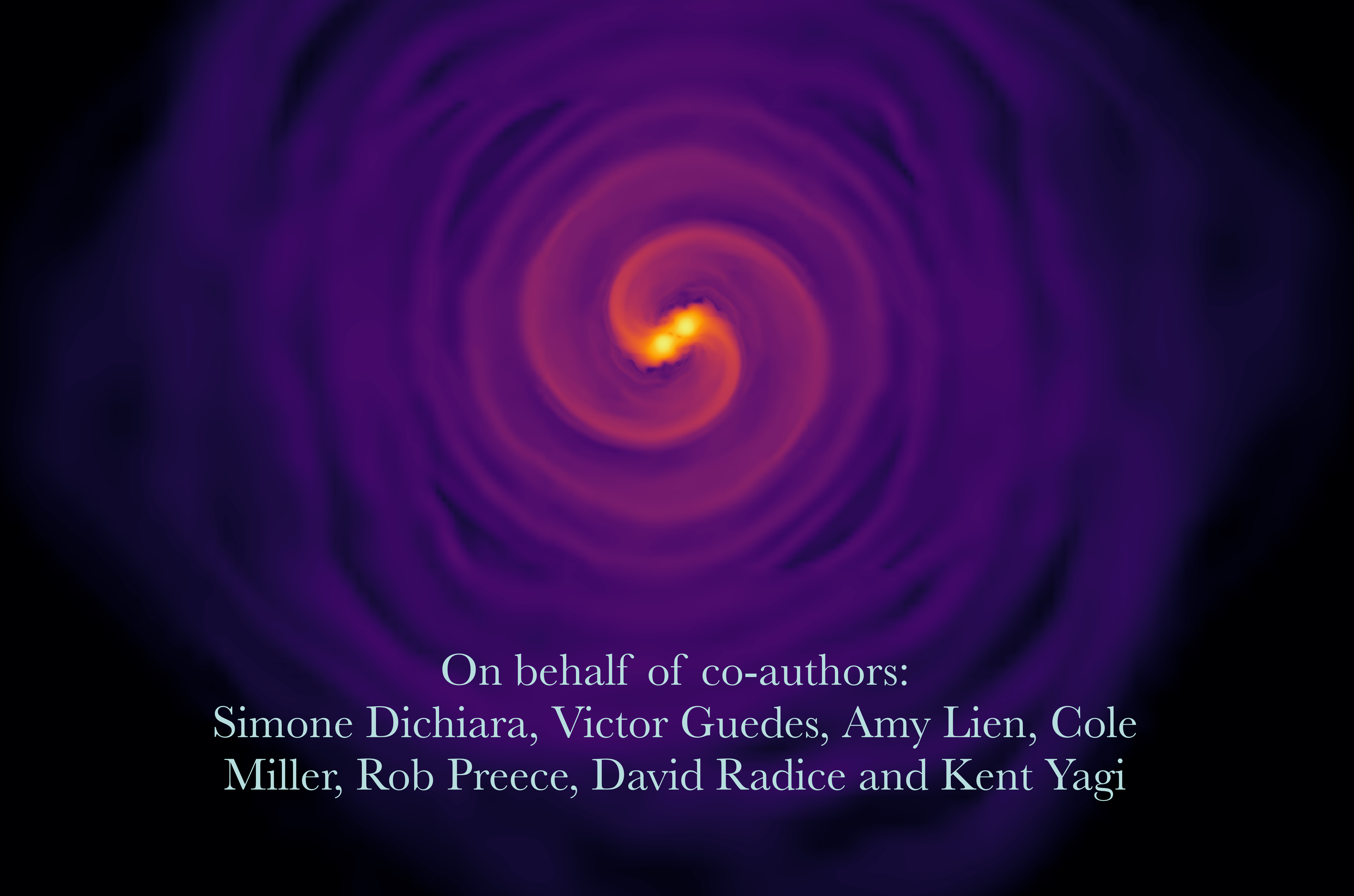
Astrophysical constraints on the neutron star equation of state from short gamma-ray bursts

Cecilia Chirenti

Based on:
Nature **613** 253 (2023)
and arXiv:2408.16534

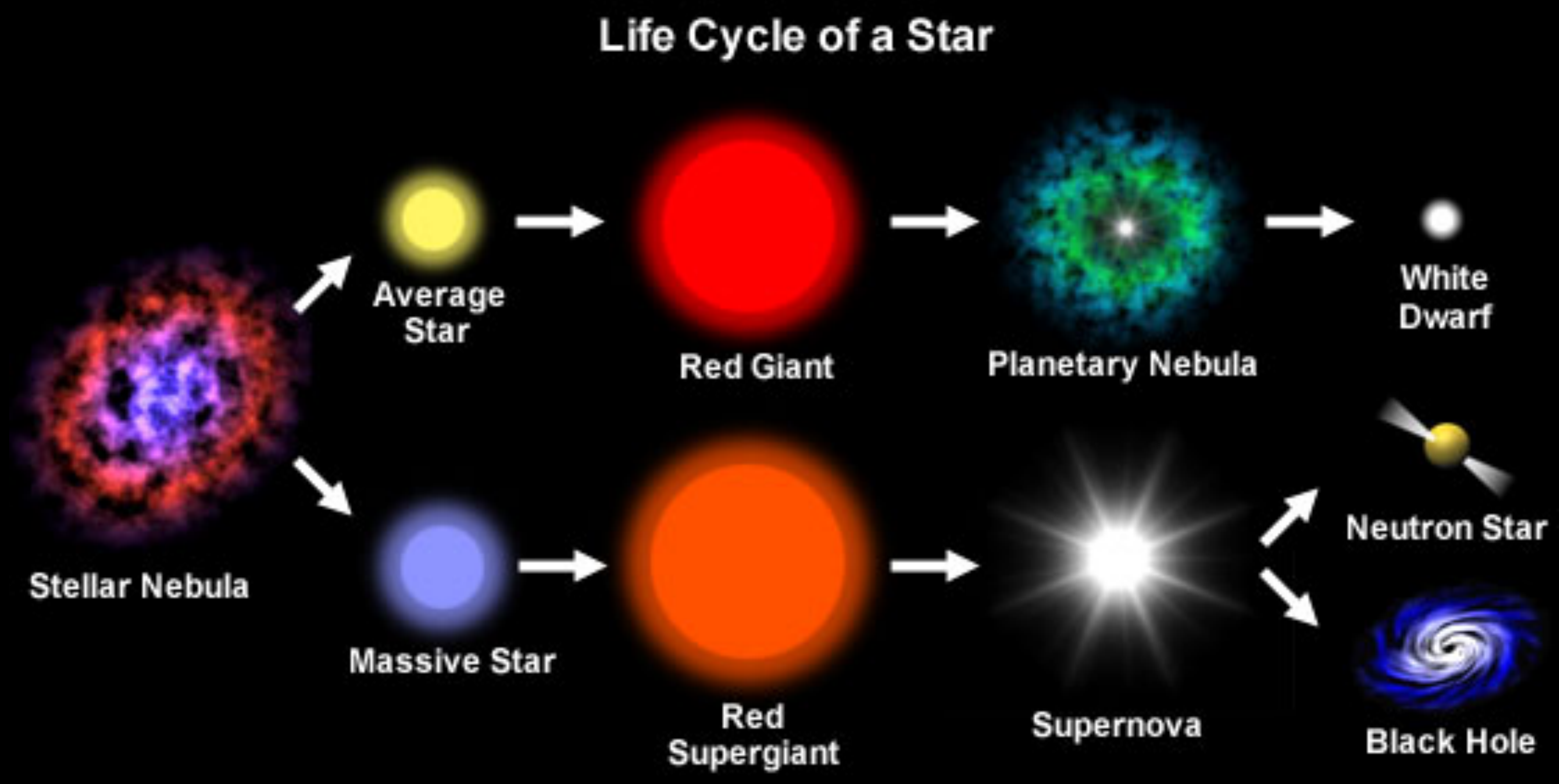
Partner



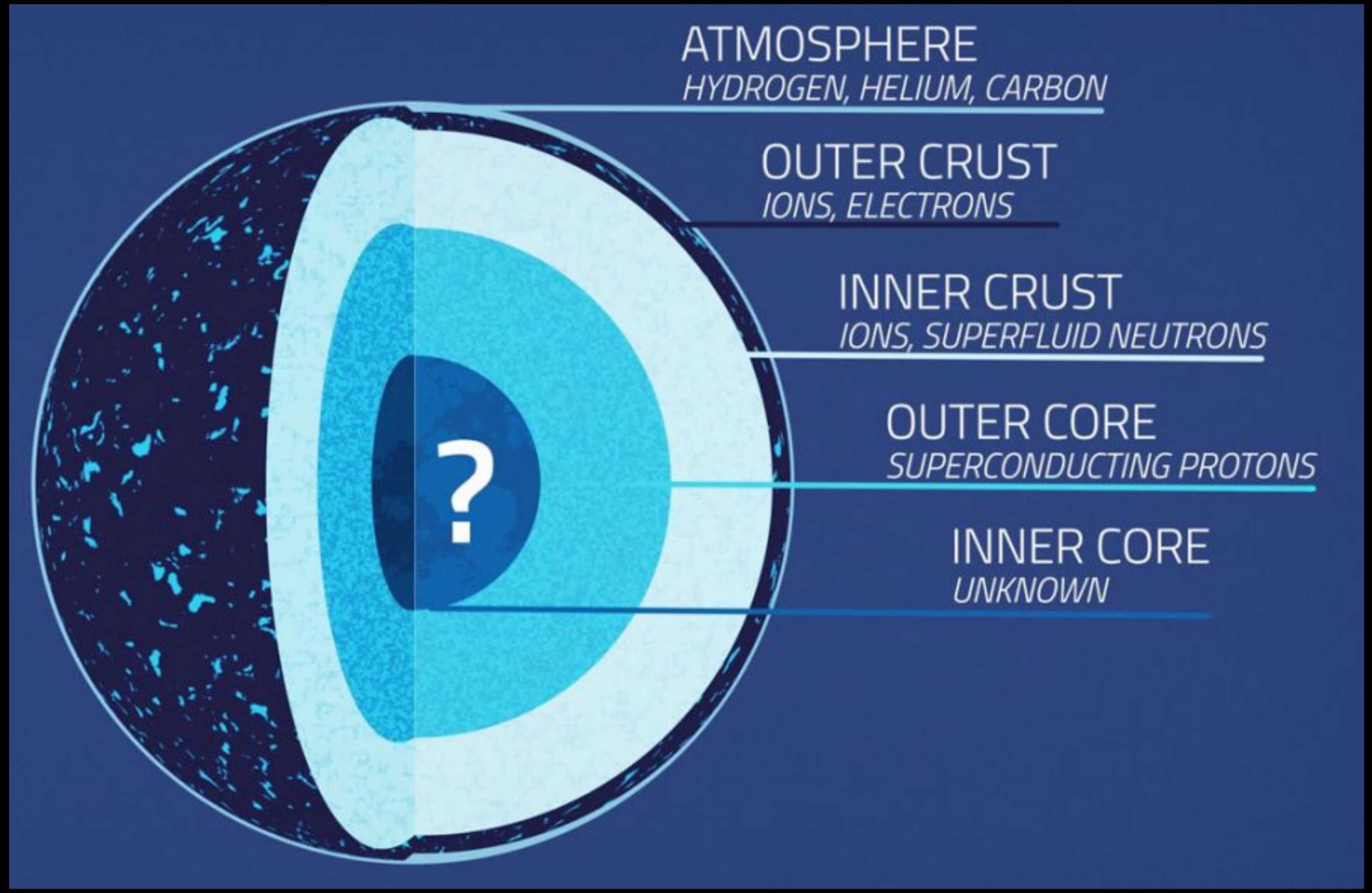
On behalf of co-authors:
Simone Dichiara, Victor Guedes, Amy Lien, Cole Miller, Rob Preece, David Radice and Kent Yagi

Bormio Conference, 27/01/2025

Neutron Stars

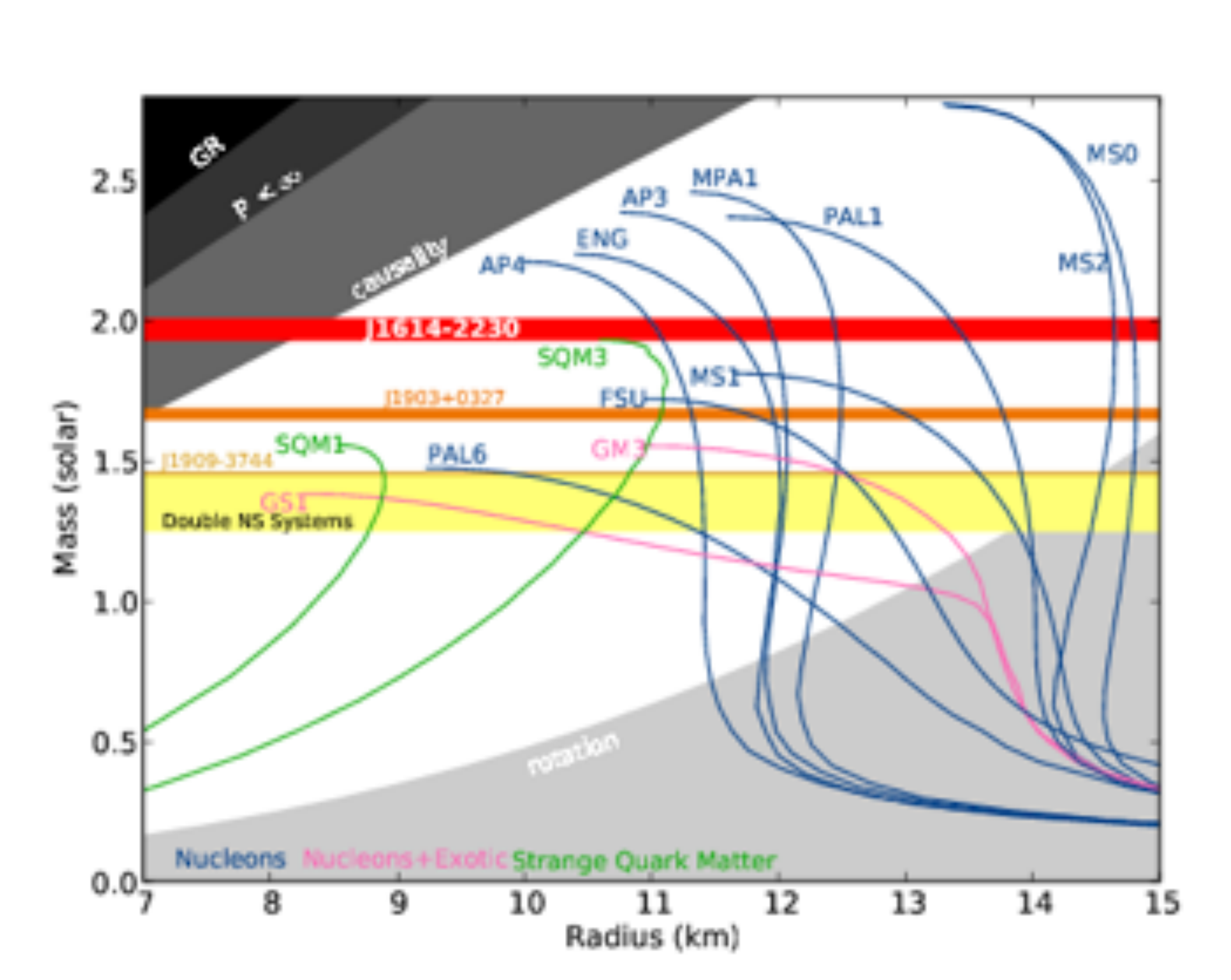


Possible final stage of stellar evolution



Maximum mass: ~ 2.2 – 3 solar masses
Radius: ~ 12 km

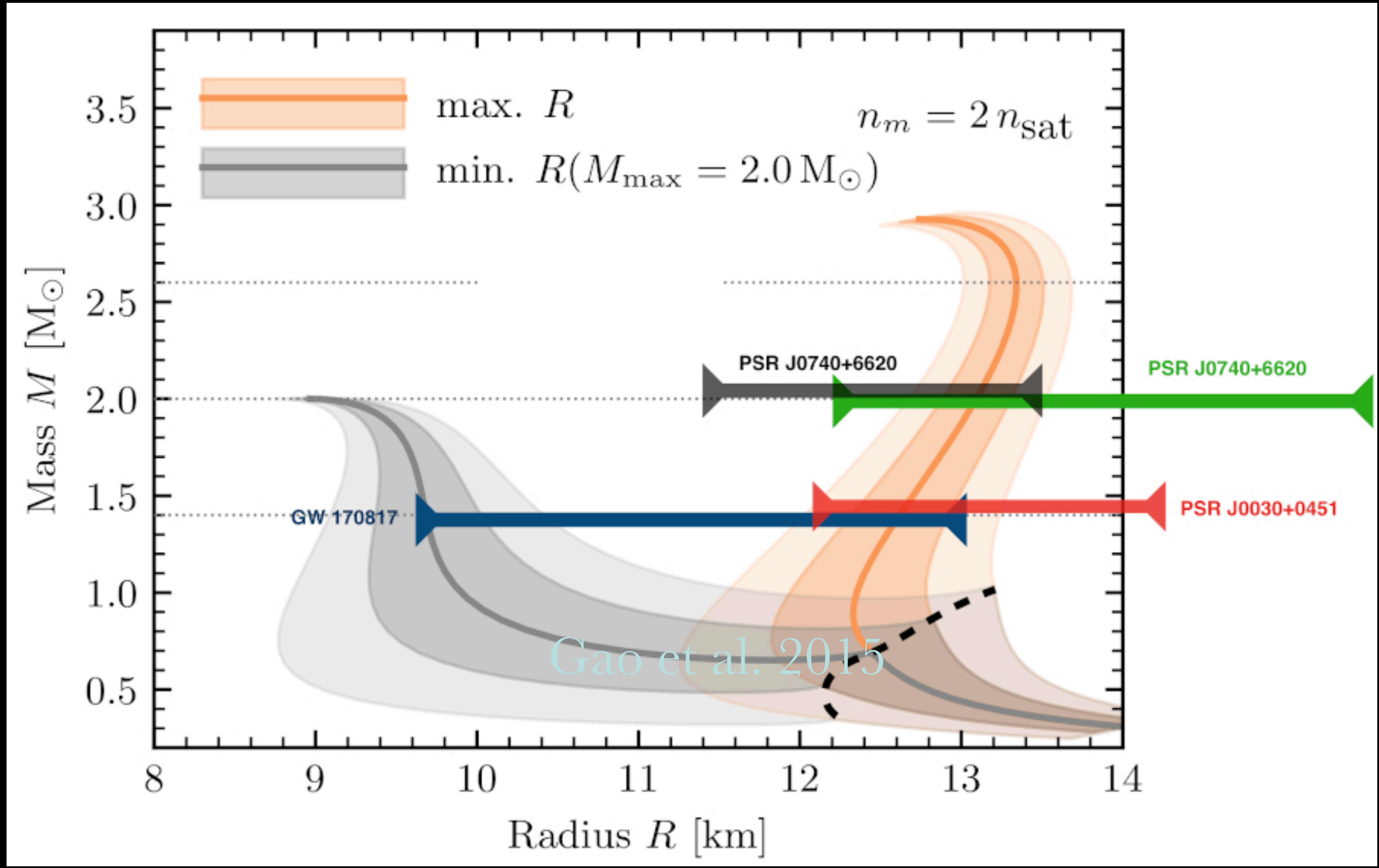
Neutron Star Masses and Radii



Demorest et al. 2010

Different models for the equation of state (EOS) have different maximum masses and radii

Mass and radius constraints from radio, X-ray (NICER) and gravitational wave observations help inform EOS models

