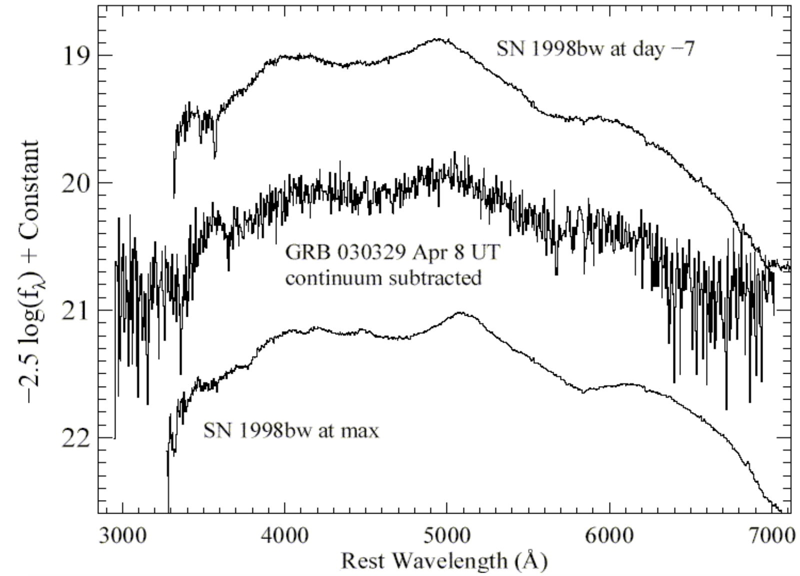
Search for gravitational-wave bursts associated with gamma-ray bursts using the LIGO detectors

Soumya D. Mohanty
On behalf of the LIGO Scientific Collaboration
University of Texas at Brownsville

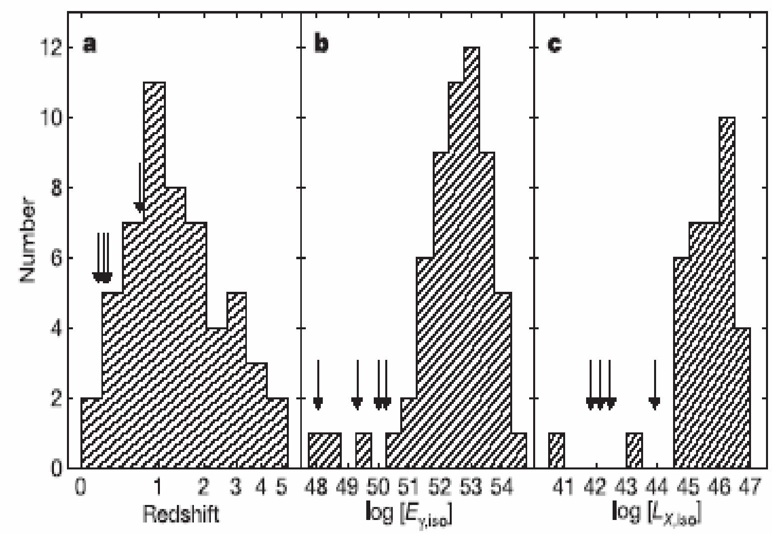
LIGO G060652-00-Z

Gamma Ray Bursts

- Transient Gamma Ray/high energy X-ray events
- Long-soft bursts (LSB): Stellar core collapse to Black Holes
  - or core collapse to magnetars for anomalously long and soft bursts, e.g., 060218, 1998bw (980425)
- Short hard bursts (SHB): NS-NS, NS-BH, BH-WD mergers following GW driven inspiral
- Central engine: Black Hole with an accretion disc $\rightarrow$ relativistic jets $\rightarrow$ shocks $\rightarrow$ γ-rays



- Both classes are exciting GW sources! But …
- Distance scales:
  - LSB should follow massive Star Formation Rate $\Rightarrow$ pdf of observed redshifts peaks at z > 1 (zpeak ~ 2 likely)
  - SHB pdf should peak at lower redshifts (zpeak~ 0.5) but still far away
  - Beaming of gamma rays implies a larger rate of unobserved nearby events – may show up at lower energies that are not yet monitored
- We may get lucky ! (1998bw occurred at 35 Mpc)



