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

**On the Occasion of the Inauguration of LIGO**

*LIGO Livingston Obs*

*11 November*

*Albert Lazzarini*

*LIGO Laboratory*

*California Institute of Technology*

*Pasadena, California 91125*



## *Ultimate Goals for the Detection of Gravitational Waves*

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- 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*

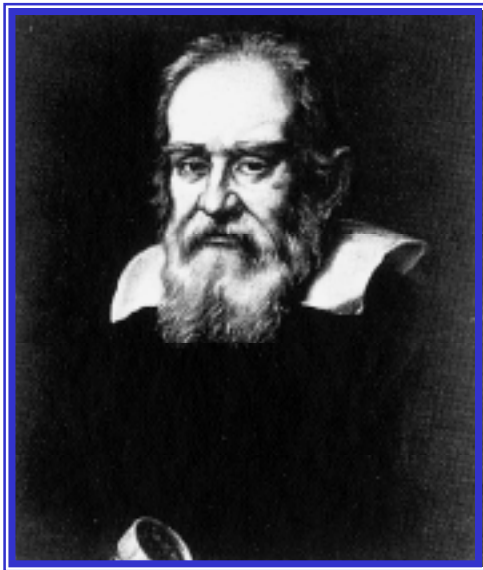
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- Galileo Galilei, 1610
  - *Improves on Lipperhey's opera glass to make a 9x telescope --*
    - *! discovers Gallilean moons of Jupiter*
- Karl Jansky, 1933
  - *Builds directional radio antenna to study RF interference in trans-Atlantic telephone 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  $\gamma$ -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 “Galilean” moons of Jupiter*



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



Voyager 1, 1979

<http://photojournal.jpl.nasa.gov>



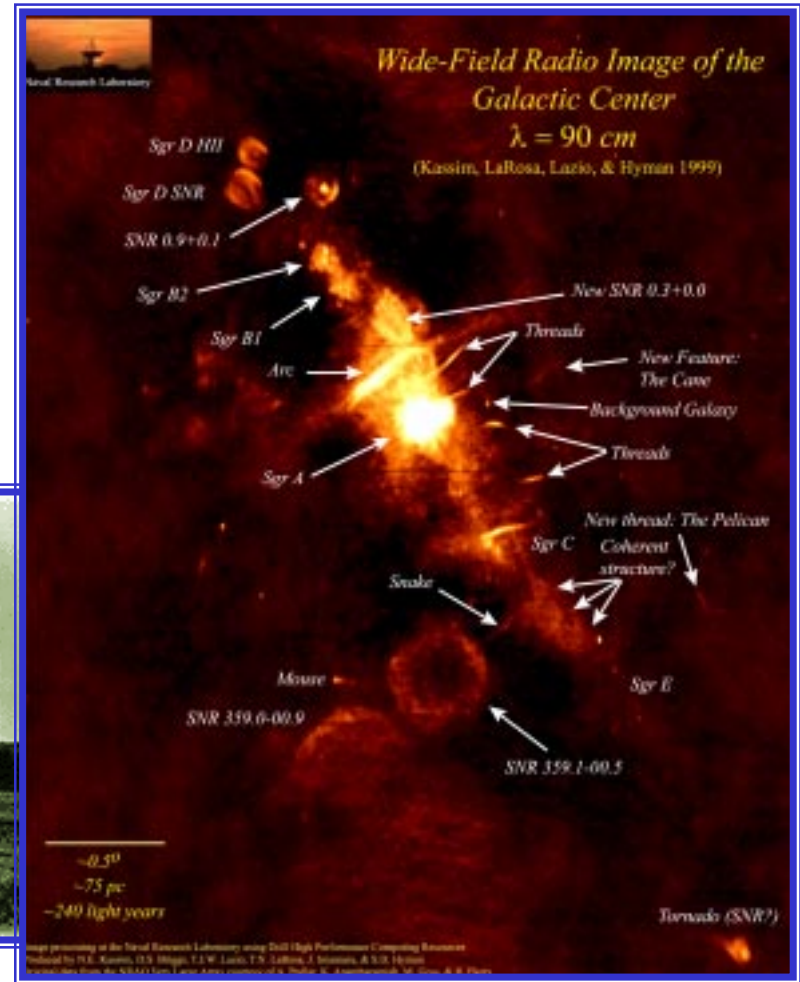
# The Opening of a New Observational Window on the Universe

- Karl Jansky, 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/>



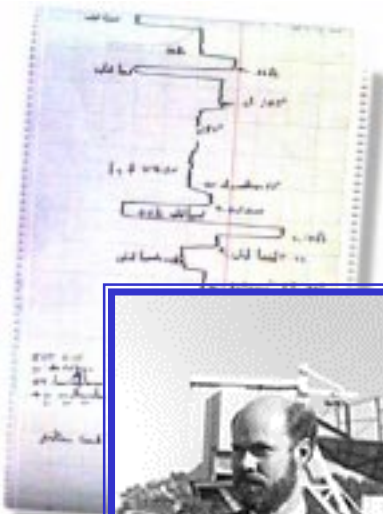
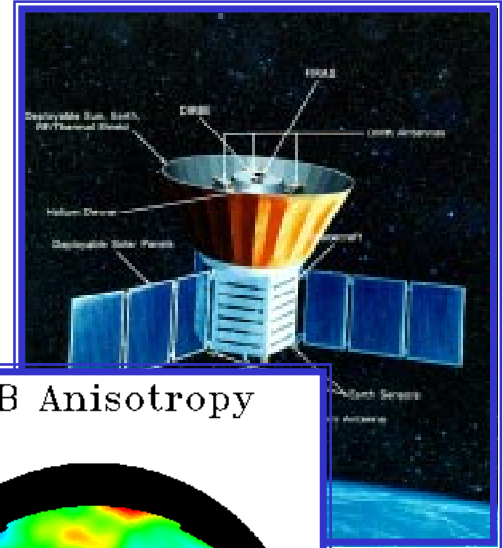


