All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run

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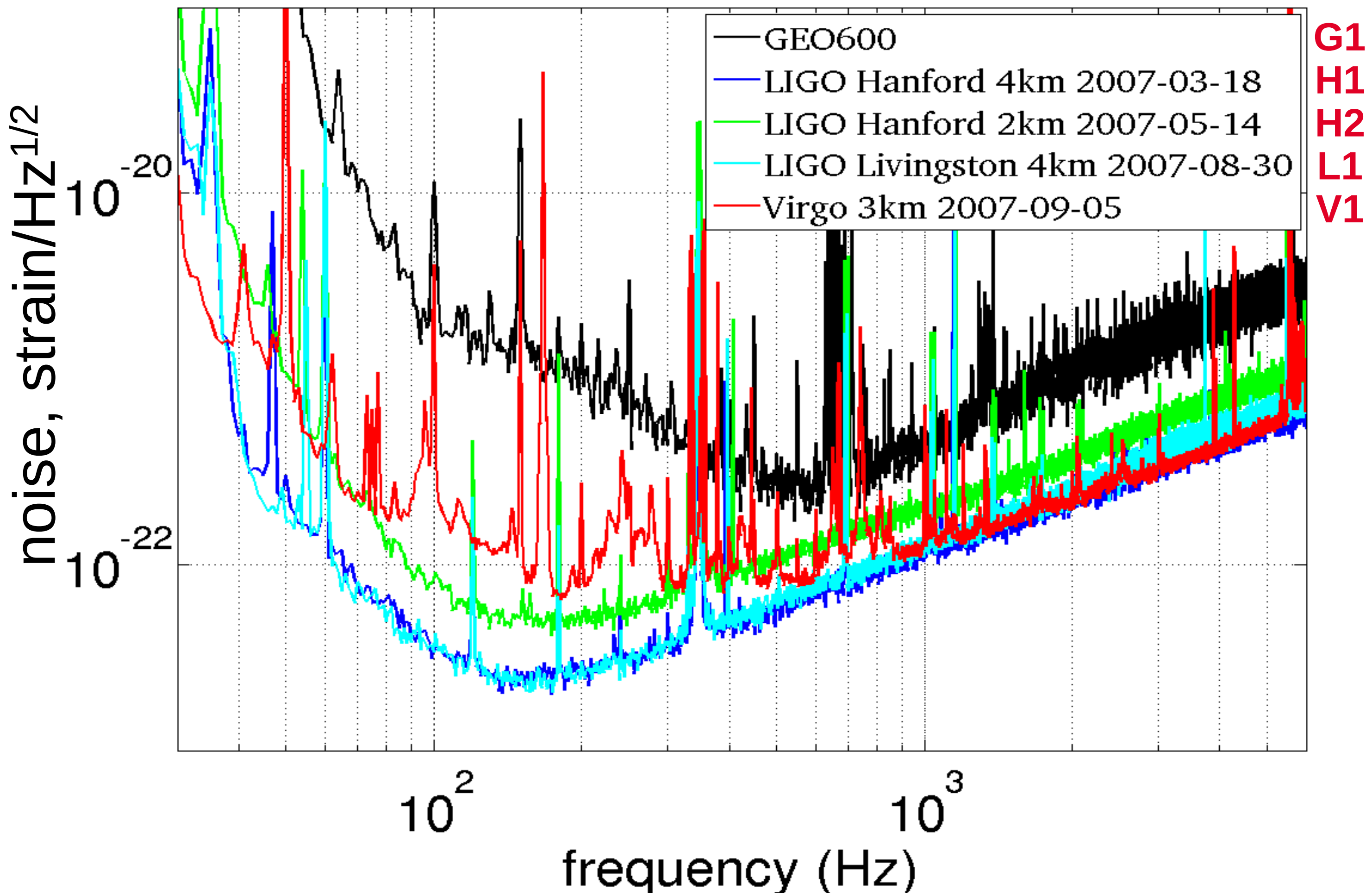
S5/VSR1 all-sky burst search

- Potential sources: supernova, binary mergers, SGRs, GRBs and any other transient sources with duration < few seconds.
- Several all-sky searches for un-modeled gravitational-wave bursts have been conducted in the data collected by the LIGO, GEO600 and Virgo detectors during S5/VSR1 run (Nov.2005-Oct.2007).
  - First S5 year (Nov.2005-Nov.2006), 64-2048 Hz:
    Phys Rev D **80** (2009) 102001
  - First S5 year (S5y1) (Nov.2005-Nov.2006), 1-6 kHz:
    Phys Rev D **80** (2009) 102002
  - S5y2/VSR1 (Nov.2006-Oct.2007), 50-6000Hz, to be published
    this talk presents the first all-sky burst search to use data from the LIGO and Virgo detectors together
- No events produced by search algorithms survived selection cuts
- The combined upper limit (for the entire S5/VSR1 run) on the rate of detectable gravitational-wave bursts is ~2.0 events per year for a 90% confidence level.

Detectors

- This is the first untriggered all-sky search with LIGO and Virgo detectors
  - Complementary antenna patterns



Search overview

- Collected data is calibrated and checked against data quality (DQ) conditions of different categories.
- Candidate events are produced with 3 different algorithms
- Vetoes from auxiliary data channels are applied
- Sensitivity of search algorithms is tested with simulated GW signals injected into the detector data.
- Background is estimated by analyzing time-shifted data streams
- Blind cuts are used for selection of events with the target FAR of 0.01-0.1 events per observation time - the same selection cuts are applied to simulated injections for estimation of the detection efficiency.
- Extensive follow up of any events above the threshold, estimation of their significance.