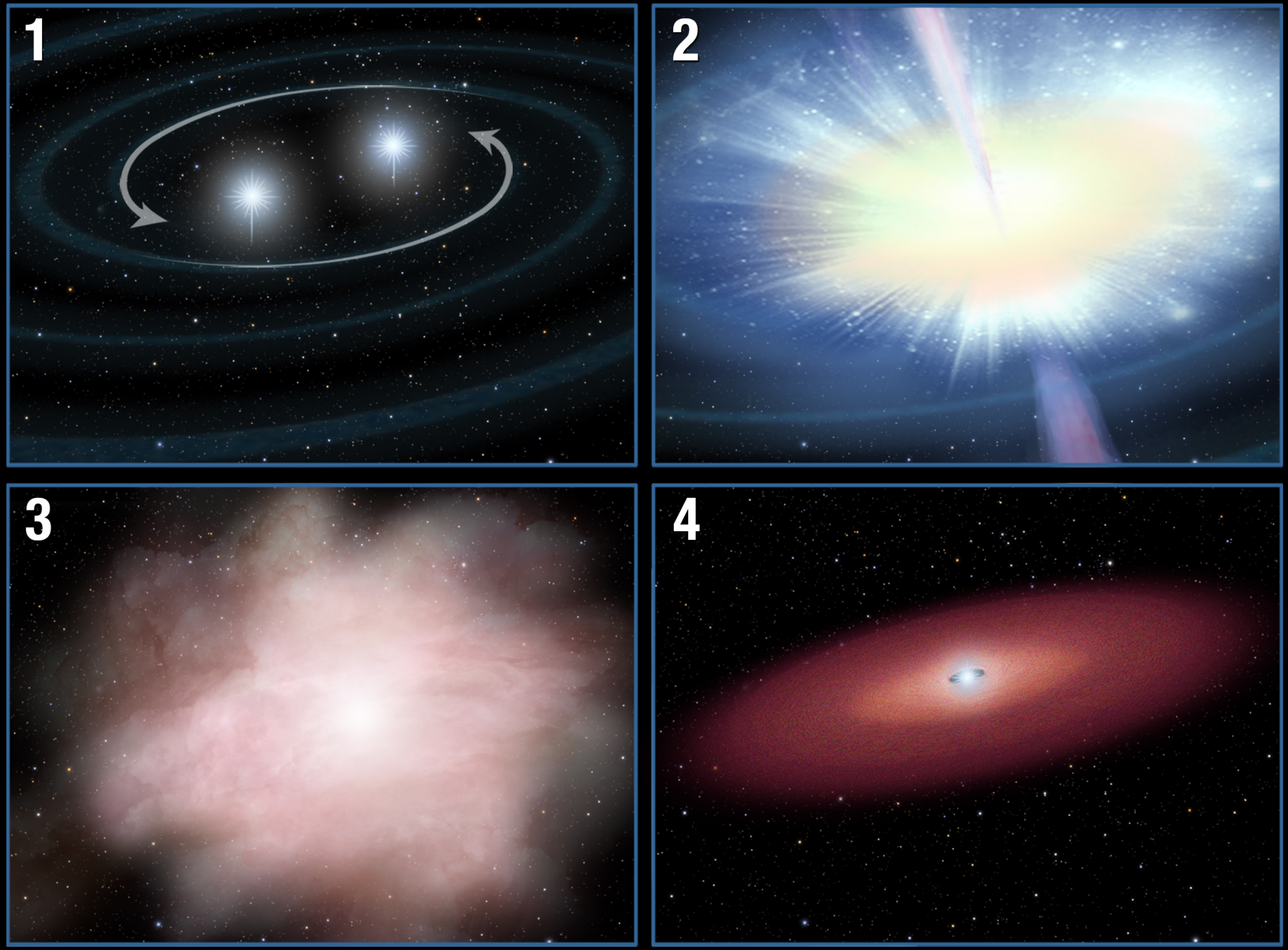


Reddy 2021

Neutron Star Mergers: GW170817

Gravitational Waves

Stellar Merger Model for a Short-Duration Gamma-Ray Burst



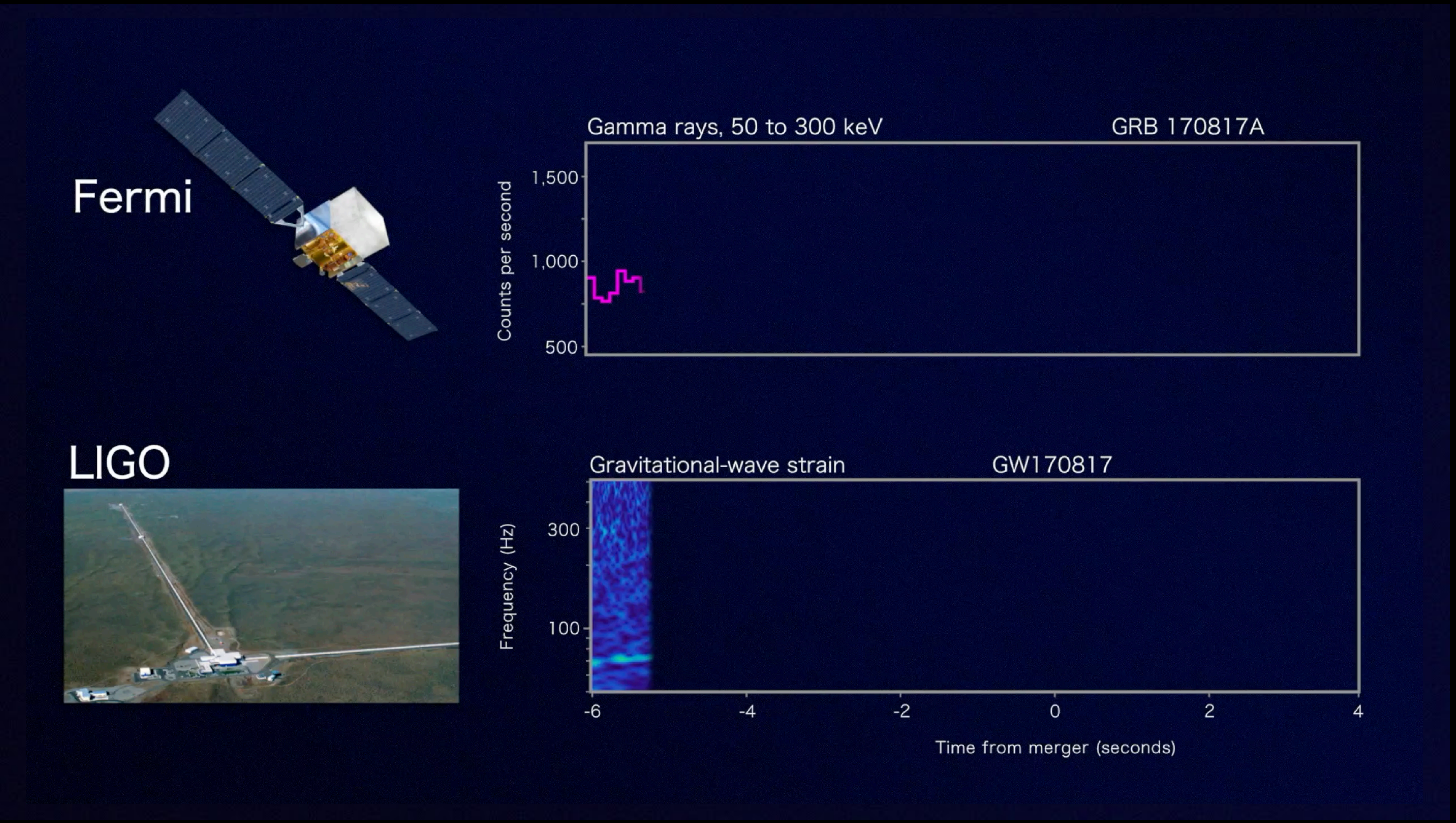
Gamma-ray burst

Kilonova:
UV, optical,
infrared…

Merger remnant
+ disk

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

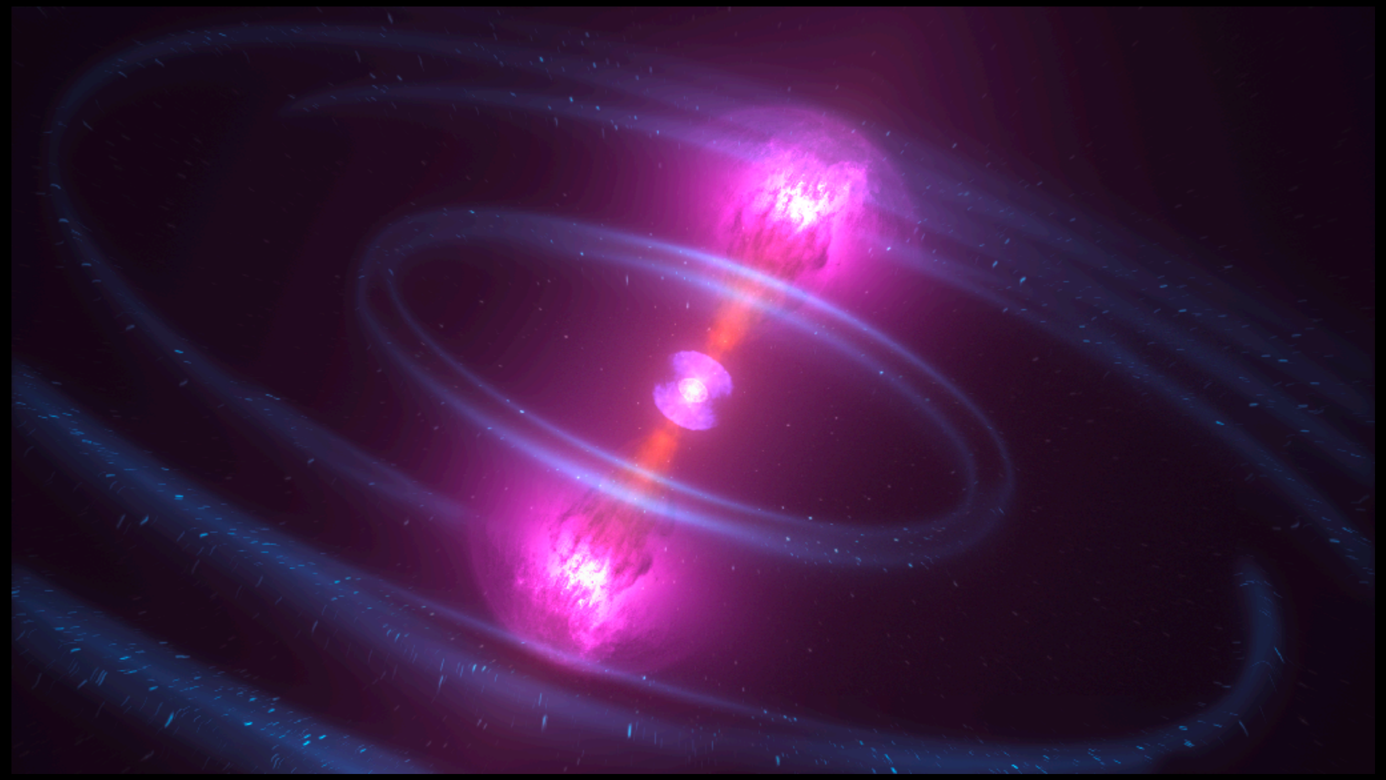
Binary neutron star merger



→ **GRB**
ding!

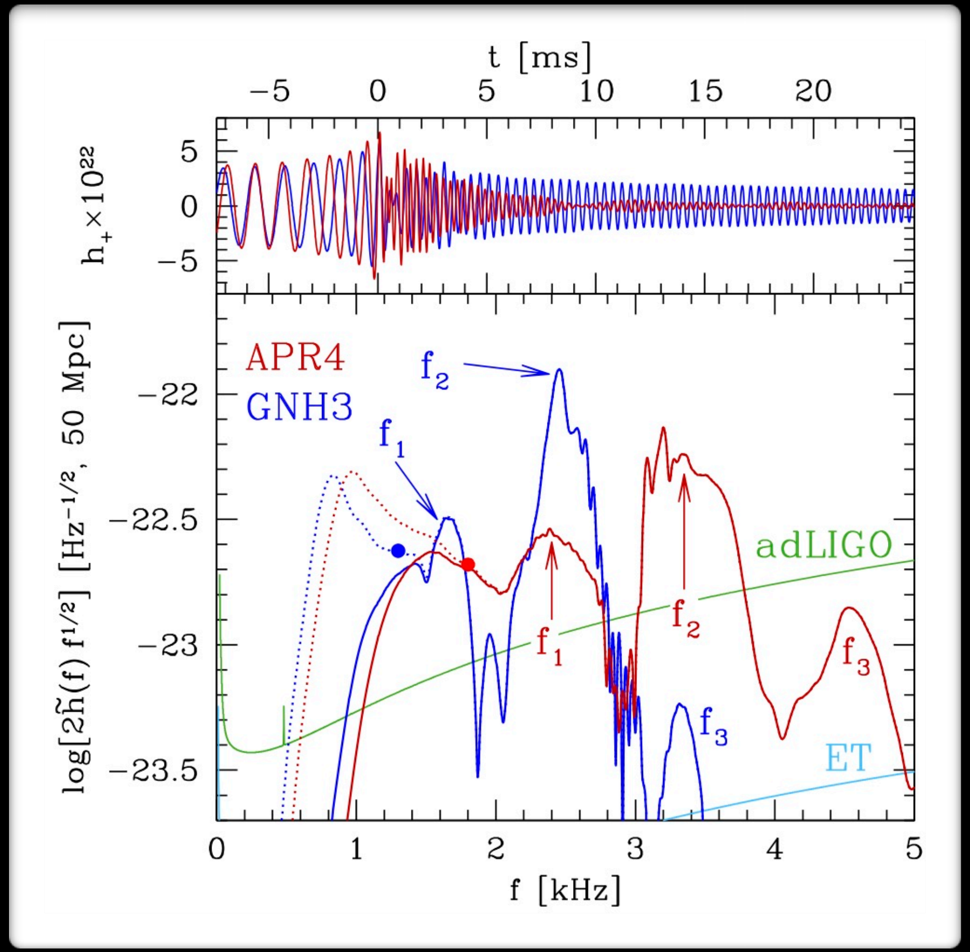
→ **GWs**
whoop!

When is the GRB launched?



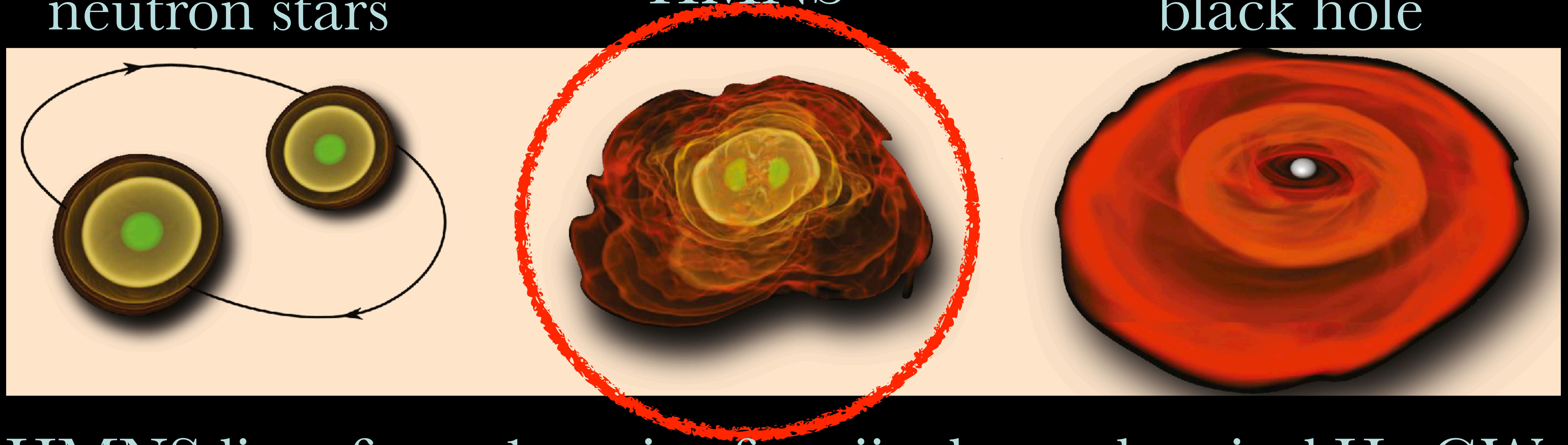
Or: Is the central engine
a black hole
or
a neutron star?

… a hypermassive neutron star?



Takami, Rezzolla & Baiotti, 2014

neutron stars HMNS black hole



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)

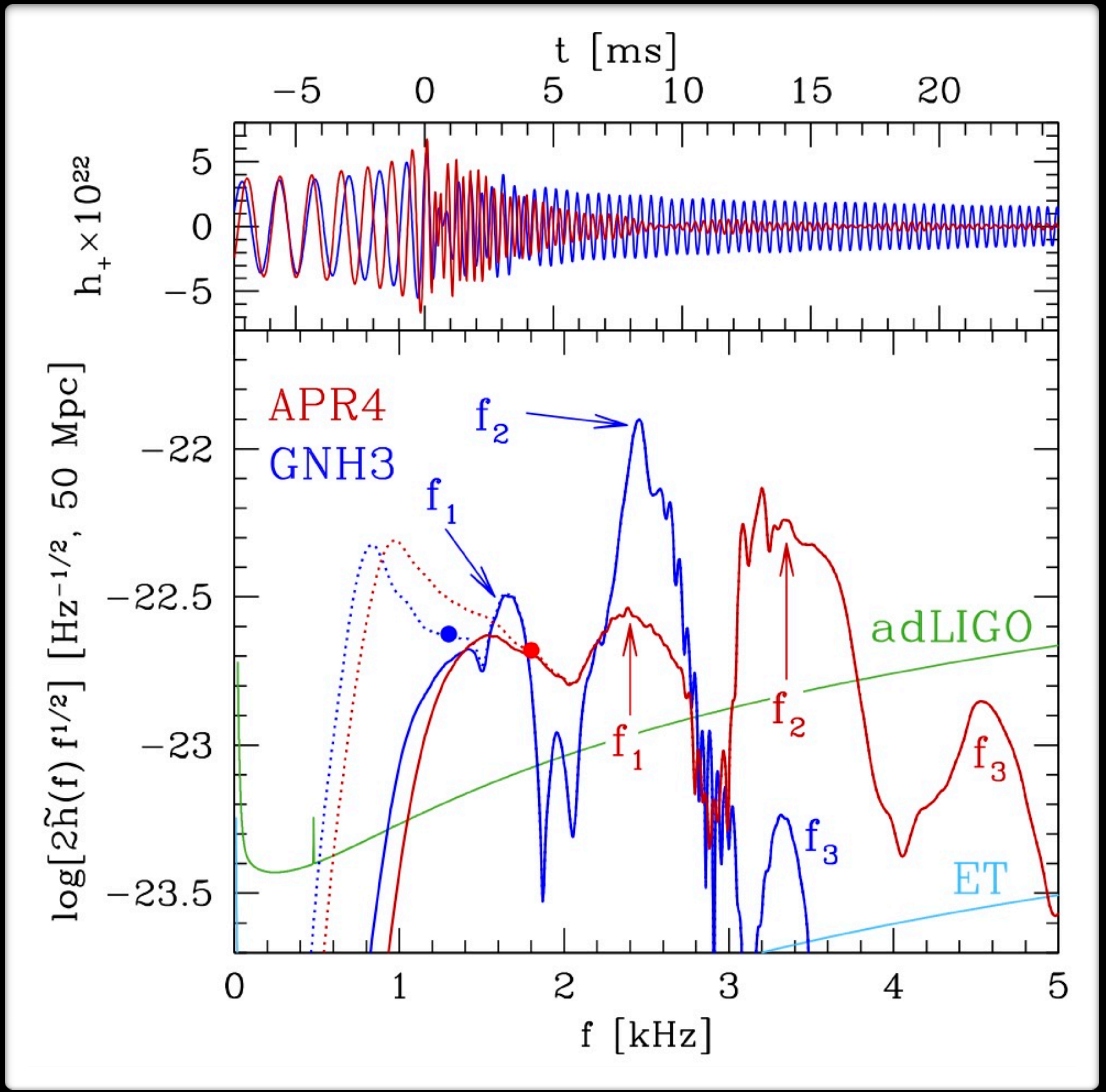
HMNS Quasi-periodic oscillations

HMNS signal:

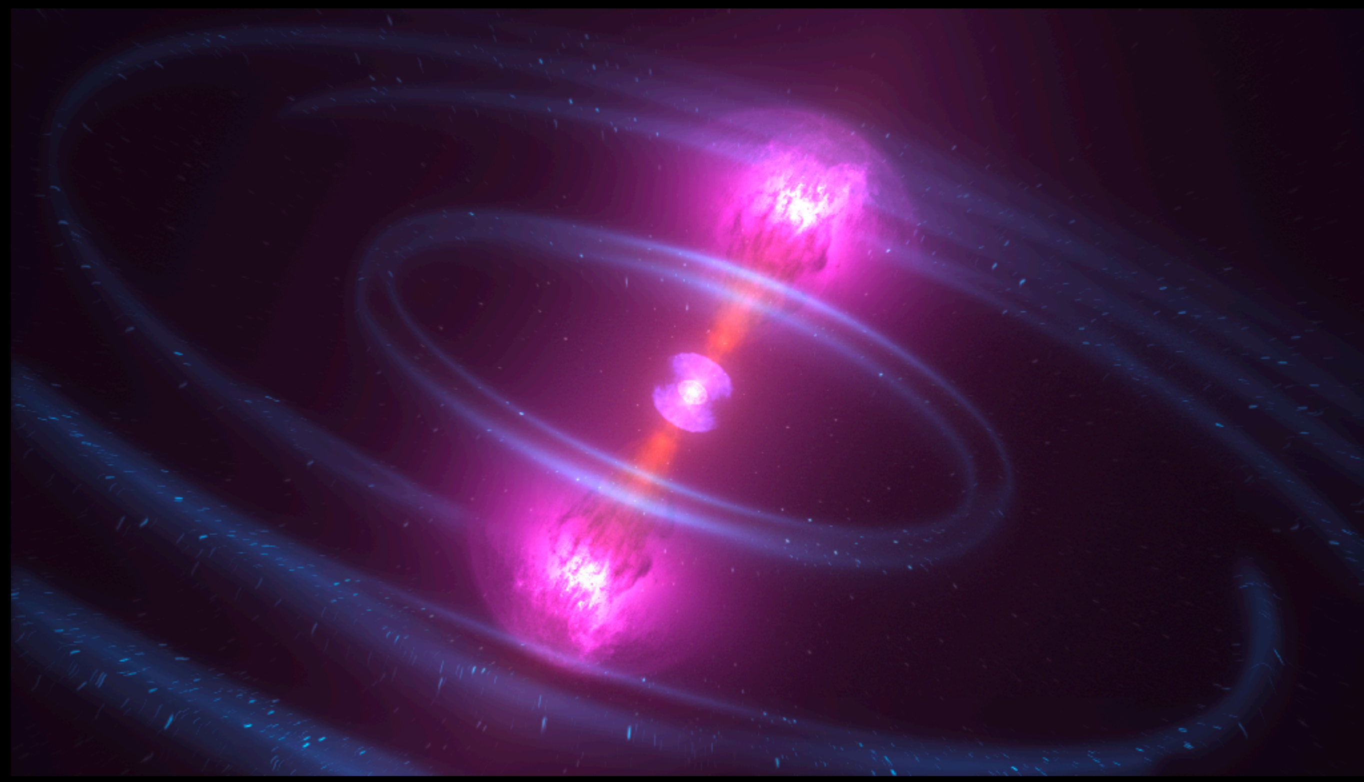
short-lived
time-evolving
dissipative*

⇓

quasi-periodic oscillations
(QPOs)



Takami, Rezzolla & Baiotti, 2014

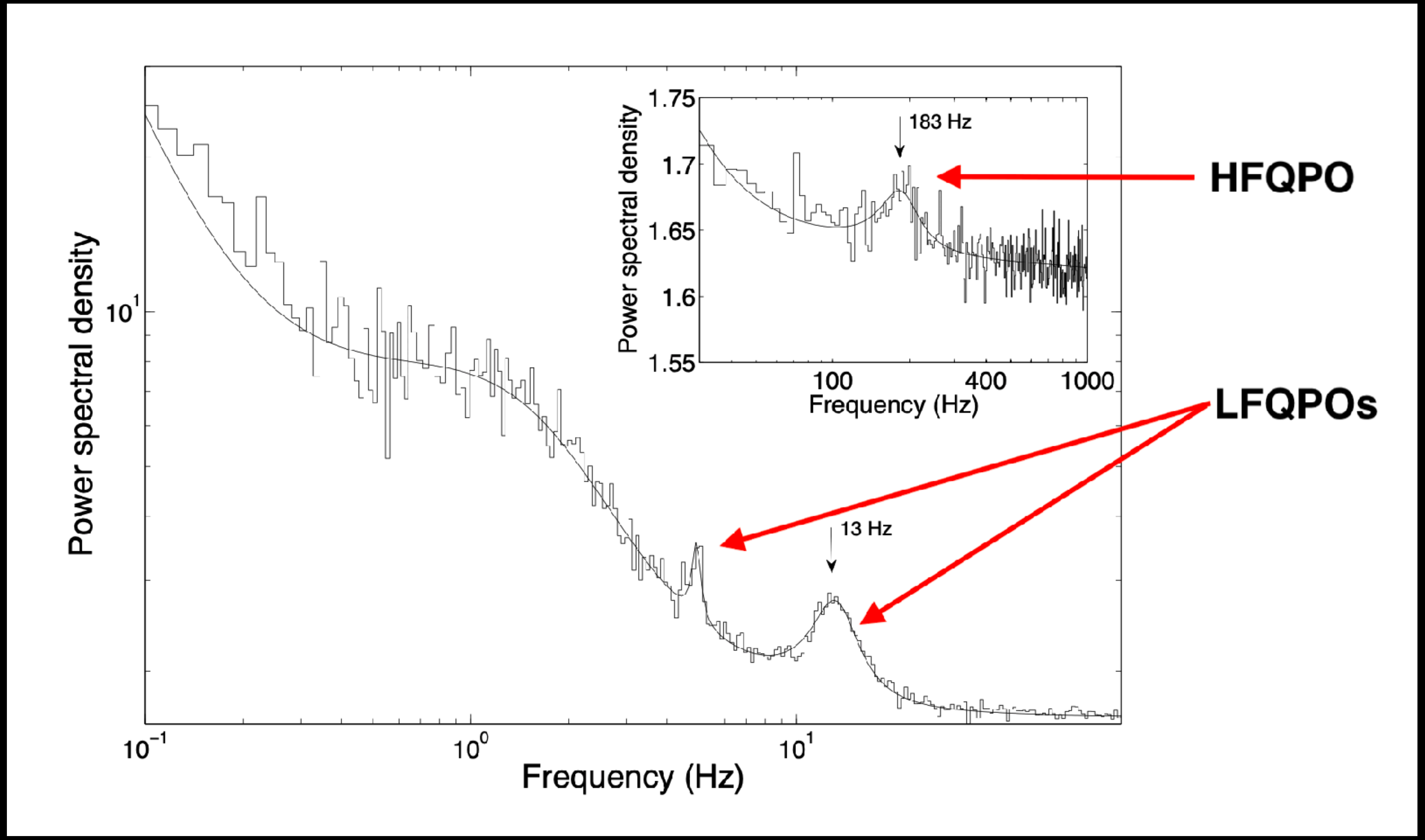


Could the
GRB show
these QPOs?

