SciNeGHE 2016 ***20/10/2016***

Gravitational waves transients : Sources and Searches

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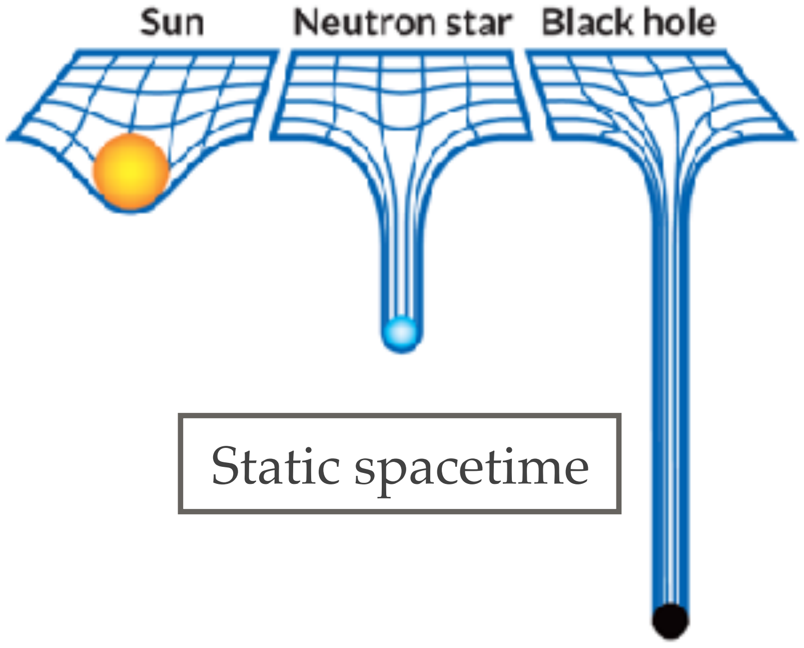
DCC number :G1602143

Outline

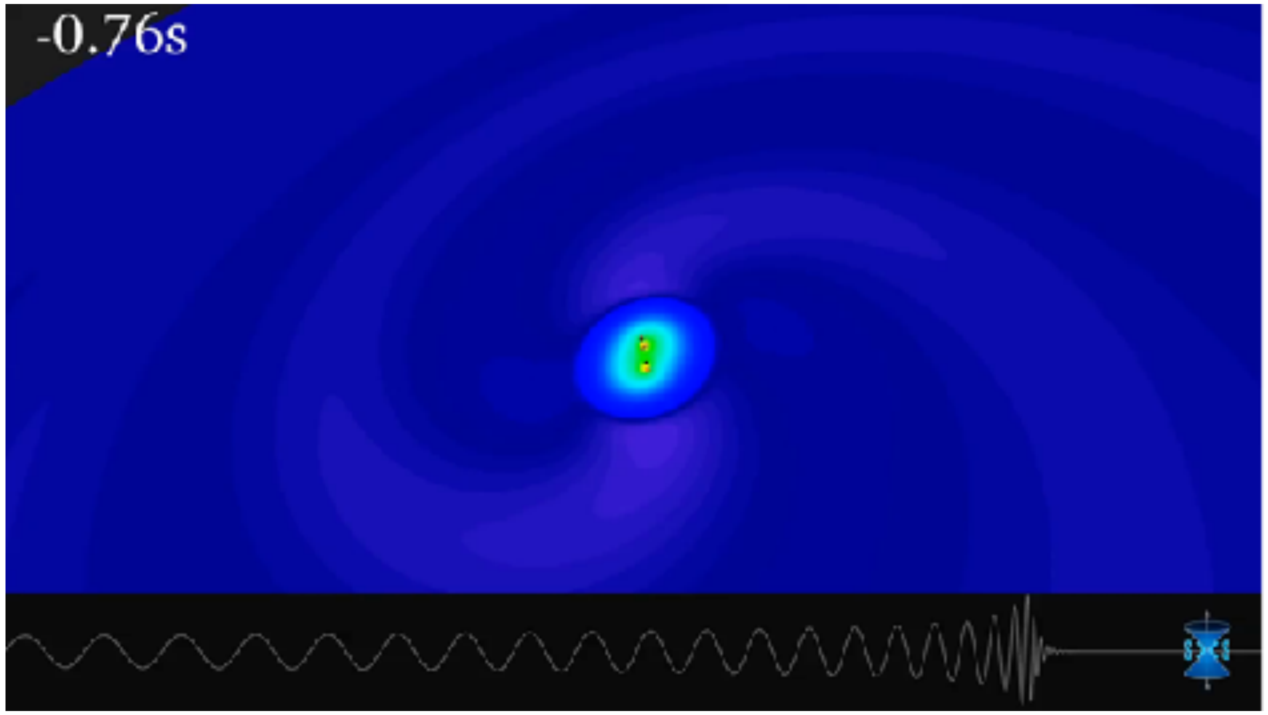
- Gravitational waves
- A brief history of gravitational waves
- Sources and searches
  - “Known” transient sources
  - Modelled searches
  - Un-modelled searches
  - Modelled sources in un-modelled search
  - Computation of background and significance
  - Data quality and glitches
- Gravitational Waves observations : A proof that the system works
- Future outlook

Gravitational Waves

- **Spacetime** is a mathematical quantity and is defined as a 4 dimensional, smooth, connected (affine and torsion free connection) Lorentzian Manifold (M,g), this implies that the metric (g) has signature (3,1) or (1,3)
- This metric determines the geometry of spacetime
- In GR spacetime is a **deformable object**, gravity is responsible for this, perturbation on spacetime are represented as perturbation of the metric
- The tensorial perturbation of this metric are known as **gravitational waves**
- It has two polarisation : plus + and cross **x**
- We observed for the first time this fundamental process of nature i.e. **dynamical spacetime** on Sept. 14th



Static spacetime



Dynamical spacetime
Credits: SXS collaboration

A brief history of gravitational waves : formalism

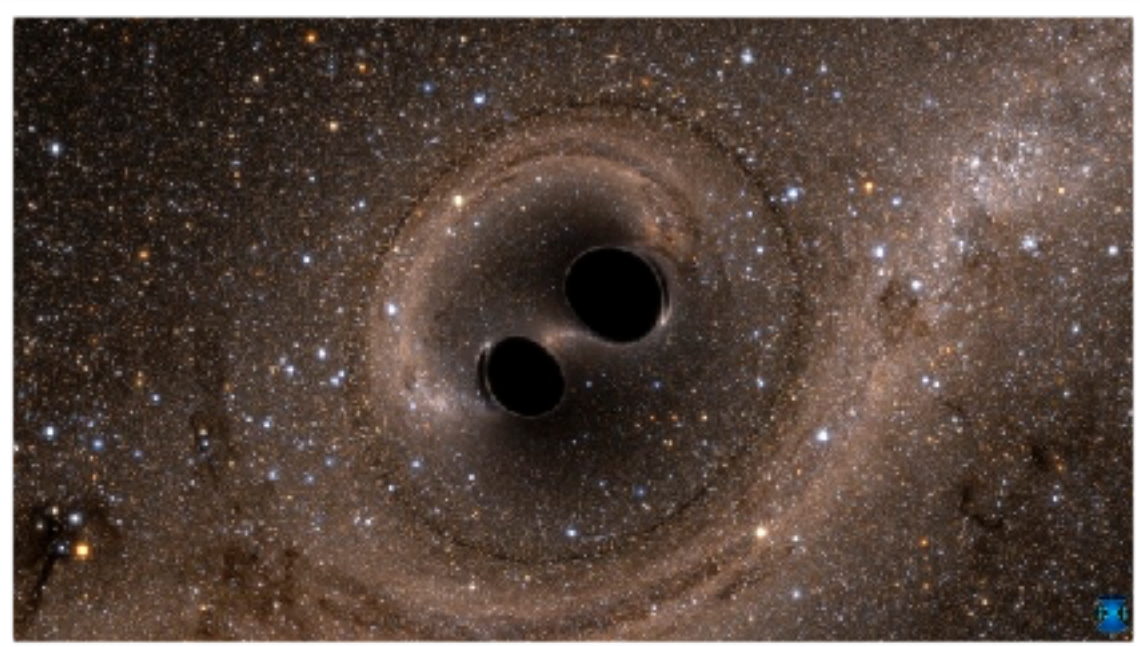
- **1916** : final formulation of the Einstein's field equations of general relativity
- **1918** : the effect of gravitational waves (GWs) was calculated, resulting in Einstein's famous "quadrupole formula"
- **1936** : Einstein rejects the existences of gravitational waves calling it an artefact of linearisation
- **1957 - 1970** : Goldberg, Pirani, Bondi, Sachs and others proved the physical reality of GWs
- **1991 - now** : Damour, Iyer, Blanchet et al develops post-Newtonian theory for compact binary coalescence and further developments are going on (valid during inspiral)
- **1999 - now** : Buonanno, Damour et al develops effective one body approach for two body dynamics (valid till late inspiral)
- **2005 - now** : Numerical relativity matured and provides exact solutions for compact binaries

A brief history of gravitational waves : experiments

- **1962** : Russian physicists M. E. Gertsenshtein and V. I. Pustovoit publish paper sketch optical method for detecting gravitational waves
- **1969** : Physicist Joseph Weber claims gravitational wave detection using massive aluminium cylinders—replication efforts fail
- **1972** : Rainer Weiss of the Massachusetts Institute of Technology (MIT) in Cambridge independently proposes optical method for detecting waves
- **1974** : Astronomers discover pulsar orbiting a neutron star that appears to be slowing down due to gravitational radiation—work that later earns them a Nobel Prize
- **1995** : Construction starts on GEO600 gravitational wave detector in Germany, which partners with LIGO and starts taking data in 2002
- **1996** : Construction starts on VIRGO gravitational wave detector in Italy, which starts taking data in 2007
- **2002–2010** : Runs of initial LIGO—no detection of gravitational waves
- **2007** : LIGO and VIRGO teams agree to share data, forming a single global network of gravitational wave detectors
- **2015** : Advanced LIGO begins initial detection runs in September
- **2016** : On 11 February, NSF and LIGO team announce successful detection of gravitational waves
- **2016 - now** : Major upgrades in the detectors and the two LIGOs detected gravitational waves from binary black hole merger

