Title: Hypermassive neutron stars: from numerical relativity simulations to gamma-ray data

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Series: Strong Gravity

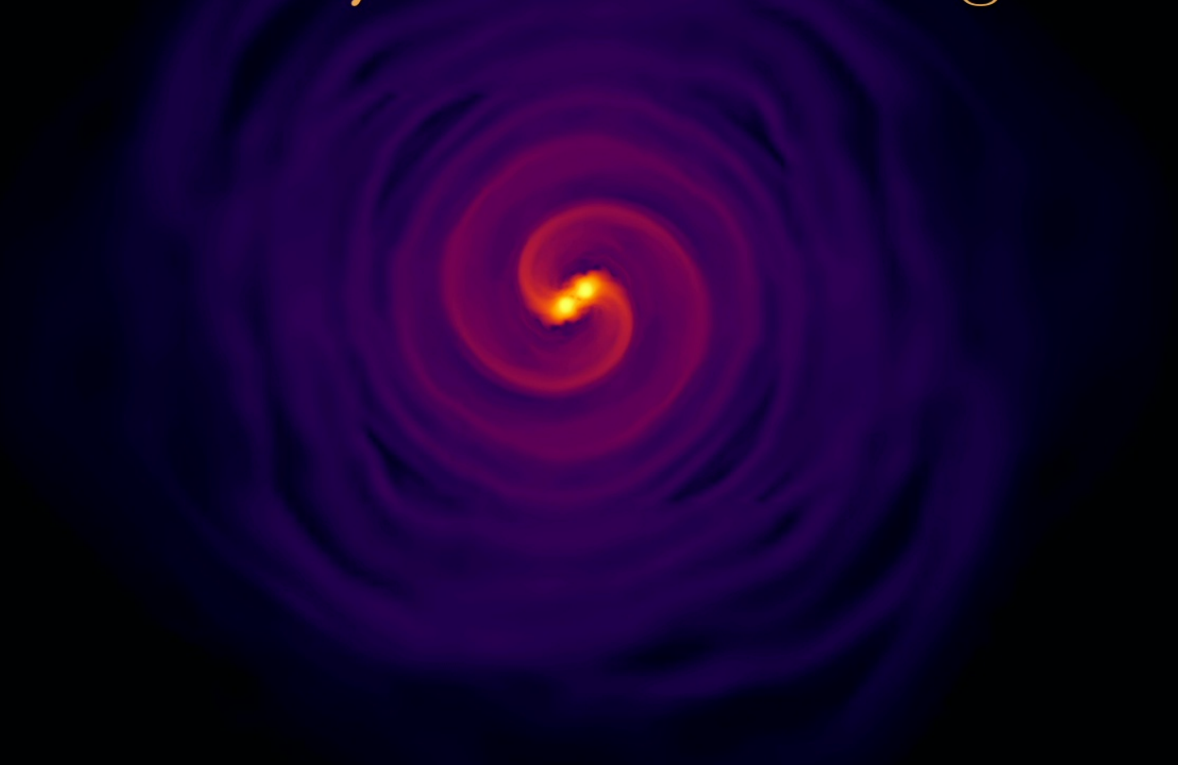
Date: March 09, 2023 - 1:00 PM

URL: https://pirsa.org/23020029

Abstract: Gamma ray bursts (GRBs) are the most luminous electromagnetic events in the universe. Short GRBs, typically lasting less than 2 seconds, have already been associated with binary neutron star (BNS) mergers, which are also sources of gravitational waves (GWs). The ultimate fate of a BNS, after coalescence, is usually expected to be a black hole (BH) with 2-3 solar masses. However, numerical relativity simulations indicate the possible formation of a short-lived hypermassive neutron star (HMNS), lasting for tens to hundreds of milliseconds after the BNS merger and before gravitational collapse forms a BH. The HMNS is expected to emit GWs with kHz frequencies that will be detectable by third generation ground-based GW detectors in the 2030s. I will present results from a recent analysis that revealed evidence for HMNSs by looking for kHz quasiperiodic oscillations in gamma-ray observations obtained in the 1990s with the Compton Gamma Ray Observatory.

Zoom link: https://pitp.zoom.us/j/96687956901?pwd=MkgrUGlqY3IyRCs2bXJYVkhUVEpPZz09

Hypermassive neutron stars: from numerical relativity simulations to gamma-ray data



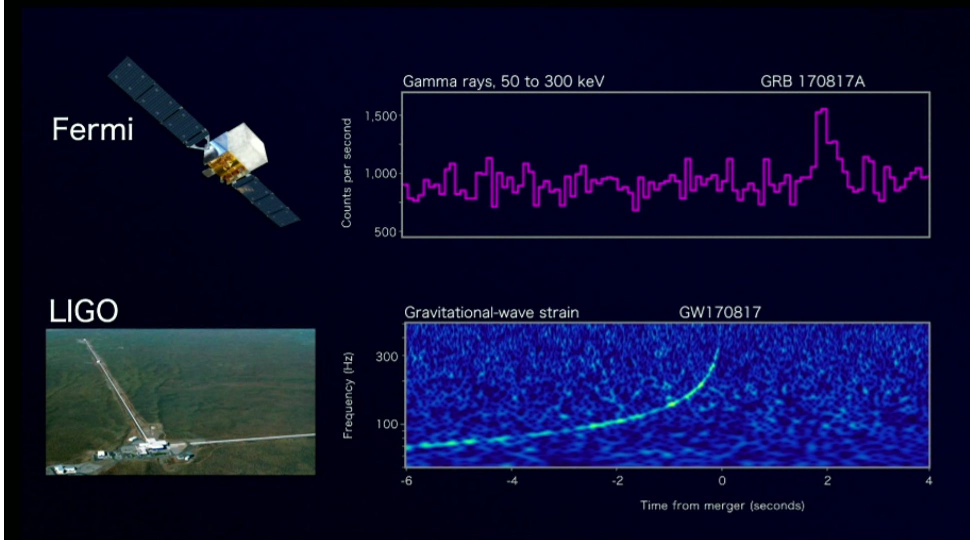
Cecilia Chirenti

On behalf of co-authors: Simone Dichiara, Amy Lien, Cole Miller and Rob Preece

Strong Gravity Seminar - Perimeter Institute - March 9 2023

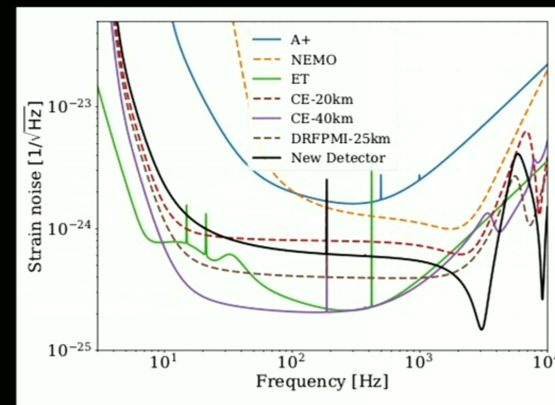
Between the "*whoop*" and the "*ding*"…

Binary neutron star merger

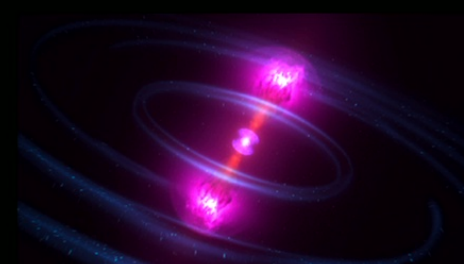


→ **GRB**
ding!