# The Opening of a New Observational Window on the Universe

- Penzias & Wilson, 1963
  - Track down excess antenna noise

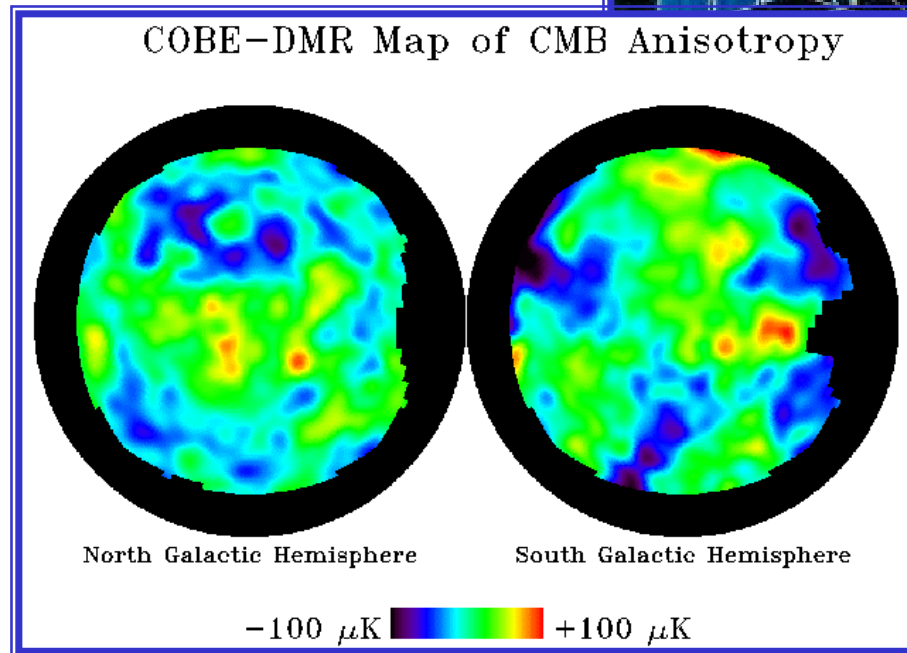
**! Observe the cosmic microwave background radiation (CMBR)**

[http://www.gsfc.nasa.gov/astro/cobe/cobe\\_home.html](http://www.gsfc.nasa.gov/astro/cobe/cobe_home.html)



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

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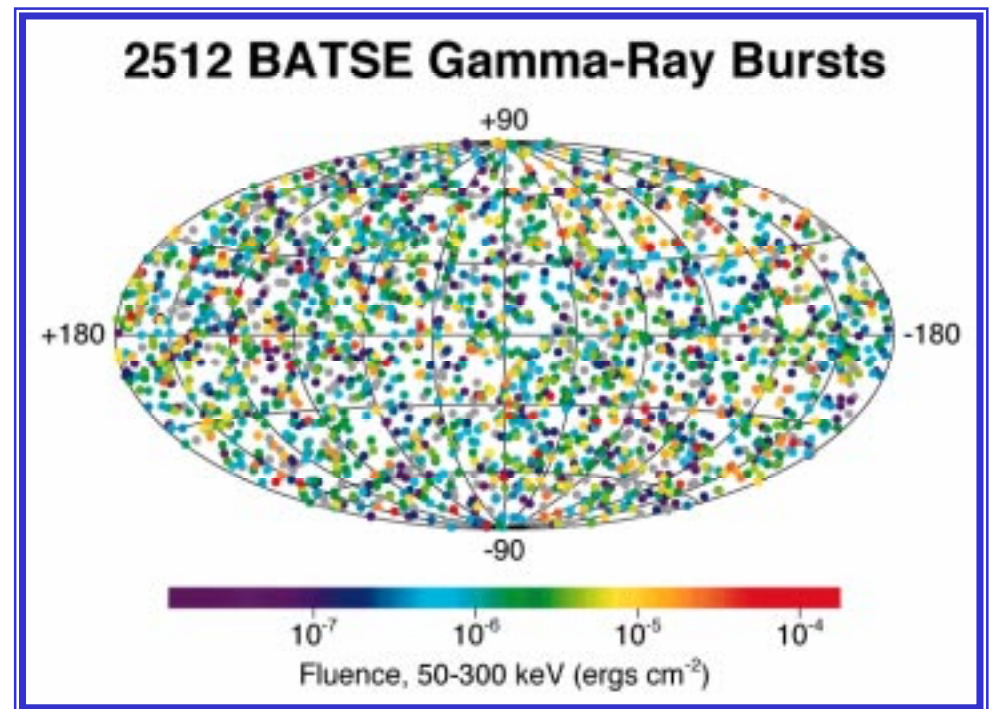
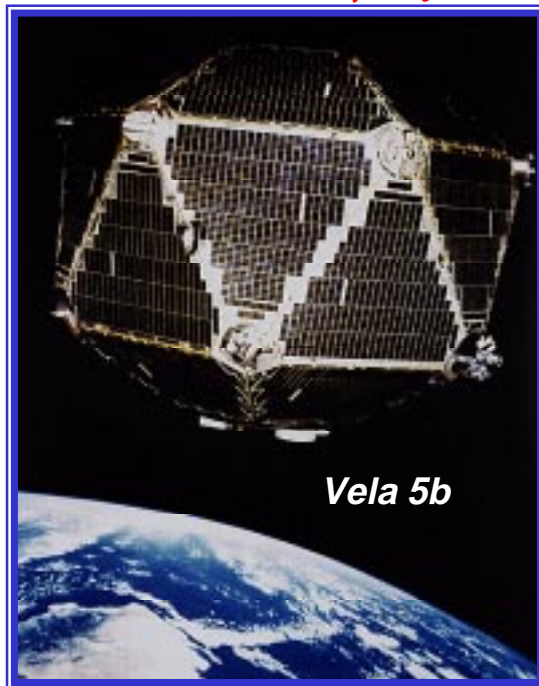


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## *The Opening of a New Observational Window on the Universe*

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



[http://science.msfc.nasa.gov/newhome/headlines/ast19sep97\\_2.htm](http://science.msfc.nasa.gov/newhome/headlines/ast19sep97_2.htm)

