Detection of Gravitational Waves with LIGO, VIRGO, ...

On the Occasion of the Inauguration of LIGO

LIGO Livingston Observatory

Livingston, Louisiana

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LIGO-G990102-00-E

Ultimate Goals for the Detection of Gravitational Waves

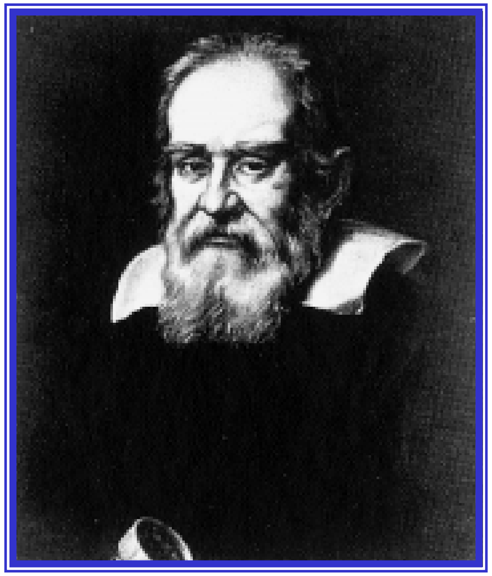
- Tests of Relativity
  - *Black holes & strong-field gravity (ringdown of excited BH)*
  - *Spin character of the radiation field (polarization of radiation from CW sources)*
  - *Wave propagation speed (delays in arrival time of bursts)*
- Gravitational Wave Astronomy
  - *Compact binary inspirals*
  - *Gravitational waves and gamma ray burst associations*
  - *Black hole formation*
  - *Supernovae in our galaxy*
  - *Newly formed neutron stars - spin down in the first year*
  - *Pulsars and rapidly rotating neutron stars*
  - *LMXBs*
  - *Stochastic background*

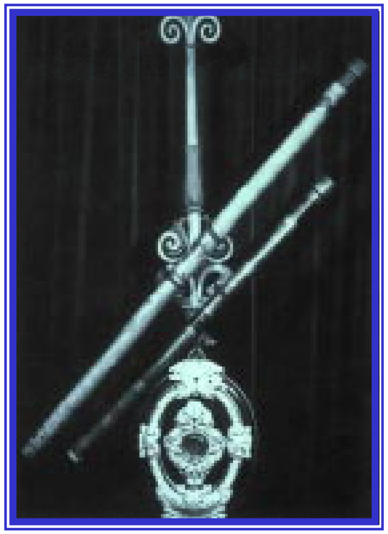
The Opening of a New Observational Window on the Universe

- Galileo Galilei, 1610
  - ***Improves on Lipperhey's opera glass to make a 9x telescope --***
    - ***discovers Gallilean moons of Jupiter***
- Karl Jansky, 1933
  - ***Builds directional radio antenna to study RF interference in trans-Atlantic telephone communications --***
    - ***discovers radio emissions from our galaxy***
- Penzias & Wilson, 1963
  - ***Investigate excess microwave receiver noise in satellite communications antenna --***
    - ***observe cosmic microwave background***
- Klebesadel & Olson, 1969
  - ***Study Vela satellite data for evidence of clandestine nuclear tests by Soviet Union***
    - ***discover γ-ray burst of non-terrestrial origin***
- ...

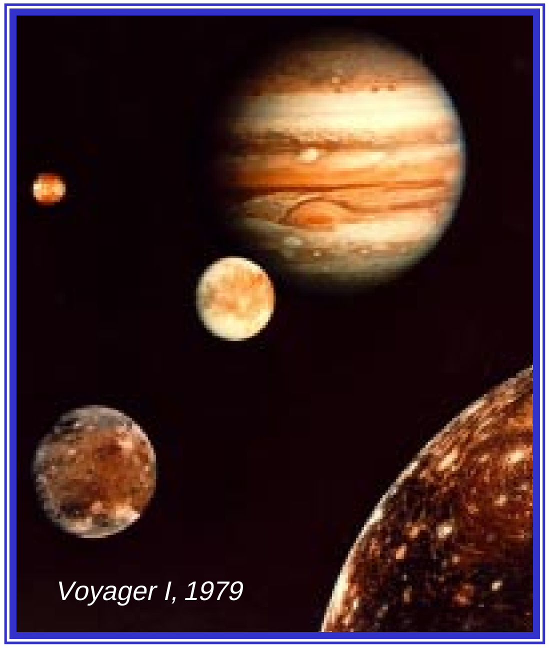
The Opening of a New Observational Window on the Universe

- Galileo Galilei, 1610
  - *Improves on an invention by Hans Lipperhey to build a 9X telescope*
    - ! ***Discovers the "Gallilean" moons of Jupiter***





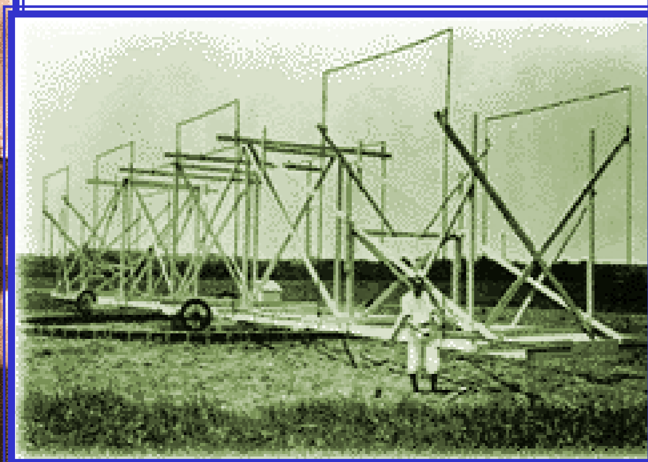
http://es.rice.edu:80/ES/humsoc/Galileo//

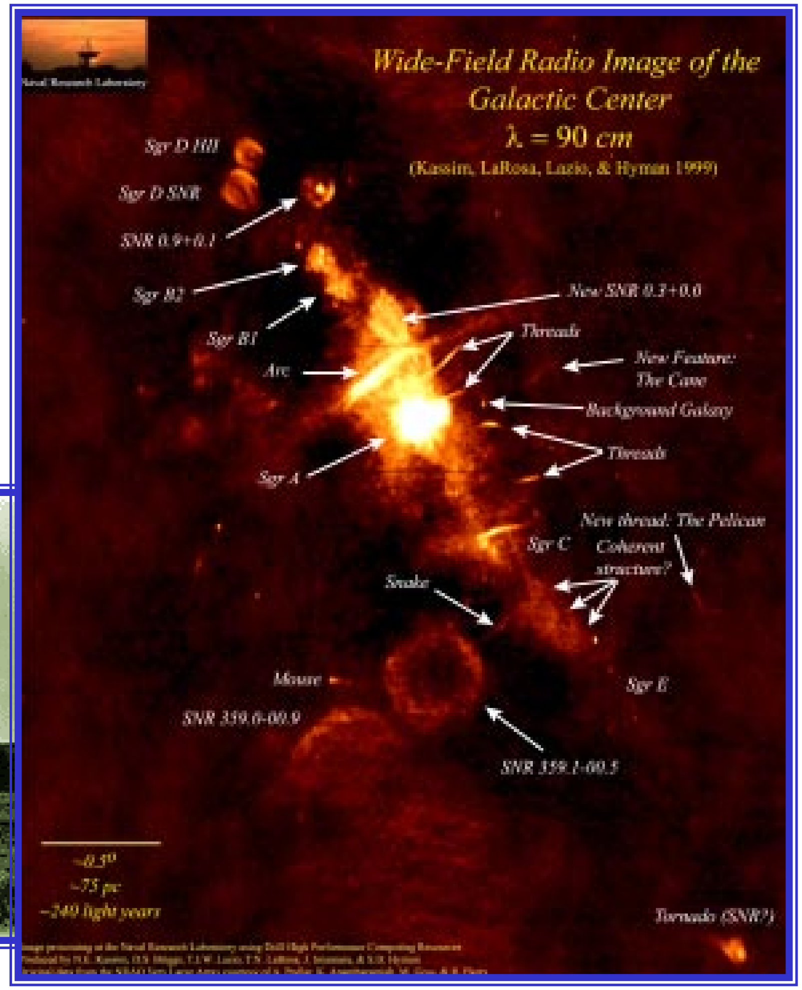


http://photojournal.jpl.nasa.gov

The Opening of a New Observational Window on the Universe

- Karl Janksy, 1933
  - *Builds a radio antenna array to study interference in transatlantic telecommunications*
    - ***Discovers radio emissions from the galactic center***



