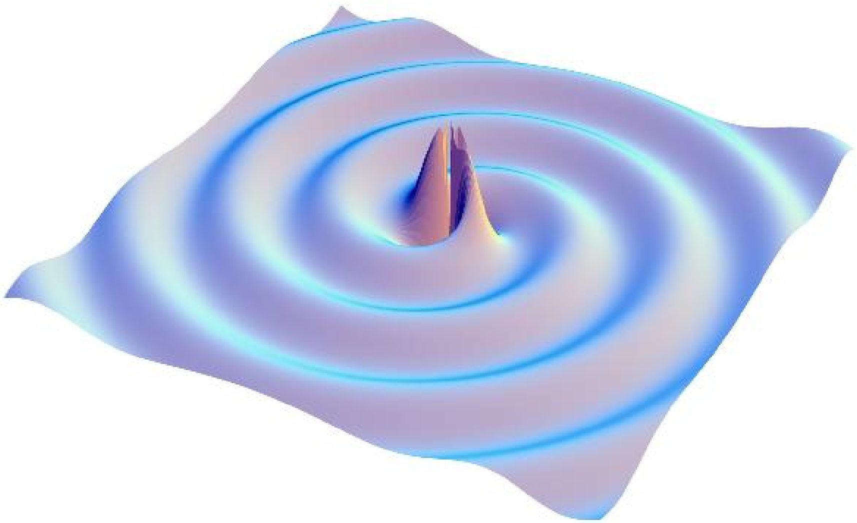
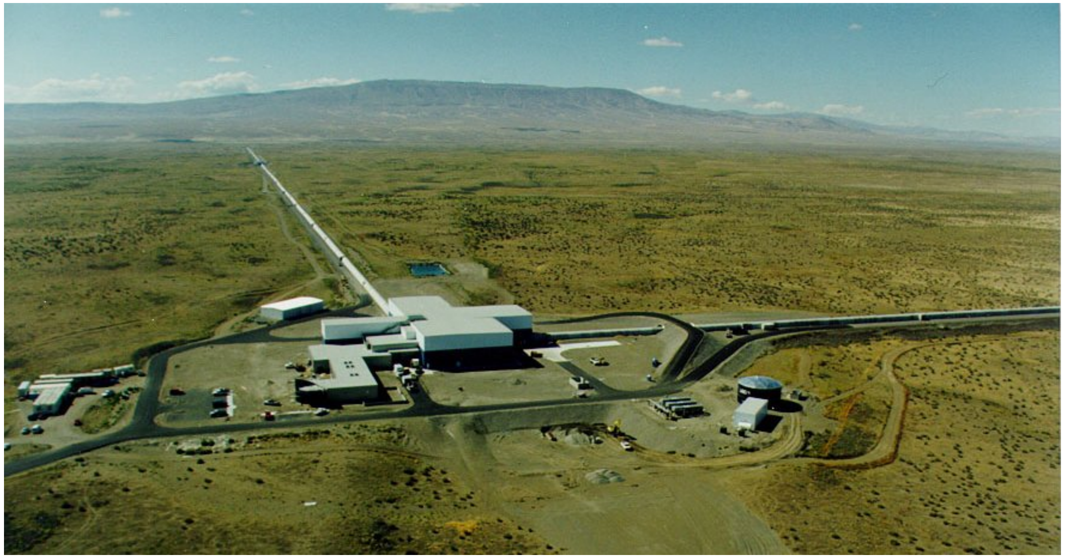
First Results from LIGO



Keith Riles
University of Michigan



High Energy Physics Seminar

Wayne State University

March 11, 2005

LIGO-G050667-00-Z

Outline

- Nature & Generation of Gravitational Waves
- Detecting Gravitational Waves with the LIGO Detector
- Data runs and Early Results
- Looking Ahead – Advanced LIGO

Nature of Gravitational Waves

- Gravitational Waves = "Ripples in space-time"

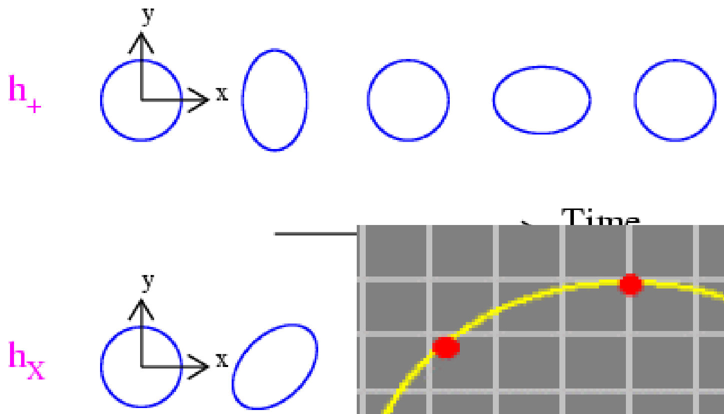
- Perturbation propagation similar to light (obeys same wave equation!)
  - **Propagation speed = c**
  - **Two transverse polarizations - quadrupolar:** + and x

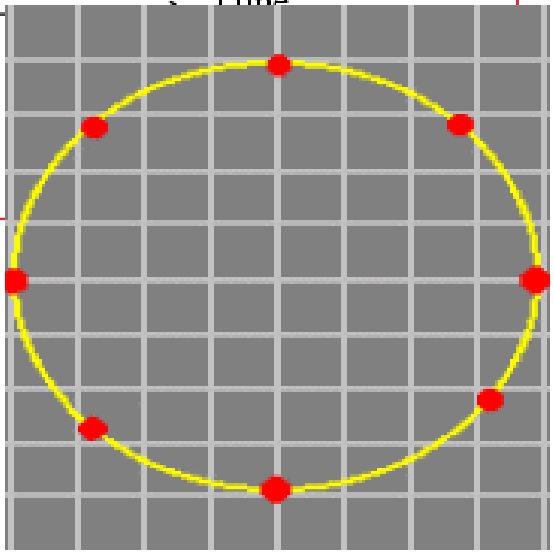
Example:

Ring of test masses

responding to wave

propagating along z



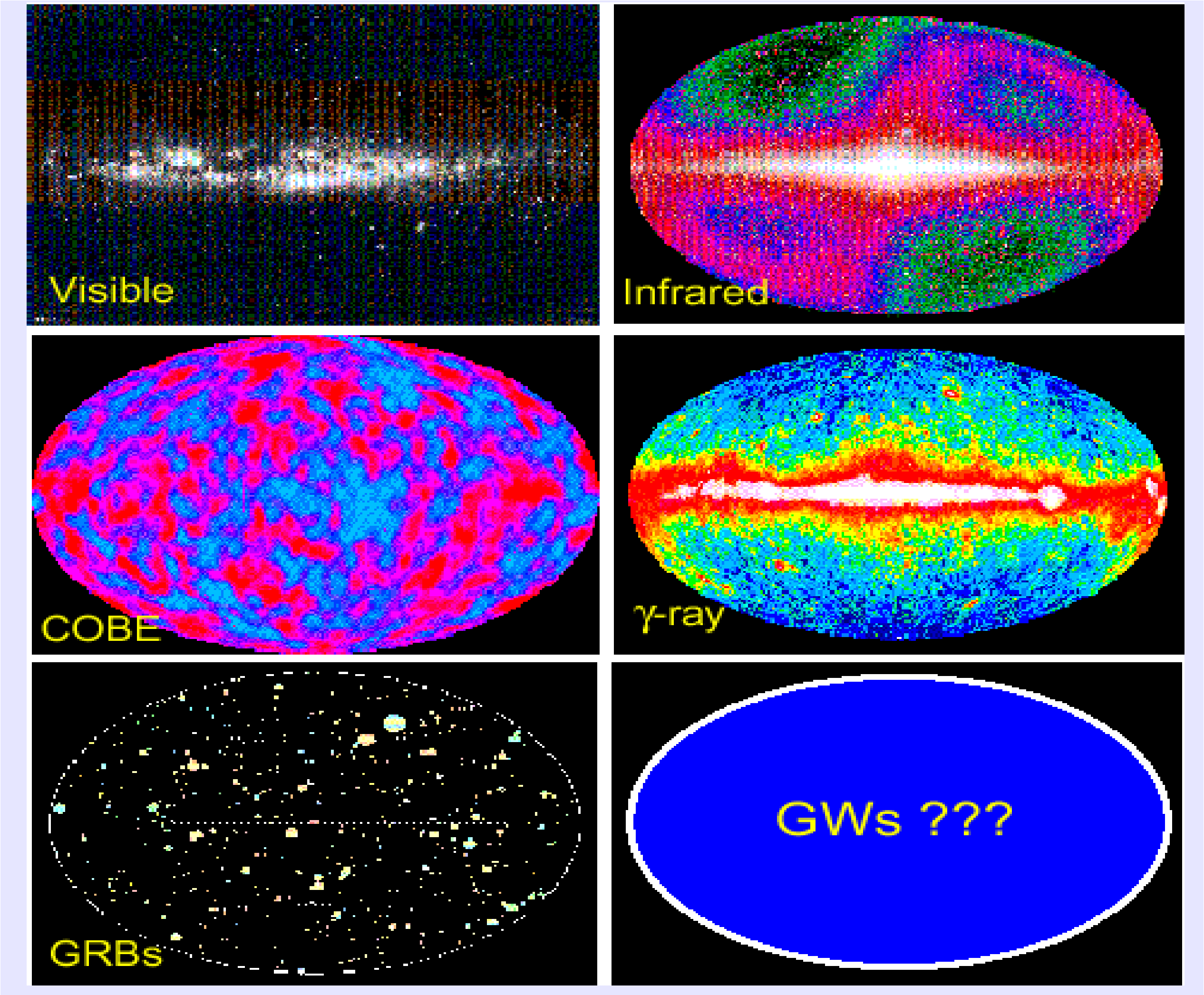


- Amplitude parameterized by (tiny) dimensionless strain h: $\Delta L \sim h(t) \times L$

Why look for Gravitational Radiation?

- Because it's there! (presumably)
- Test General Relativity:
  - Quadrupolar radiation? Travels at speed of light?
  - Unique probe of strong-field gravity
- Gain different view of Universe:
  - Sources cannot be obscured by dust
  - Detectable sources some of the most interesting, least understood in the Universe
  - <u>**Opens up entirely new non-electromagnetic spectrum**</u>

What will the sky look like?



Generation of Gravitational Waves

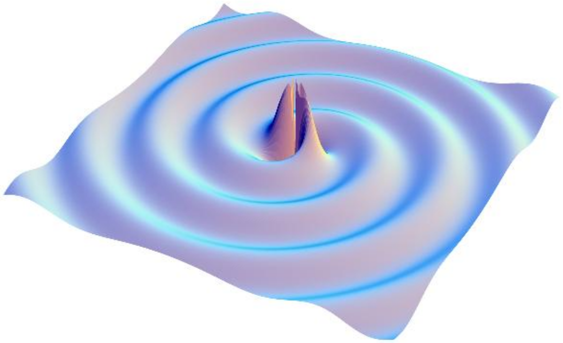
- Radiation generated by quadrupolar mass movements:

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}(I_{\mu\nu})$$

(with $I_{\mu\nu}$ = quadrupole tensor, r = source distance)

- Example: Pair of 1.4 M_{solar} neutron stars in circular orbit of radius 20 km (imminent coalescence) at orbital frequency 400 Hz gives 800 Hz radiation of amplitude:

$$h \approx \frac{10^{-21}}{(r/15\mathrm{Mpc})}$$



Generation of Gravitational Waves

Major expected sources in 10-1000 Hz “terrestrial” band:

- Coalescences of binary compact star systems
  (NS-NS, NS-BH, BH-BH)
- Supernovae
  (requires asymmetry in explosion)
- Spinning neutron stars, e.g., pulsars
  (requires axial asymmetry or wobbling spin axis)

Also expected (but probably exceedingly weak):

- Stochastic background – Big Bang remnant
- Or from cosmic strings in early universe?

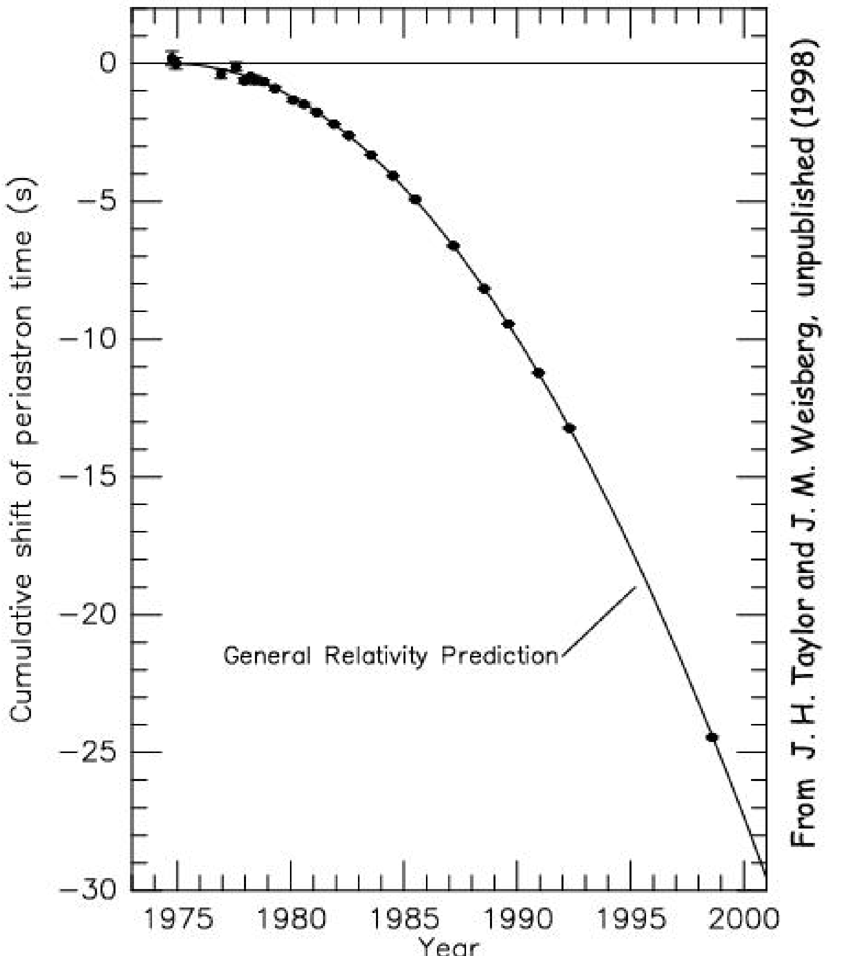
Generation of Gravitational Waves

- Strong <u>indirect</u> evidence for GW generation:

