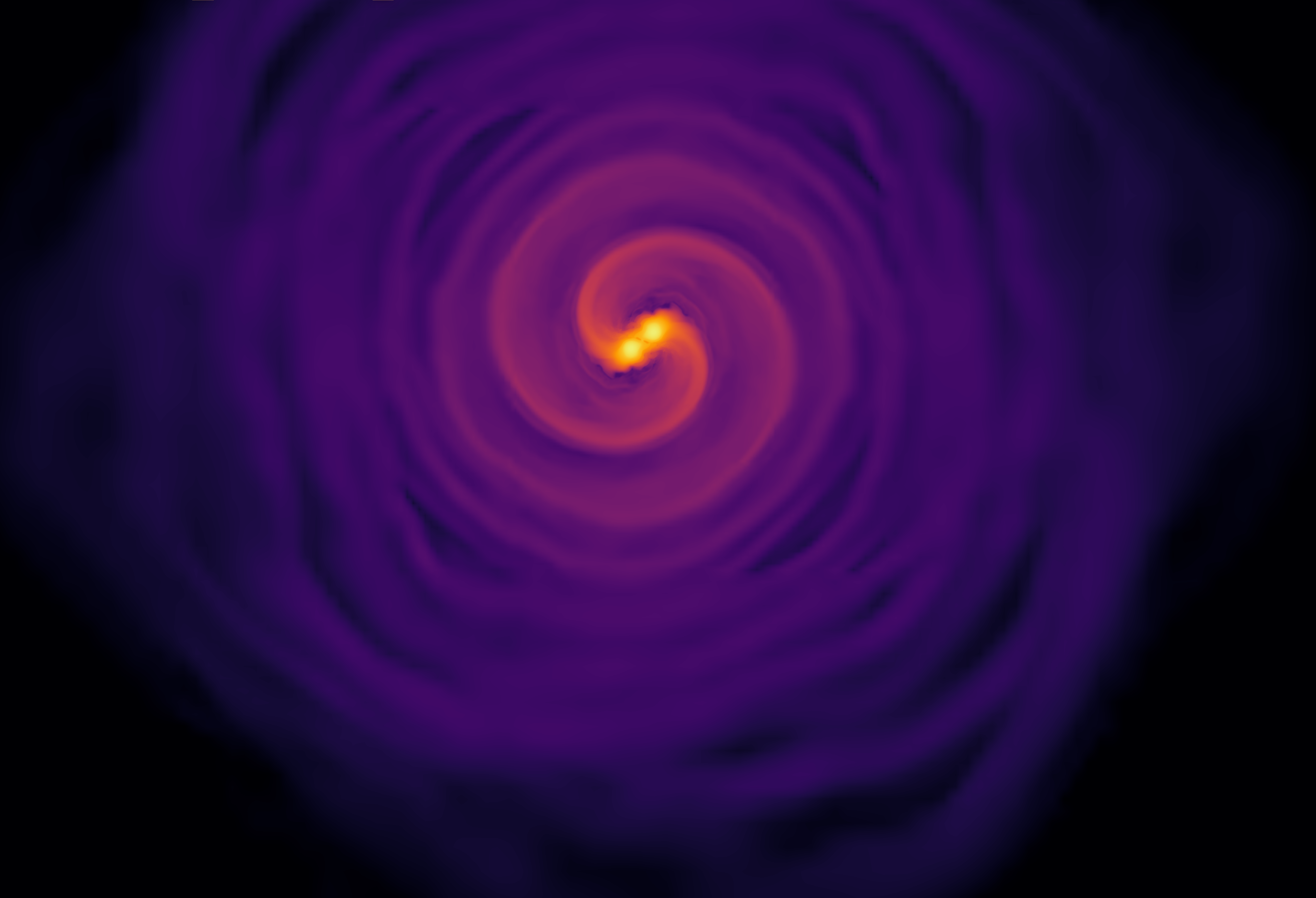
Constraining the Neutron Star EOS with quasiperiodic oscillations from short GRBs



Cecilia Chirenti

[Nature **613** 253 (2023)]

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

Partner

UFABC

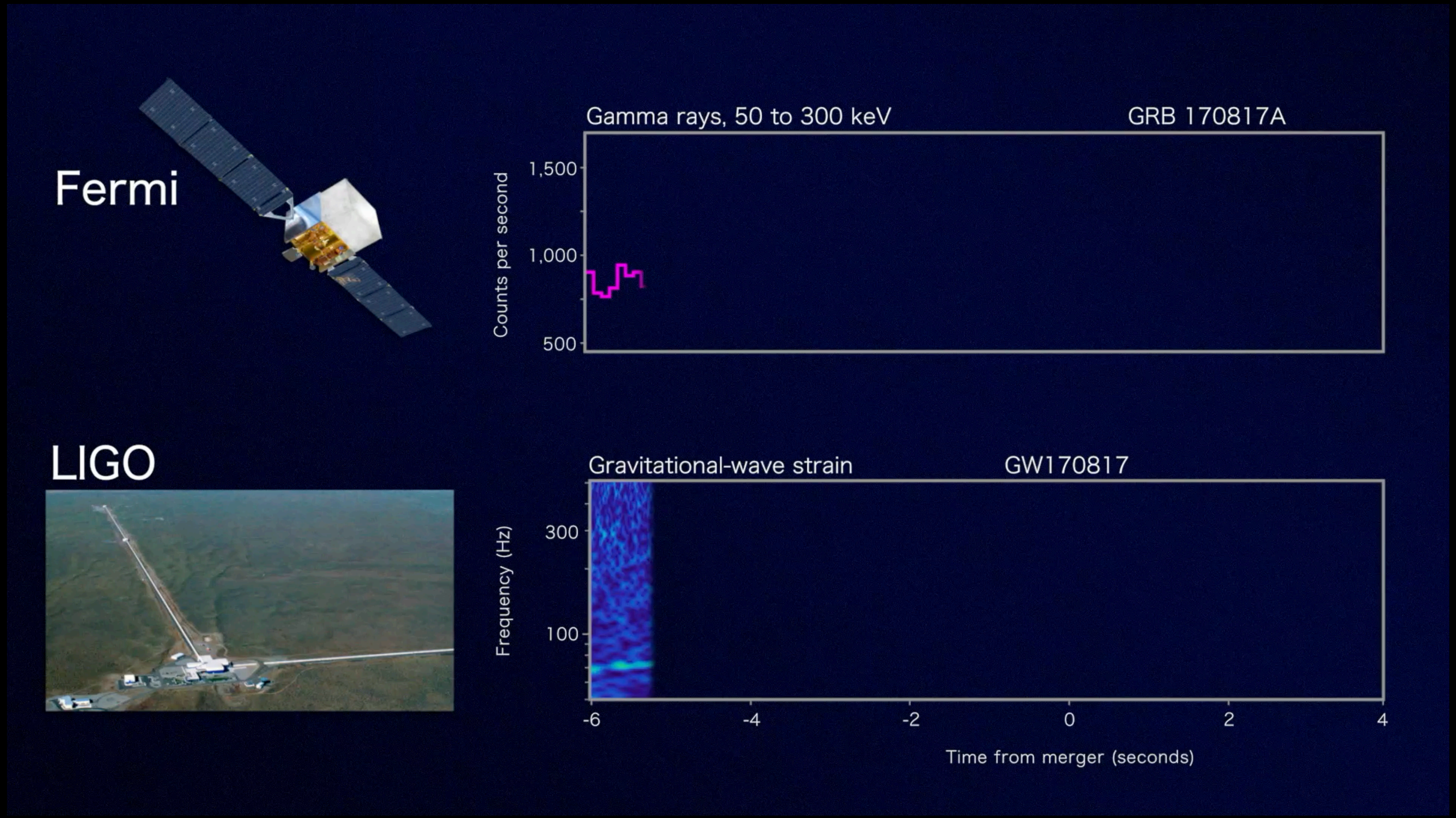
PennState

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

NP3M Virtual Seminar - August 24 2023

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

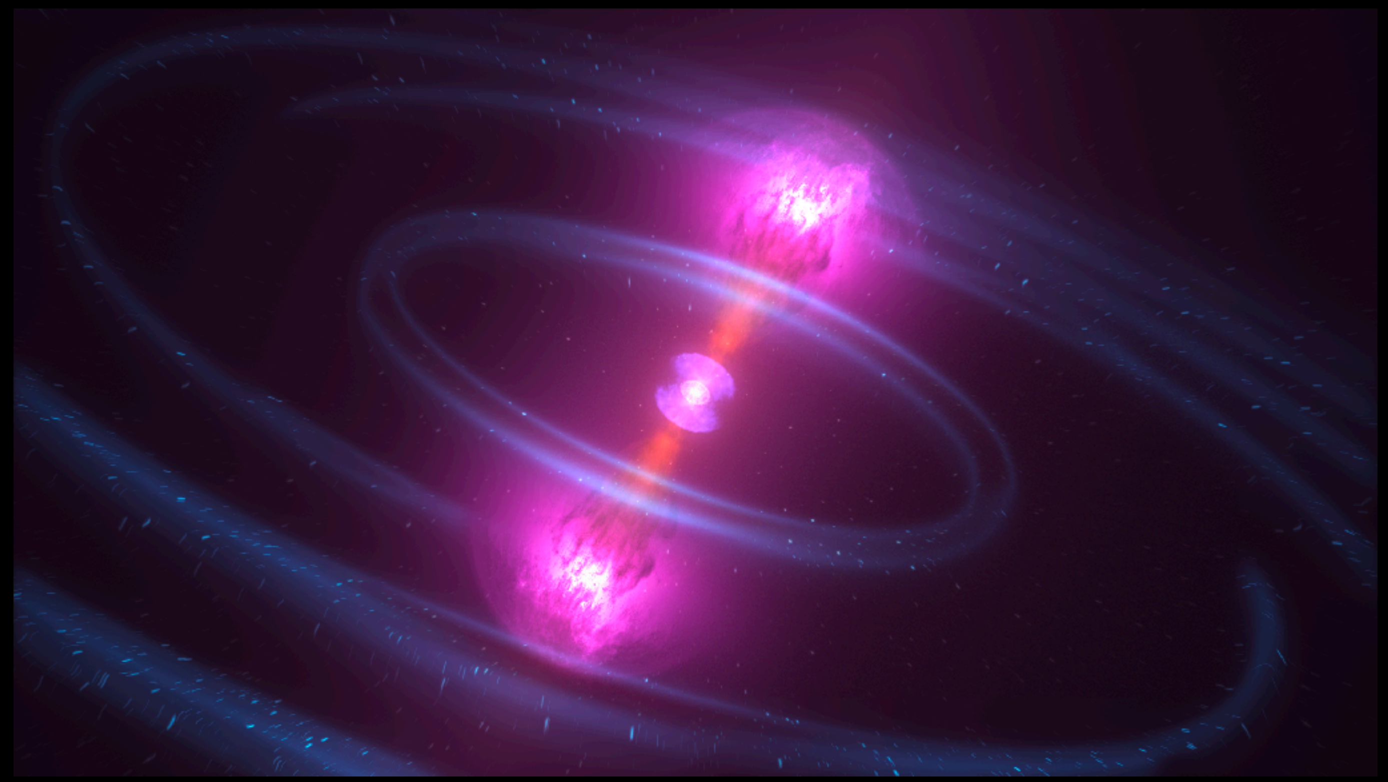
Binary neutron star merger



→ **GRB**
ding!

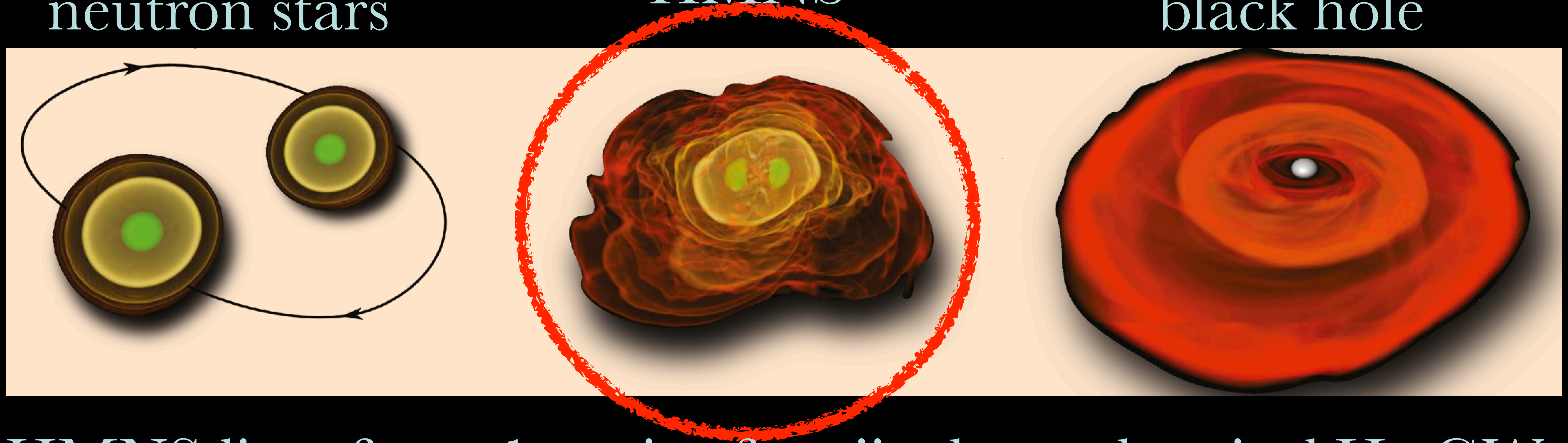
→ **GWs**
whoop!

When is the GRB launched?



… a hypermassive neutron star?

