Towards the first detection of Gravitational Waves: Challenges and Prospects

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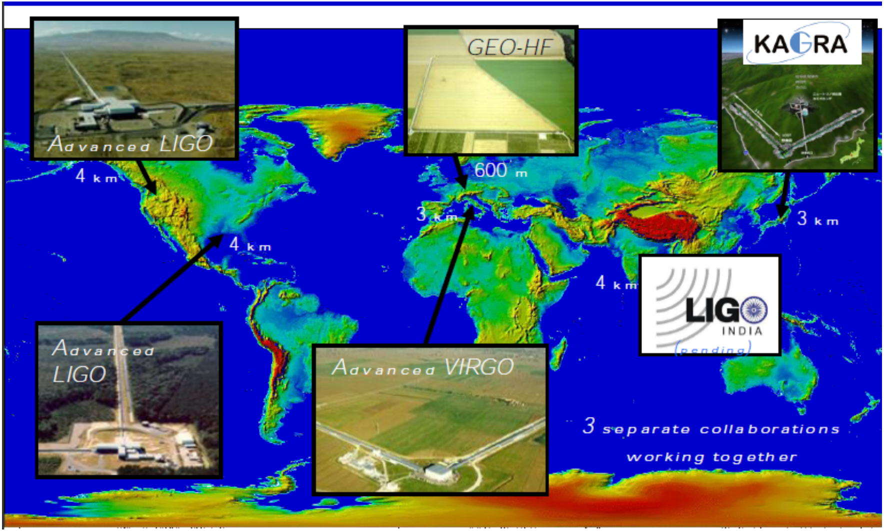
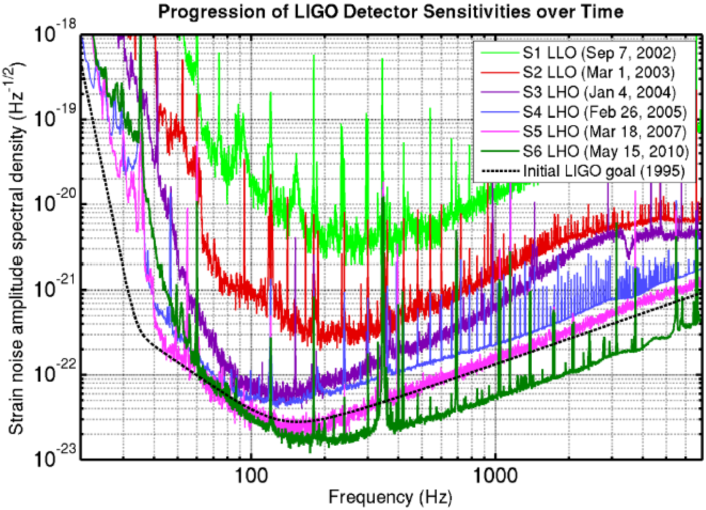
Views presented in this talk are personal.

Upcoming Gravitational Wave Detector Network



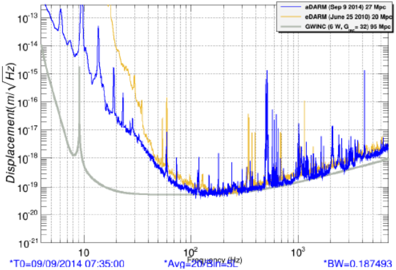
[Slide borrowed from Peter Shawhan's Talk]

How Initial LIGO achieved its design Sensitivity



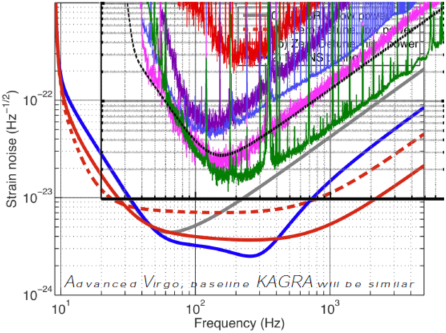
Gearing towards first Science Run (O1)

