Overview of LSC-Virgo Externally-Triggered searches

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GWDAW-12, Boston

Why to Use External Triggers?

Establish astrophysical observation based association between gravitational waves and

- Gamma-ray bursts (GRBs)
  - » Short hard GRBs -- coalescing NS-NS(BH) binaries
- Soft gamma-ray repeaters (SGRs) flares
- Optical transients such as supernovae
- Neutron star quasi-normal modes
- Neutrino events
  - » Galactic supernova -- optical, neutrino, GW signature
- …

Correlation in time (and direction) between LIGO/VIRGO and the astrophysical trigger event ->confident detection of GWs (eventually)

Better background rejection, higher sensitivity to GW signals

Information from External Observations

1. Trigger Time Poster by E. Kahya et al.

Search within an astrophysically motivated trigger time window
-> higher detection probability at fixed false alarm probability
-> better limits in absence of detection

2. Source Direction

Search only the relevant portion of the sky or
Veto candidates not consistent with expected Δt

3. Frequency Range

Frequency-band specific analysis of data set (e.g. SGR QPOs)

4. Progenitor Type

Model dependent search can be performed, e.g.
search for burst (long GRBs, hypernovae)
search for CBC (short hard GRBs)

Search Methods

Cross-correlation of data from multiple detectors (S2-S4 GRB search)

Excess power (single or double detector)
Excess power in astrophysically motivated frequency bands (SGR QPO search)
Wavelet Detection Filter (VIRGO)

Combine data from several GW detectors: **Network Methods**

Arnaud et al., 2003 PRD **68** 102001;

Chatterji et al., 2006 PRD **74** 082005; Klimenko et al., 2005 PRD 72 122002; Rakhmanov M, 2006 CQG **23** S673

- Take advantage of known sky location of trigger event
- Consistency test of candidate events in different detectors

Better sensitivity at a given false alarm rate.

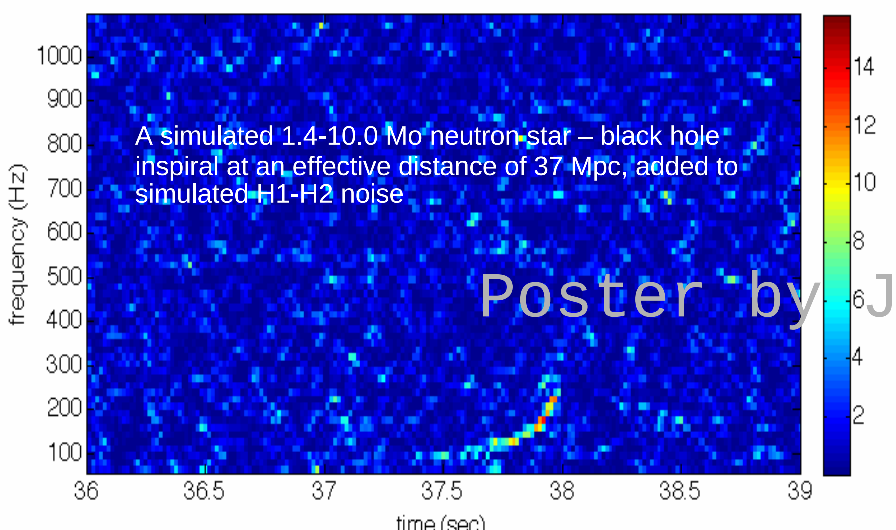
Network Methods: X-Pipeline for triggered searches

$$\overbrace{\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_D \end{bmatrix}}^{\text{whitened data}} = \overbrace{\begin{bmatrix} F_1^+(\Omega)/\sigma_1 & F_1^\times(\Omega)/\sigma_1 \\ F_2^+(\Omega)/\sigma_2 & F_2^\times(\Omega)/\sigma_2 \\ \vdots & \vdots \\ F_D^+(\Omega)/\sigma_D & F_D^\times(\Omega)/\sigma_D \end{bmatrix}}^{\text{antenna response (noise-weighted)}} \overbrace{\begin{bmatrix} h^+ \\ h^\times \end{bmatrix}}^{\text{GWB}} + \overbrace{\begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_D \end{bmatrix}}^{\text{whitened noise}}$$

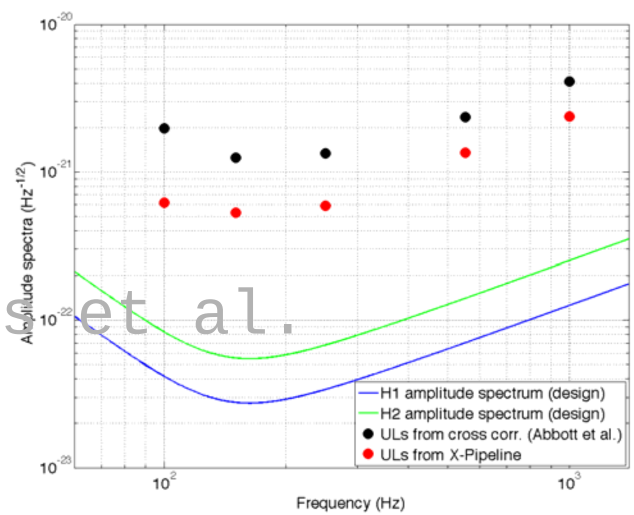
Aperture synthesis:
- time-shifting the data from each detector
- coherent sum of GW contributions (h_+ and h_x) from a particular sky position Ω
- GW-free *null stream* for consistency testing

Chatterji *et al*. PRD **74** 082005 (2006)

Event identification:
- time-frequency maps of the energy in the reconstructed h_+, h_x, and null streams
- identify clusters of pixels with large E_+ (Klimenko *et al*., PRD **72** 122002 (2005))



Poster by Jones et al.



