Title: Search and parameter estimation for gravitational-waves transients in the advanced detectors era (covering the detection of Gravitational wave GW 150914!)

Date: Feb 18, 2016 01:00 PM

URL: http://pirsa.org/16020090

Abstract: <p>The Advanced LIGO observatories have successfully completed their first science run. Data were collected from September 2015 to January 2016, with a sensitivity a few times better than initial instruments in the hundreds of Hertz band. In this talk I will describe the searches for gravitational-wave transients performed during the first few weeks of the science run. Furthermore, I will describe the methods devised to characterize transient gravitational-wave sources and their applications in the advanced gravitational-wave detector era.</p>

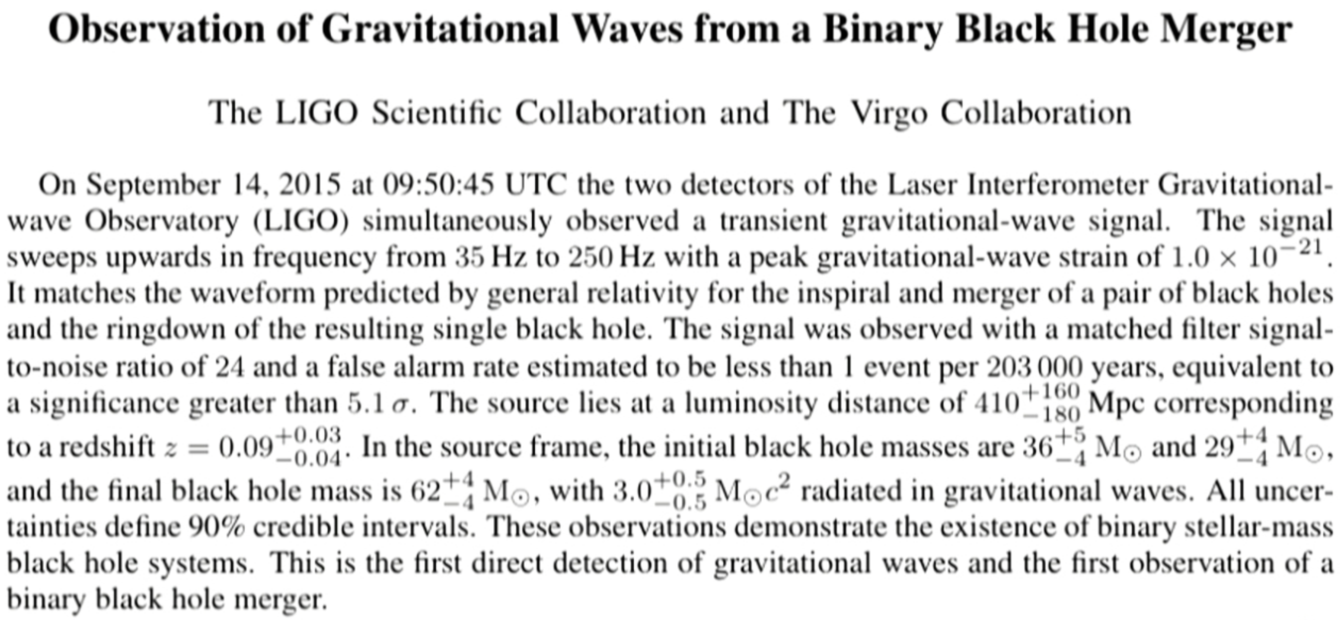
LIGO

GW150914 and the first years of gravitational-wave astronomy

Salvatore Vitale
MIT

Perimeter Institute
Feb. 18Th 2016

You might have heard...



Observation of Gravitational Waves from a Binary Black Hole Merger

The LIGO Scientific Collaboration and The Virgo Collaboration

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-wave Observatory (LIGO) simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from $35\,\mathrm{Hz}$ to $250\,\mathrm{Hz}$ with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per $203\,000$ years, equivalent to a significance greater than $5.1\,\sigma$. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4}\,\mathrm{M}_\odot$ and $29^{+4}_{-4}\,\mathrm{M}_\odot$, and the final black hole mass is $62^{+4}_{-4}\,\mathrm{M}_\odot$, with $3.0^{+0.5}_{-0.5}\,\mathrm{M}_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

LVC, PRL 116, 061102 (2016).

