The promise and the prospects of gravitational wave astronomy

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NAOC
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Gravitational waves offer astronomers a means of probing extreme states of matter beyond the reach of electromagnetic astronomy, from the earliest moments of the big bang to the vibrating event horizons of black holes. Through 40 years of effort, the flux sensitivity of gravitational wave detectors has been improved by a factor of $10^{16}$. Gravitational waves have not yet been detected but the latest generation of detectors now under construction promise certain detections of known sources. Of particular interest is the coalescence of binary black holes. These systems are the most energetic sources of radiation in the universe. Their gravitational wave luminosity is $10^{23} \text{L}_{\text{sun}}$.

In 40 years with no gravitational wave signals, theorists have amassed a large array of predictions. Indeed, I suggest that there is no other field of science with such a rich range of testable predictions. A few of the testable predictions are: black hole normal modes, the structure of the Kerr metric, the black hole no-hair theorem, cosmic censorship, the black hole surface area theorem, cosmological stochastic backgrounds, fluid modes in neutron stars, magnetic mountains on neutron stars.

The development of gravitational wave detectors such as the Laser Interferometer Gravitational Observatory (LIGO) in the USA is technologically very significant. Beverley Berger, past National Science Foundation Director for Gravitational Physics stated: “Of all the large scientific projects out there, this one is pushing the greatest number of technologies the hardest. Every single technology they’re touching they’re pushing, and there’s a lot of different technologies they’re touching…..It’s the ultimate high-risk, high-payoff research project.”

The world requires a southern hemisphere detector to obtain accurate direction information on sources that can allow X-ray telescopes and optical telescopes to follow up the signal sources. An international detector in Australia would be a pivotal element in a world array of detectors, enabling all sky imaging of sources with adequate angular resolution.
Outline

• Historical Quest to Understand Space and Time
• What are Gravitational Waves
• The GW Spectrum
• Status of Ground based detectors
• Prospects of detectors now being commissioned
• Future Prospects for the Field
  • Expanded array
  • Quantum Technologies
Euclid

Most influential science book of all time.
1000 editions, 2300 years
Taught in every school
\[\pi = \text{circumference/diameter of a circle}\]

- Calculating \(\pi\) uses flat space Euclidean geometry
- All calculations of \(\pi\) assume flat space
- Digits in \(\pi\) = theoretical precision of flatness
- If space is different the experimental value of \(\pi\) will differ from the calculated value.
Zu Chongzhi 480AD

- Landmark in the 4000 year history of determining $\pi$.
- Record 7-digit precision in value of $\pi$ held from 480AD for ~ 800 years.
Jamshīd al-Kāshī ~1400AD

- Computed $\pi$ to 17 decimal places!
- Enough to easily compare with modern “experimental” values
Carl Friedrich Gauss

Why should we believe the 2300 year old geometry of Euclid?

Theorema Egregium 1828

The shape of space can be determined by measuring angles and distances
Gauss’s Question

• Do triangles in 3D have same properties as triangles on flat paper?
• Measure triangles: determine the shape of space.
Georg Friedrich Riemann 1854

Gauss’s student

1854: On the hypothese which underlie geometry (Published 1868)

Riemann curvature tensor
1916: General Relativity

Space, time and matter are connected

Spacetime is elastic, it has energy, and it has shape determined by matter.

Curvature defined in terms of the Riemann curvature tensor
Mass = $10^{43} \times \text{Curvature}$

$$T = \frac{c^4}{8\pi G}$$

Matter tells space how to curve
Space tells matter how to move
Space is elastic...

...it must be able to sustain waves
...gravitational waves
...waves of geometry
...shape-changing waves
Waves unstoppable by matter

- Vast stiffness $\sim c^4/8\pi G$
- Enormous energy
- Small amplitude
- Travel at the speed $c$

For typical waves the fractional change in shape is $\sim 10^{-24}$

The gravitational wave luminosity of black hole binary coalescence $= c^5/G = 10^{23} \times L_{\text{sun}}$!
History of Gravitational Waves

• 1916: Predicted by GR
  – of academic interest only -- Coordinate problems
    “gravitational waves travel at the speed of thought”

• 1957: Feynman
  – sticky beads thought experiment: existence
    resolved theoretically.

