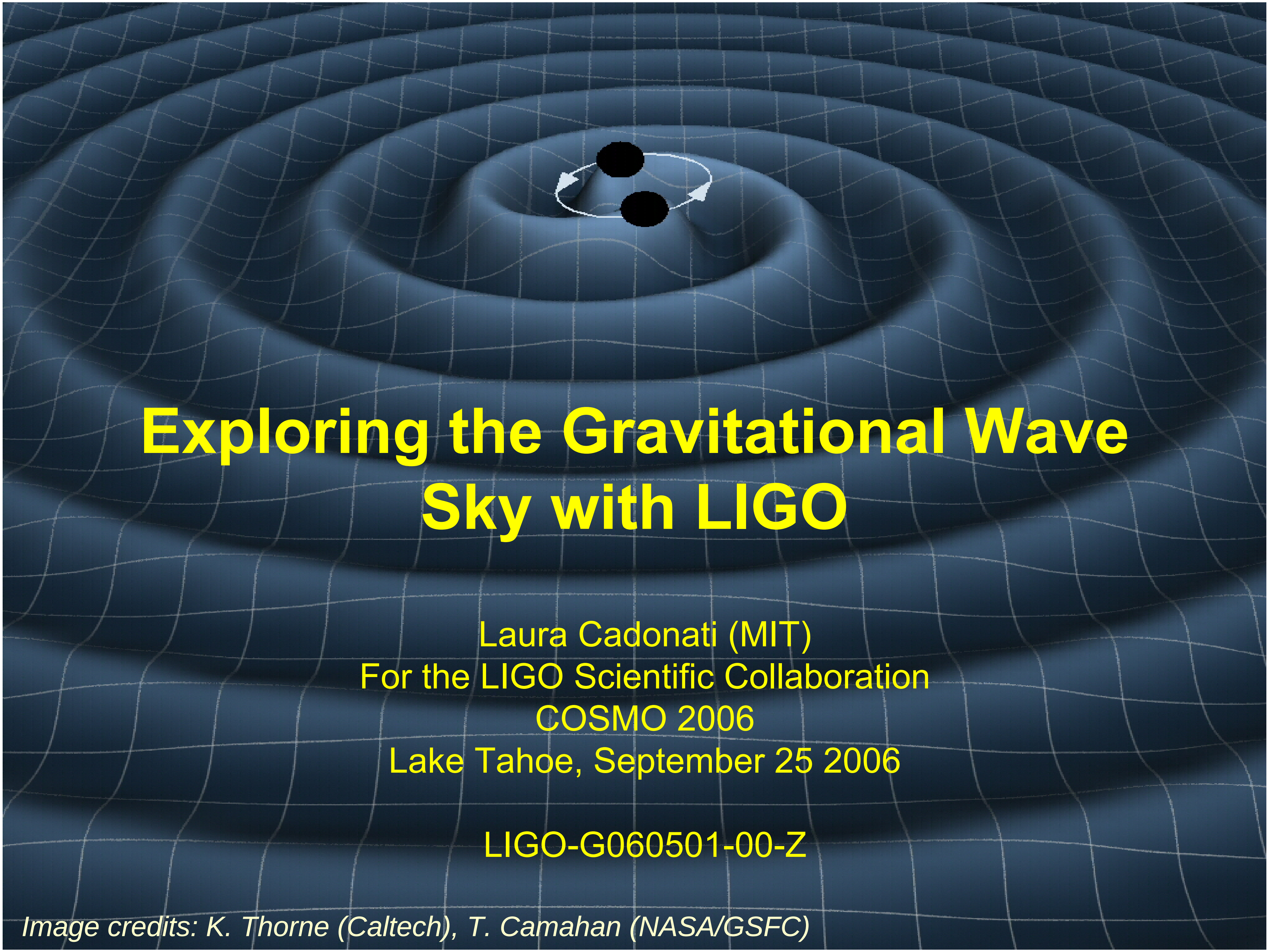


Exploring the Gravitational Wave Sky with LIGO

Laura Cadonati (MIT)
For the LIGO Scientific Collaboration

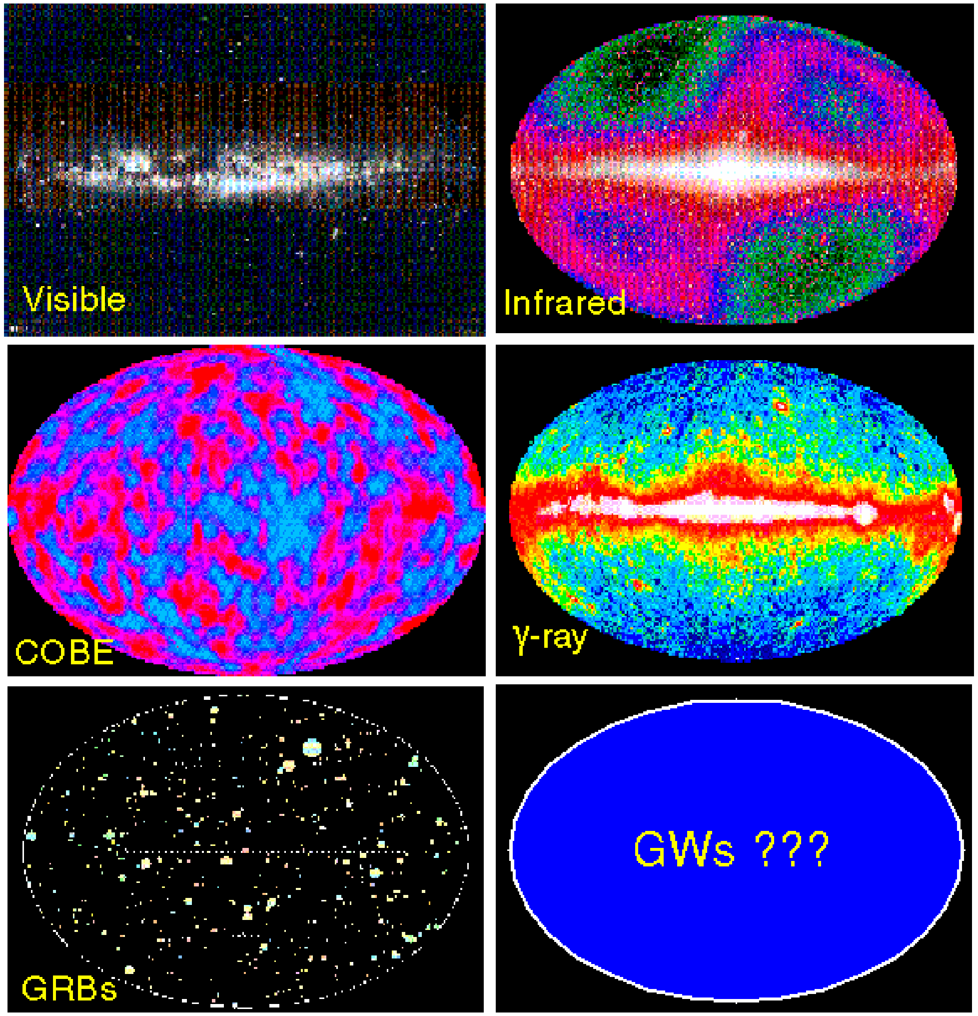
COSMO 2006
Lake Tahoe, September 25 2006

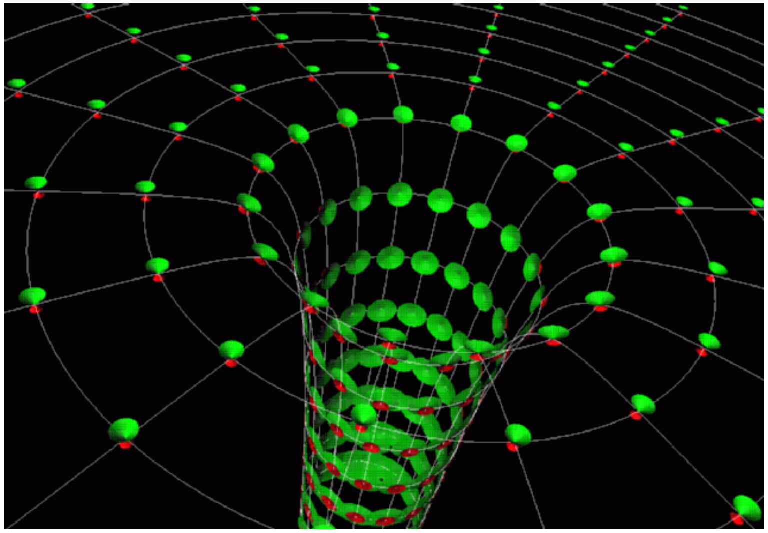
LIGO-G060501-00-Z

Image credits: K. Thorne (Caltech), T. Camahan (NASA/GSFC)

Why gravitational waves

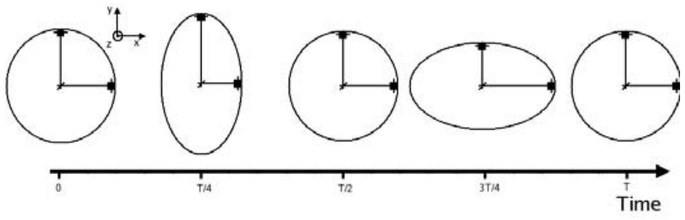
GW: a new “sense” to probe the Universe





Gravitational Waves will provide complementary information, as different from what we know as sound is from sight.