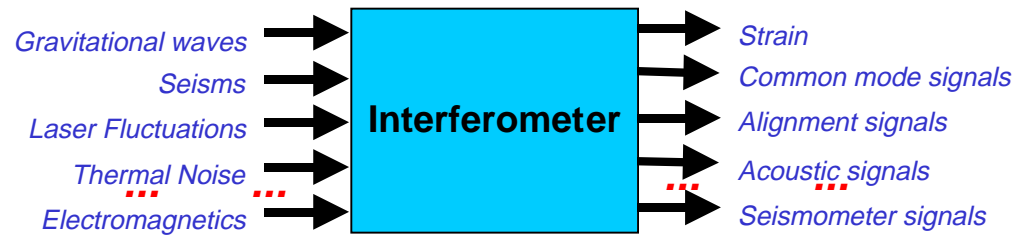
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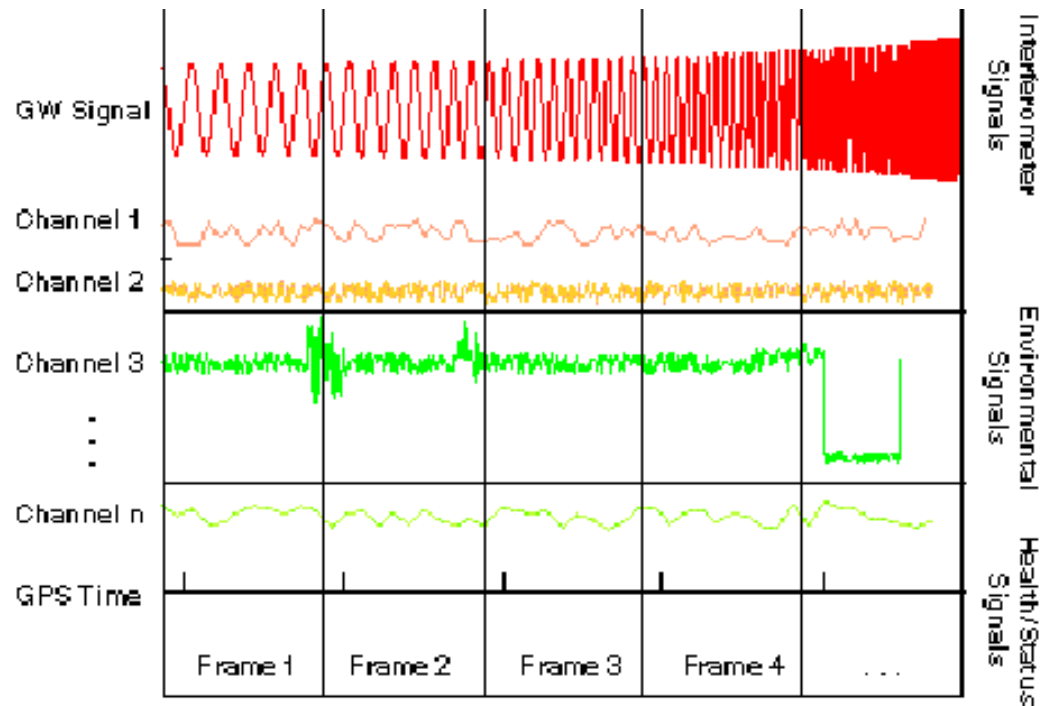
<http://www.batse.com/>



# Interferometer Data Channels



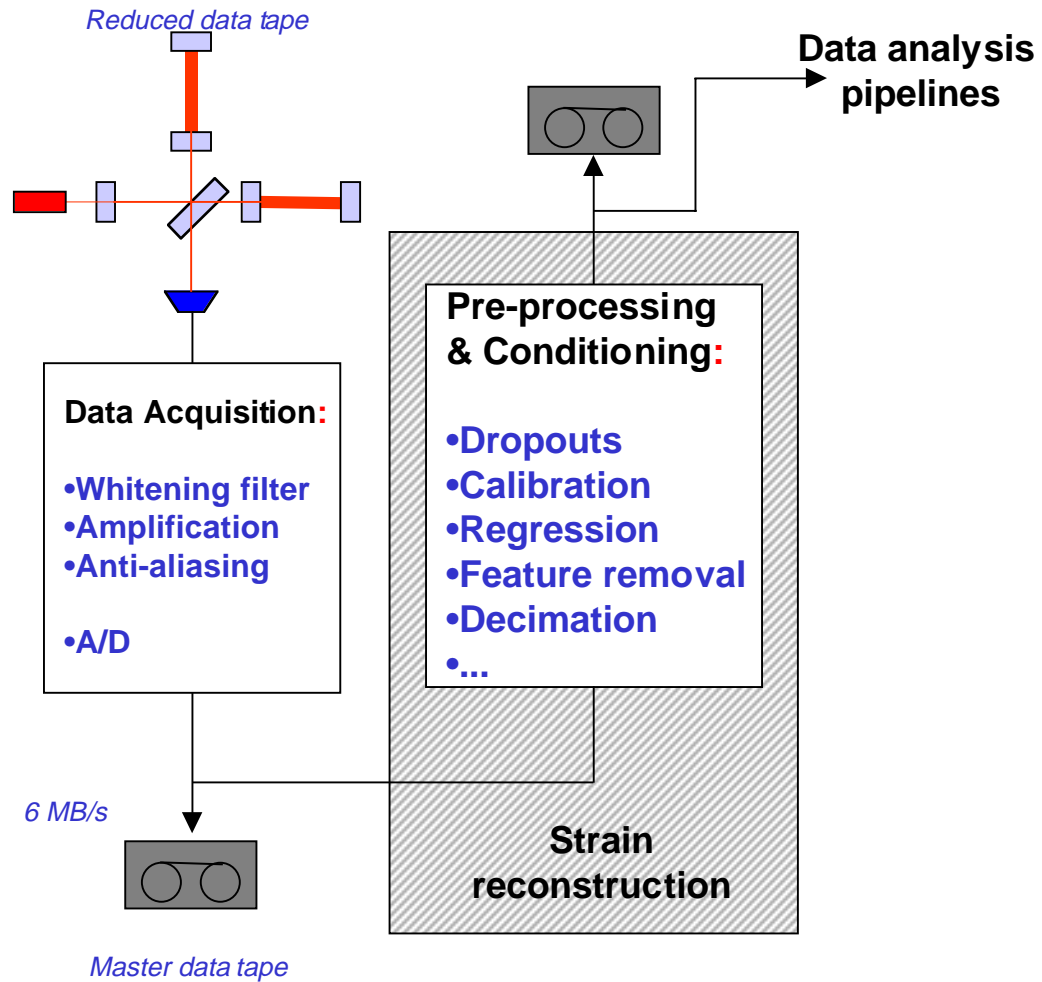
- All interferometric detector projects have agreed on a standard data format
- Anticipates joint data analysis
- LIGO Frames for 1 interferometer are ~3MB/s
  - 32 kB/s strain
  - ~2 MB/s other interferometer signals
  - ~1MB/s environmental sensors
- Strain is ~1% of all data