*simulations also have numerical dissipation!

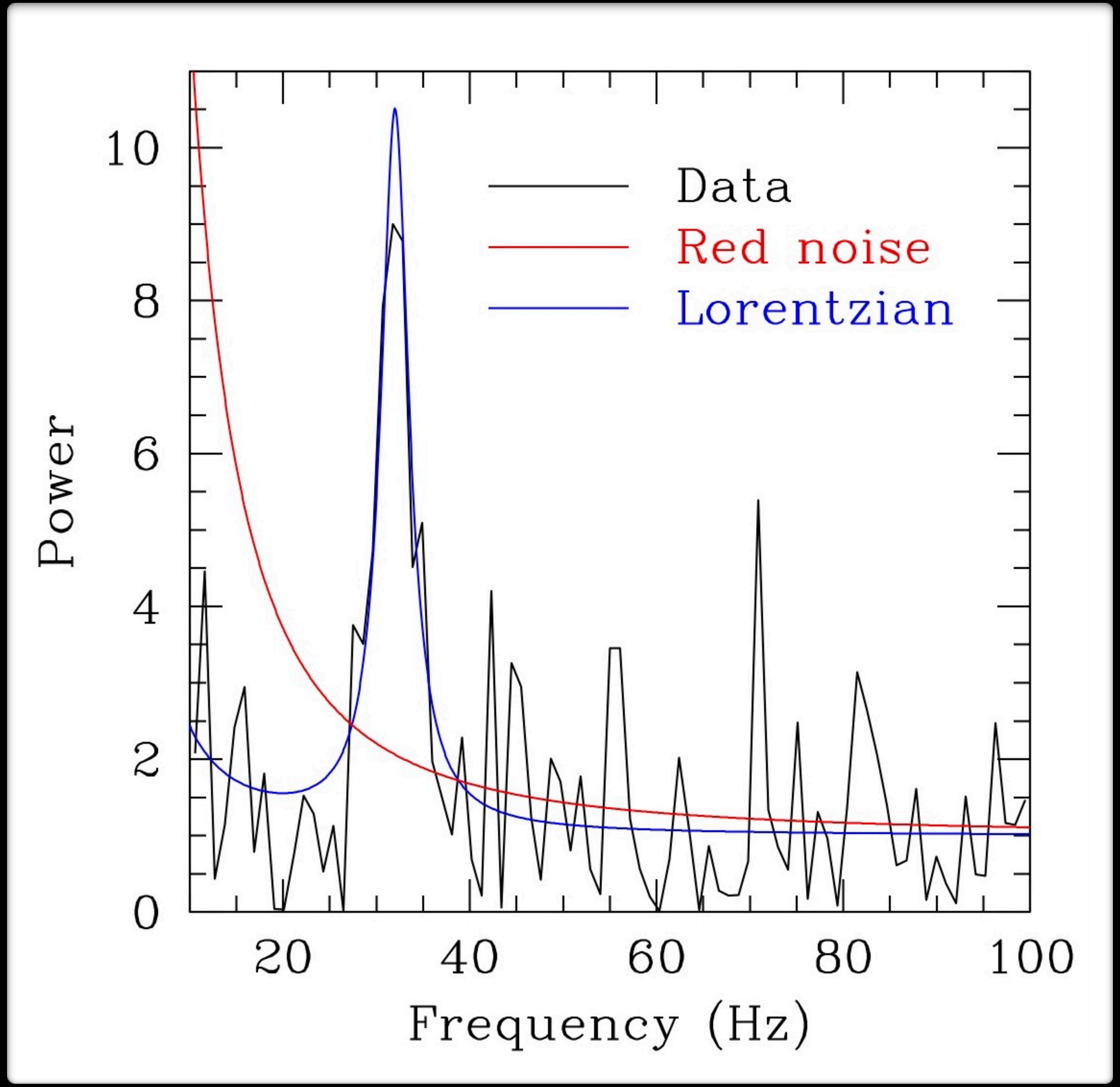
Examples of quasi-periodic oscillations

black hole X-ray binary XTE J1550-564



Motta et al. 2018

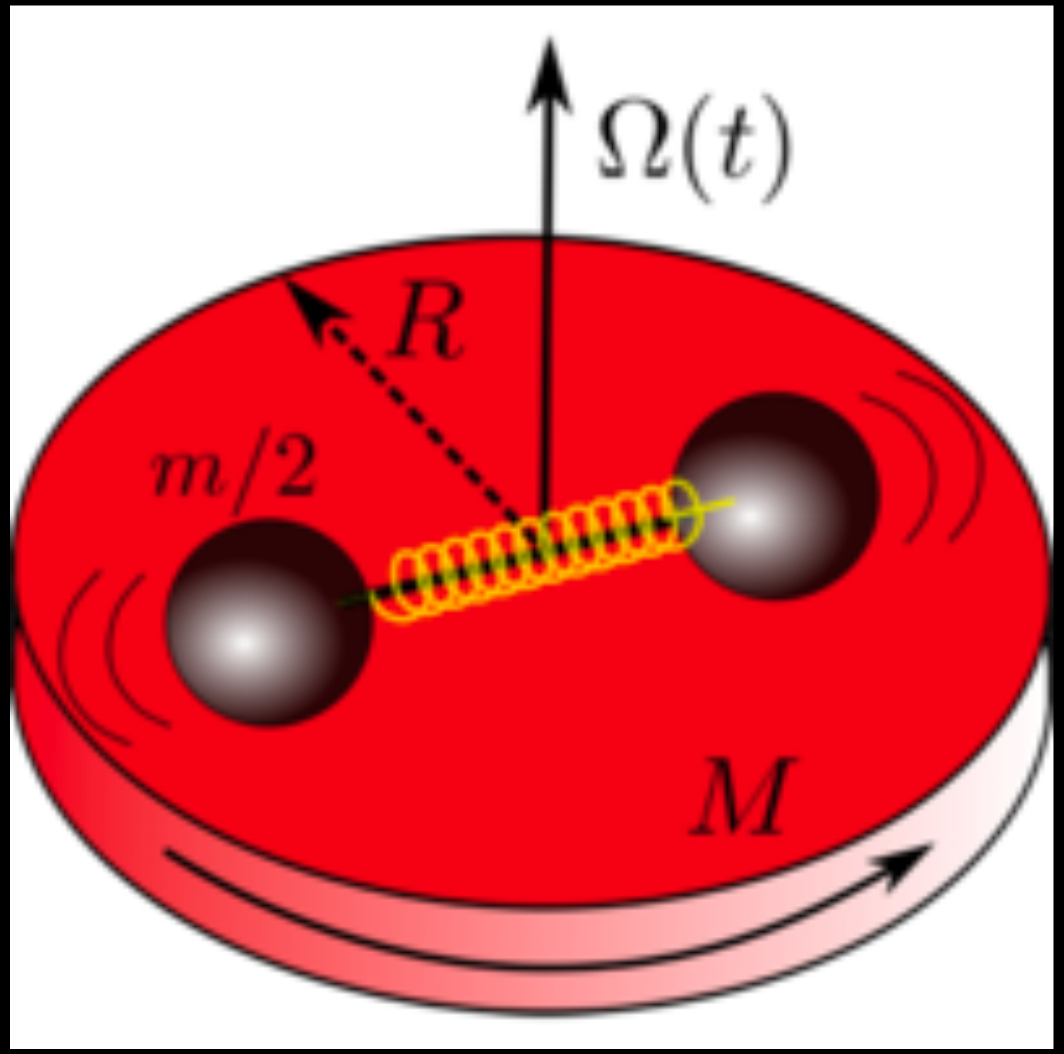
X-ray tail of SGR 1806-20 giant flare



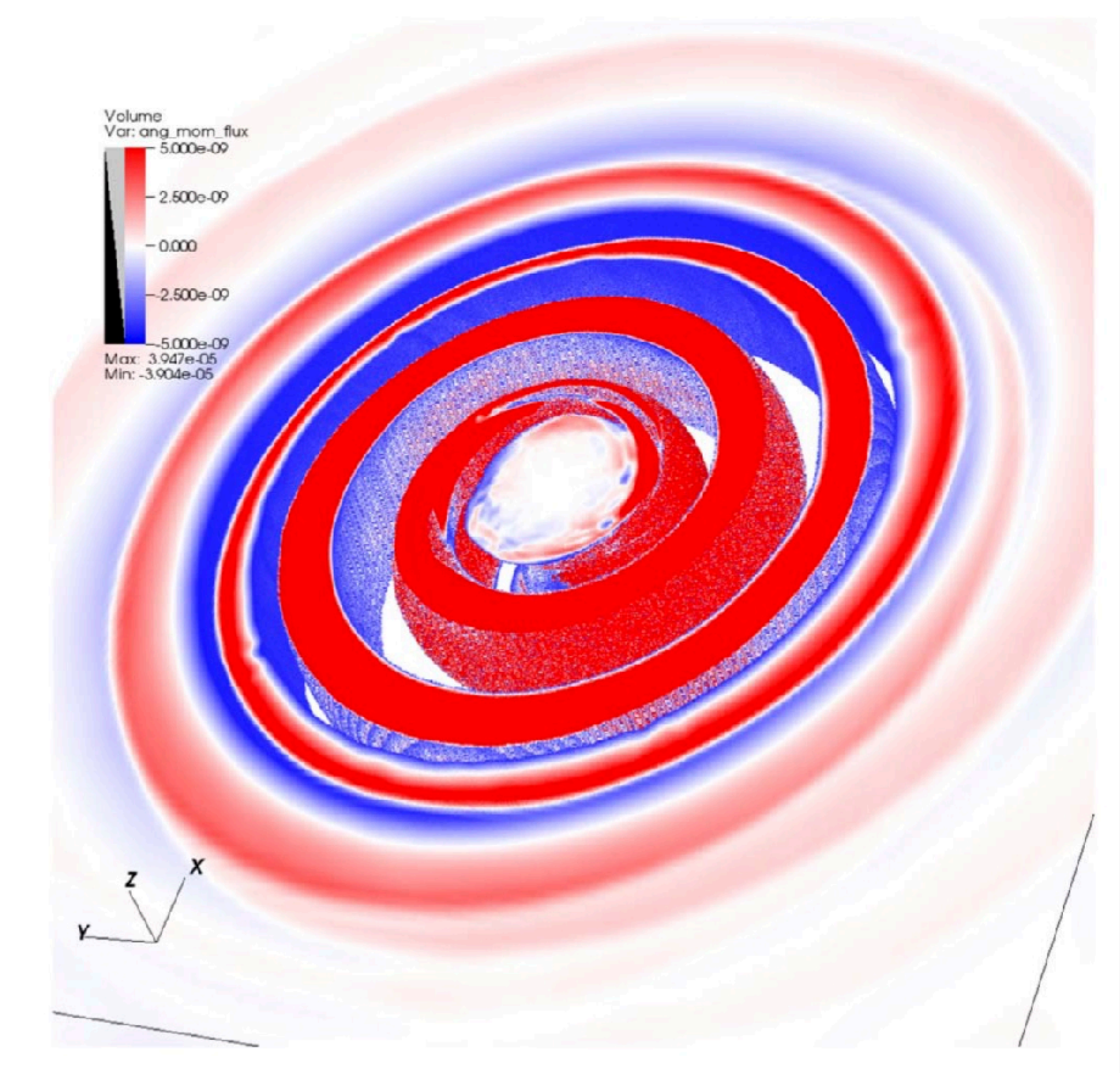
Miller, Chirenti & Strohmayer 2019

GRB QPOs?

Dynamical origin

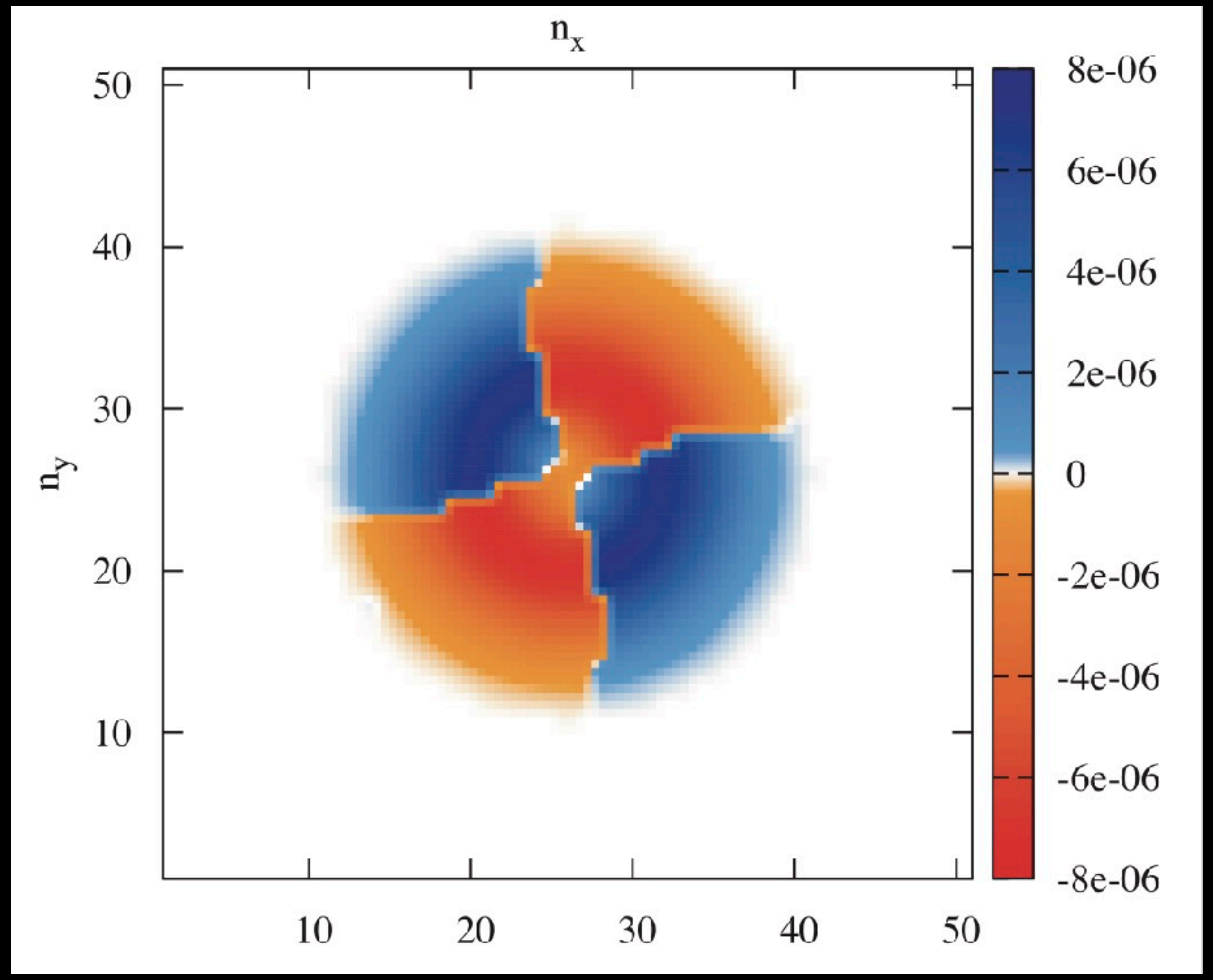


Takami, Rezzolla & Baiotti, 2015

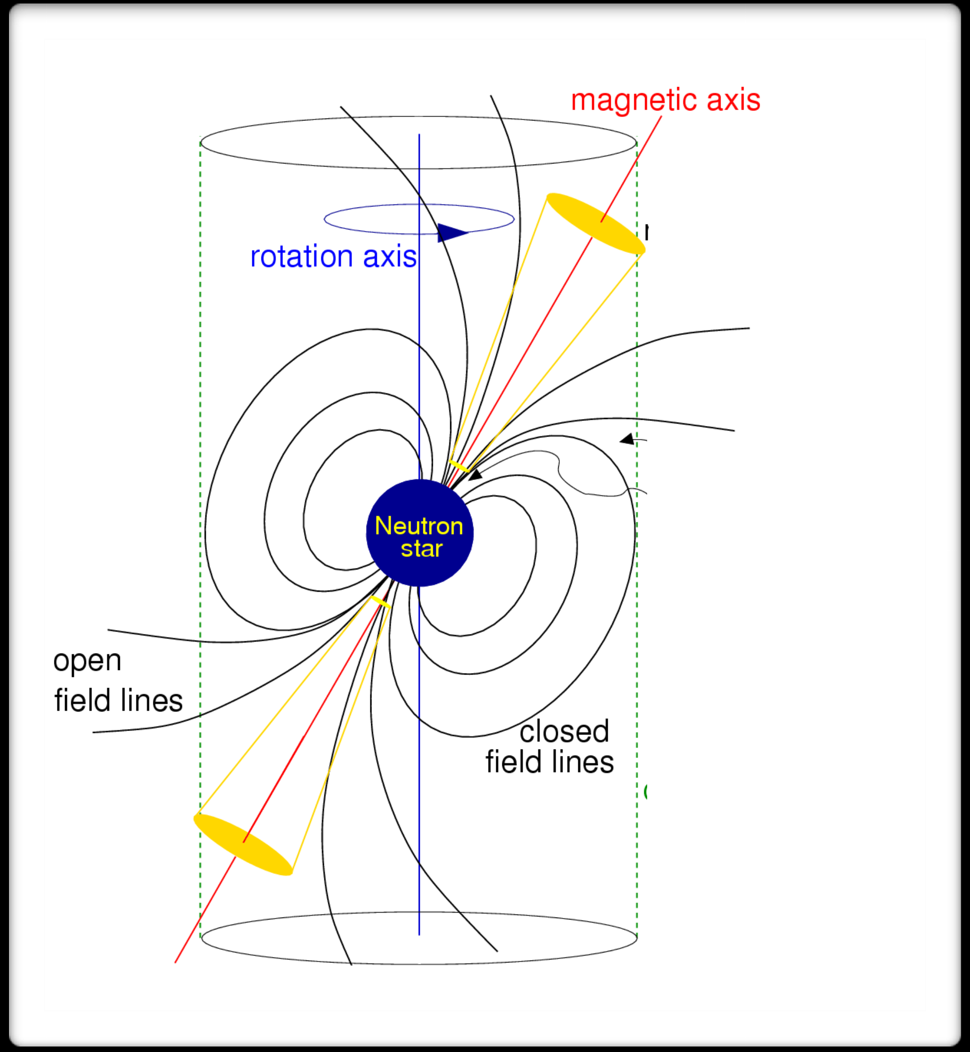


Nedora et al. 2019

Characteristic modes

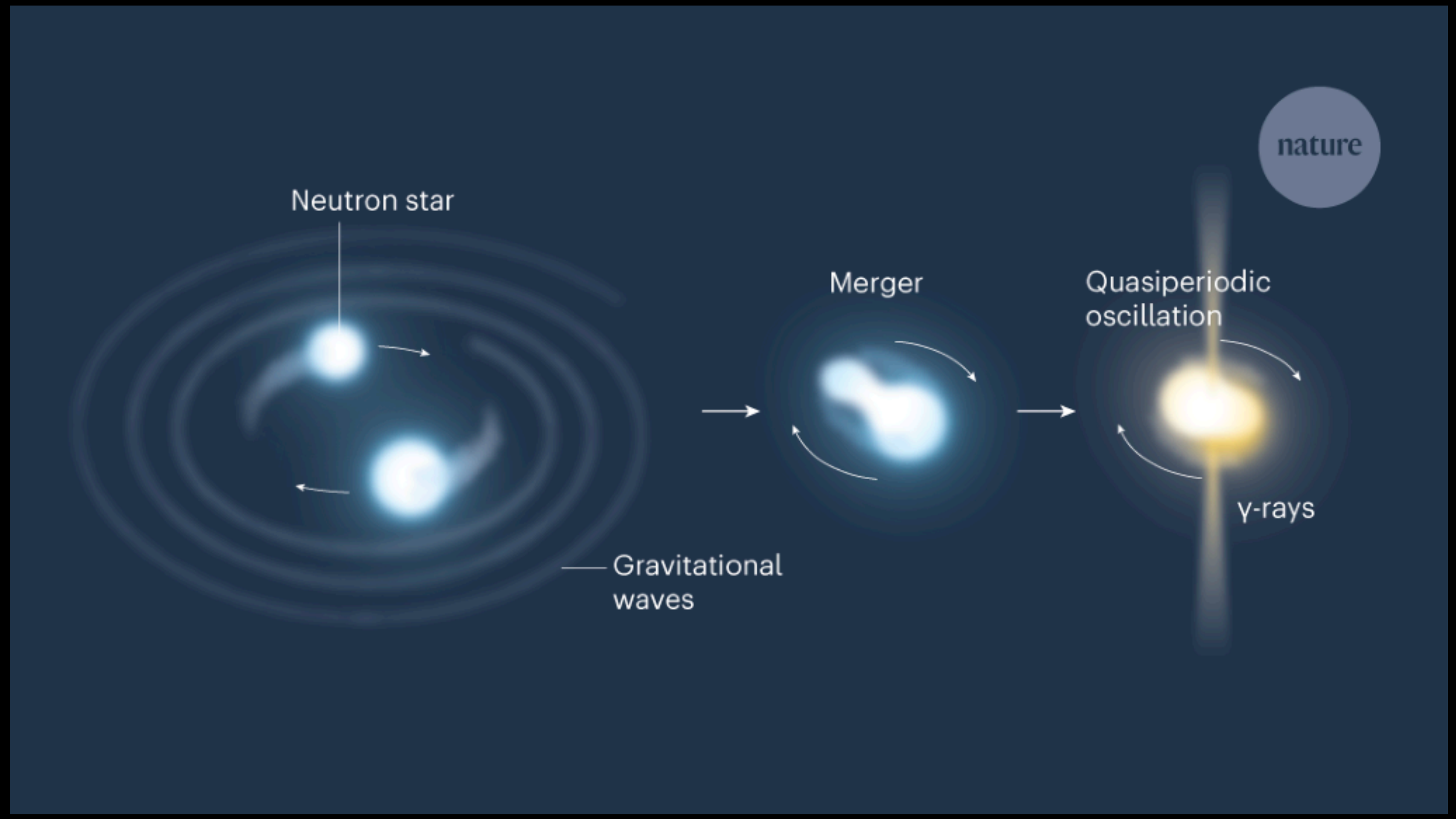


Stergioulas et al. 2011



adapted from Lorimer & Kramer, 2004

How does the HMNS oscillate?