Ongoing commissioning of aLIGO



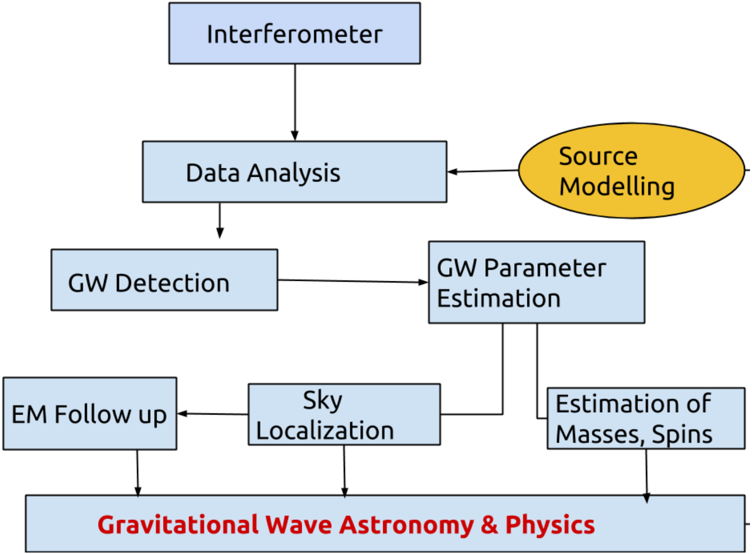
Double NS distance reach of $\sim 60\,Mpc$ is achieved.

Designed sensitivity of aLIGO



aLIGO will access roughly 1000 times the volume that was accessible by Initial LIGO.

Route to Gravitational Wave Astronomy



What are the challenges to be met?

I will focus on one challenge each in

Challenge

- **Data Analysis**
- **Source modelling**
- **Astrophysics & Fundamental Physics**

Data Analysis

Rapid Follow up of GW events and Multi-messenger Astronomy.

Following up a GW event Electromagnetically: Multi-messenger Astronomy

Motivation

* Candidate events in the GW interferometers will be followed up with various Electromagnetic telescopes in search of accompanying EM emission from the source. Detection of such a EM counterpart will add even more confidence to the first detection.
* Depending on the source, there are wide variety of proposals about the nature and frequency of accompanying EM counterparts (e.g.: Short GRB afterglow [Xray to Radio], Kilonova[Optical/IR], Unknown/Unexpected)

Challenge: Low latency data analysis Pipelines

- Gravitational Wave Astronomy requires **real time detection** and **rapid sky localization** of GW events.
- Reasonable sky localization using GW network.

EM follow up of a short Gamma Ray Burst: Timeline

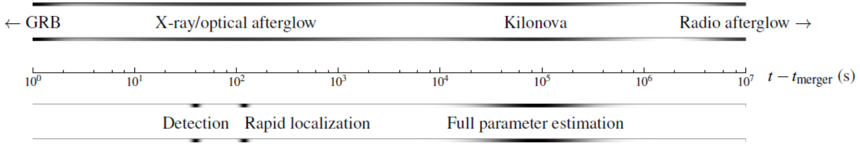
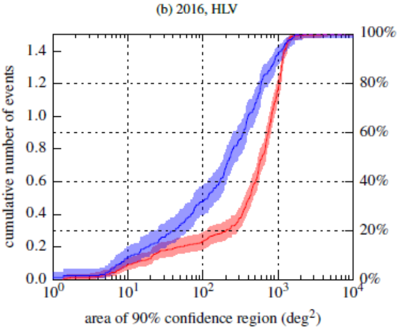


Figure 2. Rough timeline of compact binary merger electromagnetic emissions in relation to the timescale of the Advanced LIGO/Virgo analysis described in this paper. The time axis measures seconds after the merger.

Accurate sky maps may be available minutes after detection!

[Singer+ 2014]

Sky localization: 3 detector (HLV)



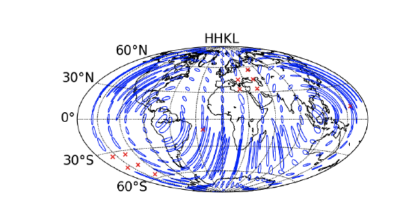
[Singer+ 2014]

Source Localization with a World wide Network

[Fairhurst, 2012]

Future

Figure: DNS system at 160 Mpc, 90% confidence region for localization errors.



