Duncan and Thompson proposed **anomalous X-ray pulsars may also be magnetars**, later shown to emit short bursts like soft gamma repeaters

- **1998:** Another giant flare detected

Magnetars: Discovery and Historical Background

- **2004 Hyper Flare** (X-ray and gamma ray detectors saturated, onboard particle detectors measured peak)

- **2005 quasiperiodic oscillations (QPOs)** detected in tail of hyper flare

- **Recent observations** have shown magnetars share features with **high magnetic-field radio pulsars** (X-ray bursts), some magnetars have radio emissions

- **April 2020** a galactic magnetar was observed emitting a **fast radio burst (FRB)**

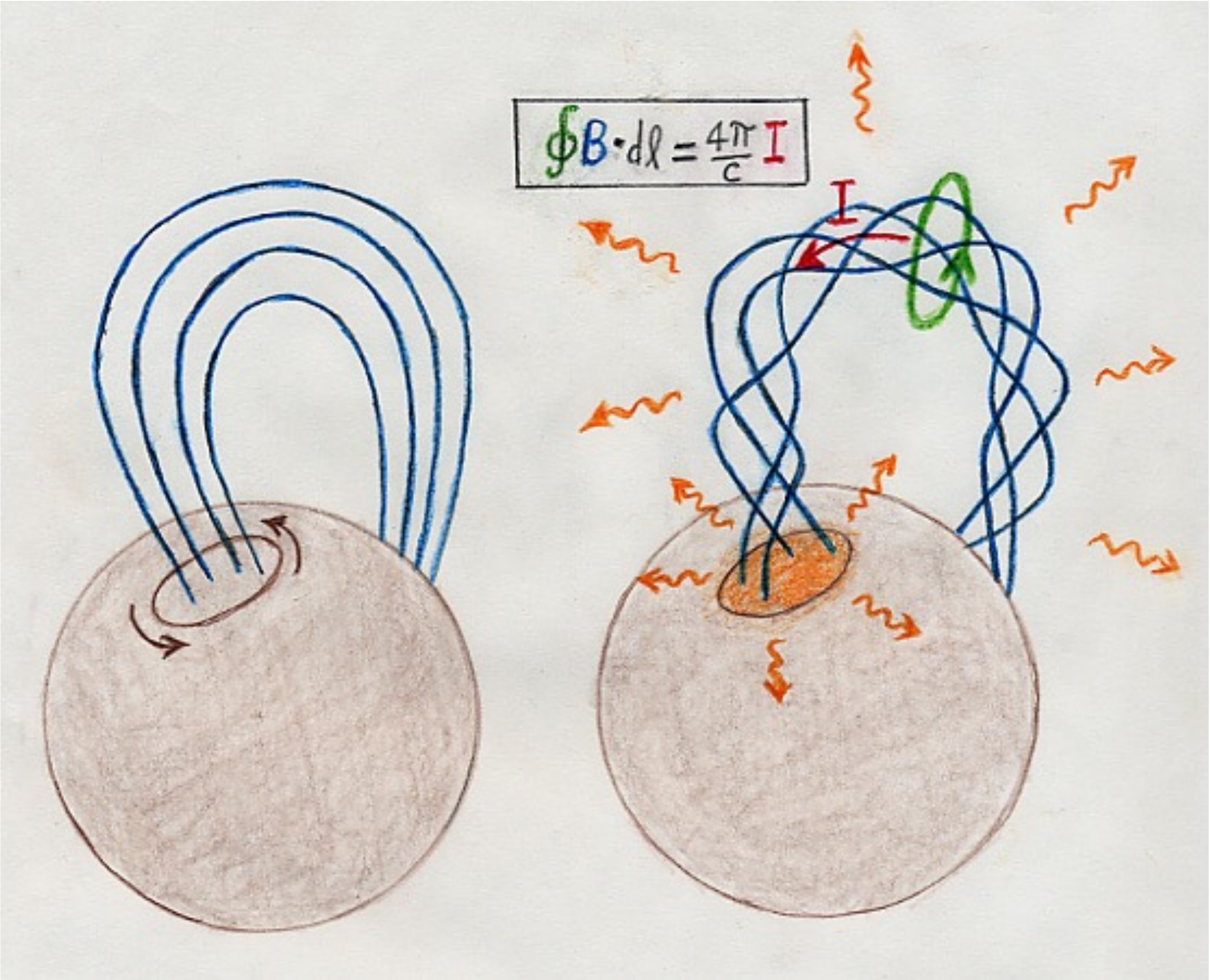
Magnetars

Neutron star with very strong magnetic dipole field (~10^{14}–10^{15} G) (may have stronger internal toroidal field)

- Model for **SGRs** and **AXPs**
- **Intermittent bursts** of **hard X-rays** and **soft gamma rays** (up to 10^{42} erg) and rarer giant flares (10^{44} - 10^{46} erg)
    - Short bursts seen down to the lower limit of X-ray sensitivity
- **30 Magnetars** (24 confirmed as SGRs or AXPs, 6 candidates)

X-ray Burst Mechanisms

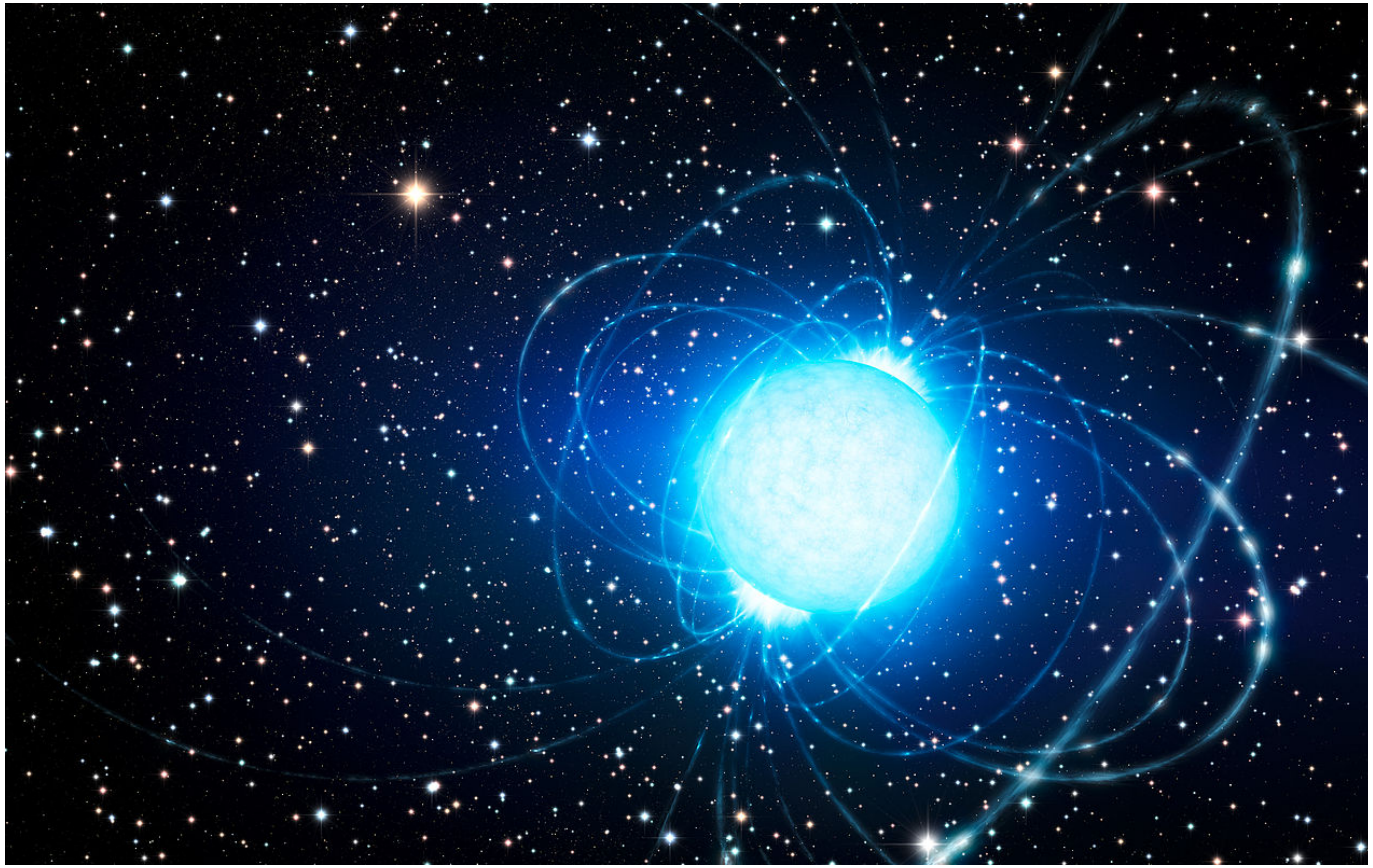
- **Crust Cracking**
  - $10^{44} - 10^{46}$ ergs (10^{50} ergs if the crust and/or core are quark matter)
  - Can cause torsional modes
- **Magnetic Reconnection**
  - Pair fireball and trapped pair plasma
  - Can occur with crust cracking or by itself