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

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

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

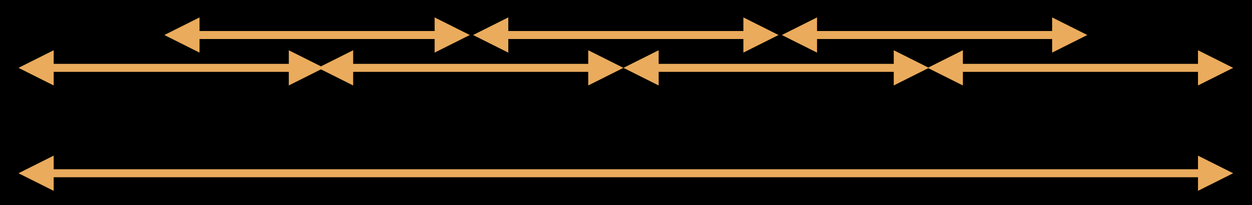
How: Bayesian model comparison

Model 0: White noise only

Model 1: White noise + QPO

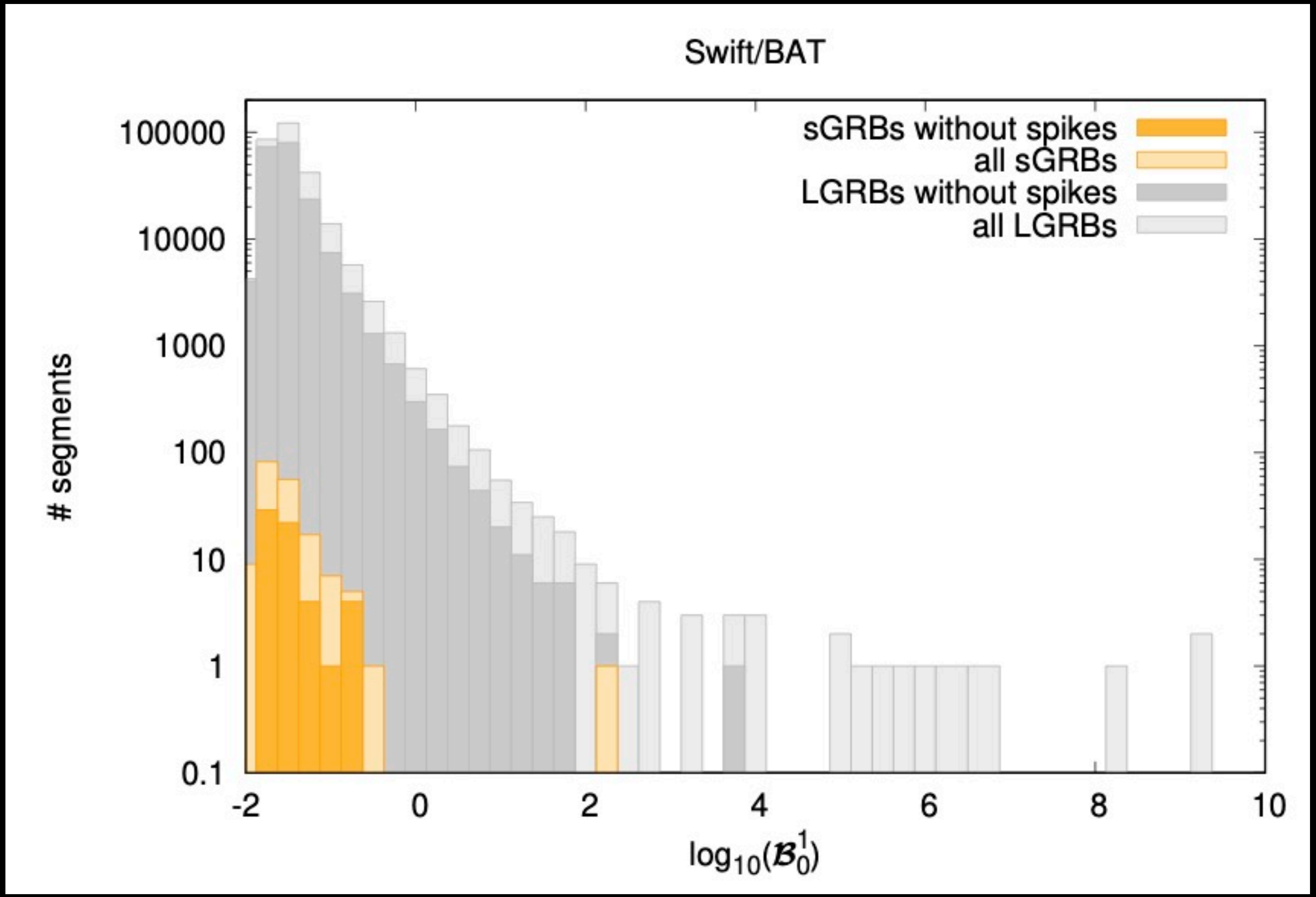
We analyze each burst divided into short segments and quote the Bayes factor in favor of the noise + QPO model for each segment

half-overlapping segments
(approx 100 ms)



total burst duration

Initial analyses: Lessons learned



Causes of fake QPOs

Cosmic rays

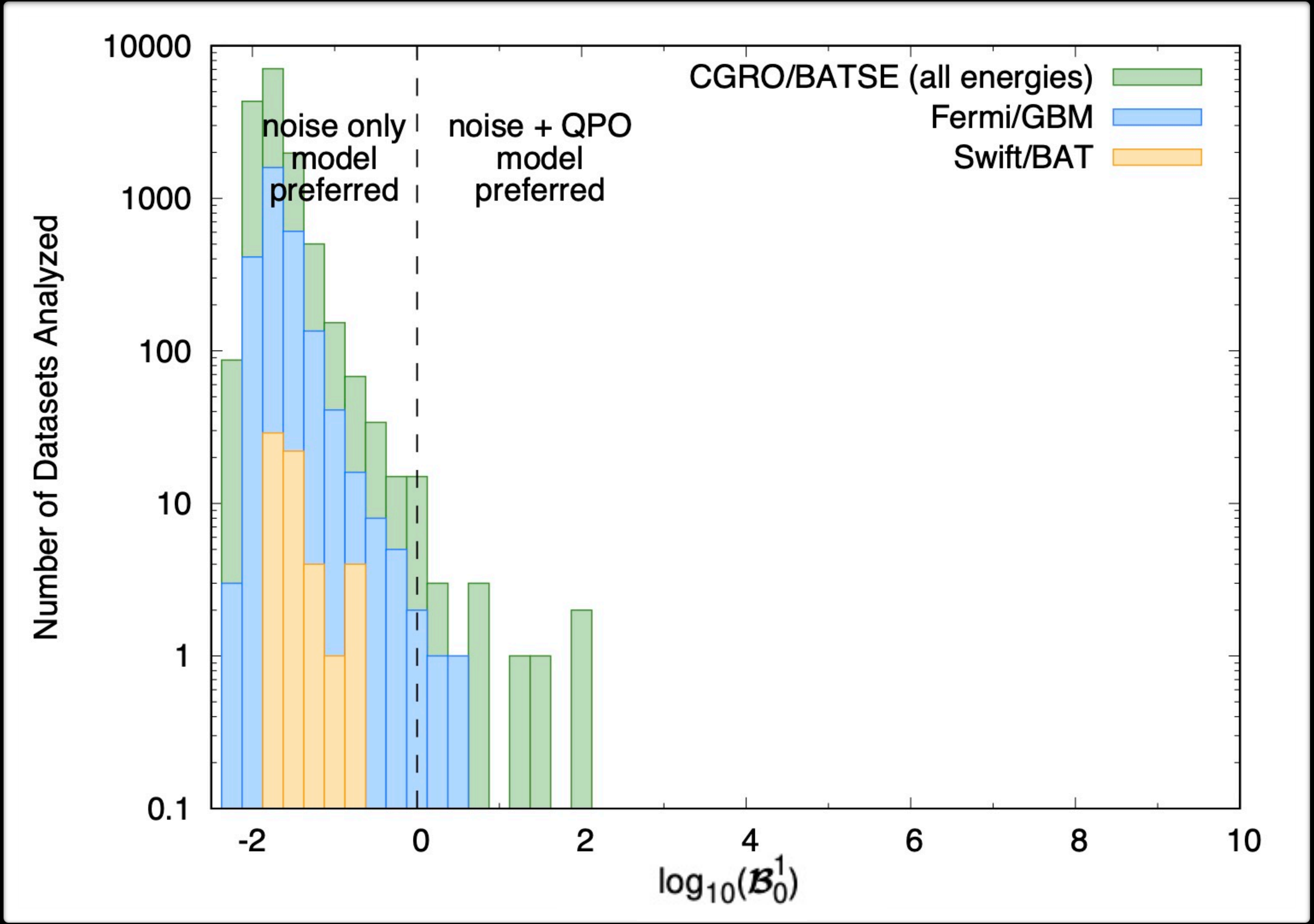
Detector artifacts*

(Data corruption)

Red noise contamination

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

Opening the treasure trove



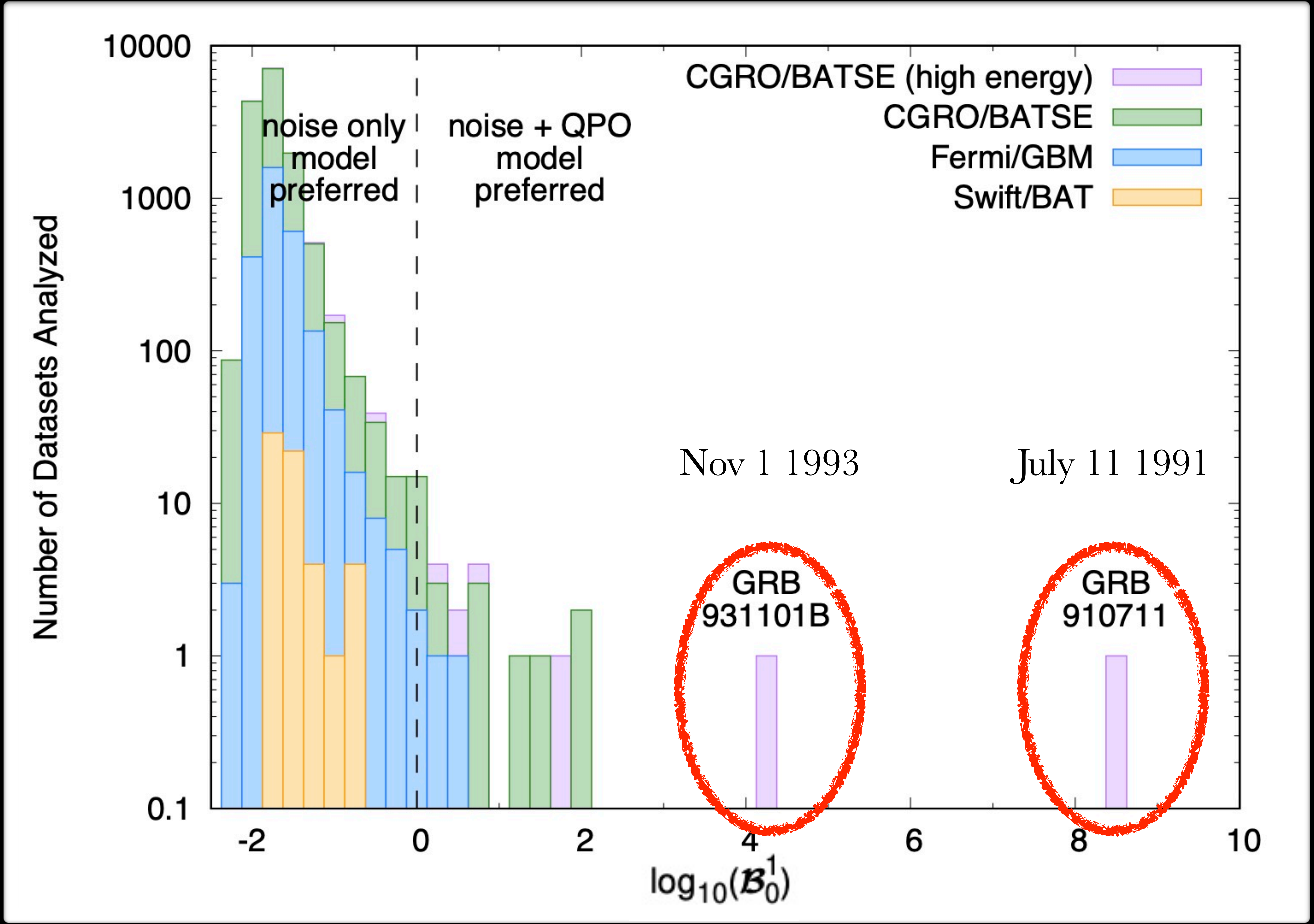
More than 700 short GRBs analyzed

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.

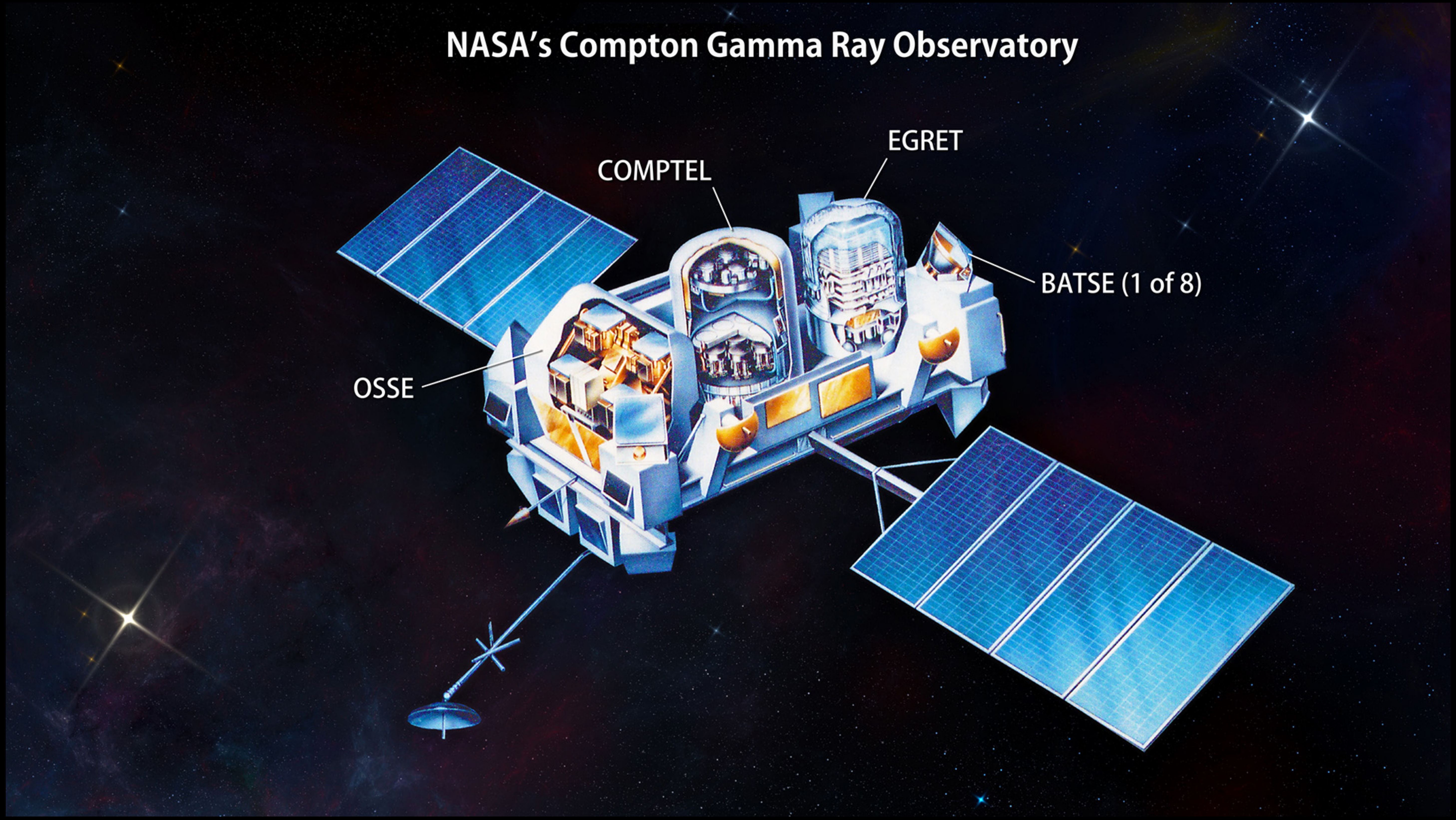
Opening the treasure trove



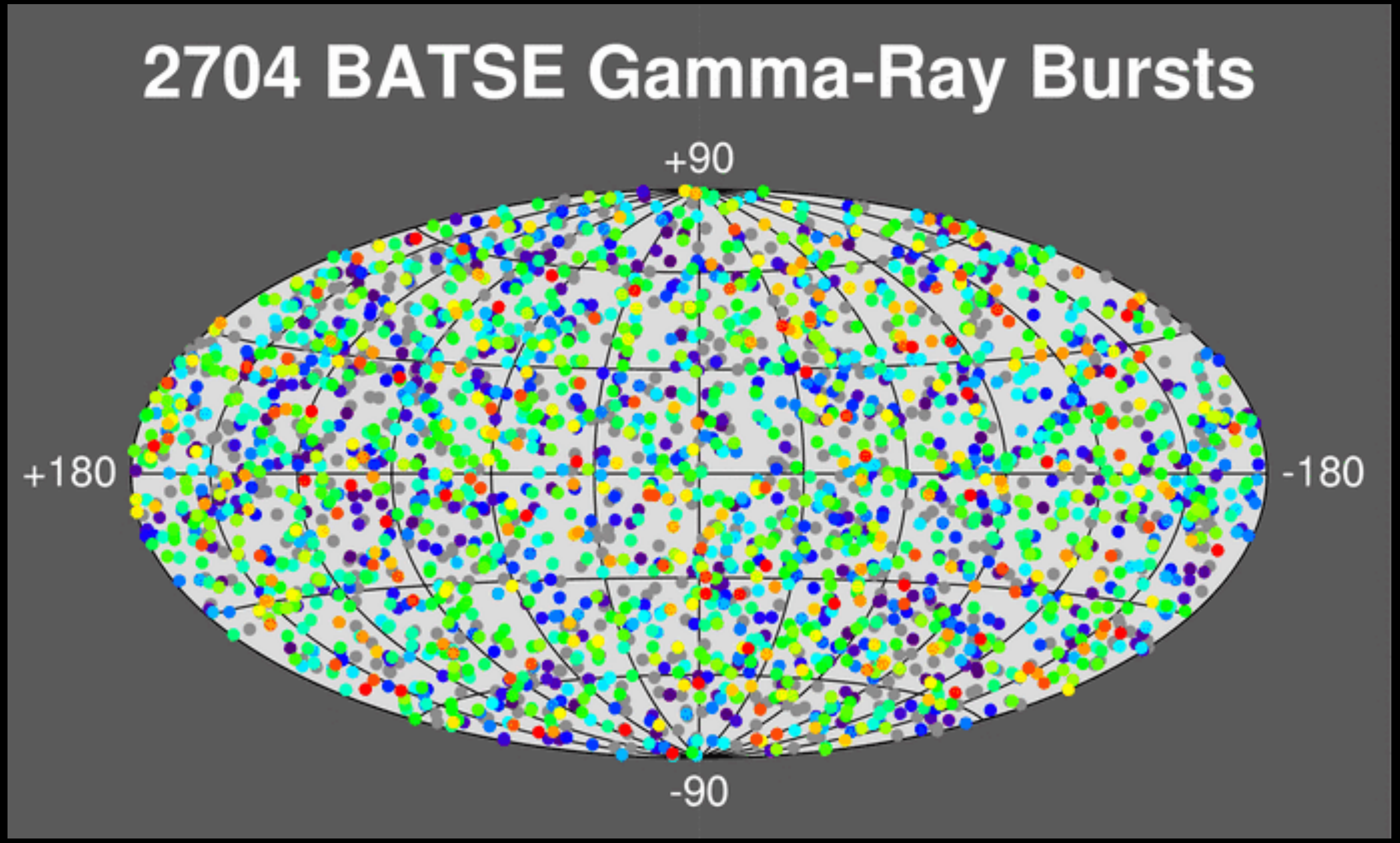
… and **bang**! Two signals. The combined false positive rate is 1 in 3.3 million!

