Detecting hypermassive neutron stars with short gamma-ray bursts

Cecilia Chirenti

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

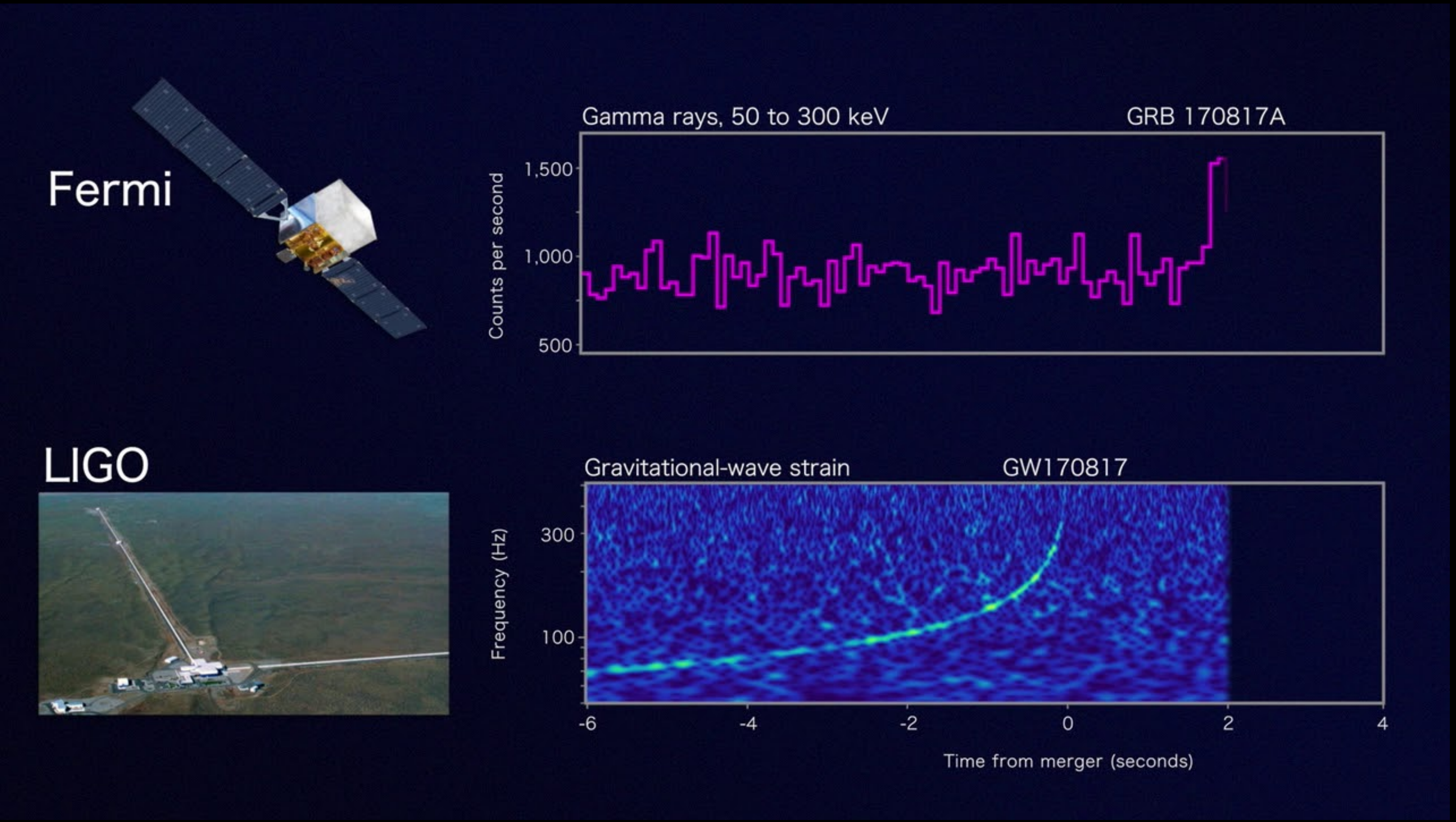
Or: Can we measure f_2 right now?

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

INT Workshop EOS Measurements with Next-Gen GW Detectors, 9/5/2024

Between the “*whoop*” and the “*ding*”…

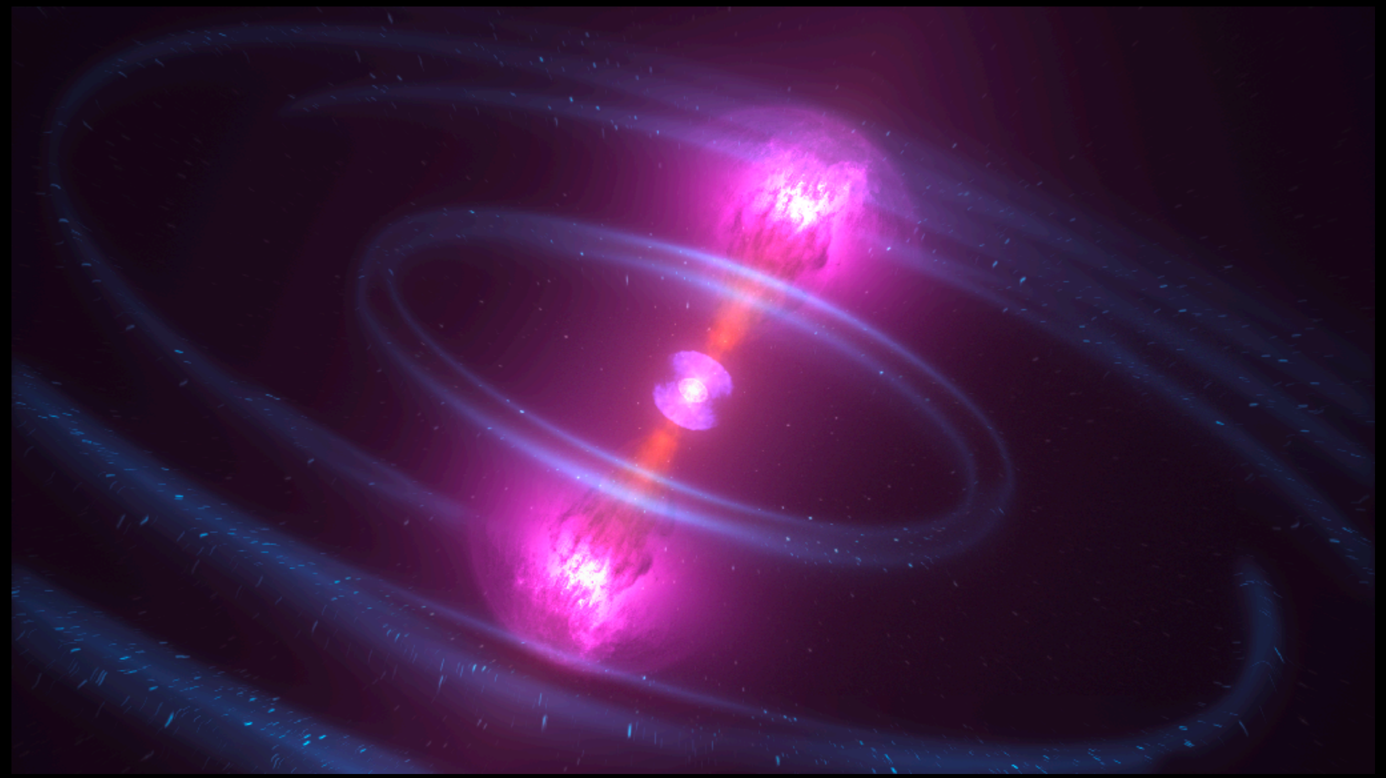
Binary neutron star merger



→ **GRB**
ding!

→ **GWs**
whoop!

When is the GRB launched?



Or: Is the central engine
a black hole
or
a neutron star?

… a hypermassive neutron star?

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

Can the HMNS power the short GRB?

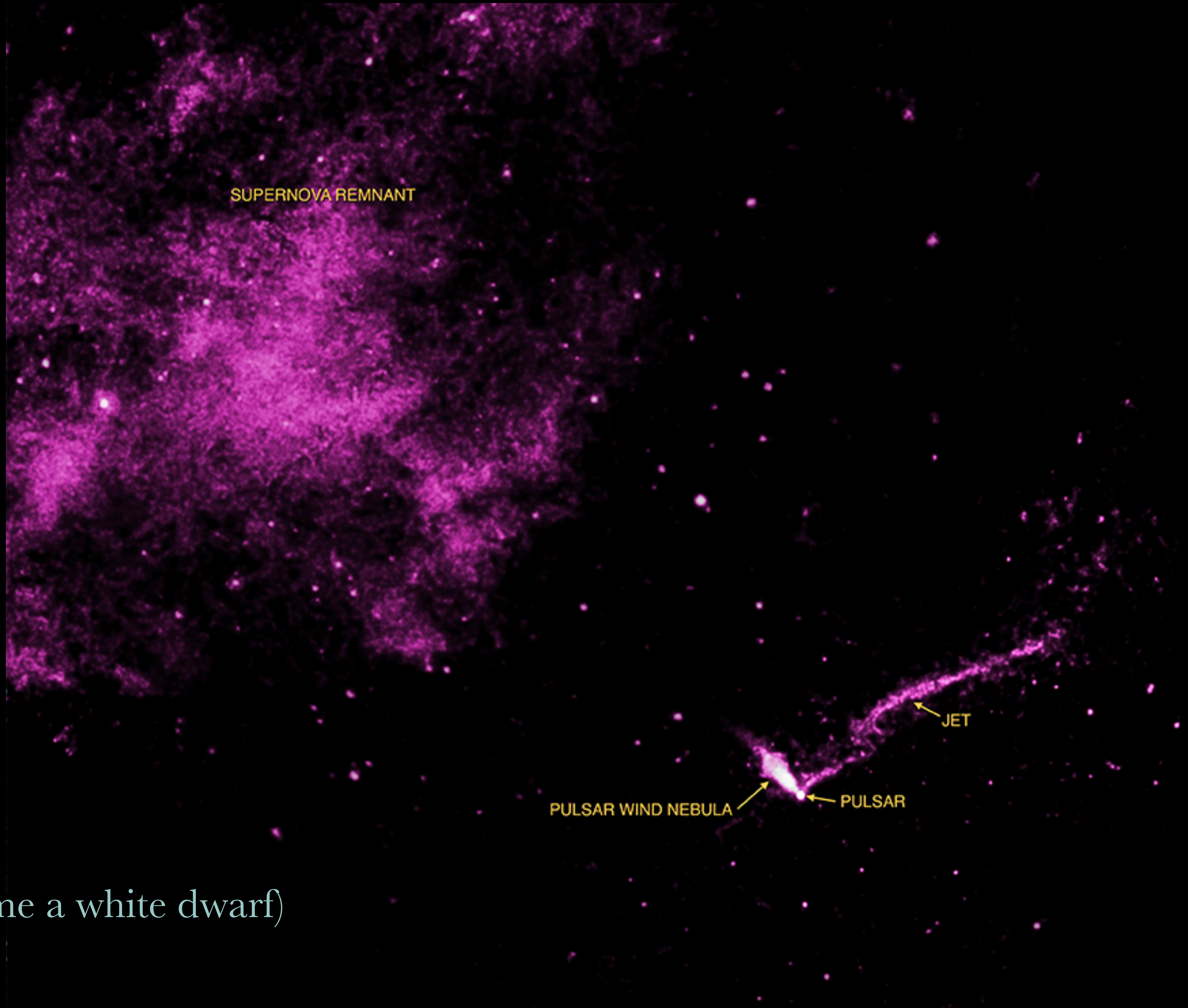
(In the astro community: millisecond magnetar scenario)

Can Neutron Stars launch jets?

Yes!

We see jets from NSs all the time (pulsars, LMXBs…)

Typically, Lorentz factor Γ of the jet corresponds to the escape velocity of the star



Other stars can also launch jets: e.g.

- TTauri (young, low mass, variable stars)
- planetary nebulae (red giant on its way to become a white dwarf)

Can Neutron Stars launch GRBs?

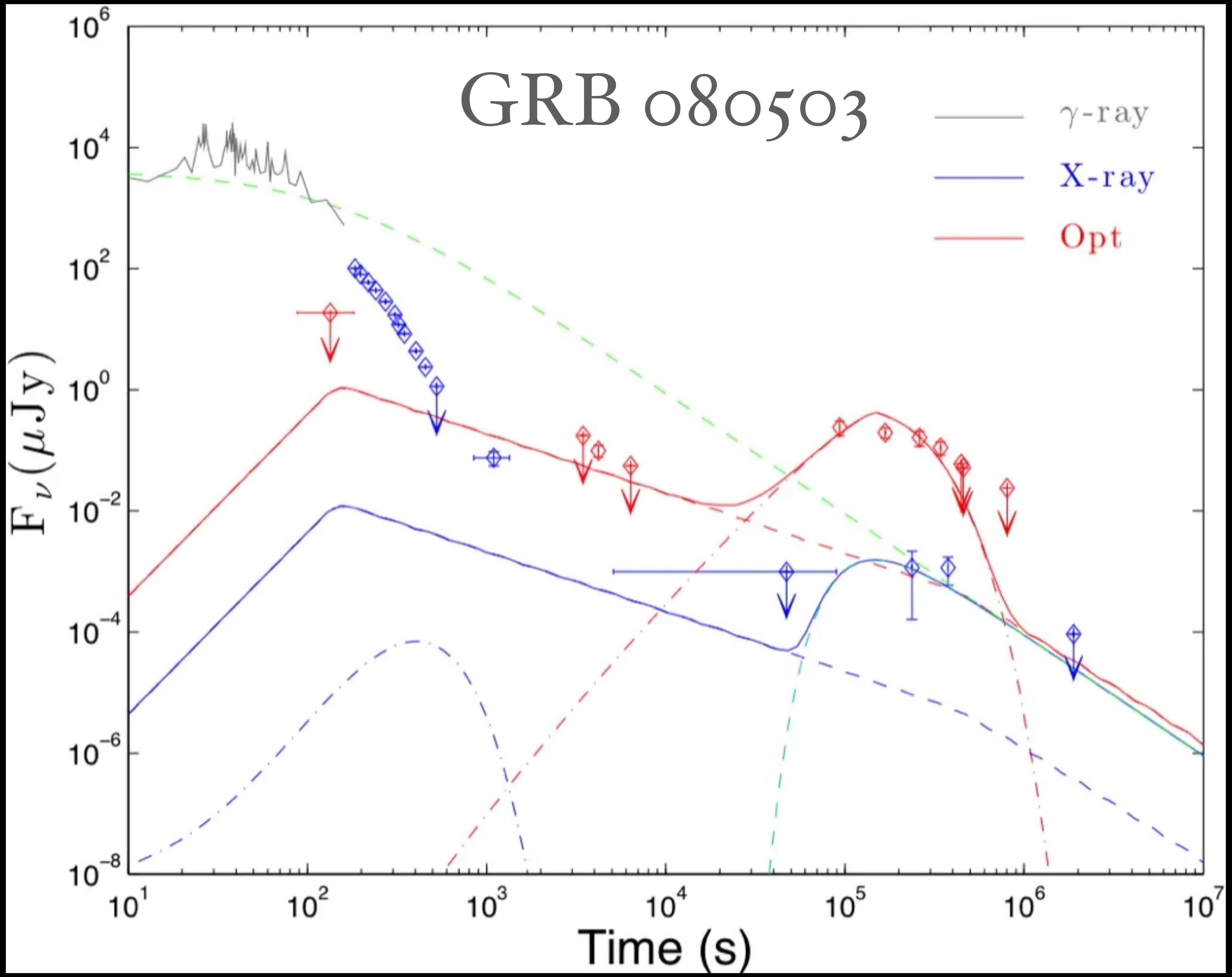
Maybe!

