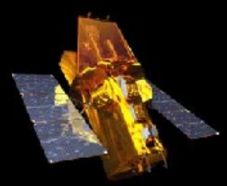
Search for Gravitational-Wave Bursts Associated with Gamma-Ray Bursts using LIGO and Virgo



Swift/HETE-2/
IPN/INTEGRAL

RXTE/RHESSI

Patrick Sutton

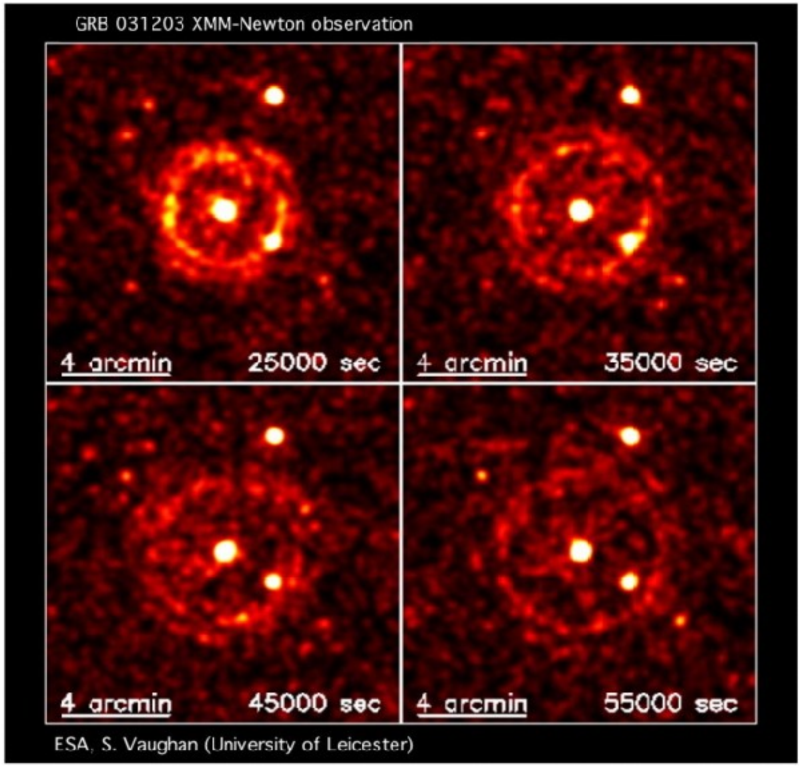
Cardiff University, for the

LIGO Scientific Collaboration

& the Virgo Collaboration

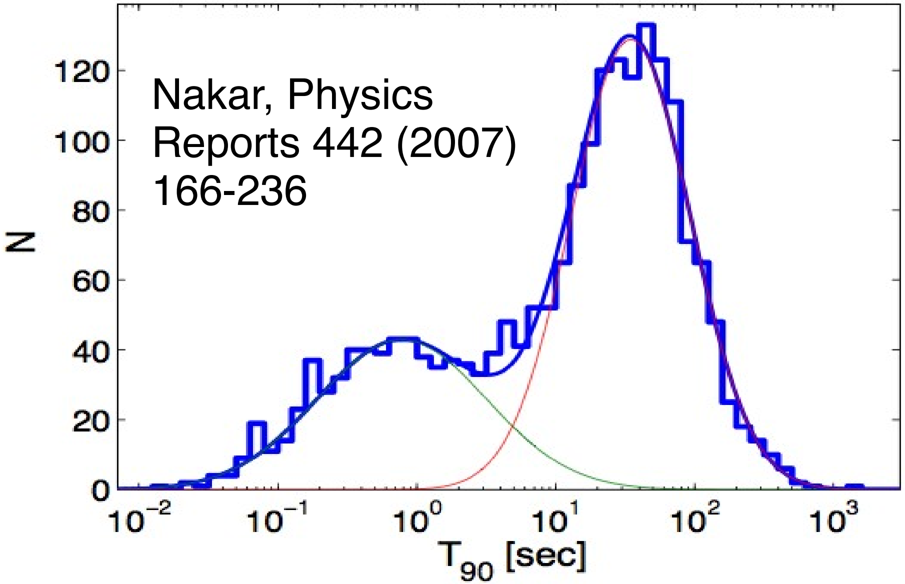
Overview

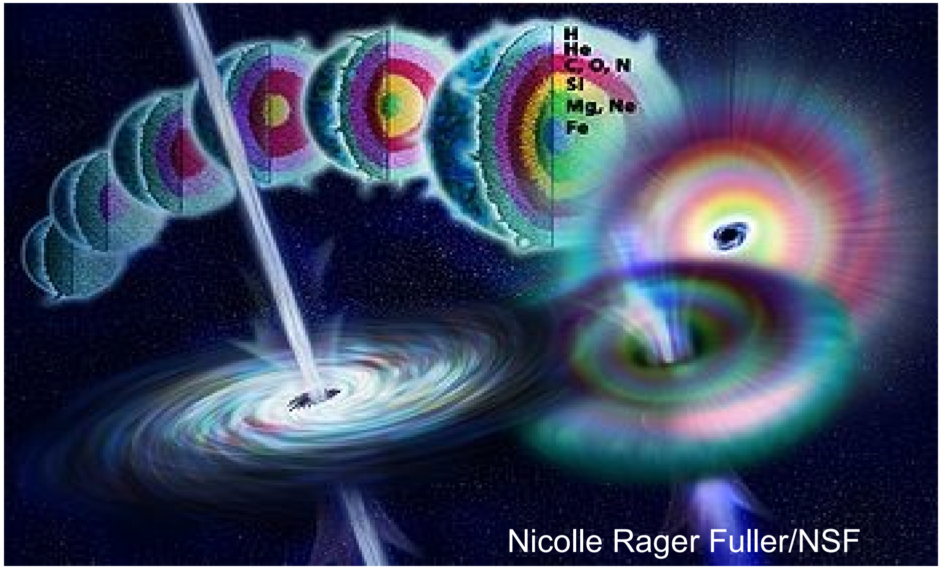
- Gamma-ray bursts and gravitational waves.
- Techniques for searching for GWs from GRBs.