- First detection of gravitational waves (GW)
- First observation of binary black hole (BBH) merger
- First test of general relativity in its strong field dynamical regime
- Existence of tens of solar masses black holes (BH)

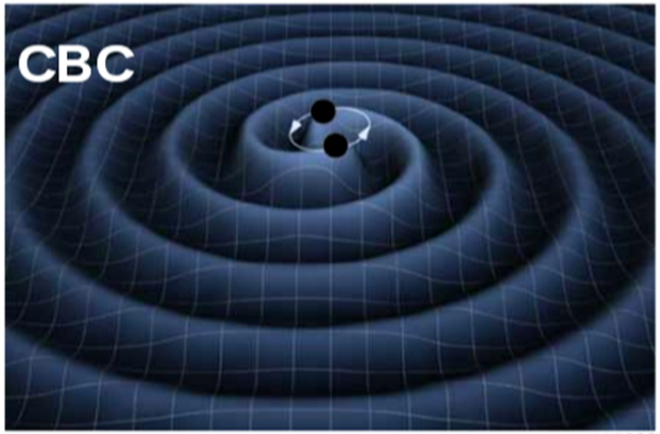
Outline

- GW sources and advanced gravitational wave detectors
- Detection and characterization of GW150914
- Conclusions

Gravitational wave sources

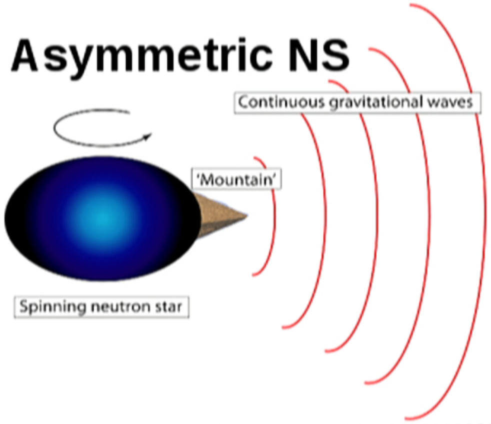
TRANSIENT

PERSISTENT