Observed γ-ray extended emission, X-ray plateaus, and optical rebrightening can signal late time energy injection from magnetar central engine

But GRBs typically have
$\Gamma \sim 100 - 1000$
(magnetic fields?)

Recent simulations:

- see e.g. Mösta et al. 2020
- it is easier to simulate jets with black holes
- HMNS scenario requires dynamo amplification of B field



Gao et al. 2015

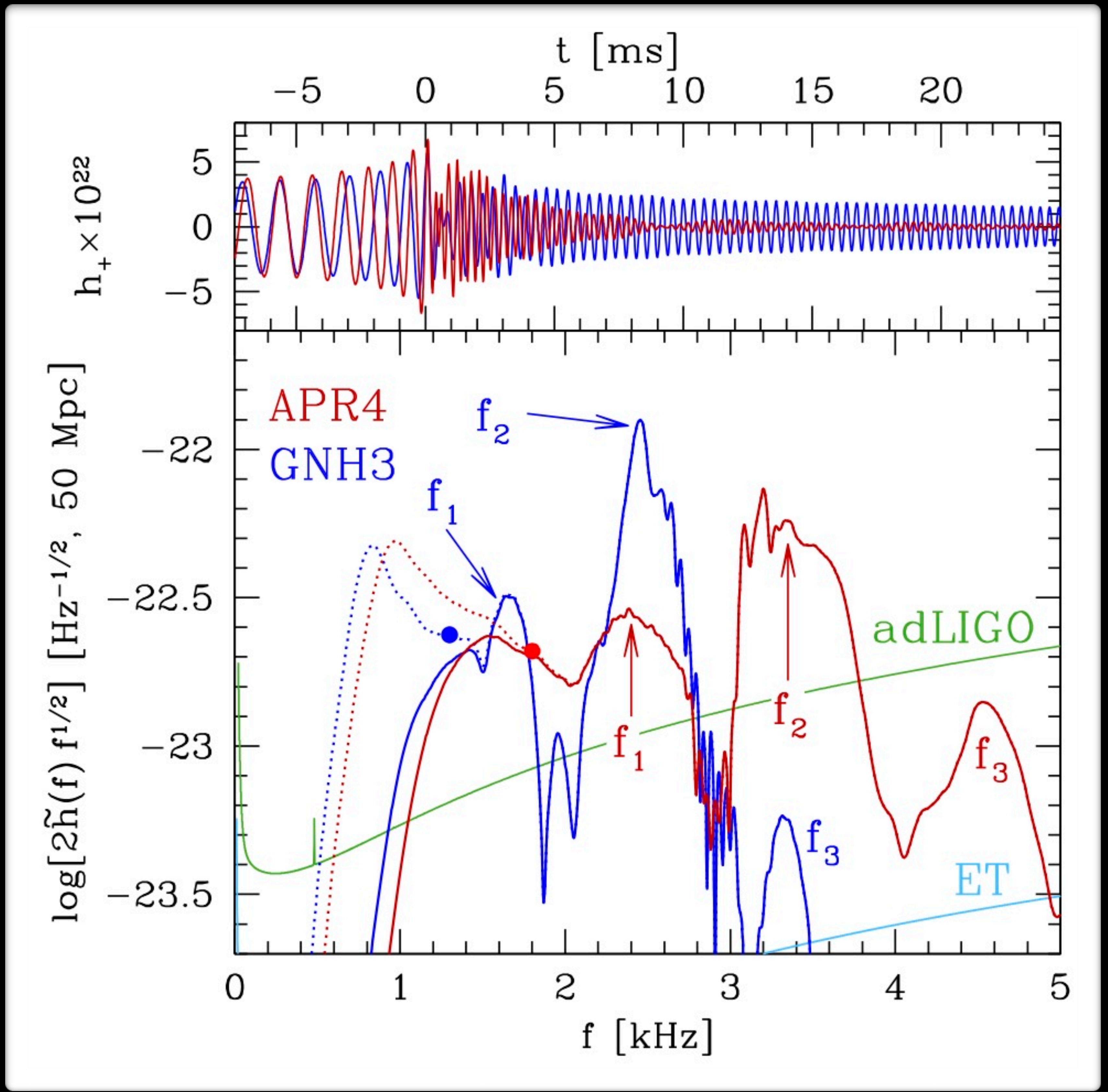
HMNS Quasi-periodic oscillations

HMNS signal:

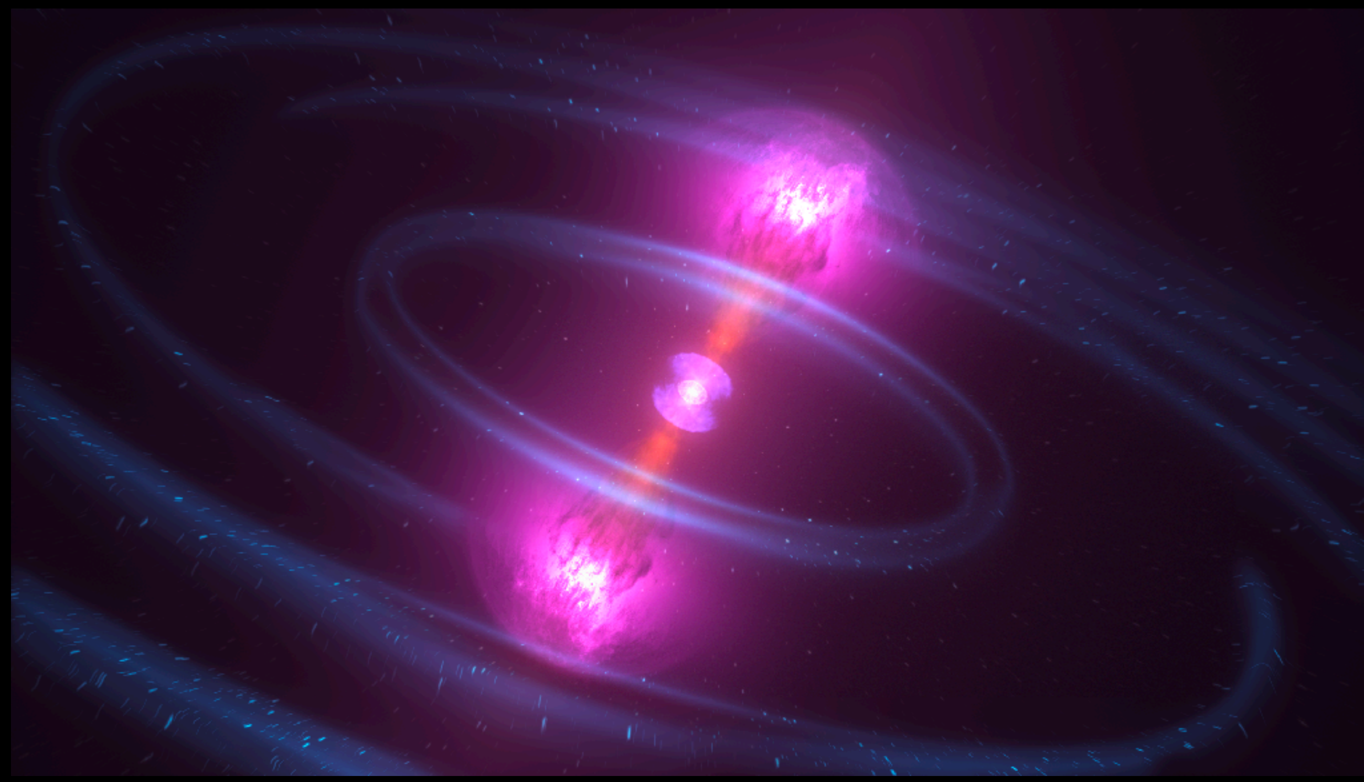
short-lived
time-evolving
dissipative*

⇓

quasi-periodic oscillations (QPOs)



Takami, Rezzolla & Baiotti, 2014

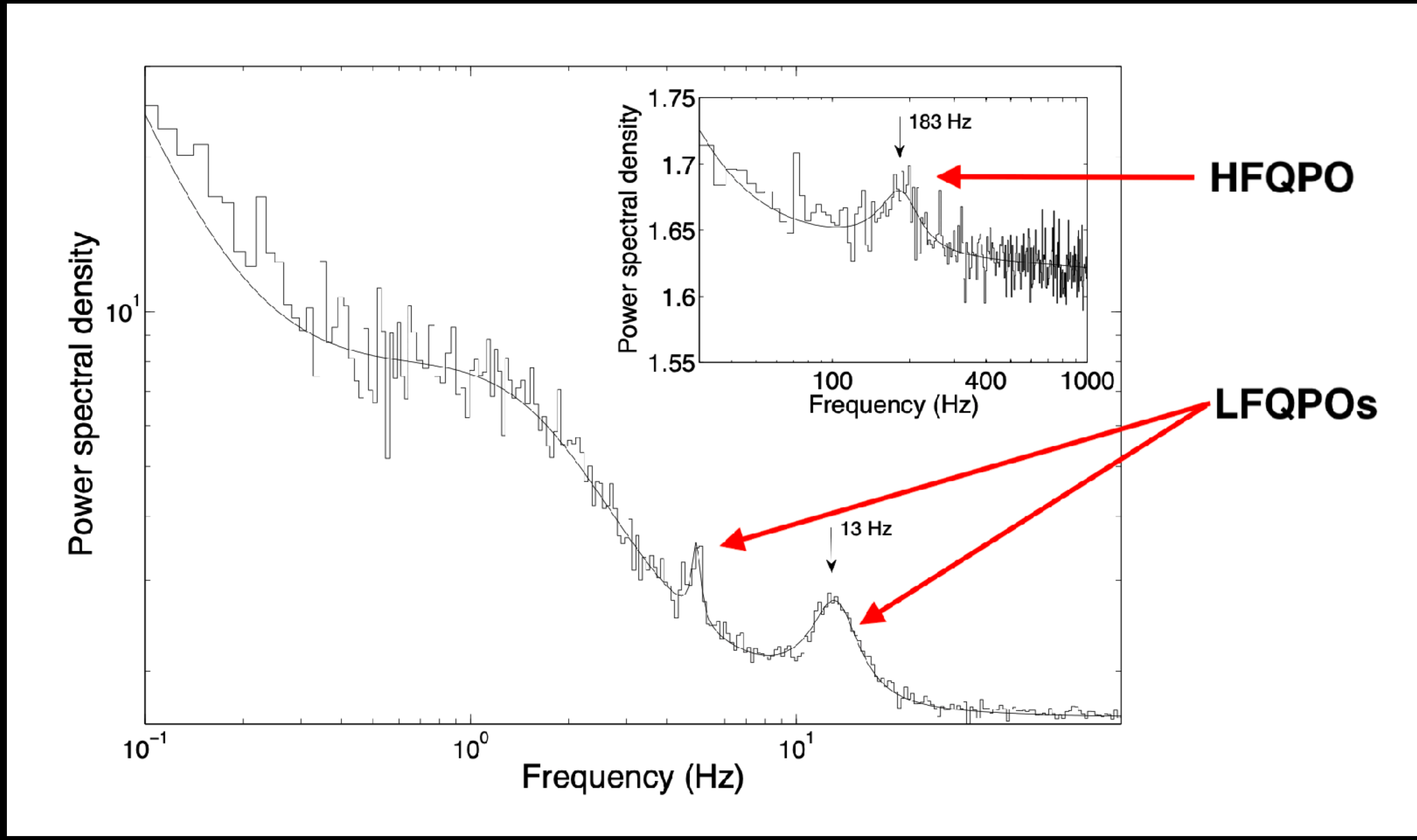


Could the GRB show these QPOs?

*simulations also have numerical dissipation!

