The View from the Ground: Gravitational Wave Detectors and Data Analysis Techniques

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Gravitational Wave / Cosmology Workshop
East Tennessee State University
November 4-5, 2005

LIGO-G050571-00-Z

Outline

Ground-based GW detectors

GW signal types

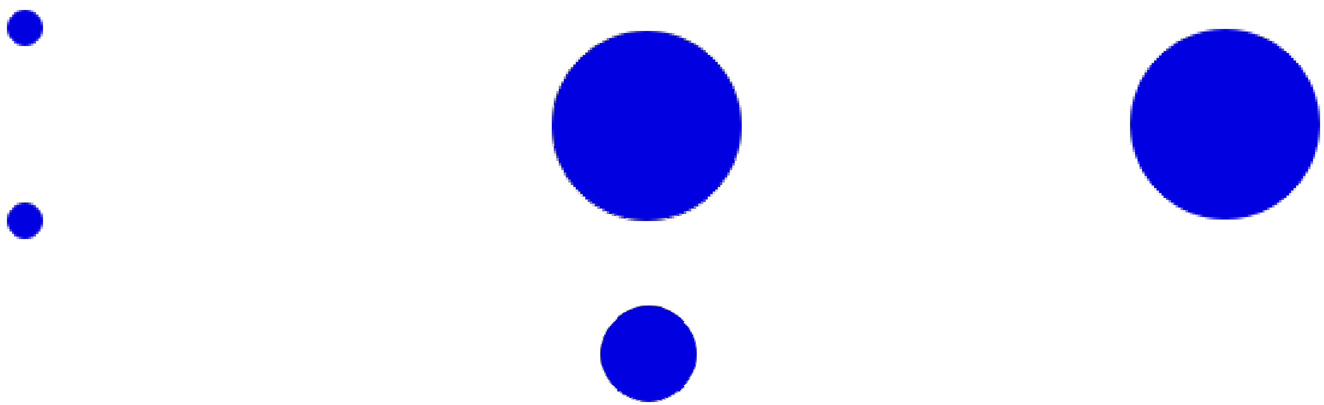
Analysis Techniques

Statistical issues

Multi-site coherent analysis

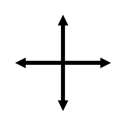
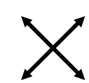
Gravitational Wave Basics

Two massive, compact objects in a tight orbit deform space (and any object in it) with a frequency which is twice the orbital frequency