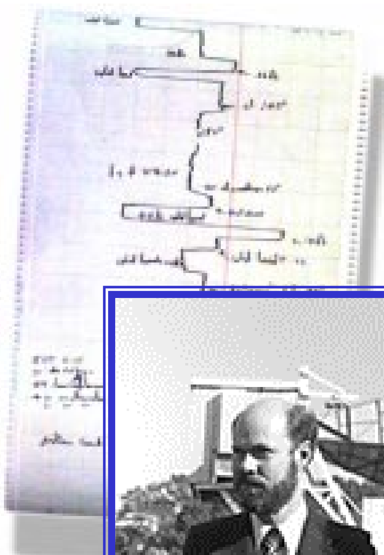


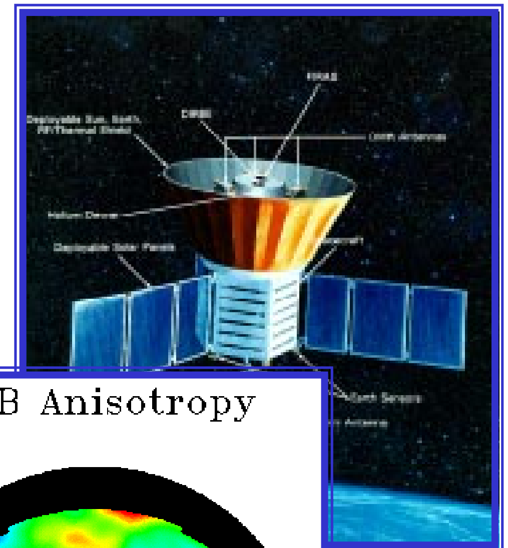
http://www.lucent.com/museum/1933rt.html

//http://rsd-www.nrl.navy.mil/7213/lazio/GC/

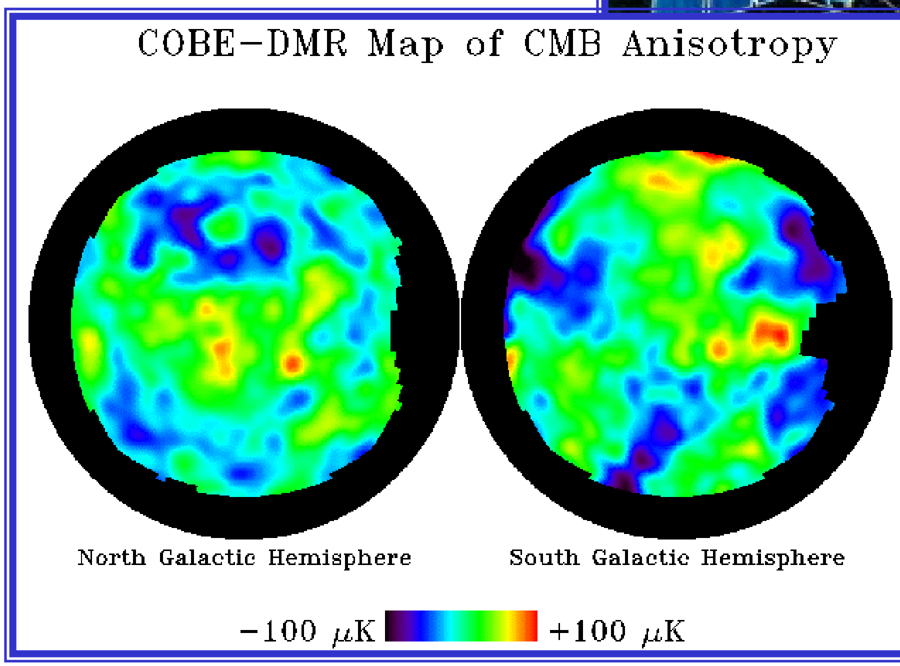
The Opening of a New Observational Window on the Universe

- Penzias & Wilson,1963
  - *Track down excess antenna noise*
    - ! ***Observe the cosmic microwave background radiation (CMBR)***





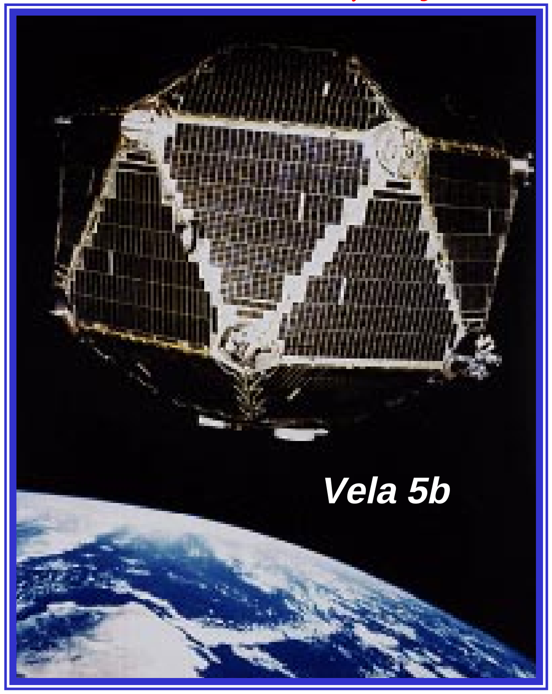
http://www.gsfc.nasa.gov/astro/cobe/cobe_home.html



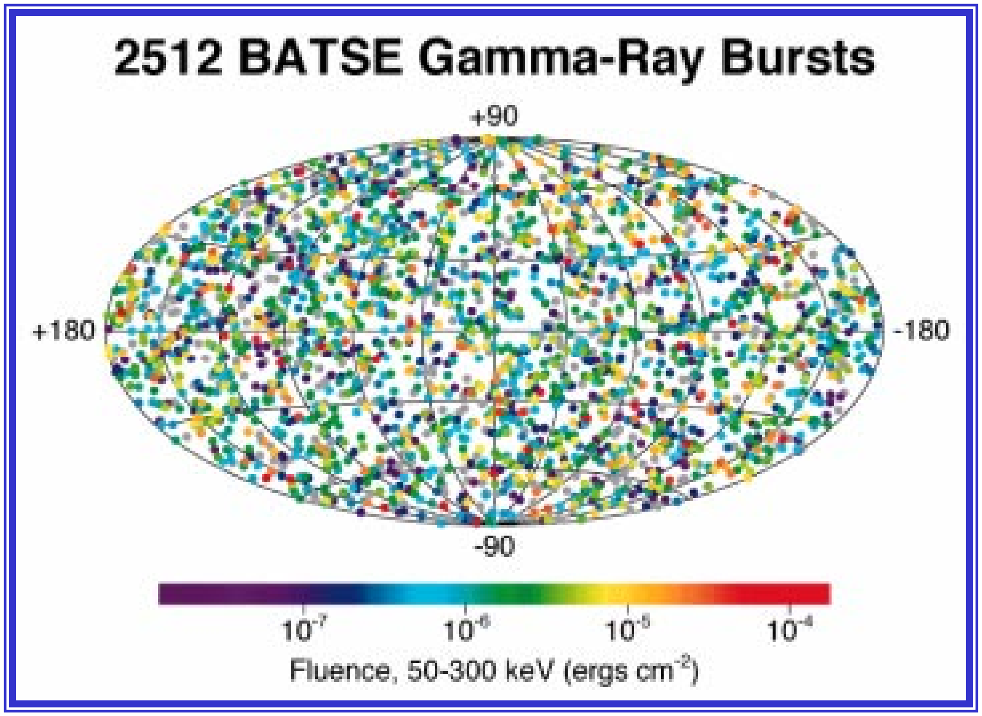
http://www.lucent.com/museum/1964bang.html

