Searching for Gravitational-Wave Bursts with LIGO

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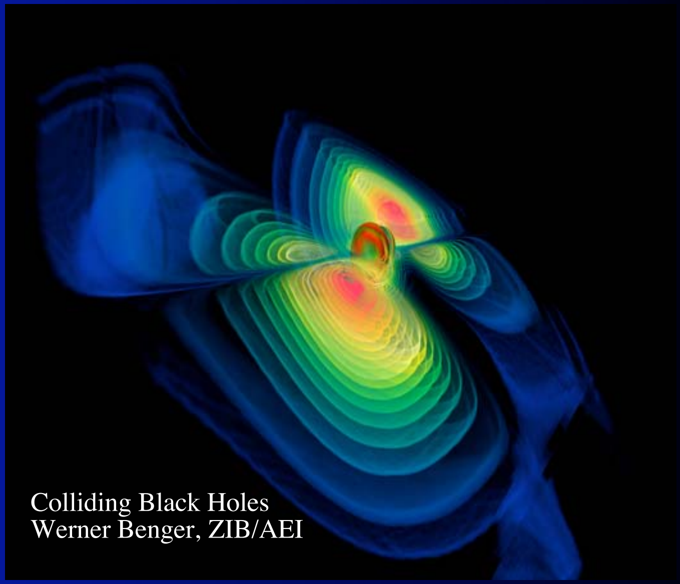
The Big Picture

- The new generation of gravitational-wave (GW) detectors promises to open a new window on the universe: *gravitational-wave astronomy*.
- GW bursts (GWBs) are one of the most exciting types of signals. GWBs from violent events like black-hole mergers & supernovae can tell us about, e.g.,
  - Dynamical gravity with event horizons
  - Behaviour of matter at densities so high that it is opaque to neutrinos (!)



The Big Picture

- GWB sources are typically not well understood, involving complicated (and interesting!) physics.
  - GWBs are more difficult to detect
  - Scientific payoff from GWB detections could be very high.

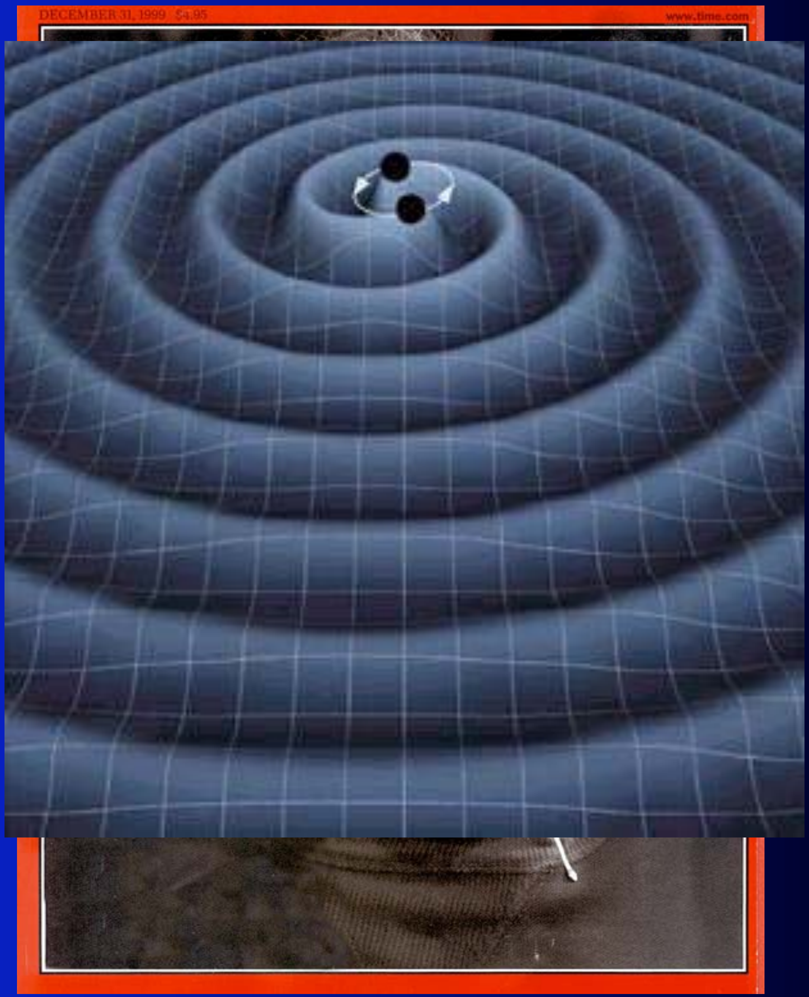
- This talk: How we face the challenges of GWB detection in the LIGO Scientific Collaboration.

Outline

- Gravitational Waves and GW Detectors
- Gravitational-Wave Burst Sources
- Detection Techniques
  - “All sky” searches
  - Triggered searches
- Interesting New Developments
- Future Prospects

Gravitational Waves

- Special relativity imposes finite limit of speed of any type of communication.
- Apply to gravity: changes in gravitational fields must propagate at finite speed: gravitational waves.
- Example: binary black-hole system.



The Details

- Concrete treatment of GWs based on linearized perturbations around a fixed background metric in general relativity. Perturbation obeys a wave equation. E.g., in flat space:

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\bar{h}_{ab} = -\frac{16\pi G}{c^4} T_{ab}$$

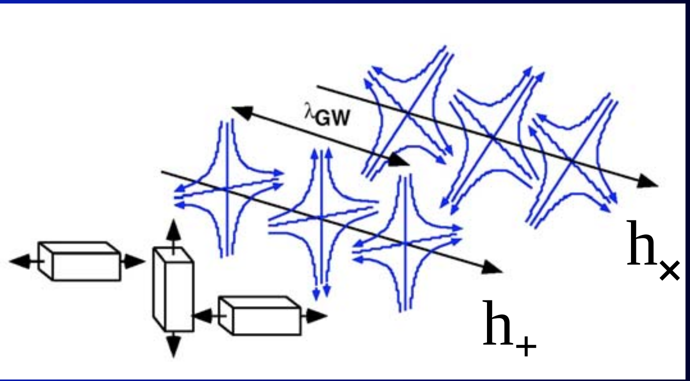
source stress tensor (density of mass & energy)

wave operator

perturbation (trace-reversed)

coupling constant (10^{-42}/N)

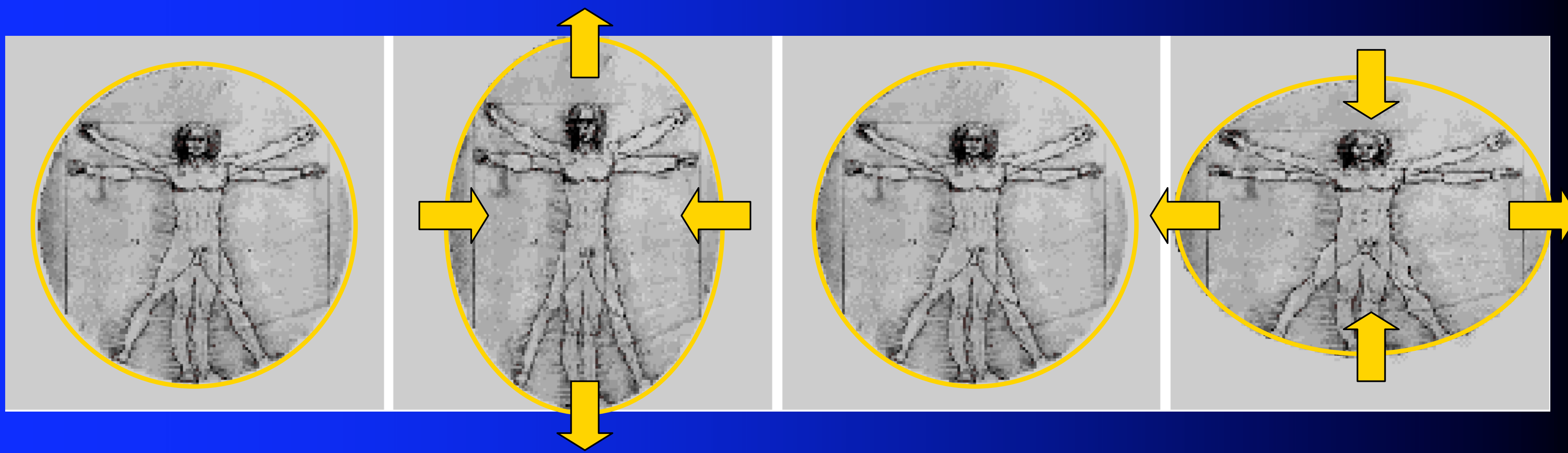
- Solution: 2 radiative polarization states (“+” and “×”) rotated by 45º
  - Quadrupolar (tidal) fluctuations in geometry



The Effect of GWs

- Effect of a gravitational wave coming out of the screen on da Vinci's Vitruvian Man:

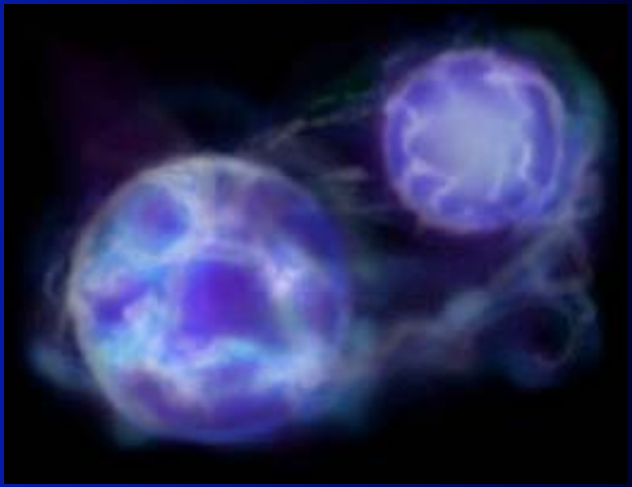
$h_+ = 0$ $h_+ > 0$ $h_+ = 0$ $h_+ < 0$



Weakness of GWs

- Weak coupling to matter (10^{-42} / N):
  - Produced by bulk motion of ~solar masses of material.
  - Eg: For a neutron-star binary in the Virgo cluster (15 Mpc away) :

$$h \approx \frac{m_1 m_2}{r\,R} \leq 10^{-21}$$



For 4 km detector (LIGO) this length change is < 1/1000 proton diameter!