Taylor-Hulse Pulsar System (PSR1913+16)

- **Two neutron stars (one=pulsar) in elliptical 8-hour orbit**

- **Measured periastron advance quadratic in time in agreement with absolute GR prediction**
  → Orbital decay due to energy loss

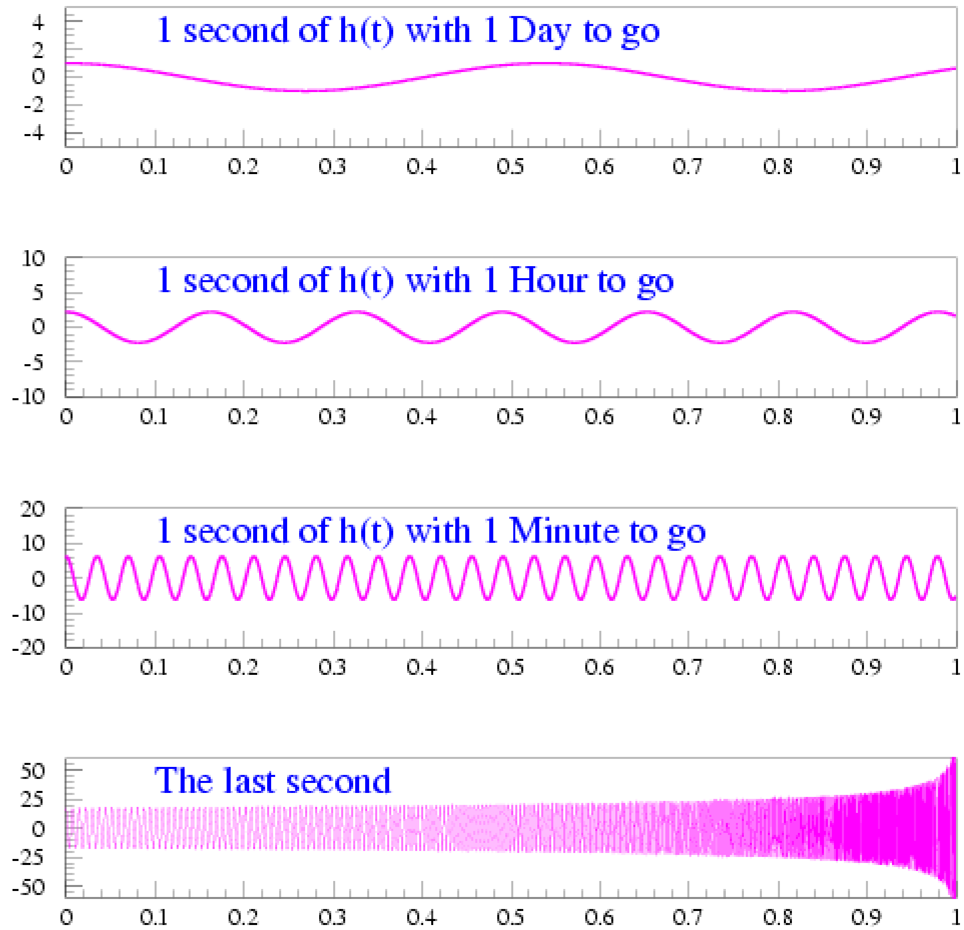


Generation of Gravitational Waves

Can we detect this radiation directly?

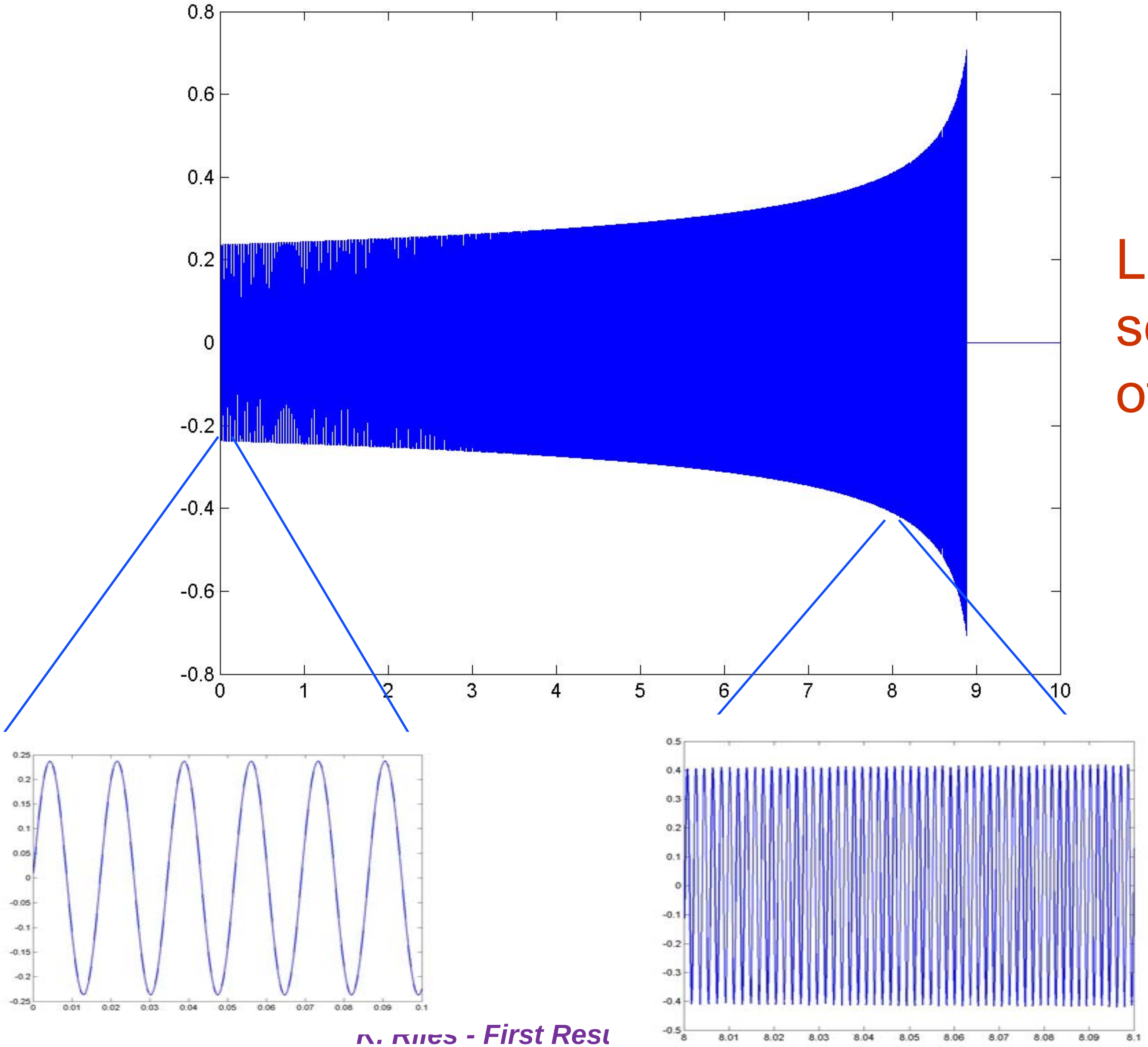
NO - freq too low

Must wait ~300 My for characteristic “chirp”:



Generation of Gravitational Waves

Audio



Last nine seconds of inspiral

Generation of Gravitational Waves

Coalescence rate estimates based on two methods:

- Use known NS/NS binaries in our galaxy (three!)
- *A priori* calculation from stellar and binary system evolution

→ Large uncertainties!

For initial LIGO design "seeing distance" (~20 Mpc):

Expect 1/(70 y) to 1/(4 y)

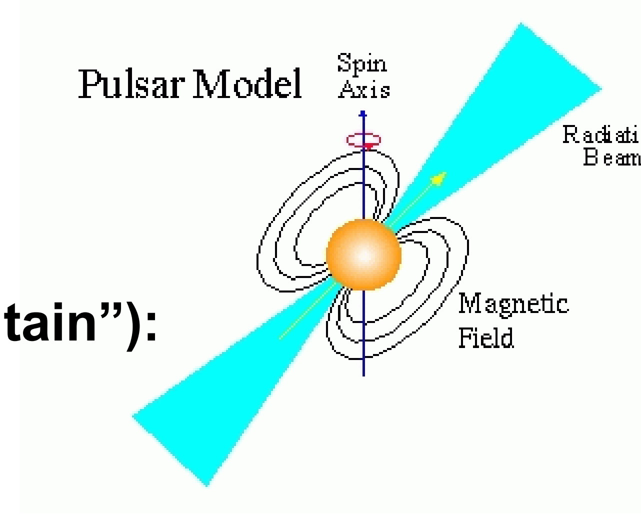
→ Will need Advanced LIGO to ensure detection

Generation of Gravitational Waves

Most promising periodic source: Rotating Neutron Stars (e.g., pulsar)

But axisymmetric object rotating about symmetry axis
Generates NO radiation

Need an asymmetry or perturbation:



- **Equatorial ellipticity** (e.g., – mm-high "mountain"):

$$h \;\alpha\; \varepsilon_{equat}$$

- **Poloidal ellipticity** (natural) + **wobble angle** (precessing star):

$$h \;\alpha\; \varepsilon_{pol} \times \Theta_{wobble}$$

(precession due to different L and Ω axes)

Periodic Sources of GW

Serious technical difficulty: Doppler frequency shifts

- Frequency modulation from earth's rotation ($v/c \sim 10^{-6}$)
- Frequency modulation from earth's orbital motion ($v/c \sim 10^{-4}$)

Additional, related complications:

- Daily amplitude modulation of antenna pattern
- Spin-down of source
- Orbital motion of sources in binary systems

Modulations / drifts complicate analysis enormously:

- Simple Fourier transform inadequate
- Every sky direction requires different demodulation

$\rightarrow$ All-sky survey at full sensitivity = Formidable challenge

Periodic Sources of GW

But two substantial benefits from modulations:

- Reality of signal confirmed by need for corrections
- Corrections give precise direction of source

- ❑ **Difficult to detect spinning neutron stars!**
- ❑ **But search is nonetheless intriguing:**
  - Unknown number of electromagnetically quiet, undiscovered neutron stars in our galactic neighborhood
  - Realistic values for ε unknown
  - A nearby source could be buried in the data, waiting for just the right algorithm to tease it into view

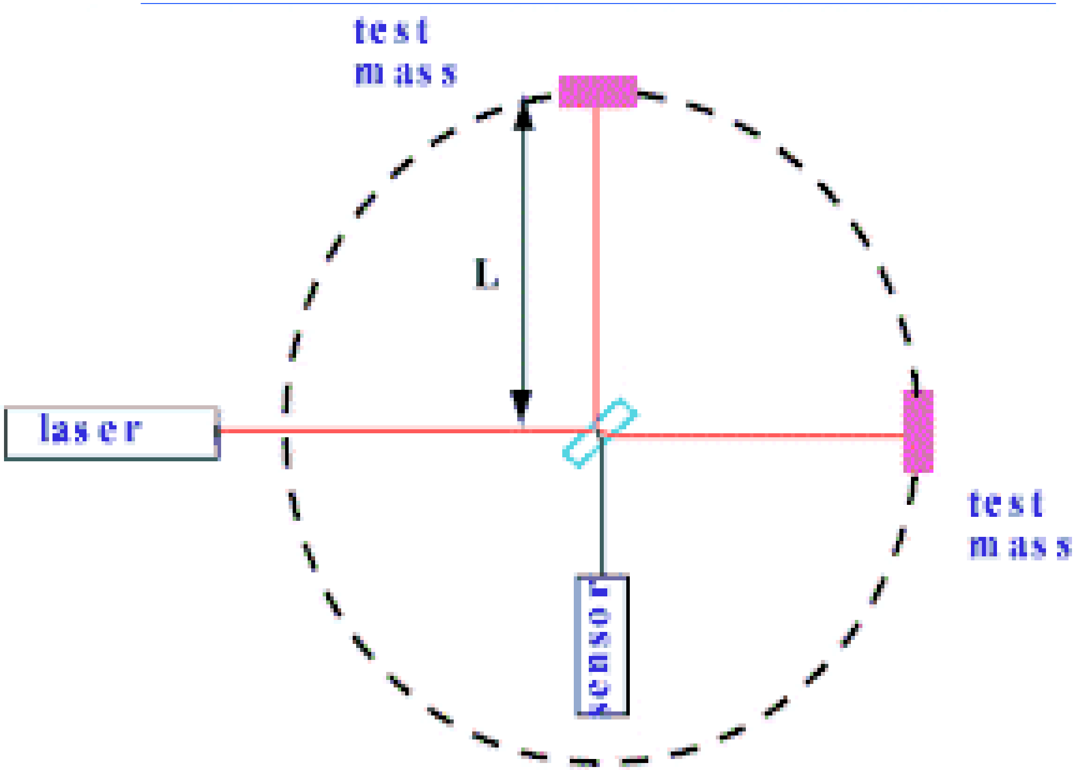
Ongoing effort → Expect broadband results by summer

Outline

- Nature & Generation of Gravitational Waves
- Detecting Gravitational Waves with the LIGO Detector
- Data runs and Early Results
- Preparing for Advanced LIGO

Gravitational Wave Detection

- Suspended Interferometers (IFO's)
  - **Suspended mirrors in "free-fall"**
  - **Broad-band response**
    (~50 Hz to few kHz)
  - **Waveform information**
    (e.g., chirp reconstruction)
  - **Michelson IFO is**
    "natural" GW detector



