Gravitational waves and fundamental physics

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Experimental situation

Timeframe:
• present (LIGO, Virgo)
• \(~2011-2014\) advanced LIGO/Virgo
• \(2018+\)
  – \(3^{rd}\) generation ground based intf (ET)
  – LIGO
Present situation

- LIGO reached its target sensitivity in Nov. 2005
  S5 run: 1yr worth of triple coincidence data
  between its three intf (L1, H1, H2)
  completed on Oct. 1, 2007

  distance to NS-NS coalescence ~ 15 Mpc
  (SNR =8, average orientation)

  - still analyzing data (no GW detected yet)
  - some physically interesting negative results:
• **GRB 070201**
  - sky position overlaps (within the error box) with spiral arms of Andromeda (770 kpc)
LIGO detectors H1 and H2 were in Science mode: no GW observed
- binary NS star merger excluded at 99% c.l. (d< 3.5 Mpc excluded at 90% c.l.)
- if in Andromeda, energy radiated in GWs is $E < 4.4 \times 10^{-4} \, M_\odot c^2 = 7.9 \times 10^{50}$ erg consistent with models of Soft Gamma Repeaters
- if in Andromeda, the isotropic e.m. energy release was $10^{45}$ erg, typical of giant flares in SGR

LSC, arXiv:0711.1163
• upper limit on stochastic backgrounds

\[ \Omega_{GW}(f) = \frac{1}{\rho_c \cdot d \log f} \frac{\rho_{gw}}{d \log f} \]

bound from BBN:

\[ \int d(\log f) \ \Omega_{GW}(f) < 1.5 \times 10^{-5} \]

bound from LIGO (S4)

\[ \Omega_{GW}(f) < 6.5 \times 10^{-5} \]

(50 Hz < f < 150 Hz)

factor 10-100 of improvement with S5?
Mid-term future (~2011-2014?)

- 1\textsuperscript{st} generation detectors have no assured source. Then, proceed to
- Advanced LIGO, Virgo+, Adv. VIRGO
  - improve sensitivity in $h$ by a factor $\sim 15$
    $\rightarrow$ a factor 3000 in volume explored
  - NS/NS inspiral up to 300 Mpc
  - BH/BH inspiral (10 M$_{\odot}$ each) up to 1-2 Gpc
  - galactic pulsars with $\epsilon \sim 10^{-6}$
Advanced LIGO

- Initial LIGO
- Advanced Interferometers
- Open up wider band
- ~15 in h
- ~3000 in rate

- Higher power laser (10 W → 180 W)
- New seismic isolation system (active)
- Fused silica suspension wires
3\textsuperscript{rd} generation detectors (2018+)

**LISA**: moved into ESA cosmic vision 2015-2025. If approved, first possible launch slot in 2018

- supermassive BHs with $10^6 \, M_\odot$ would be visible out to $z = 10$

- $\Omega_{GW}(f) \sim 10^{-11} - 10^{-12}$
2018+ (2) Ground-based interferometers of 3rd generation

- cryogenic mirrors (20 K)
- underground detector

Proposed Japanese project: LCGT, in the Kamioka mine

Sensitivity of LCGT will be comparable to Advanced LIGO (its prototype, CLIO, is already testing these techniques.)
→ 3rd generation LIGO and Virgo ? (Einstein Telescope?)
What can we hope to learn about fundamental physics from the observation of GWs?

• Coalescing binaries:
  – probing the non-linearities of GR
  – standard candles and dark energy

• Neutron stars and the ground state of QCD
Coalescing binaries

• the slow inspiral phase probes the non-linearities of GR
• the merging probes the strong gravity regime
• the ringdown phase allows us to measure BH quasinormal modes

• Cosmological standard candles
  → dark energy
Probing the non-linearities of GR

If we know the form of the signal, we can dig deeply into the noise floor.

A simplified example: \[ s(t) = n(t) + h(t) \]

\[
\int_0^T dt \ s(t)h(t) = \int_0^T dt \ n(t)h(t) + \int_0^T dt \ h^2(t)
\sim T^{1/2}
\sim T
\]

We gain a factor \((T/\tau)^{1/2} \equiv N_c^{1/2}\)

ms pulsar observed for one year: \[ N_c = 3 \cdot 10^7 / 10^{-3} \]

Coalescing binaries at ground-based ifos \[ N_c \sim 10^4 \]
• The inspiral phase is driven by radiation reaction → both the frequency and amplitude of the waveform increase.