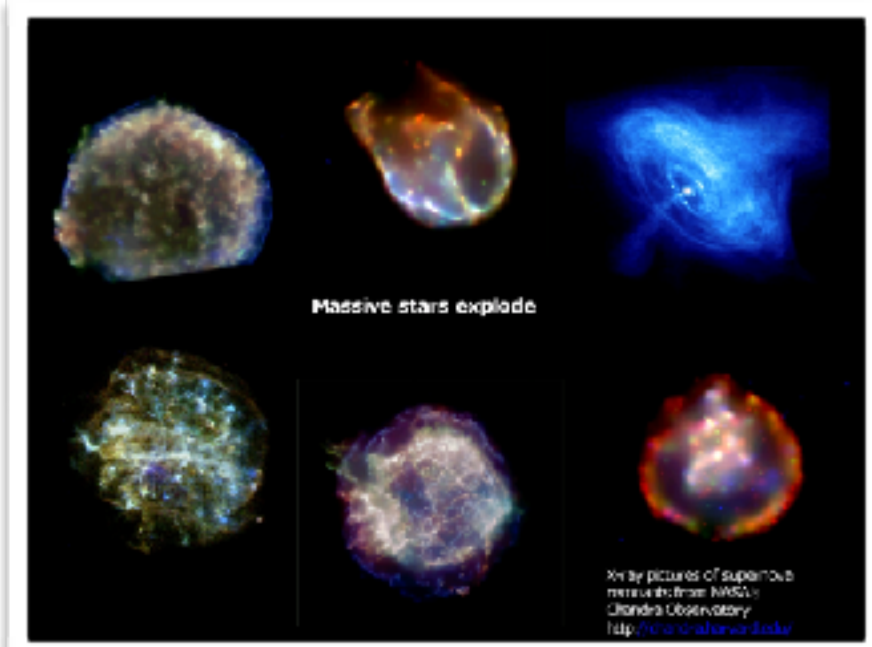
Sources and searches : “known” transient sources

Modelled Sources



- Compact binary coalescence
  - Binary Neutron Stars
  - Binary Black Holes
  - Black Hole - Neutron Stars
- Cosmic strings

Un -Modelled Sources



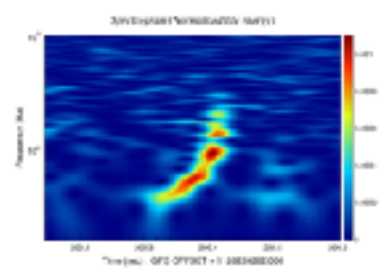
- Supernovae
- Some non vanilla CBC
  - highly eccentric
  - highly precessing, high mass ratio etc
  - exotic CBC
- Surprises

Image Credit : SXS & NASA

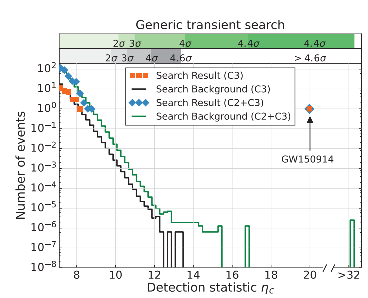
Sources and searches : Generic scheme for gravitational wave search

GW Strain from detectors

Trigger generation



Calculation of significance



Data Quality, validation

Environmental monitering

Source identification (paramaters)

Fundamental physics (Test of GR etc)

Astrophysics

Rates

Sources and searches : Detector response

- GWs interferometers are not pointing type detectors, detector's response is directionally dependent called as detector response given in TT gauge as

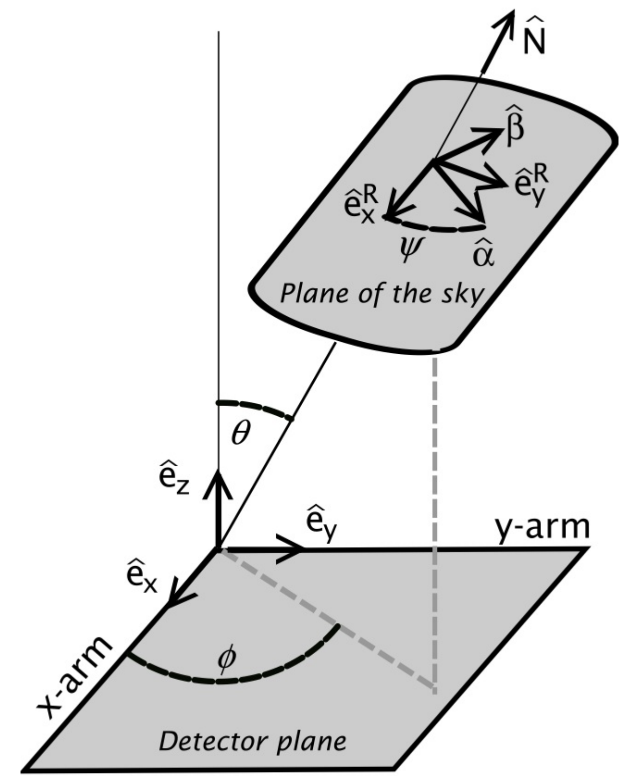
$$\xi(t) = F_{+}(\Theta,\Phi,\Psi)h_{+}(t) + F_{\times}(\Theta,\Phi,\Psi)h_{\times}(t)$$

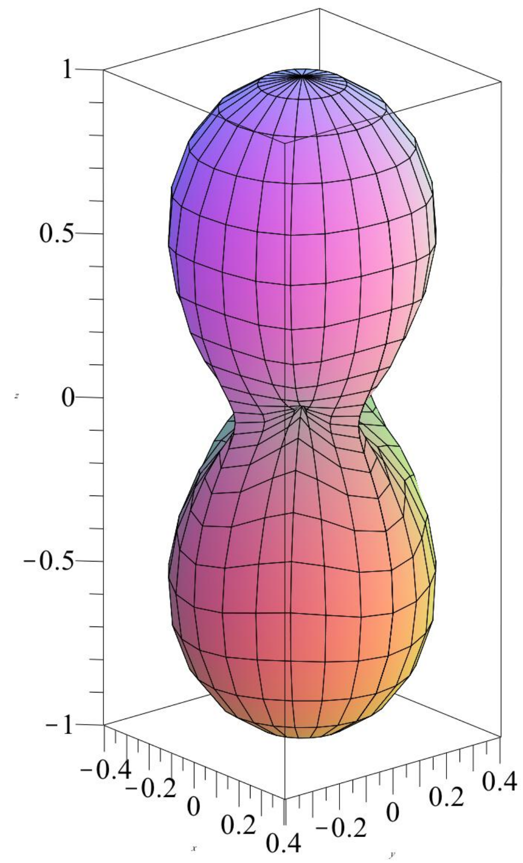
- Where

$$F_{+}(\Theta,\Phi,\Psi) = \frac{1}{2}(1+\cos^2\Theta)\cos 2\Phi\cos 2\Psi - \cos\Theta\sin 2\Phi\sin 2\Psi$$

$$F_{\times}(\Theta,\Phi,\Psi) = \frac{1}{2}(1+\cos^2\Theta)\cos 2\Phi\sin 2\Psi - \cos\Theta\sin 2\Phi\cos 2\Psi$$

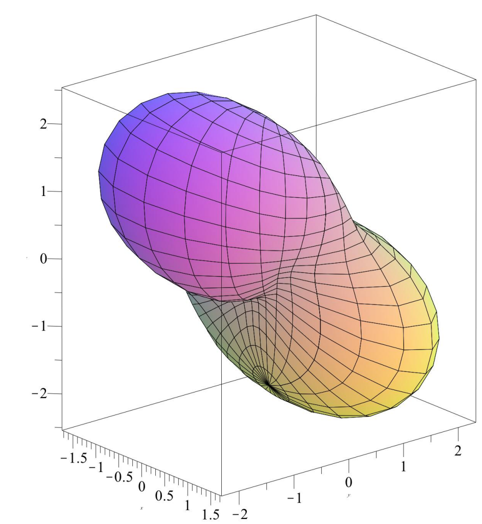
- and $h_{\times}(t)$ and $h_{+}(t)$ are the source parameters