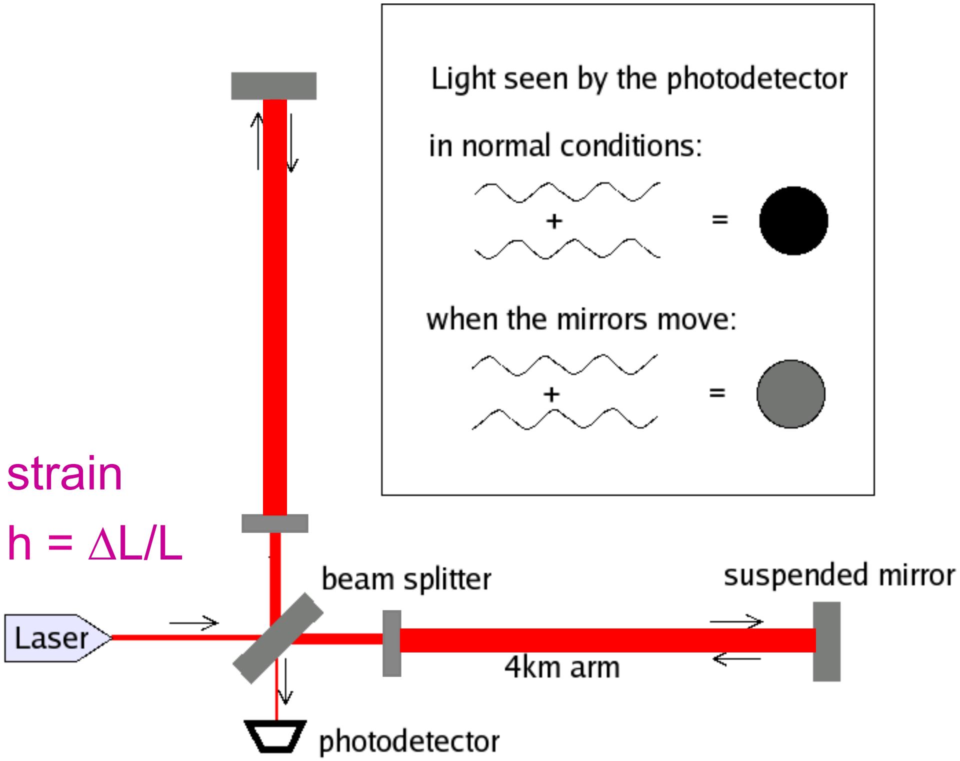
The LIGO Observatory

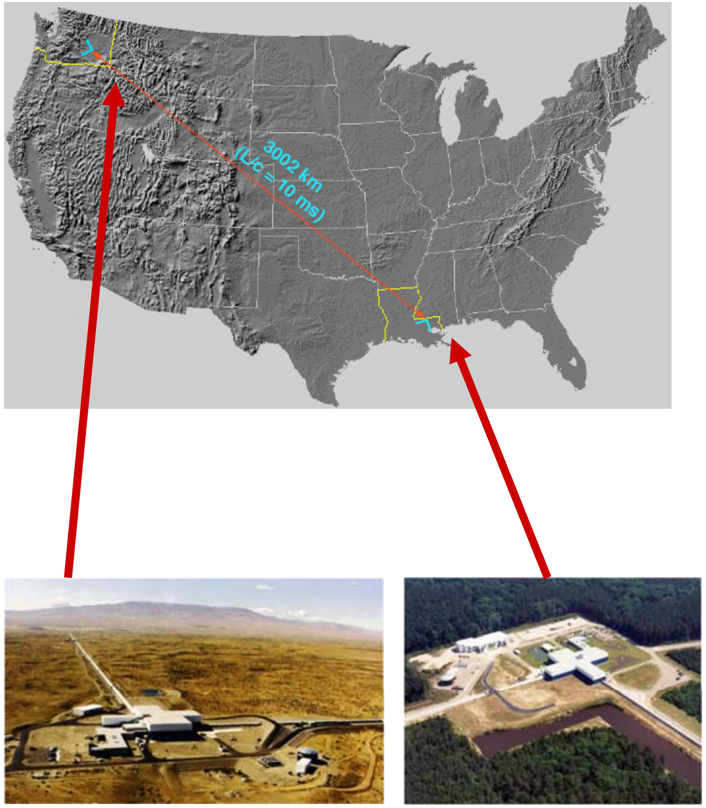


Initial goal: measure difference in length to one part in 10^{21}, or 10^{-18} m

strain

$h = \Delta L/L$





Hanford Observatory
4 km and 2 km
interferometers

Livingston Observatory
4 km interferometer

The LIGO Scientific Collaboration

NSF

UTB TSC

SOUTHEASTERN LOUISIANA UNIVERSITY

LOYOLA UNIVERSITY NEW ORLEANS

UNIVERSITY OF MARYLAND

LSU

GEO 600

NORTHWESTERN UNIVERSITY

Universitat de les Illes Balears

SOUTHERN UNIVERSITY

HOBART AND WILLIAM SMITH COLLEGES

THE UNIVERSITY OF ADELAIDE AUSTRALIA

CALIFORNIA INSTITUTE OF TECHNOLOGY

UNIVERSITY OF FLORIDA

NAOJ 国立天文台

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

UNIVERSITY of WISCONSIN UWMILWAUKEE

CARLETON COLLEGE

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

THE UNIVERSITY OF BIRMINGHAM

THE UNIVERSITY OF TEXAS AT AUSTIN

SYRACUSE UNIVERSITY

IGR

Universität Hannover

WASHINGTON STATE UNIVERSITY

EMBRY-RIDDLE AERONAUTICAL UNIVERSITY

CARDIFF UNIVERSITY

THE UNIVERSITY OF WESTERN AUSTRALIA

MICHIGAN

The Physics of the Universe PPARC

PAH

PENNSTATE 1855

UNIVERSITY of GLASGOW

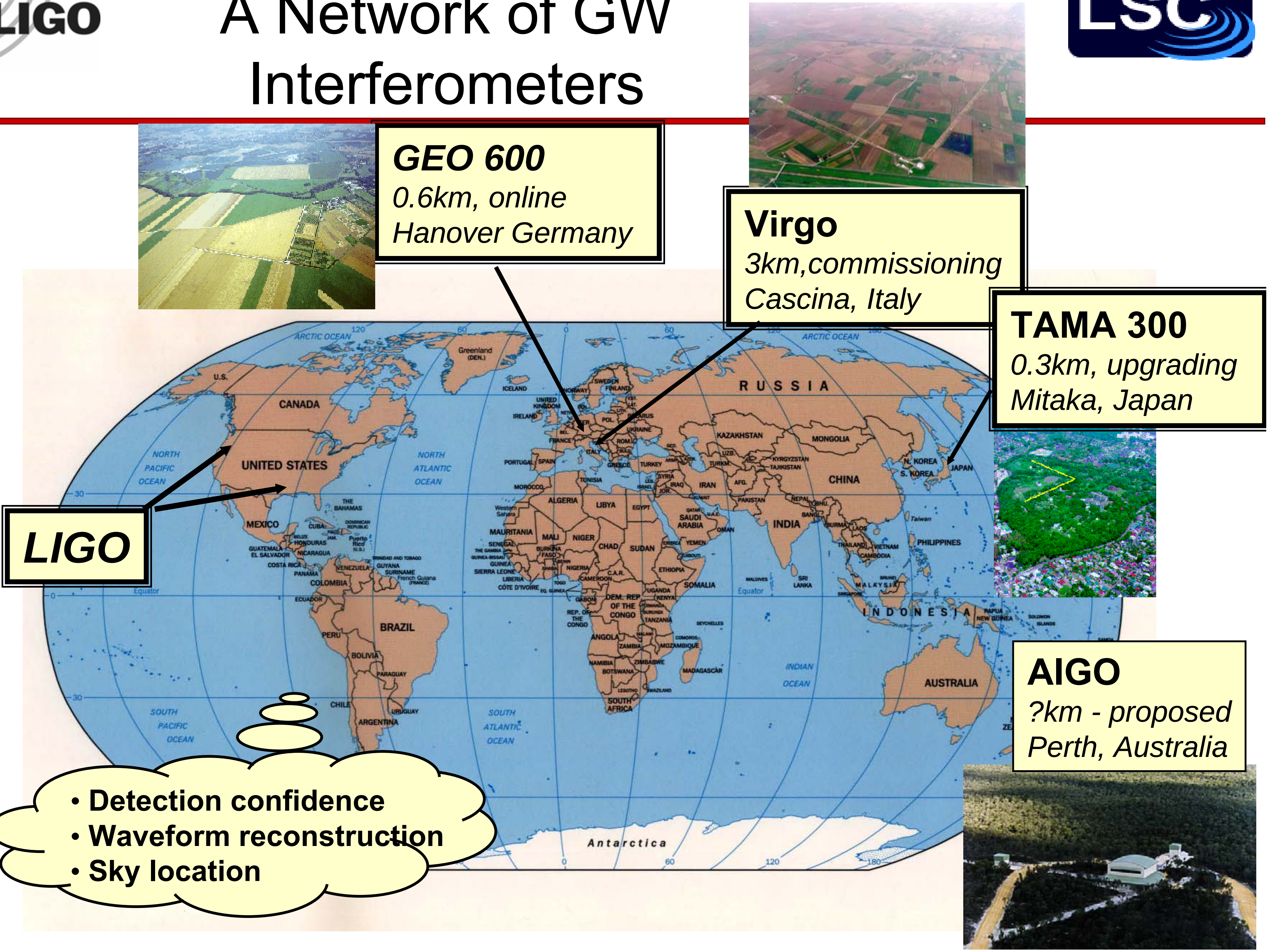
Andrews University

SEEK KNOWLEDGE. AFFIRM FAITH. CHANGE THE WORLD.

