Searching for Gravitational Waves with Ground-Based Detectors

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Motivation: Gravitational-Wave Astronomy

- Most astro observations use some form of EM radiation (radio/μW/IR/optical/UV/Xray/γray)

- Gravitational Waves can provide a whole new spectrum with which to observe the universe

- LISA to observe GWs in 10^{-4}–1 Hz band

- Ground-based detectors looking in 10s-1000s of Hz seek first direct detection of gravitational waves

Outline

- Gravitational Waves

- Ground-Based GW Detectors

- GW Signal Types & Detection Methods

Crash Course in Grav Wave Physics

- In Newtonian gravity, force depends on distance btwn objects

- If massive object suddenly moved, grav field at a distance would change instantaneously

- In relativity, no signal can travel faster than light
  $\longrightarrow$ time-dependent grav fields must propagate like light waves

Relativist's Perspective: Gravity as Geometry

- Minkowski Spacetime: invariant spacetime interval

$$ds^2 = -(c\,dt)^2 + (dx)^2 + (dy)^2 + (dz)^2 = \eta_{\mu\nu} dx^\mu dx^\nu$$

- General Spacetime: ST geom determined by metric $g_{\mu\nu}$:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

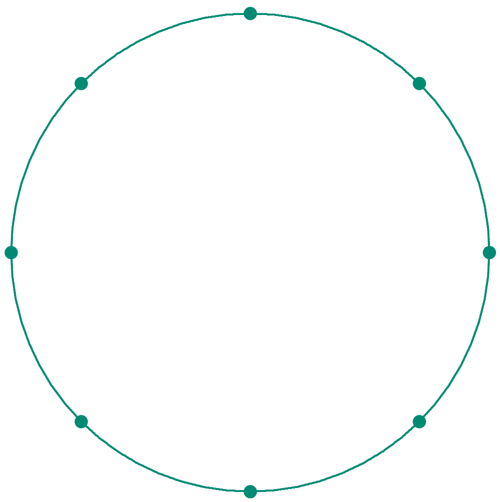
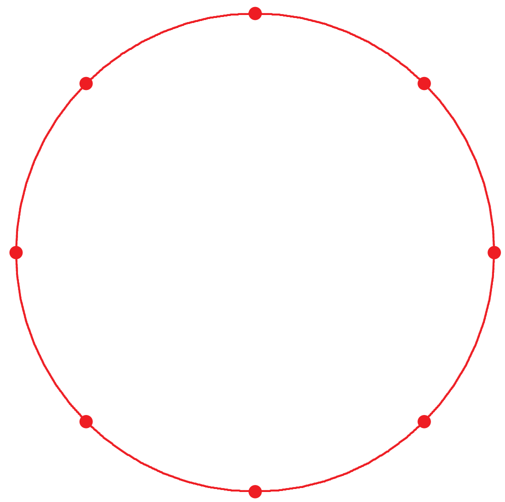
- Actual metric = flat metric + perturbation ($g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$)
  ($h_{\mu\nu}$ "small" in weak-field regime, e.g. for GW detection)
- GW Transverse & traceless, e.g. Plane wave in z direction

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

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

Effects of Gravitational Wave

Fluctuating geom changes distances btwn particles in free-fall:

Plus (+) Polarization	Cross (×) Polarization
	

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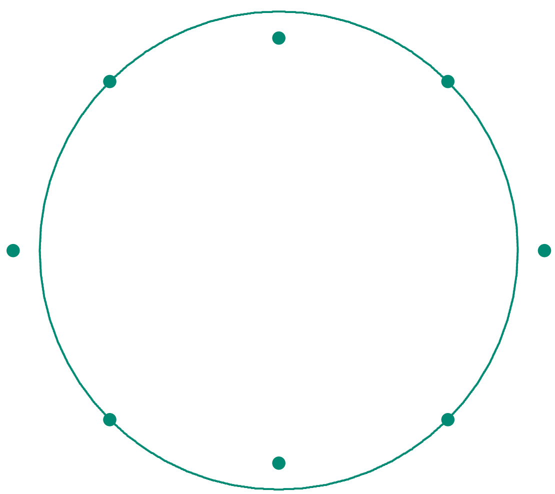	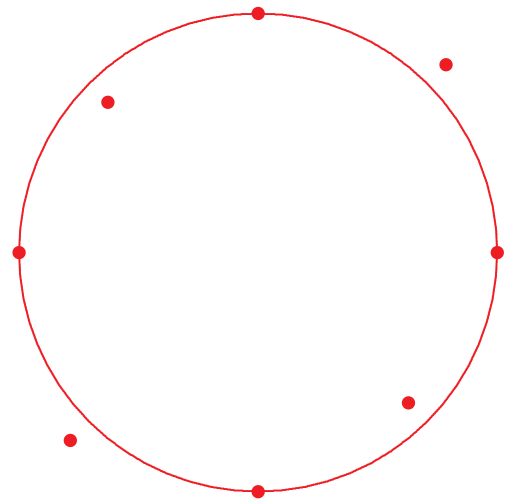