• followed by merging and ringdown
• waveform known → matched filtering
  very accurate computations are needed
  (Newtonian phase is of order \((v/c)^{-5}\) )
corrections \(O(v^7/c^7)\) to the phase recently completed
  (Blanchet, Damour, Jaronowski, Schaefer)
• we probe the non-linearities of GR
  – GWs computed at a given order are source of further
    GWs at higher orders
  – backscattering of GWs on the background curvature
These effects are crucial for extracting the signal from the
noise!
The computation is extremely difficult. However, in this way we probe the non-linearities of GR

- GWs computed at a given order are sources of further GWs at higher orders
- backscattering of GWs on the background curvature

These effects are crucial for extracting the signal from the noise!
Merging phase

• Recent breakthroughs in numerical relativity. It is now possible to simulate the last few orbits before coalescence and extract the waveform.  
  (Pretorius 2005)

( Buonanno, Cook and Pretorius 2007)
• The matching from inspiral to merge is well reproduced by an analytic method, the effective one-body (EOB) action

(Buonanno and Damour 1999, 2000)

• The final ringdown phase is very well reproduced by the quasinormal modes of the final BH

→ check the near-horizon BH metric
Expected rates for compact binaries

- various theoretical uncertainties
  - reduction of rates because of common envelope evolution of progenitor stars
    (Belczynski et al. 2007)
  - distribution of kick velocities
NS-NS binaries (pessimistic)

\[ \rightarrow \text{a few/yr at advanced ifos} \]

(optimistic: \( O(100)/\text{yr at adv ifos} \) )
BH-BH binaries

• pessimistic: ~ 2/yr at adv ifos if CE evolution kills most potential progenitors

• however: production of compact binaries is enhanced if BH-BH are formed in dense clusters. If the initial mass fraction in dense clusters is $f > 0.001$, we get 25-300 events/yr at adv ifos (Sadowski et al., arXiv:0710.0878)

bottomline: large theoretical uncertainties, but detection very likely at adv ifos
Coalescing binaries as standard candles

\[ h_+ = \frac{2}{r} \frac{M_c^{5/3}}{r} (\pi f)^{2/3} (1 + \cos^2 \iota) \cos \Phi \]

\[ h_\times = \frac{4}{r} M_c^{5/3} (\pi f)^{2/3} \cos \iota \sin \Phi \]

\[ M_c = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5} \]

\[ f = (96/5) \pi^{8/3} M_c^{5/3} f^{11/3} \]

\[ \Phi(t) = 2\pi \int^t dt' f(t') \]

\[ h_+/h_\times \rightarrow \cos \iota \quad (f, \dot{f}) \rightarrow M_c \]

\[ \Rightarrow \text{We get the distance } r \quad ! \]
for sources at cosmological distances:

- \( M_c \rightarrow (1 + z) M_c \)
- \( r \rightarrow d_L(z) \)  \hspace{1cm} \text{luminosity distance}

\[
F = \frac{\mathcal{L}}{4\pi d_L^2} \\
H_0 d_L = z + \frac{1}{2} (1 - q_0) z^2 + \ldots
\]

For a spatially flat Universe:

\[
d_L(z) = (1 + z) \int_0^z \frac{dz'}{H(z')}
\]
• having $d_L$ (and measuring also $z$) we get a gravitational standard candle

• out to what distance? At the level of 3$^{rd}$ generation VIRGO/LIGO:
  – NS/NS coalescences out to 2 Gpc
  – BH/BH coalescences, $10 \, M_\odot$, out to $z \sim 2-3$

• At LISA, supermassive BHs with $10^6 \, M_\odot$, would be visible out to $z = 10$
probe the equation of state of dark energy

gravitational standard candles can extend the results from SN to higher $z$, and have different systematics
What is the true ground state of QCD?

- $T<T_c$: quarks and gluons confined into hadrons

- strange quark matter hypothesis:
  at high density, deconfined $u,d,s$ mixture.
  The price paid to deconfinement and to $m_s$ is compensated by the opening of a third Fermi sea

The true vacuum could be separated from ours by an energy barrier
The energy barrier could be overcome in the core of NS

Crust: lattice of heavy nuclei

n, p, e, µ superfluid

QCD regime: quark-hadron mixed phase?