The Opening of a New Observational Window on the Universe

- Klebesadel, Strong & Olsen (LANL), 1969
  - *Review of Vela 5 satellite data from 1967.07.02 shows a γ event of non-terrestrial origin*
    - **! *Discover γ–ray bursts (GRBs), X-ray sources***

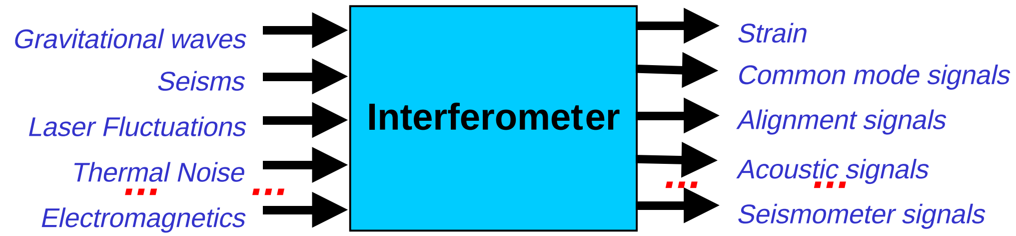


http://science.msfc.nasa.gov/newhome/headlines/ast19sep97_2.htm

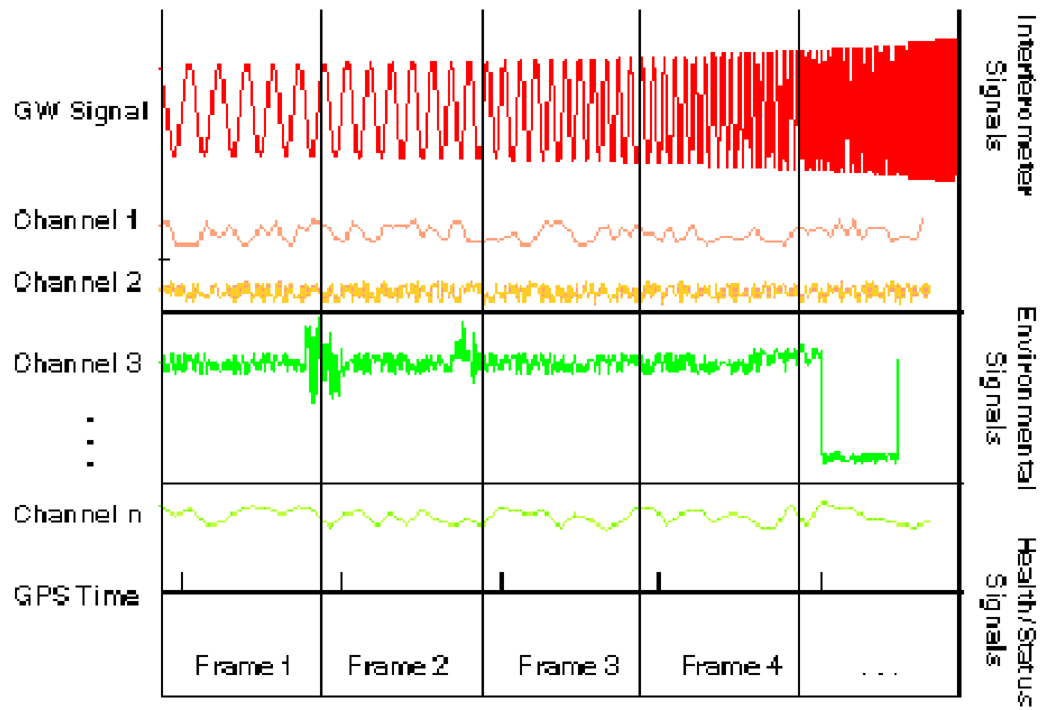


http://www.batse.com/

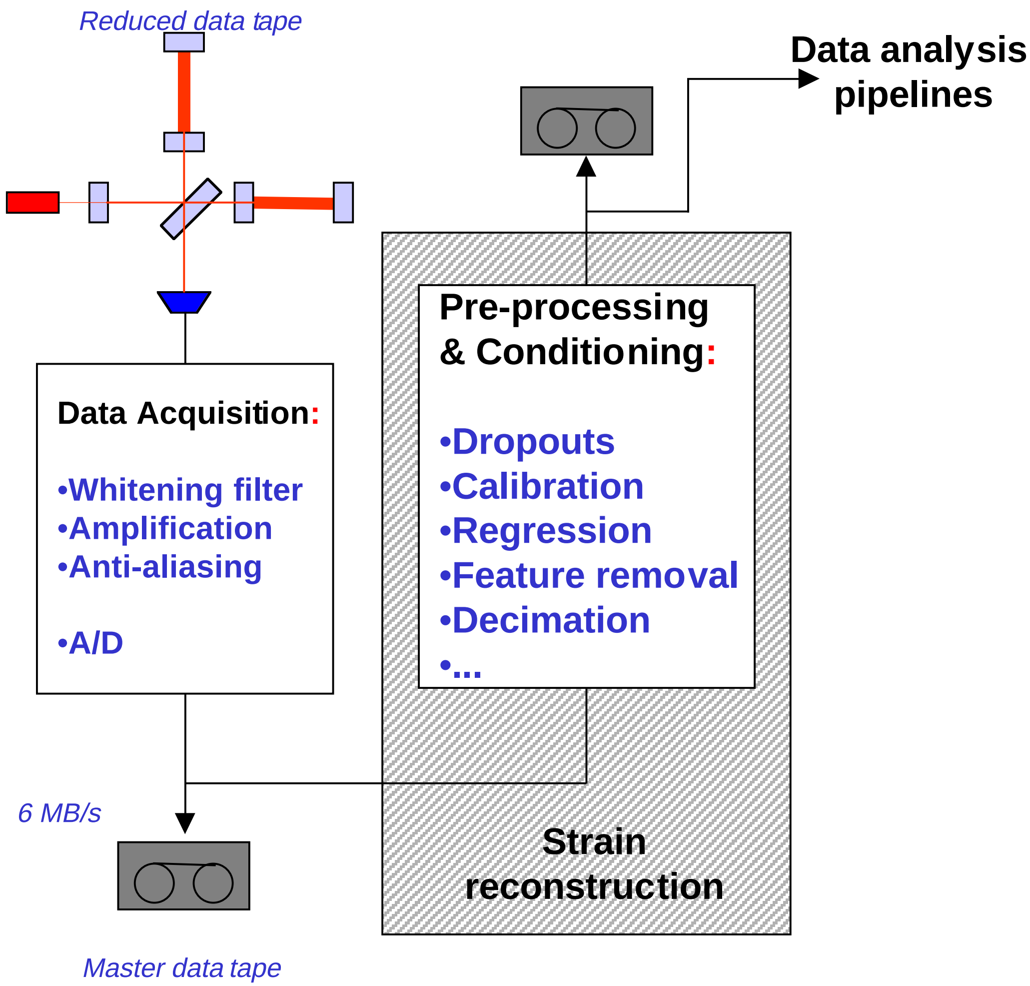
Interferometer Data Channels



- **All interferometric detector projects have agreed on a standard data format**
- **Anticipates joint data analysis**
- **LIGO Frames for 1 interferometer are ~3MB/s**
    - **32 kB/s strain**
    - **~2 MB/s other interferometer signals**
    - **~1MB/s environmental sensors**
    - ***Strain is ~1% of all data***



