Detection of Gravitational Waves

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Enormous range of frequencies, signatures of sources

- stochastic background at 10^{-8} Hz
- inspiraling binaries from 10^{-5} to 10^{-2} Hz
- supernovae at 10^{4} Hz

Limitations to detector sensitivity

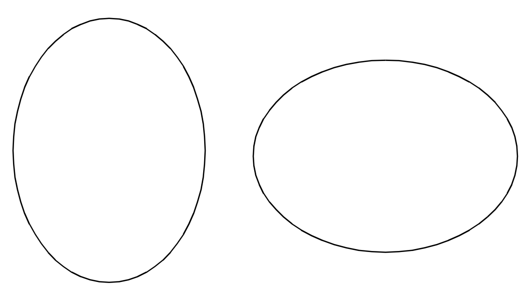
- fundamental noise terms
- technical problems, interesting or not

Which detector to focus on?

- source of interest: frequency, bandwidth,
- detector status: in planning, in construction, built, working

Assume GR: $h = \delta l / l$

- transverse waves, speed c, spin 2
- detectors respond to strain in space



High Frequencies (300 Hz-10 kHz)

some possible sources:

- end of binary ‘chirp’
- supernovae
- collapse to BH

possible instruments:

Resonant Mass Detector

- fundamental longitudinal mode excited by GW strain
- readout using PZTs, Squids, parametric converters
- Weber ‘59; Stanford, LSU, Rome, Perth, others

High Frequencies (300 Hz-10 kHz)

present day Resonant Detector

fundamental limitation: thermal noise

- detector used on resonance of mechanical system
- in thermal equilibrium with environment (300 °K or 4 or X mK)
- $\tau_{\text{bar}} = Q / \pi f_0$ sets time scale for randomization of phase
- leads to requirement for high Q, low T, large M

technical limitation: transducer noise

- straightforward noise of motion detector
- back-action excites bar; trade-off for coupling β

present/near future sensitivity:

- a nearby quite asymmetric SN

High Frequencies (300 Hz-10 kHz)

another possible detector:

Ground Based Interferometers

- GW strain induces differential length changes in arms
- distances are measured using light beams, interference
- at least four independent discoveries:
  - Pirani ('56) Gerstenshtein and Pustovoit, Weber, Weiss
  - Weiss '72 practical approach, scaling laws, limitations

High Frequencies (300 Hz-10 kHz)

Detectors for year ~2000

fundamental limitation 300 Hz - 10 kHz

- shot noise (counting statistics of photons)
- possibly thermal excitation of masses OFF resonance
  - › if a narrow-banding of interferometer is employed

technical limitation 300 Hz - 10 kHz

- laser noise sources (frequency, intensity)
- thermally excited test-mass, suspension resonances
  - › predictable fixed narrow peaks

sensitivity 300 Hz - 10 kHz

- in ~2000: $10^{-5}\varepsilon$ SN 10 kpc, 1% BH collapse 10 Mpc
- later detectors: $10^{-8}\varepsilon$ SN 10 kpc, 0.01% BH collapse 10 Mpc

Mid Frequencies (1 Hz - 300 Hz)

some possible sources:

- binary coalescence: minutes of chirp
- possible cosmic background
- periodic sources (crab)

possible instruments:

Tuned Resonant Mass Detector

attractive way to take advantage of resonant detector

- use EM observations to get frequency/ies, phase
- narrow-band advantageous
- spherical ‘bars’ another possibility

Mid Frequencies (1 Hz - 300 Hz)

another possible detector:

Ground Based Interferometers

fundamental limitation 1Hz - 300 Hz

- thermal noise in pendulum suspension of test masses
- possibly thermal excitation of masses OFF resonance

technical limitation 1Hz - 300 Hz

- seismic noise (can always work harder on this)
- gravity gradient noise (hard limit at about 10 Hz)
  - contribution from ground (can be changed) and atmosphere

Note: why must interferometers be long?

- some noise sources appear as physical test mass displacements; some impossible, others difficult to reduce
- longer baselines make given displacement less important
- already at 3-4 km; practical limit for ground-based systems

sensitivity 1Hz - 300 Hz

- in ~2000: NS-NS coalescence to 23 Mpc
- later detectors: NS-NS to 1000 Mpc

Low Frequencies (1 Hz - 10^{-4} Hz)

possible sources:

- coalescence of Massive Black Holes, compact object+MBH
- stochastic background (primordial or confusion)

possible instruments:

Doppler tracking of spacecraft

- ground based transmitter sends out ‘fixed’ frequency
- received by satellite, transponded, re-received on earth
- passing GW doppler-shifts the frequency
- baseline long compared with GW burst size, so separate pulses
- suggested by Braginsky and Gertsenshtein in 67;
- Anderson on existing data 71, feasibility etc. Wahlquist 77

Low Frequencies (1 Hz - 10^{-4} Hz)

for doppler ranging,

fundamental limitations: thermal and sensing (shot)

technical limitations: propagation in interstellar plasma

present sensitivity: $\Omega_{GW} = 10^{-2}$

- presently best instrument in this range
- possible improvement to $\Omega_{GW} = 10^{-6}$

Low Frequencies (1 Hz - 10^{-4} Hz)

possible instrument:

Space-based Interferometers

- extend interferometer notion to much larger scale
- lowers primary frequency range to mHz region, $\lambda_{GW} \geq 5\times10^{9}$ m
- different trade-offs, different sources than ground-based ifos
- discussed by Forward, Weiss ‘75; Bender, Faller 81

Low Frequencies (1 Hz - 10^{-4} Hz)

fundamental limitations:

- shot noise (light lost due to finite collimation, laser limitations)
- gravity gradients

technical limitations:

- wavefront flatness and alignment variations
- thermal distortions

planned sensitivity:

- MBH coalescence of $10^3 M_o$ and larger
- primordial background $\Omega_{GW} = 10^{-12}$ or less

VERY low frequencies: <10^{-5} Hz

possible source: stochastic background

possible 'instruments': Pulsar timing

- use several quiet pulsars
- look at correlations in timing to infer source properties
- Shazhin 78; Backer et al., 82: PSR 1937+21; Taylor 87

fundamental limitations: pulsar clock noise

technical limitations: the best ground-based clocks

present sensitivity: $\Omega_{GW} = 10^{-6}$

Also from pulsar timing, of course:

- observation of the Taylor-Hulse binary pulsar PSR 1913+16
- much beautiful physics
- indirect detection of GWs in weak field limit
- and (to some extent) strong field

The birth of a new field, with rich impact on

relativity, cosmology, all of astrophysics