$$P(\theta,\phi) = F_{+}(\theta,\phi,\psi)^2 + F_{\times}(\theta,\phi,\psi)^2$$

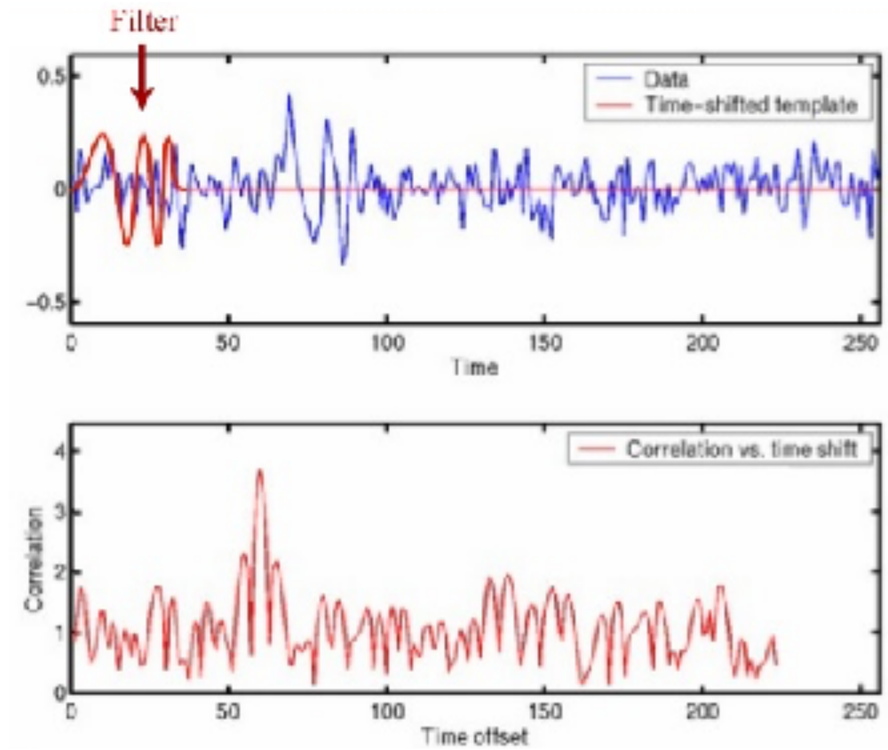
Antenna power

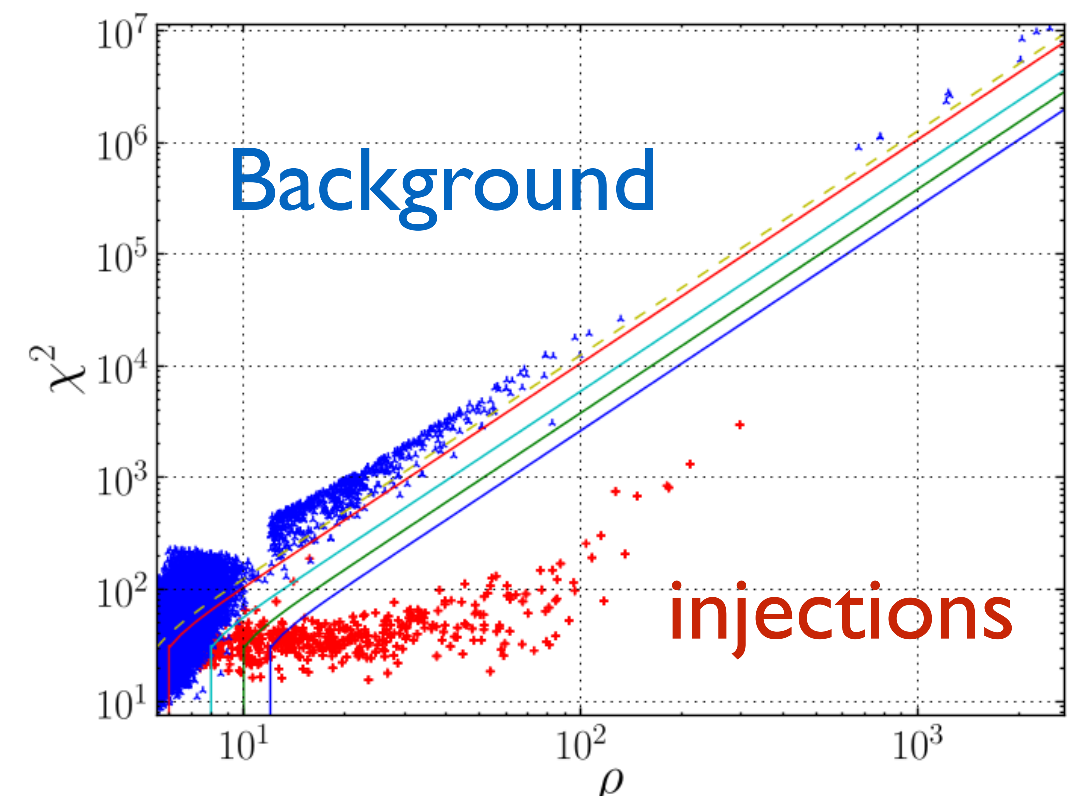


LIGO+VIRGO

Sources and searches :Modelled search for CBC sources

- Uses waveform models to search for CBC signals in the data, this technique is called **Matched Filtering**
- It uses the correlation between the data and various waveforms models called **templates**
- The goal is to find the optimal template which would maximise the **signal to noise ratio**
- The consistency check is performed by a **chi-squared test**

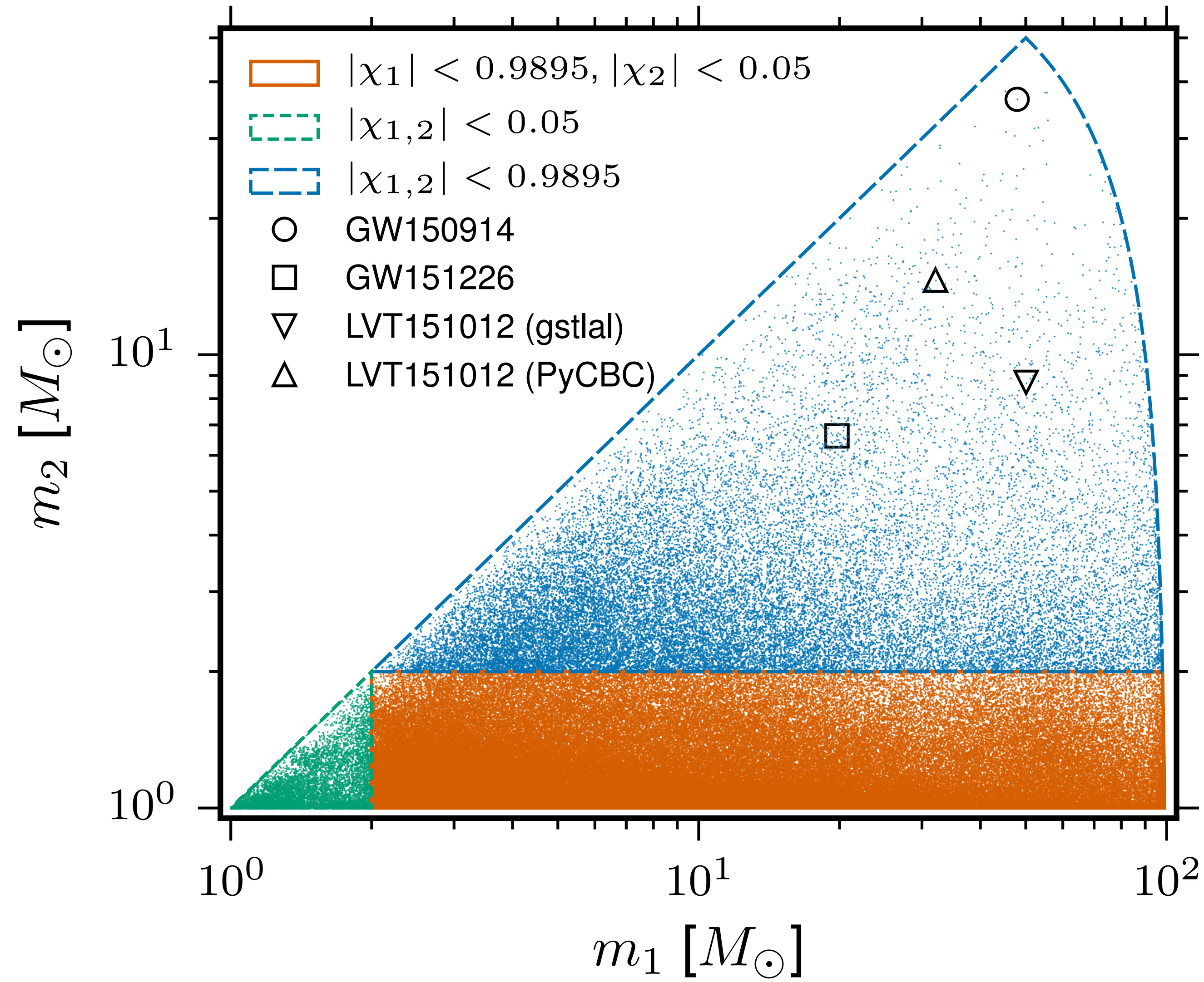




Babak+ PRD 87 024033

Sources and searches :Modelled search for CBC sources

- The four-dimensional search parameter space (component masses and spins) covered by the template bank shown projected into the component-mass plane.
- The colours indicate mass regions with different limits on the dimensionless spin parameters $\chi 1$ and $\chi 2$.
- The trigger gives the first guess of masses, spins and strength
- Sky map is generated shortly after the trigger generation

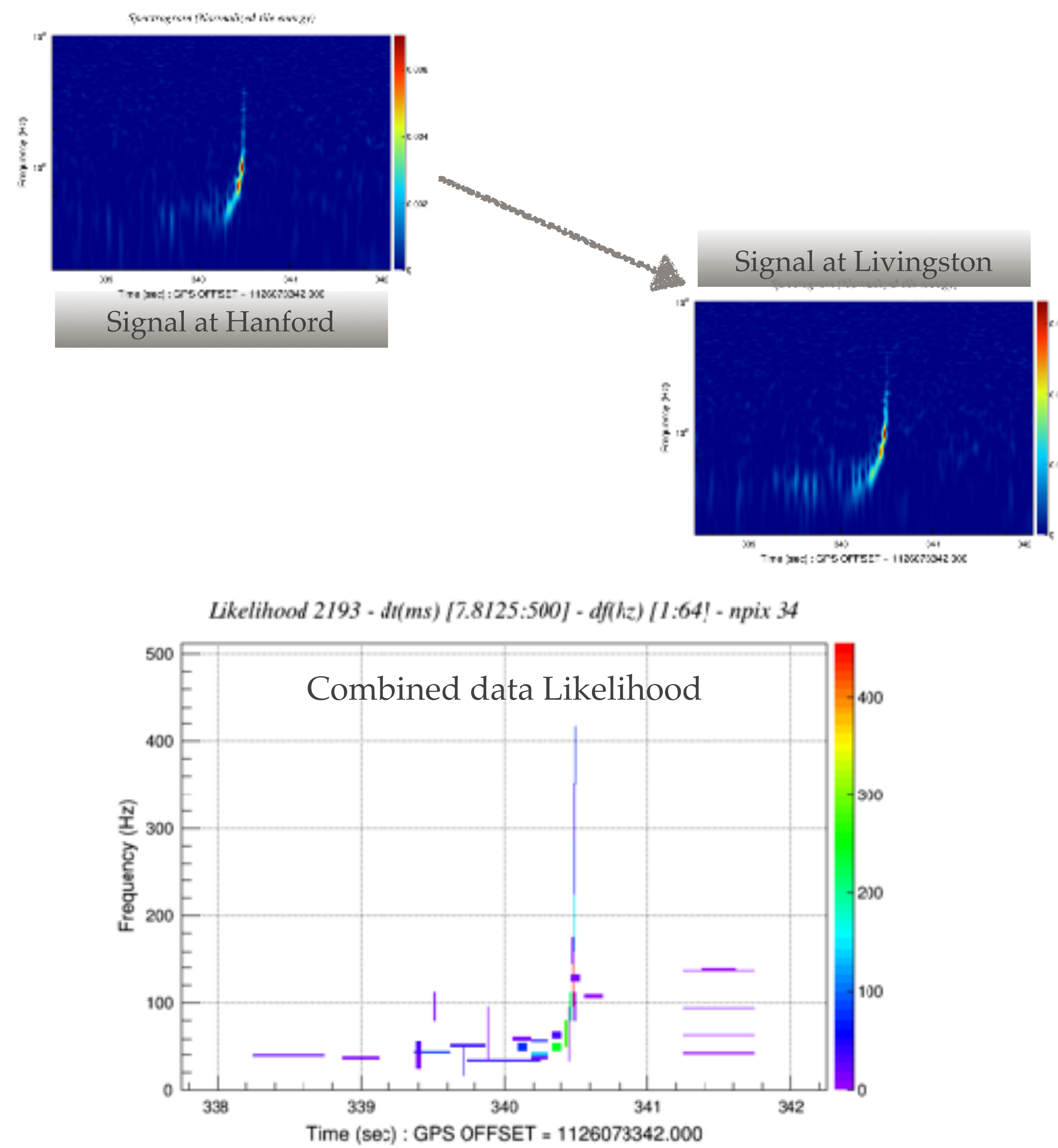


Sources and searches :Modelled search for CBC sources

- Benefits
  - Near optimal sensitivity for modelled signals with known parameters
  - Confirmation of the source of the event
- Limitations
  - Less/No sensitivity to poorly modelled or un-modelled signals