  - Positive: GW also interact weakly with intervening matter! Can "see" directly into the cores of collapsing stars, GRB engines, etc.

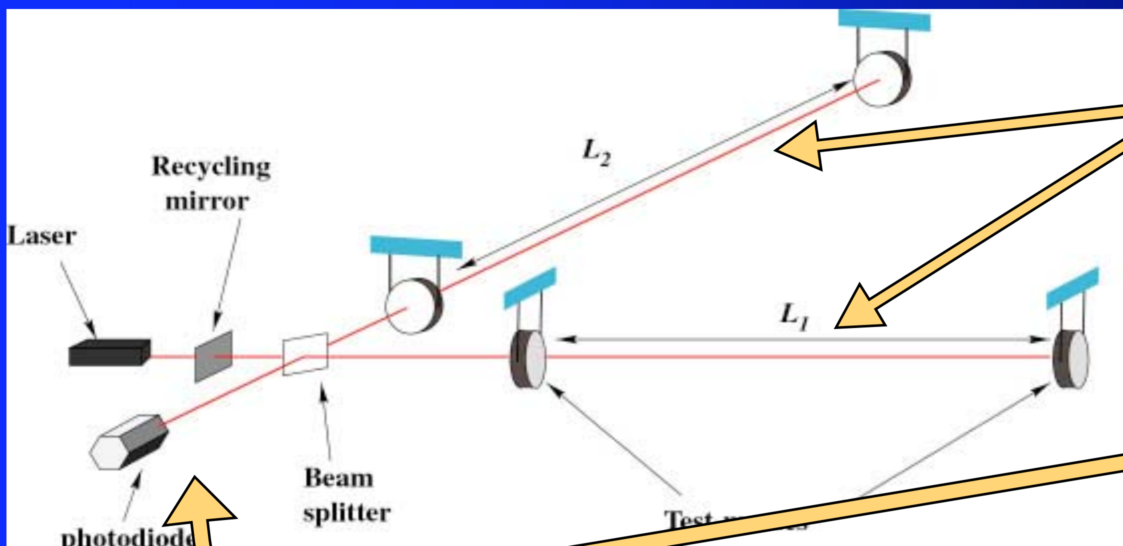
Astrophysics with GWs vs. EM

Electromagnetic Waves	Gravitational Waves
Accelerating charge	Accelerating aspherical mass
Wavelength small compared to sources → images	Wavelength large compared to sources → no spatial resolution
Absorbed, scattered, dispersed by matter	Very small interaction; matter is transparent
10 MHz and up	10 kHz and down

- Very different information, mostly mutually exclusive.
- Difficult to predict GW sources based on EM observations.

Interferometric GW Detectors

- Take advantage of the tidal nature of GWs.
- A laser is used to measure the relative lengths of two orthogonal paths ("arms").



As a wave passes, the arm lengths change in different ways …

… causing the interference patter at the photodiode to change.

- LIGO: L = 4 km. Can measure
  - $dL/L < 10^{-21}$
  - $dL < 10^{-18}$ m ~ 1/1000 the size of a proton

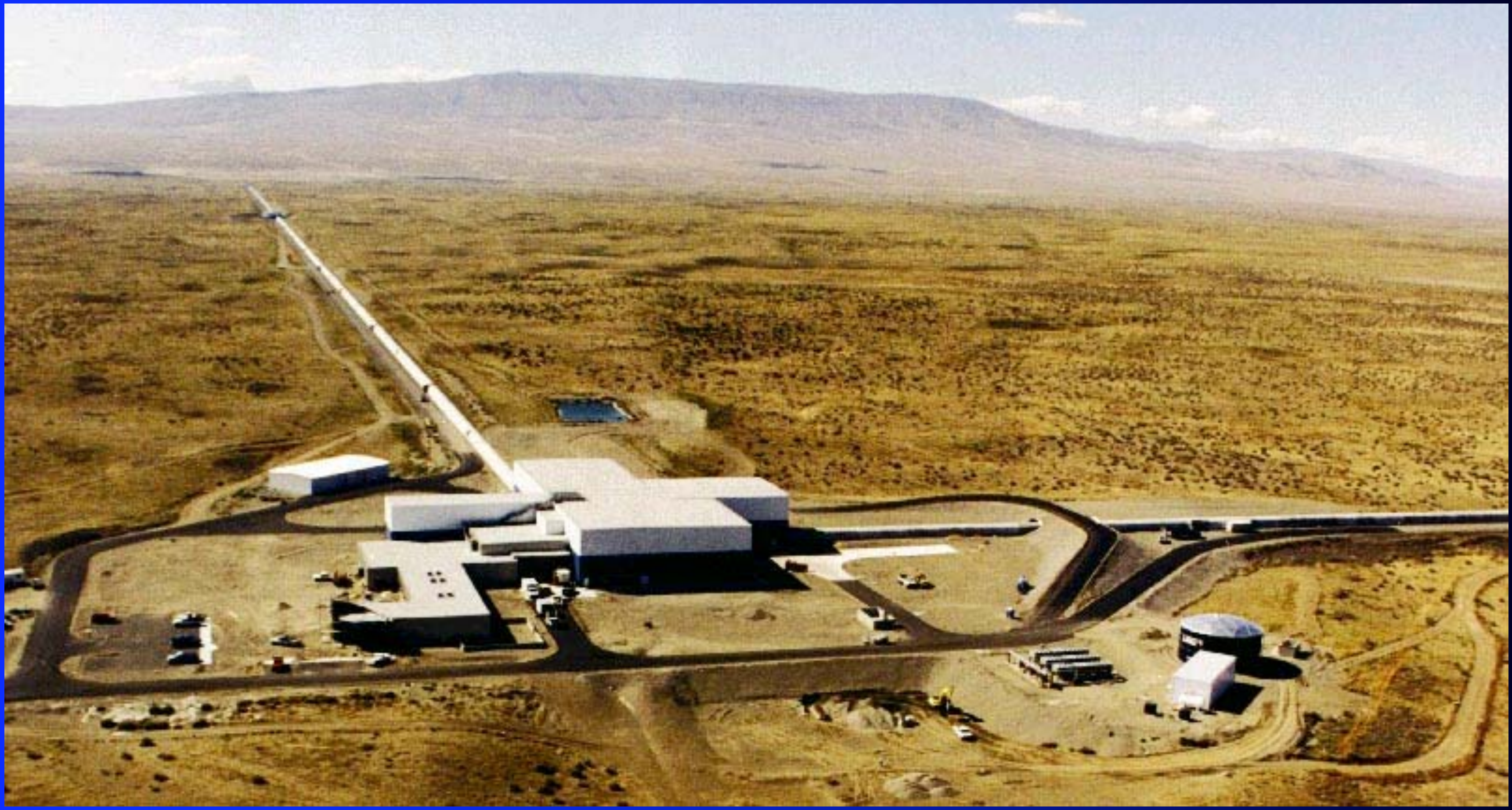
The LIGO Project

- LIGO = Laser Interferometer Gravitational wave Observatory
  - A major project of the National Science Foundation (United States).
  - 3 detectors at 2 sites.
- 2-stage project:
  - Initial LIGO (now operating!)
  - Advanced LIGO (installation starts end 2010)
    - 10 × more sensitive than Initial LIGO.
- LIGO Scientific Collaboration (LSC)
  - 400+ scientists and 42 institutions worldwide
  - LIGO + GEO 600 (Hannover)

LIGO Scientific Collaboration


The LIGO Observatories
LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms
3000 km = 10 ms
MIT
Caltech
LIGO Livingston Observatory (LLO)
L1 : 4 km arms
• Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov
• NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).