- Results of most recent search (S5/VSR1, 2005-2007).
- Future plans.



Gamma-ray bursts

- Brief flashes of gamma-rays from random directions in space, followed by X-ray, UV, optical afterglow
- Most luminous EM source since the Big Bang
- Bimodal distribution of durations:





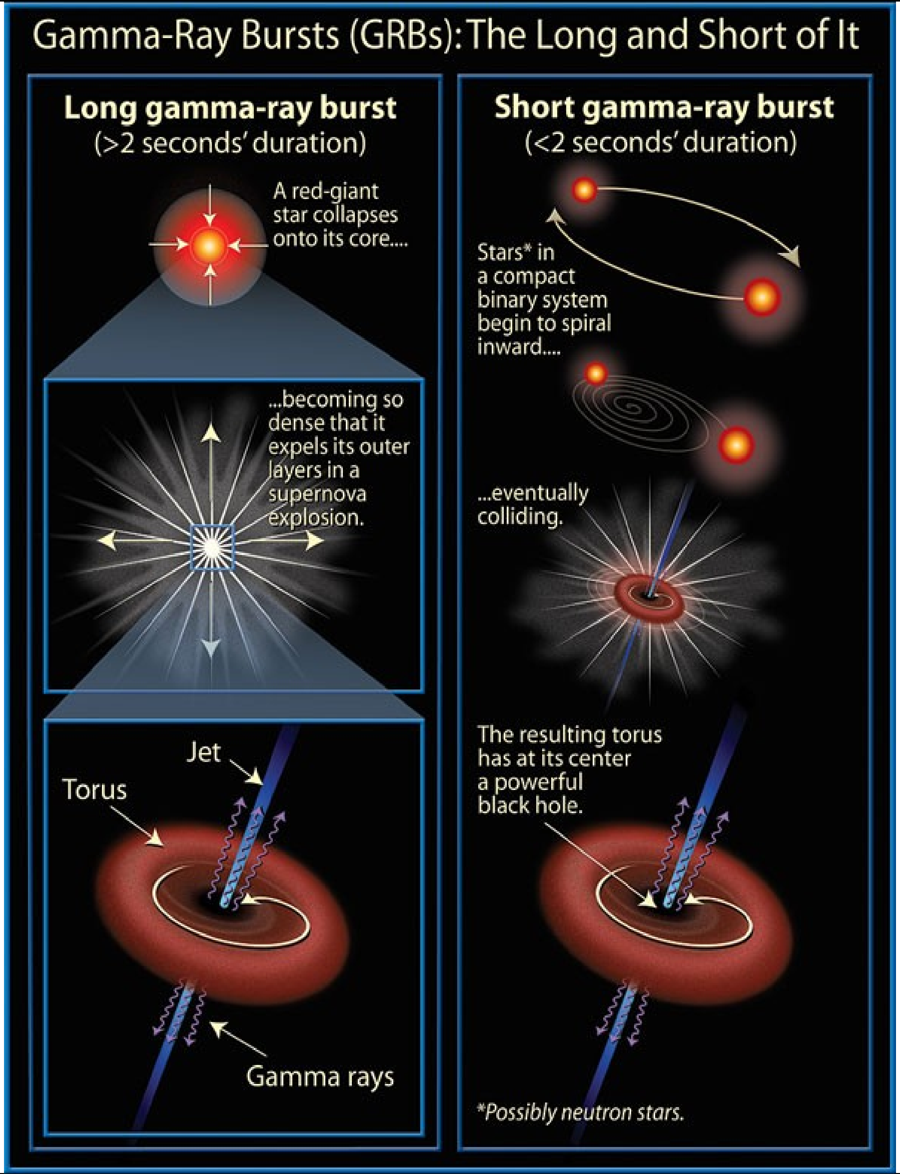
Nicolle Rager Fuller/NSF

- Short GRBs:
  - duration: $T_{90} < 2$ s.
  - Mean redshift: $z \sim 0.5$.
- Long GRBs:
  - duration: $T_{90} > 2$ s.
  - Higher z, track star formation rate.