Gravitational Wave Detection

Major Interferometers coming on line world-wide

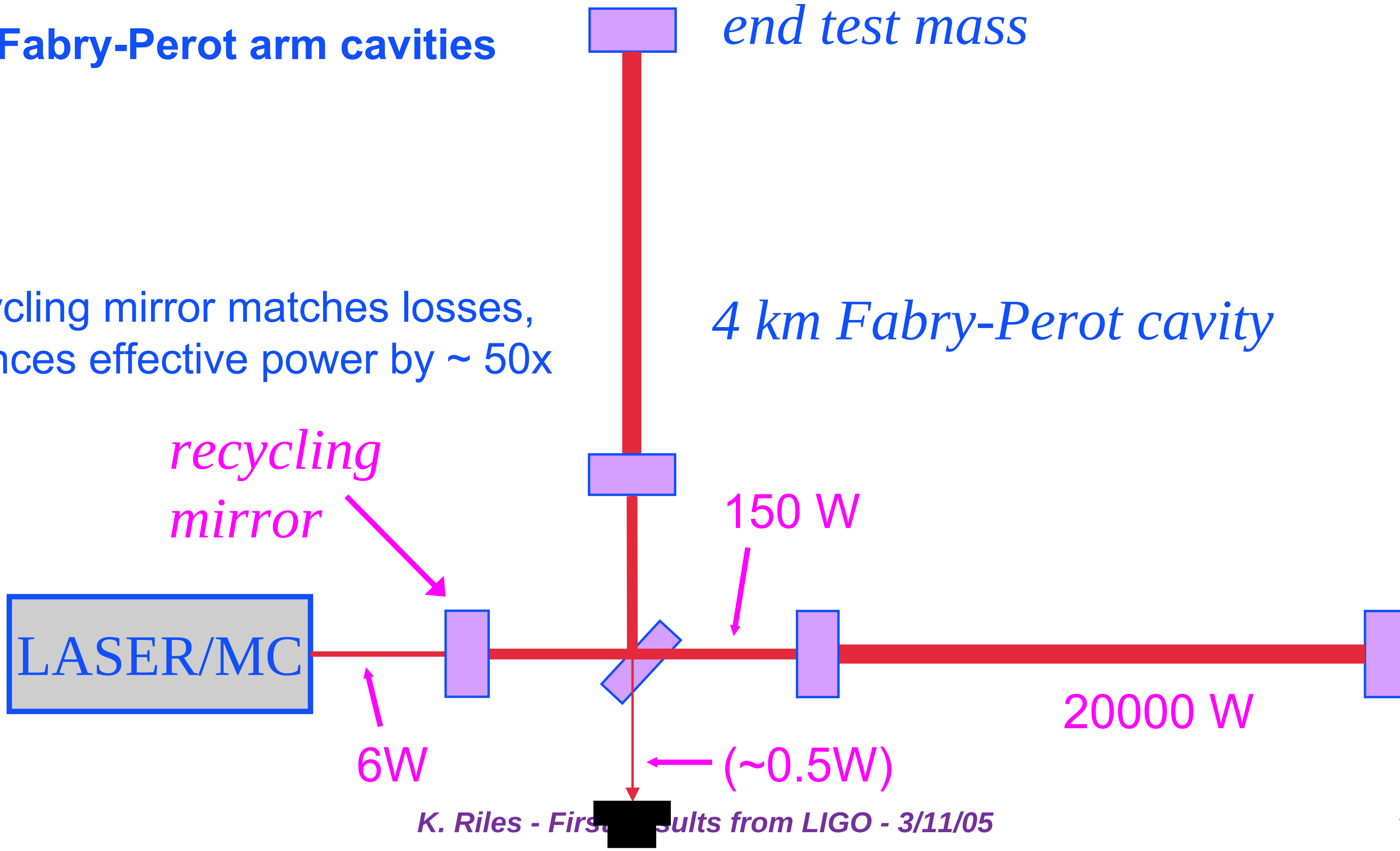
LIGO (NSF-$300M) Livingston, Louisiana & Hanford, Washington	2 x 4000-m 1 x 2000-m	Advanced Commissioning & Data Taking
VIRGO Near Pisa, Italy	1 x 3000-m	Early Commissioning
GEO Near Hannover, Germany	1 x 600-m	Advanced Commissioning & Data Taking
TAMA Tokyo, Japan	1 x 300-m	Advanced Commissioning & Data Taking

LIGO Interferometer Optical Scheme

Michelson interferometer

With Fabry-Perot arm cavities

•Recycling mirror matches losses, enhances effective power by ~ 50x



“Locking” the Inteferometer

Sensing gravitational waves requires sustained resonance in the Fabry-Perot arms and in the recycling cavity

→ Need to maintain half-integer # of laser wavelengths between mirrors

→ Feedback control servo uses error signals from imposed RF sidebands

→ Four primary coupled degrees of freedom to control

→ Highly non-linear system with 5-6 orders of magnitude in light intensity

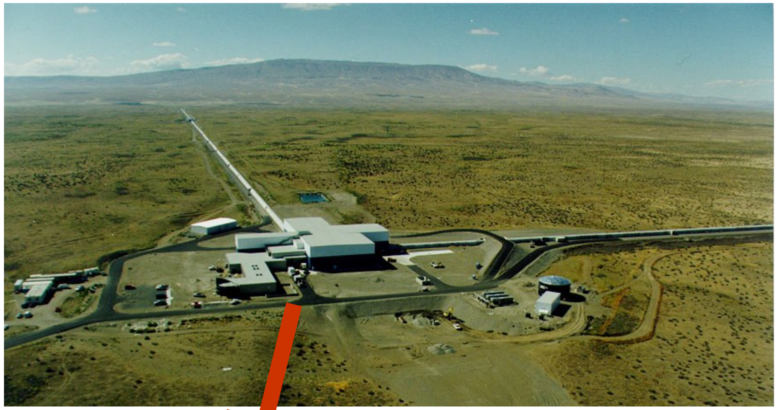
Also need to control mirror rotation (“pitch” & “yaw”)

→ Ten more DOF’s (but less coupled)

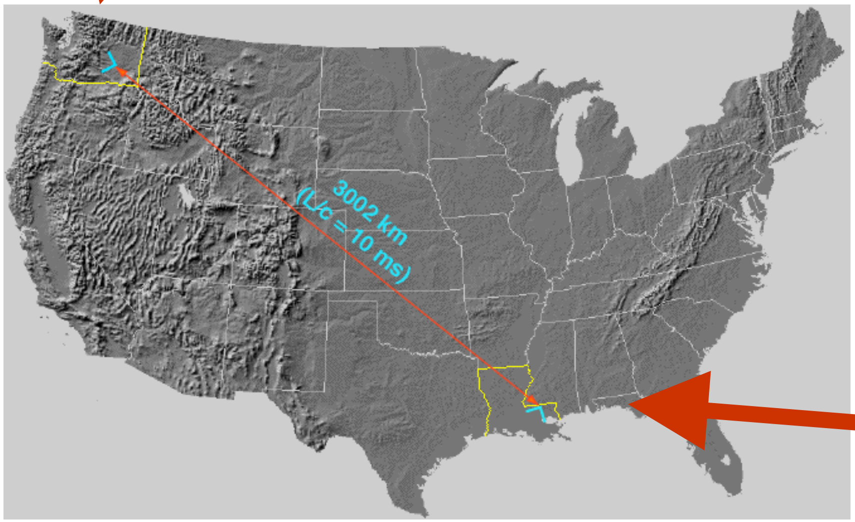
And need to stabilize laser (intensity & frequency), keep the beam pointed, damp out seismic noise, correct for tides, etc.,…

LIGO Observatories

Hanford

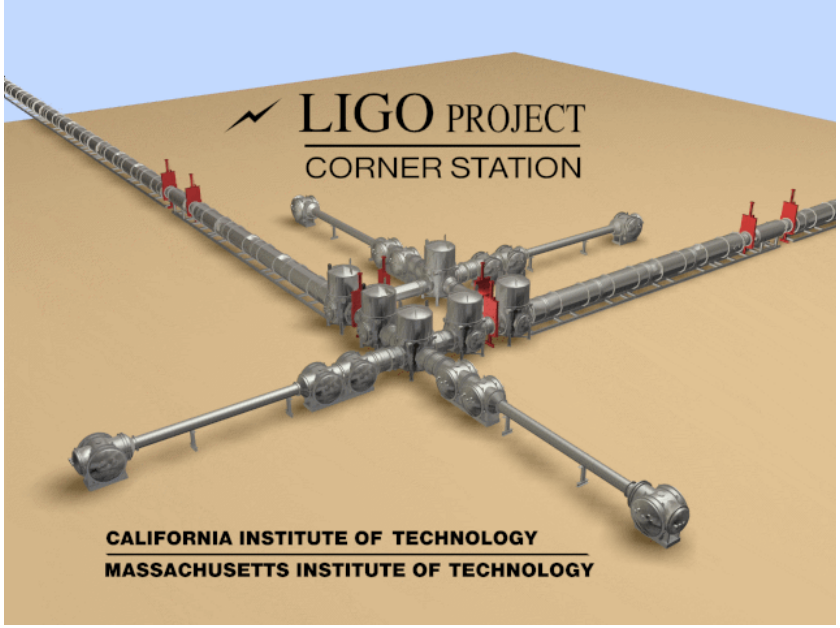


Observation of nearly simultaneous signals 3000 km apart rules out terrestrial artifacts



Livingston

LIGO Detector Facilities



- Stainless-steel tubes

  (1.24 m diameter, ~10^{-8} torr)
- Gate valves for optics isolation
- Protected by concrete enclosure

Vacuum System

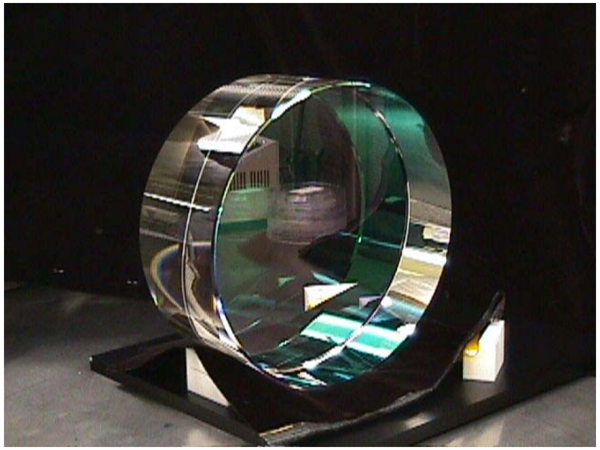
LIGO Detector Facilities

LASER

- Infrared (1064 nm, 10-W) Nd-YAG laser from Lightwave (now commercial product!)
- Elaborate intensity & frequency stabilization system, including feedback from main interferometer

Optics

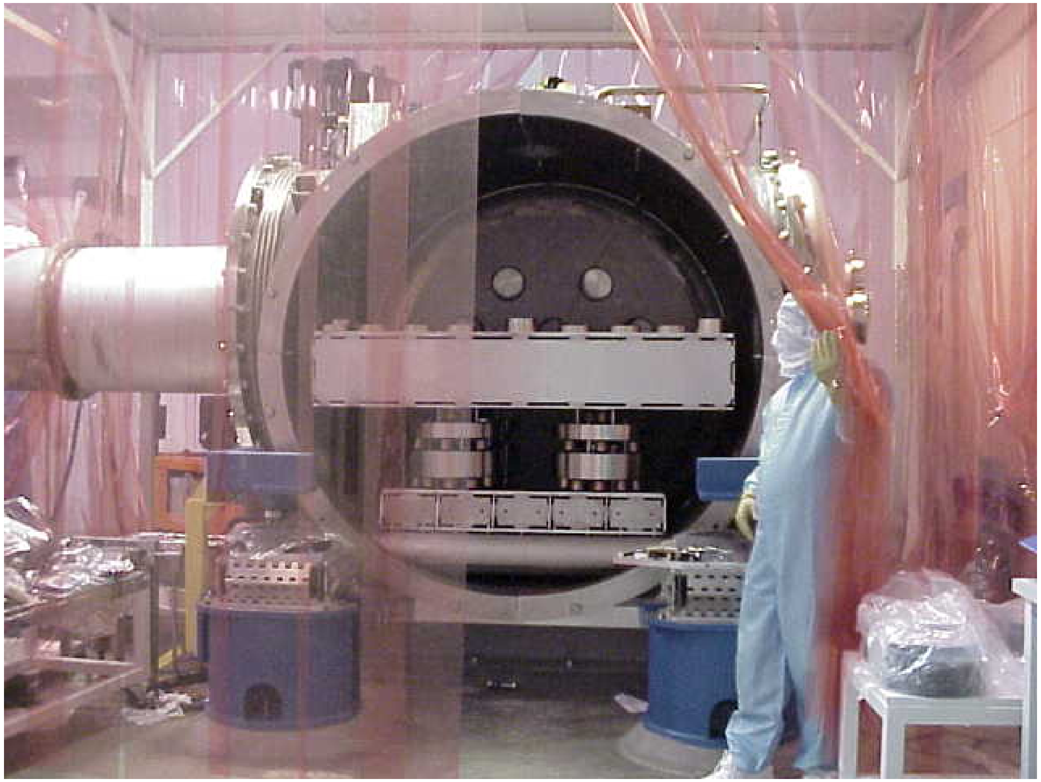
- Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)
- Suspended by single steel wire
- Actuation of alignment / position via magnets & coils