San José State UNIVERSITY

R·I·T

A Network of GW Interferometers



GEO 600

0.6km, online

Hanover Germany

Virgo

3km,commissioning

Cascina, Italy

TAMA 300

0.3km, upgrading

Mitaka, Japan

LIGO

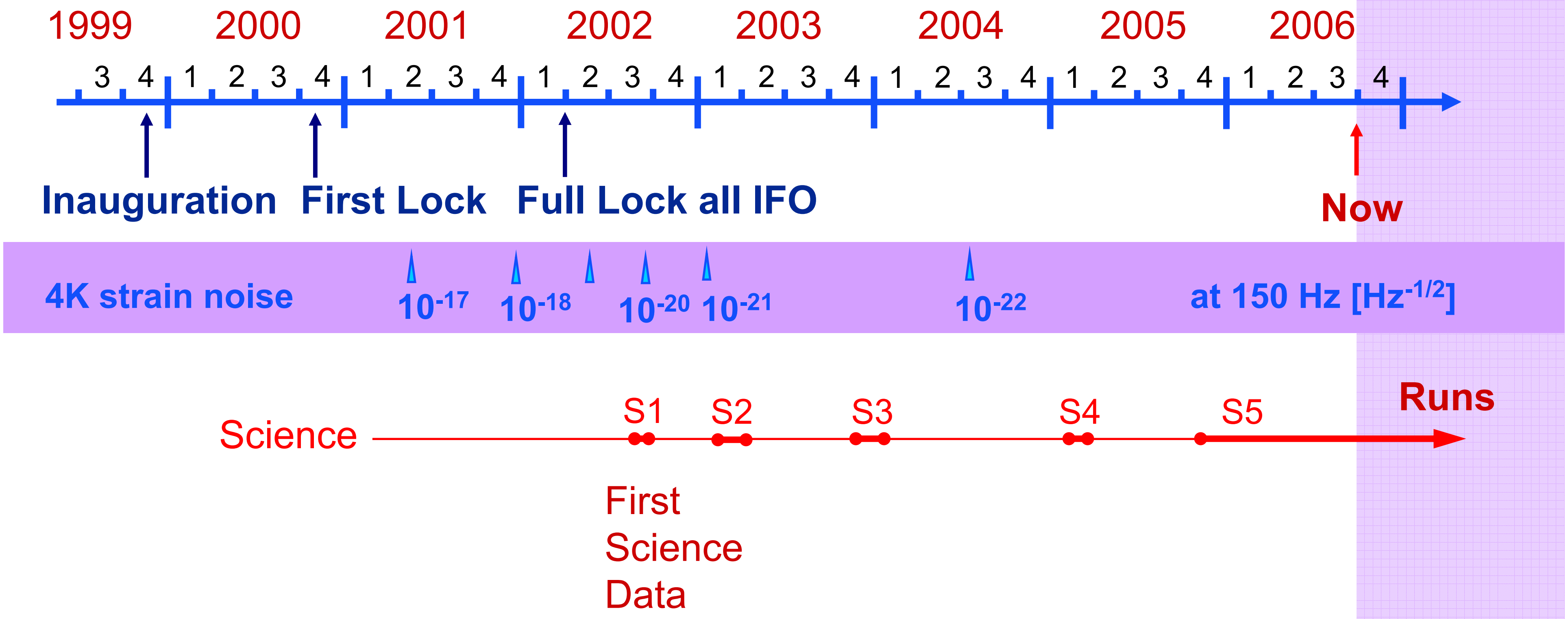
AIGO

?km - proposed

Perth, Australia

- **Detection confidence**
- **Waveform reconstruction**
- **Sky location**

LIGO Time Line



1999 2000 2001 2002 2003 2004 2005 2006

3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4

Inauguration **First Lock** **Full Lock all IFO**

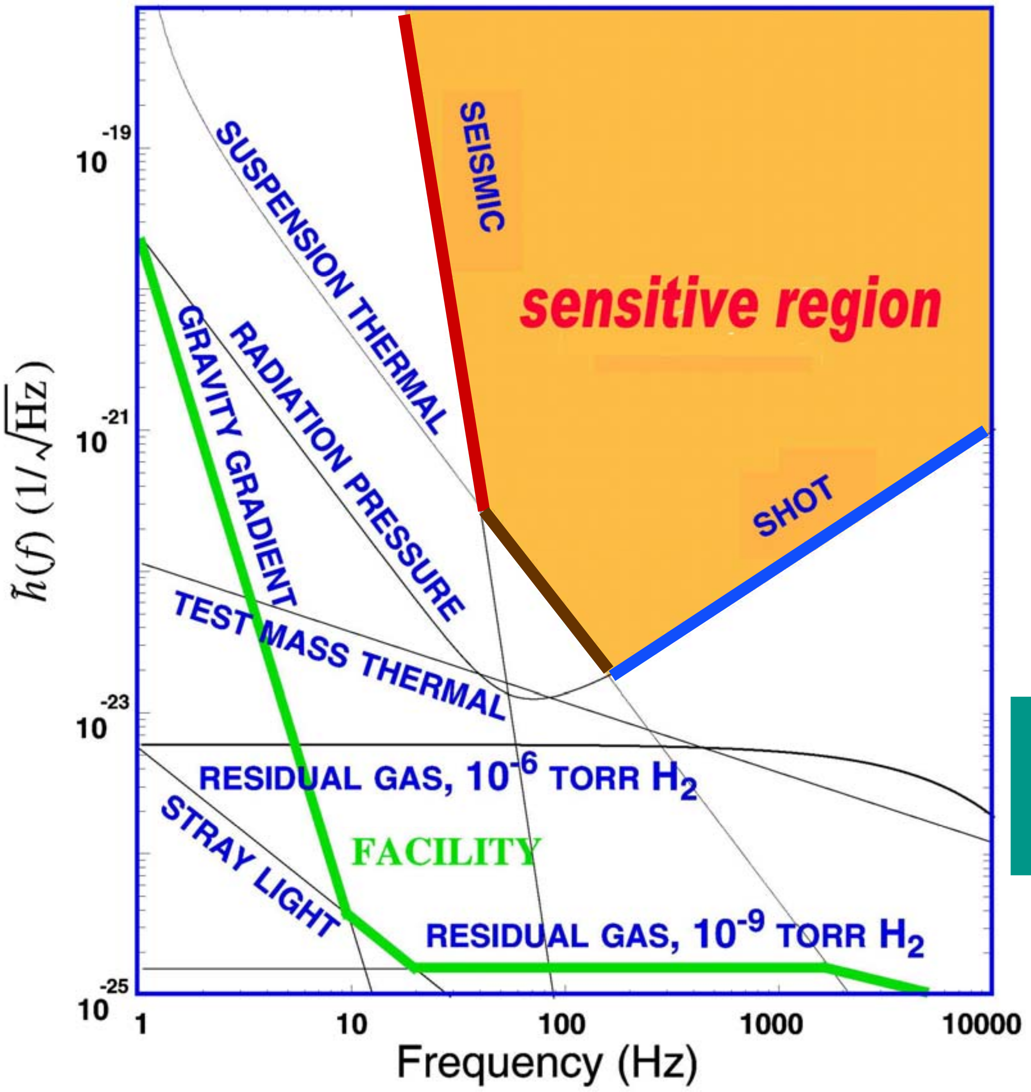
Now

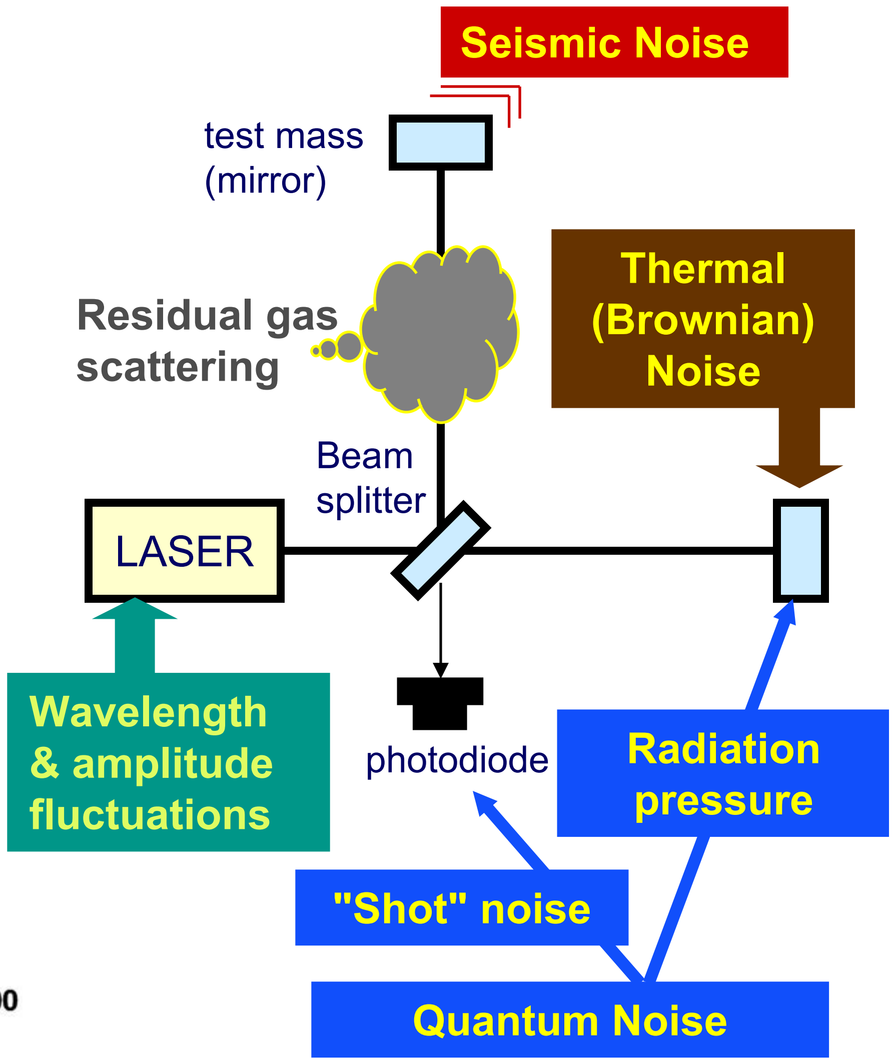
4K strain noise **10^{-17} 10^{-18} 10^{-20} 10^{-21} 10^{-22}** **at 150 Hz [$\mathrm{Hz}^{-1/2}$]**

Science S1 S2 S3 S4 S5 **Runs**

First
Science
Data

Initial LIGO Sensitivity Limits





Seismic Noise

test mass (mirror)

Residual gas scattering

Thermal (Brownian) Noise

Beam splitter

LASER

Wavelength & amplitude fluctuations

photodiode

Radiation pressure

"Shot" noise

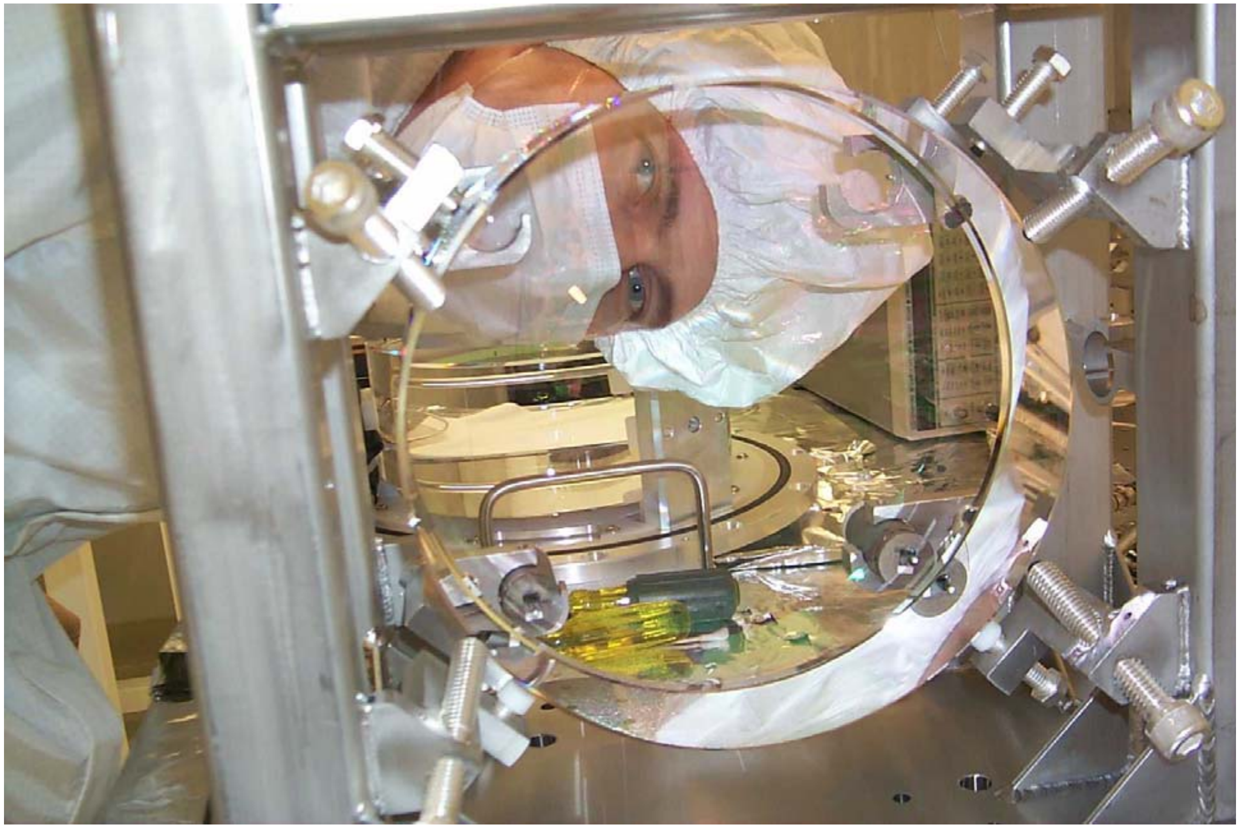
Quantum Noise

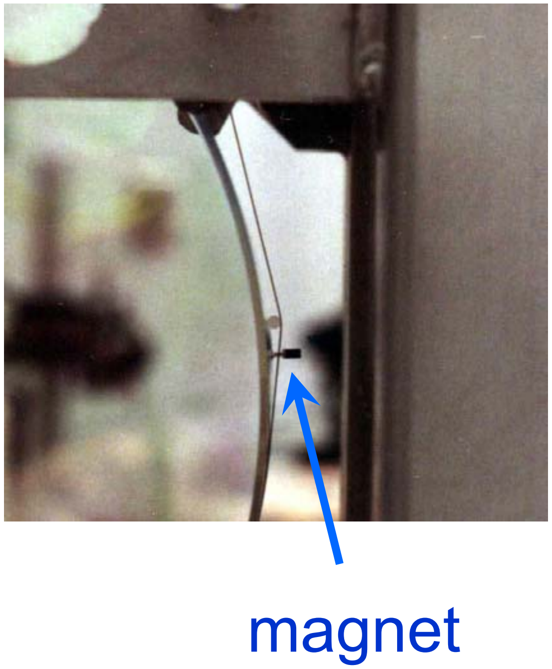
LIGO Beam Tube

LIGO Vacuum Equipment

Mirror Suspensions

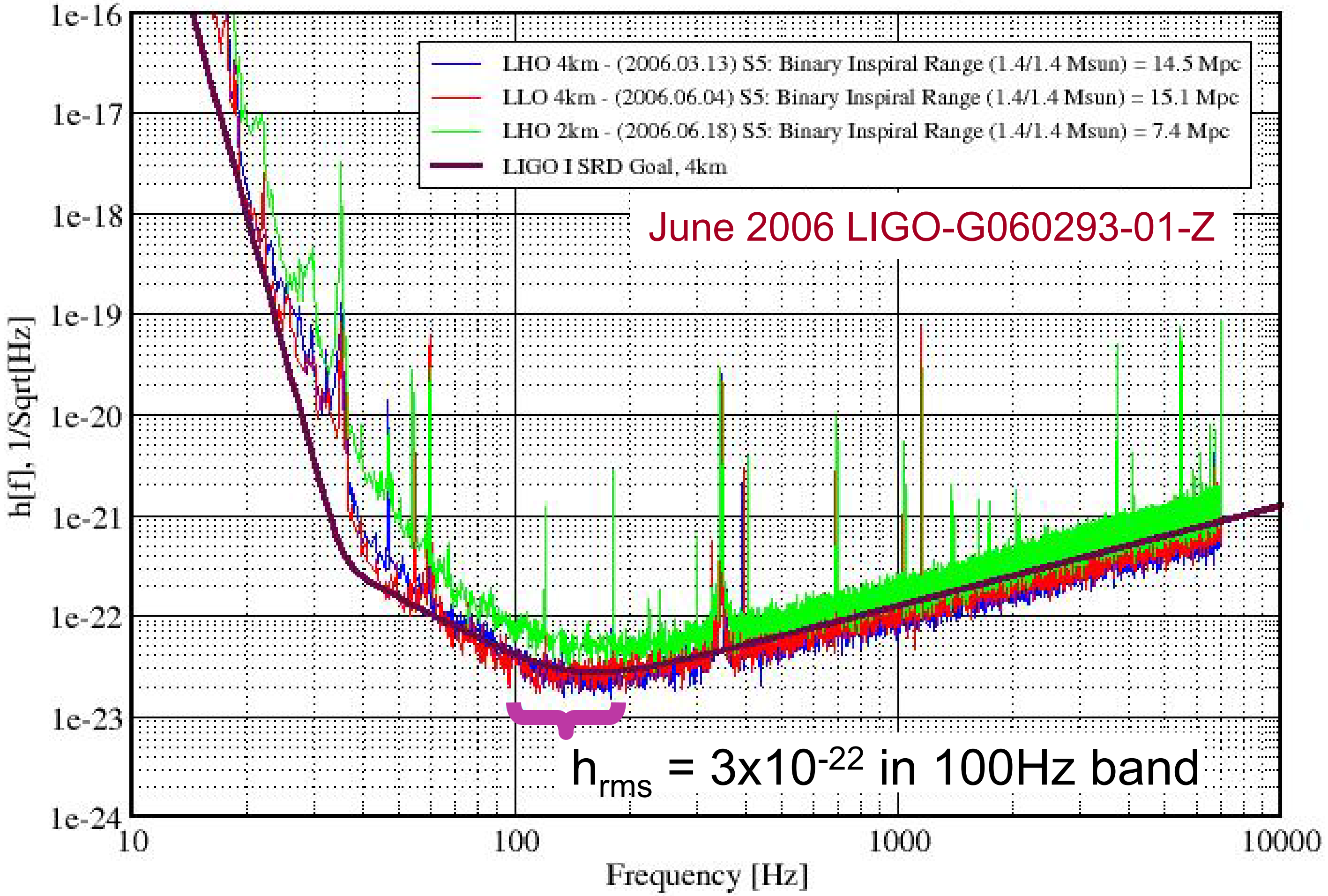
10 kg Fused Silica, 25 cm diameter and 10 cm thick





S5 Science Run: Nov '05 -…

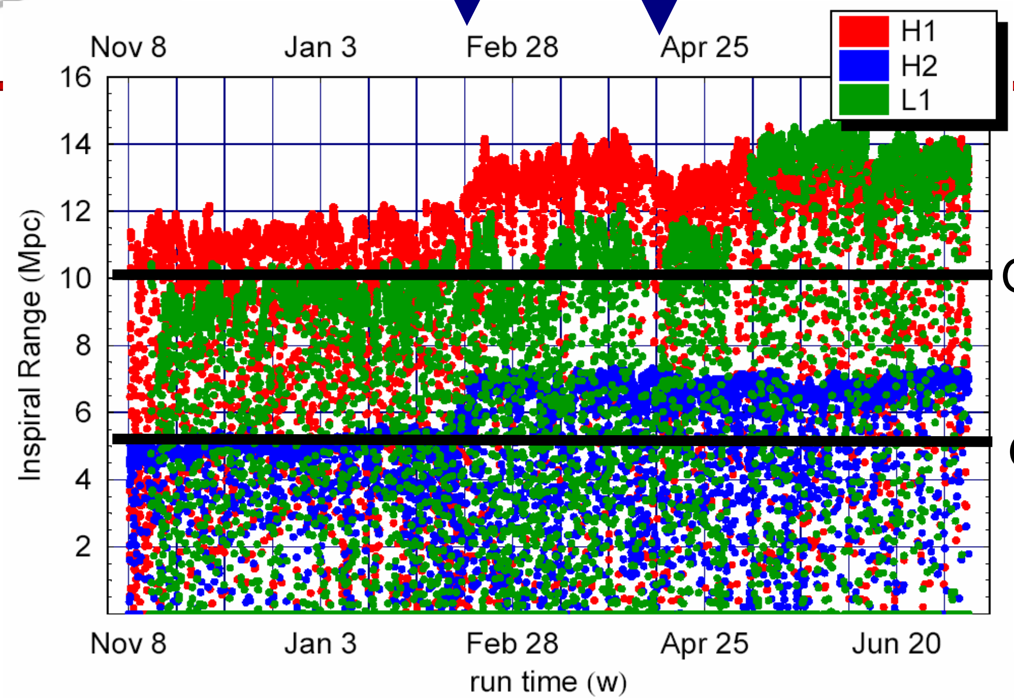
Goal: at least one year data in coincident operation at design sensitivity