Data Flow: Pre-processing



Template Loop

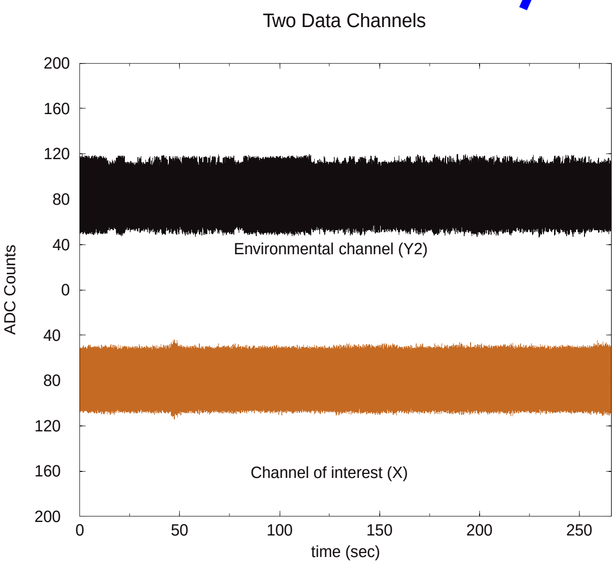
Data Pre-processing: removing instrumental effects

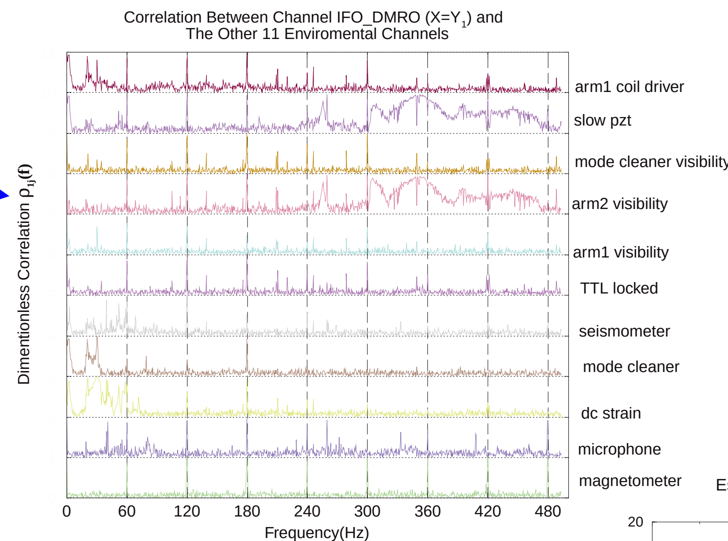
- Cross channel regression will be used to improve signal to noise ratios when possible (need adequate SNR)

Raw channel data (40m prototype)

$$s_a(t) \Rightarrow \hat{s}_a(f)$$

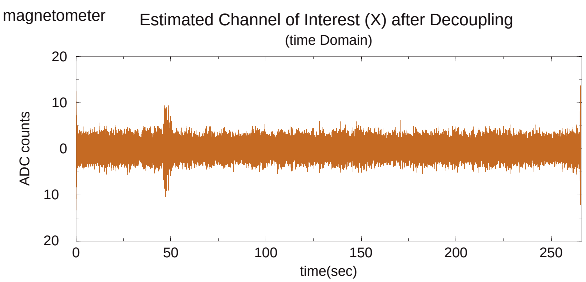
$$s_b(t) \Rightarrow \hat{s}_b(f)$$





Cross channel spectral correlation

$$\Gamma_{ab}(f) \equiv \frac{\left|\hat{s}_{ab}(f)\right|^2}{\hat{s}_a(f)\ \hat{s}_b(f)}$$



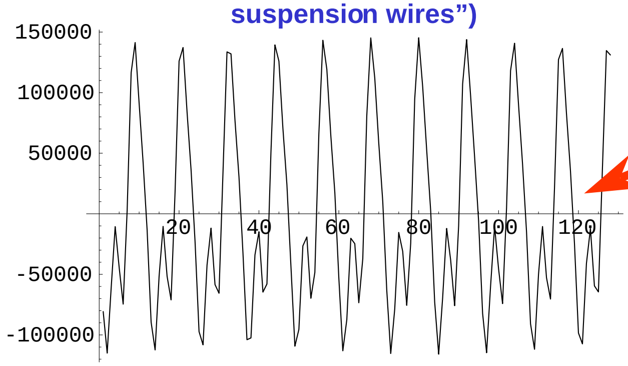
$$\begin{pmatrix} \hat{s}'_a(t) \\ \hat{s}'_b(t) \end{pmatrix} \Leftarrow \begin{pmatrix} \hat{s}'_a(f) \\ \hat{s}'_b(f) \end{pmatrix} = M(f) \cdot \begin{pmatrix} \hat{s}_a(f) \\ \hat{s}_b(f) \end{pmatrix}$$

Reduced data channel

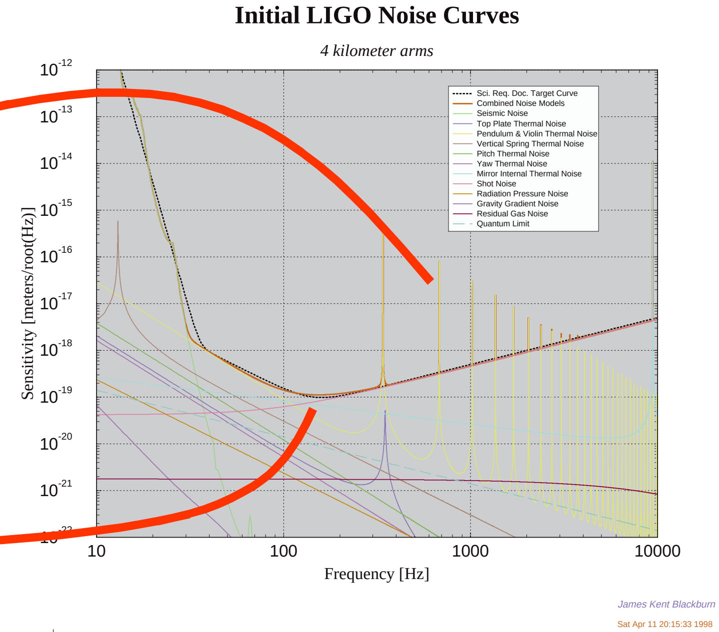
ref: Allen, Hua, Ottewill (gr-qc/9909083)

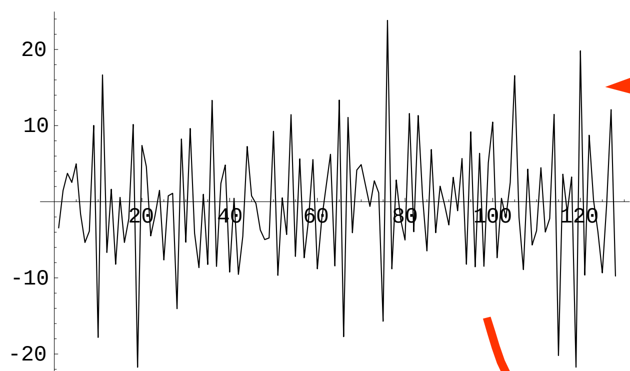
Interferometer Strain Signal (Simulated)