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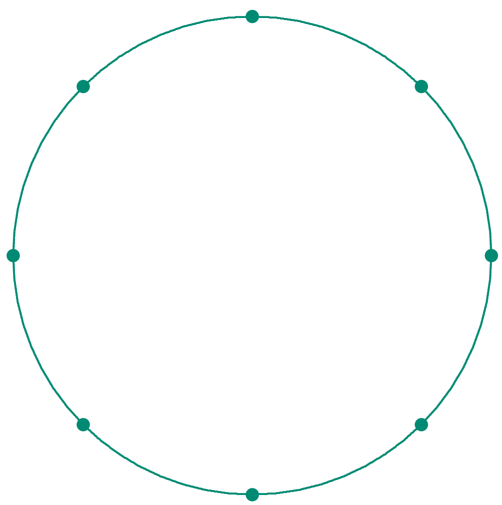	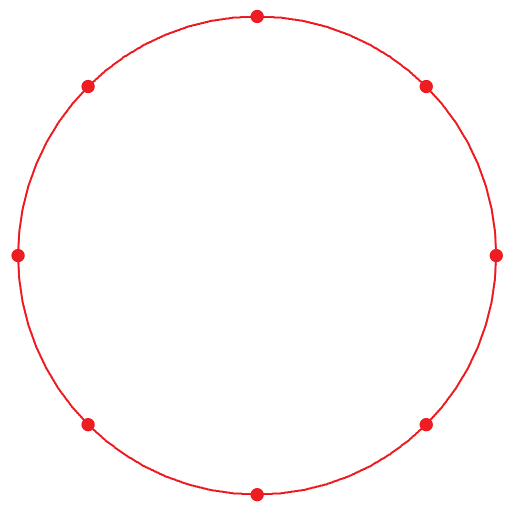

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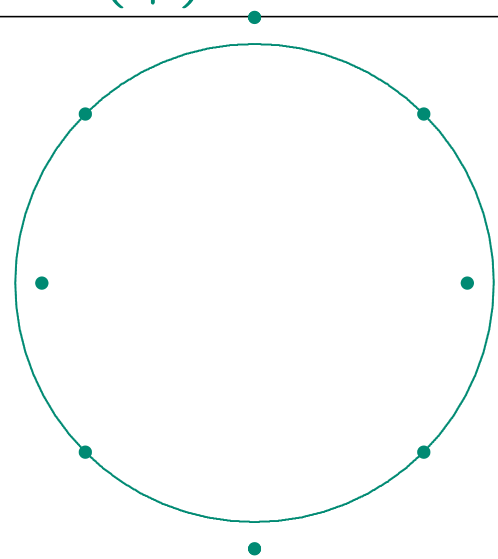	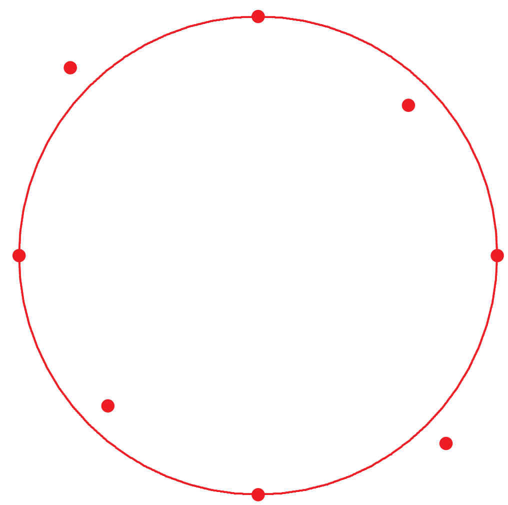

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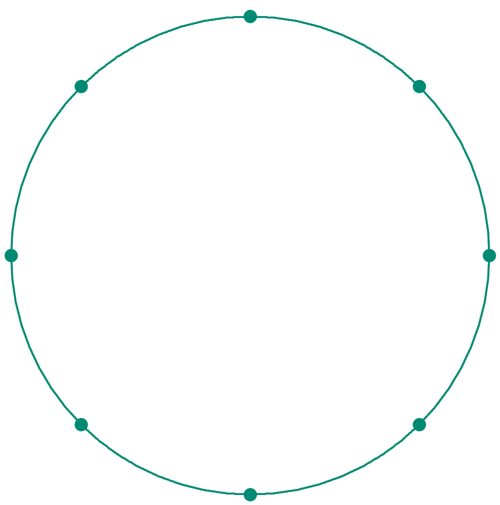	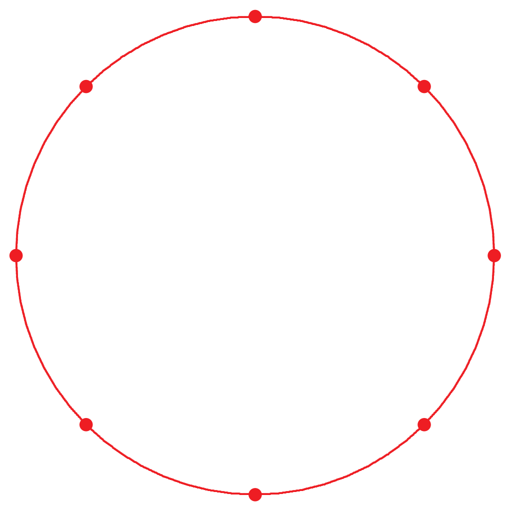