Outline of the analysis

- Search for short-duration gravitational-wave bursts (GWBs) coincident with GRBs using S2, S3 and S4 data from LIGO
  - Models exist that predict long duration (~ 10 sec) signals (Van Putten et al) but not targeted in this analysis

- Two search modes: (a) GWB associated with each GRB (b) collective GW signature of a set of GRBs

- Constraints → (a) Upper limits on h_{rss} and (b) constraint on population parameters

- The search makes no prior assumptions about waveforms of the GW signals except their maximum duration and bandwidth
  - Analysis based on pairwise crosscorrelation of two interferometers
  - Target GWB durations: ~1 ms to ~100 ms
  - Target bandwidth: 40 Hz to 2000 Hz

The GRB sample for LIGO S2/S3/S4 runs

- **S2: 28 GRBs** with at least double coincidence LIGO data
  - 24 for LHO 4km – LHO 2km
  - 9 for LHO 4km – LLO 4km
  - 9 for LHO 2km – LLO 4km
- **S3: 7 GRBs** with at least double coincidence LIGO data
  - 7 for LHO 4km – LHO 2km
  - 0 for LHO 4km – LLO 4km
  - 0 for LHO 2km – LLO 4km

IPN, HETE-2, INTEGRAL, Konus-Wind (pre-Swift)

- **S4: 4 GRBs** with at least double coincidence LIGO data
  - 4 for LHO 4km – LHO 2km
  - 3 for LHO 4km – LLO 4km
  - 3 for LHO 2km – LLO 4km

