The Search for Gravitational Radiation

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Outline

- Gravitational Waves
  - Phenomenological Perspective (Analogous to EM Waves)
  - Relativist's Perspective (Gravity as Geometry)

- GW Detectors
  - Theory (Bars & Interferometers)
  - Experiment (Roster of Current Detectors)

- GW Sources
  - Types & Detection Methods
  - Current Research

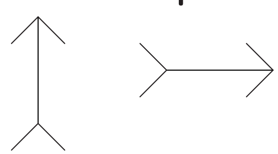
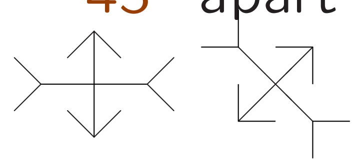
Crash Course in Grav Wave Physics

Motivation

- 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

Crash Course in Grav Wave Physics

Phenomenology: Grav vs EM Waves

Photon	Graviton
vector $A_\mu = (\varphi, \vec{A})$	sym tensor $h_{\mu\nu}$
spin-1, massless	spin-2, massless
2 pol states 90° apart 	2 pol states 45° apart 
wave speed c	wave speed c
Gauge xf $A_\mu \rightarrow A_\mu - \partial_\mu \Lambda$	Gauge xf $h_{\mu\nu} \rightarrow h_{\mu\nu} - \partial_\mu \xi_\nu - \partial_\nu \xi_\mu$

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

Relativist's Perspective: Gravity as Geometry

- Minkowski Spacetime: invariant ST interval (like distance)

$$ds^2 = -(c\,dt)^2 + (dx)^2 + (dy)^2 + (dz)^2$$

$$= \begin{pmatrix} c\,dt & dx & dy & dz \end{pmatrix} \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c\,dt \\ dx \\ dy \\ dz \end{pmatrix} = \eta_{\mu\nu} dx^\mu dx^\nu$$

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

$$ds^2 = \begin{pmatrix} c\,dt & dx & dy & dz \end{pmatrix} \begin{pmatrix} g_{00} & g_{01} & g_{02} & g_{03} \\ g_{10} & g_{11} & g_{12} & g_{13} \\ g_{20} & g_{21} & g_{22} & g_{23} \\ g_{30} & g_{31} & g_{32} & g_{33} \end{pmatrix} \begin{pmatrix} c\,dt \\ dx \\ dy \\ dz \end{pmatrix} = g_{\mu\nu} dx^\mu dx^\nu$$

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 $\eta_{\mu\nu}$:

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

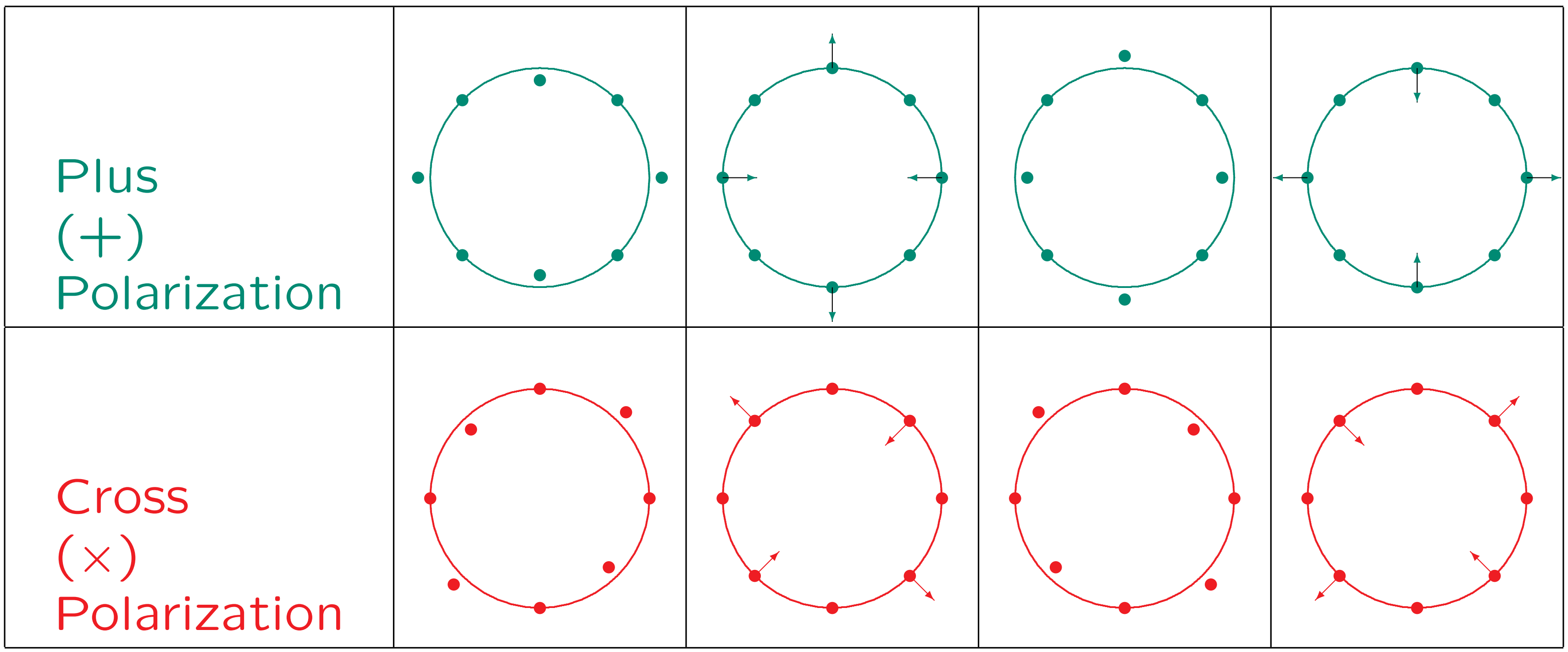
  ($h_{\mu\nu}$ “small” in weak-field regime, e.g. for GW detection)
- Gauge: transverse ($\eta^{\nu\lambda}\partial_\lambda h_{\mu\nu} = 0 = h_{0\mu} = h_{\mu 0} = 0$) & traceless ($\eta^{\mu\nu} h_{\mu\nu} = 0$)
- E.g. Plane wave propagating in z direction

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

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

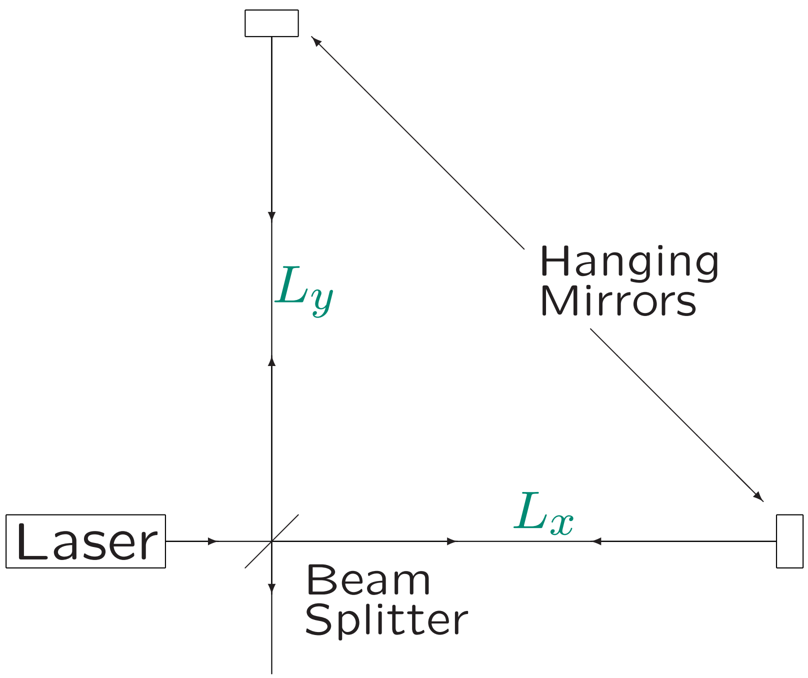
Effects of Gravitational Wave

Fluctuating geom changes distances btwn particles in free-fall:



How to Detect Gravitational Waves

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)