Source: http://solomon.as.utexas.edu/magnetar.html

Magnetar Characteristics

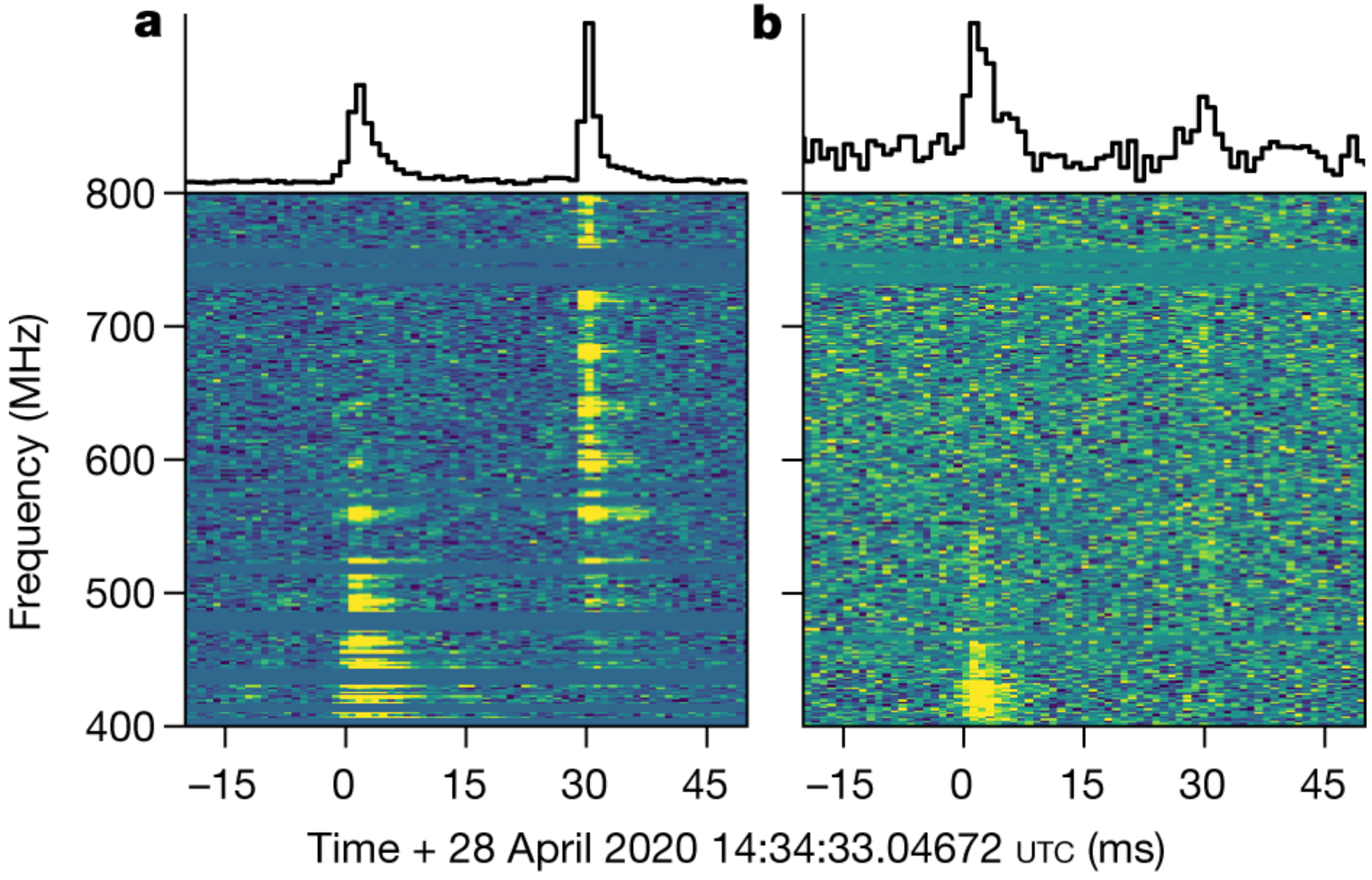
- Continuous X-ray emissions
- Continuous optical emissions (in ~1/3 of magnetars)
- More thermal energy than expected from just a hot core
- Outbursts
- Glitches (anti-glitches)
- Radio emissions



Credit: ESO/L. Calçada

Magnetars and Fast Radio Burst (FRBs)

- Fast radio bursts are ~ms bursts of radio waves
- Fast radio burst detected on April 28, 2020 from a galactic magnetar in coincidence with an X-ray burst
- Non-detection of radio emissions from other observed short bursts suggest radio emissions are:
  1) not emitted at every burst,
  2) radio bursts may be beamed, or
  3) may sometimes have very low fluence ratios (FRB/short burst)
- Magnetars could potentially explain most or all FRBs (remains to be seen)
- Some highly energetic FRBs may need an energetic giant flare or be due to something other than magnetars



Source: The CHIME/FRB Collaboration., Andersen, B., Bandura, K. et al. A bright millisecond-duration radio burst from a Galactic magnetar. Nature 587, 54–58 (2020).

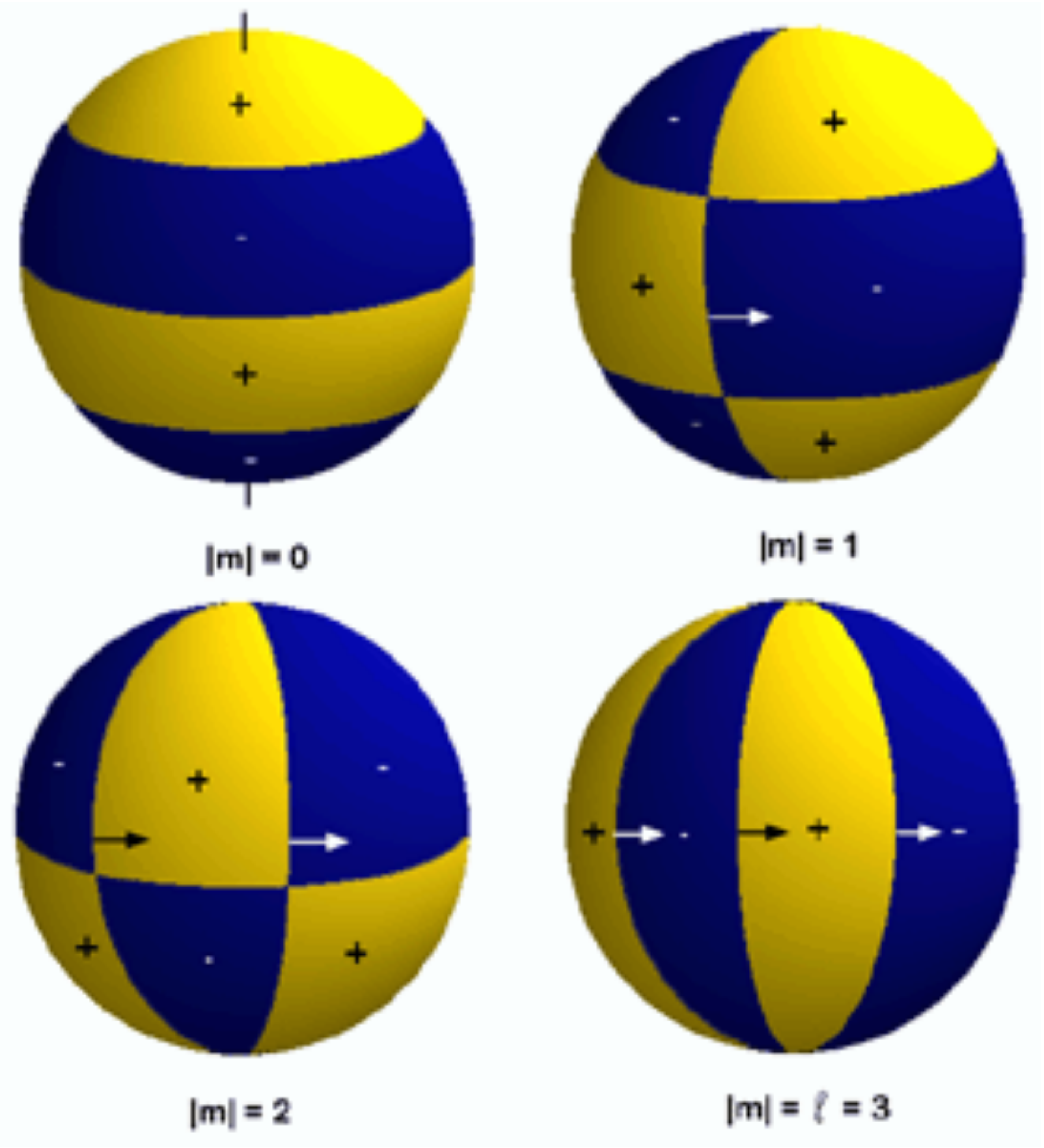
Magnetars as a Gravitational Wave Source

Direction and time known - **targeted search**

Compact object

Relatively close distances: ~1.6 - ~62.4 kpc (many around ~10 kpc)

Bursts may excite **non-radial modes** which could radiate **Gravitational Waves** (f-modes, r-modes, Alfven modes)



Source: https://www.univie.ac.at/tops/dsn/texts/nonradialpuls.html
(Credit: Zima, 1999, Master Thesis)

Past Magnetar Searches

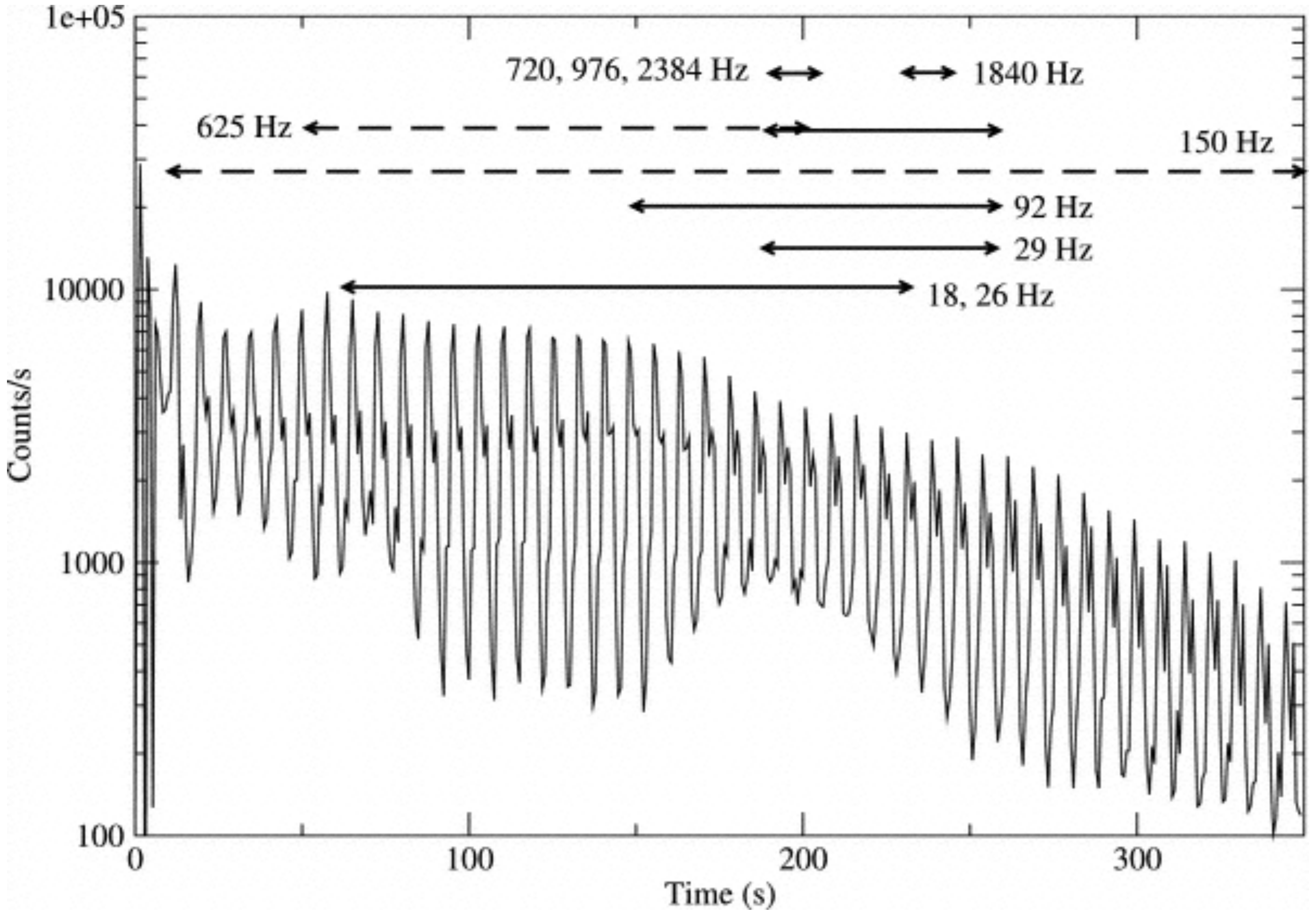
- **2004 giant flare**: https://journals.aps.org/prd/abstract/10.1103/PhysRevD.76.062003
- **First f-mode search**: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.101.211102
- **Stacking bursts**: https://iopscience.iop.org/article/10.1088/0004-637X/701/2/L68
- **S5 f-mode search**: https://iopscience.iop.org/article/10.1088/2041-8205/734/2/L35
- **Extra galactic magnetar giant flare**: https://iopscience.iop.org/article/10.1088/0004-637X/755/1/2