→ **GWs**
whoop!



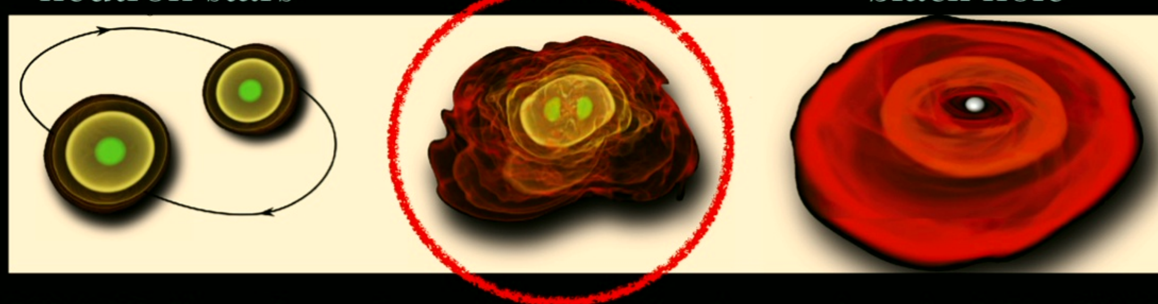
Zhang, Yang et al. 2022



When is the GRB launched?

… a hypermassive neutron star?

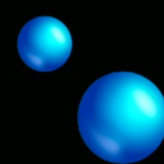
neutron stars HMNS black hole



HMNS lives for < 1s, spins fast, jiggles and emits kHz GWs
too high for current GW detectors!

From simulations:

heavier 20% more mass than the heaviest known pulsar: J0740+6620



bigger 2 times the size of a typical NS

An HMNS can be heavier than a normal NS **because** of its fast spin!

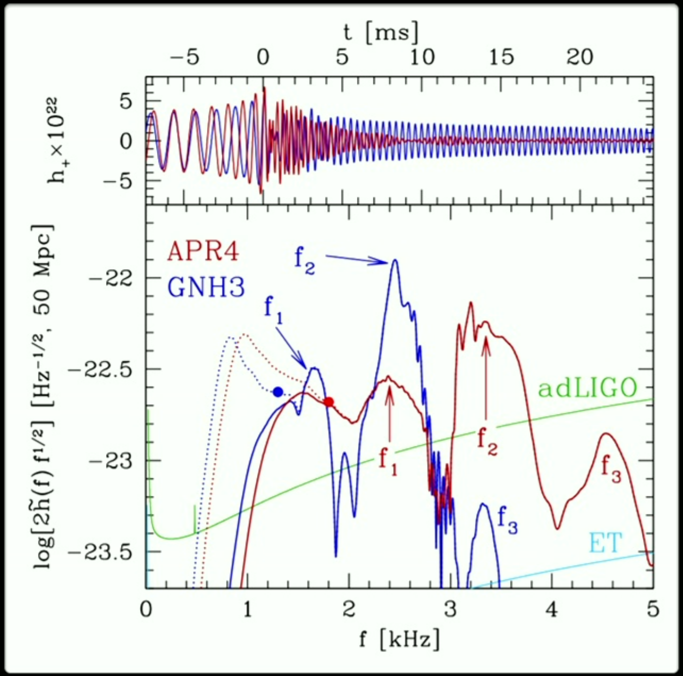
HMNS Quasi-periodic oscillations

HMNS signal:

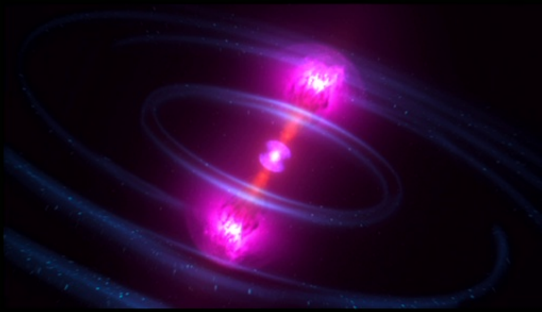
short-lived
time-evolving
dissipative*

⇓

quasi-periodic oscillations
(QPOs)



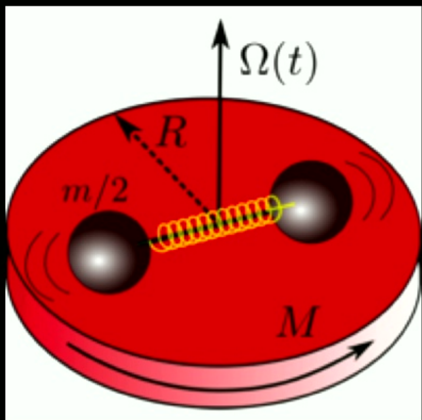
Takami, Rezzolla & Baiotti, 2014



Could the
GRB show
these QPOs?

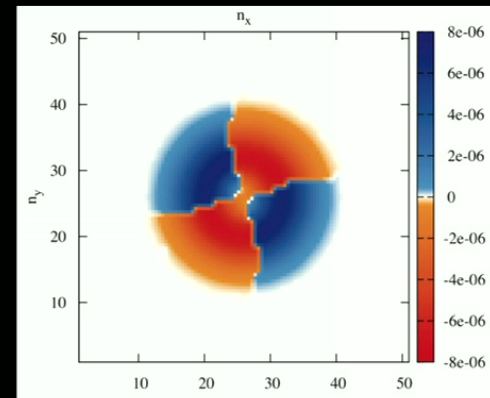
*simulations also have numerical dissipation!

GRB QPOs?