GRBs and GWs

Long GRBs:

- Core-collapse "hypernovae"
- Modelling is complicated; GW emission not well understood.
- Use "burst" detection methods (less sensitive, more robust)

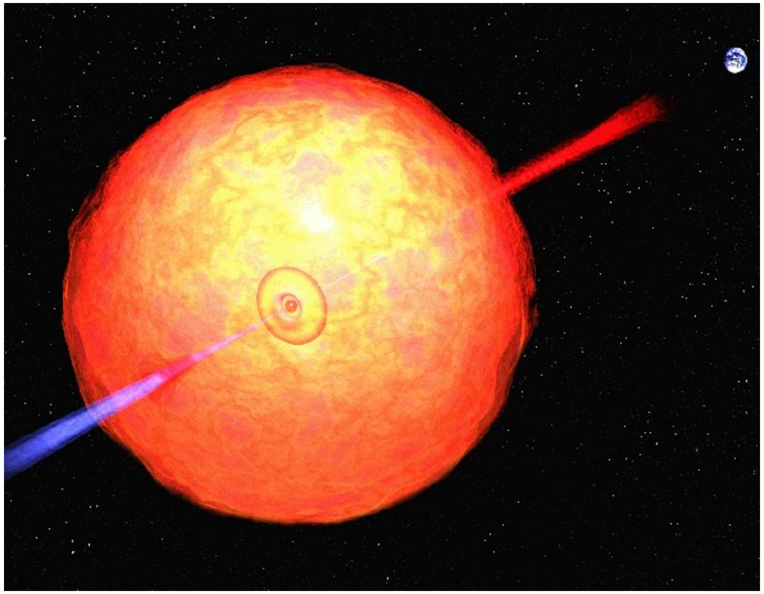


Short GRBs:

- Coalescence of NS-NS or NS-BH binaries.
- Inspiral due to GW emission, clean signal: post-Newtonian expansions, numerical relativity.
- Use "matched filtering" (more sensitive, but only for precise waveform)
  - next talk