S5/VSR1 data

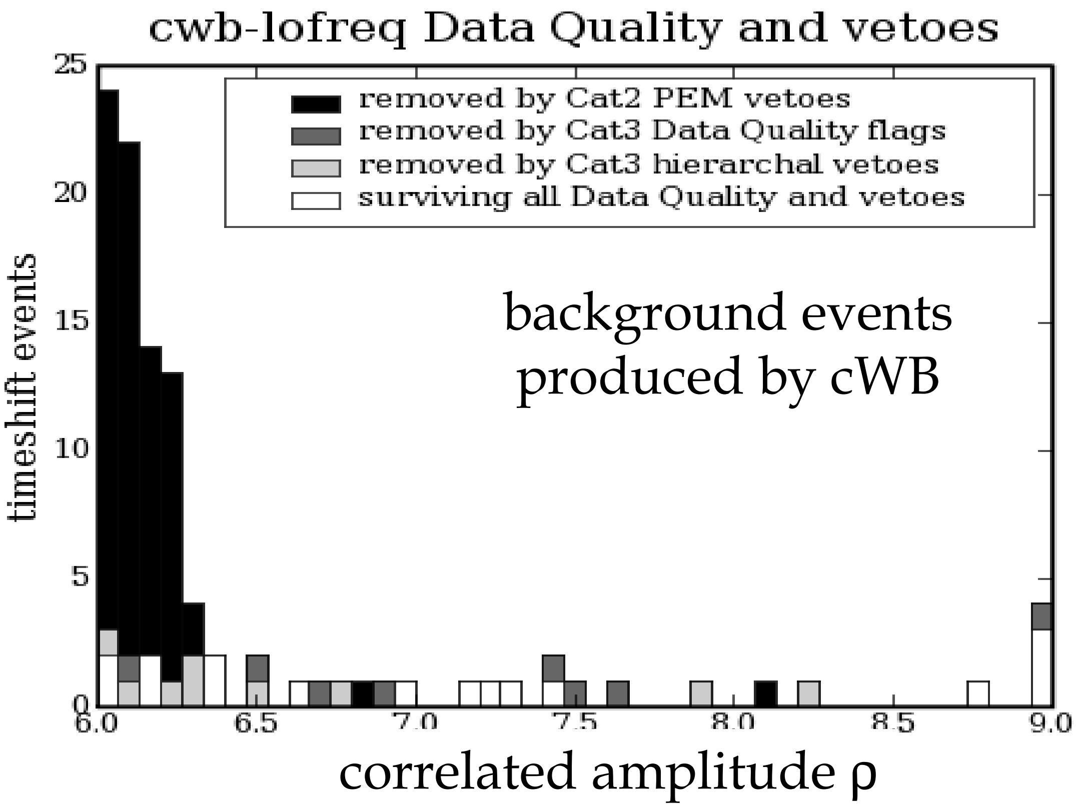
- Total analyzed time (after DQ) is 266 days
- Analysis of 8 network configurations with 3 search algorithms
- L1H1H2V1 + L1H1H2 + H1H2 used for UL results

network	live time	cWB	Ω	EGC
H1H2L1V1	68.9	68.2	68.7	66.6
H1H2L1	124.6	123.2	123.4	16.5
H1H2V1	15.8	15.7	15.1	15.3
H1L1V1	4.5	4.2	-	4.4
H1H2	35.4	35.2	34.8	-
H1L1	7.2	5.9	-	-
L1V1	6.4	-	6.3	-
H2L1	3.8	3.5	-	-

- combined analyzed time (first+second years) is 534 days

Data quality and Veto

- Low quality data segments are tagged by DQ flags divided in 3 categories. DTF – Dead Time Fraction introduced by DQ flags
  - 1 – define data segments accepted for analysis (fDTF: few %)
  - 2 – unconditional flags applied to any generated events (DTF:0.1-0.6%)
  - 3 – define a clean set used for calculation of ULs (DTF: 5-8%)
- Event-by-event vetoes from auxiliary channels processed with the KleineWelle algorithm (LIGO-G050158-00-Z (2005))

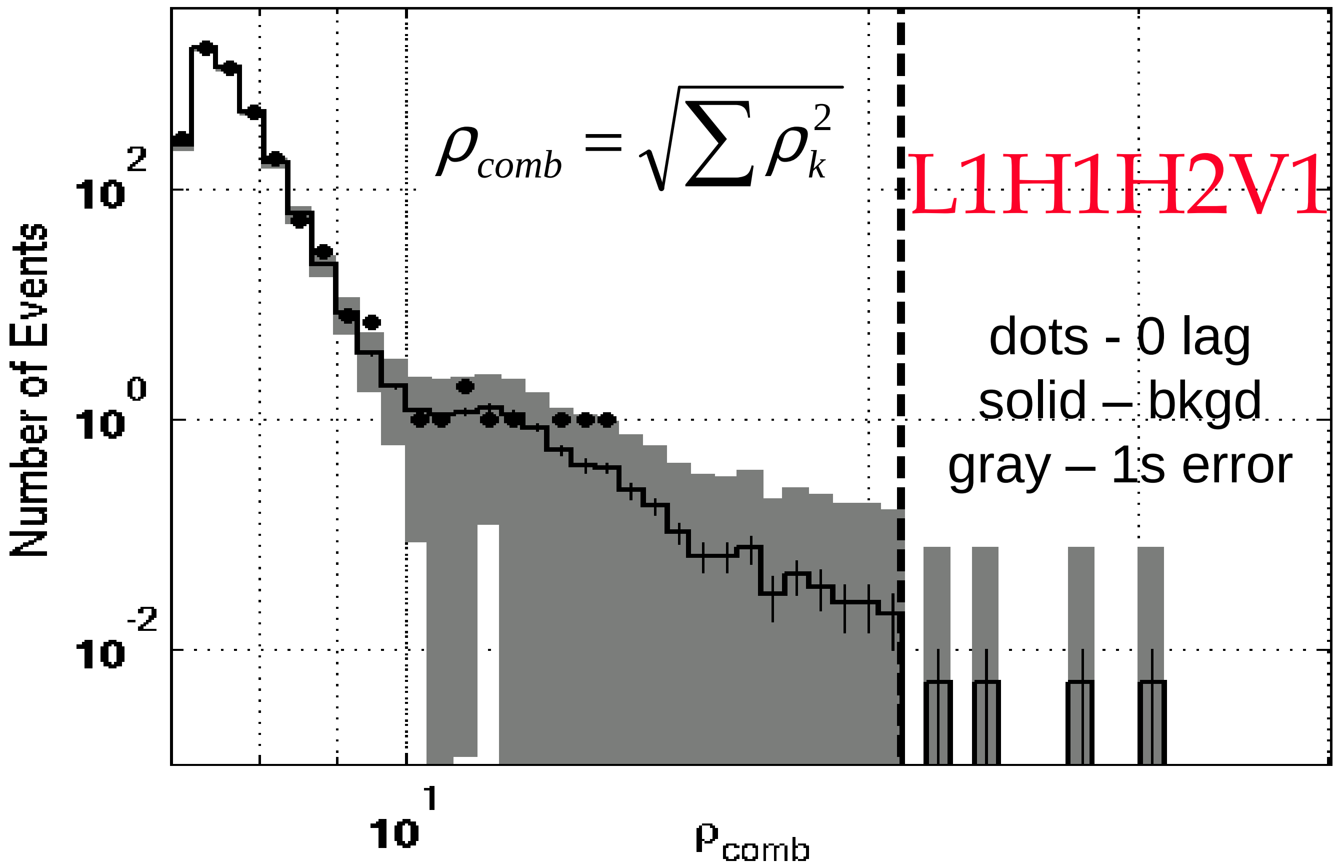


S.Klimenko, GWDAW14, January 26, 2009, Rome, LIGO-G1000033-v8

Search Algorithms: EGC

- **a matched filter using exponential Gaussian templates**
- **time-frequency coincidence: 300-5000 Hz**
- **Detection statistic: ρ_k = single detector SNR**

CQG 25, 045002 (2008)