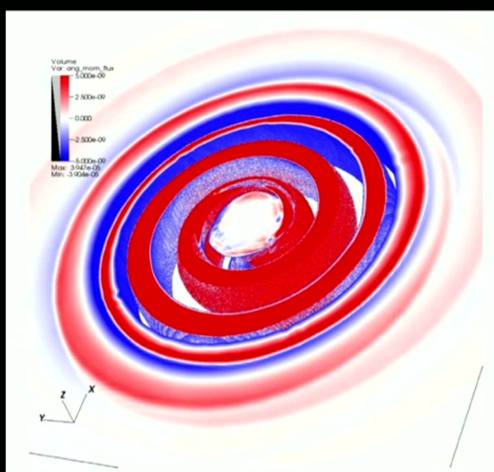


Takami, Rezzolla & Baiotti, 2015

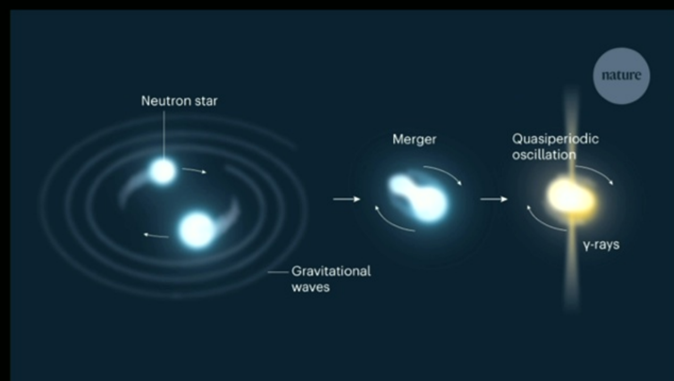
How does the HMNS oscillate?



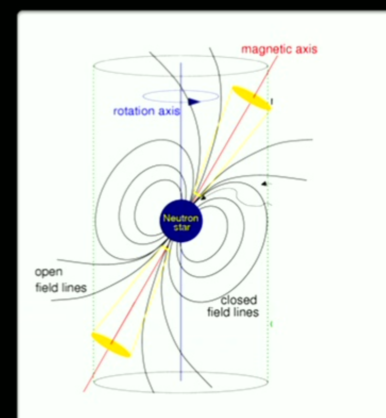
Stergioulas et al. 2011



Nedora et al. 2019



How (and when) could the oscillations transmitted to the GRB?



adapted from Lorimer & Kramer, 2004

What we are looking for:

Oscillations that

* last for approx 100 ms (lifetime of an HMNS)
* have frequencies in the range 500 – 5,000 Hz

$$n_\sigma = \frac{1}{2} I a_{\rm osc} \sqrt{\frac{\Delta t}{\Delta f}}$$

How: Bayesian model comparison

Model I: White noise only

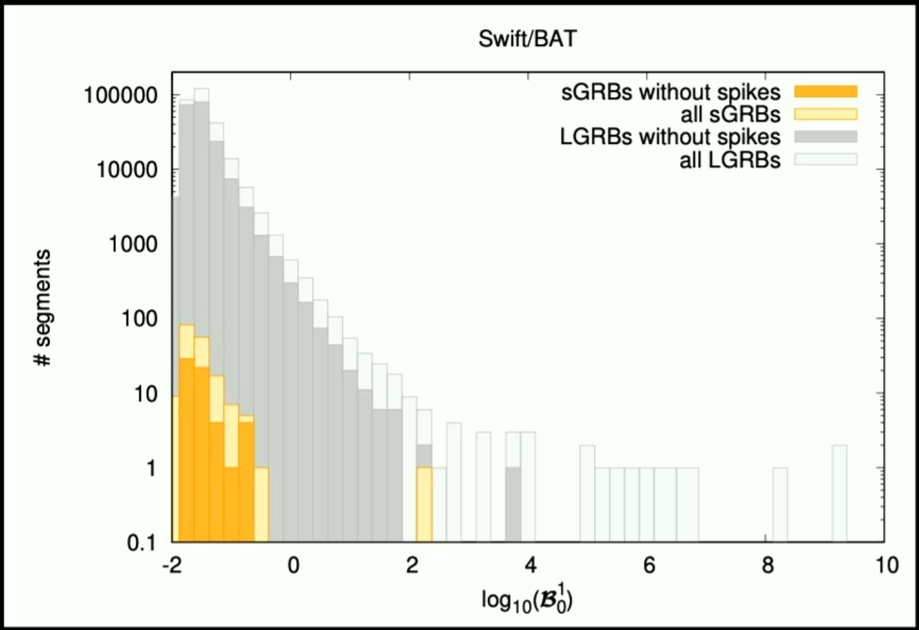
Model II: White noise + QPO

We analyze each burst divided into short segments and quote the Bayes factor in favor of the noise + QPO model for each segment

half-overlapping segments
(approx 100 ms)

total burst duration

Initial analyses: Lessons learned



Causes of fake QPOs

Cosmic rays

Detector artifacts*

(Data corruption)