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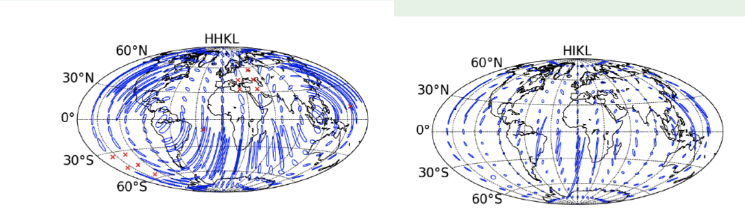

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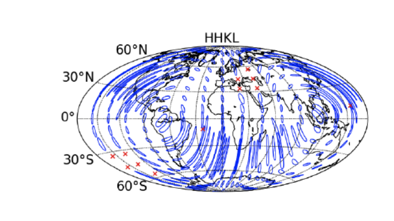
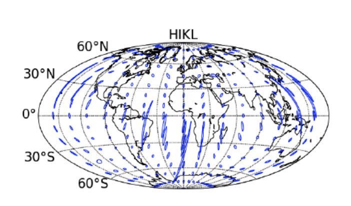
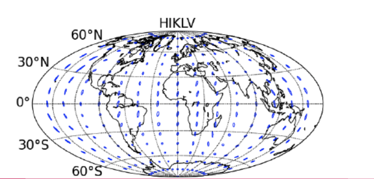


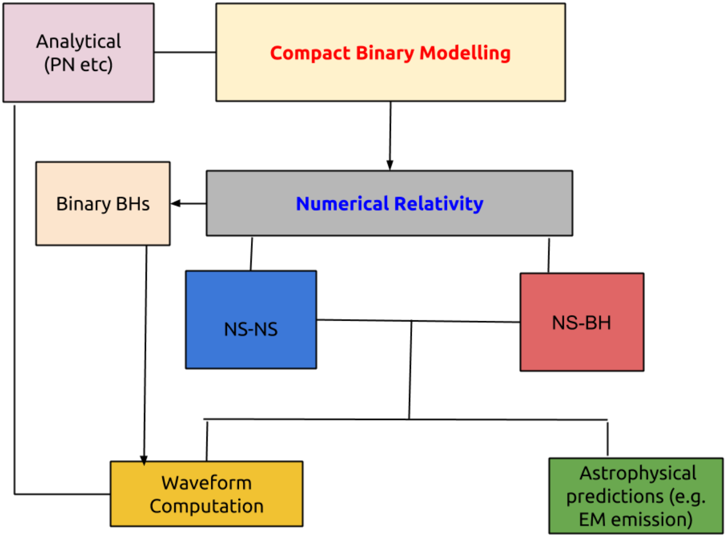




Source Modelling

Taming the compact binaries with NSs

Modelling Compact Binaries

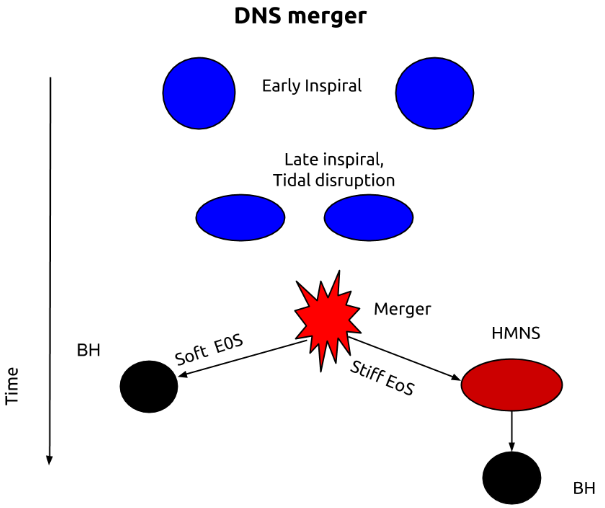


Mergers of Compact Binaries with NS

Challenge

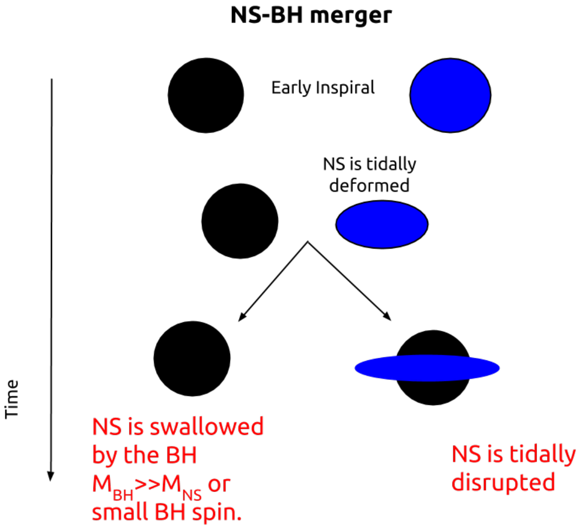
- Solve Einsteins Equations + Equations for Magneto-hydrodynamics.
- Dependence of the Simulation on Equation of state of the Neutron Star(s).