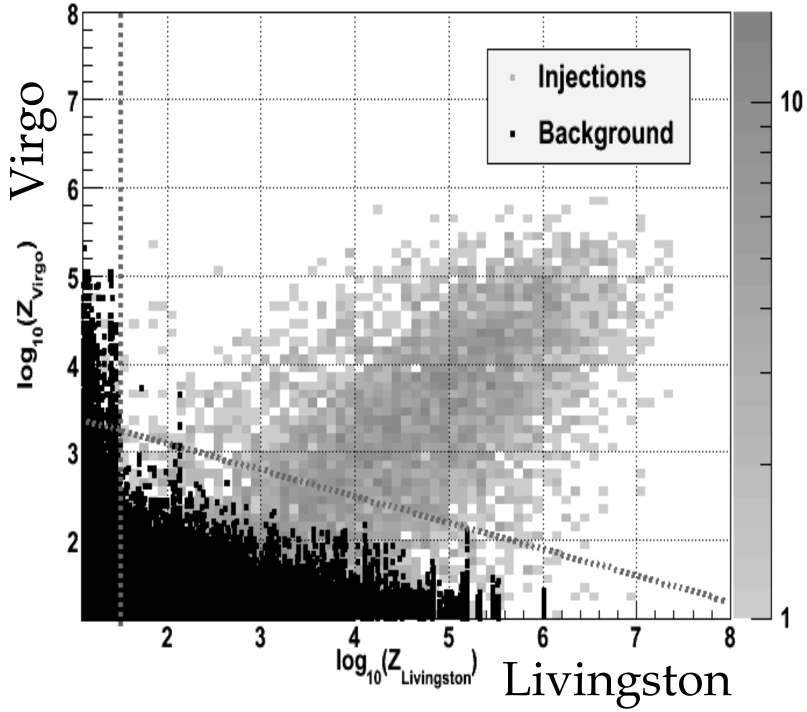


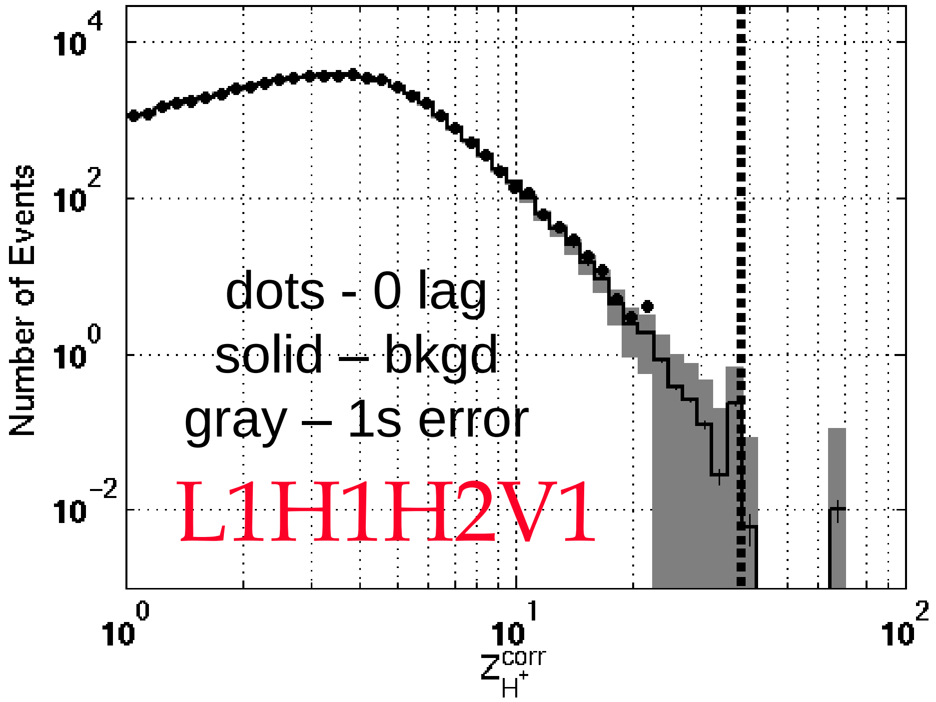
Search Algorithms: Omega

- a matched filter using sine-Gaussian templates
- time-frequency coincidence: 50-2048 Hz
- performs coherent combination of H1 and H2 detectors
- Used for UL calculation together with cWB algorithm

$$SNR = \sqrt{2Z}$$

CQG 21, S1809 (2004)