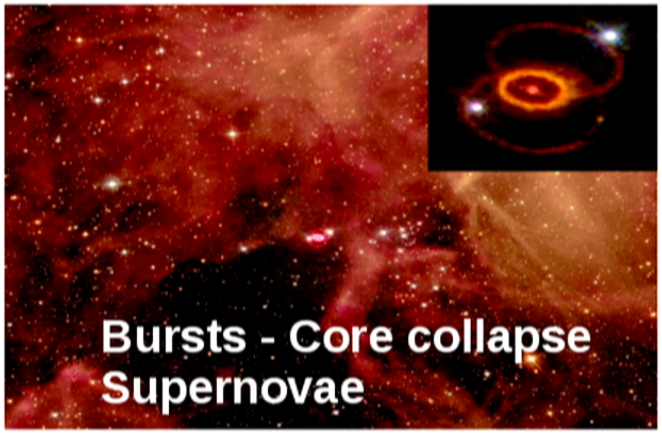


CBC

Asymmetric NS

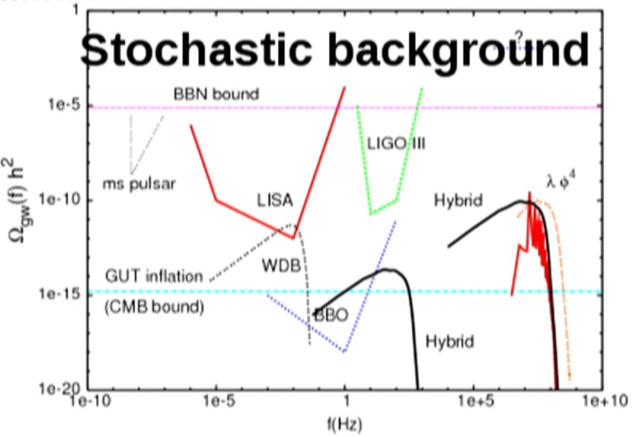


MATCH FILTER



Bursts - Core collapse Supernovae

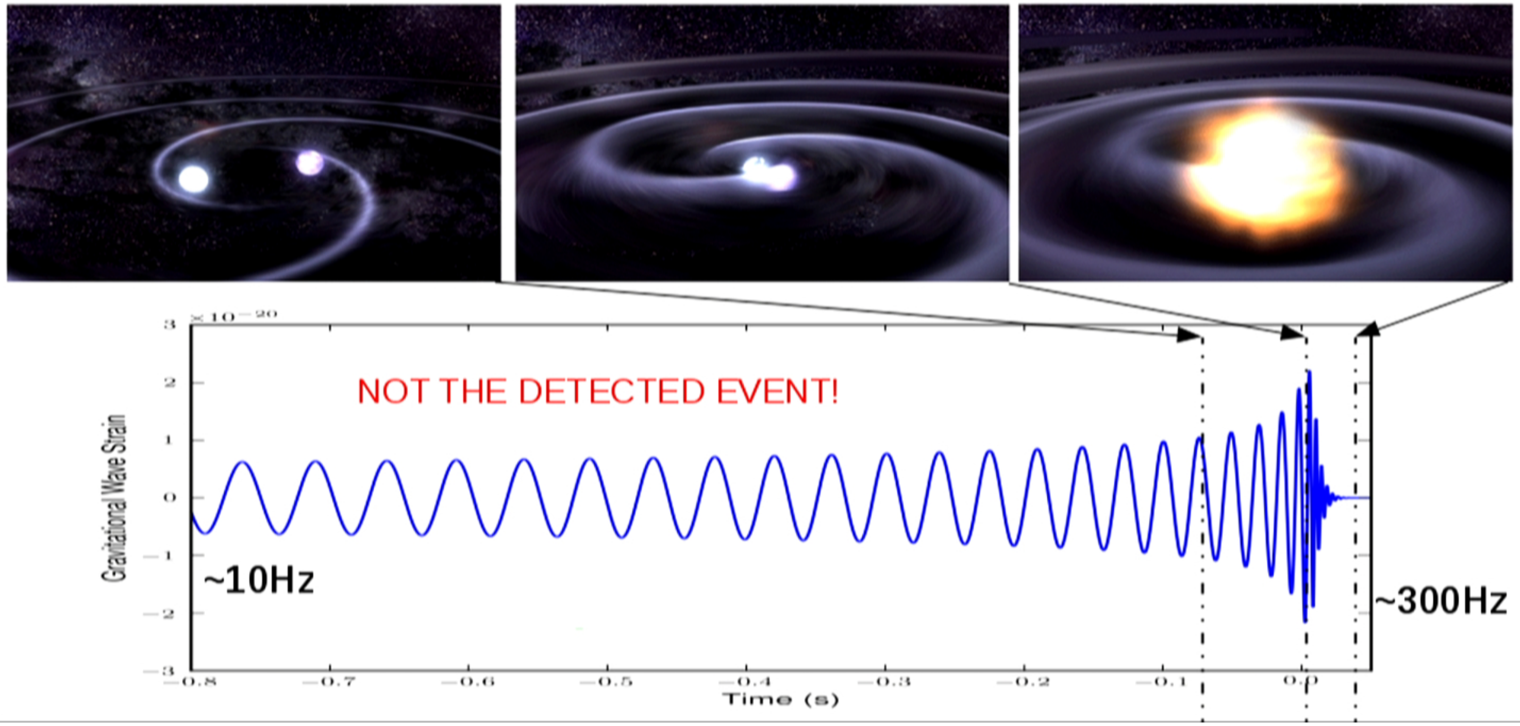
Stochastic background



UNMODELED

Compact binary coalescences

- GW signals very well understood
  - Inspiral described post-Newtonian theory
  - Merger calculated with numerical relativity
  - Ringdown described with perturbation theory

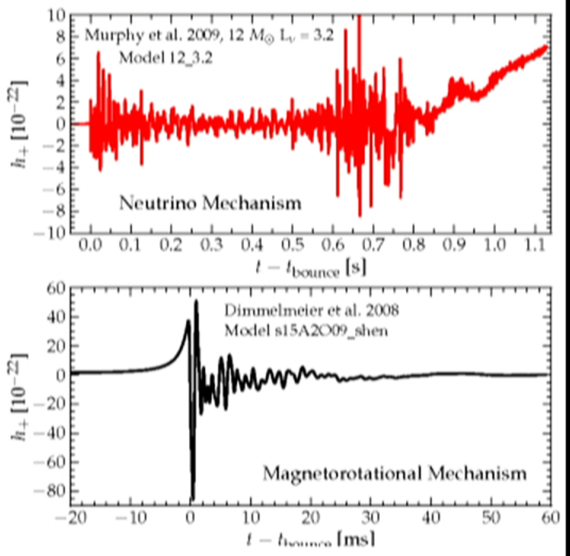


NOT THE DETECTED EVENT!