Long-duration Transient Magnetar Searches

- **S6**: https://iopscience.iop.org/article/10.1088/1361-6382/aa7d5b
- **O2**: https://iopscience.iop.org/article/10.3847/1538-4357/ab0e15

Search for Gravitational Waves from Magnetar Bursts: Methodology

- <u>Targeted search</u>
- <u>Short duration</u>
    - **X-pipeline**: two windows
        - [-4, 4] seconds and [50, 4000] Hz
        - [4, 500] seconds and [50, 4000] Hz
    - Unmodeled search (upper limits on sensitivity follow previous f-mode searches using white noise bursts and ringdowns as well as chirplets)
- <u>Long duration</u>
    - **STAMP**: [-4, 1600] seconds and [24, 2500] Hz
    - Unknown signal, searching for long duration transient signals (based on **quasiperiodic oscillations (QPOs)** in X-ray tails of giant flairs)
        - Many observed QPOs occur in frequency ranges LIGO is sensitive to



Source: <u>Tod E. Strohmayer and Anna L. Watts 2006 ApJ 653 593</u>

Long-Duration Search with STAMP

- **Single pixel SNR**

$$\mathrm{SNR}(t;f,\hat{\Omega}) = \mathrm{Re}\left[\frac{\tilde{Q}_{IJ}(t;f,\hat{\Omega})}{|\tilde{Q}_{IJ}(t;f,\hat{\Omega})|}\frac{\tilde{s}_I^*(t;f)\tilde{s}_J(t;f)}{\sqrt{\frac{1}{2}\langle|\tilde{s}_I(t;f)|^2\rangle\langle|\tilde{s}_J(t;f)|^2\rangle}}\right]$$

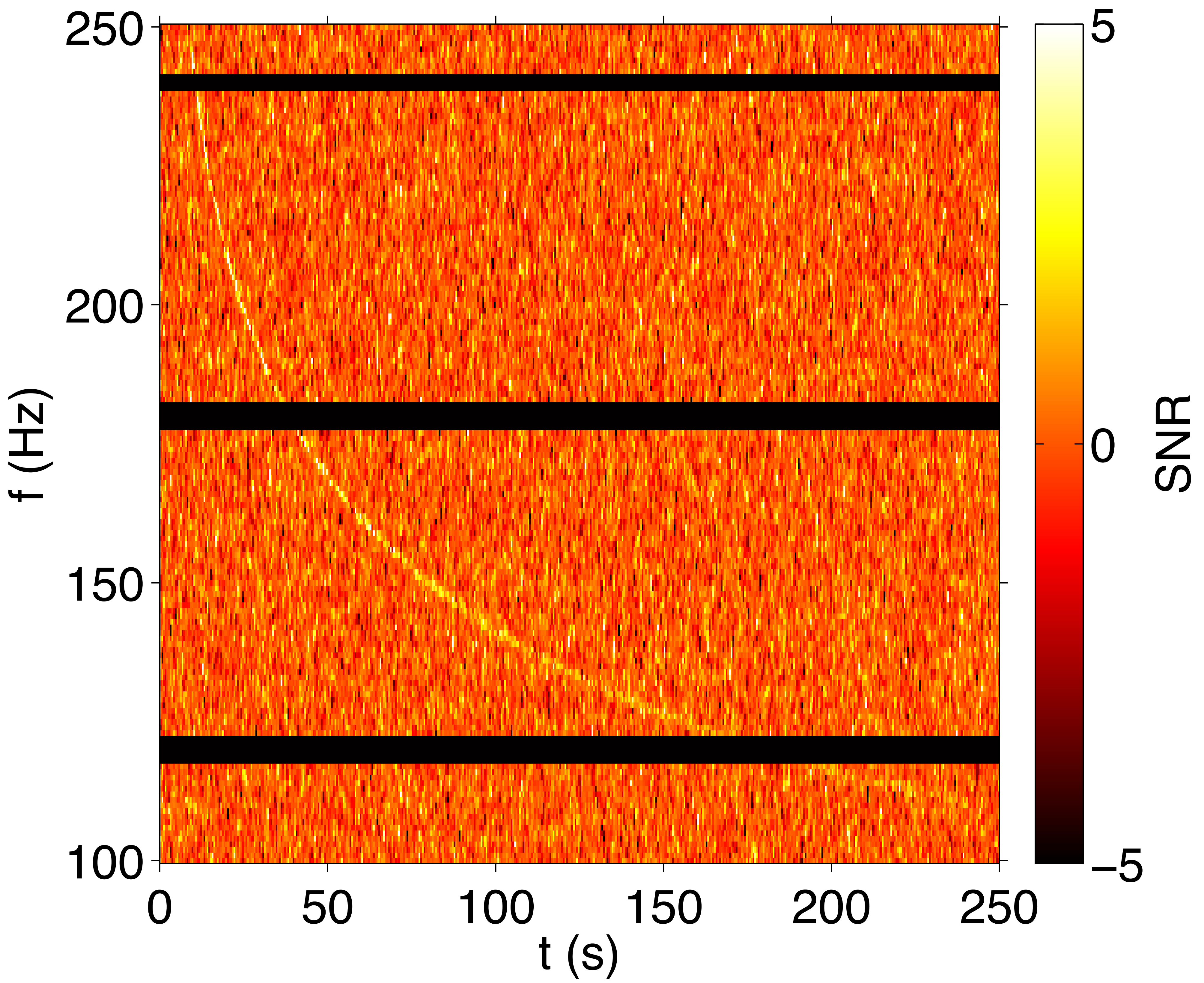
$$\tilde{Q}_{IJ}(t;f,\hat{\Omega}) = \frac{1}{\epsilon_{IJ}(t;\hat{\Omega})}e^{2\pi i f\hat{\Omega}\cdot\Delta\vec{x}_{IJ}/c}$$

$$\epsilon_{IJ}(t;\hat{\Omega}) \equiv \frac{1}{2}\sum_A F_I^A(t;\hat{\Omega})F_J^A(t;\hat{\Omega})$$

- **SNR for cluster**

$$\mathrm{SNR}_\Gamma(\hat{\Omega}) = \frac{\sum_{t;f\in\Gamma}\mathrm{SNR}(t;f,\hat{\Omega})}{\sqrt{N}}$$

- **Cluster generation**
  - Seedless clusters

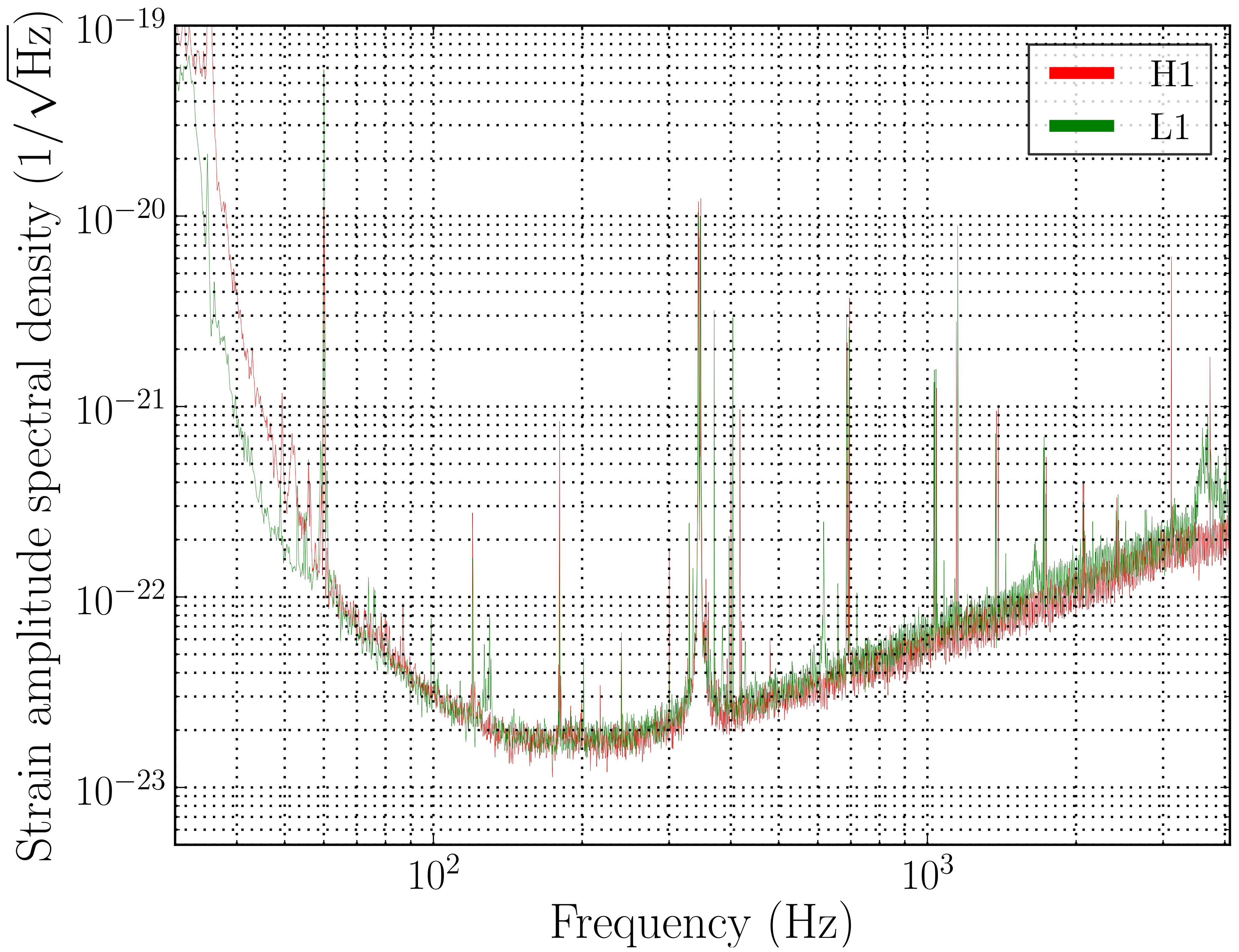


Source: Thrane and Coughlin, Phys. Rev. D, 083010 (2013)

Quadratic Bezier Curve $\begin{pmatrix} t(\xi) \\ f(\xi) \end{pmatrix} = (1-\xi)^2 P_0 + 2(1-\xi)\xi P_1 + \xi^2 P_2$

Notch Spectral Lines (Example: S6)

- 60 Hz harmonics
- Pulsar injections
- 16 Hz harmonics
- 2 Hz harmonic at 372 Hz
- Calibration lines



