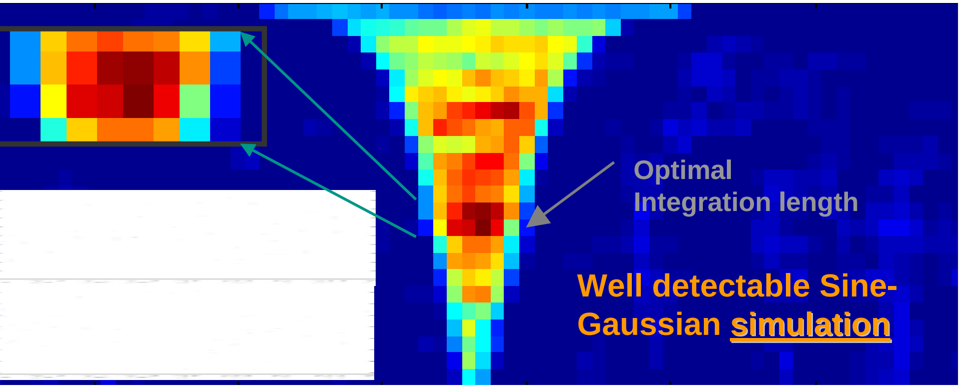
Search for the gravity wave signature of GRB030329/SN2003dh

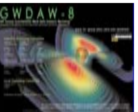


ABSTRACT

One of the major goals of gravitational wave astronomy is to explore the astrophysics of phenomena that are already observed in the particle/electromagnetic bands. Among potentially interesting sources for such collaboration are gravitational wave searches in coincidence with Gamma Ray Bursts. On March 29, 2003, one of the brightest ever Gamma Ray Burst was detected and observed in great detail by the broader astronomical community. The uniqueness of this event prompted our search as we had the two LIGO Hanford detectors in coincident lock at the time. We will report on the GRB030329 prompted search for gravitational waves, which relies on our sensitive multi-detector data analysis pipeline specifically developed and tuned for astrophysically triggered searches. We did not observe a gravity wave burst, which can be associated with GRB030329. However, the search provided us with an encouraging upper limit on the associated gravity wave strain at the Hanford detectors.

Szabolcs Márka

for the LIGO Scientific Collaboration



The 8th Gravitational Wave Data Analysis Workshop (GWDAW-8)
from December 17 to 20th, 2003, in Milwaukee, Wisconsin, USA

Externally initiated search for gravity waves

Violent cosmic events can be seen as optical supernovae, neutrino bursts, GRBs, etc…

We expect such events to produce a significant flux of gravitational waves in the LIGO frequency band.

Various trigger and data distribution networks:

International Supernovae Network (I.S.N.)

Supernovae Early Warning System (SNEWS)

The GRB Coordinates Network (GCN)

The third InterPlanetary Network (IPN3)

….

Measured trigger properties

Time of arrival

Source direction

Duration, distance, type, etc…

Targeted coherent search for gravity wave counterpart

Timing and direction information is crucial for improved efficiency

Measured parameters are essential for astrophysical interpretation of results

Each trigger type has advantages and disadvantages

Gamma-Ray Bursts (GRB)

- Gamma-Ray Bursts (GRB) are short but very energetic pulses of gamma-rays emitted at cosmological distances.
- They originate from 'random' sky locations (~isotropically distributed on the sky).
- They are quite frequent and their detection rate can be as high as one event a day.
- They are the result of various ultra-relativistic processes, and can be accompanied by X-ray, radio and/or optical afterglows.
- GRBs require very energetic sources (10^{51} - 10^{53} erg), and can be as short as 10 ms and as long as 100 s.
- GRBs can be classified based on their duration as "short" (<2s) and "long" (>2s).
- The present consensus is that GRB emission is associated with black hole formation processes such as hypernovae, compact binary inspirals and collapsars. A very good reason to expect strong association between GRBs and gravitational waves.
  - » They are short, violent events that could produce significant fractions of a solar mass of gravitational waves within the LIGO band
  - » The frequency of the waves could be set by the timescale associated with the black hole dynamics, which allows for "high frequency" gravitational waves.

Relatively large number of events are detected ⟹ (Statistical analysis approaches are useful!)

Good timing information

Various levels of source direction information

Usual sources are at very large distances

Model dependent results

Only 1 in ~500 GRBs are detected by present satellites

GRBs and their coverage during S2/DT8

http://darkwing.uoregon.edu/~ileonor/ligo/s2/grb/s2grbsligotama.txt

GRB	GPS time	Locked IFO	LIGO segment	Location error
030217	729485155.00	H2/L1	27	well-defined
030218	729603771.00	H1/H2/L1/TA	39	annulus
030220	729792777.00	H1/TA	39	annulus
030223	730028719.00	H1/H2/L1/TA	60	annulus
030225	730220586.00	H2/TA	70	annulus
030226	730266404.99	H1/H2/L1	68	well-defined
030227	730370549.25	H1/H2/TA	89	well-defined
030228	730499219.00	H1/H2/TA	107	annulus
030301	730585653.00	H1/H2	119	annulus
030304	730856078.00	L1/TA	189	annulus
030306	730957115.00	H2/TA	156	well-defined
030307	731082733.00	H1/H2/TA	170	annulus
030317	731919546.00	H1/L1	276	annulus
030320a	732190313.00	H1/H2/L1/TA	236	well-defined
030320b	732221370.00	H1/H2/TA	226	annulus
030323a	732444157.00	H1/H2/L1/TA	267	well-defined
030323b	732491830.60	H1/H2/L1/TA	273	well-defined
030324	732510775.80	H1/H2	249	well-defined
030325	732636923.00	H1/H2/L1/TA	294	well-defined
030326	732710634.00	H1/H2/L1/TA	304	well-defined
030328	732885671.34	H2/TA	295	well-defined
030329a	732973047.67	H1/H2/TA	292	well-defined
030329b	732987268.35	H1/H2/TA	294	well-defined
030331	733124333.82	H1/L1	428	well-defined
030403	733376279.00	H1/L1(6s)	455	annulus
030405	733544261.00	H1/H2/L1/TA	387	well-defined
030406	733704140.00	H1/L1/TA	487	well-defined
030410	734009035.00	H1/H2/TA	385	annulus
030413	734254490.00	H2/L1/TA	494	well-defined
030414	734363320.00	H1/H2/TA	411	well-defined

http://darkwing.uoregon.edu/~ileonor/ligo/s2/grb/s2grbstama.html

Locked IFOs	# of GRBs	# well-located
H1/H2/L1/TA	8	6
H1/H2/L1 only	1	1
H1/H2/TA only	8	4
H1/L1/TA only	1	1
H2/L1/TA only	1	1
H1/H2 only	2	1
H1/L1 only	3	1
H2/L1 only	1	1
H1/TA only	1	0
H2/TA only	3	2
L1/TA only	1	0
Total	**30**	**18**

- 30 = number of GRBs with GCN notices and position information
- 25 = number of GCN GRBs occurring when LIGO had at least two IFOs in science mode
- 30 = number of GCN GRBs occurring when there were at least double coincidence (LIGO-LIGO or LIGO-TAMA)
- 23 = number of GCN GRBs occurring when TAMA was in lock
- But need the TAMA collaboration to verify their locked segments.

