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Virgo-EGO Science Forum school on Gravitational Waves

Coalescing binaries: PN signal modeling

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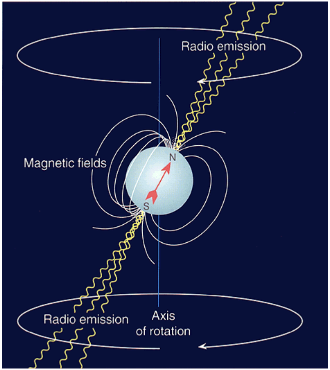
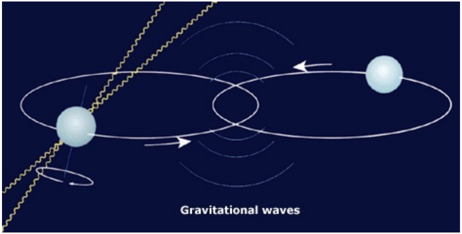
The binary pulsar PSR 1913+16 [Hulse & Taylor 1974]

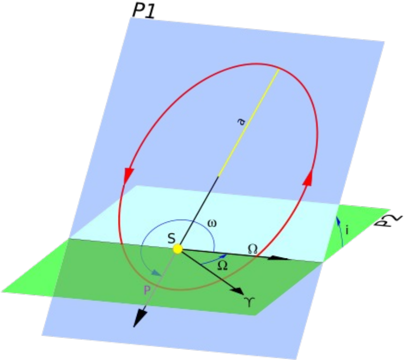




- The pulsar PSR 1913+16 is a rapidly rotating neutron star emitting radio waves like a lighthouse toward the Earth.
  Non-orbital parameters
  1. $P_{\text{pulsar}} = 59\,\text{ms}$ pulsar period
  2. $\dot{P}_{\text{pulsar}} < 10^{-12}$ pulsar spin-down
- This pulsar moves on a (quasi-)Keplerian close orbit around an unseen companion, probably another neutron star

The Keplerian orbit of the binary pulsar

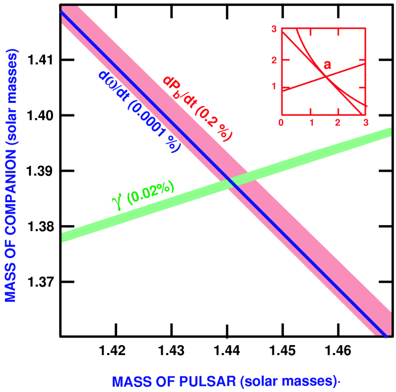
The analysis of the arrival time of successive pulsar's radio pulses yields an accurate determination of the Keplerian orbit



Keplerian parameters

1. $a \sin i = 700\,000\,\text{km}$ projected semi-major axis
2. $e = 0.617$ eccentricity
3. $P = 7.75\,\text{h}$ orbital period

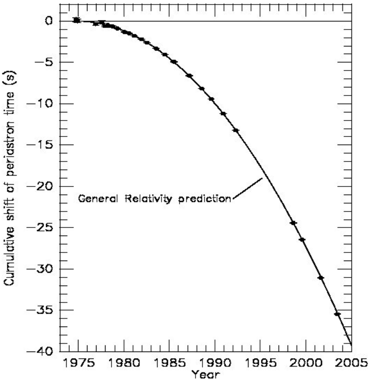
Measurement of general relativistic effects



Post-Keplerian parameters

1. $\dot{\omega} = 4.2\,°/\text{yr}$ relativistic advance of periastron
2. $\gamma = 4.3\,\text{ms}$ gravitational red-shift and second-order Doppler effect
3. $\dot{P} = -2.4 \times 10^{-12}\text{s/s}$ secular decrease of orbital period

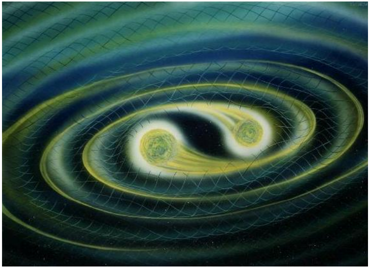
The orbital decay of the binary pulsar [Taylor & Weisberg 1982]



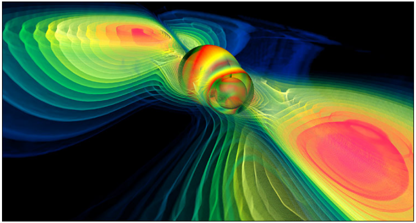
Prediction from general relativity theory [Peters & Mathews 1963, Damour & Deruelle 1983]

$$\dot{P} = -\frac{192\pi}{5c^5}\,\frac{\mu}{M}\left(\frac{2\pi G\,M}{P}\right)^{5/3}\frac{1+\frac{73}{24}e^2+\frac{37}{96}e^4}{(1-e^2)^{7/2}} \approx -2.4\times 10^{-12}$$