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

CGRO transformed GRB science



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



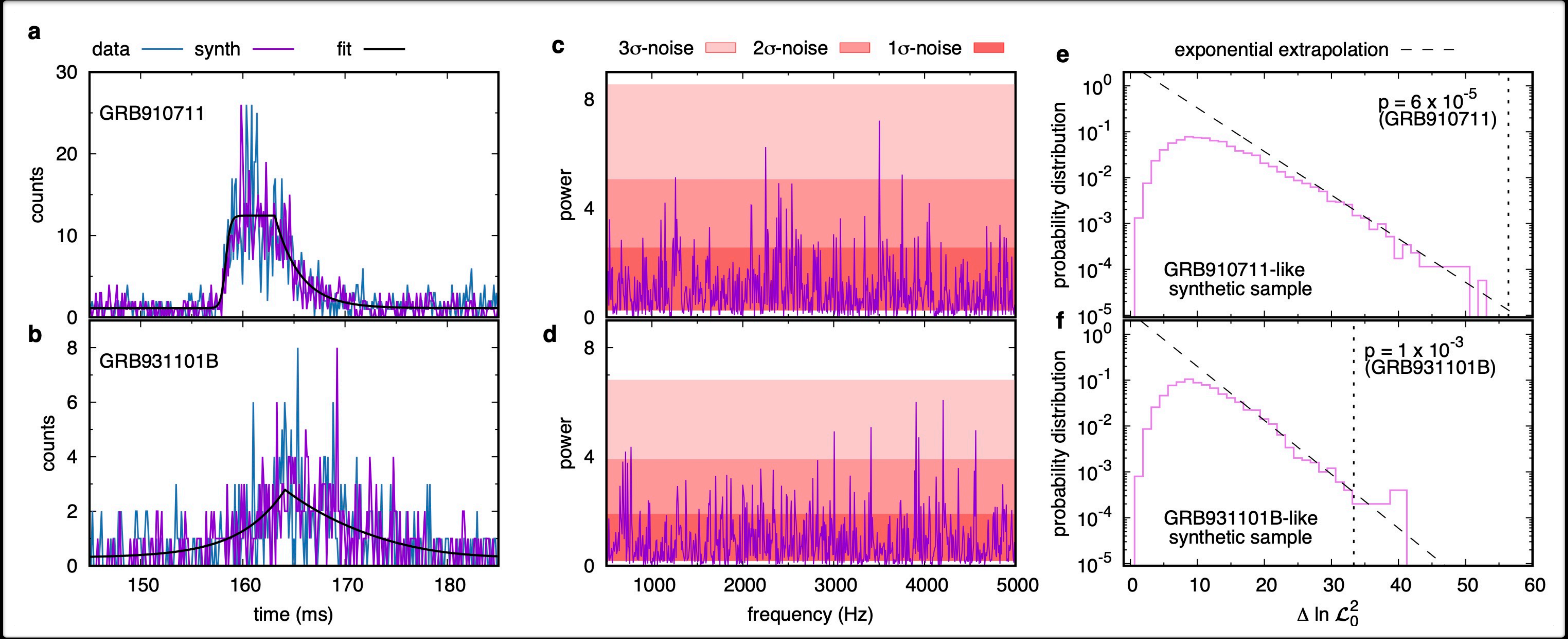
Launched in 1991
De-orbited in 2000

Past and Future

"Why BATSE"? | Future missions:

	BATSE	BAT	GBM	StarBurst 2026	COSI 2027	AMEGO-X
Effective area (cm^2)	2,000/ LAD	1.400	240	3.000	256 (physical area)	1.200
Timing (microsec)	2	100	2	2	3	10

False positive estimate

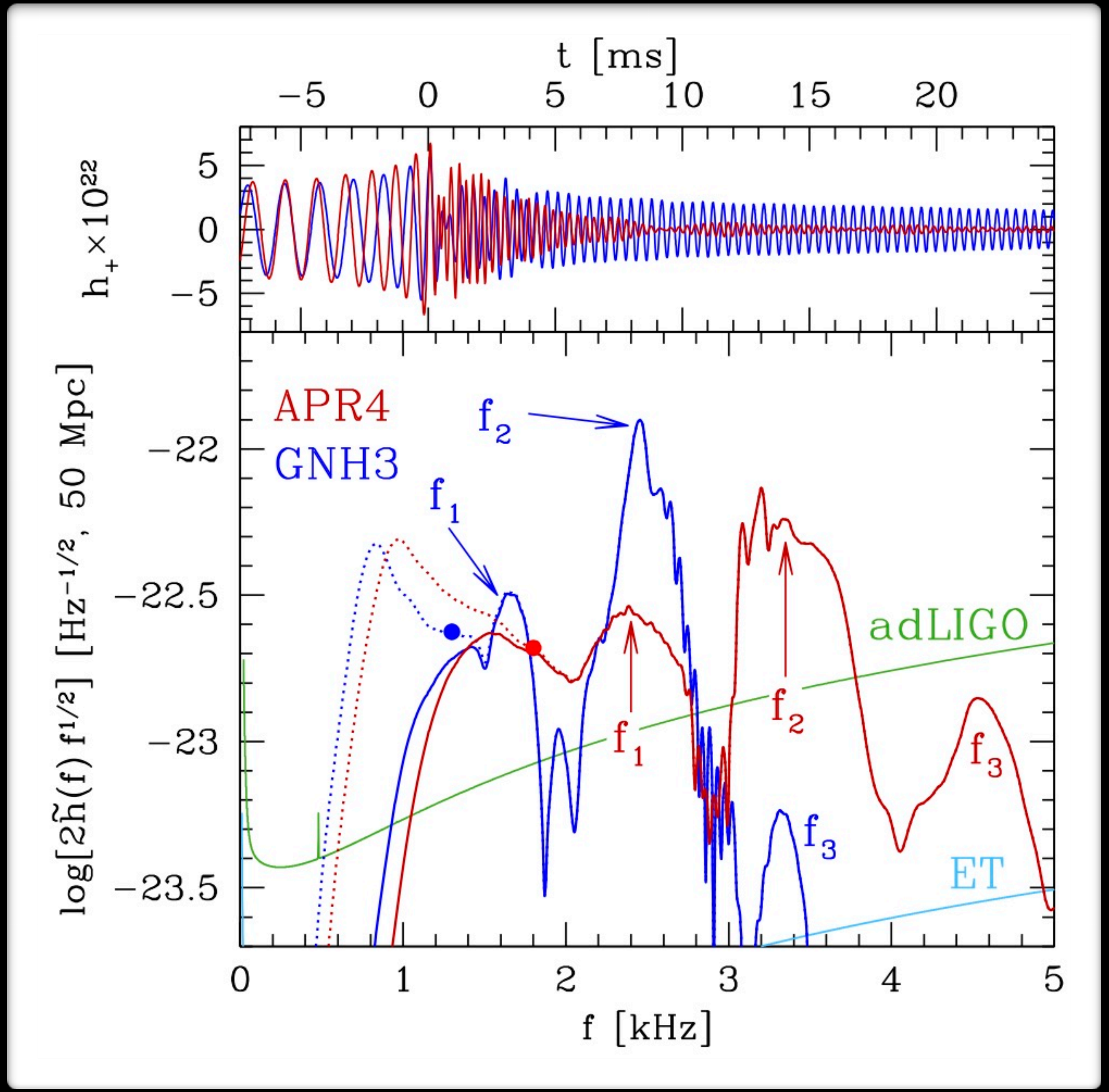


Interpretation?

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

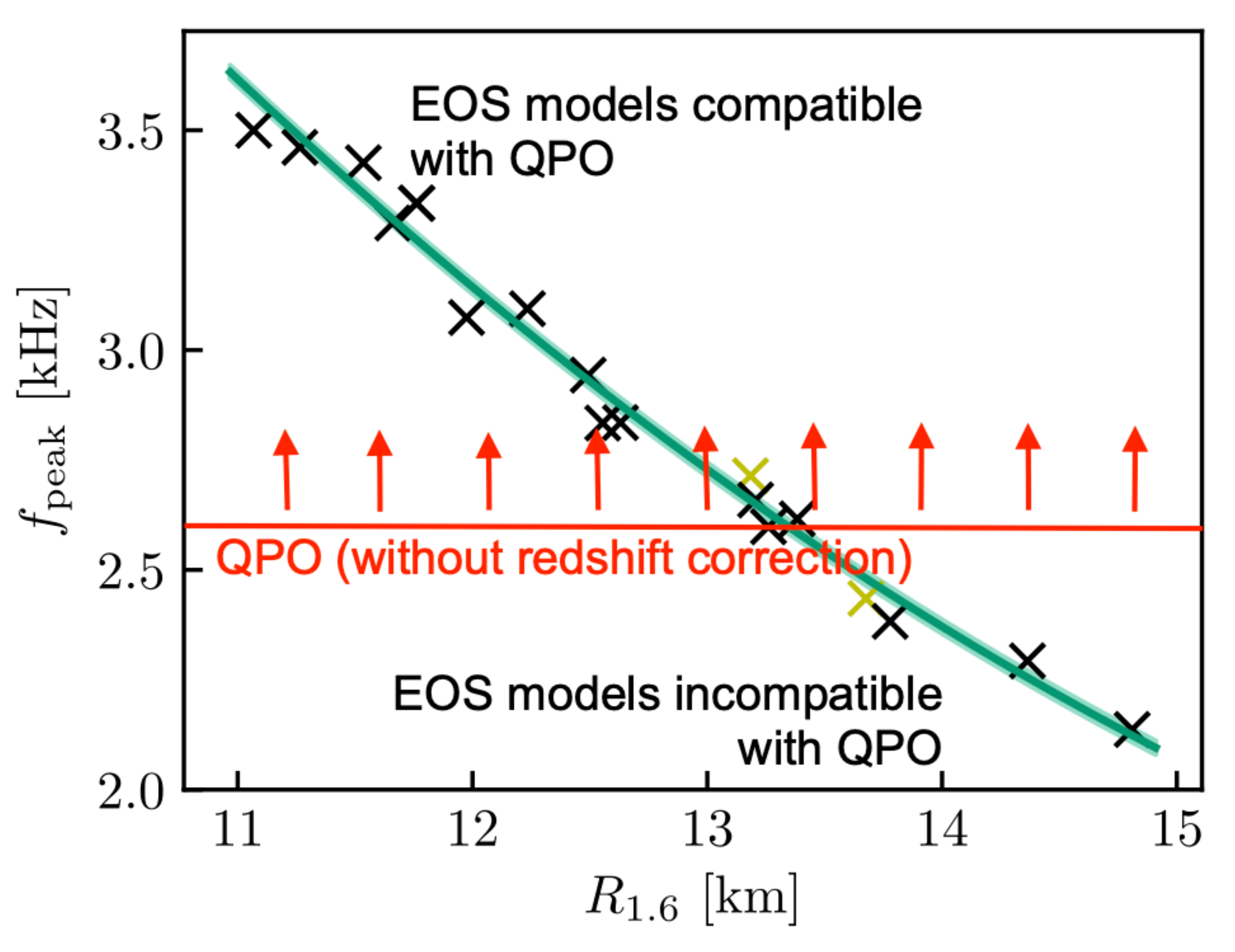


Important: The *redshift* of these GRBs is not know; the QPO frequencies are detected in the detector frame!


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

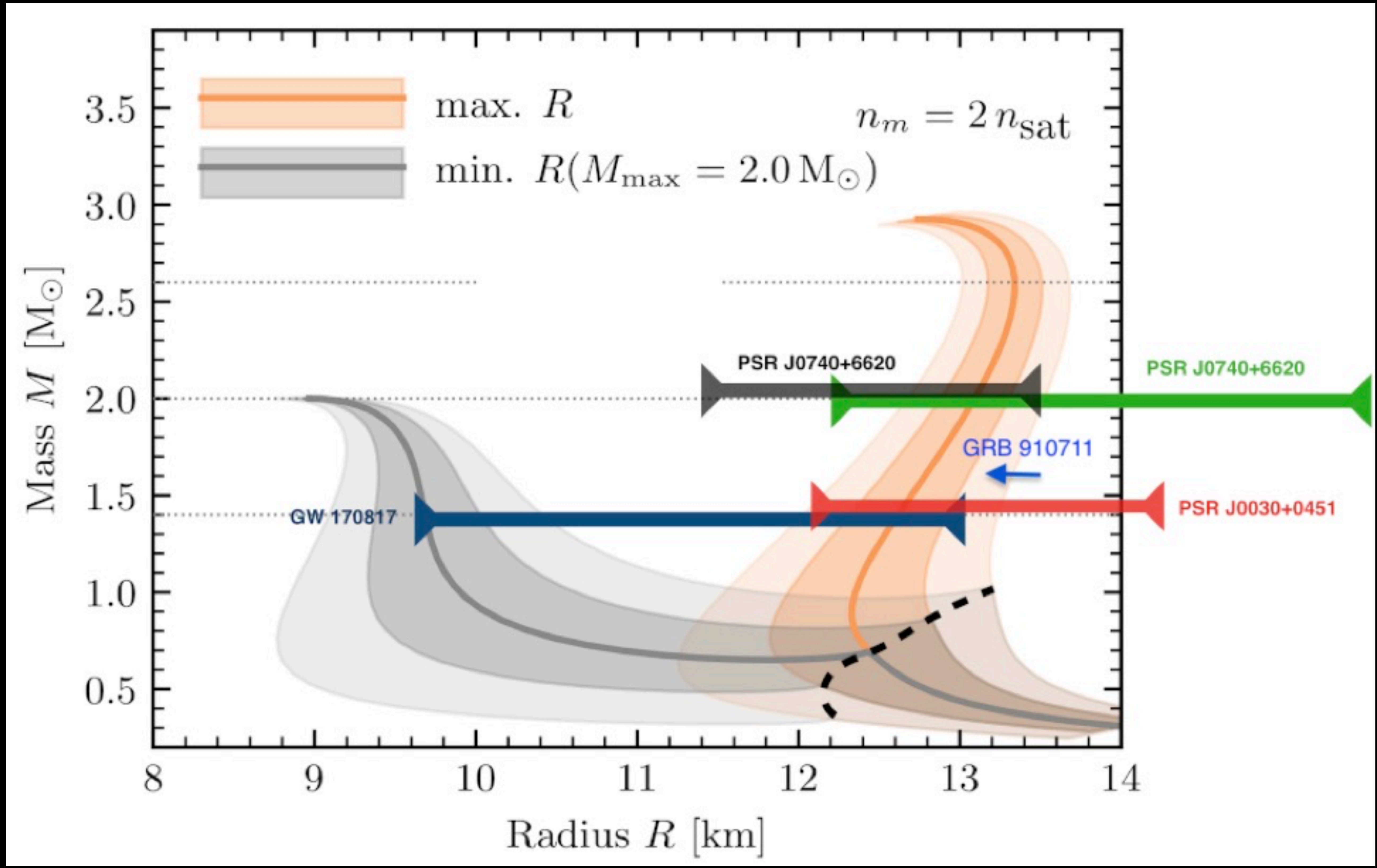
Learning about the neutron star equation of state

QPOs + NR



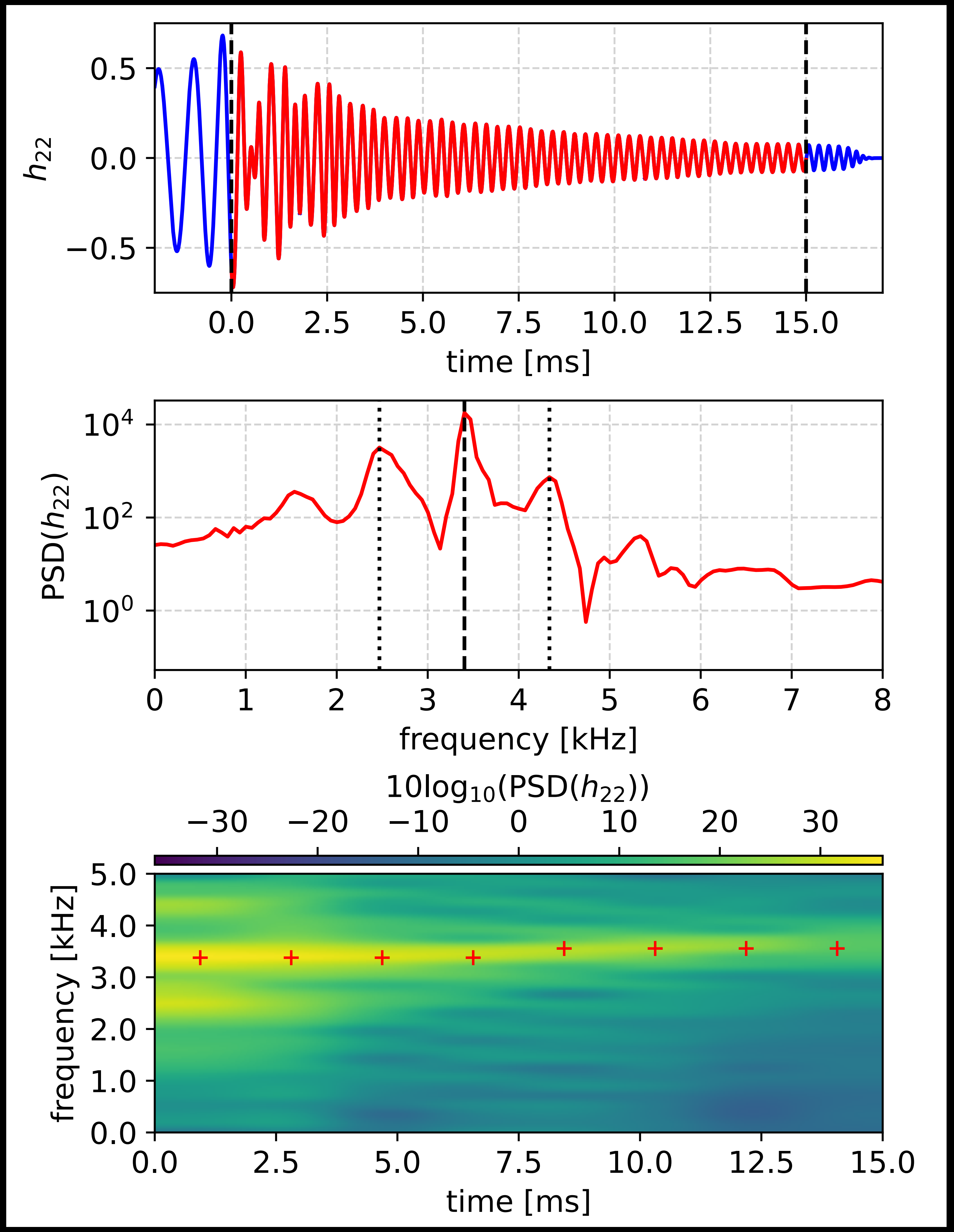
adapted from Lioutas et al., 2021

NICER + GWs + GRB



adapted from Reddy, 2021

Leveraging numerical relativity results



Guedes et al. 2024

Example post-merger GW waveform
(1.35 + 1.35, SLy EOS)

Frequencies:

- $f_1 = f_2 - f_0$
- f_2
- $f_3 = f_2 + f_0$

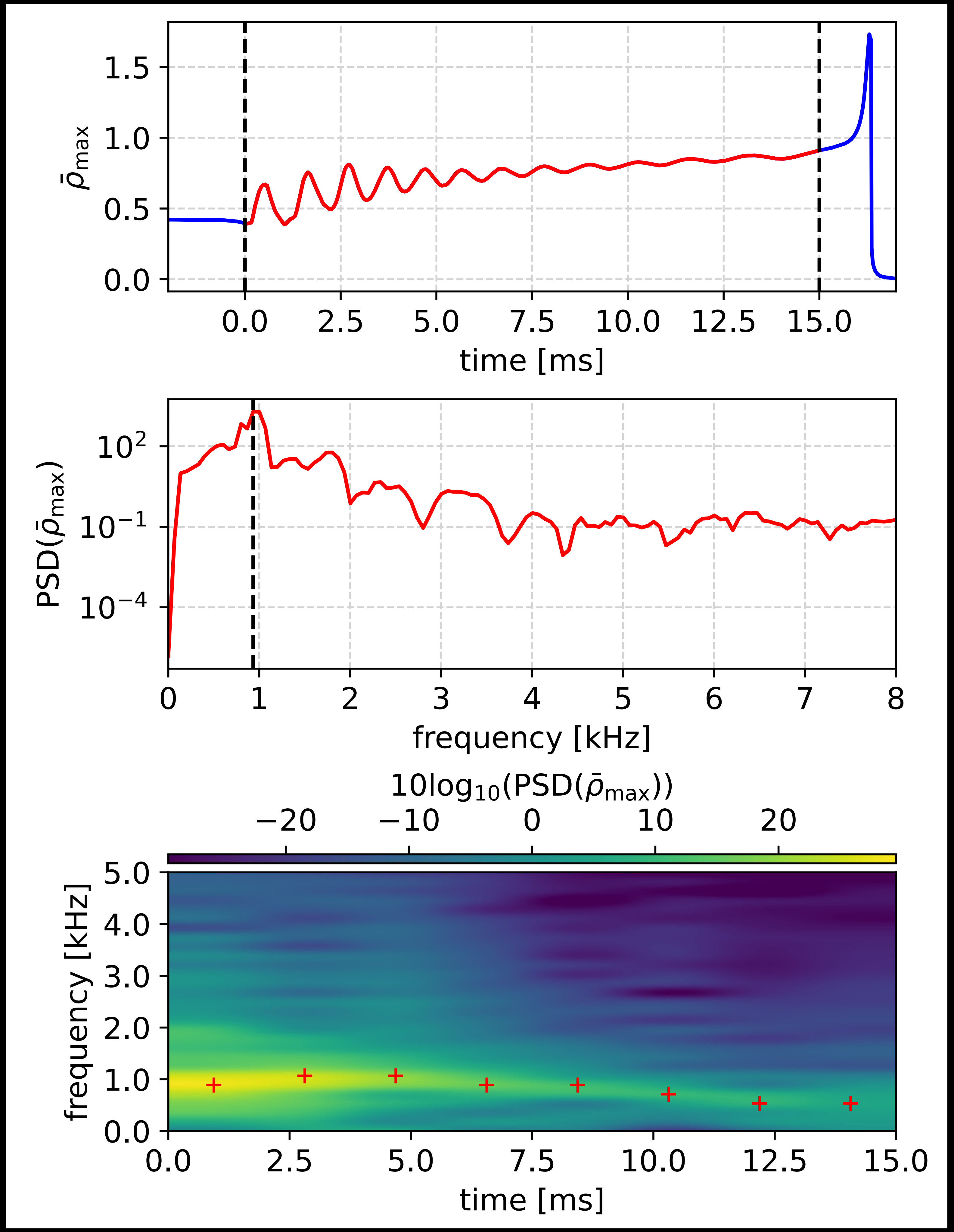
f_2 is the quadrupolar mode, strongly excited
f_0 is the radial mode, not so easy to determine