LIGO

GRB030329

TITLE: GCN GRB OBSERVATION REPORT NUMBER: 2120 SUBJECT: GRB 030329: Supernova Confirmed DATE: 03/04/08 20:13:40 GMT FROM: T. Matheson et al.

"…The spectral features discovered by Matheson et al. (GCN 2107) and confirmed by Garnavich et al. (IUAC 8108) continue to develop. Subtracting a scaled version of the Apr. 4.27 UT power-law spectrum from the Apr. 8.13 spectrum reveals an energy distribution remarkably similar to that of the SN1998bw a week before maximum light (Patat et al. 2001, ApJ, 555, 900). This spectrum can be seen at http://cfa-www.harvard.edu/~tmatheson/compgrb.jpg The spectral similarity to SN 1998bw and other 'hypernovae' such as 1997ef (Iwamoto et al. 2000, ApJ, 534, 660) provides strong evidence that classical GRBs originate from core-collapse supernovae. This message may be cited.

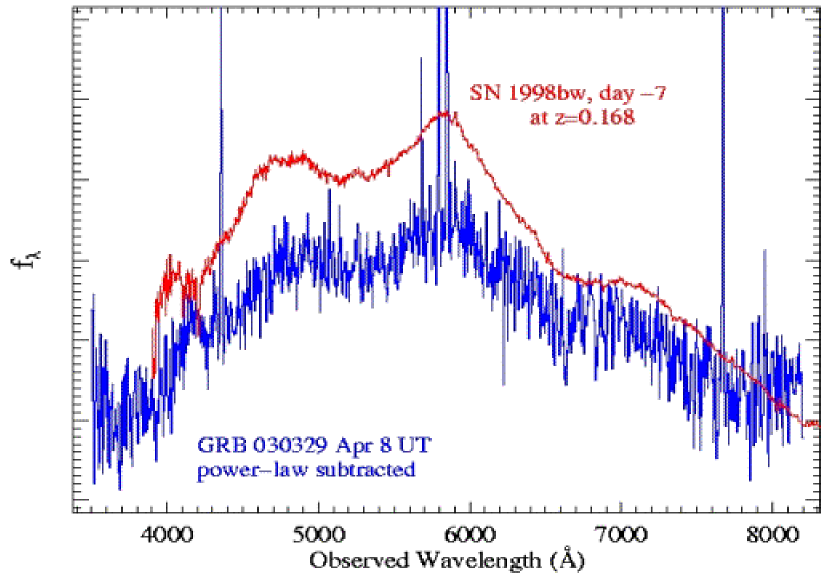
http://www.cerncourier.com/main/article/43/7/12

"…We've been waiting for this for a long, long time," said lead author Jens Hjorth. "This GRB gave us the missing information. From these detailed spectra we can now confirm that this burst, and probably other long GRBs, are created through the core collapse of massive stars. Most other leading theories are now unlikely…"

Supernova Spectrum Emergence

GRB 030329 is now also SN2003dh

http://space.mit.edu/HETE/Bursts/GRB030329/



T. Matheson (CfA), GCN 2120

TITLE: GCN GRB OBSERVATION REPORT NUMBER: 2176 SUBJECT: GRB030329 observed as a sudden ionospheric disturbance (SID) DATE: 03/04/28 22:38:19 GMT FROM: Doug Welch et al.,

"…A disturbance of the Earth's ionosphere was observed coincident with the HETE detection of GRB030329. This SID was seen as an increase in the signal strength from a Low Frequency (LF) radio beacon received in Kiel, transmitted as a time signal from station HBG (75 kHz) near Geneva, 920 km from the receiver. (Note: This is not a radio detection of GRB030329; this disturbance was caused by the prompt X-rays and/or gamma-rays from GRB030329 ionizing the upper atmosphere and modifying the radio propagation properties of the Earth's ionosphere.) Due to the sub-burst longitude and latitude and the geographical distribution of LF/VLF beacons and monitoring stations, this was the only recording (positive or negative) where GRB030329 illuminated the ionosphere along a signal path. …"

Signal region and GRB030329 trigger

-Theories prefer

- very short ~10ms burst
- long (~1-10s) quasi-sinusoids
(Araya-Góchez, M. Van Putten)

- Relative delay between the gravity wave and GRB is predicted to be small ~O(s)

  - Signal region: [To-120s, To+60s] to cover most predictions
  - Model specific ranges can also be considered