Sources and searches : Un-modelled search

- Uses the estimation of excess energy in the detectors
- Exploits the presence of signal (energy) in multiple detectors to appear coherently i.e. consistent in time and sky location
- Data is combined from the networks of detectors
- No templates/waveforms models are required/used



Sources and searches : Un-modelled search schematic 1

Read Data → Data conditioning → Time frequency transform and selection of pixels → Clustering →

Data conditioning

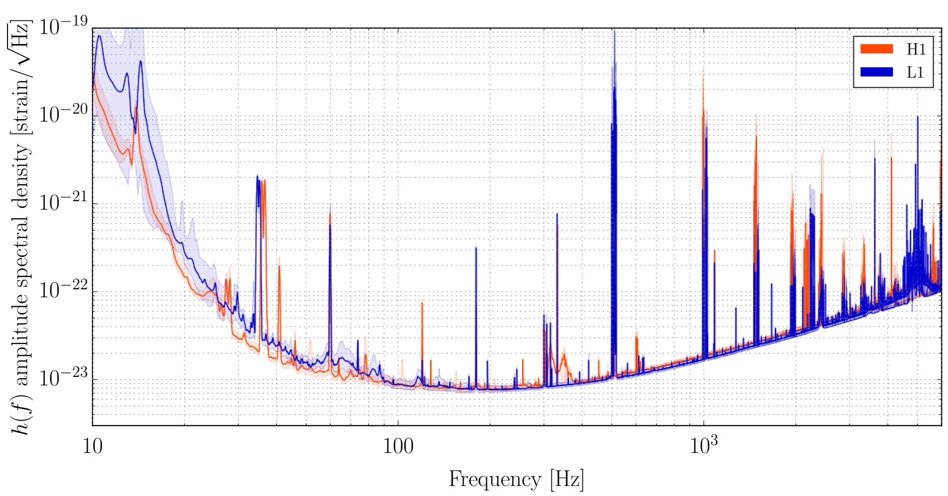
- Regression to get rid of stationary noise (resonances)
- Non uniform noise in frequency are conditioned with whitening

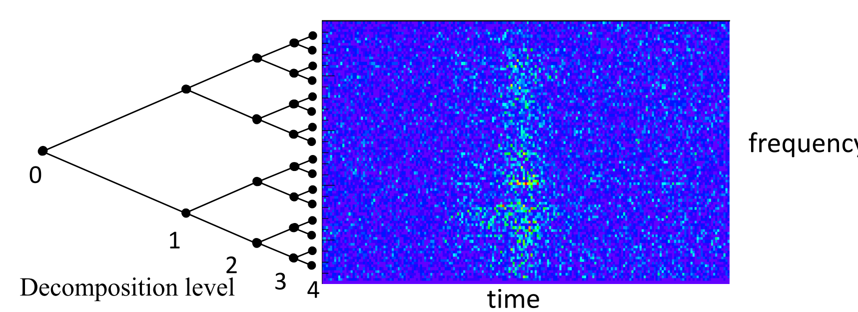
Time frequency transform and selection of pixels

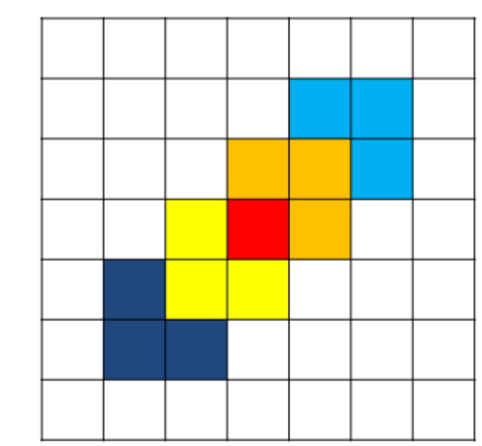
- TF transform such as WDM are used
- Pixels which are over the threshold from the data conditioning step are selected

Clustering

- Pixel with most energy and surrounding pixels are selected
- Various methods to cluster







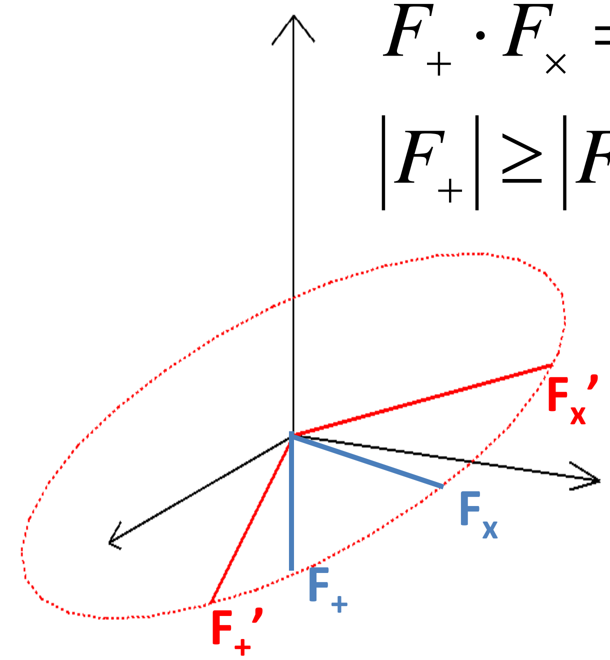
Sources and searches : Un-modelled search schematic 2

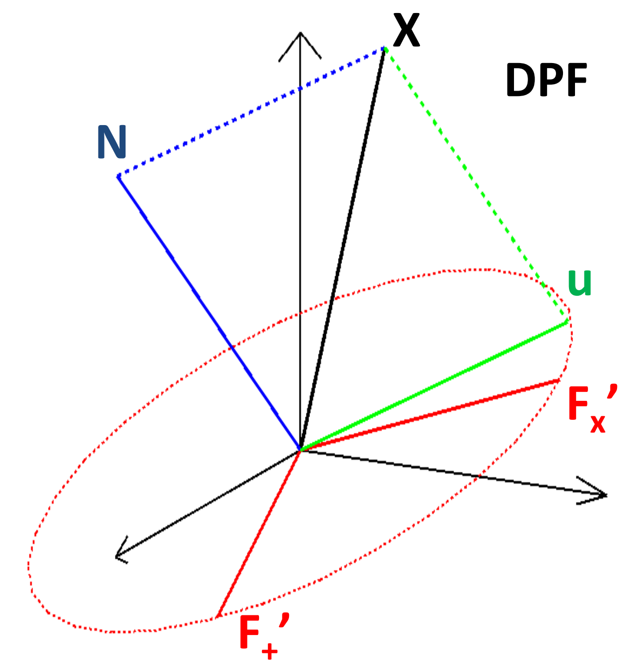
Likelihood analysis

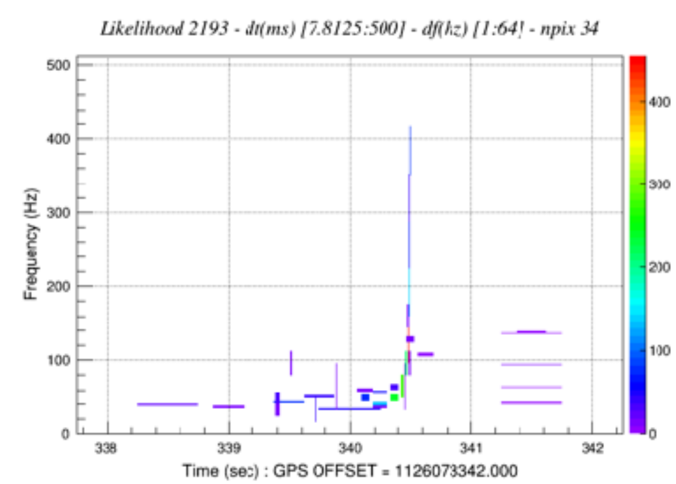
- Define a multidimensional space N = number of detector and detector data on axes
- Likelihood is wave frame rotation invariant
- We rotate it in such a way that the antenna pattern function are orthogonal and + is dominant called dominant polarisation frame (DPF)
- In this frame detector response corresponding to maximum likelihood is projection of data vector X on the DPF
- Orthogonal to this plane is the Null Stream (N) which describes the noise
- Maximum likelihood points to the reconstructed direction
- We get sky map, polarisation, reconstructed waveform and coherent signal strength as output

$$F_+ \cdot F_\times = 0$$

$$|F_+| \geq |F_\times|$$







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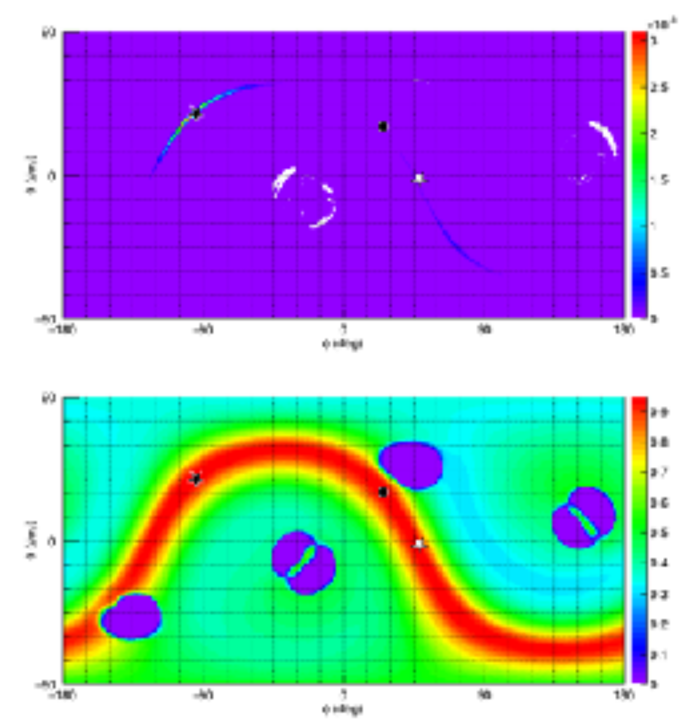

Sources and searches : Un-modelled search

- Benefits
  - No dependance on the waveform models
  - Can detect surprises
- Limitations
  - Background is not as clean as the modelled search which limits the sensitivity to the know sources
  - Single detector triggers are less important

Sources and searches : CBC sources in un-modelled search

- Some “non-vanilla CBC” sources for which the modelling is not precise/expensive are covered by un-modelled searches
  - eccentric Black Hole binaries
  - Intermediate mass ratio inspirals
  - exotic binaries
- Some CBC sources will have very short presence is our detectors and will be very burst like
  - Heavy black holes (IMBBH)