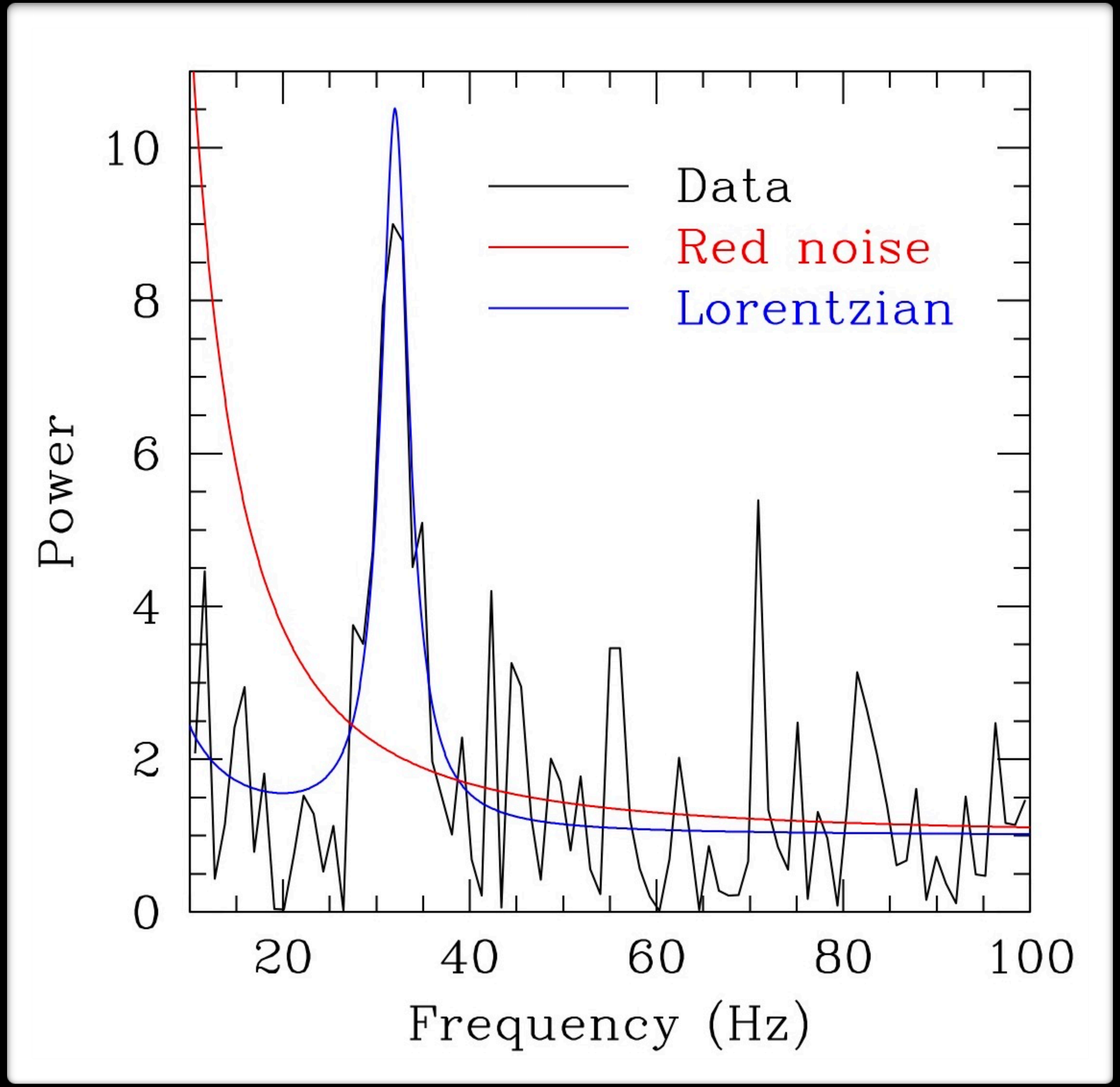
Examples of quasi-periodic oscillations

black hole X-ray binary XTE J1550-564



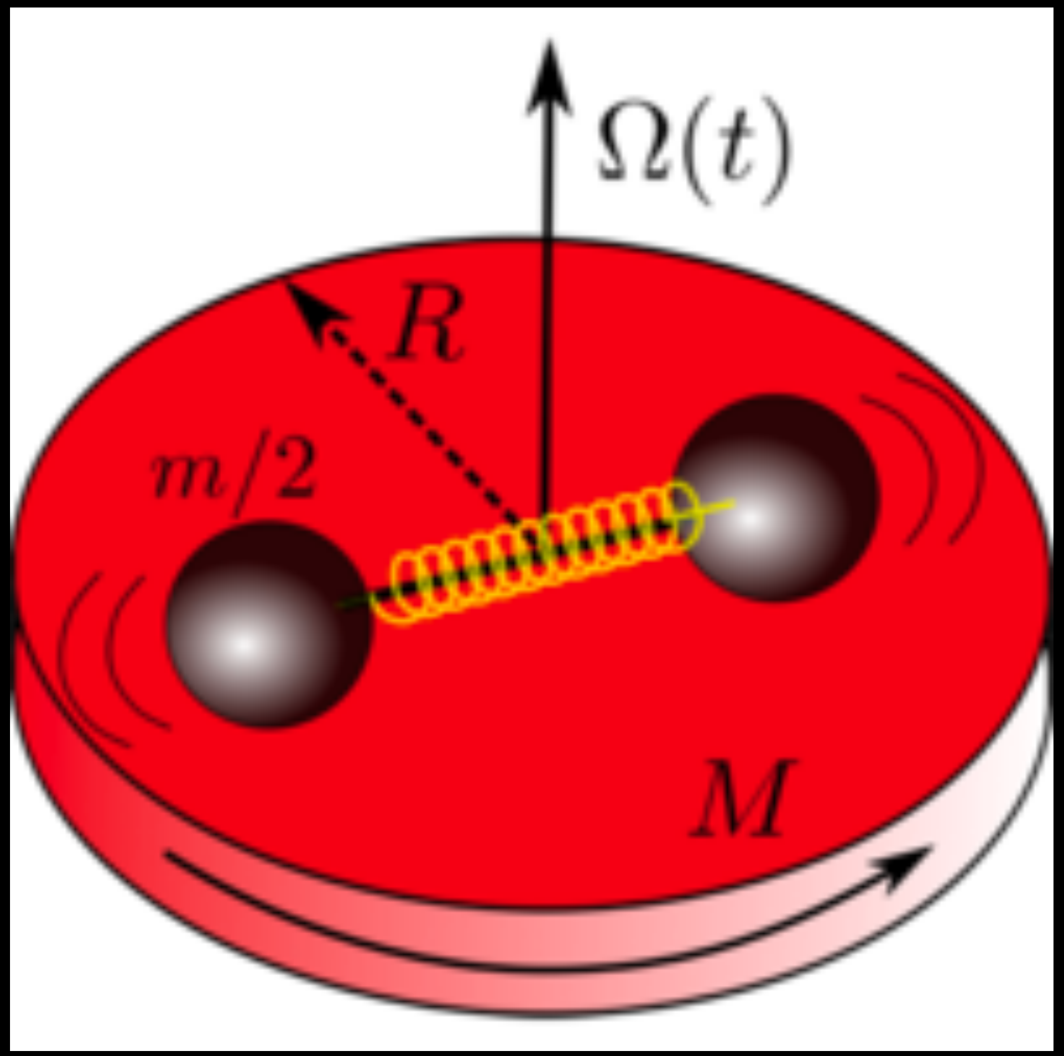
Motta et al. 2018

X-ray tail of SGR 1806-20 giant flare



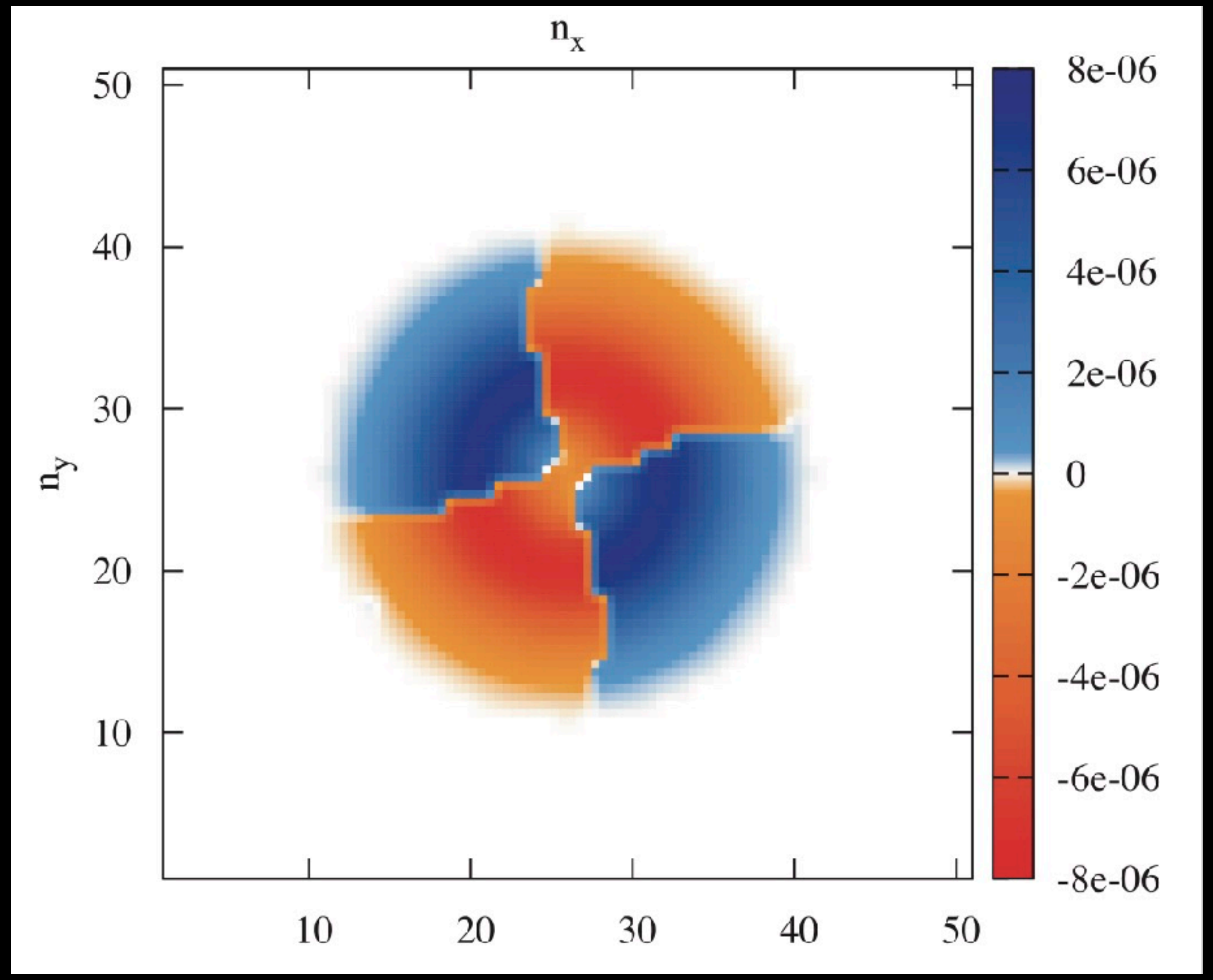
Miller, Chirenti & Strohmayer 2019

GRB QPOs?

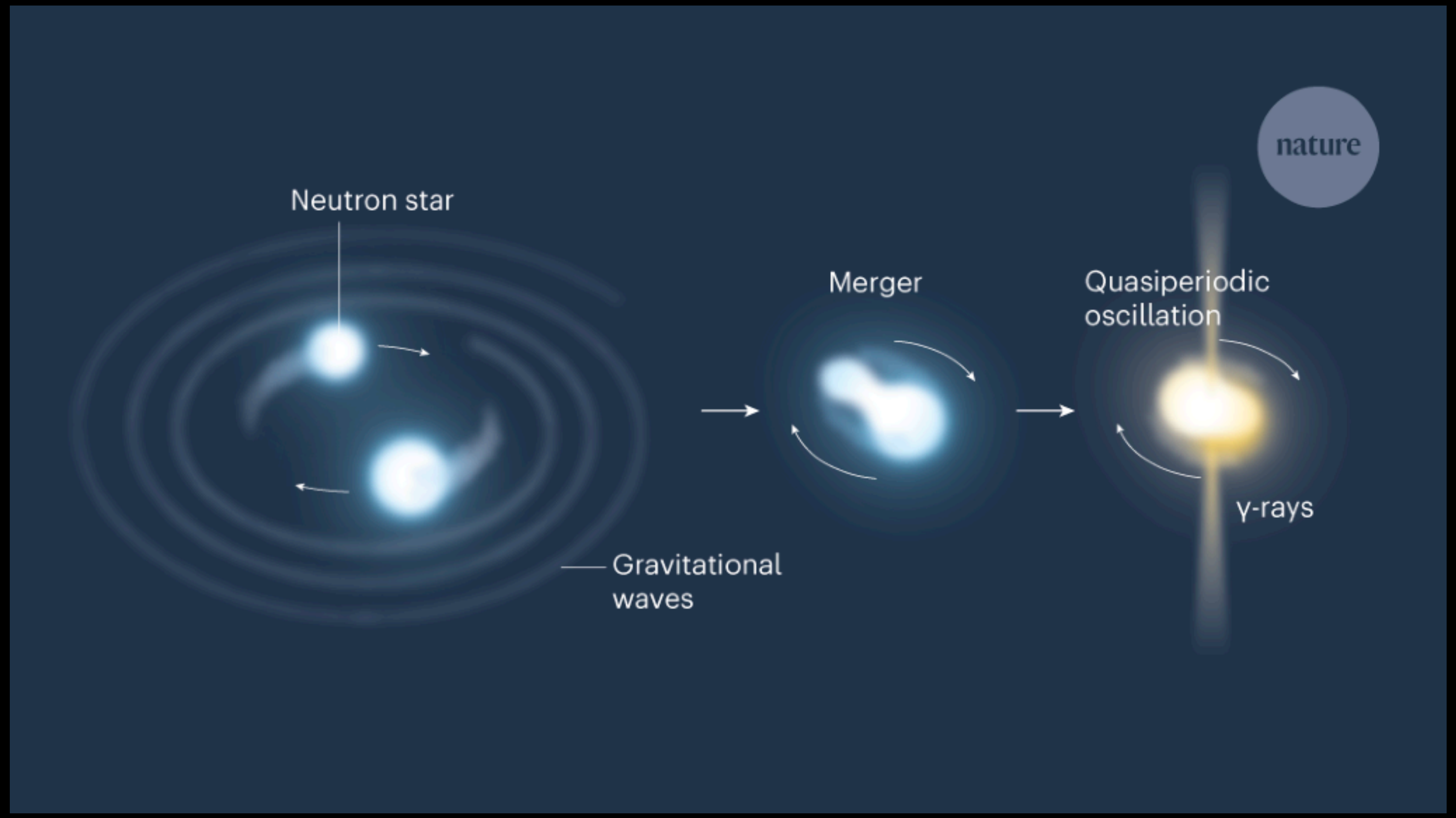


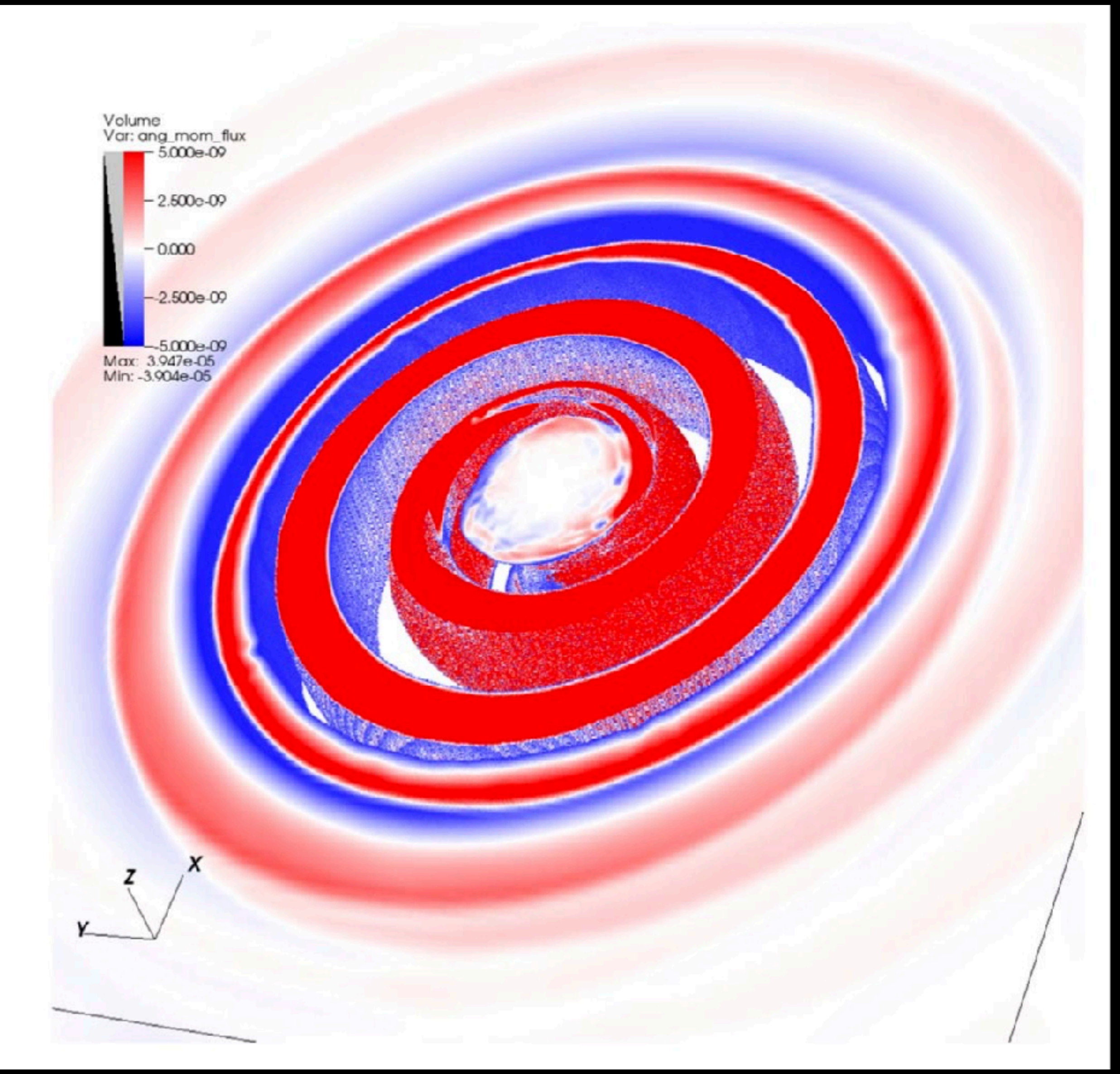
Takami, Rezzolla & Baiotti, 2015

How does the HMNS oscillate?