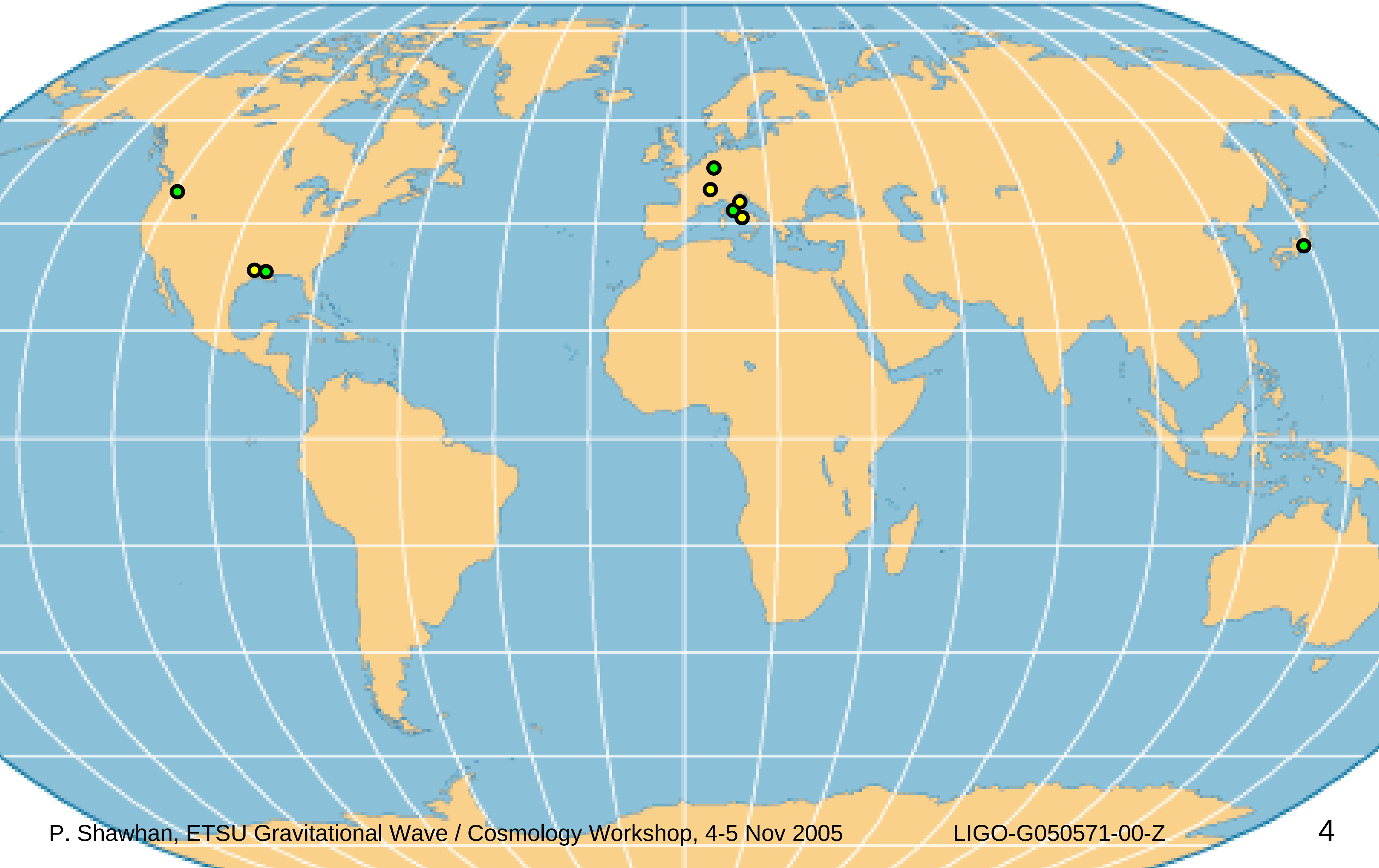


The stretching is described by a dimensionless strain, $h = \Delta L / L$

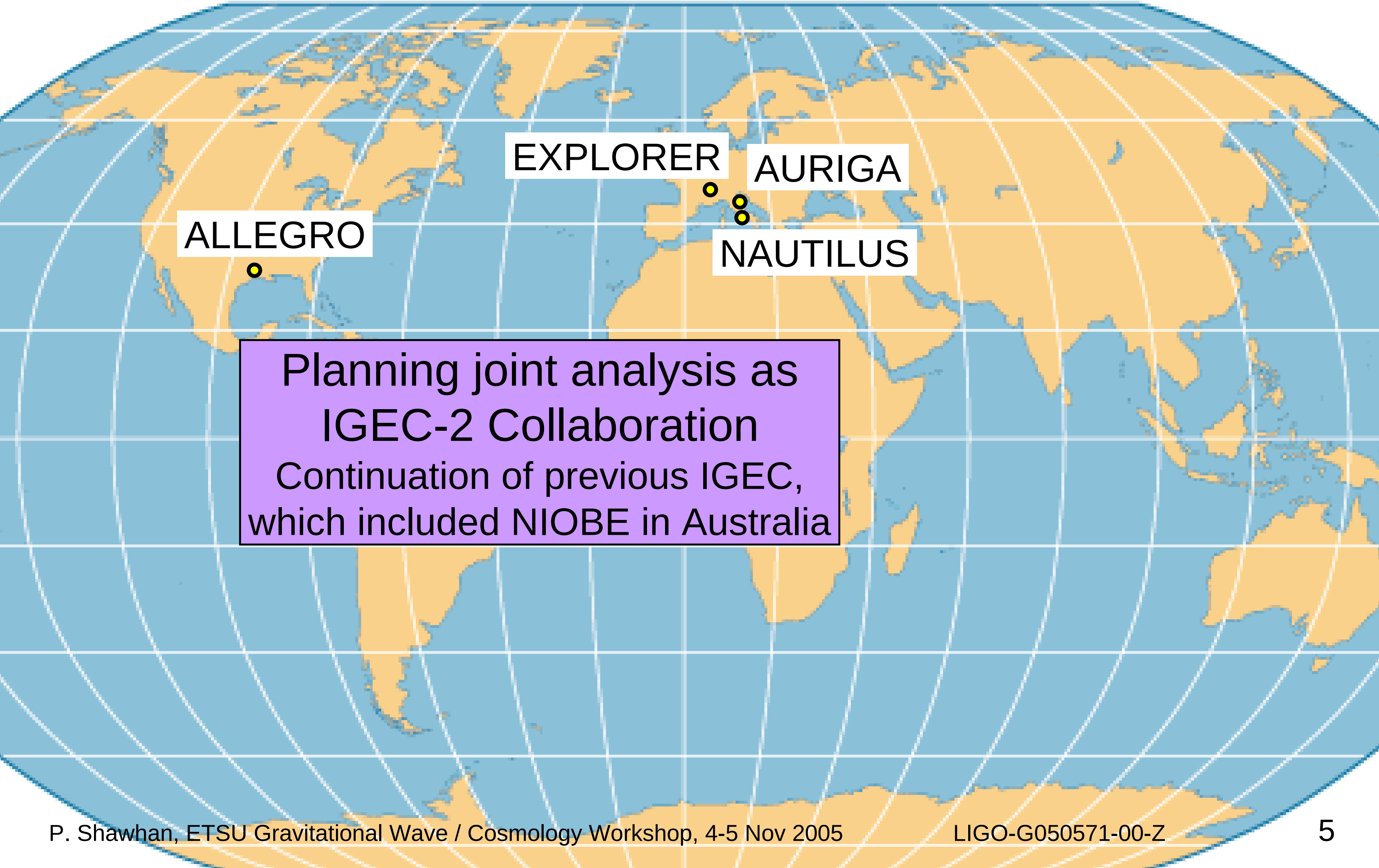
h is inversely proportional to the distance from the source

A general GW signal has two polarizations:  and 

GW Detectors Around the World



Resonant "Bar" Detectors



Planning joint analysis as
IGEC-2 Collaboration

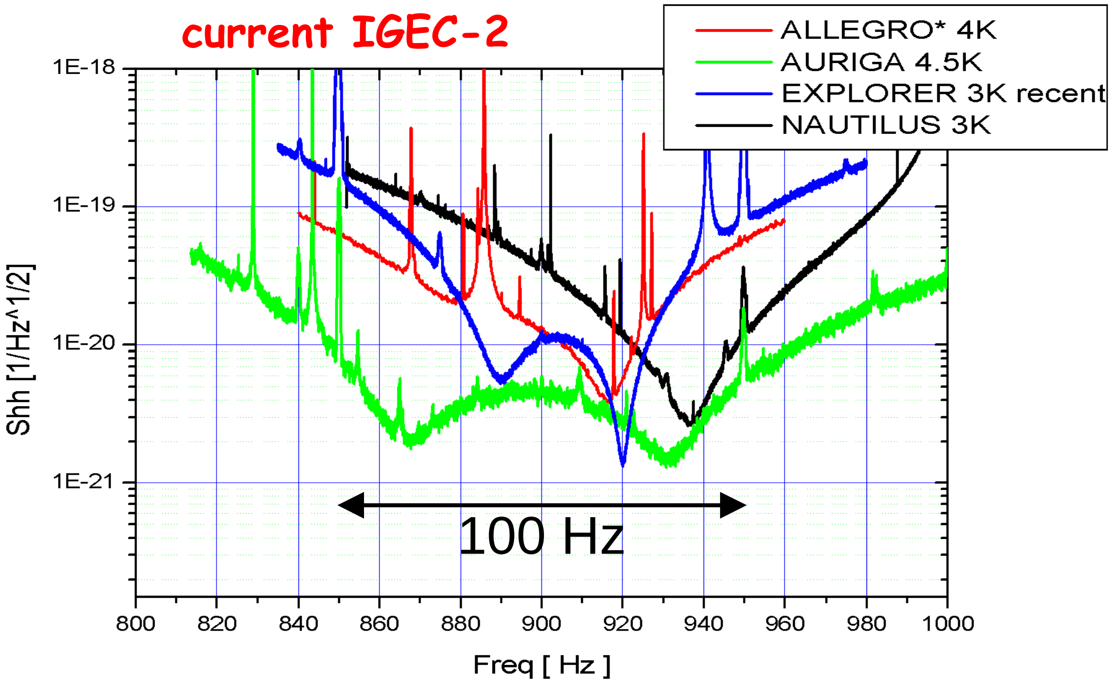
Continuation of previous IGEC,
which included NIOBE in Australia

