The Universe in a New Light @ *ICTS-TIFR, Bengaluru*

Discovery of GW150914: Indian contributions

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indigo

Outline

- Contributions to foundations of the field
- Contributions specific to GW150914

Contributions to the Foundations

Theoretical

- Stability of BH solutions & Quasi-normal modes (C V Vishveshwara)
- Post-Newtonian Waveform modelling (The RRI group lead by Bala Iyer with Blanchet, Damour, Will, Wiseman+) lead to 3.5PN accurate phasing formula.
  - Formed the basis for data analysis and drove the experimental efforts for two decades.
  - Formed the basis for Effective One Body (EOB) approach (semi-analytical way of solving two body problem)
  - Forms the basis for Phenomenological parametrizations of Numerical Relativity waveforms (first work on Phenom by P Ajith+ 2007).
- EOB and IMRPhenomP waveforms are the waveform models used in the analysis of GW150914

Data Analysis Strategies [IUCAA]

- Fundamental work on geometrical aspects of Template placement problem (S V Dhurandhar, B S Sathyaprakash, R Balasubramaniam)
- Theory of data analysis for a network of detectors (A Pai, S Bose, S V Dhurandhar)
- Many other works of S V Dhurandhar with students S Mitra, A Sengupta, H Mukhopadhyay