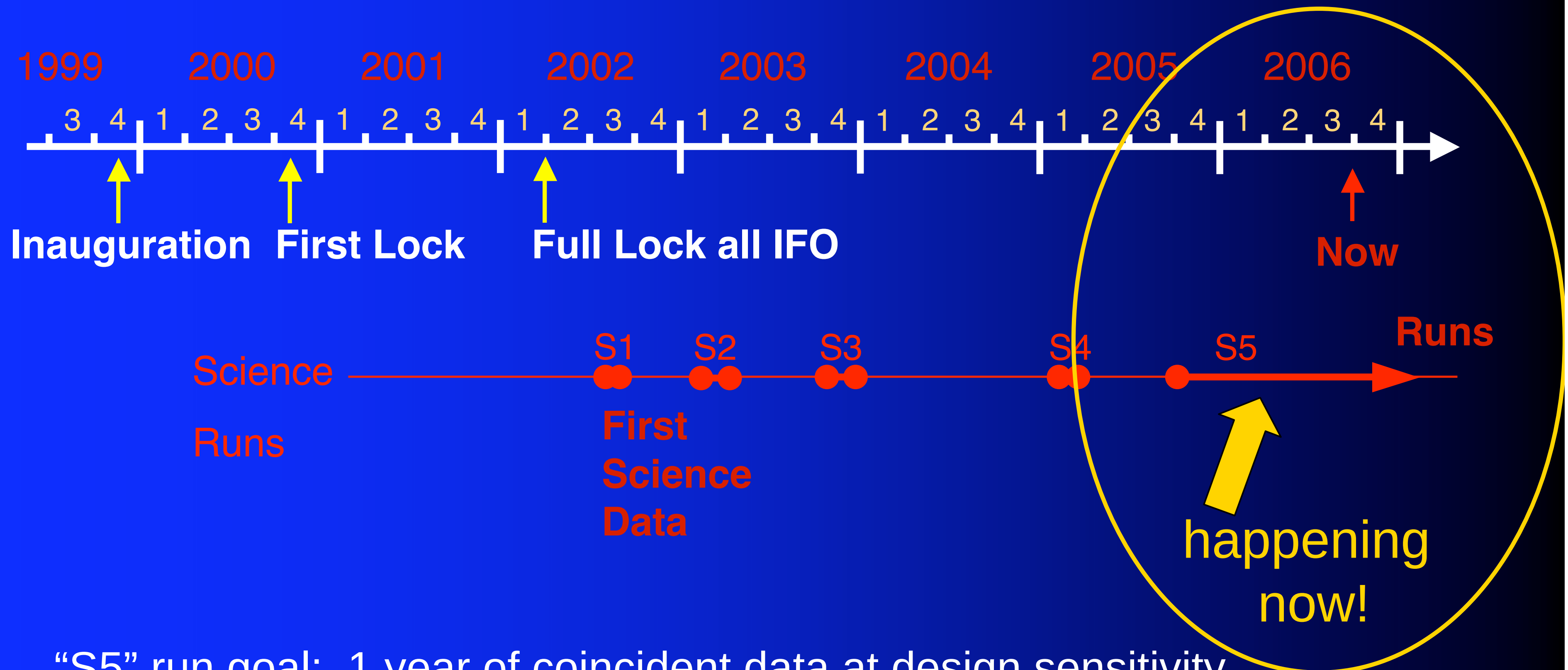
LIGO Hanford Observatory



LIGO Livingston Observatory

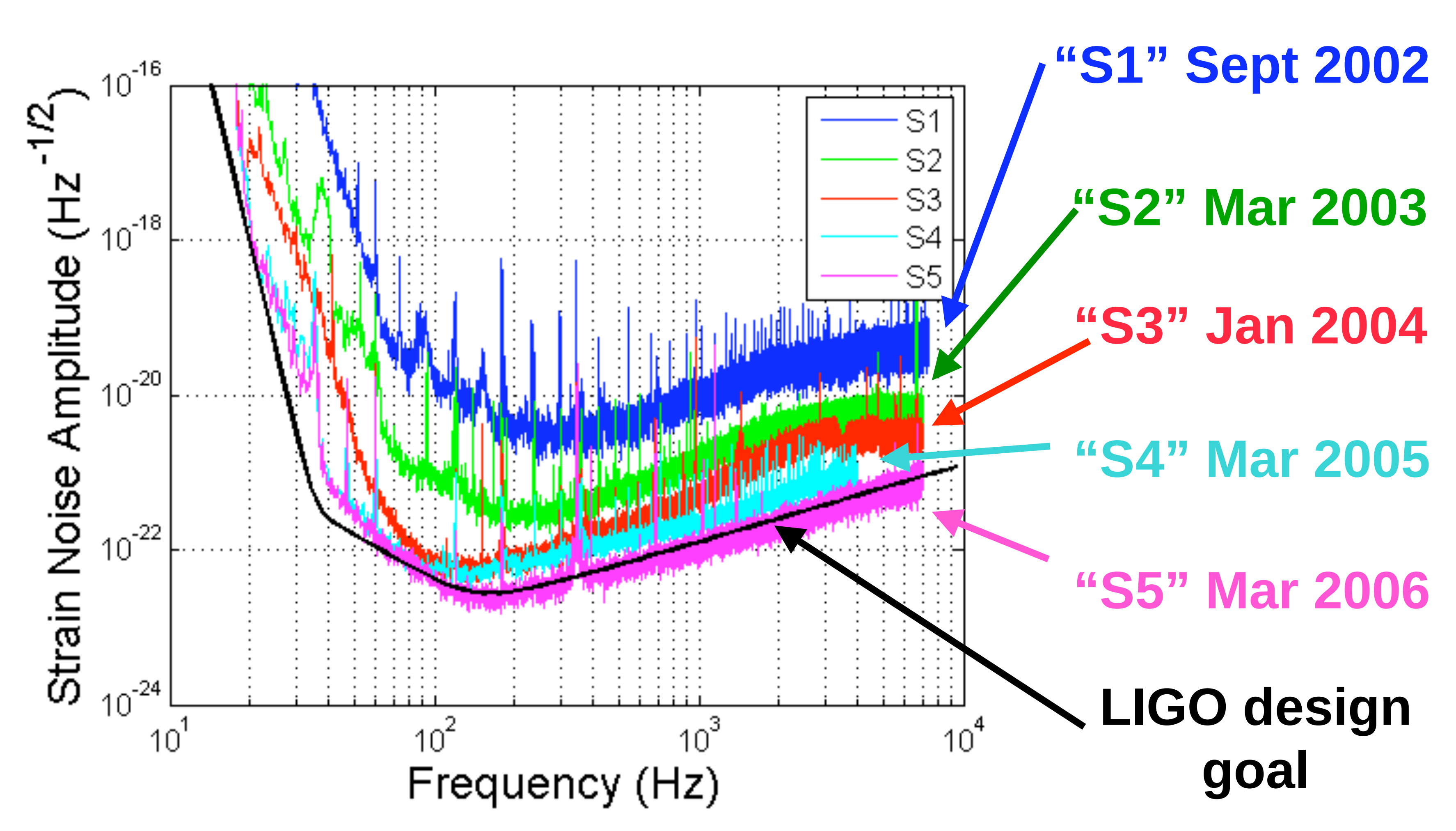
GEO600 Observatory

LIGO Time-Line



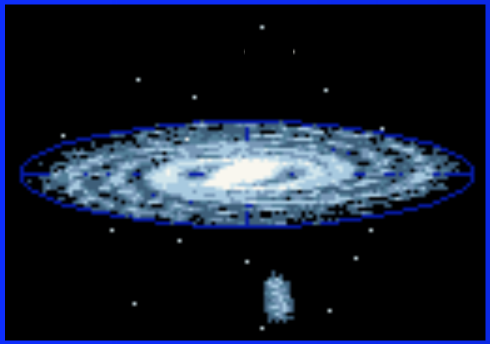
"S5" run goal: 1 year of coincident data at design sensitivity.
Expected end date ~ August 2007.

Progress in Sensitivity



Progress in Sensitivity

- Average distance for detecting a coalescing neutron-star binary:



Milky Way
(8.5 kpc)

Sept 2002
[~1 galaxy]

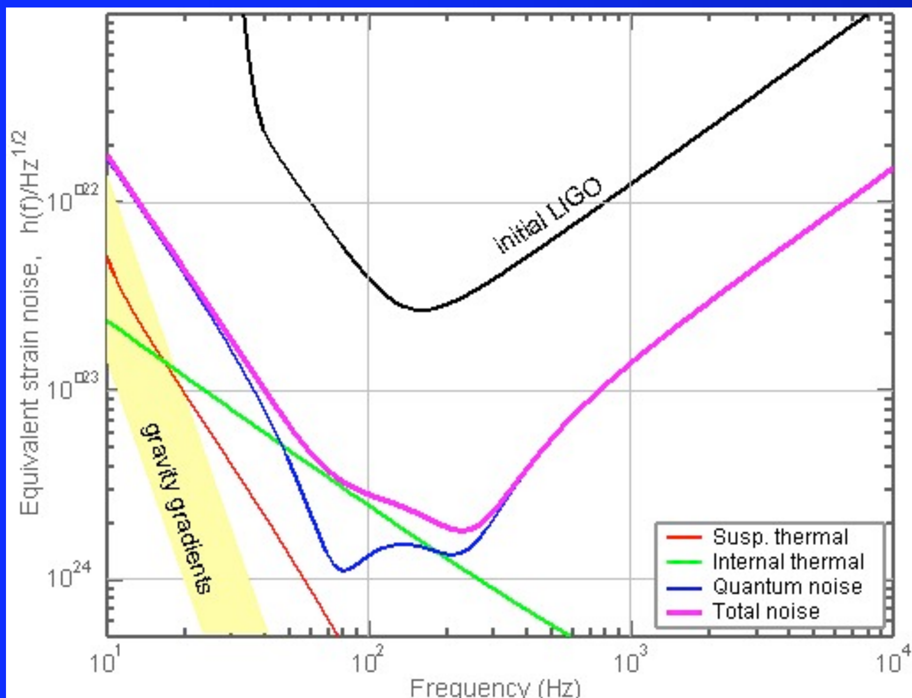
Andromeda
(700 kpc)

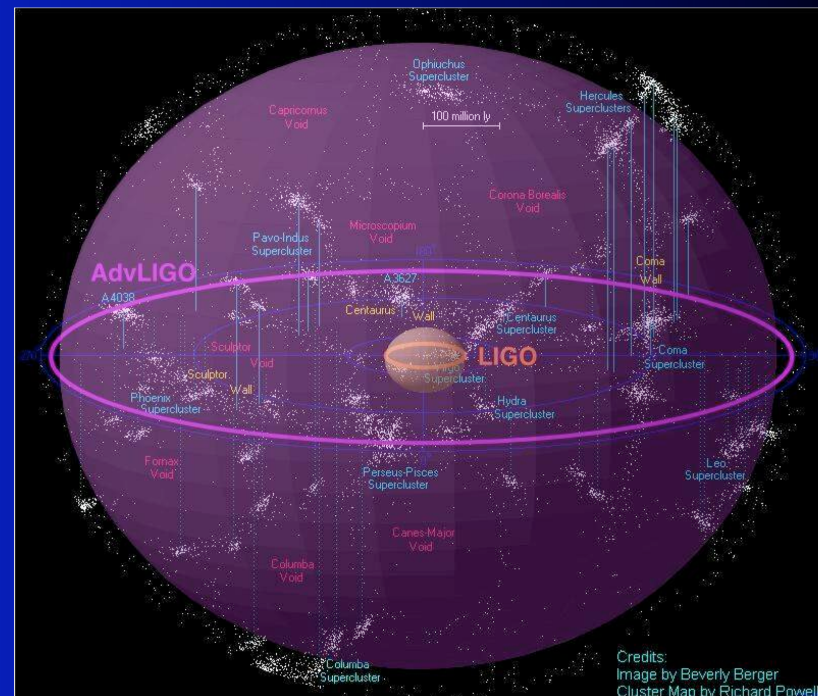
March 2003
[~2 galaxies]

Virgo Cluster
(15 Mpc)

now
[~10^3 galaxies]

Advanced LIGO detectors: 2010+





E.g.: Neutron Star Binaries:

- Initial LIGO: ~15 Mpc (~1 signal per 10 years)
- Advanced LIGO: ~200-350 Mpc (~1 signal every 2 days) !

x10 better amplitude sensitivity

⇒ x 1000 rate (volume)

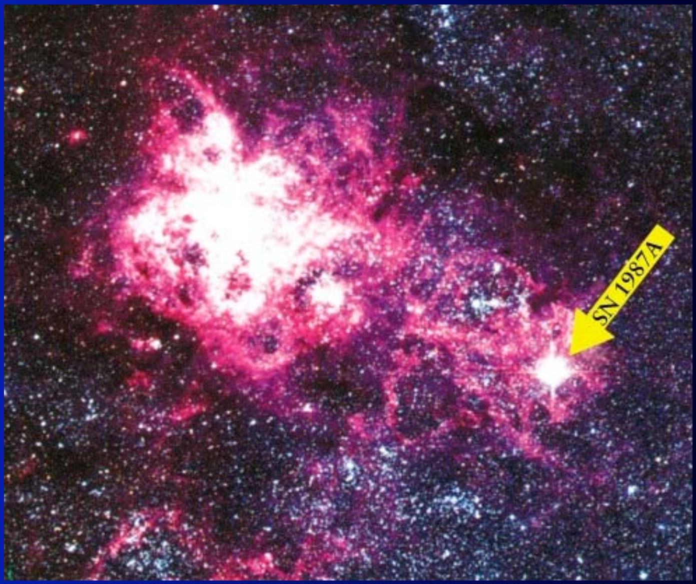
⇒ 1 year of Initial LIGO
< 1 day of Advanced LIGO!