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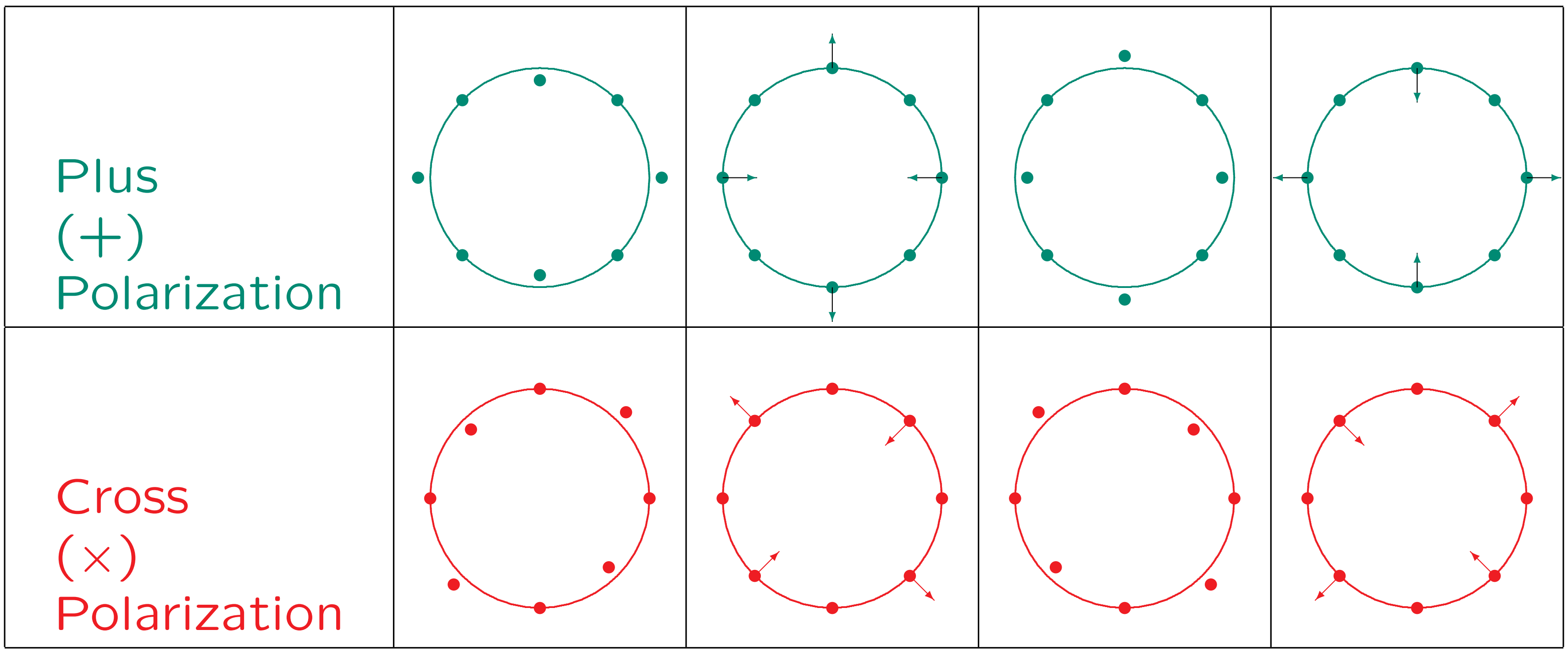
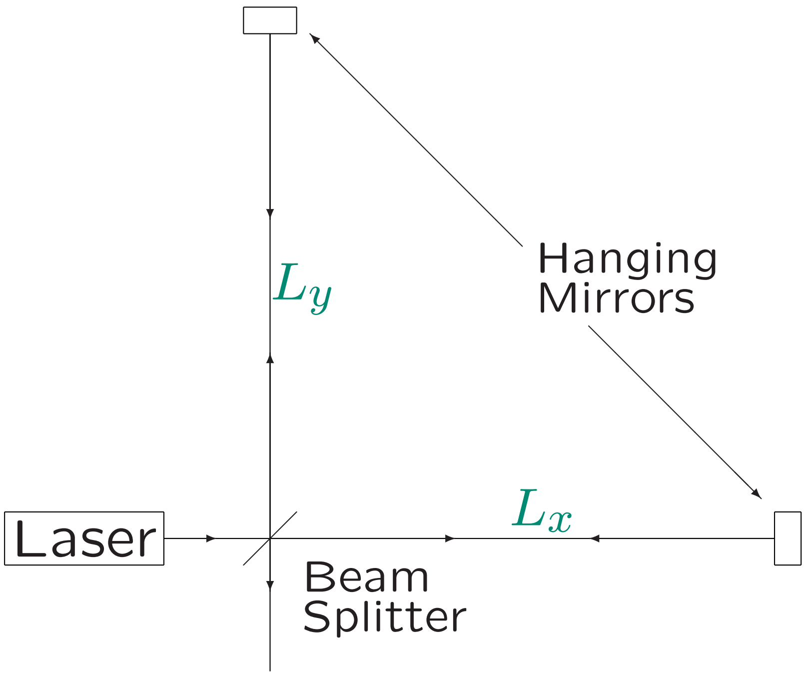