Dominated by narrowband features in spectrum (“violin resonances” of suspension wires”)

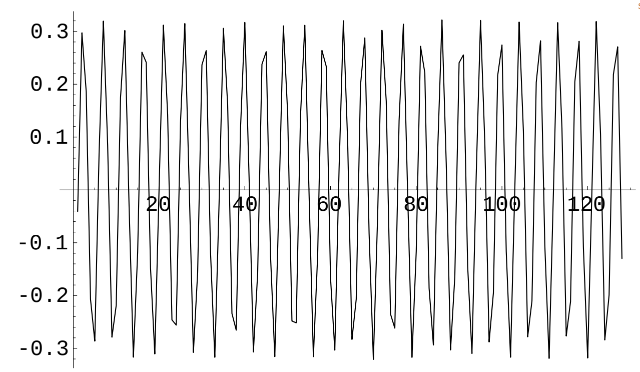


Design LIGO I limiting strain sensitivity



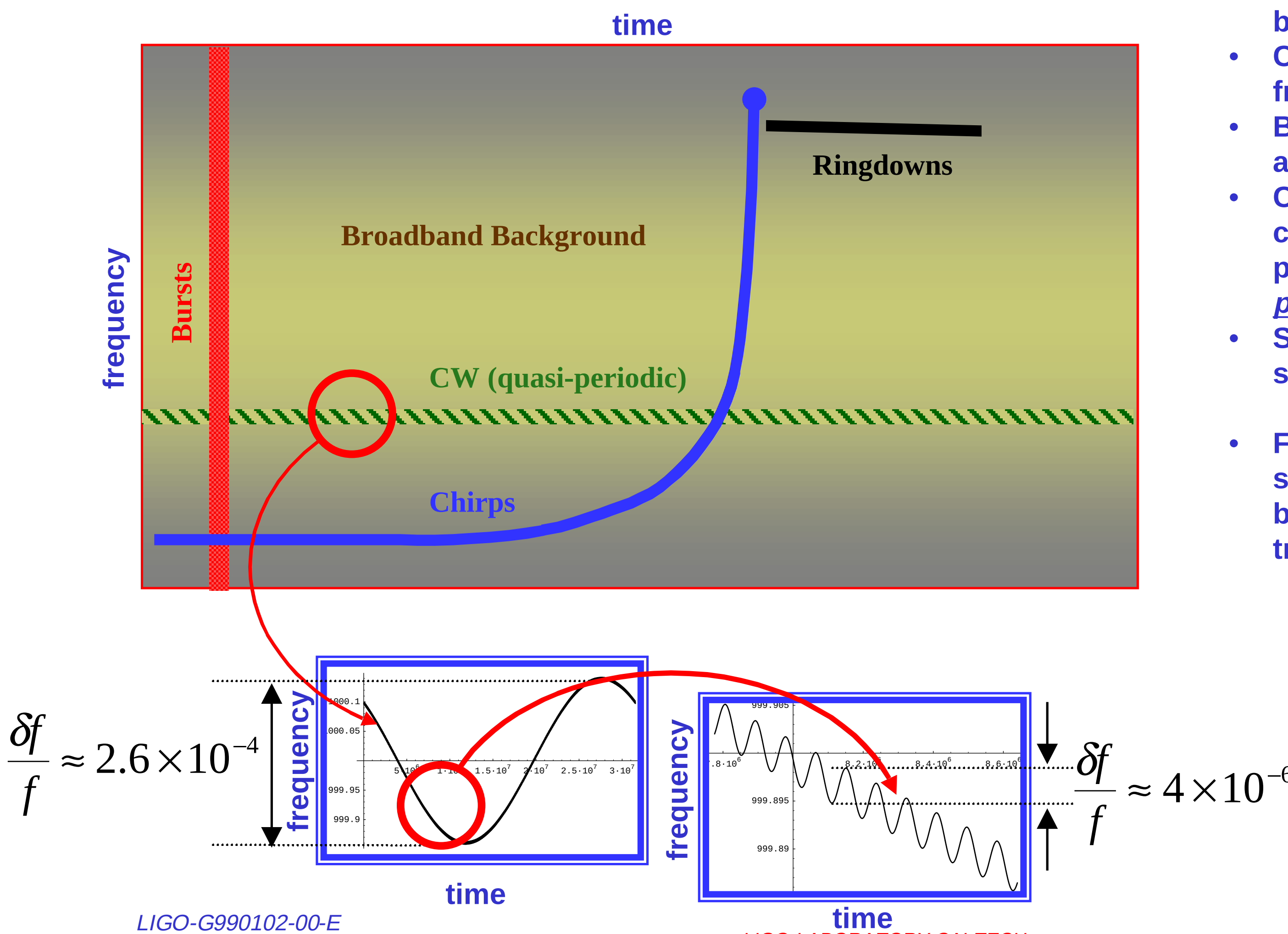


Broadband noise spectrum



Chirped waveform

Frequency-Time Characteristics of GW Sources



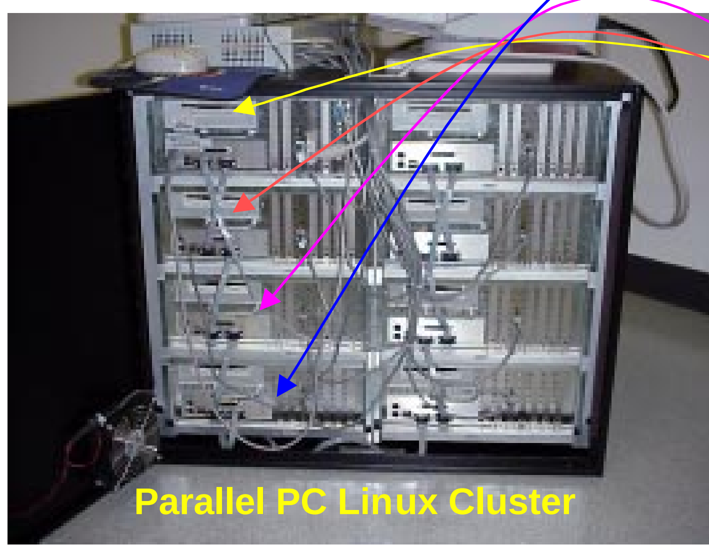
- **Bursts are short duration, broadband events**
- **Chirps explore the greatest time-frequency area**
- **BH Ringdowns expected to be associated with chirps**
- **CW sources have FM characteristics which depend on position on the sky (*and source parameters*)**
- **Stochastic background is stationary and broadband**

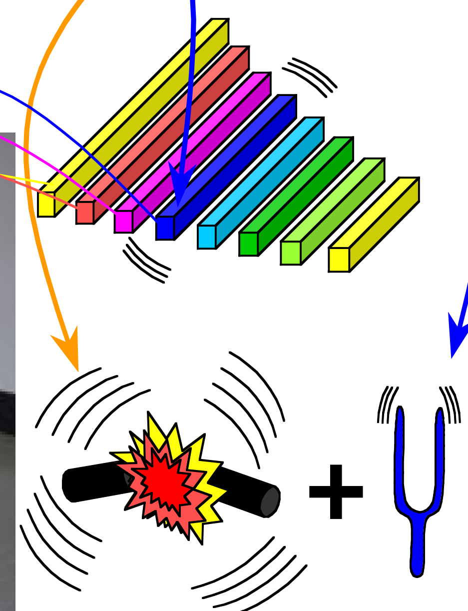
- **For each source, the optimal signal to noise ratio is obtained by integrating signal *along* the trajectory**
  - **If SNR >> 1, kernel ∝ |signal|^2**
  - **If SNR ≤ 1, kernel ∝ |template* signal| or $|signal_j^* signal_k|$**
  - **Optimal filter: kernel ∝ 1/(noise power)**