June 2006 LIGO-G060293-01-Z

h_{rms} = 3×10^{-22} in 100Hz band

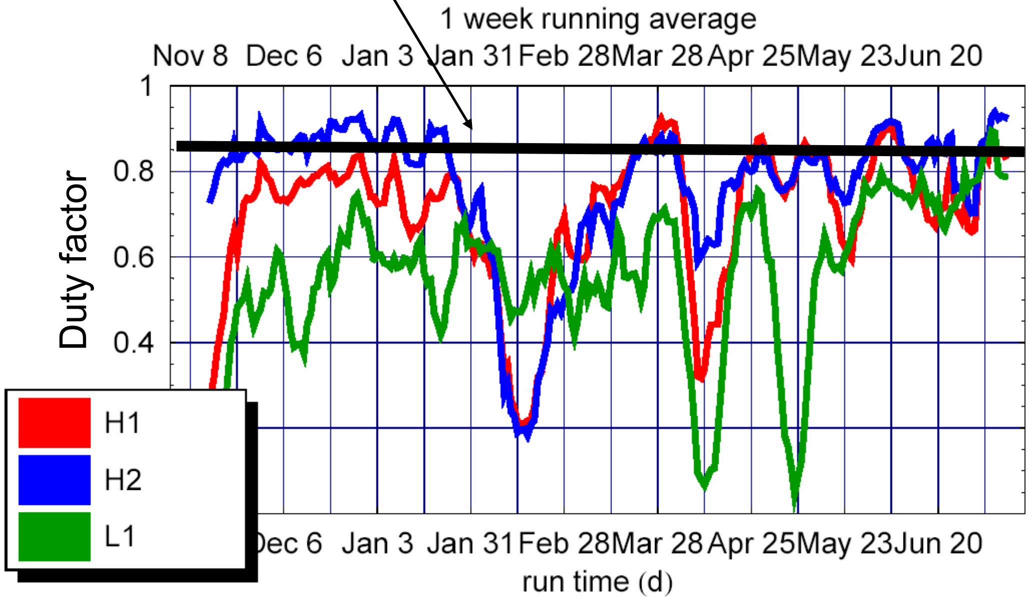
Commissioning breaks



Goal for 4km: 10 MPc

Goal for 2km: 5 MPc

Goal: 85% single, 70% triple



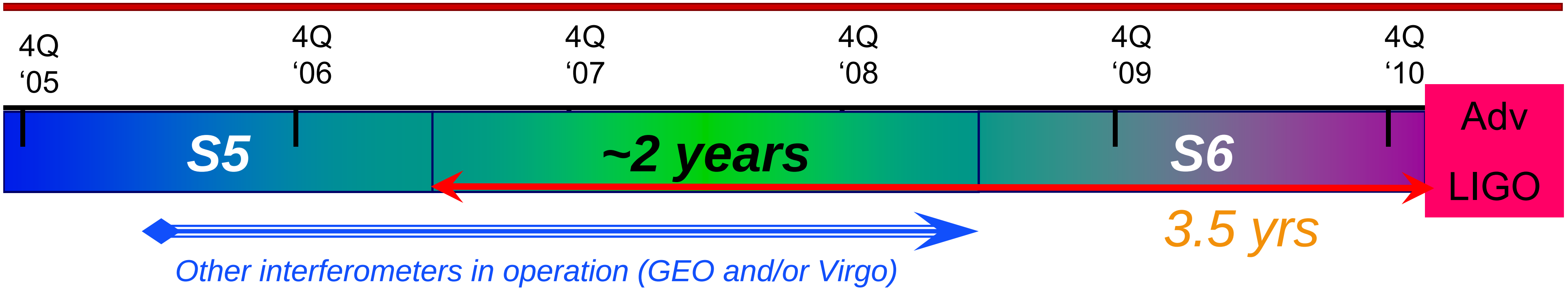
Inspiral range

how far we can see a 1.4-1.4 $M_\odot$ binary neutron star system with SNR>8 (average over direction, polarization, inclination)

Duty factor:

Fraction of time in Science Mode

Enhanced LIGO for S6



Other interferometers in operation (GEO and/or Virgo)

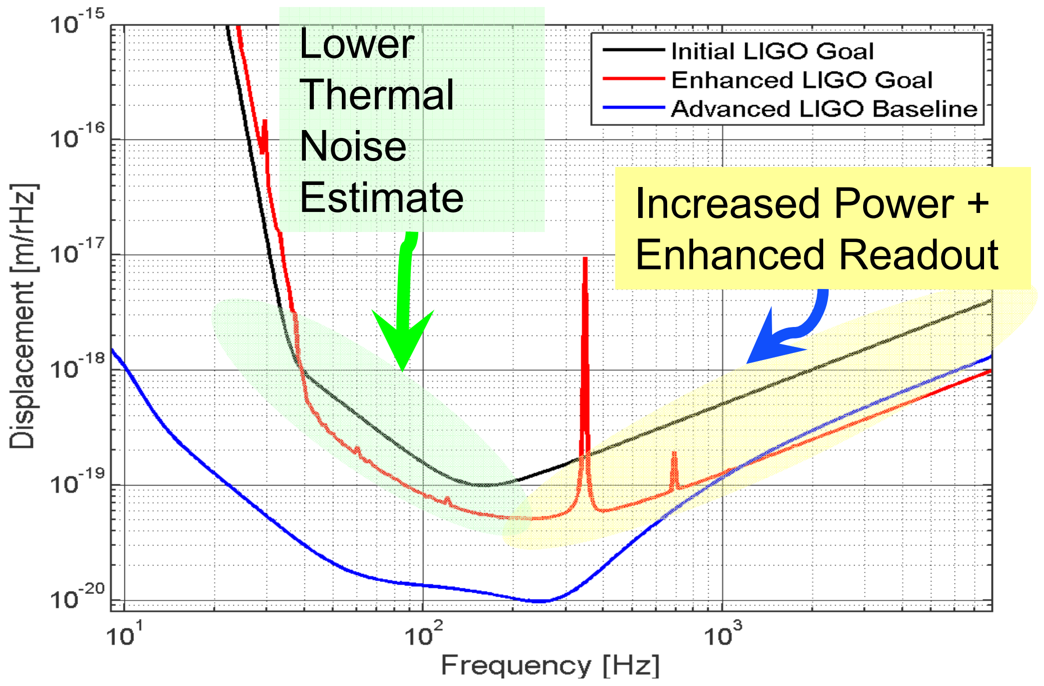
Motivation:

Factor of ~2.5 in noise improvement above 100 Hz

Factor ~5-10 in inspiral binary neutron star event rate

Debug new Advanced LIGO technology in actual low noise interferometers

Reduce the Advanced LIGO commissioning time



Lower Thermal Noise Estimate

Increased Power + Enhanced Readout

Advanced LIGO

Goal: quantum-noise-limited interferometer

x10 better amplitude sensitivity

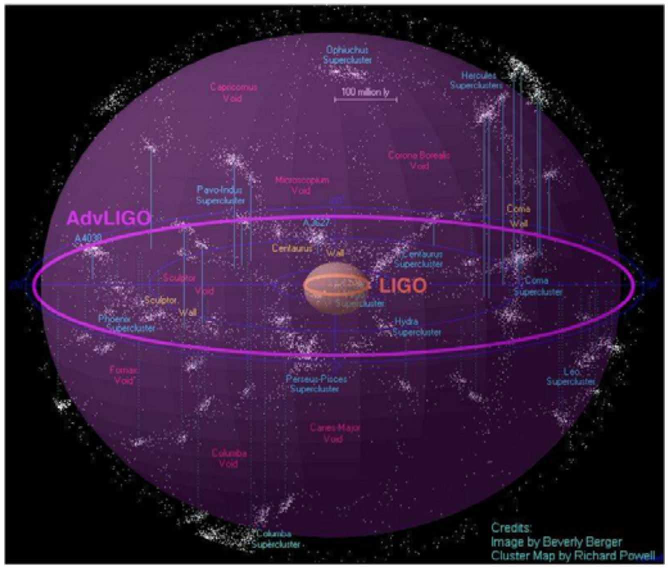
x1000 rate=(reach)^3

x4 lower frequency bound

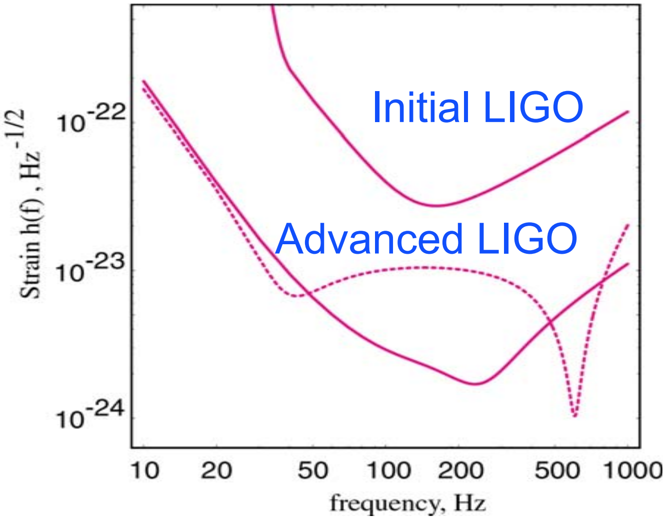
40Hz → 10Hz

x100 better narrow-band at high frequencies

The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

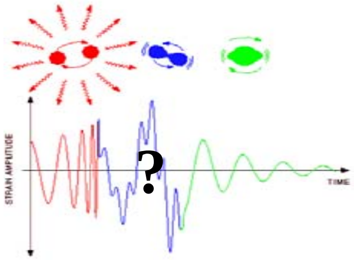


- Approved by NSF – to be proposed for Congress approval in FY2008
- Begin installation: 2010
- Begin observing: 2013

Sources targeted by LIGO

Compact binaries

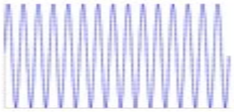
- » Black holes & neutron stars
- » Inspiral and merger
- » Probe internal structure, populations, and spacetime geometry

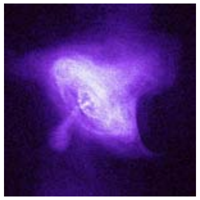



John Rowe, CSIRO

Spinning neutron stars

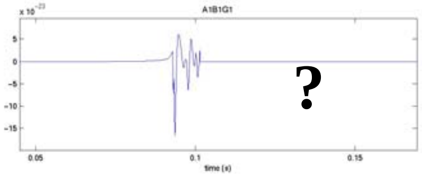
- » Isolated neutron stars with mountains or wobbles
- » Low-mass x-ray binaries
- » Probe internal structure and populations

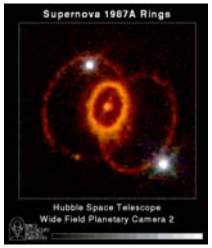



Crab pulsar (NASA, Chandra Observatory)

Bursts

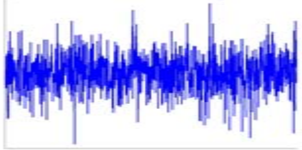
- » Neutron star birth, tumbling and/or convection
- » Cosmic strings, black hole mergers, ...
- » Correlations with electro-magnetic observations
- » Surprises!