Ground-Based GW Detectors

Interferometry: Measure GW-induced distance changes



- Measure small change in

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

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

  * by terrestrial standards

Another Method: Resonance

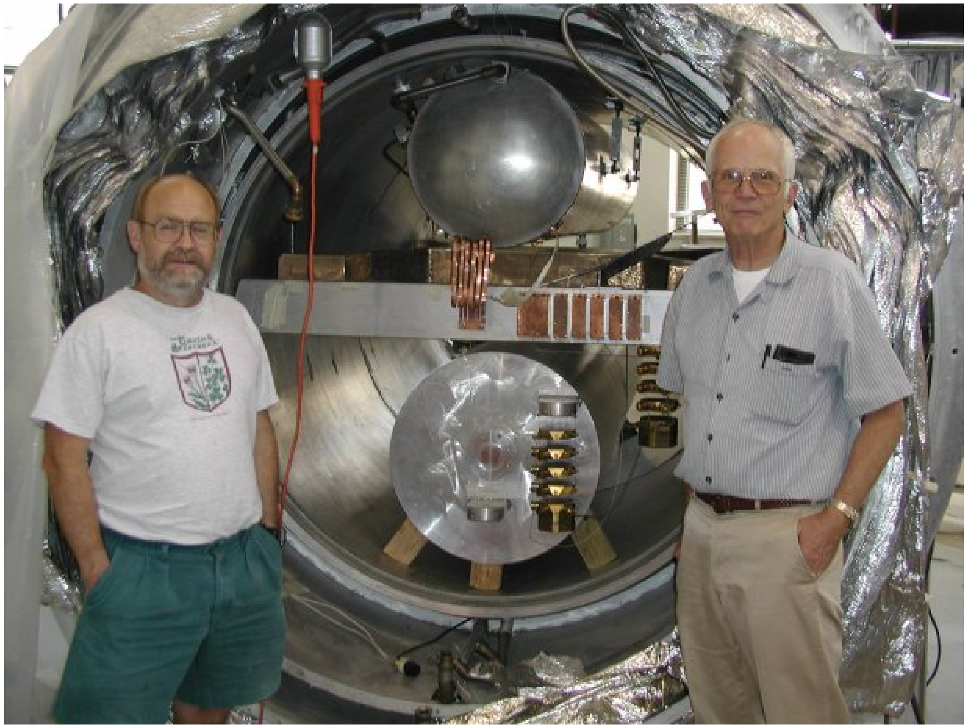
- Suspend a cylindrical bar of Al (or Nb)

- Passing grav wave expands & contracts bar along long axis
  $\longrightarrow$ Oscillations at resonant frequency

- Resonance gives measurable $\Delta L \gg hL$ over narrow freq band

- Modern resonant bars @ low temp (minimize thermal noise)

ALLEGRO Detector
(LSU)

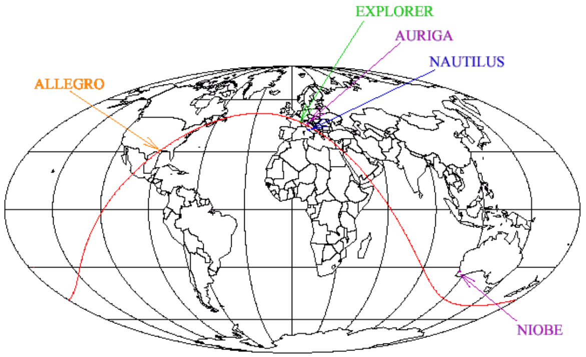


W. Johnson, ALLEGRO & W. Hamilton from LSU Website

Roster of Modern GW Detectors

Resonant Bars

Name	Location
ALLEGRO	Baton Rouge, LA
AURIGA	Padova, Italy
EXPLORER	Geneva, Switzerland
NAUTILUS	Rome, Italy
[NIOBE	Perth, Australia]



(figure from IGEC homepage)

Interferometers

Name	Location	Arm Length	On Line
TAMA-300	Tokyo, Japan	300m	1997
LIGO-LA	Livingston, LA	4km	2002
LIGO-WA	Hanford, WA	2/4km	2002
GEO-600	Hannover, Germany	600m	2002
Virgo	Pisa, Italy	3km	2006

Cartoon courtesy of E. Coccia, NAUTILUS Group (Rome)