DNS merger



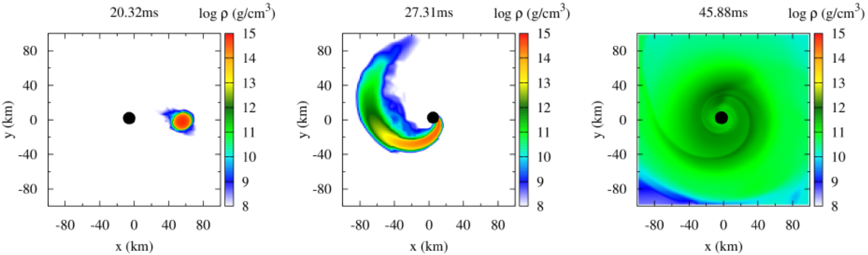
[Cartoon based on Kyutoku+ Numerical Simulations]

NS-BH Mergers



[Cartoon based on Kyutoku+ Numerical Simulations]

Tidal Disruption is important



[Kyutoku+, 2015]

- Imprints on the gravitational waveform [Relevant for GW data analysis]
- Mass ejected during disruption can give rise to EM emission [Relevant for understanding associated EM emissions]

NS-BH Waveforms with and without Tidal disruption

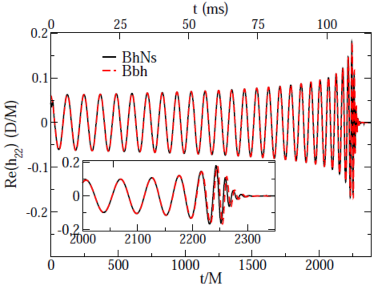


FIG. 8: Dominant (2,2) mode of the gravitational waveform for the NSBH ('adaptive' run) and BBH mergers. The insert zooms on the time of merger. A time and phase shifts have been applied to the BBH waveform in order to minimize the phase difference with the NSBH results in the interval $675 < t/M < 2175$.

[Foucart+ 2013]

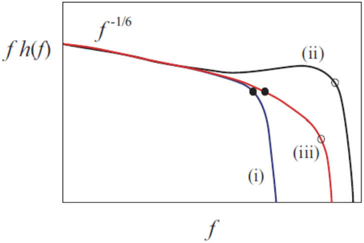


FIG. 21. A schematic figure of three types of gravitational-wave spectra. Spectrum (i) is for the case in which tidal disruption occurs far outside the ISCO, and spectrum (ii) is for the case in which tidal disruption does not occur. Spectrum (iii) is for the case in which tidal disruption occurs and the QNM is also excited. The filled and open circles denote $f_{\rm tidal}$ and $f_{\rm QNM}$, respectively.

[Kyutoku+ 2011]

NS-BH waveform without tidal disruption is extremely close to the BBH waveform.

Beyond the Merger

Another exciting possibility of these simulations is that it can predict the amount of mass ejected during the merger as a function of various parameters (such as Mass and Spin of the BH, mass ratio of the binary, EoS of the NS etc.

Dynamical Mass ejection in NS-BH mergers

- Ejection is anisotropic with a opening angle 10-20 deg around the orbital plane.
- Ejected Mass can be as big as $0.1M_\odot$ and sub-relativistic ($v \sim 0.2 - 0.3c$)
- System gets a kick velocity $\mathcal{O}(100km/s)$.

[Kyutoku+ 2015]

Very important in understanding EM counterparts to the GW events, such as Kilonova.

Astrophysics

What can GWs tell us?

GW measurements

Gravitational waveforms are functions of the following variables:

$$\lambda^{\mathbf{i}} = \{\mathbf{m_1}, \mathbf{m_2}, \mathbf{s_1}, \mathbf{s_2}, \mathbf{D_L}, \theta, \phi, \iota, \mathbf{e}, \mathrm{EOS}\}$$

GW observations would allow us to measure these (or a subset of these).