Gravitational-Wave Bursts

Gravitational-Wave Bursts

- Catastrophic events involving solar-mass (1-100 M_o) compact objects.
  - core-collapse supernovae
  - accreting/merging black holes
  - gamma-ray burst engines
  - other … ???

- Uncertainty in waveforms complicates searches



SN 1987 A

E.g.: Core-Collapse Supernovae

- Death of massive stars ($M>8M_o$)
  - Iron core collapses to form a proto-neutron star (or black hole if $M>40M_o$).
  - The collapse halts suddenly when the core neutronizes; a shock wave from the bounce propagates out.
  - Eventually the outer layers of the star are blown off (mechanism uncertain).
  - Electromagnetic display visible hours after core collapse.

Courtesy of NASA (D. Berry)

Supernovae & GWs

- GW emission affected by physics in and around the proto-neutron star:
  - rotation of core
  - asymmetries from explosive burning
  - convection
  - neutrino burst
  - Eg: Fryer et al. astro-ph/0403188.

- Simulations often fail to explode (!)

- A GWB from a supernova provides a direct probe of the collapsing stellar core.

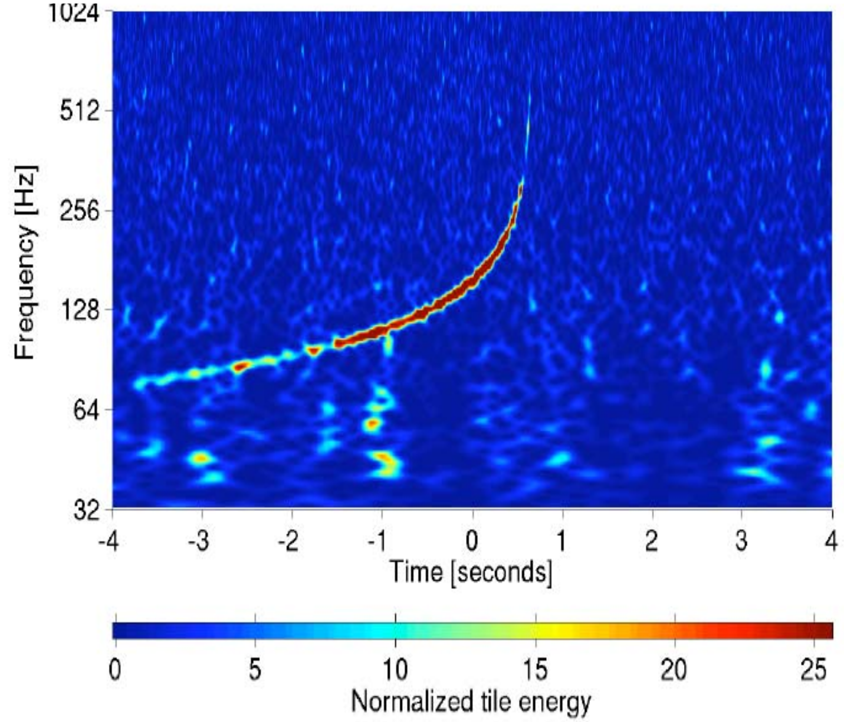
Burst Search Techniques

- Two main types of burst searches:
- Untriggered: Scan ~all data, looking for excess power indicative of a transient signal.
  - Robust way to detect generic GW waveforms.
- Triggered: Scan small amount of data around time of astronomical event (e.g., GRB), by cross-correlating data from pairs of detectors.
  - Exploits knowledge of time of and direction to astronomical event.
- Always: Use techniques that make minimal assumptions about the signal.
  - Be open to the unexpected!

Excess power detection

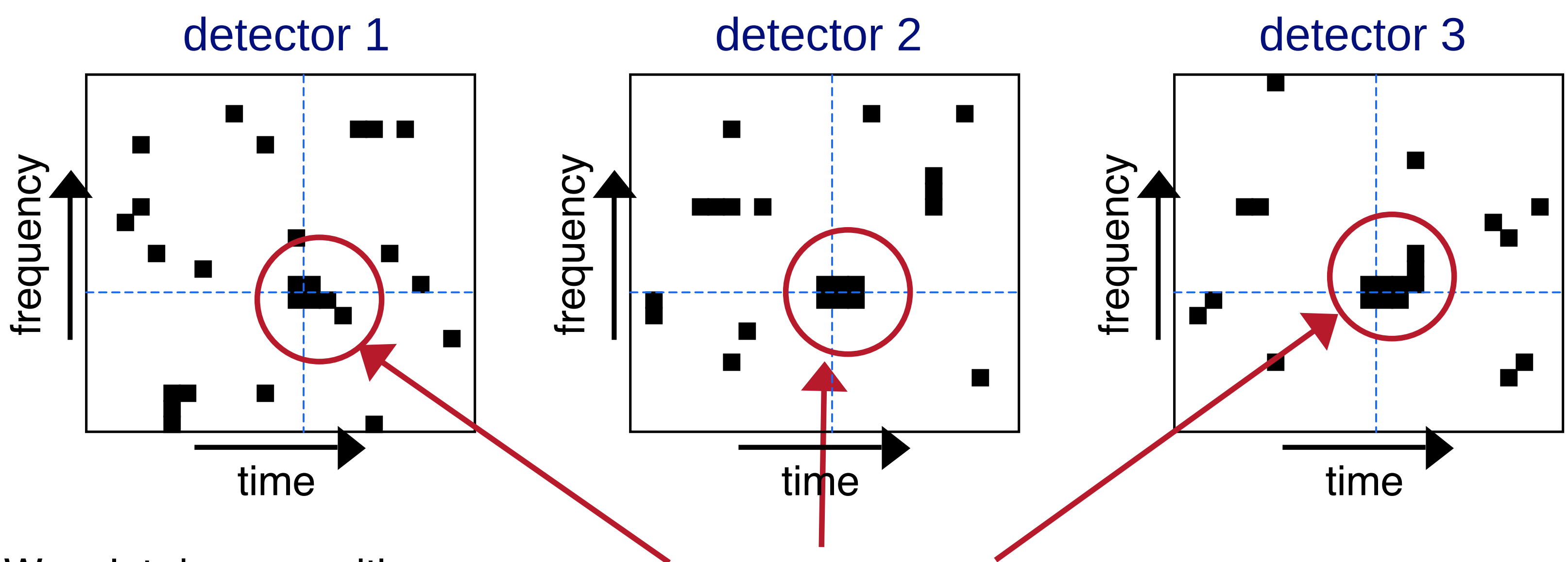
- Look for transient increase in power in some time-frequency region:
  - Minimal assumptions about signal
  - Duration: 1 to 100 ms
    - Characteristic time scale for stellar mass
      objects
  - Frequency: 60 to 2,000 Hz
    - Determined by detector's sensitivity
  - Many different implementations
    - Fourier modes, wavelets, sine-Gaussians
    - Multiple time/frequency resolutions
    - Provide redundancy and robustness

Simulated binary inspiral signal in S5 data



"WaveBurst"

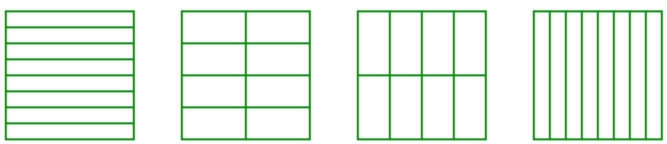
excess power detection in wavelet time-frequency plane



candidate event

**statistical significance,
time, duration, frequency,
signal amplitude**

Wavelet decomposition:
64–2048 Hz with 6 different
time resolutions: 1/16 sec × 8 Hz
to 1/512 sec × 256 Hz



Threshold on significance of the triple-coincident event (GC)

Class. Quantum Grav. 21 (2004) S1819

Removing Noise Events

- WaveBurst detection algorithm also picks up noise “glitches”.