GW150914

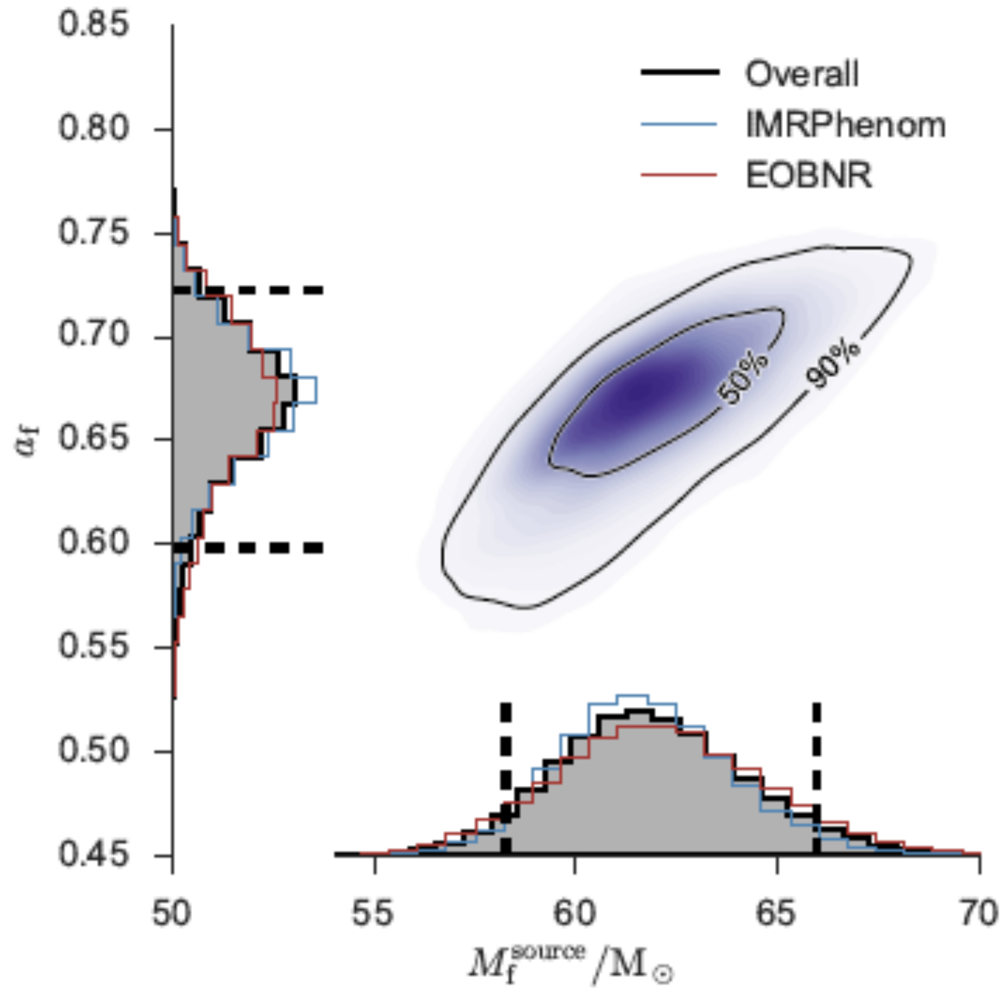
Detector characterisation

- Works of S Bose, A Gupta, S V Dhurandhar helped to charaterize the detector leading to reliable estimates of the statistical significance.

Waveforms

- Waveforms used in the data analysis which lead to the discovery was based on the post-Newtonian waveforms developed by the RRI group (in collaboration with other international groups).

Mass and Spin of the Remnant BH



Astrorel group @ ICTS: Archisman Ghosh, Abhirup Ghosh, P Ajith, N J-Mcdaniel+

Used fitting formulae from GR numerical simulations that relate masses and spins of component BHs to the final remnant.

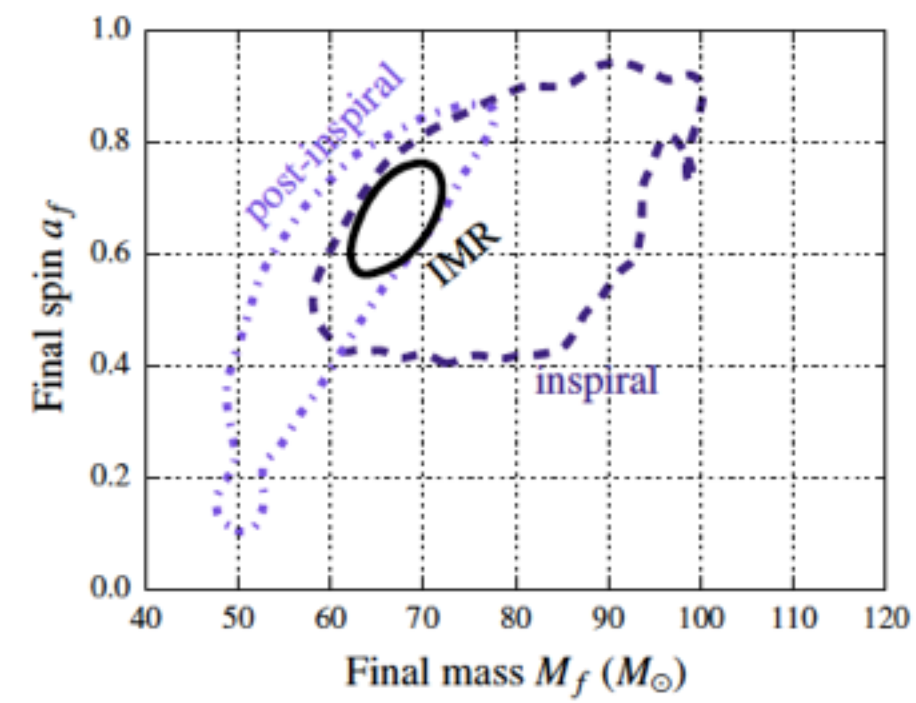
Spins of the component BHs is badly constrained.

Was the binary circular?

Efforts were made to constrain eccentricity and study systematics which concluded that the eccentricities ~0.1 at 10 Hz may not induce measurable deviations from the circular orbit waveforms