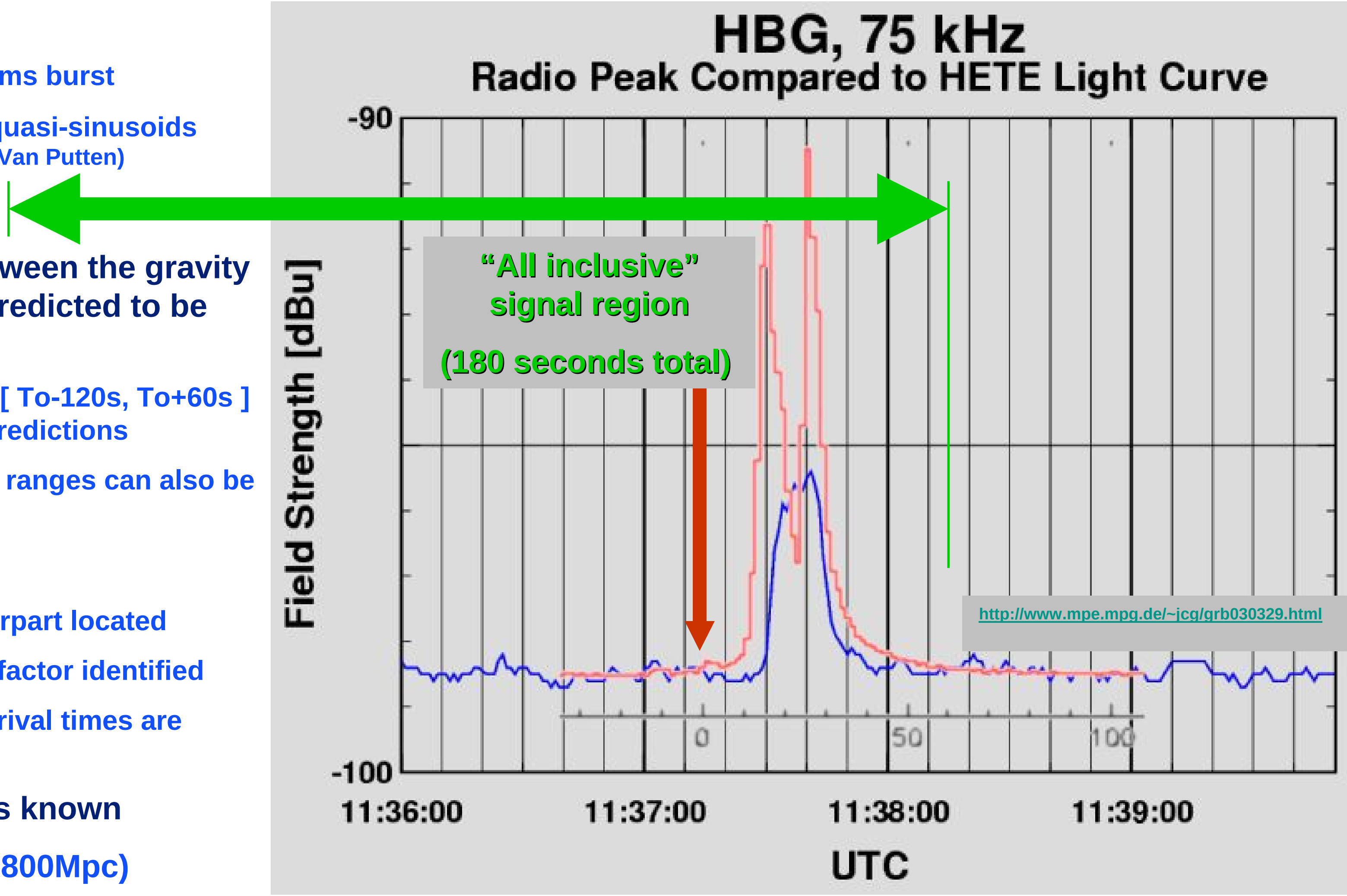
- Known direction

  - Optical counterpart located
  - LIGO antenna factor identified
  - LIGO/TAMA arrival times are known

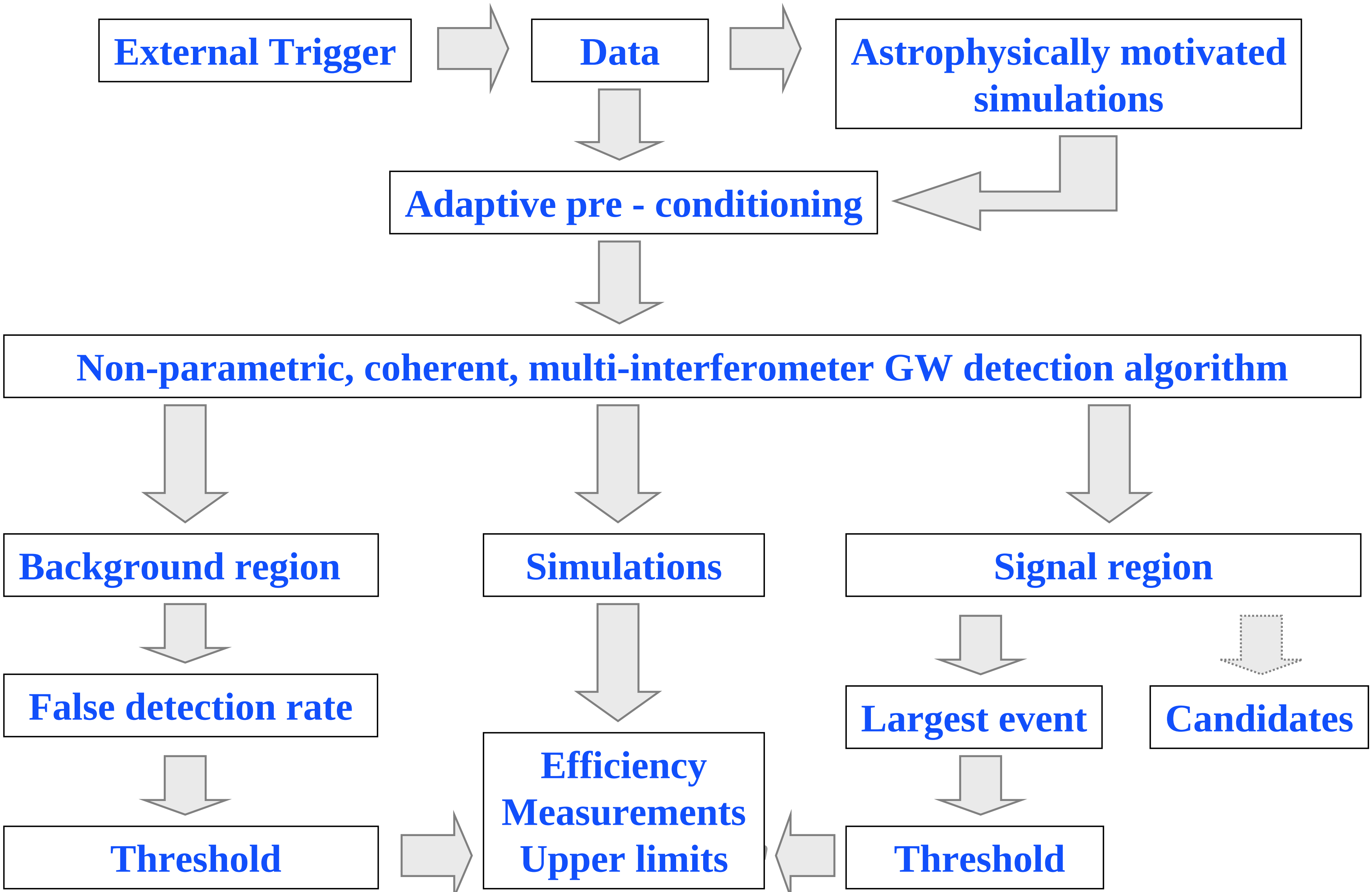
- Source distance is known

  - z=0.1685 (d~800Mpc)