Another Method: Resonance

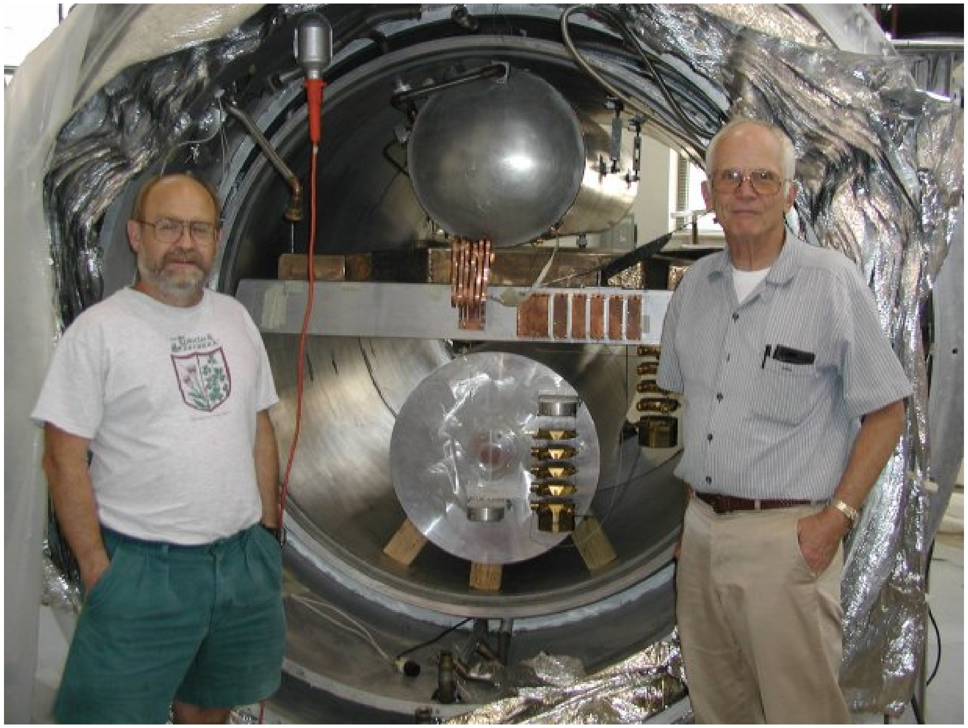
- Suspend a cylindrical bar of Al (or Nb)

- 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)

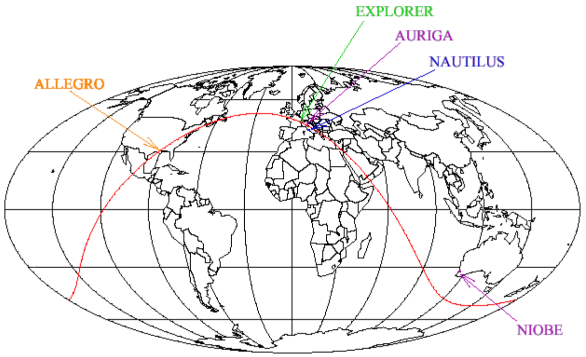


W. Johnson, ALLEGRO & W. Hamilton from LSU Website

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	Soon!