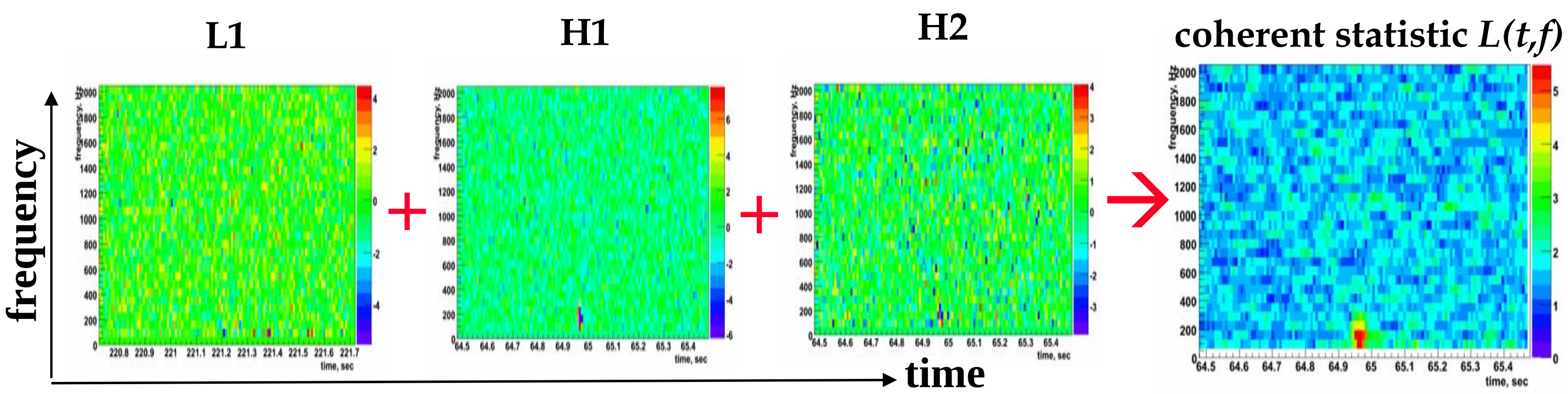
Use the EM sky positions of known GRBs to perform targeted searches for their GW emission

Network Methods: cWB for triggered searches

End-to-end multi-detector coherent pipeline

- Based on constrained likelihood method (PRD 72, 122002, 2005)
- handle arbitrary number of co-aligned and misaligned detectors
- reconstruction of GW waveforms & detector responses
- use coherent statistics for rejection of instrumental/environmental artifacts
- used also for all sky burst searches

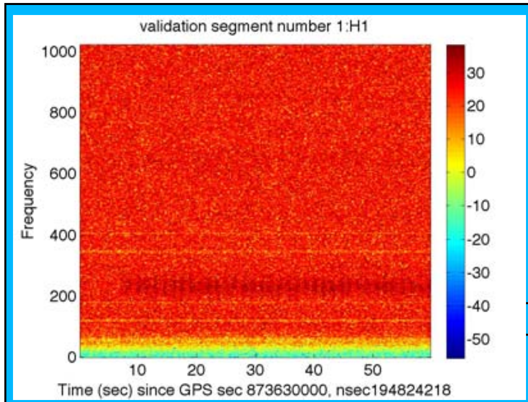
Combines detector data streams into coherent statistic (likelihood) representing total SNR detected by the network



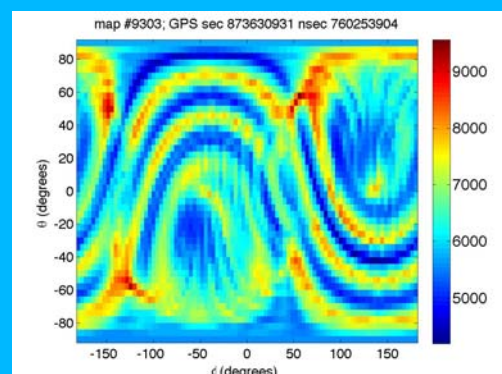
$$L(t,f) = \max_{h_+ h_\times} \sum_k \frac{x_k^2[t,f] - \left(x_k[t,f] - \xi_k[t,f]\right)^2}{\sigma_k^2(f)} \qquad \xi_k = h_+ F_{+k} + h_x F_{xk}$$

Network Methods: **Ridge** for triggered searches

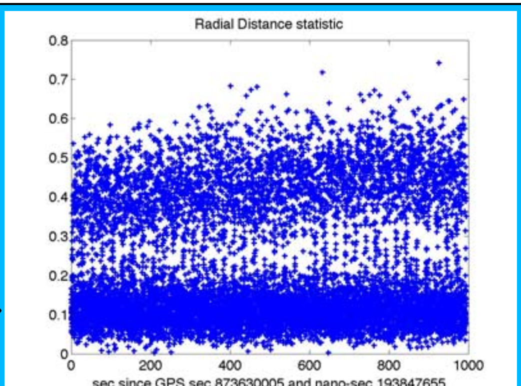
- Implements Maximum likelihood with Tikhonov regularization (Rakhmanov, CQG, 2006)
  - » Tikhonov regularization goes into hard constraint for large regulator gain: continuous bridge between standard likelihood and regularized methods
- Data conditioning steps:
  - » Noise floor whitening (MNFT; Mukherjee, CQG, 2003)
  - » Line estimation and removal in the time domain (MBLT; Mohanty, CQG, 2002)
- Differs in all steps from other coherent network methods: an independent look at the data
- An effective glitch veto has been developed and is under test with real data



Data conditioning



H1L1V1 Skymap



Detection statistic

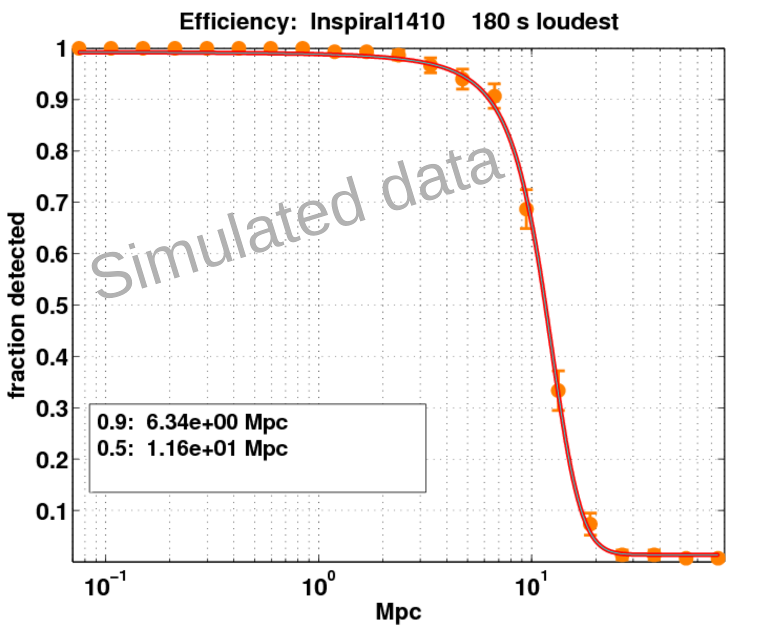
Coherent Excess Power: **Flare** for triggered searches

Single and dual detector networks analyzed

Background sets FAR detection threshold
- simulations -> upper limit estimate

Poster by Kalmus et al.

