Astrophysics and Cosmology with Gravitational Waves

Saeed Mirshekari

ICTP-SAIFR, LIGO

7 December 2014, ICTP Workshop on Observational Cosmology

Outline

- **Introduction**: Phenomenology and Observables
- **Sources**: Where do GWs[1] come from?
- **Detectors**: How we can detect GWs?
- **Data Analysis**: How to analyze the detector's data?
- **GW Astronomy**: Physics, Astrophysics, and Cosmology

---

[1] GW = Gravitational Wave

Introduction

Phenomenology

A few general reminders...

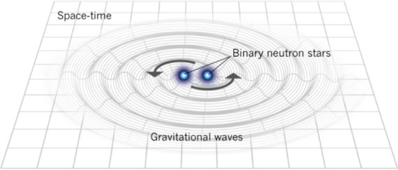
Gravitational Waves (GWs)

- GWs are ripples in the curvature of spacetime, predicted by Einstein's General Relativity (GR).

Wheeler's succinct summary of GR

- Spacetime tells matter how to move!
- Matter tells spacetime how to curve!

$$G_{\alpha\beta} = \frac{8\pi G}{c^2} T_{\alpha\beta}$$

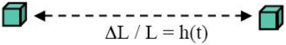


Phenomenology

A few technical reminders...

- $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ where $h_{\mu\nu} \ll 1$
- Wave Equations: $\Box h_{\mu\nu} = 0$
- h interpretation: physical strain in space

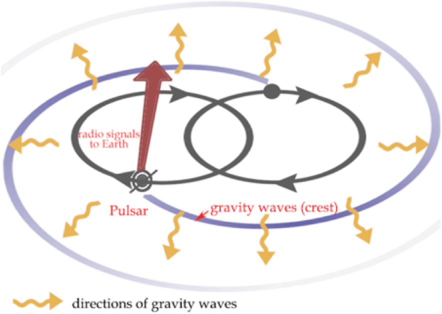
$$h = \frac{\Delta L}{L} \sim 10^{-20}$$



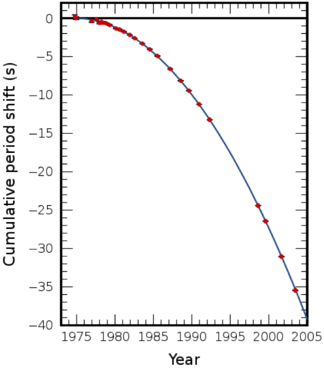
- in GR: $v_{GW} = c$, quadrupole radiation, transverse, tensor fields, 2-modes of polarization, graviton spin $= 2$
- First generation of GW detectors have been built and operated in 2000-2010 (LIGO and Virgo).
- No gravitational wave has been detected directly, yet!
- Advanced detectors will be operating soon.

Phenomenology

Do GWs exist?



THE NOBEL PRIZE IN PHYSICS 1993
RUSSELL A. HULSE, JOSEPH H. TAYLOR JR.



[Weisberg and Taylor, arXiv: 0407149]

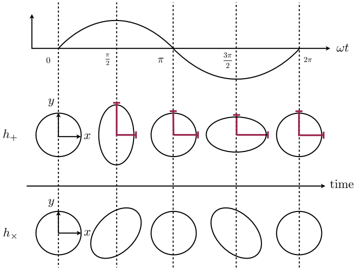
GW Observables

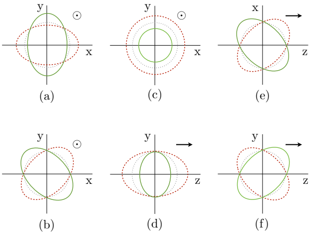
- **Amplitude, Frequency**
- **Direction to the source**:

  Directional sensitivity is not very good. (3+ detectors are needed: triangulation!)

- **Polarization**:

  in GR, only two polarization modes: $+$ and $\times$.





