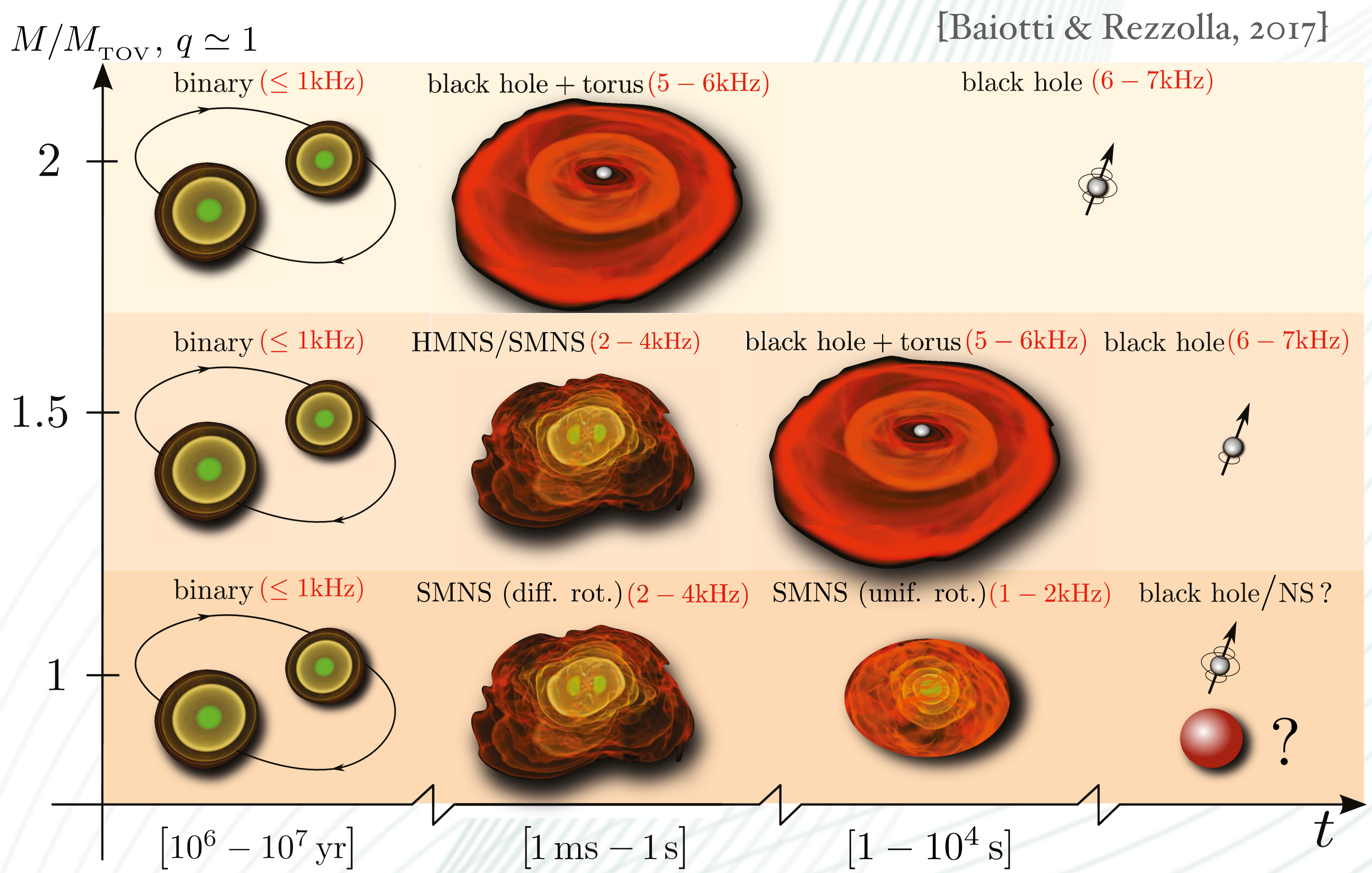
Telltale signs of a hypermassive neutron star: a search for kHz QPOs in short GRBs



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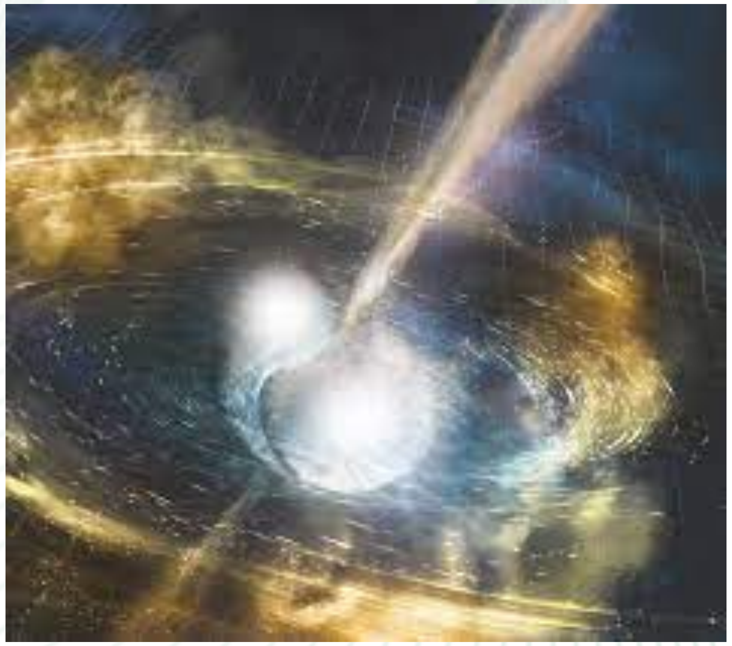
in collaboration with Amy Lien, Simone Dichiara and Cole Miller