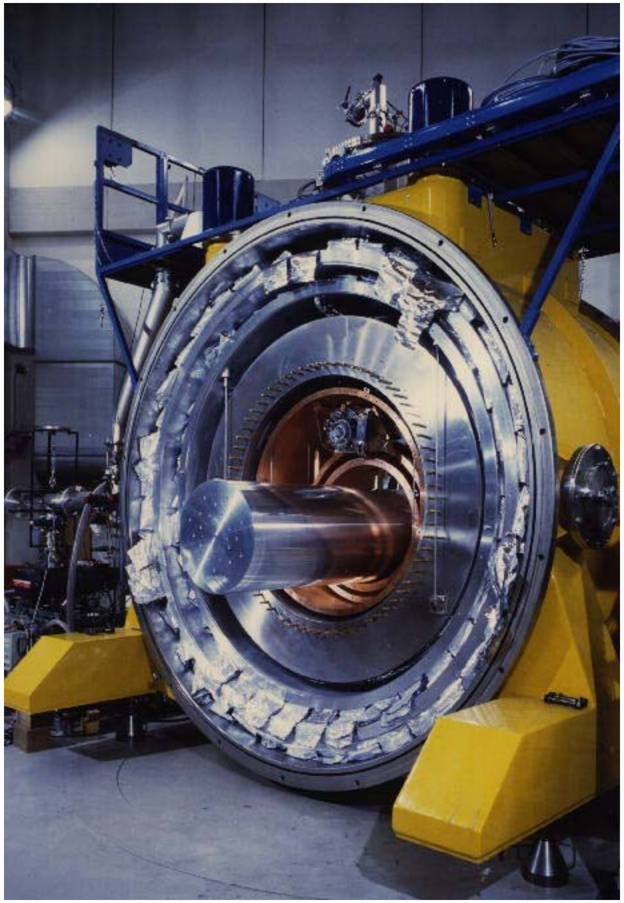
Resonant “Bar” Detectors

Aluminum cylinder, suspended in middle

GW causes it to ring at one or two resonant frequencies near 900 Hz

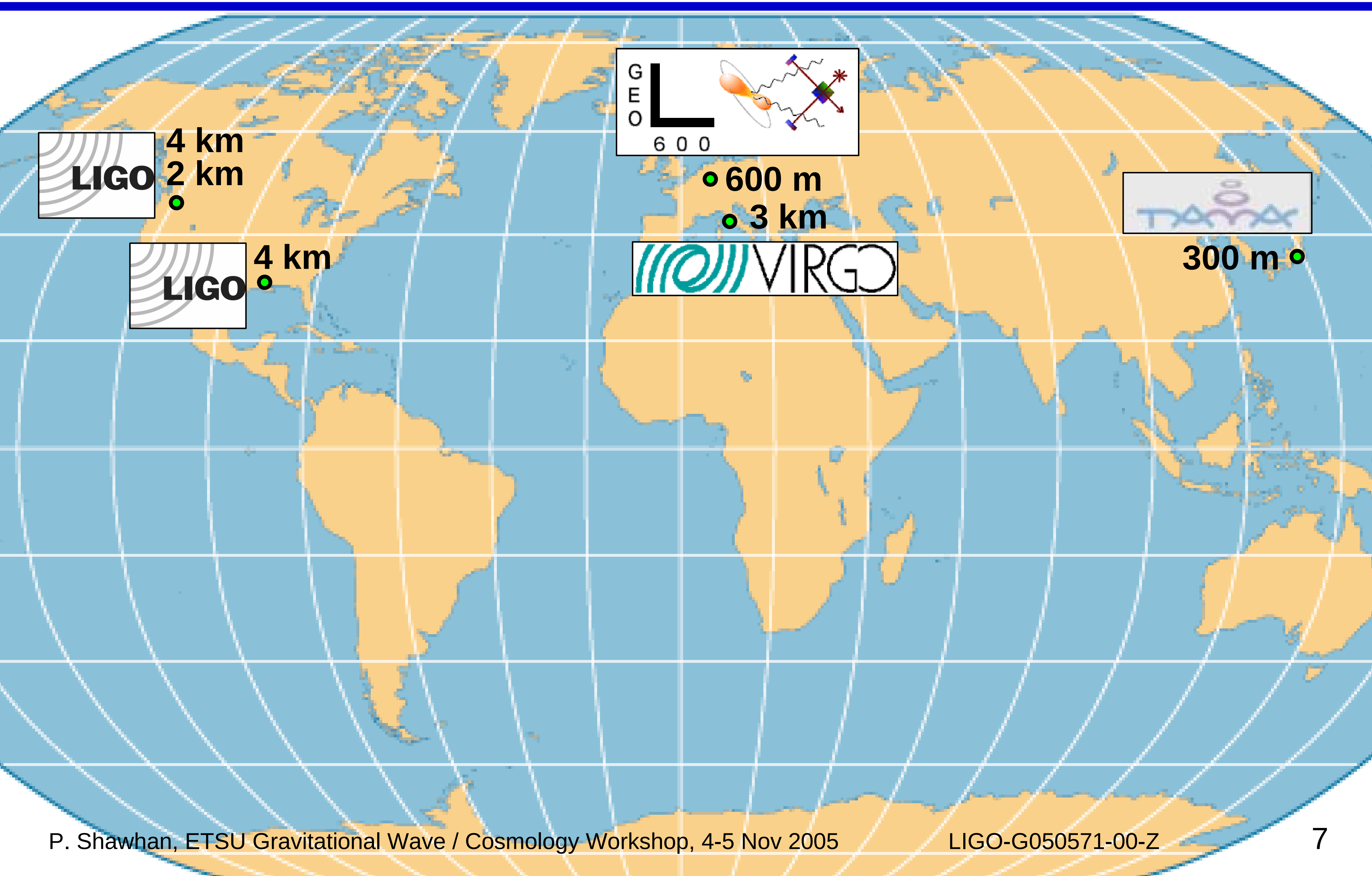
Sensitive in fairly narrow band (up to ~100 Hz)