Simple and effective
- **Independent of other methods**
- **Performance comparable to other methods**



Data conditioning in time domain
- Bandpassing and automated (self-training) line notching

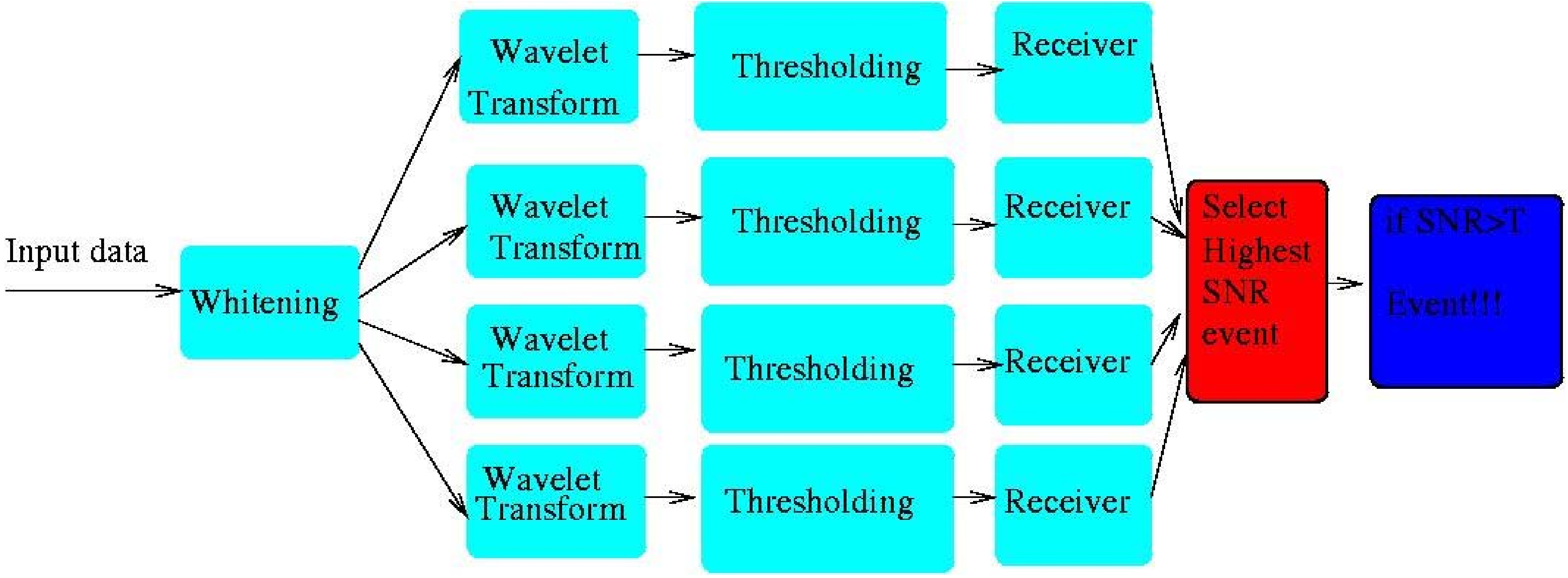
Spectrogram transformation at pre-determined resolution -> PSD TF tilings
- TF tilings are combined (dual detector) using pixel correlation method
- Background subtraction -> excess power TF tiling

Clustering applied to pixels above significance threshold

Kalmus P et al., 2007 CQG **24** 659

WDF: Wavelet Detection Filter

- The filter is based on a wavelet decomposition of the whitened data. To find the best matching, an empirical set of different orthogonal wavelet basis is used.
- The coefficients of each wavelet transform are than thresholded in such a way to retain only the ones which could be considered above the noise level.
- The squared sum of the selected coefficients reprensent the Energy of the signal. The best matching will produce the highest SNR value.
- If the SNR is above a fixed threshold, an event is recorded.



GRB050915a poster by Corsi et al.

Simulations for Triggered Searches

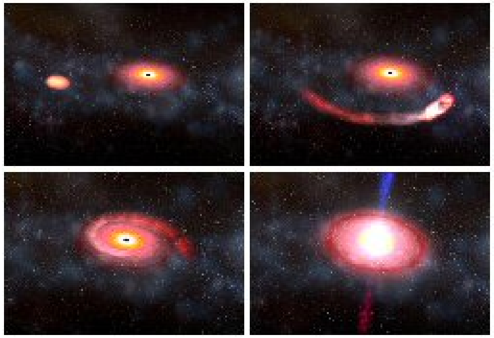
Monte-Carlo simulations of realistic waveforms

- based on `GravEn` package (developed by A. Stuver and has been used for untriggered searches). Wrapper around `GravEn` allows per-detector frame generation and a separate channel for each injection.
- The package is able to read in GRB information and randomly inject specified waveforms into on- and off-source data for any GRB using its trigger time and sky location.
- This allows us to test the efficiency of pipelines for externally triggered searches.
- Simulations contain a variety of diagnostic information at the 5 detector sites (LHO, LLO, GEO, VIRGO, TAMA).
- For triggered searches, multiple waveforms created at the same time and location but stored in many different channels.