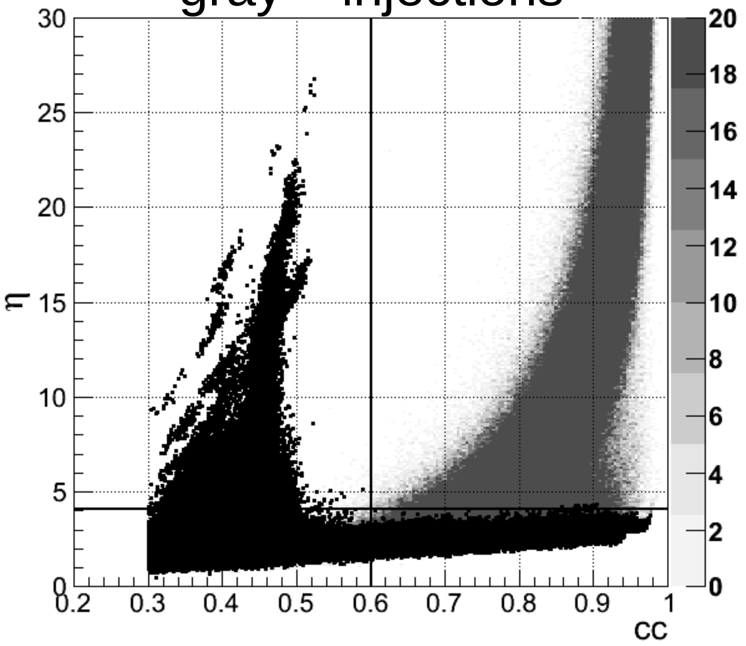




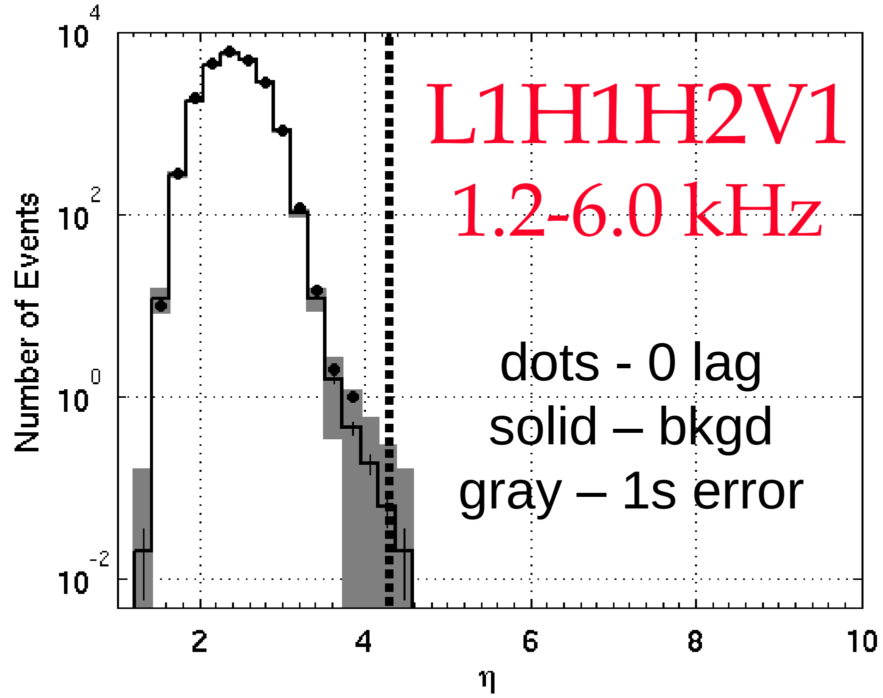
Search Algorithms: cWB

- **Coherent WaveBurst: coherent network algorithm based on constrained likelihood analysis. (64-6000Hz)**
- **Detection statistics**
  - **Network correlation coefficient cc - rejection of glitches**
  - **network correlated amplitude η – event ranking statistic**

black - background
gray – injections

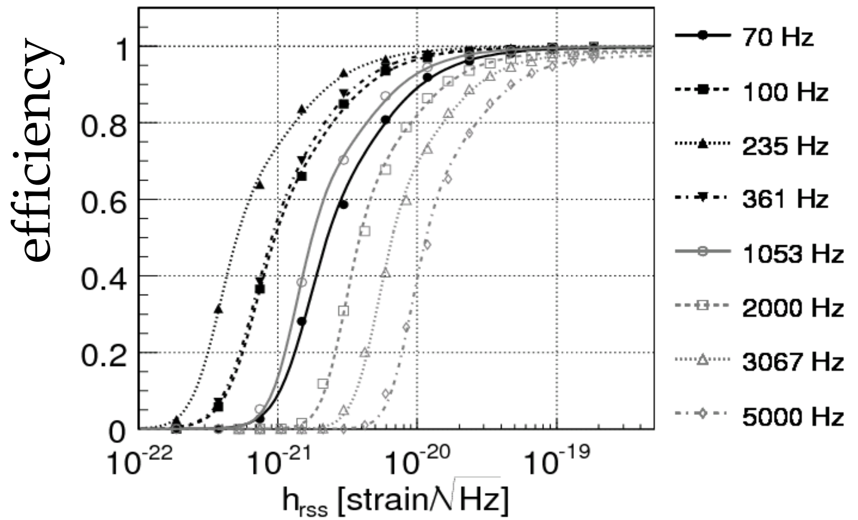


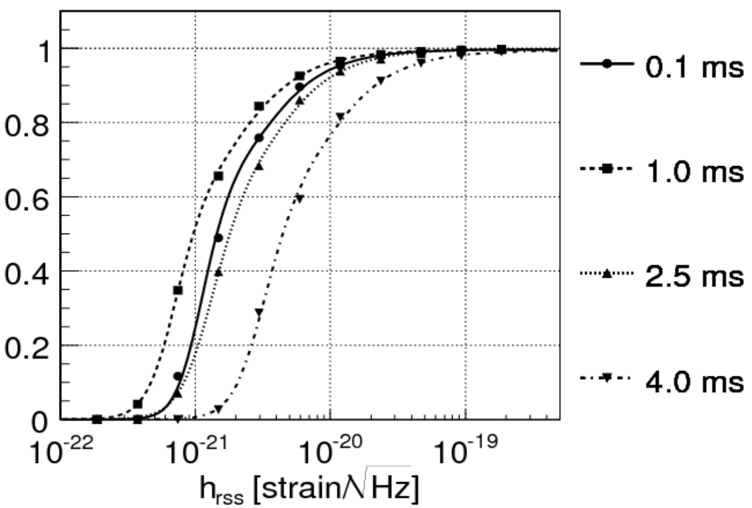
CQG 25, 114029 (2008)



Simulated signals & efficiency

- A large number of ad hoc waveforms was used for estimation of the search sensitivity
  - Sine-Gaussian waveforms (q=3,9,100) with linear polarization and frequency between 70 – 6000 Hz
  - Gaussian waveforms with linear polarization and decay time between 0.1-8.0 ms
  - Ring-down waveforms with linear and circular polarization
  - Band-limited white noise signals with random polarization