Optimal Wiener Filtering

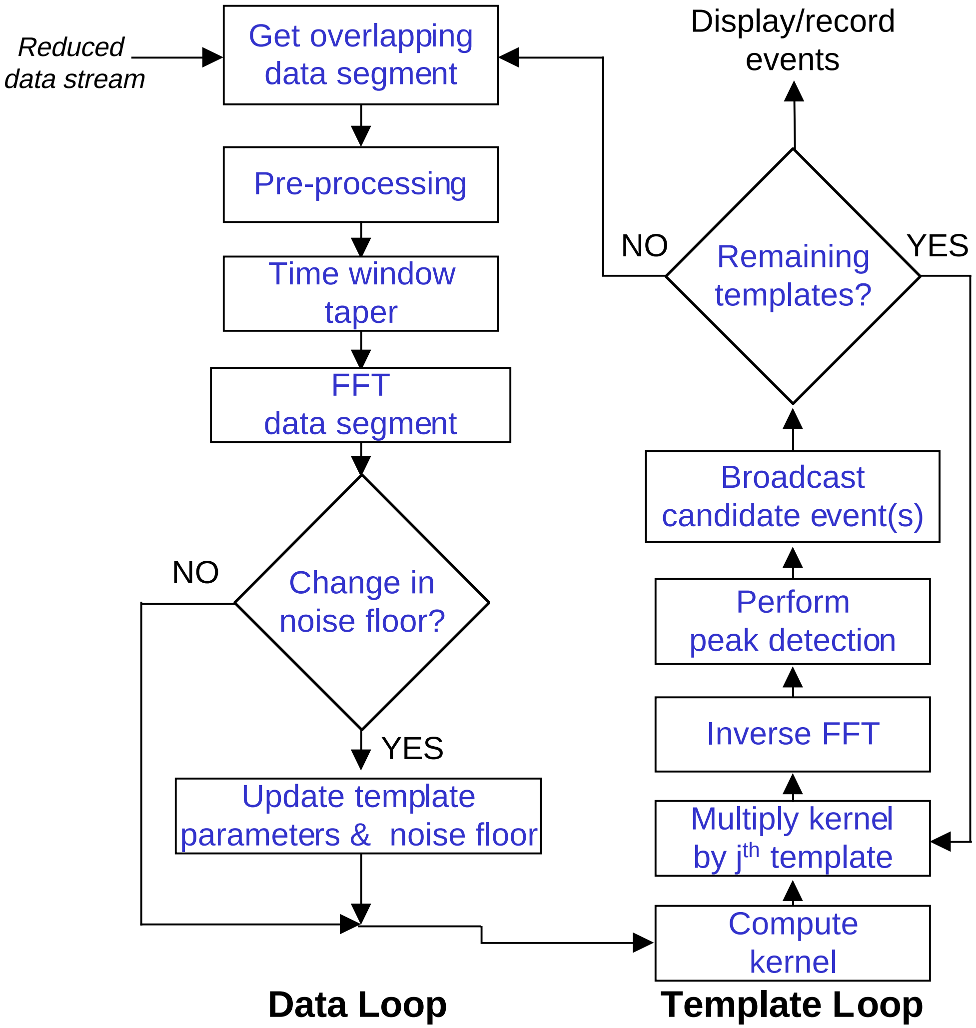
- Matched filtering (optimal) looks for best overlap between a signal and a set of expected (template) signals in the presence of the instrument noise -- correlation filter
- Replace the data time series with an SNR time series
- Look for excess SNR to flag possible detection

$$\xi_p[t_c] = \int \frac{\hat{T}_p^*(f)\ \hat{s}(f)}{\hat{S}_n(|f|)} e^{-2\pi i f t_c} df$$





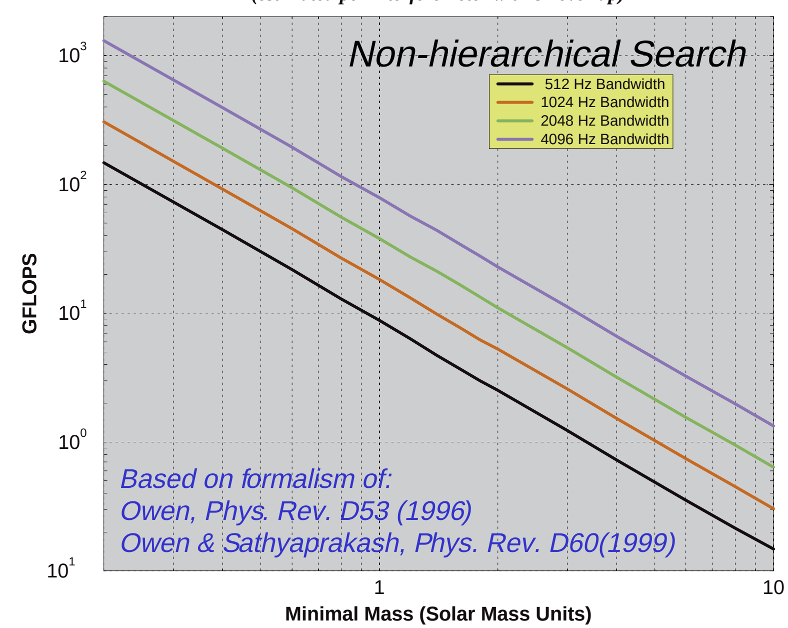
Compact Binary Inspirals Data Analysis Flow



$$\xi_p[t_c] = 2\int \frac{\hat{T}_p^*(f)\ \hat{s}(f)}{\hat{S}_n(|f|)} e^{-2\pi i f t_c} df$$

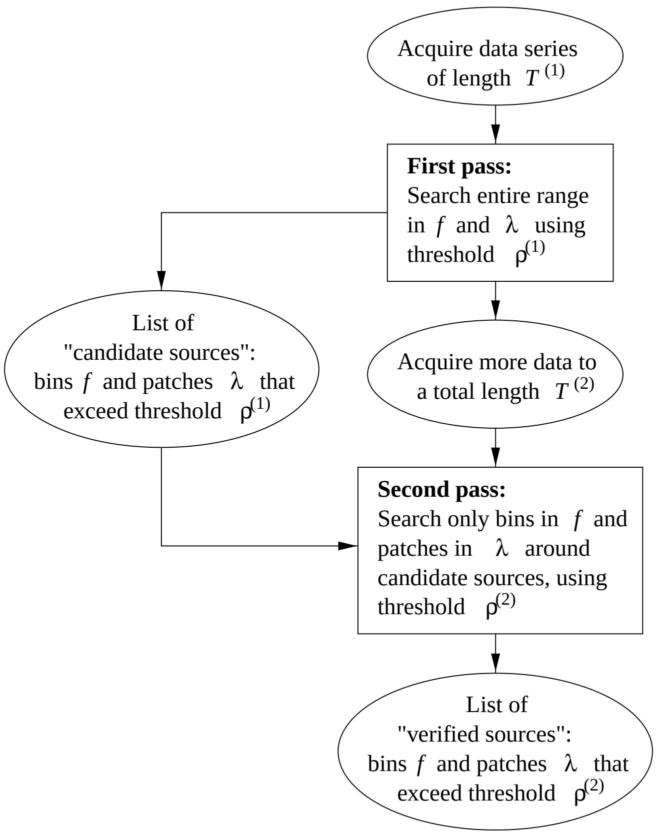
Binary Inspiral Template Compute Requirements