• 1960s: Resonant Mass + Free Mass Detectors
  Neutron Stars and Black Holes Discovered

• 1973: Binary neutron stars discovered

• 1990s: Large Interferometer Projects begin

• 2016 direct detection???
150 years ago Maxwell predicted EM waves

- Todays GW receivers are like the first radios built by Hertz and Marconion.
- State of the art quantum optics and cutting edge technology:
  - high power lasers,
  - nanometer precision mirrors,
  - world’s largest ultrahigh vacuum systems,
  - state of the art vibration isolation,
  - frontier quantum technology,
  - teraflop computing.

....but enormous improvements are possible
Threshold of Discovery

• Coalescing neutron star binaries
  – Known population, good rate estimates
  – new Advanced detectors designed for detection.

• Bonus sources: black hole binaries, stochastic backgrounds, spinning neutron stars
  – Less certainty (event rates/signal strengths)

• Like Higgs
  – Firm predictions, well understood detectors
  – Hopes for surprises
Worldwide Effort

• More than 1000 physicists, $10^9$
• Two detectors in USA (LIGO) two in Europe (GEO, VIRGO)
• New detectors Japan, India
• Main targets:
  – Binary black holes
  – Binary neutron stars
  – black hole births
• #1 challenge in fundamental physics
• New spectrum for astrophysics
In the next few years…

• LIGO type detectors will achieve sensitivity sufficient to detect 20-40 GW events per year from the known population of binary neutron stars…

• …plus many signals from black hole binary coalescence and other less understood sources.
Neutron Star Binary Coalescence
known and detectable source
Numerical Simulation - Two 1.3 M\(_{\odot}\)
Electromagnetic Counterparts of NS-NS/NS-BH Mergers

Jet–ISM Shock (Afterglow)
- Optical (hours–days)
- Radio (weeks–years)

GRB
(t ~ 0.1–1 s)

Ejecta–ISM Shock
Radio (years)

Merger Ejecta
Tidal Tail & Disk Wind
v ~ 0.1–0.3 c

Kilonova
Optical (t ~ 1 day)

Short GRB

‘Kilonova’

Metzger & Berger 2012
# Timeline of NS-NS/NS-BH Mergers (B. Metzger)

<table>
<thead>
<tr>
<th>Event</th>
<th>Time Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pre-Cursors: X-ray / [Coherent] Radio (crust cracking, NS B-field)</td>
<td>t(minus) ~ hrs-ms</td>
</tr>
<tr>
<td>✓ NS Crust Properties ✓ Magnetospheric Plasma Physics</td>
<td></td>
</tr>
<tr>
<td>2. Chirp enters LIGO Bandpass</td>
<td>t(minus) ~ mins-hr</td>
</tr>
<tr>
<td>3. Last Orbit, Plunge &amp; BH Formation (if prompt)</td>
<td>t ~ 1-10 ms</td>
</tr>
<tr>
<td>✓ Dynamical GR ✓ Nuclear-Density Equation of State</td>
<td></td>
</tr>
<tr>
<td>4. Accretion of Remnant Disk, Jet Formation (γ-ray burst)</td>
<td>t ~ 0.1-1 s</td>
</tr>
<tr>
<td>✓ Weak Interactions, ✓ Relativistic MHD, ✓ Collisionless Shocks</td>
<td></td>
</tr>
<tr>
<td>5. He-Recombination + Disk Evaporation</td>
<td>t ~ 0.3-3 s</td>
</tr>
<tr>
<td>6. R-Process Nucleosynthesis in Merger Ejecta -</td>
<td>t ~ few s</td>
</tr>
<tr>
<td>✓ Nuclear properties far from β-stability</td>
<td></td>
</tr>
<tr>
<td>7a. Late “Fall-Back” Accretion (ongoing weaker jet, X-rays)</td>
<td>t &gt;~ few s</td>
</tr>
<tr>
<td>7b. Long-Lived Neutron Star (magnetar?, X-rays)</td>
<td></td>
</tr>
<tr>
<td>8. “Kilonova” (Optical, UV-lines?)</td>
<td>t ~ 1 hrs-days</td>
</tr>
<tr>
<td>✓ Radiative transfer through “exotic” heavy nuclei (opacities)</td>
<td></td>
</tr>
<tr>
<td>9. On[Off]-Axis GRB Afterglow (X-ray, Optical, Radio)</td>
<td>t ~ hrs-yrs</td>
</tr>
</tbody>
</table>
Central Parsec of Milky Way