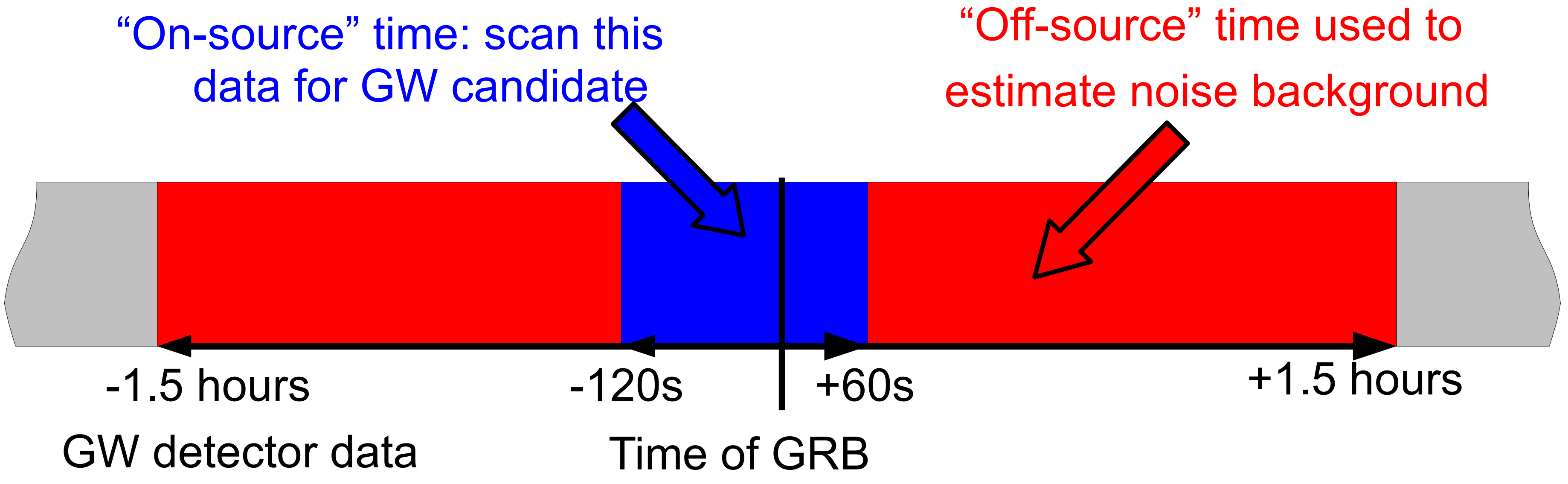
Motivation

- Correlation in time & direction between the GW signal and the GRB gives
  - Better background rejection, higher sensitivity to GW signals
  - More confident detection of GWs
  - Ready association of GW with known astrophysical system will help extract maximum scientific information ("*the whole is greater than the sum of the parts*").



- **Goal:** Search for **unmodelled gravitational wave signals** coincident in time and sky position with GRBs during LIGO Science Run 5 / Virgo Science Run 1 (Nov 2005 – Oct 2007).
  - Complementary search for GWs associated with short GRBs assuming binary inspiral progenitor also in progress (Fotopoulos talk, next).

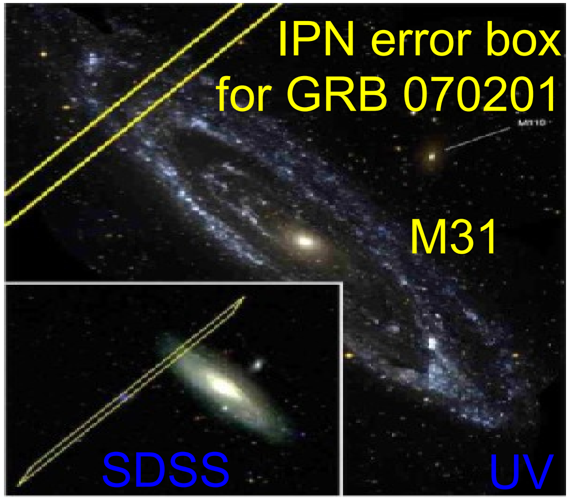
A GRB-triggered search



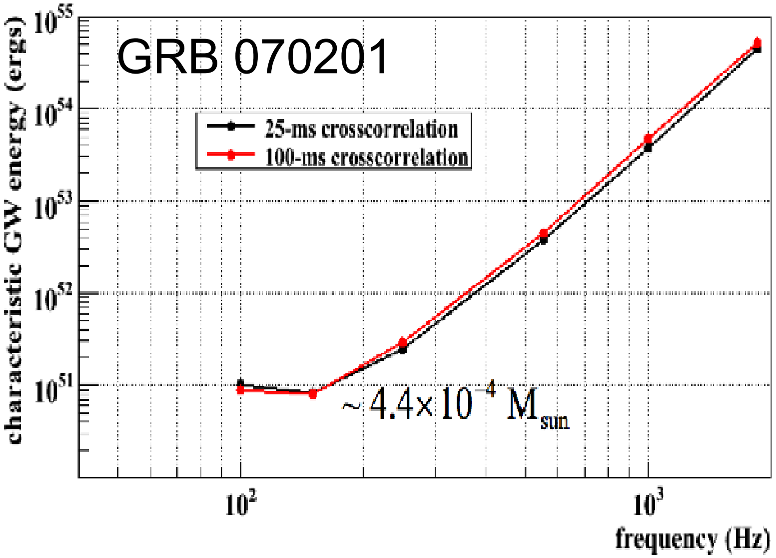
- Estimate significance of on-source events by comparing to off-source.
  - Possible GW detection := significant event
- Estimate minimum detectable GW signal amplitude by adding simulated GWs to the data and re-analysing.
  - Upper limit := signal amplitude/energy at which 90% of simulated GWs are louder than the loudest on-source event.

Recent GRB burst searches

- GRB 030329/SN 2003dh
  - (LSC) **PRD 72 042002 2005**
- GRB 050915a
  - (Virgo) **CQG 25 225001 2008**
- 39 GRBs, S2-S4 (2003-2005)
  - (LSC) **PRD 77 062004 2008**
  - Cross-correlate data from pairs of detectors