~300Hz

Bursts

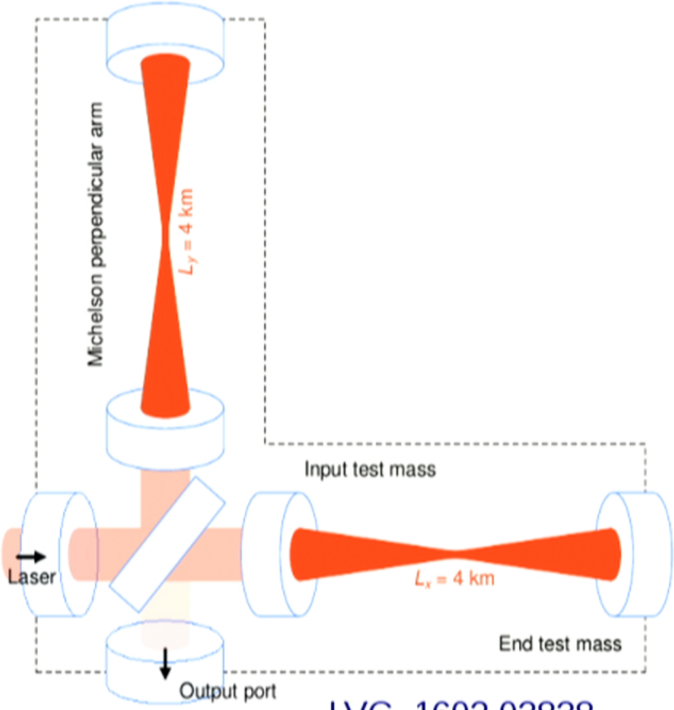
- Any violent astrophysical or cosmological phenomenon
  - Core collapse supernovae
  - Cosmic strings
  - Post-merger signal from hypermassive neutron stars
  - Something unexpected
- Uncertain or no knowledge of gravitational-wave signal morphology
- Less advertised but not less interesting than CBCs



Logue+, PRD 86 044023

The network of GW detectors

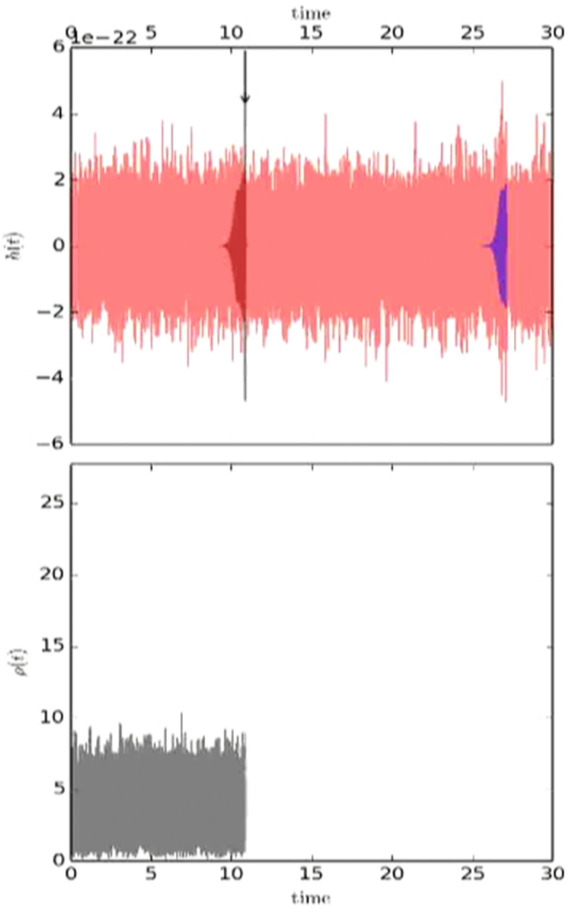
- Based on interferometry
- **LIGO** – two 4-km instruments in the USA
- **Virgo** – a 3-km instrument in Italy
- **GEO –** a 600-m instrument in Germany
- Coming soon: KAGRA (Japan) and LIGO India