Cross Power Polarization and Filter Function

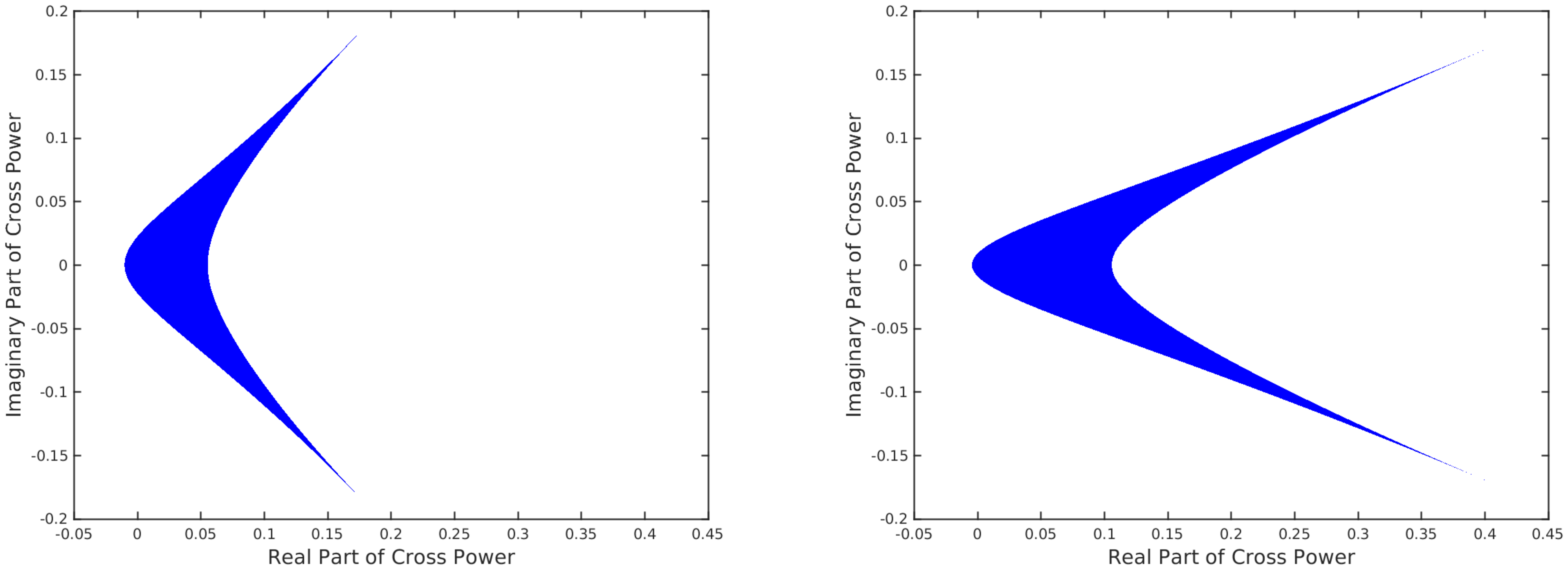
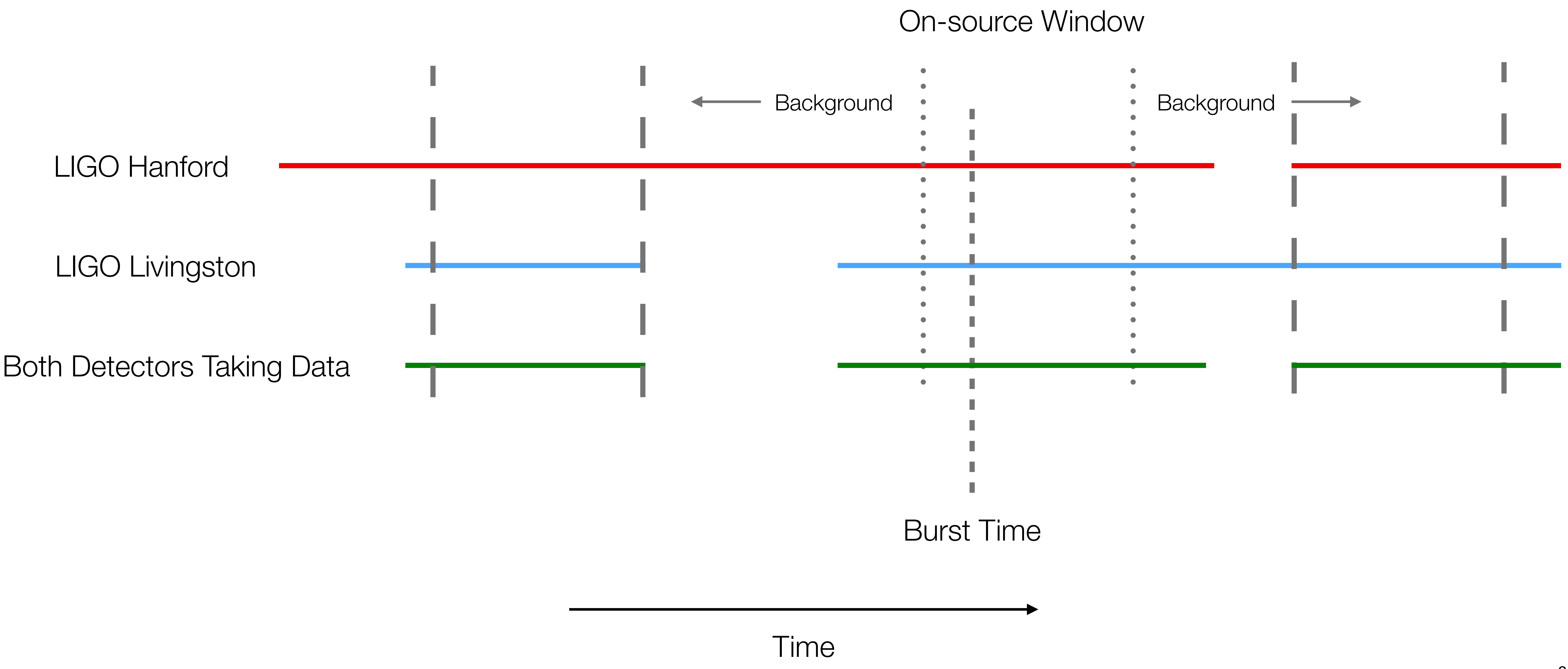


Figure 6. Parametric plots of the complex valued cross power due to elliptically polarized signals of varying polarizations from two different sky locations (left: SGR 1806-20 during the event on April 29, right: SGR 1806-20 during the event on February 25). The polarization of incoming GWs is defined by two angles, ι and ψ. ι is the angle between the vector from Earth to the source and the source's rotation vector, while ψ indicates the orientation of the source's rotation vector when projected into a plane perpendicular to the propagation vector. The ends of the boomerang are at $\iota = 0, \pi$; changing ψ changes the real part only. For ideal sky positions, the boomerang collapses to the real axis and reaches about 0.95. It does not reach 1 because the detectors are not aligned.

Source: B. P. Abbott et al 2019 ApJ 874 163

Selecting On-source Window and Background Data



Background Distribution from Time-Shifted Data

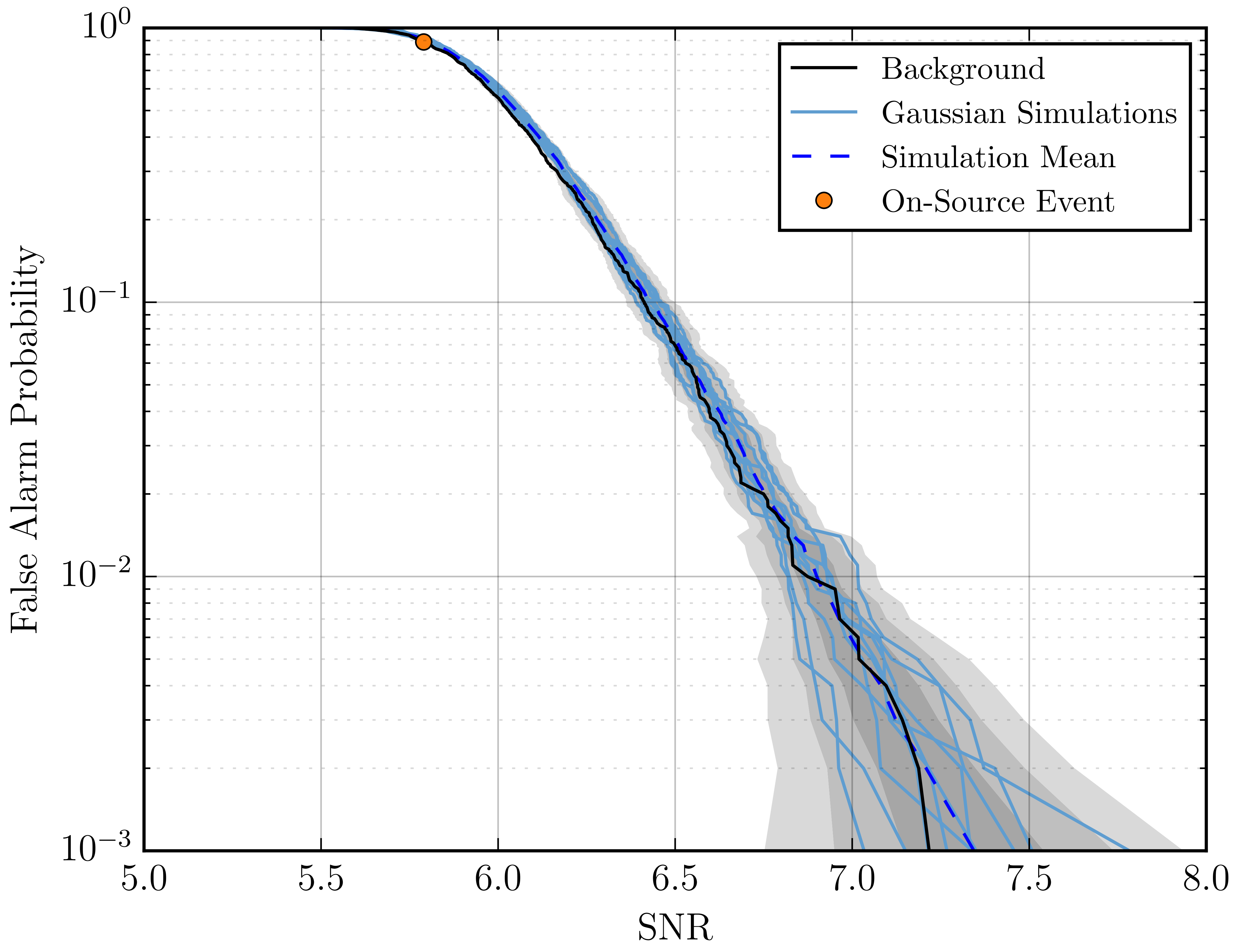
Background distribution from time shifted data

$$\mathrm{FAP}_\alpha = N_{\mathrm{SNR} \geqslant \mathrm{SNR}_\alpha} / N_{\mathrm{Total}}$$

