Fundamental Physics and Cosmology
with interferometric gravitational wave detectors

B.S. Sathyaprakash
Stochastic Background Landscape

\[ \Omega_{gw} \] vs. \( v_0 \) Hz

- string theory
- Ad LIGO
- cosmic strings
- DNS
- pulsars
- magnetars
- BH ringdown
- bar mode
- de Sitter inflation
- slow roll inflation

Friday, 4 September 2009
What this talk is about

- Interferometric Detectors
  - Antenna pattern and reconstructing the source
  - GW Interferometers: Current status and future prospects

- Science from Standard Sirens of gravity
  - Cosmological parameters with standard sirens
  - Stochastic backgrounds
  - Black hole “no-hair” theorem

What I won’t talk about

- Seeds of galaxy formation,
- Mass function of neutron stars
- History of star formation rate
- Black hole spectroscopy
- Limits on mass of the graviton
- And many other interesting physics questions ...
Detector response and reconstructing the source

Antenna response is a linear combination of the two polarizations:

\[ h(t) = F_+ h_+ + F_x h_x \]

In the case of a binary inspiral signal the response can be written as:

\[ h(t) = A_+ H_+ + A_x H_x \]

where \( A_+ \) and \( A_x \) are functions of \((\alpha, \delta, \psi, D_L, i)\): right ascension \( \alpha \), declination \( \delta \), polarization angle \( \psi \), luminosity distance \( D_L \), orientation of the binary wrt the line of sight \( i \).

\( H_+ \) and \( H_x \) contain only the intrinsic parameters (masses and spins) and time and phase at coalescence.

Need at least three detectors to reconstruct the source.
American Laser Interferometer Gravitational-Wave Observatory (LIGO) at Hanford
LIGO at Livingstone, Louisiana
Japanese Large Cryogenic Gravitational-Wave Telescope (LCGT)
S5 Sensitivity

Strain Sensitivity for the LIGO 4km Interferometers

S5 Performance - June 2006

LIGO-G060293-01-Z

- LHO 4km - (2006.03.13) S5: Binary Inspiral Range (1.4/1.4 Msun) = 14.5 Mpc
- LLO 4km - (2006.06.04) S5: Binary Inspiral Range (1.4/1.4 Msun) = 15.1 Mpc
- LHO 2km - (2006.06.18) S5: Binary Inspiral Range (1.4/1.4 Msun) = 7.4 Mpc
- LIGO I SRD Goal, 4km

G070221-00

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Recent Results from LIGO Scientific Collaboration and Virgo
Stochastic Backgrounds

- Primordial background
- Phase transitions in the Early Universe
- Astrophysical background
  - A population of Galactic white-dwarf binaries produces a background above instrumental noise in LISA
- At the moment we have no way of disentangling different spectra
Detector output = true signal + noise

\[ s_1(t) = h_1(t) + n_1(t) \]
\[ s_2(t) = h_2(t) + n_2(t) \]

Normally detector noise are uncorrelated:

\[ \langle n_1(t)n_2(t') \rangle = 0 \]

SGWB signal is characterized by correlation

Cross-correlation (CC) statistic is the best choice

\[ \langle s_1(t)s_2(t') \rangle \]

One detector’s signal is the filter for other detector’s data
Generalized Overlap Reduction Function

\[ \gamma^I_{\alpha}(f, t) := \sum_{A=+, \times} \int_{S^2} d\hat{\Omega} F^A_{I_1}(\hat{\Omega}, t) F^A_{I_2}(\hat{\Omega}, t) e^{2\pi i f \hat{\Omega} \cdot \Delta x(t)/c} e^{\alpha(\hat{\Omega})} \]

Isotropic search: \( e_{\alpha}(\hat{\Omega}) := 1 \)
Searching for a Stochastic Background

\[ \Omega_{gw}(f) = \frac{1}{\rho_{\text{crit}}} \frac{d\rho_{gw}}{d \ln f} \]

- **Nucleosynthesis upper-limit**
  \[ \int \frac{df}{f} \Omega_{gw}(f) \lesssim 1.5 \times 10^{-5}. \]

- **Upper limit from LIGO data from the 4th Science run**
  \[ \Omega_{gw}(f) < 6.5 \times 10^{-5}. \]

- **S5 data has improved this better than the nucleosynthesis limit**
  \[ \Omega_{GW} < 6.9 \times 10^{-6} \]