Fermi Symposium, April 12 2021

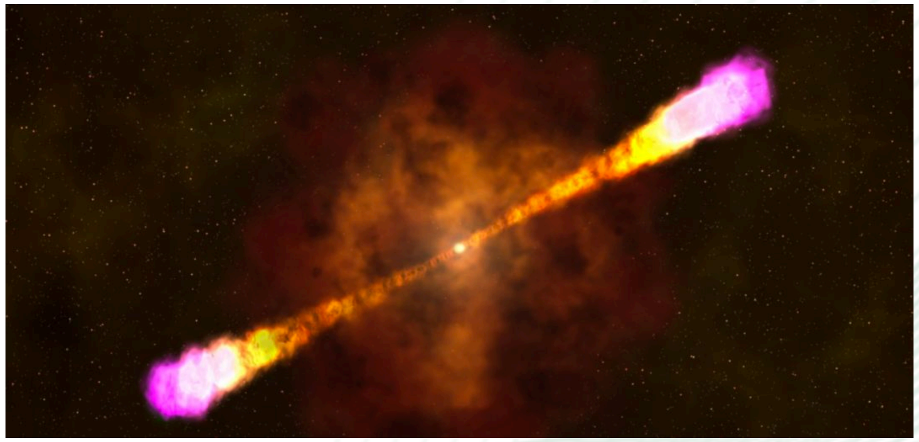
Partner

Physical Background

* binary neutron star mergers are sources of (at least some) short GRBs, e.g. GW170817
* a hypermassive neutron star (HMNS) may be formed depending on the initial binary masses, before the collapse to form a black hole



[NSF/LIGO/Sonoma State University/A. Simonnet]



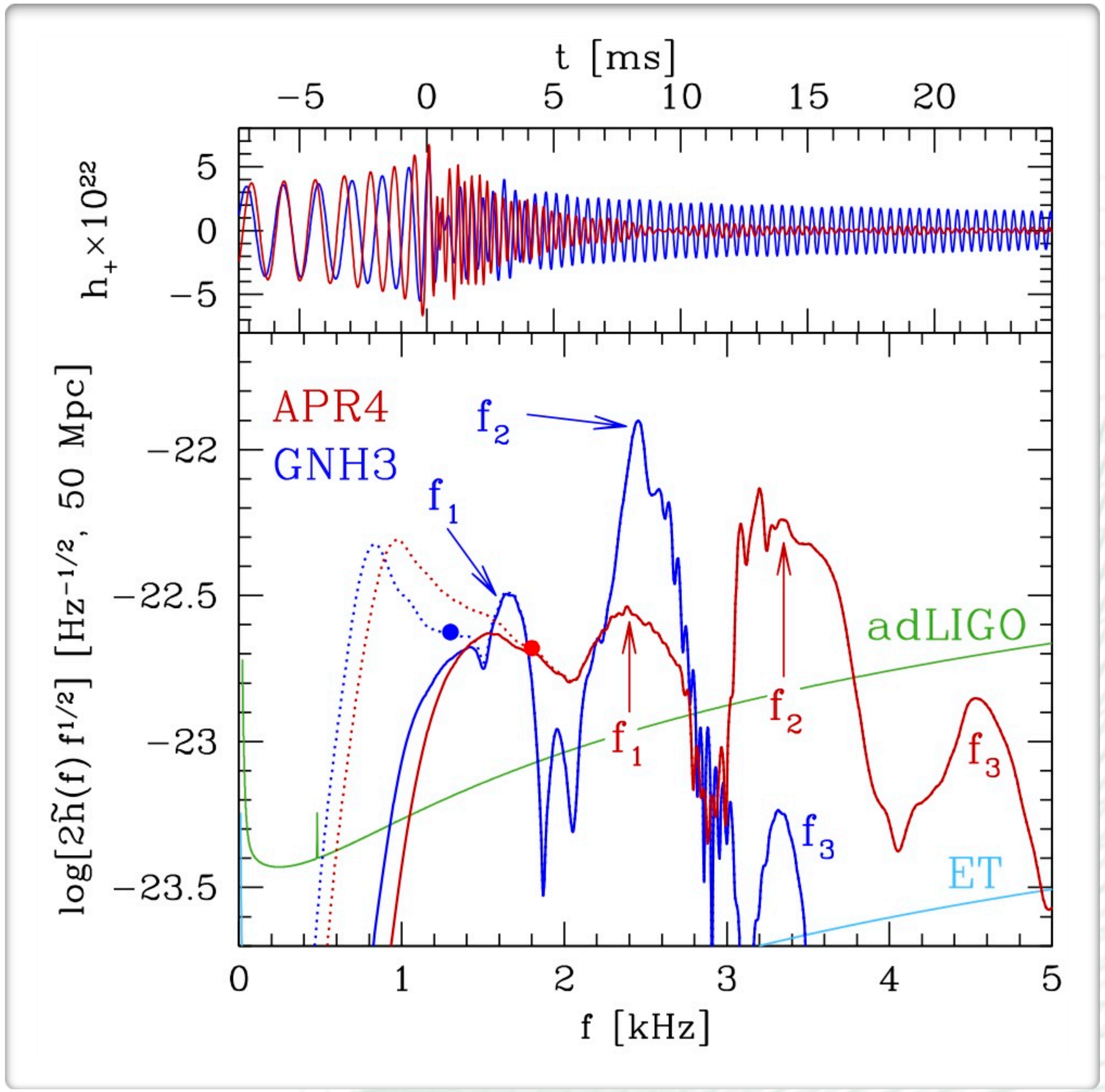
{NASA/GSFC}

Questions:

* can we tell in which events an HMNS is formed?
* when is the jet launched? possibilities: before/during/after the merger/collapse