- 1 supermassive black hole
- 20,000 stellar mass black holes
- 50 intermediate mass black holes
- $10^7$ stars
- 3-body interactions
- Close binary black holes forming

Genzel et al. 20”x20”
Bence Kocsis 2013
BH Capture Events create extreme eccentric binaries

Repeated bursts – eccentric chirp

Kocsis, Gaspar, Marka 2006; O’Leary, Kocsis, Loeb 2009; Kocsis & Levin 2012

Wen 2003; Antonini & Perets (2012); Naoz, Kocsis, Loeb, Yunes (2012)
Rich unique waveform

Repeated Bursts

First 3 passages (shifted by 34 sec)

Final Chirp

Final 10 seconds before merger
Repeated bursts detectable at 100Mpc

Kocsis and Levin 2012
# Expected Inspiral Detections

<table>
<thead>
<tr>
<th>95% confidence</th>
<th>NS-NS</th>
<th>NS-BH</th>
<th>BH-BH</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIGO range Mpc</td>
<td>20</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>Adv-LIGO range Mpc</td>
<td>350</td>
<td>700</td>
<td>1500</td>
</tr>
<tr>
<td>LIGO events per year</td>
<td>$6 \times 10^{-3} - 0.7$</td>
<td>$3 \times 10^{-4} - 0.3$</td>
<td>$4 \times 10^{-3} - 3$</td>
</tr>
<tr>
<td>Adv-LIGO events</td>
<td>5 - 3700</td>
<td>1.5 - 1500</td>
<td>15 - 10,000</td>
</tr>
</tbody>
</table>
Four GW bands

CMB polarisation

Pulsar timing

\[ \log_{10}(h) = -10 \]
kHz band Detectors Today

- Most sensitive instruments of any kind ever created ~ $10^{-32}$ J
- Working close to limits set by the uncertainty principle
- New advanced detectors limited by quantum noise.

- How can we surpass current limits and test fundamental physics and astrophysics?

Initial LIGO strain sensitivity
Gravitational Wave Detector

Virgo Cascina, Italy
Classical Force + Quantum Detector

Gravitational wave is a classical wave with enormous occupation number

Detector is a Mechanical Oscillator in Quantum Regime
Gravitational Wave Interferometer

Laser

Power recycling mirror

end test mass

Very long optical cavities build up light by resonance

input test mass

Photodetector

Signal recycling mirror

Light intensity ~MW can create optical spring stiffer than diamond!
Quantum Picture

a) Anti-Stokes process

- Phonon $\Omega$
- Photon $\omega_0 + \Omega$
- Photon $\omega_0$

b) Stokes process

- Phonon $\Omega$
- Photon $\omega_0$
- Photon $\omega_0 - \Omega$

Creates an optical spring

Nulls the optical spring
Improving Detector Sensitivity $\Delta L / L$

- **Seismic vibration**
  - Many stages
- **Suspension thermal noise**
  - Very low loss pendulums
- **Test mass thermal noise**
  - Very low acoustic loss materials (sapphire, silicon or fused silica)
- **Newtonian background**
  - Local Gravity fluctuations
- **Quantum noise**
  - Uncertainty principle
  - High optical power

Factor of 10 improvement in sensitivity

©LIGO Scientific Collaboration
What Next after GW Detection

Expect GW detection before 2020

• Next steps
  1. Improve world array with more detectors
     • Angular resolution, polarisation (for source reconstruction), noise reduction
  2. Improve detectors with advanced quantum measurement techniques.
     • Optical springs and quantum squeezing

• Science goals
  – The physics of black holes
  – Black holes in the universe
  – Neutron star structure
Existing Array: Can’t tell source direction, much worse interference
A southern hemisphere detector

- Science benefits of GW detection greatly reduced without detector in southern hemisphere
  - Source localisation
  - Source parameters
  - Source distance
  - EM identification
  - Noise reduction
    - China’s HXMT will search for x-ray counterparts
    - SKA will search for radio afterglows
    - Optical transient telescopes will search for optical afterglows.
- South West Australia best location for optimum array
Proposed AIGO Detector

Proposed AIGO site: Gingin, Western Australia, 80 km north of Perth,
Same site as ACIGA’s 80 m high optical power interferometer facility
Adds 5 long baselines out of the plane.
Expanded array: pinpoint sources, reduce interference
Existing Array: Can’t tell source direction, much worse interference
Two approaches to improved sensitivity

1. Reduce effect of the quantum fluctuations which enter the detector at the dark port and set the standard quantum limit.