Sources: Gamma Ray Bursts (GRBs)

Short-duration GRBs (less than ~2 s) (review: Nakar, E. 2007, Phys. Rep., 442, 166)

- coalescing compact binaries
  e.g. neutron star—black hole merger
- SGR flares



The black hole first stretches the neutron star into a crescent, swallowing it, and then gulping up crumbs of the broken star in the minutes and hours that followed. Courtesy of NASA

Long-duration GRBs

- Supernovae
  GRB030329/SN2003dh (Hjorth, J. et al. 2003, Nature., 423, 847)
  GRB060218/SN2006aj (Campana, S. et al. 2006, Nature, 442, 1008)
  GRB031203/ SN2003lw (Malesani, D et al. 2004, ApJ, 609, L5)
  GRB980425/SN1998bw (Galama, T. J. et al. 1998, Nature, 395, 670)

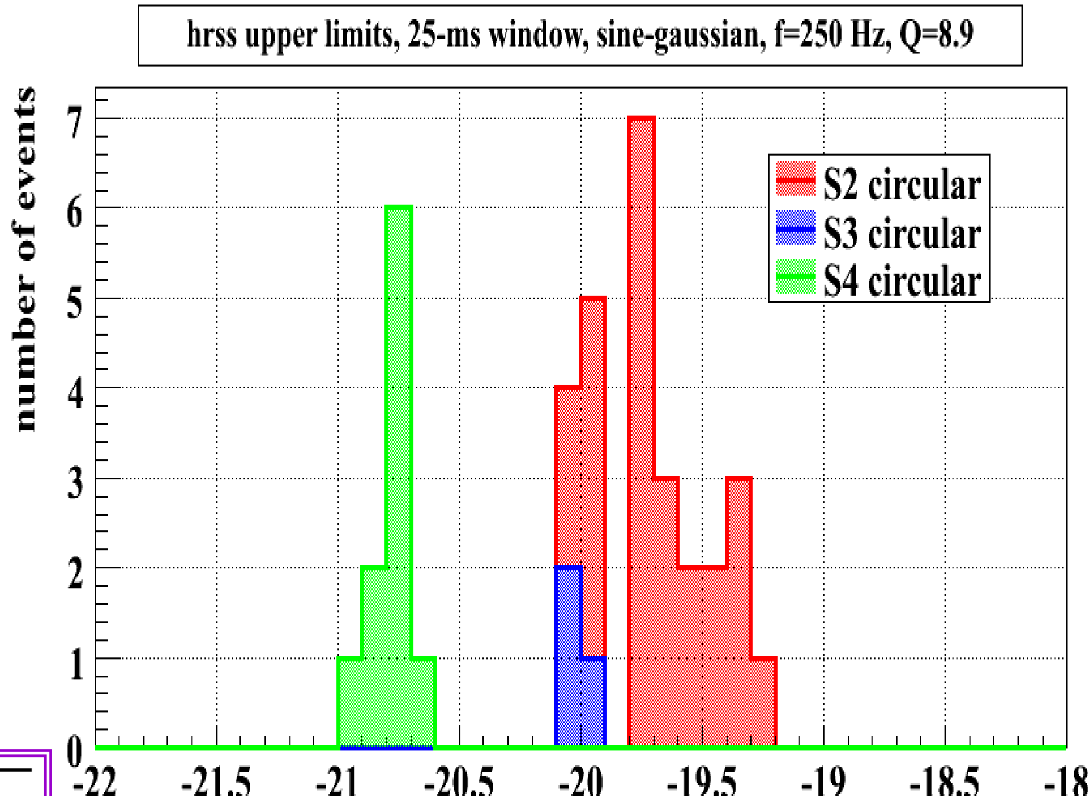
GRB central engine: accreting solar-mass BH (CBC or hypernova)
-> strong GW emission

Inspiral phase of CBCs well-modeled -> matched filtering techniques
Merger phase of CBCs and hypernovae not well-understood
-> burst search techniques

Sources: GRBs (LIGO S2-S4 Results)

- Search for short-duration gravitational-wave bursts (GWBs) coincident with GRBs
  - using S2, S3 and S4 data from LIGO
  - Analysis based on pair-wise cross-correlation of two interferometers
  - Target GWB durations: < 100 ms; Bandwidth: 40-2000 Hz

No gravitational-wave burst signal found associated with 39 GRBs in S2,S3,S4 runs



$\mathrm{Log}_{10}(h_{rss}, 1/\sqrt{\mathrm{Hz}})$

$$h_{\rm rss} \equiv \sqrt{\int \left(|h_+(t)|^2 + |h_\times(t)|^2\right) dt}$$

submitted to Phys. Rev. D [arXiv:0709.0766]

Sources: GRBs (GRB070201 Result)

Short-hard GRB search strategy

Exercise matched filtering techniques for inspiral waveform search

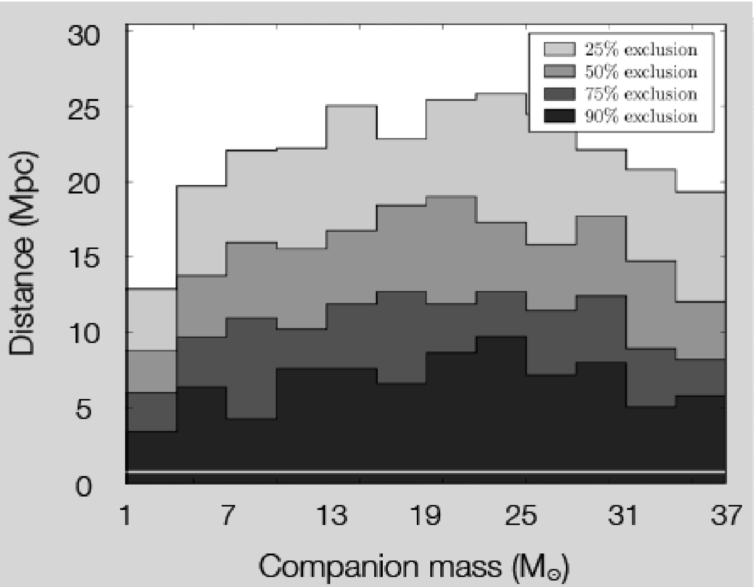
Use burst search techniques to cover unmodeled waveforms (merger phase or exotic inspiral waveform types; SGR GW emission)

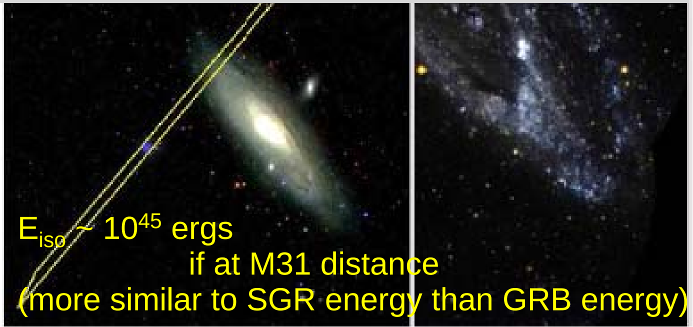
->No plausible gravitational waves identified