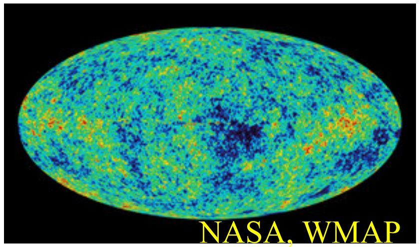




Stochastic background

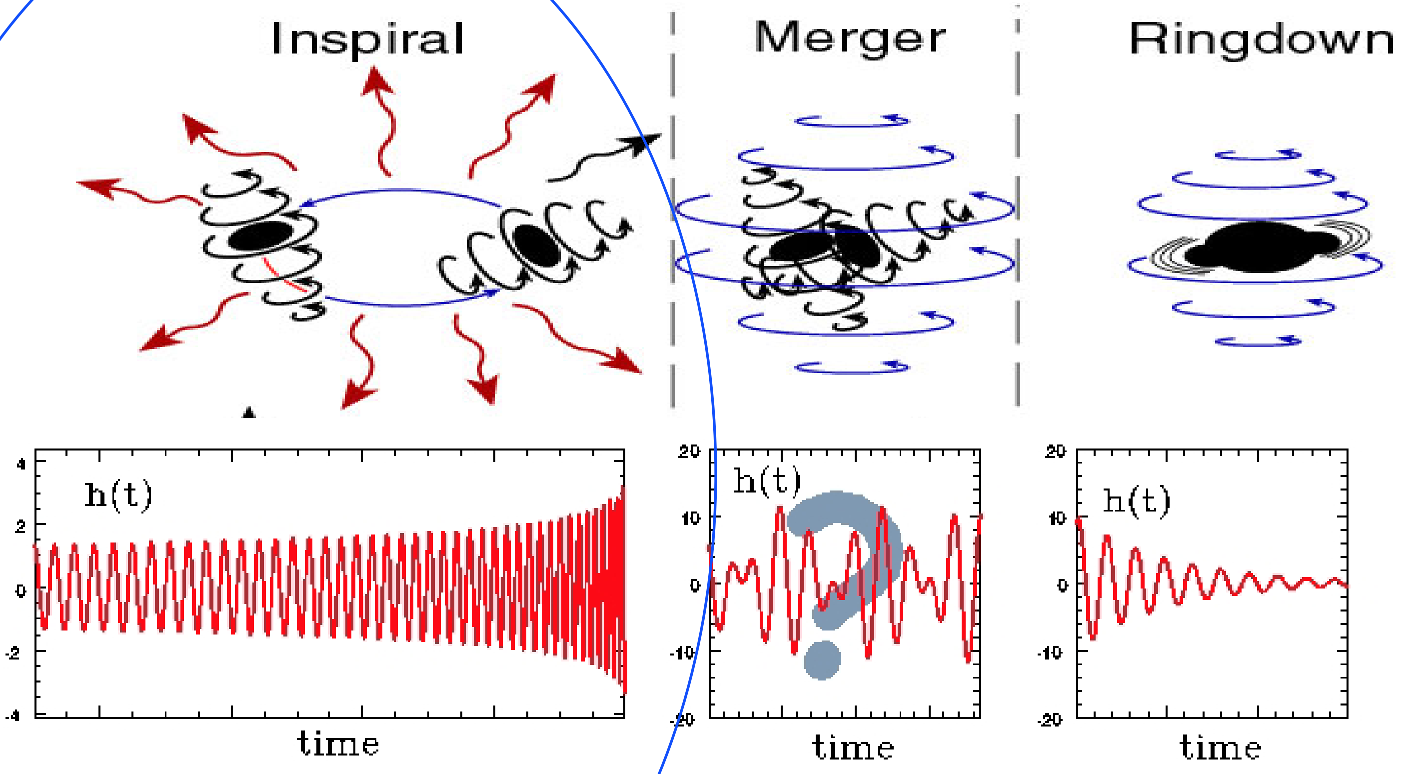
- » Big bang & early universe
- » Background of gravitational wave bursts




NASA, WMAP

Coalescing Binaries

LIGO is sensitive to gravitational waves from neutron star (BNS) and black hole (BBH) binaries



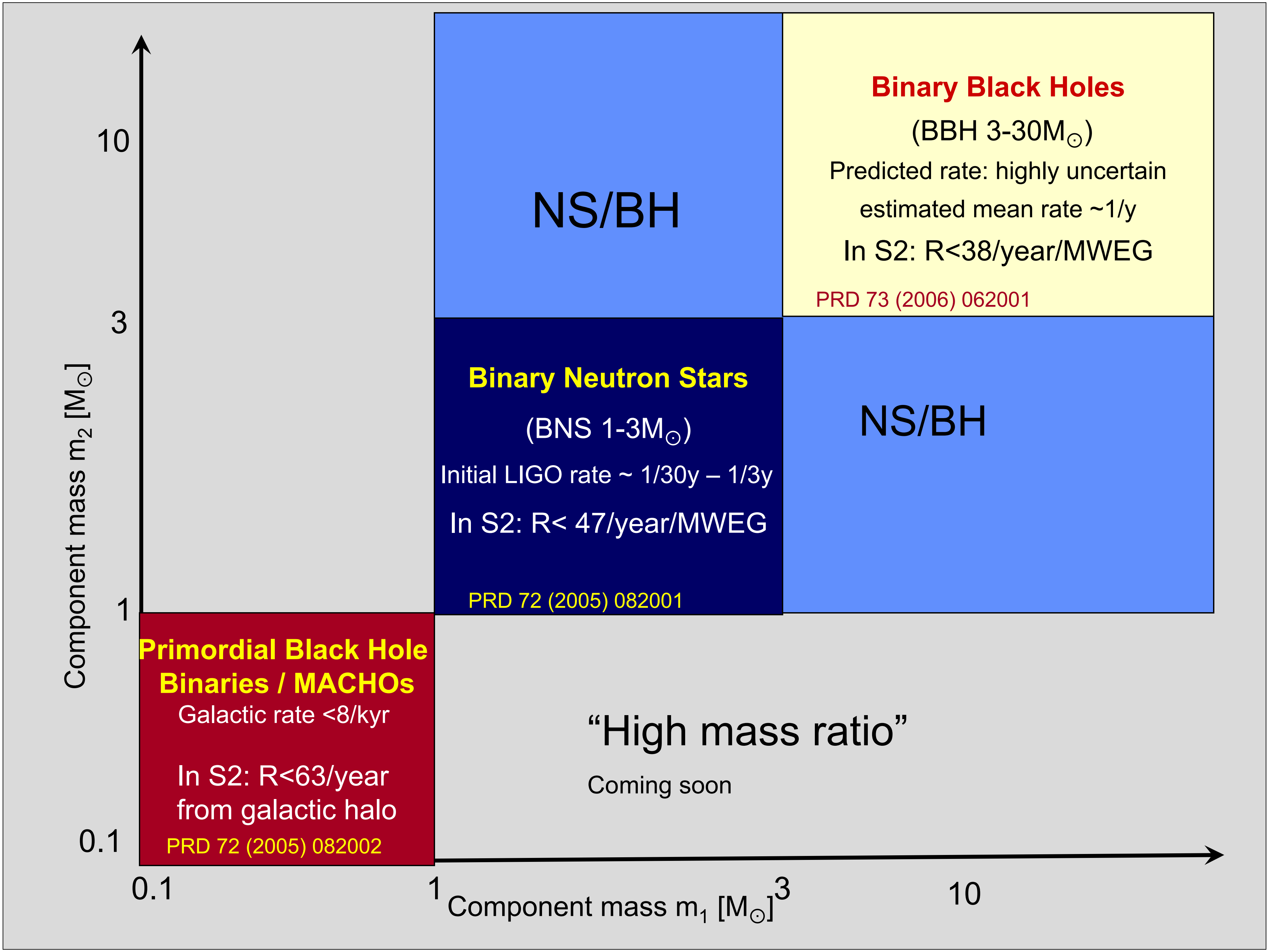
Matched filter

Template-less

Matched filter

Best detection chance in LIGO for BNS and BBH to $30M_\odot$

Best detection chance in LIGO above $100M_\odot$



NS/BH

Binary Black Holes

(BBH 3-30$M_\odot$)

Predicted rate: highly uncertain

estimated mean rate ~1/y

In S2: R<38/year/MWEG

PRD 73 (2006) 062001

Binary Neutron Stars

(BNS 1-3$M_\odot$)

Initial LIGO rate ~ 1/30y – 1/3y

In S2: R< 47/year/MWEG

PRD 72 (2005) 082001

NS/BH

Primordial Black Hole Binaries / MACHOs

Galactic rate <8/kyr

In S2: R<63/year from galactic halo

PRD 72 (2005) 082002

“High mass ratio”

Coming soon

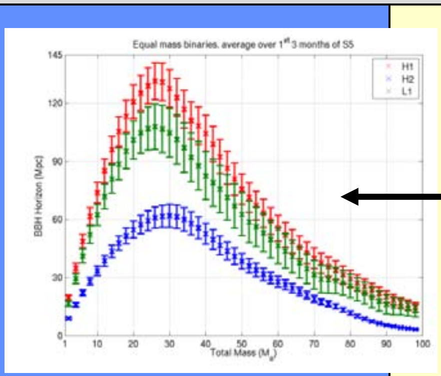
Binary Black Holes

Early S5:

Mass-dependent horizon

Peak for H1:

130Mpc ~ $25 M_\odot$



Binary Neutron Stars

Early S5 BNS horizon:

Hanford-4km: 25 Mpc

Livingston-4km: 21 Mpc

Hanford-2km: 10Mpc

Was 1.5 Mpc in S2

NS/BH

Primordial Black Hole Binaries / MACHOs

S4 reach:

3 Milky Way-like halos

S5 in progress

BNS horizon:
distance of optimally oriented and
located 1.4-1.4 $M_\odot$ binary at SNR=8

Component mass m_2 [$M_\odot$]

10

3

1

0.1

Component mass m_1 [$M_\odot$]

0.1

1

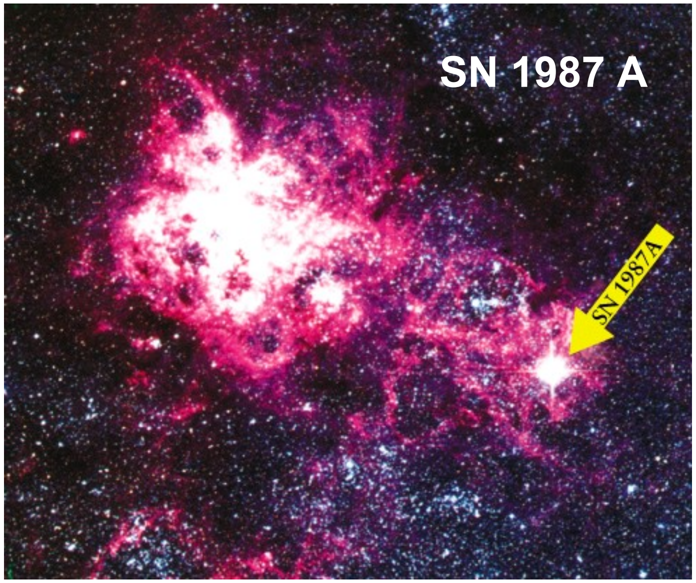
3

10

Gravitational-Wave Bursts

Any short duration (< 1s) “pop” in the data

Plausible sources:
core-collapse supernovae
Accreting / merging black holes
gamma-ray burst engines
Instabilities in nascent neutron stars
Kinks and cusps in cosmic strings
SURPRISES!



Probe interesting new physics
Dynamical gravitational fields, black hole horizons, behavior of matter at supra-nuclear densities

Uncertain waveform complicate detection ⇒ minimal assumptions, open to unexpected

“Eyes-wide-open”, all-sky, all times search
excess power indicative of a transient signal; coincidence among detectors.

Targeted matched filtering searches
e.g. to cosmic string cusps or black hole ringdowns (in progress).

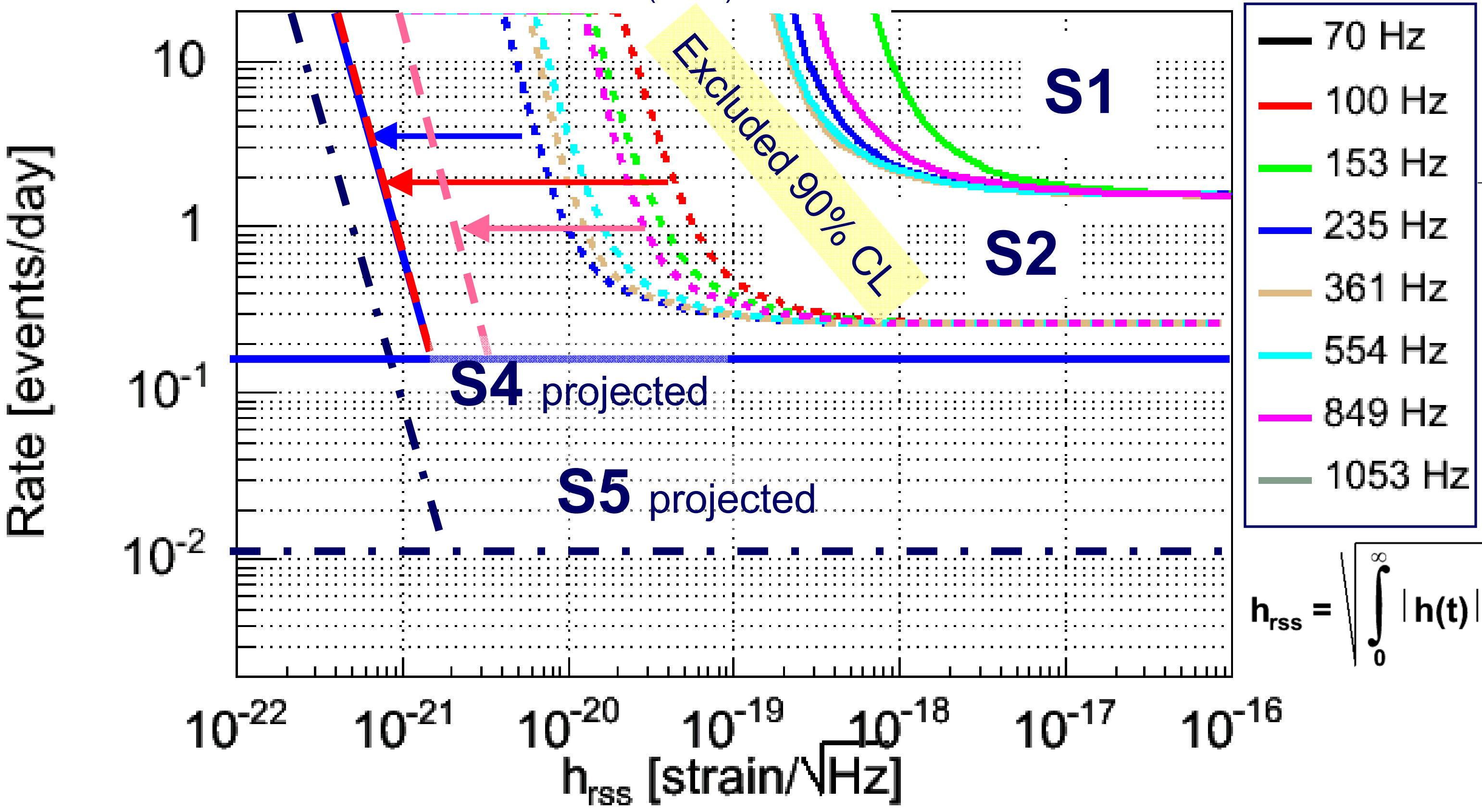
Triggered search
Exploit known direction and time of astronomical events (e.g., GRB), cross correlate pairs of detectors.