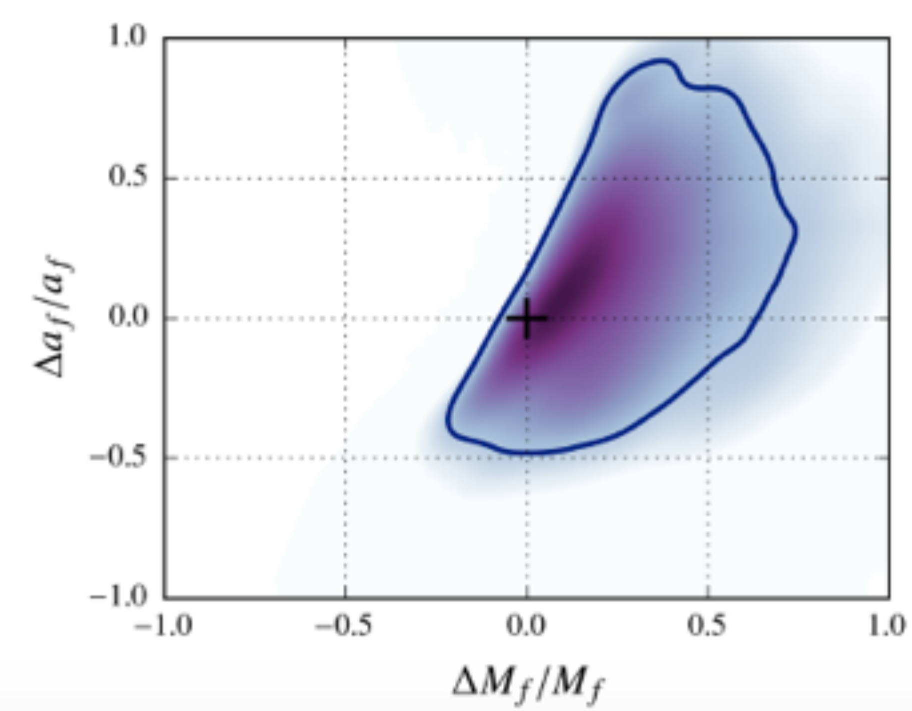
M Haney, A Gopakumar+

Tests of GR: The Inspiral Merger Ringdown consistency Test



Comparing mass and spin of the remnant BH estimated from different parts of the gravitational waveform using General Relativistic predictions provided by NR simulations.

[Ghosh+ 2016]



[Abhirup Ghosh, Archisman Ghosh, P Ajith, N J-McDaniel, C K Mishra+]

Quasi-normal modes

The data after the peak of the waveform is consistent with the least damped, quasi-normal mode ringing of the remnant BH