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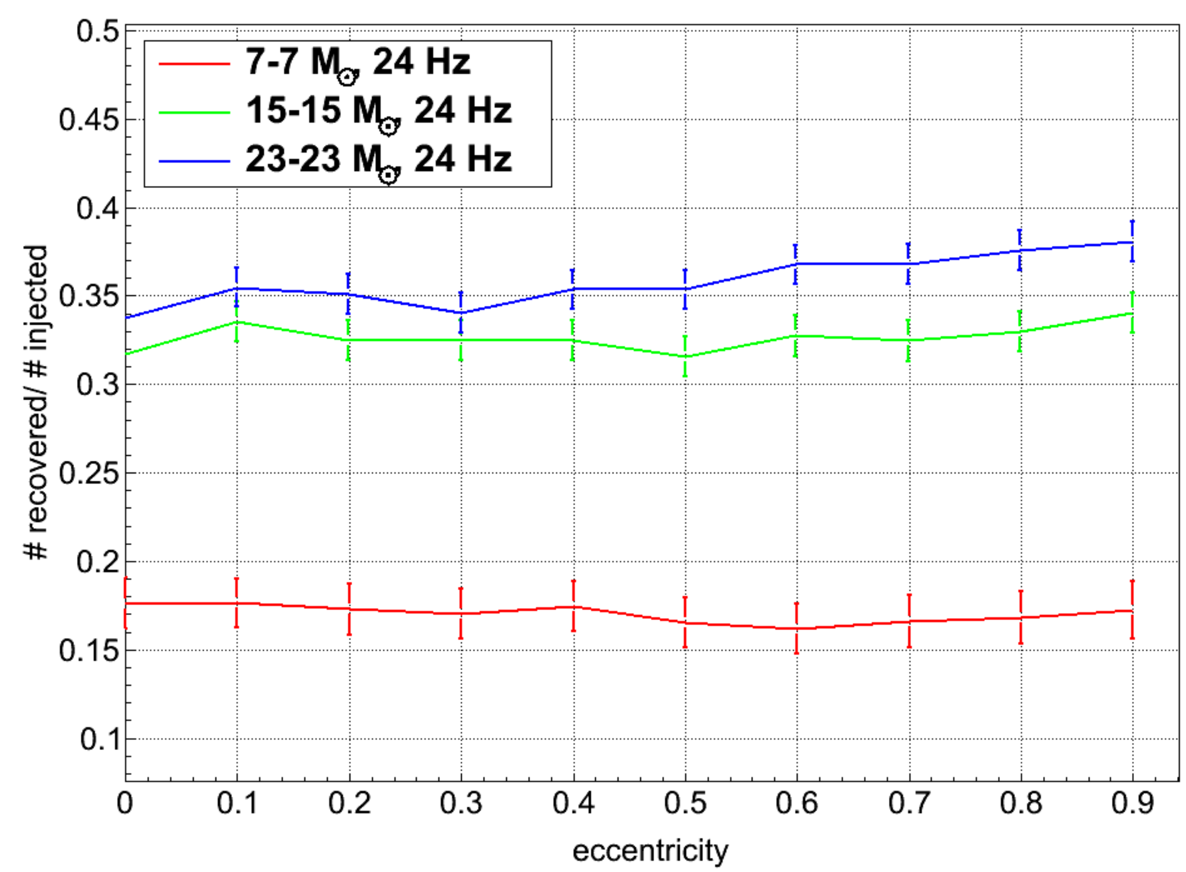
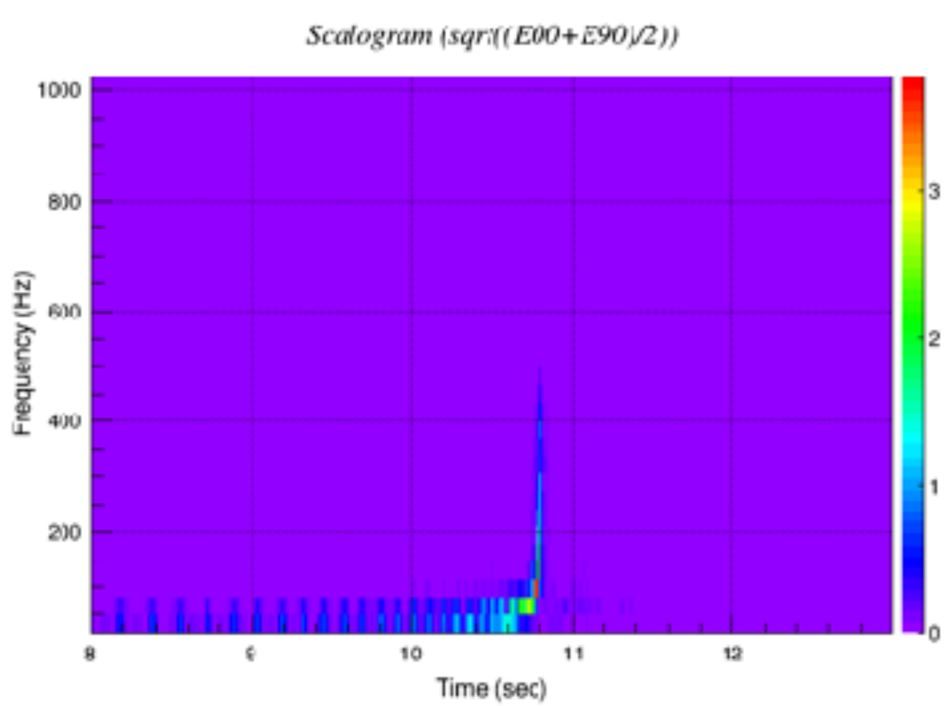
- An example of eBBH in un-modelled search
- The efficiency of detection is independent of eccentricity
- Will be interesting to follow up as they are expected to come from galactic nuclei

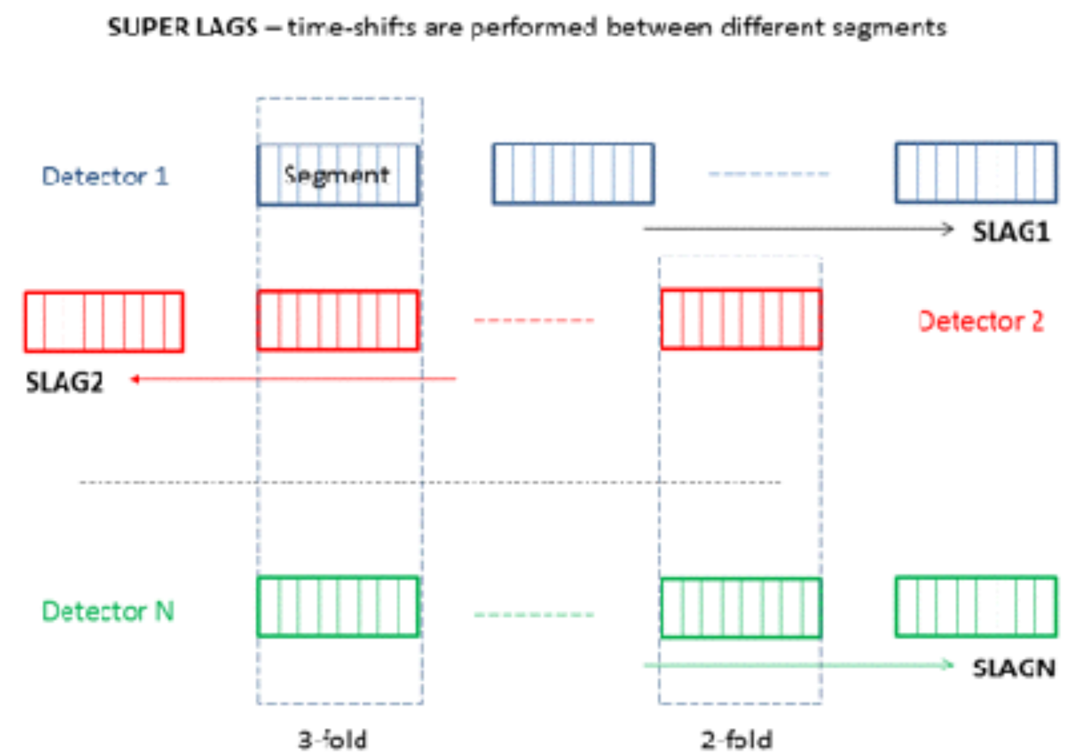


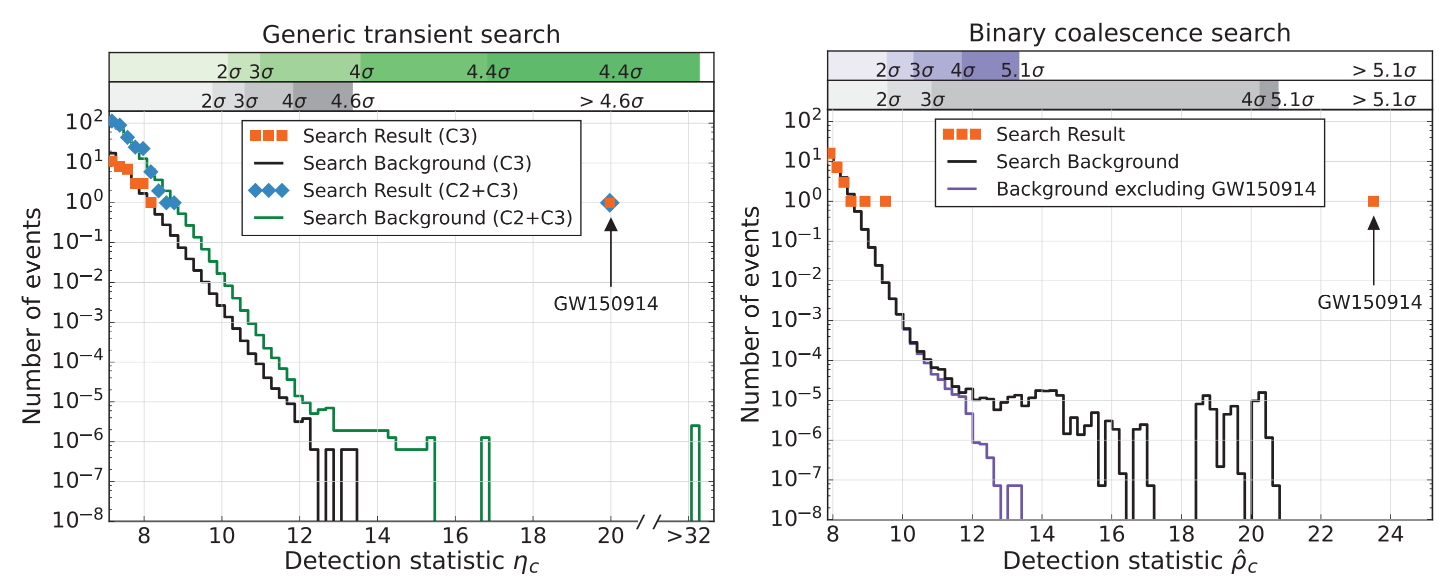


V Tiwari+ Phys.Rev. D93 (2016) no.4, 043007

Sources and searches : background and significance

- Background is generated by unphysical time sliding the data to eliminate real signals
- Rank the background triggers (either the modelled way or the un modelled way) according to the detection statistics
- estimated p-value from CDF
- minimum p-value estimate is limited by the number of time slides one can perform
- There is also a Bayesian way using KDE of foreground and background in SNR chi-squared space.