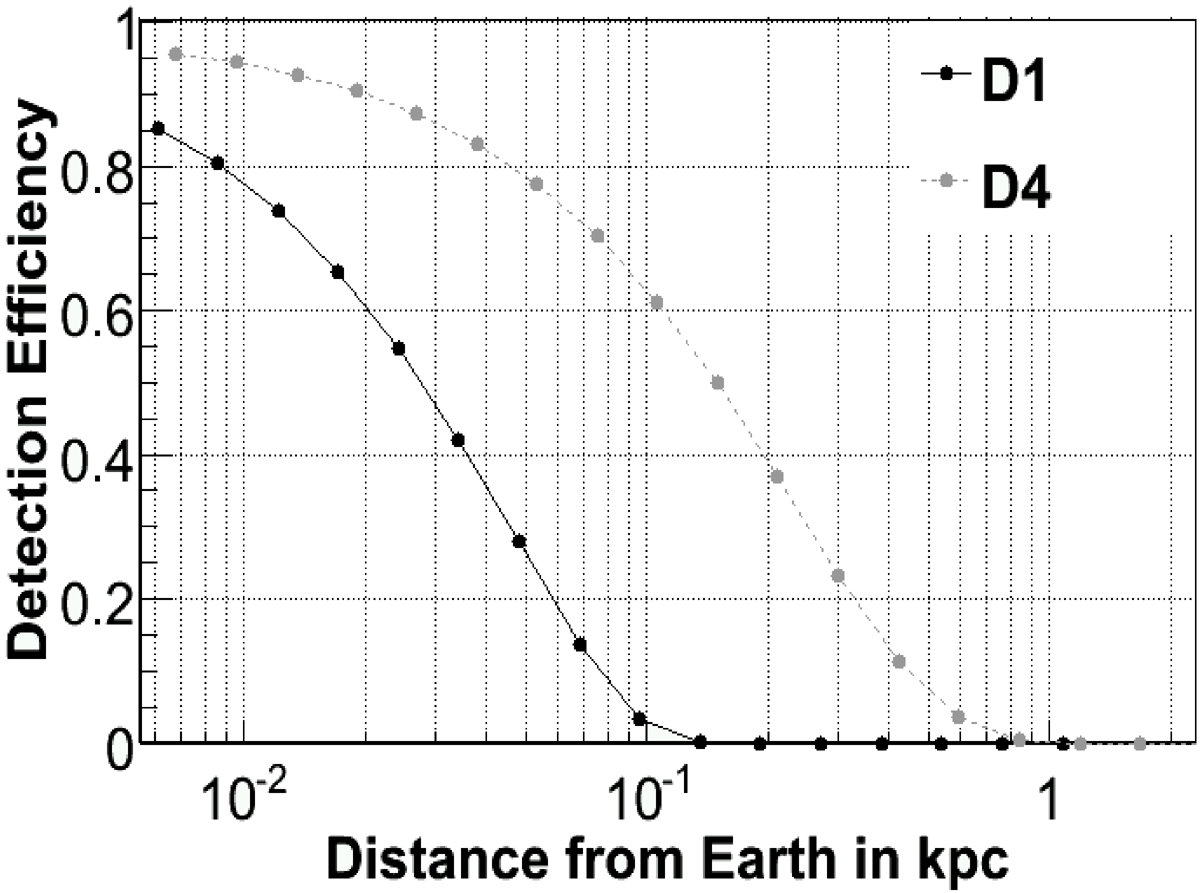


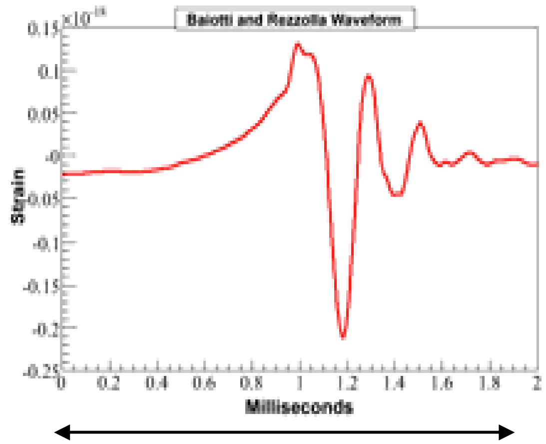


$$h_{rss} = \sqrt{\int [h_+^2(t) + h_\times^2(t)]dt}$$

Supernova simulations

- Injected two waveforms taken from simulations by Baiotti et al [28], which models gravitational wave emission from neutron star gravitational collapse and the ring-down of the subsequently formed black hole.
- The two scenarios we studied are designated D1, a nearly spherical 1.26 solar mass star, and D4, a 1.86 solar mass star





@1kpc

h_{rss}=2.5 x10^{-21} Hz$^{-1/2}$

fcentral @ few kHz

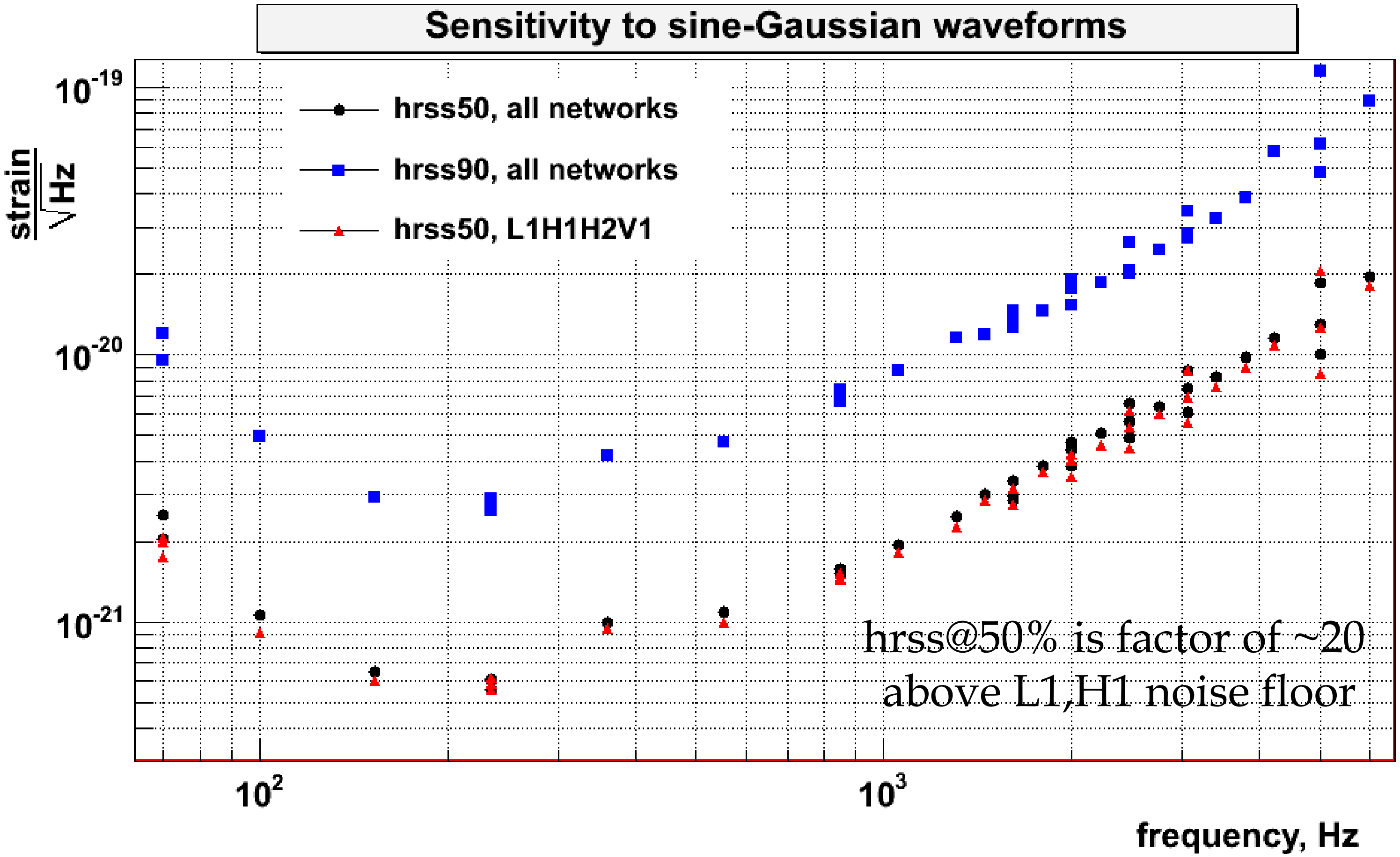
Combined Sensitivity

- **Combine CWB and Omega search algorithms**
- **Combined efficiency for L1H1H2V1 or L1H1H2 or H1H2**