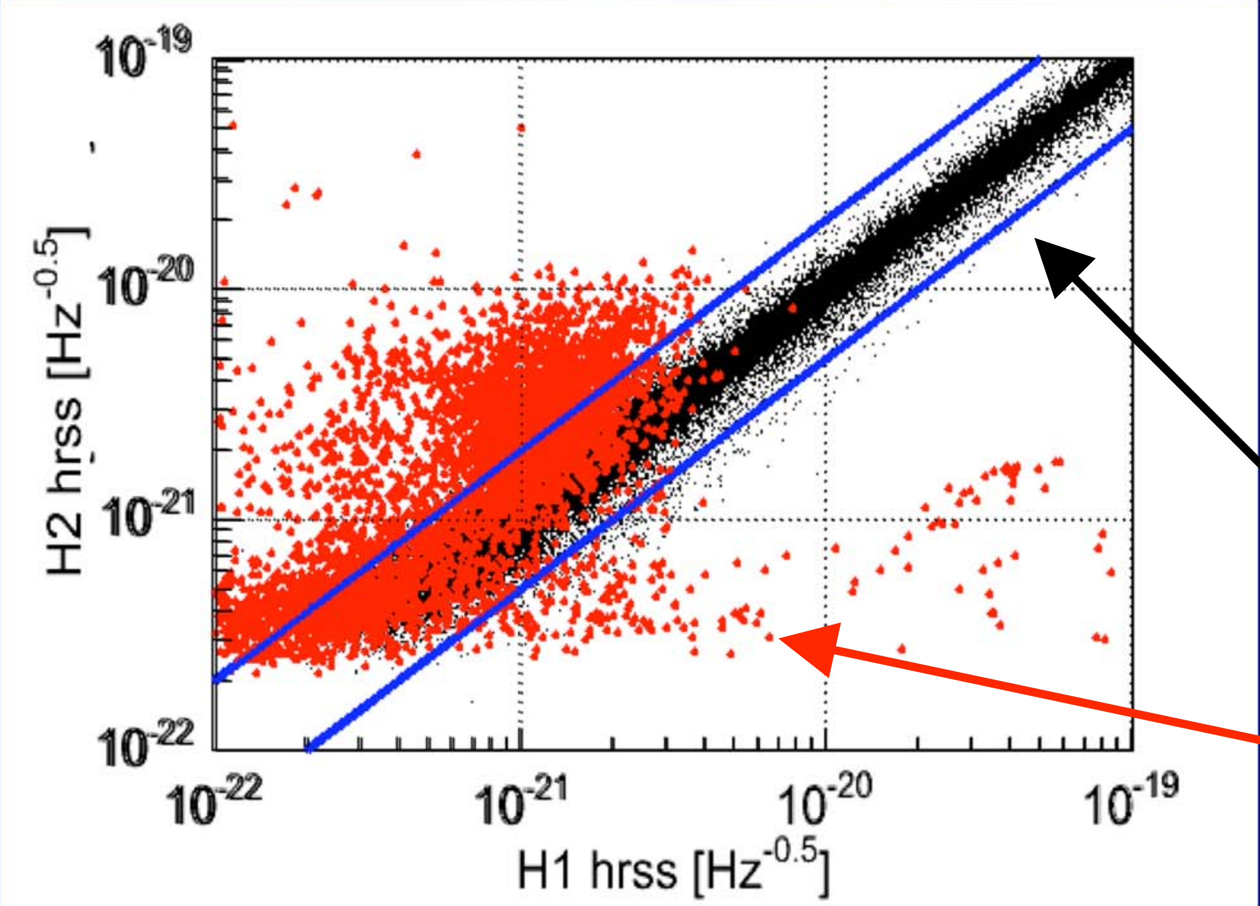
- Follow-up tests for consistency with GWs:
  - amplitude consistency (as measured by the two co-aligned Hanford detectors)
  - require cross-correlation of data from pairs of detectors exceed threshold:

- Check environmental and auxiliary channels for:
    - Earthquakes, airplanes, trains, instrumental misbehaviour, ...
  - Remove times of poor data quality
  - Veto events associated to known noise sources

- Compare remaining events with background estimated by repeating analysis with large time shifts of detector data.

H1-H2 Amplitude Test

- The two detectors at Hanford site ("H1" and "H2") should see the same signal amplitude if it is a true GWB.



Require:

0.5 < (H1/H2) < 2

for h_{rss} amplitude estimated by WaveBurst

$$h_{rss} = \sqrt{\int_0^\infty |h(t)|^2 dt}$$

Simulated narrow-band signals (0.5% fail test)

S4 noise events from time shifts (~50% fail test)

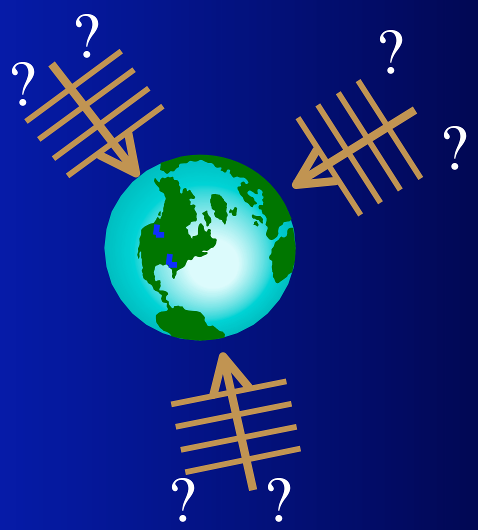
Waveform Consistency

» Require cross-correlation of normalized data from pairs of detectors exceed threshold:

$$r_k = \frac{\sum_i (x_i - \bar{x})(y_{i+k} - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2} \sqrt{\sum_i (y_{i+k} - \bar{y})^2}}$$

("Pearson r-statistic")

» Strong reduction of false alarm rate (~99%) with little loss of efficiency



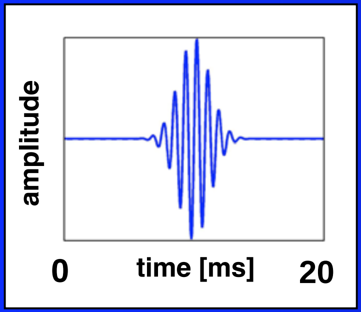
– Test with different physical time-lags (+/-10ms), range of target signal durations (<100ms)

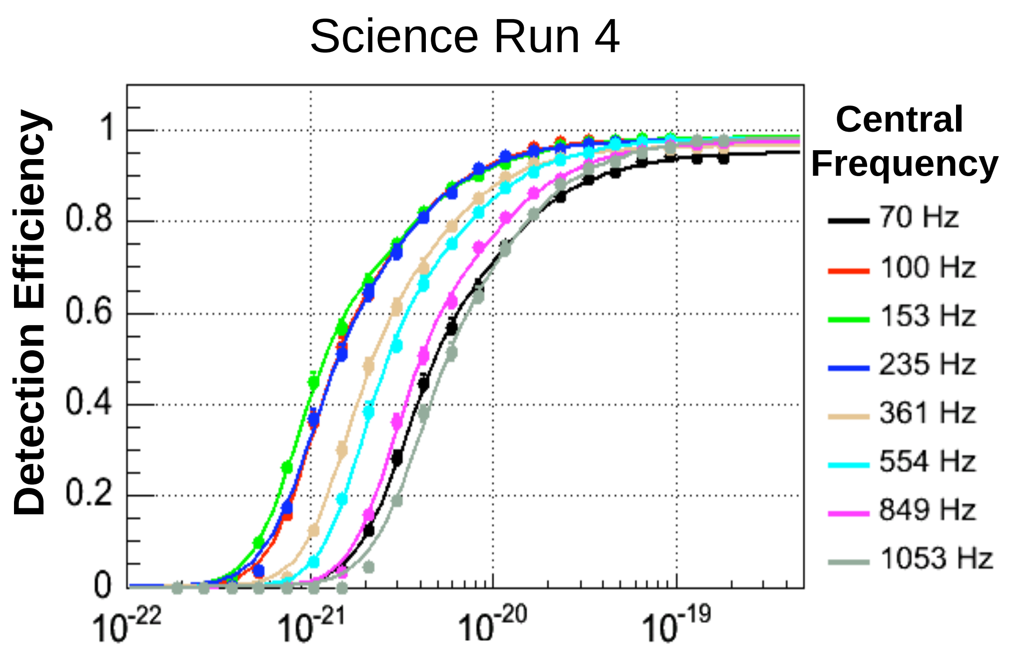
Cadonati CQG *21* S1695 (2004)

Detection Efficiency

Test sensitivity by adding simulated GWBs to the data.

- Eg: Gaussian-modulated sinusoid.





$$h_{rss} = \sqrt{\int |h(t)|^2 dt}$$

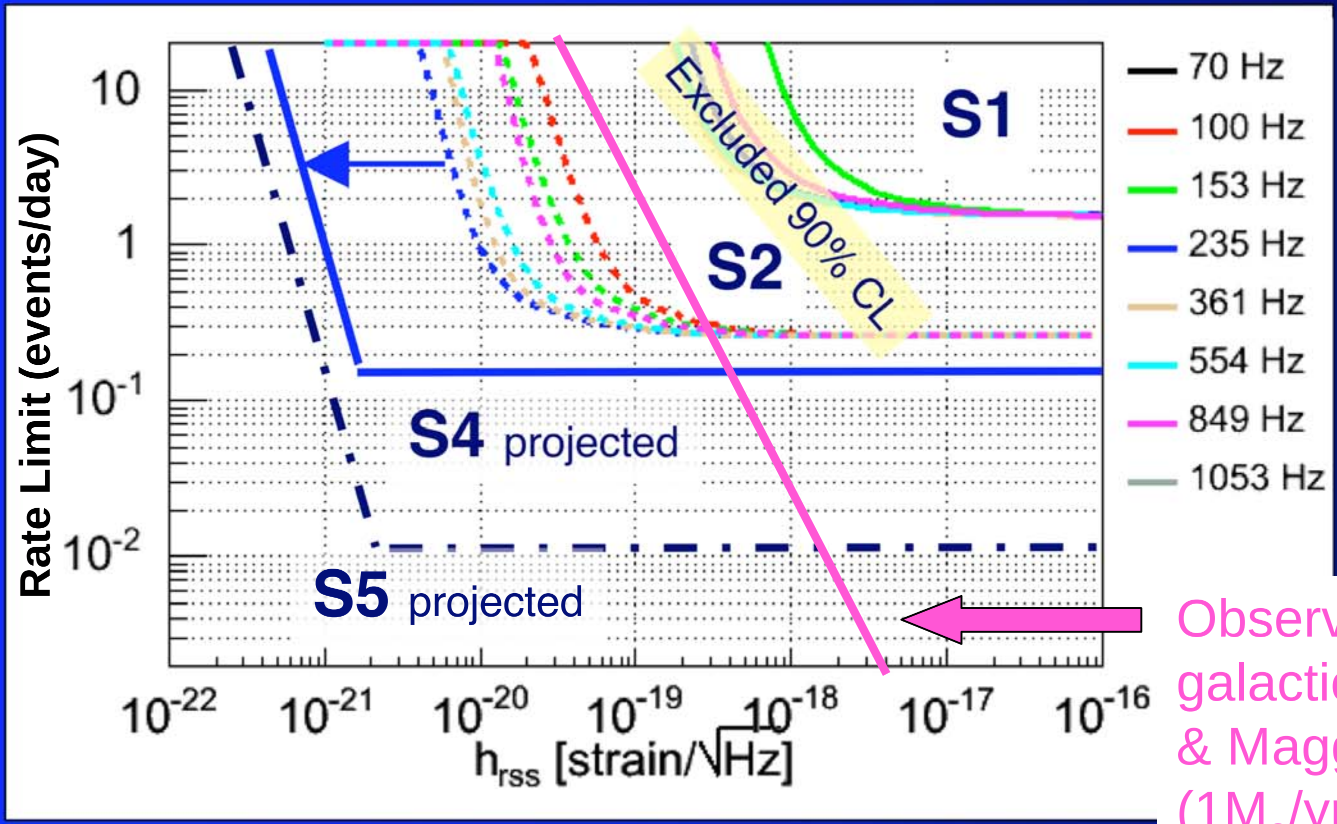
Astrophysical interpretation:

Minimum detectable in-band energy in GWs (early S5):

- $E_{GW} > 1\ M_o$ at $r \sim 75$ Mpc
- $E_{GW} > 0.05\ M_o$ at $r \sim 15$ Mpc (~ distance to Virgo cluster)

Progress in Upper Limits

- No GWBs detected through S4.
- Set limits on GWB rate as a function of amplitude.



Lower rate limits from longer observation times

Lower amplitude limits from lower detector noise

Observational limits from galactic mass loss: Dubath & Maggiore gr-qc/0604048 ($1M_o$/yr, 1 ms Gauss pulses)

Network Searches

The Global Network

- Several km-scale detectors, bars now in operation
- Network gives:
  - Detection confidence
  - Direction by triangulation
  - Waveform extraction

Coherent Network Analysis

- *What did the GWB look like? Where did it come from?*
  - Excess-power algorithms (e.g., WaveBurst) can't answer these questions well.
- Coherent analysis (combining data from multiple detectors) with the global network can do it:
  - For detection, noise rejection, source location determination, waveform extraction
  - E.g.: Gursel & Tinto, PRD **40** 3884 (1989); Klimenko et al, PRD **72** 122002 (2005); Chatterji et al., gr-qc/0506002.
- The next "big thing" in GWB searches.
  - several LIGO institutions active in this area

The Basic Problem & Solution

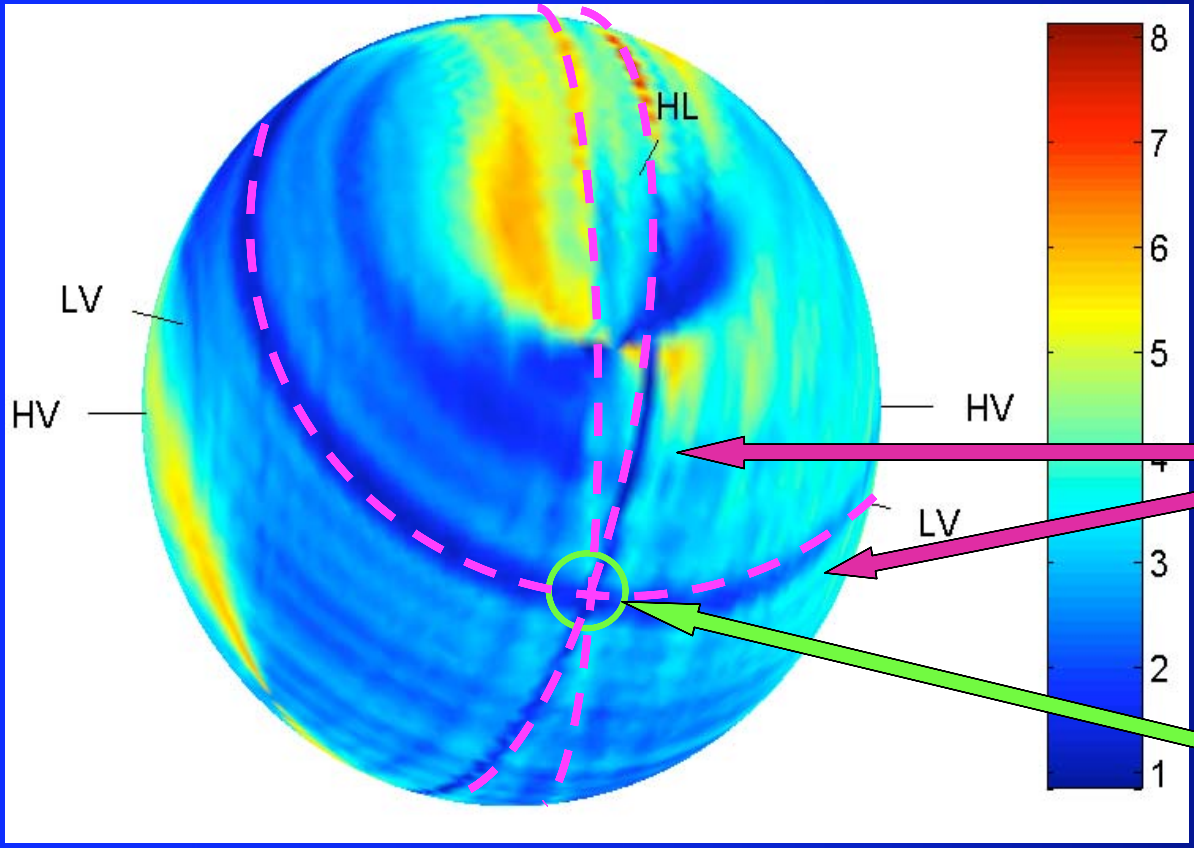
- Output of D detectors:
  - Waveforms $h_+(t)$, $h_x(t)$, source direction Ω all unknown.
  - How do we find them?

data — detector antenna responses — GWB (unknown) — noise (unknown)

$$\begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_D \end{bmatrix} = \begin{bmatrix} F_1^+(\Omega) & F_1^\times(\Omega) \\ F_2^+(\Omega) & F_2^\times(\Omega) \\ \vdots & \vdots \\ F_D^+(\Omega) & F_D^\times(\Omega) \end{bmatrix} \begin{bmatrix} h^+ \\ h^\times \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_D \end{bmatrix}$$

- Approach: Treat Ω, h_+ & h_x at each instant of time as independent parameters to be fit by the data.
  - Scan over the sky (Ω).
  - At each sky position construct the least-squares fit to h_+, h_x from the data (“noisy templates”).
  - Amplitude of the template and the quality of fit determine if a GWB is detected.

Example: Supernova GWB



χ^2 / DOF consistency with a GWB as a function of direction for a simulated supernova (~1 kpc)

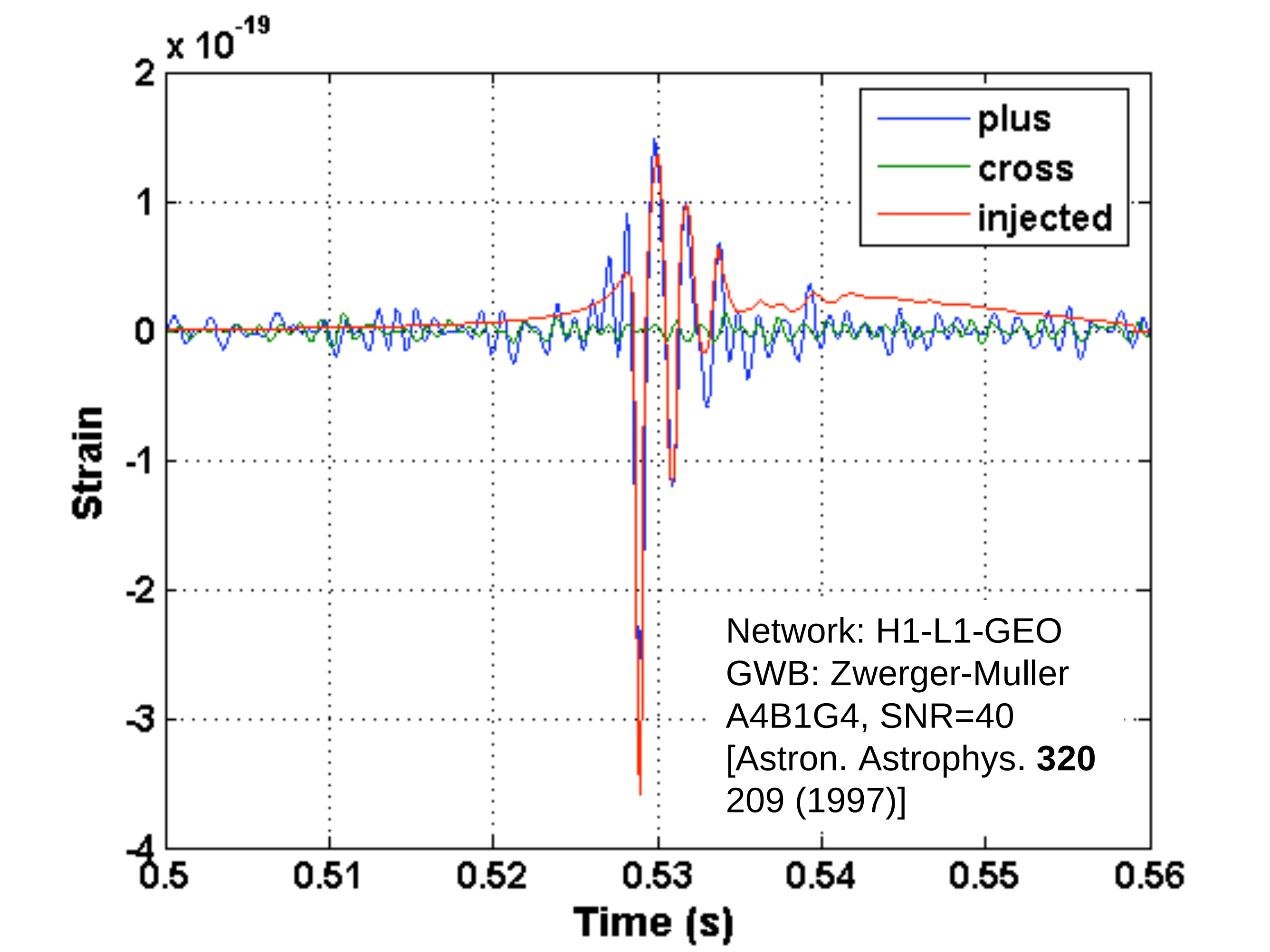
Interference fringes from combining signal in two detectors.

