S5y1 SGR burst search

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Photo: Joe Becker

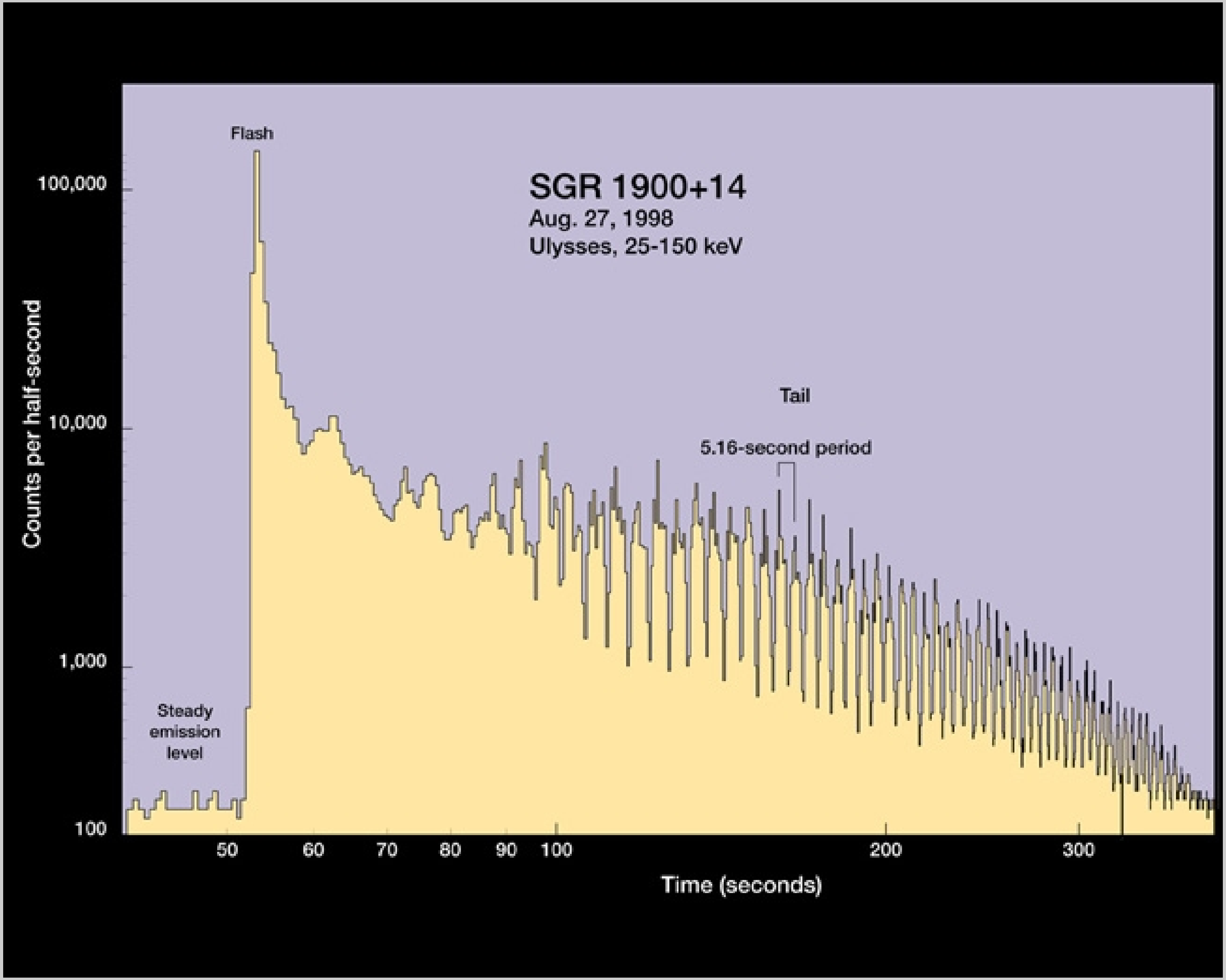
LIGO-G080410-00-Z

Plan of the Talk

GW burst analysis: conception to publication

1. Soft Gamma Repeaters
2. Designing the Search
3. Flare Pipeline
4. Results
5. What's Next

1. Soft Gamma Repeaters



http://solomon.as.utexas.edu/~duncan/magnetar.html

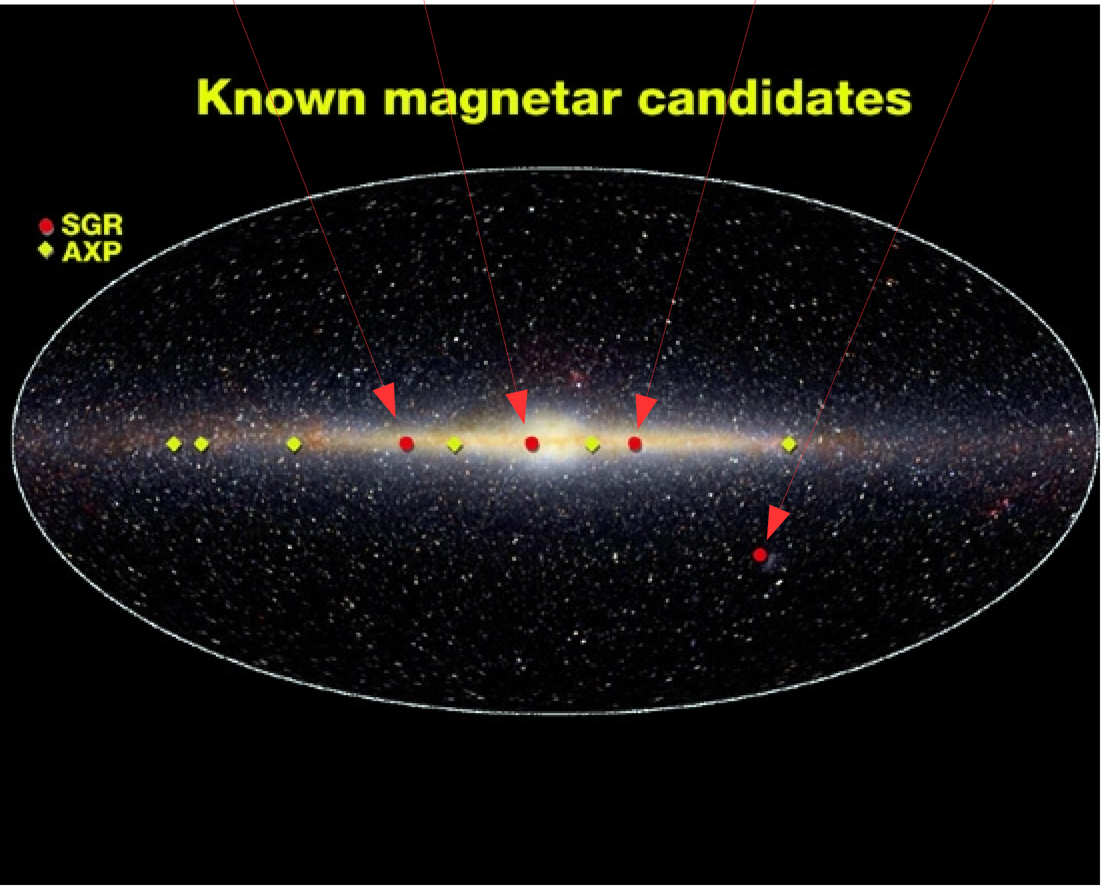
Where are the sources?

SGR 1627-41

SGR 1806-20

SGR 1900+14

SGR 0526-66



http://solomon.as.utexas.edu/~duncan/magnetar.html

SGR 1806-20

- $18^h08^m39.32^s$ -20°24' 39.5" [1]
  - Chandra localization, X-Ray counterpart
- 15.1 (+1.8 -1.3) kpc [2]
  - CO emission, NH3 absorption along line of sight to radio nebula G10.0-0.3

SGR 1900+14

- $19^h07^m14.33^s$ 9°19' 20.1" [3]
  - localization of radio counterpart
- 12-15 kpc [4]
  - interstellar extinction to pair of supergiants, possible counterparts

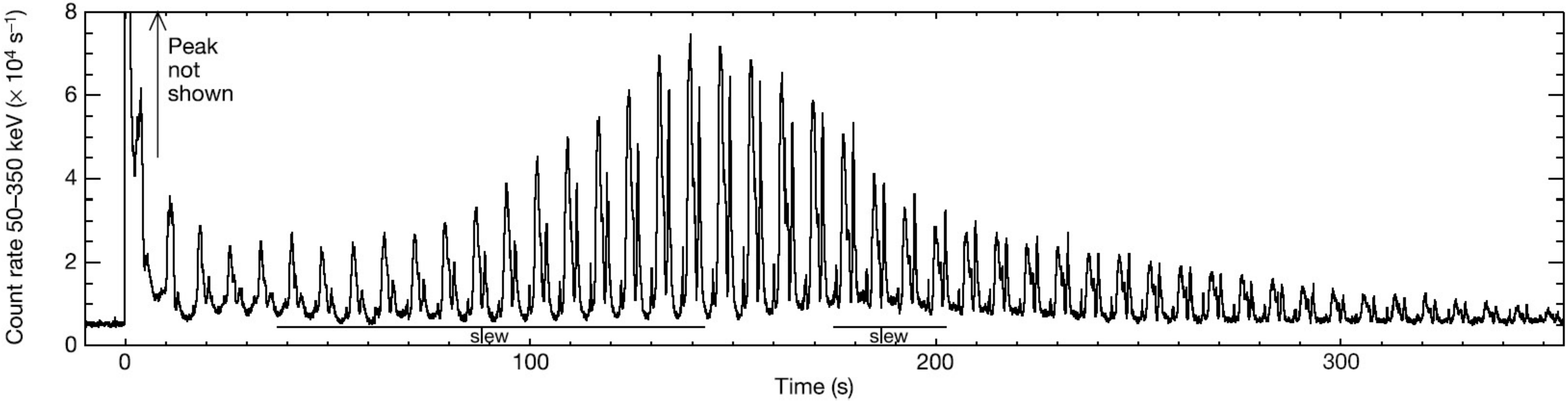
[1] D. L. Kaplan et al. *ApJ.* 564:935–940, January 2002
[2] S. Corbel and S. S. Eikenberry. *AA.*, 419:191-201, May 2004
[3] D. A. Frail, S. R. Kulkarni, and J. S. Bloom. *Nature*, 398:127, 1999
[4] Vrba, F. J., et al. 1996, *ApJ*, 468, 225