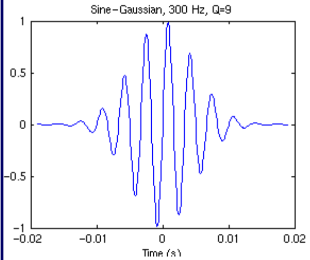
GRB030329: PRD 72, 042002, 2005

All-Sky Burst Search

No GW bursts detected through S4: set limit on rate vs signal strength

PRD 72 (2005) 042002





$$R \propto \frac{1}{\epsilon(h_{\mathrm{rss}})\ T}$$

$$h_{rss} = \sqrt{\int_{0}^{\infty} |h(t)|^2 dt} = \sqrt{\int_{-\infty}^{\infty} |\tilde{h}(f)|^2 df}$$

S5 sensitivity: minimum detectable in-band GW energy

$E_{GW} > 1\ M_{\odot}$ @ 75Mpc

$E_{GW} > 0.05\ M_{\odot}$ @ 15Mpc (Virgo cluster)

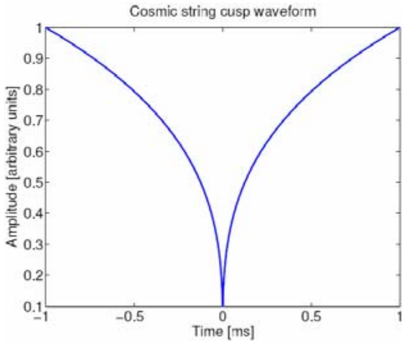
Detectability of string cusps

Targeted matched filtering search (in progress) for GW bursts from cosmic strings and superstrings – see Damour, Vilenkin (200, 2001, 2005)

$$h(f) = A|f|^{-4/3}\Theta(f_h - f)\,\Theta(f - f_l)$$

$$A \sim \frac{G\mu L^{2/3}}{r} \qquad f_h \sim \frac{2}{\theta^3 L}$$

L=size of feature producing the cusp
θ=angle between line of sight and cusp direction
f_l=cutoff – instrumental limitation (seismic wall)



$$h(t) \propto |t - t_0|^{1/3}$$

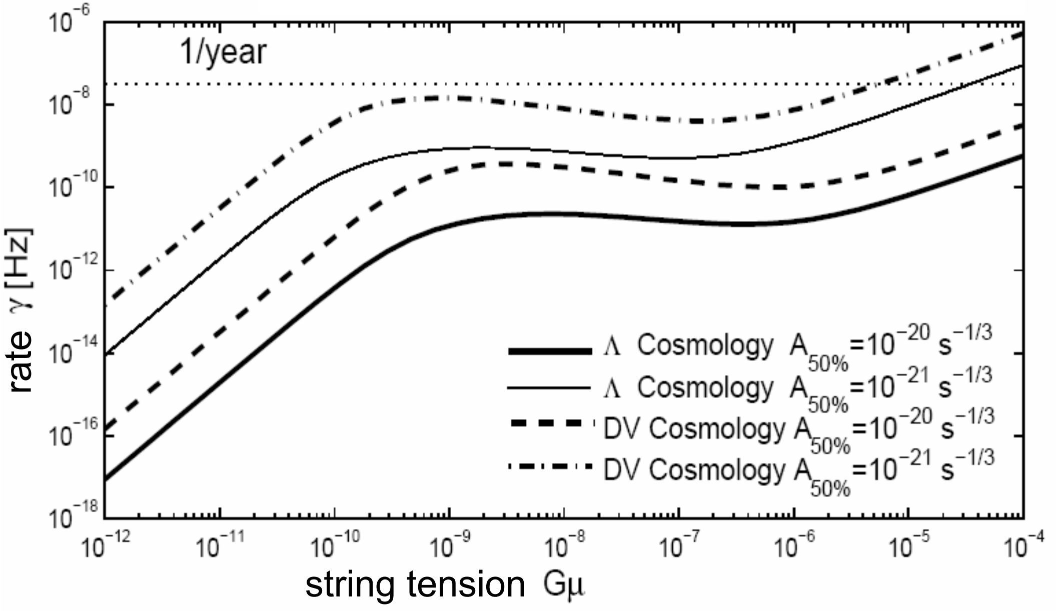
Initial LIGO estimated:

$$A_{50\%} = 10^{-20}\ \mathrm{s}^{-1/3}$$

Advanced LIGO estimated:

$$A_{50\%} = 10^{-21}\ \mathrm{s}^{-1/3}$$

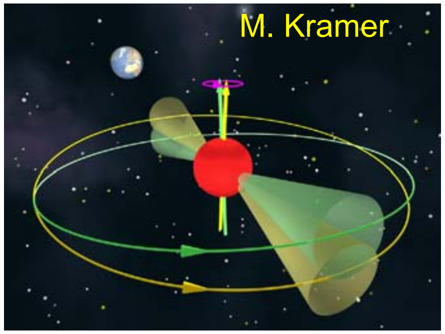
Siemens et al PRD 73 105001,2006



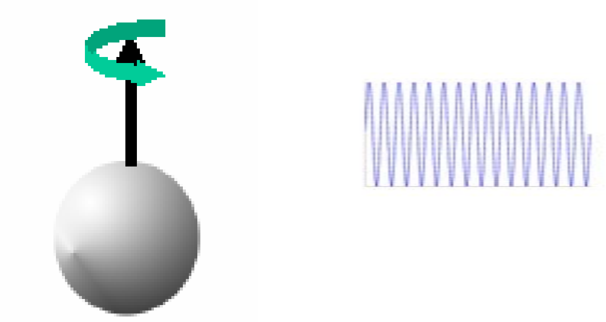
Continuous Waves


Dana Berry/NASA

Accreting neutron stars


M. Kramer

Wobbling neutron stars


“bumpy” neutron stars

- Known pulsar searches
  - » Catalog of known pulsars
  - » Narrow-band folding data using pulsar ephemeris
- All sky incoherent searches
  - » Sum many short spectra
- Wide area search
  - » Doppler correction followed by Fourier transform
  - » Computationally very costly
  - » Hierarchical search under development

Results from S2:

- No GW signal.
- First direct upper limit for 26 of 28 sources studied (95%CL)
- Equatorial ellipticity constraints as low as: $\varepsilon < 10^{-5}$

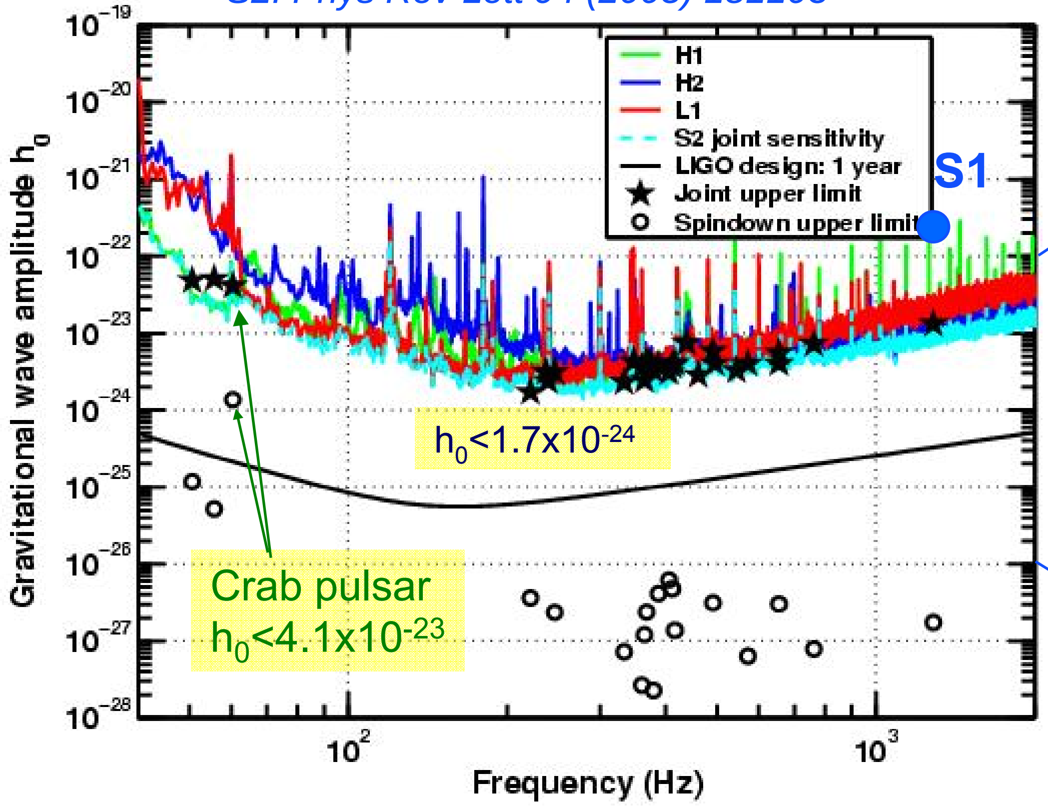
$$\epsilon = (I_{xx} - I_{yy})/I_{zz}$$

See also the Einstein@home project: http://www.physics2005.org

Known pulsars

ephemeris is known from EM observations

S2: Phys Rev Lett 94 (2005) 181103

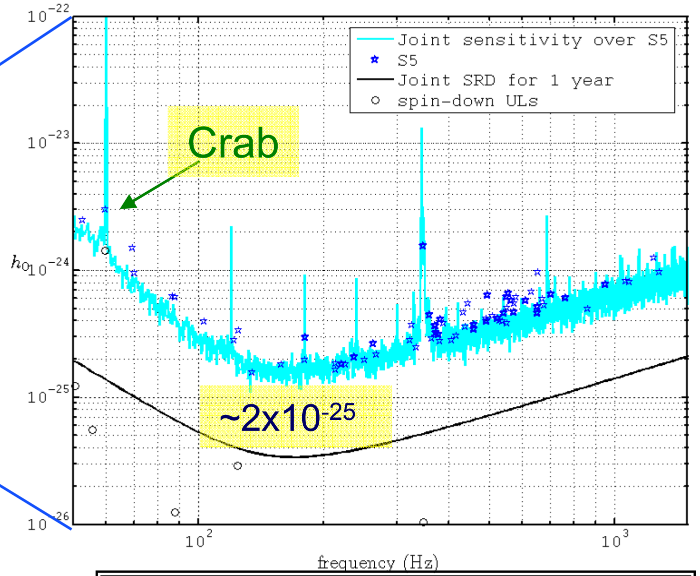


$h_0 < 1.7 \times 10^{-24}$

Crab pulsar
$h_0 < 4.1 \times 10^{-23}$

early S5

PRELIMINARY



Crab

$\sim 2 \times 10^{-25}$

Lowest ellipticity upper limit:
PSR J2124-3358
(f_{gw} = 405.6Hz, r = 0.25kpc)
ellipticity = 4.0×10^{-7}

$$\langle h_0 \rangle = 11.4 \sqrt{S_h(f) / T_{obs}}$$

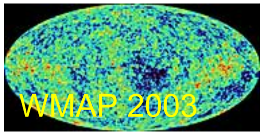
sensitivity for actual observation time
1% false alarm, 10% false dismissal

Crab pulsar approaching
The spin-down limit
(factor 2.1)