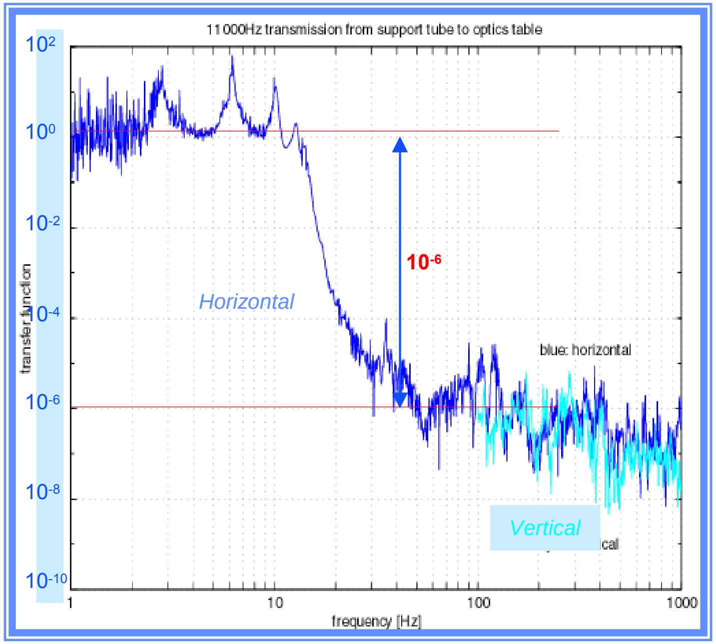


LIGO Detector Facilities

Seismic Isolation

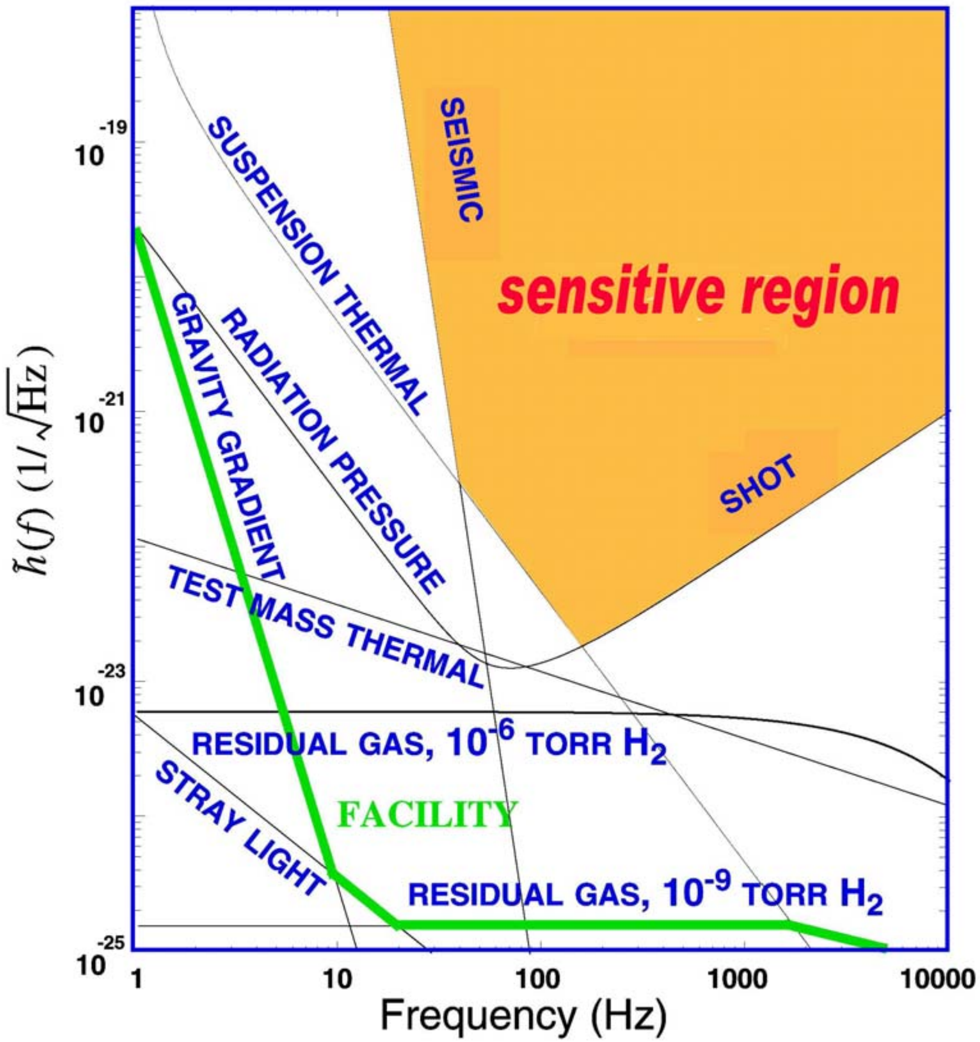
- Multi-stage (mass & springs) optical table support gives 10^6 suppression
- Pendulum suspension gives additional $1 / f^2$ suppression above ~1 Hz





What Limits the Sensitivity of the Interferometers?

- Seismic noise & vibration limit at low frequencies
- Atomic vibrations (Thermal Noise) inside components limit at mid frequencies
- Quantum nature of light (Shot Noise) limits at high frequencies
- Myriad details of the lasers, electronics, etc., can make problems above these levels



Best design sensitivity:

~ 3 x 10^{-23} $Hz^{-1/2}$ @ 150 Hz

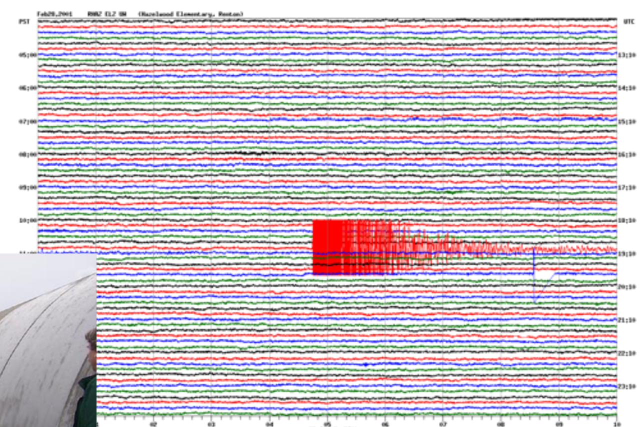
Some interesting problems at Hanford…

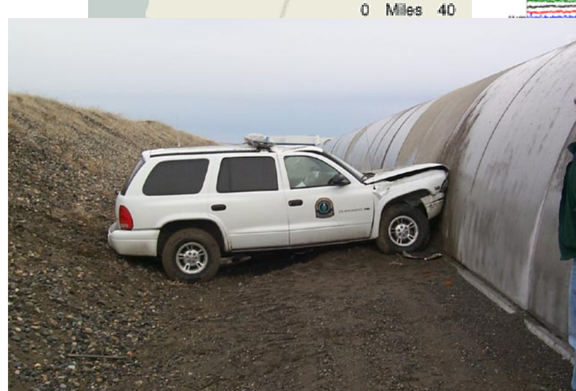
Brush fire sweeps over site – June 2000

Charred landscape, but no IFO damage!

Tacoma earthquake – Feb 2001

- **Misaligned optics**
- **Actuation magnets dislodged**
- **Commissioning delay**





Human error too!

And a new problem to worry about…

Mt. St. Helens has awoken!

Micro-quakes in late September interfered with commissioning

Eruption in early October helped – relieved pressure!

Livingston Problem -- Logging

Livingston Observatory located in pine forest popular with pulp wood cutters

Spiky noise (e.g. falling trees) in 1-3 Hz band creates dynamic range problem for arm cavity control

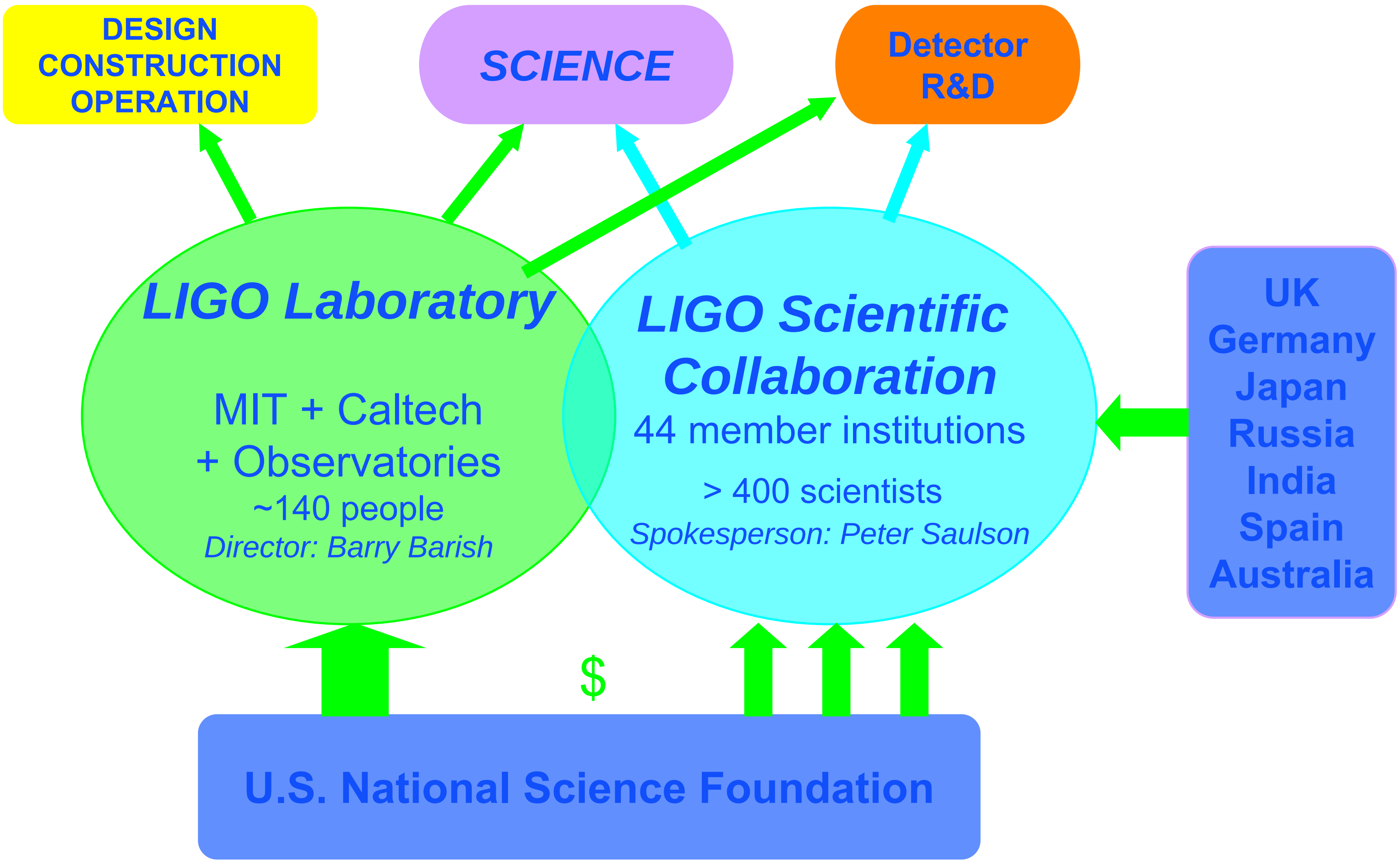
→ **40% livetime**

Solution: Retrofit with active feed-forward isolation system (using technology developed for Advanced LIGO)

→ Work started January 2004

→ Commissioning complete – **Looks very promising!**

LIGO Organization & Support



LIGO Scientific Collaboration

The LIGO Logo's

GEO 600

NSF

UTB TSC

Southeastern Louisiana University

Loyola University New Orleans

University of Rochester

Northwestern University

Universitat de les Illes Balears

LSU

Southern University

Hobart and William Smith College

The University of Adelaide Australia

California Institute of Technology

University of Florida

NAOJ 国立天文台

Cornell University

SKC

UW Milwaukee

IGR

Syracuse University

Universität Hannover

Washington State University

Cardiff University

The University of Western Australia

Michigan

The Physics of the Universe PPARC

PAH

PennState

Massachusetts Institute of Technology

University of Glasgow

GEO600

Work closely with the GEO600 Experiment (Germany / UK / Spain)

- **Arrange coincidence data runs when commissioning schedules permit**
- **GEO members are full members of the LIGO Scientific Collaboration**
- **Data exchange and strong collaboration in analysis now routine**
- **Major partners in proposed Advanced LIGO upgrade**

600-meter Michelson Interferometer just outside Hannover, Germany

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Data Runs

Have carried out a series of Engineering Runs (E1--E12) and <u>Science Runs</u> (S1--S4) interspersed with commissioning

S1 run:

17 days (August / September 2002)

Four detectors operating: LIGO (L1, H1, H2) and GEO600

H1 (235 hours) H2(298 hours) L1(170 hours)

Triple-LIGO-coincidence (96 hours)

Four S1 astrophysical searches published (Physical Review D):

» **Inspiraling neutron stars -- PRD 69 (2004) 122001**

» **Bursts -- PRD 69 (2004) 102001**

» **Known pulsar (J1939+2134) – PRD 69 (2004) 082004**

» **Stochastic background -- PRD 69 (2004) 122004**

Data Runs

S2 run:

- 59 days (February—April 2003)
- Four interferometers operating: LIGO (L1, H1, H2) and TAMA300 plus Allegro bar detector at LSU
- H1 (1044 hours)   H2 (822 hours)   L1 (536 hours)
- Triple-LIGO-coincidence (318 hours)