Leveraging numerical relativity results

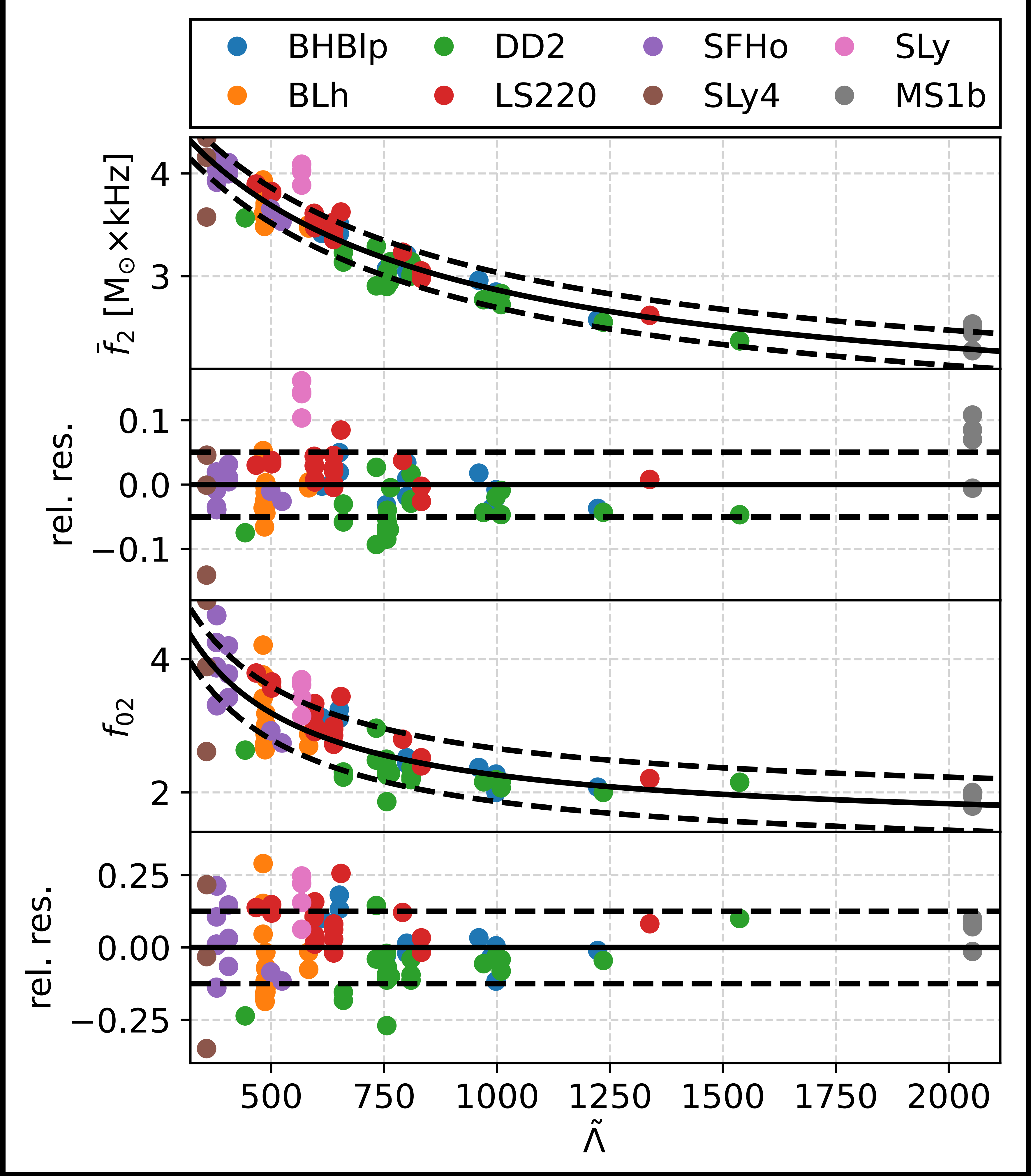
Oscillations in the maximum (central) density of the remnant star

f_0 is the peak frequency

f_0 is easy to determine



New (quasi-)universal relations



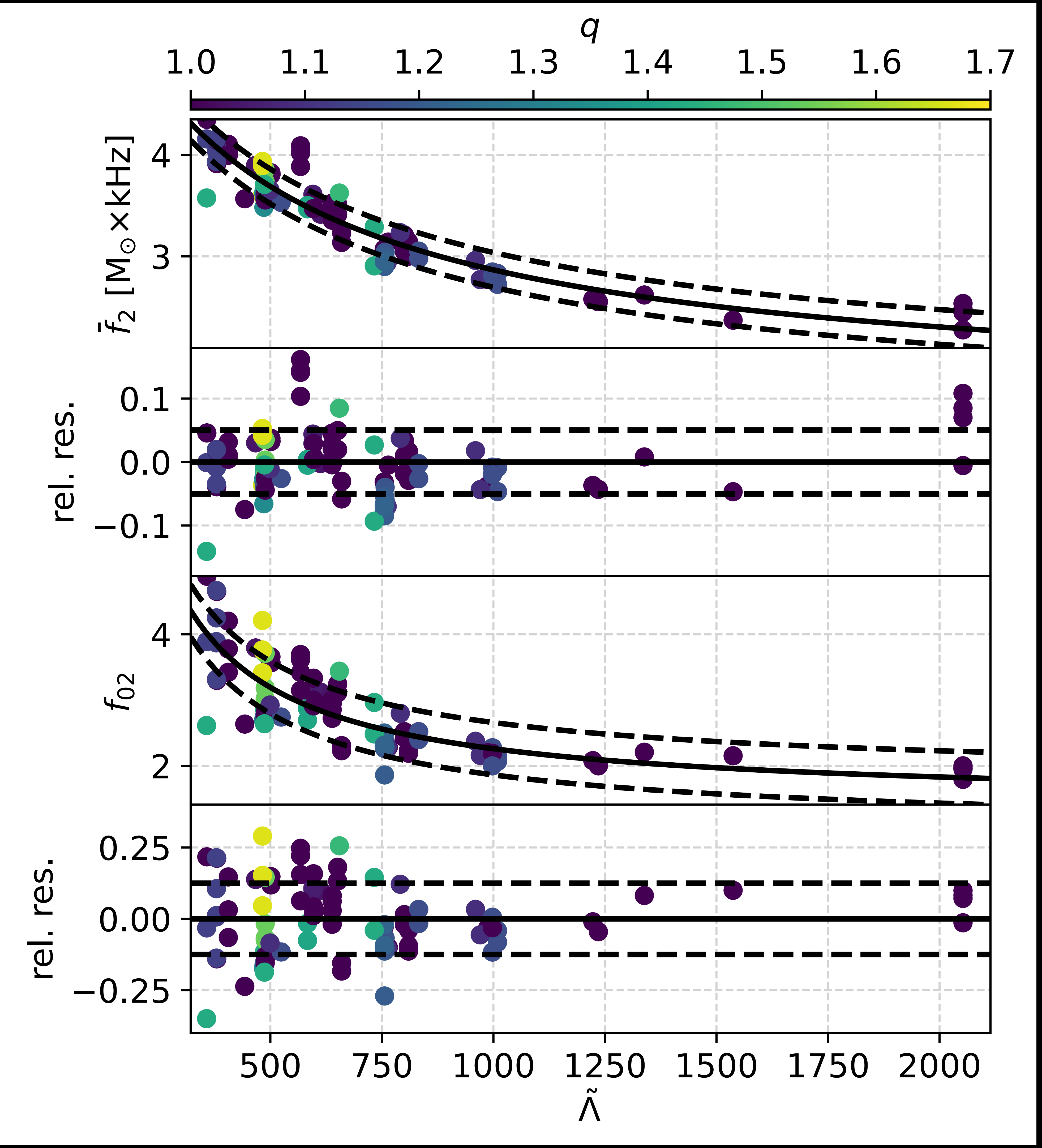
Guedes et al. 2024

$\mathscr{M}$ is the chirp mass of the binary
$\bar{f}_2 \equiv \mathscr{M} f_2$ has a tight correlation with the binary tidal deformability $\tilde{\Lambda}$

$f_{02} \equiv f_2/f_0$ has a larger spread, but this relation is independent of the redshift

New (quasi-)universal relations

Same points, but highlighting the variation in mass ratio: these relations are free from assumptions about the binary masses



Bayesian inference

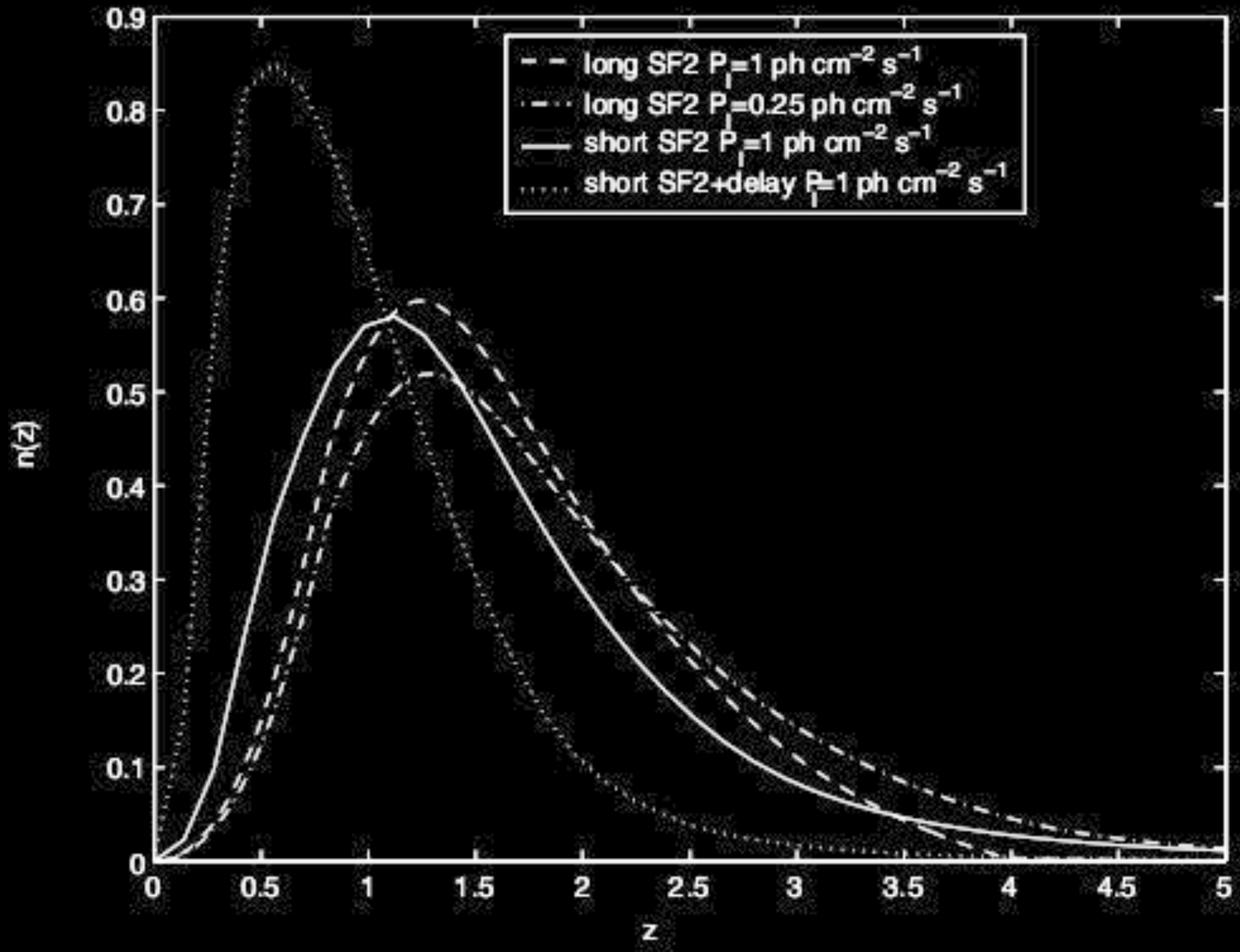
Assumption: We can identify the QPOs ν_2 and ν_0 detected in GRBs 910711 and 931101B with f_2 and f_0

Using the quasi-universal relations
$\bar{f}_2 \times \tilde{\Lambda}$, $f_{02} \times \tilde{\Lambda}$ and $\mathscr{M} \times \tilde{\Lambda}$

we can constrain
$\mathscr{M}, \tilde{\Lambda}$ and the redshift z
for each GRB

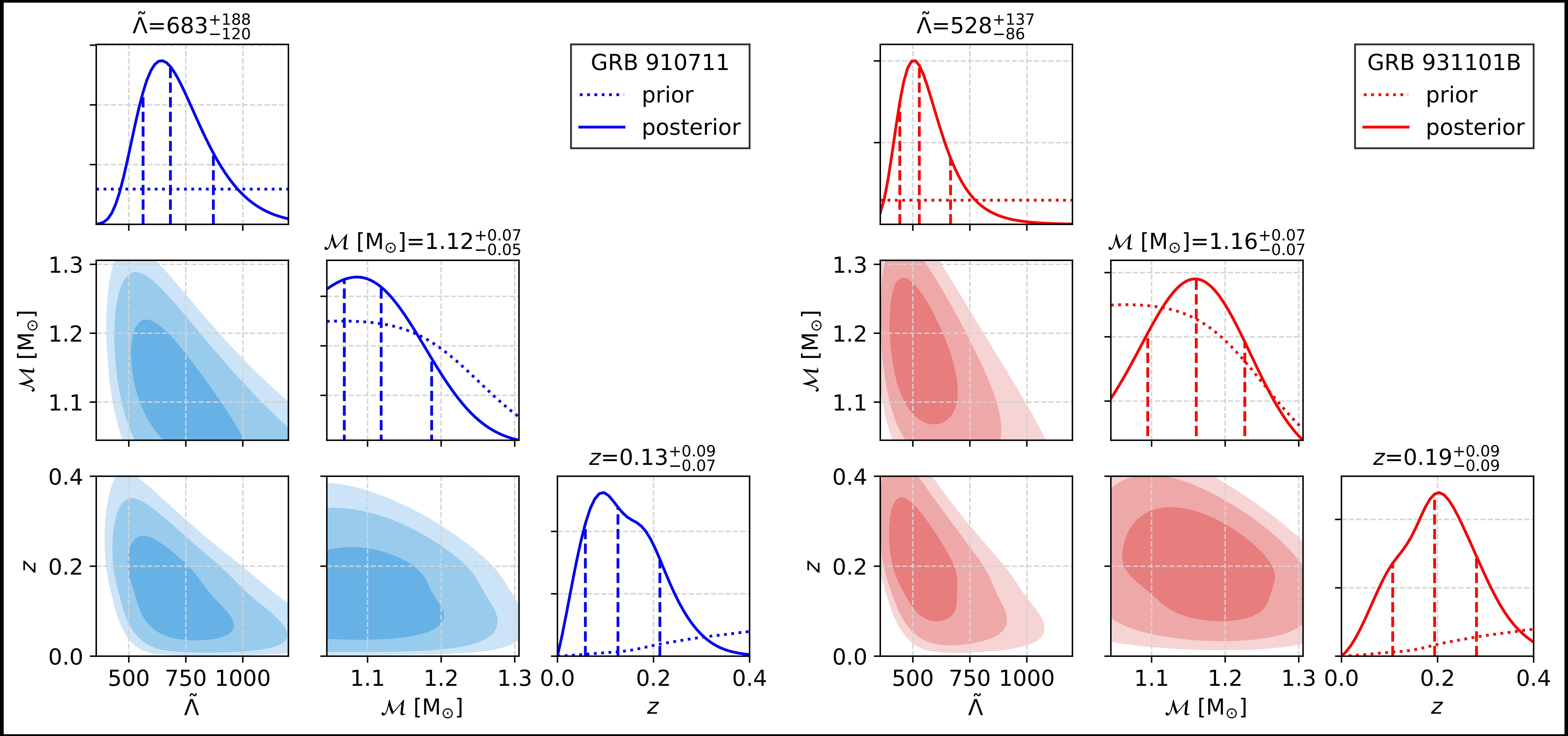
with the product of the likelihoods
$\mathscr{L}(\nu_{02}\,|\,f_{02}(\tilde{\Lambda}))\mathscr{L}(\nu_2\,|\,f_2^{\rm obs}(\mathscr{M}, \tilde{\Lambda}, z))$

Redshift prior distribution for short GRBs



Guetta & Piran 2005

Posterior Distributions

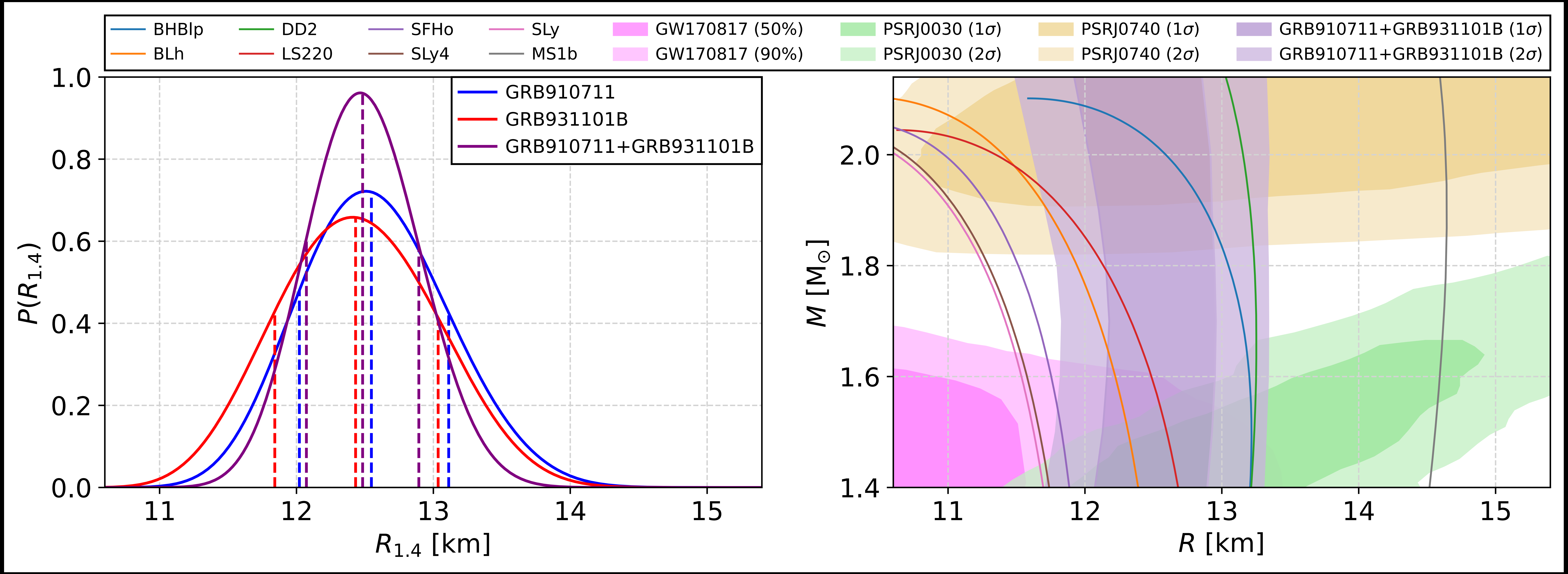


Guedes et al. 2024

Constraining $R_{1.4}$ and the EOS

$$R_M(\mathscr{M}, \tilde{\Lambda}) = \alpha \left(\frac{\mathscr{M}}{1M_\odot}\right)\left(\frac{\tilde{\Lambda}}{800}\right)^{\frac{1}{\beta}}$$