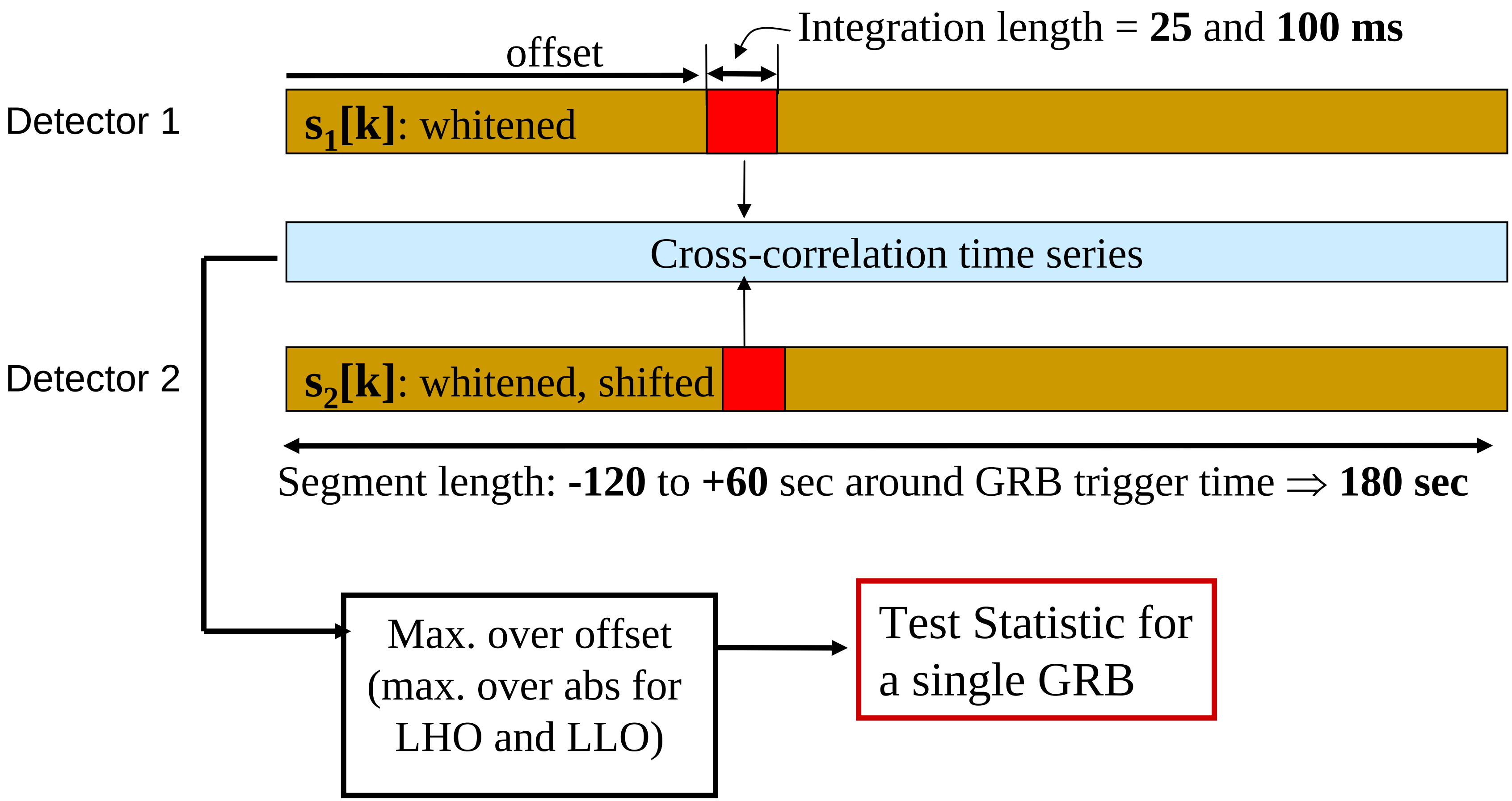
start of Swift era

59 LIGO on-source pairs analyzed

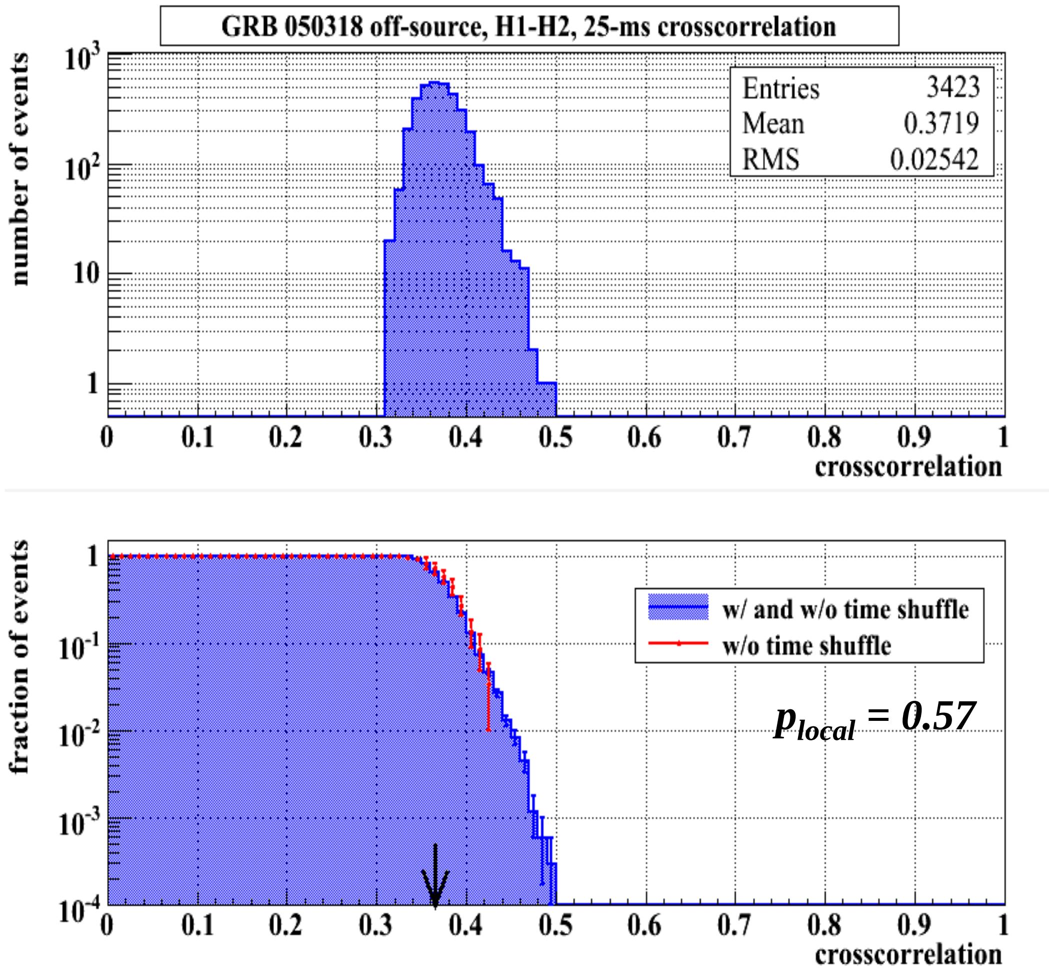
- Only well-localized GRBs considered for LHO – LLO search
- Only H1-H2 cross-correlation used for population constraints
- Standard data quality cuts such as science mode, high rate of seismic transients