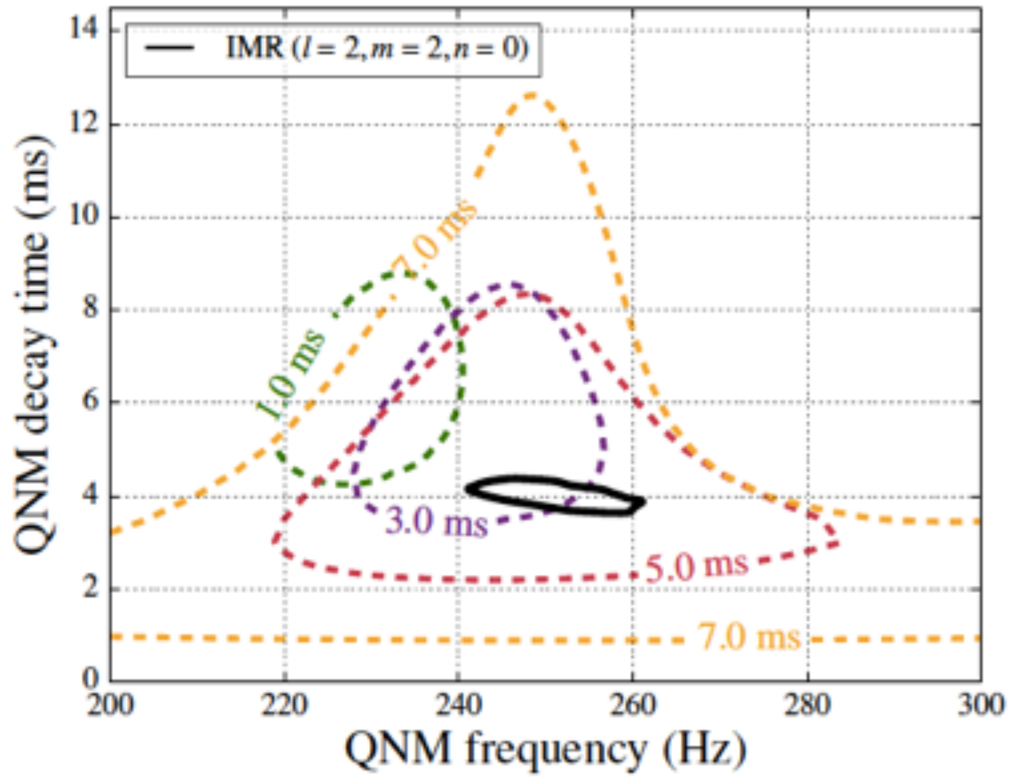


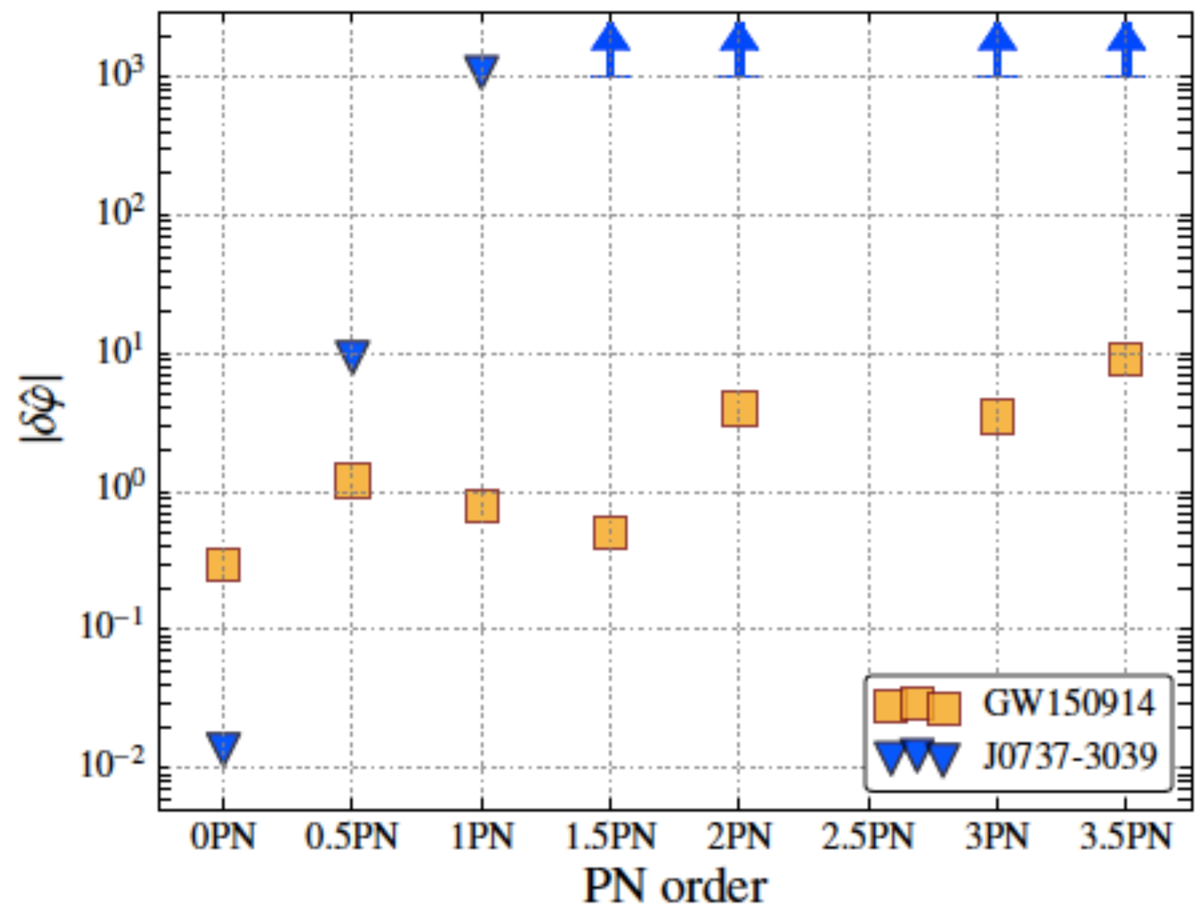
FIG. 4. We show the posterior 90% confidence regions from Bayesian parameter estimation for a damped-sinusoid model, assuming different start-times $t_0 = t_M + 1, 3, 5, 7$ ms, labeled by offset from the merger time t_M of the most-probable waveform from GW150914. The black solid line shows contours of 90% confidence region for the frequency f_0 and decay time τ of the $\ell = 2$, $m = 2$ and $n = 0$ (i.e., the least damped) QNM obtained from the inspiral-merger-ringdown waveform for the entire detector's bandwidth.