A short hard gamma-ray burst (Feb. 1st 2007)
Detected by
Konus-Wind, INTEGRAL, Swift, MESSENGER

Progenitors: possibly NS/NS or NS/BH mergers
Emits strong gravitational waves
Other possibility: SGR (may emit GW but weaker)

- Exclude progenitor in mass-distance region
  CBC is excluded 3.5Mpc away at 90% CL
- Exclude progenitor of various masses at hypothetical GRB distance (M31)
  CBC is excluded at > 99% confidence level
- Bound the GW energy emitted by a source at M31: 8.2×10^{50} erg (90% CL, SG injection 150Hz)
- Possible statement on progenitor model
  does not exclude SGR at the M31 distance





A detection of GWs could have

- confirmed the progenitor (e.g. coalescing binary system)
- determined the distance to the GRB source

submitted to ApJ; http://arxiv.org/pdf/0711.1163

Sources: GRBs (LIGO S5 triggers)

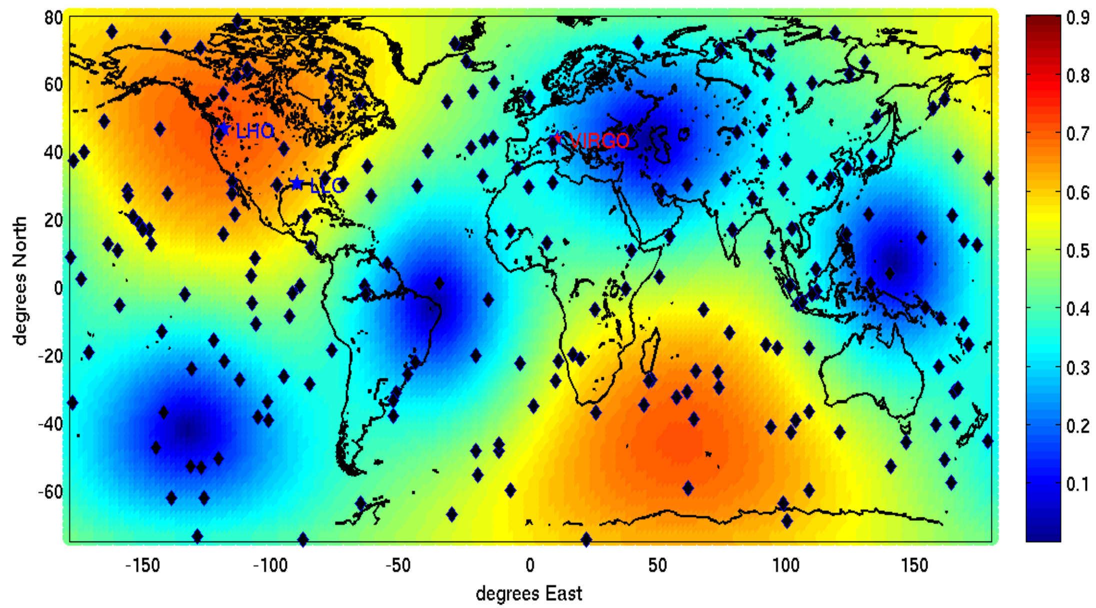
213 GRB triggers

mostly from Swift

some from IPN, INTEGRAL and HETE-2

- **~70%** with double-IFO coincidence LIGO data
- **~40%** with triple-IFO coincidence LIGO data
- **~25%** with redshift
- **~10%** short-duration GRBs
- all but a handful have position information

Polarization-averaged LHO antenna factor F_{ave}



LIGO sensitivity depends on GRB position

Search Methods:

on-line pair-wise cross correlation based search

network methods are/will be exercised for S5 GRB triggers

Sources: GRBs (LIGO-Virgo network search)

VIRGO data is beneficial for triggered searches when VIRGO antenna factors are more advantageous at the received trigger time.

~50 GRB triggers (May 18 – Oct 1, 2007)

Methods:

- **Wavelet Detection Filter (WDF)** – wavelet based transient detection tool (VIRGO) (GRB 050915a: Acernese et al. 2007 Class. Quantum Grav. 24 S671)

  in conjunction with

- one or more **network methods** developed by LSC

WDF provides robustness against possible noise non-stationarities.

Ongoing preliminary search sensitivity studies:

The first triple coincident LIGO-VIRGO GRB event: **GRB 070520B** (Swift observation)

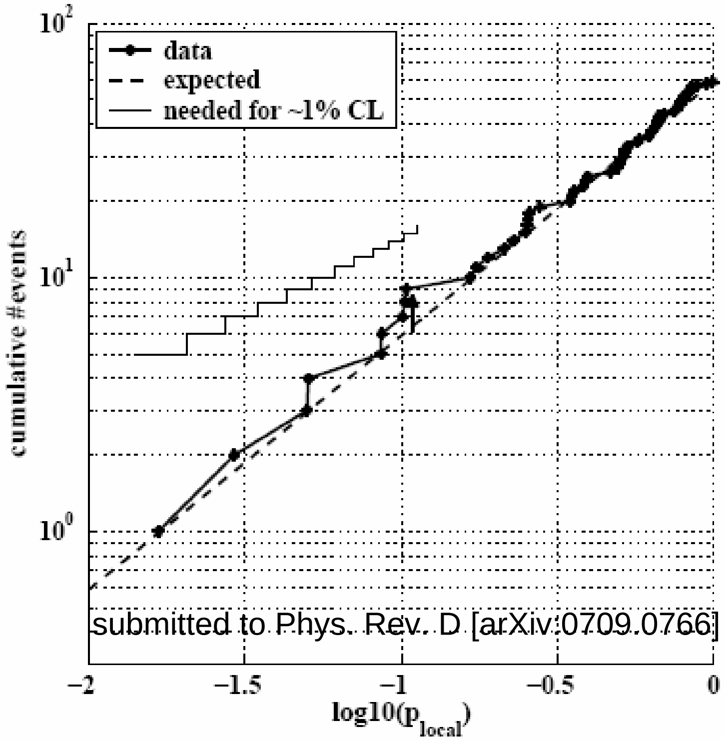
Trigger time: May 20, at 17:44:53 UT (GPS 863718307 s)