Red noise contamination

*https://swift.gsfc.nasa.gov/analysis/bat_digest.html#spurious-signal

CGRO transforms GRB science

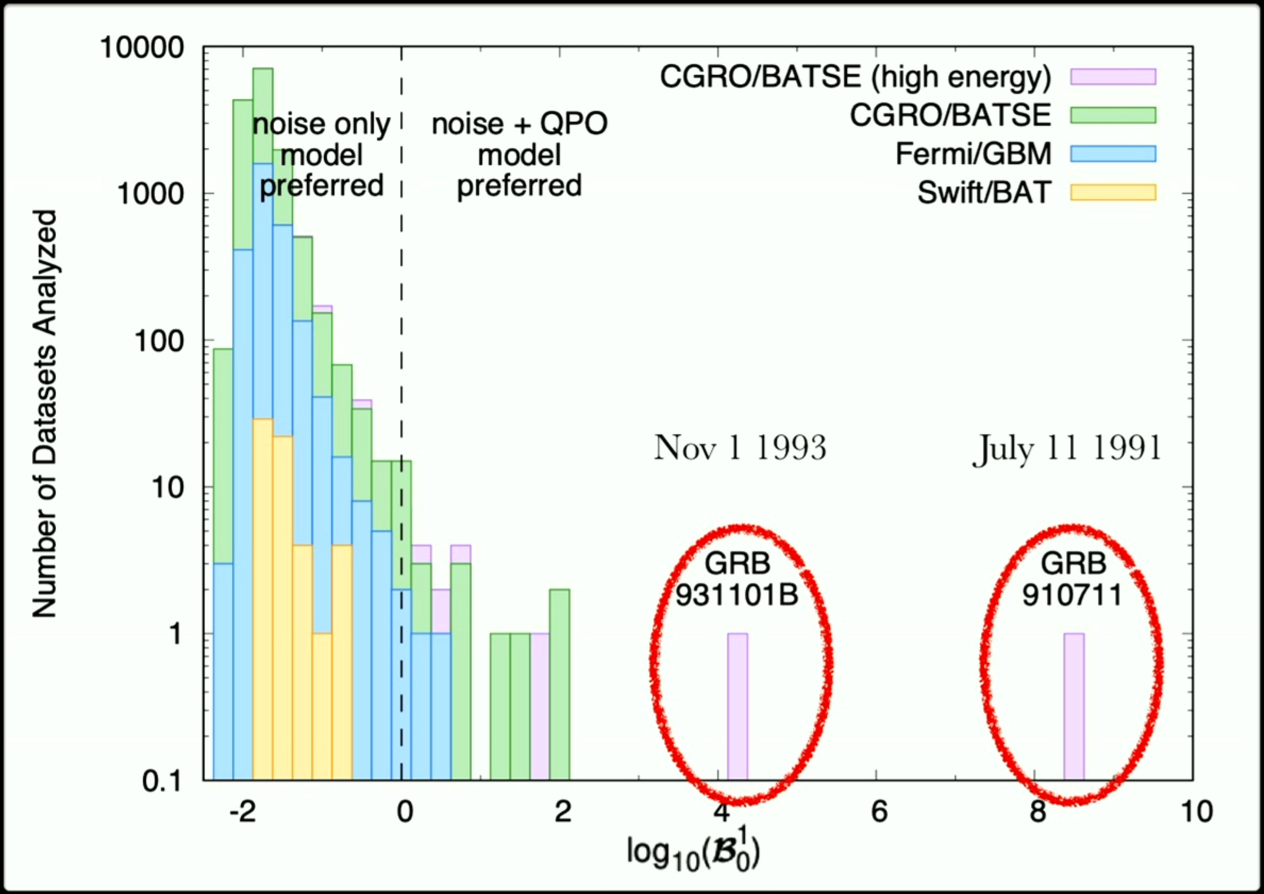
Launched in 1991
De-orbited in 2000

Over 2,700 GRBs detected

Compton Gamma-Ray Observatory
was one of NASA's Great Observatories

Astronaut Jerry Ross had to whack the antenna in space to release it.

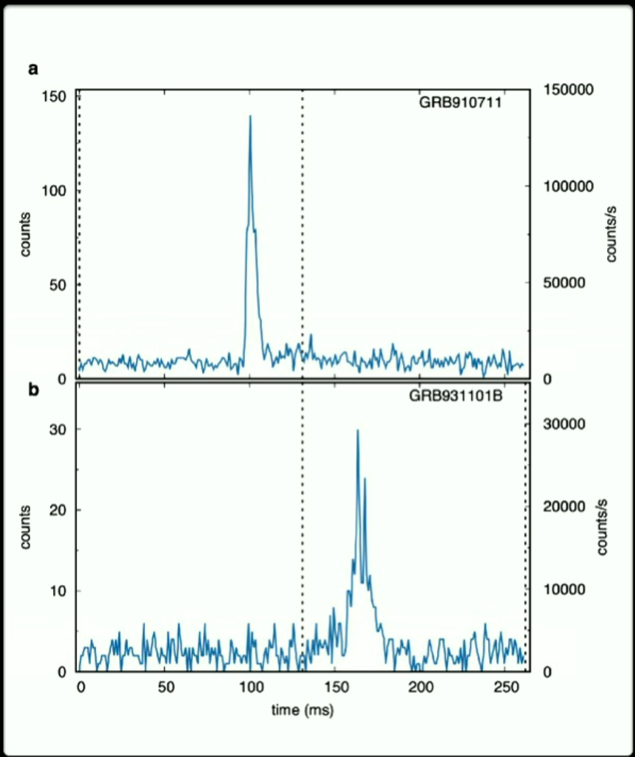
Opening the treasure trove

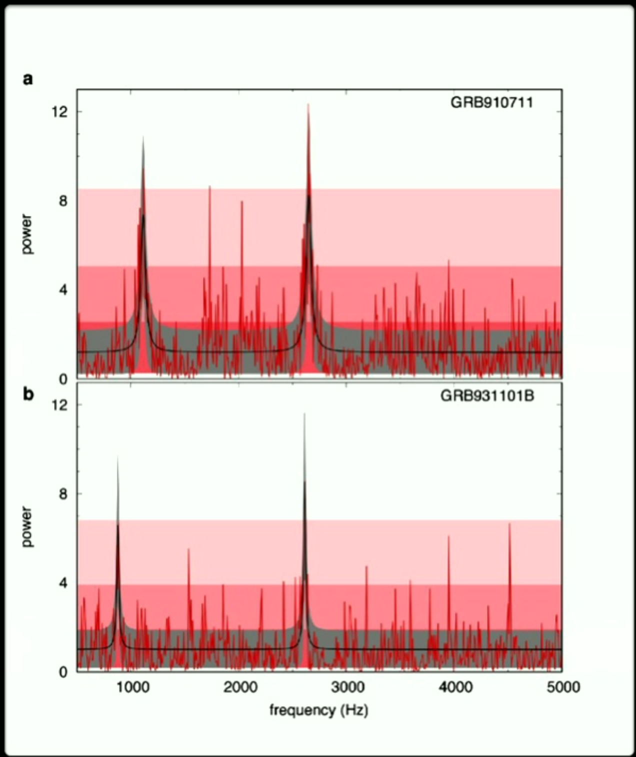


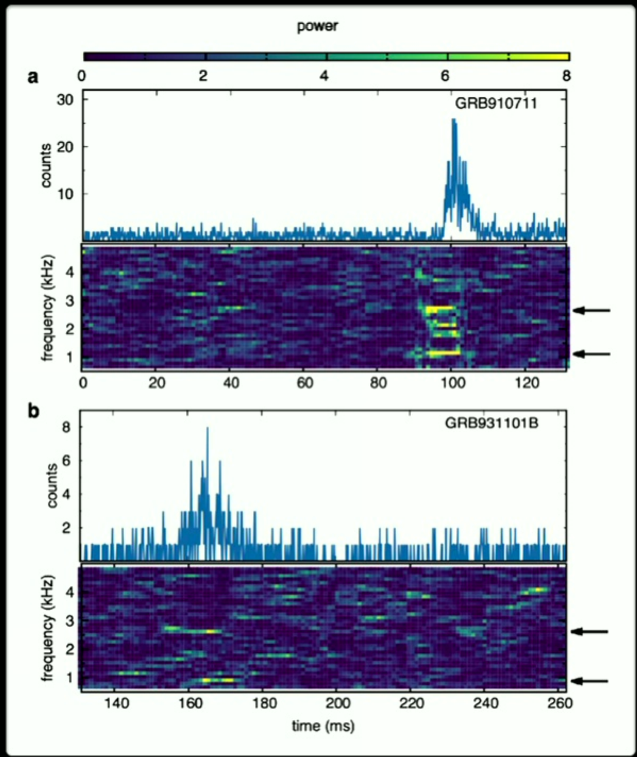
… and **bang**! Two signals. The combined false positive rate is 1 in 3.3 million!