Soft Gamma Repeaters

- SGRs – sporadic gamma ray bursts
  - Typical bursts last ~100 ms with peak luminosities ~10^{42} erg/s [1]
  - Rare giant flares have tails, peak luminosities up to10^{47} erg/s
    - SGR 0526-66, SGR 1900+14, SGR 1806-20
  - Multi-episodic bursts
  - Set of relaxation systems - “crustquake” model[2]
- Short hard GRB progenitor candidate [3]
- X-Ray counterparts – quiescent but variable emission ~10^{35} erg/s
- Conventional model: Magnetar
  - Neutron stars with B ~10^{15} G [4]
  - Bursts: interaction of B with solid crust leads to crustal cracking [5]
- Alternative model: Solid quark star
  - Bursts caused by starquakes [6]

[1] Woods P M and Thompson C 2004 *Compact Stellar X-Ray Sources (*Cambridge University Press)
[2] Palmer, D. 1999 *Astrophysical Journal* 512:L113-L116
[3] Hurley, K. et al. 2005 Nature 434 1098-1103
[4] Duncan R C and Thompson C 1992 Astrophys. J. Lett. 392 L9-L13
[5] Palmer D M et al. 2005 Nature 434 1107-1109
[6] Xu R X 2006 Mon. Not. R. Astron. Soc. 373, L85–L89

SGR 1806-20 Giant Flare

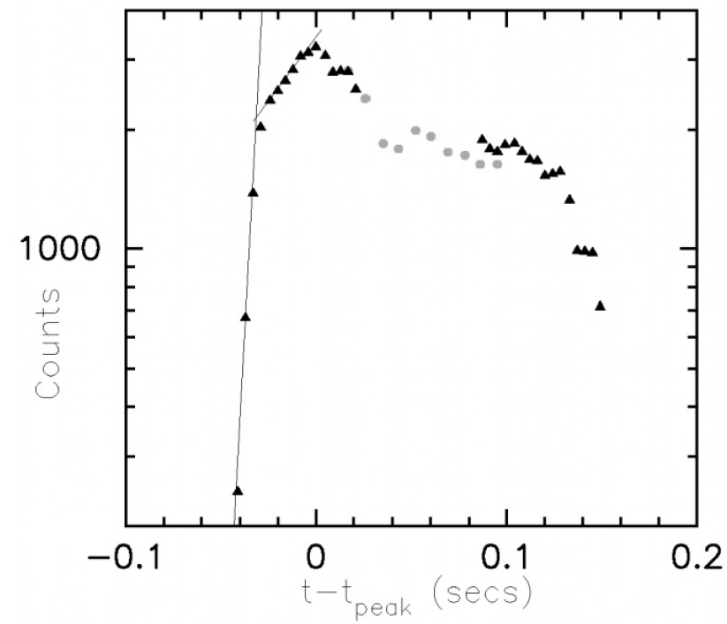


BAT light curve from D. M. Palmer et al. *Nature*, 434:1107–1109, April 2005.

Spike 15 kpc isotropic energy: $(3.7 \pm 0.9) \times 10^{46}\, d_{15}^{2}$ erg [1]

7.56 s rotation period evident in tail

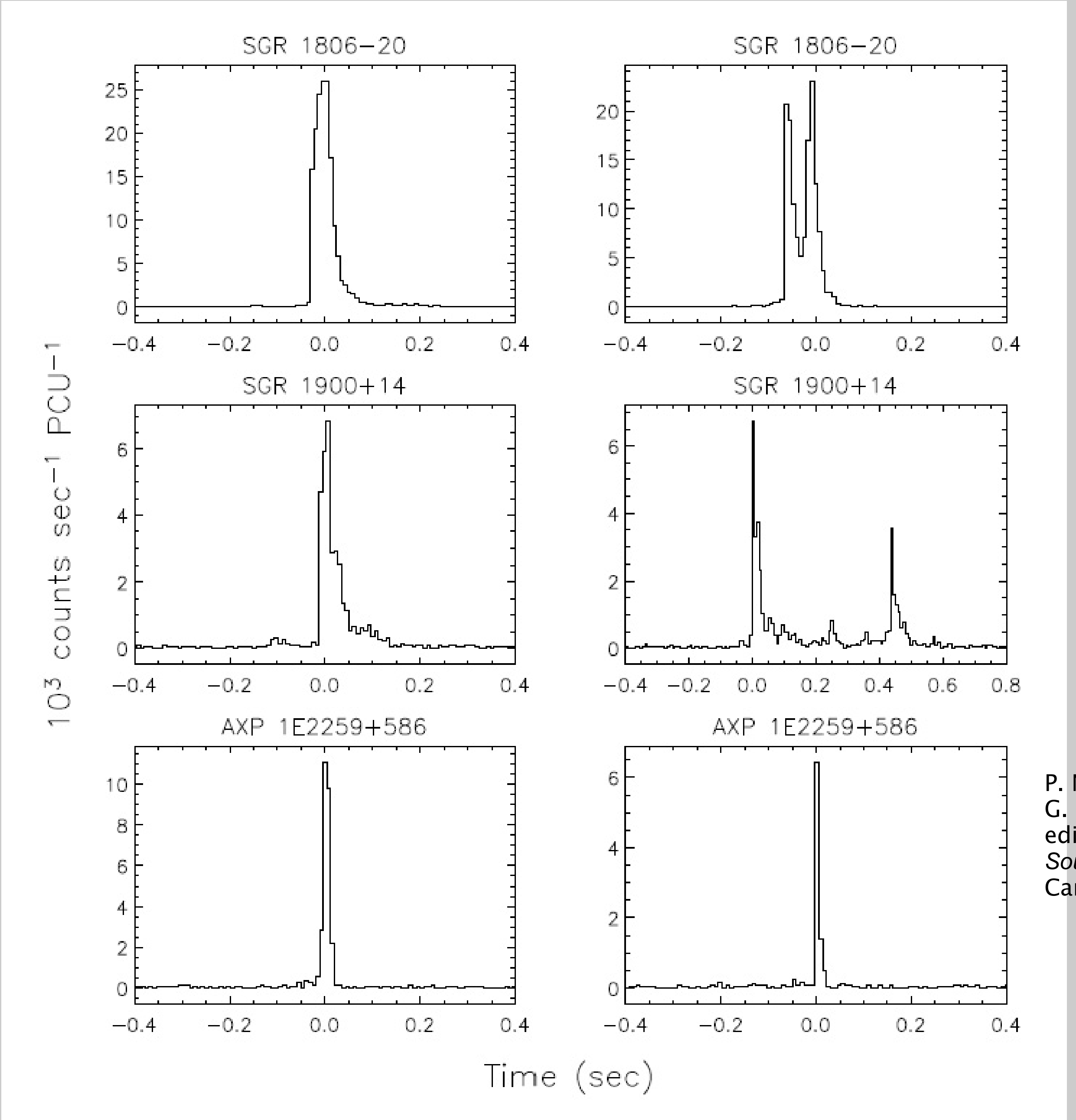
Spike timescales ~5-200 ms



[1] K. Hurley et al. *Nature*, 434:1098–1103, April 2005.

S. J. Schwartz et al. *AstrophysJ. Lett.*, 627:L129–L132, July 2005.

2. Designing the Search



P. M. Woods and C. Thompson. In W. G. H. Lewin and M. van der Klis, editors, *Compact Stellar X-Ray Sources*. Cambridge Univ. Press, Cambridge, 2004.

Science Goals

Sample:

SGR 1806-20 giant flare

2/4 known **galactic** Soft Gamma Repeaters gave over 214 bursts during S5y1

Goals:

1. detection statement
2. upper limits via plausible waveforms
3. use detection / upper limits to make astrophysics statements

http://geco.phys.columbia.edu/~peter/protected/flare/review/

Burst sample

SGR 1806-20 giant flare, H1 astrowatch

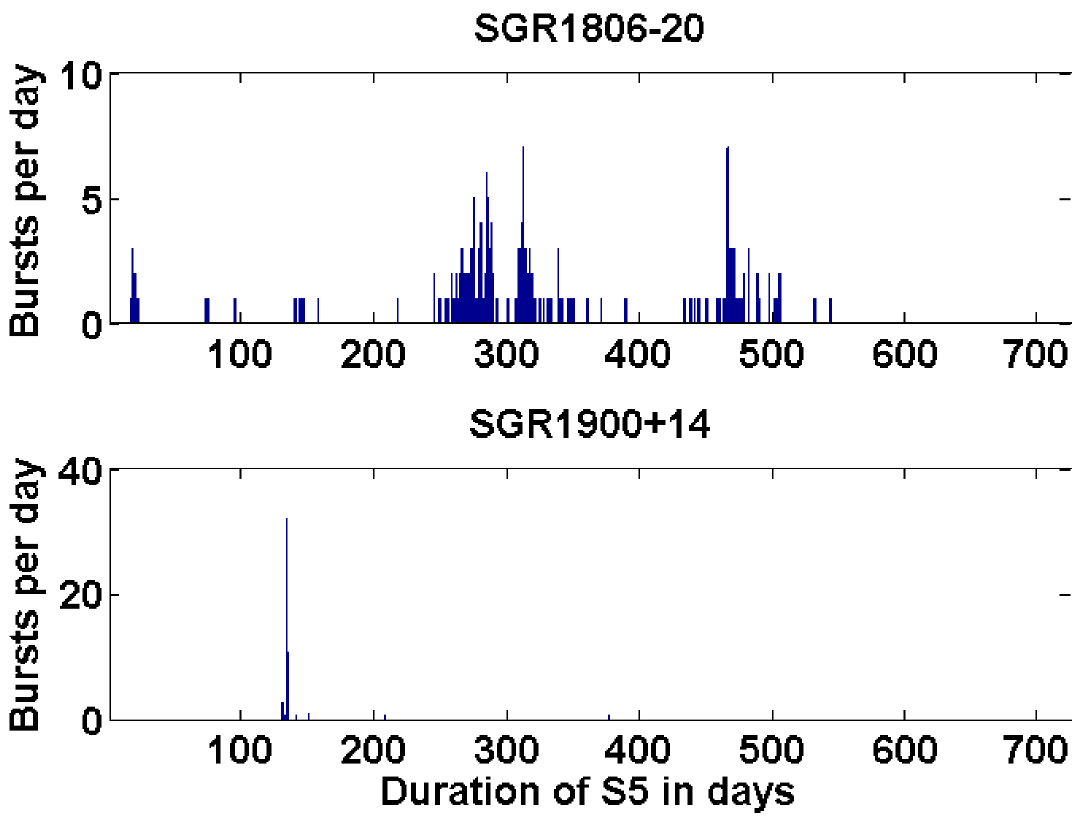
214 S5y1 bursts listed by K. Hurley (IPN3)