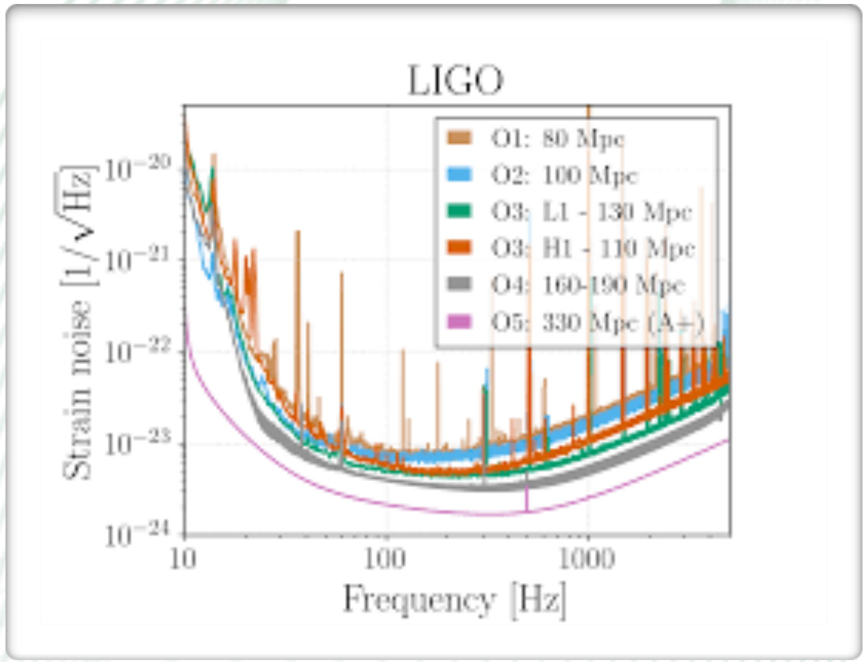
an HMNS oscillates…

… and generates gravitational waves (GWs)!
Frequencies carry information on the hot EOS.



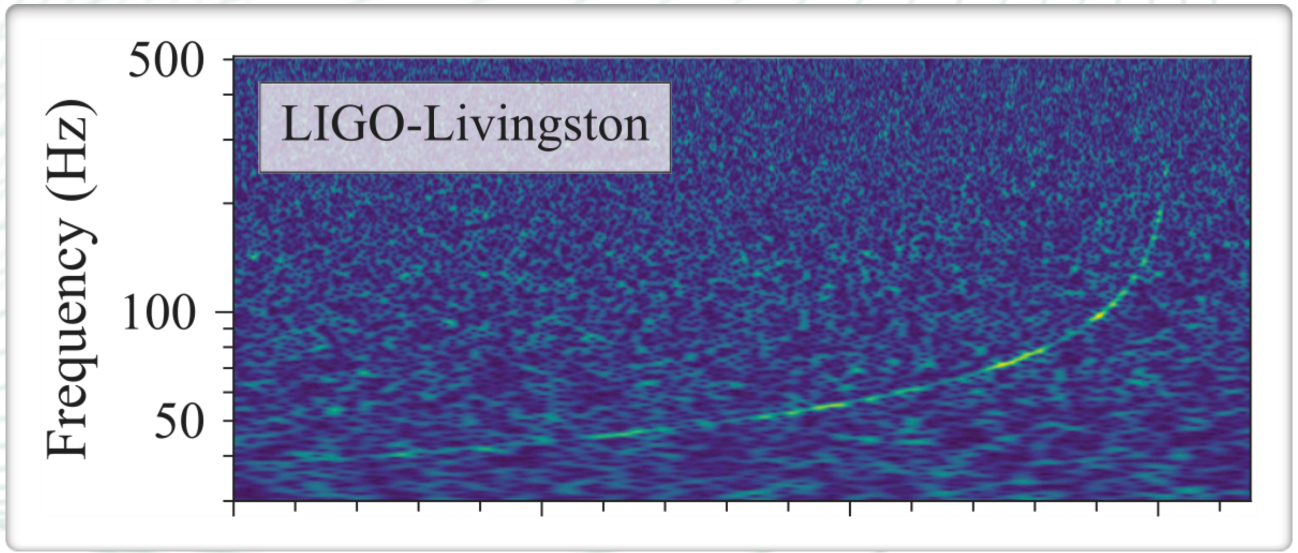
NS-NS numerical relativity simulation

[Takami et al., 2014]



Unfortunately, the post-merger signal frequencies are too high for LIGO

even the GW frequency at merger (~ 1.2 kHz) is too high for LIGO!



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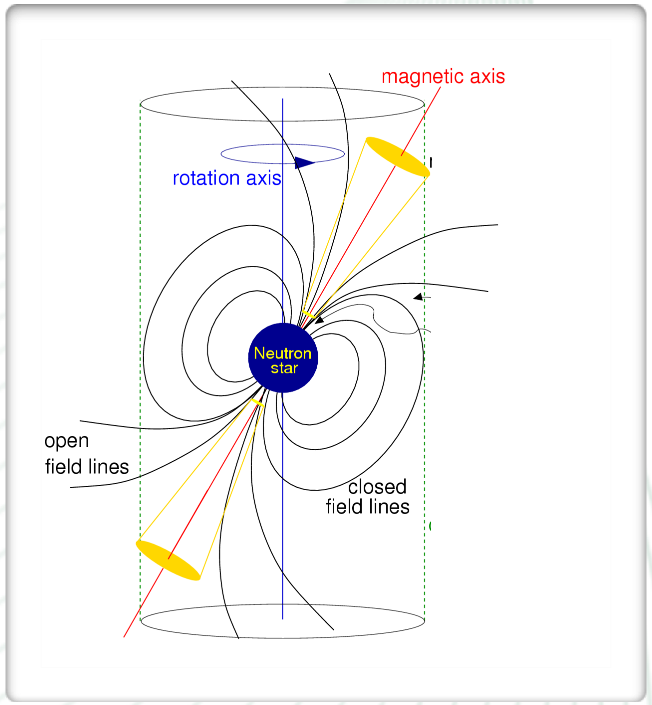
An HMNS signature in the GRB ?