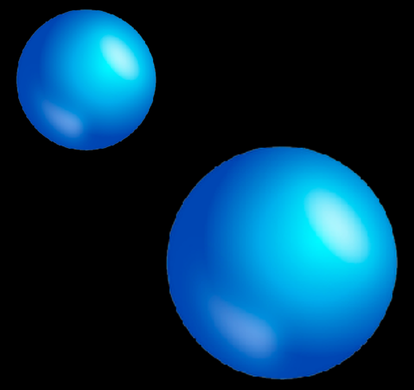
neutron stars HMNS black hole



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

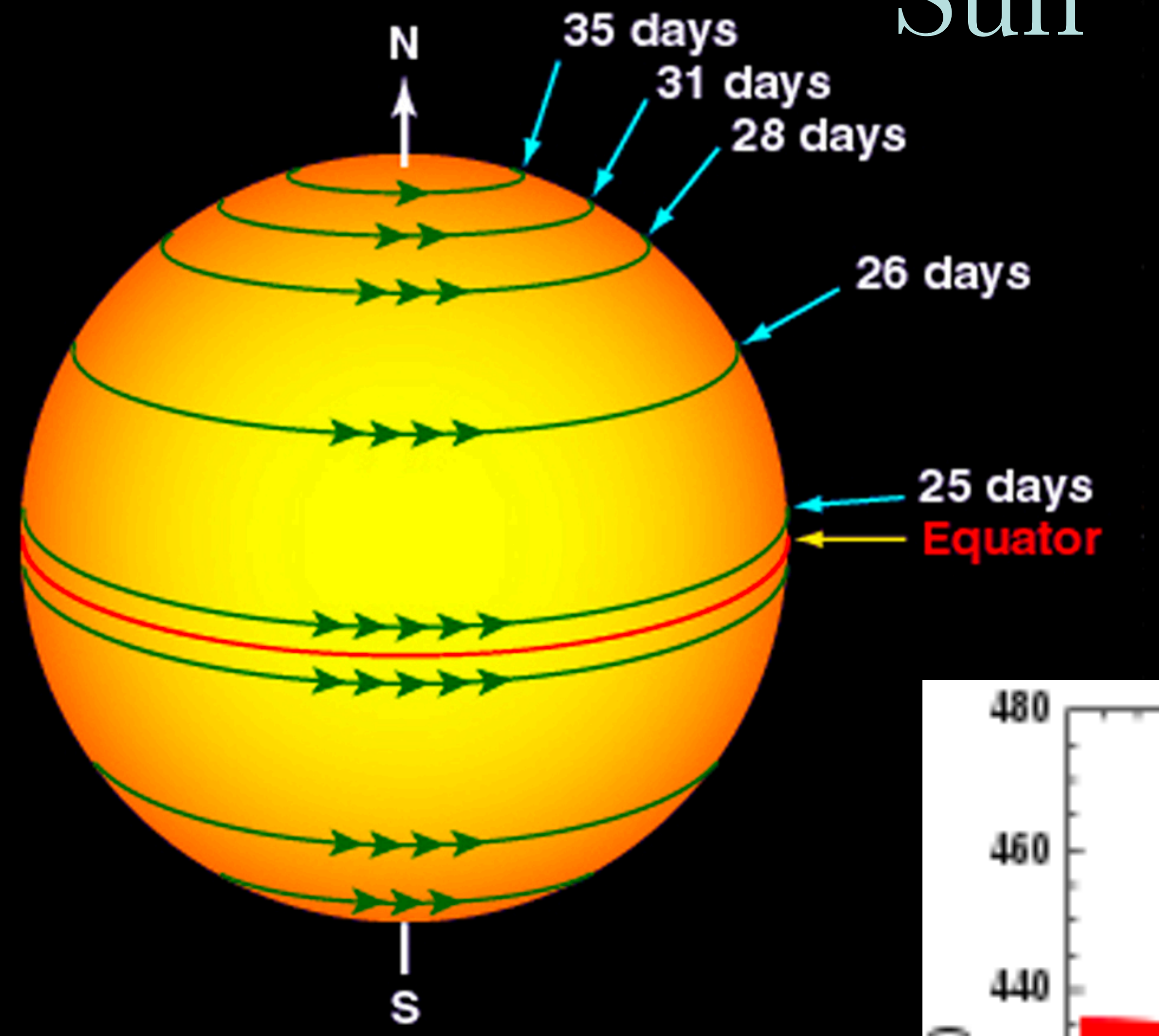


bigger 2 times the size
of a typical NS

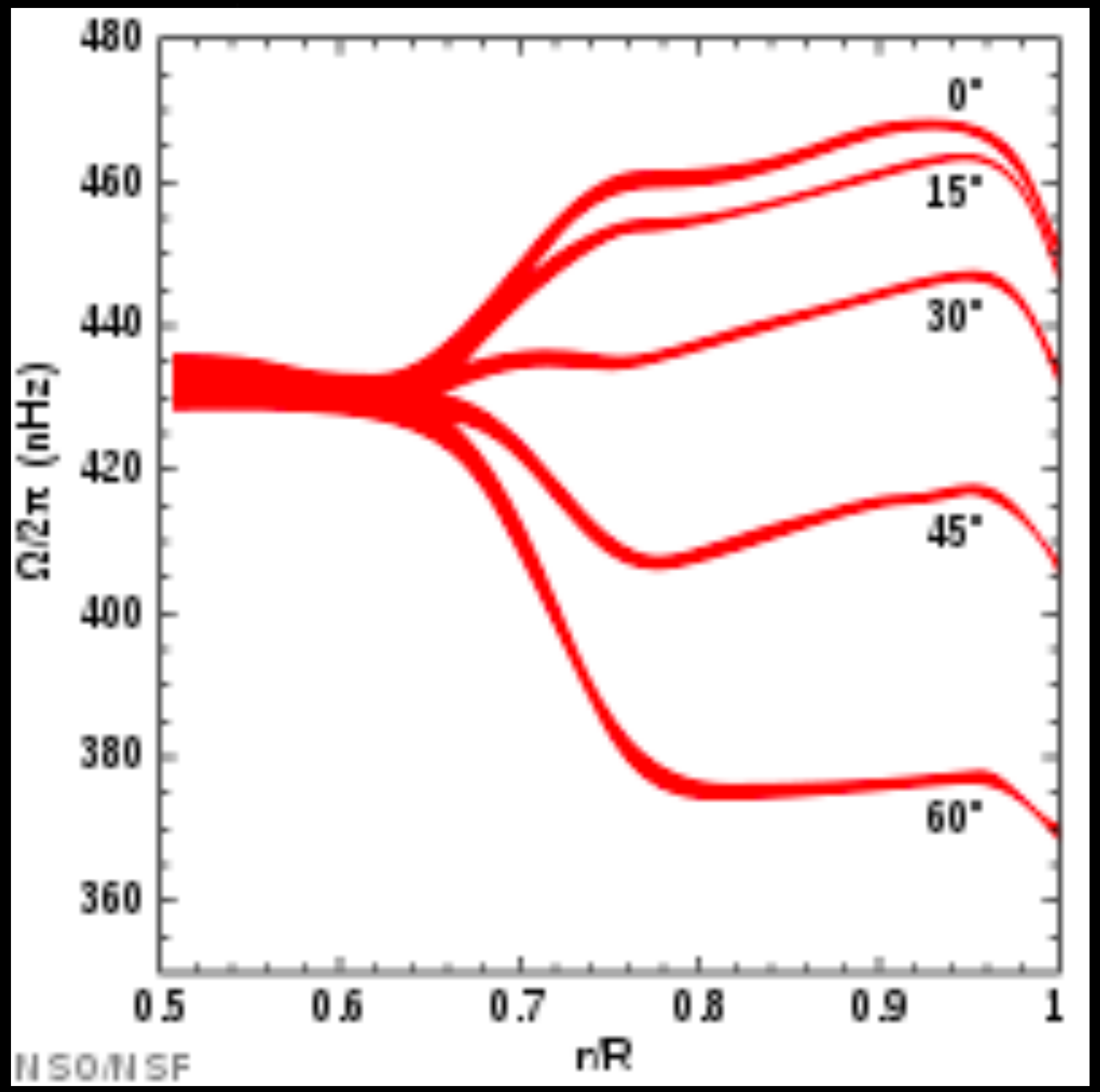
An HMNS can be heavier than a normal NS **because** of its fast spin!

Differential rotation

Sun

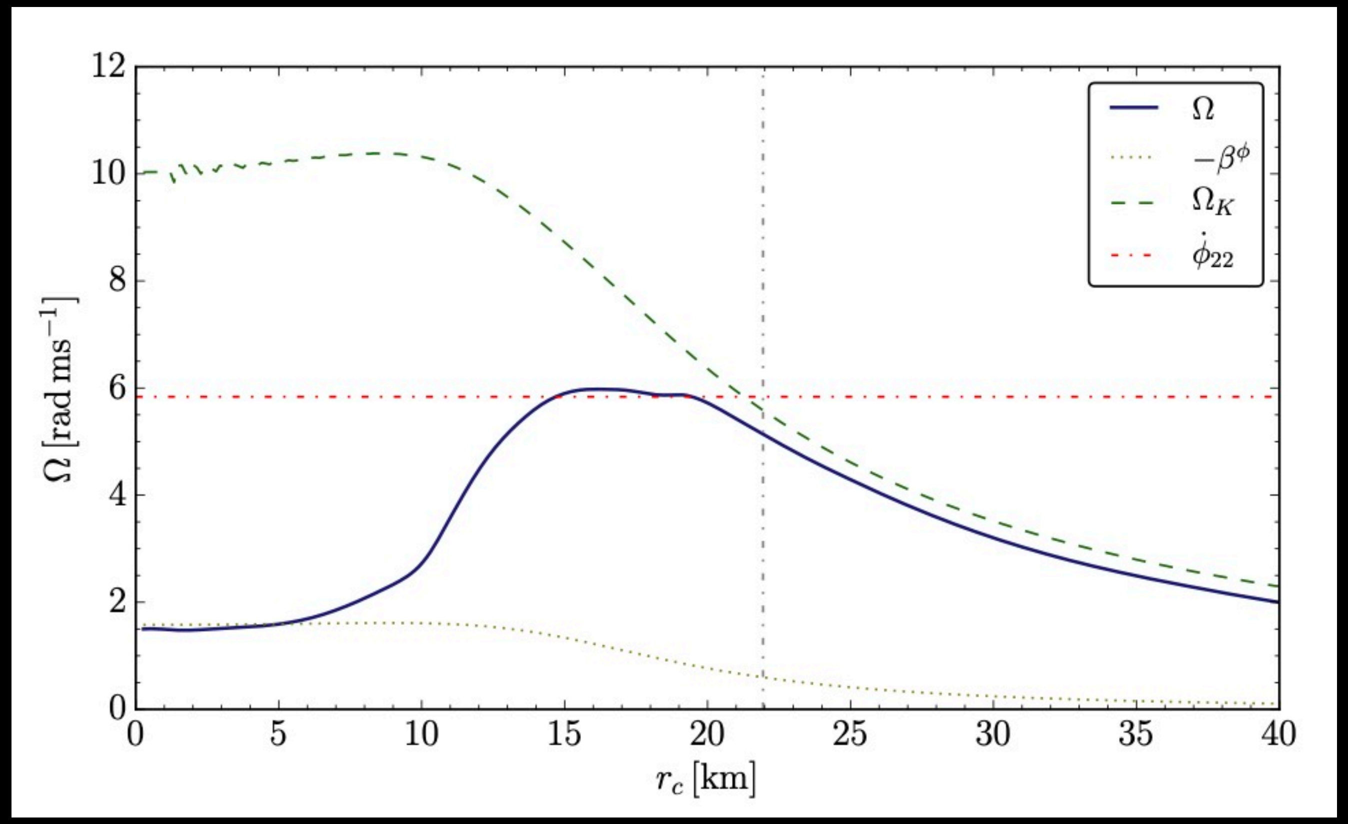


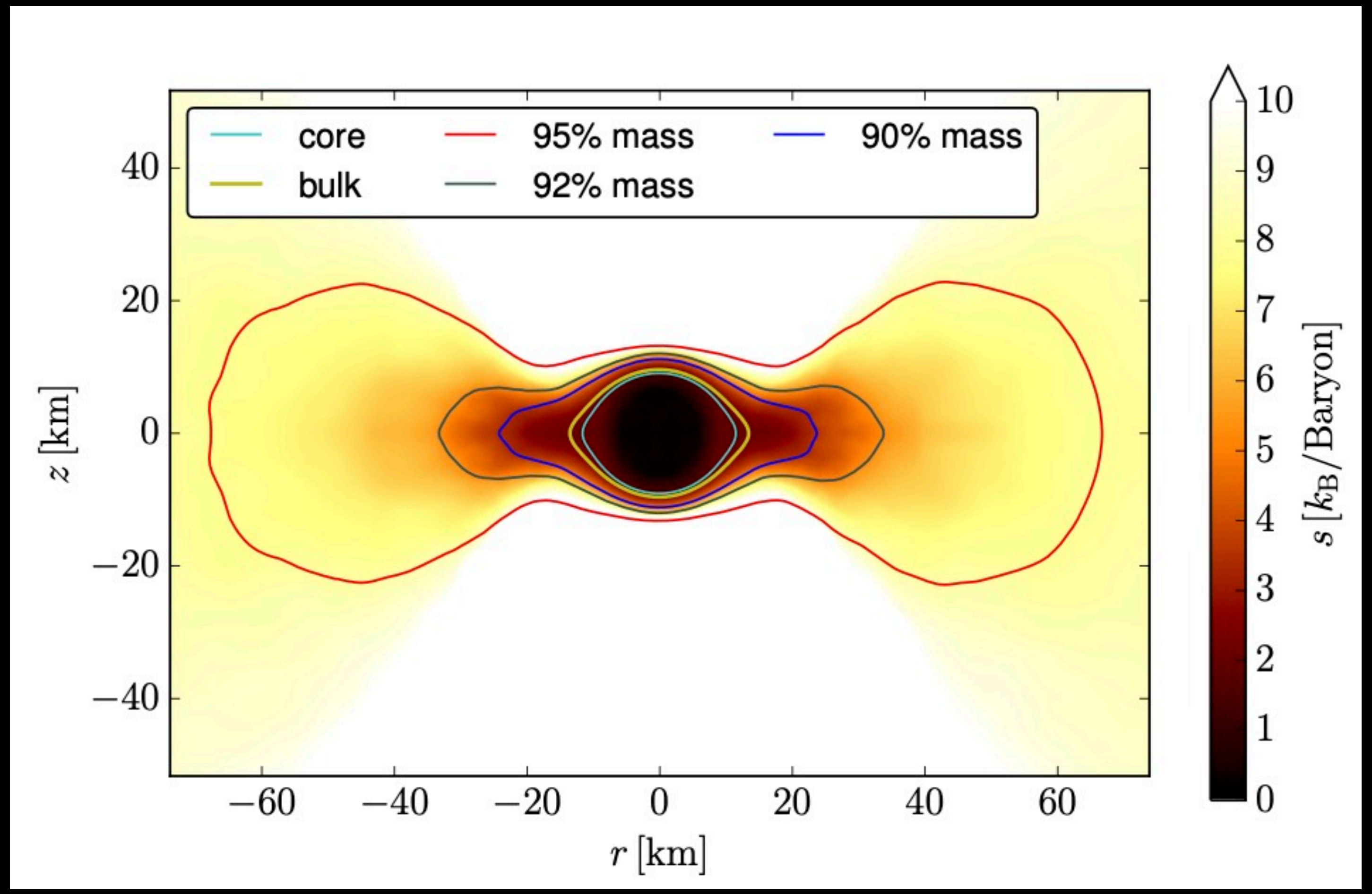
NASA



Wikipedia

HMNS





Kastaun, Ciolfi & Giacomazzo, 2018

Periodic signal

single frequency

astrophysical example: pulsars

Periodic signal

single frequency

astrophysical example: pulsars

Quasi-periodic signal

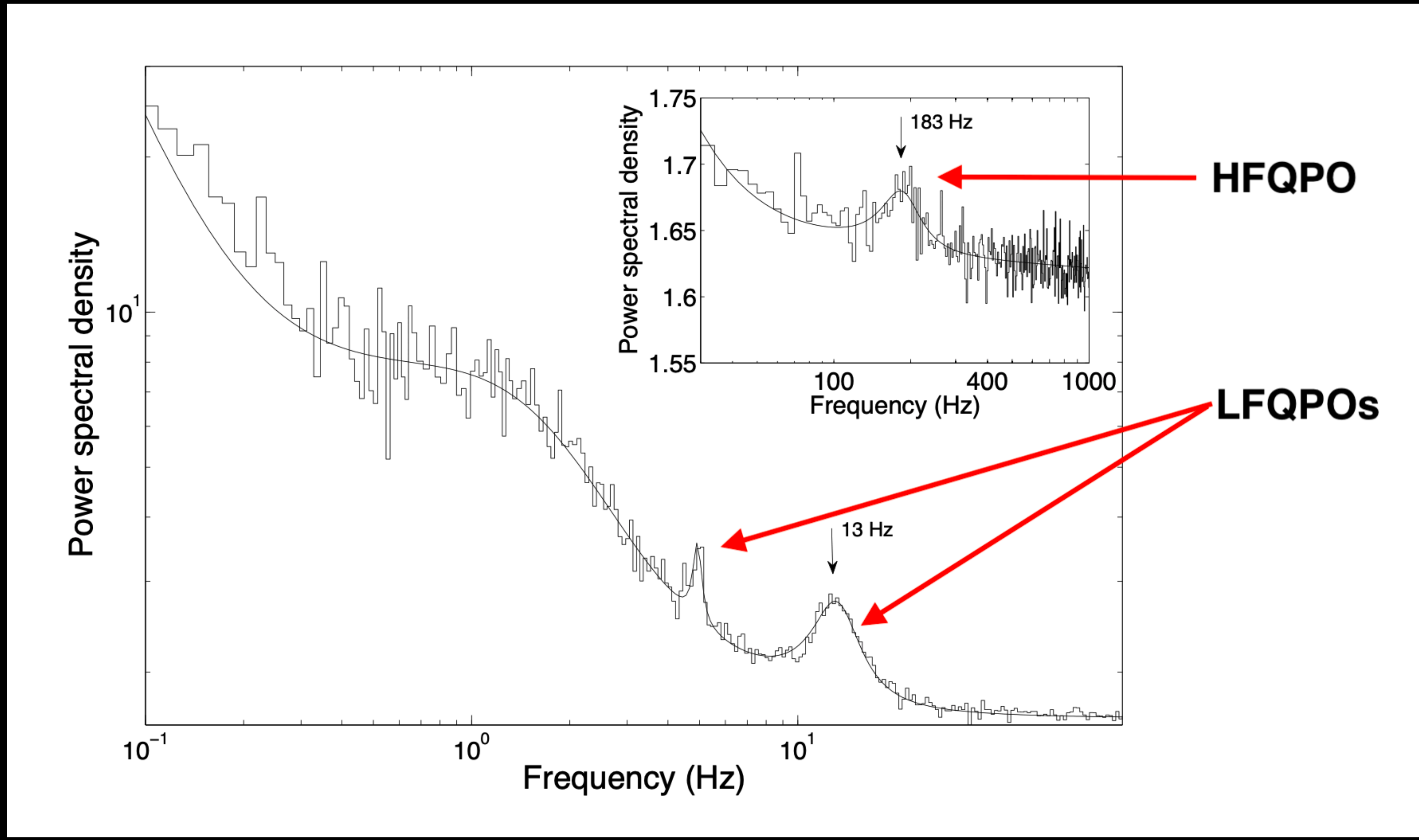
not a single frequency

causes of quasi-periodicity:

many close frequencies,
dissipation or time variation

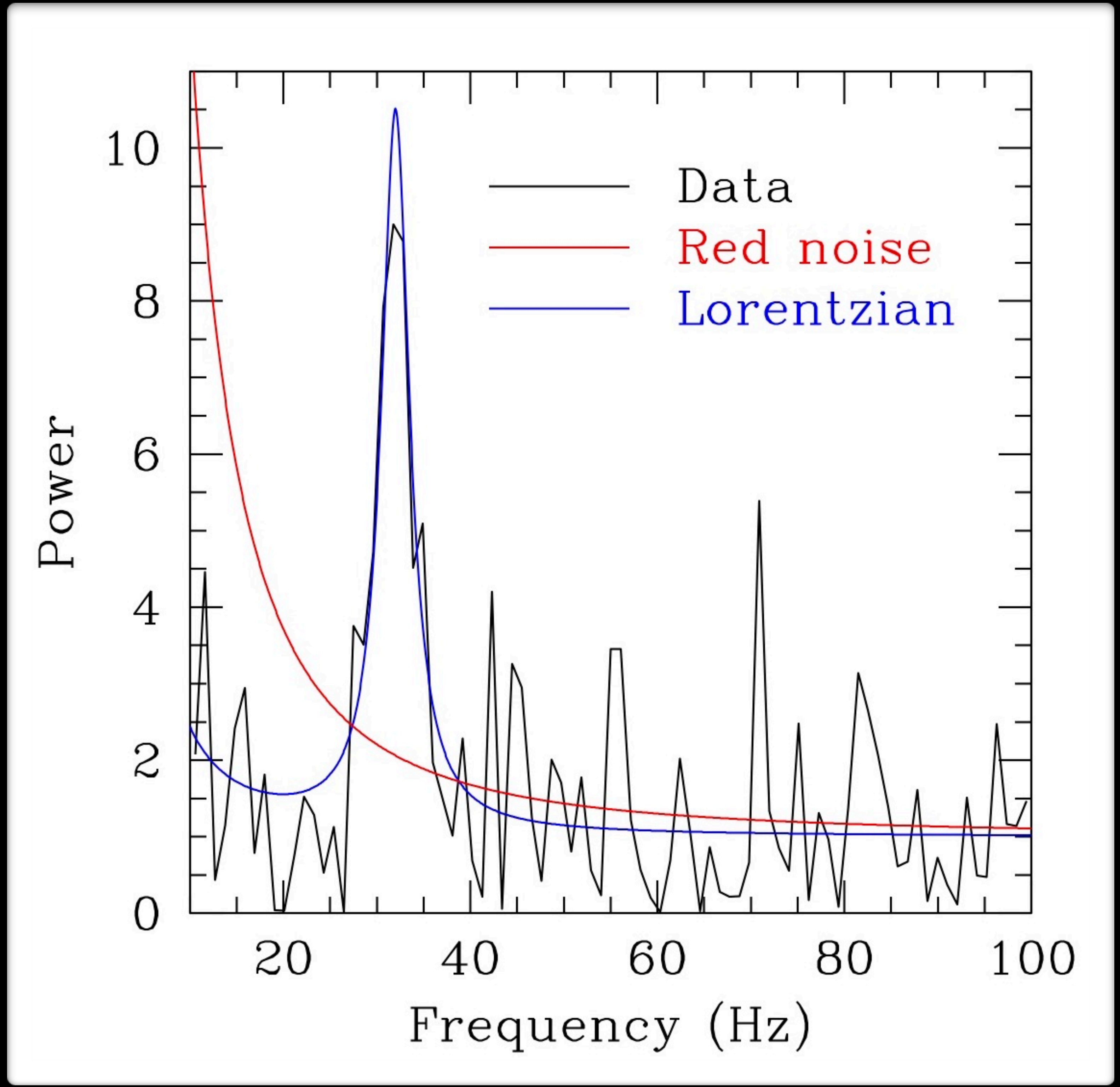
Examples of quasi-periodic oscillations

black hole X-ray binary XTE J1550-564



Motta et al. 2018

X-ray tail of SGR 1806-20 giant flare



Miller, Chirenti & Strohmayer 2019

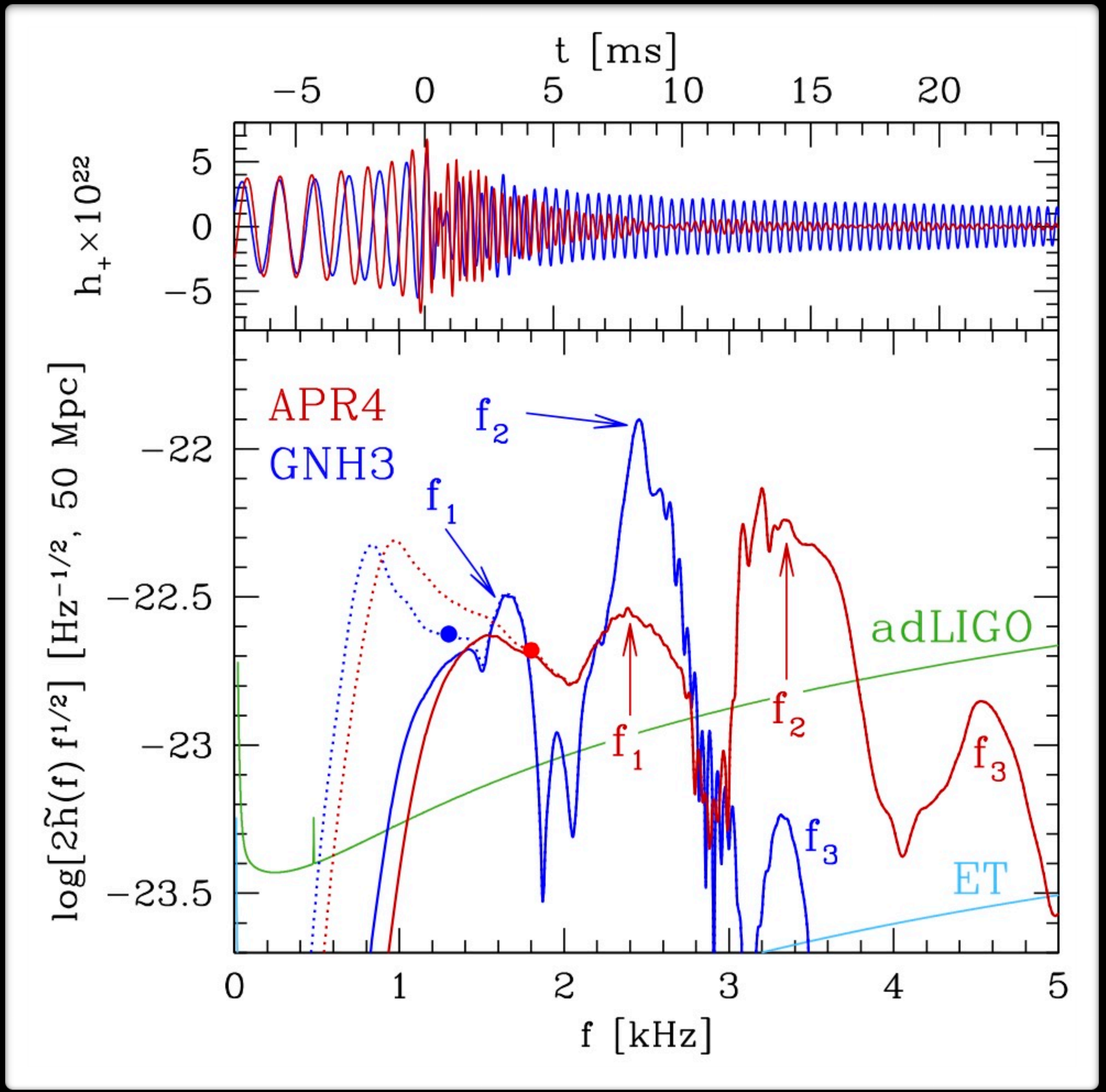
HMNS Quasi-periodic oscillations

HMNS signal:

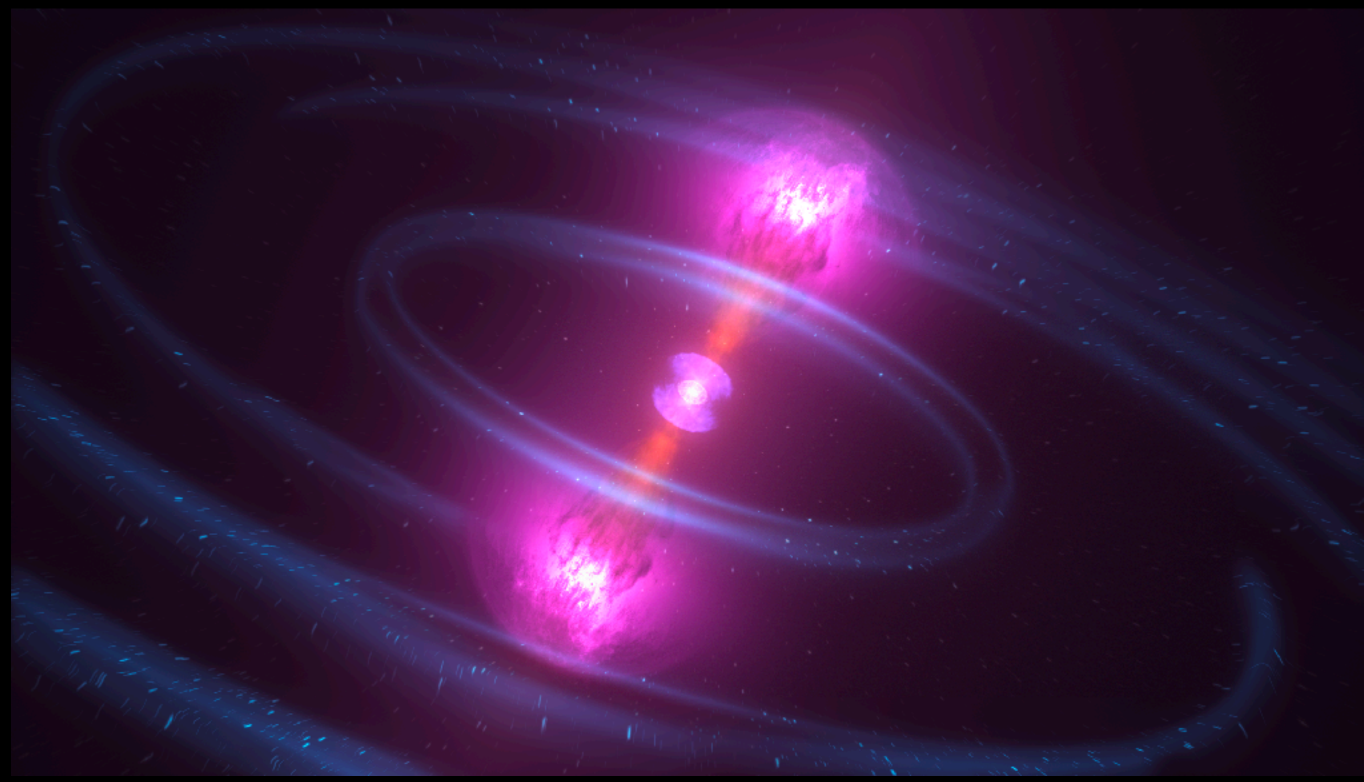
short-lived
time-evolving
dissipative*

⇓

quasi-periodic oscillations (QPOs)



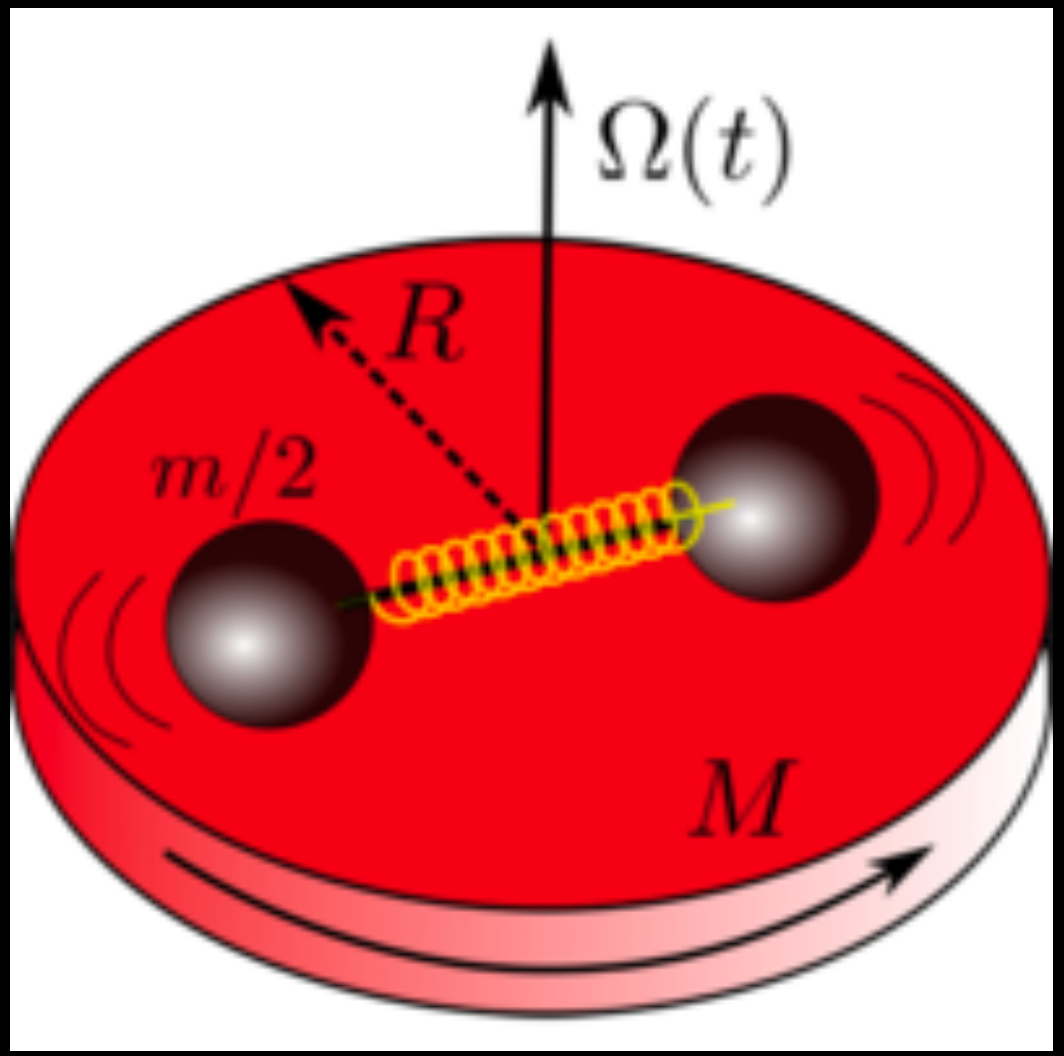
Takami, Rezzolla & Baiotti, 2014



Could the GRB show these QPOs?