$f_{\rm low}$ [Hz]	Δf [Hz]	τ [ms]	H1H2L1V1, $h_{\rm rss}^{50\%}$ cWB	Ω	cWB or Ω	all networks $h_{\rm rss}^{50\%}$	$h_{\rm rss}^{90\%}$
100	100	0.1	7.6	13.6	7.6	8.4	19.6
250	100	0.1	9.1	10.2	8.8	8.6	18.7
1000	10	0.1	20.9	28.6	21.0	21.8	52.6
1000	1000	0.01	36.8	38.2	35.0	36.3	74.7
1000	1000	0.1	60.3	81.7	60.7	63.5	140
2000	100	0.1	40.4	-	40.4	44.1	94.4
2000	1000	0.01	60.7	-	60.7	62.4	128
3500	100	0.1	74.3	-	74.3	84.8	182
3500	1000	0.01	103	-	103	109	224
5000	100	0.1	101	-	101	115	255
5000	1000	0.01	152	-	152	144	342

Sensitivity

- SG (Q=3,9,100) sensitivity vs frequency

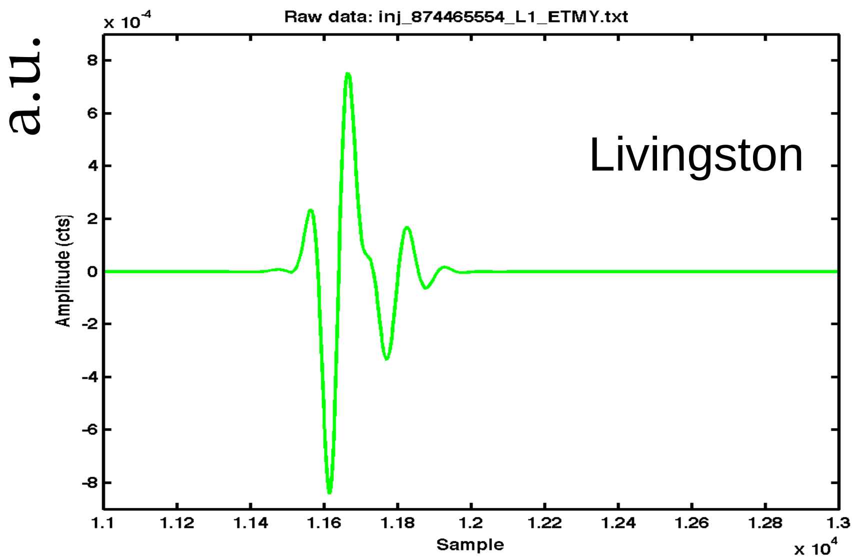


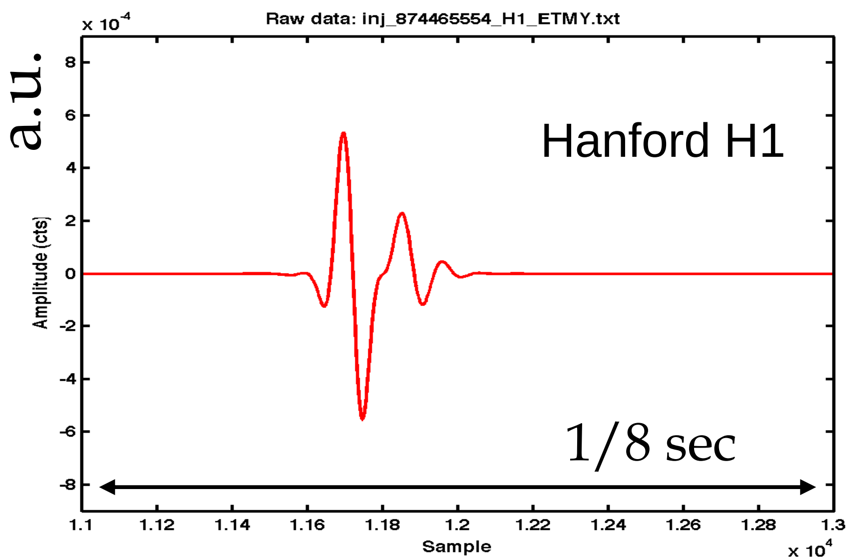
- Measured hrss increased by 3%-14% (depending in frequency) to take into account calibration uncertainties

Event Candidates

- One event passed the blind selection cuts
  - produced by cWB algorithm
  - central frequency 102 Hz (not processed by EGC)
  - reconstructed SNR: L1-12.0, H1-13.3, H2-5.3 (not visible in V1)
- *Later in the analysis this event was revealed to have been injected as a part of the "blind injection challenge" and it was removed from the analysis by the cleared injection data quality flag.*

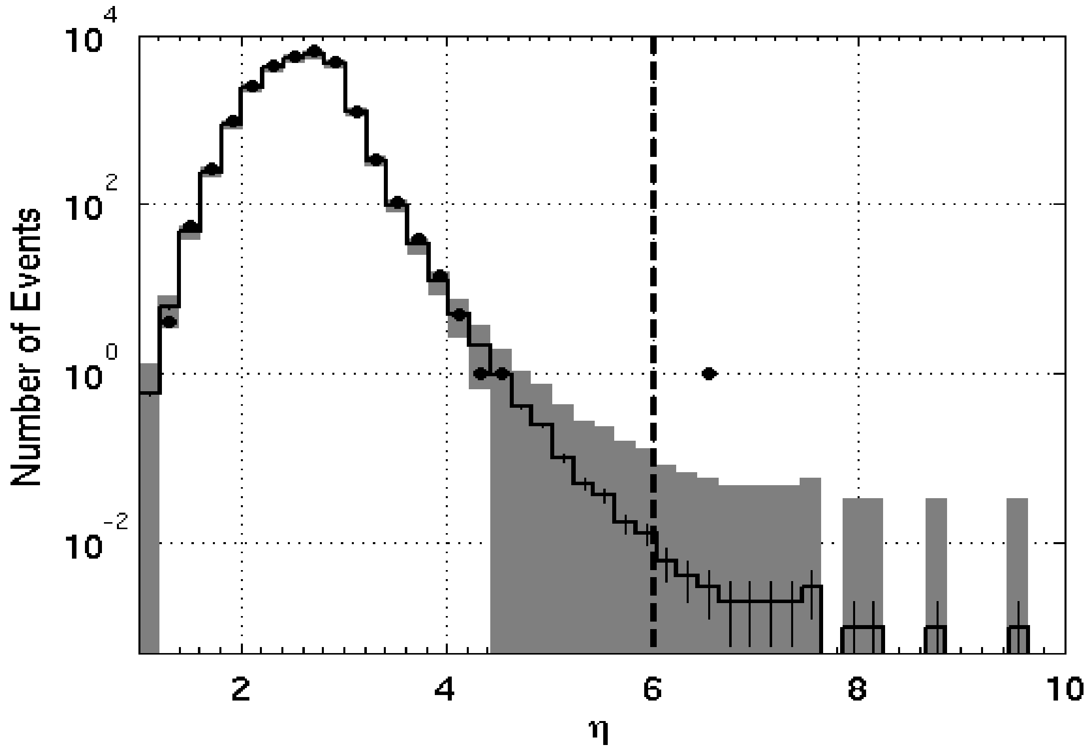
Injected signal $h_{rss} = 10^{-21} \frac{strain}{\sqrt{Hz}}$ (about the same as h_{rss}50% for SGQ9 at 100Hz)