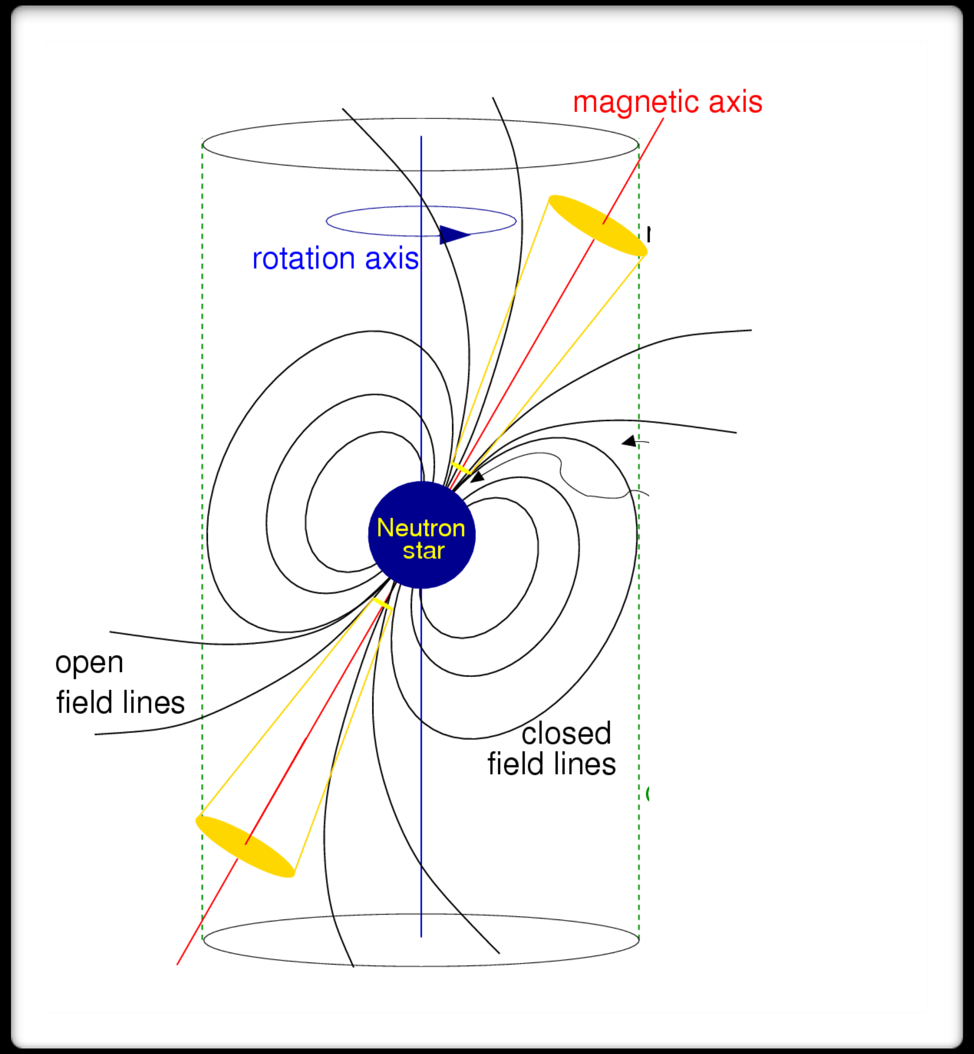
Stergioulas et al. 2011





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

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

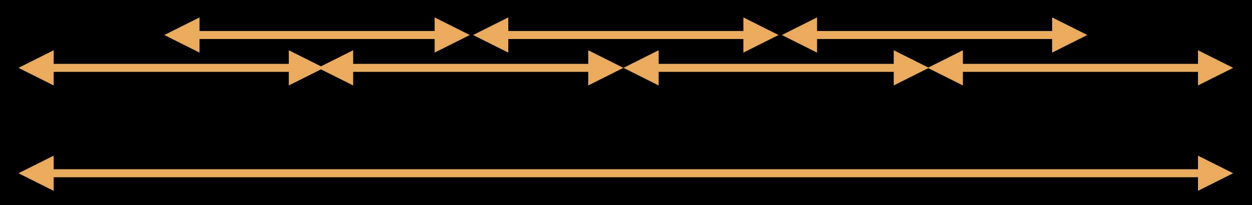
How: Bayesian model comparison

Model 0: White noise only

Model 1: White noise + QPO

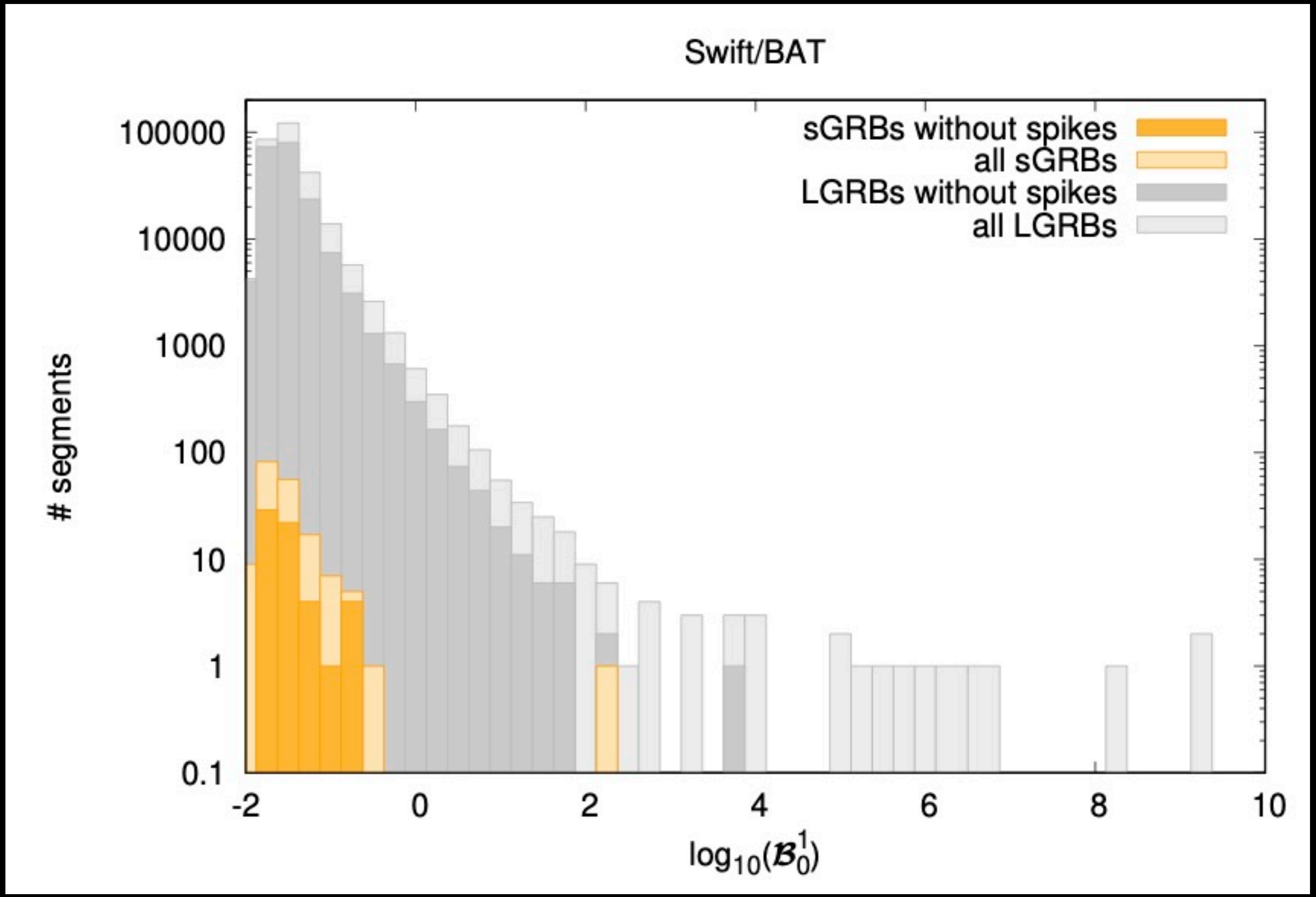
We analyze each burst divided into short segments and quote the Bayes factor in favor of the noise + QPO model for each segment

half-overlapping segments (approx 100 ms)



total burst duration

Initial analyses: Lessons learned



Causes of fake QPOs

Cosmic rays

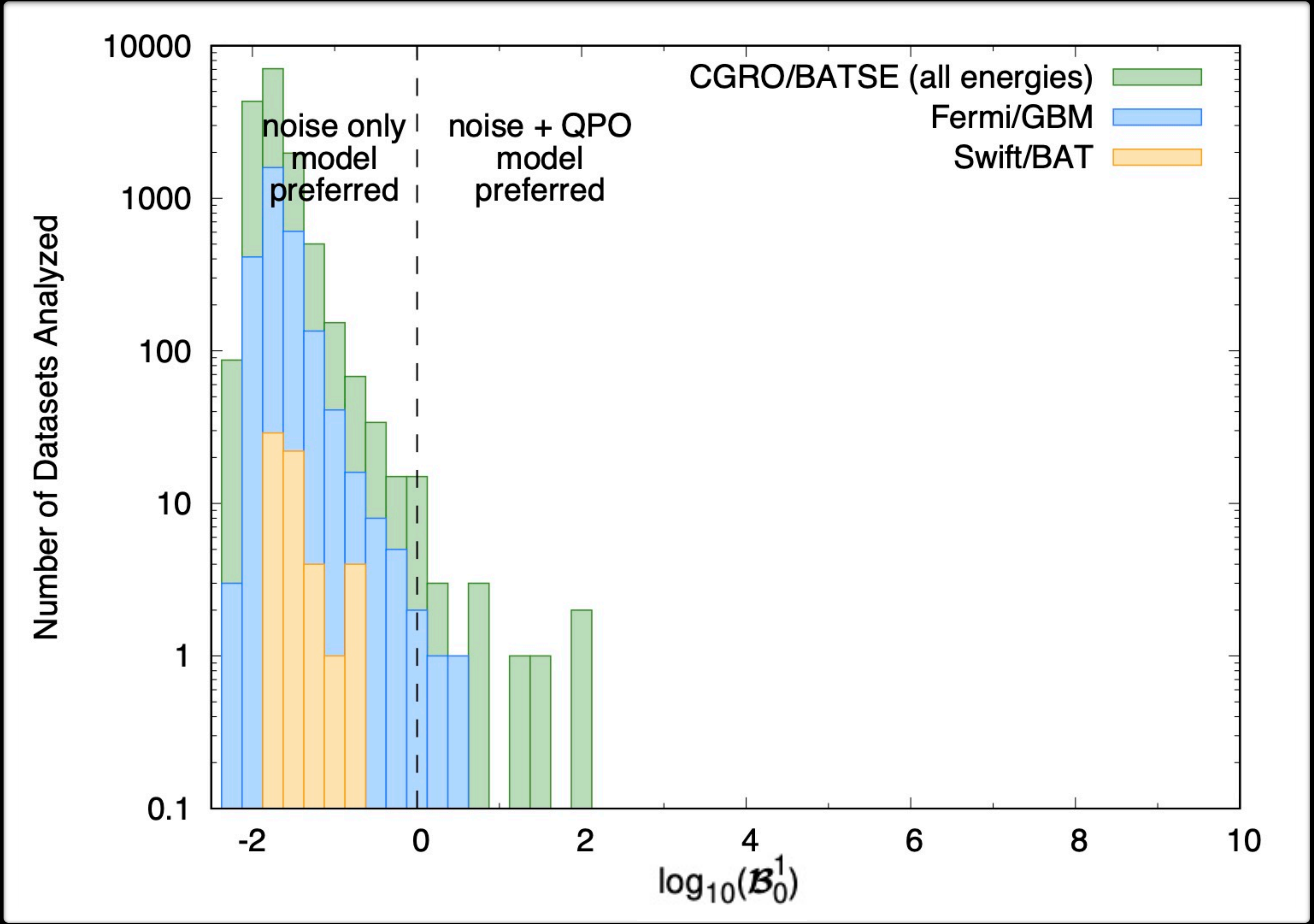
Detector artifacts*

(Data corruption)