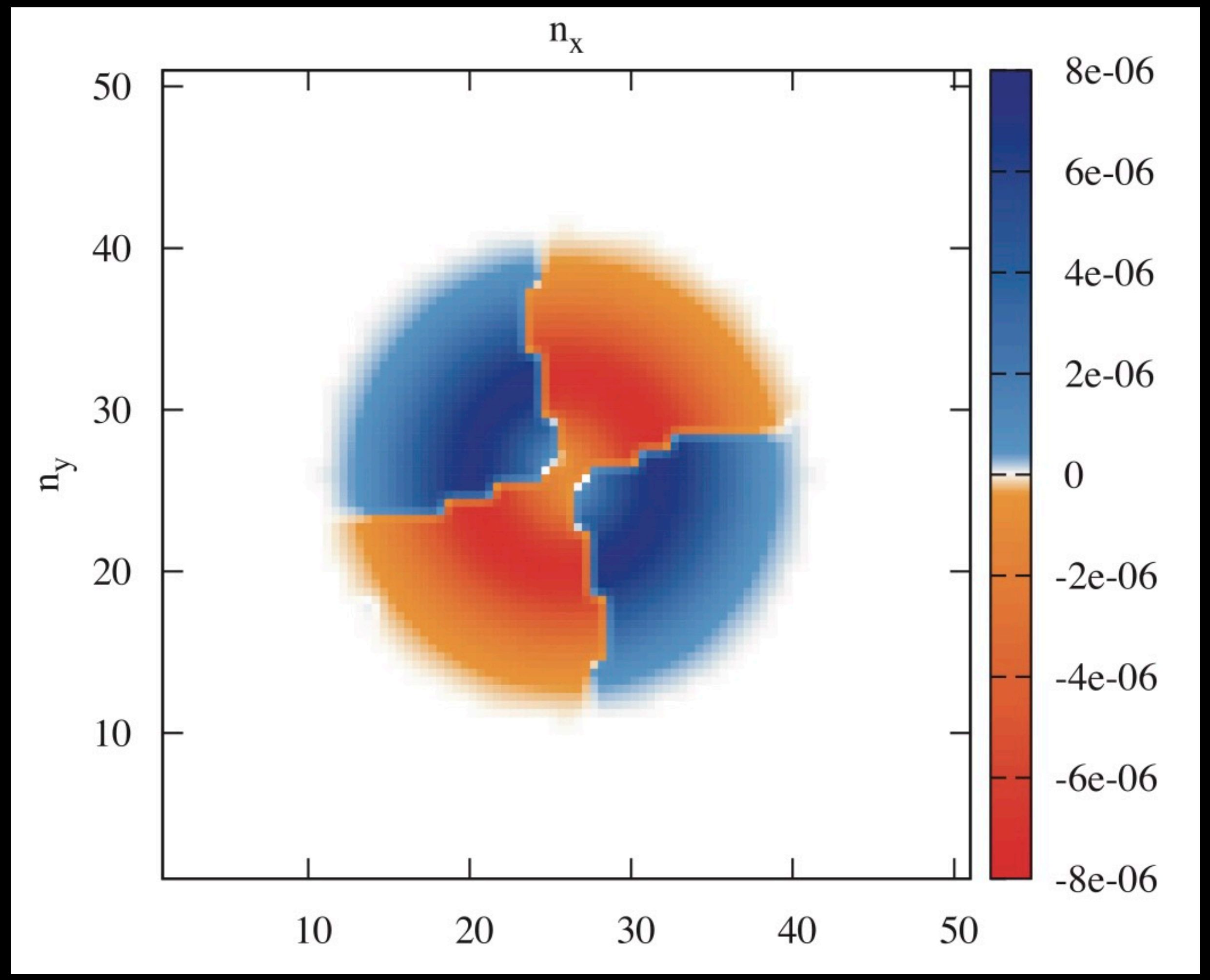
*simulations also have numerical dissipation!

GRB QPOs?

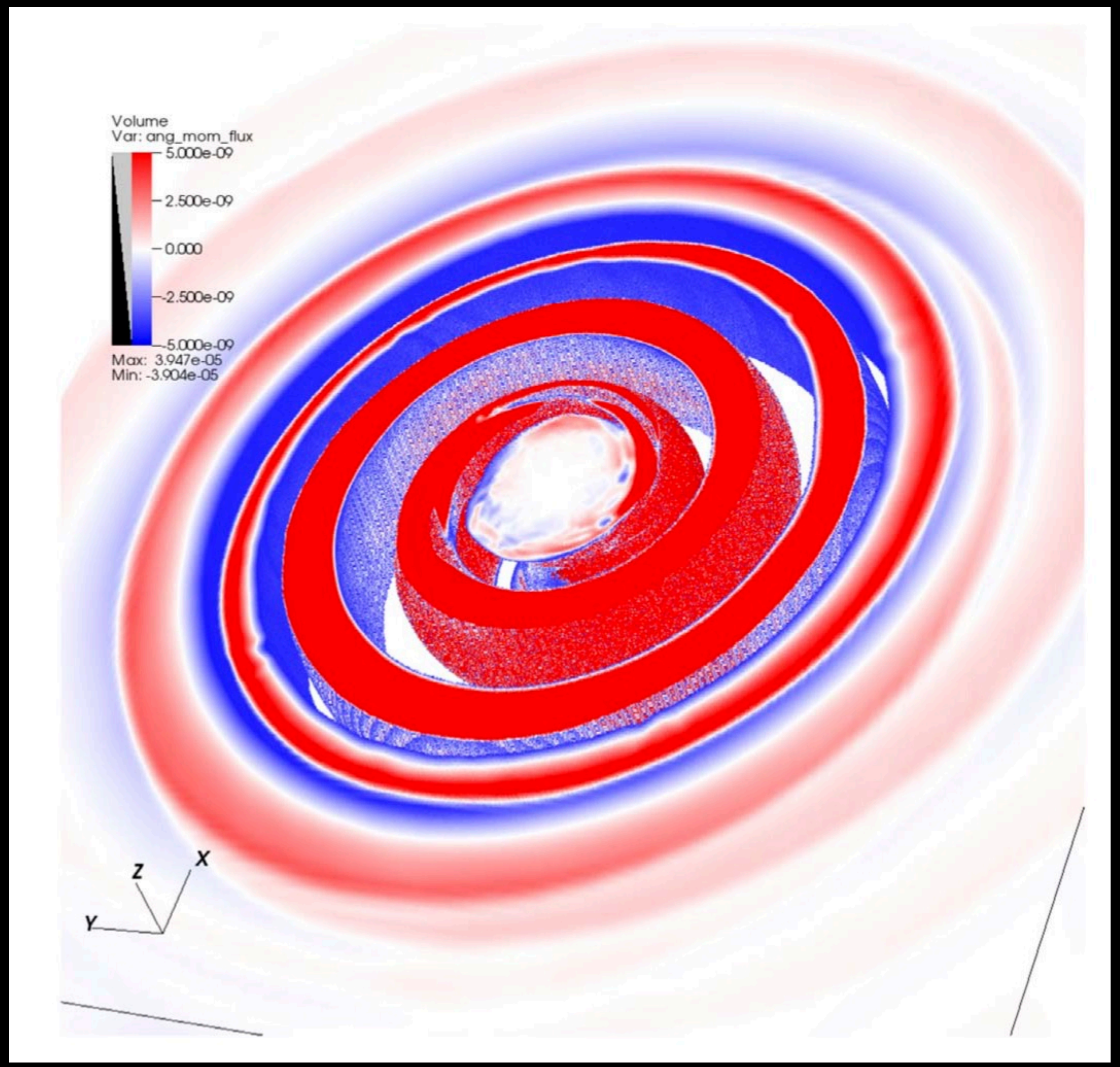


Takami, Rezzolla & Baiotti, 2015

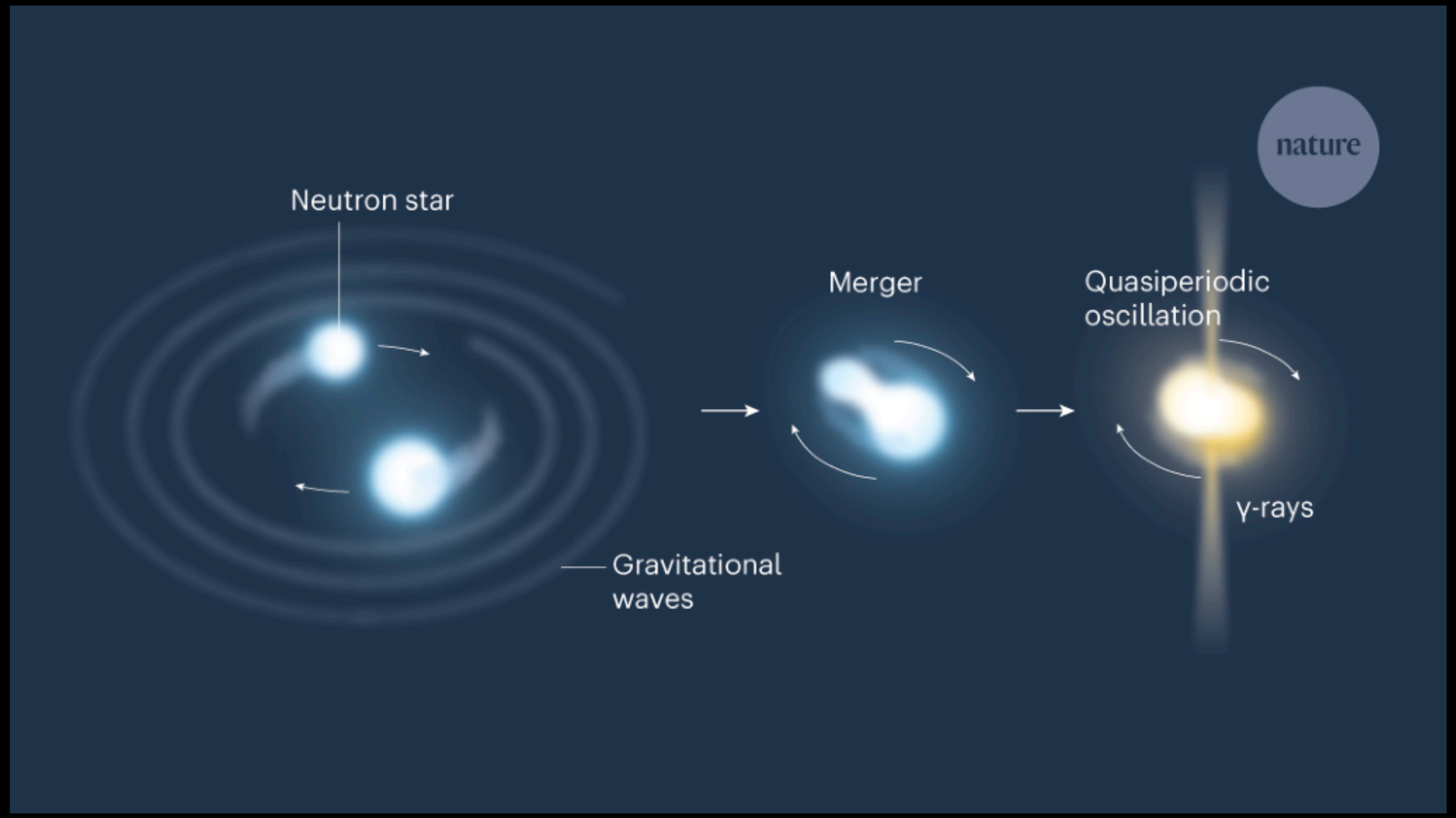
How does the HMNS oscillate?