Vishu's work on BHs & Quasi-normal modes

Bounds on post-Newtonian phasing coefficients

Use GW observations to bound PN coefficients in the phasing formula

[Arun+ 2006a,b, Mishra+2010]



[A Samajdar, M Saleem, R Nayak, A Pai, N J-McDaniel, others]

Mass of the graviton

$m_g \leq 1.2 \times 10^{-22}$ eV/c^2 at 90% confidence.

Beats the solar system (static) bound by a factor of ~3 and Binary pulsar (dynamical) bound by a factor of 1000.

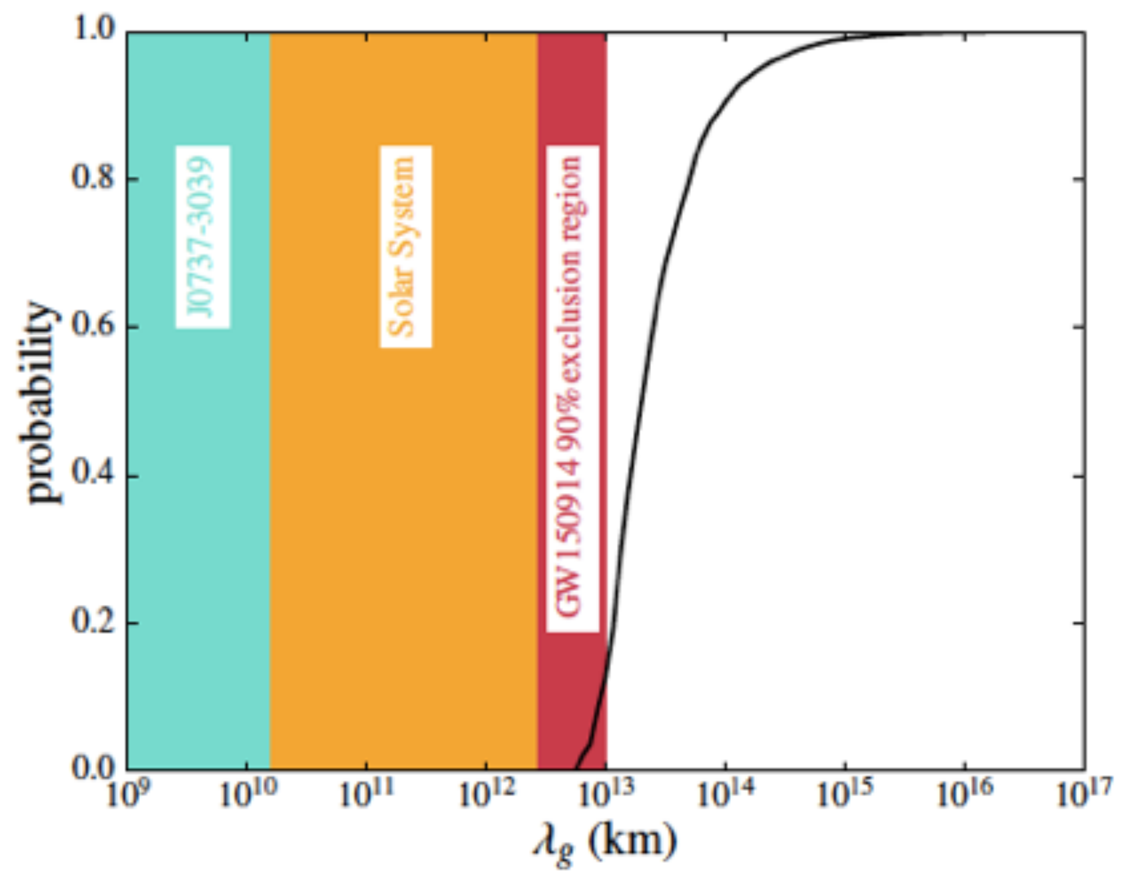


FIG. 8. Cumulative posterior probability distribution for λ_g (black curve) and exclusion regions for the graviton Compton wavelength λ_g from GW150914. The shaded areas show exclusion regions from the double pulsar observations (turquoise), the static Solar System bound (orange) and the 90% (crimson) region from GW150914.

Arun+

Localisation & EM Follow up