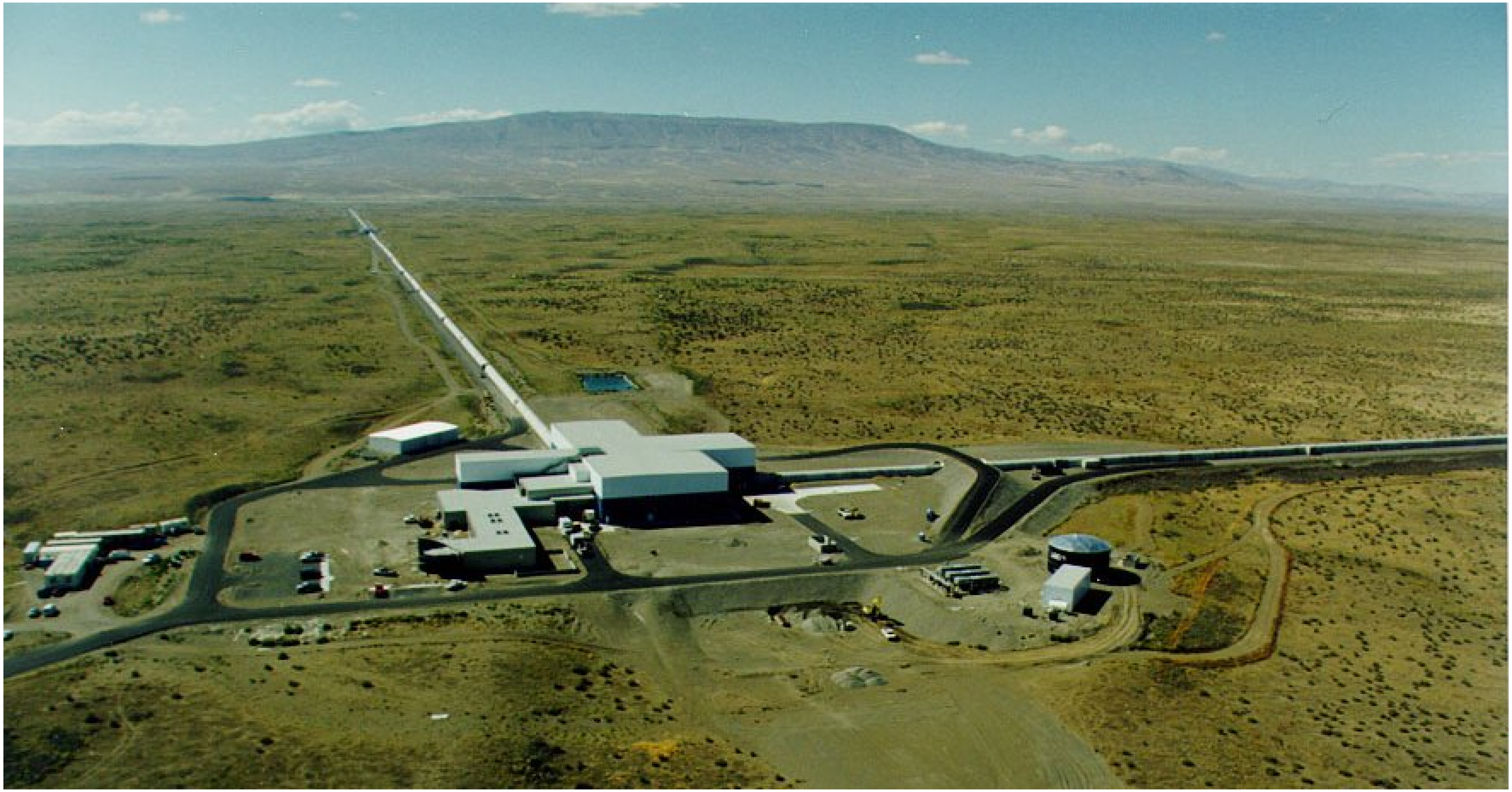
AURIGA detector (open)