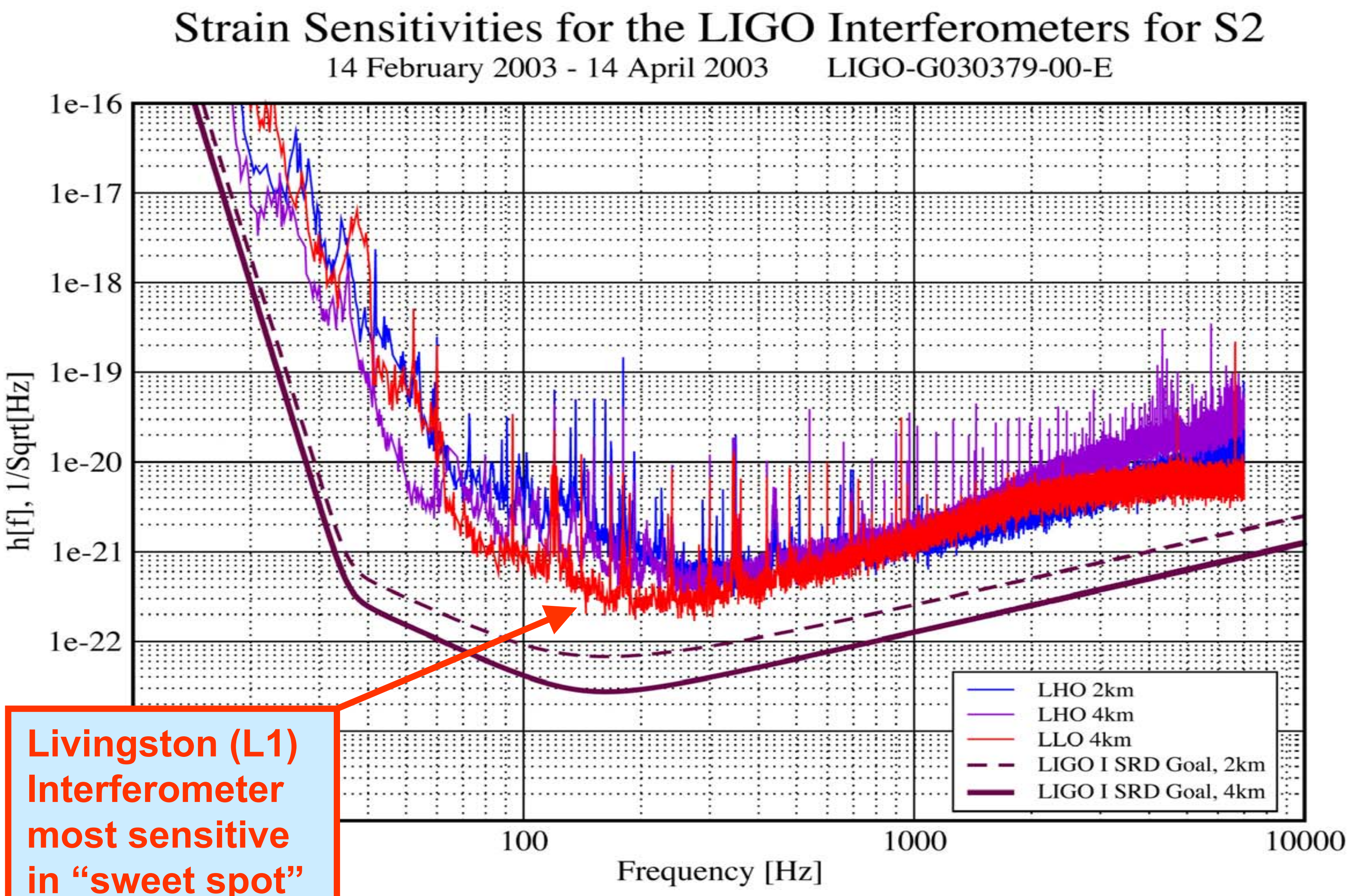
Many S2 searches underway – some prelim./final results for today:

- » Inspiraling neutron stars
- » Coincidence with gamma ray burst GRB030329
- » 28 known pulsars
- » Stochastic background

S3 run:

- 70 days (October 2003 – January 2004) – Analysis underway…

S2 Sensitivities



Livingston (L1) Interferometer most sensitive in "sweet spot"

Inspiraling Neutron Stars – S2 Results

S2 sensitivity permitted seeing the Andromeda Galaxy with L1 whenever live, with H1 seeing it at times
(when noise low and antenna pattern favorable)

Analysis based on matched filtering in Fourier domain
(hundreds of templates in bank for $M_\odot < M_1, M_2 < 3\, M_\odot$)

Inspiral triggers parameterized by signal-to-noise ratio and frequency-domain χ^2

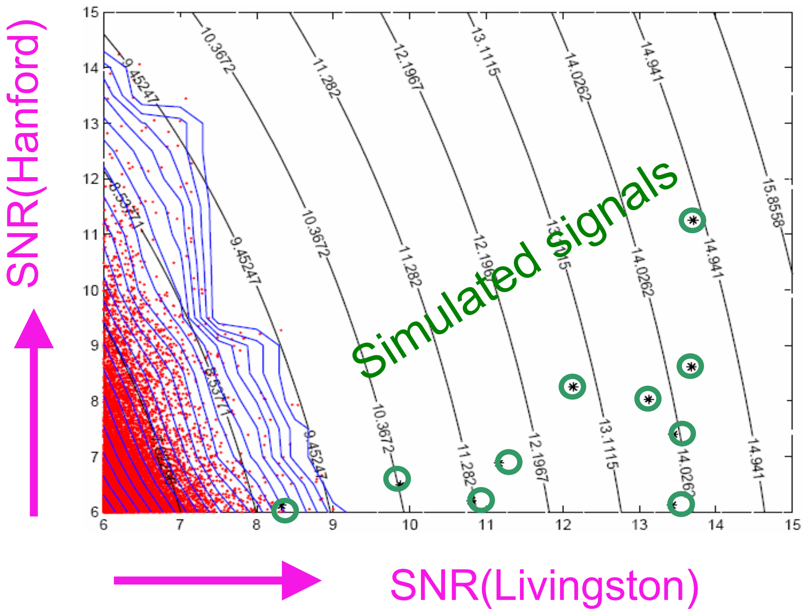
Vetoes on L1 triggers coincident with auxiliary channel artifacts

"Playground" (10%) data used to tune thresholds, vetoes for remaining 90%

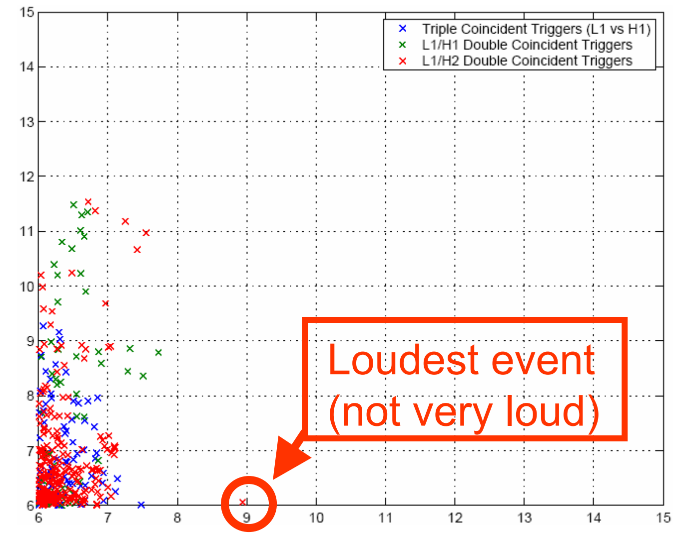
Hanford-Livingston coincidence required

Inspiraling Neutron Stars

Background with simulated signals



Observed events



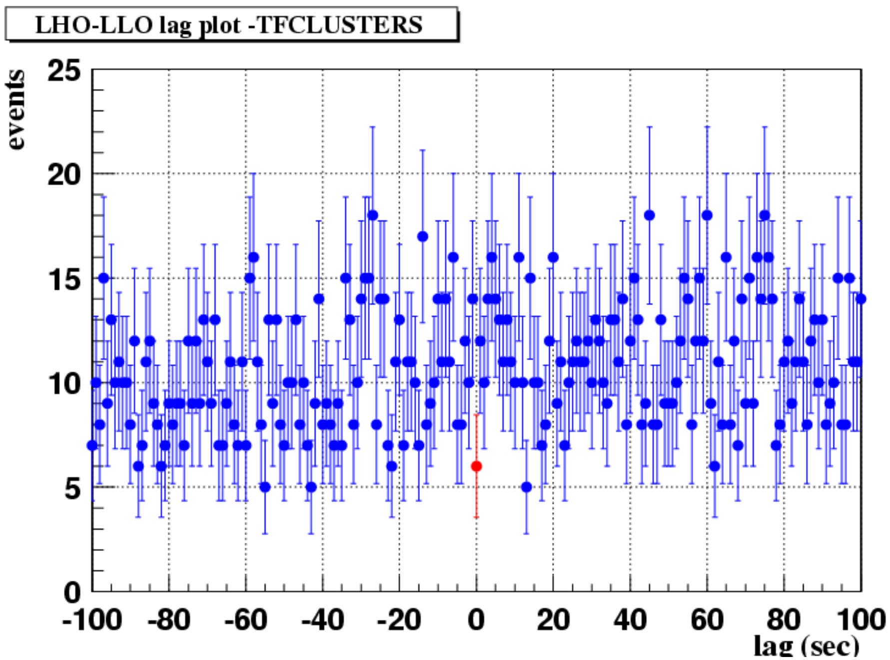
No evidence for excess events

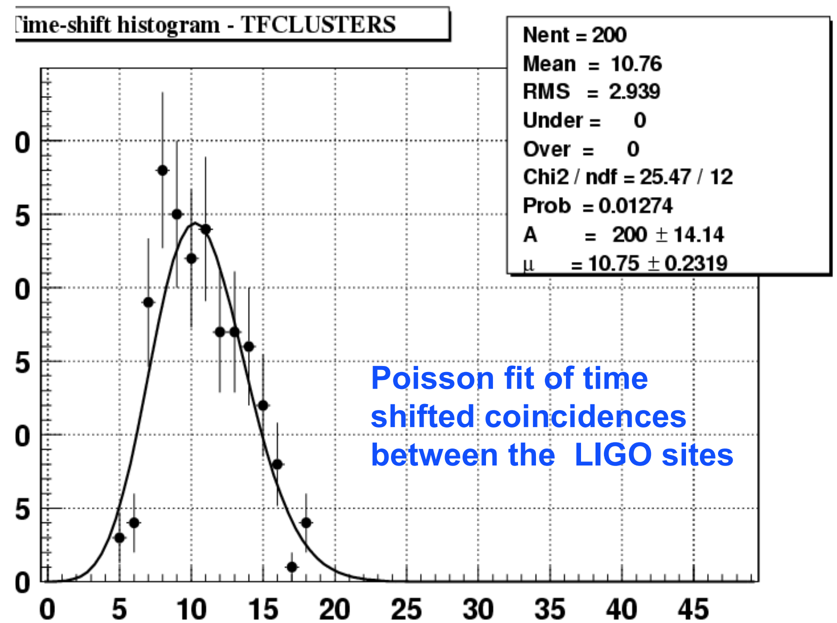
→ Set limit based on "Loudest event statistic"

→ Obtain <u>preliminary</u> rate:

$R_{90\%}$ < 50 inspirals per year per "milky-way-equivalent-galaxy"

Search for "Generic" Bursts (S1 results)
(look for coincident pulses in time-freq plane)





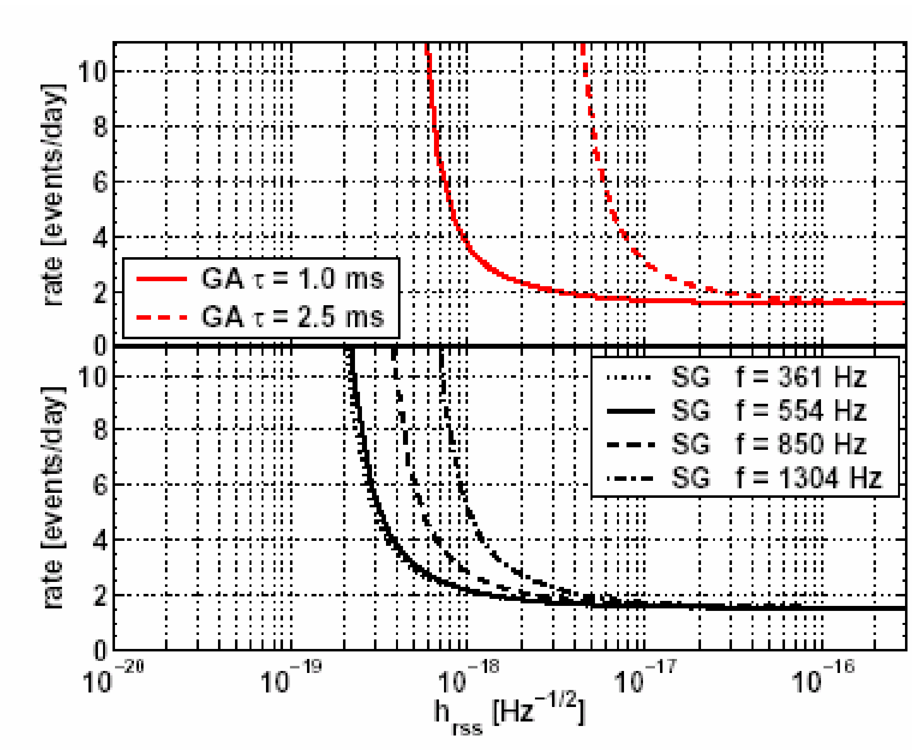
Poisson fit of time shifted coincidences between the LIGO sites

Background rates measured from non-zero

time shifts between interferometers

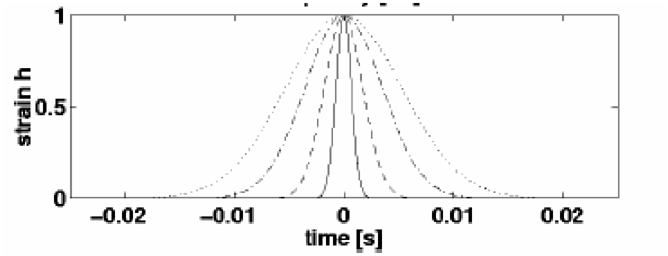
Feldman-Cousins 90% CL upper limit: < 1.6 events/day

90% CL rate limit vs. strength plots for two burst models



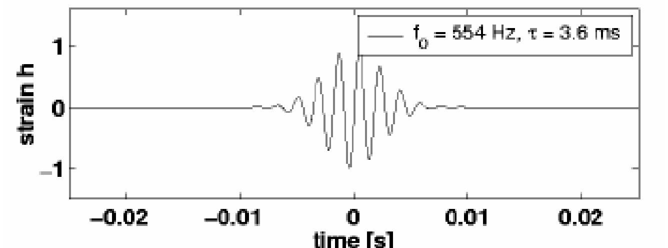
Burst model:

1ms, 2.5 ms Gaussian impulses



Burst model:

Sine-Gaussians with varying central frequencies



- Determined **detection efficiency** via **signal injections**
- Assumed a **population** of such sources **uniformly** distributed on a concentric sphere

Gamma Ray Burst 030329 – S2 Results

GRB030329 was a powerful burst that occurred during the S2 run

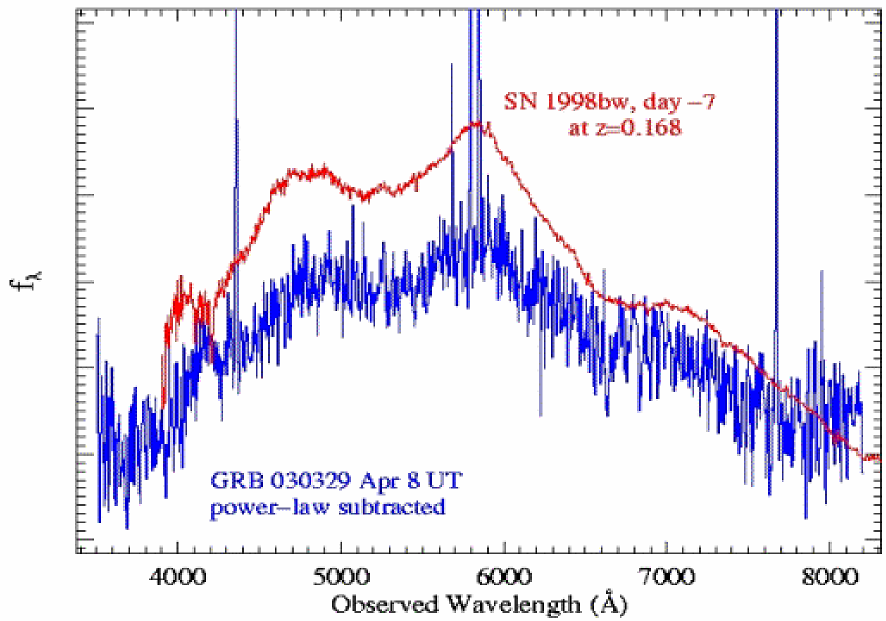
Identified in gammas, x-rays, and optical

Spectroscopy strongly suggests Supernova origin:

Distance (800 Mpc!) made it unlikely to be detectable by LIGO, but event provides interesting "practice run" for GRB detection (L1 off at time ☹)

Supernova Spectrum Emergence

GRB 030329 is now also SN2003dh



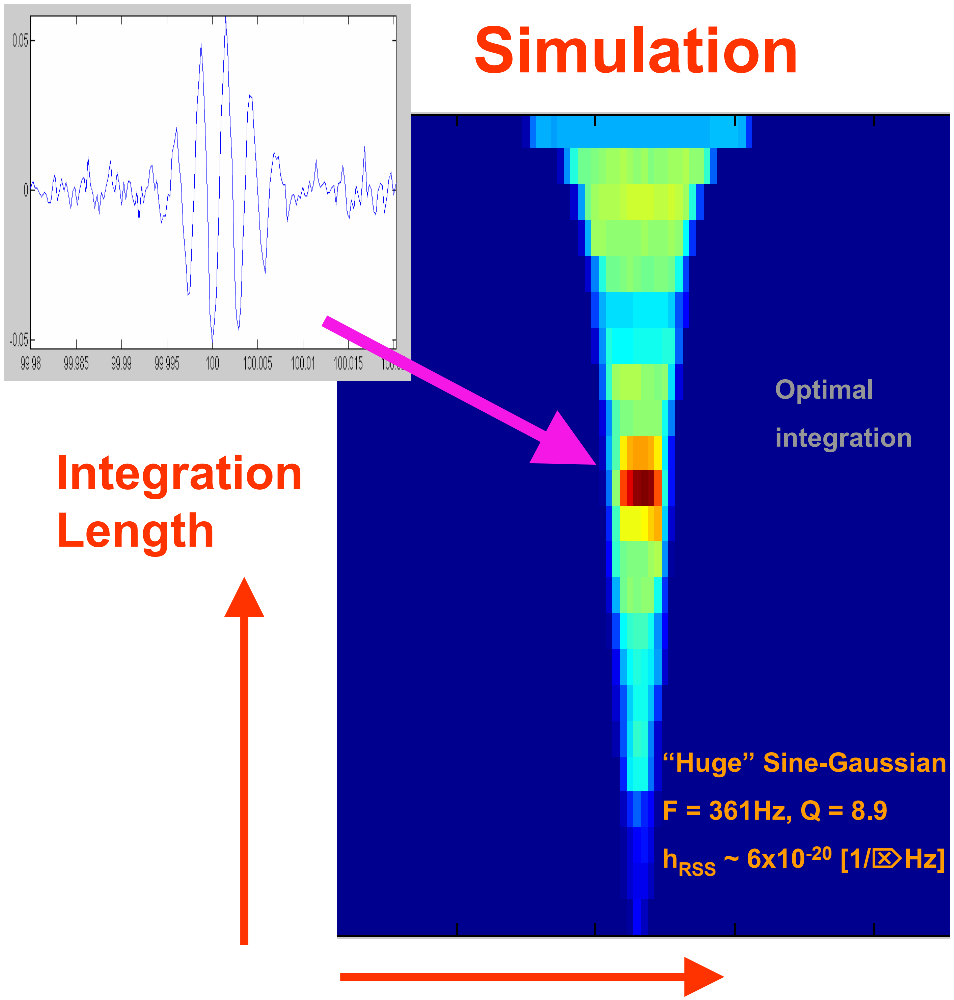
T. Matheson (CfA), GCN 2120

Gamma Ray Burst 030329

Searched for excess cross-correlation between Hanford Interferometers

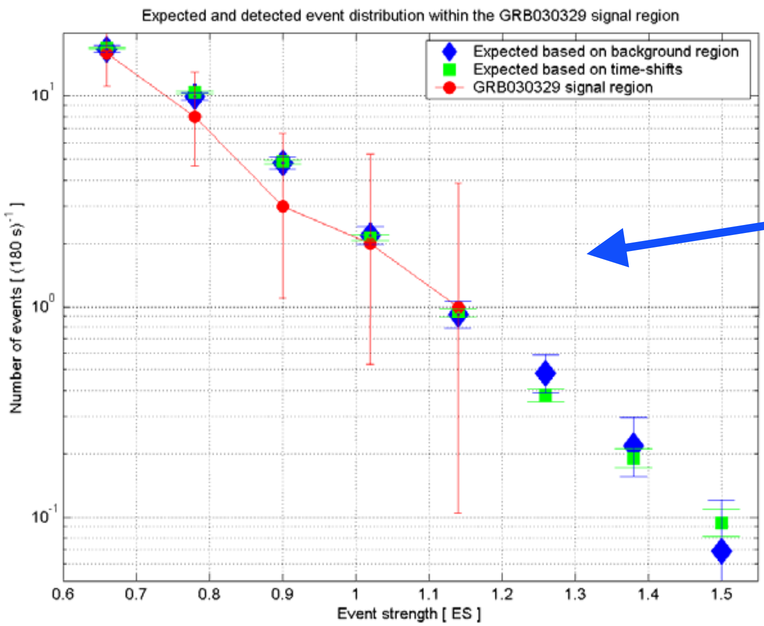
Examined background noise and set false alarm probability for 3-minute interval around GRB to be ~10%

Estimated efficiencies from generic (sine-Gaussian) signal injections for varying central frequencies & Q's



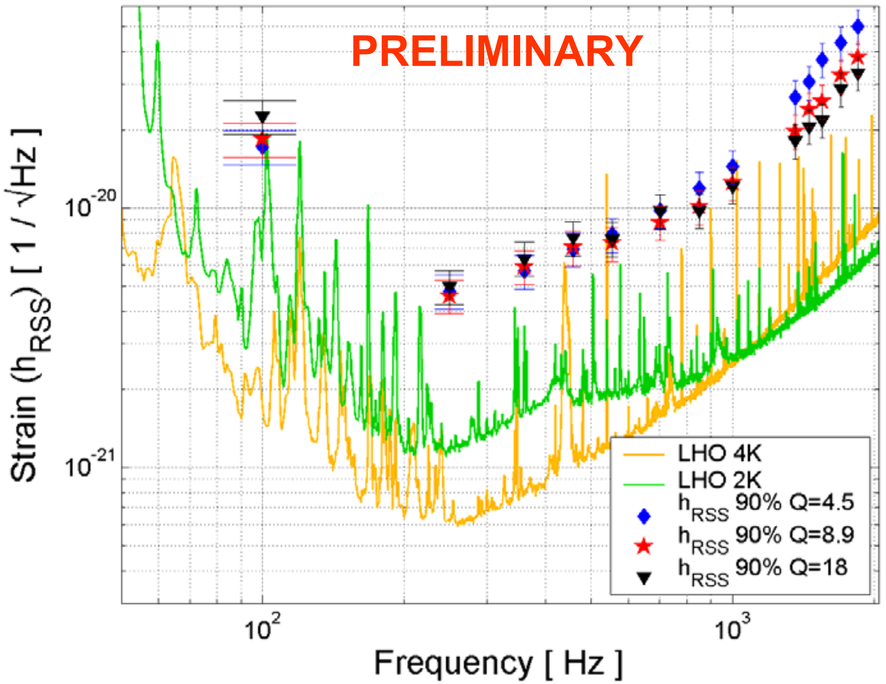
Time

Gamma Ray Burst 030329

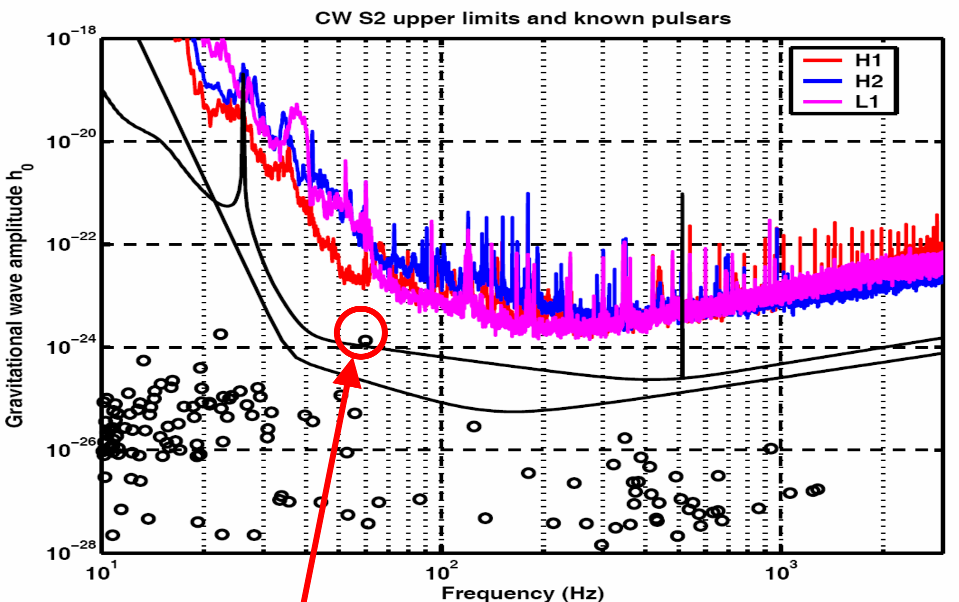


Expected numbers of events (using two different background estimates) and observed numbers of events vs "event strength"

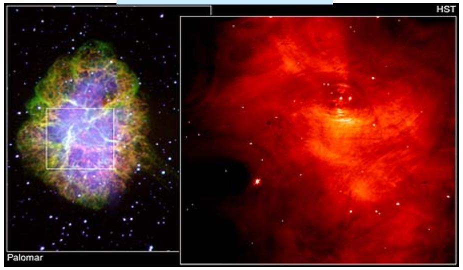
No candidates above (or even near) threshold
→ Set upper limits:

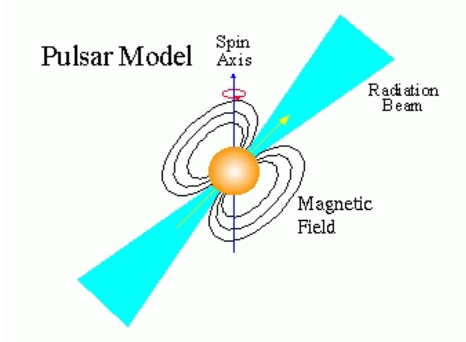


Known Pulsars – S2 Results



Crab pulsar





- **Detectable amplitudes** with a 1% false alarm rate and 10% false dismissal rate by the IFOs during S2 (colored curves) and at design sensitivities (black curves)

- **Upper limits** on **<h_o>** from spin-down measurements of known radio pulsars (filled circles)