Both signals have:
2 QPOs each
with similar frequencies
and good agreement with
simulations

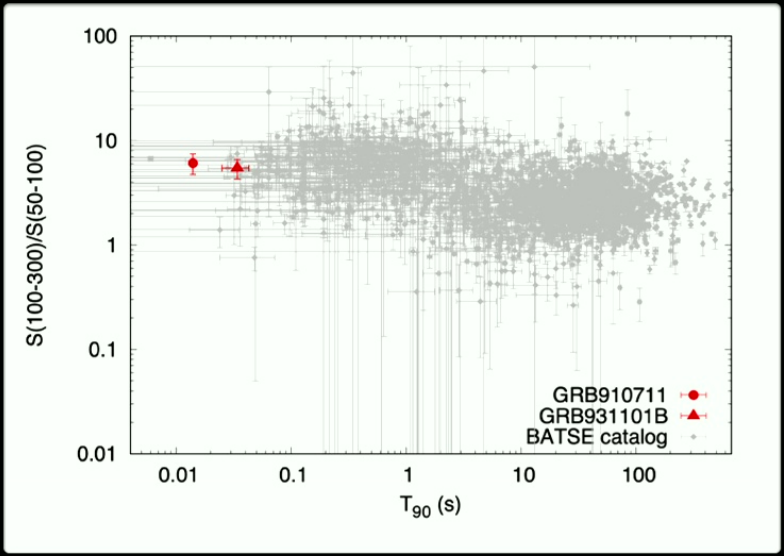
Light curves and power spectra

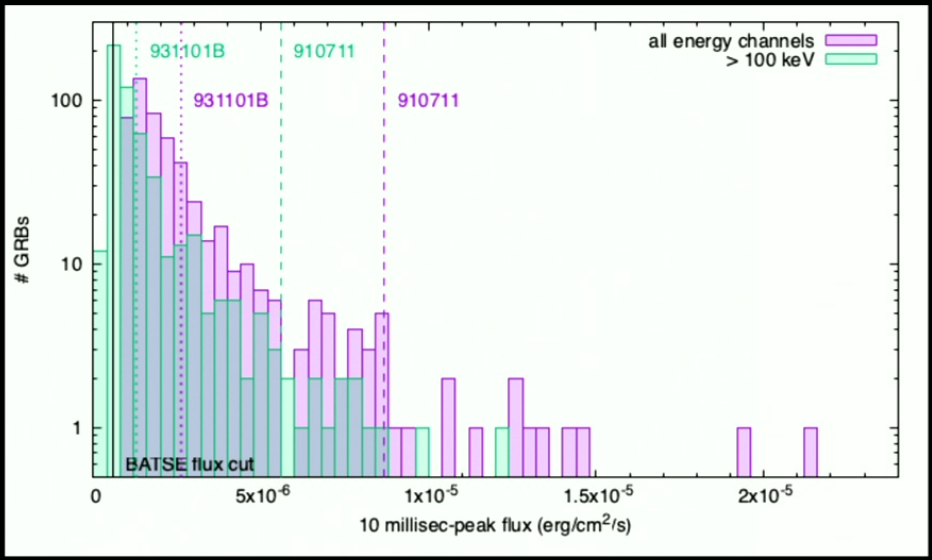






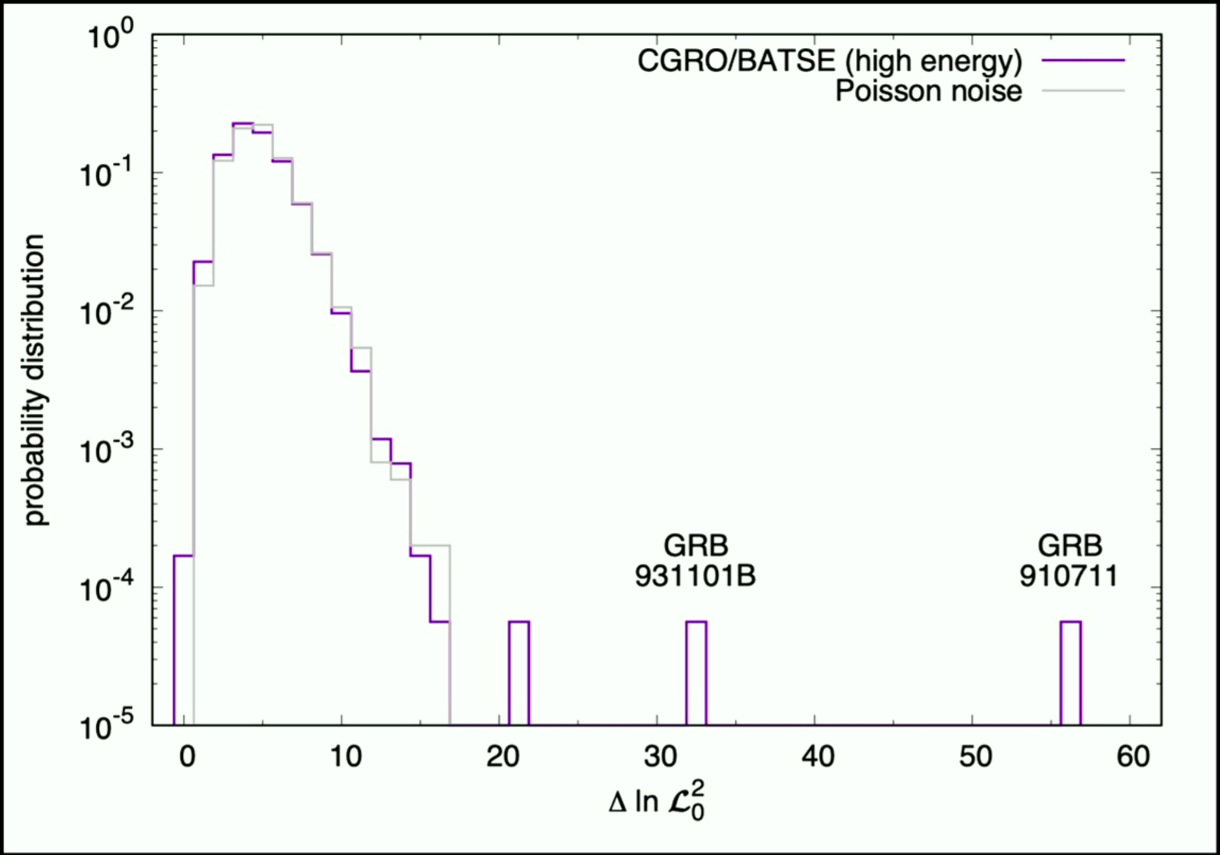
BATSE GRB distribution



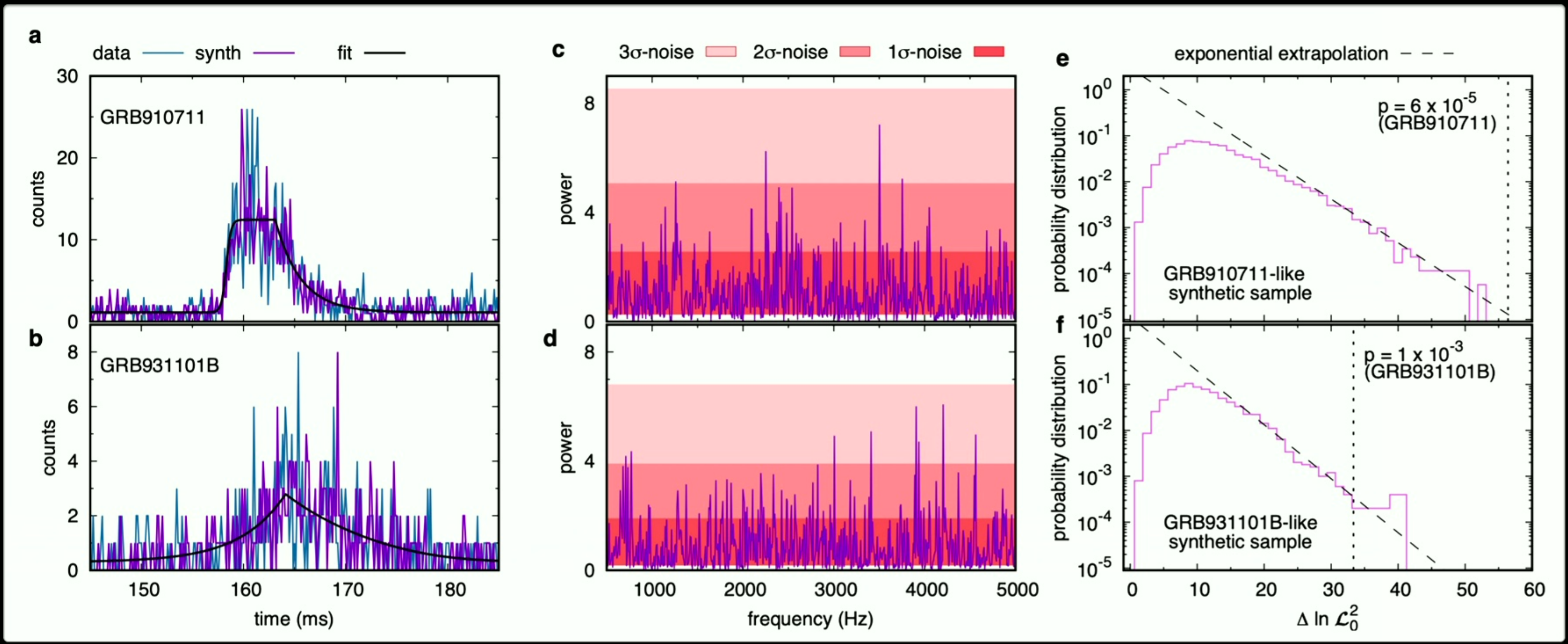


How special are these bursts?