Directed Search

\[ e_\alpha(\hat{\Omega}) := \delta(\hat{\Omega} - \hat{\Omega}_\alpha) \]

\[ \gamma_{\hat{\Omega}}(t, f) := \left[ F_1^+(\hat{\Omega}, t) F_2^+(\hat{\Omega}, t) + F_1^\times(\hat{\Omega}, t) F_2^\times(\hat{\Omega}, t) \right] e^{2\pi i f \hat{\Omega} \cdot \Delta x(t)/c} \]

\[ X_{\hat{\Omega}} \propto \sum_{t=0}^{T} \int_{-\infty}^{\infty} df \tilde{s}_1^*(t, f) \tilde{s}_2(t, f) G(t, f) \gamma_{\hat{\Omega}}^*(t, f) \]

Essentially Earth Rotation Synthesis Imaging

Slide from Mitra
Directed Search Upper Limit

Upper limit map from LIGO’s 4th Science run

- limits derived from dirty map
- rigorous treatment requires deconvolution

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Continuous Wave Sources

- Rapidly spinning neutron stars or other objects
  - Mountains on neutron stars
- Low mass X-ray binaries
  - Accretion induced asymmetry
- Magnetars and other compact objects
  - Magnetic field induced asymmetries
- Relativistic instabilities
  - r-modes, etc.
Spin-down limit on the Crab pulsar

2 kpc away, formed in a spectacular supernova in 1054 AD
Losing energy in the form of particles and radiation, leading to its spin-down

spin frequency of $\nu = 29.78 \text{ Hz}$
spin-down rate, $\dot{\nu} \approx -3.7 \times 10^{-10} \text{ Hz s}^{-1}$
$\dot{E} = 4\pi^2 I_{zz} \nu |\dot{\nu}| \approx 4.4 \times 10^{31} \text{ W}$
$h_{0}^{\text{sd}} = 8.06 \times 10^{-19} I_{38} r_{\text{kpc}}^{-1} (|\dot{\nu}|/\nu)^{1/2}$

We have searched for gravitational waves in data from the fifth science run of LIGO detectors
The search did not find any gravitational waves
Lack of GW at S5 sensitivity means a limit on ellipticity a factor 4 better than spin-down upper limit - less than 4% of energy in GW

$h_{0}^{95\%} = 3.4 \times 10^{-25}, \quad \varepsilon = 1.8 \times 10^{-4}$
Compact Binary Mergers

- Binary neutron stars
- Binary black holes
- Neutron star–black hole binaries

Loss of energy leads to steady inspiral whose waveform has been calculated to order $v^7$ in post-Newtonian theory.

Knowledge of the waveforms allows matched filtering.
**Examples of Merging Neutron Star Binaries**

- PSR 1913+16, J0737-3039
- J0737-3039 - the fastest
  - Strongly relativistic, $P_b = 2.5$ Hrs
  - Mildly eccentric, $e = 0.088$
  - Highly inclined ($i > 87$ deg)

The most relativistic
- Greatest periastron advance: $d\omega/dt$: 16.8 degrees per year (almost entirely general relativistic effect), compared to relativistic part of Mercury’s perihelion advance of 42 sec per century
- Orbit is shrinking by a few millimeters each year due to gravitational radiation reaction

Burgay et al Nature 2003

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**LIGO Sensitivity to Binary Mergers**

S5 data Horizon distance (in Mpc) versus total mass (in $M_\odot$) for inspiral phase of binary black holes

![Graph showing horizon distance versus total mass for S5 data from 1st 3 months of S5. The graph includes data points for H1, H2, and L1.](Image)
Burst Sources

- Gravitational wave bursts
  - Black hole collisions
  - Supernovae
  - Gamma-ray bursts (GRBs)
- Short-hard GRBs
  - Could be the result of merger of a neutron star with another NS or a BH
- Long-hard GRBs
  - Could be triggered by supernovae
Origin of GRB 070201 from LIGO Observations

- Null inspiral search result excludes binary progenitor in M31
- Soft Gamma-ray Repeater (SGR) models predict energy release \( \leq 10^{46} \) ergs.
- SGR not excluded by GW limits

Future Improvements

- Enhanced Detectors (2009-11)
- Advanced Detectors, LIGO and Virgo (2014+)
  - 12 x increase in sensitivity
  - Over 1000 x increase in rate
  - Can detect $\Omega_{GW} > 10^{-9}$
- 3G Detectors: (2025+)
  - Einstein Telescope 100 x increase in sensitivity
  - $10^6$ increase in rate
  - Can detect $\Omega_{GW} > 10^{-12}$
ET is a conceptual design study supported, for about 3 years (2008-2011), by the European Commission under the Framework Programme 7

