LIGO and the Search for Gravitational Waves

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(for the LIGO Scientific Collaboration)

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Outline

1. Gravitational Waves
    - Crash Course in Gravitational Wave Physics
    - Gravitational Wave Detectors
    - GW Sources and Detection Techniques
2. LIGO Science
    - The LIGO Scientific Collaboration
    - LIGO Results (S1-S4)
    - LIGO S5 Run

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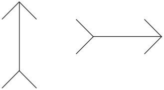
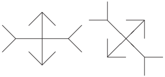
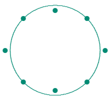
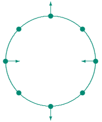
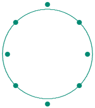
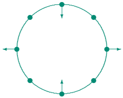
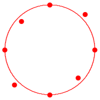
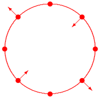
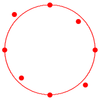
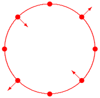
Particle Physicist's Perspective

Weyl Neutrino	Photon	Graviton
spin-$\frac{1}{2}$, massless	spin-1, massless	spin-2, massless
spinor ψ	vector A_μ	sym tensor $h_{\mu\nu}$
2 pol states 180° apart 	2 pol states 90° apart 	2 pol states 45° apart 
wave speed c	wave speed c	wave speed c
Gauge xf $\psi \to e^{i\alpha}\psi$	Gauge xf $A_\mu \to A_\mu - \partial_\mu \Lambda$	Gauge xf $h_{\mu\nu} \to h_{\mu\nu} - \partial_\mu \xi_\nu - \partial_\nu \xi_\mu$

- Newtonian Gravity $\longleftrightarrow$ Electrostatics
- Gravitational Waves $\longleftrightarrow$ EM waves

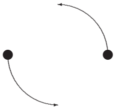
Effects of Gravitational Wave

Fluctuating geom changes distances btwn particles in free-fall:

Plus ($+$) Polarization				
Cross ($\times$) Polarization				

Gravitational Wave Generation

- Generated by moving/oscillating mass distribution
- Lowest multipole is quadrupole
- Classic example: orbiting binary system



(e.g., Binary Pulsar 1913+16
– Observed energy loss agrees w/GW prediction)

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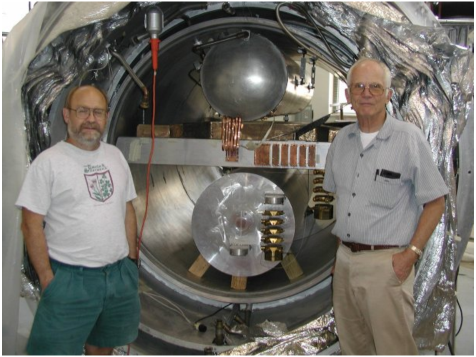
Resonant-Mass GW Detectors

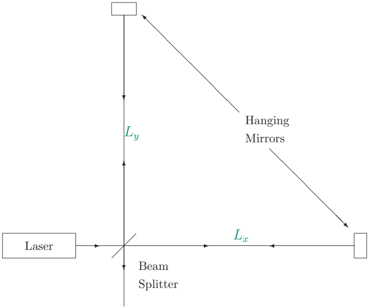
4 cryogenic bars still in operation; won't discuss today



W. Johnson, ALLEGRO & W. Hamilton from LSU Website

Measuring GWs w/Laser Interferometry

Interferometry: Measure GW-induced distance changes



- Measure small change in

$$\begin{aligned} L_x - L_y &= \sqrt{g_{11} L_0^2} - \sqrt{g_{22} L_0^2} \\ &= \sqrt{(1+h_{11})L_0^2} - \sqrt{(1+h_{22})L_0^2} \\ &\approx L_0 \frac{h_{11}-h_{22}}{2} \sim L_0 h_+ \end{aligned}$$

- Problem: need to measure $h \sim \Delta L / L \lesssim 10^{-21}$ $\rightarrow$ BIG L ($\sim$ km)

Measuring GWs w/Laser Interferometry

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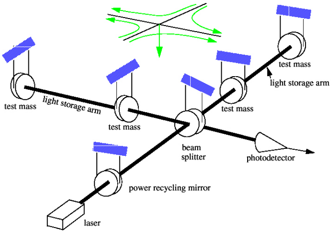