Red noise contamination

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

Opening the treasure trove



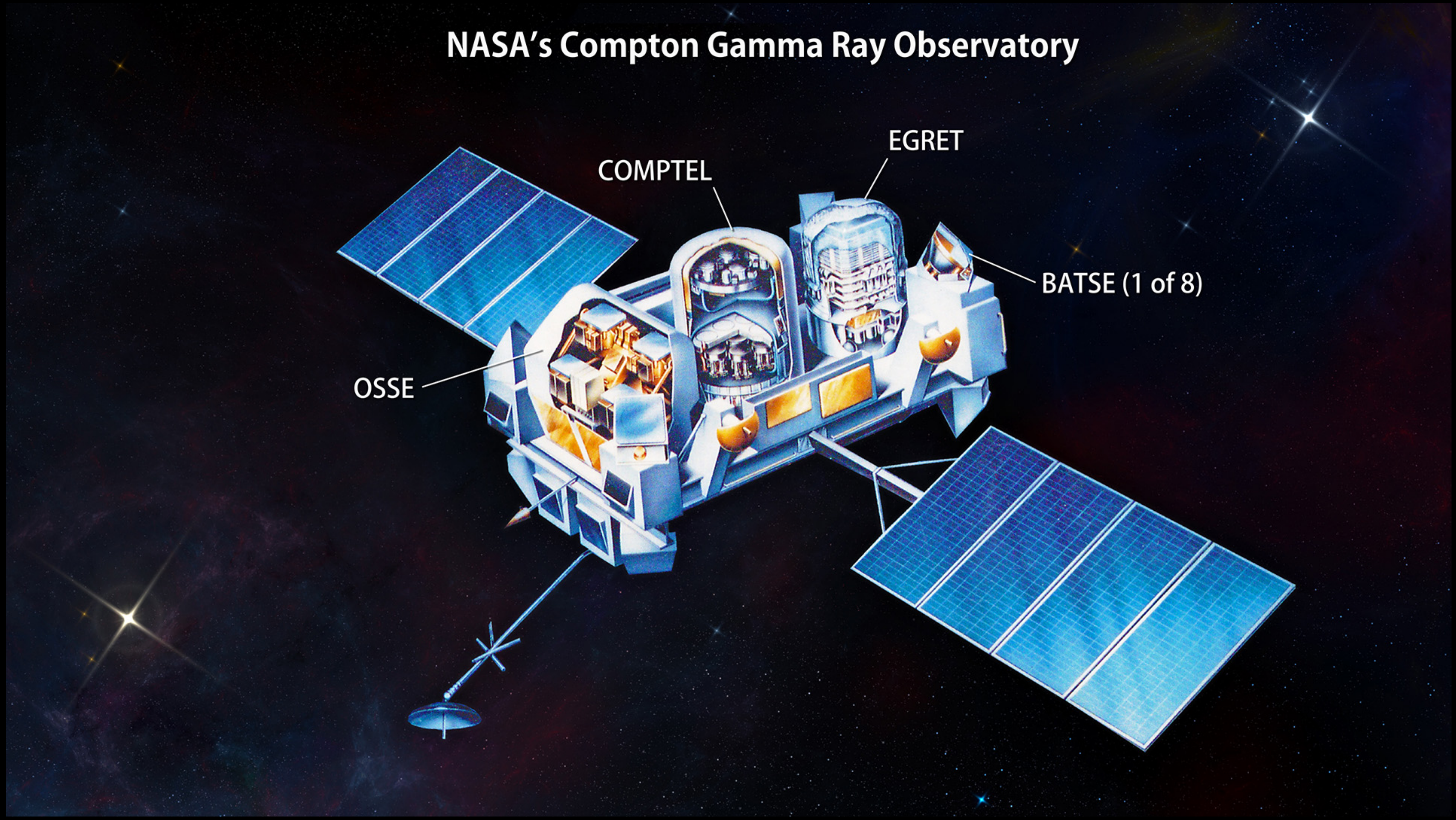
More than 700 short GRBs analyzed

Each GRB split in smaller segments for analysis

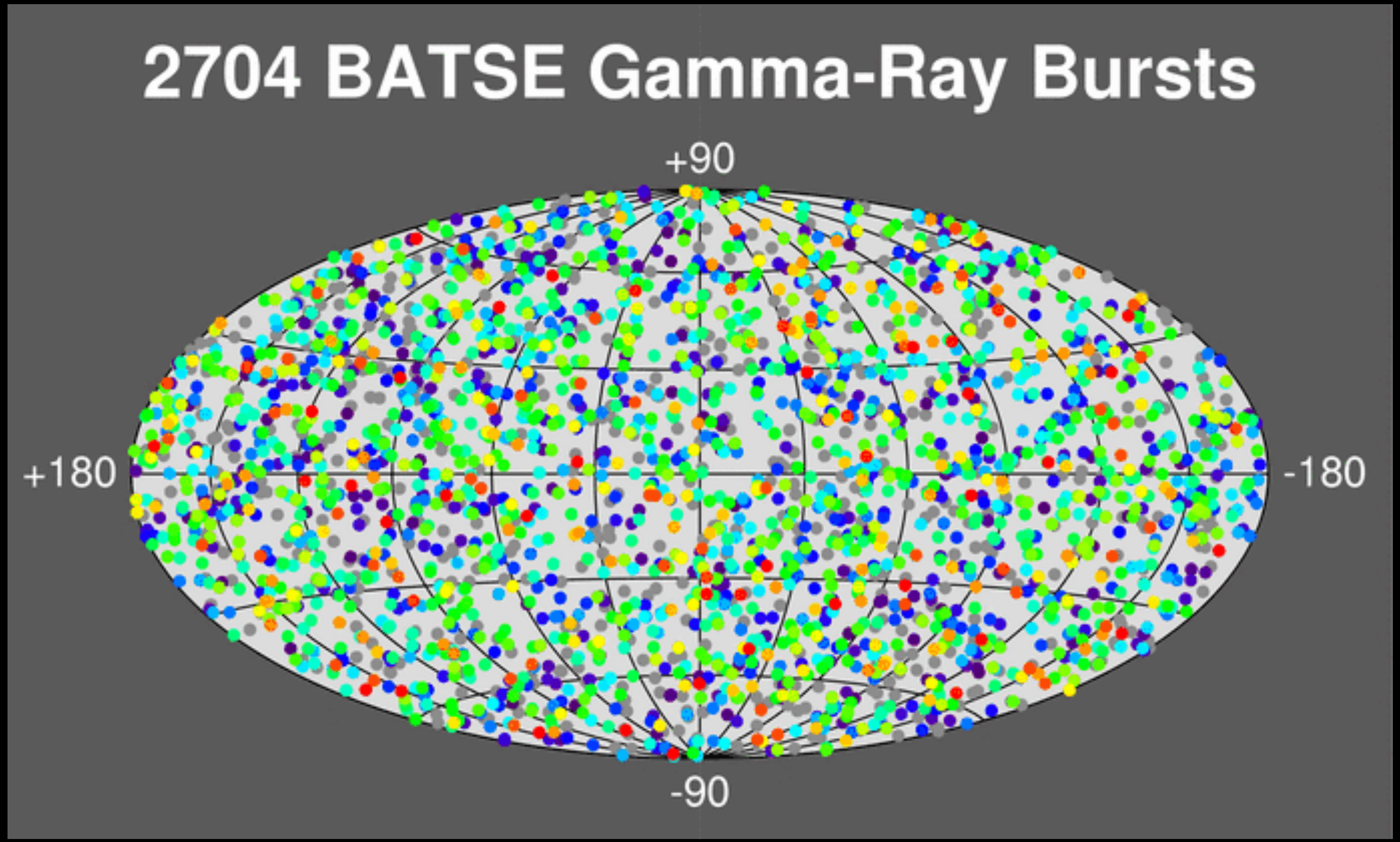
Nothing pops up in Fermi or Swift data

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

CGRO transformed GRB science