Detection Statistic: single GRB search

$$cc = \frac{\sum_{i=1}^{n}[s_1(i)-\mu_1][s_2(i)-\mu_2]}{\sqrt{\sum_{j=1}^{n}[s_1(j)-\mu_1]^2}\sqrt{\sum_{k=1}^{n}[s_2(k)-\mu_2]^2}} \quad ; \quad \mu_i = \sum_{k=1}^{n} s_i[k]$$



Significance of test statistic using off-source data



❖Apply search to off-source segments to obtain distribution of test statistic

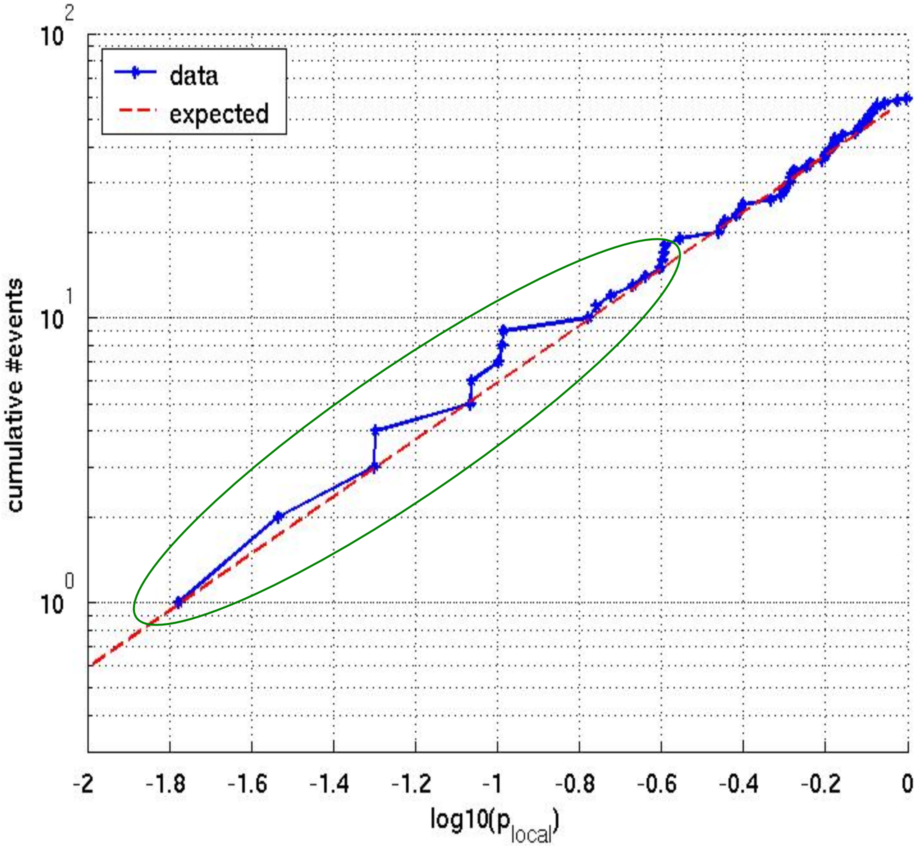
❖Use time shifts to get large sample size for the distribution estimation

❖Test statistic value found in on-source search indicated by black arrow

❖Significance: Fraction of off-source values greater than the on-source value

❖Large significance means on-source data is consistent with no signal hypothesis

Testing the significance of the entire sample



- Some small significance values but also large number of trials (59 values)
- Expected distribution of significance under null hypothesis is uniform from 0 to 1
- Are the observed significances consistent with random drawings from a uniform pdf ?
- Which is the most anomalous value?