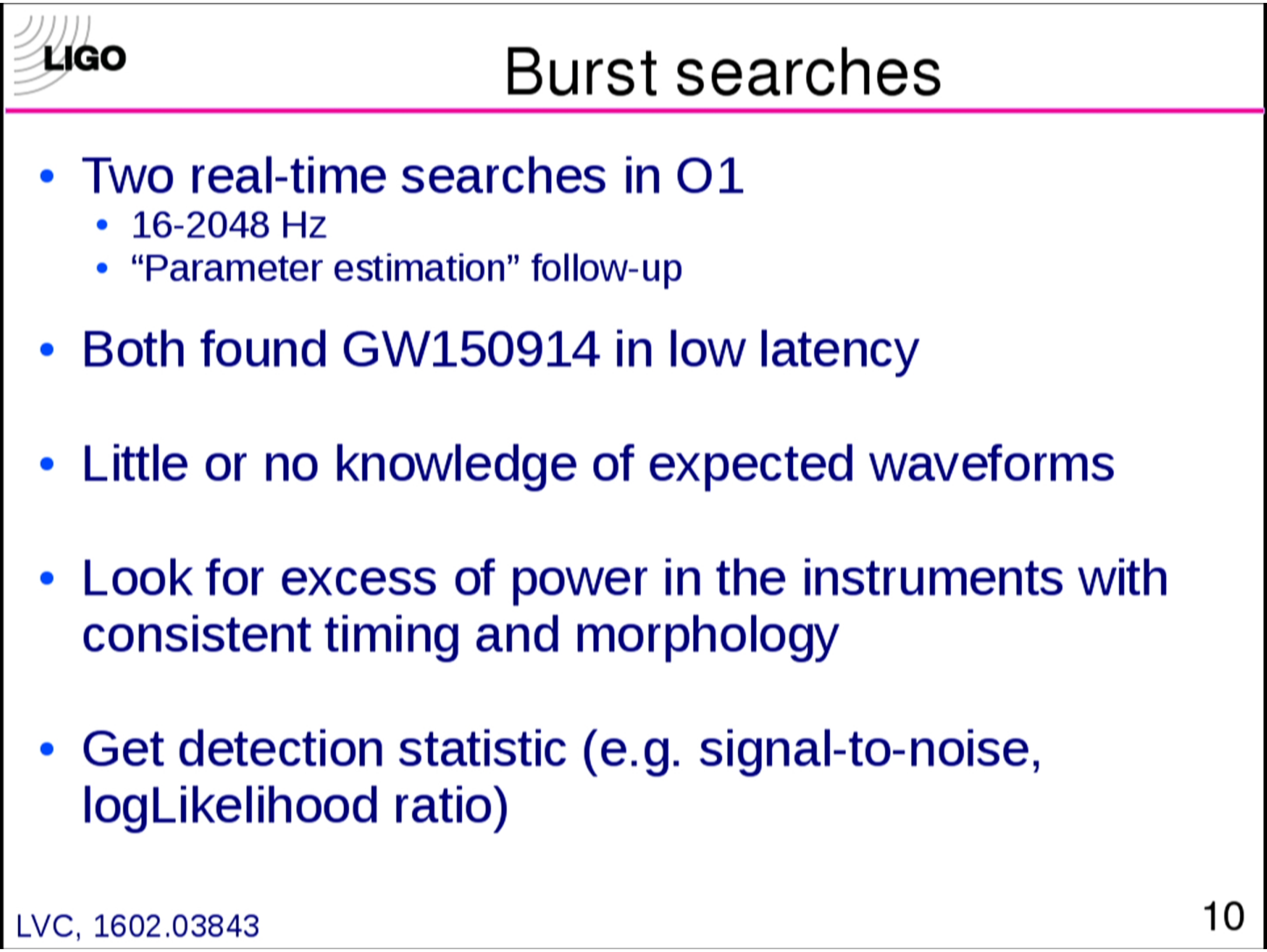
LVC, 1602.03838

CBC searches

- Two low latency searches + one offline in O1
  - Cover 2-100 Msun total
  - Aligned spin -0.99 – 0.99
- Can exploit the good knowledge of waveforms to dig into the data using match filtering
- Don't know real parameters, must try ~1e5 waveform templates