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$$L_x - L_y = \sqrt{g_{11} L_0^2} - \sqrt{g_{22} L_0^2}$$
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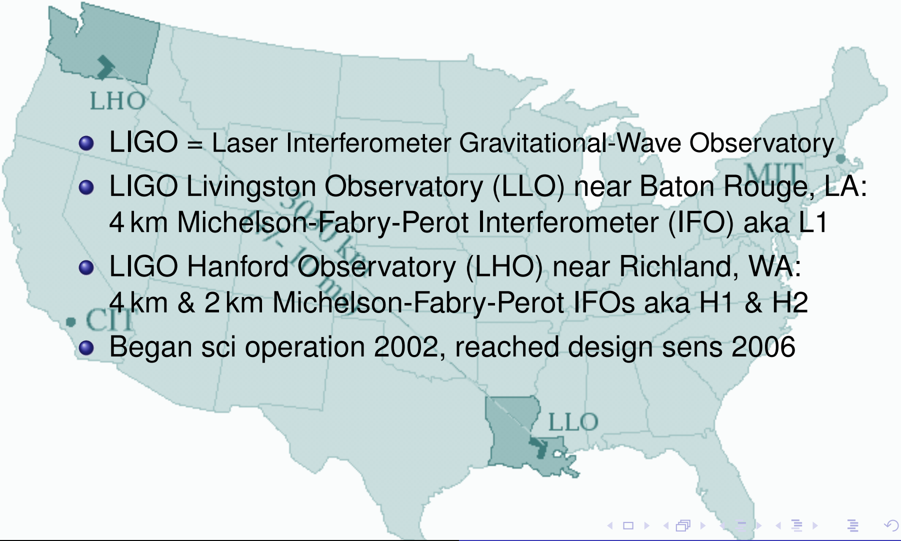
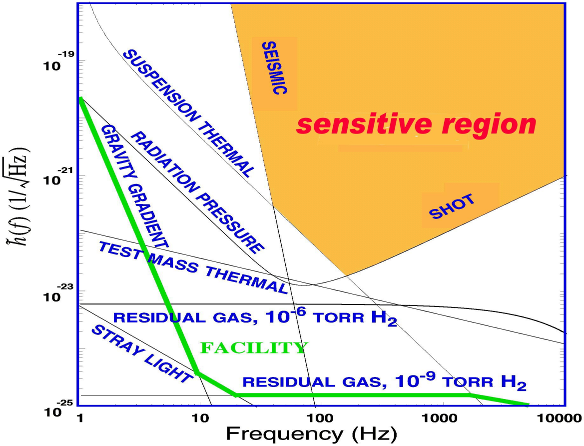
The LIGO Observatories



- LIGO = Laser Interferometer Gravitational-Wave Observatory
- LIGO Livingston Observatory (LLO) near Baton Rouge, LA: 4 km Michelson-Fabry-Perot Interferometer (IFO) aka L1
- LIGO Hanford Observatory (LHO) near Richland, WA: 4 km & 2 km Michelson-Fabry-Perot IFOs aka H1 & H2
- Began sci operation 2002, reached design sens 2006

LIGO's Sensitive Frequency Band



Worldwide GW Detector Network

Cartoon courtesy of E. Coccia,

NAUTILUS Group (Rome)

Also includes

- GEO near Hannover, Germany
  600 m folded-arm IFO
- Virgo near Pisa, Italy
  3 km IFO
  1st sci run started 2007!
- Four cryogenic resonant bars

  (ALLEGRO, AURIGA, EXPLORER, NAUTILUS)

Rogues’ Gallery of Interferometers

LHO

LLO

GEO-600

Virgo

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Classification of GW Signals

In LIGO band (10s-1000s of Hz), natural division of sources:

	modelled	unmodelled
long	Periodic Sources (e.g., Rotating Neutron Star)	Stochastic Background (Cosmological or Astrophysical)
short	Binary Coälescence (Black Holes, Neutron Stars)	Bursts (Supernova, BH Merger, etc.)