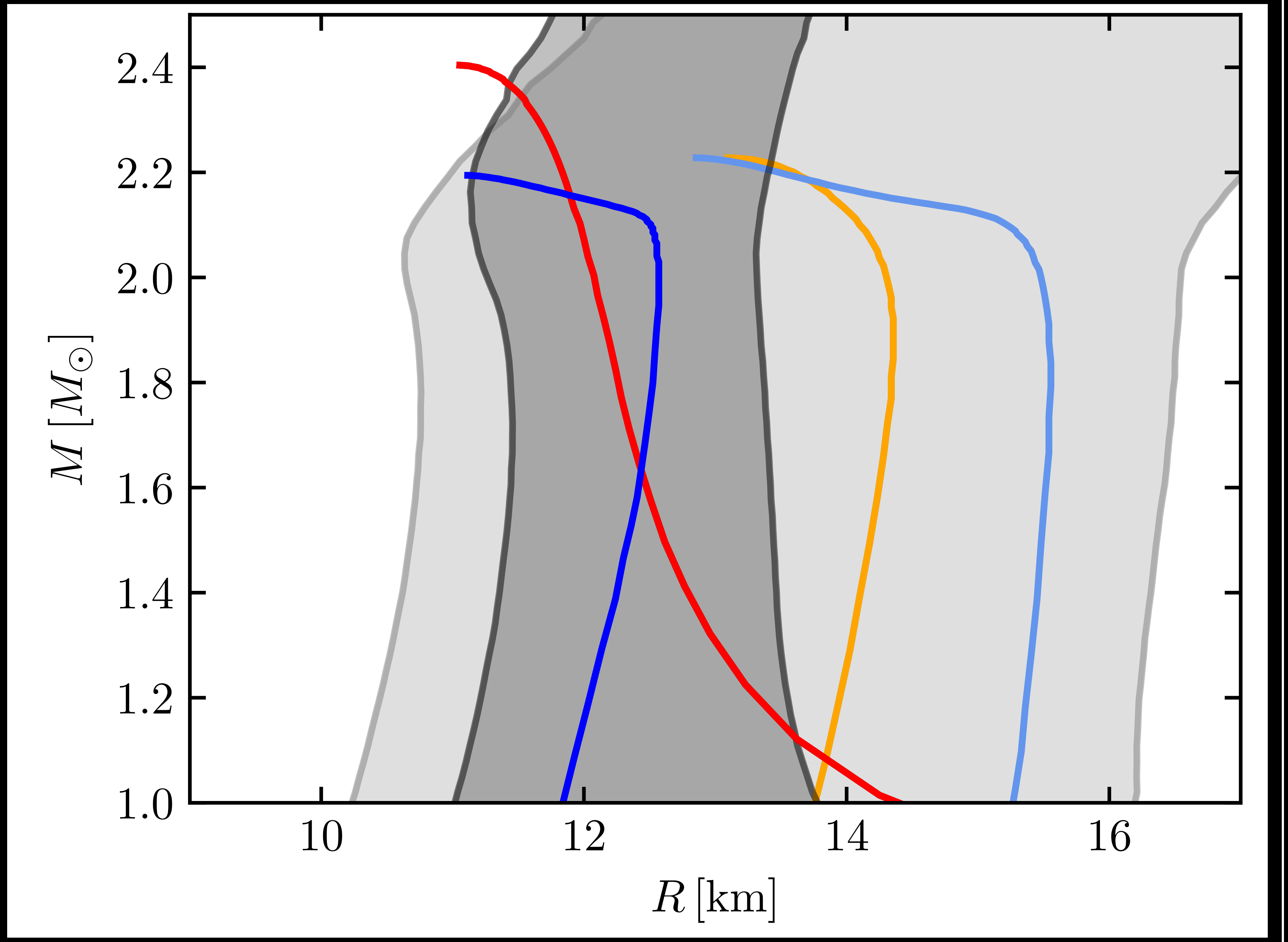
Godzieba & Radice, 2021



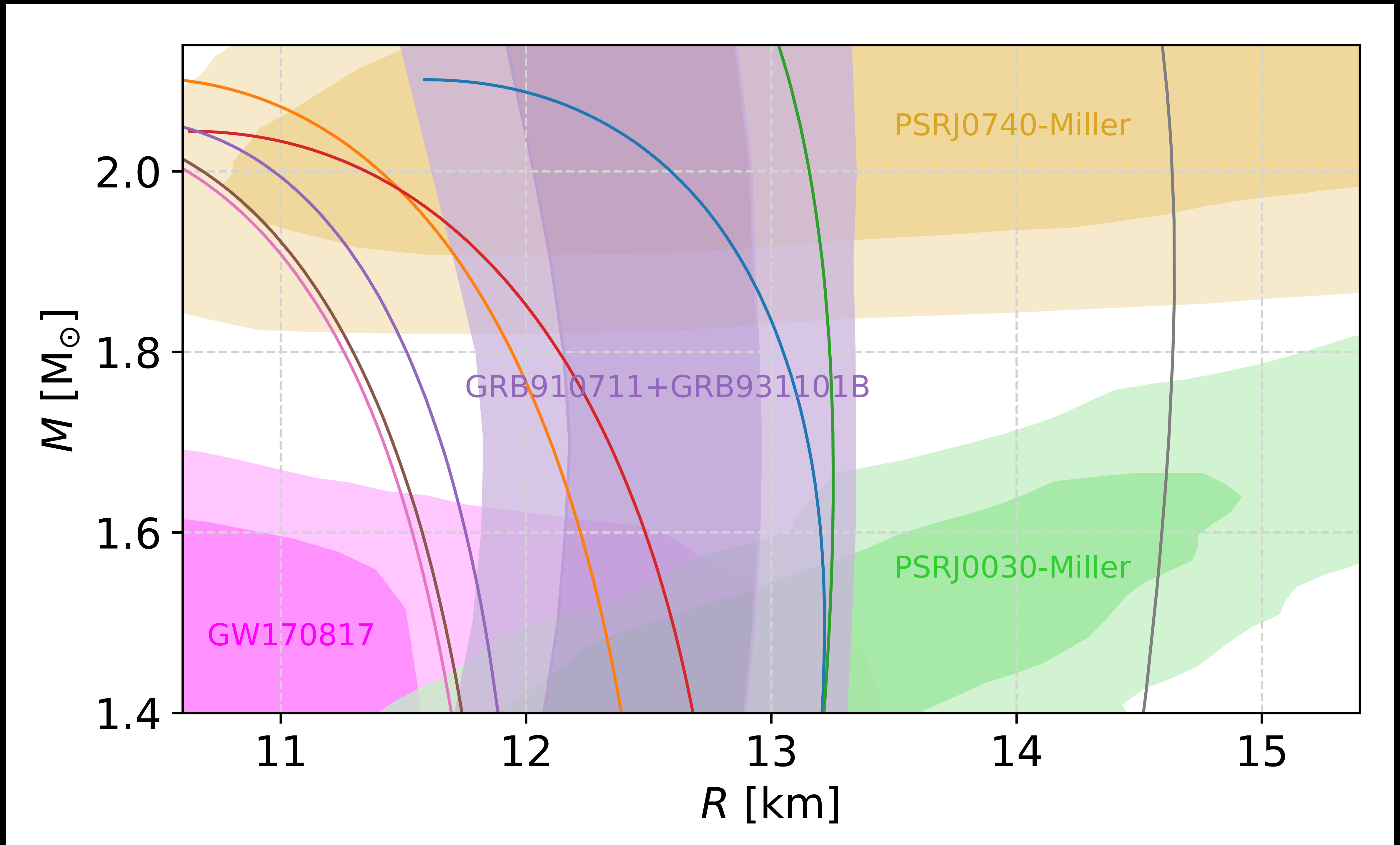
Guedes et al. 2024

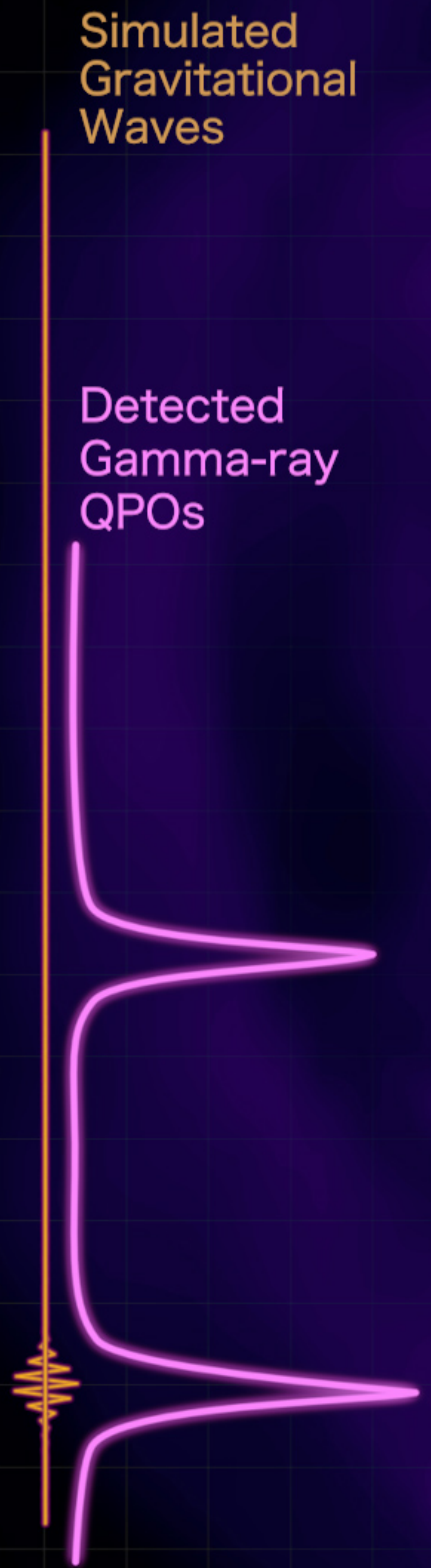
Constraining $R_{1.4}$ and the EOS

Pulsar masses, NICER radii and GWs

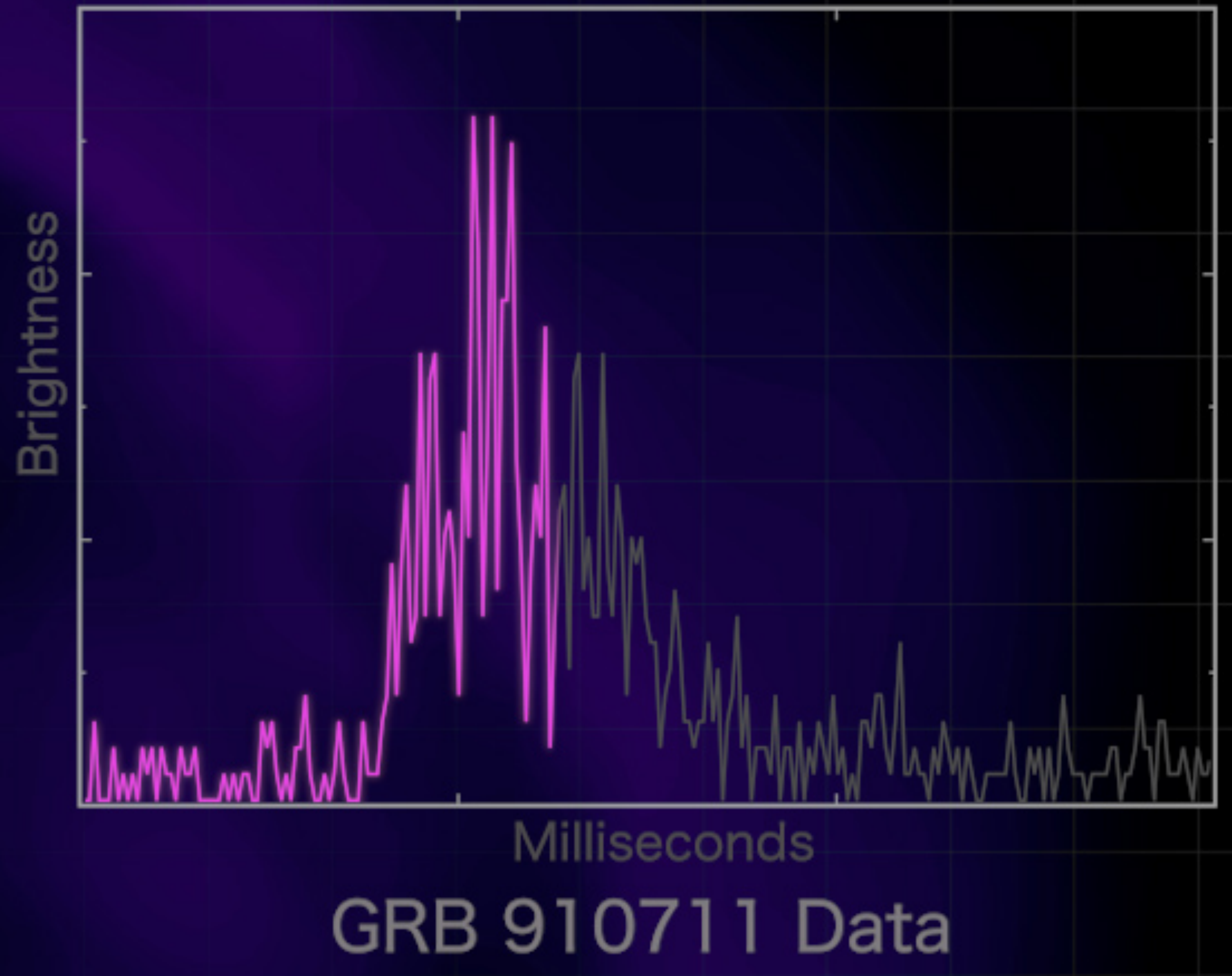


Essick et al. 2023

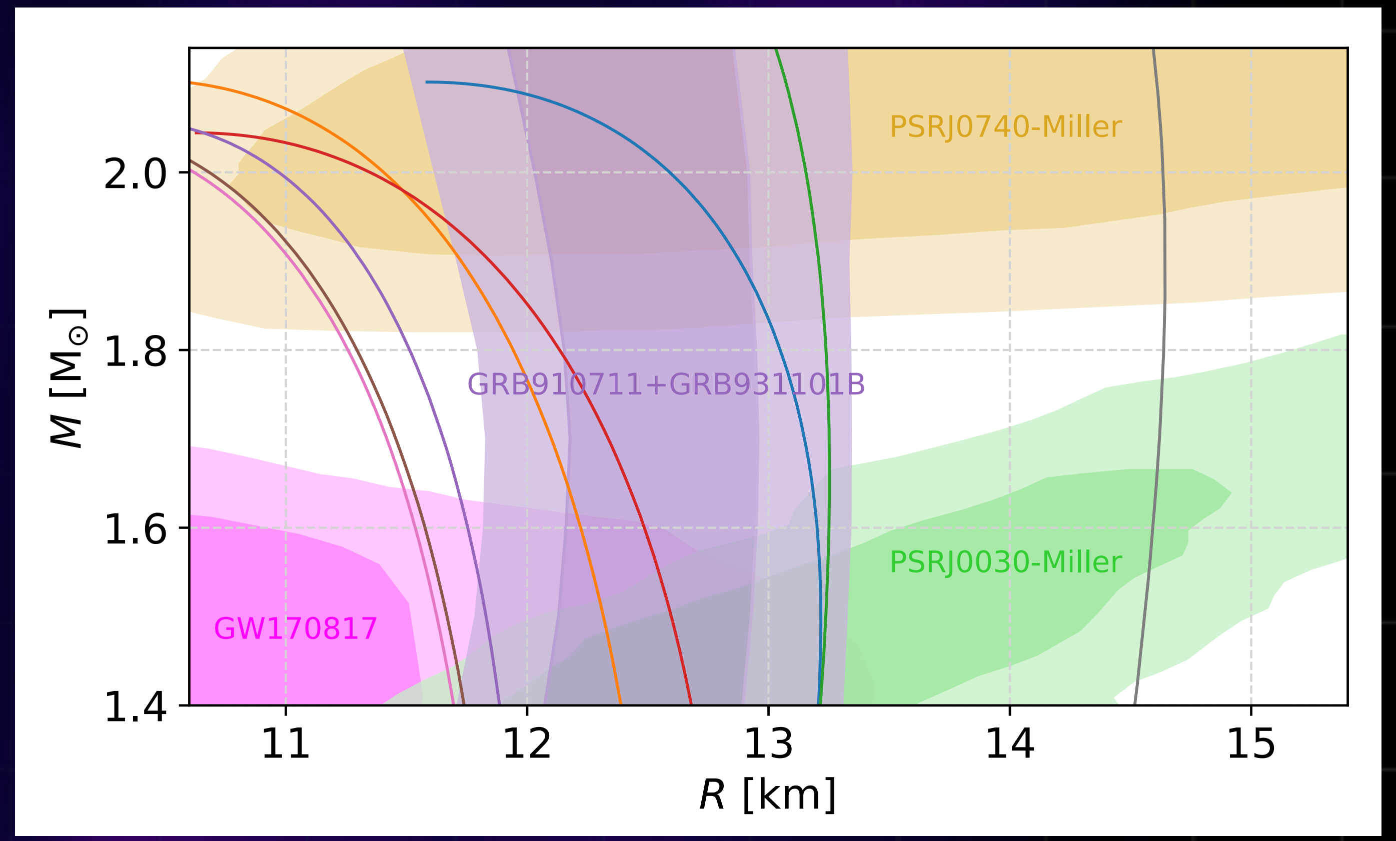




Between the *whoop* and the *ding* of a binary NS merger, an HMNS can be formed. We looked for them and found two: GRB 910711 and GRB 931101B.



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 and we can already use them to constrain the EOS inside NSs.



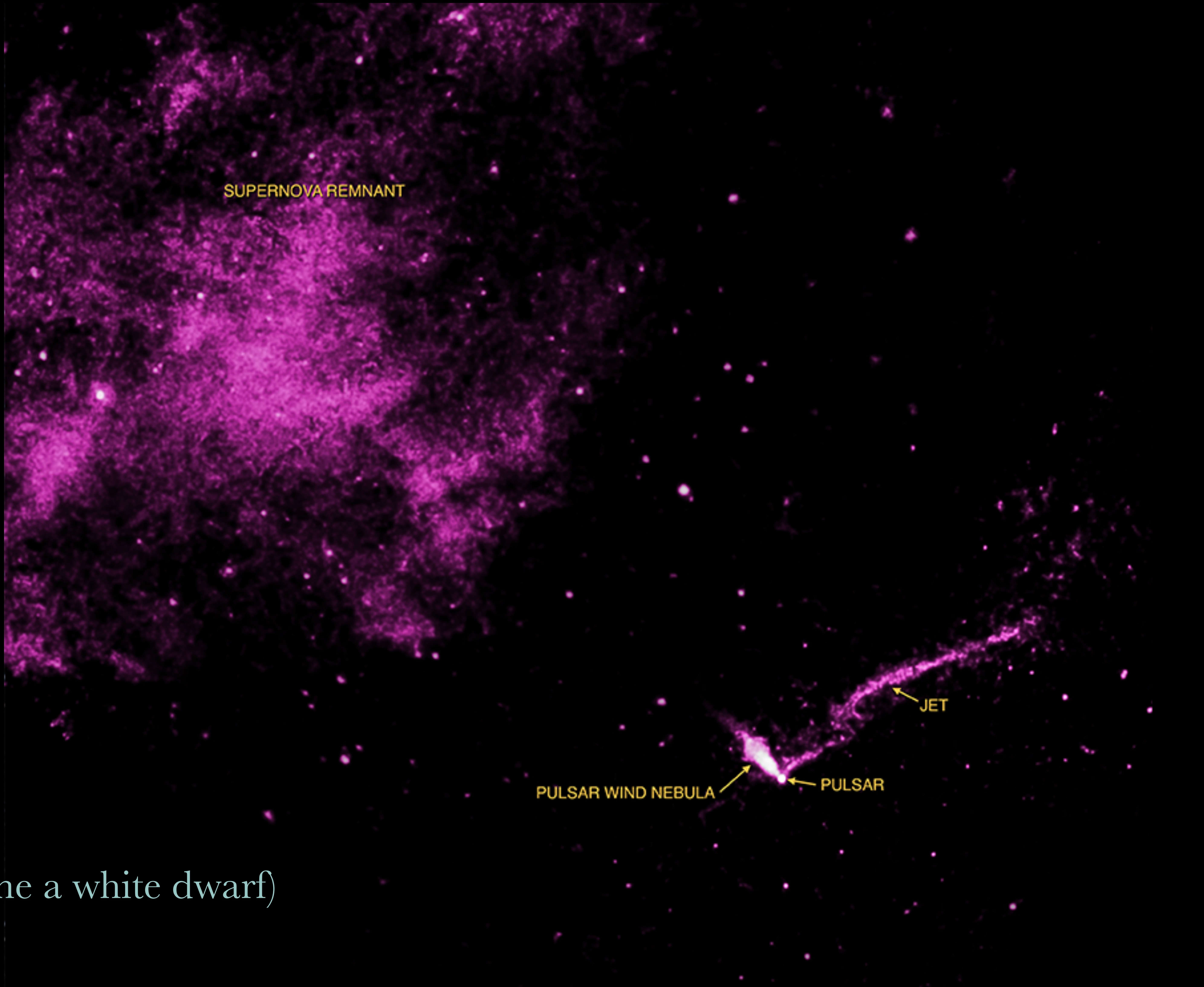
Backup slides

Can Neutron Stars launch jets?

Yes!

We see jets from NSs all the time (pulsars, magnetars, 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?

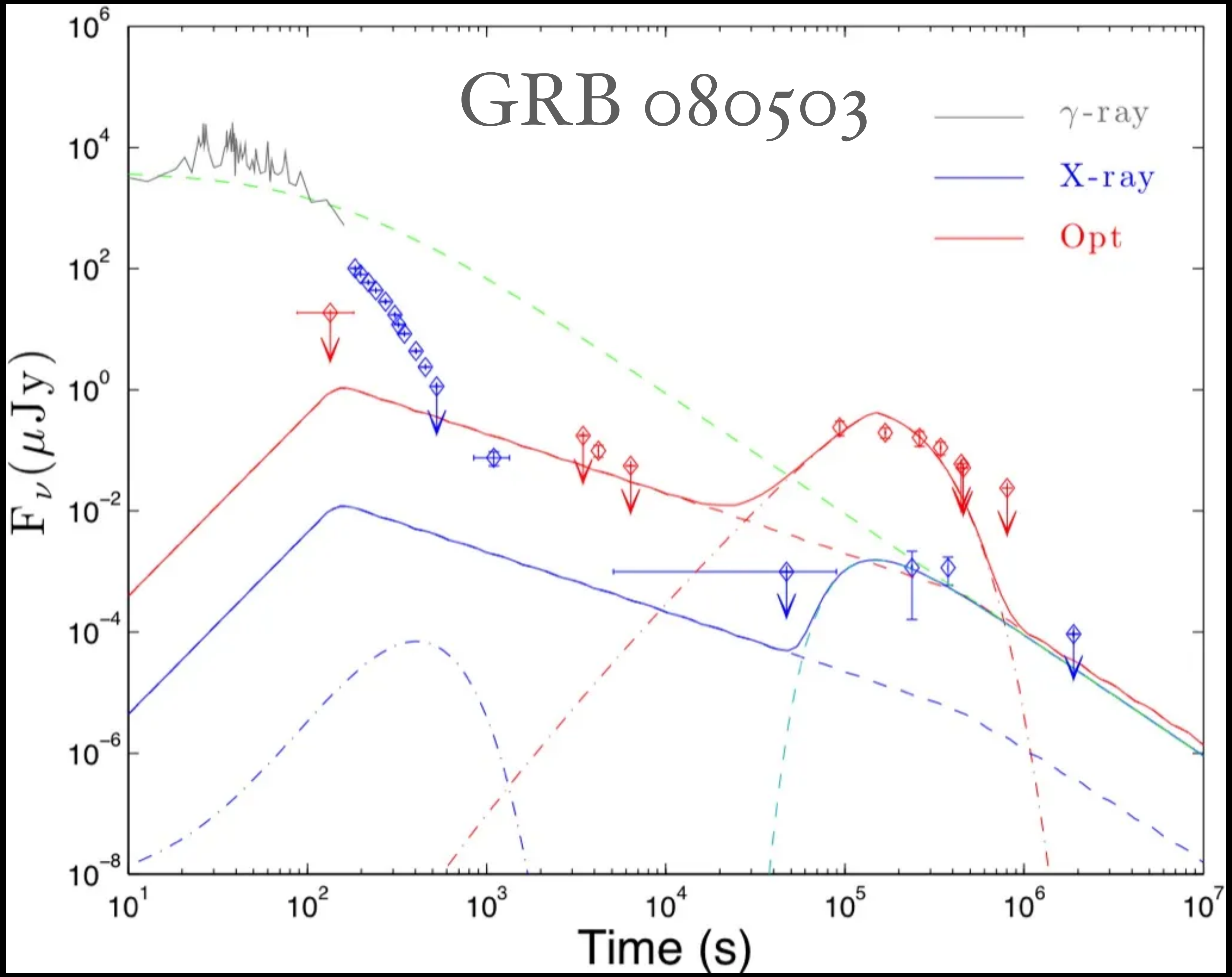
Maybe!

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
$\Gamma \sim 100 - 1000$
(but see Dereli-Bégué et al. 2022)

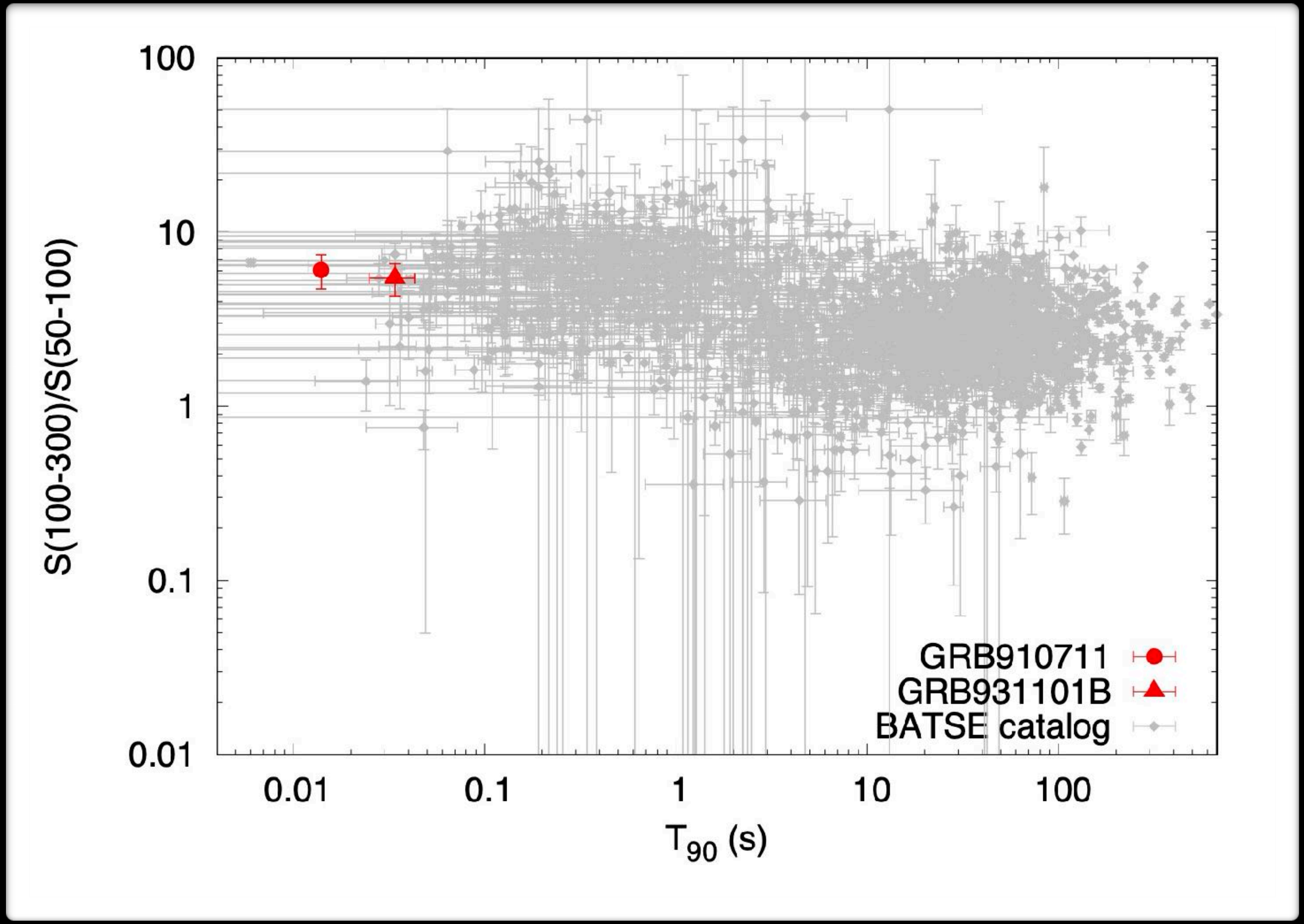
Recent simulations:

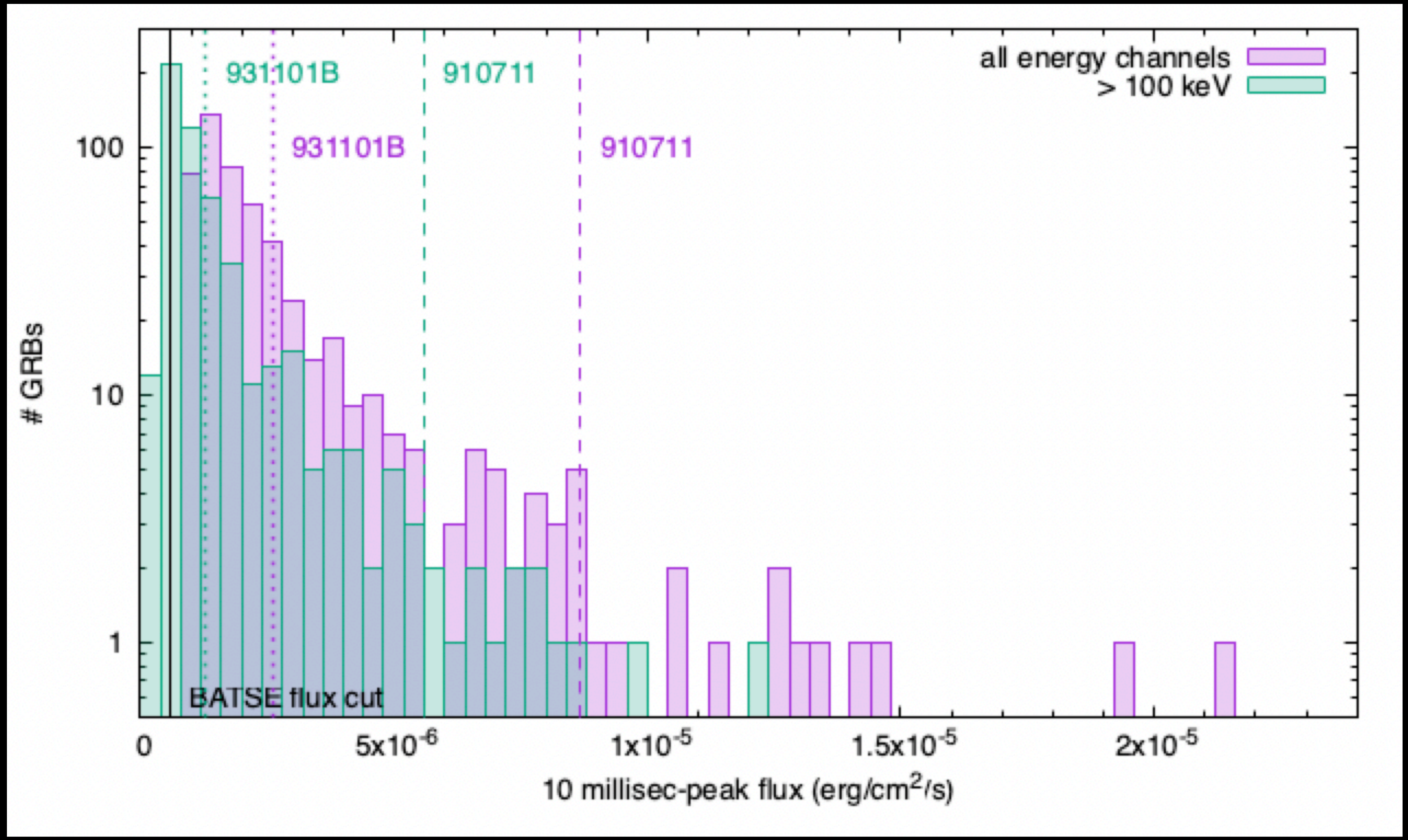
- see e.g. Mösta et al. 2020, Bamber et al. 2024
- it is easier to simulate jets with black holes
- HMNS scenario requires dynamo amplification of B field



Gao et al. 2015

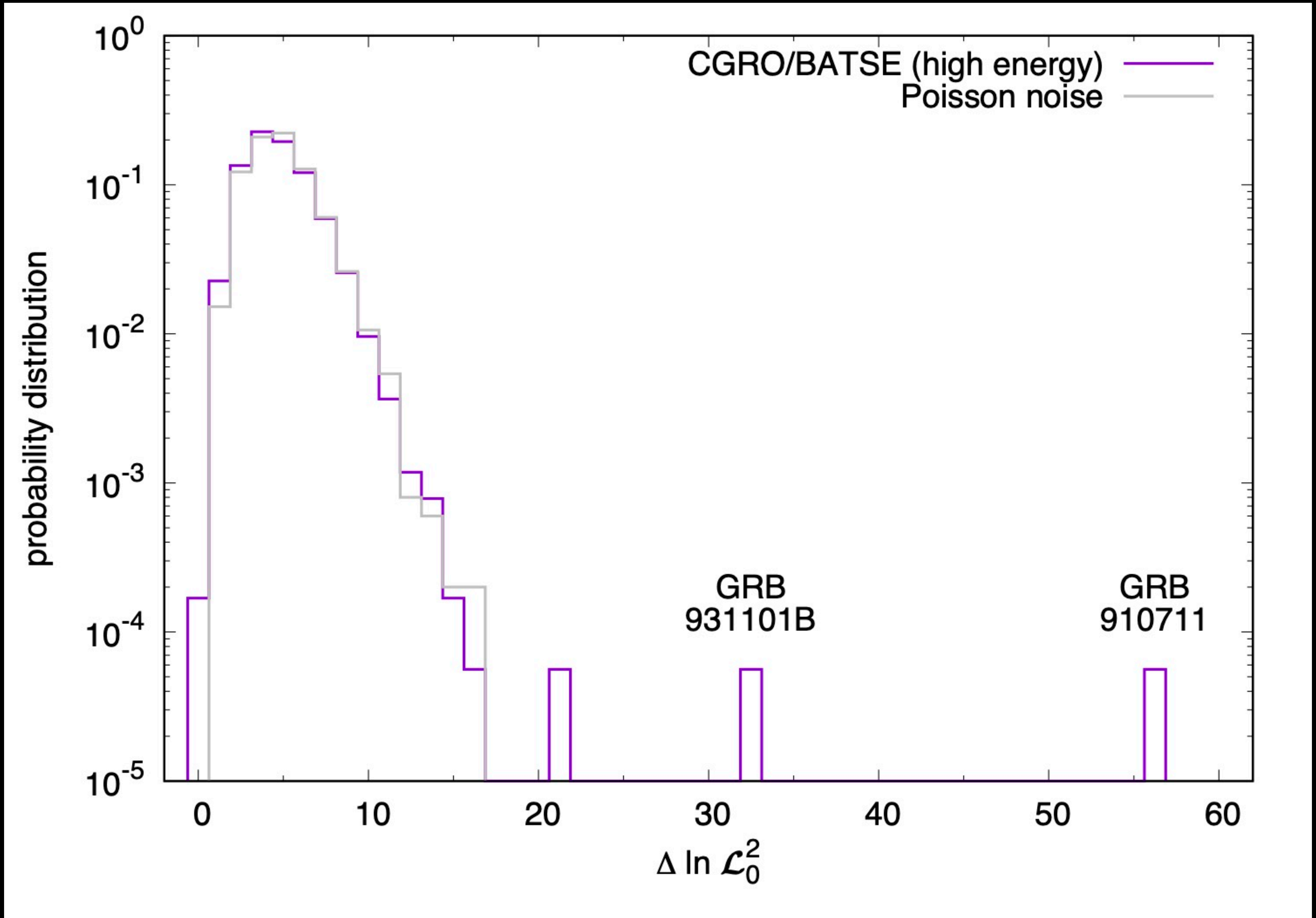
BATSE GRB distribution



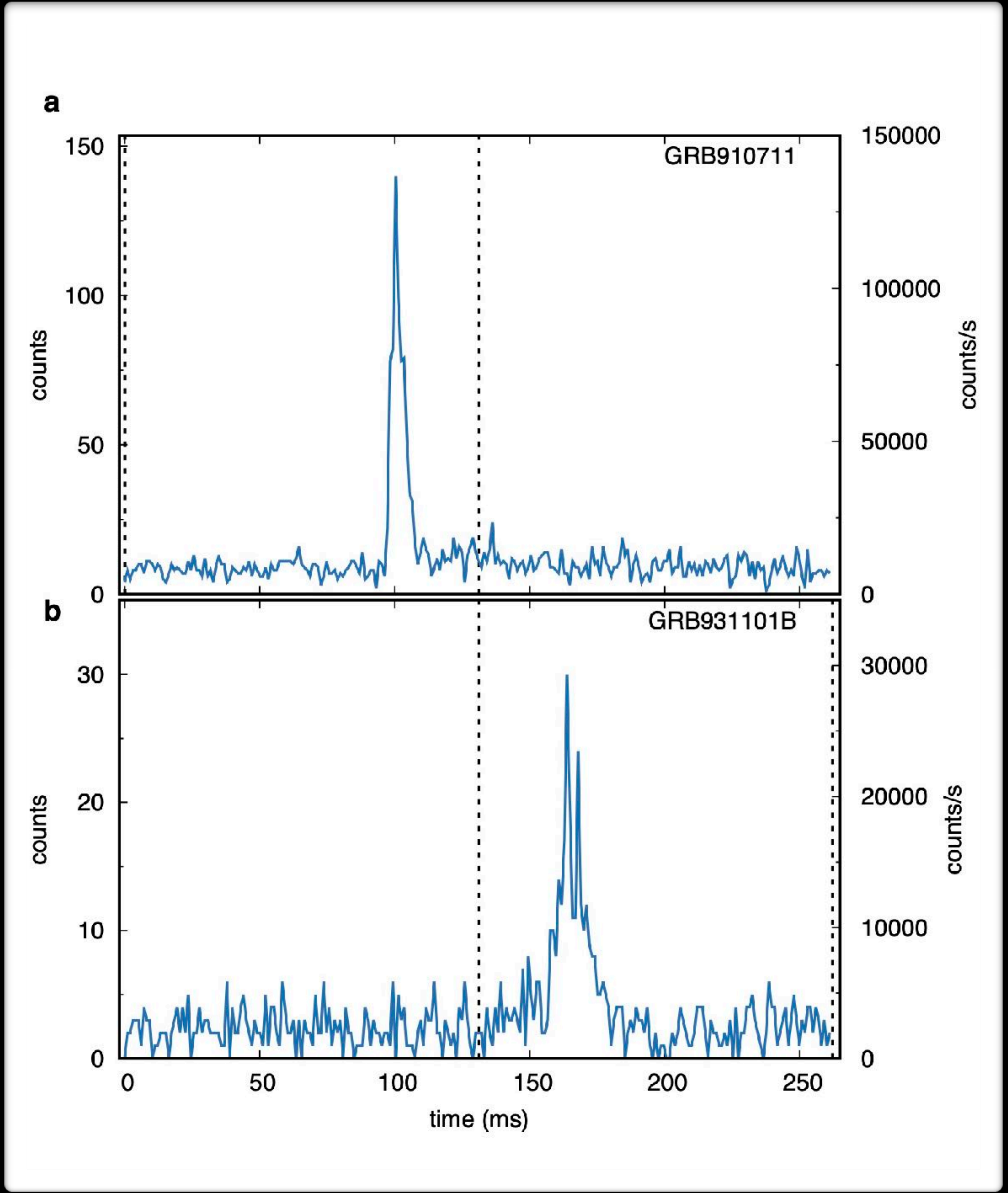


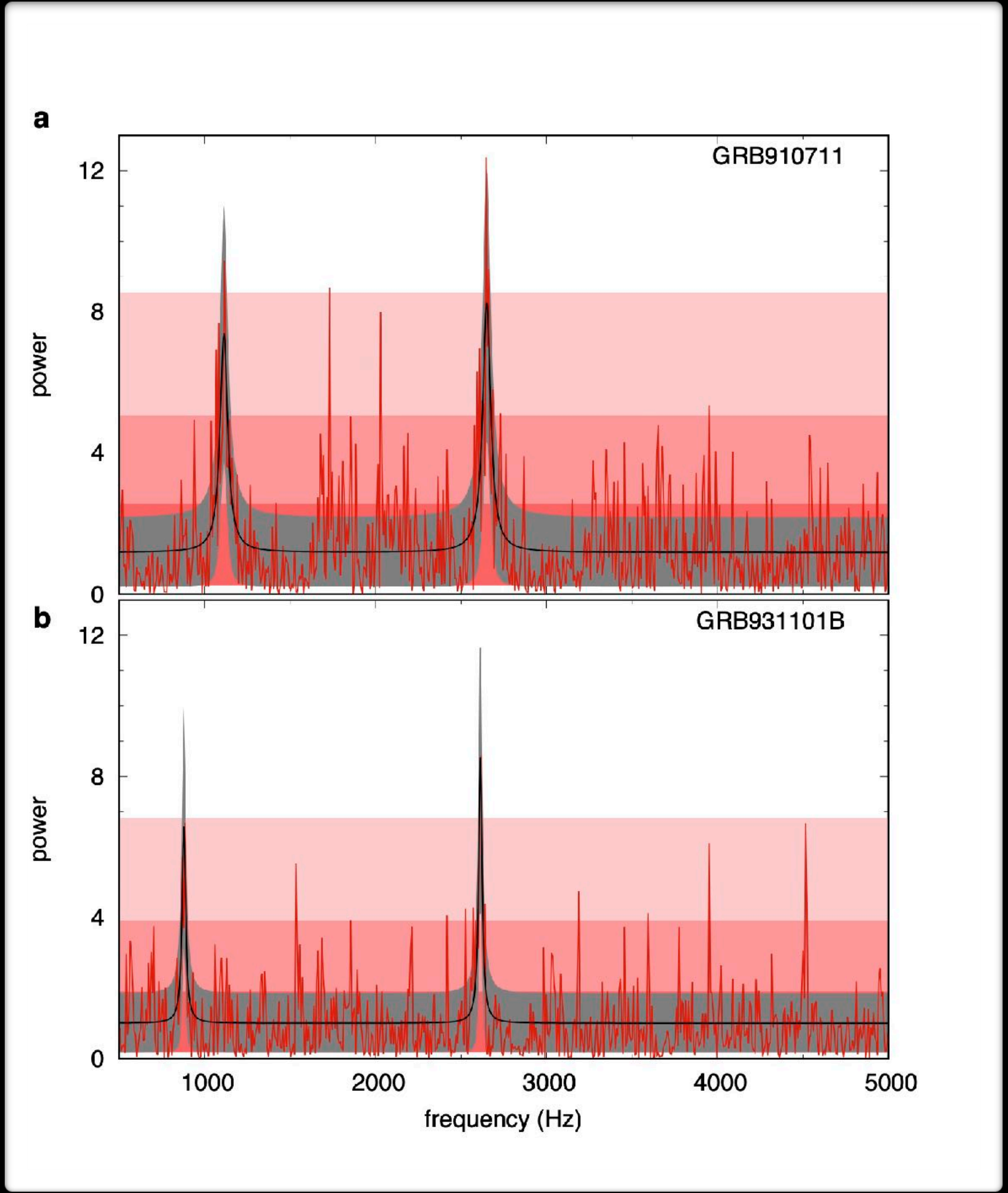
How special are these bursts?

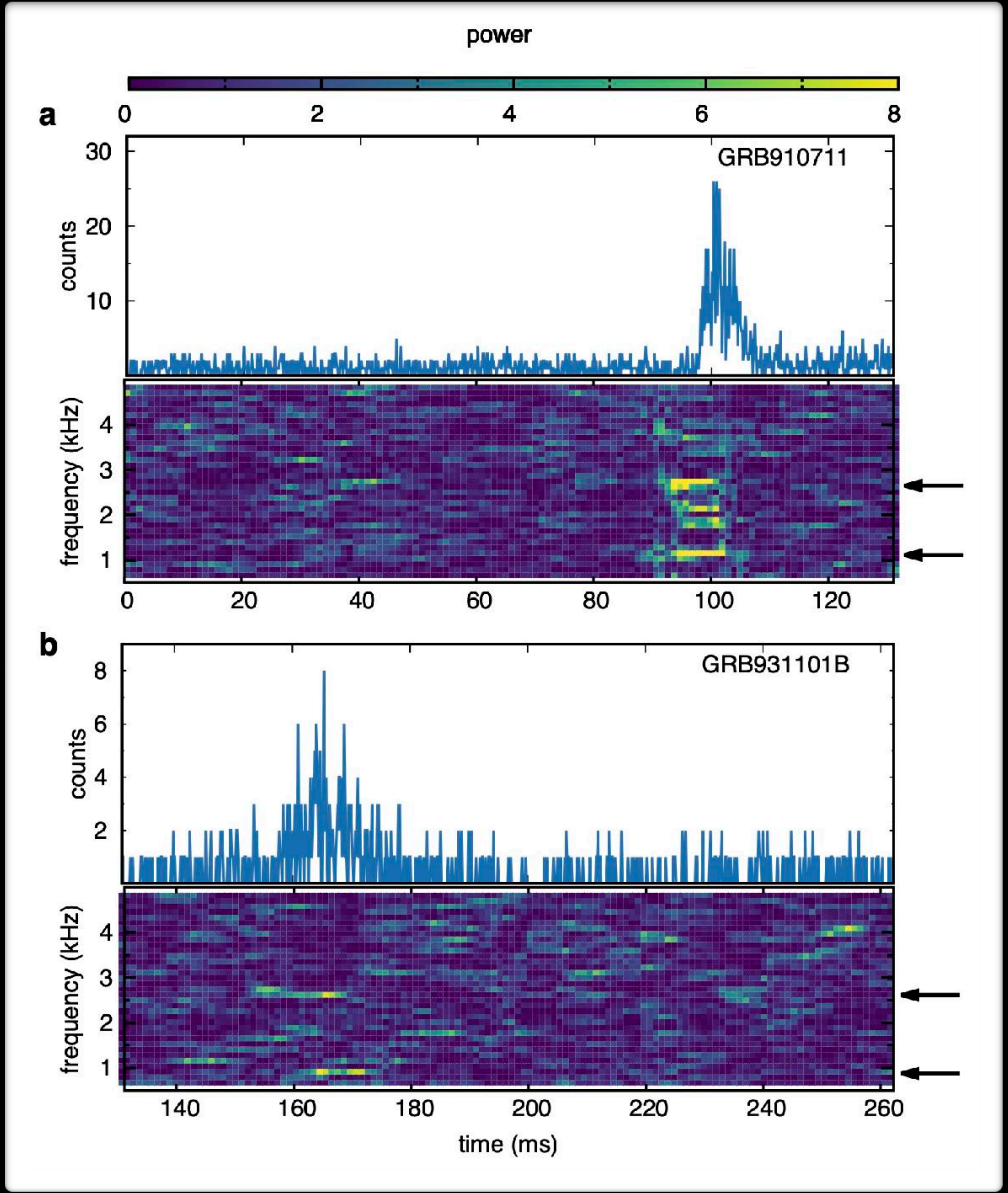
False positive estimate I



Light curves and power spectra







Chirenti et al. 2023

False positive estimate III

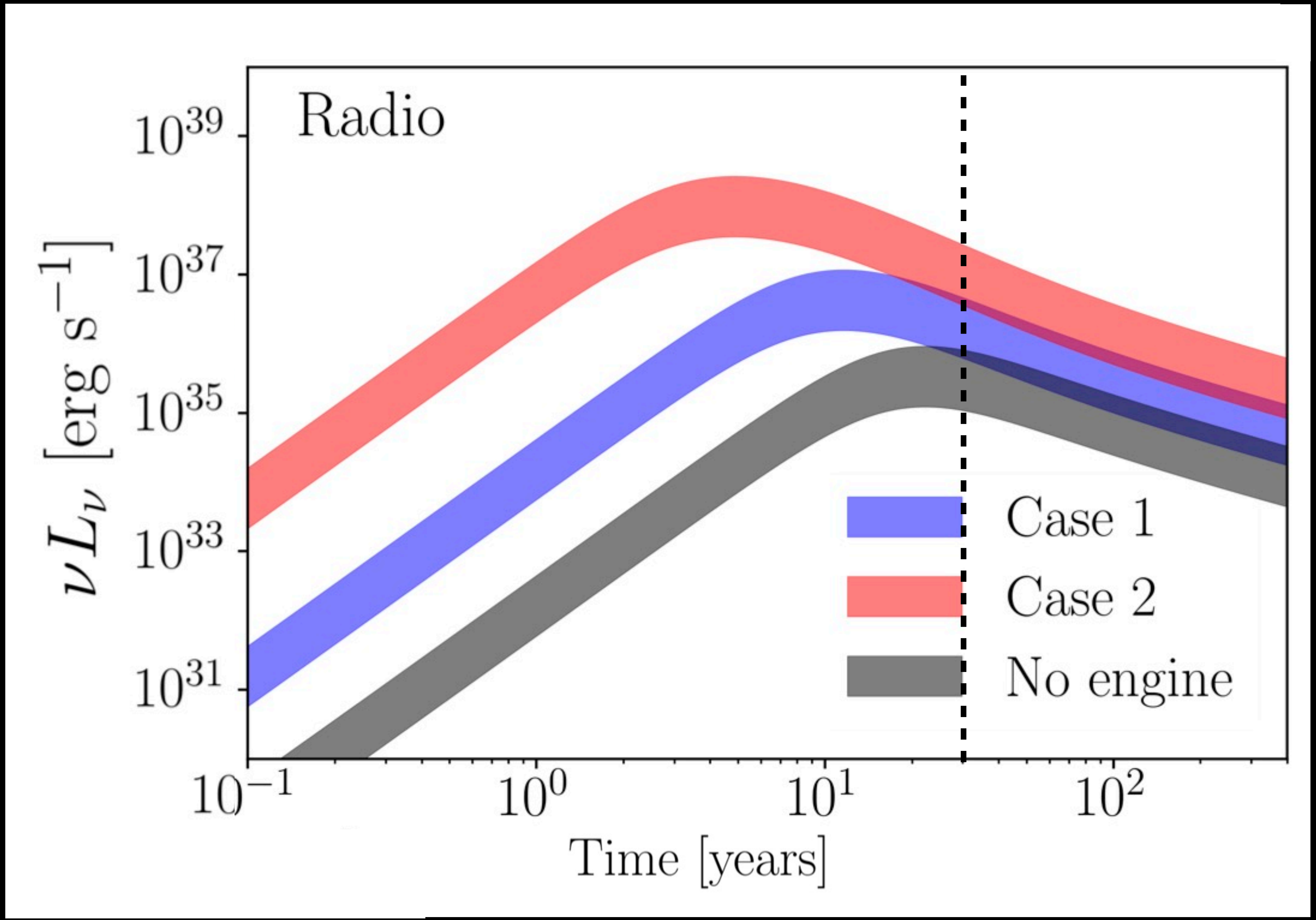
GRB	Trigger #	T_{90} (ms)	Counts	Prob($\Delta \ln \mathcal{L}_0^2 > 56.4$)	Prob($\Delta \ln \mathcal{L}_0^2 > 33.3$)
910711	512	14	1790	5.9×10^{-5}	9.2×10^{-3}
910508	207	30	1254	2.2×10^{-6}	1.6×10^{-3}
931101B	2615	34	524	2.6×10^{-6}	1.3×10^{-3}
910625	432	50	1810	7.2×10^{-7}	9.3×10^{-4}
910703	480	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 $\sim 3 \times 10^{-7}$

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