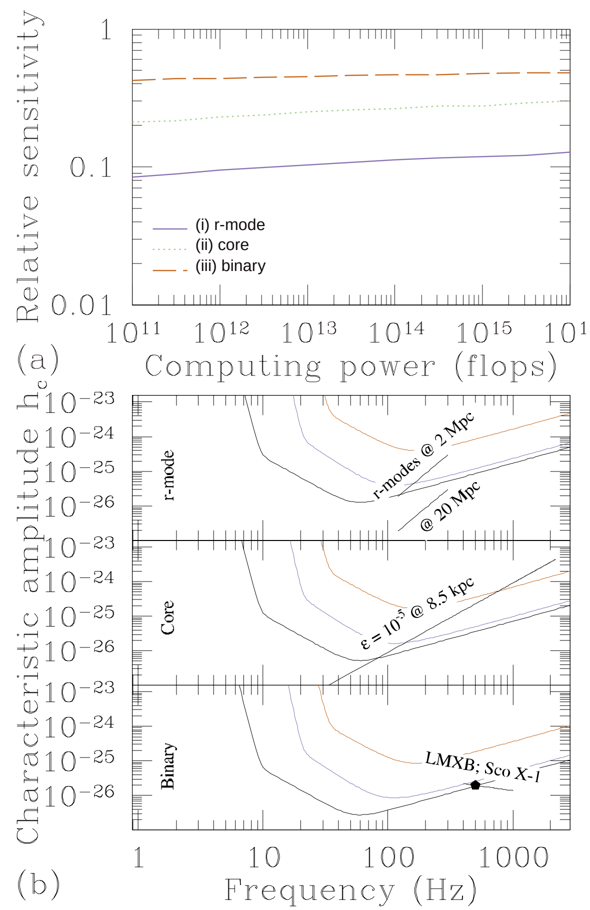
(estimated per interferometer with 8x overlap)



- **Process data at real time rate**
- **Improvements:**
  - ***Hierarchical searches being developed***
  - ***Phase coherent analysis of multiple detectors (Finn, in progress)***

CW Sources
Hierarchical (Constrained) Search





ref: Brady & Creighton gr-qc/981204

Search Approaches for Other GW Sources

- Burst events (unmodeled)
  - *Cross correlate detector outputs over narrow time window*
  - *Look for excess power*
  - *Use environmental vetoes*
  - *Look for few parametric templates (e.g., wavelets)*
  - *CPU: Workstation(s)*

$$S(t) = \iint_0^{T_B} dt'\, dt''\, s_1(t-t')\,Q(t''-t')\,s_2(t-t'')$$

$$Q(\tau) = \int df \quad e^{-2\pi i f \tau} \frac{\hat{h}^*_{B,1}(f)\hat{h}_{B,2}(f)}{S_1(|f|)S_2(|f|)}$$

ref: Finn, Mohanty, Romano gr-qc/9903101

- Stochastic background search
  - *Correlate & integrate signals from pairs of interferometers*
  - *Look for excess power in band consistent with baseline separation*
  - *CPU: Workstation(s)*

$$S_{(\alpha)} = T_{\text{int}} \int_{f_{\min}}^{f_{\max}} \frac{\hat{s}^*_1(f)\hat{s}_2(f)\Omega^{(\alpha)}_{GW}(|f|)\gamma(|f|)}{f^3 S_1(|f|)S_2(|f|)} df$$

ref:
Michelson, 1987
Christensen, 1992
Flannigan, 1993
Allen & Romano gr-qc/9710117

Joint Data Analysis Among GW projects
From detection to validation

- For a *putative* detection:
  - Environmental, instrumental vetoes?
  - (Δt_i, $\Delta\Omega_i$): Seen by all detectors within consistent (time, position) windows?
  - Δh_i: Is the amplitude of the signal consistent among detectors*?
  - $\Delta\alpha_i$: Are the deduced model parameters consistent?
- Follow up analyses
  - Independent
  - Coherent multi-detector analysis - maximum likelihood over all detectors: {t,Ω,h,α}
- Discrepancies should be explainable, e.g.:
  - Not on line
  - Below noise floor
  - *Different polarization sensitivity*, etc.*