Detection Methods

- Periodic: Waveform well-modelled & long-lived
  Sky position via Doppler modulation
- Stochastic: Cross-correlate detector outputs
  → Signal-to-noise improves with time
- Bursts: Signal unmodelled
  → Look for unusual features & coïncident events
  Recent searches incl GRB triggers
- Inspiral: Signal well modelled (at least early)
  → Matched Filtering

Inspiral Search Methods

- Compact object binary coälescence consists of inspiral / plunge / merger / ringdown
- For first part of inspiral, orbits not too relativistic can expand in powers of $\frac{v}{c}$ $\longrightarrow$ post-Newtonian methods
  Can estimate orb vel from Kepler's 3rd law: $v \approx (\pi G M f)^{1/3}$
  - Low Mass $\longrightarrow$ plunge @ high freq
    $1.4M_\odot/1.4M_\odot$ NS/NS binary has $v \approx 0.3c$ @ 800 Hz;
    PN OK in LIGO band
  - High Mass $\longrightarrow$ plunge @ low freq
    $10M_\odot/10M_\odot$ BH/BH binary has $v \approx 0.4c$ @ 200 Hz;
    merges in LIGO band

Continuous Waves (aka Periodic)

- Canonical source is deformed rotating neutron star
- Signal nearly monochromatic, maybe spinning down
  Doppler modulation depends on sky position
- Signal model: $x(t;\mathcal{A},\lambda) = n(t) + \mathcal{A}^{\mu} h_{\mu}(t;\lambda)$
- $\mathcal{F}$-statistic search method (Jaranowski/Krolak/Schutz 1998)
  maximizes analytically over amplitude params
  $\mathcal{A}$ (amplitude, inclination, polarization, phase);
  Templates labelled by Doppler params λ=α,δ,f,$\dot{f}$...
- Astrophysical limit for (non-accreting) known pulsars:
  GW amplitude can't be inconsistent
  w/observed energy loss (spindown)

Computing Costs for Coherent CW Searches

Doppler resolution, & # of templates, grows rapidly w/ T_{obs}
Fully coherent search of long stretches of data prohibitive
Alternatives:

- Target known pulsars (know freq, spindown & sky pos)
- Search coherently w/small amount of best data
- Combine short data stretches incoherently:
  semi-coherent methods: stack-slide, Hough, powerflux
- Harness more computers!

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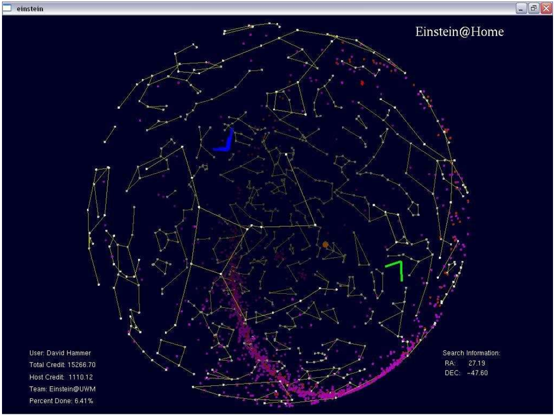
- Harness more computers!
  Einstein@Home: BOINC screensaver running on
  100s of 1000s of computers worldwide

Einstein@Home

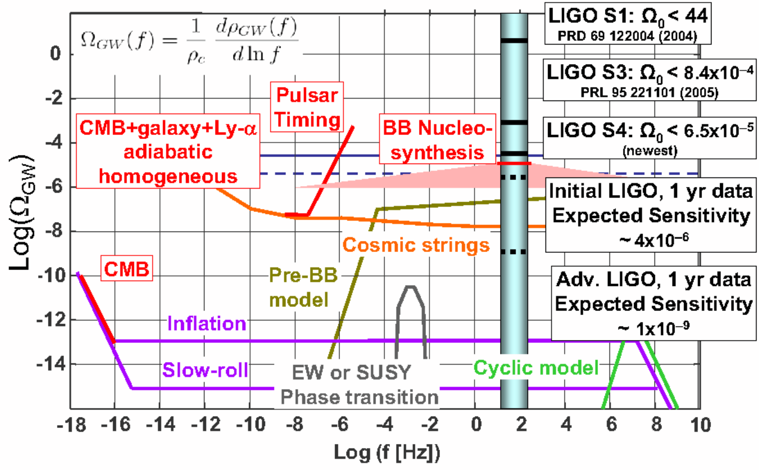


User: David Hammer
Total Credit: 15266.70
Host Credit: 1110.12
Team: Einstein@UWM
Percent Done: 6.41%