152 SGR 1806-20 events:

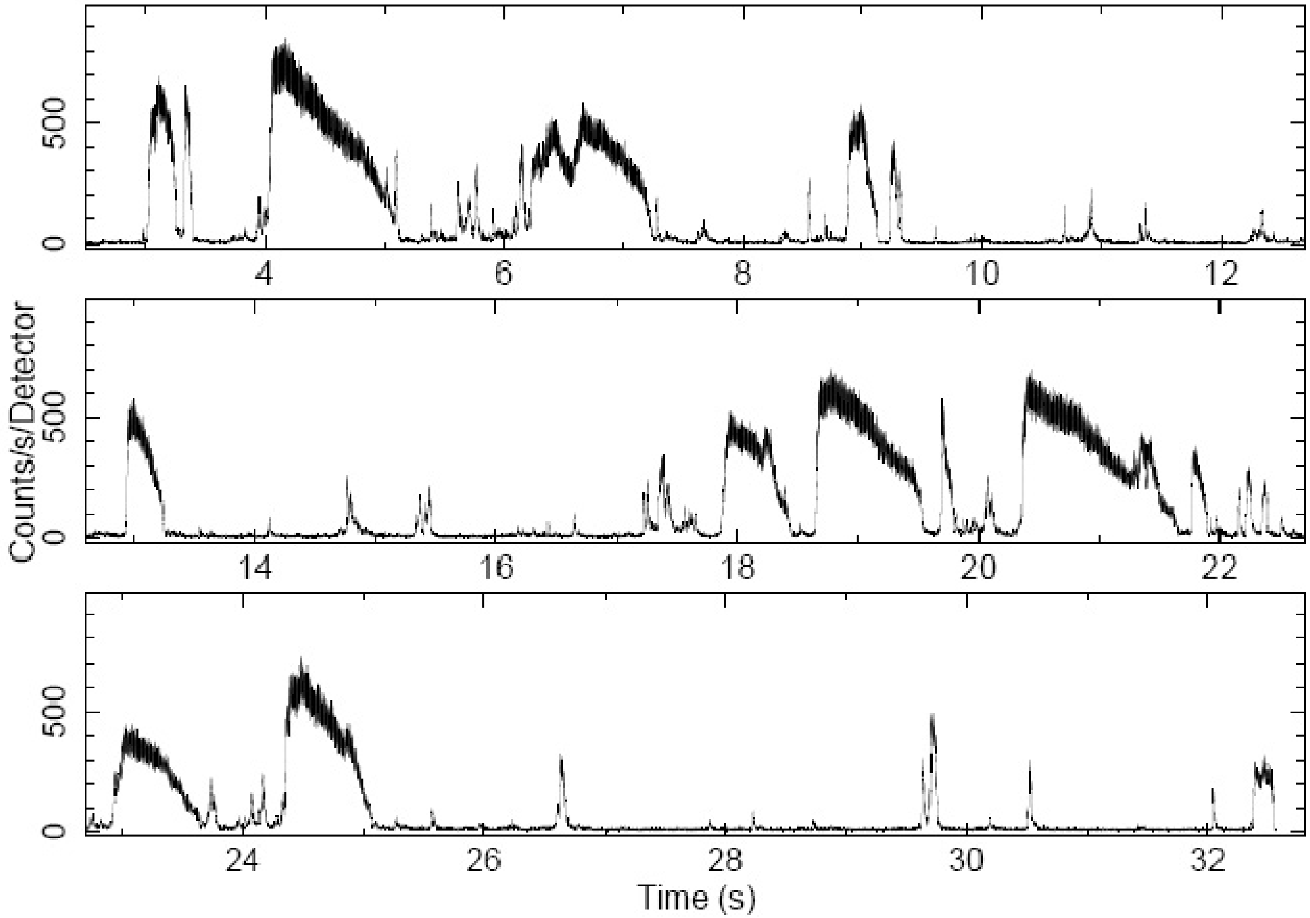
- 74 L1H1H2
- 41 two detectors
- 18 single detector
- 19 -

62 SGR 1900+14 events (including a storm):

- 43 L1H1H2
- 12 two detectors
- 2 single detector
- 5 -

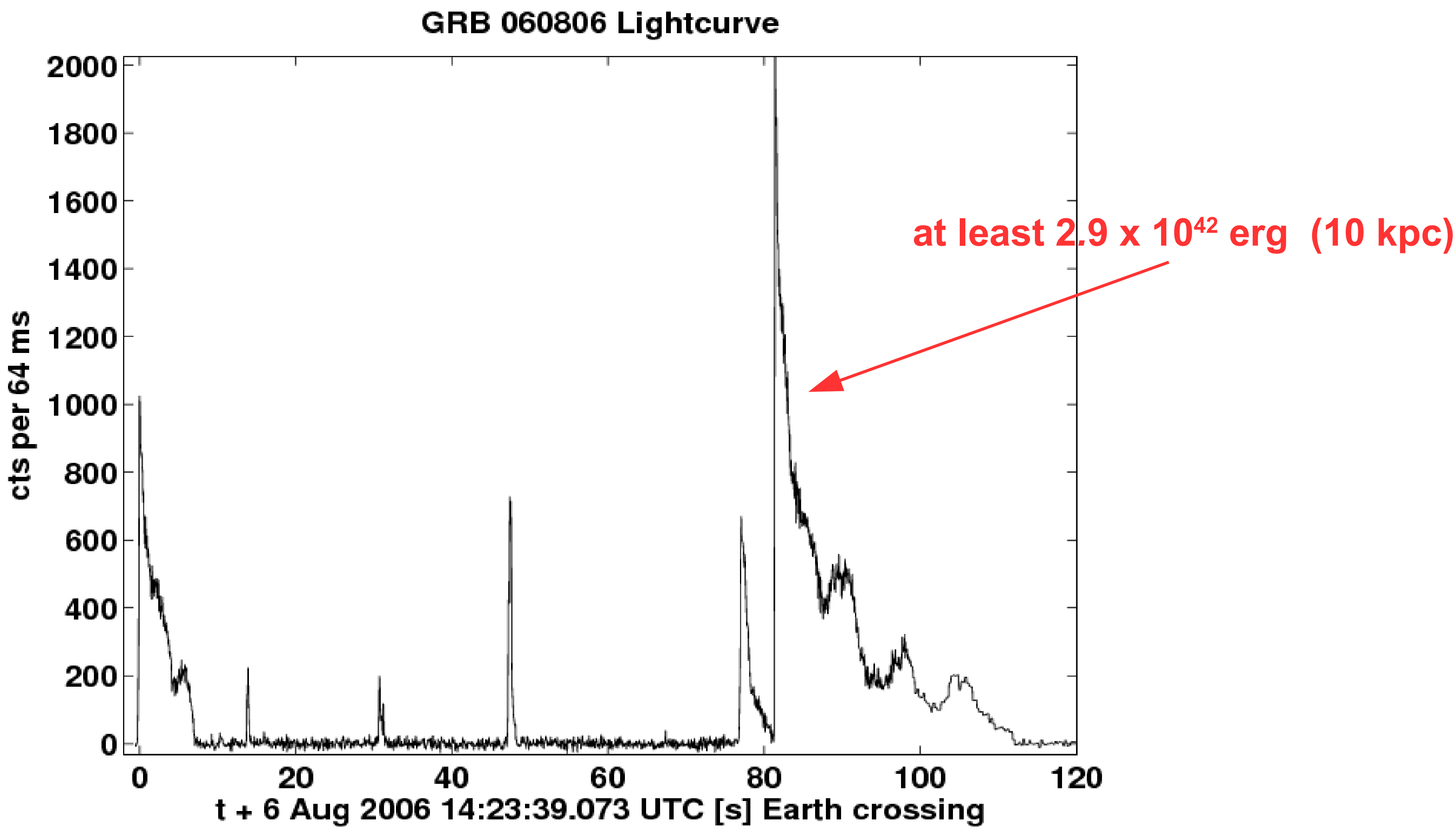


SGR 1900+14 storm



Swift/BAT
G. L. Israel et al., ArXiv e-prints 805 (2008), 0805.3919.