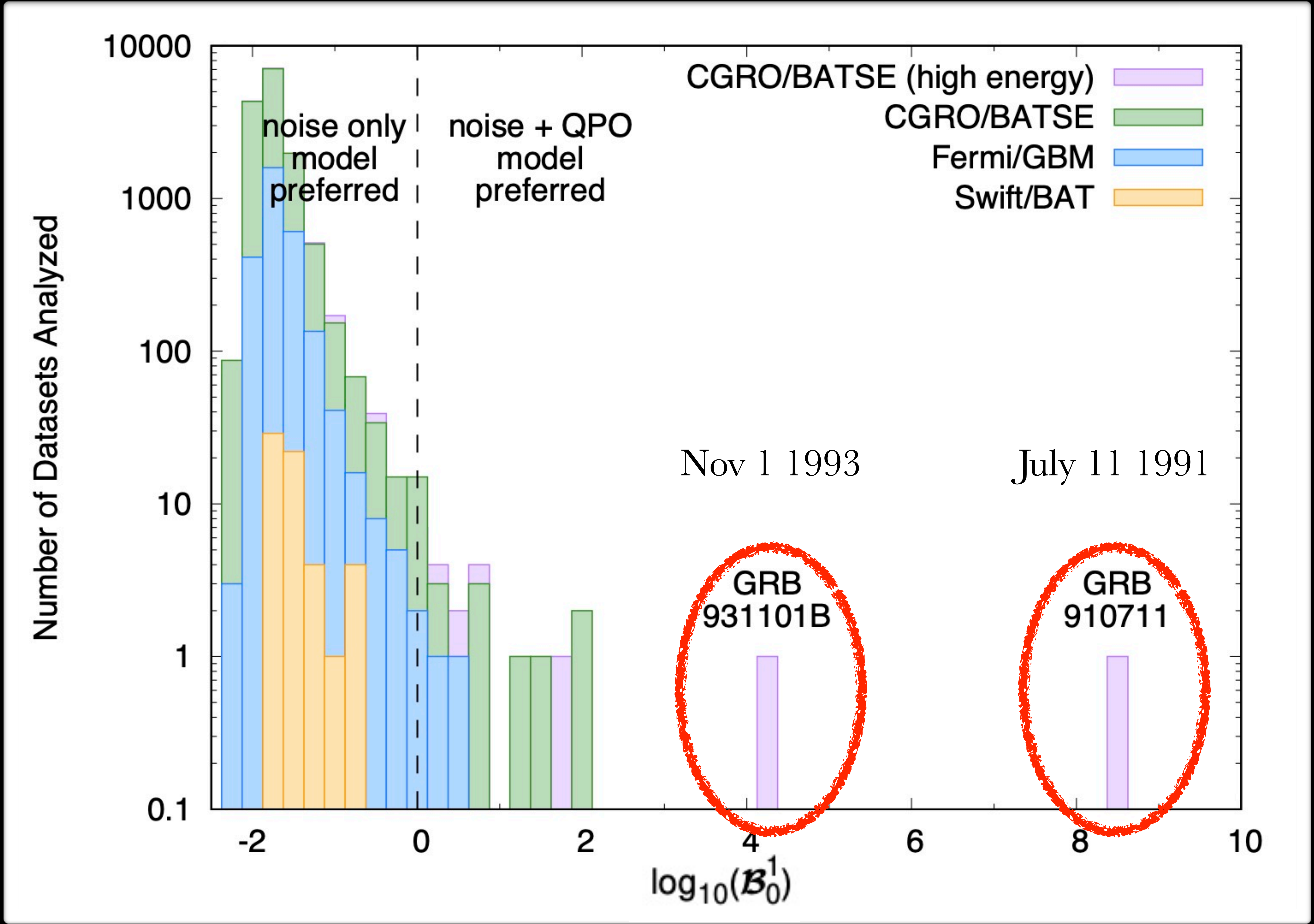


Compton Gamma-Ray Observatory
was one of NASA's
Great Observatories



Launched in 1991
De-orbited in 2000

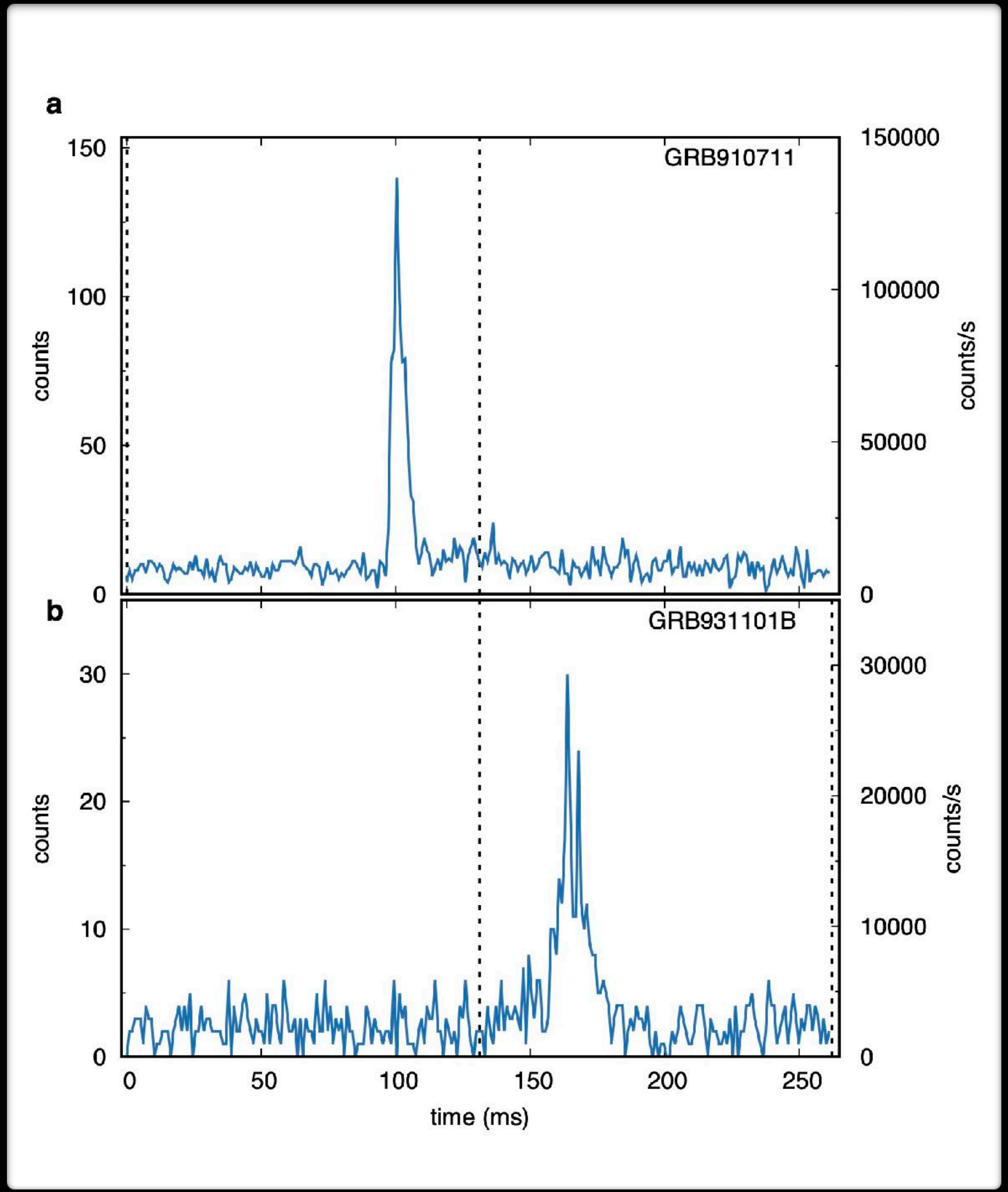
Opening the treasure trove

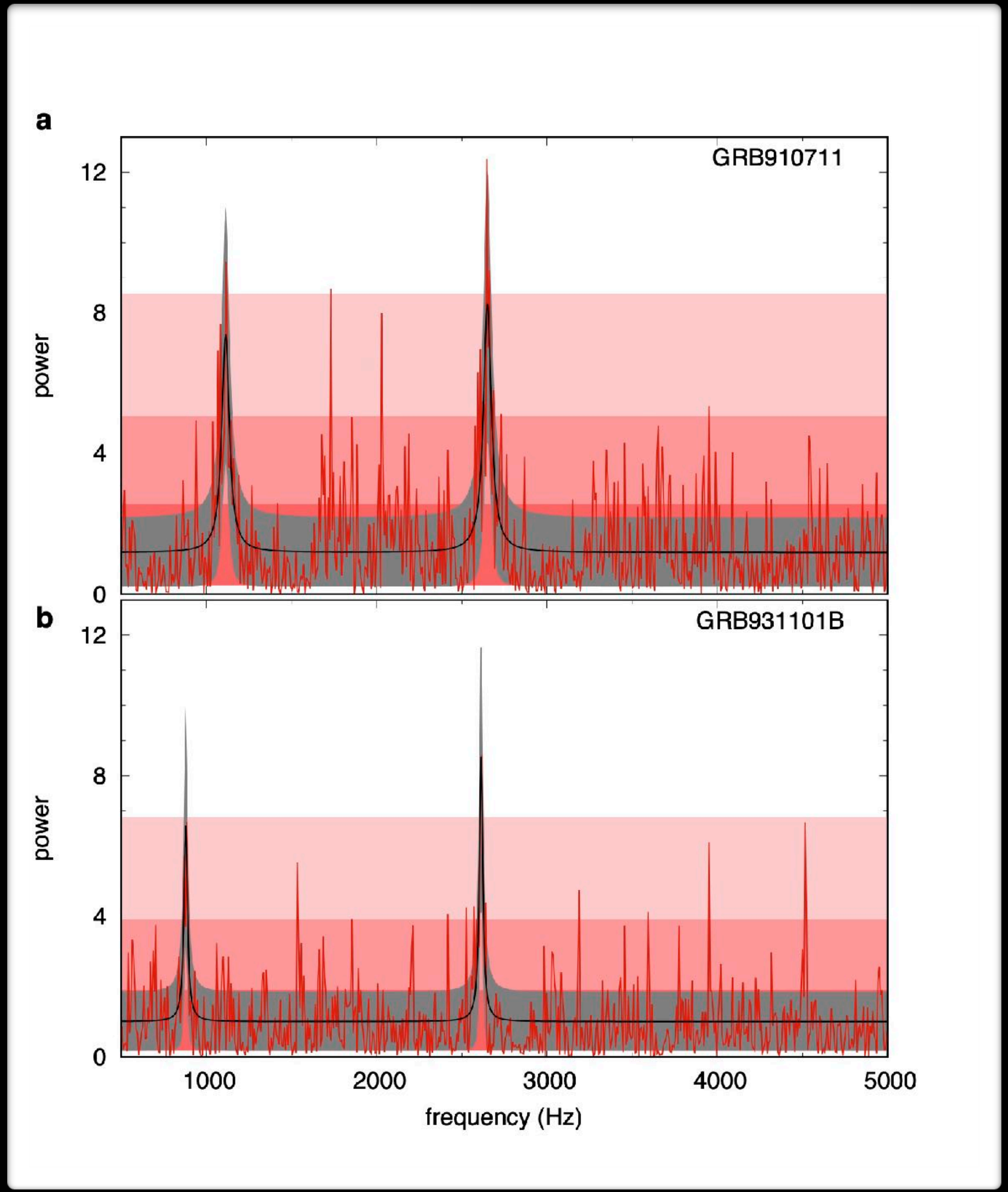


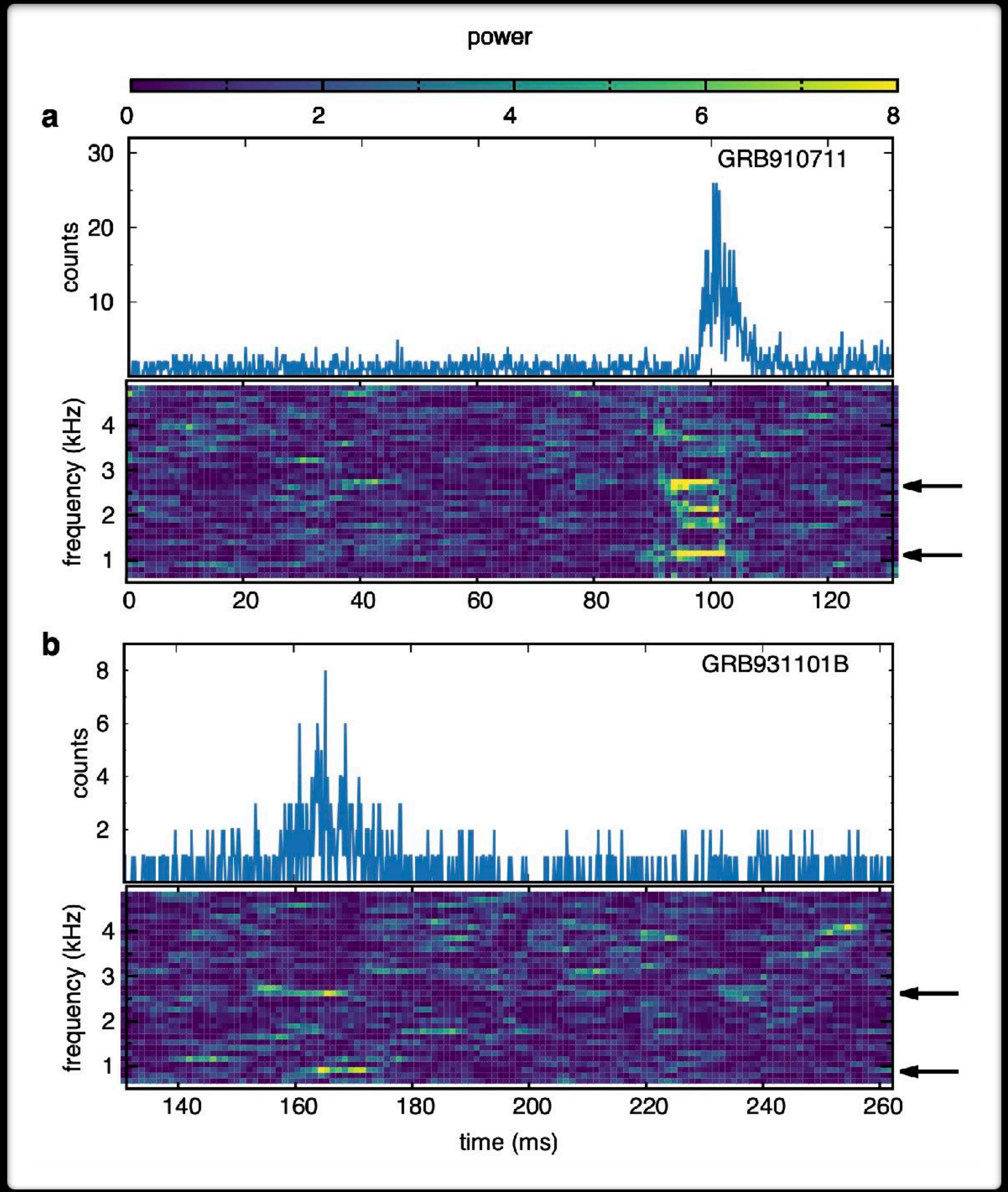
… and **bang**! Two signals. The combined false positive rate is 1 in 3.3 million!