Large Interferometers



LIGO Hanford Observatory

Located on DOE Hanford Nuclear Reservation north of Richland, Washington

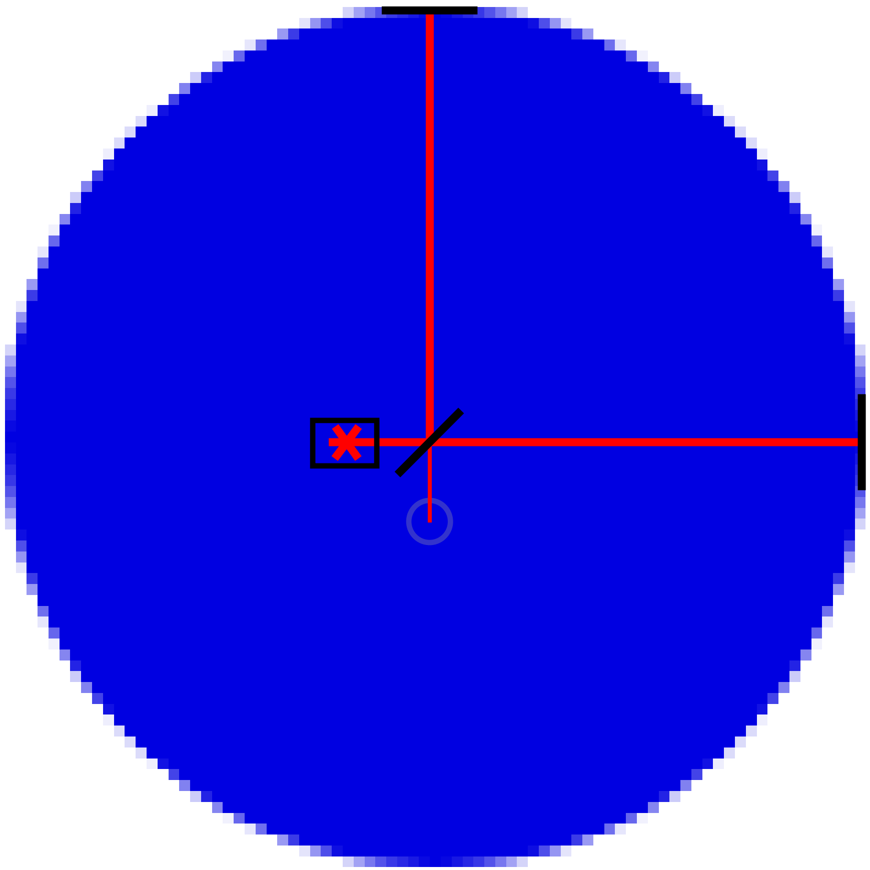


Two separate interferometers (4 km and 2 km arms) coexist in the beam tubes

Interferometer Response to a GW

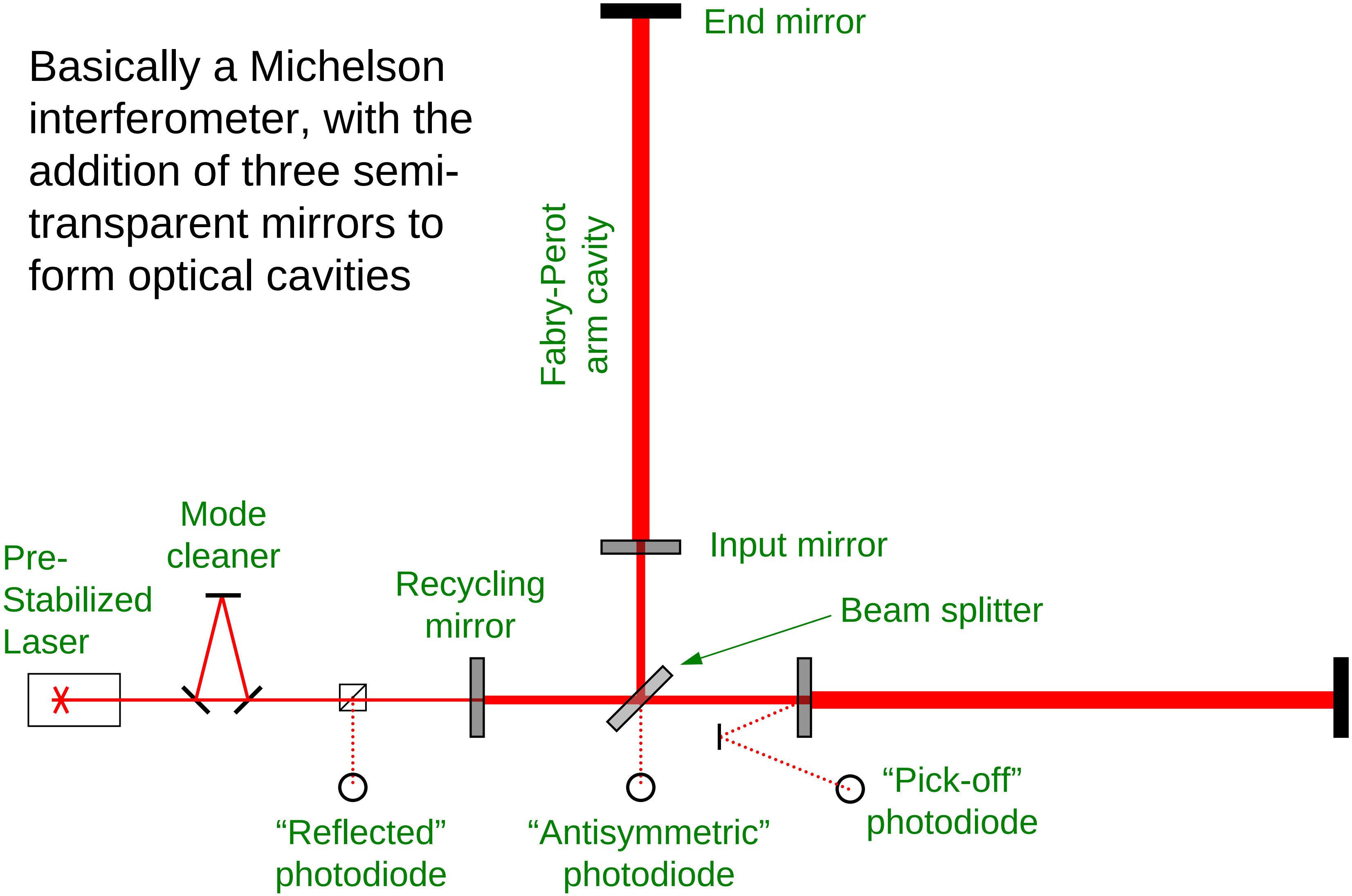
GW causes *differential* changes in arm lengths, sensed interferometrically by photodiode

Response depends on direction and polarization of incoming wave



LIGO Optical Layout (Simplified)

Basically a Michelson interferometer, with the addition of three semi-transparent mirrors to form optical cavities



Status of LIGO and GEO

Four "science runs" conducted since 2002

- Durations up to 2 months
- Rest of the time spent improving detectors

New science run (S5) starting this month

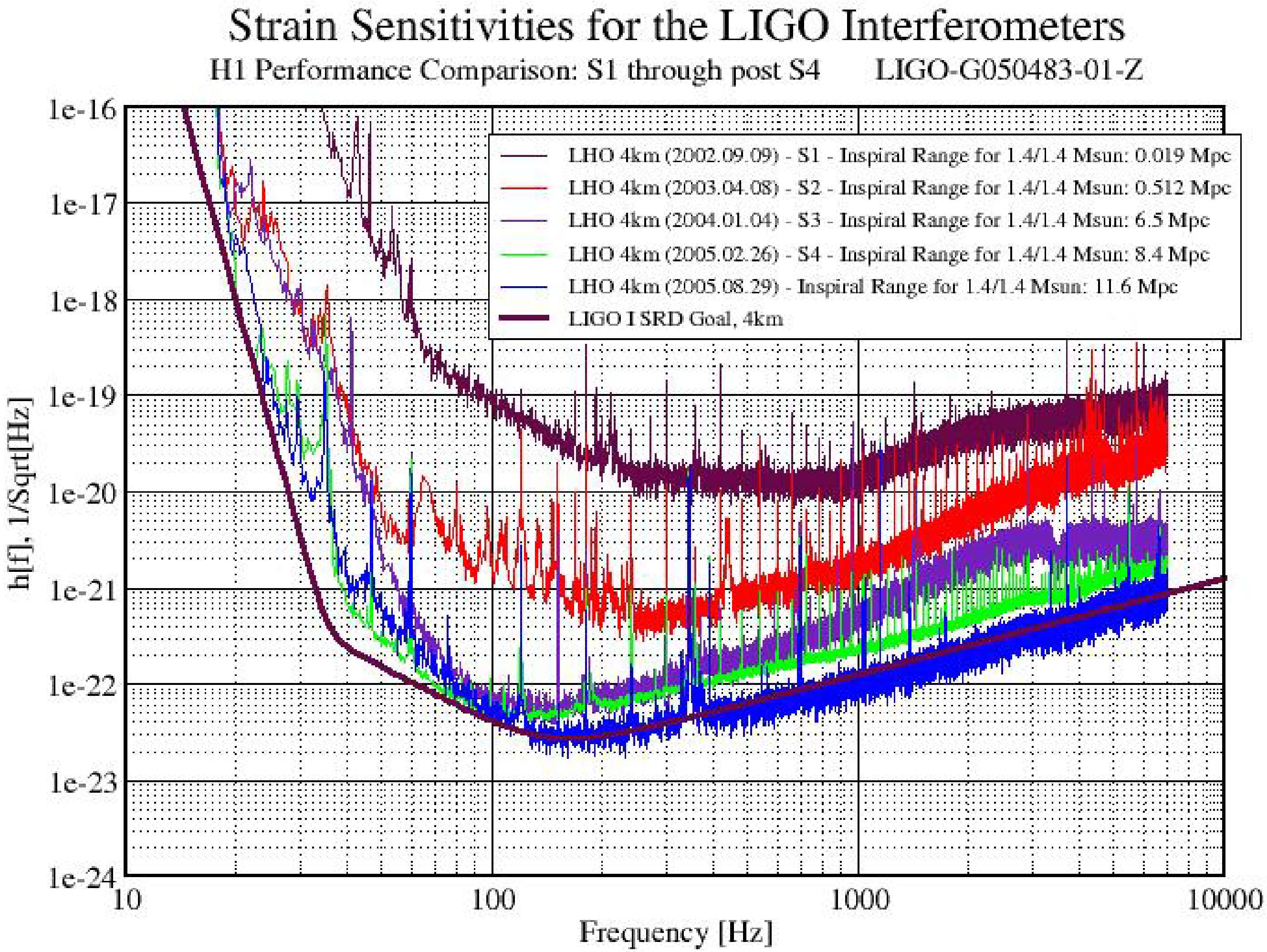
- Will collect data for over a year!

GEO collected data too during S1, S3, S4 ; plans to join S5 partway through

LIGO and GEO data are analyzed jointly by the LSC

Various analyses published using data from the first three science runs; analysis of S4 in progress

LIGO Sensitivity History
(Hanford 4km)



Now essentially at design sensitivity!