Binomial test

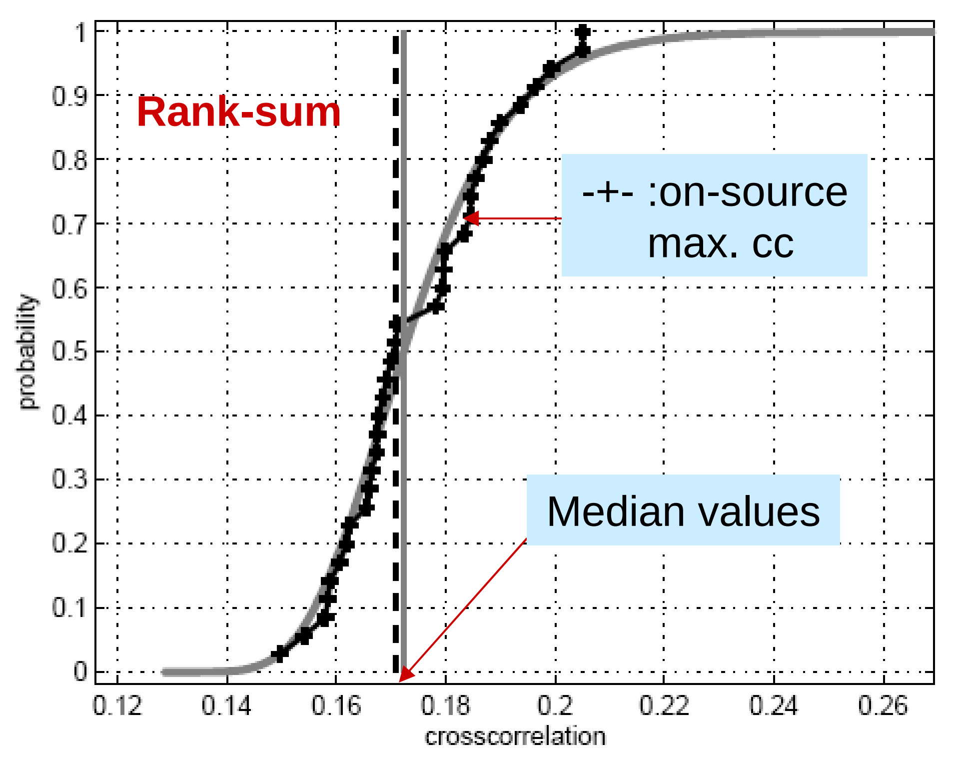
- Find the probability of obtaining N–k values that are smaller than the k^{th} smallest value
- Find the lowest such probability among the points in the tail of the sample (smallest 25% of the observed significances)

Maximum Likelihood Ratio approach

- Unknown GW signal waveform and unknown delay
  - Assume a maximum duration and bandwidth for the signals
- Stationary, Gaussian noise and two identical detectors
- At present: no prior knowledge of GRB redshift or other characteristics used (work for the future)
- We can obtain the Maximum Likelihood Ratio statistic
  - Maximum of the likelihood of the total data collected over *N* GRBs
  - Parameters of the likelihood to be maximized over are the set of
    - ***N* unknown offsets and**
    - ***N* unknown waveforms**
  - Analytic derivation of the maximum possible under the above simplifications
- Test statistic: Simply the average, over the N GRBs, of the single GRB test statistic
  - Caveat: not the correlation coefficient as used here but including non-stationarity may result in the same
- Non-parametric version: Two sample Wilcoxon rank-sum test on the on-source and off-source samples of test statistic values

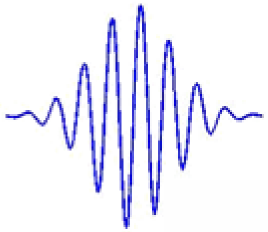
Results of search (Preliminary)

- binomial test
  - 25 ms search: binomial probability 0.153, significance 0.48
  - 100 ms search: binomial probability 0.207, significance 0.58
- rank-sum test (only H1,H2): significance 0.64