Trigger FAP estimated from background

Background estimated with 1000 time shifted off-source window pairs

Once the background distribution is calculated, calculate the on-source FAP

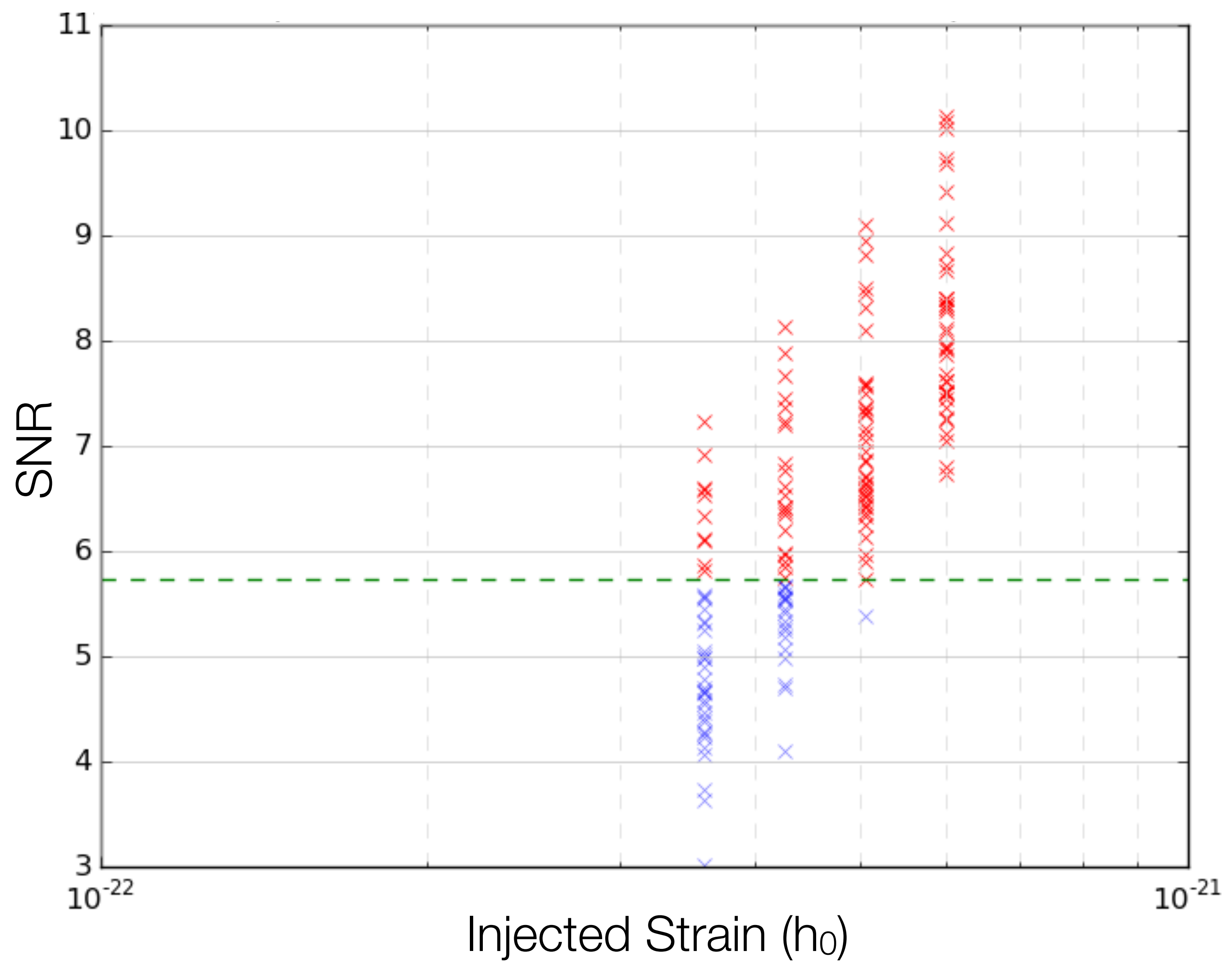


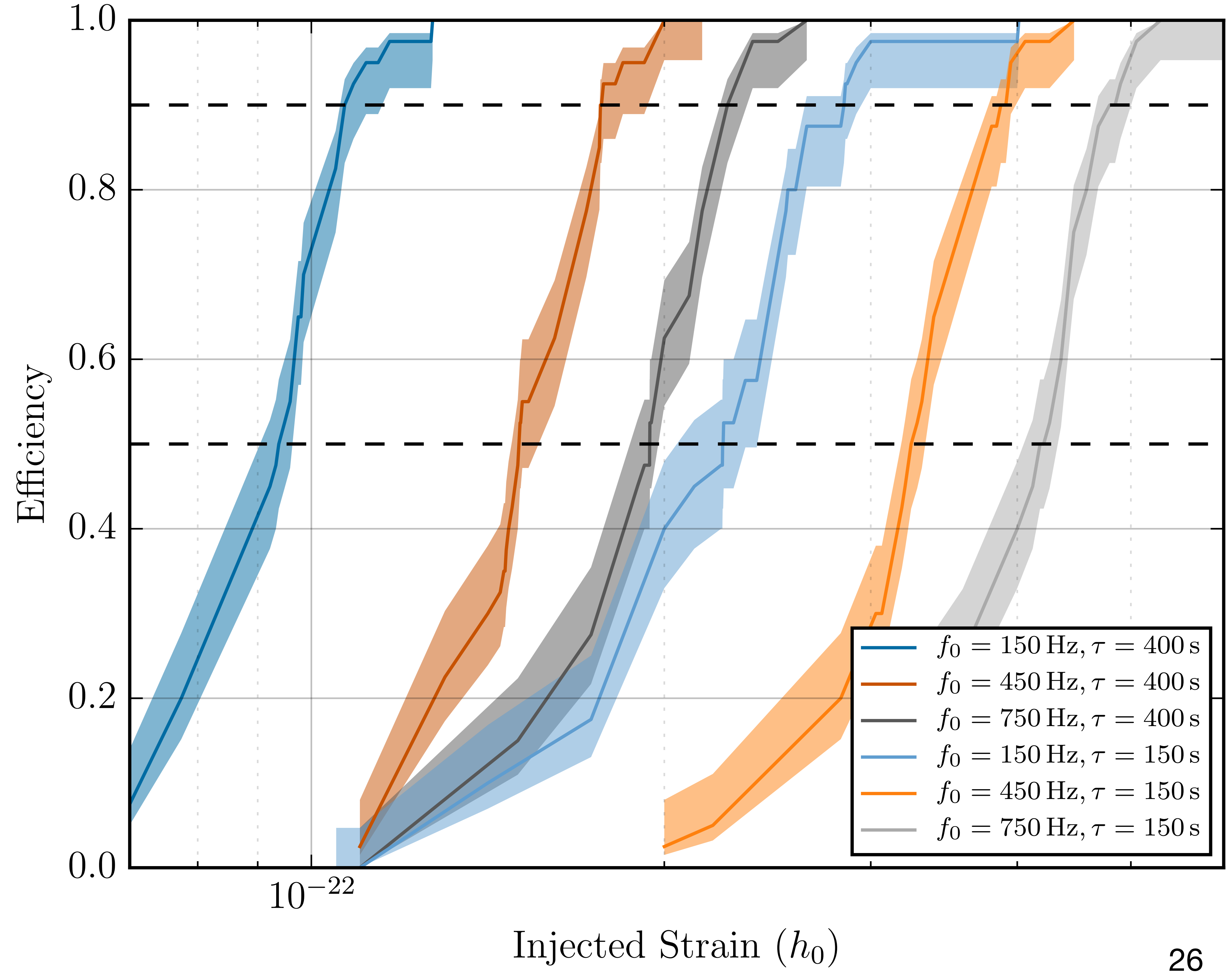
Source: R. Quitzow-James. Thesis. LIGO DCC P1600095

If No Detection: Finding Upper Limits

- Waveforms half sine-Gaussian and sine-exponential
- White noise bursts, ringdowns, chirplets
- Detection efficiency calculated for a specific number of injections
- Injections above on-source SNR are successfully "recovered"

$$\text{Efficiency} = N_{\text{SNR}>\text{SNR}_{\text{TH}}}/N_{\text{Injected}}$$

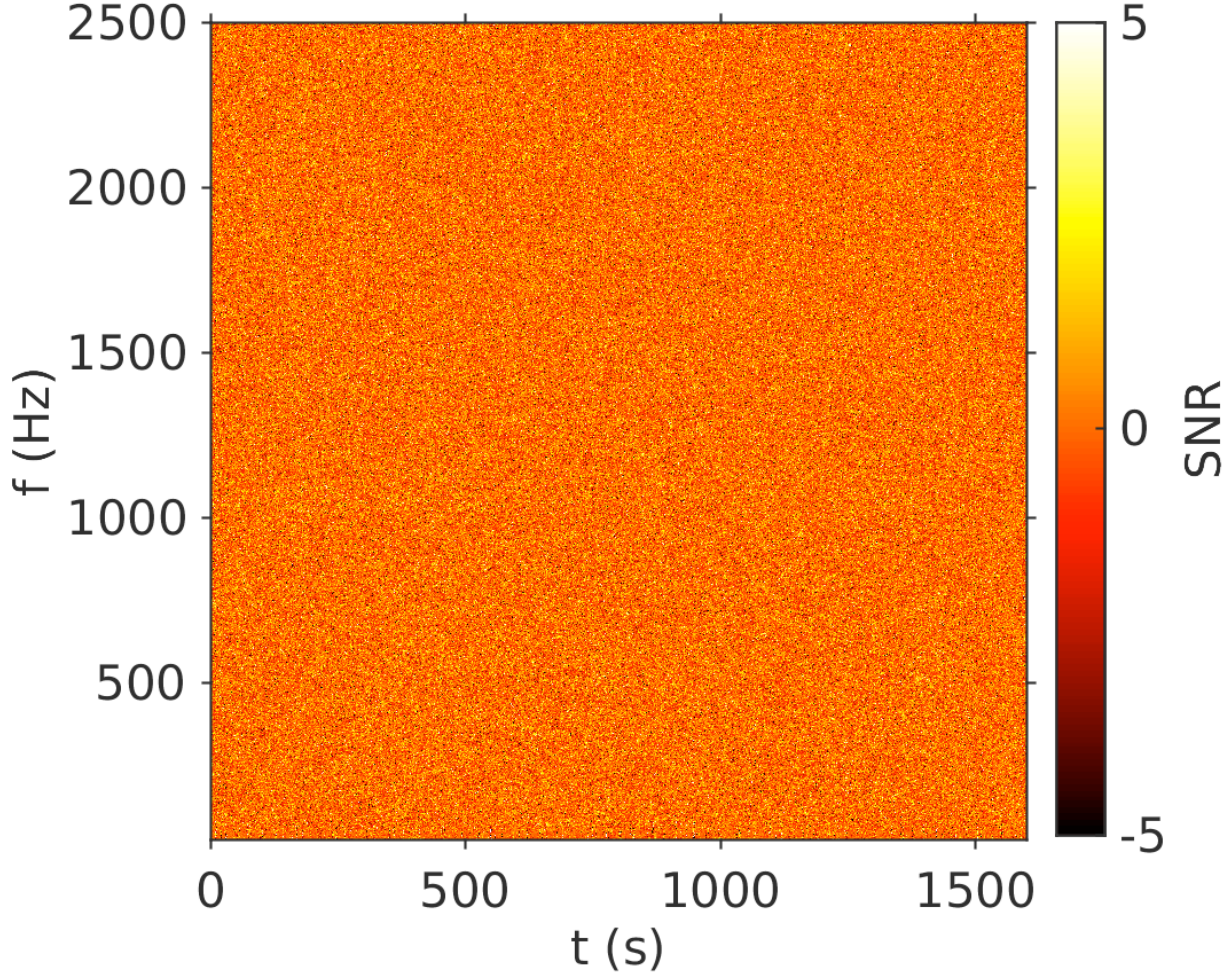




Computational Challenges of Long-Duration Search

- Frequency range of 24 Hz - 2500 Hz => 2477 pixels in frequency
- Duration of 1604 s with 4 s pixels overlapping 2 s => 801 pixels in time
- Searching 2477 x 801 = 1,984,077 pixels for signal (nearly 2 million)
- Search each window with 30 million clusters (6 random numbers per cluster)

$$\begin{pmatrix} t(\xi) \\ f(\xi) \end{pmatrix} = (1-\xi)^2 P_0 + 2(1-\xi)\xi P_1 + \xi^2 P_2$$



Gaussian data

How long does it take to run?