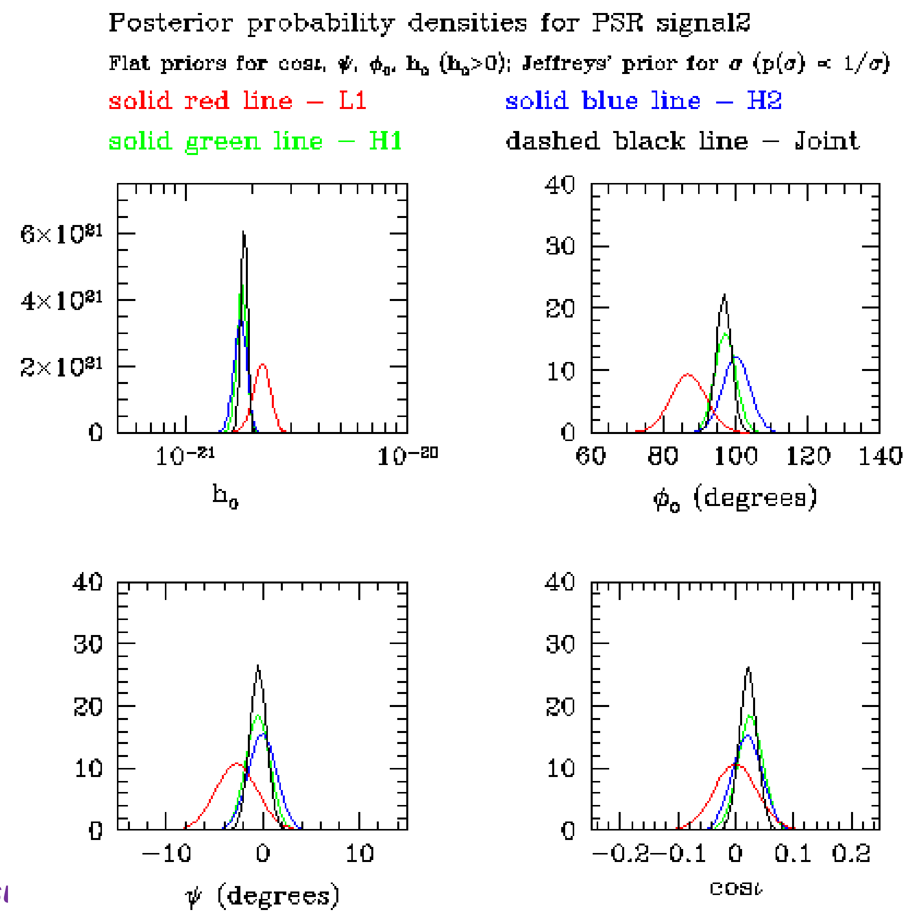
Searched for 28 known isolated pulsars for which precise timing information is available from radio astronomers

Known Pulsars

Search based on coherent time-domain heterodyne, accounting for Doppler shifts due to Earth's spin and orbital motion; and accounting for antenna pattern amplitude modulations

Can reconstruct amplitude, phase, polarization and orientation of strong source

Parameter fitting for hardware-injected fake pulsar during S2:



Known Pulsars

No signals detected

Obtained upper limits on source strengths:

• Amplitudes h_0

• Pulsar ellipticities ε

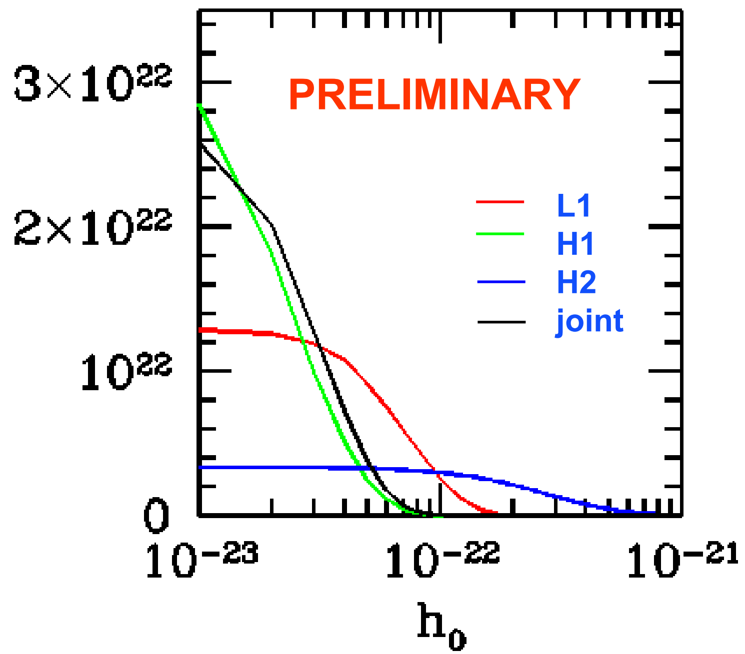
based on inferred Bayesian posterior probability density functions (pdf's) (flat prior for h_0)

Best 95% CL upper limit on h_0:

1.7 x 10^{-24} (J1910-5959D)

Sample pdf for the Crab pulsar (B0531+21)

→ 95% CL upper limit on h_0: 4.1 x 10^{-22}



Stochastic Background – S2 Results

- **Sources:** early universe, many weak unresolved sources emitting gravitational waves independently → Random radiation described by its spectrum (isotropic, unpolarized, stationary and Gaussian)

- **Analysis goals:** constrain contribution of stochastic radiation's energy ρ_{GW} to the total energy required to close the universe $\rho_{critical}$:

$$\int_0^\infty (1/f)\,\Omega_{GW}(f)\,df = \frac{\rho_{GW}}{\rho_{critical}}$$

- Use optimally filtered **cross-correlation** of detector pairs: L1-H1, L1-H2 and H1-H2
  → Report L1-H1 results today

Stochastic Background

Detector separation and orientation reduce correlations at high frequencies ($\lambda_{GW} \geq$ 2xBaseLine)

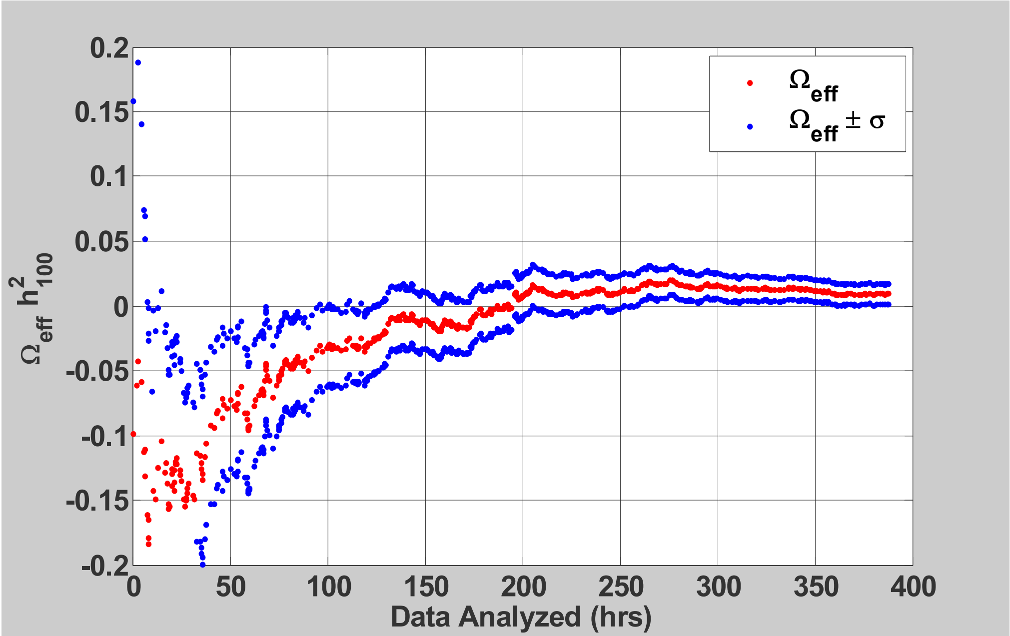
H1-H2 most sensitive
(but instruments correlated!)

L1-H1(H2) most sensitive < 50 hz

Known inter-site correlated lines removed in analysis

Assume simple model: $\Omega(f) = \Omega_0$

Cumulative measure of Ω_0 during the S2 run

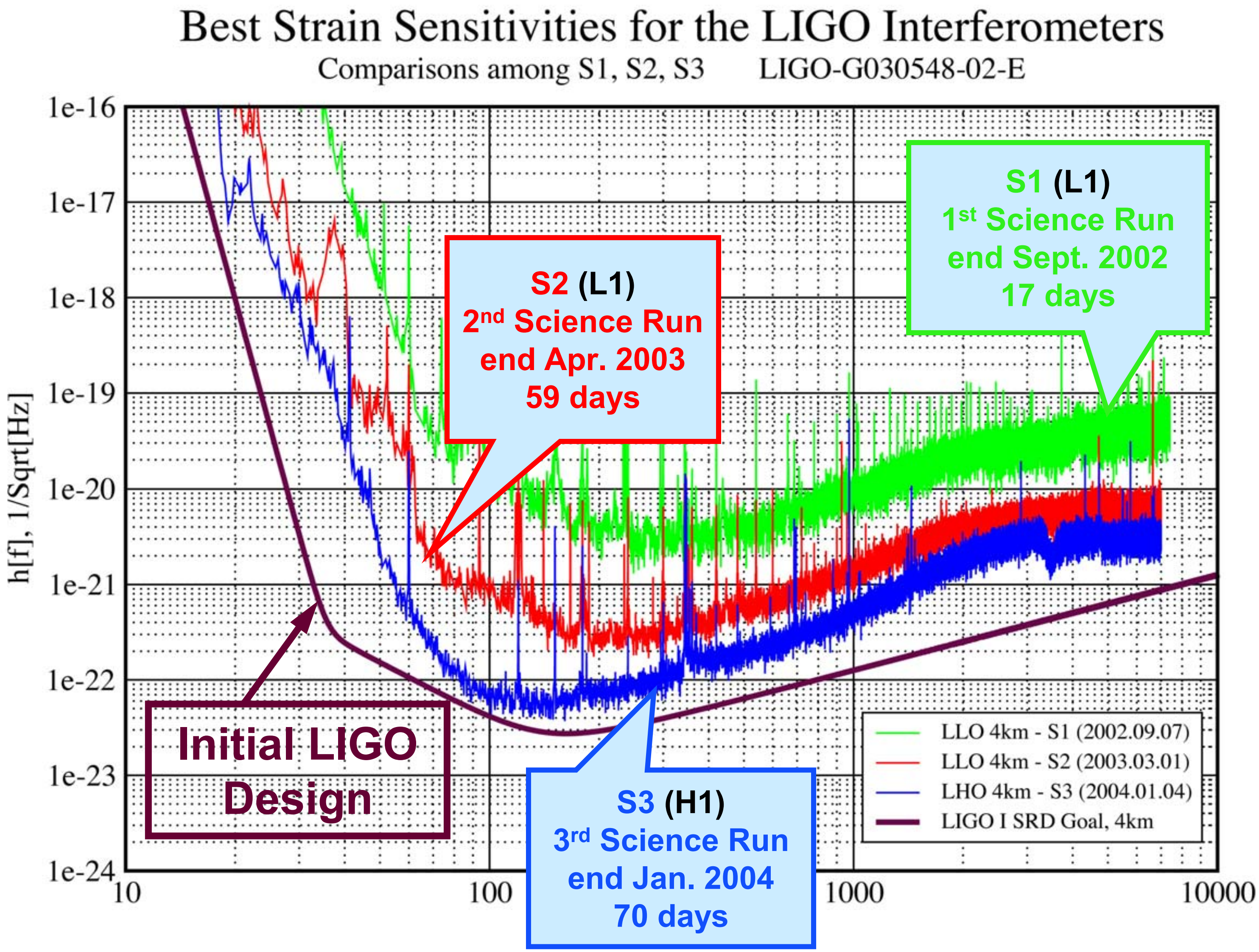


Preliminary 90% CL limit: $\boxed{\Omega_0\ (h_{100})^2 \ < \ 0.017}$

Outline

- Nature & Generation of Gravitational Waves
- Detecting Gravitational Waves with the LIGO Detector
- Data runs and Early Results
- Looking Ahead – Advanced LIGO

Looking Ahead

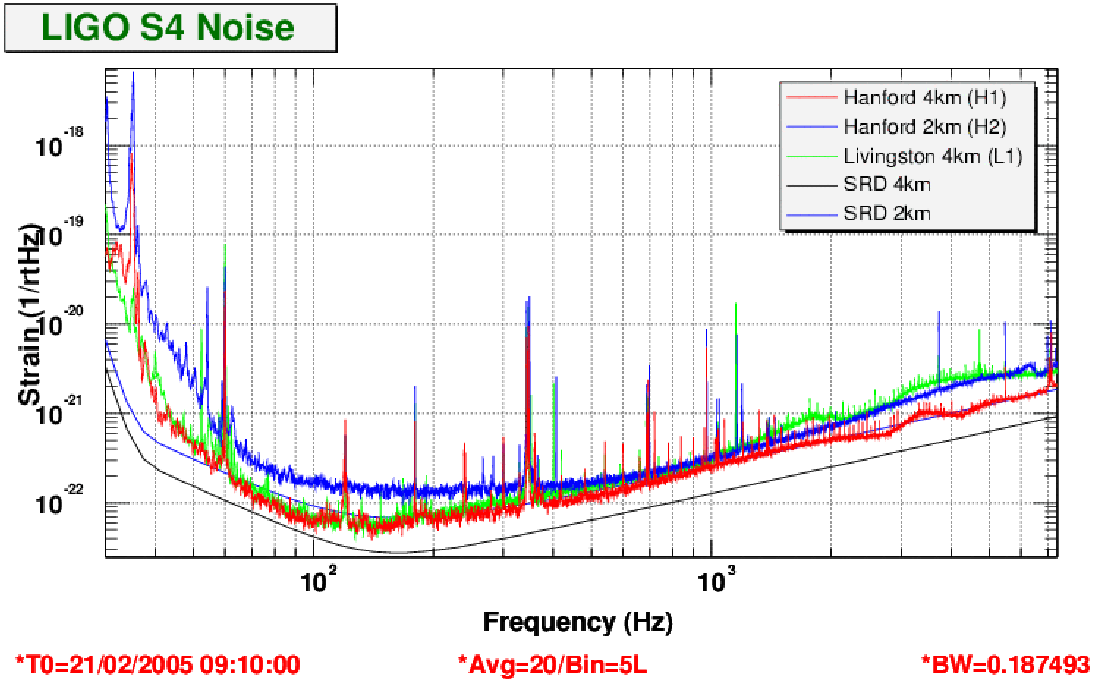


Looking Ahead

Resumed data runs in February 2005: → S4 Run

- **Verified success of Livingston seismic retrofit**
- **Verified success of sensitivity improvements**