# Data Flow: Pre-processing





# Data Pre-processing: removing instrumental effects

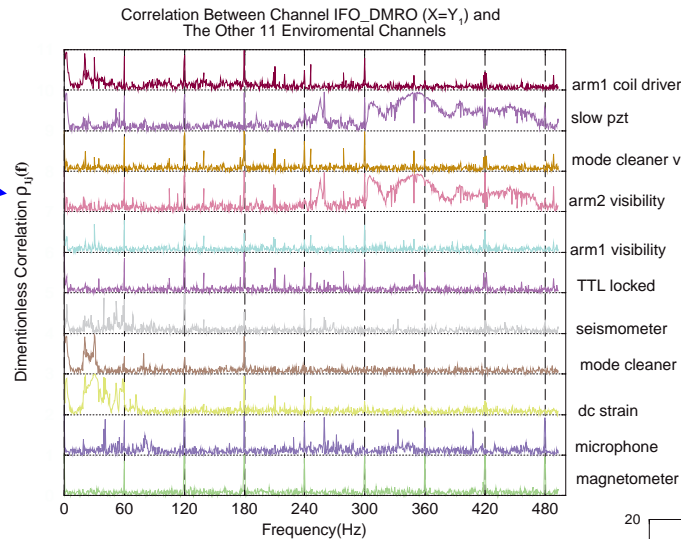
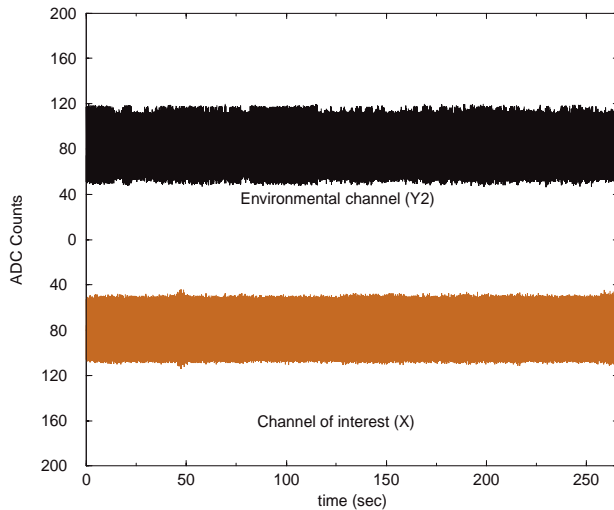
- Cross channel regression will be used to improve signal to noise ratios when possible (need adequate SNR)

Raw channel data (40m prototype)

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

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

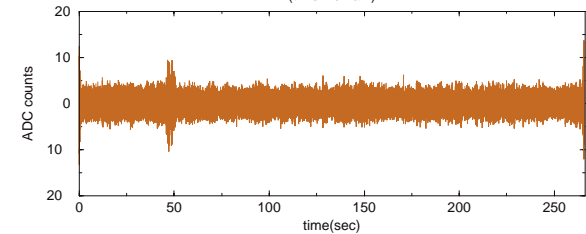
Two Data Channels



Cross channel spectral correlation

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

Estimated Channel of Interest (X) after Decoupling (time Domain)



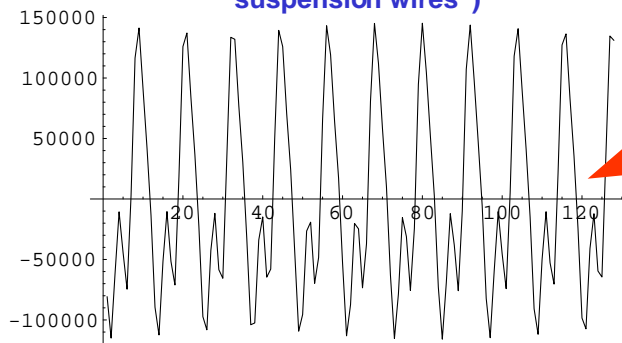
$$\begin{pmatrix} \hat{s}'_a(t) \\ \hat{s}'_b(t) \end{pmatrix} \Leftarrow \begin{pmatrix} \hat{s}'_a(f) \\ \hat{s}'_b(f) \end{pmatrix} = M(f) \cdot \begin{pmatrix} \hat{s}_a(f) \\ \hat{s}_b(f) \end{pmatrix}$$

Reduced data channel

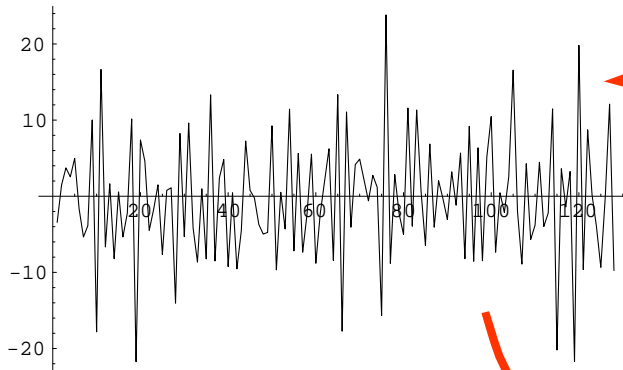
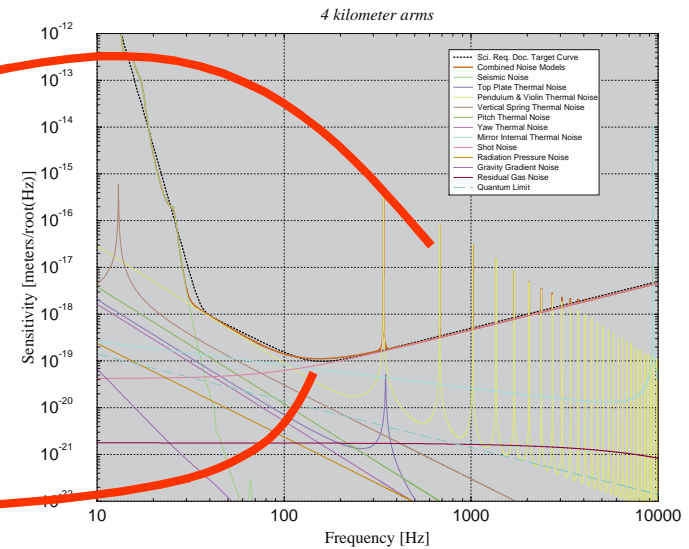


# Interferometer Strain Signal (Simulated)

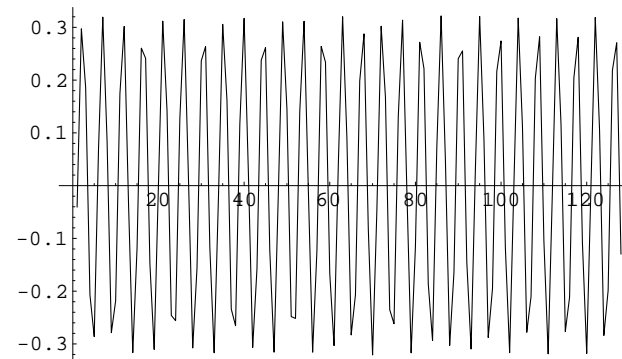
Dominated by narrowband features in spectrum  
("violin resonances" of suspension wires)