- Previous version ran using GPUs and took about ~15 minutes per window
- Hardware and MatLab updated, now runs CPU only
    - Usually 1.5 - 3 hours (sometimes ~12 hours!) > 5 times longer
- Building up a significant background takes a lot of time
- Current search is planning to run 1260 background sections per trigger and takes about a day to run on the cluster for each burst

How to reduce time for analysis?

- There is a new python version of STAMP in development
- GPU options with Python (such as CuPy) might be able to speed up clustering algorithm
  - TensorFlow could provide some potential speed ups
- Maybe parallelize looking at the clusters in each window
- Open problem to speed up analysis…

Results of Past searches

- 2004 giant flare search: **7.67 × 10^{46} erg** (hrss = 4.53 × 10^{-22} $s^{1/2}$) for 92.5 Hz
- Best S6 upper limit (**1.01 x 10^{46} erg**) comparable to 2004 giant flare EM energy (**~10^{46} erg**)
- O2 long-duration upper limit at 150 Hz (**3.4 x 10^{44} erg**)
- S6 and O2 burst EM energy much smaller (~7x10^{39} erg and ~10^{36} erg)
- aLIGO could probe burst mechanism energy budgets for a giant flare

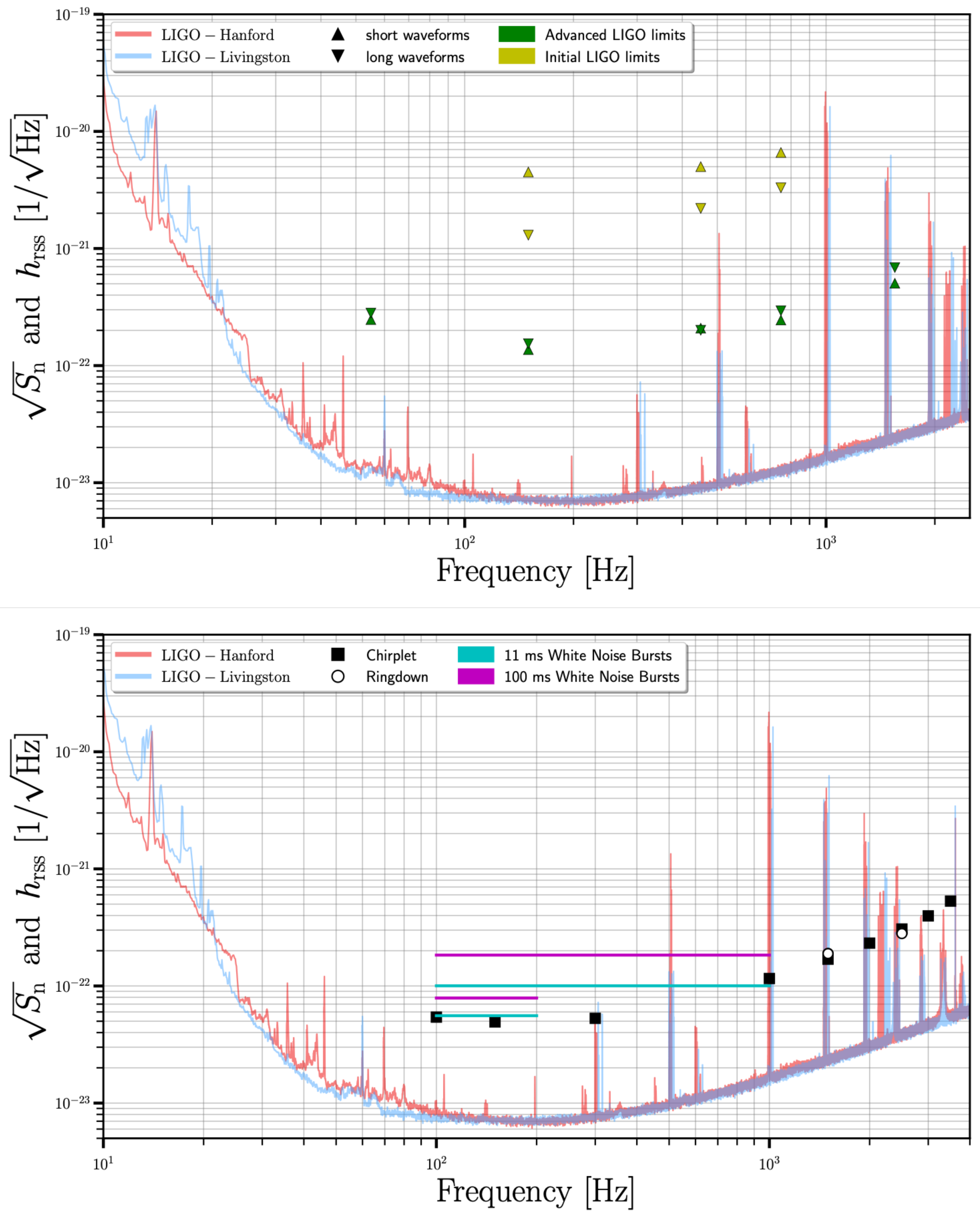


Figure 3. Upper limits for the the intermediate-duration search (above) and short-duration search (below), along with the sensitivity of the detectors. We plot h_{rss} at 90% detection efficiency for the intermediate-duration search here to allow direct comparison to published figures for the previous search in initial LIGO (Quitzow-James et al. 2017). Short-duration limits are for 50% efficiency as before. The advanced LIGO search limits are for the February 25 burst from SGR 1806-20 during the second observing run, and detector sensitivity is calculated from data during the analysis window.

Source: B. P. Abbott et al 2019 ApJ 874 163

Energy Upper Limit vs Distance

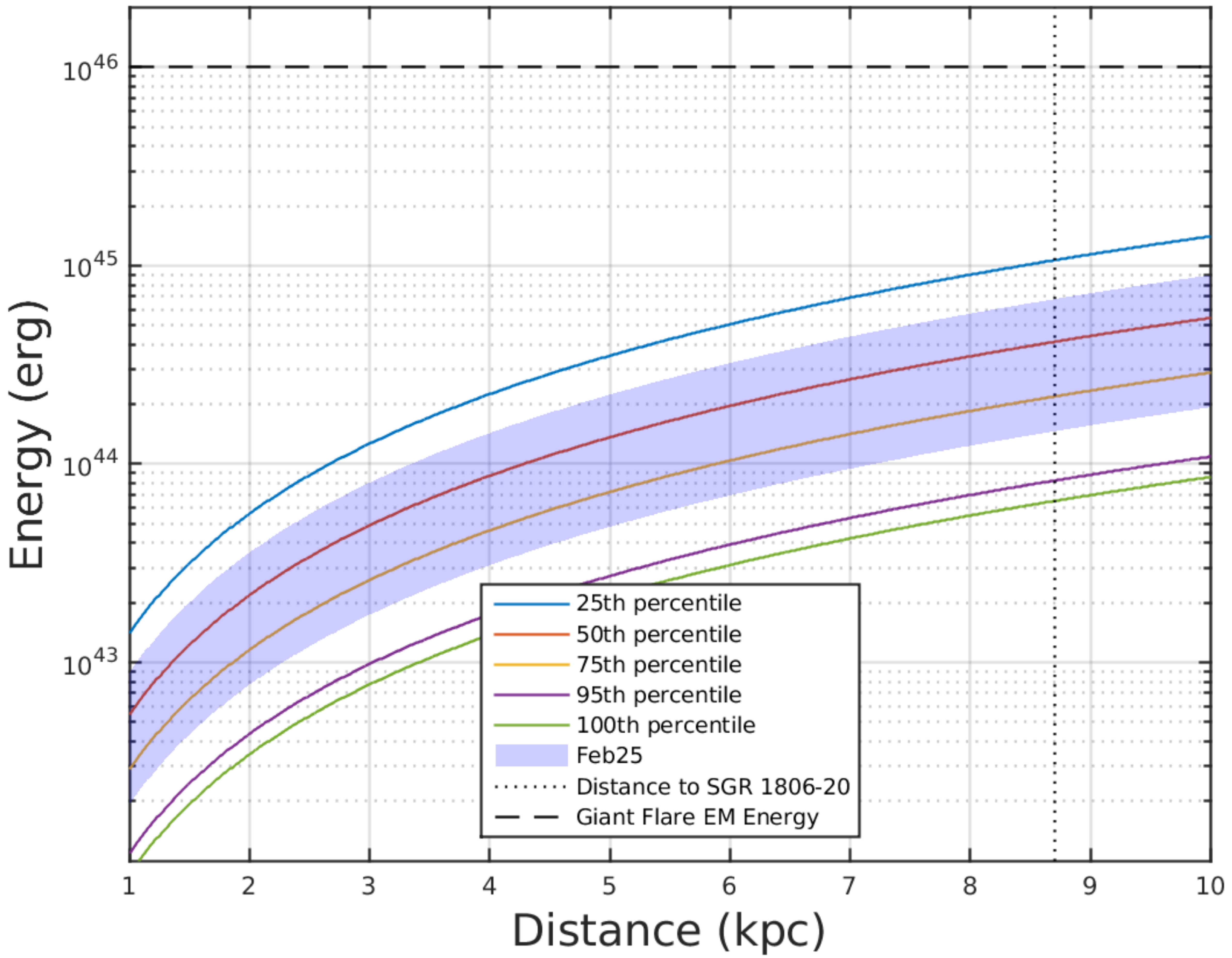


Figure 4. Minimum detectable energy for the intermediate duration search vs distance for SGR 1806-20 for varied sky locations and GW polarizations at 55 Hz. The lines show how the variation in sky position (caused by the earth's rotation) and polarization (assumed to be random) affects the sensitivity; the purple 95^{th} percentile line indicates that the network sensitivity will be better than indicated by that line only 5% of the time. The shaded region indicates the sensitivity to GW energy from the burst on February 25. Here, the uncertainty is only due to the unknown polarization.