True source location:
- intersection of fringes
- χ^2 / DOF ~ 1

GWB: Dimmelmeier et al. A1B3G3 waveform, Astron. Astrophys. 393 523 (2002) , SNR = 20
Network: H1-L1-Virgo, design sensitivity

Supernova GWB Recovery

(least squares)



Recovered signal (blue) is a noisy, band-passed version of injected GWB signal (red)

Injected GWB signal has $h_x = 0$.

Recovered h_x (green) is just noise.

Maximum Entropy Waveform Estimation

- *This section: work by T. Summerscales, Ph.D. Thesis, Pennsylvania State University (2006).*
  - Regularize waveform reconstruction and minimize fitting to noise.
  - Common image reconstruction technique.
  - Add entropy prior P(h) to maximum-likelihood formulation:

I: model

$$P(\mathbf{h} \mid \mathbf{d}, I) \propto P(\mathbf{d} \mid \mathbf{h}, I) P(\mathbf{h} \mid I)$$

standard likelihood

prior on GWB waveform

Maximum Entropy Cont.

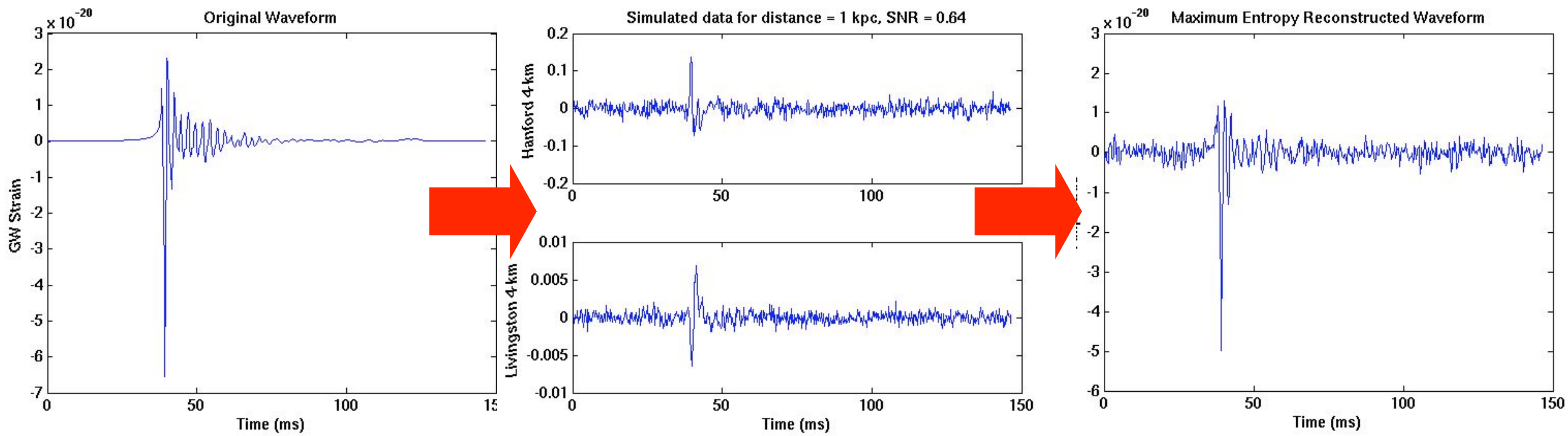
- Choice of prior:

$$P(\mathbf{h} \mid I) = \exp[\alpha S(\mathbf{h},\mathbf{m})]$$

$$S(\mathbf{h},\mathbf{m}) = \sum_{time\ i} \left(4m_i^{\ 2} + h_i^{\ 2}\right)^{1/2} - 2m_i - h_i \log \frac{\left(4m_i^{\ 2} + h_i^{\ 2}\right)^{1/2} + h_i}{2m_i}$$

  – S: Related to Shannon Information Entropy (or number of ways quanta of energy can be distributed in time to form the waveform).
    - Not quite usual $\rho \ln \rho$ form of entropy because h can be negative.
    - Hobson and Lasenby MNRAS **298** 905 (1998).
  – Model m_i: Mean number of "positive" or "negative" quanta per time bin *i*.
    - Determined from data **d** using Bayesian analysis.
  – α is a Lagrange parameter that balances being faithful to the signal (minimizing χ^2) and avoiding overfitting (maximizing entropy)

Maximum Entropy Performance, Weak Signal



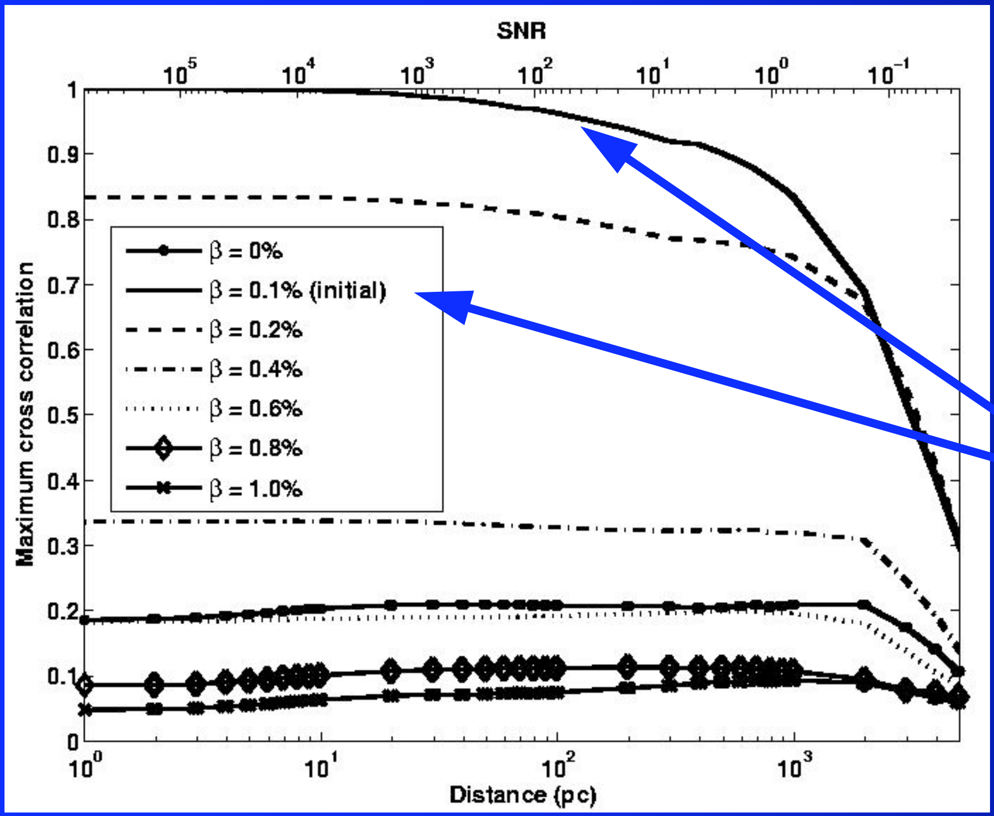
input GWB signal

noisy data from two detectors

recovered GWB signal

Summerscales, Finn, Ott, & Burrows (in preparation): study ability to recover supernova waveform parameters (rotational kinetic energy, degree of differential rotation, equation of state polytropic index).

Extracting Rotational Information



- Cross correlations between reconstructed signal and waveforms from models that differ only by rotation parameter β (rotational kinetic energy).
- Reconstructed signal most closely resembles waveforms from models with the same rotational parameters

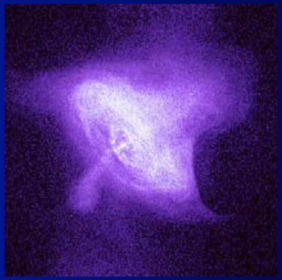
Summerscales, Finn, Ott, & Burrows (in preparation)

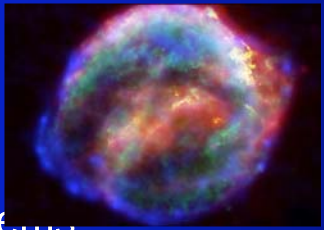
When will we see something?

When will we see something?

Predictions are difficult… many unknowns!

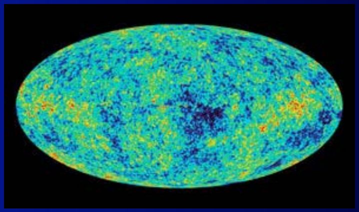
- Supernovae, gamma ray bursts:
  how strong are the waves
  (and what do they look like)?



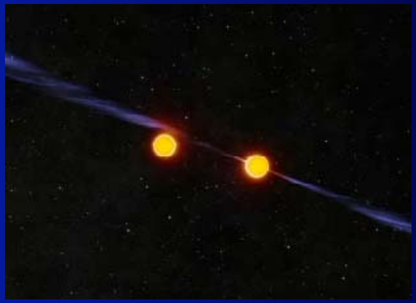


- Binary black holes: how many are there?
  What masses do they have?