Even if the HMNS signal is not yet detectable in GWs, the oscillations could produce a detectable modulation of the short GRB signal [Chirenti et al., 2019]

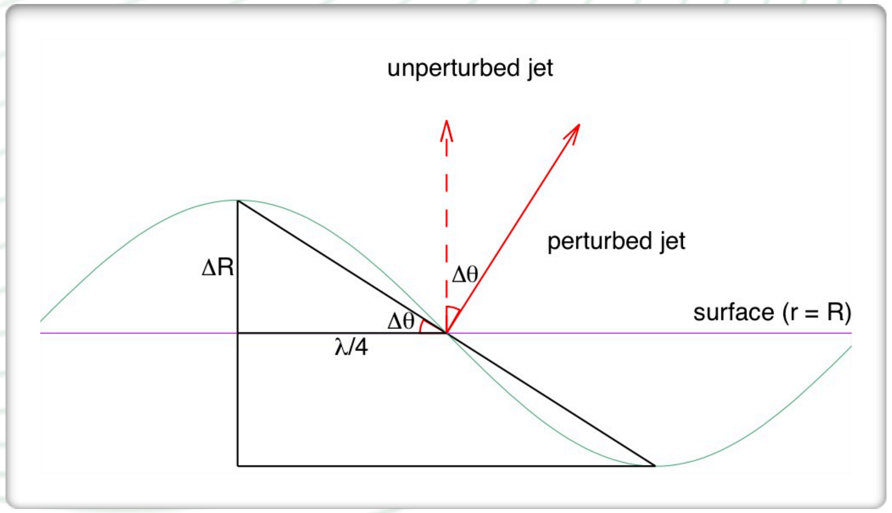
* if jet is launched before collapse to a black hole [Fong et al. 2020; Mösta et al. 2020]

* jet needs to break free from ejecta; relatively free polar region helps [Rosswog 2004; Perego et al. 2017]

adapted from Lorimer & Kramer, 2004



toy model



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What we are looking for:

Oscillations that

- last for approx 100 ms (lifetime of an HMNS)
- have frequencies in the approx range 1 – 5 kHz (from NR simulations)

<u>Bonus</u>:
numbers also work for long GRBs
alternative physical scenario:
formation of a magnetar after the SN explosion

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
(1024 bins of 100 μs)

total burst duration

Our sample of bright short and long GRBs

26 (14 short and 12 long) Swift BAT GRBs

9 (6 short and 3 long) Fermi GBM GRBs

criterion for flux cutoff: $n_\sigma = \frac{1}{2} I a_{\rm osc}^2 \sqrt{\frac{\Delta t}{\Delta f}} > 5$

Fermi

GRB name	peak flux	T90
GRB200415367	5.140883E-05	0.144
GRB170127067	6.082716E-05	0.128
GRB120323507	6.276456E-05	0.384
GRB150819440	6.320557E-05	0.96
GRB090228204	6.375704E-05	0.448
GRB090227772	8.375982E-05	0.304
GRB160625945	6.874007E-05	453.385
GRB131014215	9.147279E-05	3.2
GRB130427324	0.0001960235	138.242

not yet analyzed

approx. 7000 segments analyzed so far

Swift

GRB name	T100 flux	T90
GRB130408A	3.588641E-07	4.24
GRB161104A	3.660834E-07	0.1
GRB100816A	3.788087E-07	2.884
GRB190427A	3.795684E-07	0.192
GRB171011A	3.795771E-07	2.28
GRB070508	4.115191E-07	20.9
GRB131226A	4.48229E-07	7.228
GRB160601A	4.491692E-07	0.120
GRB090515	4.647827E-07	0.036
GRB191004A	4.715524E-07	2.444
GRB080605	4.8197E-07	18.056
GRB090618	4.997583E-07	113.34
GRB130427A	5.24276E-07	244.332
GRB051221A	5.45042E-07	1.392
GRB130912A	5.52968E-07	0.284
GRB091109B	5.795354E-07	0.272
GRB190610A	5.880172E-07	0.632
GRB170101A	6.190418E-07	3.104
GRB180728A	8.181821E-07	8.684
GRB120804A	8.812721E-07	0.808
GRB100206A	1.052858E-06	0.116
GRB091127	1.133105E-06	6.956
GRB191031D	1.19754E-06	0.288
GRB060313	1.294971E-06	0.744
GRB120305A	1.551708E-06	0.1
GRB130603B	2.486852E-06	0.176