Design LIGO I limiting strain sensitivity  
Initial LIGO Noise Curves



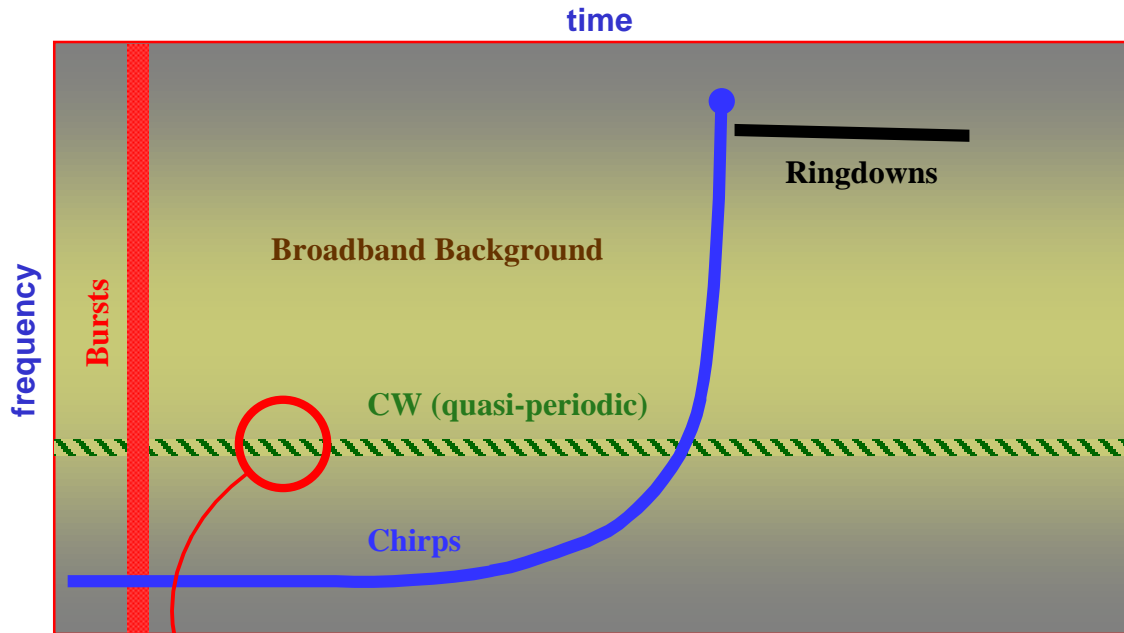
Broadband noise spectrum



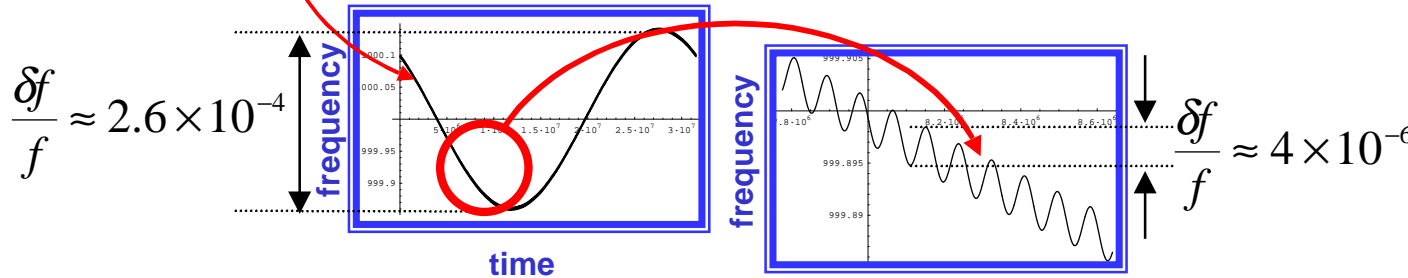
Chirped waveform



# 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  $SNR \gg 1$ , kernel  $\propto |\text{signal}|^2$
  - If  $SNR \leq 1$ , kernel  $\propto |\text{template}^* \text{signal}|$  or  $|\text{signal}_j^* \text{signal}_k|$
- Optimal filter: kernel  $\propto 1/(\text{noise power})$



$$\frac{\delta f}{f} \approx 2.6 \times 10^{-4}$$

$$\frac{\delta f}{f} \approx 4 \times 10^{-6}$$

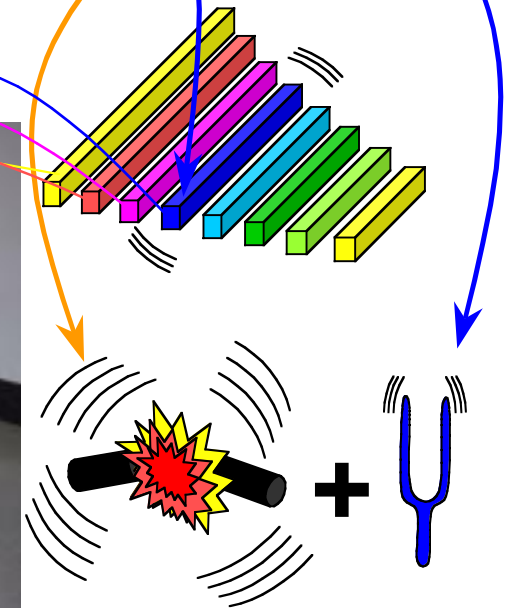
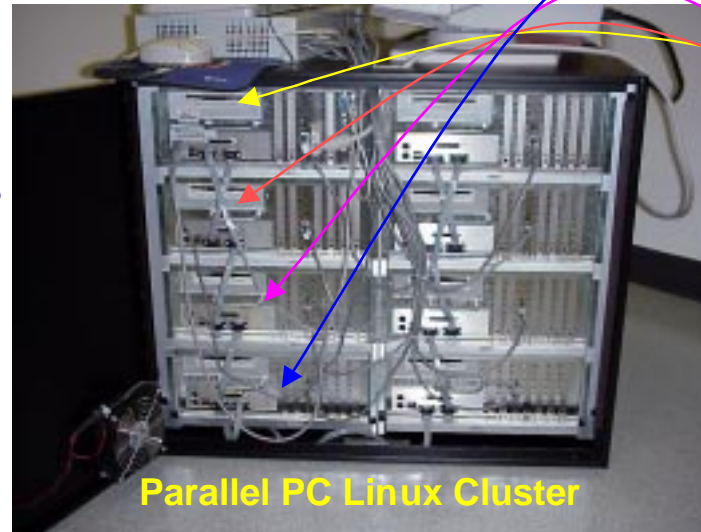
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## Optimal Wiener Filtering