EU financial support ~ 3M€

Aim of the project is the delivery of a conceptual design of a 3rd generation GW observatory

Sensitivity of the apparatus ~ 10 better than advanced detectors
Expected Future Sensitivities

- Virgo+ 2008
- LIGO 2005
- AURIGA 2005
- Virgo Design
- GEO-HF 2009
- DUAL Mo (Quantum Limit)
- Advanced LIGO/Virgo (2014)
- Einstein GW Telescope

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A Triangle: Total Beam Tube of 30 km

10 km
A Triangle: Total Beam Tube of 30 km

10 km

π/3

Three detectors
Antenna Pattern of ET
SNR in ET for coalescences at z=0.5

Bose et al, 2009

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Distance Reach of ET

![Graph showing Luminosity Distance vs. Total mass (in \( M_\odot \)) for different values of \( \nu \).]

- Sky-ave. dist. Vs. Obs. \( M \), \( \nu = 0.25 \)
- Sky-ave. dist. Vs phys. \( M \), \( \nu = 0.25 \)
- Sky-ave. dist. Vs Obs. \( M \), \( \nu = 0.10 \)
- Sky-ave. dist. Vs phys. \( M \), \( \nu = 0.10 \)

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Sensitivity to (Stochastic) Sources in ET
What do we expect to learn from future GW observations: Focus here only on Compact Binaries
Late-time dynamics of compact binaries is highly relativistic, dictated by non-linear general relativistic effects.

Post-Newtonian theory, which is used to model the evolution, is now known to $O(v^7)$.

The shape and strength of the emitted radiation depend on many parameters of the binary: masses, spins, distance, orientation, sky location, ...

$$h(t) = 4\eta \frac{M}{D} \frac{M}{r(t)} \cos 2\varphi(t)$$
Compact binaries standard sirens

- Amplitude of gravitational waves depends on:
  - Chirp-mass $= \mu^{3/5} M^{2/5}$

- Gravitational wave observations can measure both:
  - Amplitude (this is the strain caused in our detector)
  - Chirp-mass (because the chirp rate depends on the chirp mass)

- Therefore, binary black hole inspirals are standard sirens:
  - From the apparent luminosity (the strain) we can conclude the luminosity distance

- However, GW observations alone cannot determine the red-shift to a source

- Joint gravitational-wave and optical observations can facilitate a new cosmological tool
Structure of the waveform

- Radiation is emitted not just at twice the orbital frequency but at all other harmonics too.

\[ h(t) = \frac{2M_0}{D_L} \sum_{k=1}^{7} \sum_{n=0}^{5} A_{(k,n/2)} \cos \left[ k\Psi(t) + \phi_{(k,n/2)} \right] x^{n+1}(t) \]

- These amplitude corrections have a lot of additional structure.

  - Increased mass reach of detectors
  - Greatly improved parameter estimation accuracies

Blanchet, Damour, Iyer, Jaranowski, Schaefer, Will, Wiseman

Andrade, Arun, Buonanno, Gopakumar, Joguet, Esposito-Farase, Faye, Kidder, Nissanke, Ohashi, Owen, Ponsot, Qusaillah, Tagoshi …
Edge-on vs face-on binaries

Time domain rep of the optimal template (LIGO I)

(2, 10) Msun  (2, 15) Msun  (2, 30) Msun

Pol angle=0, xy-scale same for a given system
All sources at 100 Mpc $i=45$ deg

- (3,10) $M_\odot$, 5 harmonics
- (3,15) $M_\odot$, 5 harmonics
- (3,30) $M_\odot$, 5 harmonics

Frequency (Hz) vs. Signal Spectra as seen in LIGO
Black Hole Mergers from Numerical Relativity

After several decades NR is now able to compute accurate waveforms for use in extracting signals and science

- New physics - e.g. super-kick velocities
- Analytical understanding of merger dynamics

We should be able to see further and more massive objects
Close Agreement b/w NR and EOB

How further can we see with Inspiral, Merger and Ringdown?

Initial LIGO  Virgo design  Advanced LIGO

700 Mpc  1 Gpc  z=1.8

PN templates  EOB w/o ring-down  IMR/EOBNR

Ajith et al
**Expected Annual Coalescence Rates**

Rates quoted are mean of the distribution; In a 95% confidence interval, rates uncertain by 3 orders of magnitude.