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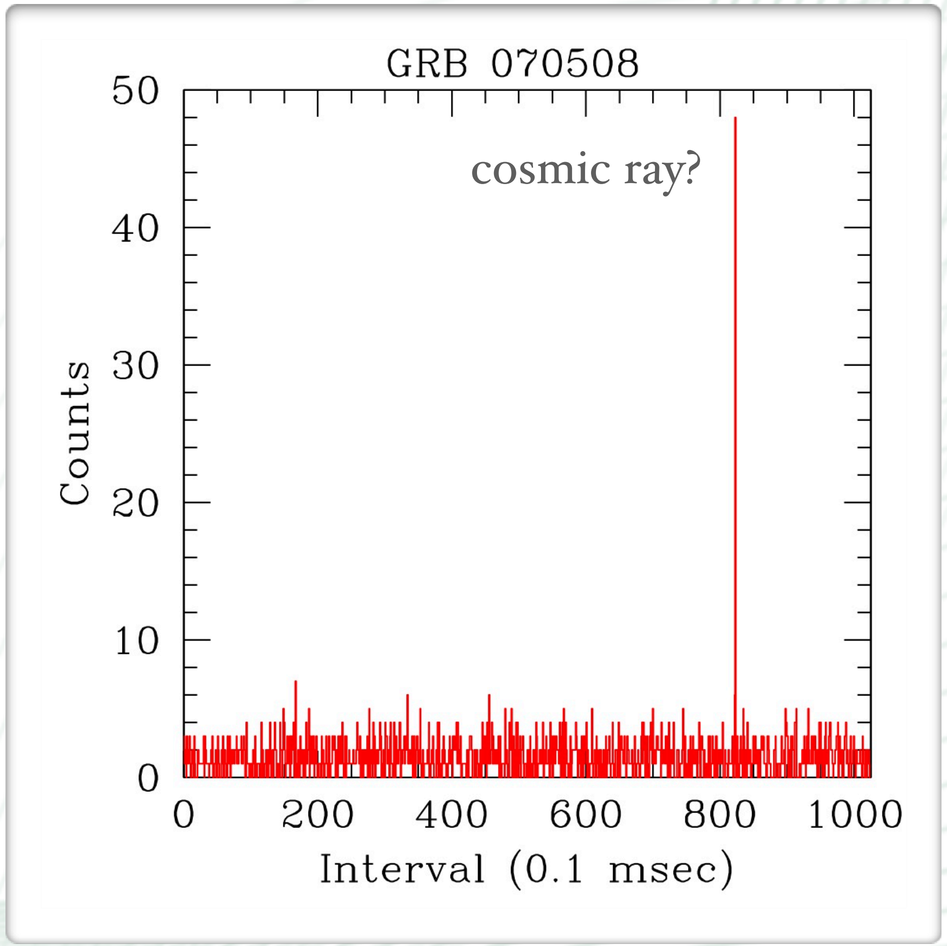
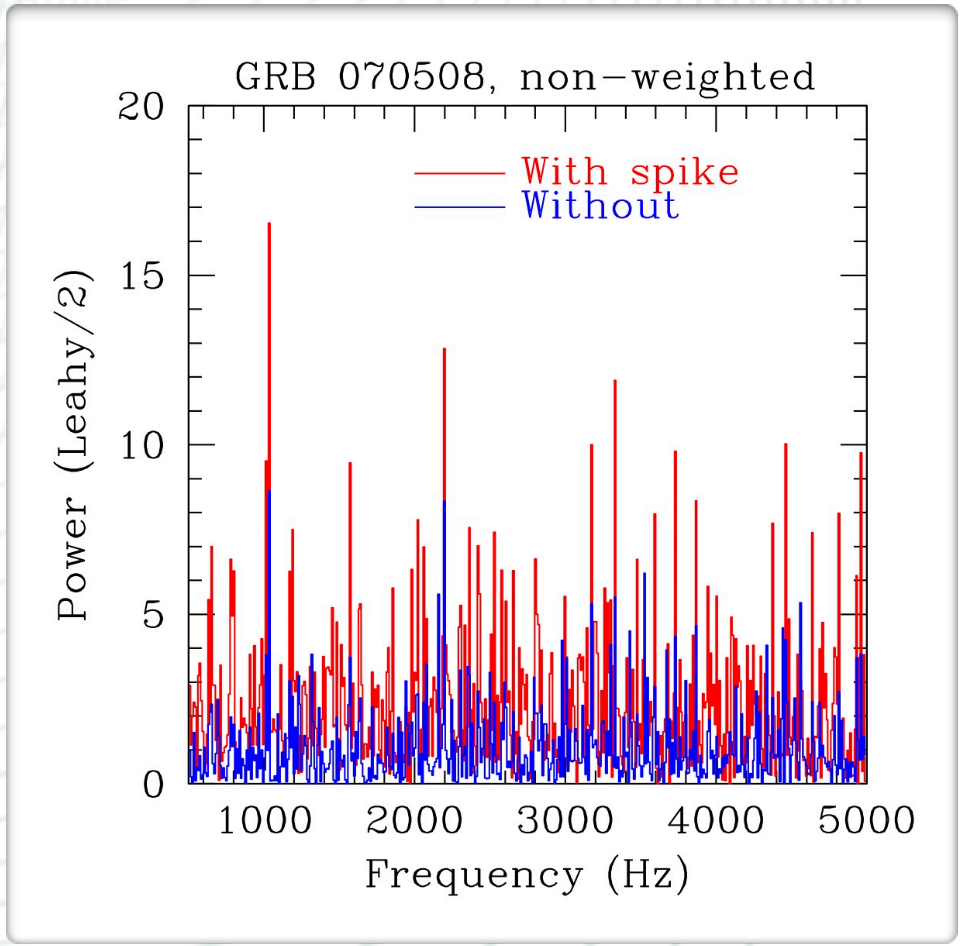
But GRB light curves are funny…

We use non-mask-weighted data (Swift) and non-background-subtracted data (Fermi).

Reason: we don't want to throw away a weak signal by accident…
But we need to be careful!