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

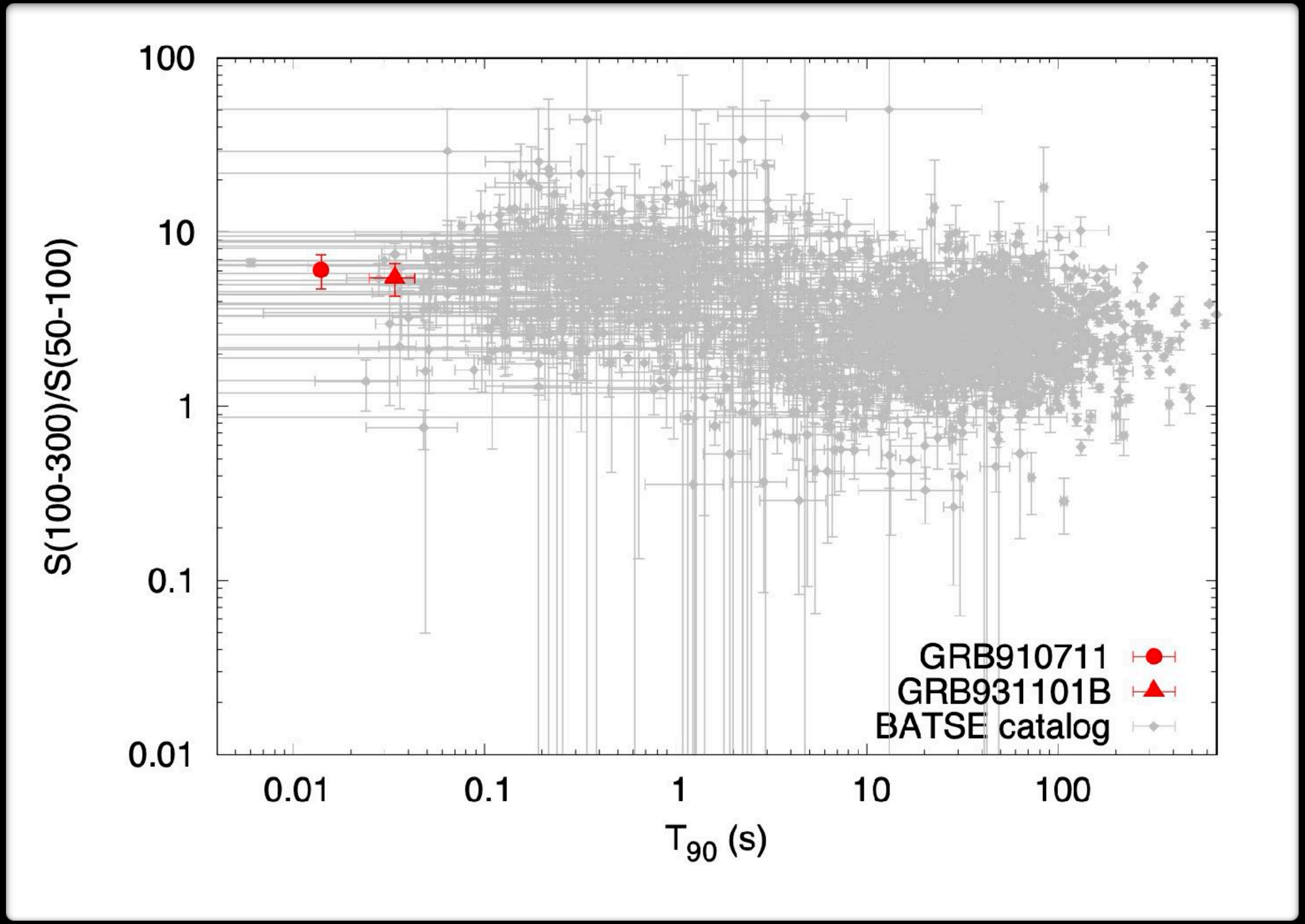
Light curves and power spectra

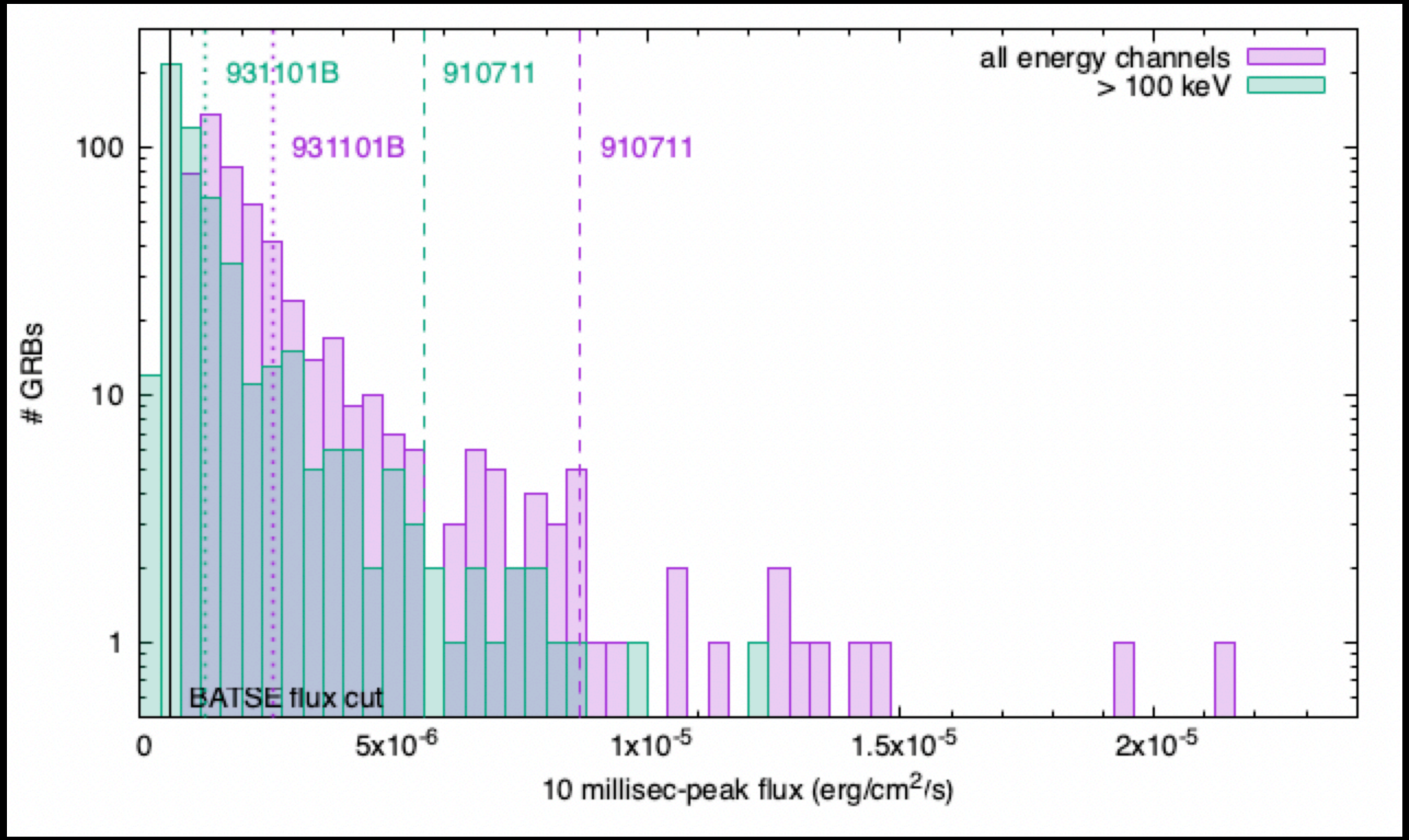






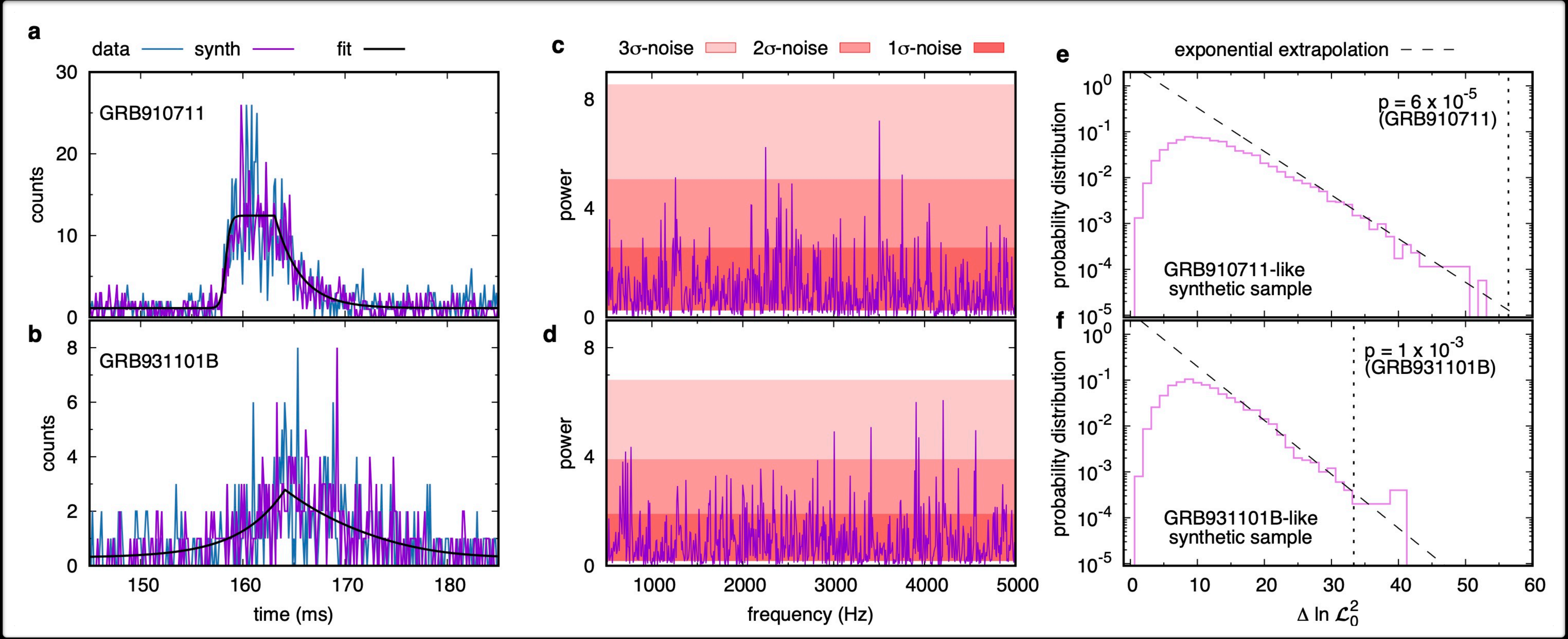
BATSE GRB distribution





How special are these bursts?

False positive estimate II



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

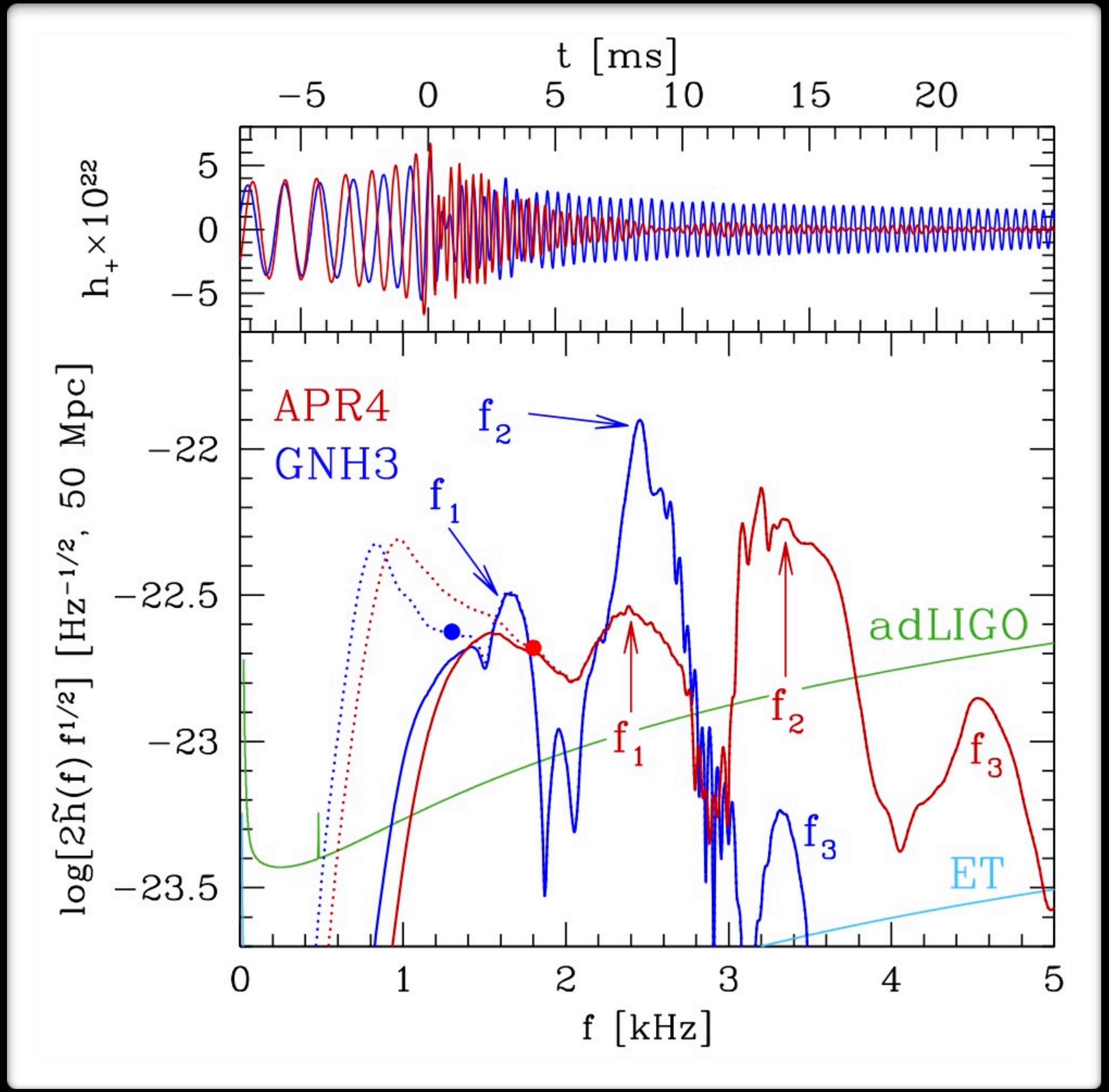
https://www.youtube.com/watch?v=IMcU2m5YbFE

Interpretation?

These signals are consistent with an HMNS:

QPO 1 High frequency!
~ 1kHz
lower amplitude

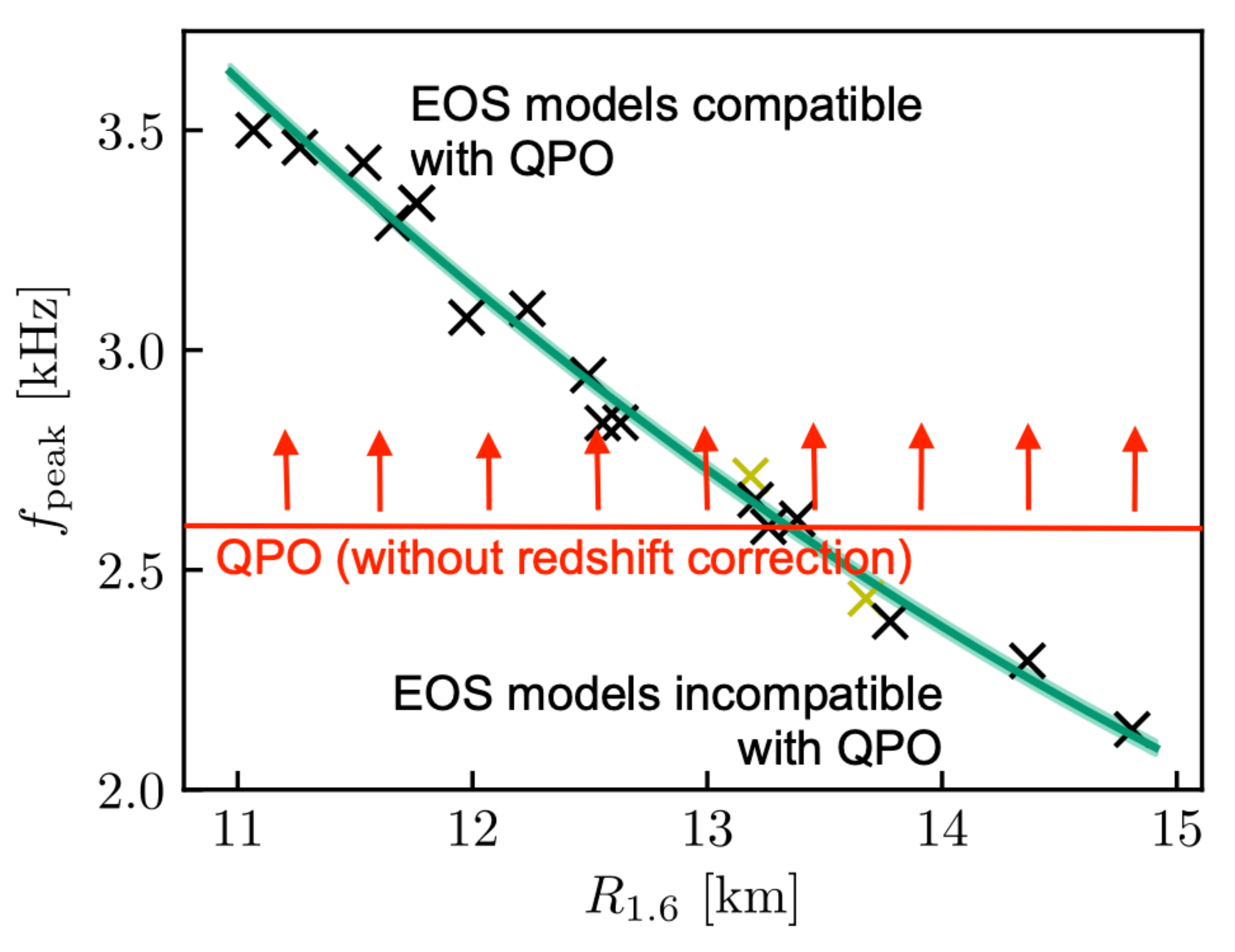
QPO 2 *Higher* frequency!
~ 2.6 kHz, higher amplitude
info on NS composition



Important: The *redshift* of these GRBs is not know; the QPO frequencies are detected in the detector frame!

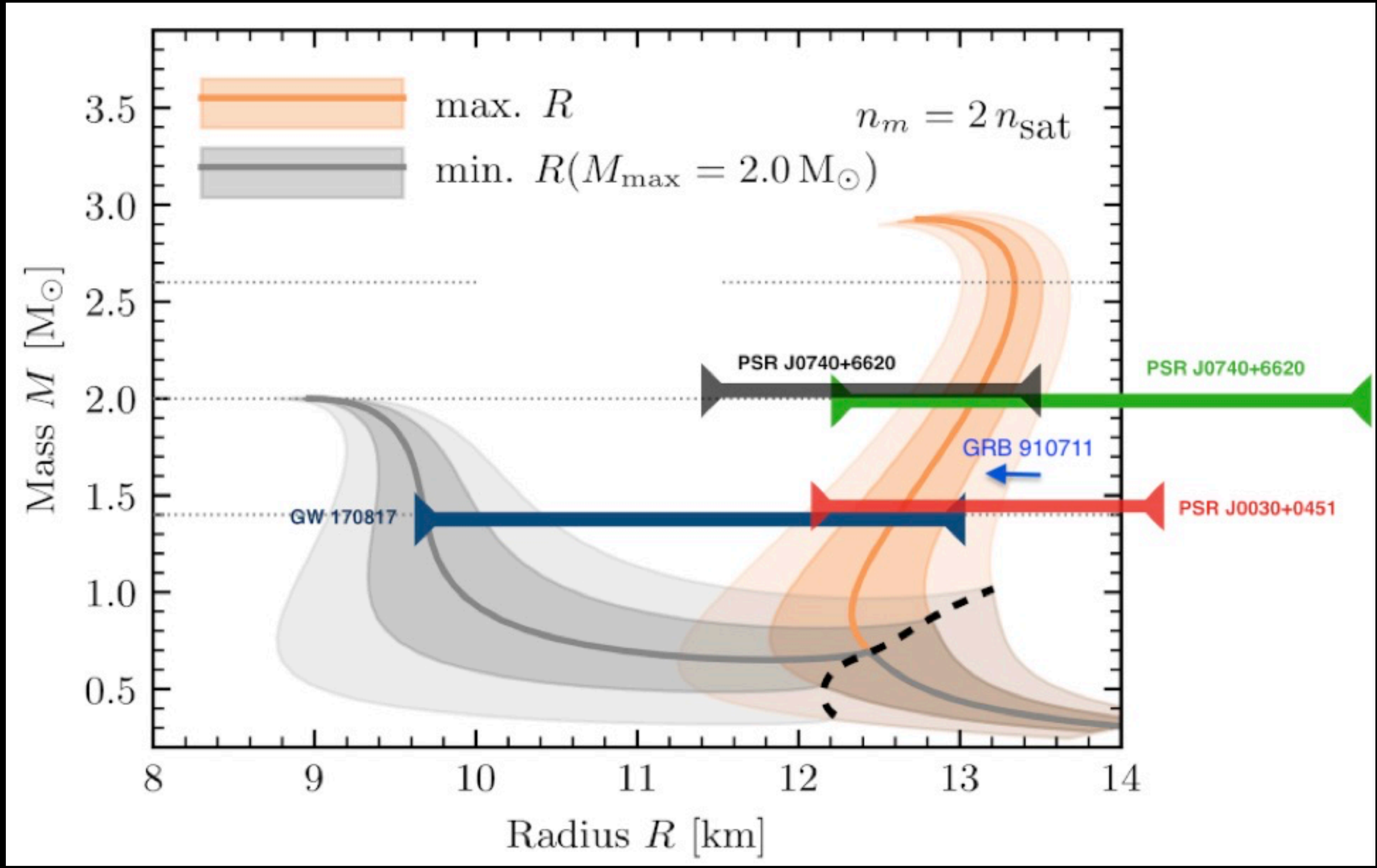
Learning about the neutron star equation of state