GRB 060806 (SGR 1806-20)



data courtesy Konus-Wind team

Search strategy

[-2,2] second on-source region for isolated bursts (cat2 DQ)

- accounts for satellite timing uncertainty
- expect GW – EM coincidence $<$100 ms

[-1000,1000] second background region (cat2 DQ)

- estimate μ(f), σ(f) used by Flare pipeline
- estimate local false alarm rate (FAR)

Multi-episodic burst treated with extended on-source regions

Follow up on-source analysis events with significant FAR

- In no-detection case we expect loudest on-source event to occur at rate of 1/Σ(on-source durations) Hz

Loudest event upper limits

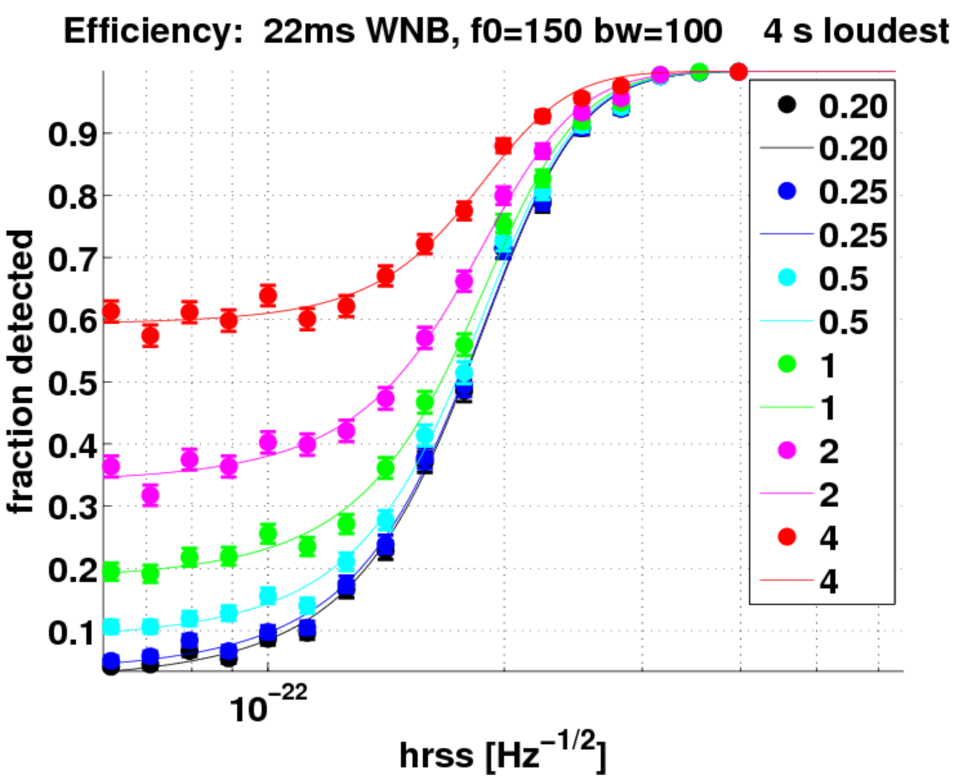
Depend on waveform for injections

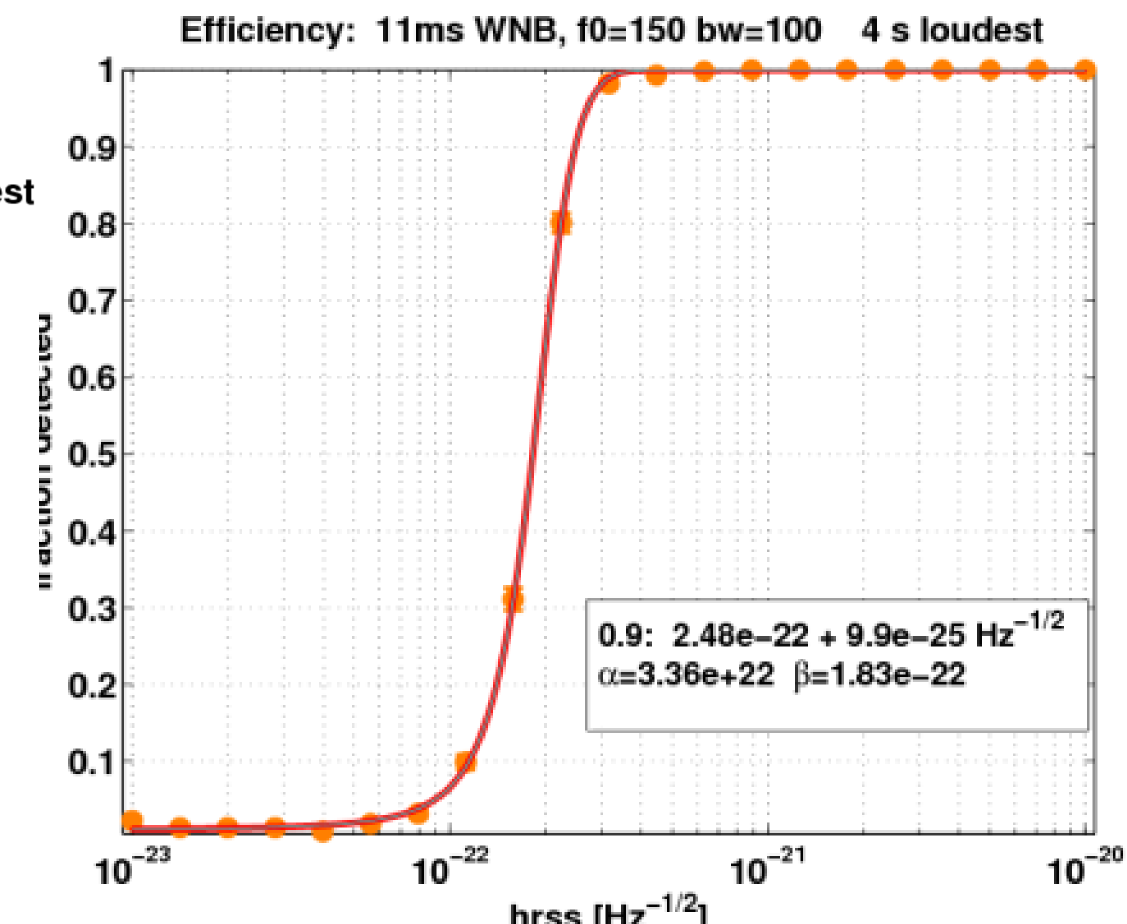
Search on-source region and record **loudest on-source event** (cat2 DQ only)

Inject simulations into BG (vary hrss)

Search for injection within coincidence time window

- Anything louder than loudest on-source event?
- Construct efficiency curve





Ringdowns 1 – 3 kHz

Simulation frequencies: 1090, 1590, 2090, 2590 Hz

f-mode frequencies depend on star's density

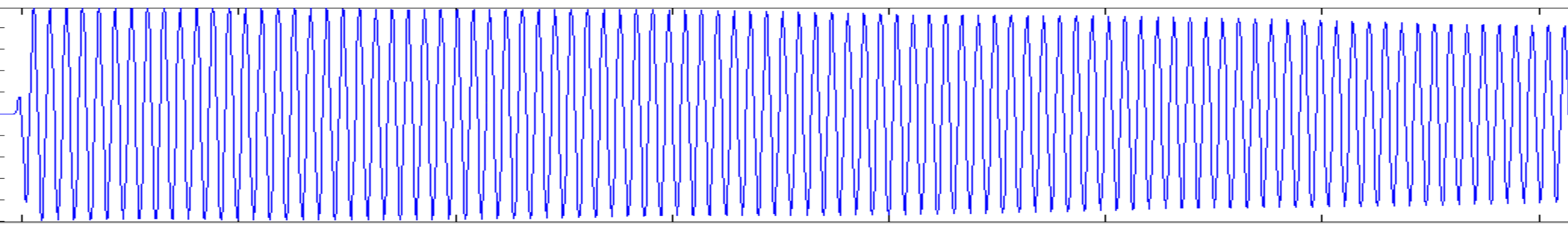
3 kHz upper bound: strange quark stars

1.5 kHz lower bound: lightweight star with stiff EOS [1]

Simulation tau: 200 ms

predicted range is 140-380 ms

we observe <15% sensitivity loss for RDs with tau in range 100-300 ms



[1] O. Benhar, V. Ferrari, and L. Gualtieri, Phys. Rev. D 70,124015 (2004)

Below 1 kHz

SGR burst timescales set search time window

5 ms – 200 ms

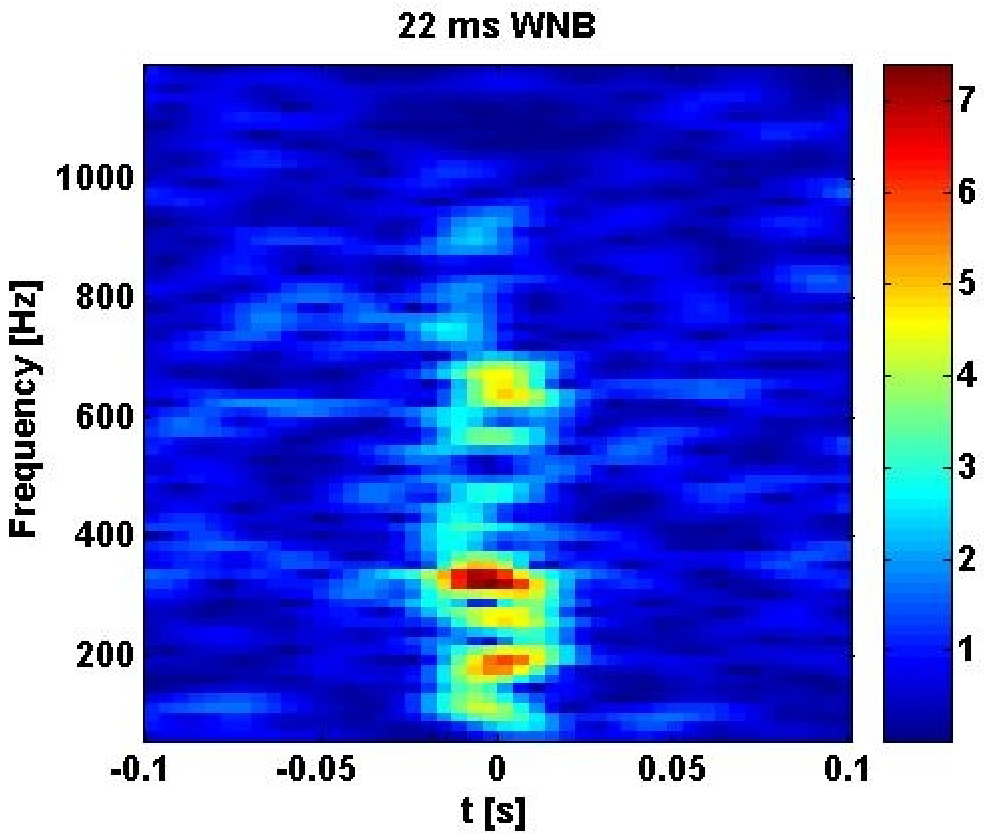
Band-limited to detector's sensitive regions:

100 – 200   Hz (small band)