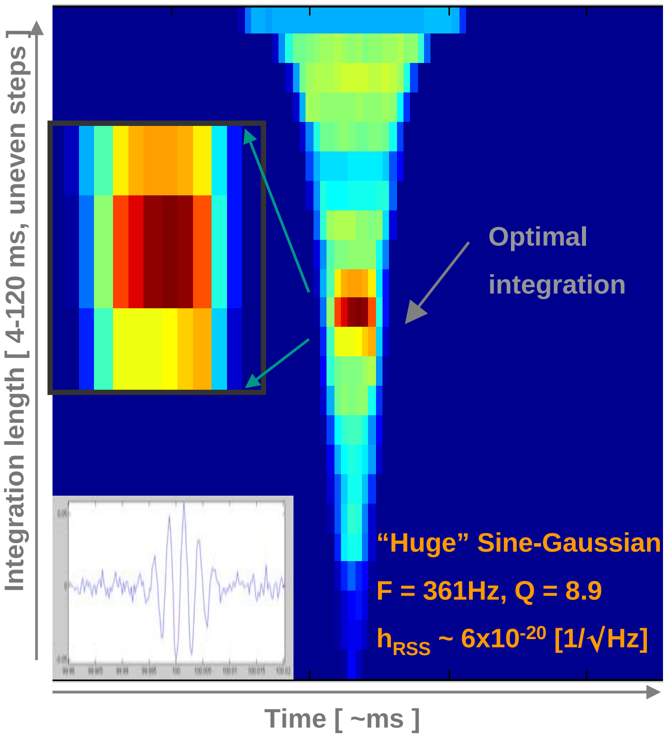
- Unknown waveform/duration

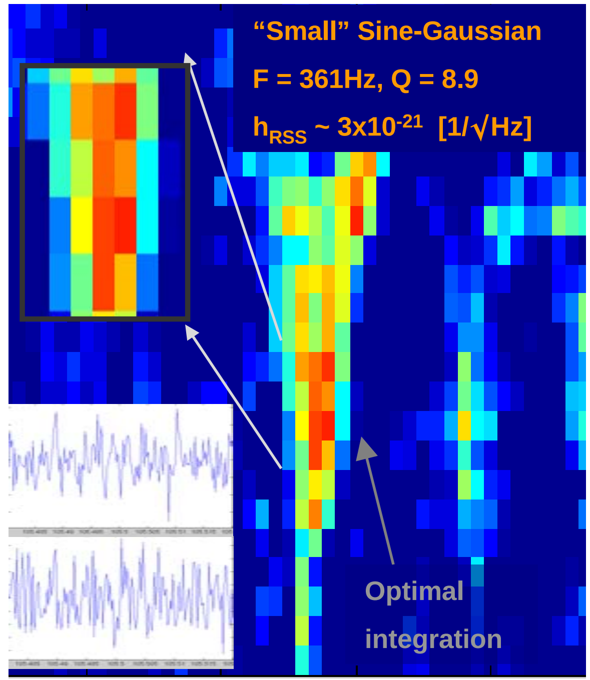


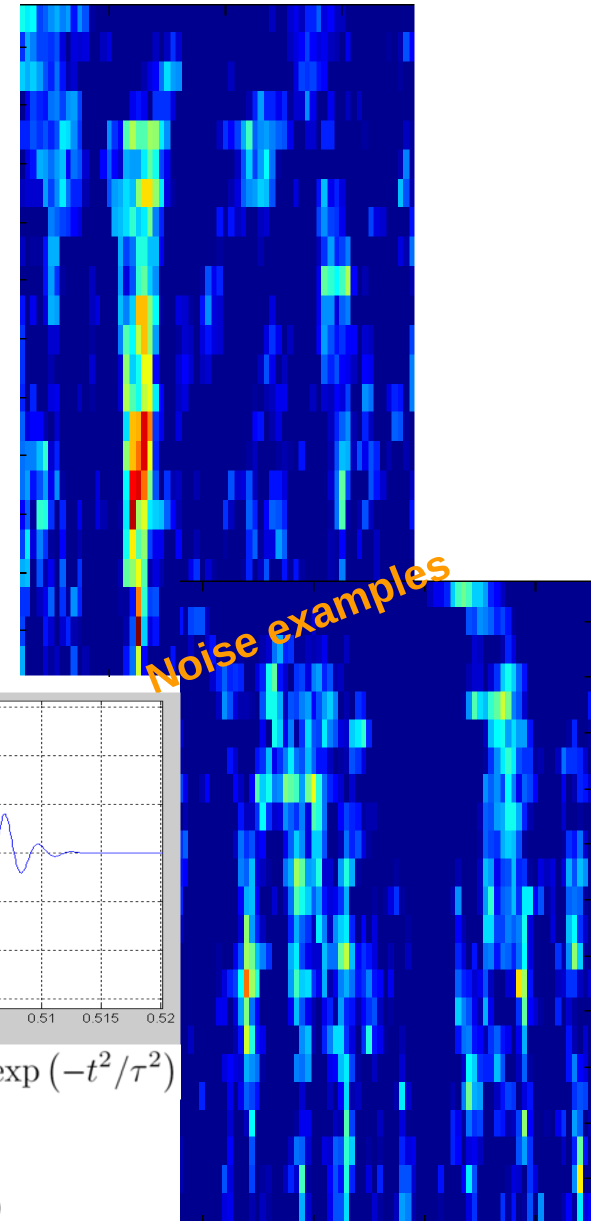
Schematic analysis flow chart

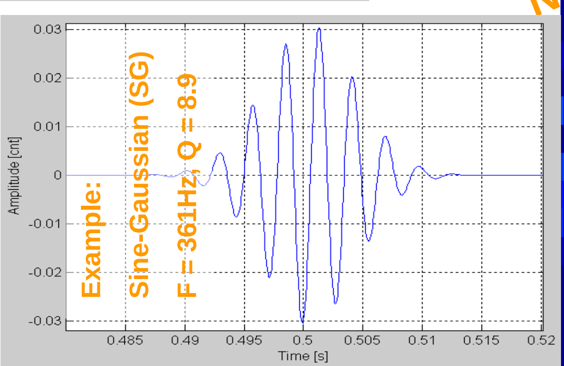


Cross-correlated signal anatomy I.