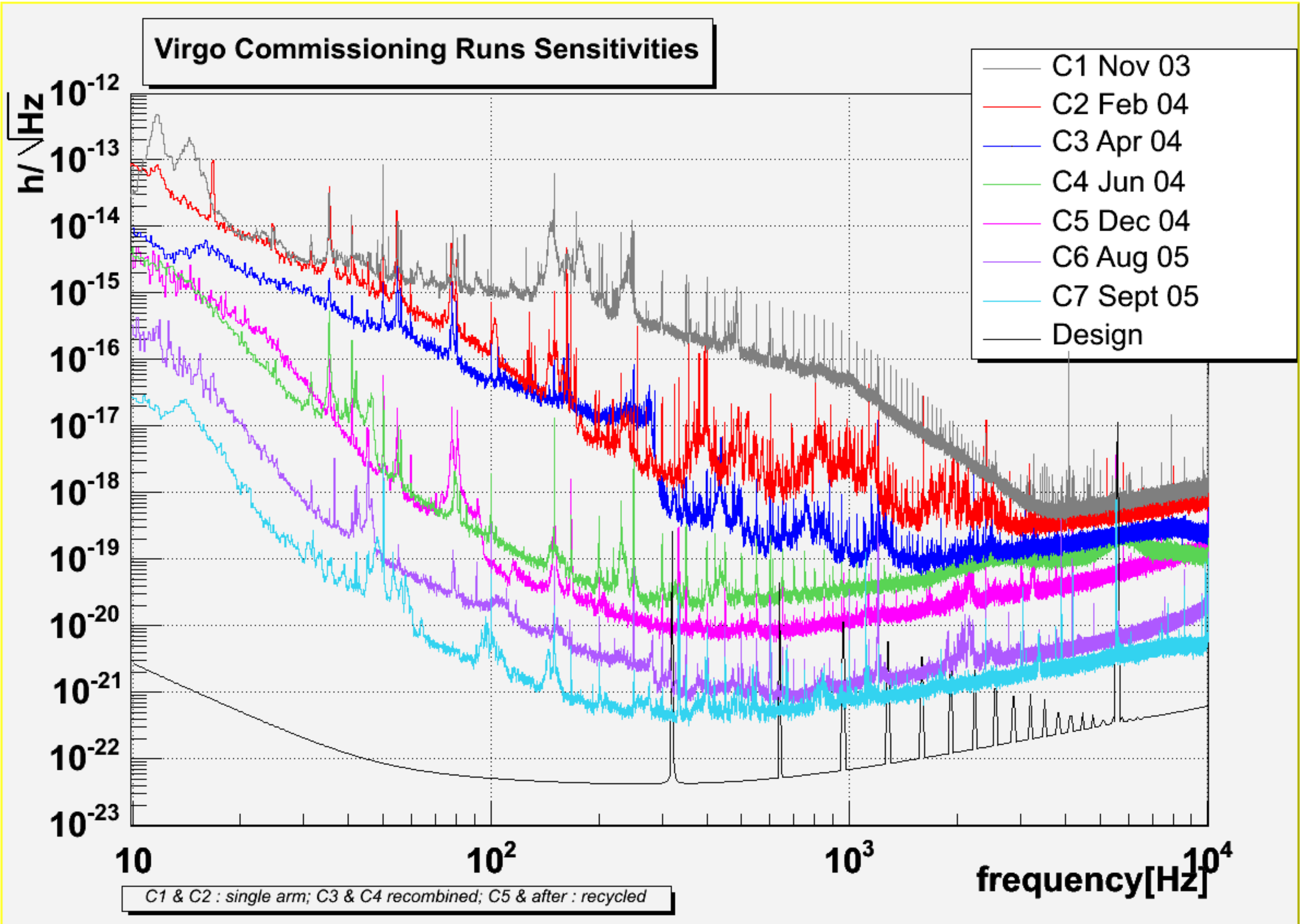
Detectable range for neutron star binary: ~10 Mpc

For black hole binary: ~100 Mpc

For supernova: probably limited to Milky Way

GEO: currently 1-2 orders of magnitude less sensitive

VIRGO Sensitivity History



Prospects for Future Large Interferometers

Advanced LIGO

- Order-of-magnitude sensitivity improvement
- Received scientific approval from National Science Board
- NSF planning to request funding starting in FY 2008
- Three advanced detectors observing by 2013 ?

VIRGO upgrade – Being thought about

LCGT (Japan)

- Two 3-km interferometers in Kamioka mountain
- Sensitivity comparable to Advanced LIGO
- Hope for funding beginning in FY 2007 ; begin observations in 2011 ?

AIGO (Australia)

- Considering adding 2 km arms to current facility at Gingin

CEGO (China) ?

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GW signal types

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Statistical issues

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The GW Signal Tableau
for ground-based detectors, at least

Short duration ⟷ Long duration

Waveform known ↕ Waveform unknown

Cosmic string cusp / kink

NS / BH ringdown

Low-mass inspiral

Asymmetric spinning NS

High-mass inspiral

Rotation-driven instability

Cosmological stochastic background

Stellar collapse

Binary merger

Many overlapping signals

??? ??? ???

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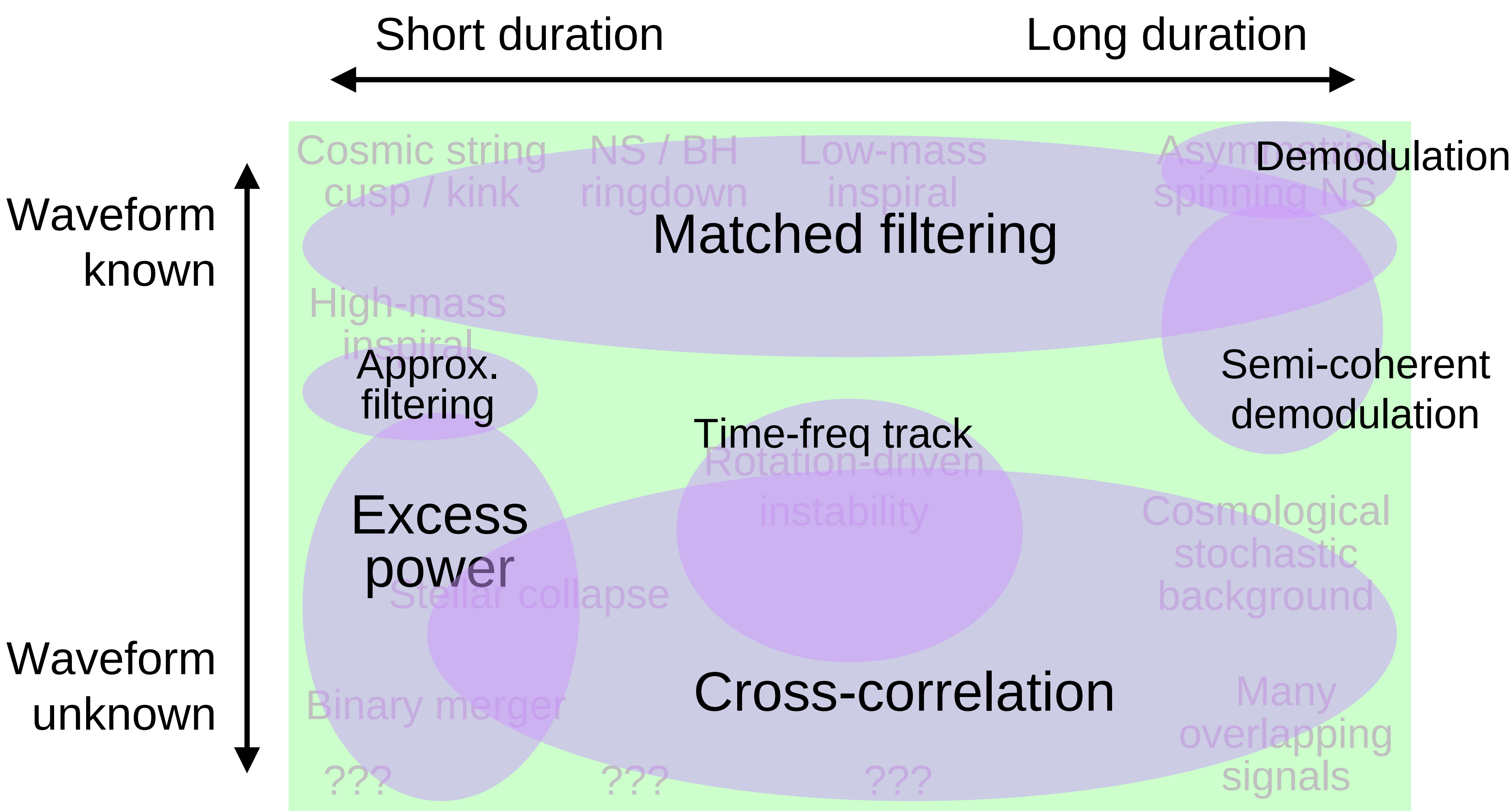
General Analysis Approaches