Sources

Sources

A General Classification

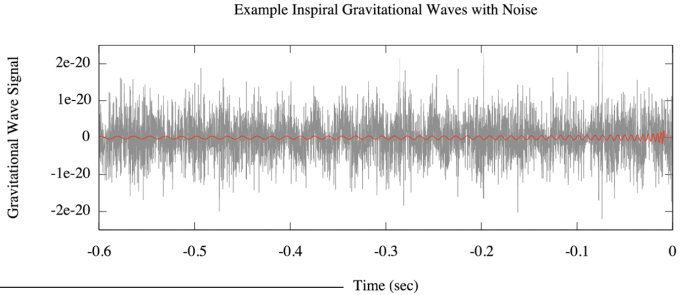
- Burst Sources: (un-modeled sources, signals lasting less than 20 sec)
  example: supernova explosion
- Periodic Sources: (short term or long term sources):
  example: rotating neutron stars (NSs)
- Stochastic Background: (sources contributing to a noisy background of GWs)
  example: GWs from inflation

Sources

Listening to a Few Sample GWs

- Binary black-hole merger: PLAY
- Supernova explosion PLAY
- Spinning pulsar PLAY

- What we actually receive (@ground-based detectors)! PLAY[2]



---

[2] Scott A. Hughes' Webpage

Inspiralling Compact Binaries:

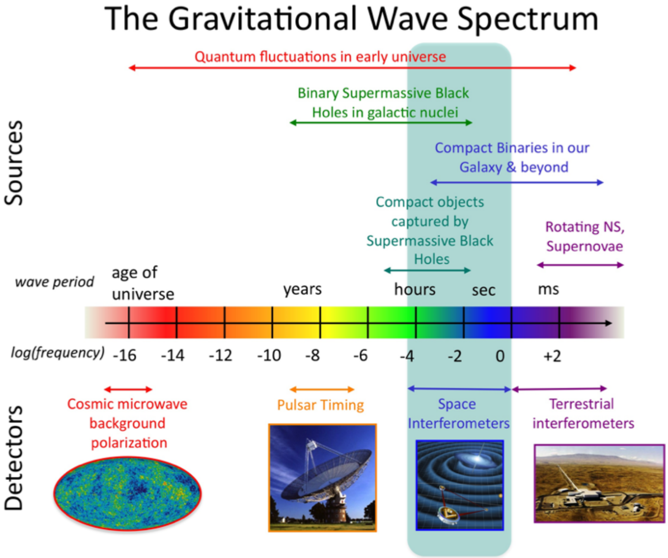
The Most Promising Sources of GWs. Simulation Credit: Caltech's TAPIR