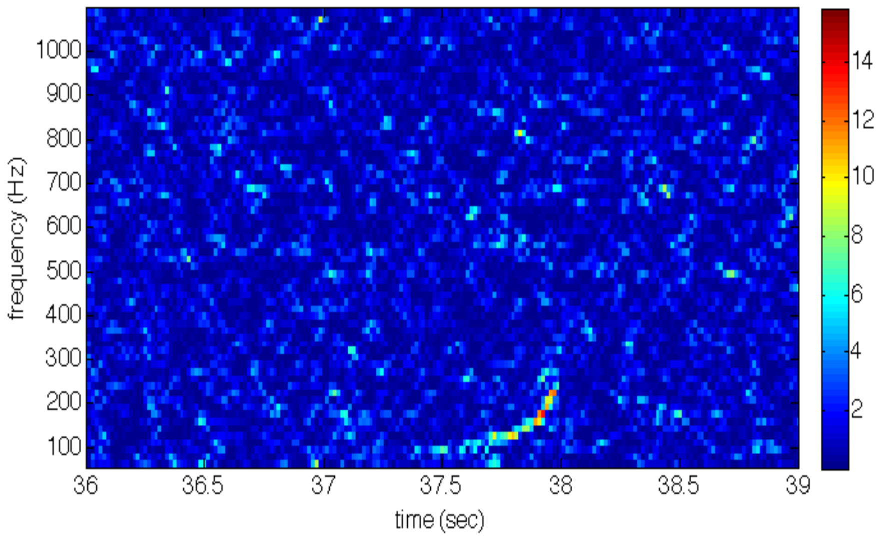
- GRB 070201
  - (LSC) **ApJ 681 1419 2008**
  - Null inspiral result excludes binary progenitor in M31!
  - Soft Gamma-ray Repeater (SGR) models predict energy release <= 10^{46} ergs.
    - Not excluded by GW limits



New for S5-VSR1

- Use X-Pipeline search package
  - Coherent multi-detector analysis
  - Use all combinations of detectors, not just pair-wise correlations.
  - Coherent glitch-rejection tests, individually tuned for each GRB.
  - Net result: factor ~2 amplitude sensitivity improvement over previous GRB searches.
- Look for any GW signal in the sensitive band of the detectors (60 – 2000 Hz) with duration from ~1 ms to ~1 sec.
  - No prior knowledge of GW waveform needed.

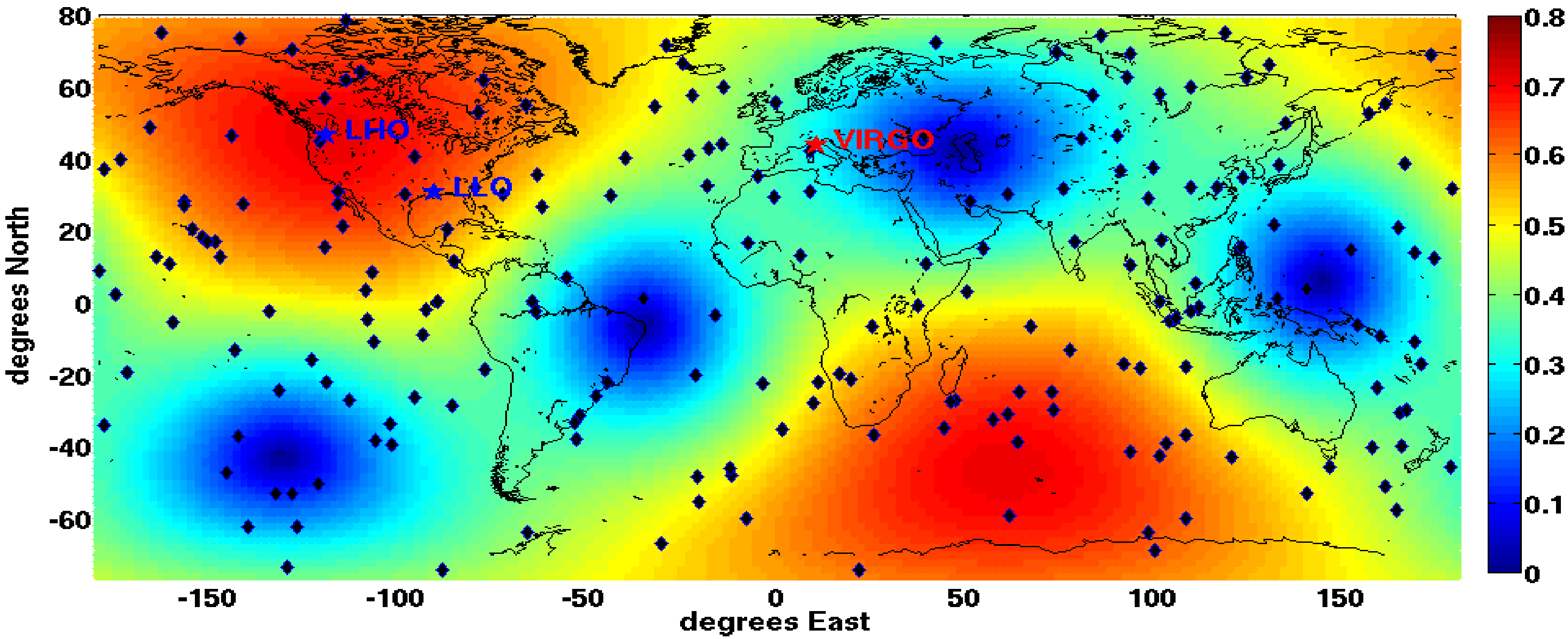
Coherent time-frequency map: A simulated 1.4-10.0 M_o neutron star – black hole inspiral at an effective distance of 37 Mpc, added to simulated H1-H2 noise



https://geco.phys.columbia.edu/xpipeline/browser/trunk/docs/T080088/T080088-02.pdf