$\rho \sim 1 \text{ GeV/fm}^3 \rightarrow$ high-density QCD

$\Rightarrow$ hybrid stars, quark stars?
• astrophysical processes can induce non-radial oscillations of NS
  – SN→NS
  – starquakes (e.g. magnetars)
  – (phase transitions in a quark core ?)
• the normal modes decay by emission of GWs;
  their frequency depends on the internal structure of the NS
  → GWs can probe the core of a NS
Benhar, Ferrari and Gualtieri, 2004
Typical energy released in GWs:

$$10^{-10} - 10^{-6} \, M_\odot c^2$$

- with present detectors, a sine-gaussian burst centered at a frequency $f$ can be detected if it releases at least

$$E \sim 0.1 M_\odot c^2 \left( \frac{r}{20 \text{Mpc}} \right)^2 \left( \frac{f}{150 \text{Hz}} \right)^2$$

$$\sim 2 \times 10^{-10} M_\odot c^2 \left( \frac{r}{1 \text{kpc}} \right)^2 \left( \frac{f}{150 \text{Hz}} \right)^2$$

- at advanced, and especially 3rd generation detectors, galactic events are accessible
Precision measurement from binary pulsars
• Pulsars are clocks with an exceptional intrinsic stability (comparable to atomic clocks)

• For pulsars in binary systems, the timing residuals are affected by various effects due to special and general relativity (e.g. Roemer, Einstein and Shapiro time delays)
• Fitting the timing formula (with 27 yrs of data!), all Keplerian parameters are known very precisely

\[ a_1 \sin \iota = 2.341774(1) \text{ s}, \quad e = 0.6171338(4) \]

\[ T_0 (\text{MJD}) = 46443.99588317(3), \quad \omega = 226.57518(4) \text{ deg} \]

\[ P = 27906.9807807(9) \text{ s} \]

• 3 post-Keplerian parameters:

\[ d\omega/dt = 4.226607(7) \text{ deg/yr}, \quad \gamma = 0.004294(1) \]

\[ dP/dt = -2.4211(14) \times 10^{-12} \]
• \( \frac{d\omega}{dt}, \gamma \) fixed by GR in terms of \( m_p \) and \( m_c \)

• \( \frac{dP}{dt} \) fixed by the quadrupole formula for GW emission, once \( m_p \) and \( m_c \) are known

\[
\rightarrow \quad m_p = 1.4408(3) \, M_\odot, \quad m_c = 1.3873(3) \, M_\odot
\]

\[
\frac{(dP/dt)_{\text{exp}}}{(dP/dt)_{GR}} = 1.002 \pm 0.005
\]
Hulse and Taylor, Nobel prize 1993
double pulsar PSR J0737-3039

- both neutron stars detected as pulsars
- orbital period 2.4 hr!
- almost edge-on (large Shapiro delay)
- large flux density, narrow pulse, very small proper motion, d=500 pc (small correction due to differential acceleration of the Galaxy)

  5 post-Keplerian parameters measured

after just 2.5 years of data, test of GR at the 0.05% level, far better than the Hulse-Taylor
very recent development

(Bhat et al. astro-ph 0804.0956)

NS-WD binary PSR J1141-6545

• 4 post Keplerian parameters measured
• \( \frac{(dP/dt)_{\text{exp}}}{(dP/dt)_{\text{GR}}} = 1.04 \pm 0.06 \)
• very asymmetric system (very different values of the compactness \( GM/c^2 \) )

→ large amount of dipolar scalar radiation in scalar-tensor theories
• matter couples to $\tilde{g}_{\mu\nu} = A^2(\varphi)g_{\mu\nu}$

$$\ln A(\varphi) = \alpha_0(\varphi - \varphi_0) + O(\varphi - \varphi_0)^2$$

$$\gamma^{PPN} - 1 = -\frac{2\alpha_0^2}{1 + \alpha_0^2}$$

• limit from the NS-WD binary:

$$\alpha_0^2 < 3.4 \times 10^{-6}$$

(3 times better than the Cassini bound)
More details:
MM, Gravitational waves.
Vol. I: Theory and Experiments, 546 pages,
Oxford Univ. Press, 2007