Source: B. P. Abbott et al 2019 ApJ 874 163

Search Outlook for O3

- **Thirteen magnetar bursts:**
  - Following up six short bursts with the LIGO detectors
  - Following up seven additional bursts with LIGO and Virgo detectors
- Includes magnetar **discovered in 2020** and magnetar which **emitted the fast radio burst**

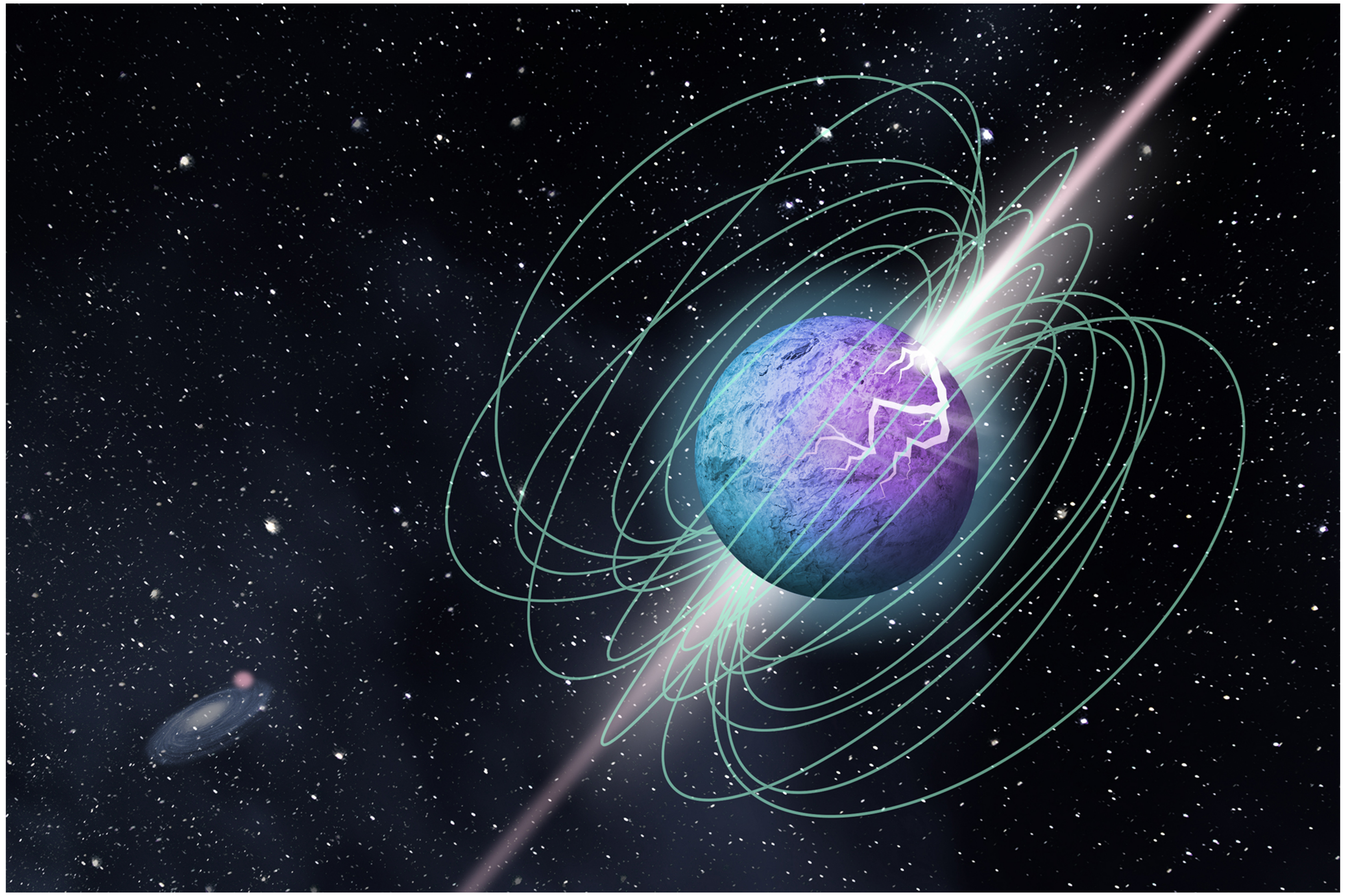


Image: McGill University Graphic Design Team

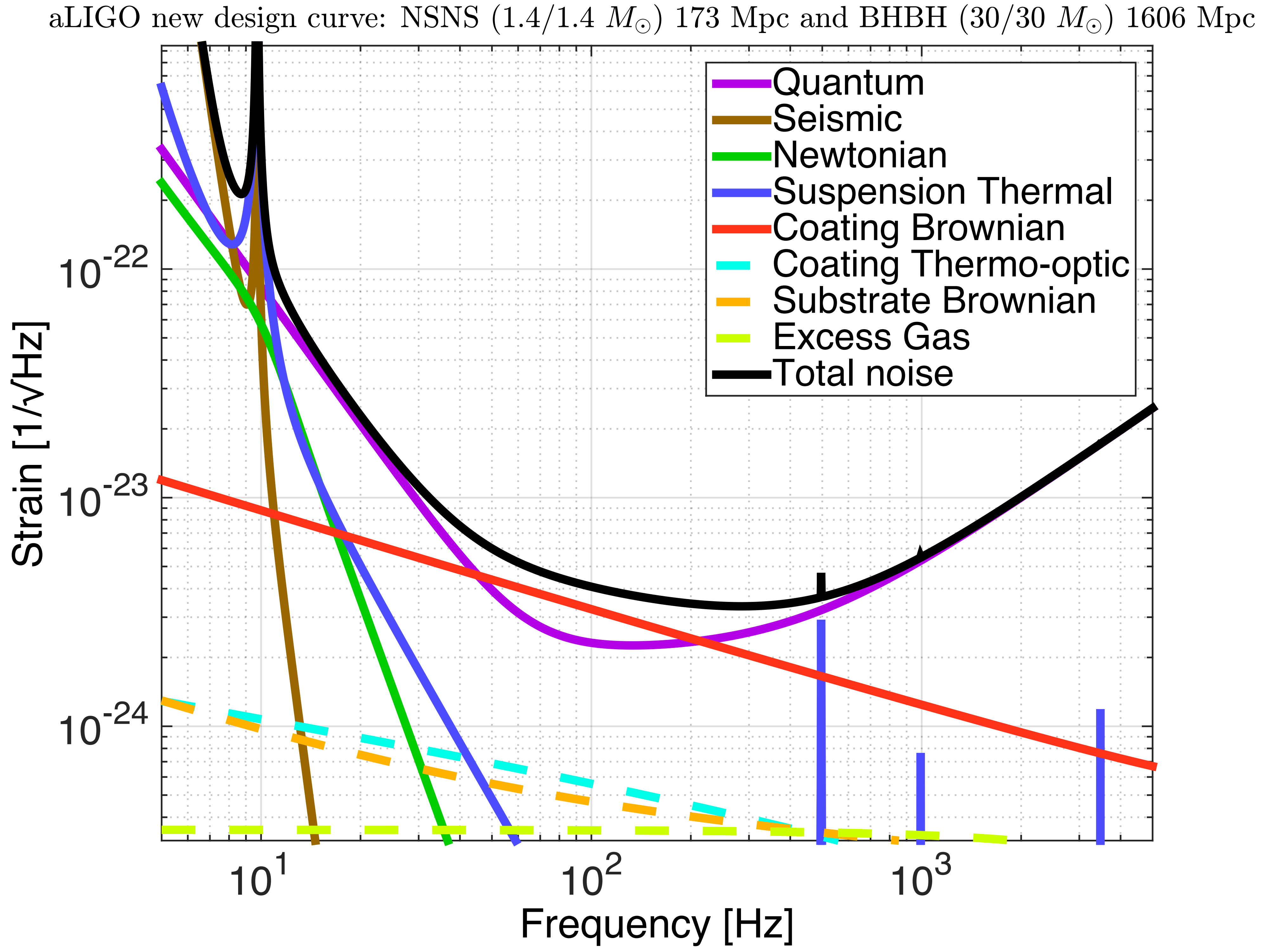
EM Energy of bursts in O3

- Two bursts from new magnetar detected in March 2020 (Swift J1818.0-1607)
    - EM energy up to order 10^{37} erg
- Remaining bursts from the magnetar that emitted FRB (SGR 1935+2154)
    - At least one burst has EM energy of order 10^{38} erg
- Simulation paper estimates 10^{44} erg EM energy could give f-mode GW energy of ~10^{38} erg — Zink, Lasky, and Kokkotas, Phys. Rev. D 85, 024030 (2012)
    - Also suggests that if lower frequency modes last long enough (~100 s), they may reach energies detectable by aLIGO or Einstein telescope for giant flares

Estimated Sensitivities for O2-like Bursts in O3 and O4

- Comparison waveforms:
  - Half sine-Gaussian at 150 Hz
  - Ringdown at 1500 Hz
- O3 sensitivity estimated from A. Buikema et al., Phys. Rev. D 102, 062003 (2020)

	Half sine-Gaussian	E_{GW} (erg)	Ringdown	E_{GW} (erg)
O2	1.14E-22	3.4E+44	1.89E-22	2.25E+47
O3	~8E-23	~2E+44	~1E-22	~1E+47
O4 (aLIGO design)	~6E-23	~1E+44	~7E-23	~3E+46



https://dcc.ligo.org/LIGO-T1800044/public

Future (3rd Generation) Detectors are Being Designed!