S5-VSR1 GRB set

- Nov 2005 – Oct 2007: 212 GRBs
  - 137 with 2+ LIGO-Virgo detectors operating.
  - ~25% with redshift ~10% short duration
- Polarization-averaged antenna response of LIGO-Hanford
  - dots show location of GRBs during S5-VSR1

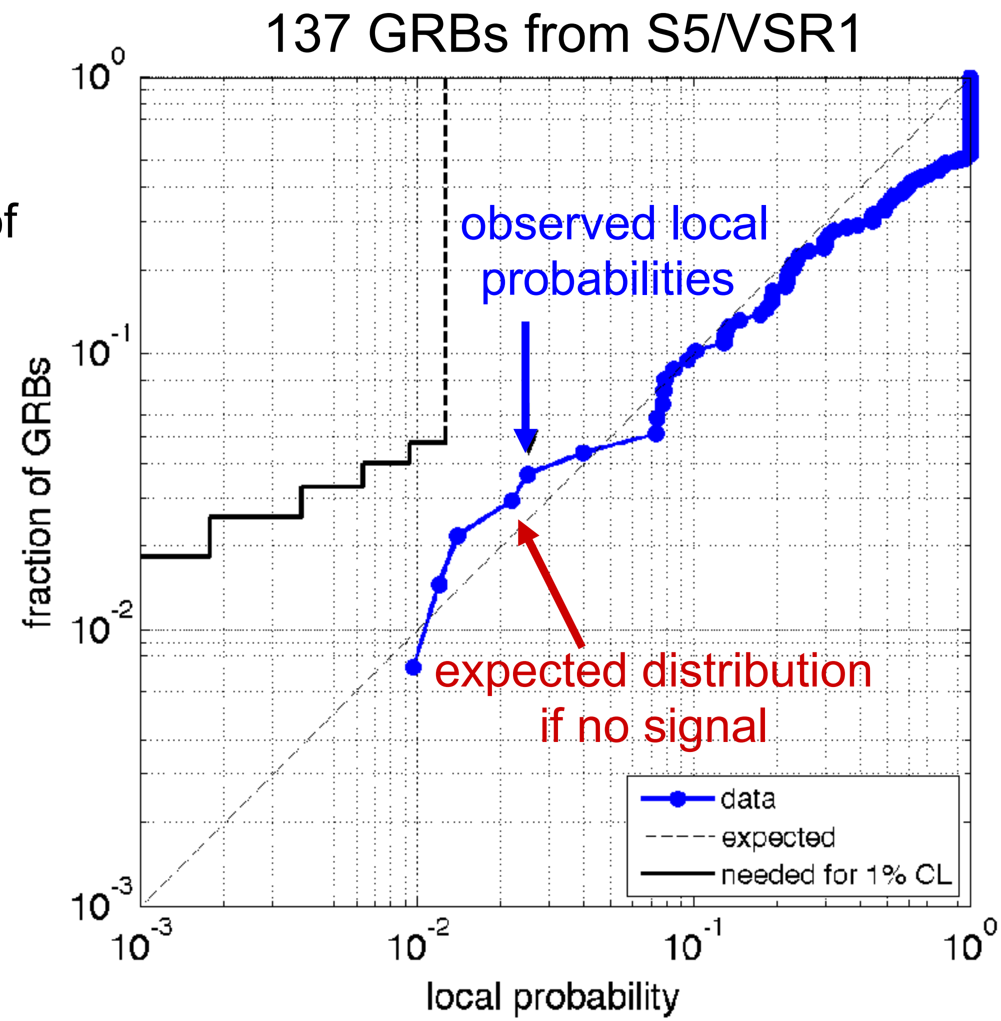


Results

- Consider as "candidate" any GRB for which on-source event is less than 5% probable based on background studies.
  - 137 GRBs: expect ~7 "candidates" from the null hypothesis.
- Found only 5 GRBs with $p < 5\%$:
  - 060807 ($p = 0.0097$)
  - 060510B (0.0124)
  - 061201 (0.0222)
  - 060116 (0.0402)
  - 070529 (0.0776) (p > 5% after additional background tests were performed)
- Follow-up checks for each "candidate" GRB:
  - consistency of the candidate with background (in energy, frequency, ...)
  - checks of detector performance at the time of the GRB
  - checks for anomalies in detector and environmental monitoring equipment
- No indication of a GW origin for any of these "candidates".