- 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

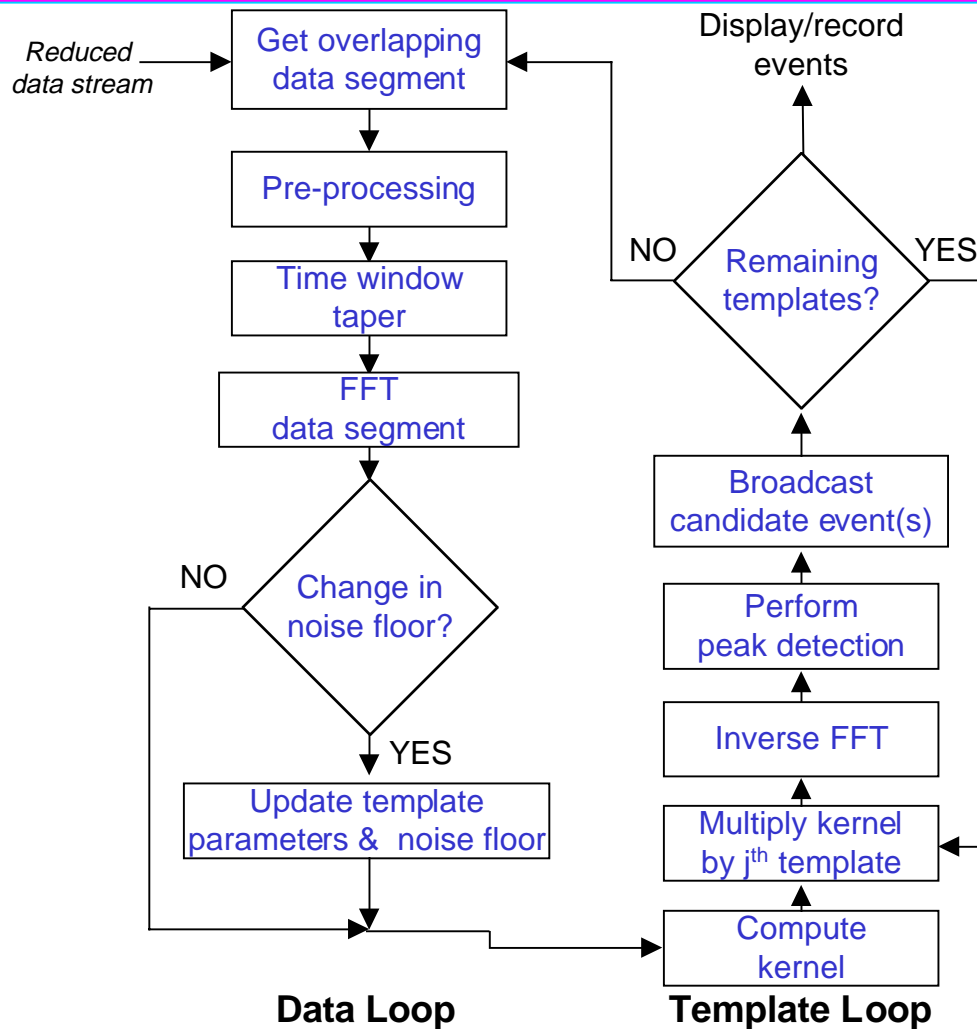
$$\xi_p[t_c] = \int \frac{\hat{T}_p^*(f) \hat{s}(f)}{\hat{S}_n(|f|)} e^{-2\pi i f t_c} df$$





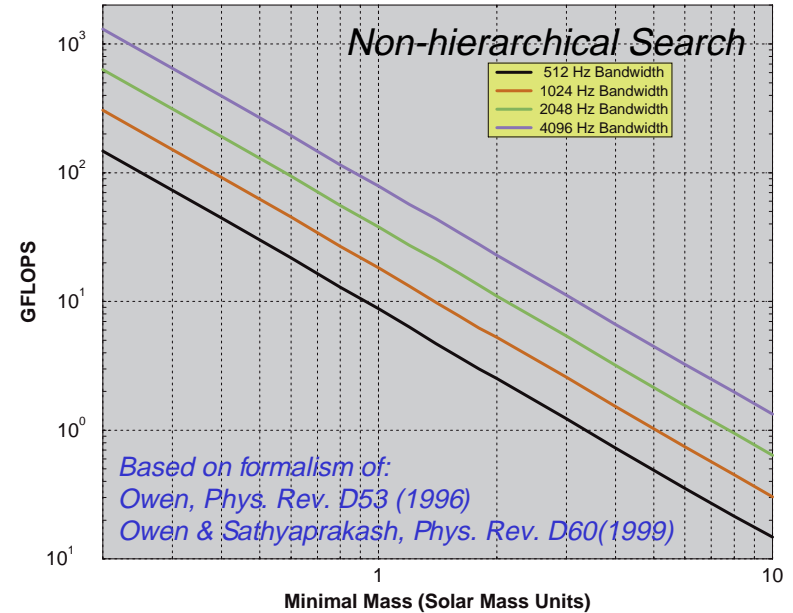


# Compact Binary Inspirals Data Analysis Flow



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

Binary Inspirals Template Compute Requirements  
(estimated per interferometer with 8x overlap)