hyperlink to the video

Detectors

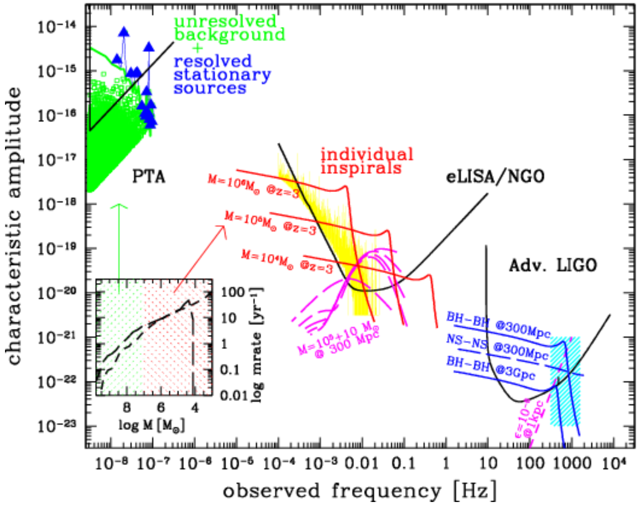
Detectors

Frequency Spectrum and the Corresponding Sources/Detectors



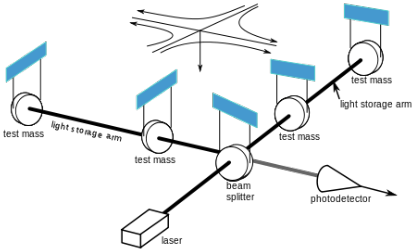
Detectors

Sensitivity Curves



Detectors

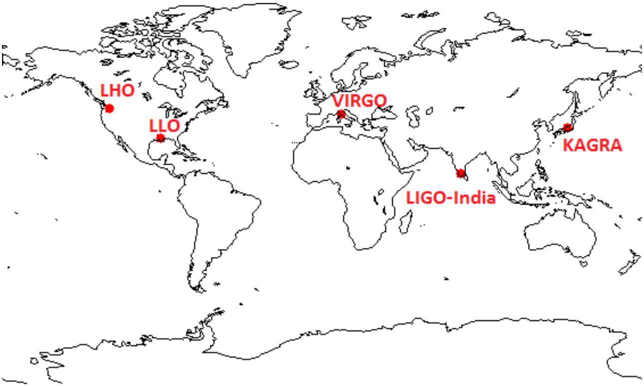
Interferometric Ground-based Detectors



Detector	Country	Arm length	Approximate date	Generation
GEO600	Germany	600 m	2001-present	1st
TAMA300	Japan	300 m	1995-present	1st
iLIGO	US	4 km	2004-2010	1st
iVIRGO	Italy	3 km	2007-2010	1st
aLIGO	US	4 km	*est.* 2016	2nd
KAGRA	Japan	3 km	*est.* 2018	2nd
aVIRGO	Italy	3 km	*est.* 2017	2nd
ET (Einstein Telescope)	Italy	10 km	*est.* 2025	3rd

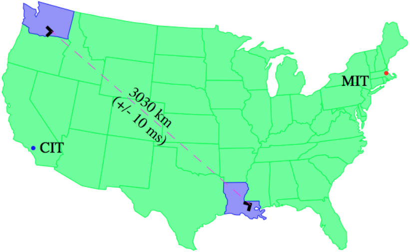
Detectors

Advanced Ground-Based Detectors (2nd generation)



LSC: LIGO Scientific Collaboration

LSC in Sao Paulo, Brazil



LIGO   LSC   LIGO Scientific Collaboration

What is LSC?

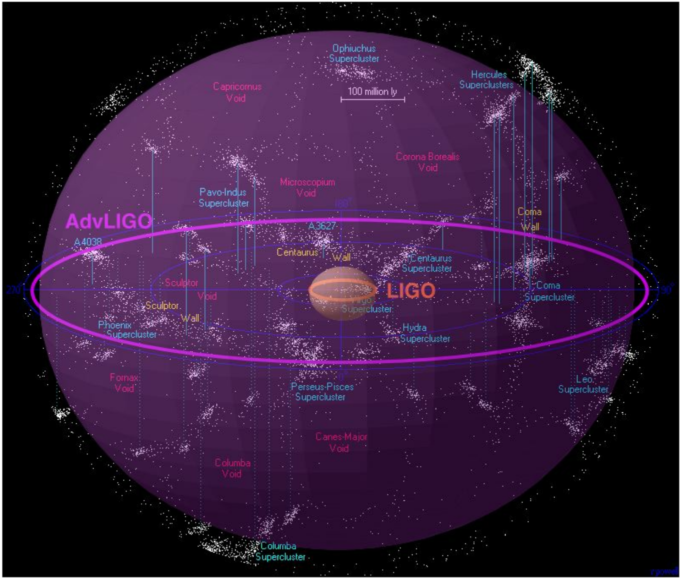
- 900+ scientists contribute from 50+ research institutes all around the globe (ICTP-SAIFR joined @2013).

Detectors

Some Photos of the Actual LIGO Detectors

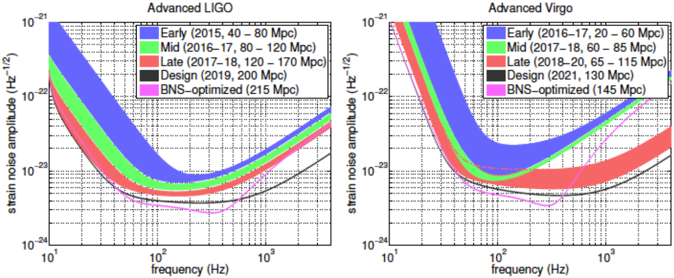
Detectors

Advanced LIGO vs initial LIGO



Detectors

Sensitivity Curve Time Plan and The Estimated Rate of BNS sources in Advanced LIGO