Matched Filtering

Can be done with short or long templates

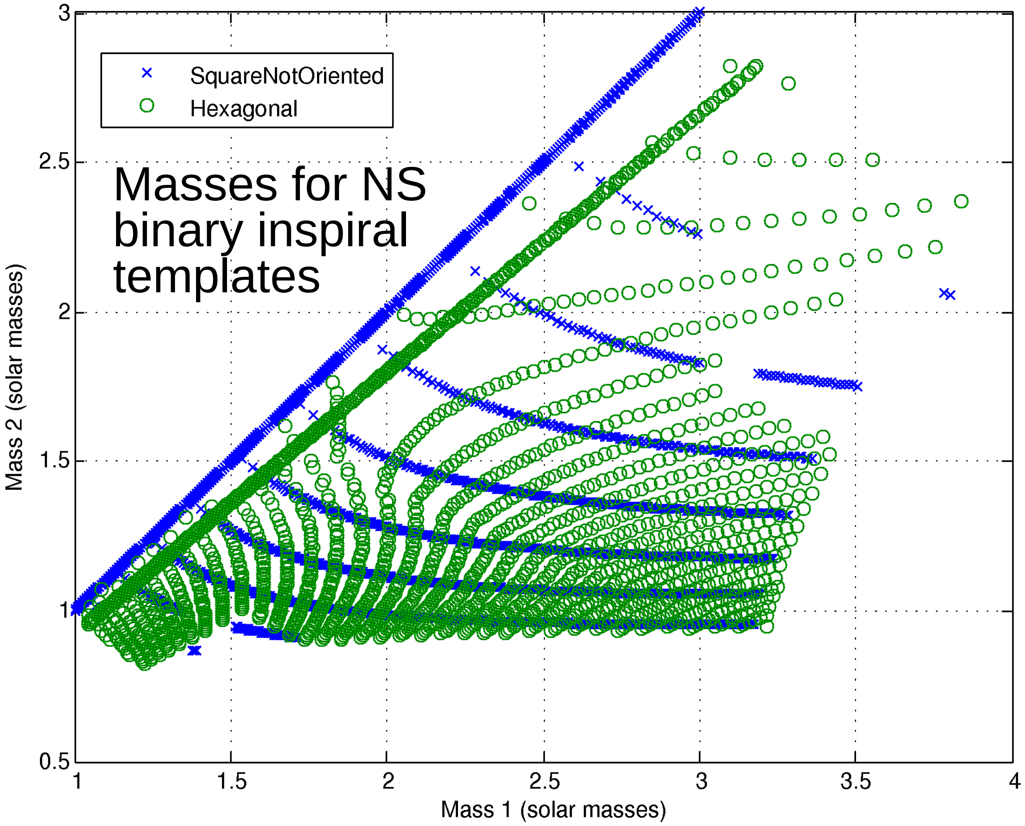
***Optimal* filtering weights frequency components according to noise**

Use a *bank* of templates to cover desired region of signal space

Generally, construct to give a certain *minimal match*

May use a non-physical parametrization to try to cover desired signal space

If parameter space is large, may need to do a hierarchical search



“Excess Power” Methods

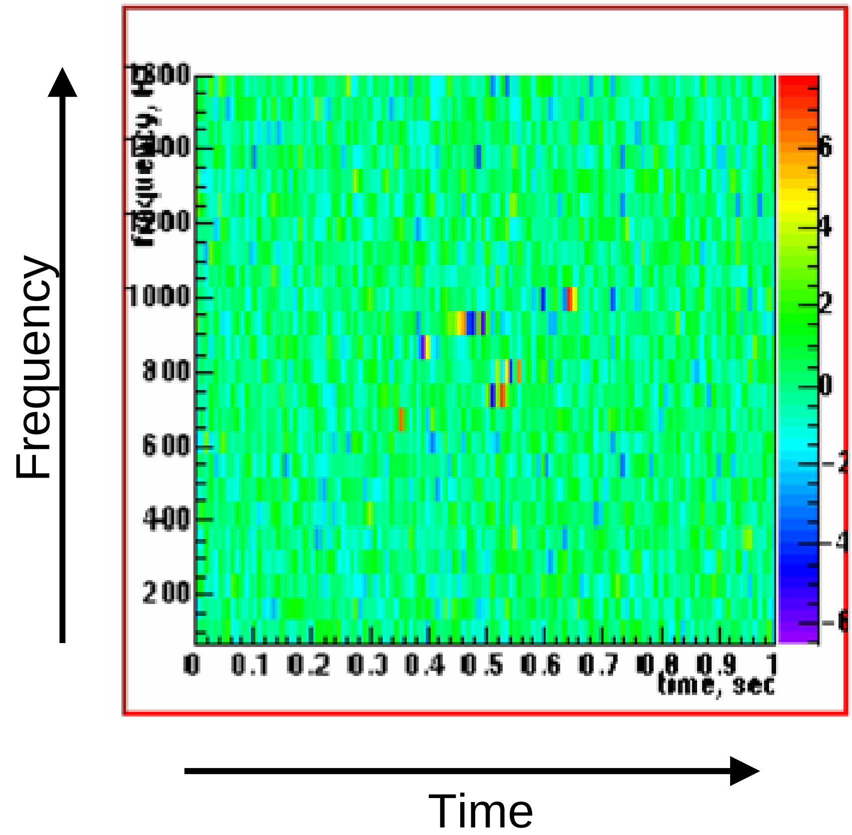
Look for an increase in signal power in a time interval, compared to baseline noise