- Binary neutron stars: from observed systems
  in our galaxy, predictions are up to 1/3yrs,
  but most likely one per 30 years,
  at LIGO's present sensitivity



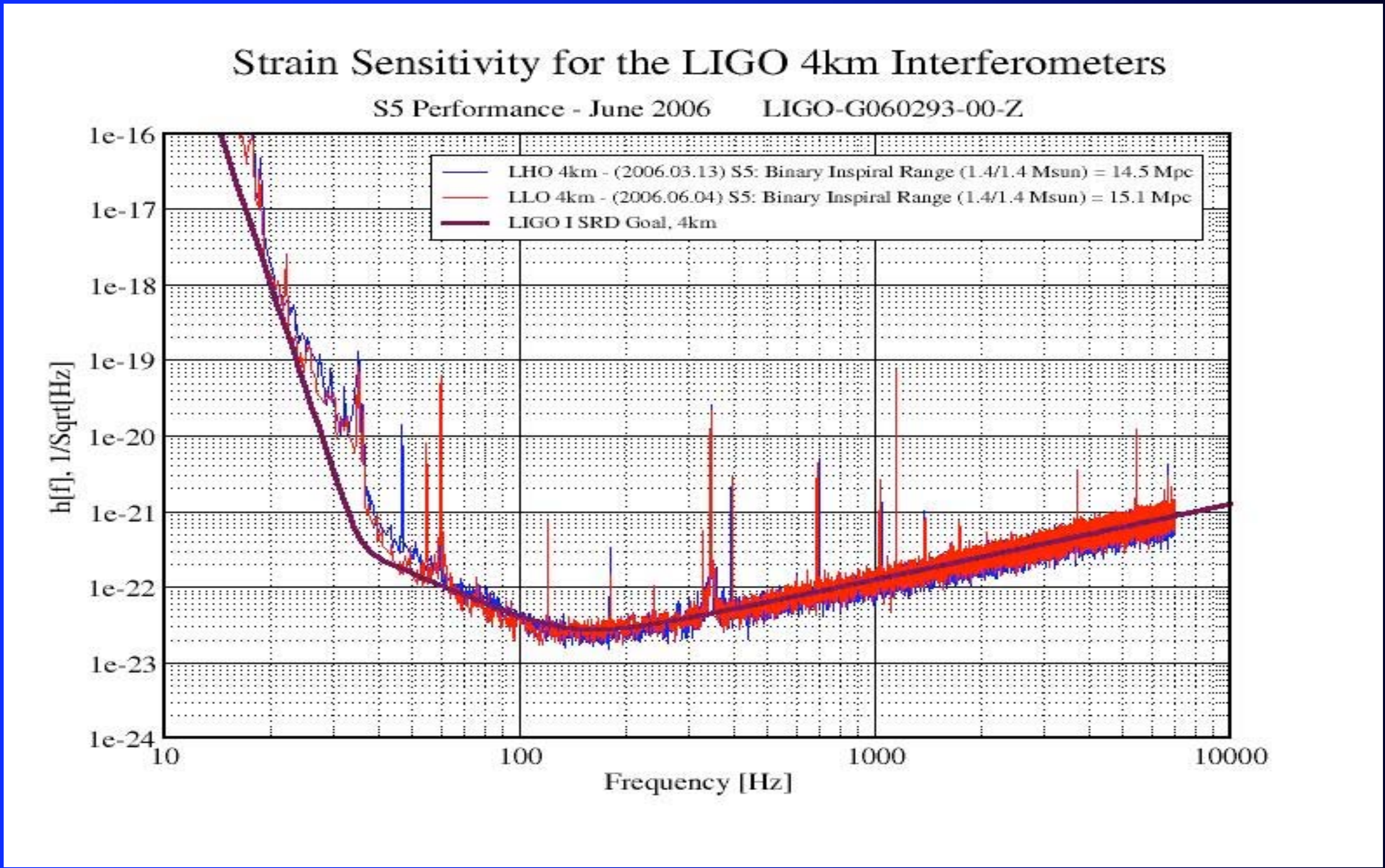
- From rate of short GRBs, much more optimistic predictions for BNS and BBH rates? Ready to be tested with S5!



- Rotating stars: how lumpy are they?

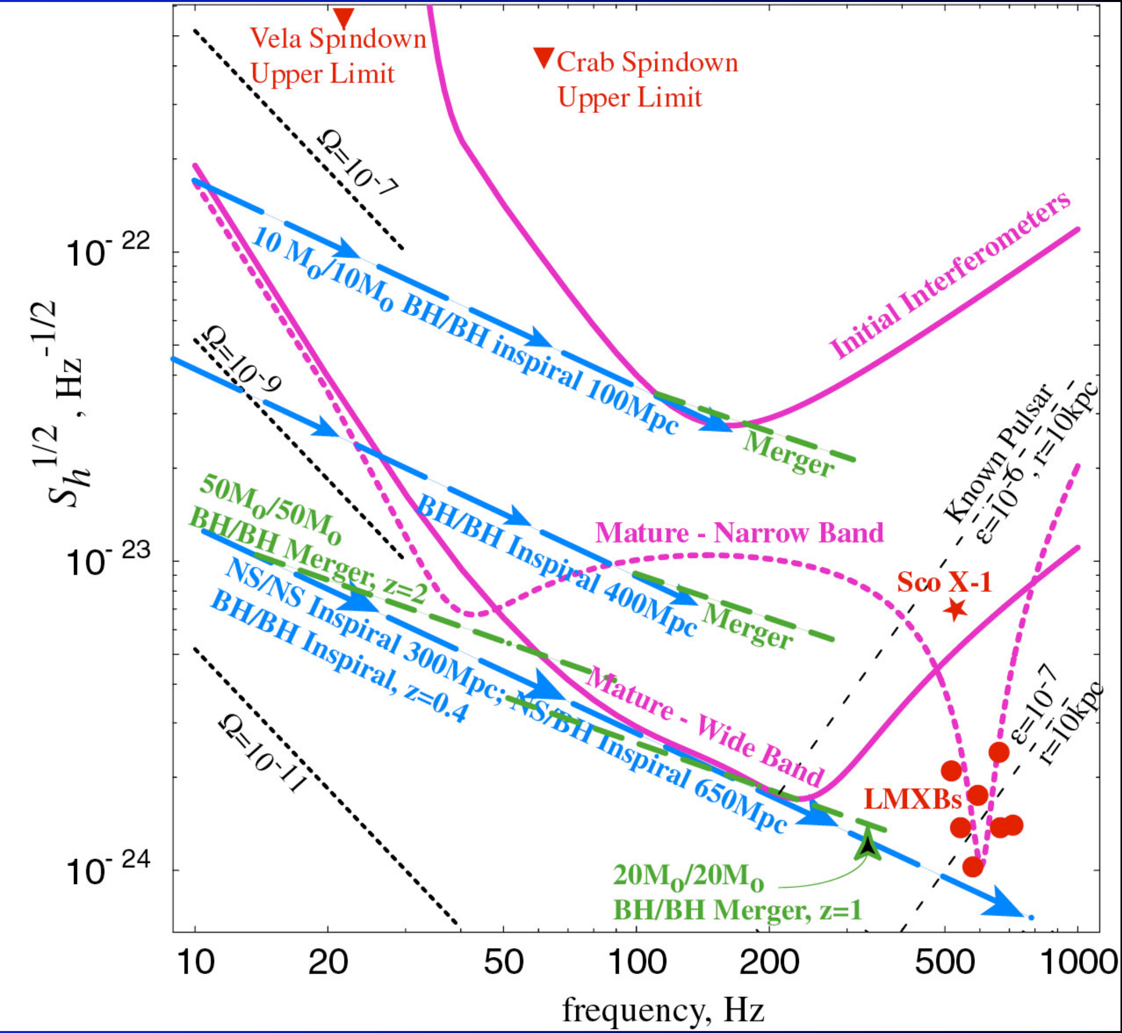
- Cosmological background:
  how did the Universe evolve?

Looking Forward



From Initial to Advanced LIGO

- **NS-NS Binaries:**
  Reach:
  ~20 Mpc → ~350 Mpc
  Rate:
  1/30y (>1/3y) → 1/2d (>5/d)
- **BH-BH Binaries:**
  10 M_o, 100 Mpc → 50 M_o, z=2
- **Known Pulsars:**
  $\varepsilon = 3\times10^{-6}$ → $\varepsilon = 2\times10^{-8}$
- **Stochastic background:**
  $\Omega\sim3\times10^{-6}$ → $\Omega\sim 3\times10^{-9}$



Summary

- The new generation of GW detectors has unprecedented sensitivity.
- GW bursts one of the most exciting but challenging sources to study.
- LIGO collaboration has developed robust algorithms for detecting GWBs.
  - Excess power techniques for “all sky” searches, cross-correlations for following up astronomical events like GRBs.
  - Searches through first 4 science runs completed.
  - First searches with TAMA, GEO, AURIGA done / in progress.
  - Currently sensitive to E_{GW} ~ O(1) M_o at r < O(100) Mpc.
- Techniques for taking full advantage of the global network to detect and study GWBs are in development.
  - GWB localization & waveform extraction techniques are now being developed.

Summary

- Near future:
  - Currently collecting 1 year of data for 5th "science run"
  - GEO participating in search, Virgo will join around end of 2006 / early 2007.
  - Joint searches for GWBs being planned.
  - First direct detection of GWs may happen soon (odds?).
- Advanced LIGO construction: 2010-2013.
  - ~10 x better sensitivity to most GW sources.
  - Should detect many GWs.
- *Gravitational-wave astronomy will become a reality in the next few years, and we'll be ready!*

LIGO Burst Publications

- Analysis of data from first 3 science runs completed:
  - B. Abbott et al. (LSC), *First upper limits from LIGO on gravitational wave bursts.* Phys. Rev. D **69**, 102001 (2004)
  - B. Abbott et al. (LSC), *A Search for Gravitational Waves Associated with the Gamma Ray Burst GRB030329 Using the LIGO Detectors.* Phys. Rev. D **72**, 042002 (2005)
  - B. Abbott et al. (LSC), *Upper Limits on Gravitational Wave Bursts in LIGO's Second Science Run.* Phys. Rev. D **72**, 062001 (2005)
  - B. Abbott et al. (LSC), T. Akutsu et al. (TAMA), *Upper Limits from the LIGO and TAMA Detectors on the Rate of Gravitational-Wave Bursts.* Phys. Rev. D **72**, 122004 (2005)
  - B. Abbott et al. (LSC), *Search for gravitational wave bursts in LIGO's third science run.* Class. Quant. Grav. **23**, S29-S39 (2006)

- Science run 4: paper drafts being finalized.
  - All-sky search
  - GRB searches
  - SGR 1806-20 giant flare

- Science run 5: in progress!