Source localisation of GW150914 was ~590 sq. degrees.

GW150914 was followed up in various EM bands.

Lesson: A world-wide network of GW detectors is crucial for good localisation

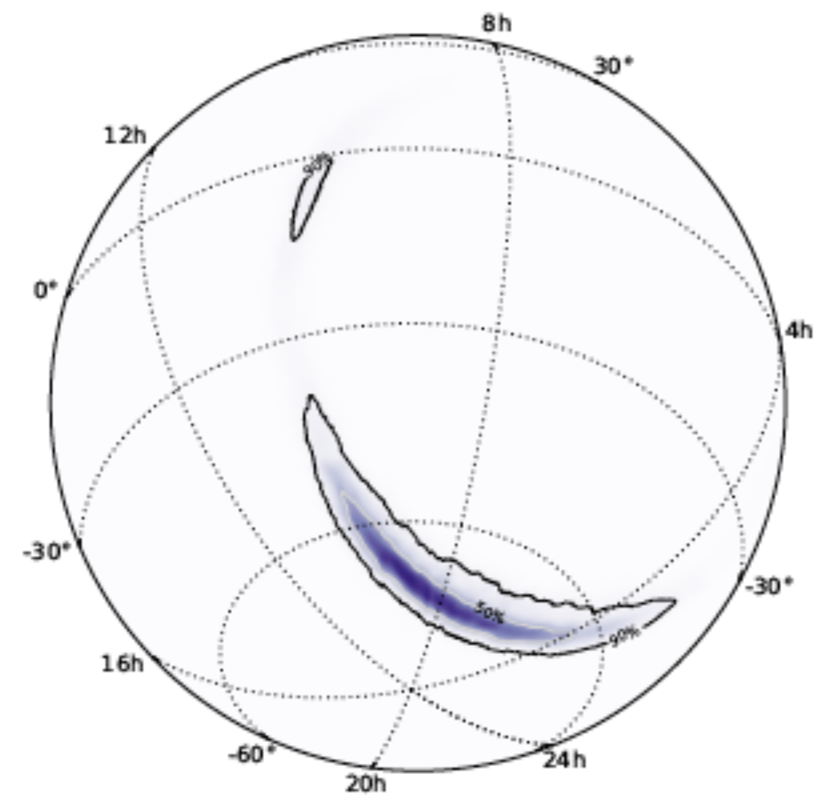


FIG. 4. Lambert projection of the posterior probability density for the sky location of GW150914 showing contours of the 50% and 90% credible regions plotted over a colour-coded posterior density function. The sky localization forms part of the ring, set by the time delay of $6.9^{+0.5}_{-0.4}$ ms between the Livingston and Hanford detectors.

EM follow up (Indian efforts): V Bhalerao, S Bose, J Rana, B Gadre, M Singal+

Summary

- Significant contributions from the Indian scientists to the discovery and consequent analysis of GW150914
- Astrorel group @ ICTS-TIFR plays crucial roles in the parameter estimation and test of GR with GW150914