- Evaluate significance of the excess

Typically start by decomposing data into a time-frequency map

- Each row (frequency) normalized
- Could be wavelets instead of Fourier components
- Might use multiple resolutions

Look for “hot” pixels, alone or in clusters



Cross-Correlation

Uses data from a pair of detectors – try to pick out common signal

Assumes that detector noise is uncorrelated

- This assumption needs to be checked

Can integrate over short or long time interval

- Ideally, integration length should match length of signal

Real Detectors …

… do not always work well ⇒ *Data quality cuts*

… have non-stationary noise ⇒ *Dynamic trigger thresholds*

⇒ *Waveform consistency tests*
(χ^2 ; excess-noise checks)

… have time-varying response ⇒ *Track calibration*

… are affected by environment ⇒ *Auxiliary-channel vetoes*

Even with these measures, get some false alarms

Require Coincidence to Reduce False Alarm Rate

Require consistent signals to be seen in multiple detectors

- Arrival time (for short-duration signals)
- Signal amplitude
- Signal phase, etc.

} Have to allow for different antenna responses

Allows lower thresholds to be used

- For a target false alarm rate

Networks which have been used for coincidence analyses:

- IGEC bar network
- Two or three LIGO detectors
- LIGO-GEO (LSC)
- LIGO-TAMA
- LIGO-AURIGA

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"Detection" of a GW signal

Current detectors have no guaranteed sources

Want to be conservative about announcing a "detection"

Frequentist point of view: demand a high *p*-value

Bayesian point of view: prior is heavily weighted toward undetectability, so need strong evidence

- Is it even possible to choose a meaningful prior?
- How to deal with the combination of a discrete case (no signal) and a continuum of possible signals?

Trickiness of the question: "Is a signal present?"

- Observational equivalence of "no signal" and "undetectably small signal"

In this regime, "upper limits" are tricky for *any* approach

- One-sided vs. Feldman-Cousins-based frequentist upper limits
- Upper limit derived from a Bayesian posterior pdf ?

Potential Bias from Choices of Event Selection Criteria

_e.g._ auxiliary-channel veto conditions

Can't choose them based on the final set of event candidates !

Could invalidate frequentist confidence interval

Formally, could fold arbitrary information from auxiliary channels into a Bayesian analysis, but hard to do in practice

Hundreds of possibly relevant channels

Presence of a coincident glitch in an auxiliary channel should reduce belief that an event candidate is a real GW, but by how much

Does *absence* of a coincident glitch in some arbitrary auxiliary channel *increase* belief?

General technique for sidestepping issues of bias: "blind" analysis

Choose event selection criteria based on a "playground" subsample, or on a set of time-shifted coincidences

Extracting Astrophysical Information

Physically identical *sources* may produce a distribution of observed *signals*

Due to different sky positions, orientations, distances

Might not have a reliable model to calculate signal from physical parameters

So even if a strong signal is seen, may not be able to tell physical params

A *population* of sources may have a range of physical parameters

… as well as a spatial distribution, of course

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LIGO

What Can We Learn from Multiple Sites?

The signal observed in a given detector *i* is

$$s_i(t) = n_i(t) + F_{+,i}\, h_+(t - d_i) + F_{\times,i}\, h_\times(t - d_i)$$

noise

Antenna pattern coefficients

Time delay relative to center of Earth

IF **sky position were known and there were no noise, then two data streams (from different sites) would completely determine** $h_+(t)$ **and** $h_\times(t)$ **at all times**

Three or more data streams over-determine $h_+(t)$ **and** $h_\times(t)$

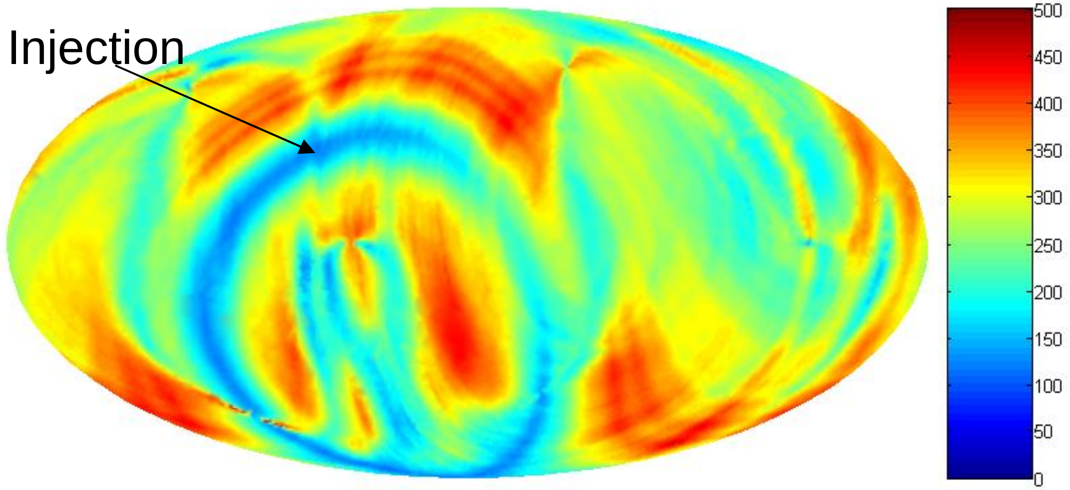
In principle, should be able to separate out a consistent GW signal from the uncorrelated noise, without any assumptions about the source **except** its sky position

Multi-site extension of pairwise cross-correlation

How Can We Apply This Concept?

For an assumed sky position, can form a *null stream* linear combination of any two data streams

- Can combine these with appropriate weights to form an overall null stream with minimal noise
- Then look at the power in the null stream as a function of sky position



Other combinations of data streams: *excess energy* ; *correlation*

What Questions Can We Ask?

Is there a GW source?

Null stream power is near zero for some sky position (consistency test)

Where is the source?

Sky location of minimum of null stream (parameter estimation)

What is best estimate of the signal waveform?

Some sort of weighted sum of data streams, for a certain sky position

*** Problem with maximum likelihood with finite set of antennas**

“Best estimate” tends to be a large GW signal which happens to have an unfavorable sky position / polarization

Should we “penalize" large-amplitude signals in some way?
(Like a prior favoring small signals)

Discussion Topics

"Detection" criteria

Setting upper limits

How to incorporate information from auxiliary channels

Associating signals with astrophysical sources and populations

Multi-site coherent analysis

- Data stream combinations
- “Questions” to ask
- How to get “best estimate” of the signal waveform