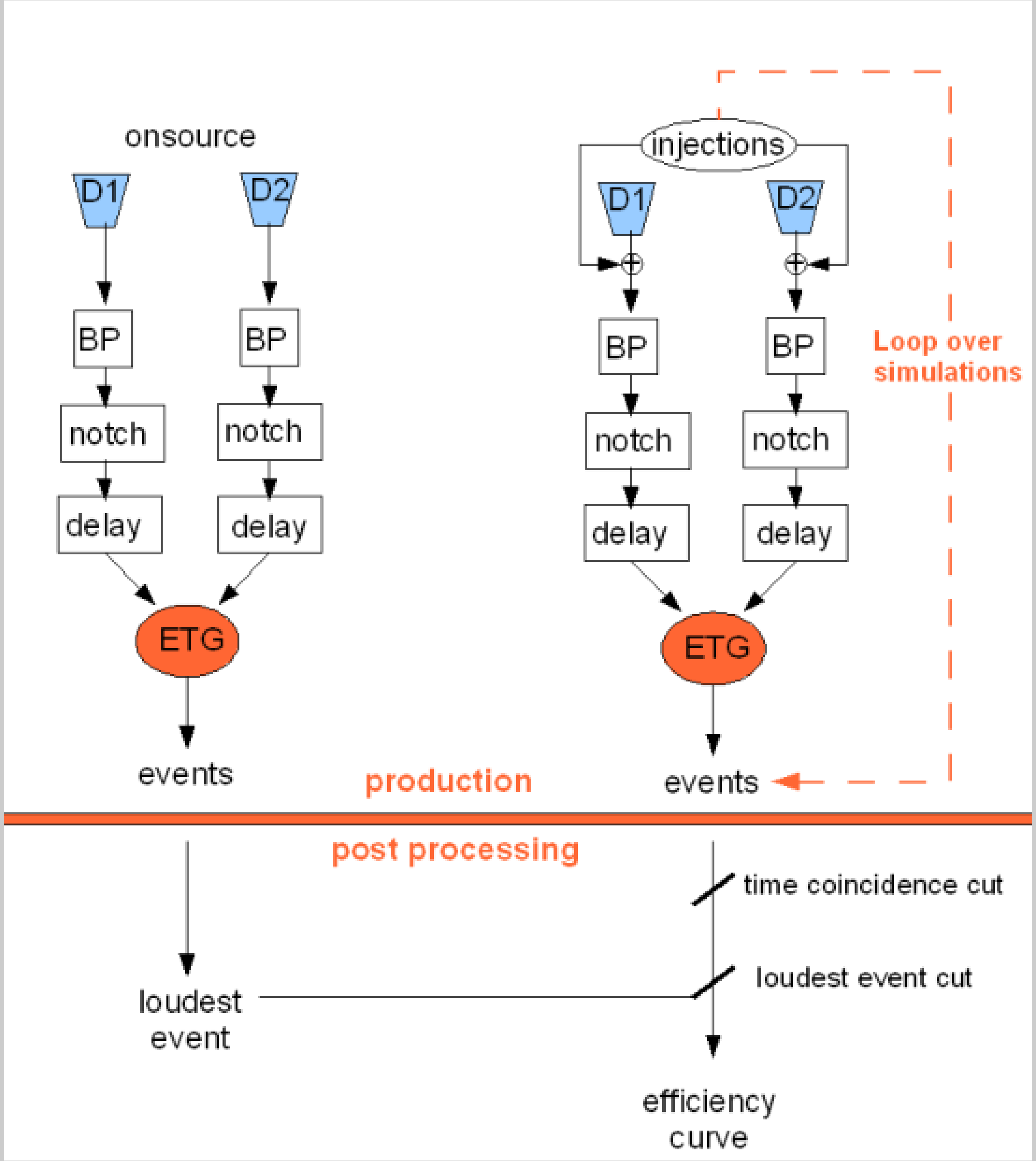
100 – 1000 Hz (large band)

WNB injections to estimate upper limits

11 ms and 100 ms durations



3. Flare Pipeline



Flare Pipeline

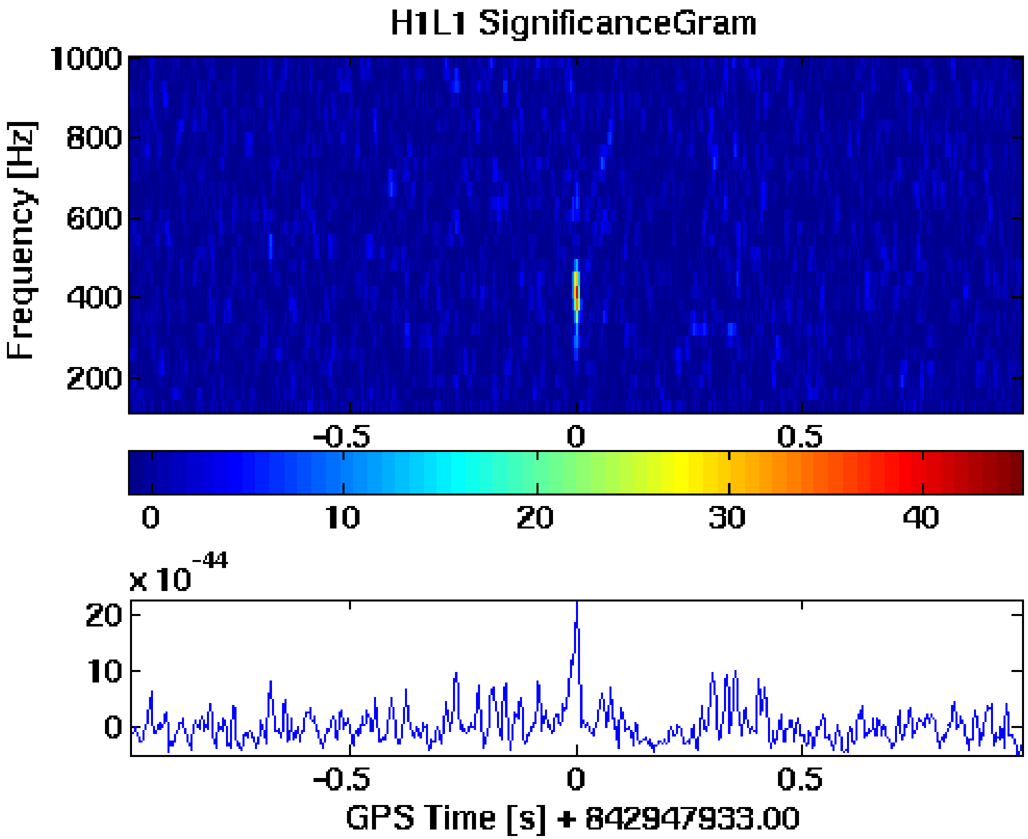
Simple but effective coherent excess power type method
Single and dual detector networks
Spectrogram transformation produces PSD TF tilings
- Tilings combined (dual detector) using pixel correlation method
- Background at each frequency used to make significance TF tiling

Clustering routine applied to pixels above significance threshold
Fully automated for multi-trigger searches

On-the-fly simulations or MDCs:

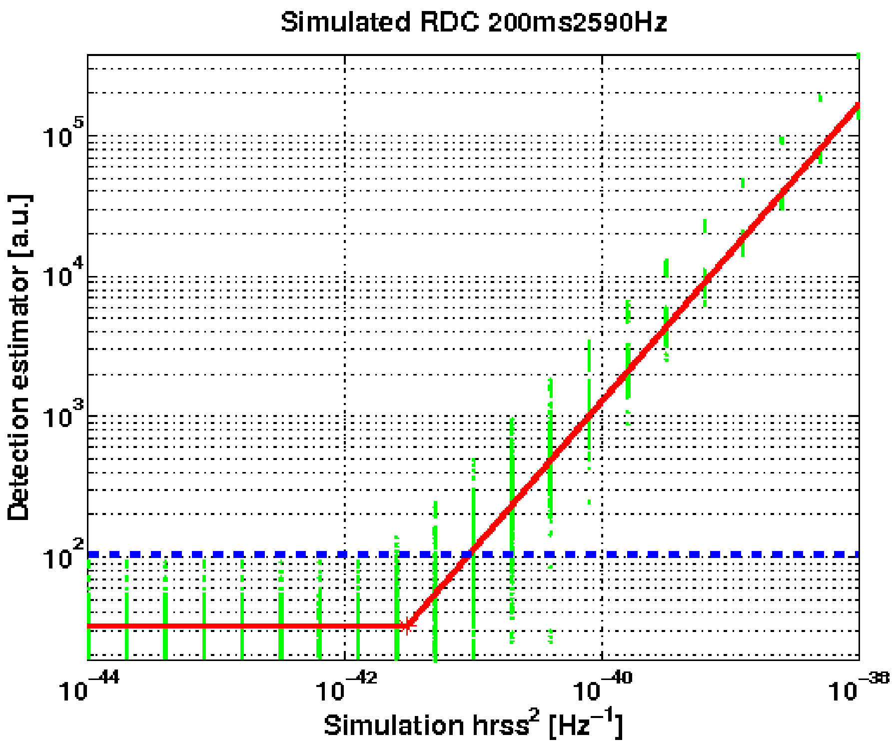
$$\xi_d^{\rm sim}(t) = F_d^{+}(\theta,\phi,\psi)h_{+}^{\rm sim}(t) + F_d^{\times}(\theta,\phi,\psi)h_{\times}^{\rm sim}(t)$$

$$P_{tf}^{(12)} = \mathrm{Re}\left[T_{tf}^{(1)}T_{tf}^{(2)^*}e^{-i2\pi f dt}\right]$$

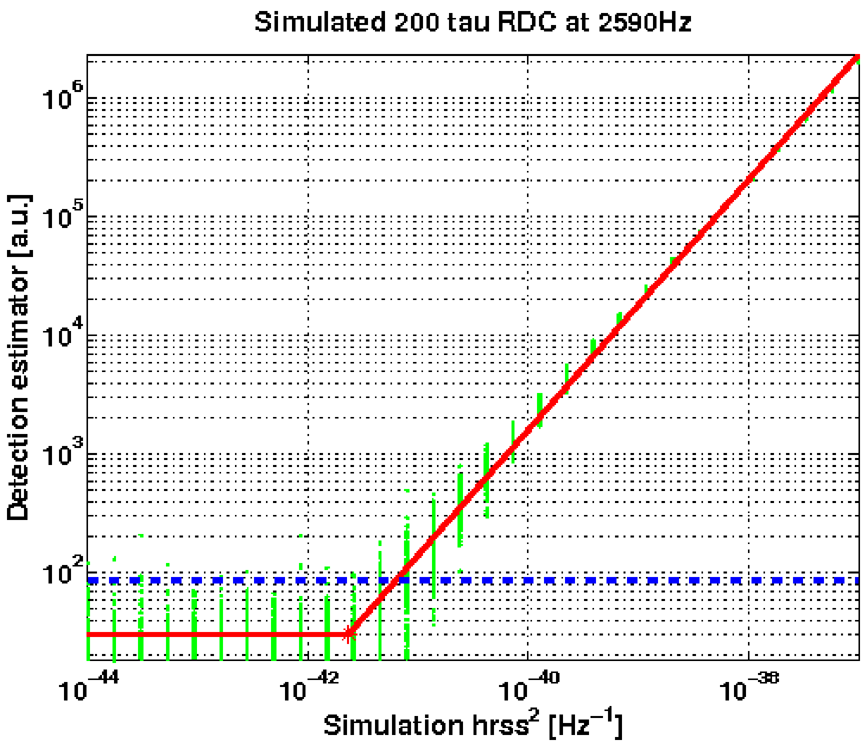


Sub-sample time delays

rounding to nearest sample $\Longrightarrow$ subsample delays in frequency domain