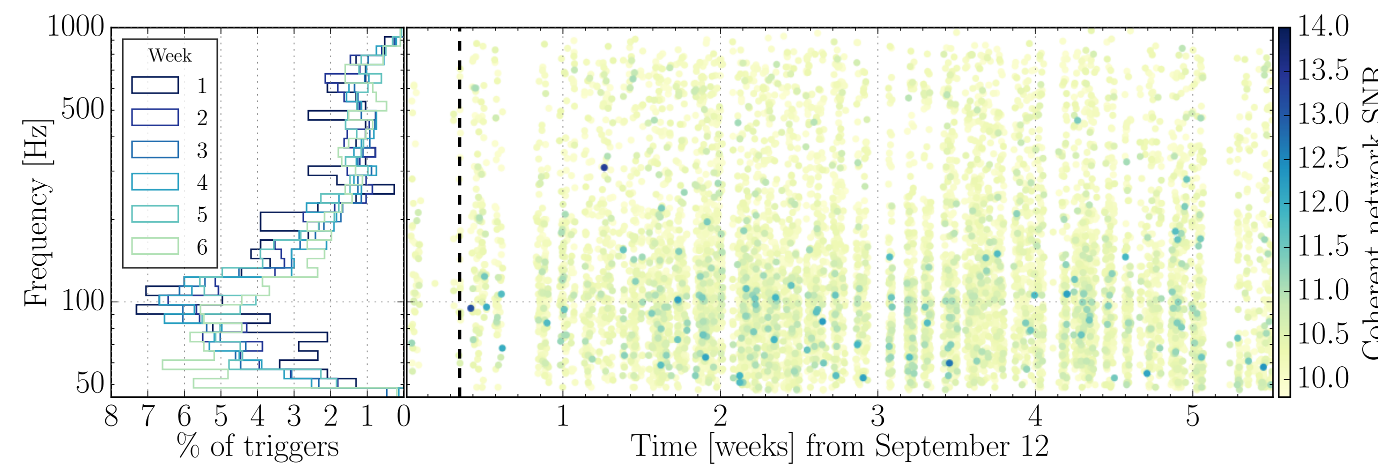


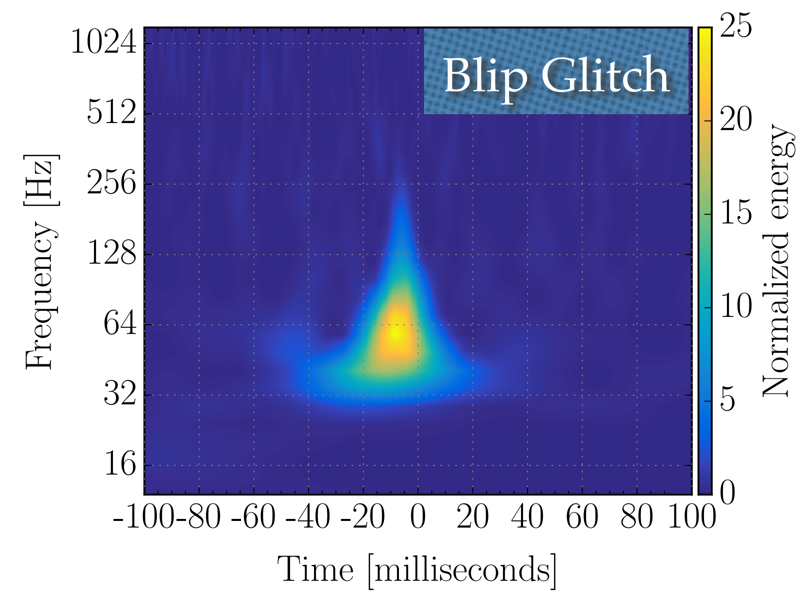


LVC Phys.Rev.Lett. 116 (2016) no.6, 061102

Sources and searches : Data quality and glitches

- Answers the important question, was the signal an artefact or real astrophysical one, apart from a random noise fluctuation?
- The environmental factors effect the ever so sensitive detectors and they are characterised and vetoed, few glitches during last observation run
  - Anthropogenic (man made)
  - Seismic activity (earth made)
  - RF laser modulation noise
  - “blips“ (unknown source)
- You wanna hunt glitches, here is your opportunity GravitySpy
  - https://www.zooniverse.org/projects/zooniverse/gravity-spy

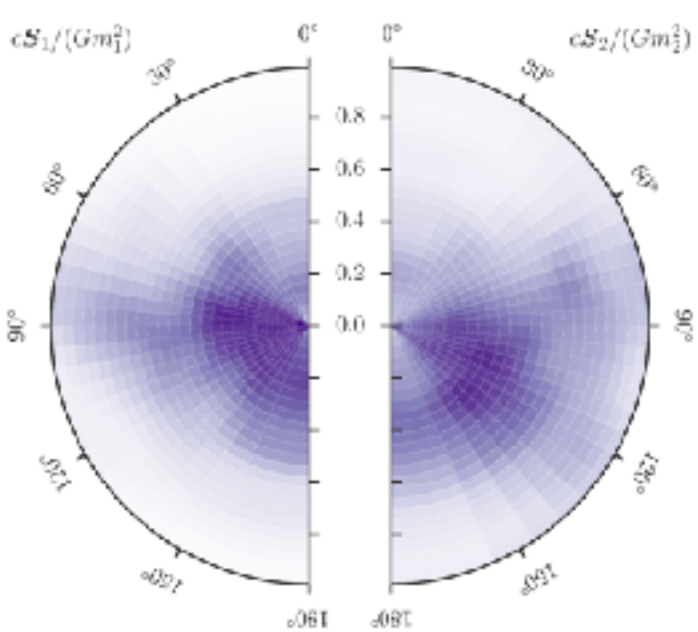


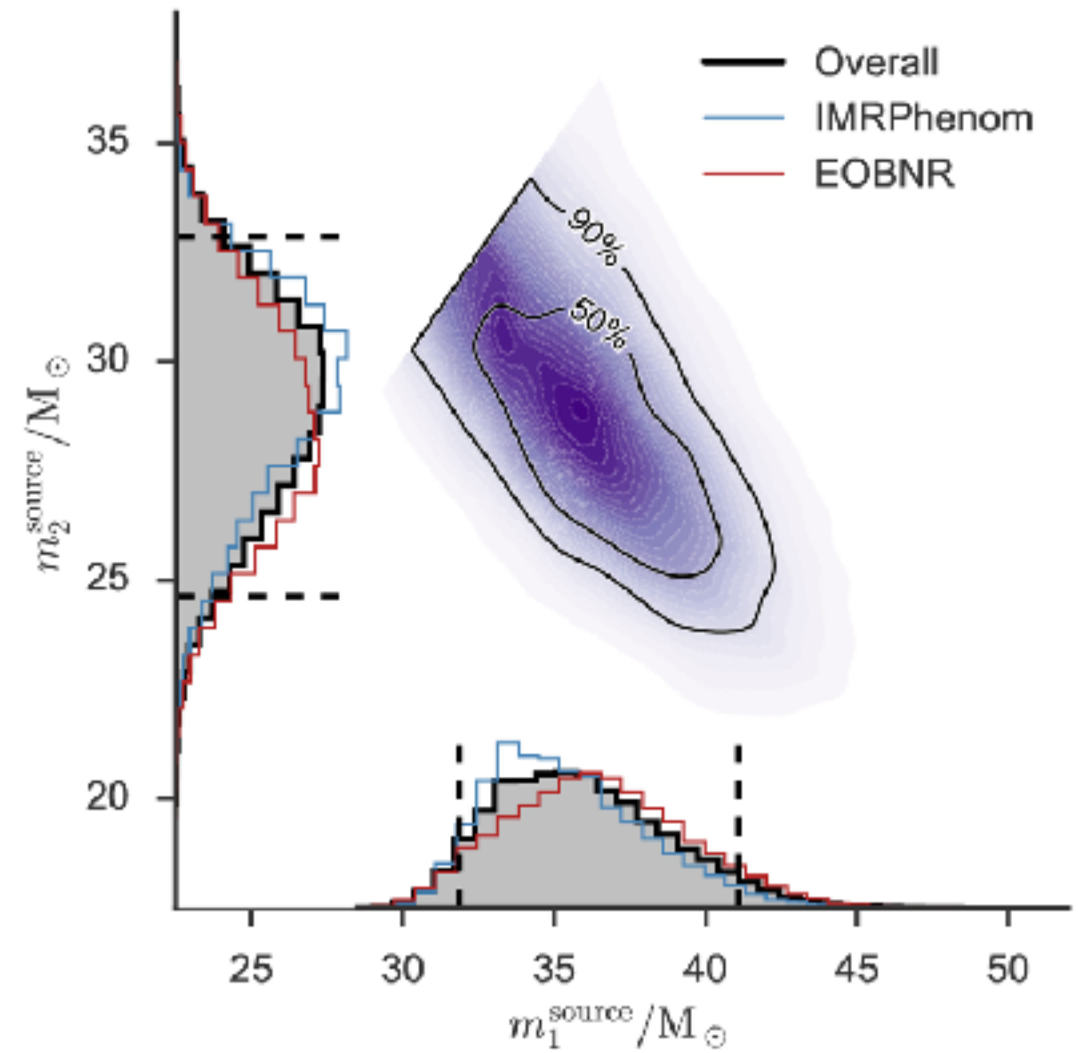


LVC Class.Quant.Grav. 33 (2016) no.13, 134001

Sources and searches : Source Identification

- For the signals for which we have good models we can have straight forward application of Bayes' theorem to get a posterior PDF for various parameters (masses, spins, distance etc)
- Two waveform models are used namely EOB (effective one body) and IMRPhenom(phenomenological wavefom)