Spin-down limits assume ALL angular momentum is radiated as GW

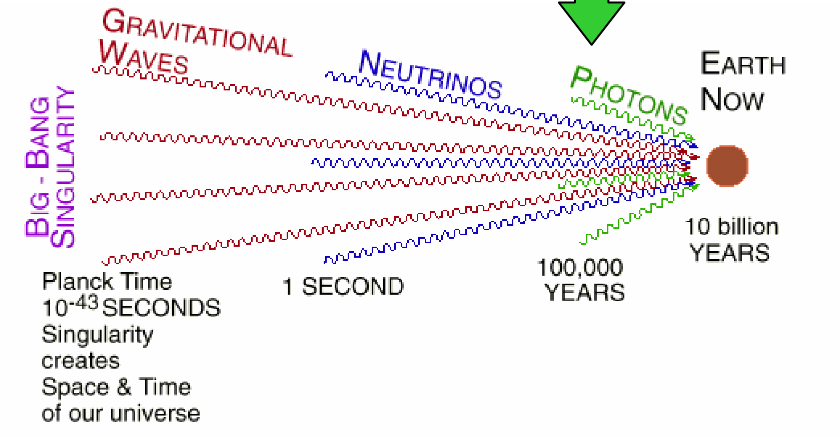
Stochastic GW Backgrounds

Cosmological background: Big Bang



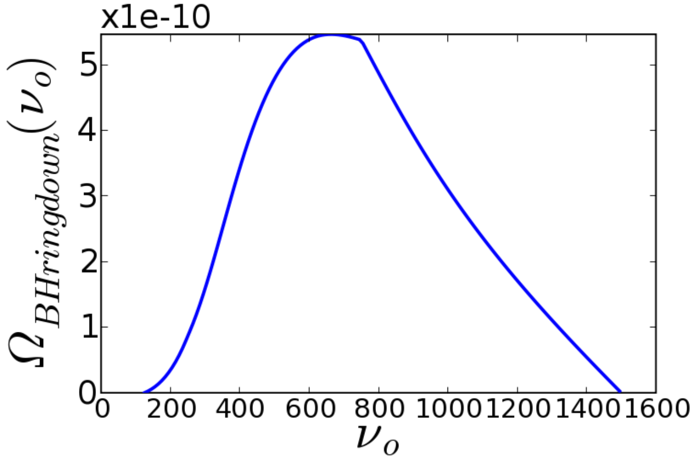
cosmic GW background (10^{-22}s)

CMB (10^{+12}s)

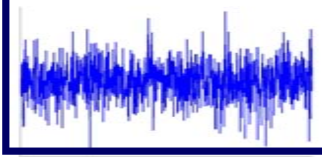


Astrophysical background: Unresolved individual sources

e.g.: black hole mergers, binary neutron star inspirals, supernovae



GW spectrum due to ringdowns of 40-80 $M_\odot$ black holes out to z=5 (Regimbau & Fotopoulos)



$$\Omega_{GW}(f) = \frac{1}{\rho_c}\frac{d\rho_{GW}(f)}{d\ln f}$$

Detection strategy:

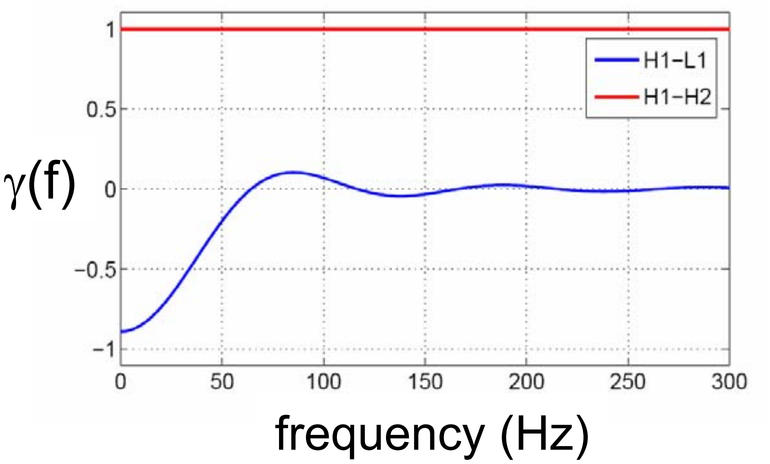
cross-correlate output of two GW detectors

- Cross-correlate two data streams x_1 and x_2
- For isotropic search optimal statistic is

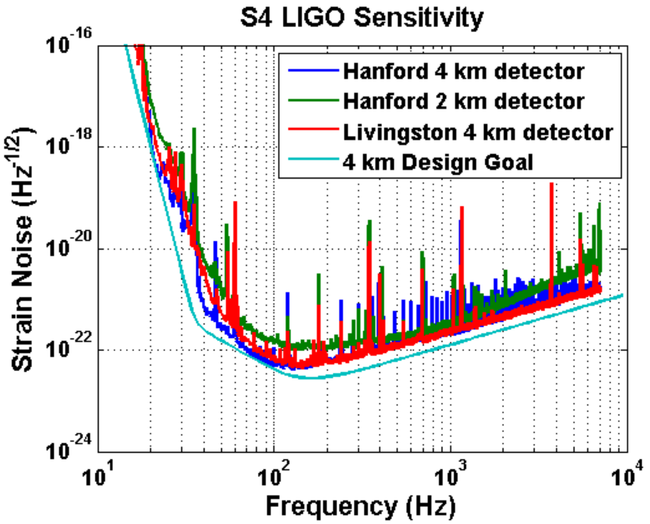
$$Y = \int_{-\infty}^{\infty} df\, \tilde{x}_1^*(f) \frac{\boxed{\gamma(f)}\, \Omega_{GW}(f)}{N f^3\, \boxed{P_1(f)\, P_2(f)}} \tilde{x}_2(f)$$

“Overlap Reduction Function”

(determined by network geometry)



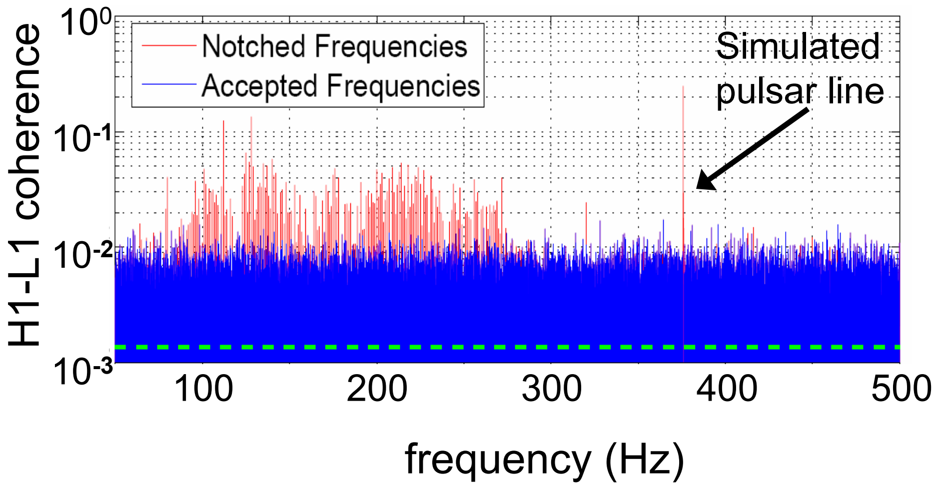
Detector noise spectra



Technical Challenges

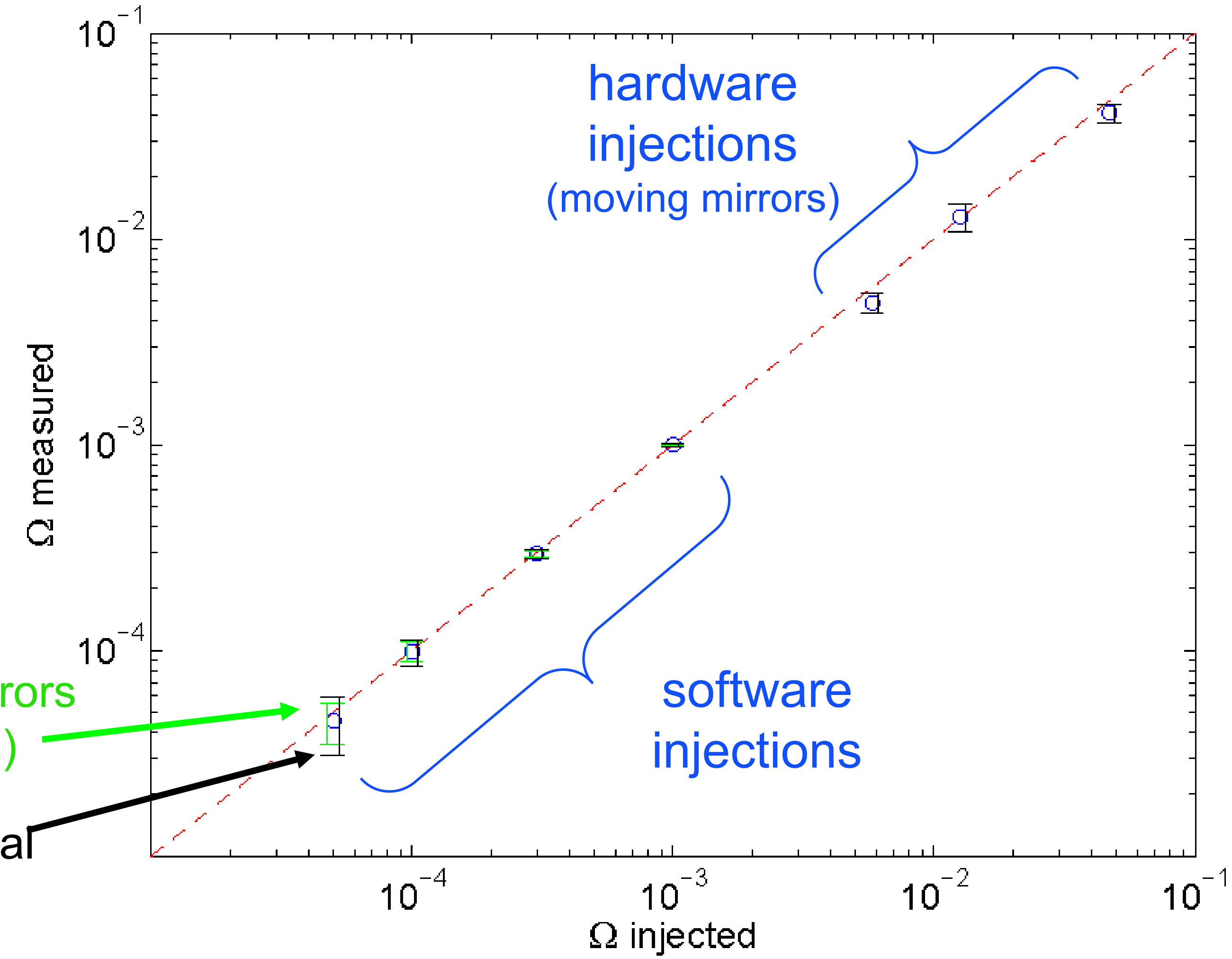
- Digging deep into instrumental noise looking for small correlations.
- Need to be mindful of possible non-GW correlations
  - » common environment (two Hanford detectors)
  - » common equipment (could affect any detector pair!)

- Example:
  - » Correlations at harmonics of 1 Hz.
  - » Due to GPS timing system.
  - » Lose ~3% of the total bandwidth (1/32 Hz resolution).



Signal Recovery

Demonstrated ability to estimate Ω_{GW} accurately:



hardware injections (moving mirrors)

software injections

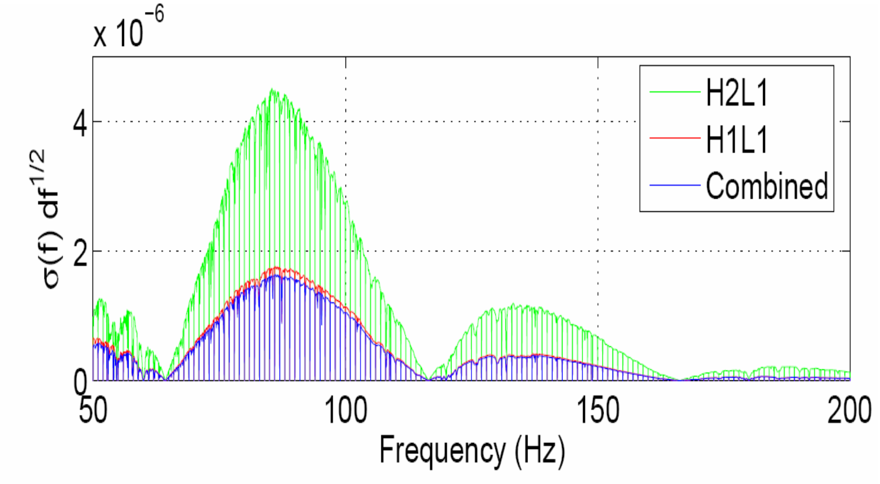
standard errors (10 trials)

theoretical errors

S4 Analysis Details

- Cross-correlate Hanford-Livingston
  - Hanford 4km – Livingston
  - Hanford 2km – Livingston
  - Weighted average of two cross-correlations (new in S4).
  - Do not cross-correlate the Hanford detectors.