Einstein Telescope

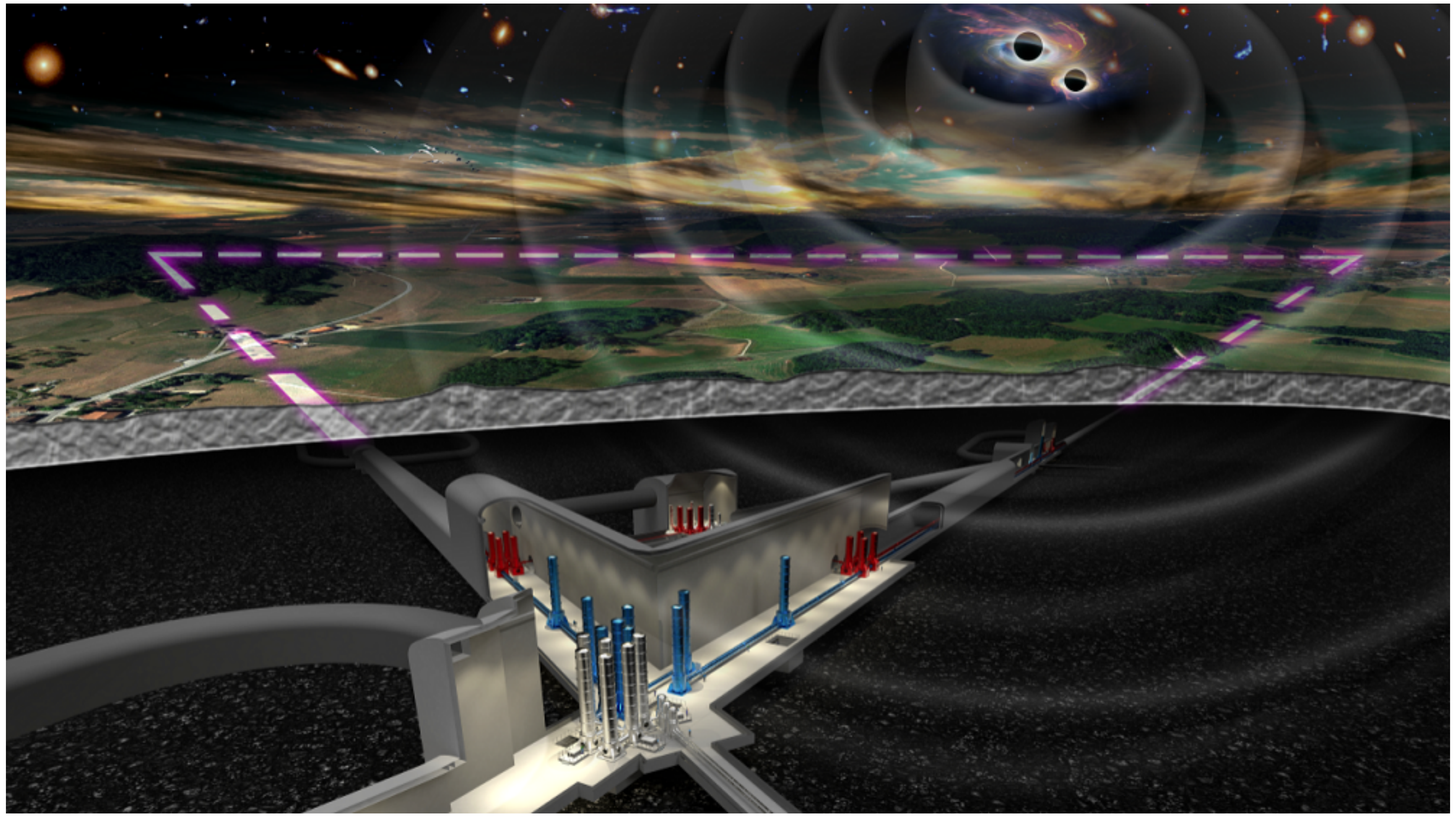


Image source and website: https://www.et-gw.eu/

Cosmic Explorer

https://cosmicexplorer.org

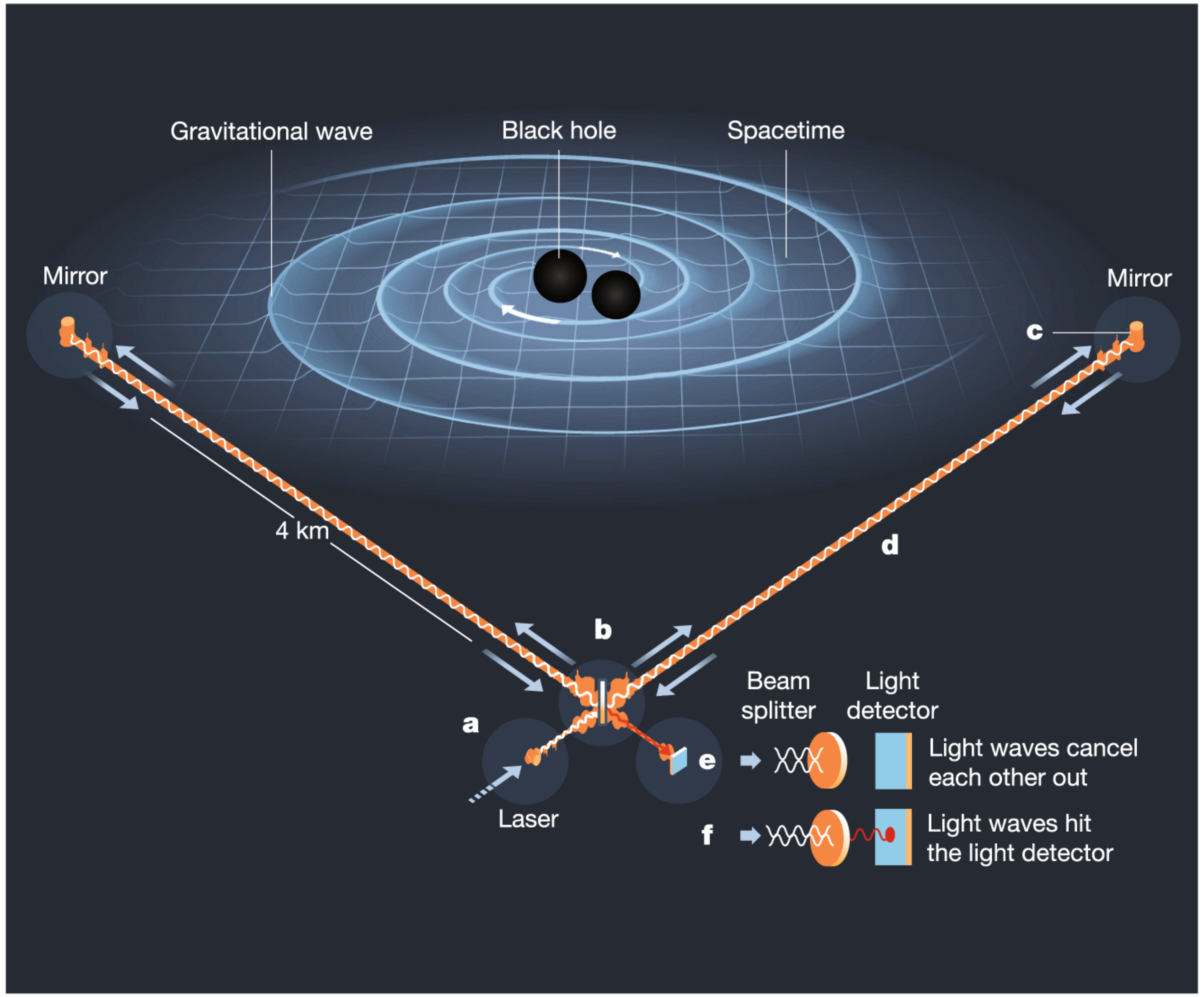
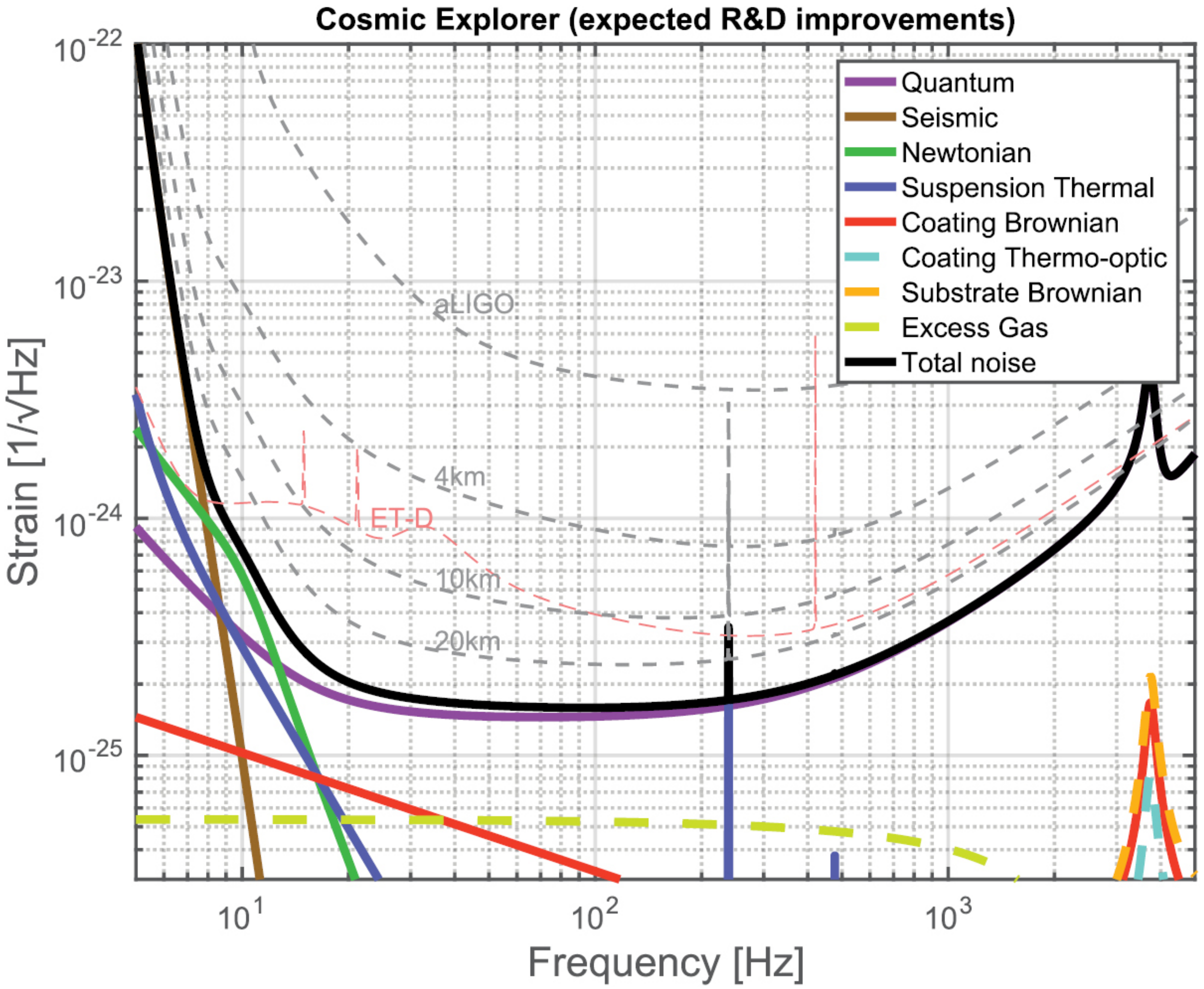


Image: Miller, M.C., Yunes, N. Nature 568, 469–476 (2019).

Estimated Sensitivities for 3rd Generation Detectors

- Comparison waveforms:
  - Half sine-Gaussian at 150 Hz
  - Ringdown at 1500 Hz

	Half sine-Gaussian	E_{GW} (erg)	Ringdown	E_{GW} (erg)
O2	1.14E-22	3.4E+44	1.89E-22	2.25E+47
Einstein Telescope (ET-D)	~6E-24	~1E+42	~8E-24	~4E+44
Cosmic Explorer	~3E-24	~2E+41	~5E-24	~2E+44



B P Abbott et al 2017 Class. Quantum Grav. 34 044001

Summary

1. Magnetars are potentially interesting candidates for searching for GWs

2. Thirteen bursts with identified source objects occurred when O3 data was available

3. Sensitivity to magnetar bursts in the galaxy comparable to giant flare EM energy and below hyper flare EM energy

4. Expect search sensitivity to improve as detectors increase sensitivity

I gratefully acknowledge the human and material resources of the LIGO Scientific Collaboration and the Virgo Collaboration that have made possible the results presented in this talk, and the National Science Foundation for its continuous support of LIGO science. I am grateful for computational resources provided by the LIGO Laboratory and supported by National Science Foundation Grants PHY-0757058 and PHY-0823459. This work has been supported by NSF grants PHY-1921006 and PHY-2011334.

I thank all the essential workers who put their health at risk during the COVID-19 pandemic, without whom we would not have been able to complete this work.

Thank you!