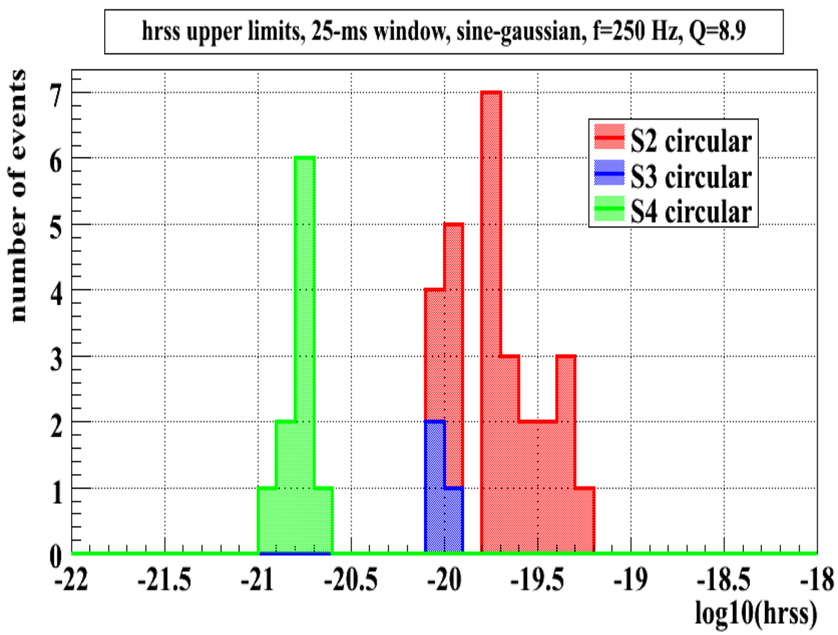


Result of tests: Null hypothesis cannot be rejected.
No GW signal seen from both statistical searches.

h_{rss} 90% upper limits for sine-gaussians (preliminary)



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



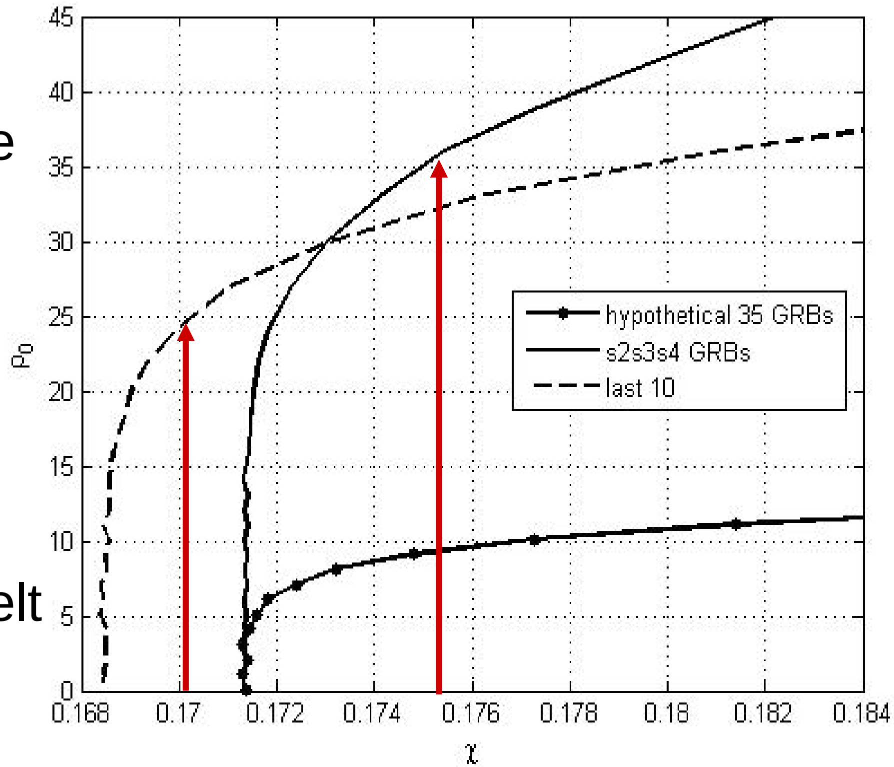
- Inject simulated sine-gaussians into data to estimate single GRB search sensitivity
- Use linear and circular polarizations
- Take into account antenna response of interferometers
- The h_{rss} upper limits can be turned into astrophysical quantities for various source models
- Example: Isotropic emission of 1 $M_\odot c^2$ in the source frame $\rightarrow$ 27 Mpc for the best h_{rss} limit in the plot