e.g. occasional weird spikes increase the level of the white noise

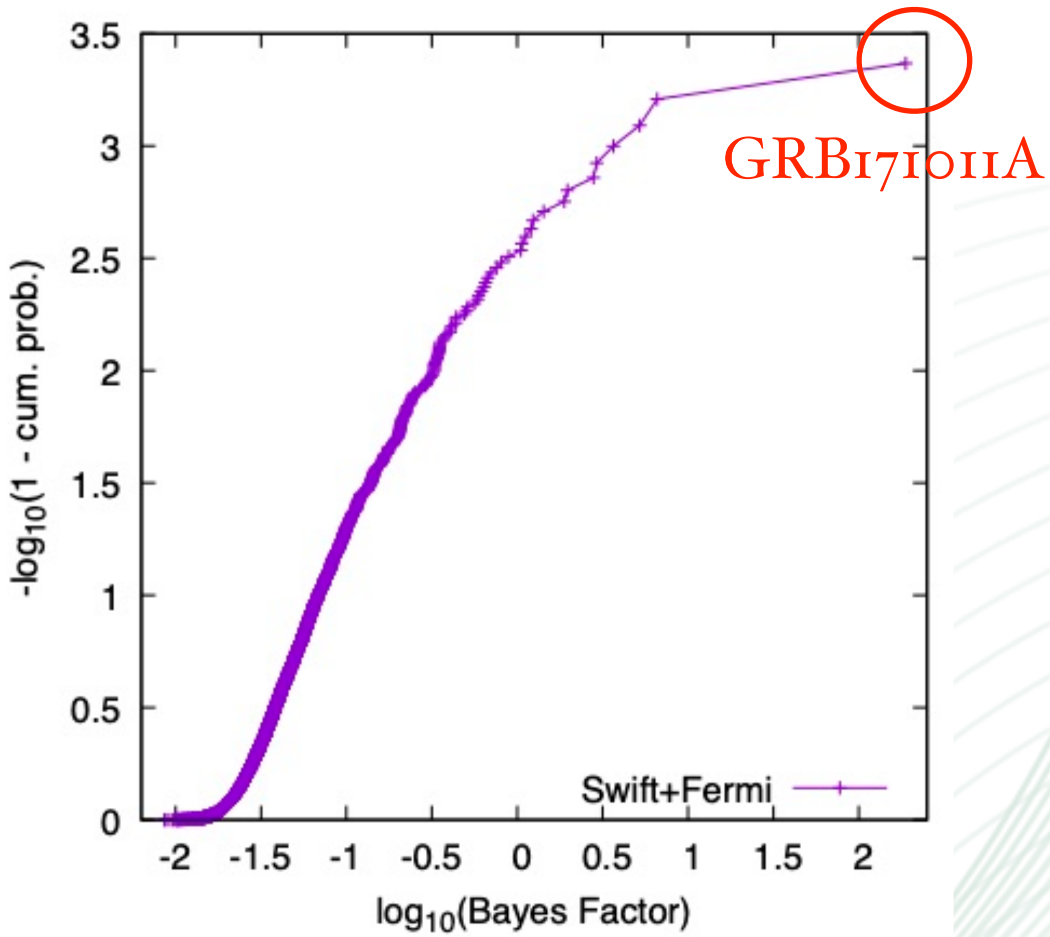




solution: allow noise level to vary in models I and II

What have we found so far?

Best candidate so far has Bayes factor $\mathscr{B} \sim 180$ in favor of the noise + QPO model



One candidate found!

$1 < \mathscr{B} < 3.2$ "Not worth more than a bare mention"
$3.2 < \mathscr{B} < 10$ "Substantial"
$10 < \mathscr{B} < 100$ "Strong"
$\mathscr{B} > 100$ "Decisive"

not exactly...

GRB171011A deserves additional investigation, but is it a real QPO?

Unfortunately only Swift BAT reported on detecting the prompt emission for this event...

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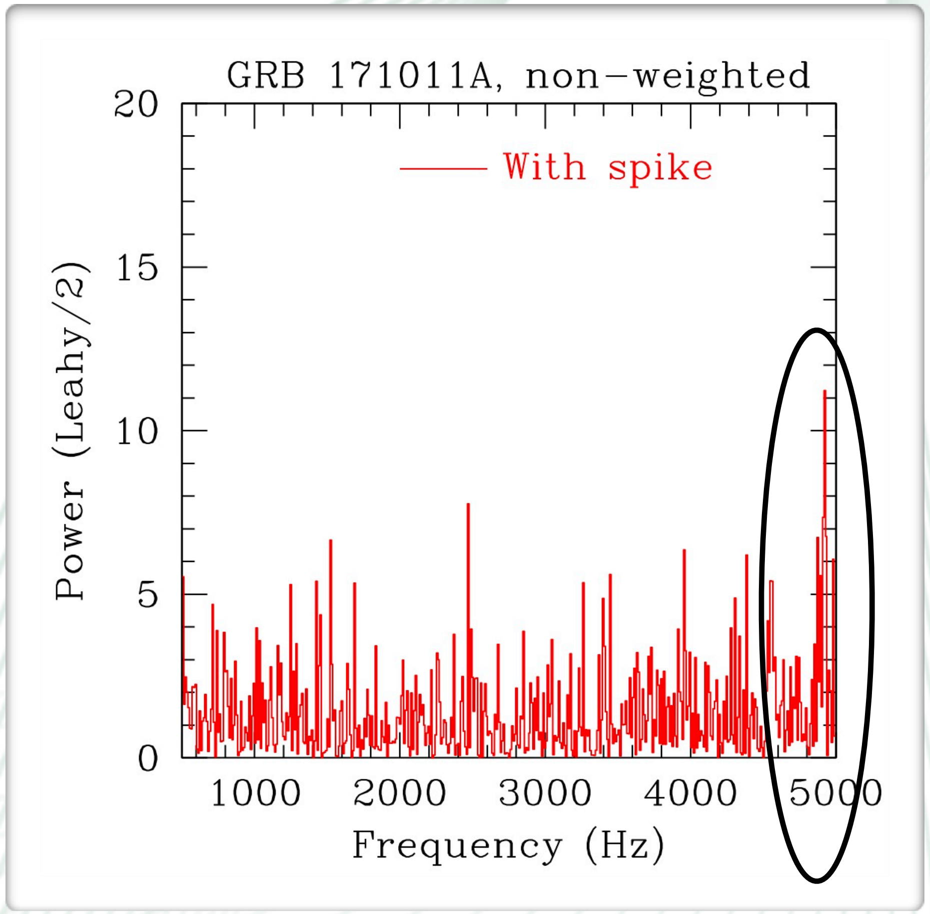
Our "gold" event