RA = 121.951, DEC=57.617

Averaged antenna factors: 0.411322 (LHO); 0.372445 (LLO); 0.828336(VIRGO)

Sources: Large GRB Data Set

- statistical search: search for weak signals which, individually, would not comprise a detection, but together could have a detectable cumulative effect on measured distributions
- binomial test: search local probability distribution for deviation from expected distribution
- rank-sum test: test if medians of on-source cross-correlation distribution and off-source cross-correlation distribution are consistent with each other

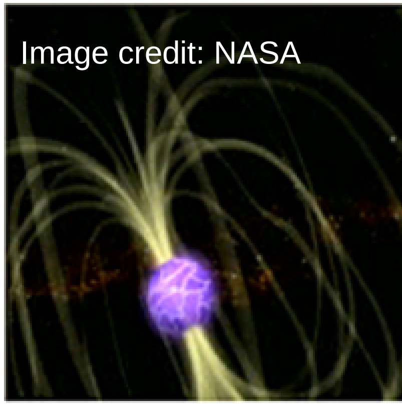


submitted to Phys. Rev. D [arXiv:0709.0766]

Constraining population parameters (S2,S3,S4): demonstrated with standard candle GW emission model and Bromm, Loeb, ApJ, 2002 long-soft GRB redshift distribution. Upper limit on mean GW energy emitted.

S5 plan: Incorporate priors, such as a redshift distribution model, in the derivation of the population study statistic itself.
Benefit: optimal selection of GRBs from a given sample

Sources: Soft Gamma-ray Repeaters (SGRs)



Possibly highly magnetized neutron stars
Emit short duration X- and gamma-ray bursts at irregular intervals
Occasional giant flares (e.g. SGR1806-20, Dec 27, 2004)
<~ 10^{47} erg/s peak EM luminosity
Up to 15% of GRBs can be accounted for SGR flares

May induce catastrophic non-radial motion in stellar matter
-> Galactic SGRs are plausible sources for detection of GWs

X-ray lightcurve of some giant flares showed quasiperiodic oscillations (QPOs)
possibly due to seismic modes of neutron star (Israel et al. 2005, Watts & Strohmayer 2006)
-> GW emission?
well-defined frequencies

Strategy:

Search for instantaneous GW emission at the burst and also GWs associated with QPOs.

SGRs: S5 SGR Burst Search

-Search for GW excess associated with two known Galactic SGRs

-Sky position known to high accuracy

Transient Search

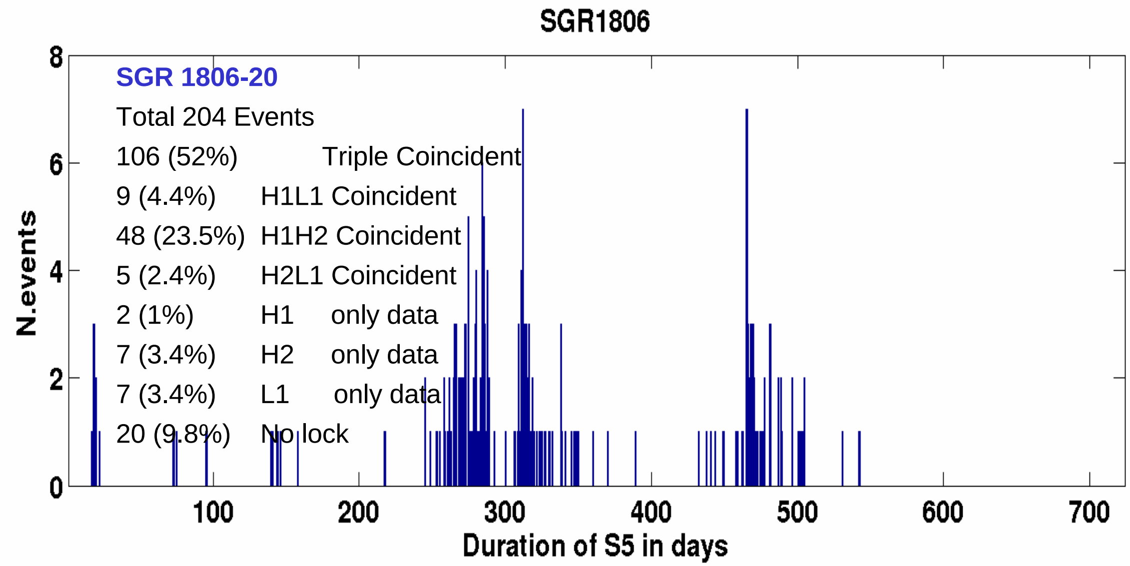
1. Unmodeled emission strategy: Search up to 1 kHz, with durations set by EM timescales. White noise burst injections.

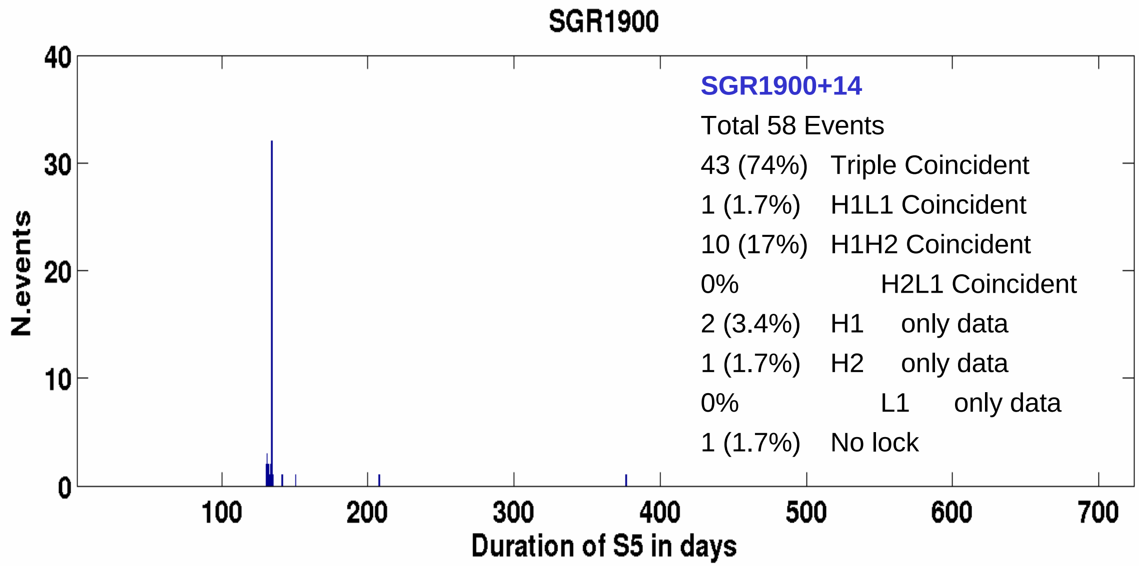
2. Ringdown emission strategy: Search between 1-3 kHz, durations set by model predictions. Ringdown waveform injections.