$$h(t+t_0) = h_0 \sin(2\pi f_0 t) \exp\left(-t^2/\tau^2\right)$$

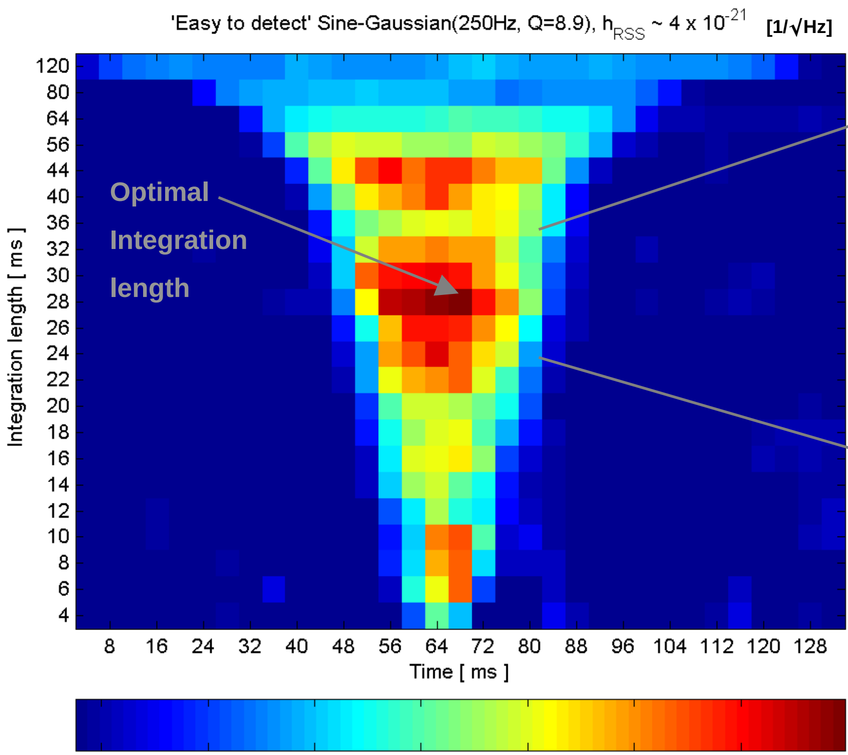
$$Q \equiv \sqrt{2}\pi\tau f_0 \simeq 8.9$$

$$h_{rss} \equiv \sqrt{Q/(4\sqrt{\pi} f_0)}h_0$$

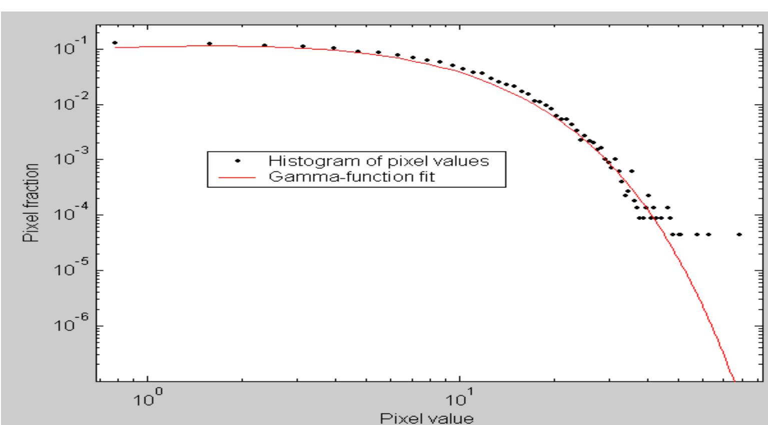
- Co-located detectors can have correlated signals
  - Various environmental effects
- The optimal integration length depends on:
  - the base noise
  - the signal duration
  - the signal strength

LIGO

Cross-correlated signal anatomy II.

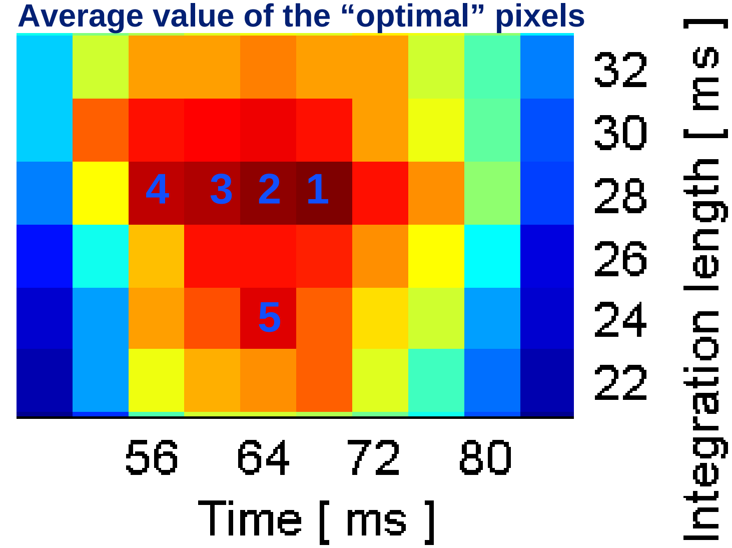


Color coding: "Number of variances above mean" [ES']



Event strength [ES] calculation:

Average value of the "optimal" pixels



Notes:

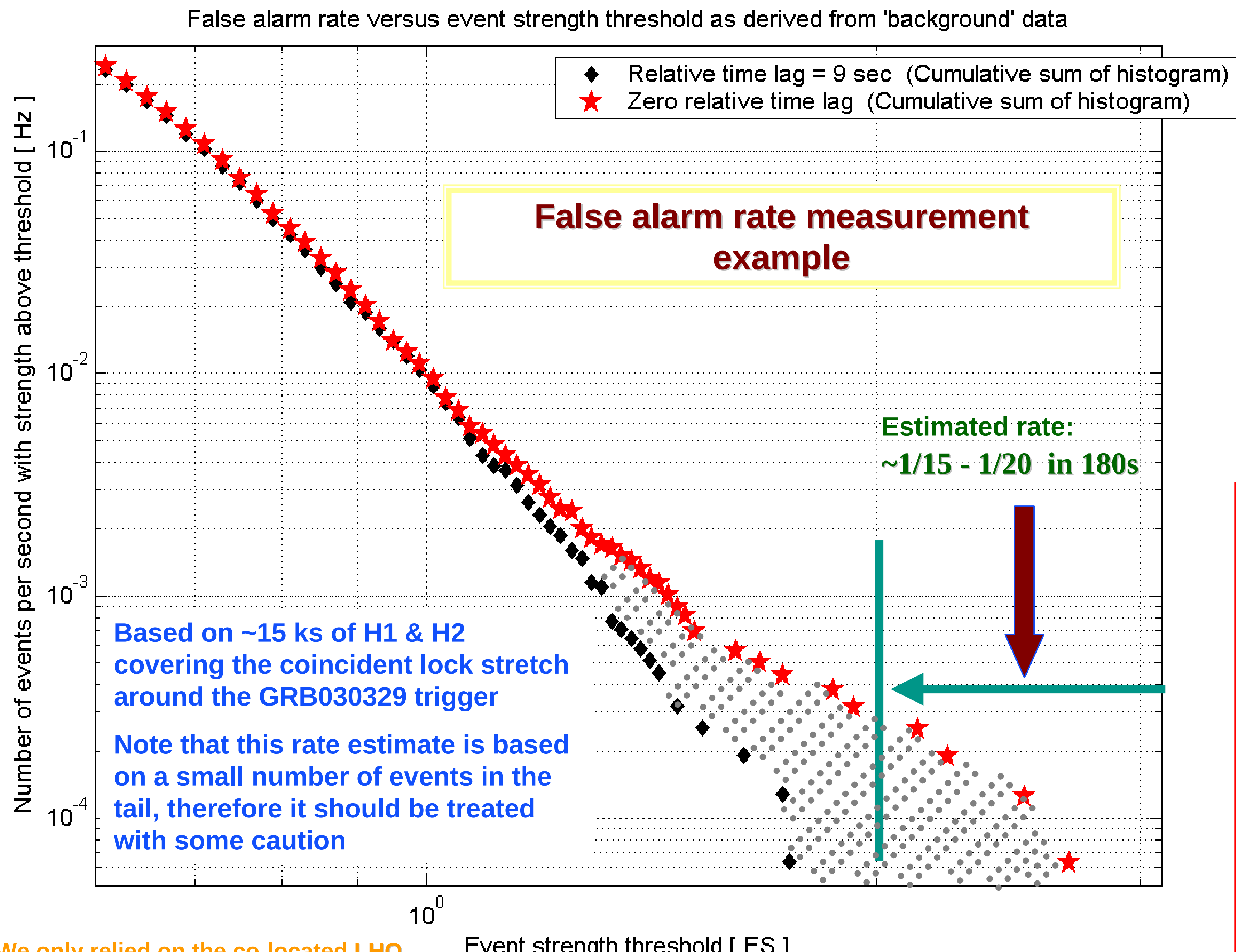
The pipeline is based on relative measurements

Raw data and raw data with injections are processed through the very same pipeline

Calibrated injections are cross verified to LDAS

The method targets only short bursts

False alarm rate measurement example



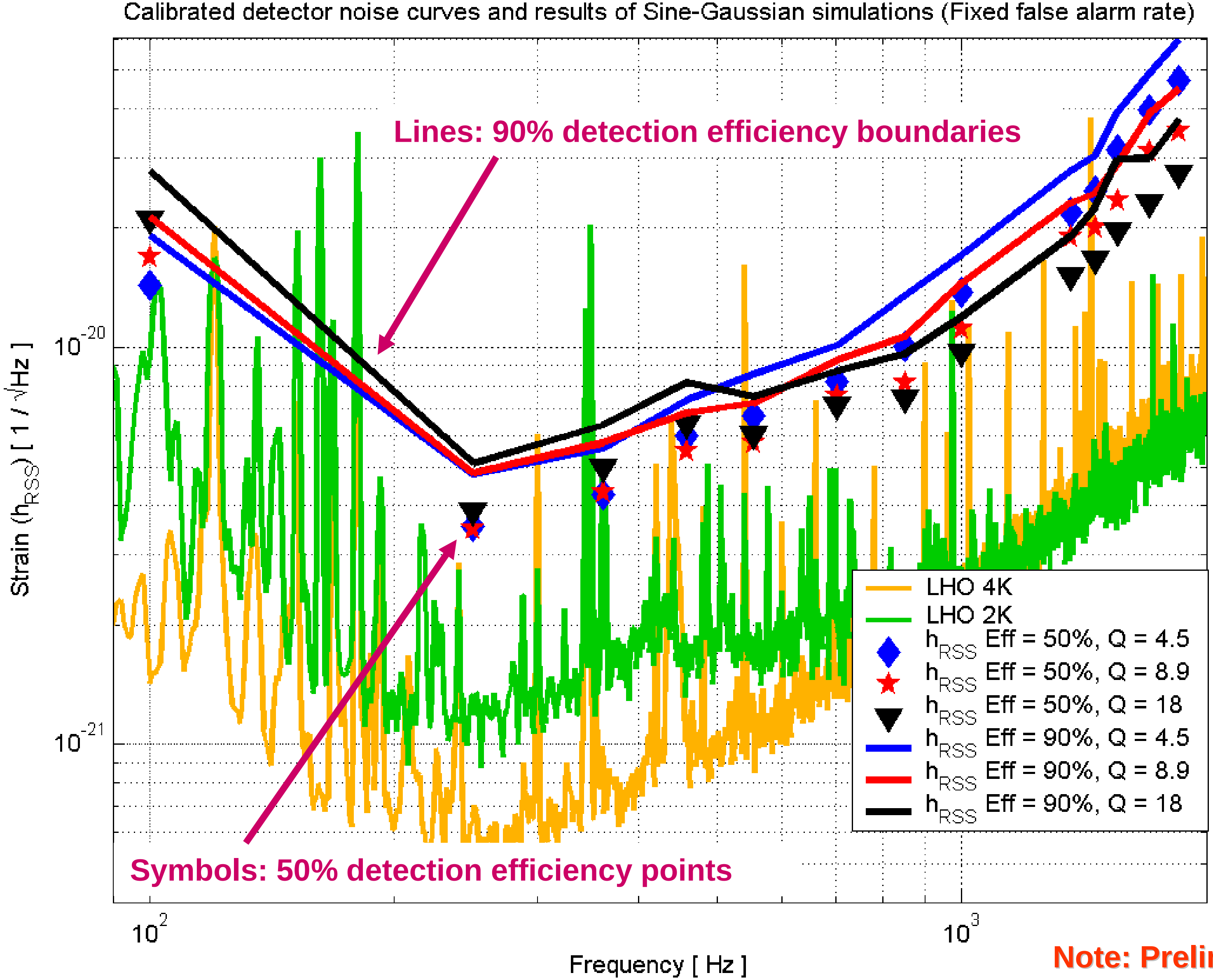
Based on ~15 ks of H1 & H2 covering the coincident lock stretch around the GRB030329 trigger