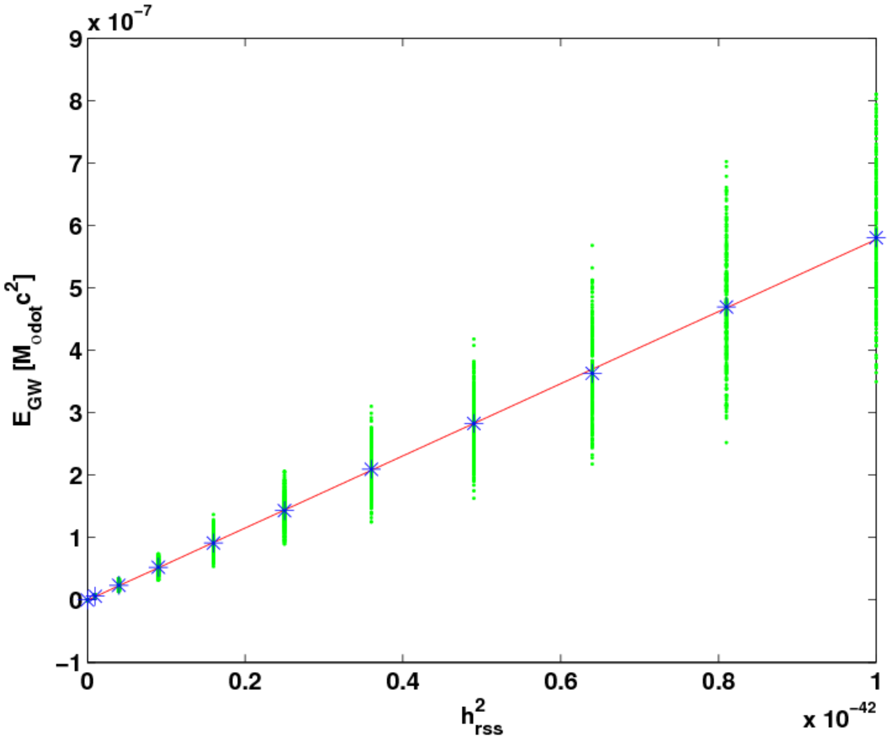


$\Longrightarrow$

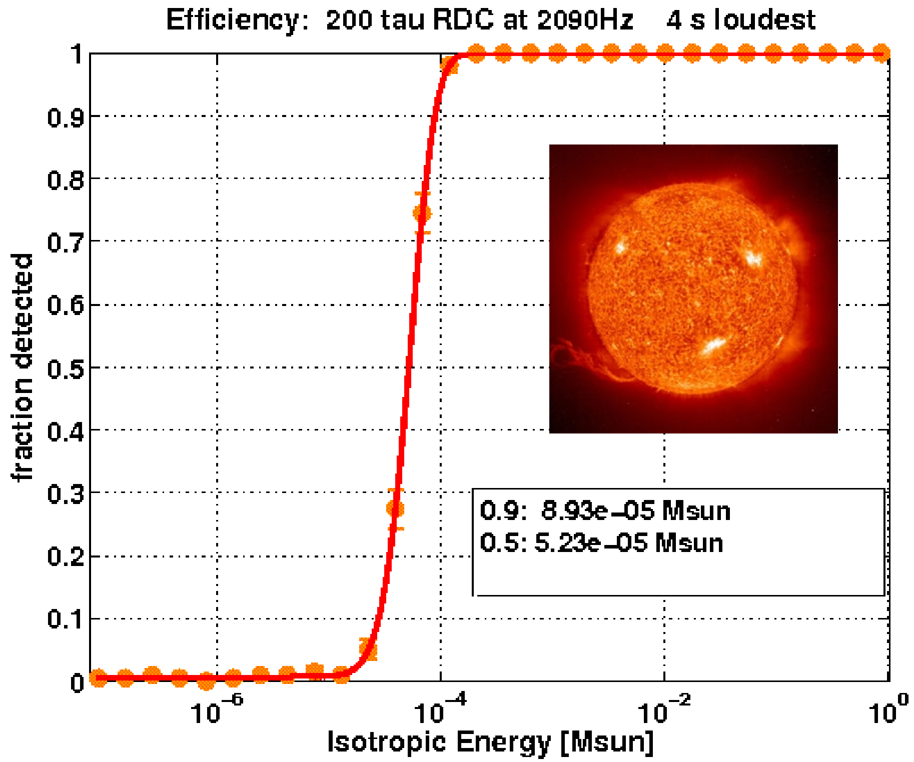


E/r² on-the-fly

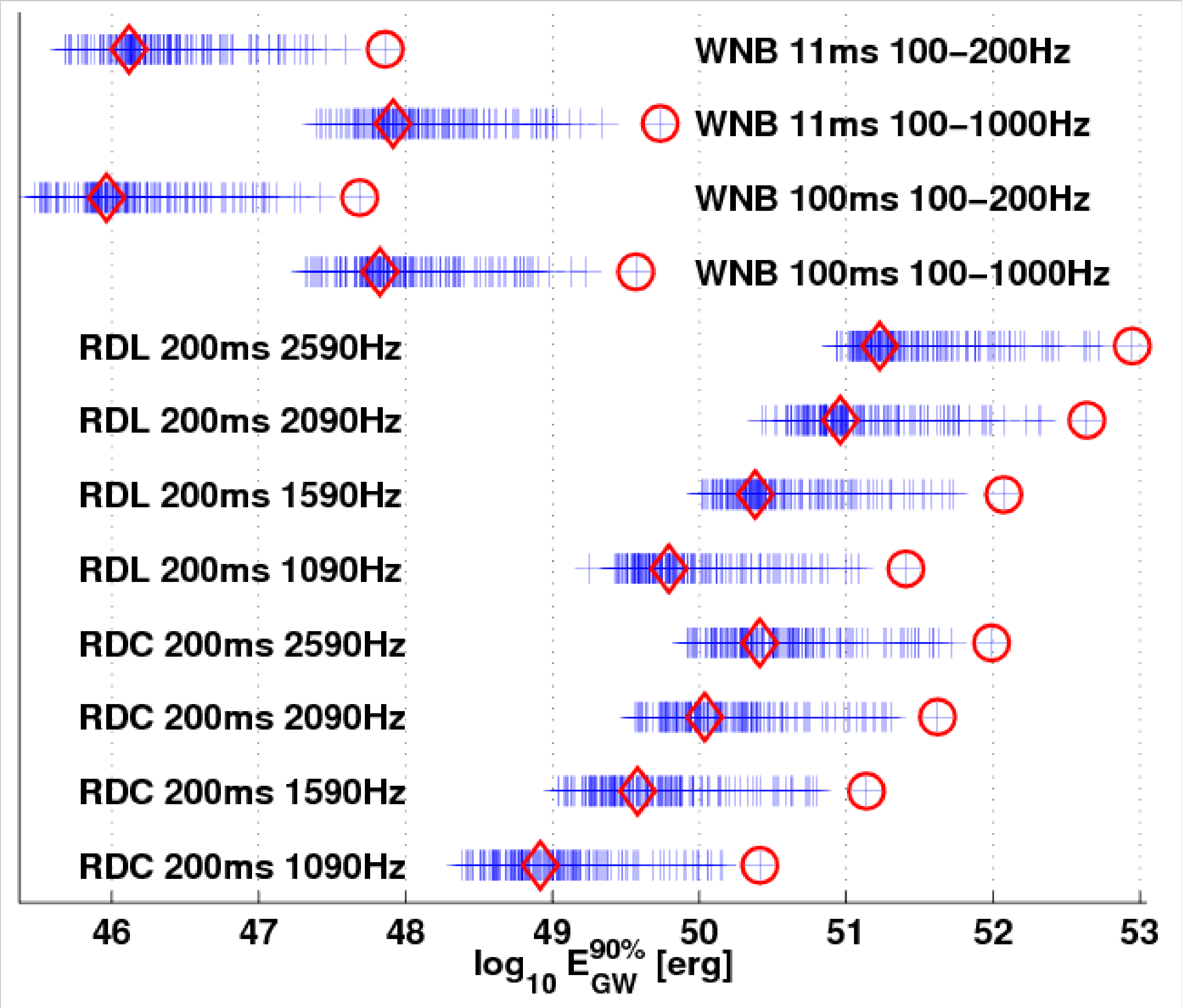
Post-production monte carlo E_{GW} estimate ⟹ E/r² recorded when simulation produced