`Flare` pipeline - one-detector and two-detector searches

`cWB` - two-detector and three-detector searches

* Event list provided by K. Hurley

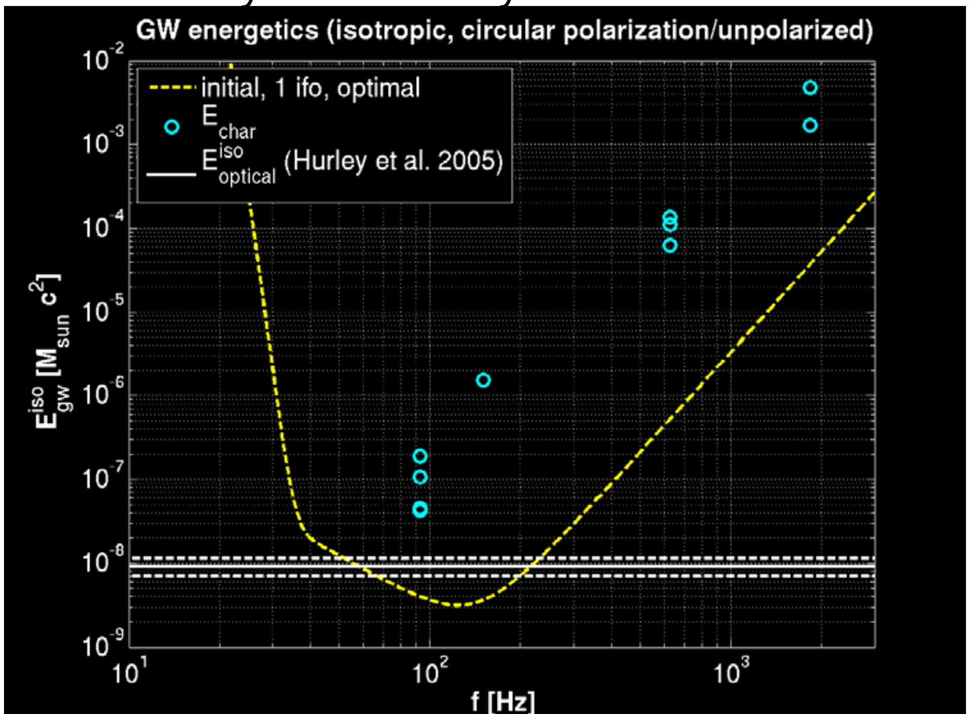




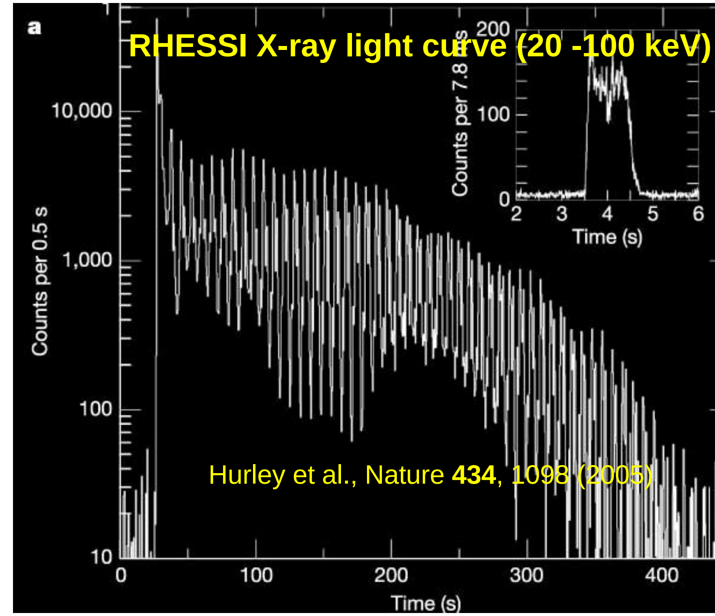
SGRs: QPO Search

- Distance [6 - 15] kpc
- Energy ~10^{46} erg
- Plausibly mechanically driven

SGR1806-20 12/27/04 event



E(GW)$_{iso}$,- characteristic energy radiated in the duration and frequency band we searched (90 % CL)



For the 92.5Hz QPO observation (150s-260s)

$$E^{iso,90\%} = 4.3 \times 10^{-8}\ M_{sun}c^2$$

Comparable to the energy released by the flare in the electromagnetic spectrum

Abbott B et al 2007 Phys. Rev. D 76 062003

S5 search

Extend the QPO search pipeline by implementing coherent search capability
Use the same flare list as for transient search (SGR 1806-20 and SGR 1900+14)
Strain equivalent noise improvement (>3x at 150 Hz)

Sources: Pulsar Glitches

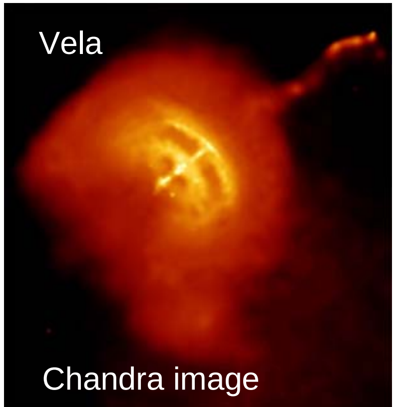
- Radio and anomalous X-ray pulsars occasionally exhibit "glitches" in their inferred spin-down rates