LIGO Livingston Observatory

Rogues' Gallery of Interferometers

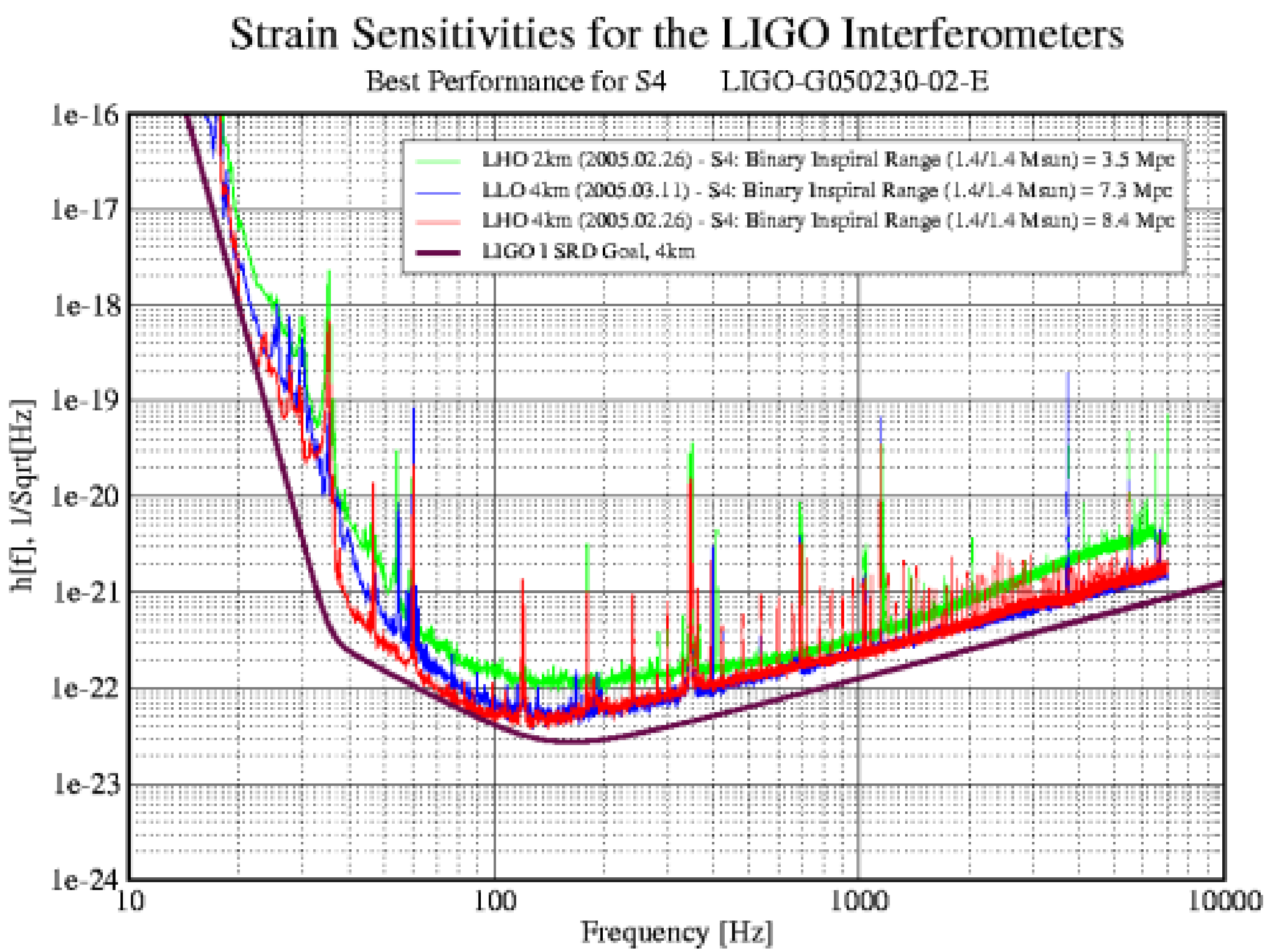
LIGO (Hanford)