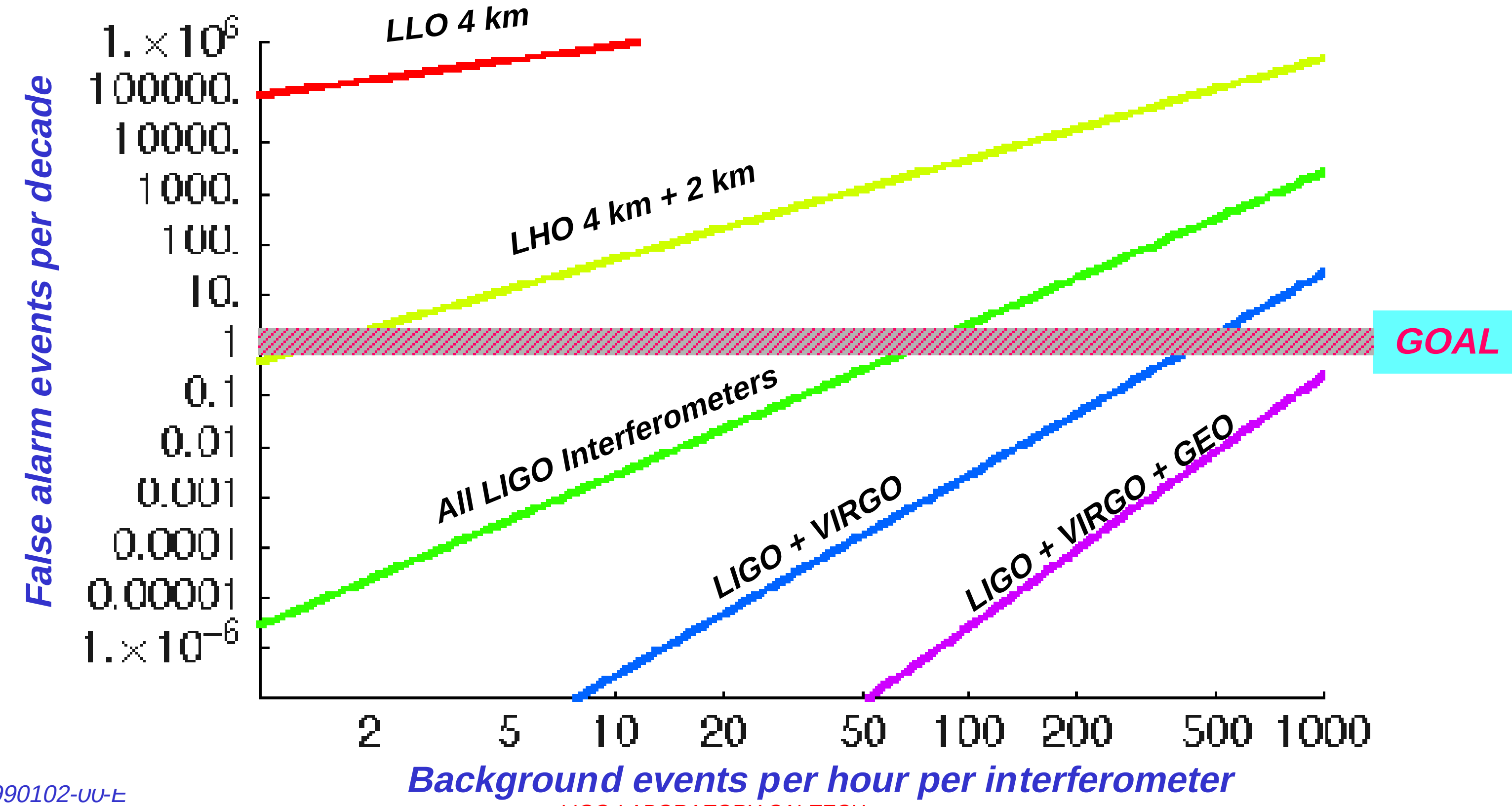
$$h_i \to \vec{h}$$

$$\ln\Lambda(h_i,\theta_i) \to \ln\Lambda(\vec{h},\vec{\theta})$$

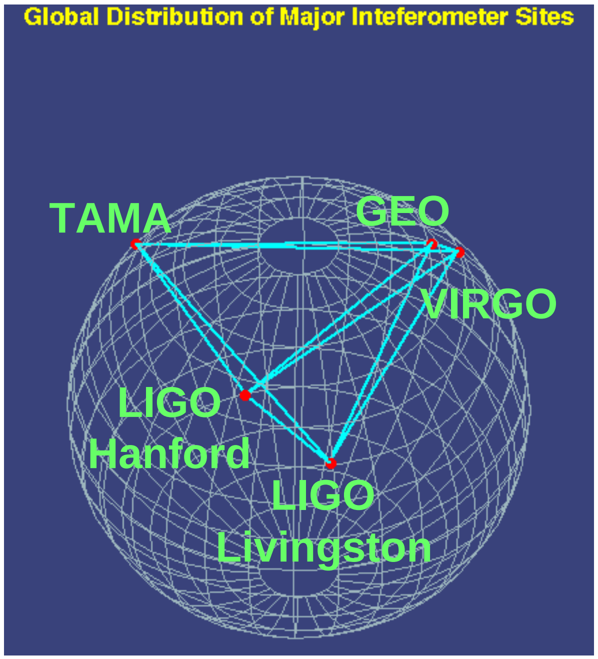
$$\sigma_i^2 \to C_{kl} \equiv \langle \vec{n}_k \otimes \vec{n}_l \rangle$$

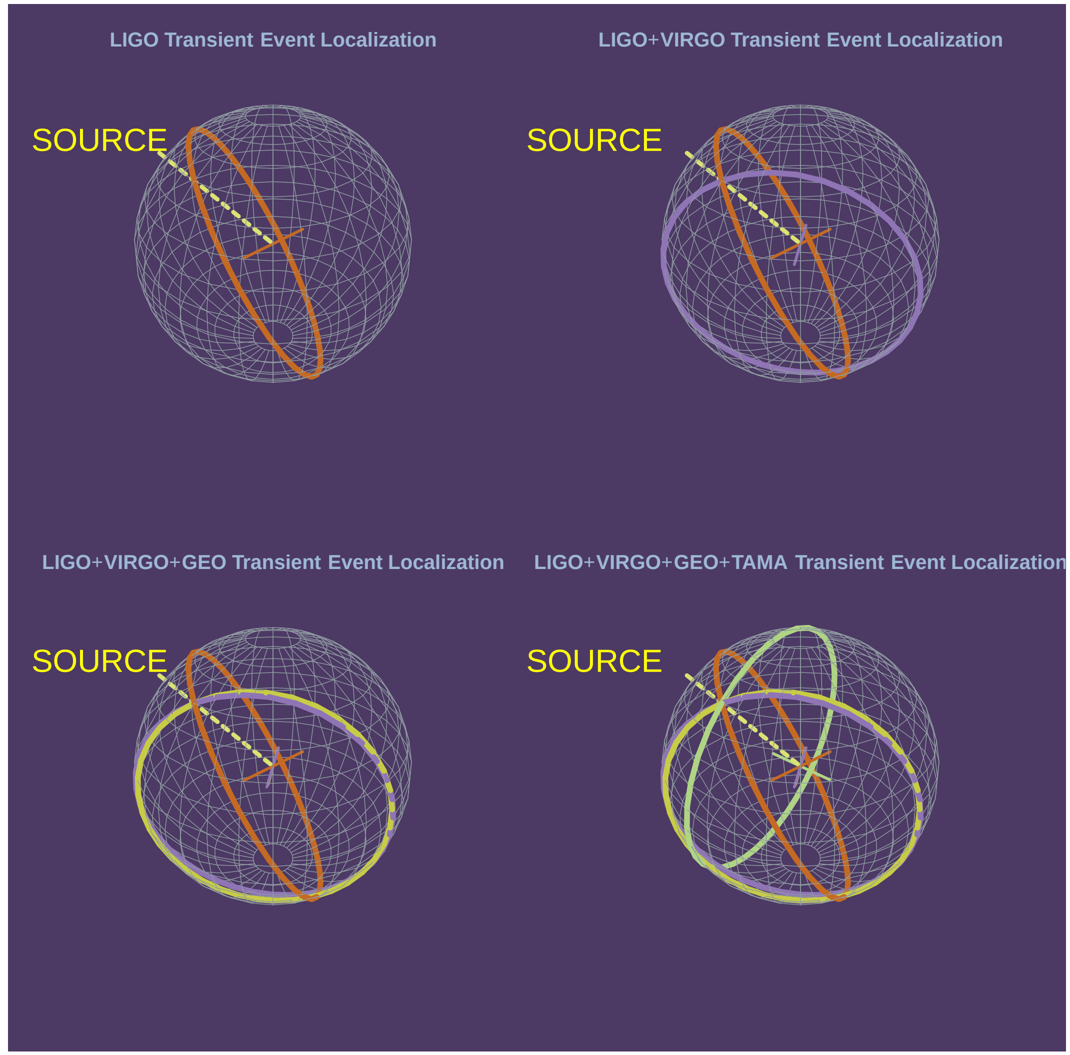
Coincidence windows among detectors

- Rejection of statistically <u>uncorrelated</u> random events
  - *Coincidence window duration determine by baselines*



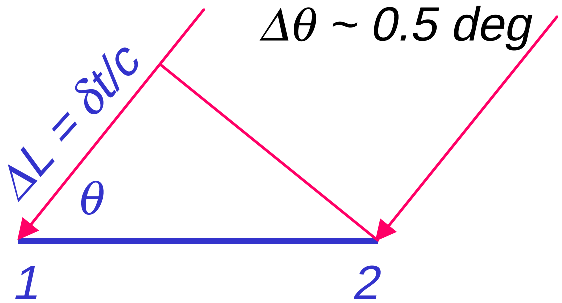
Event Localization With An Array of GW Interferometers





$\cos\theta = \delta t / (c\, D_{12})$

$\Delta\theta \sim 0.5$ deg



Joint Data Analysis Among GW projects

- Protocols being put in place by GWIC (Gravitational Wave International Committee)
  - *Commonality of data*
    - *Formats*
    - *Reduced data sets*
  - *Standards for software, validation techniques*
  - *Techniques to combine data from the elements of a network for different types of searches*
    - *Event lists (first pass)*
    - *Phase coherent processing (second pass)*
  - *Shared computational facilities, resources*
  - *Concepts for a common publication policy*
  - *Concepts for establishing an astronomical alert*

The Opening of a New Observational Window on the Universe

- LIGO, VIRGO, GEO, TAMA … ca. 2003+
  – *4000m, 3000m, 2000m, 600m, 300m interferometers built to detect gravitational waves from compact objects*

! *Discover ...*