LVC, 1602.03839

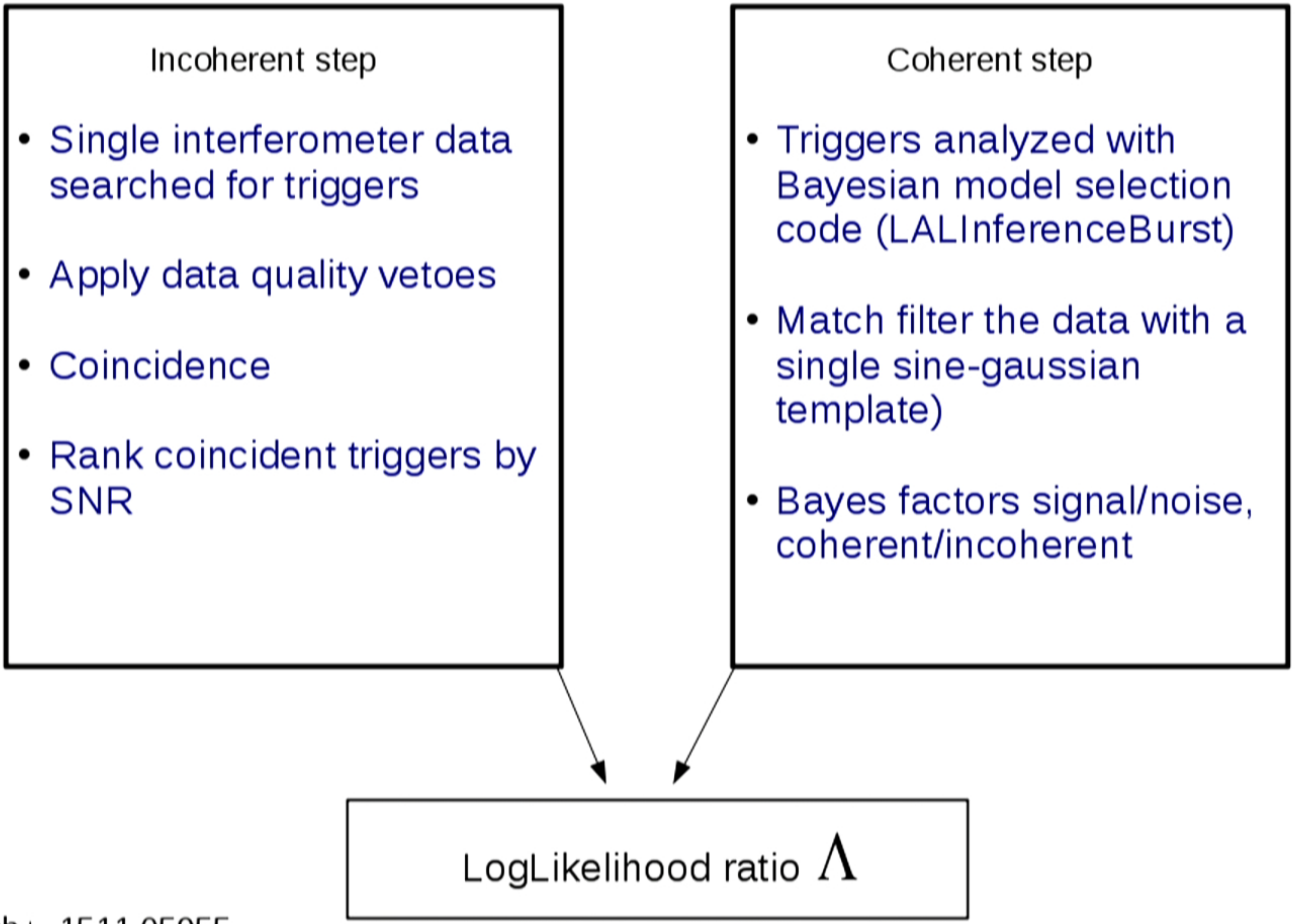


Burst searches

- Two real-time searches in O1
  - 16-2048 Hz
  - “Parameter estimation” follow-up
- Both found GW150914 in low latency
- Little or no knowledge of expected waveforms
- Look for excess of power in the instruments with consistent timing and morphology
- Get detection statistic (e.g. signal-to-noise, logLikelihood ratio)