GEO-600

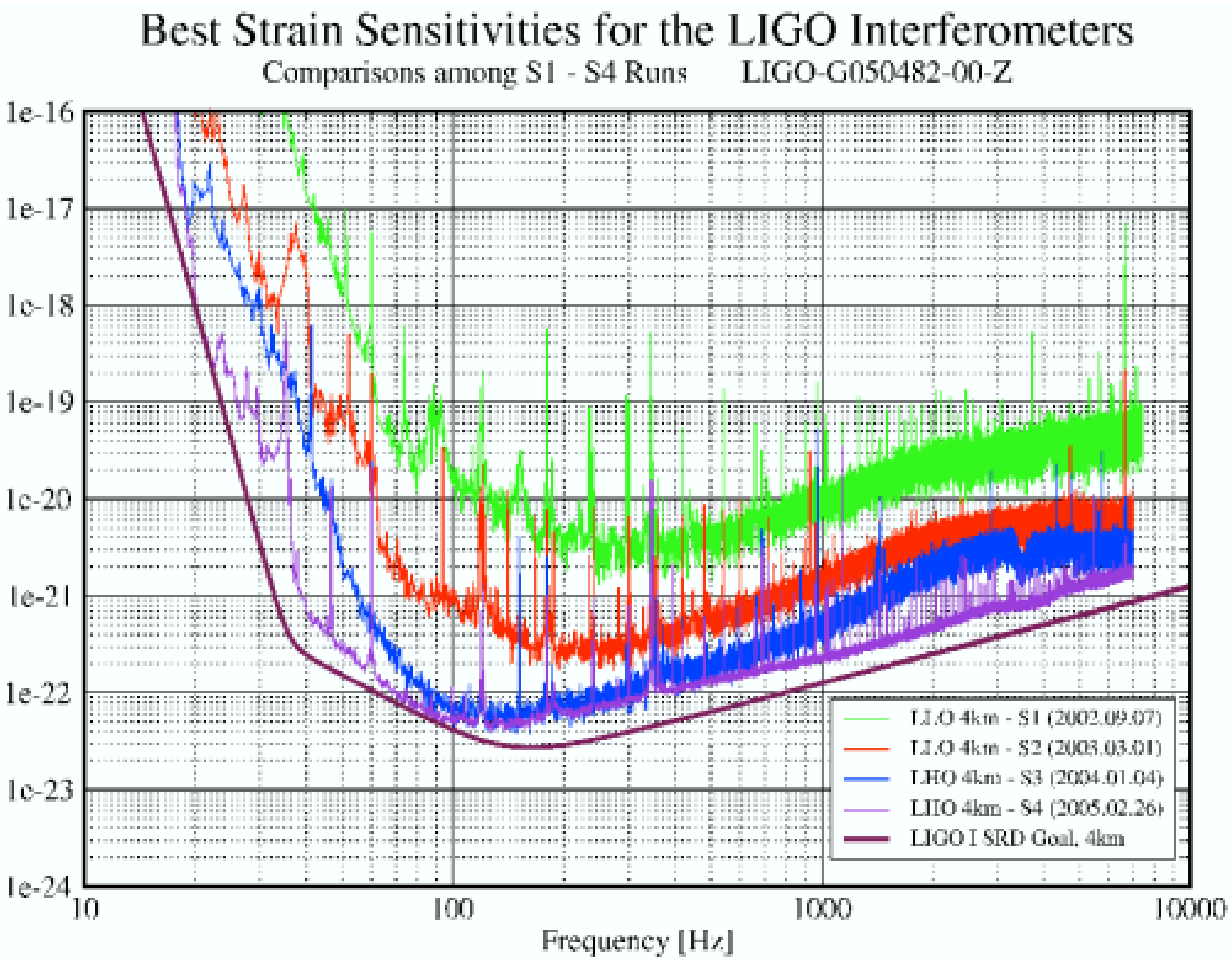
Virgo

TAMA-300

Typical Interferometer Sensitivity



LIGO Approaching Design Sensitivity



LIGO “Science Runs”

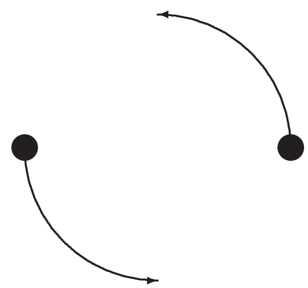
- 4 runs so far: S1 (2002 Aug–Sep), S2 (2003 Feb–Apr), S3 (2003 Oct–2004 Jan), S4 (2005 Feb–Mar)

- 10+ papers posted or published analyzing S1 & S2 data; S3 & S4 data being analyzed

- S5 to start soon, aiming for LIGO goal of 1 year of data @ design sensitivity

Gravitational Wave Sources

- 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)

Classification of GW Signals

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

- Periodic Sources (e.g., Rotating Neutron Star)
- Stochastic Background (Cosmological or Astrophysical)
- Bursts (Supernova, Black Hole Merger, etc.)
- Binary Inspiral (Black Hole, Neutron Star)

Detection Methods

- Periodic: Look for repeated waveform
  (Complicated by Doppler modulation)
  Techniques include F-statistic & Hough Transform
  General public involved via Einstein@Home

- Stochastic: Cross-correlate detector outputs
  $\longrightarrow$ Signal-to-noise improves with time

- Bursts: Signal unmodelled
  $\longrightarrow$ Look for unusual features & coïncident events
  Recent searches incl GRB triggers & LIGO-TAMA collab

- Inspiral: Signal well modelled (at least early)
  $\longrightarrow$ 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
    $1.4 M_\odot / 1.4 M_\odot$ NS/NS binary has $v \approx 0.3c$ @ 800 Hz;
    PN OK in LIGO band
  - High Mass $\longrightarrow$ plunge @ low freq
    $10 M_\odot / 10 M_\odot$ BH/BH binary has $v \approx 0.4c$ @ 200 Hz;
    merges in LIGO band

Inspiral Searches

- Searches for low-mass binaries w/post-Newtonian templates:
  NS-NS [S1: PRD **69**, 122001 (2004);
  S2: gr-qc/0505041 UL 47/yr/MWEG];
  MACHO-MACHO [S2: gr-qc/0505042 UL 63/yr/halo]

- Search for higher-mass binaries uses "detection templates"
  [Buonanno, Chen & Vallisneri PRD **67**, 024016 (2003)]
  S2 search result just posted as gr-qc/0509129

- BH searches in S3 and beyond will include effects of spin

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

$$\langle s_1 s_2 \rangle = \overbrace{\cancel{\langle n_1 n_2 \rangle}}^{\text{avg to 0}} + \overbrace{\cancel{\langle n_1 h_2 \rangle}}^{\text{avg to 0}} + \overbrace{\cancel{\langle h_1 n_2 \rangle}}^{\text{avg to 0}} + \langle h_1 h_2 \rangle$$

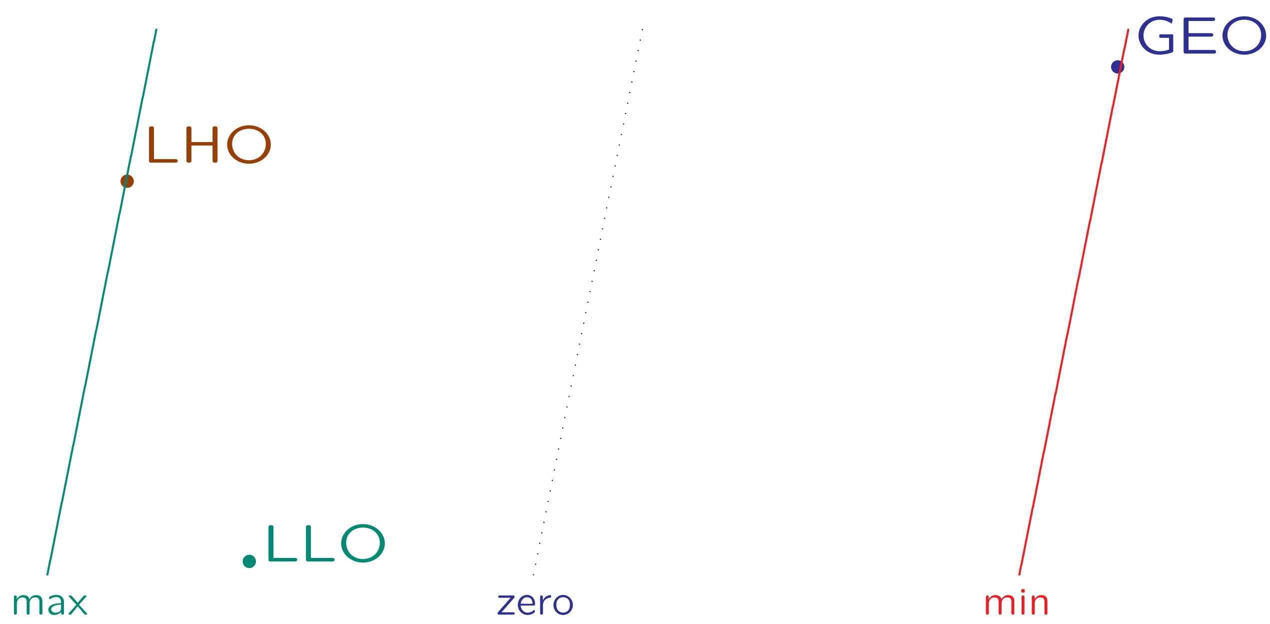
- $\langle \widetilde{h}_1^*(f) \widetilde{h}_2(f') \rangle = \frac{1}{2}\delta(f - f')\gamma_{12}(f) S_{\mathrm{GW}}(f)$
  Expected CC depends on obs geom via
  overlap reduction function $\gamma_{12}(f)$