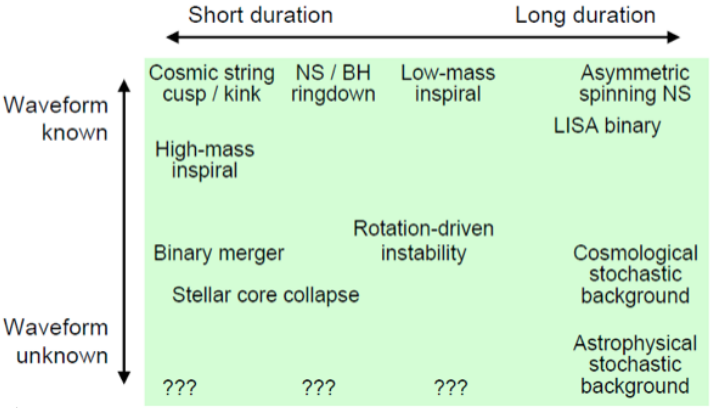


Epoch	Estimated Run Duration	$E_{\rm GW}=10^{-2}M_{\odot}c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

see arXiv: 1304.0670

Data Analysis

Data Analysis



Short duration

Long duration

Waveform known

Waveform unknown

Cosmic string cusp / kink

NS / BH ringdown

Low-mass inspiral

Asymmetric spinning NS

LISA binary

High-mass inspiral

Rotation-driven instability

Binary merger

Cosmological stochastic background

Stellar core collapse

Astrophysical stochastic background

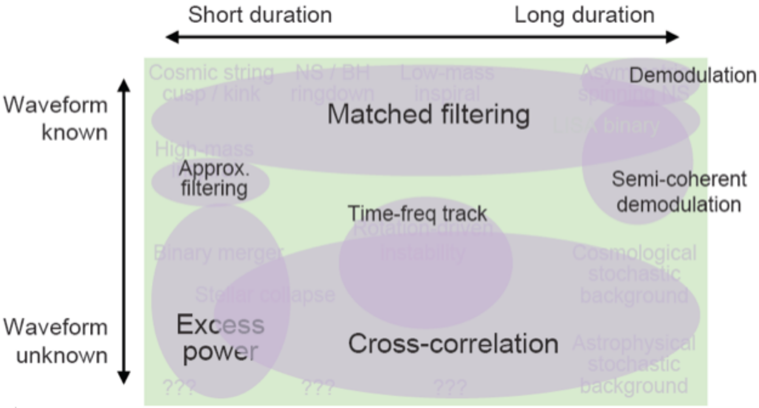
???

???

???

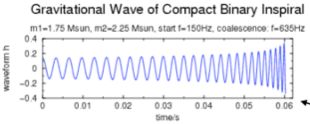
Data Analysis

Search Techniques



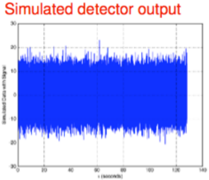
Data Analysis

Matched Filtering



Gravitational Wave of Compact Binary Inspiral

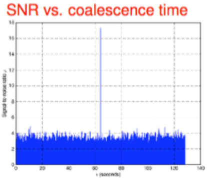
m1=1.75 Msun, m2=2.25 Msun, start f=150Hz, coalescence: f=635Hz



Simulated detector output

Waveform Template, h_T

Detector output, s



SNR vs. coalescence time

$$SNR = \frac{< s, h_T >}{\sqrt{< h_T, h_T >}}$$

$$< a, b > = \int df \, \frac{\tilde{a}(f)\tilde{b}^*(f)}{S_n(f)}$$

GW Astronomy

- Speed of GWs
- Polarization of GWs
- Gravitational Radiation Reaction
- The two-body problem: EOM ⇒ Energy Flux ⇒ Waveform

  in ST see: [Mirshekari and Will, PRD 87 (2013)], [Lang PRD 89, (2014)] [Lang arXiv:1411.3073]
- Black-hole Spectroscopy:

  Testing no-hair theorem. Does Kerr metric explain the exterior geometry of a rotating black-hole?
- Lorentz Symmetry Violation: See [Mirshekari, Yunes, and Will, PRD 85, (2012)]

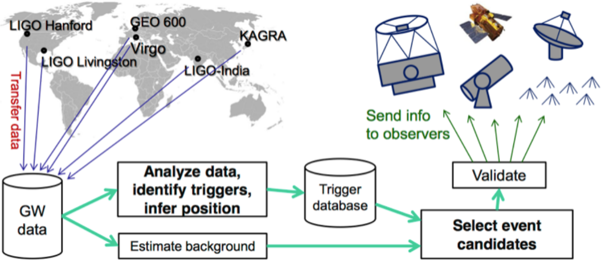
Astrophysics with GWs

Possible Astrophysics using GWs

- Interacting compact binaries: See [Stroeer and Vecchio, CQG 23, (2006)].
- Resolving the mass-inclination degeneracy
- Black-Hole Astrophysics
- Neutron Star Astrophysics
- Multi-messenger GW Astronomy See next slide!

Astrophysics with GWs

Multi-Messenger Astronomy: Electro-Magnetic (EM) counterparts



- Simultaneous EM observations⇒ better science!
- Better localization of GW sources
- Prompt public release of triggers (after 4 detection!)

Cosmology with GWs

Possible Cosmology using GWs

- GWs may inform us about cosmology in at least two ways:
  1. Astrophysical GW Background
  2. Cosmic GW Background
- Stochastic GW background may be observed by interferometric GW detectors, Pulsar Timing Array, and CMB polarization (BICEP2). See [Creminelli's lecture on 3 Dec].
- Ground-based Ad. LIGO detectors should be able to see a few individual sources @z∼1 but future space-based detectors will be a significant tool for cosmology.
- Future Deci-hertz Interferometer GW Observatory (DECIGO) and Big Bang Observatory (BBO).

Cosmology with GWs

Measuring Cosmological Parameters

- Measuring luminosity distance

  [Schutz 1986, 2002], [Holz and Hughes, Astrophys. J. 629 (2005)]
- An accurate measurement of Hubble constant

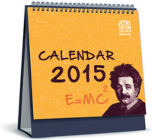
  [Jackson, Living Rev. Relativity, 10, lrr-2007-4, (2007)], [MacLeod and Hogan, PRD 77 (2008)]
- Characterizing the evolution of Dark Energy

  [Dalal, Holz, Hughes, S.A., Jain, PRD 74 (2006)]

Summary

Summary

1. First generation of GW detectors have been built and operated for ∼10years (2000-2010).
2. No detection has been made. Upper limits have been set on the population rate of astronomical sources.
3. Second generation of GW detectors will be online in a few months! (April 2015): 10X better @designed sensitivity
4. Soon, GW astronomy (with multi-messenger astronomy) will open a new window to do astrophysics and cosmology and to test fundamental theory of gravity in strong fields.



@2015&16, we hope not only celebrate 100th birthday of GR but also the first direct detection of GWs!

Thank You[3]!

---

[3] all for your attention and Riccardo, Fabian, and Irène for useful comments.

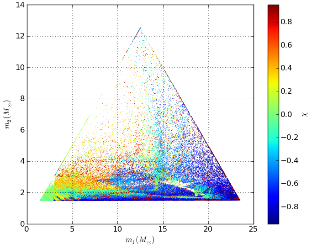
Bonus Slides

Data Analysis

Template Banks: How we can be sure that we can find the extremely small GW signal in a sea of noise without loosing a certain level of accuracy?