The inspiral and merger of compact binaries



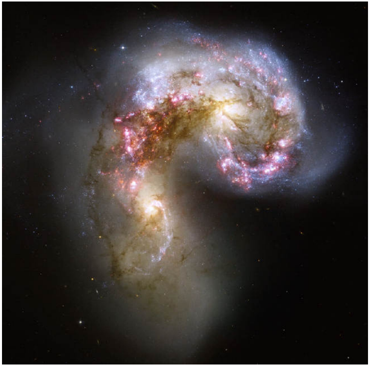
Neutron stars spiral and coalesce



Black holes spiral and coalesce

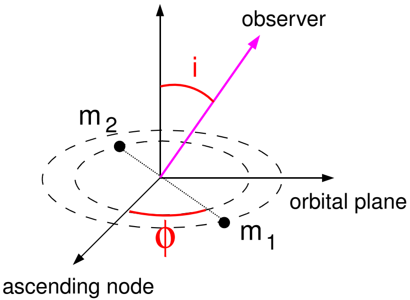
1. Neutron star ($M = 1.4\,M_\odot$) events will be detected by ground-based detectors LIGO/VIRGO/GEO
2. Stellar size black hole ($5\,M_\odot \lesssim M \lesssim 20\,M_\odot$) events will also be detected by ground-based detectors
3. Supermassive black hole ($10^5\,M_\odot \lesssim M \lesssim 10^8\,M_\odot$) events will be detected by the space-based detector LISA

Supermassive black-hole coalescences as detected by LISA



When two galaxies collide their central supermassive black holes may form a bound binary system which will spiral and coalesce. LISA will be able to detect the gravitational waves emitted by such events anywhere in the Universe

Compact binary systems are standard GW sirens



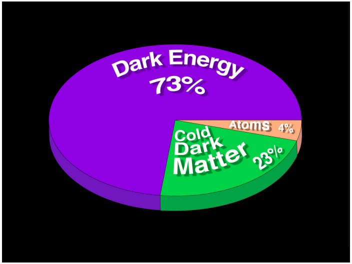
Polarisation states of GW from a compact binary system

$$h_+ = \frac{2G\mu}{c^2 D_\mathsf{L}} \left(\frac{GM\omega}{c^3}\right)^{2/3} \left(1 + \cos^2 i\right) \cos\left(2\phi\right)$$

$$h_\times = \frac{2G\mu}{c^2 D_\mathsf{L}} \left(\frac{GM\omega}{c^3}\right)^{2/3} \left(2 \cos i\right) \sin\left(2\phi\right)$$

The distance of the source D_L is measurable from the GW signal

Supermassive black-hole binaries as dark energy probes

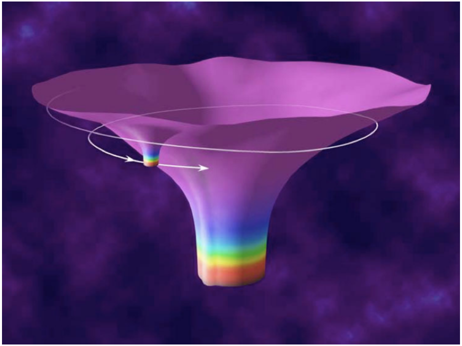


Supermassive black-hole coalescences will be observed by LISA up to high red-shift z. In the concordance model of cosmology the distance D_L is

$$D_\mathsf{L}(z) = \frac{1+z}{H_0} \int_0^z \frac{\mathrm{d}z'}{\sqrt{\Omega_\mathsf{M}(1+z')^3 + \Omega_\mathsf{DE}(1+z')^{3(1+w)}}}$$

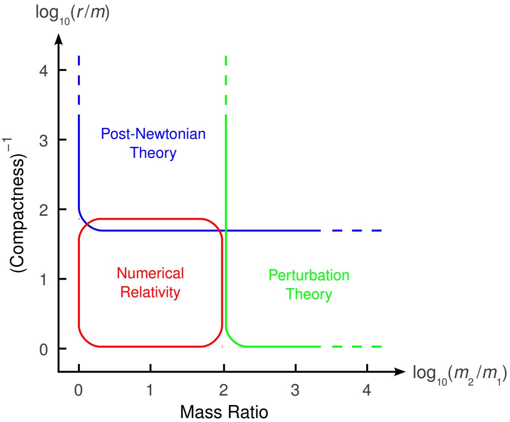
LISA will be able to constrain the equation of state of dark energy $w = p_\mathsf{DE}/\rho_\mathsf{DE}$ to within a few percent

Extreme mass ratio inspirals (EMRI) for LISA



- A neutron star or a stellar black hole follows a highly relativistic orbit around a supermassive black hole. The gravitational waves generated by the orbital motion are computed using black hole perturbation theory
- Observations of EMRIs will permit to test the no-hair theorem for black holes, i.e. to verify that the central black hole is described by the Kerr geometry