Constraining population parameters (preliminary results)

- Maximum Likelihood Ratio test statistic(χ): average of individual GRB test statistic (H1,H2 only)
- PDF depends only on the matched filtering signal to noise ratio ρ of the GW signal in the detectors
- Use an astrophysical model of observed z distribution
- Redshifts from afterglows may not be good indicators of the z distribution of S2, S3, S4 GRBs
- ρ at peak redshift = ρ_0
- Construct frequentist confidence belt in ρ_0 , χ plane

•z pdf : Bromm, Loeb, ApJ, 2002

•Standard candles in GWs



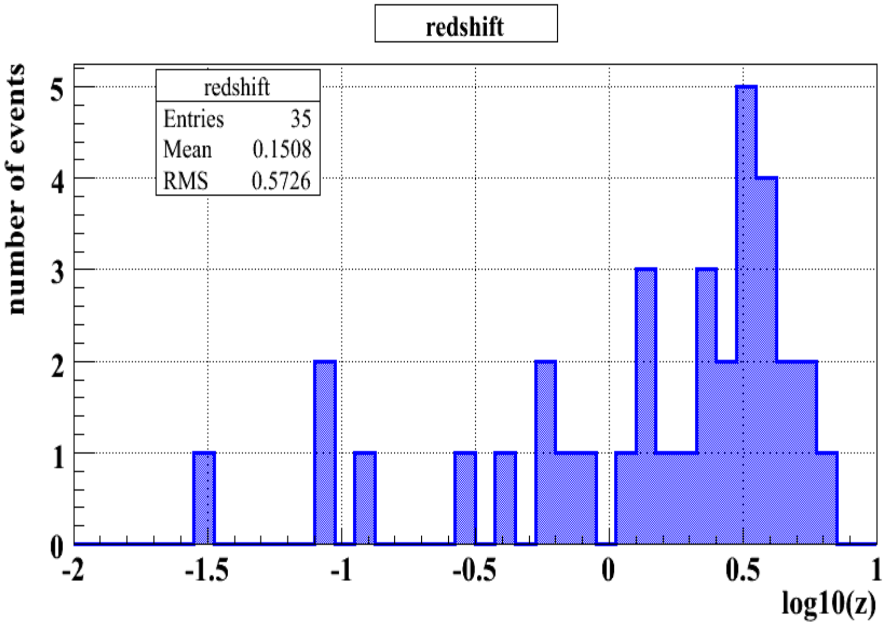
- **z_{peak} = 1.8** $\rightarrow$ $E_{gw} \leq 3\times10^4 M_\odot c^2$
- Hypothetical (same z values as current sample but H1,L1 and optimal locations) : $\approx$ 10 better

•ρ: snr w.r.t 4km Science Requirement Document sensitivity

•Isotropic emission of GWs, detected frequency 200 Hz

The GRB sample for LIGO S5 run

129 GRB triggers in LIGO S5 run
(as of Nov 27, 2006)



- **most from Swift**
- **40% triple-IFO coincidence**
- **68% double-IFO coincidence**
- **9 short-duration GRBs**
- **35 GRBs with redshift**
  - z = 6.6, farthest
  - z = 0.0331, nearest

GW burst search on this sample using the same pipeline is in progress

Summary and Prospects

- Analysis pipelines for single and statistical GRB triggered searches for short GWBs
- Results obtained with S2, S3, S4 GRBs: Hypotheses tests and upper limits (single and population)
- Prospects for S5:
  - Significant improvement in noise level over S2, S3, and S4
  - Much larger GRB sample $\Rightarrow$ possibility of making cuts on the GRB triggers
  - Subset of close GRBs; LSBs v/s SHBs; optimally located
- Further significant improvements in base sensitivity possible with the use of fully coherent burst search methods (in progress)