Search Information:
RA: 27.19
DEC: -47.60

You can help too: http://www.einsteinathome.org/

Stochastic Background “Landscape”



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LIGO Scientific Collaboration

- 100s of scientists at dozens of institutions working to analyze LIGO and GEO data
- LIGO just entered a data-sharing agreement with Virgo ⟶ now working together with Virgo scientists

LSC Member Institutions

LIGO Scientific Collaboration

- •Australian Consortium for Interferometric Gravitational Astronomy
- •The Univ. of Adelaide
- •Andrews University
- •The Australian National Univ.
- •The University of Birmingham
- •California Inst. of Technology
- •Cardiff University
- •Carleton College
- •Charles Stuart Univ.
- •Columbia University
- •Embry Riddle Aeronautical Univ.
- •Eötvös Loránd University
- •University of Florida
- •German/British Collaboration for the Detection of Gravitational Waves
- •University of Glasgow
- •Goddard Space Flight Center
- •Leibniz Universität Hannover
- •Hobart & William Smith Colleges
- •Inst. of Applied Physics of the Russian Academy of Sciences
- •Polish Academy of Sciences
- •India Inter-University Centre for Astronomy and Astrophysics
- •Louisiana State University
- •Louisiana Tech University
- •Loyola University New Orleans
- •University of Maryland

- •Max Planck Institute for Gravitational Physics
- •University of Michigan
- •Massachusetts Inst. of Technology
- •Monash University
- •Montana State University
- •Moscow State University
- •National Astronomical Observatory of Japan
- •Northwestern University
- •University of Oregon
- •Pennsylvania State University
- •Rochester Inst. of Technology
- •Rutherford Appleton Lab
- •University of Rochester
- •San Jose State University
- •Univ. of Sannio at Benevento, and Univ. of Salerno
- •University of Sheffield
- •University of Southampton
- •Southeastern Louisiana Univ.
- •Southern Univ. and A&M College
- •Stanford University
- •University of Strathclyde
- •Syracuse University
- •Univ. of Texas at Austin
- •Univ. of Texas at Brownsville
- •Trinity University
- •Universitat de les Illes Balears
- •Univ. of Massachusetts Amherst
- •University of Western Australia
- •Univ. of Wisconsin-Milwaukee
- •Washington State University
- •University of Washington

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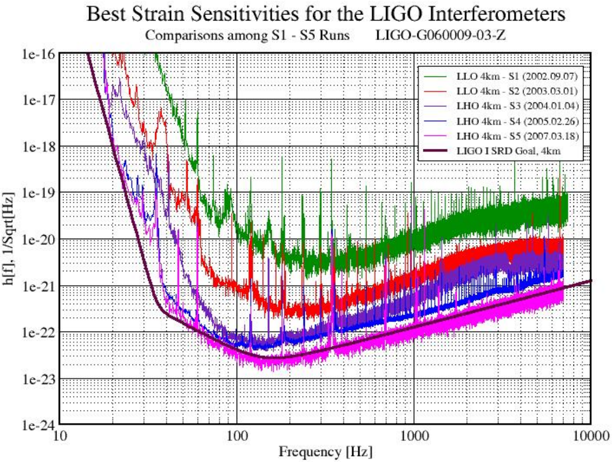
Evolution of LIGO Sensitivity S1-S5



Inspiral Upper Limits Papers (B. Abbott et al=LSC)