Overlap Reduction Function

Depends on alignment of detectors (polarization sensitivity)

Frequency dependence from cancellations when $\lambda \lesssim$ distance

$\longrightarrow$ Widely separated detectors less sensitive at high frequencies



This wave drives LHO & GEO out of phase

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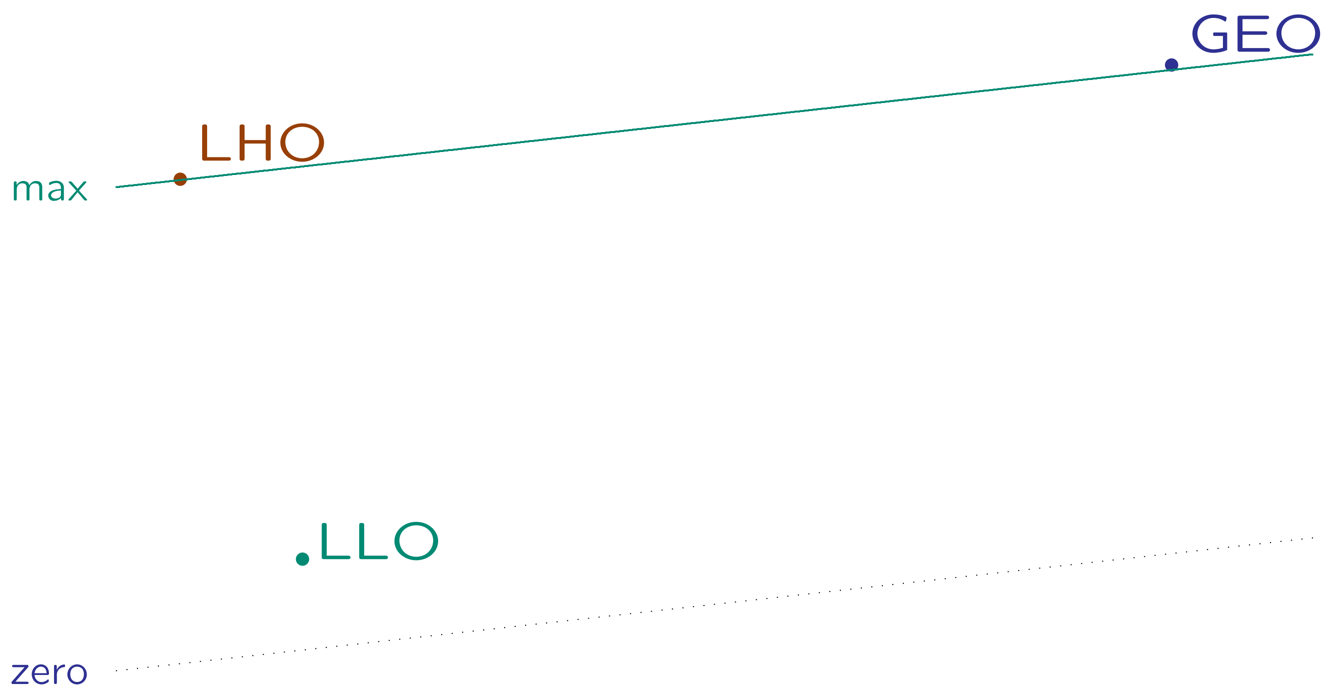
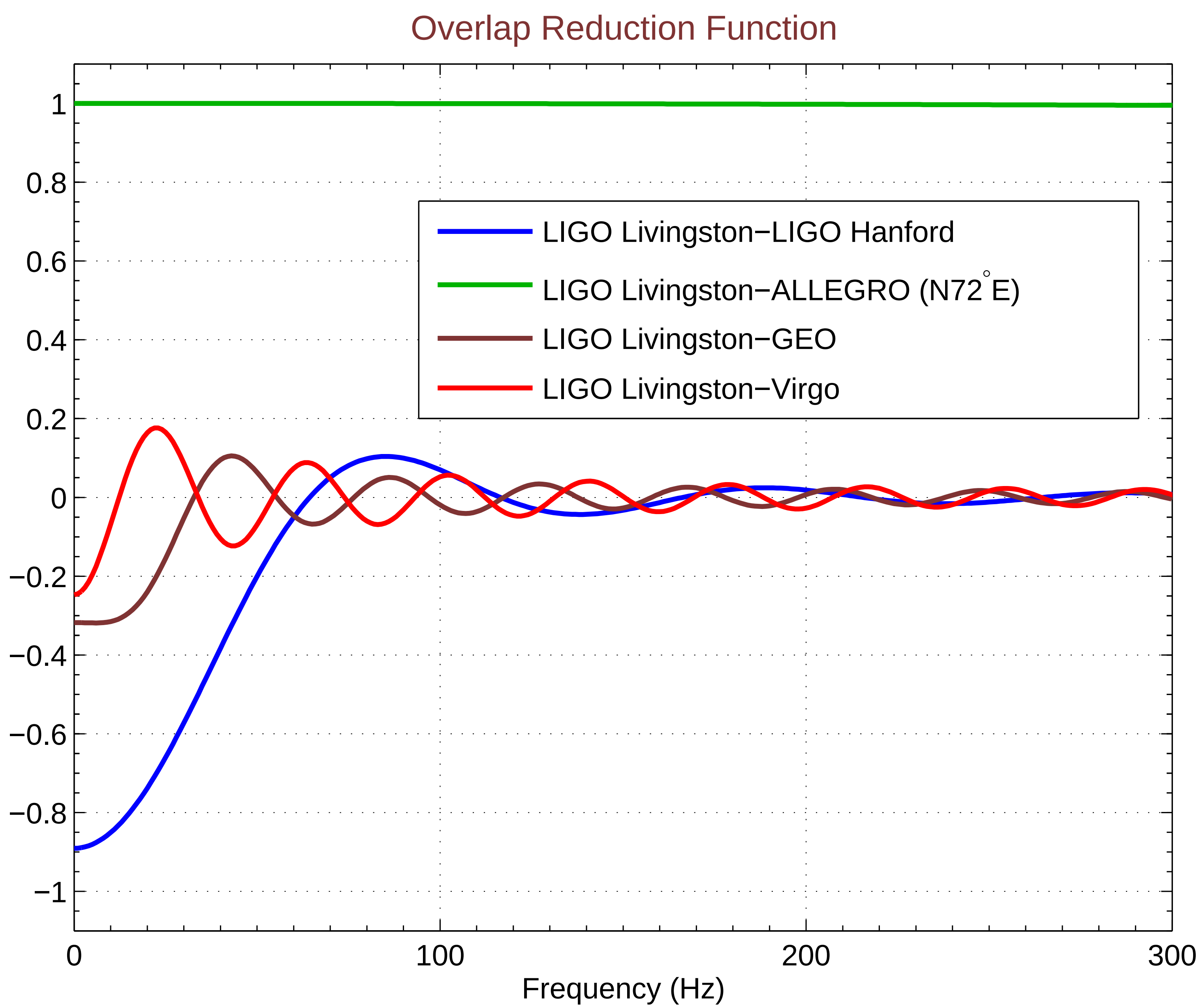