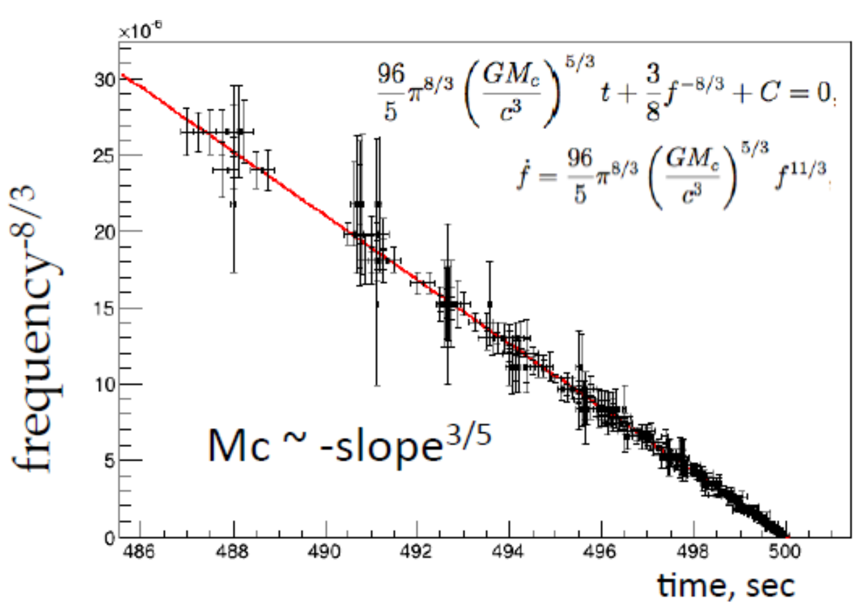


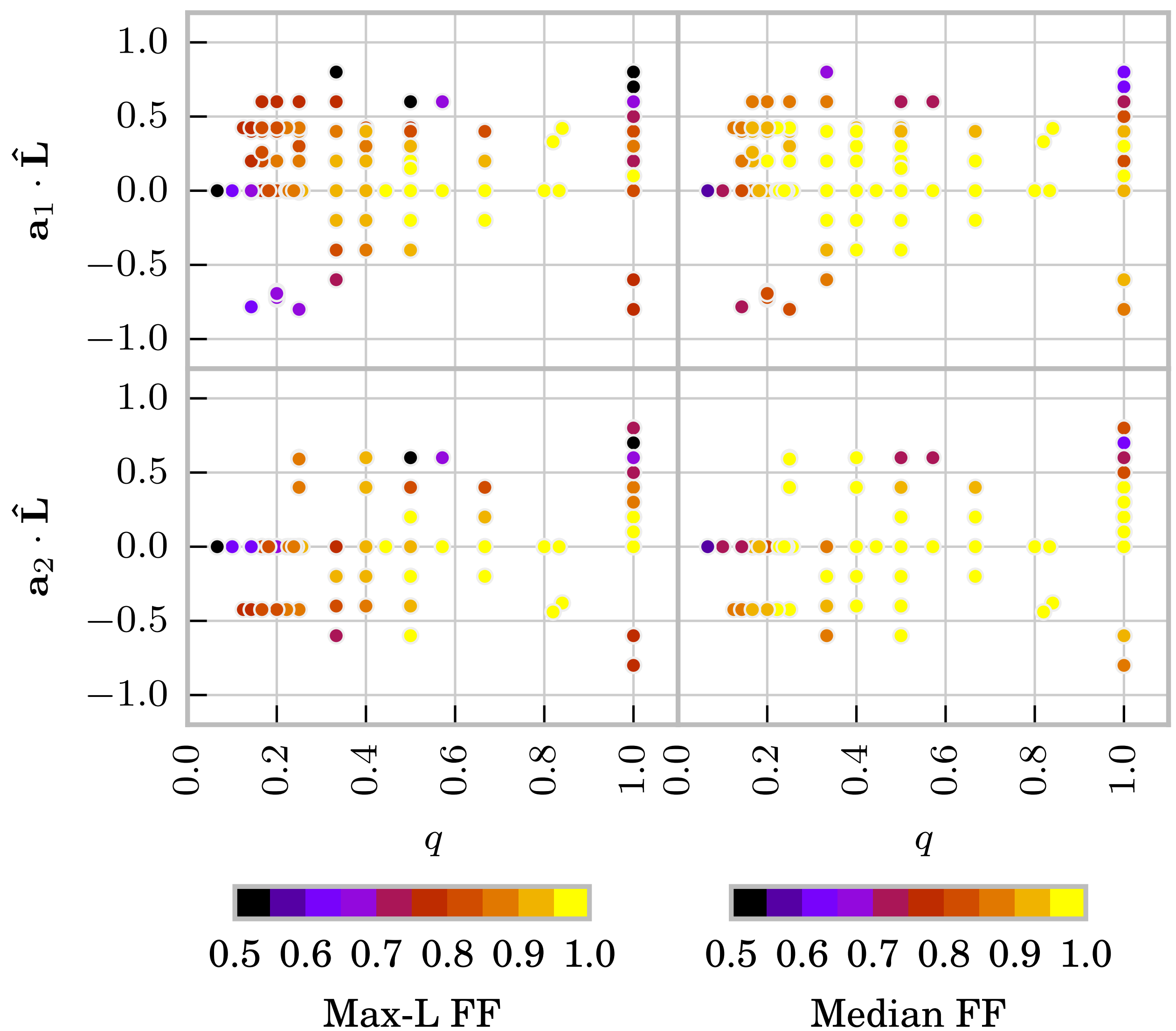


LVC Phys.Rev.Lett. 116 (2016) no.24, 241102

Sources and searches : Source Identification

- For the signals not having accurate waveforms
  - Time frequency behaviour gives a hint about the source
  - EM counterpart can provide smoking gun for SNs etc
  - Directly comparing the reconstructed waveform with Numerical relativity





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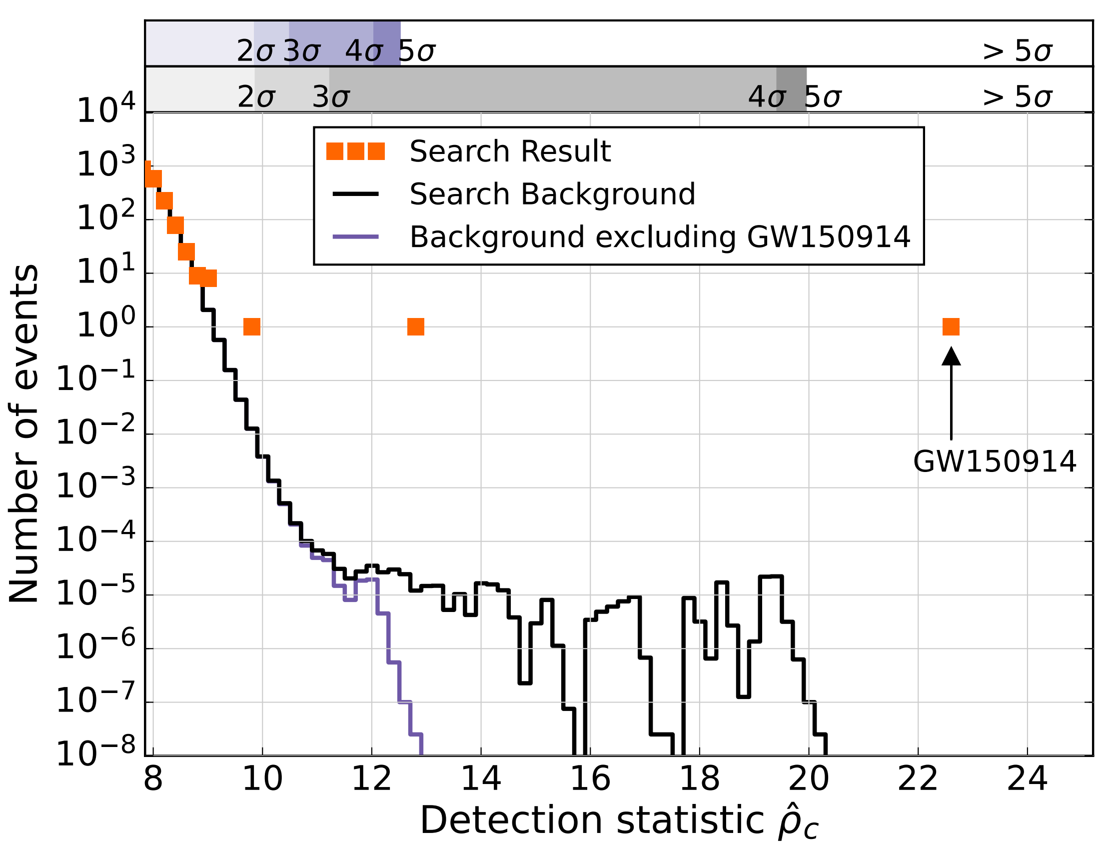
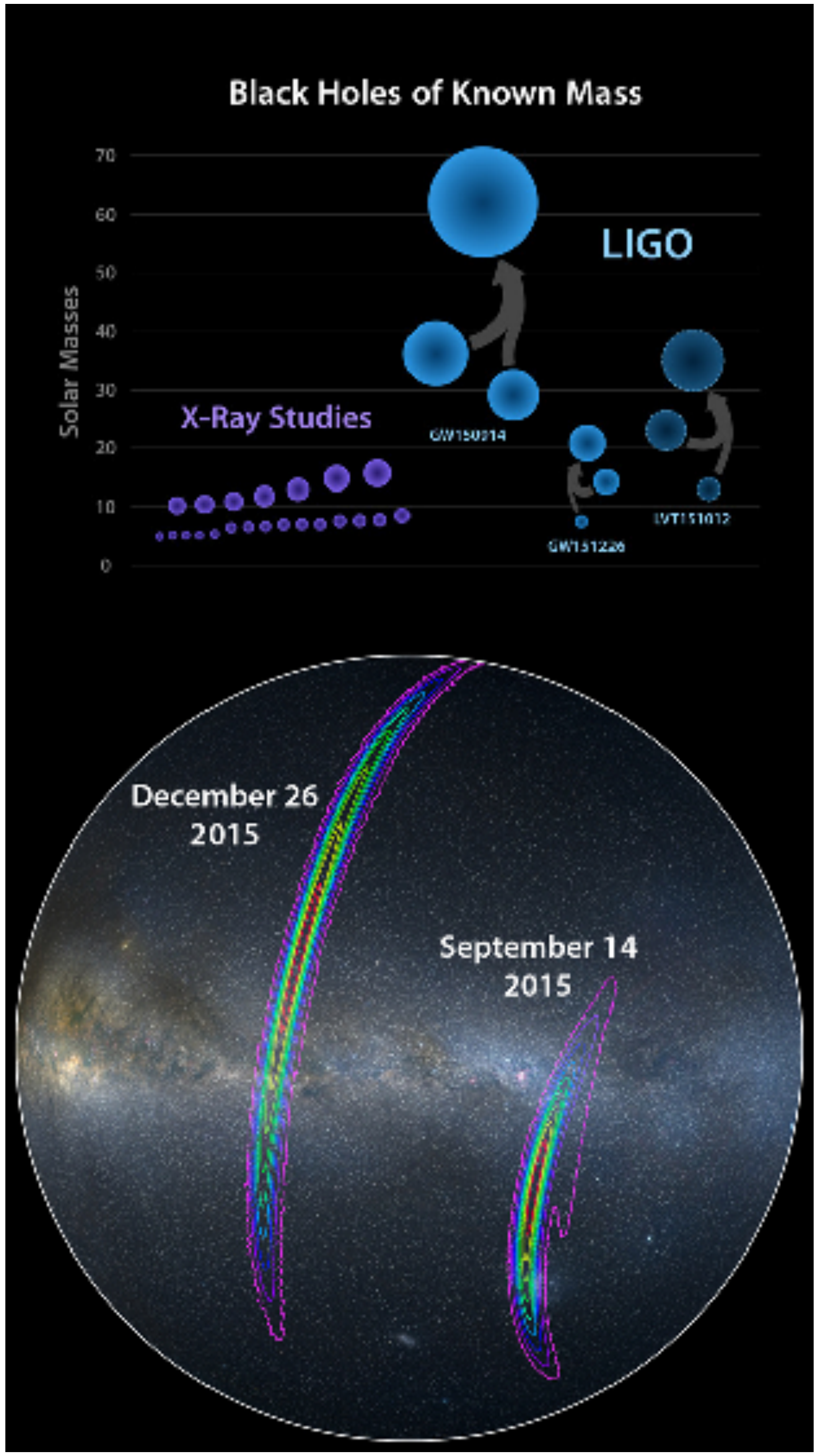
Gravitational Waves observations : A proof that the system works