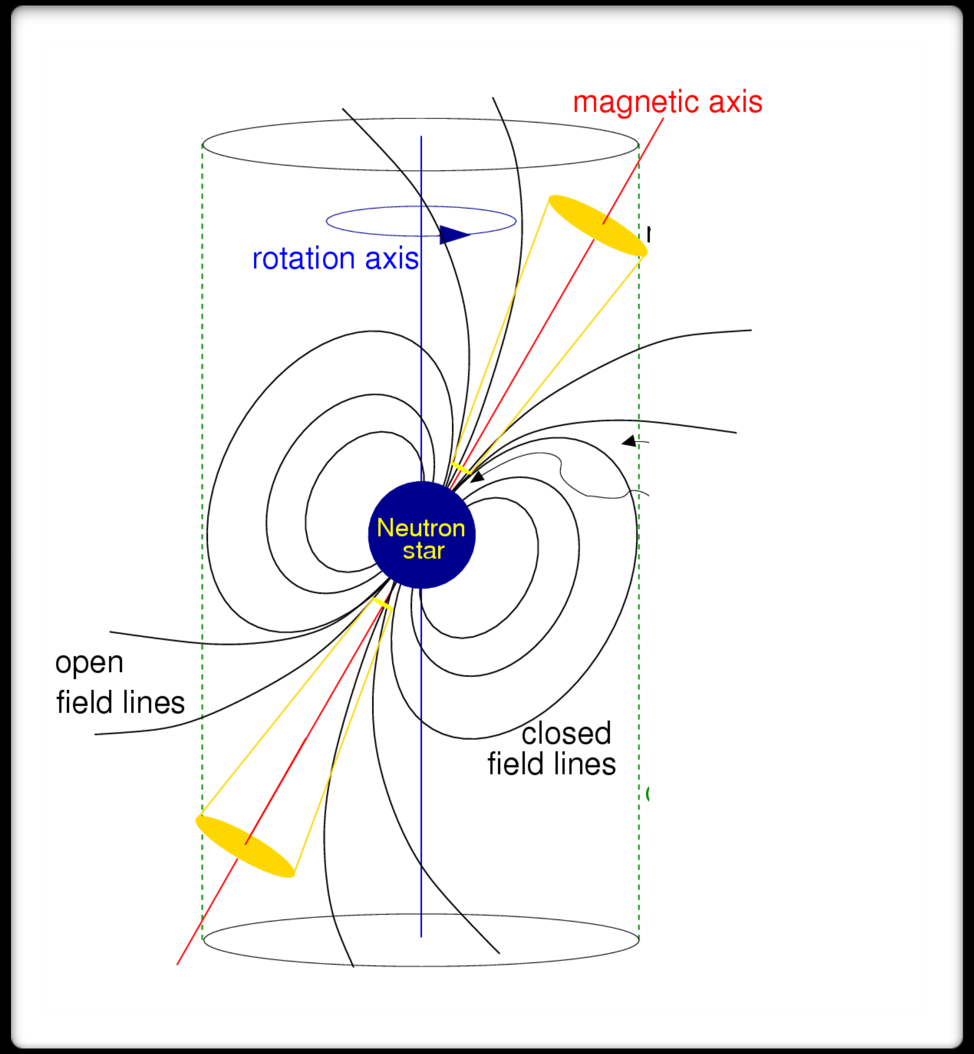
Stergioulas et al. 2011



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

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

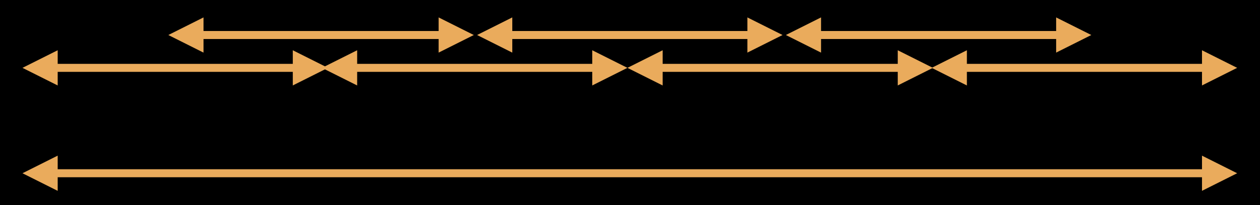
How: Bayesian model comparison

Model 0: White noise only

Model 1: White noise + QPO

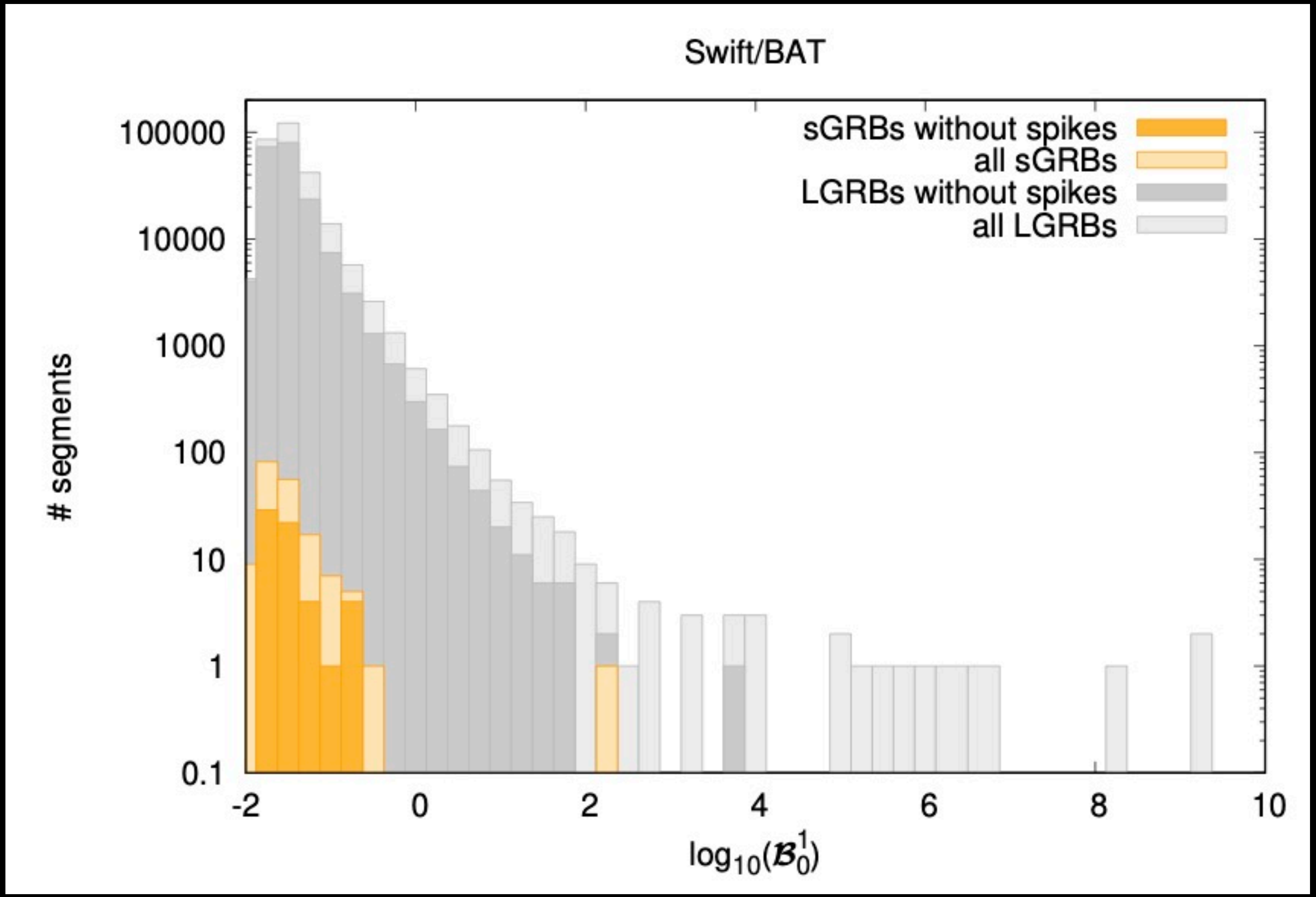
We analyze each burst divided into short segments and quote the Bayes factor in favor of the noise + QPO model for each segment

half-overlapping segments (approx 100 ms)



total burst duration

Initial analyses: Lessons learned



Causes of fake QPOs

Cosmic rays

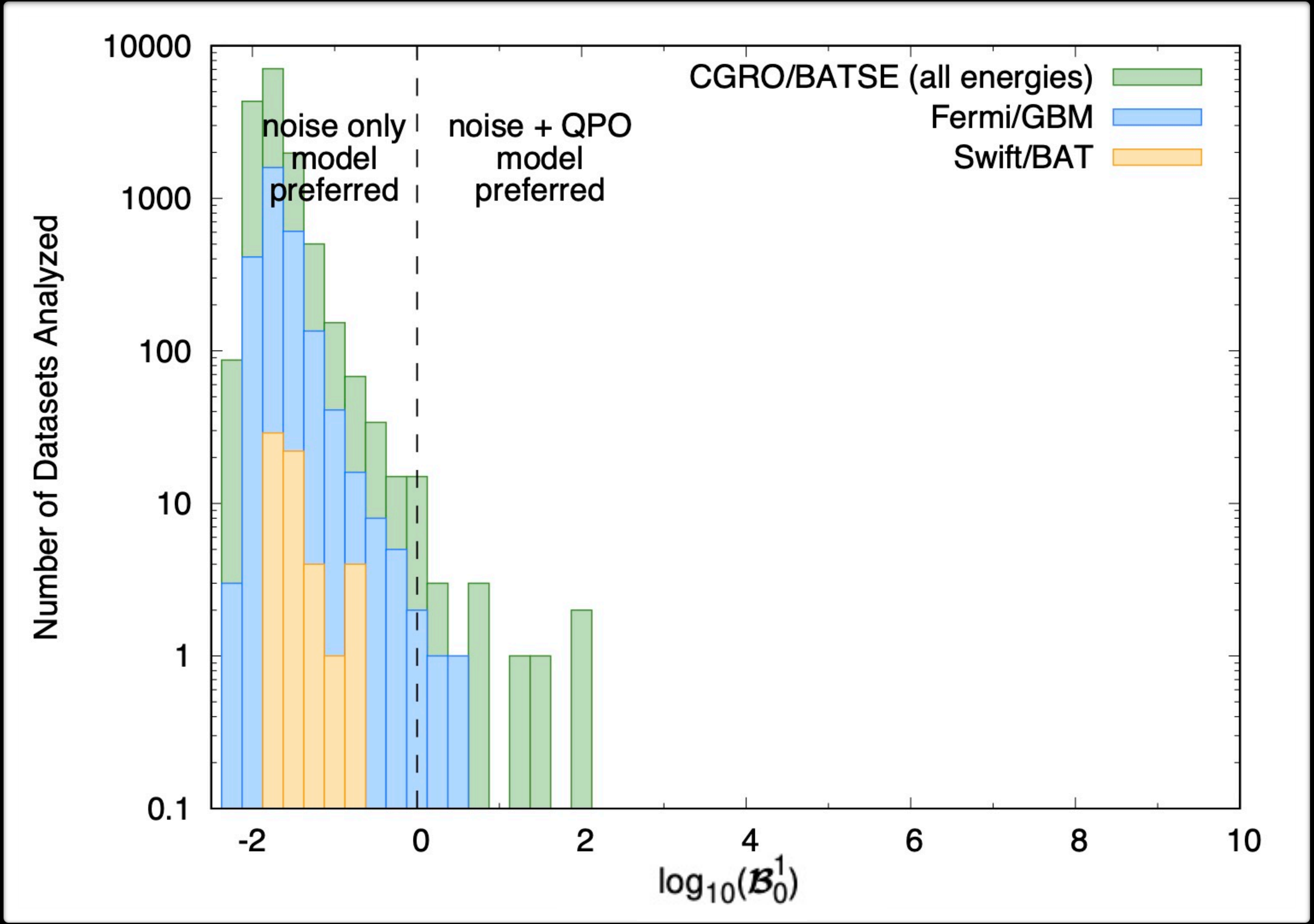
Detector artifacts*

(Data corruption)

Red noise contamination

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

Opening the treasure trove



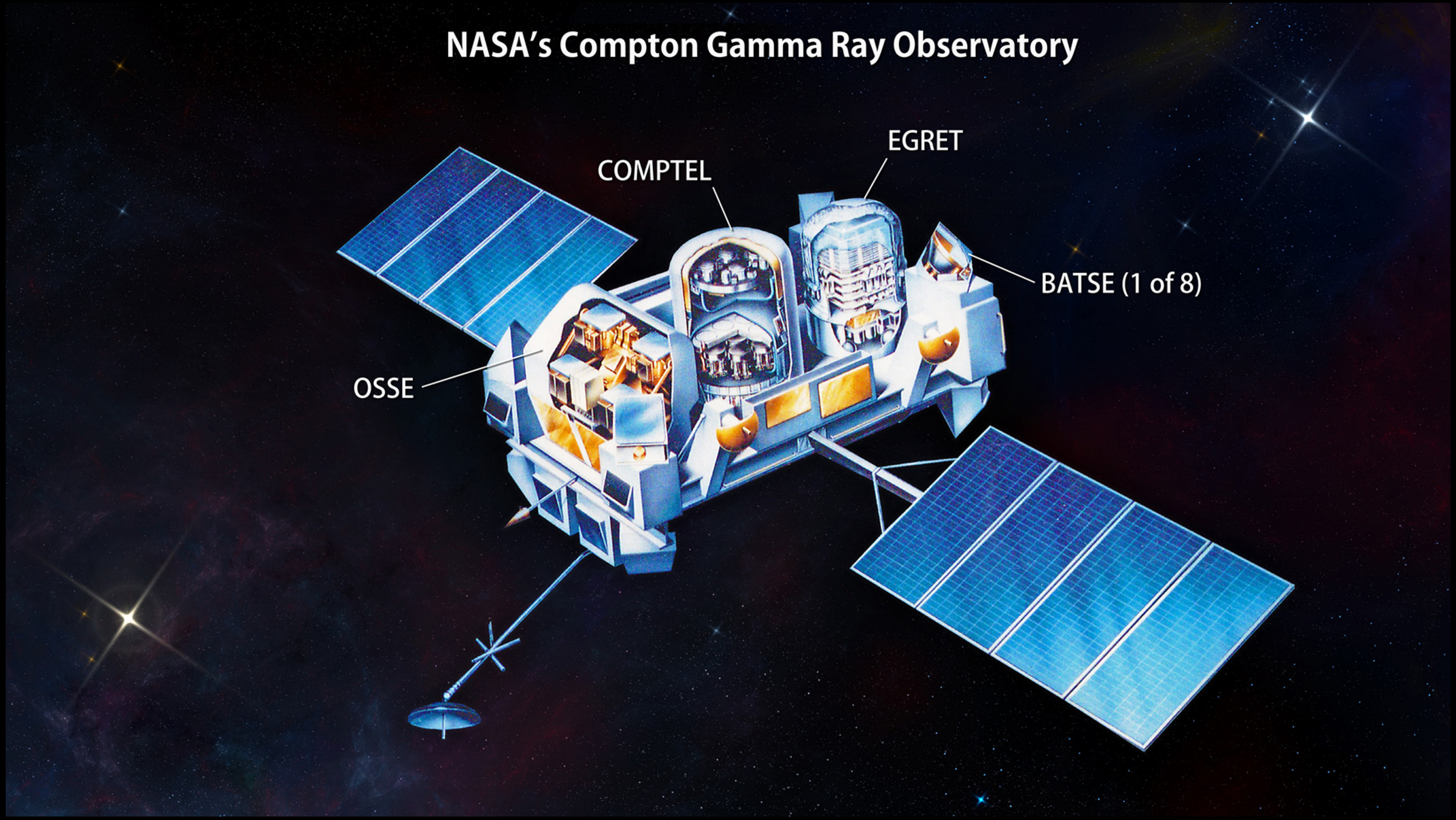
More than 700 short GRBs analyzed

Each GRB split in smaller segments for analysis

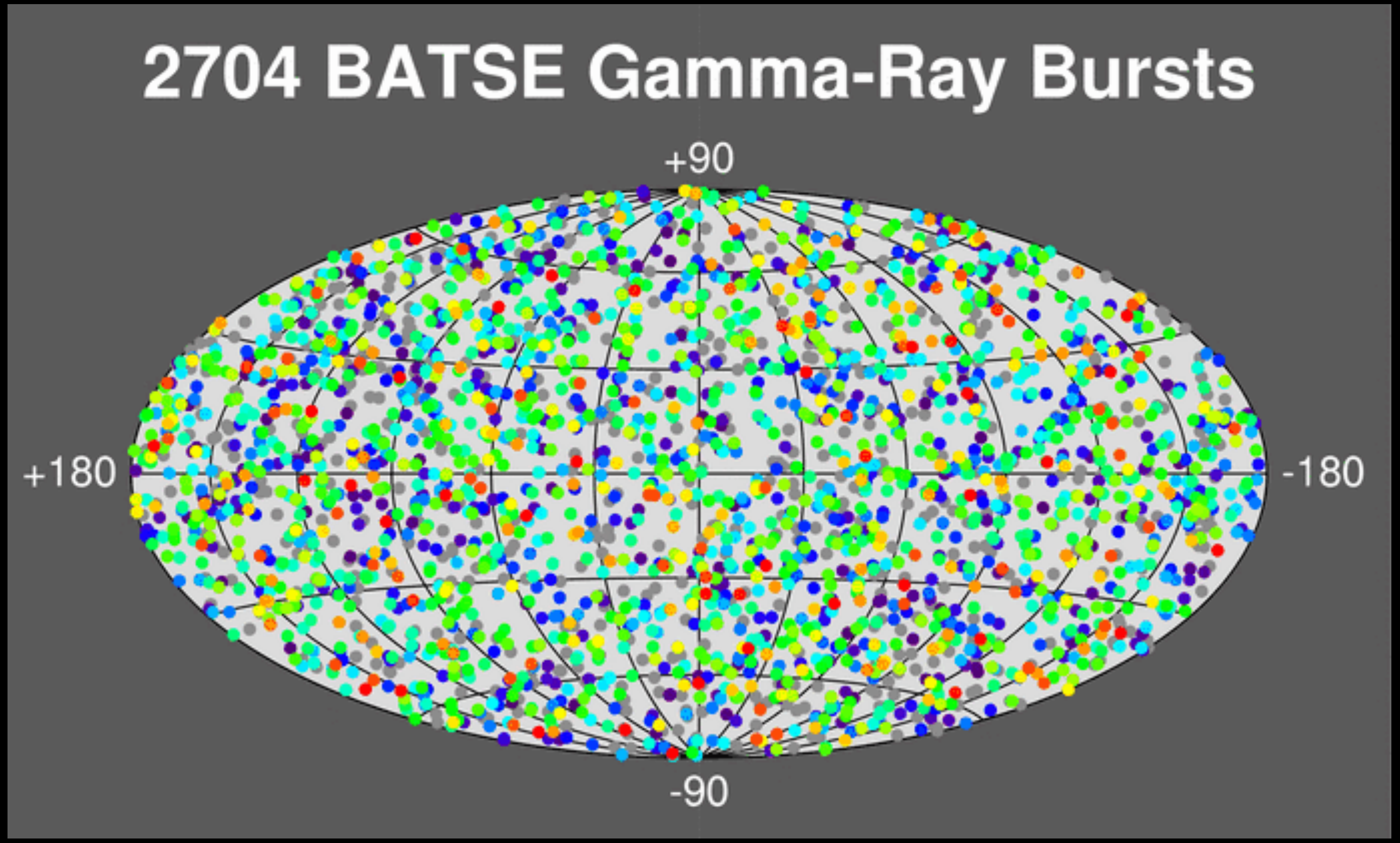
Nothing pops up in Fermi or Swift data

Something in the BATSE data?
Let's look more closely.