- S3/S4: arXiv:0704.3368
  “Search for gravitational waves from binary inspirals in S3 and S4 LIGO data”
  $R_{\mathrm{PBHB}} \leq 0.5\,\mathrm{yr}^{-1} L_{10}^{-1}$; $R_{\mathrm{BNS}} \leq 1.2\,\mathrm{yr}^{-1} L_{10}^{-1}$; $R_{\mathrm{BBH}} \leq 0.5\,\mathrm{yr}^{-1} L_{10}^{-1}$
- S2 LIGO/TAMA: *PRD* **73**, 102002 (2006); gr-qc/0512078
  “Joint LIGO and TAMA300 Search for Gravitational Waves from Inspiralling Neutron Star Binaries”
- S2 BBH: *PRD* **73**, 062001 (2006); gr-qc/0509129
  “Search for gravitational waves from binary black-hole inspirals in LIGO data”
- S2 PBHB: *PRD* **72**, 082002 (2005); gr-qc/0505042
  “Search for gravitational waves from primordial black hole binary coalescences in the galactic halo”
- S2 BNS: *PRD* **72**, 082001 (2005); gr-qc/0505041
  “Search for gravitational waves from galactic and extra-galactic binary neutron stars”
- S1 BNS: *PRD* **69**, 122001 (2004); gr-qc/0308069
  “Analysis of LIGO data for gravitational waves from binary neuton stars”

Stochastic Upper Limits Papers (B. Abbott et al=LSC)

- S4 LHO-LLO: *ApJ* **659**, 918 (2007); astro-ph/0608606

  "Searching for Stochastic Background of Gravitational Waves with LIGO"

  $h_{72}^2\Omega_{\text{gw}}(51 - 150\,\text{Hz}) \leq 6.5 \times 10^{-5}$
- S4 LLO-ALLEGRO: gr-qc/0703068

  "First Cross-Correlation Analysis of Interferometric and Resonant-Bar GW Data for Stochastic Backgrounds"

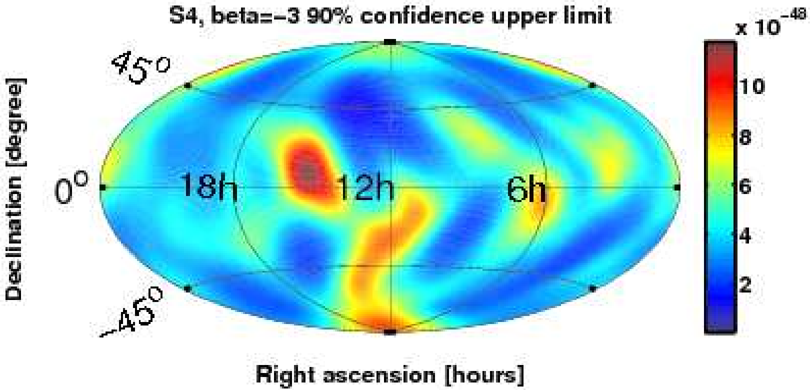
  $h_{72}^2\Omega_{\text{gw}}(850 - 950\,\text{Hz}) \leq 1.02$
- S4 directed search: astro-ph/0703234

  "Upper limit map of a background of gravitational waves"
- S3 LHO-LLO: *PRD* **95**, 221101 (2005); astro-ph/0507254

  "Upper limits on a stochastic background of gravitational waves"
- S1 LHO-LLO: *PRD* **69**, 122004 (2004); gr-qc/0312088

  "Analysis of first LIGO science data for stochastic gravitational waves"

S4 Stochastic Upper Limit Map



Note: 10^{-48} in these units $\cong h_{72}^2 \Omega_{\rm gw}(100\,\mathrm{Hz}) \sim 4 \times 10^{-7}$
(all from one point)

Burst Upper Limits Papers (B. Abbott et al=LSC)

- S4: arXiv:0704.0943
  “Search for gravitational-wave bursts in LIGO data from the fourth LSC science run”
  $R \leq 0.15\,\mathrm{dy}^{-1}$ for $h_{\mathrm{rss}} \sim 10^{-21} - 10^{-20}\,\mathrm{Hz}^{-1/2}$
- S4 triggered: astro-ph/0703419
  “Search for GW rad’n associated w/pulsating tail of SGR 1806-20 hyperflare of Dec 27, 2004 using LIGO”
  $h_{\mathrm{rss}} \leq 4.5 \times 10^{-22}\,\mathrm{Hz}^{-1/2} \equiv E_{\mathrm{GW}} \leq 4.3 \times 10^{-8} M_{\odot} c^2$
- S3: *CQG* **23**, S29 (2006); gr-qc/0511146

  “ Search for gravitational-wave bursts in LIGO’s third science run”
- S2 LIGO-TAMA: *PRD* **72**, 122004 (2005); gr-qc/0507081