Note that this rate estimate is based on a small number of events in the tail, therefore it should be treated with some caution

Note: We only relied on the co-located <u>LHO 2K and 4K</u> interferometers for this analysis!

Note: Preliminary information !

Fixed False Alarm Rate Efficiencies and Upper Limits



-The calibration is known within ~10%

- Uncertainty due to variations in data and method is measured/estimated to be ~10% (1.5σ)

- Data reflects efficiencies obtained by choosing a threshold corresponding to ~4 x 10^{-4} Hz false alarm rate

- Averaged H1/H2 noise curves reflect calibrations at GRB030329 arrival time

- Please note that limits at high frequencies and low Qs can be overestimated (by ~30%) due to the time resolution of this preliminary search

Note: Preliminary information !

Fixed False Alarm Rate Efficiencies; Numerical simulations

Source distance [pc]

Waveform	E50%	E90%
A1B1G1	192	144
A1B2G1	392	276
A1B3G1	486	374
A1B3G2	392	318
A1B3G3	132	111
A1B3G5	21	16
A2B4G1	203	161
A3B1G1	271	225
A3B2G1	428	341
A3B2G2	349	257
A3B2G4	87	73
A3B3G1	239	184
A3B3G2	508	391
A3B3G3	341	256
A3B3G5	62	50
A3B4G2	189	146
A3B5G4	195	142
A4B1G1	283	229
A4B1G2	250	189
A4B2G2	394	325
A4B2G3	299	247
A4B4G4	678	499
A4B4G5	868	628
A4B5G4	427	346
A4B5G5	1120	907

For optimally oriented sources!

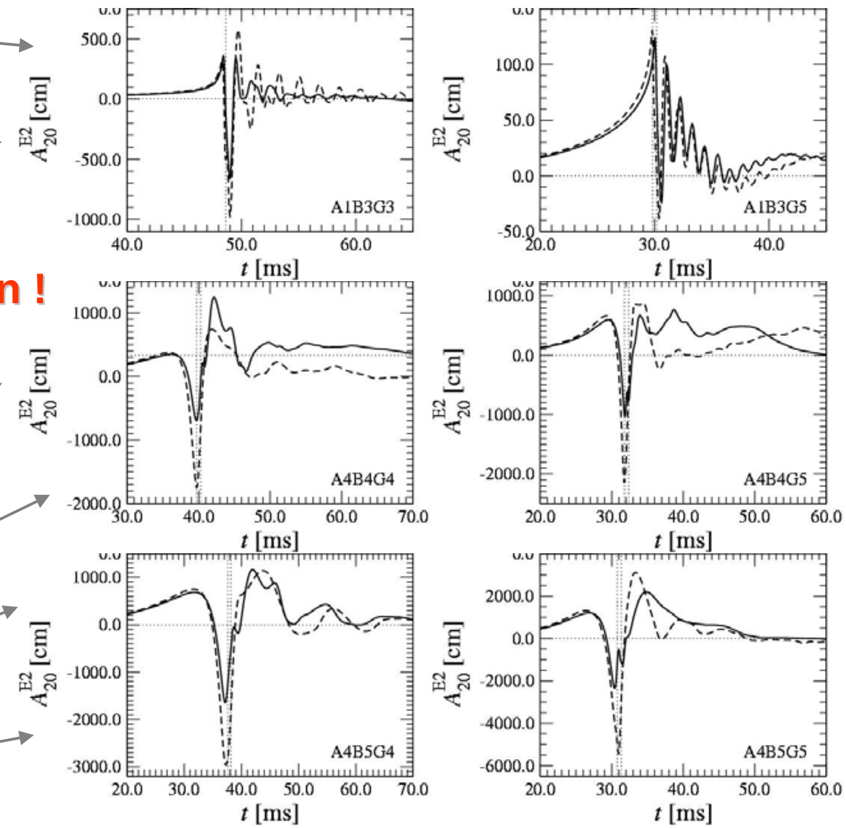
http://www.mpa-garching.mpg.de/Hydro/RGRAV/index.html

http://www.mpa-garching.mpg.de/Hydro/RGRAV/figures_jpg.html

http://www.mpa-garching.mpg.de/Hydro/RGRAV/movies.html

Note:

Preliminary information !



"Relativistic simulations of rotational core collapse. II. Collapse dynamics and gravitational radiation", Harald Dimmelmeier, Jose A. Font, Ewald Mueller, astro-ph/0204289, Astron.Astrophys. 393 (2002) 523-542

Note: These ranges are provided to illustrate our sensitivity to some of the numerically simulated supernovae waveforms. They are by no means an indication of close association between GRBs and such simulated waveforms.