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

LIGO Livingston Observatory

Rogues' Gallery of Interferometers

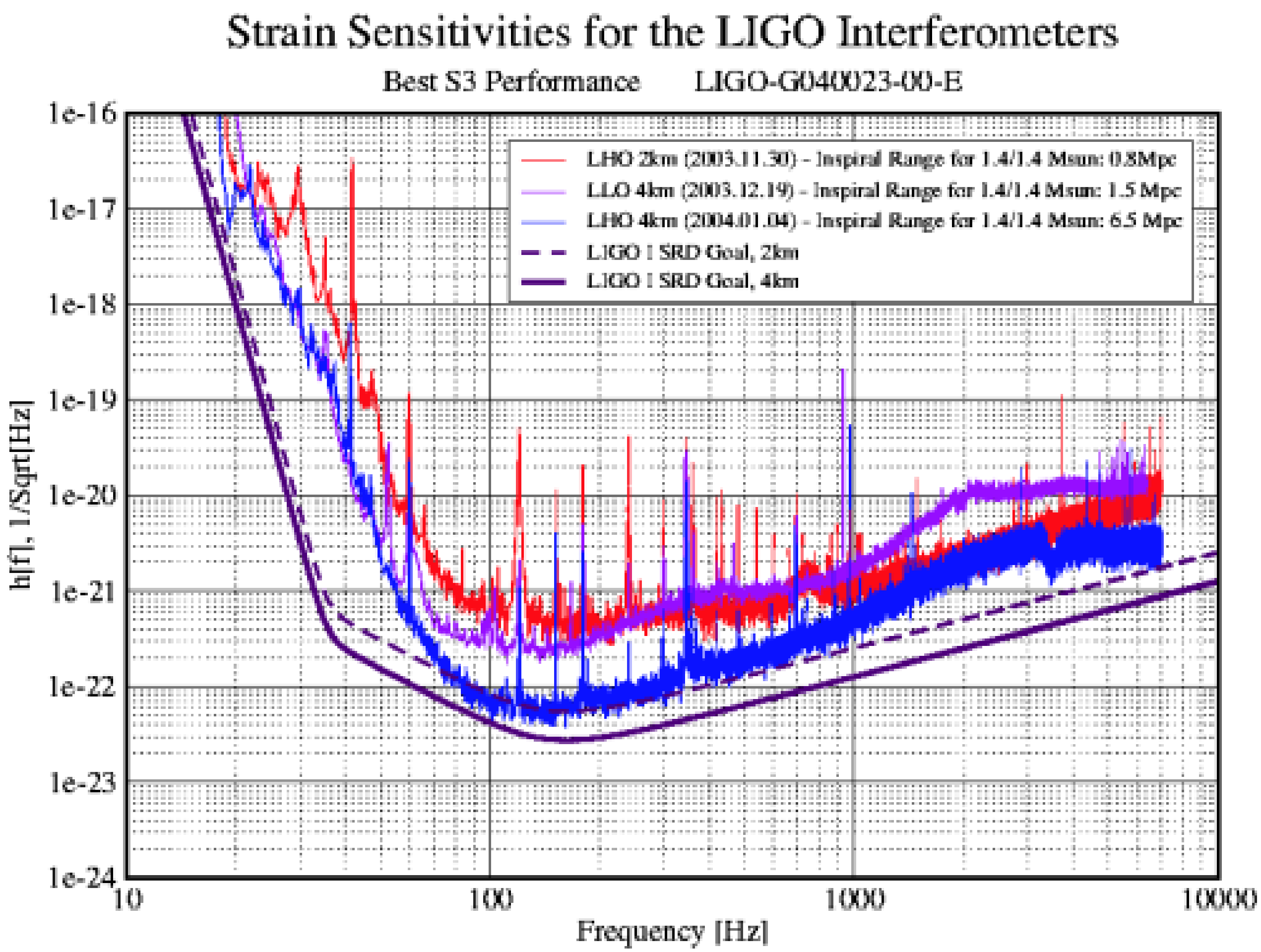
LIGO (Hanford)