⟹



4. Results



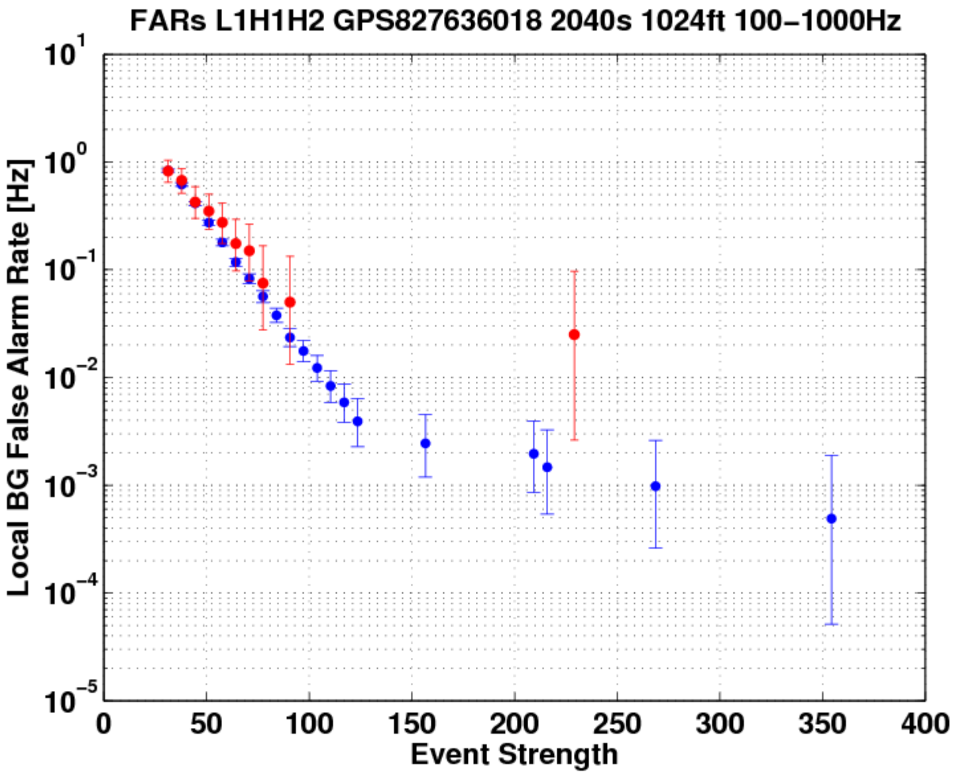
WNB 11ms 100–200Hz
WNB 11ms 100–1000Hz
WNB 100ms 100–200Hz
WNB 100ms 100–1000Hz
RDL 200ms 2590Hz
RDL 200ms 2090Hz
RDL 200ms 1590Hz
RDL 200ms 1090Hz
RDC 200ms 2590Hz
RDC 200ms 2090Hz
RDC 200ms 1590Hz
RDC 200ms 1090Hz
46
47
48
49
50
51
52
53
$\log_{10} E_{GW}^{90\%}$ [erg]

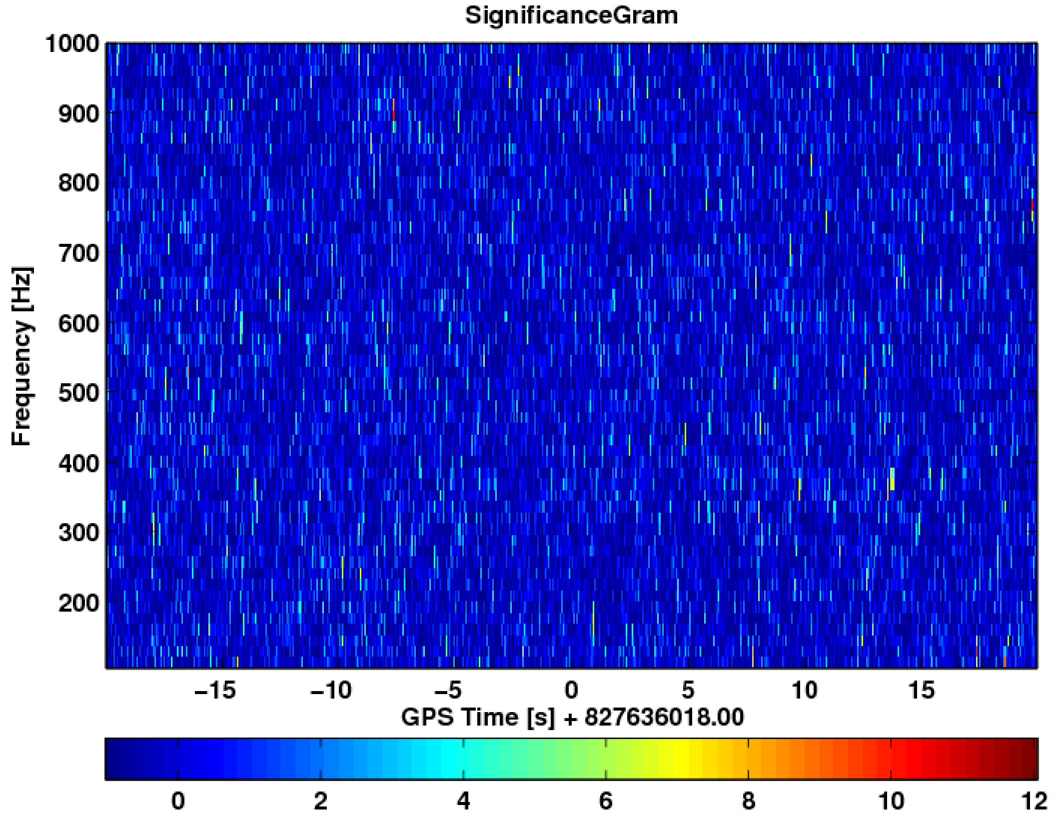
Most significant on-source events

1 per 741 seconds

triggerGPS	network	simulation	hrss90	egw90	loudest	FAR [Hz]
827636018	L1H1H2	WNB11ms100-1000Hz	1.110e-21	1.570e+48	2.290e+02	**1.350e-03**
827636018	L1H1H2	WNB100ms100-1000Hz	1.041e-21	1.218e+48	2.290e+02	1.350e-03
840943021	L1	WNB11ms100-200Hz	1.441e-21	1.938e+47	9.510e+02	1.510e-03
840943021	L1	WNB100ms100-200Hz	1.098e-21	1.080e+47	9.510e+02	1.510e-03
840943021	L1	RDC200ms1090Hz	2.867e-21	3.692e+49	4.180e+02	1.550e-03
840943021	L1	RDC200ms1590Hz	4.275e-21	1.727e+50	4.180e+02	1.550e-03
840943021	L1	RDC200ms2090Hz	5.832e-21	5.499e+50	4.180e+02	1.550e-03
840943021	L1	RDC200ms2590Hz	7.148e-21	1.296e+51	4.180e+02	1.550e-03
840943021	L1	RDL200ms1090Hz	1.075e-20	5.208e+50	4.180e+02	1.550e-03
840943021	L1	RDL200ms1590Hz	1.582e-20	2.494e+51	4.180e+02	1.550e-03
840943021	L1	RDL200ms2090Hz	2.062e-20	6.930e+51	4.180e+02	1.550e-03
840943021	L1	RDL200ms2590Hz	2.906e-20	2.151e+52	4.180e+02	1.550e-03
840943021	L1	WNB11ms100-1000Hz	2.870e-21	1.023e+49	1.390e+03	2.030e-03
840943021	L1	WNB100ms100-1000Hz	2.371e-21	6.818e+48	1.390e+03	2.030e-03
839252573	L1H1H2	RDC200ms1090Hz	1.208e-21	6.273e+48	1.680e+02	2.480e-03
839252573	L1H1H2	RDC200ms1590Hz	1.691e-21	2.614e+49	1.680e+02	2.480e-03
839252573	L1H1H2	RDC200ms2090Hz	2.304e-21	8.628e+49	1.680e+02	2.480e-03
839252573	L1H1H2	RDC200ms2590Hz	2.837e-21	1.951e+50	1.680e+02	2.480e-03
839252573	L1H1H2	RDL200ms1090Hz	4.485e-21	9.006e+49	1.680e+02	2.480e-03
839252573	L1H1H2	RDL200ms1590Hz	7.281e-21	5.060e+50	1.680e+02	2.480e-03
839252573	L1H1H2	RDL200ms2090Hz	8.571e-21	1.190e+51	1.680e+02	2.480e-03
839252573	L1H1H2	RDL200ms2590Hz	1.302e-20	4.116e+51	1.680e+02	2.480e-03

No Detection





"We find no evidence for GW associated with any of the SGR burst events in the sample. The significance of on-source analysis events is inferred by assigning rates at which background analysis events of equal or greater loudness occur. We find the most significant on-source analysis event occurs at a rate of 1 per 741 s which is consistent with the expectation for the 803 s of on-source data in the sample."

Gamma ≡ E_{GW} / E_{EM}

Measures the extent to which an energy upper limit probes the GW emission efficiency.

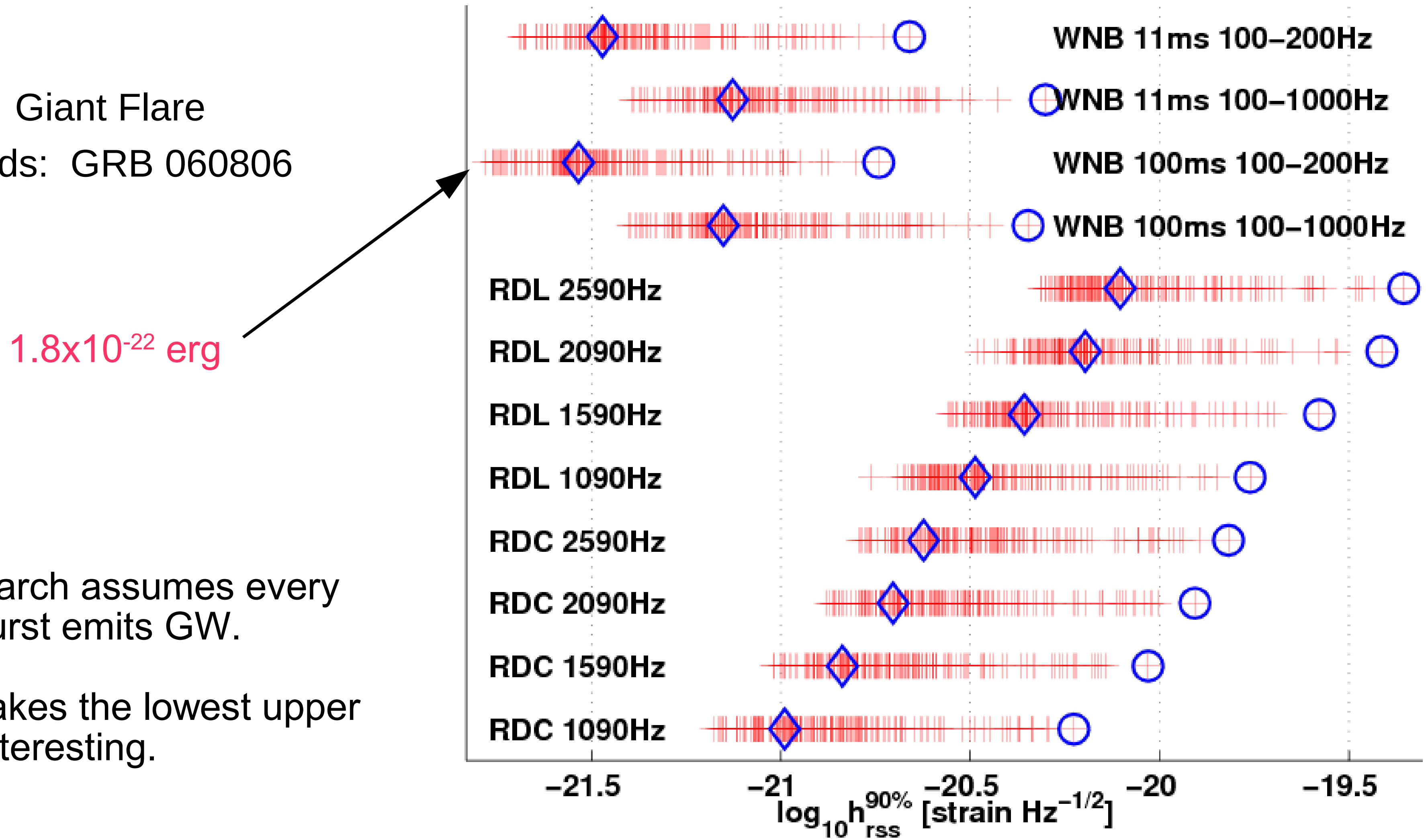
These two events were picked for the short paper as they yield the lowest gamma.