False positive estimate I



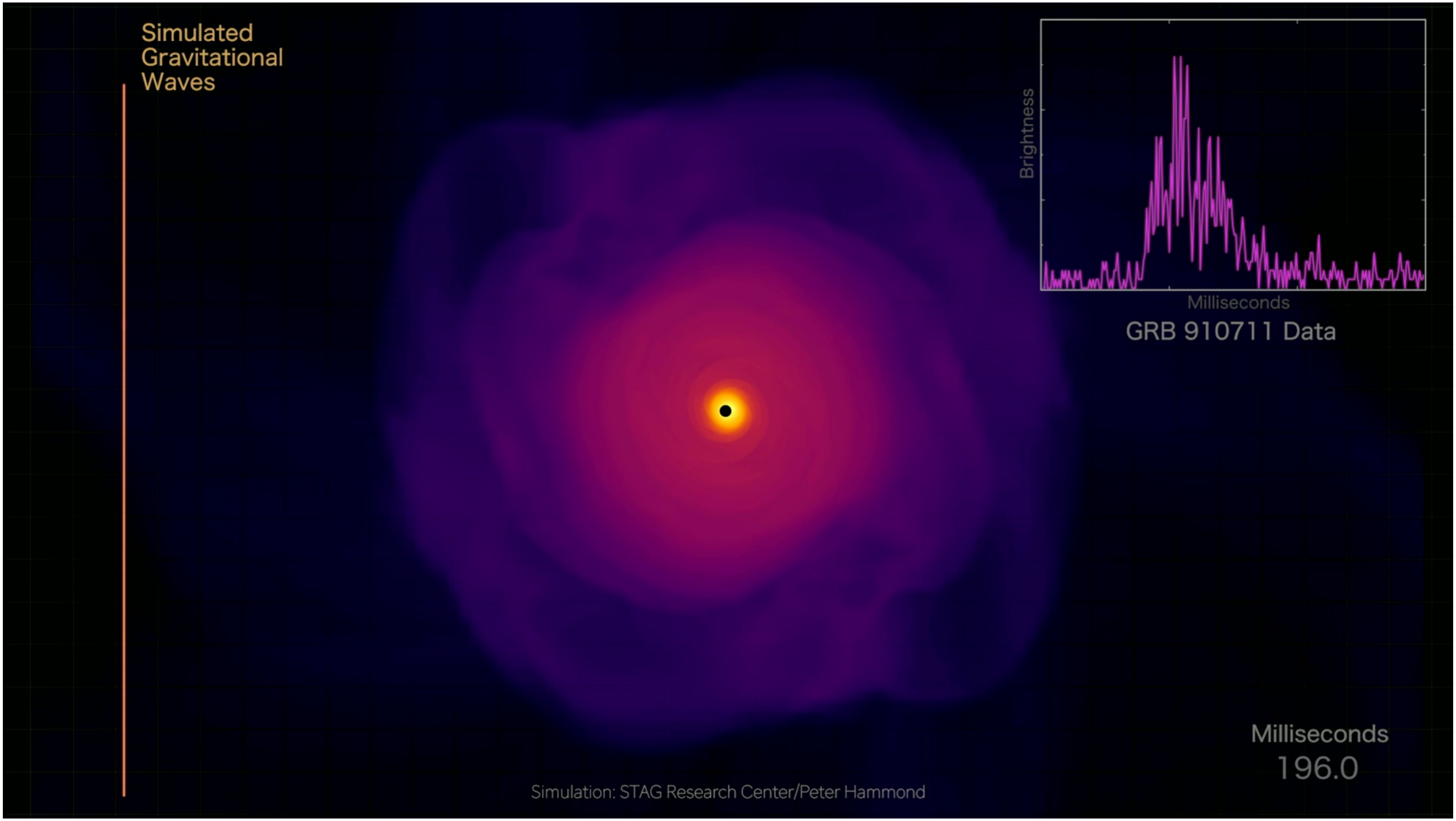
False positive estimate II

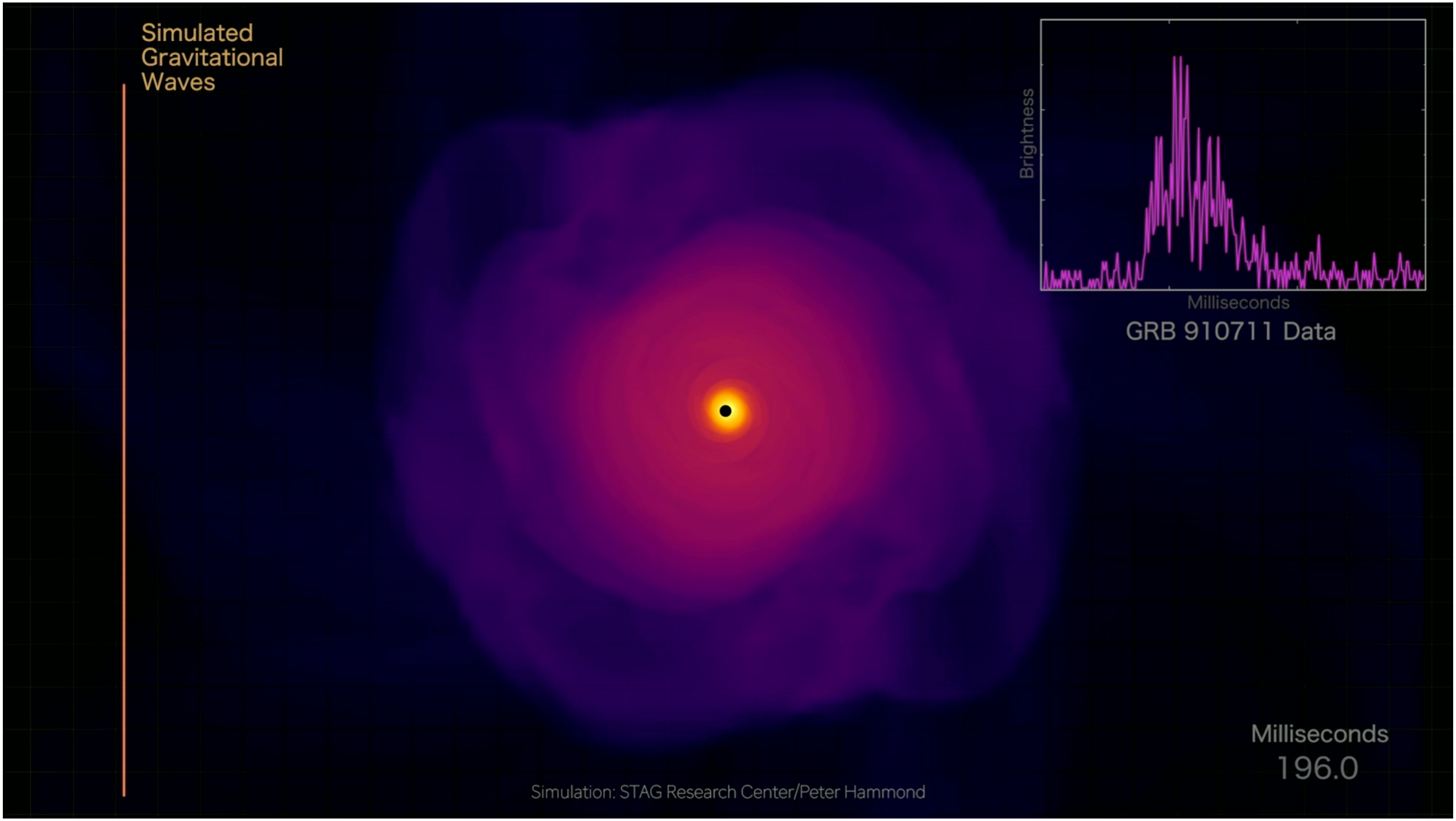


False positive estimate III

GRB	Trigger #	T_{90} (ms)	Counts	Prob($\Delta \ln \mathcal{L}_0^2 > 56.4$)	Prob($\Delta \ln \mathcal{L}_0^2 > 33.3$)
910711	512	14	1790	5.9×10^{-5}	9.2×10^{-3}
910508	207	30	1254	2.2×10^{-6}	1.6×10^{-3}
931101B	2615	34	524	2.6×10^{-6}	1.3×10^{-3}
910625	432	50	1810	7.2×10^{-7}	9.3×10^{-4}
910703	480	62	2278	1.8×10^{-7}	7.5×10^{-4}
940621C	3037	66	710	2.0×10^{-10}	7.9×10^{-6}
930113C	2132	90	612	4.1×10^{-11}	2.9×10^{-6}

The combined false positive probability is $\sim 3 \times 10^{-7}$