CGRO transforms GRB science

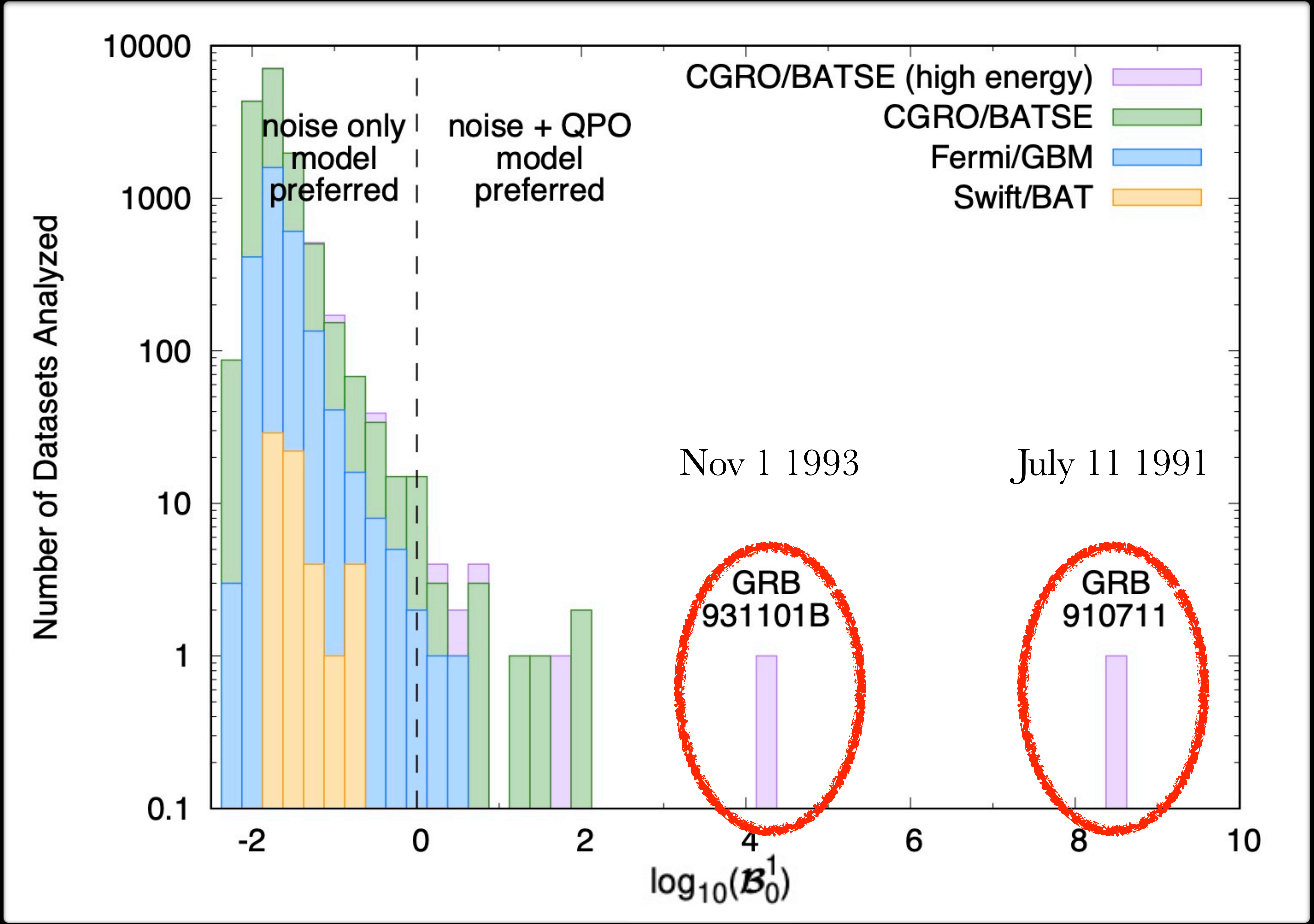


Compton Gamma-Ray Observatory
was one of NASA's
Great Observatories



Launched in 1991
De-orbited in 2000

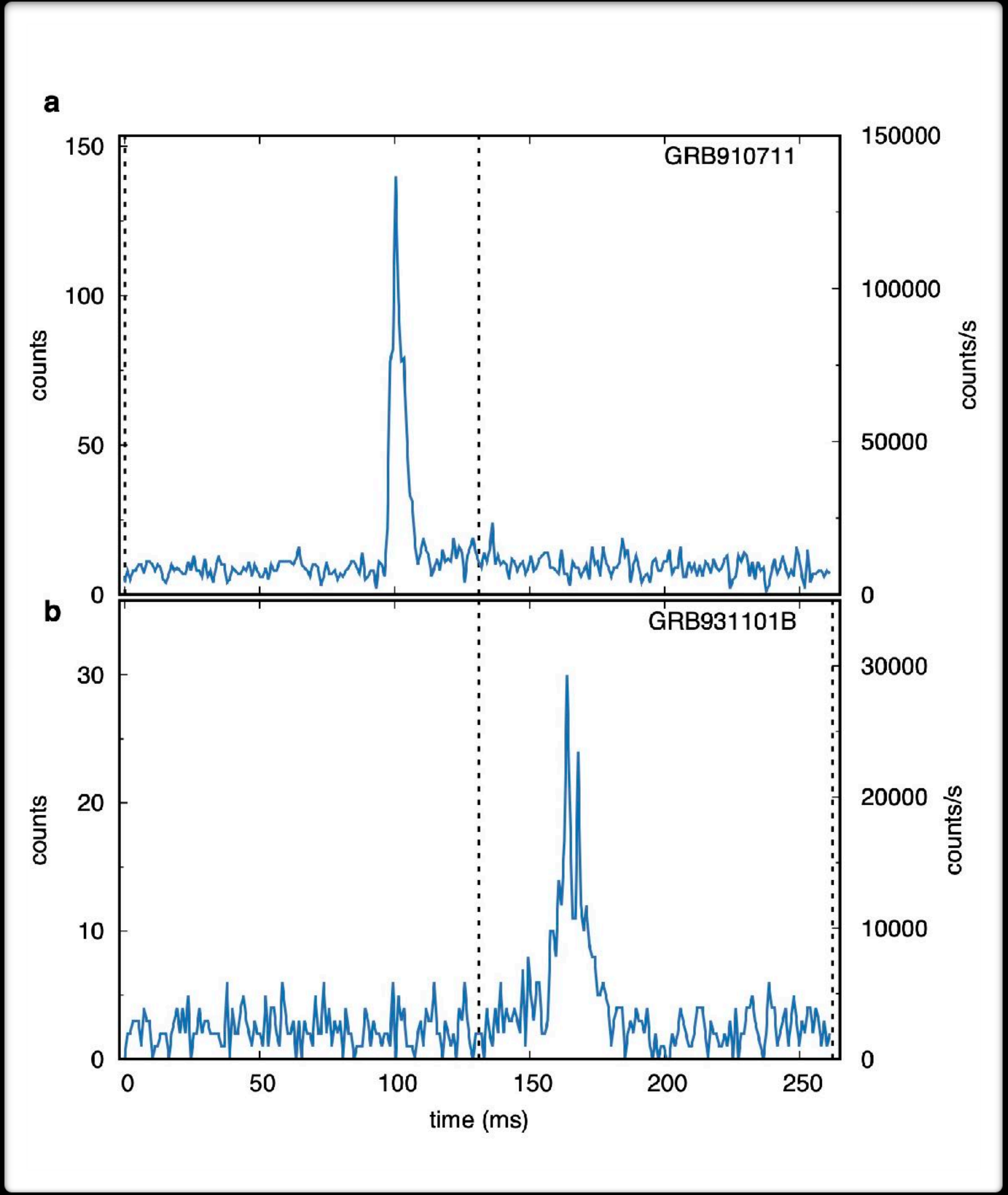
Opening the treasure trove

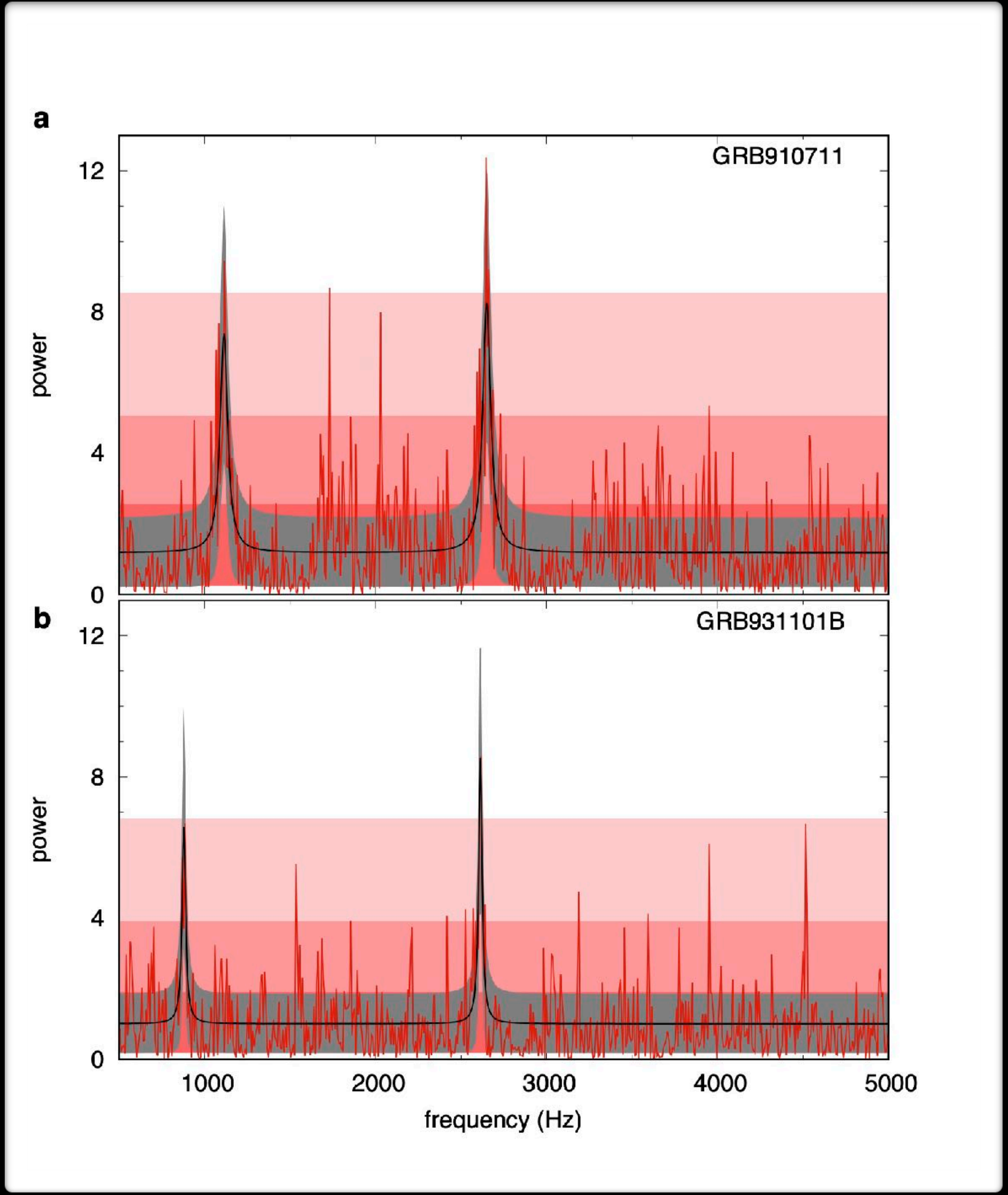


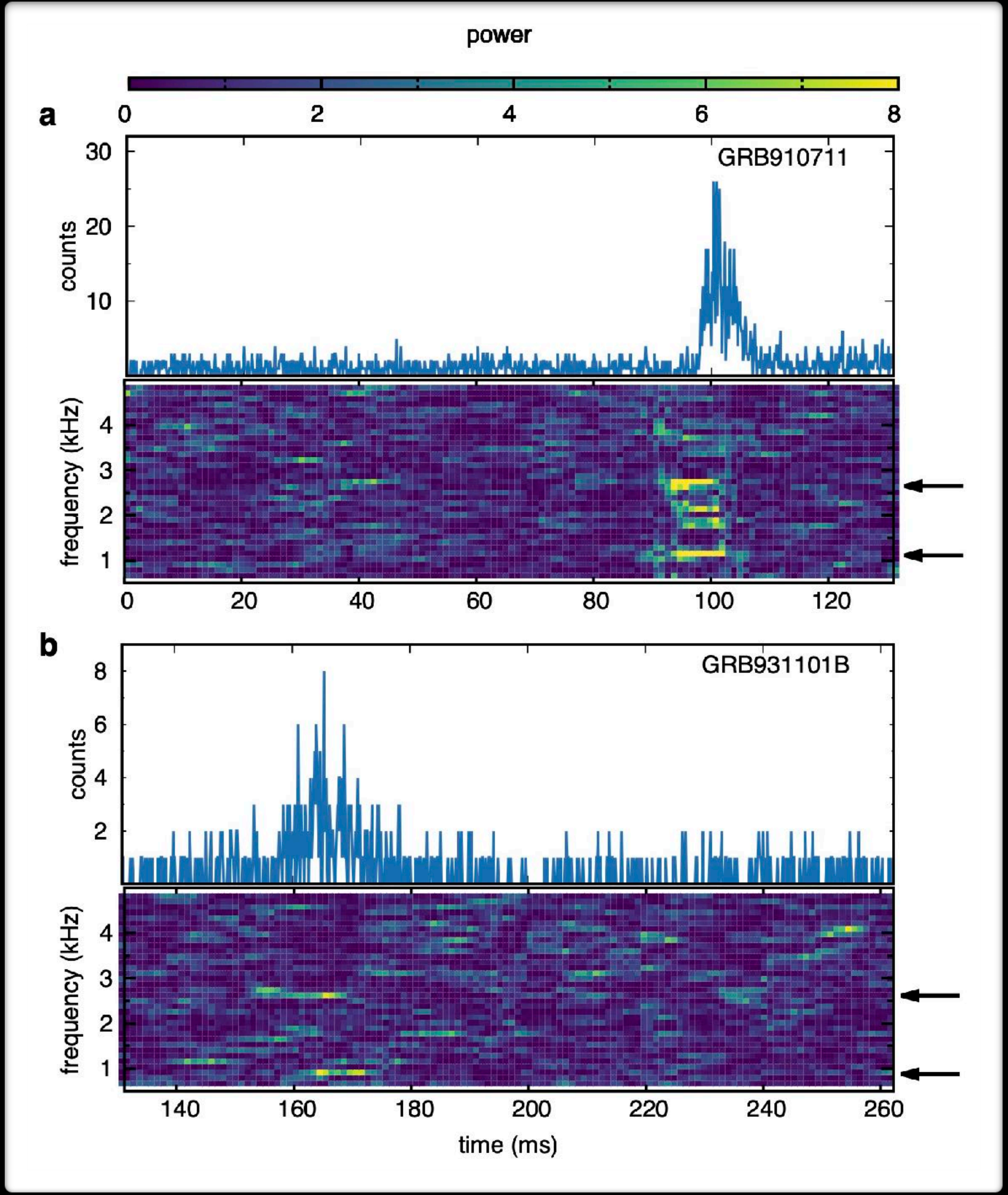
… and **bang**! Two signals. The combined false positive rate is 1 in 3.3 million!