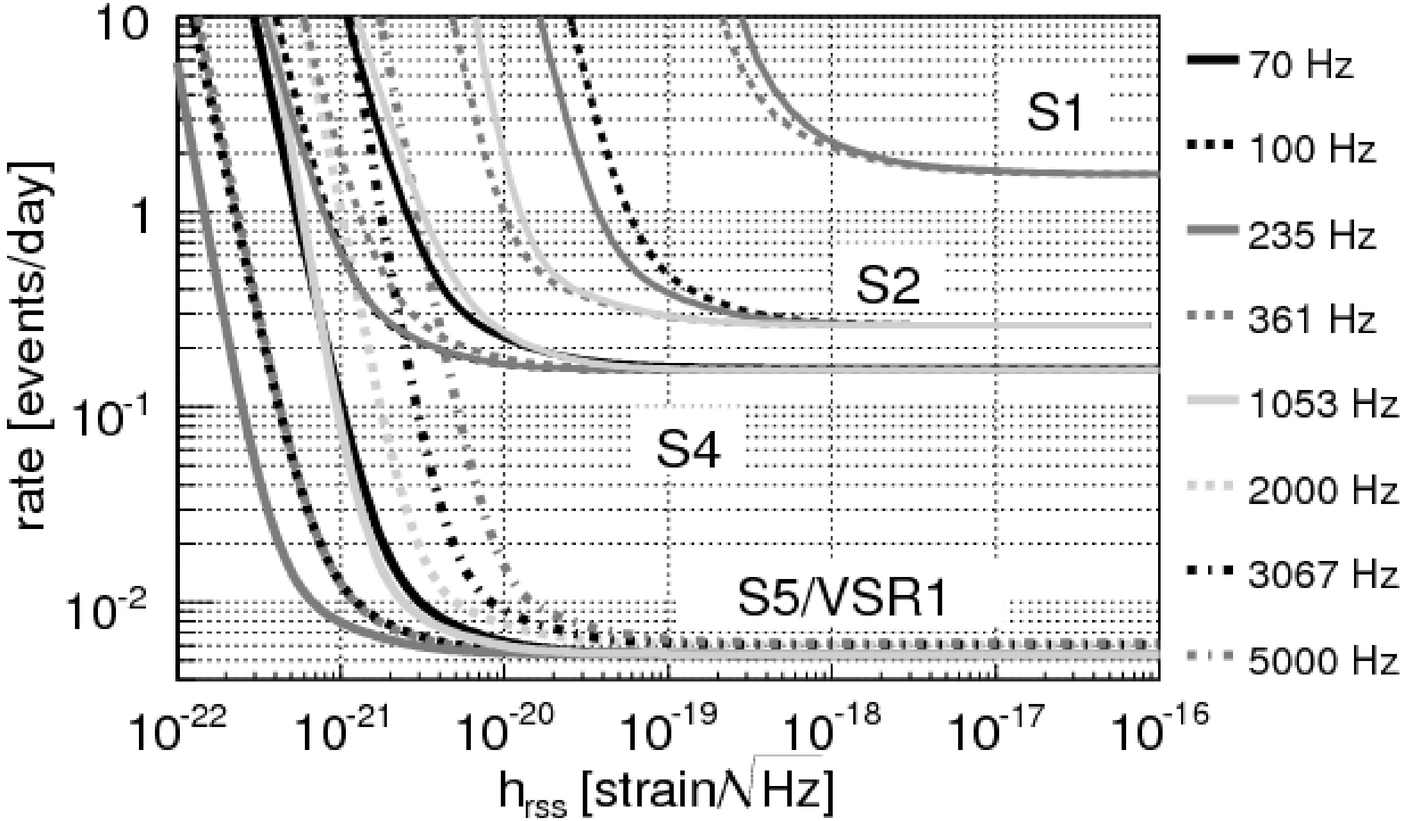
Background & Significance

- **Extensive studies with cWB - 500 years of accumulated background sample produced with time shifts**
- **Measured false alarm rate is once per 43 years for the cWB algorithm and the H1H2L1 detector network.**
- **with “trials factor” - once per 5.1 years or ~10% probability to be produced by a background**



dots - 0 lag
solid – bkgd
gray – 1s error

Search results: ULs



- **Combined upper limits for the entire S5/VSR1**
- **Extended frequency range 50-6000 Hz**
- **ULs for selected sine-Gaussins and Gaussians waveforms**

Comparison with previous measurements

- LIGO 2009: first year of S5 run (64-6000 Hz) PRD **80** 102001 (2009) PRD **80** 102002 (2009)

  3.6 events/year below 2kHz and 5.4 events/year above 2kHz at 90% and best sensitivity of 6×10^{-22} $Hz^{-1/2}$

- IGEC 2007: (~50 Hz around 900 Hz) PRD 76, 102001 (2007)

  8.4 events/year at 95% CL and sensitivity of $\sim10^{-20}$ $Hz^{-1/2}$

- LIGO 2007: S4 run (64-1600Hz) CQG **24** (2007)

  55 events/year at 90% and best sensitivity of 1.5×10^{-21} $Hz^{-1/2}$

- IGEC 2003: (few Hz around 900 Hz) PRD 68, 022001 (2003)

  1.5 events/year at 95% CL, and sensitivity of $\sim10^{-19}$ $Hz^{-1/2}$

- LIGO-Virgo 2010: (50-6000kHz) entire S5/VSR1 run

  2 events/year below 2kHz and 2.2 events/year above 2kHz at 90% and best sensitivity of 5.6×10^{-22} $Hz^{-1/2}$

  the most sensitive un-triggered burst search performed so far

Astrophysical sensitivity

- To estimate the astrophysical sensitivity we calculate the amount of mass (M_{GW}), converted into isotropic GW burst energy at a given distance r, that would be sufficient to be detected by the search with 50% efficiency.