- Using the prescribed machinery we have detected two events both binary black holes
- We are starting to fill up the gravitational waves transients sky
- O2 will start soon and VIRGO will join breaking a lot of degeneracies in the parameters





Gravitational Waves observations : Exciting times ahead

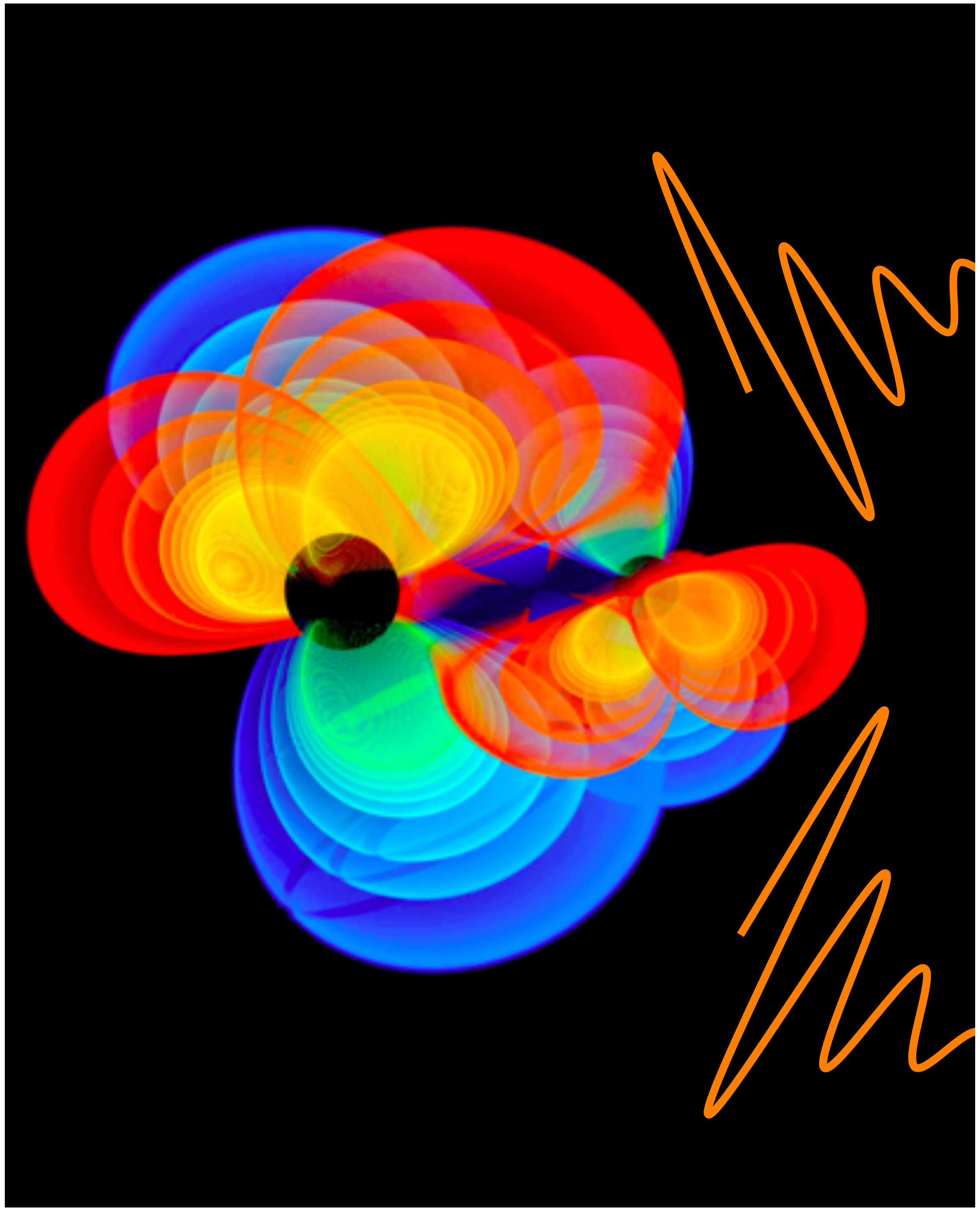
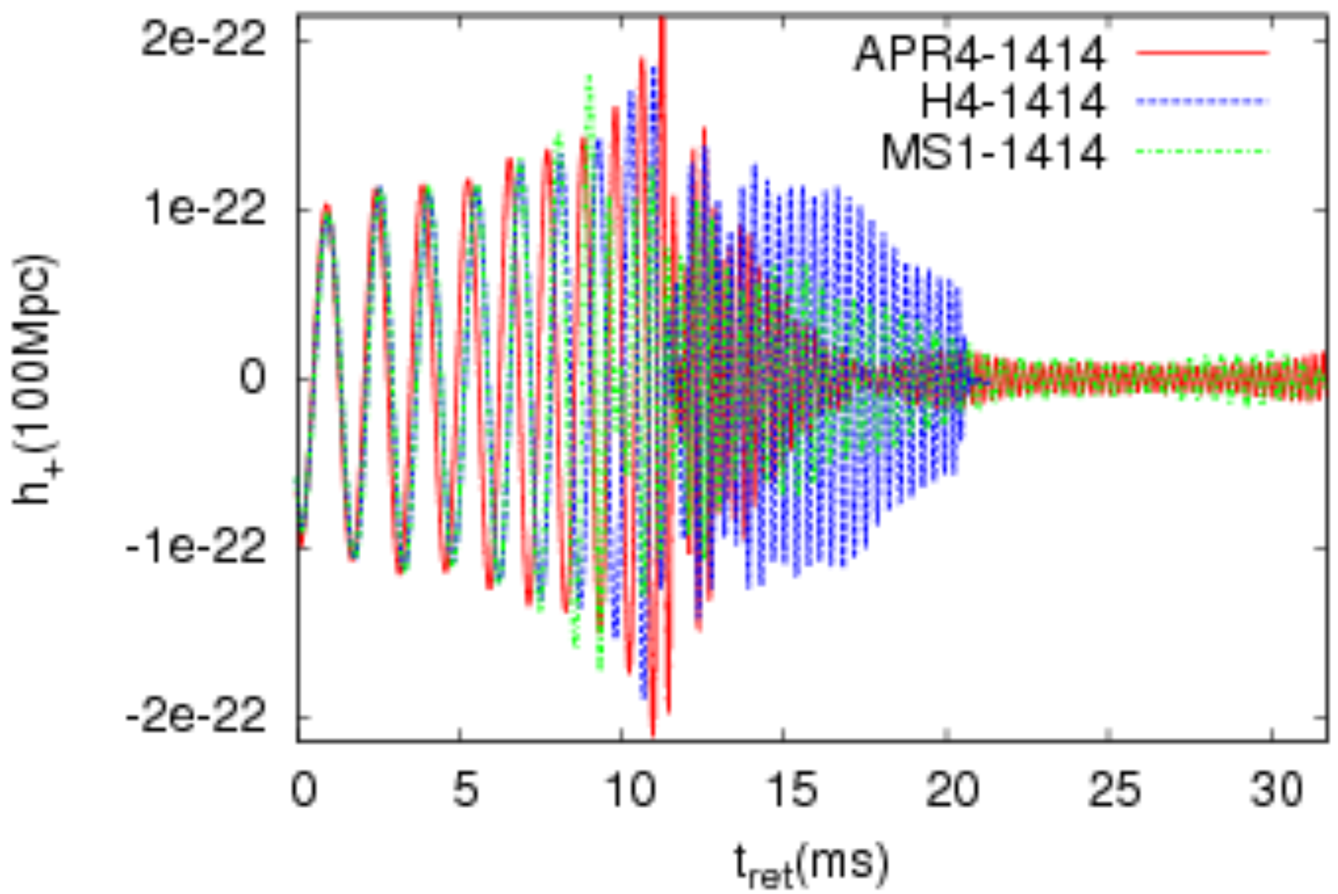


Image Courtesy : ICRAR

- Black Holes are inevitable in GR
- We have detected two events both binary black holes mergers, but the story is far from finished, we want to see
  - Long adiabatic inspiral
  - Higher harmonics
  - Constrain Hawking's area theorem
  - Late time QNM
  - Constrain Cosmic Censorship and no hair theorem

Gravitational Waves observations : Exciting times ahead

- Black holes are pure spacetime we look forward to detect some matter
  - Detect a Binary Neutron Star
    - With EM counterpart (GRBs and afterglows)
    - constrain Equation of State
  - Detect Collapsing star
    - With EM counterpart and neutrinos
    - understand the mechanism
- Be surprised



Choptuik+ arXiv:1502.06853

Thank you

"Yesterday's discovery is todays calibration and tomorrow's background."

–Richard Feynman