Statistical analysis

- Binomial test for cumulative effect of several weak GWs associated with GRBs.
  - Local probability := probability of background yielding event as significant as that measured in the on-source data.
  - Compare distribution of local probabilities (blue dots) that expected for null hypothesis (dashed line).
- Most significant excess has 56% chance of occurring under null hypothesis.
  - No evidence for GWs.



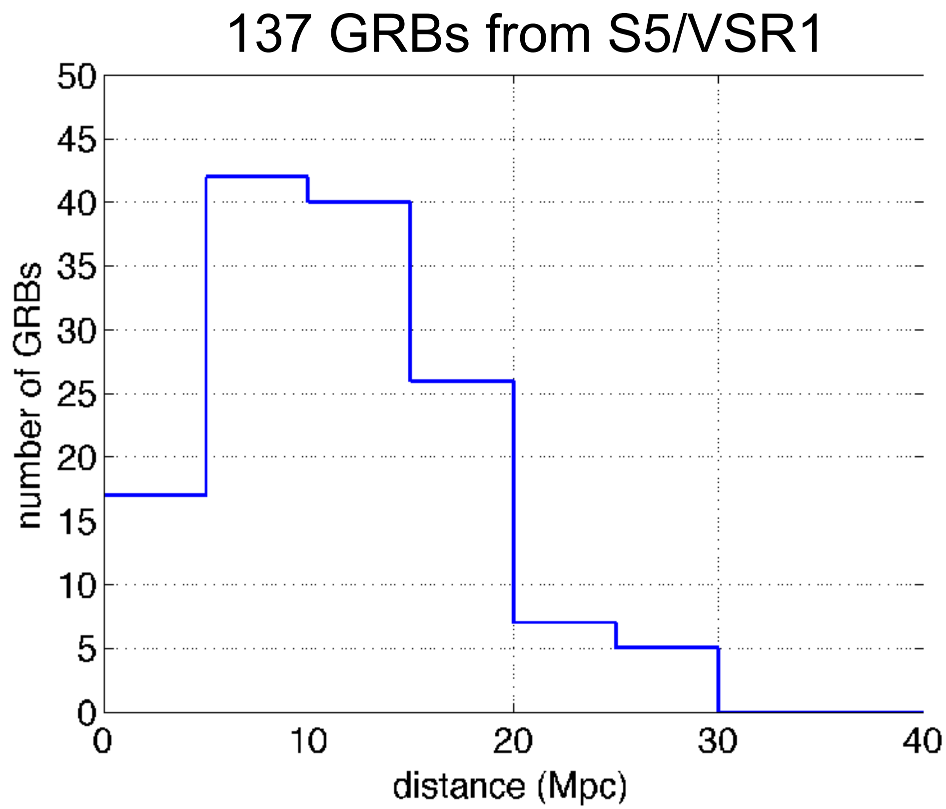
see also: Abbott et al., PRD **77** 062004 (2008)

Search Sensitivity

- For narrowband signals, can convert upper limit on GW amplitude to lower limit on distance assuming some E_{GW}:

$$D = \left(\frac{G}{\pi^2 c^3} \frac{E_{GW}}{f_0^2 h_{rss}^2} \right)^{1/2}$$

- Lower limits on distance D for circularly polarized sine-Gaussian signals:
  - f_0 = 150Hz
  - E_{GW} = 0.01 Msol c^2



Short GRBs: Merger of NS-BH: 0.01-0.1 M_o c^2 in 100-200Hz
Long GRBs: Fragmentation of collapsar core: 0.001-0.01 M_o c^2 (Davies et al. 2002; King et al. 2005; Piro & Pfahl 2007). Van Putten torus model: up to 0.1 M_o c^2 in 100-200 Hz

Rate density of GRBs

- **Typical distance limits:**

$$D \sim 15 \text{ Mpc} \left(\frac{E_{\rm GW}^{\rm iso}}{0.01 M_\odot c^2} \right)^{1/2}$$

- **Long GRBs**:
  - Local rate density of low-luminosity long GRBs is estimated at R_{obs} ~ 300 - 700 $\text{Gpc}^{-3}\ \text{yr}^{-1}$
    - Liang et al., ApJ 662 1111 2007, Chapman et al., MNRAS 382 L21 2007
  - *A priori* probability of observing GWs from a low-luminosity GRB during S5-VSR1:

$$\langle N_{\rm long} \rangle \simeq R_{\rm long}^{\rm obs} \left(\frac{4}{3} \pi D^3 \right) T \frac{\Omega}{4\pi}$$

$$\langle N_{\rm long} \rangle \simeq 1.0 \times 10^{-3} \left(\frac{R_{\rm local}^{\rm obs}}{500 \text{ Gpc}^{-3} \text{yr}^{-1}} \right) \left(\frac{E_{\rm GW}^{\rm iso}}{0.01 M_\odot c^2} \right)^{3/2}$$

$0.01\ M_o c^2$ optimistic for long GRBs!