- Binary Neutron Stars (BNS)
- Binary Black Holes (BBH)
- Neutron Star-Black Hole binaries (NS-BH)

<table>
<thead>
<tr>
<th></th>
<th>BNS</th>
<th>NS-BH</th>
<th>BBH</th>
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<tbody>
<tr>
<td><strong>Initial LIGO</strong></td>
<td>0.02</td>
<td>0.006</td>
<td>0.009</td>
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<td>(2002-06)</td>
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<tr>
<td><strong>Enhanced LIGO</strong></td>
<td>0.1</td>
<td>0.04</td>
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<tr>
<td>x2 sensitivity</td>
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<td>(2009-10)</td>
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<tr>
<td><strong>Advanced LIGO</strong></td>
<td>40</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>x12 sensitivity</td>
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<tr>
<td>(2014+)</td>
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</table>
What can we expect to learn from GW observations?
Testing the no-hair theorem
Capture of Small Black Holes by Super-massive Black Holes
Testing the No-Hair Theorem

Ryan

Image: AEI/Einstein Online
Testing the No-Hair Theorem

Ryan

Image: AEI/Einstein Online
Gravitational Capture and Testing Uniqueness of Black Hole Space-times

Image: Glampedakis and Babak
Audio: Scott Hugues
Measuring Cosmological Parameters with Interferometers
Measuring the Hubble Parameters with LIGO, Virgo, LCGT

- Advanced detectors is expected to detect 100 binary neutron stars in a 3-year time-scale.
- Up to 20-25 binary neutron stars might be observed in coincidence with short-hard GRBs.
- Coincident GW/EM observation will give accurate estimation of the red-shift and luminosity distance.
- Adv. detectors will see sources from 600 Mpc (NS-NS) to 1400 Mpc (NS-BH).
- Can measure the Hubble parameter to within 1% using the network of LIGO-Virgo-LCGT-AIGO.
- By the time of LISA/ET Hubble parameter should have been determined independently by GW and EM observations quite accurately.

Nissanke et al, arXiv:0904:1017
How can we measure other cosmological parameters?

- Luminosity distance Vs. red shift depends on a number of cosmological parameters $H_0$, $\Omega_M$, $\Omega_b$, $\Omega_\Lambda$, $w$, etc.

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{\left[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)}\right]^{1/2}}$$

- LISA SMBBH observations can measure $w$ to within a few percents with just one or two observations

- LISA EMRI observations can measure Hubble constant to within fraction of a percent: MacLeod and Hogan (PRD 2008)

- Einstein Telescope will detect 1000’s of compact binary mergers for which the source can be identified (e.g. GRB) and red-shift measured.

- A fit to such observations can determine the cosmological parameters
Problem with Pointing?

Although binary black holes are standard sirens, LISA’s angular resolution might not be good enough to locate the host galaxy. It might not be possible to measure red-shift.

Weak gravitational lensing could limit the LISA’s ability to measure the dark energy equation of state parameter $w$.

The breakthrough came from the work of Arun, et al: Higher Harmonics will enable better pointing of sources. Should enable more precise measurements of masses, luminosity distance and sky position. LISA should be able to measure $w$ to within a few percent.

Hughes and Holz (2002)  
Arun Et Al (2007)
Inspiral signal with all the harmonics

Arun et al (2007a)
Measuring $w$ with LISA

<table>
<thead>
<tr>
<th>$\Delta \ln D_L$</th>
<th>$\Delta \Omega_S$</th>
<th>$\Delta \ln M$</th>
<th>$\Delta \delta$</th>
<th>$\Delta t_C$</th>
<th>$N_{\text{clusters}}$</th>
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<td>$(10^{-6})$</td>
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<td>0.74</td>
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<td>⋮</td>
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$$(m_1, m_2) = (10^5, 10^6) M_\odot$$
Measuring $w$: Another Example

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<td>⋯</td>
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<td>4.2</td>
<td>1.1</td>
<td>7.1</td>
<td>⋯</td>
</tr>
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</table>

$$(m_1, m_2) = (6.45 \times 10^4, 1.29 \times 10^6) M_\odot$$

Friday, 4 September 2009
Measurement of $DM$, $DE$, $w$

$\Omega_M^w = 0.254$  $\sigma_{\Omega_M} = 0.045$

$\Omega_\Lambda^w = 0.739$  $\sigma_{\Omega_\Lambda} = 0.031$

$<w> = -0.96$  $\sigma_w = 0.18$

$\sigma_{\Omega_M} = 0.035$

$\sigma_{\Omega_\Lambda} = 0.026$

$<w> = -0.96$  $\sigma_w = 0.15$


Friday, 4 September 2009
Measurement of DM and $w$

$\Omega_M$:
- $\langle \Omega_M \rangle = 0.269$
- $\sigma_{\Omega_M} = 0.025$
- $\Omega_M > = 0.268$
- $\sigma_{\Omega_M} = 0.022$