S4: Sensitivity vs Frequency

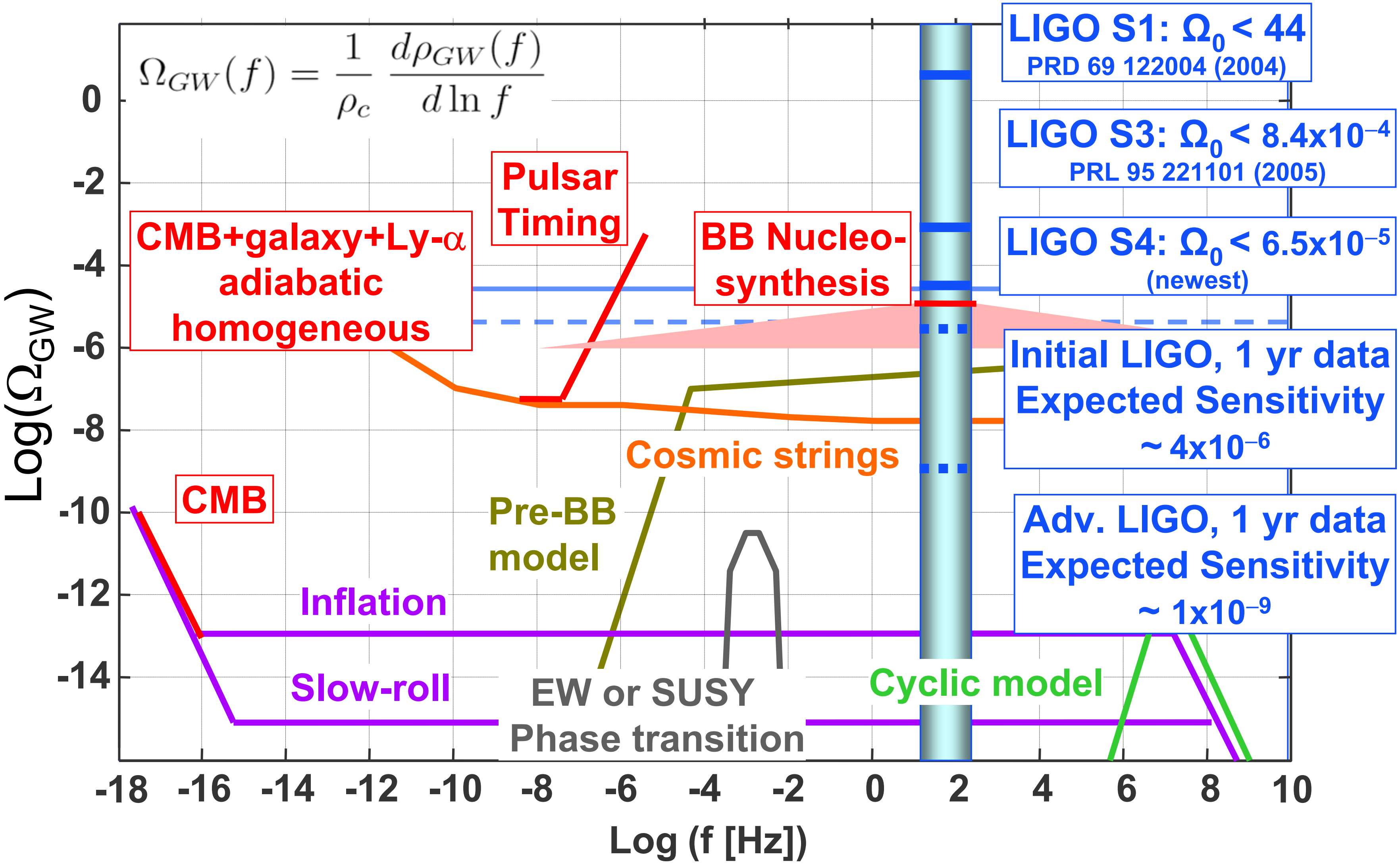


- Data quality:
  - Drop segments when noise changes quickly (non-stationary).
  - Drop frequency bins showing instrumental correlations (harmonics of 1 Hz, bins with pulsar injections).

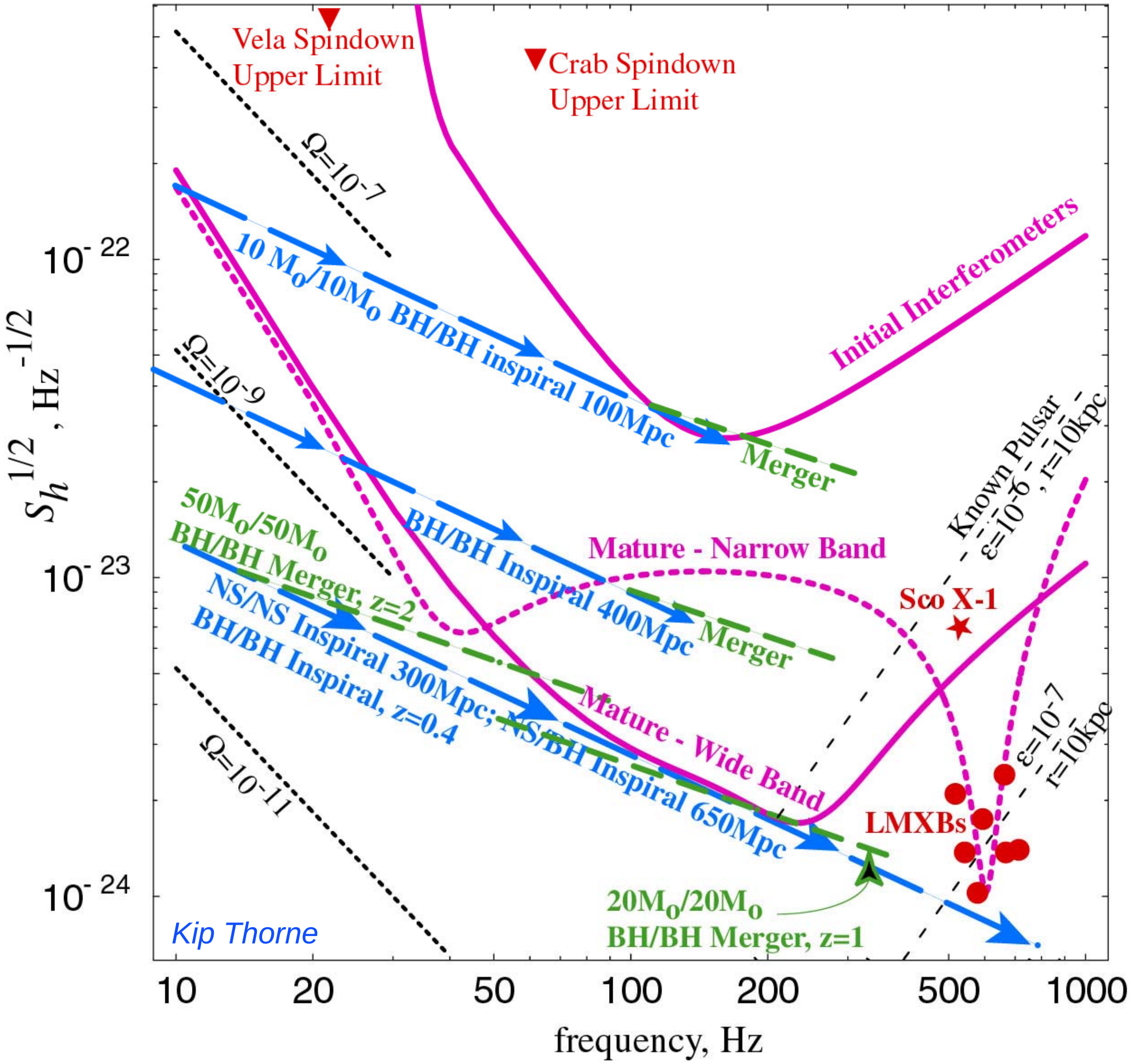
- Bayesian UL: $\Omega_{90\%} = 6.5 \times 10^{-5}$
  - Use S3 posterior distribution for S4 prior.
  - Marginalized over calibration uncertainty with Gaussian prior (5% for L1, 8% for H1 and H2).

ALSO COMING SOON:
Directional search (“GW Radiometer”)
Use cross-correlation kernel optimized for un-polarized point source
Ballmer, gr-qc/0510096

Landscape


$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d \ln f}$
LIGO S1: $\Omega_0 < 44$
PRD 69 122004 (2004)
LIGO S3: $\Omega_0 < 8.4\times10^{-4}$
PRL 95 221101 (2005)
LIGO S4: $\Omega_0 < 6.5\times10^{-5}$
(newest)
Initial LIGO, 1 yr data
Expected Sensitivity
~ 4×10^{-6}
Adv. LIGO, 1 yr data
Expected Sensitivity
~ 1×10^{-9}
Pulsar Timing
CMB+galaxy+Ly-α adiabatic homogeneous
BB Nucleo-synthesis
Cosmic strings
CMB
Pre-BB model
Inflation
Slow-roll
EW or SUSY Phase transition
Cyclic model
0
-2
-4
-6
-8
-10
-12
-14
$\text{Log}(\Omega_{GW})$
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
Log (f [Hz])

From Initial to Advanced LIGO



Kip Thorne

Binary neutron stars:

From ~20 Mpc to ~350 Mpc

From 1/30y(<1/3y) to 1/2d(<5/d)

Binary black holes:

From $10M_\odot$ to $50M_\odot$

From ~100Mpc to z=2

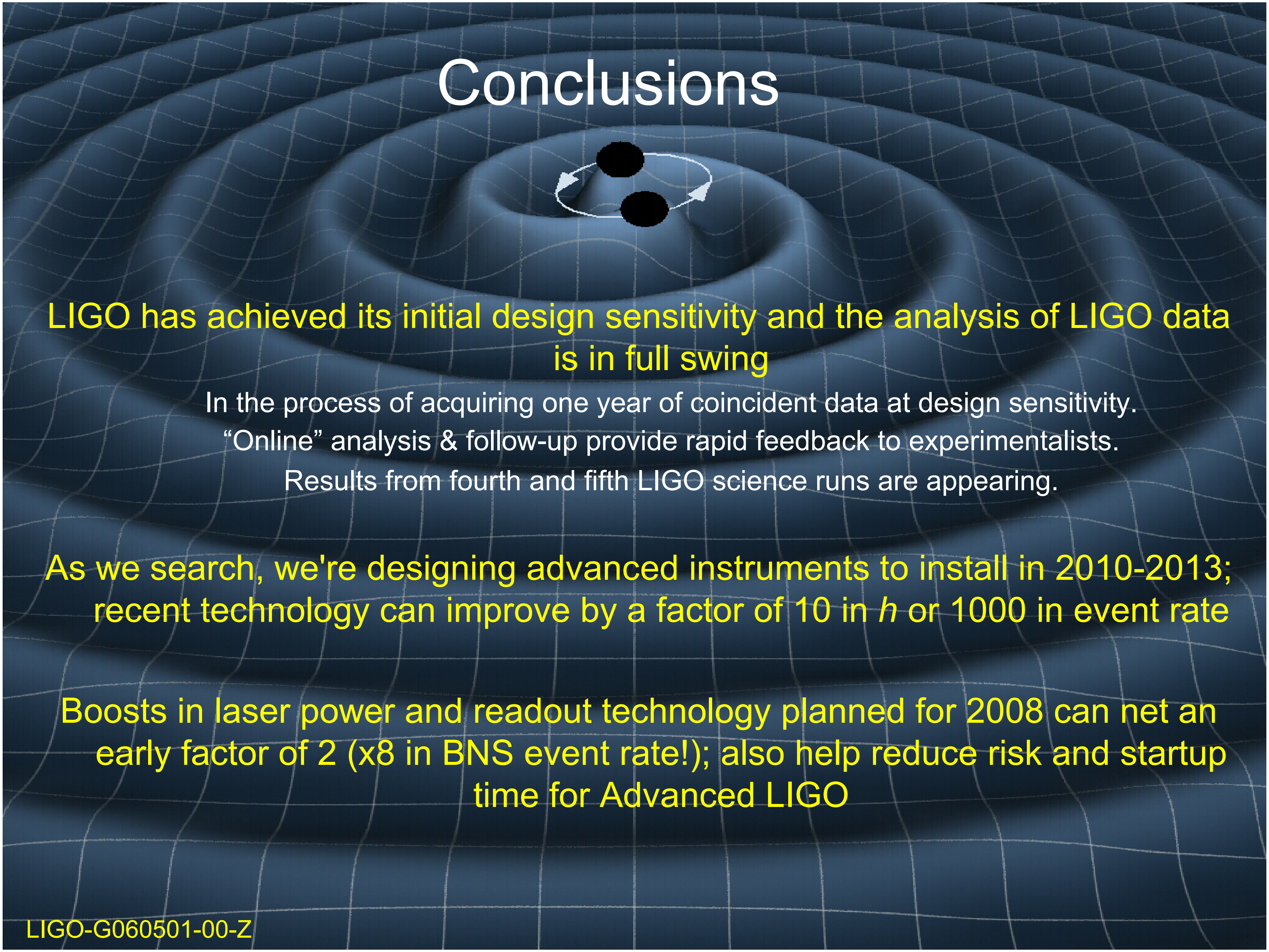
Known pulsars:

From $\varepsilon = 3\mathrm{x}10^{-6}$ to $2\mathrm{x}10^{-8}$

Stochastic background:

From Ω_{GW} ~$3\mathrm{x}10^{-6}$ to ~$3\mathrm{x}10^{-9}$

Conclusions



LIGO has achieved its initial design sensitivity and the analysis of LIGO data is in full swing

In the process of acquiring one year of coincident data at design sensitivity.
“Online” analysis & follow-up provide rapid feedback to experimentalists.
Results from fourth and fifth LIGO science runs are appearing.

As we search, we're designing advanced instruments to install in 2010-2013; recent technology can improve by a factor of 10 in *h* or 1000 in event rate

Boosts in laser power and readout technology planned for 2008 can net an early factor of 2 (x8 in BNS event rate!); also help reduce risk and startup time for Advanced LIGO