Rate density of GRBs

- **Short GRBs**: Local rate density R_{obs} ~ 8-30 $Gpc^{-3}\ yr^{-1}$

  D. Guetta & T. Piran, astro-ph/0511238

$$\langle N_{\rm short}\rangle \simeq 2.0\times 10^{-5}\left(\frac{R^{\rm obs}_{\rm short}}{10\ {\rm Gpc}^{-3}{\rm yr}^{-1}}\right)\left(\frac{E^{\rm iso}_{\rm GW}}{0.01 M_\odot c^2}\right)^{3/2}$$

$0.01\ M_o c^2$ **realistic** for short GRBs

- **S6-VSR2**: Distance sensitivity between x1 and x2 better, more GRBs from Fermi's larger field of view. Detection rates increase by factor of ~ 5 - 40:

$$\langle N_{\rm long}\rangle \simeq (0.7-6)\times 10^{-2} \ *$$

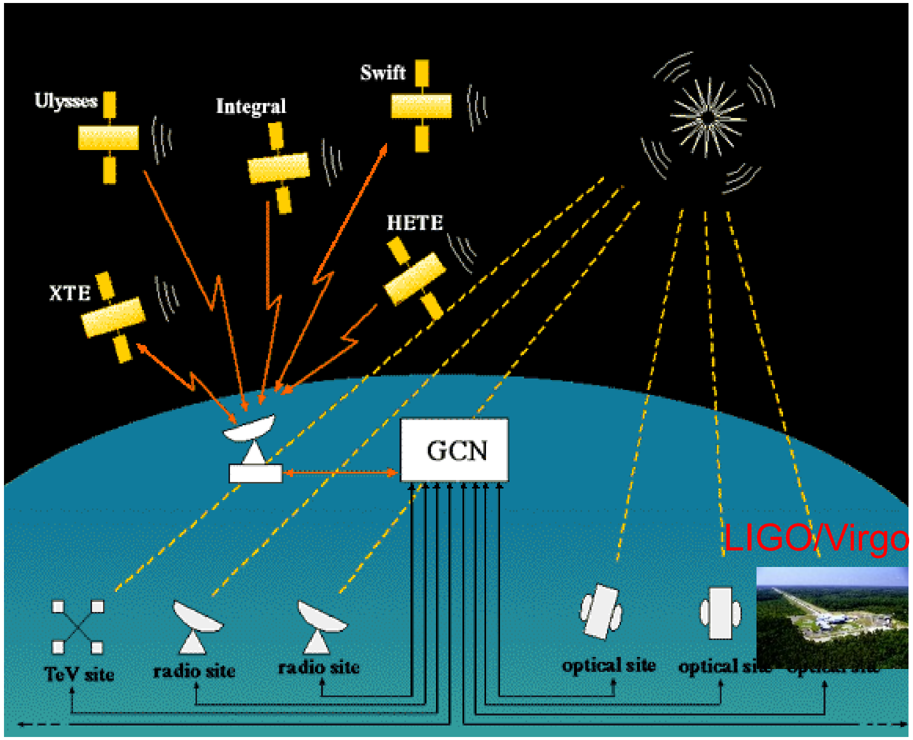
$$\langle N_{\rm short}\rangle \simeq (0.1-1)\times 10^{-3}$$

* (assuming optimistic energy emission for long GRBs)

What's next: S6-VSR2

- LIGO-Virgo to start next data taking run (S6-VSR2) in July 2009.
- Big goal for data analysts: online/low latency searches.

- GRB-triggered burst search:
  - automatically run, triggered by GCN notice
  - also automated searches triggered by SNEWS alert (**S**uper**N**ova **E**arly **W**arning **S**ystem), soft-gamma repeater flares (SGRs – previous talk by Kalmus)
  - Goal: ~1 day latency from receipt of event trigger to final results



http://gcn.gsfc.nasa.gov/

Summary

- LIGO & Virgo have looked for GW bursts associated with 137 gamma-ray bursts occurring during S5-VSR1 (2005-2007).
  - Per-GRB search and also statistical analysis.
  - Typical lower limits on distance for GW emission at 150 Hz

$$D \sim 15\ \mathrm{Mpc}\ \left(\frac{E_{\mathrm{GW}}^{\mathrm{iso}}}{0.01 M_{\odot} c^2}\right)^{1/2}$$

  - No detections (yet).
  - Dedicated search for binary inspiral signal from short GRBs in progress (next talk)

- S6-VSR2 (2009-2011) goals:
  - low-latency analysis of astrophysical triggers (~24 hr).