2. Increase the gravitational wave signal by changing the detector dynamics to enable more signal to be received.
Free Mass Standard Quantum Limit

FM SQL Line is the locus of uncertainty principle measurement limit for a free mass

Quantum non-demolition can allow FM SQL to be exceeded

Yanbei Chen J Phys B 2013
Initial LIGO Noise Spectrum

Figure 3.8 The initial LIGO strain sensitivity spectrum.
Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light

Quantum shot noise suppressed by squeezing the vacuum quantum fluctuations
Optical Springs

- Detuned optical cavities
- Radiation pressure creates optical spring
- Changes the detector dynamics to enable more GW energy to be absorbed

\[ F = K \Delta x \]

- \( P = 1 \text{MW optical power} \)
  - \( F = 2P/c \sim 10 \text{mN} \)

- \( P = 100 \text{kW} \)
  - \( F = 2P/c \sim 1 \text{mN} \)

\[ \Delta x = 1 \text{nm} \]

\[ K = \Delta F/\Delta x \sim 10 \text{mN/nm} = 10^7 \text{N/m} = 1000 \text{ tonnes/m} \]
Optical “Bar”

- Improved sensitivity due to opto-mechanical response of detector

See references in Yanbei Chen J Phys B 2013
GW Detector Sensitivity

![Graph showing GW detector sensitivity over frequency (f Hz) and signal-to-noise ratio (S_\text{b}/\Delta_f). The graph compares different detectors such as LIGO, aVirgo, aLIGO, ET-D, ET-B, and Virgo, with sensitivity levels varying from 2006-9, 2016-26, to ~2030.]
Testing the theory of black holes

- Cosmic censorship – naked singularities
- Black hole thermodynamics – surface area
- Black hole quasi-normal modes – imaging the event horizon
- Kerr metric:
- *Gravitational waves allow us to explore extreme spacetime by observing the interactions and formation of black holes.*
- Is GR valid at the event horizon?
In the next half century…

- New quantum optical techniques and improved technologies.
- GW receivers will continue to improve \( \sim 10 \times \) each decade.
- Multiple new discoveries in spacetime physics and in astrophysics…Nobel prizes!
- All this will be greatly enhanced by a southern hemisphere GW detector
Australian Consortium for Gravitational Astronomy

Gingin Facility

Australian National University

The University of Western Australia

The University of Adelaide

Monash University
Thank you!
GW Strains : Tilt + Linear Strain

Existing detectors are polarised sensitive to one polarisation only.

\[ h = \Delta L/L = \mathcal{H} \]

+  

\[ \times = \text{tilt in } + \text{ orientation} \]

If you could add a tilt sensitive gravitational receiver to an existing beam tube you could achieve full wave form reconstruction.
Unbalanced Sidebands – double optical spring interferometer

Unbalanced sidebands create optical spring, modify the detector dynamics and allow detection below the free mass SQL by increasing the energy coupling from the GW

$>10^6$ increased energy absorbed from GW
Single Sideband Tilt Interferometer

Measure second polarisation in same beam pipe

Increase the energy absorbed by GW

Tunable narrow band detector

Preliminary ideas still to be fully analysed
Tilt Interferometer

\[ \phi_{GW} = \frac{\pi}{2} + h_x \]

\[ \frac{\theta_{GW}}{2} = \frac{1}{2} h_x \]
Opto-Acoustic Interaction

Cavity Fundamental mode (Stored energy $\omega_o$)

Radiation pressure force

Stimulated scattering into $\omega_1$

Acoustic mode $\omega_m$

Input frequency $\omega_o$
Motivation: Gingin Experiment

1. ETM tilts: observed high sensitivity to test mass mode equivalent to a tilt vibration