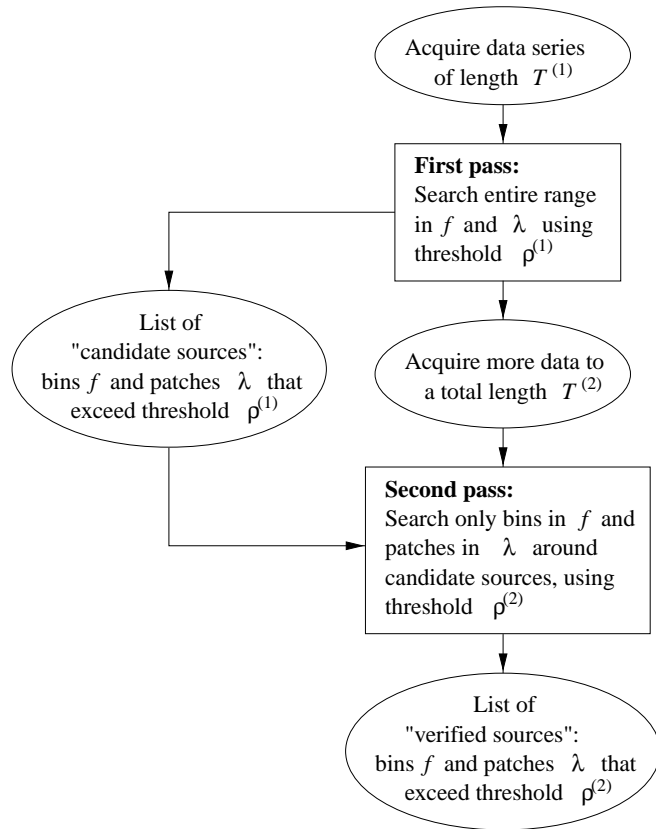


- Process data at real time rate
- Improvements:
  - Hierarchical searches being developed
  - Phase coherent analysis of multiple detectors (Finn, in progress)

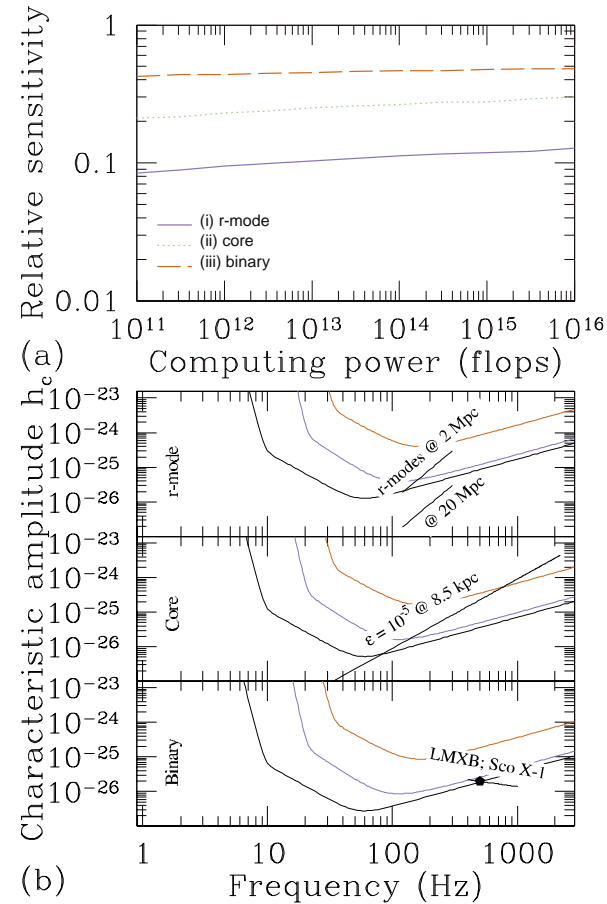


# CW Sources

## 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)

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

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

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)

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

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?

$(\Delta t_i, \Delta \Omega_i)$ : Seen by all detectors within consistent (time, position) windows?

$\Delta h_i$ : 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:  $\{t, \Omega, h, \alpha\}$

- Discrepancies should be explainable, e.g.:

- ♦ Not on line

- ♦ Below noise floor

- ♦ \*Different polarization sensitivity, *etc.*

$$h_i \rightarrow \vec{h}$$

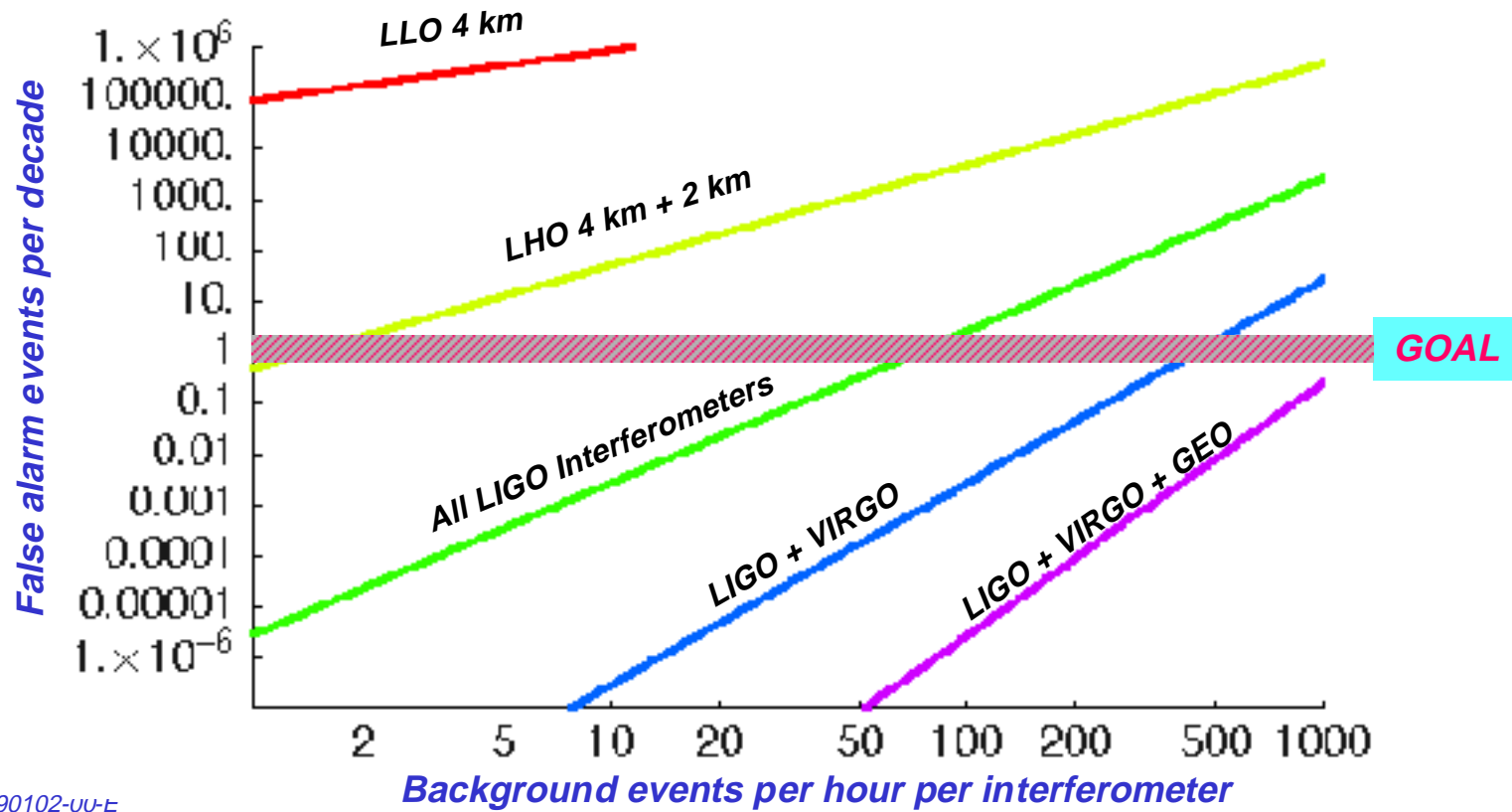
$$\ln \Lambda(h_i, \theta_i) \rightarrow \ln \Lambda(\vec{h}, \vec{\theta})$$