This wave (same λ) drives LHO & GEO in phase


Overlap Reduction Function
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
100
200
300
Frequency (Hz)
LIGO Livingston−LIGO Hanford
LIGO Livingston−ALLEGRO (N72°E)
LIGO Livingston−GEO
LIGO Livingston−Virgo

Stochastic Background Searches

- All-sky search for isotropic BG w/LLO & LHO
  S1: PRD **69**, 122004 (2004); S3: astro-ph/0507254
  UL $f\frac{d\Omega_{\mathrm{GW}}}{df} < 8.4 \times 10^{-4}$

- Directed search for anisotropic astrophysical BGs in progress

- Other searches involve LLO-ALLEGRO
  & LHO 2km/4km @ higher freqs

The Future: GW Astronomy

- Current/Improving detector sensitivity
  makes GW detection in near future conceivable

- Planned "advanced LIGO" upgrade:
  another leap in sensitivity

- LISA spacecraft mission:
  space-based interferometer surveys lower-frequency regime

- Ultimate goal is gravitational wave astronomy
  Open up a whole new spectrum to understand the universe
  Complementary to electromagnetic, neutrino & cosmic ray

GW Results Papers

1. LIGO S1 Stochastic: PRD **69**, 122004 (2004)
2. LIGO S3 Stochastic: astro-ph/0507254
3. LIGO/GEO S1 PSR $J1939 + 2134$: PRD **69**, 082004 (2004)
4. LIGO S2 targeted pulsars: PRL **94**, 181103 (2005)
5. LIGO S2 all-sky Periodic: gr-qc/0508065
6. ROG Burst: CQG **19**, 1367 (2002)
7. IGEC Burst: PRD **68**, 022001 (2003)
8. LIGO S2 Burst (GRB030329): PRD **72**, 042002 (2005)
9. LIGO S2 Burst: PRD **72**, 062001 (2005)
10. LIGO S2/TAMA DT8 Burst: gr-qc/0507081
11. TAMA DT6/DT8/DT9 Burst: PRD **71**, 082002 (2005)
12. LIGO S1 binary NS: PRD **69**, 122001 (2004)
13. TAMA/LISM binary: PRD **70**, 042003 (2005)
14. LIGO S2 binary NS: gr-qc/0505041
15. LIGO S2 binary MACHO: gr-qc/0505042
16. LIGO S2 binary BH: gr-qc/0509129