QPOs + NR



adapted from Lioutas et al., 2021

NICER + GWs + GRB

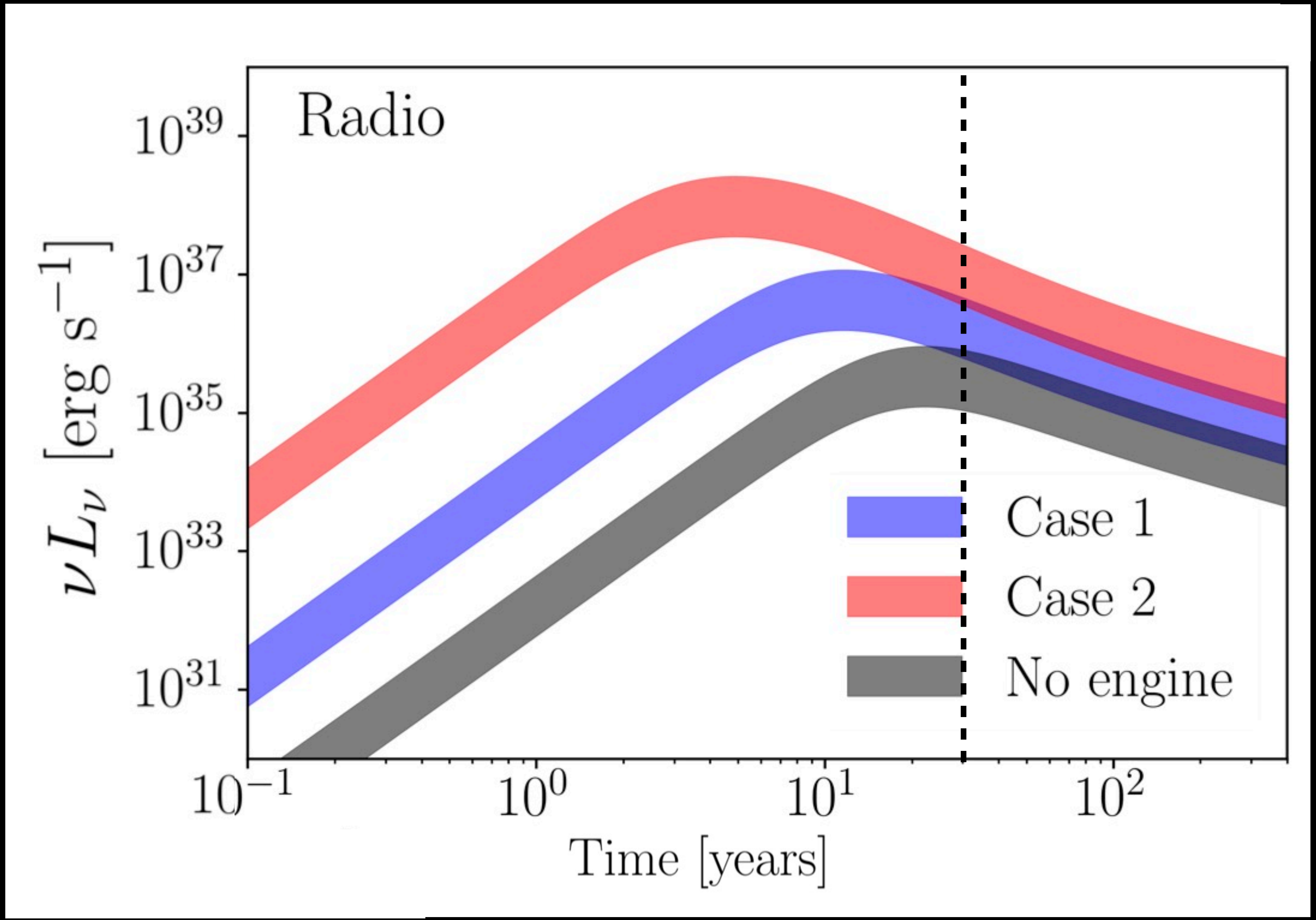


adapted from Reddy, 2021

From gamma rays to radio?

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

(for GRB 910711)



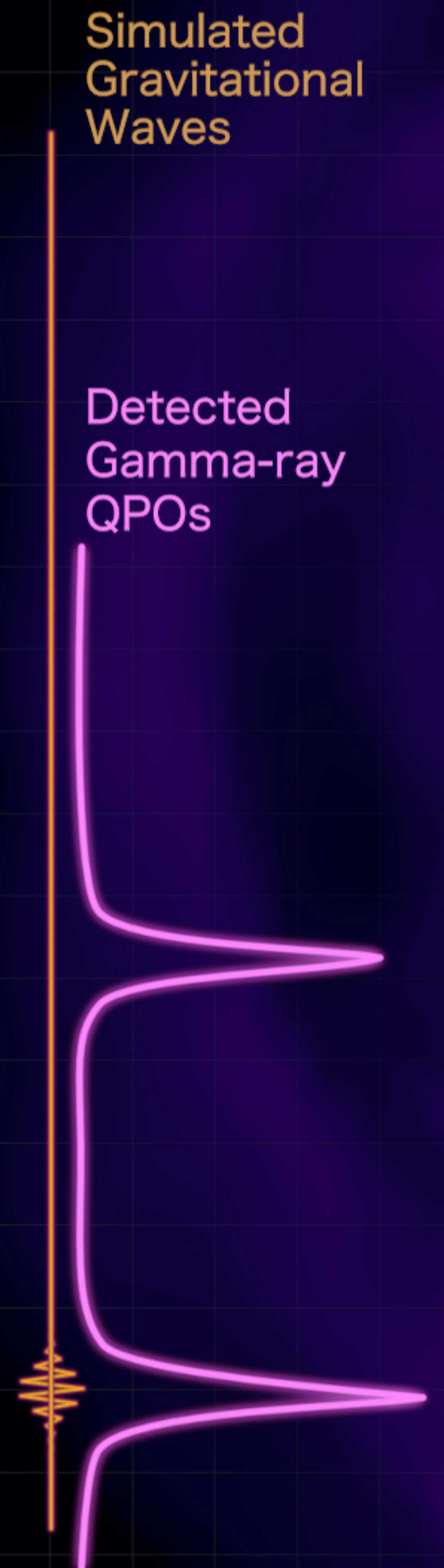
Sarin et al. 2022

"Challenge accepted!"
- radioastronomer

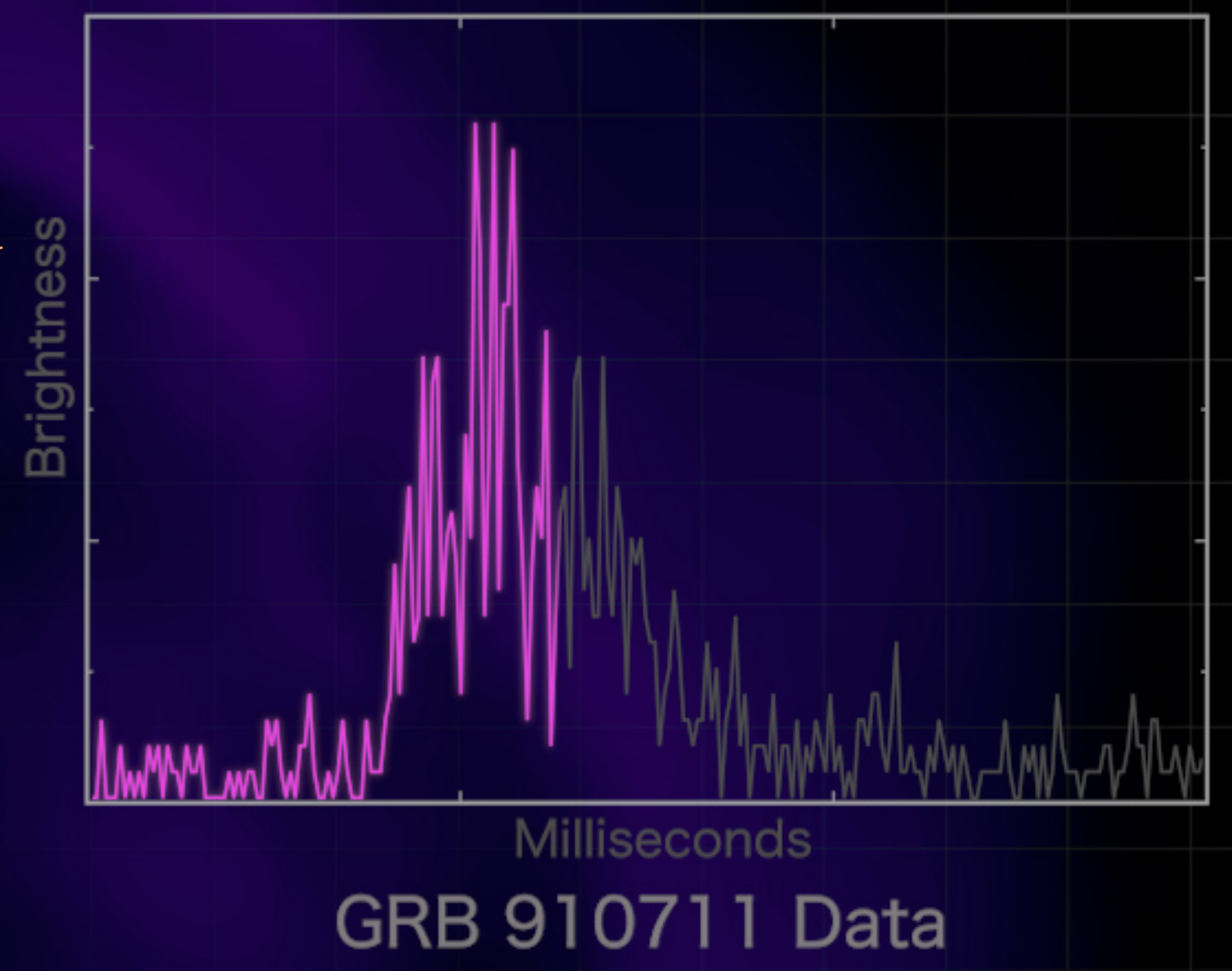
Past and Future

"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

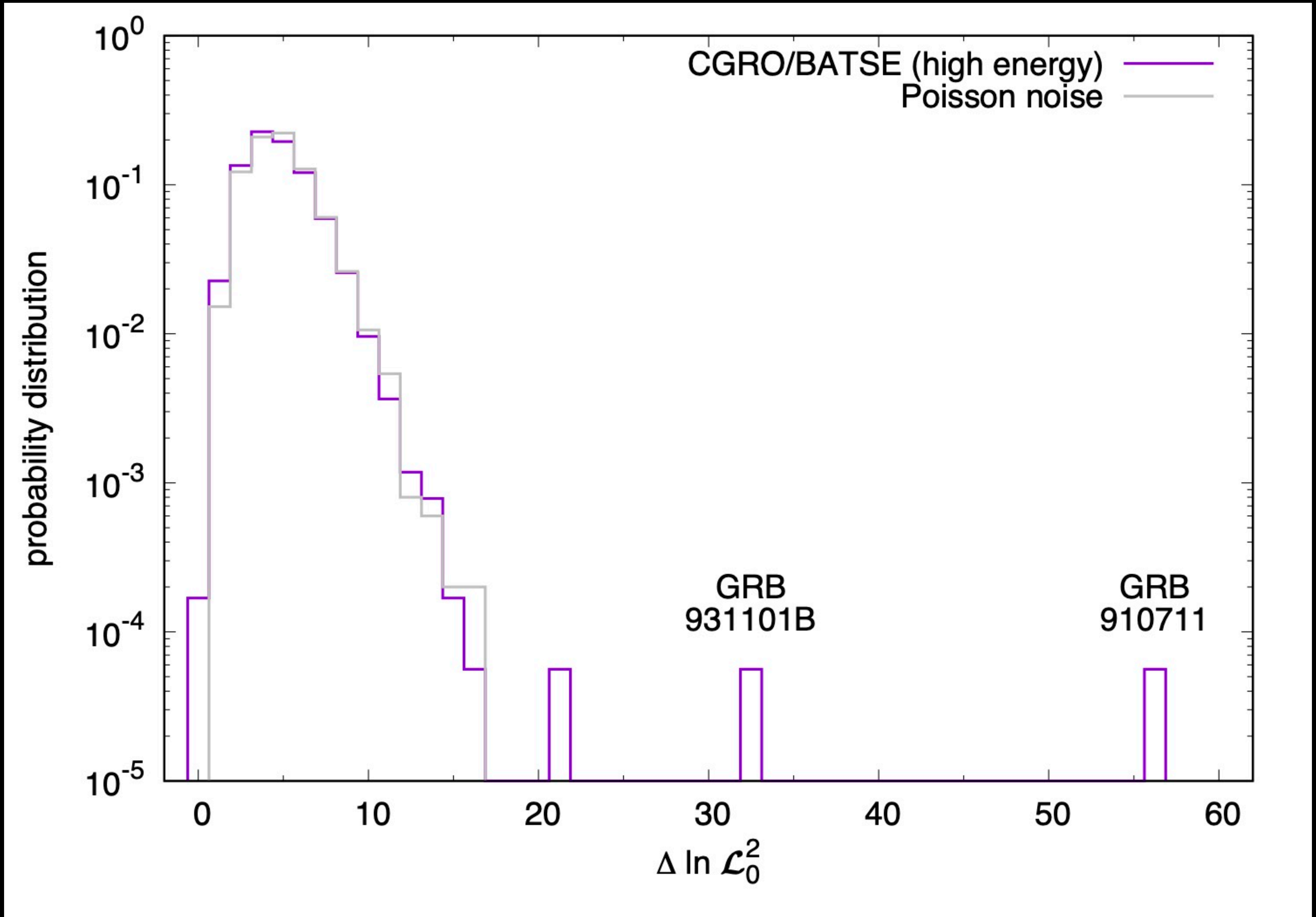


Between the *whoop* and the *ding* of a binary NS merger, an HMNS can be formed. We looked for them and found two: GRB 910711 and GRB 931101B.



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.

False positive estimate I



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