Simulated
Gravitational
Waves
Brightness
Milliseconds
GRB 910711 Data
Milliseconds
196.0
Simulation: STAG Research Center/Peter Hammond


Simulated
Gravitational
Waves
Brightness
Milliseconds
GRB 910711 Data
Milliseconds
196.0
Simulation: STAG Research Center/Peter Hammond

A record-breaking neutron star

These signals are consistent with an HMNS:

QPO 1 High frequency!
~ 1kHz
lower amplitude

QPO 2 *Higher* frequency!
~ 2.6 kHz, higher amplitude
info on NS composition

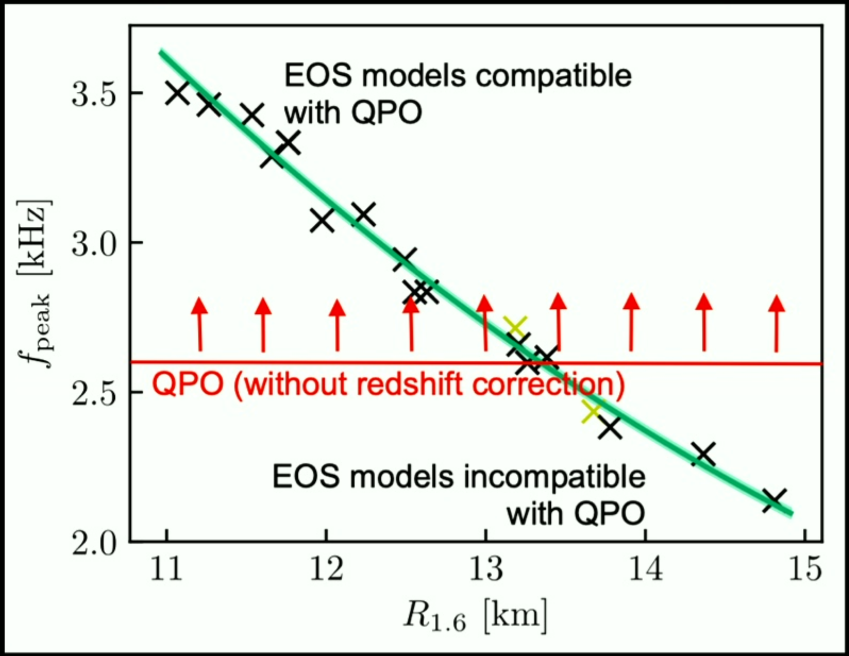
Compared with other NSs, the HMNS is:

faster 1.3 kHz, almost 2 times the spin of the fastest known pulsar: J1748−2446ad