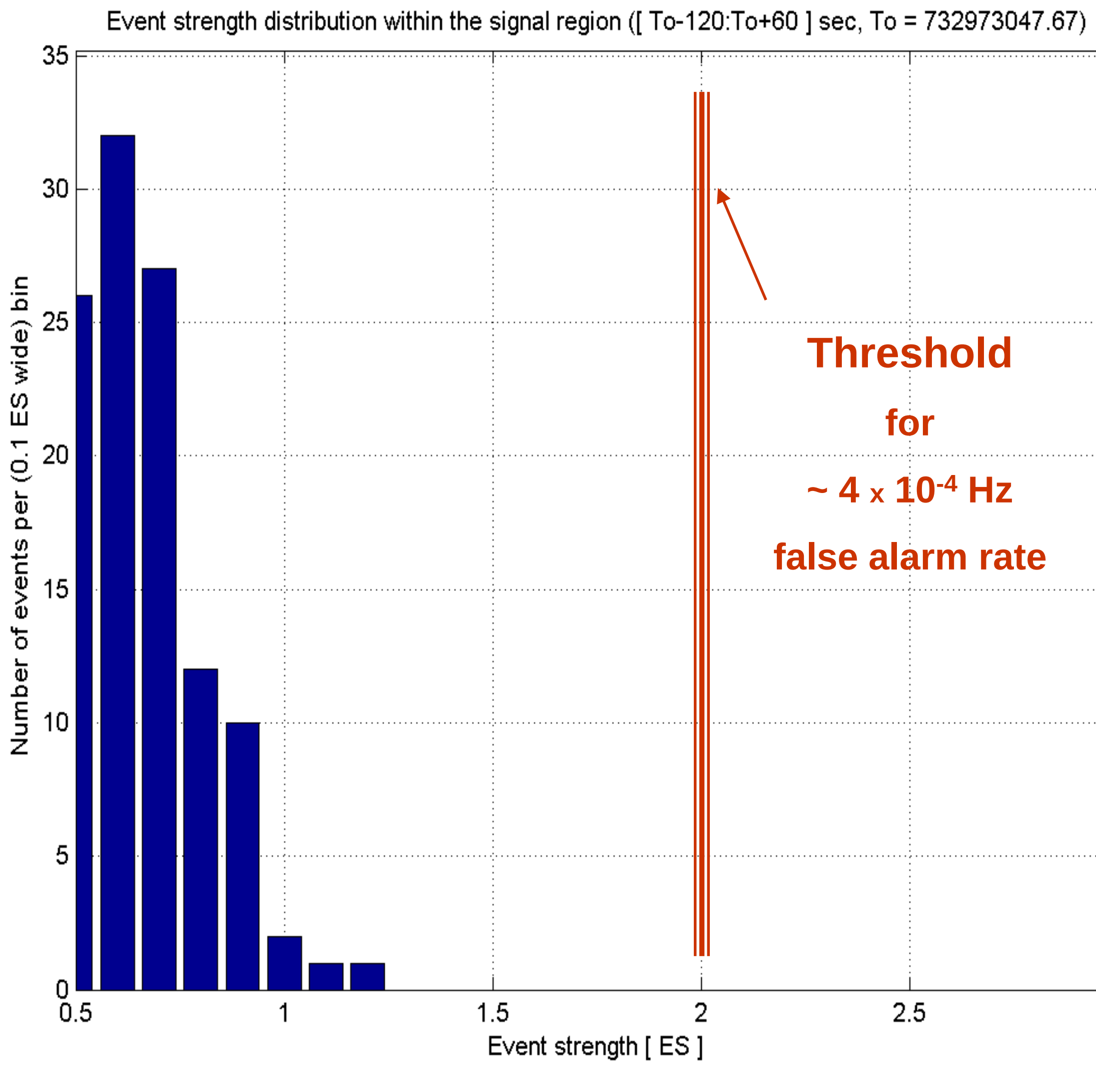
Events within the signal region around the GRB030329 trigger

-No event was detected with strength above the pre-determined threshold

- No events get even close to the threshold

- The signal region seems to be “relatively quiet” when compared to the neighboring regions

- It is an upper limit result



Note: Preliminary information !

Example: Relate observed limit on h(t) to GW Energy…

$$P_{GW} \propto \left| \frac{dh(t)}{dt} \right|^2$$

$$E_{GW} = \left(\frac{2\pi^2 c^3}{G} \right) d^2 \int_0^\infty f^2 |\tilde{h}(f)|^2 df$$

for an observation (or limit) made at a luminosity distance *d* from a source.

- **For Sine-Gaussians :**

$$E_{GW} = \left(\frac{c^3 \pi^2}{2^{3/2} G} \right) \left(\frac{f_0 d}{Q} \right)^2 h_{RSS}^2 \left(1 - e^{-2Q^2} \right)$$

Note the quadratic terms!

$$h(t + t_0) = h_0 \sin(2\pi f_0 t) \exp\left(-t^2/\tau^2\right)$$

$$Q \equiv \sqrt{2}\pi\tau f_0 \simeq 8.9$$

$$h_{rss} \equiv \sqrt{Q/(4\sqrt{\pi} f_0)}\, h_0$$

τ - ~width of Gaussian (envelope),

f_o – characteristic frequency of Sine-Gaussian

Example: Estimating E_{GW} for GRB030329

H1-H2 only

⇒ antenna attenuation factor ~0.37 (assuming optimal polarization)

$d \approx z\,(c/H_o)\,(1 + z/4)$, for Ω=1

z=0.1685 ⇒ d=800Mpc , for H_o=66 km/s/Mpc

For Sine-Gaussian with:

Q=8.9

F=250 Hz

~ 90% efficiency at $\mathbf{h_{RSS} \sim 5 \times 10^{-21}}$ $[1/\sqrt{Hz}]$

$\Rightarrow \mathbf{E_{GW}} \approx 125\ M_O\ (1\ /\ 0.37) \approx \mathbf{340\ M_O}$

Note: Preliminary information !

Summary and outlook

- We are executing a very sensitive, cross-correlation based search to identify possible gravity wave signatures around the GRB trigger times

- The present sensitivity of the search for Sine-Gaussians is ~ few x 10^{-21} h_{RSS} [1/√Hz] (when considering the low measurable false alarm rate (~4 x 10^{-4} Hz))

- The present search is broadband – an eventual narrow band version can increase sensitivity

- This result is very encouraging, as:

  - GRB030329 was not even close to the best event we can hope for

    - One year of observation will give us hundreds of GRBs with LIGO data coverage

      - We have a chance for a GRB, which will be significantly closer

      - Maybe from a more optimal direction

      - Maybe with three or four observing interferometers

  - We expect that the sensitivity of our instruments will improve with a factor of

    - 10 – 30 (Please note that $\mathbf{E_{GW} \sim h^2}$!)

- **We seem to have very realistic chance to set a <u>sub-solar mass limit</u> in the near future !**