First true "Search Run" in late 2005



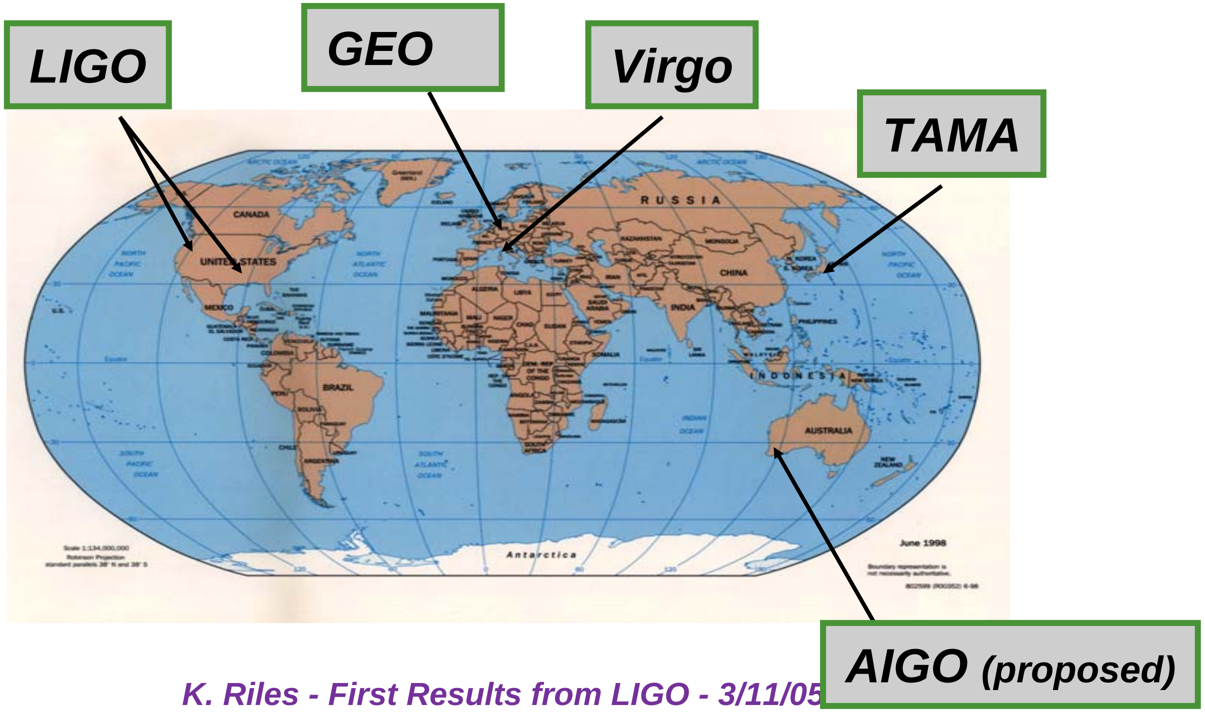
Plan before shutdown for Advanced LIGO upgrade:

≥ 1 year of running at Initial LIGO design sensitivity

Looking Ahead

The three LIGO and the GEO interferometers are part of a forming Global Network.

Multiple signal detections will increase detection confidence and provide better precision on source locations and wave polarizations

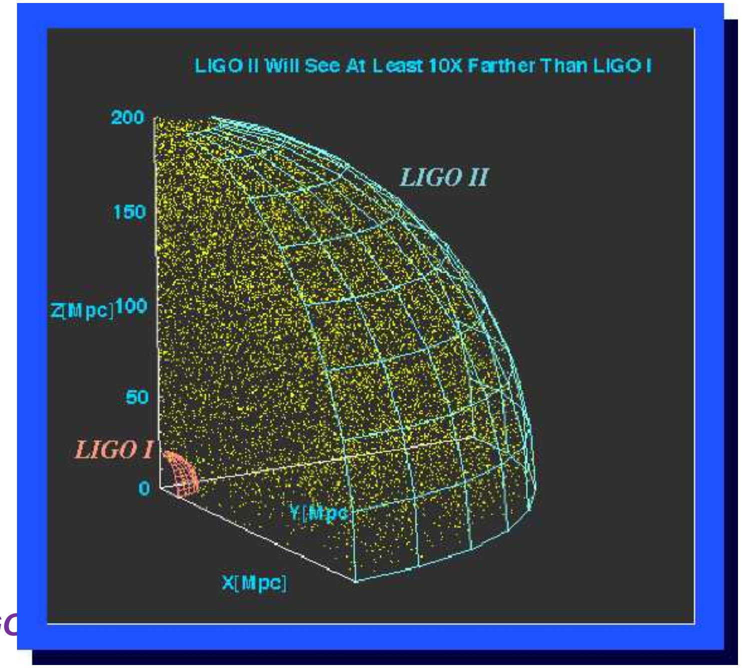


Looking Further Ahead

Despite their immense technical challenges, the initial LIGO IFO's were designed conservatively, based on "tabletop" prototypes, but with expected sensitivity gain of ~1000.

Given the expected low rate of detectable GW events, it was always planned that in engineering, building and commissioning initial LIGO, one would learn how reliably to build <u>Advanced LIGO</u> with another factor of ~10 improved sensitivity.

Because LIGO measures GW <u>amplitude</u>, an increase in sensitivity by 10 gives an increase in sampling volume, i.e, rate by ~1000



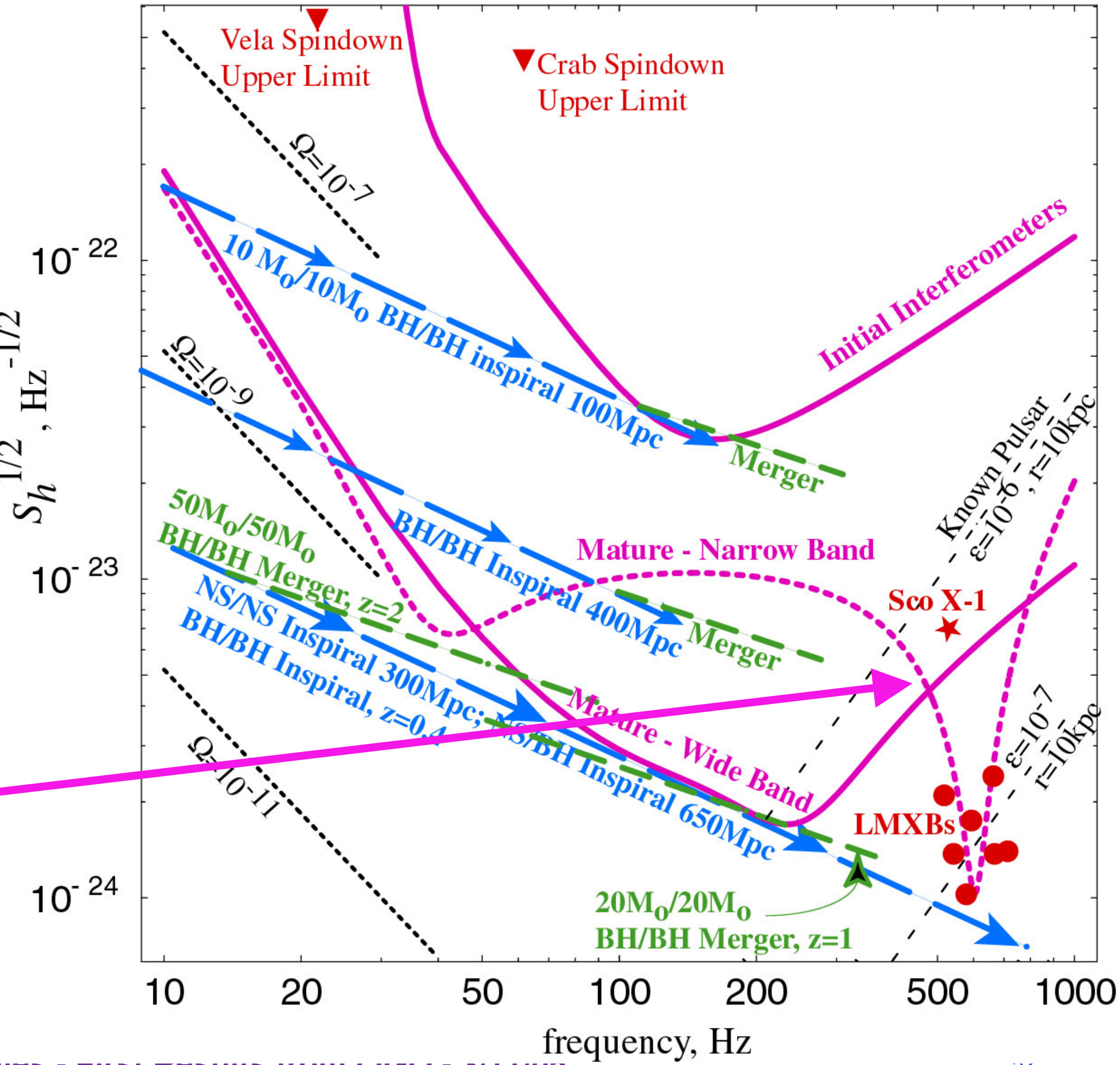
Advanced LIGO

Sampling of source strengths vis a vis Initial LIGO and Advanced LIGO

Lower h_{rms} and wider bandwidth both important

"Signal recycling" offers potential for tuning shape of noise curve to improve sensitivity in target band

(e.g., known pulsar cluster)



Advanced LIGO

Increased laser power:

- **10 W → 180 W**
- **Improved shot noise (high freq)**

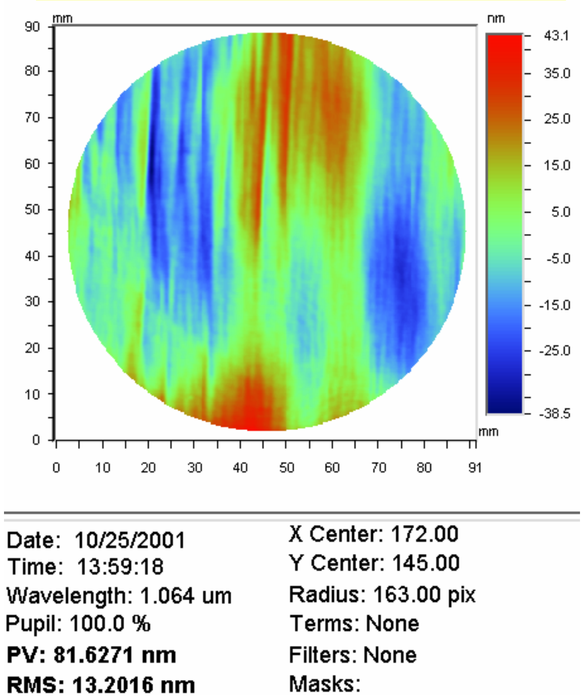
Improved test mass material:

- **Fused silica with higher mechanical Q**
- **Lower internal thermal noise in bandwidth**

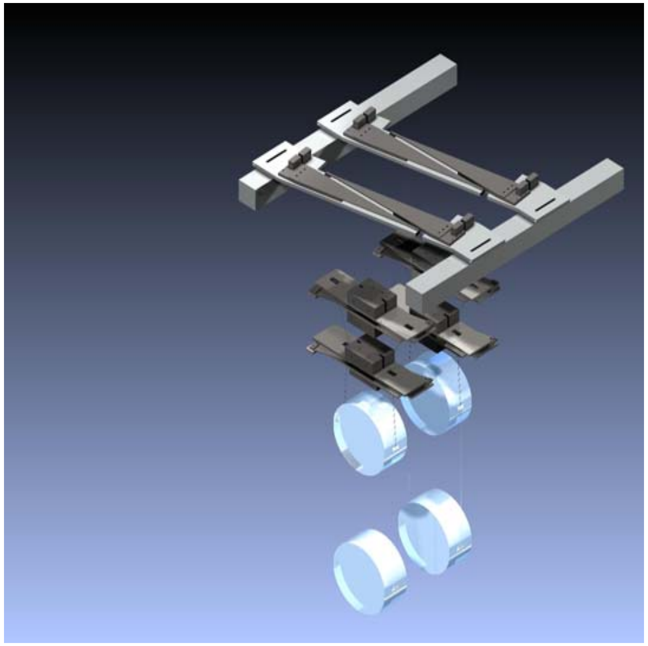
Increased test mass:

- **10 kg → 40 kg**
- **Compensates increased radiation pressure noise**

Sapphire Optics



Advanced LIGO

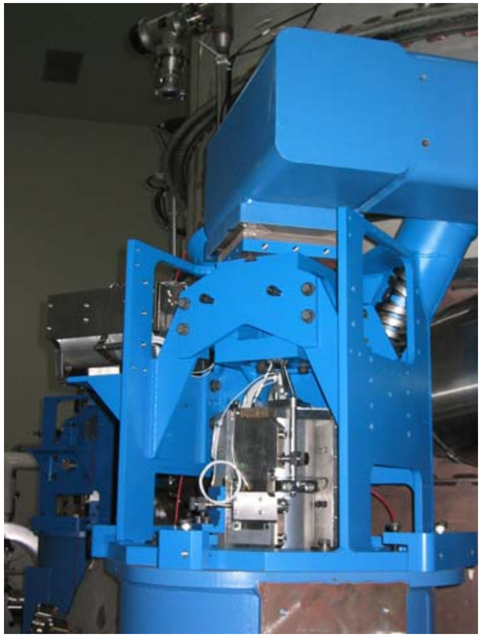


Detector Improvements:

New suspensions:

Single → Quadruple pendulum

Lower suspensions thermal noise in bandwidth



Improved seismic isolation:

Passive → Active

Lowers seismic “wall” to ~10 Hz

Conclusions

LIGO commissioning is well underway

- Good progress toward design sensitivity
- GEO, other instruments advancing as well

Science Running is beginning

- Initial results from our first two data runs

Our Plan:

- Continue commissioning and data runs with GEO & others
- Collect $\geq$ one year of data at design sensitivity before starting upgrade
- Advanced interferometer with dramatically improved sensitivity – 2009+
  (NSF MRE proposal recently approved by National Science Board)

We should be detecting gravitational waves routinely within the next 10 years!