- Mechanisms for glitches include (but are not necessarily limited to):
  - » relaxation of ellipticity in neutron star crust, inducing a star-quake (younger pulsars)
  - » sudden de-coupling of rotation between fluid core and solid crust as superfluid vortex lines come un-pinned (older pulsars)
  - » phase transitions from hadronic to quark matter, deep inside neutron star core

- Crustal disruption associated with glitch may excite non-radial oscillatory modes
- (~ 1-3 kHz for the f-mode) which are then damped by GW emission

- Search strategy based on Bayesian evidence and model selection, triggered by observations of X-ray and radio pulsar glitches looks for decaying sinusoids around the time of the glitch (Clark et al., 2007 Phys. Rev. D 76 043003)

- Search is being applied to LIGO S5 data
  from a Vela glitch in August 2006
  (August 12th, 2006 event of PSR B0833-45)



Posters by Clark et al. and Hayama et al.

Sources: Neutrinos

Galactic Supernovae:

LIGO/VIRGO is set up to receive SNEWS alert, several burst search algorithms are readily available

New information on neutrino mass

High energy neutrinos:

May be emitted along with GWs from

- long GRBs (if progenitor is hypernova)
- compact binary merger

Superior source direction information is available (1 degree)

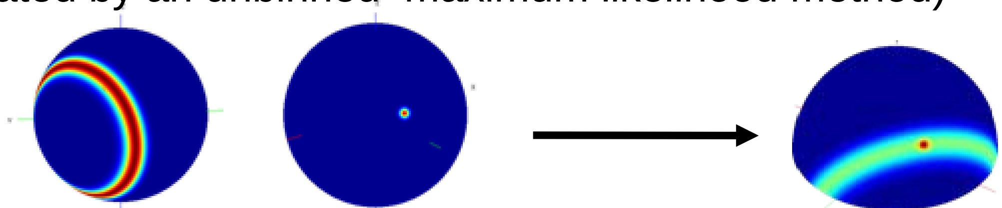
MC Simulation Case Study: **LIGO/IceCube coincidence study** Aso Y et al, ArXiv:0711.0107

Two-stage coincidence

- Event time coincidence (within a certain time window)
- Spatial coincidence (evaluated by an unbinned maximum likelihood method)

IceCube 9 string LIGO S5

Expected FAR:
(1/435 year) x (Trigger window/1 s)



LIGO event IceCube event Overlap event

Simulations for the case of LIGO-VIRGO triple coincidence and IceCube 22 string case are ongoing

Other Sources

Optical Transients

High uncertainty in trigger time (several hours)

Well-known sky position

-> directional analysis methods are applicable

Core collapse supernovae detected during S5 are subject to analysis

Uncertainty in trigger time: may not always have data from multiple detectors

Low Mass X-ray Binaries

Low mass star + compact object (neutron star or a black hole)

GW observations may be used to derive constraints on

- r-modes in young neutron star
- accreting onto neutron star


Image credit ESA

Sco X-1/RXTE: Posters by Markowitz et al. and Hayama et al.

Blazar Flares

Similarly to GRBs have a central engine and a jet

Powered by accretion onto a supermassive black hole

No theoretical estimate on GW emission in LIGO/VIRGO band

open to the unknown…

PKS 2155-304: Poster by Desai et al.

Conclusions

Published Results

GWs coincident with GRBs using S2, S3 and S4 data from LIGO -> No detections

SGR1806-20 hyperflare QPO search

Limits: comparable to the emitted energy in the electromagnetic spectrum

Search for gravitational-waves coincident with GRB070201

The achievable sensitivity with the present detectors does not exclude present models of SGRs at the M31 distance.

It is unlikely that a compact binary progenitor in M31 was responsible for GRB070201.

Expected for S5

Network methods are expected to yield better upper limits (if no detection)

Large GRB (and also SGR) dataset allows for more significant statistical studies

Explore sources beyond gamma-ray emitters

Association between GWs and their EM counterparts is likely to be confirmed during the lifetime of Advanced detectors.

SGRs: QPO Search (S5)

Interesting example SWIFT-BAT: “Storm” from SGR1900+14 on March 29, 2006

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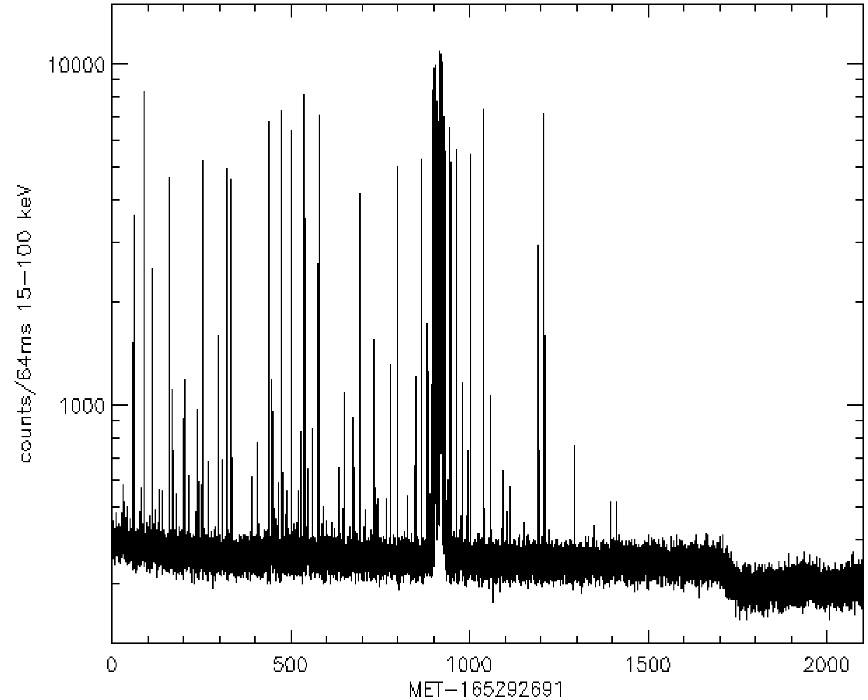

2006-03-29 02:51:39, 1ms timescale