  “Upper limits from the LIGO and TAMA detectors on the rate of gravitational-wave bursts”
- S2: *PRD* **72**, 062001 (2005); gr-qc/0505029

  “Upper limits on gravitational-wave bursts in LIGO’s second science run”
- S2 triggered: *PRD* **72**, 042002 (2005); gr-qc/0501068

  “A search for gravitational waves associated w/the gamma ray burst GRB030329 using the LIGO detectors”
- S1: *PRD* **69**, 102001 (2004); gr-qc/0312056

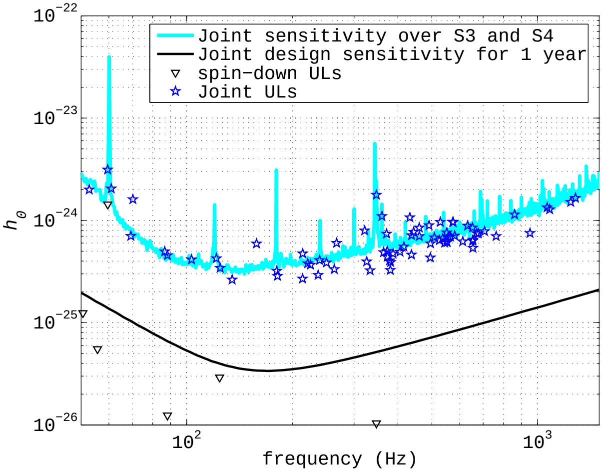
  “First upper limits from LIGO on gravitational-wave bursts”

Periodic Upper Limits Papers (B. Abbott et al=LSC)

- S3/S4 targeted: gr-qc/0702039*
  “Upper Limits on Gravitational Wave Emission from 78 Radio Pulsars”
  $\epsilon \leq 10^{-6} - 10^{-3}$ (for diff pulsars); $h_0 \lesssim 10^{-24}$
- S3 E@H report:
  `http://einstein.phys.uwm.edu/FinalS3Results/`
- S2 targeted: *PRD* **94**, 181103 (2005); gr-qc/0410007*
  “Limits on gravitational wave emission from selected pulsars using LIGO data”
- S2 semi-coherent: *PRD* **72**, 102004 (2005); gr-qc/0508065
  “First all-sky upper limits from LIGO on the strength of periodic GWs using the Hough transform”
- S2 coherent all-sky: gr-qc/0605028
  “Coherent searches for periodic GWs from unk isolated srcs and Sco X-1: results from the 2nd LIGO sci run”
- S1 targeted: *PRD* **69**, 082004 (2004); gr-qc/0308050
  “Setting ULs on strength of periodic GWs from PSR J1939+2134 using 1st sci data from GEO600 & LIGO”

* with M. Kramer and A. G. Lyne

S3/S4 Known Pulsar Upper Limits



Max-Planck-Institut
für Gravitationsphysik
(Albert-Einstein-Institut)

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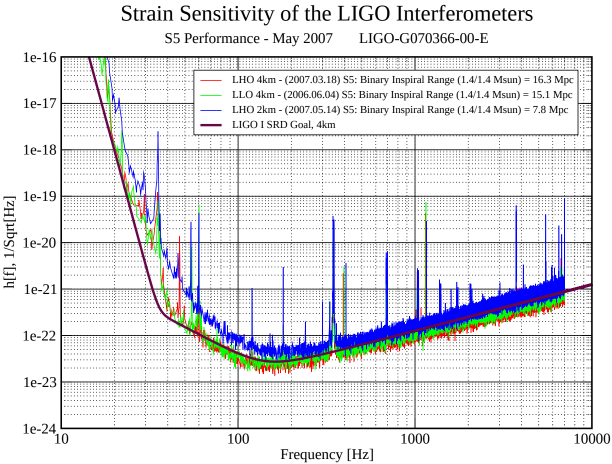
LIGO at Design Sensitivity