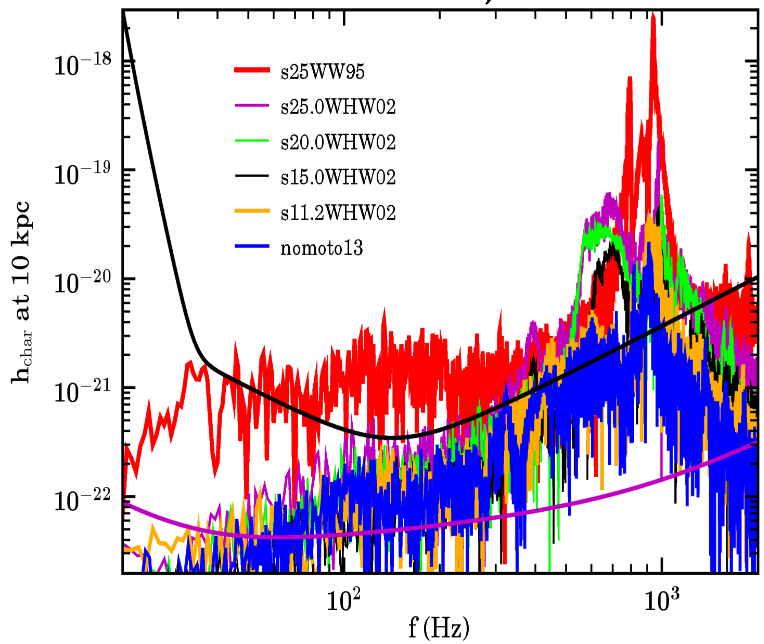
$$M_{GW} = \frac{\pi^2 c}{G} r^2 f^2 h_{rss}^2$$

- For 153 Hz, Q = 9 sine-Gaussians, $h_{rss} = 6\times10^{-22}\ \mathrm{Hz}^{-1/2}$.
- Assuming isotropic emission at a distance of 10 kpc, this corresponds to $M_{GW} = 1.8 \times 10^{-8}$ M (10^{-7} M for S4) where M is the solar mass.
- For a source in the Virgo galaxy cluster, approximately 16Mpc away, the same hrss50% would be produced by a mass conversion of roughly 0.046M (0.25 in S4).

Supernova

- **GW signals from a core collapse supernova are expected to be produced at a much higher frequency (up to a few kHz) and also with a relatively small GW energy output (10^{-9}–10^{-5} Mc^2).**
- **The axi-symmetric core collapse signals D1 and D4 have most of the signal energy in the 2−6 kHz frequency band and $M_{GW} < 10^{-8}$ M - consistent with the estimated detection range**
- **For the acoustic supernova model s25WW as much as 8×10^{-5} M may be converted to gravitational waves with frequency around 940 Hz → detection range 35 kpc.**

Ott et al, 2006



results: rate density ULs

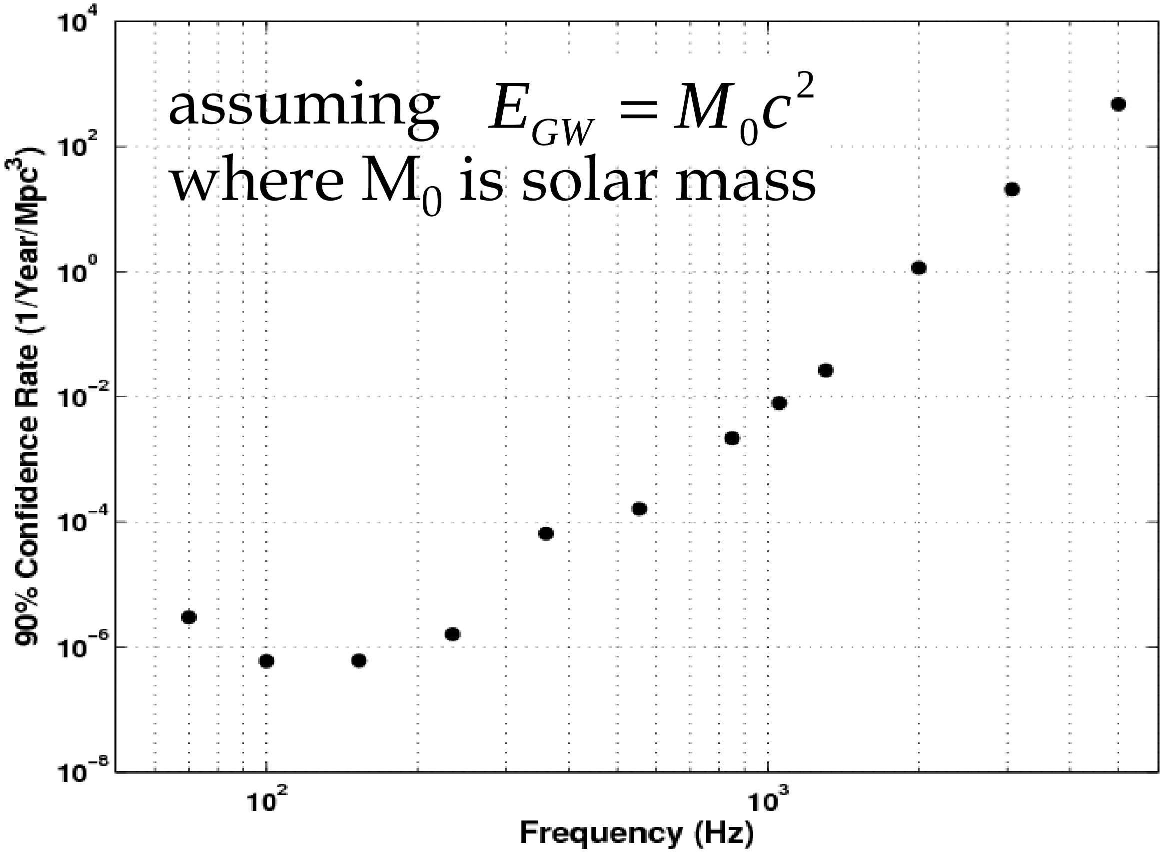
- **Given an isotropic distribution of sources with amplitude ho at a distance ro the rate density limit is**

$$R_{90} = \frac{2.3}{4\pi T (h_o r_o)^3 \int_0^\infty \varepsilon(h) h^{-4} dh}$$

- **The result can be interpreted as a rate density limit for a source with isotropic GW emission of** $E_{GW} = M_0 c^2$

$$h_0 r_0 = (\pi \cdot f)^{-1} \sqrt{\frac{GM_0}{c}}$$

results: rate density ULs



- **Rate density limit is rescaled as** $R_{90}(f,M) = R_{90}(f,M_0)\left(\frac{M_0}{M}\right)^{3/2}$

For a source emitting $E_{GW} = 0.01 M_0 c^2$ **at 150 Hz**

$$R_{90} = 6 \cdot 10^{-4}\,\mathrm{yr}^{-1}\mathrm{Mpc}^{-3}$$

Summary

- Results of the all-sky search for gravitational wave burst signals are presented for the first joint LIGO (S5) and Virgo VSR1 runs in 2006-2007.
- The analysis has been performed with three different search algorithms in a wide frequency band between 50-6000 Hz.
- No plausible GW candidates have been identified.
- As a result, a limit on the rate of burst GW signals (combined with the LIGO results from the first S5 year) has been established:

less than 2 events per year at 90% confidence level.

with sensitivity in the range 6-20 × 10^{-22} $Hz^{-1/2}$

- This rate limit is increased by more than an order of magnitude compared to the previous LIGO runs.