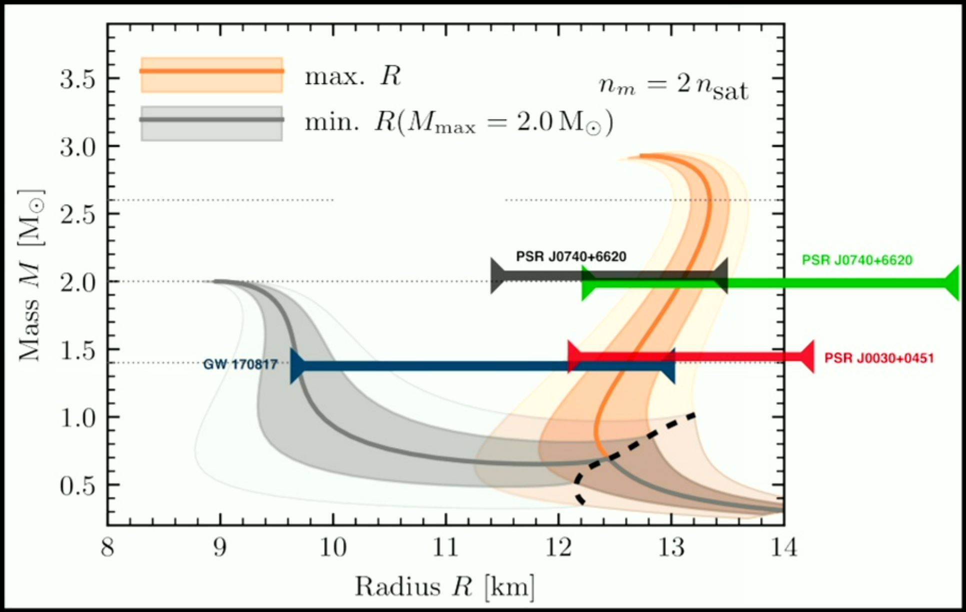
forms a black hole 10 times faster than the blink of an eye: signals last for only 10 millisecs

Learning about the neutron star equation of state

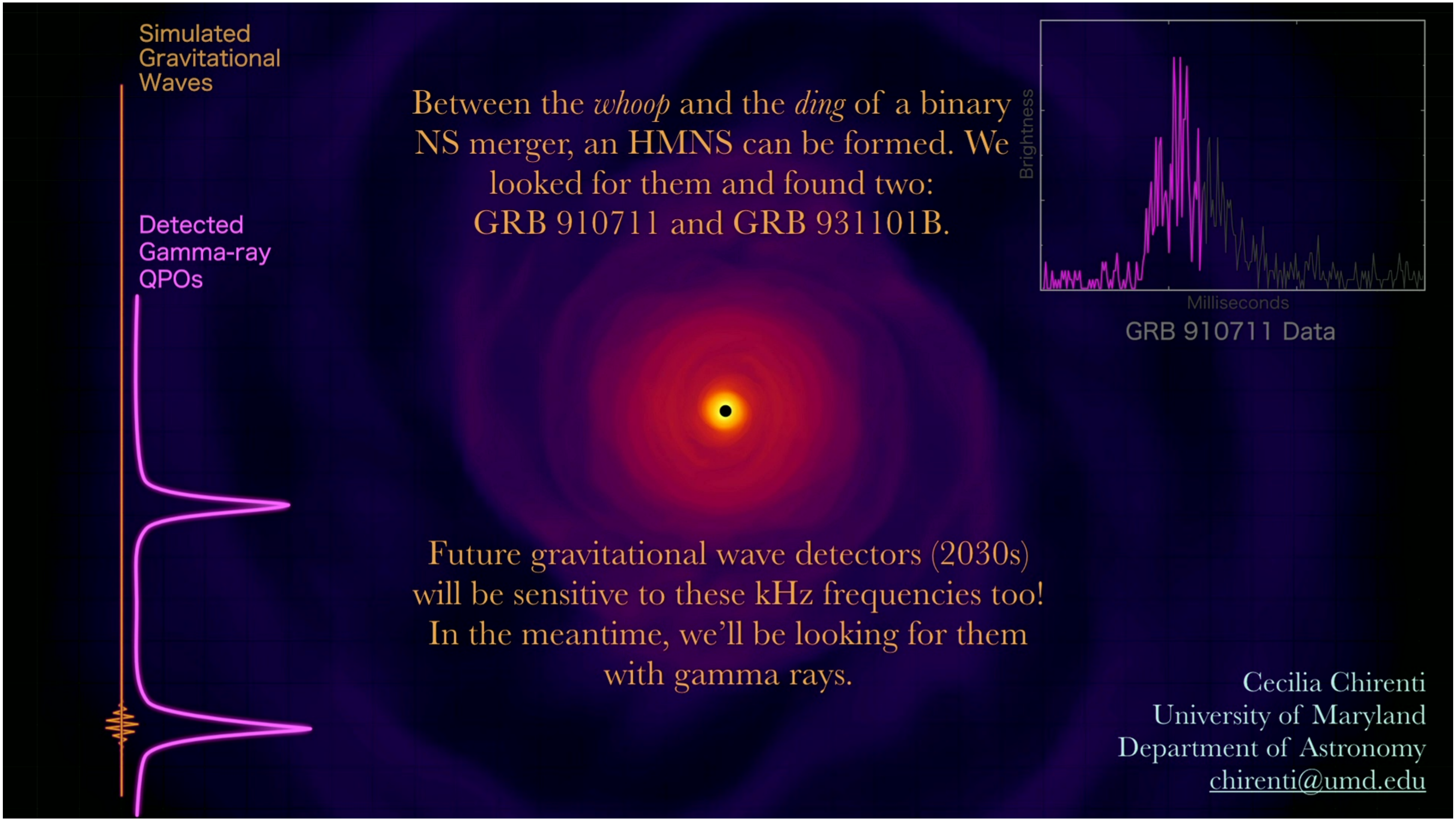
QPOs + Numerical Relativity



LIGO + NICER



S. Reddy, 2021


Simulated Gravitational Waves
Detected Gamma-ray QPOs
Between the *whoop* and the *ding* of a binary NS merger, an HMNS can be formed. We looked for them and found two: GRB 910711 and GRB 931101B.
Brightness
Milliseconds
GRB 910711 Data
Future gravitational wave detectors (2030s) will be sensitive to these kHz frequencies too! In the meantime, we'll be looking for them with gamma rays.
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