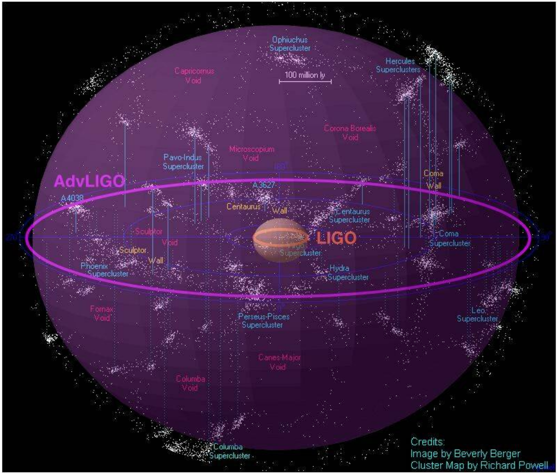
Strain Sensitivity of the LIGO Interferometers

S5 Performance - May 2007 LIGO-G070366-00-E

LIGO's S5 Run

- Stated goal of LIGO:
  1 year triple-coïnc data (H1/H2/L1) @ design sensitivity
  S5 is the run we were built to make!
- Run began November 2005; Virgo joined May 2007
  Should conclude later this year
- Should allow direct meas to surpass indirect limits
  (BBN bound for stochastic; spindown limit for crab)
  GW detectors give independent information about sky!
- Future plans include S6 w/"enhanced LIGO"
  Major upgrade to follow: Advanced LIGO

Neutron-Star Inspiral Range–Initial & Advanced LIGO



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

Summary

- Grav waves: “spin-2 massless field” predicted by GR
- km-scale IFOs like LIGO and Virgo searching for them
- Sources: Periodic, Inspiral, Stochastic, Burst
- LIGO & Virgo part of world-wide GW detector network
- LIGO S5 on now: 1 year coïncident @ design
- S5 sensitivities can surpass indirect limits

Relativist's Perspective: Gravity as Geometry

- Minkowski Spacetime:

$$ds^2 = -(dx^0)^2 + (dx^1)^2 + (dx^2)^2 + (dx^3)^2$$

$$= \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix}^{\text{tr}} \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix} = \eta_{\mu\nu} dx^\mu dx^\nu$$

- General Spacetime:

$$ds^2 = \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix}^{\text{tr}} \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix} \begin{pmatrix} dx^0 \\ dx^1 \\ dx^2 \\ dx^3 \end{pmatrix} = g_{\mu\nu} dx^\mu dx^\nu$$

Gravitational Wave as Metric Perturbation

- For GW detection, spin-2 “graviton tensor” $h_{\mu\nu}$ is difference btwn actual metric $g_{\mu\nu}$ & flat metric $\eta_{\mu\nu}$:

$$g_{\mu\nu}=\eta_{\mu\nu}+h_{\mu\nu}$$

($h_{\mu\nu}$ “small” in weak-field regime, e.g. for GW detection)

- Gauge: transverse ($\eta^{\nu\lambda}\partial_\lambda h_{\mu\nu}=0=h_{0\mu}=h_{\mu 0}=0$) & traceless ($\eta^{\mu\nu}h_{\mu\nu}=0$)
- E.g. Plane wave propagating in z direction

$$\{h_{\mu\nu}\}=\begin{pmatrix}0&0&0&0\\0&h_+&h_\times&0\\0&h_\times&-h_+&0\\0&0&0&0\end{pmatrix}e^{i2\pi f(z-t)}$$

h_+ and $h_\times$ are amplitudes of “plus” and “cross” pol states.

Stochastic Background Searches

- Look for correlated random signal in detector outputs $s_{1,2} = n_{1,2} + h_{1,2}$
- Instrument noise $n_{1,2}$ (mostly!) uncorr btwn sites
  Correlated GW part $h_{1,2}$ much weaker
  Can't do Penzias/Wilson subtraction of n;
  Look at

$$\langle s_1 s_2 \rangle = \overbrace{\cancel{\langle n_1 n_2 \rangle}}^{\text{avgto0}} + \overbrace{\cancel{\langle n_1 h_2 \rangle}}^{\text{avgto0}} + \overbrace{\cancel{\langle h_1 n_2 \rangle}}^{\text{avgto0}} + \langle h_1 h_2 \rangle$$

- $\langle \widetilde{h}_1^*(f) \widetilde{h}_2(f') \rangle = \frac{1}{2}\delta(f - f')\gamma_{12}(f) S_{\mathrm{GW}}(f)$
  Expected CC depends on obs geom via
  overlap reduction function $\gamma_{12}(f)$

Overlap Reduction Functions