	SGR 1806−20 Giant Flare			SGR 1806−20 GRB 060806		
Waveform type	$h_{\rm rss}^{90\%}\,[10^{-22}\ {\rm Hz}^{-\frac{1}{2}}]$	$E_{\rm GW}^{90\%}$ [erg]	γ	$h_{\rm rss}^{90\%}\,[10^{-22}\ {\rm Hz}^{-\frac{1}{2}}]$	$E_{\rm GW}^{90\%}$ [erg]	γ
WNB 11ms 100-200 Hz	22 +1.3 +5.6 +1.2 = 29	7.3×10^{47}	5×10^{1}	3.4 +0.03 +0.35 +0.20 = 3.8	1.3×10^{46}	4×10^{3}
WNB 100ms 100-200 Hz	18 +1.1 +4.6 +0.52 = 24	4.9×10^{47}	3×10^{1}	2.9 +0.0 +0.30 +0.13 = 3.3	9.1×10^{45}	3×10^{3}
WNB 11ms 100-1000 Hz	50 +3.0 +13 +1.3 = 66	5.4×10^{49}	3×10^{3}	7.5 +0.07 +0.77 +0.27 = 8.4	8.5×10^{47}	3×10^{5}
WNB 100ms 100-1000 Hz	45 +2.7 +12 +1.1 = 59	3.7×10^{49}	2×10^{3}	7.0 +0.0 +0.73 +0.19 = 7.8	6.7×10^{47}	2×10^{5}
RDC 200ms 1090 Hz	59 +3.6 +15 +1.7 = 78	2.6×10^{50}	2×10^{4}	10 +0.10 +1.1 +0.37 = 11	5.7×10^{48}	2×10^{6}
RDC 200ms 1590 Hz	93 +5.6 +24 +2.8 = 120	1.4×10^{51}	9×10^{4}	15 +0.44 +1.5 +0.52 = 17	2.5×10^{49}	8×10^{6}
RDC 200ms 2090 Hz	120 +7.4 +32 +3.5 = 160	4.2×10^{51}	3×10^{5}	20 +0.59 +2.0 +0.64 = 23	8.0×10^{49}	3×10^{7}
RDC 200ms 2590 Hz	150 +9.1 +39 +4.1 = 200	9.8×10^{51}	6×10^{5}	24 +0.71 +2.5 +0.92 = 27	1.8×10^{50}	6×10^{7}
RDL 200ms 1090 Hz	170 +10 +44 +36 = 240	2.6×10^{51}	2×10^{5}	33 +0.0 +3.4 +3.5 = 37	6.4×10^{49}	2×10^{7}
RDL 200ms 1590 Hz	260 +16 +68 +32 = 360	1.2×10^{52}	7×10^{5}	44 +1.3 +4.6 +6.3 = 53	2.7×10^{50}	9×10^{7}
RDL 200ms 2090 Hz	390 +23 +99 +46 = 520	4.4×10^{52}	3×10^{6}	64 +3.8 +6.6 +9.1 = 79	1.0×10^{51}	3×10^{8}
RDL 200ms 2590 Hz	440 +26 +110 +63 = 600	8.9×10^{52}	6×10^{6}	79 +5.5 +8.2 +9.7 = 97	2.3×10^{51}	8×10^{8}

H_{RSS} Upper Limits

Circles: Giant Flare

Diamonds: GRB 060806



This search assumes every SGR burst emits GW.

This makes the lowest upper limits interesting.

E_{GW} upper limits

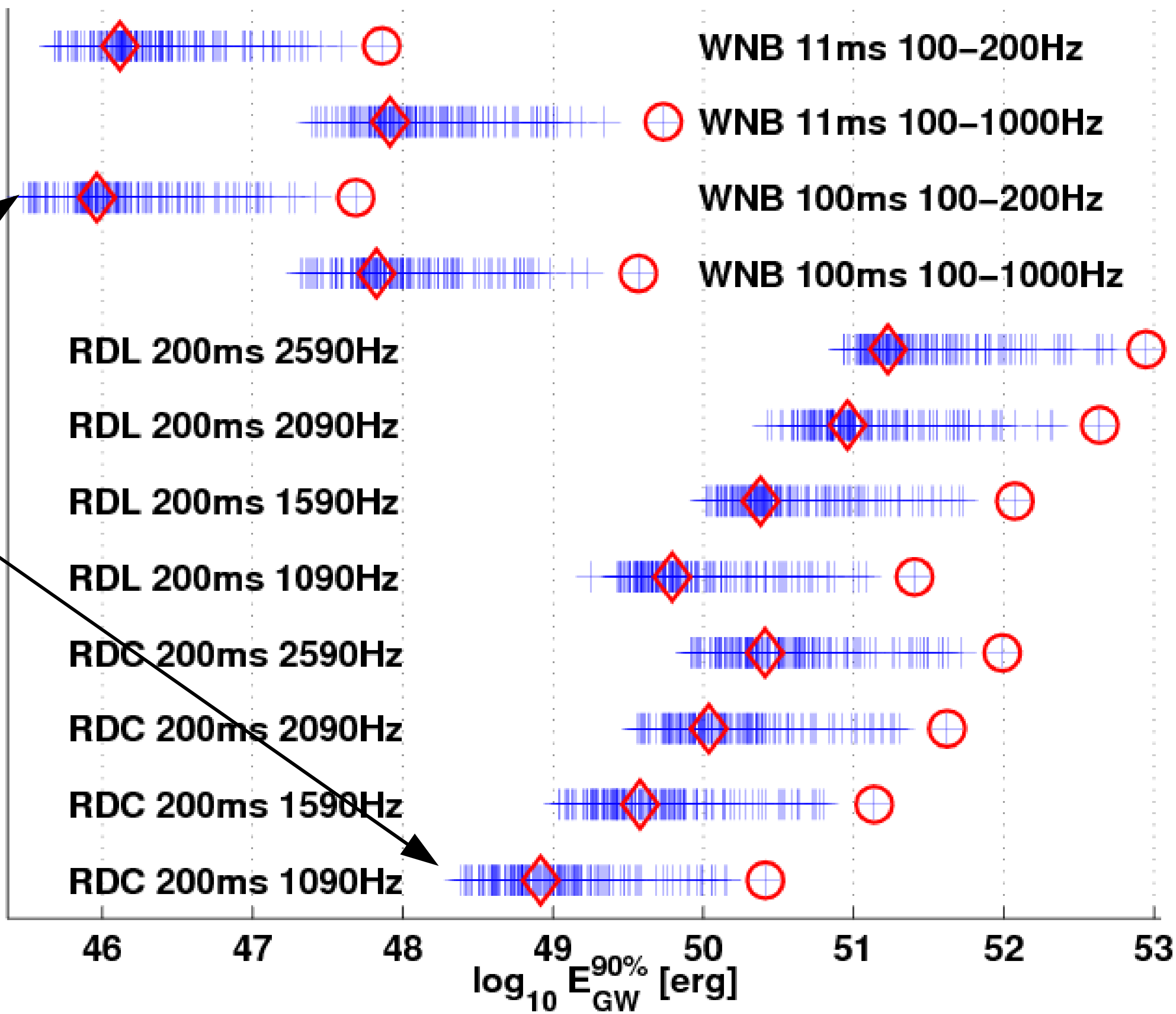
fig. 1 in paper draft

10 kpc assumed SGR distance

2.9×10^{45} erg

2.4×10^{48} erg

Circles: Giant Flare
Diamonds: GRB 060806



Context

Search highlights:

- This was the first search sensitive to neutron star f-modes
- 191 SGR events including the largest giant flare and a storm
- Upper limits on GW energy emitted assuming various plausible waveforms
- Most sensitive burst results to date by far

Models of SGR GW emission

- Ioka's is most detailed MNRAS 327, 639 (2001)
  - gamma = 10^4 may not be unreasonable
  - bursts with 10^{49} erg may not be unreasonable
- RD and unmodeled results both within these ranges

Advanced LIGO – factor of ~100 improvement in energy sensitivity

- Detection?
- upper limits on f-mode search in E_{EM} range for giant flares

5. What's Next

SGRs keep bursting.

SGR 1806-20 remains very active

SGR 1627-41 showed activity in May 2008

a “storm” or “forest”

first activity from this SGR in 9.8 years

Stack-a-flare multiple burst analysis

Prototyping has begun, you will hear about it soon!

S5 post-Virgo individual burst analysis

S6 individual burst analysis

Preparations for **fast publication** in case of another Giant Flare

Hopefully we can excite the theorists...