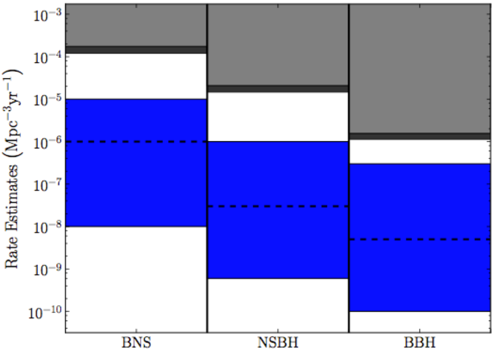
- Template banks are crucial in detection and data analysis.
- A template bank includes a huge number of waveform templates in a specific range of source parameters (like component masses and spins) such that it covers the whole parameter space with a certain level of accuracy.
- Example: $1.5 < m_{1,2} < 23.5 M_{\odot}$, $3 < m_1 + m_2 < 25 M_{\odot}$, $\frac{|s_{NS}|}{m^2} < 0.1$, $\frac{|s_{BH}|}{m^2} < 0.95$, aligned spins, Ad. VIRGO noise, representing $400K$ template waveforms.

Figure from [SM and R. Sturani (2014), in preparation] in where $\chi = \frac{s_{1z} m_1 + s_{2z} m_2}{m_1 + m_2}$.



Expected Rate of Sources in Ad. LIGO

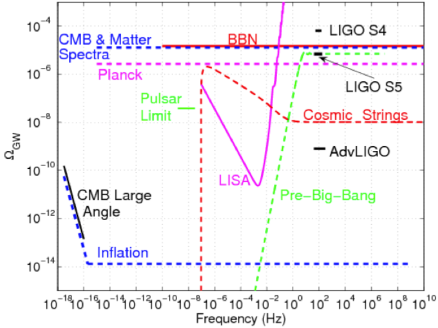
Statistical estimations for binary sources



Comparison of coalescence upper limit rates for NS-NS, NS-BH and BH-BH systems. The light gray regions display the upper limits obtained in the S5-VSR1 analysis; dark gray regions show the upper limits obtained in the S6-VSR2-3 analysis, using the S5-VSR1 limits as priors. The lower (blue) regions show the spread in the astrophysically predicted rates, with the dashed-black lines showing the "realistic" estimates. See arXiv:1003.2480 and B. Abbott et al., Phys. Rev. D 85 (2012) 082002.

Cosmology with GWs

Detector Sensitivities to Stochastic Background Sources (Cosmological Sources!)



Comparison of different stochastic gravitational wave background measurements and models. The indirect bounds due to BBN and CMBR / matter power spectra apply to the integral of $\Omega_{GW}(f)$ over the frequency bands denoted by the corresponding dashed curves. Projected sensitivities of the satellite-based Planck CMBR experiment and LISA GW detector are also shown. The pulsar bound is based on the fluctuations in the pulse arrival times of millisecond pulsars and applies at frequencies around 10^{-8} Hz. Measurements of the CMBR at large angular scales constrain the possible redshift of CMBR photons due to a stochastic gravitational wave background, and therefore limit the amplitude of that background at largest wavelengths (smallest frequencies). Examples of inflationary, cosmic strings, and pre-big-bang models are also shown (the amplitude and the spectral shape in these models can vary significantly as a function of model parameters). see Keith Riles, arXiv:1209.0667

Cosmology with GWs

Planned space-based GW observatories DECIGO and BBO sensitivity cures and CGWB signals in different inflation models.

The two concave curves are the sensitivity curves of the detectors

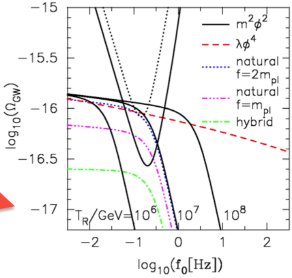


FIG. 1: Spectra of the gravitational wave background for different inflation models, shown with the sensitivity curves of DECIGO (dotted) and BBO (solid). The spectra are calculated assuming $T_{\rm RH} = 10^7$GeV. The cases of $T_{\rm RH} = 10^6$GeV and 10^8GeV are also plotted assuming the quadratic potential model. Note that the spectrum lines mean the time-averaged value of $\Omega_{\rm GW}$.

See [Kuroyanagi, Chiba, and Sugiyama PRD 83 (2011)]