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

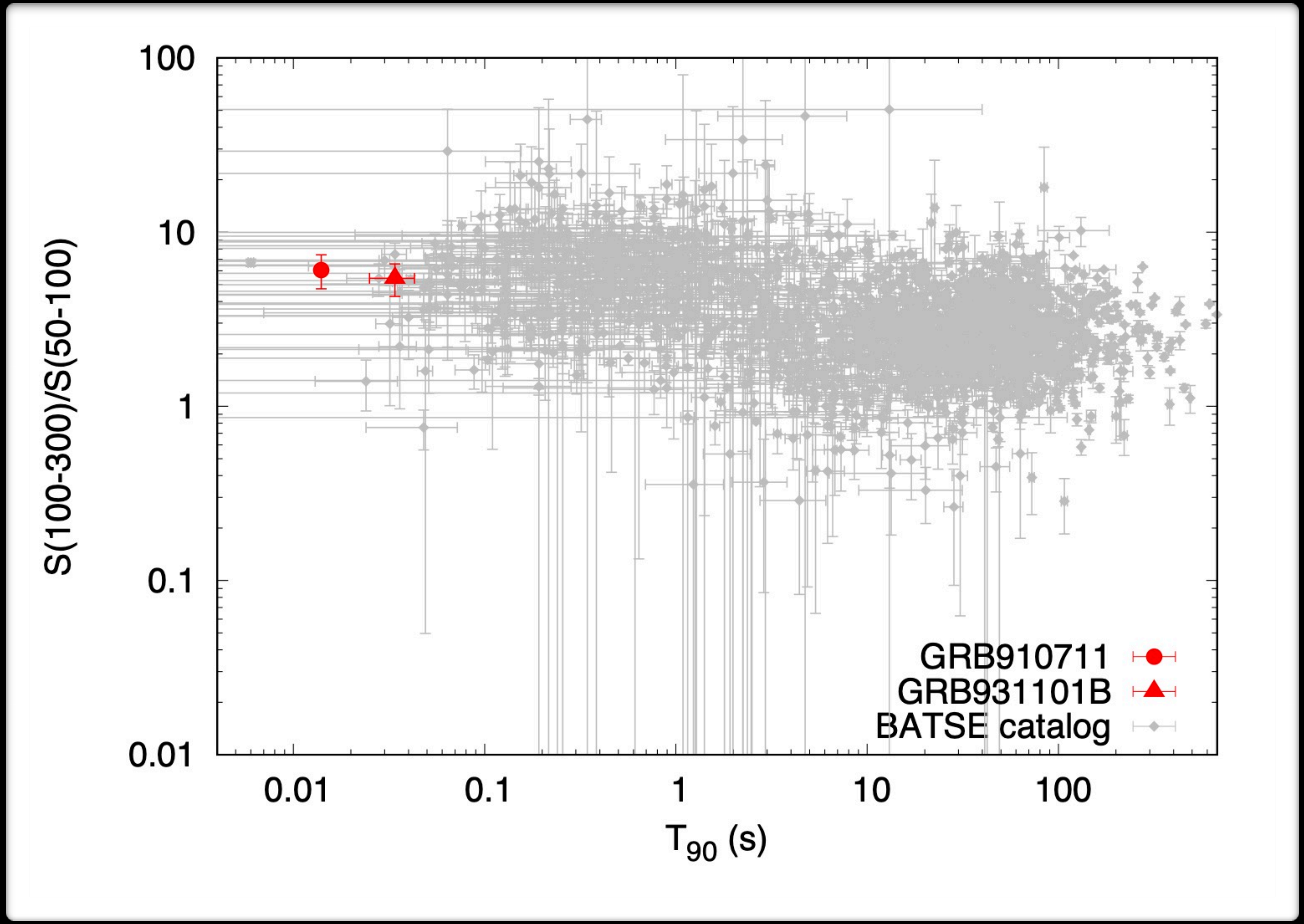
Light curves and power spectra

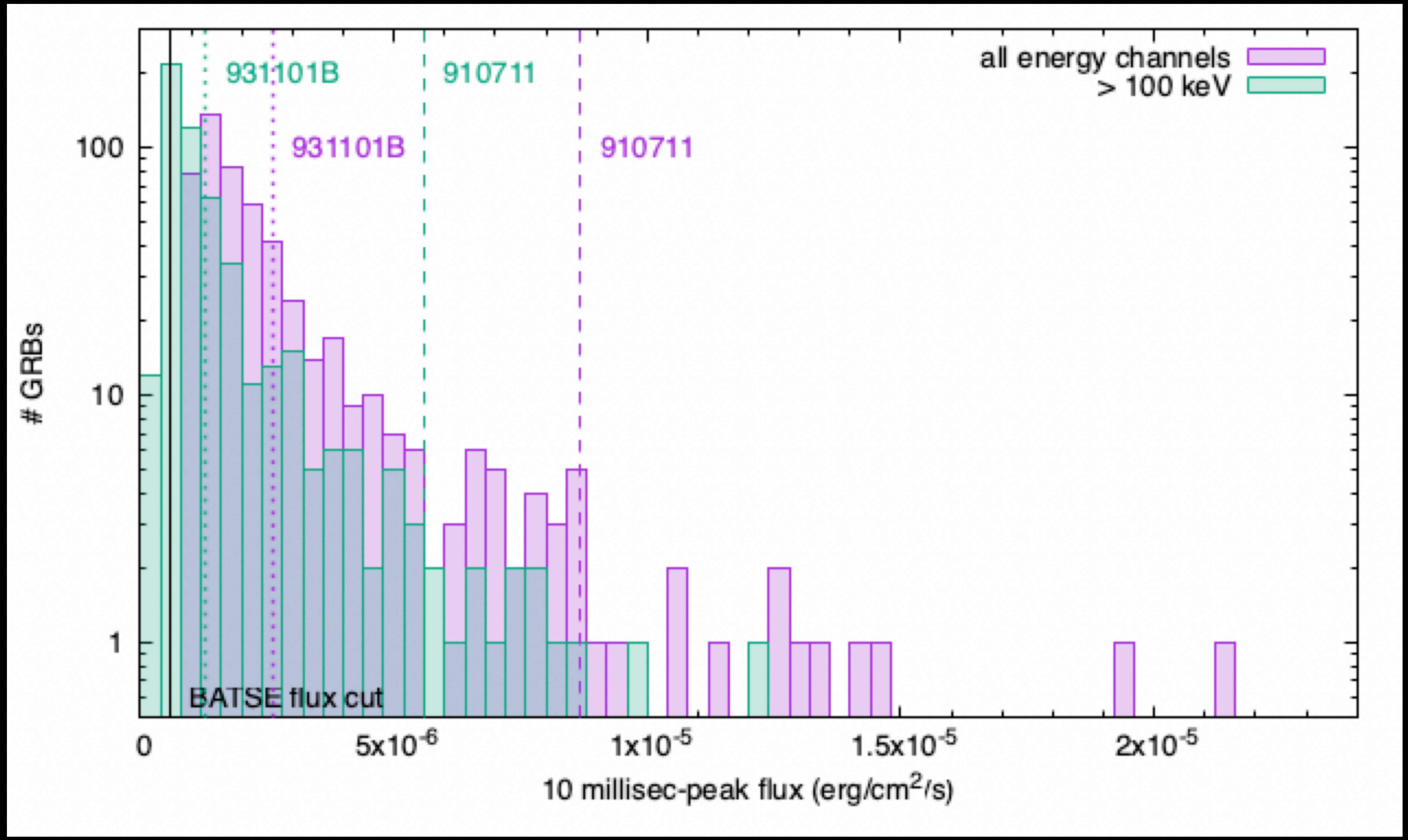






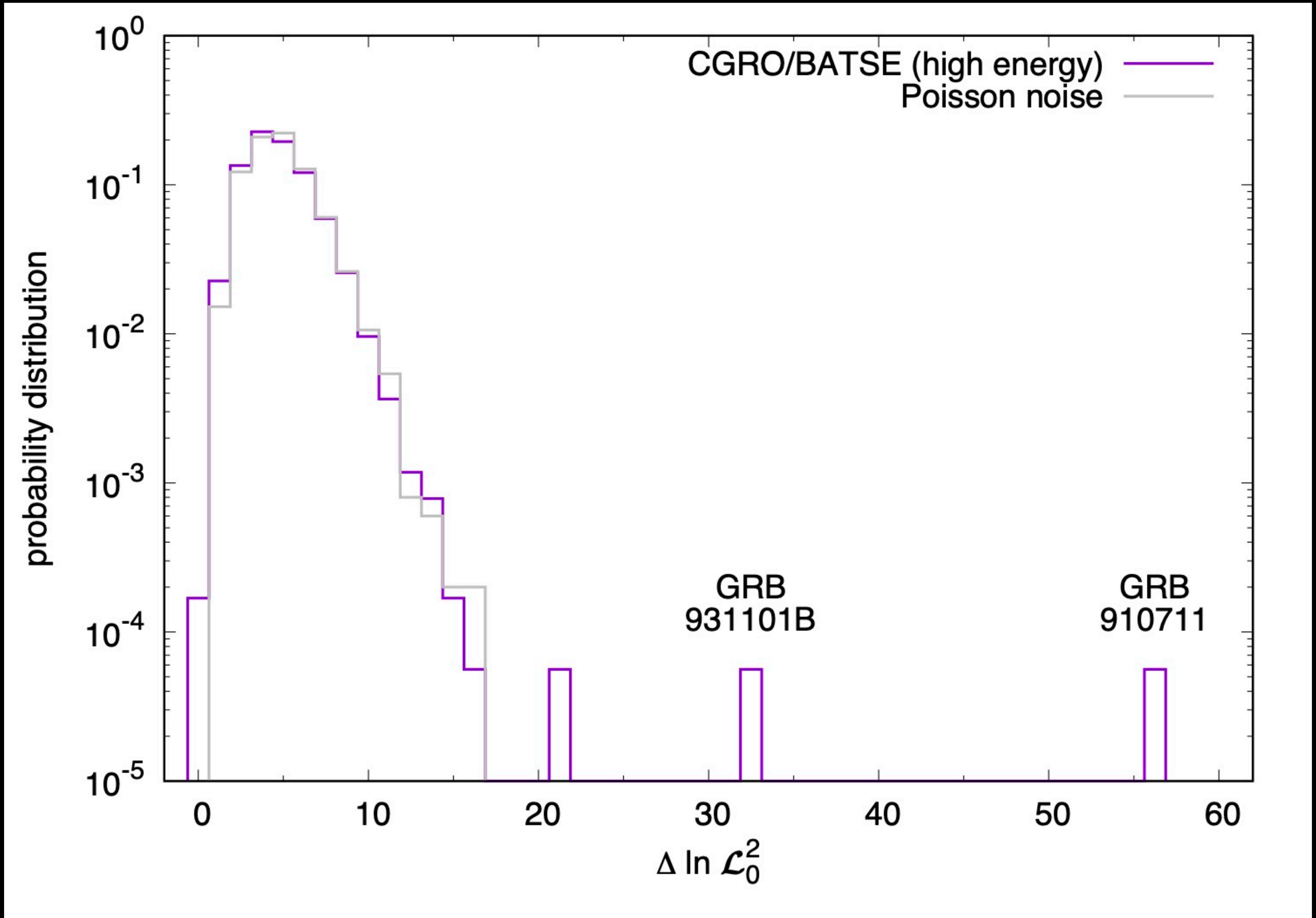
BATSE GRB distribution



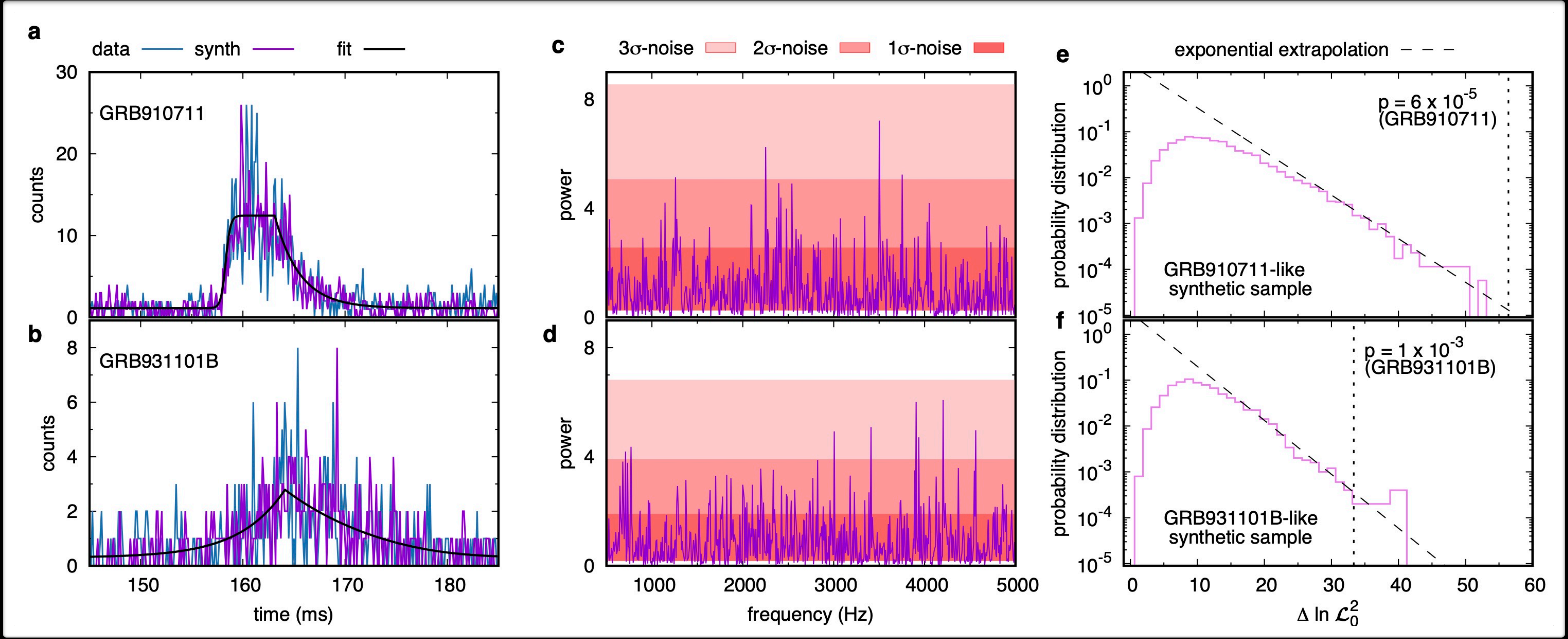


How special are these bursts?