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



## Coincidence windows among detectors

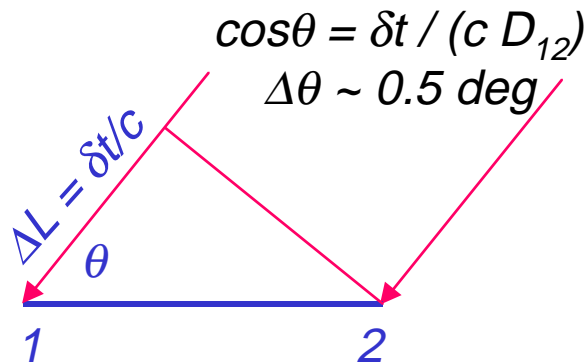
- Rejection of statistically uncorrelated random events
  - Coincidence window duration determine by baselines



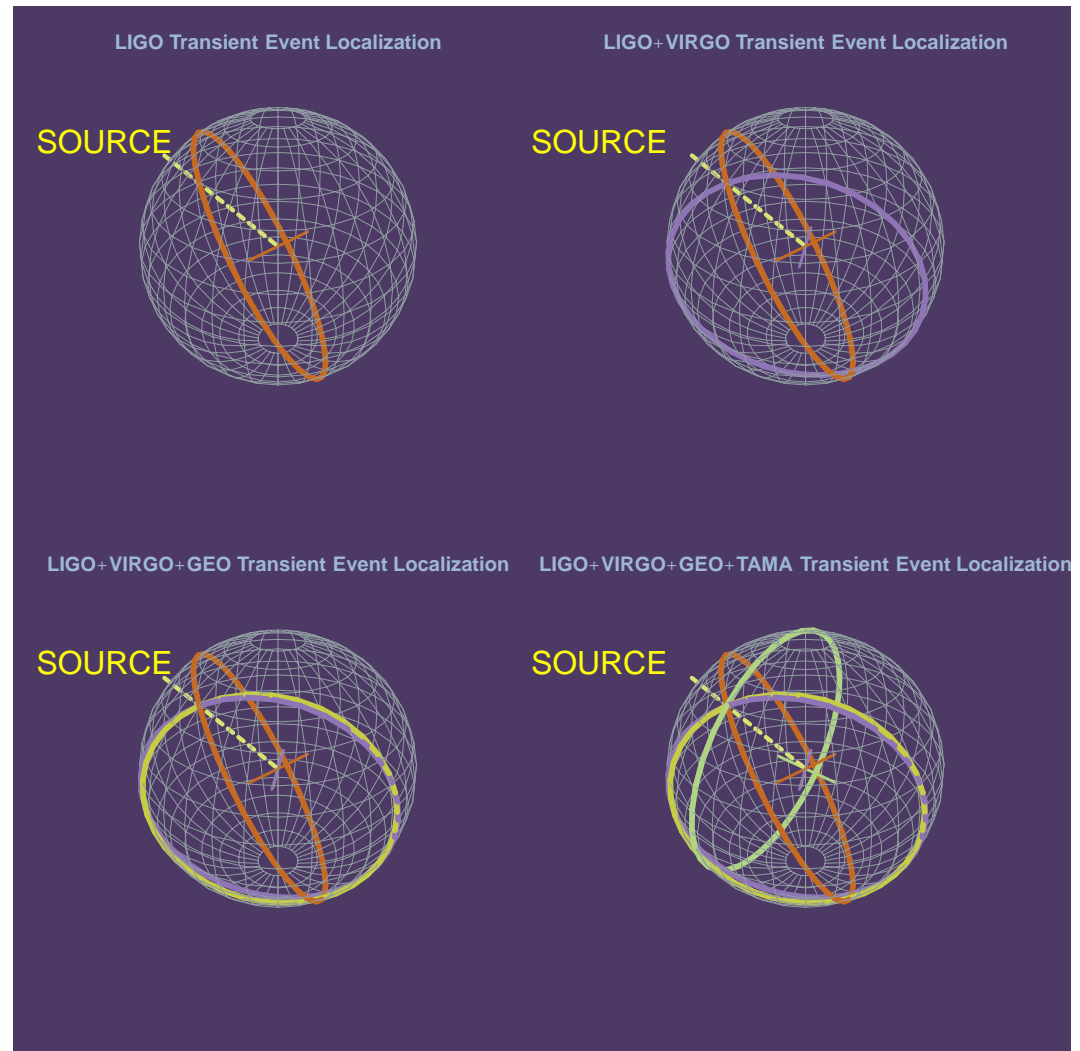




# Event Localization With An Array of GW Interferometers



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## *Joint Data Analysis Among GW projects*

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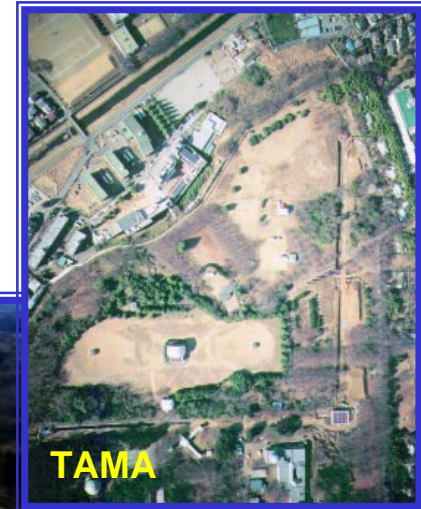
- Protocols being put in place by GWIC  
(Gravitational Wave International Committee)
  - *Commonality of data*
    - ♦ *Formats*
    - ♦ *Reduced data sets*
  - *Standards for software, validation techniques*
  - *Techniques to combine data from the elements of a network for different types of searches*
    - ♦ *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 ...*



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