Signal found in segment 48 of GRB 171011A (T90 = 2.28 s), starting at 2.4064 s

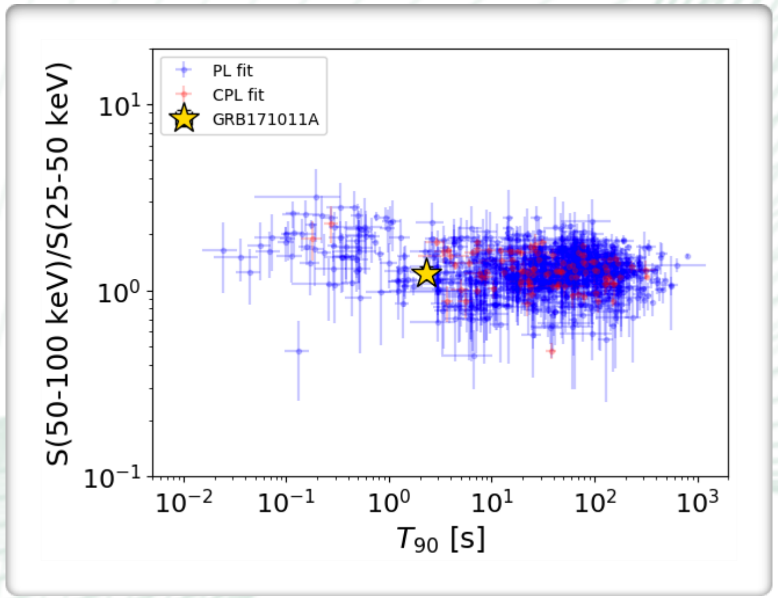
QPO frequency 4920 Hz, width 10 Hz

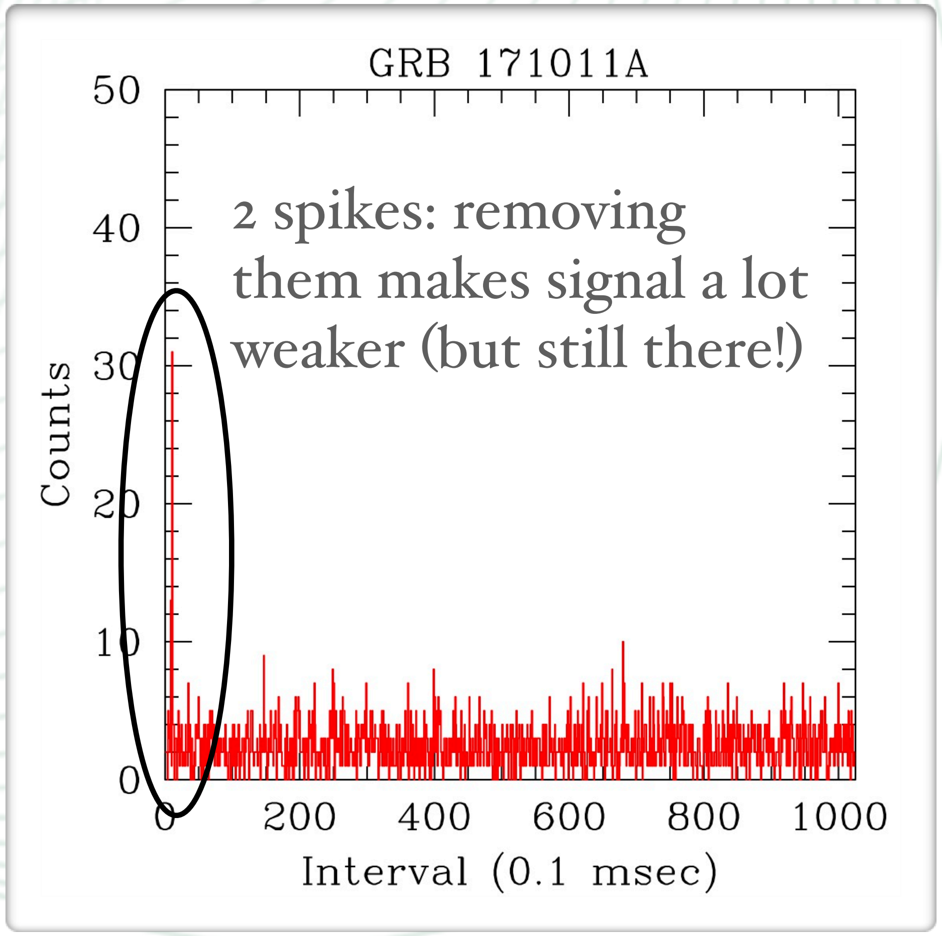
If real, QPO frequency is too high for a HMNS - then what is it???

Exciting possibility: QPO could be consistent with the oscillations of an approximately 6 solar mass black hole!