Methods to compute gravitational-wave templates



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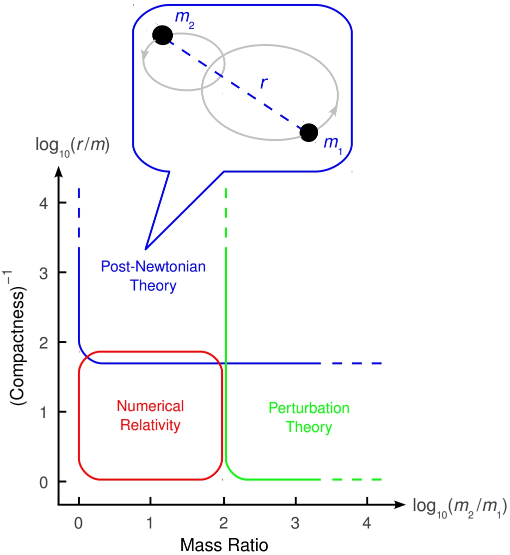

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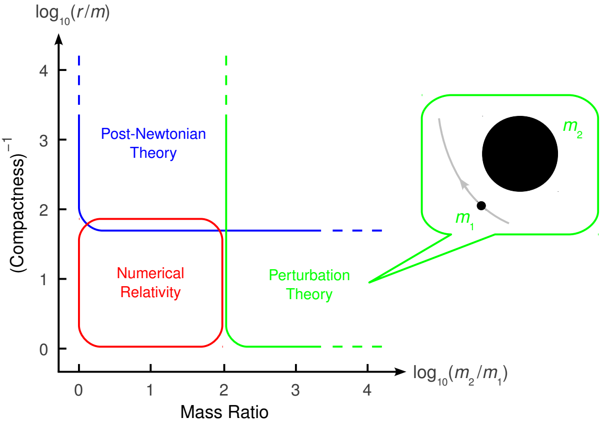

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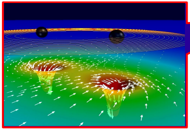

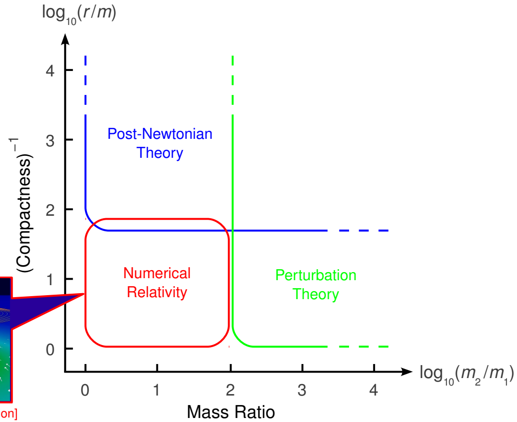

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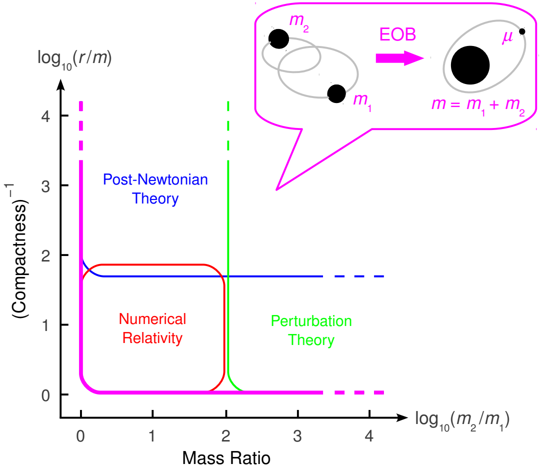
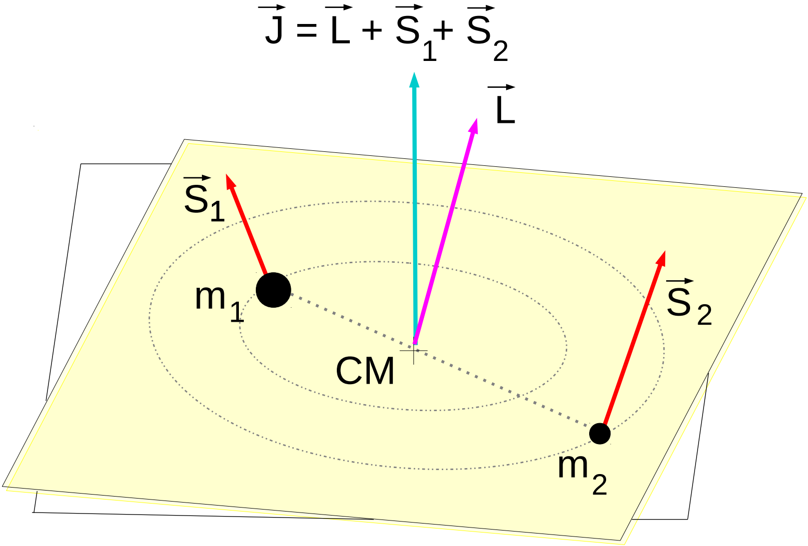


Binary System of BHs with spins



The gravitational chirp of compact binaries