GEO-600

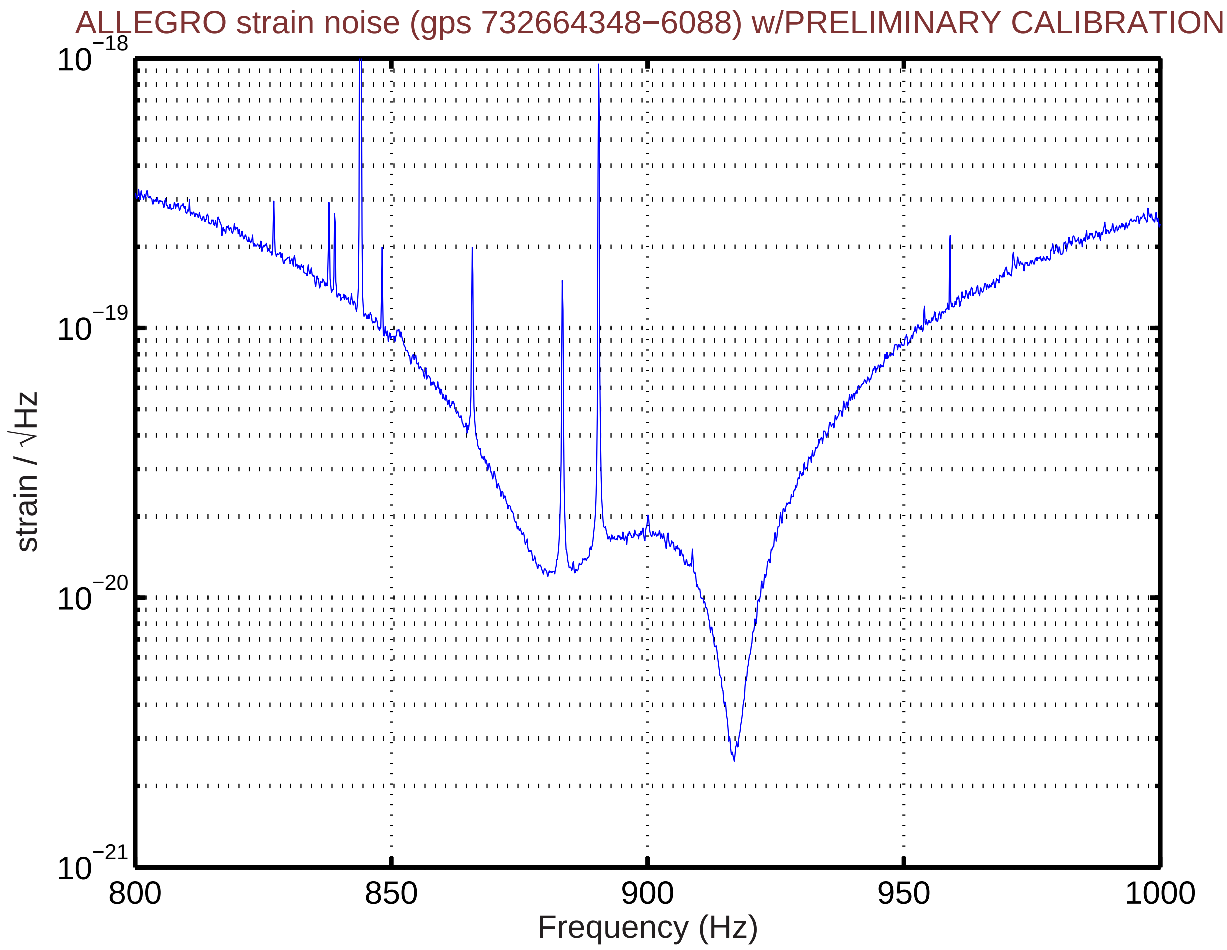
Virgo

TAMA-300

Typical Interferometer Sensitivity

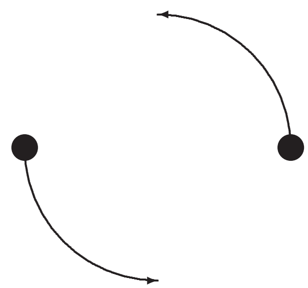


Typical Bar Sensitivity



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)

Types of Gravitational Wave Signals

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

Detection Methods

- Inspiral: Signal well modelled (at least early)
  $\longrightarrow$ Matched Filtering

- Periodic: Look for repeated waveform
  (Complicated by doppler modulation)

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

- Bursts: Signal unmodelled
  $\longrightarrow$ Look for unusual features & coïncident events

Current State of Affairs (upper limits)

- IGEC (Bar consortium): coïncident burst search 1997-2000
  PRL **85**, 5046 (2000); PRD **68**, 022001 (2003)

- TAMA: single detector inspiral search
  PRD **63**, 062001 (2001); gr-qc/0403088

- LIGO Upper limits from S1 Science Run (all sources)
  Released 2003, being published 2004

- LIGO S2 & S3 Science Data being analyzed
  Results to be released soon

LIGO S1 Publications

- Instrumental description: NIM **A517** 154 (2004)

- Upper limits (to be published in PRD)
  - Inspiralling neutron star binaries: gr-qc/0308069
  - Periodic waves from known pulsar: gr-qc/0308050
  - Stochastic GW background: gr-qc/0312088
  - Grav wave bursts: gr-qc/0312056

The Future: GW Astronomy

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

- Proposed "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

Summary

- General Relativity predicts Gravitational Radiation
  - gravitational analog of EM radiation
  - deformation of geometry

- GW Detectors measure Spacetime Distortion
  - Res Bars (ALLEGRO, Auriga, Nautilus, Explorer, Niobe)
  - Interferometers (2×LIGO, Virgo, GEO, TAMA)

- GW Observations
  - Current: upper limits on inspiral, periodic, stochastic & burst
  - Future: direct detection & GW Astronomy