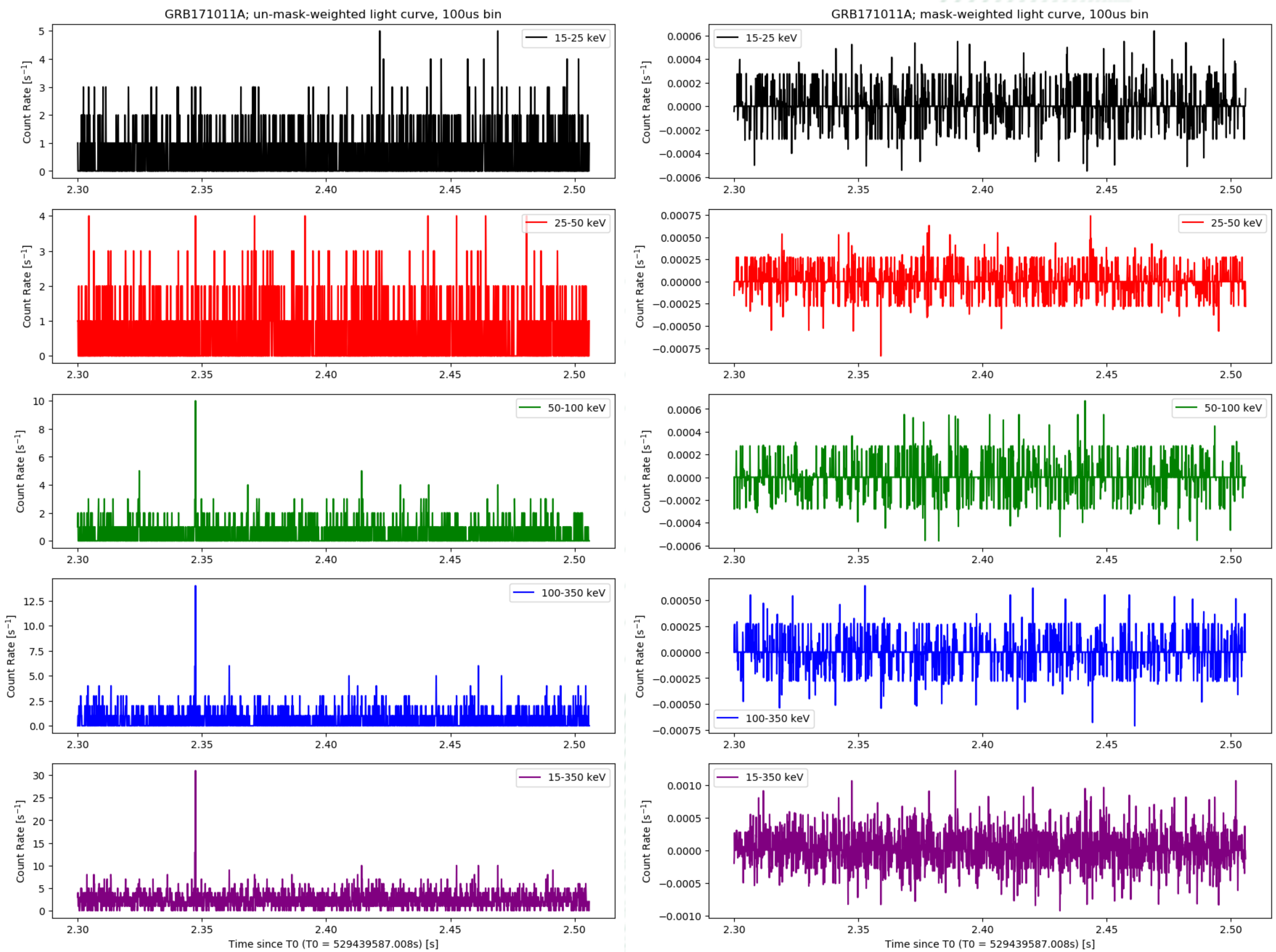
short or long?





Fool’s gold?

no spikes in the mask-weighted data: not coming from direction of the source?



Verdict: spikes are likely cosmic rays; when removed from data, QPO is not statistically significant.

spikes show only in higher energies;
interval between spikes is consistent with period of QPO

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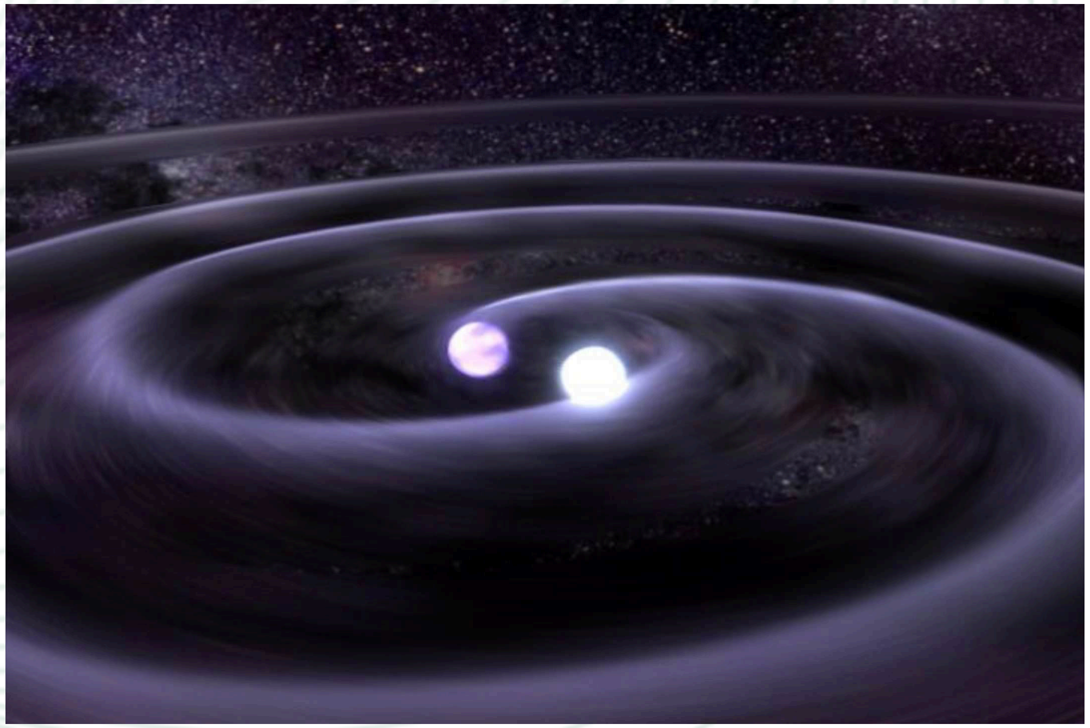
Conclusions

* We haven't found any kHz QPOs in the GRB data, yet
* But we'll keep looking: there is a large set of extant data to search
* Even one event will be transformative: a new way to connect GRB data to binary neutron star mergers and learn about the neutron star (hot) equation of state
* Non-detections place upper limits on the fractional oscillation transmitted by the source and on the modulation mechanism



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