Gravitational Wave Astronomy

Some important ideas

- Joint Short GRB + GW observations [Archana's talk + Saleem's Talk]
- Measurement of EoS of a Neutron Star[Sukanta's talk]
- Measurement of Hubble Constant [A Ghosh et al].

Fundamental Physics

Was Einstein Right?

Tests of Gravity using GWs

Philosophy

- If the underlying theory of gravity is not GR but something else, the gravitational waveforms will be different in that theory.
- Estimating the additional parameters of the alternative theory will give us an estimate or bound on the parameters. (Parameter Estimation Problem)

Signatures of Possible deviations from GR

- Monopole, Dipole GW radiation.
- Additional modes of polarization of GWs (beyond $h_+, h_\times$).
- Non-null propagation of GWs.
- Correction to the GR phasing formula.

Different alternative theories

Zoo of alternative theories

- Scalar Tensor Theories.
- Tensor-Vector-Scalar (TeVeS) Theories.
- Massive Graviton Theories.
- $f(R)$ Theories.
- Higher Dimensional Gravity.

For any theory of gravity that we want to test, we want to know if there are any features in the theory which are different from GR and can those be observed with the sensitivity of GW detectors.

Brans-Dicke theory

Phasing in BD theory

[Will 94, Krolak Kokkotas, Schäfer 1994.]

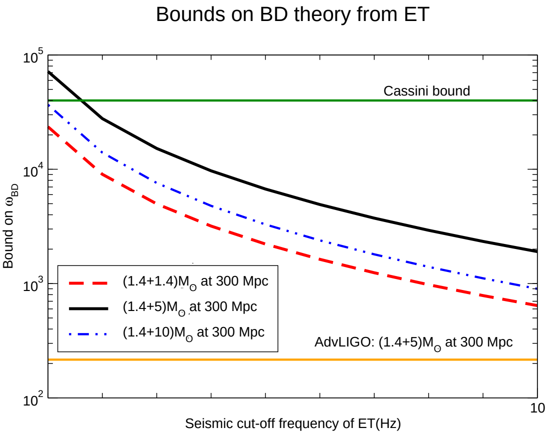
- This introduces a new term in GW phasing formula which is proportional to a parameter defined as $\omega_{\rm BD}$:

$$\Psi(f) = 2\pi f\, t_c - \phi_c + \frac{3}{128\eta} v^{-5}\left[1 + \frac{3\,\mathcal{S}^2}{84\,\omega_{\rm BD}} v^{-2} + \text{GR terms}\right]$$

where $v = (\pi m f)^{1/3}$ (characteristic velocity), $\mathcal{S} = s_2 - s_1$ (difference in 'sensitivities' of the two compact objects.)

- For binary neutron stars $\mathcal{S} \sim 0.05 - 0.1$ and for NS-BH binaries $\mathcal{S} \sim 0.3$ and for a binary BH $\mathcal{S} = 0$.
- **Hence one of the binary constituents should be a NS.**

Bounds on BD parameter



[KGA, A Pai, 2013]

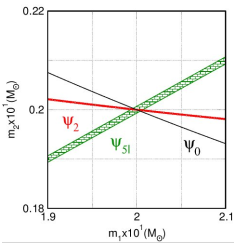
The higher the bound, the better

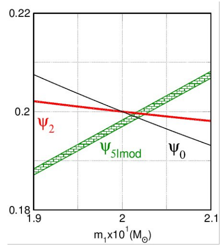
Model Independent Tests

[Blanchet & Sathyaprakash 1994, 1995, KGA, Iyer, Qusailah & Sathyaprakash, 2006a,b; Mishra, KGA, Iyer& Sathyaprakash, 2011.]

$$\psi(f) = 2\pi f t_c - \phi_c - \frac{\pi}{4} + \sum_{k=0}^{7} (\psi_k + \psi_{kl} \ln f)\, f^{\frac{k-5}{3}},$$

- For nonspinning binaries, ψ_k & ψ_{kl} are functions of the masses of the constituent binaries.
- Measure at least 3 of these coefficients and require their consistency in the Mass plane.
- Similar in spirit to binary pulsar tests!





Concluding Remarks

GW detection throws a lot of challenges and promises lots of astrophysical returns.

Complicated interplay between data analysis, source modelling and astrophysics

The first few detections can considerably change our understanding of the compact objects and related phenomena.

In addition to the astrophysics, GWs might enable tests of gravity theories in a relativistic, strong-field, radiative regime.