$w$:
- $\langle w \rangle = -1.00$
- $\sigma_w = 0.076$
- $\langle w \rangle = -1.00$
- $\sigma_w = 0.066$

BSS, Schutz, Van Den Broeck: arXiv:0906.4151

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Measurement of $w$

$\langle w \rangle = -1.000$

$\sigma_w = 0.014$

BSS, Schutz, Van Den Broeck, Preliminary

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What can gravitational waves reveal about the Universe?

Was Einstein right?
- Is the nature of gravitational radiation as predicted by Einstein?
- Are black holes hairless and are there naked singularities?

Unsolved problems in astrophysics
- What is the origin of gamma ray bursts?
- What is the structure of neutron stars and other compact objects?

Cosmology
- What is dark energy?
- How did massive black holes at galactic nuclei form?

Fundamental questions
- What were the physical conditions at the big bang?
- Are there really ten spatial dimensions?
Are Gravitons Massive?

Coincident observation of a supernova and the associated gravitational radiation can be used to constrain the speed of gravitational waves to a fantastic degree:

If $\Delta t$ is the time difference in the arrival times of GW and optical radiation and $D$ is the distance to the source then the fractional difference in the speeds is

$$\frac{\Delta v}{c} = \frac{\Delta t}{D/c} \approx 10^{-14} \left( \frac{\Delta t}{1\text{sec}} \right) \left( \frac{D}{1\text{Mpc}} \right)$$

Should also be possible to constrain the mass of the graviton as they alter GW phasing of inspiral waveform due to dispersion of gravitational waves; no EM counterpart needed.
Bound on $\lambda_g$ as a function of total mass

- Limits based on GW observations will be five orders-of-magnitude better than solar system limits.

- Still not as good as (model-dependent) limits based on dynamics of galaxy clusters.

Berti, Buonanno and Will (2006)
Counting the Polarization States

Only two states in GR: $h_+$ and $h_\times$
Counting the Polarization States

Only two states in GR: $h_+$ and $h_\times$

Parent level

Gravity's Standard Sirens

Friday, 4 September 2009
Polarization States in a Scalar-Tensor Theory

- Polarization tests are qualitative tests.
- A single measurement is good enough to rule the theory out.

Cliff Will, Living Rev. in Relativity

Friday, 4 September 2009
Testing the tail effect

Gravitational wave tails

Blanchet and Schaefer (1994)

Testing the presence of tails

Blanchet and Sathyaprakash (1995)
Testing general relativity with post-Newtonian theory

Post-Newtonian expansion of orbital phase of a binary contains terms which all depend on the two masses of the binary

\[ H(f) = \frac{A(M, \nu, \text{angles})}{D_L} f^{-7/6} \exp \left[ -i\psi(f) \right] \]

\[ \psi(f) = 2\pi ft_C + \varphi_C + \sum_k \psi_k f^{(k-5)/3} \]

\[ \psi_k = \frac{3}{128} (\pi M)^{(k-5)/3} \alpha_k(\nu) \]

\[ \alpha_0 = 1, \quad \alpha_1 = 0, \quad \alpha_2 = \frac{3715}{756} + \frac{55}{9} \nu, \ldots \]
Testing general relativity with post-Newtonian theory

Post-Newtonian expansion of orbital phase of a binary contains terms which all depend on the two masses of the binary

$$\psi_k = \frac{3}{128} (\pi M)^{(k-5)/3} \alpha_k(\nu)$$

Different terms arise because of different physical effects

Measuring any two of these will fix the masses

Other parameters will have to consistent with the first two

Arun, Iyer, Qusailah, Sathyaprakash (2006a, b)
Testing post-Newtonian theory

Arun, Iyer, Qusailah, Sathyaprakash (2006a, b)
Gravity's Standard Sirens

$\left(10^5, 10^6\right) M_\odot$

Trias and Sintes

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Gravity's Standard Sirens

$10^5, 10^7 M_\odot$

Trias and Sintes

Friday, 4 September 2009