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 $\sim 3 \times 10^{-7}$

https://www.youtube.com/watch?v=IMcU2m5YbFE

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

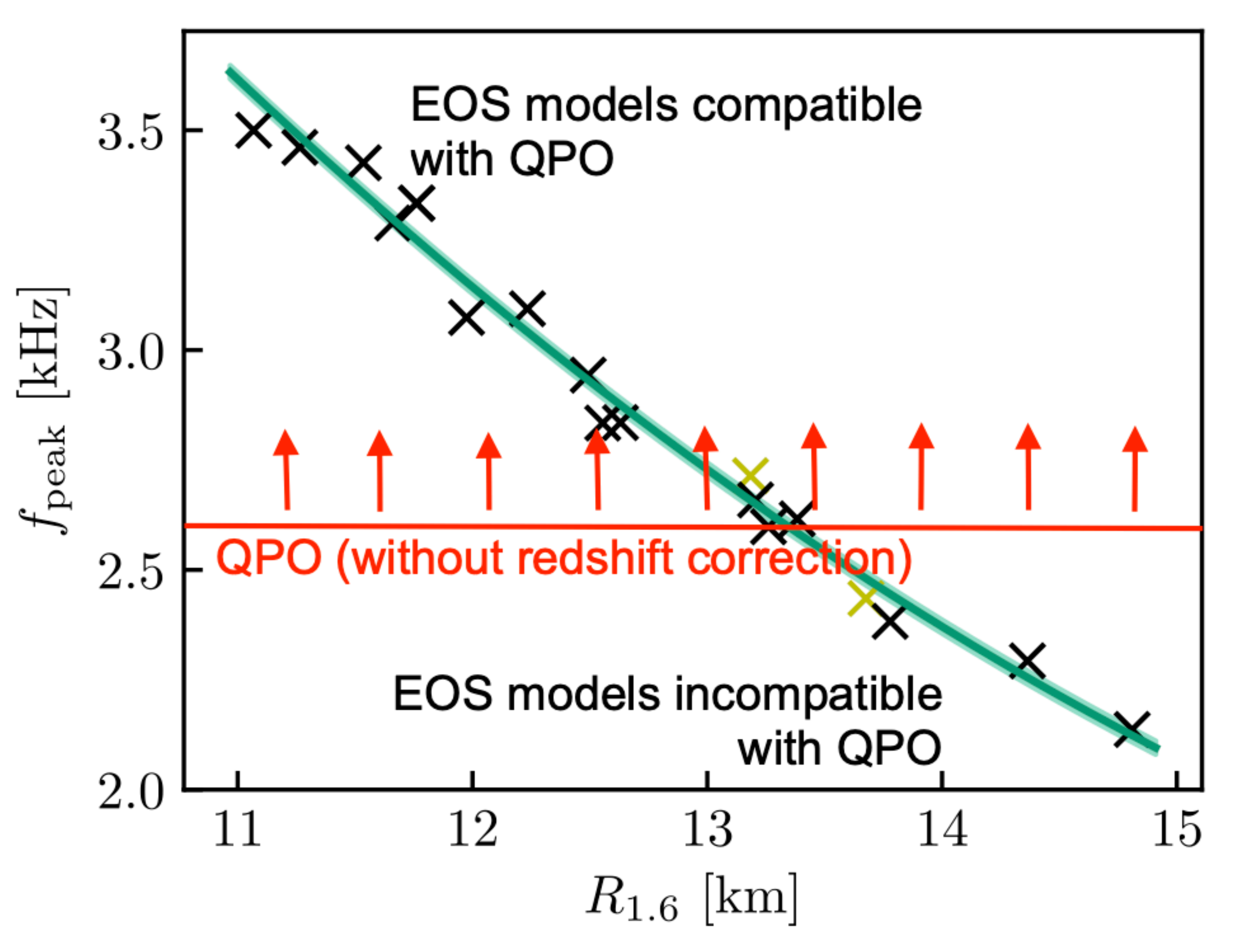
Compared with other NSs, the HMNS is:

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

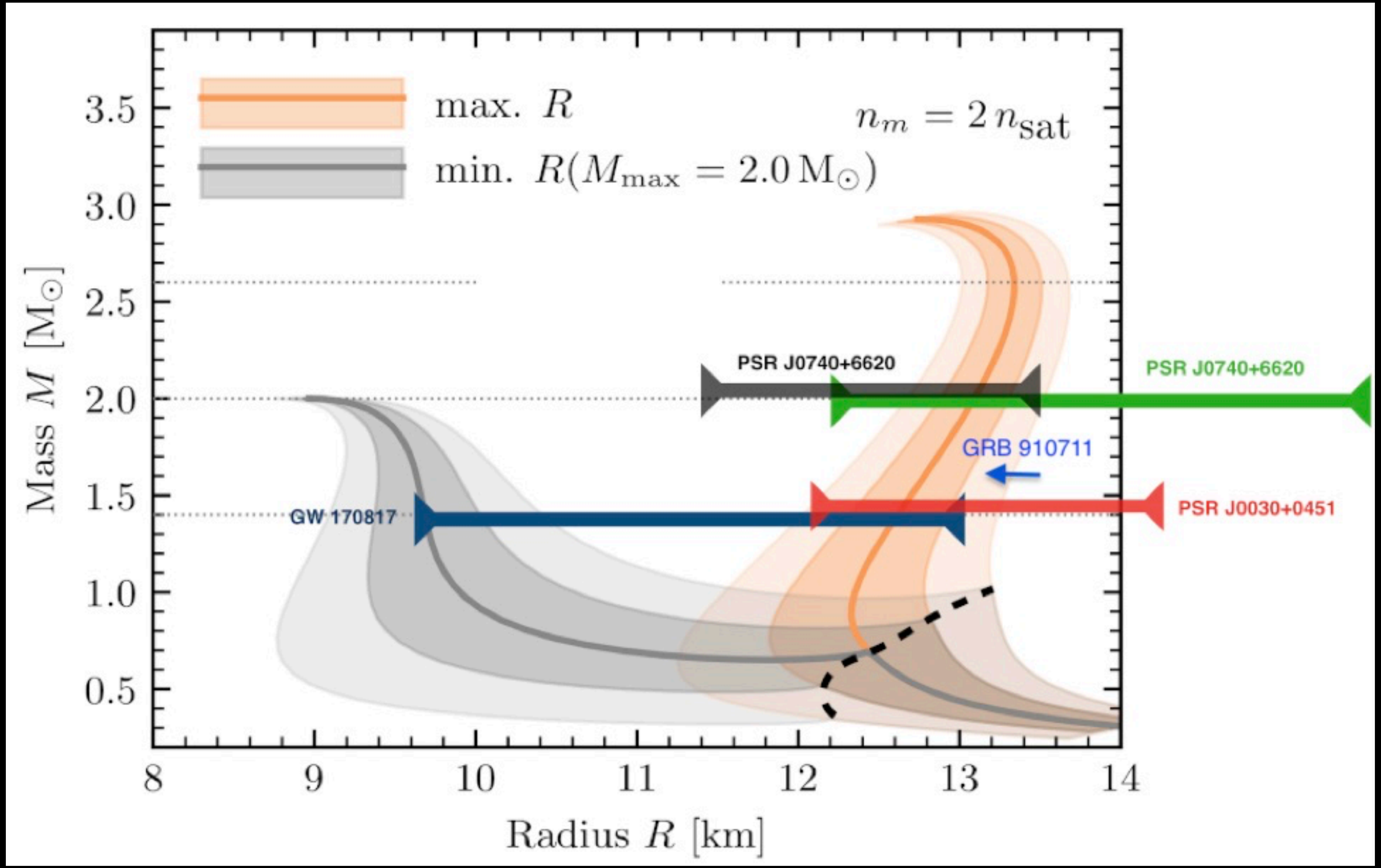
Learning about the neutron star equation of state

QPOs + NR



adapted from Lioutas et al., 2021

NICER + GWs + GRB

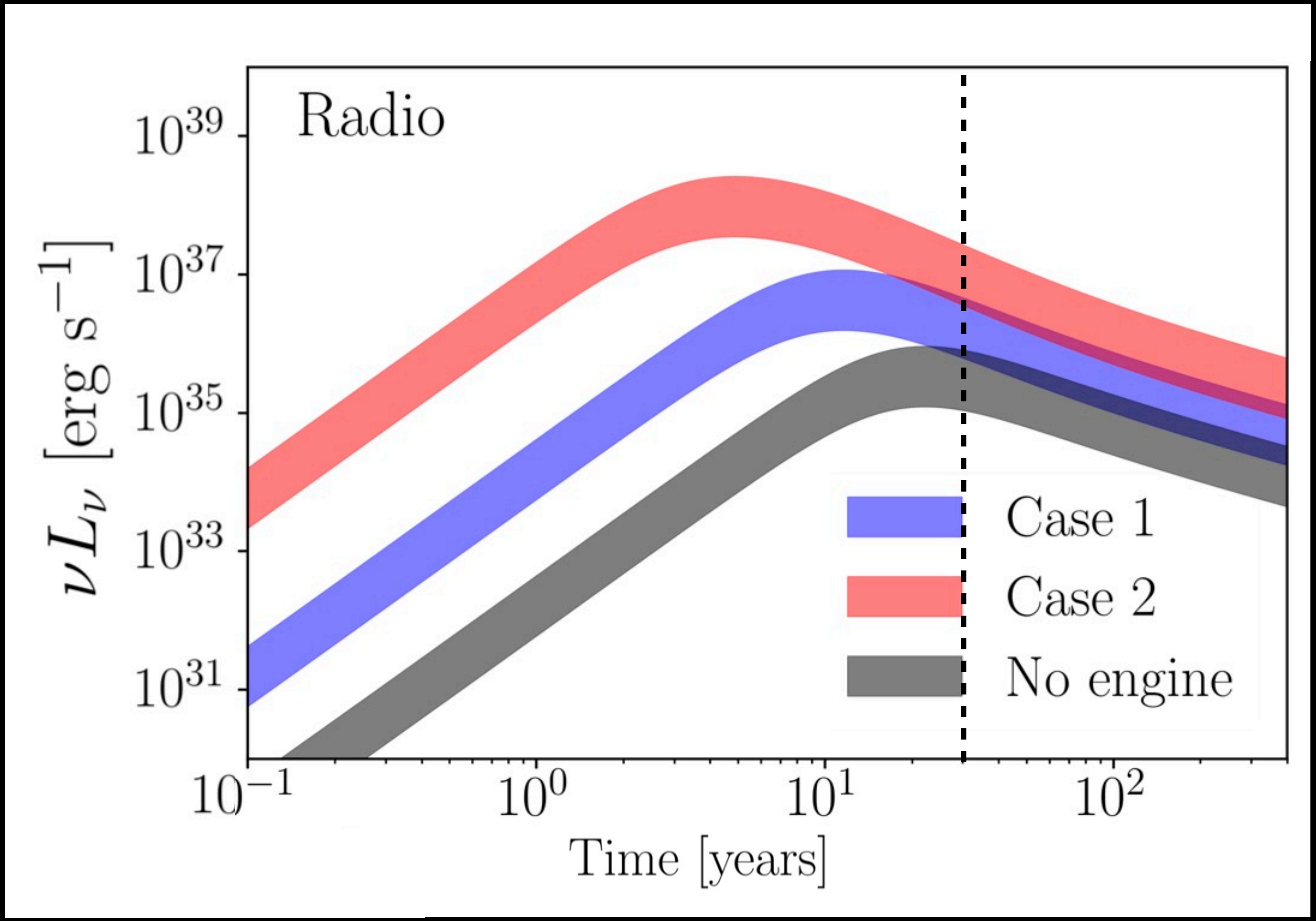


adapted from Reddy, 2021

From gamma rays to radio?

Where do we look?
R.A.: 209.9°
Dec: -16.4°
Error: 9.3°

(for GRB 910711)



Sarin et al. 2022

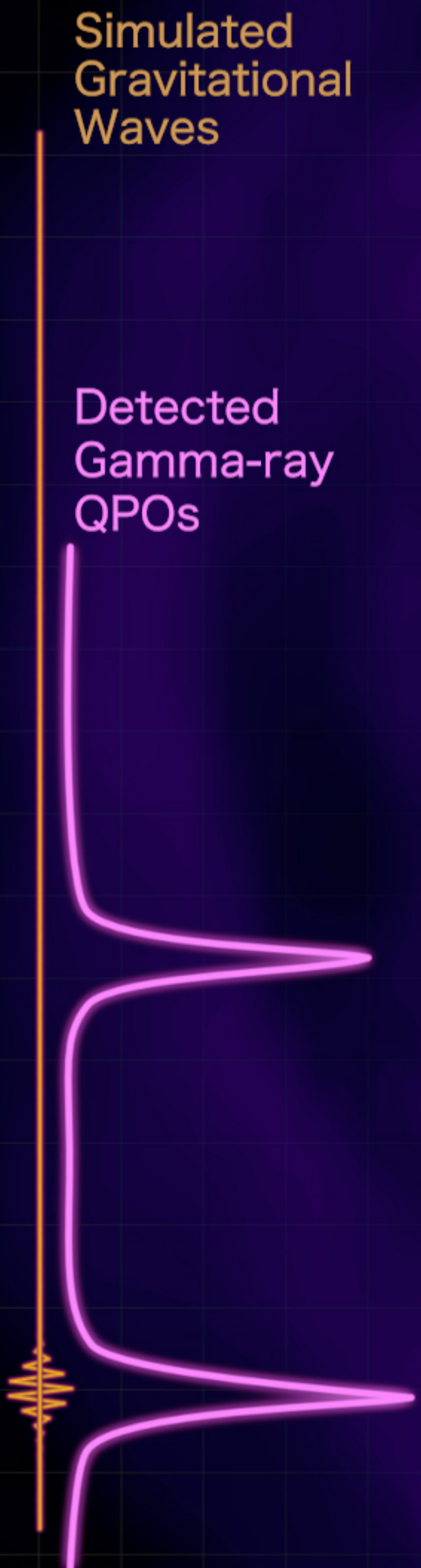
"Challenge accepted!"
- radioastronomer

Past and Future

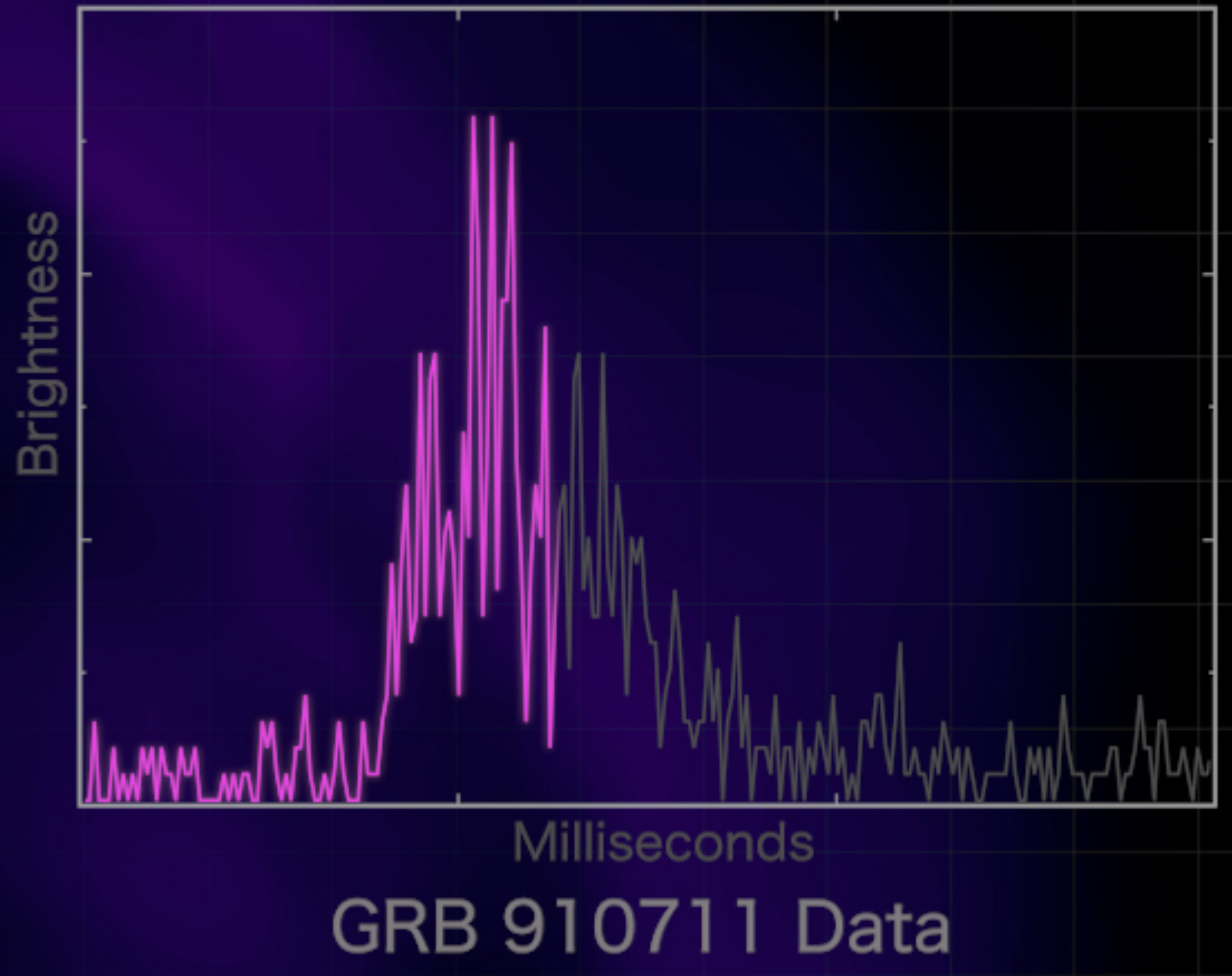
“Why BATSE”?

Future missions:

	BATSE	BAT	GBM	AMEGO-X	COSI
Effective area (cm^2)	2,000	1,400	240	1,200	256 (physical area)
Timing (microsec)	2	100	2	10	3



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.



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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