LVC, 1602.03843

oLIB



Incoherent step

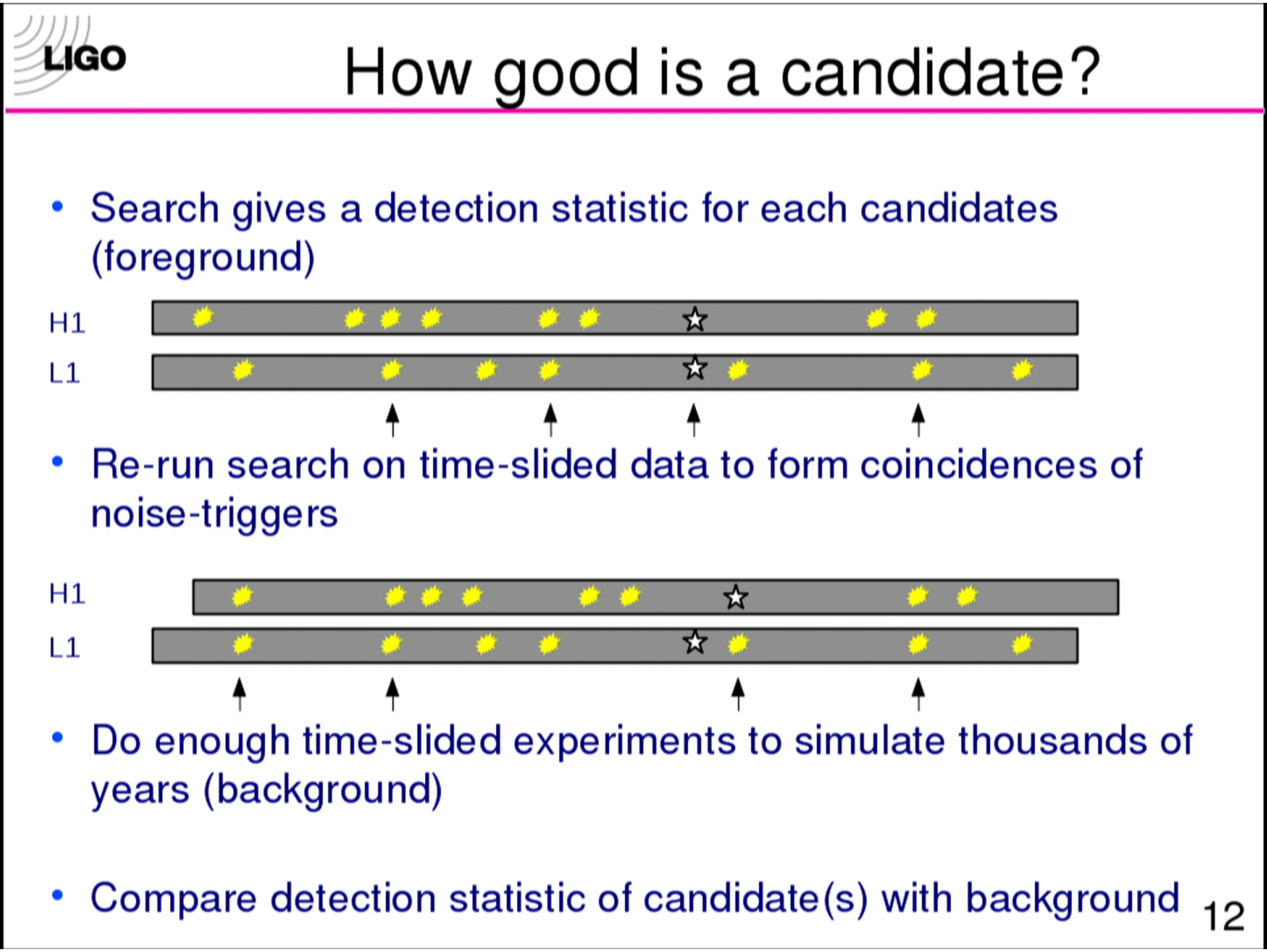
- Single interferometer data searched for triggers
- Apply data quality vetoes
- Coincidence
- Rank coincident triggers by SNR

Coherent step

- Triggers analyzed with Bayesian model selection code (LALInferenceBurst)
- Match filter the data with a single sine-gaussian template)
- Bayes factors signal/noise, coherent/incoherent

LogLikelihood ratio Λ

Lynch+, 1511.05955



How good is a candidate?

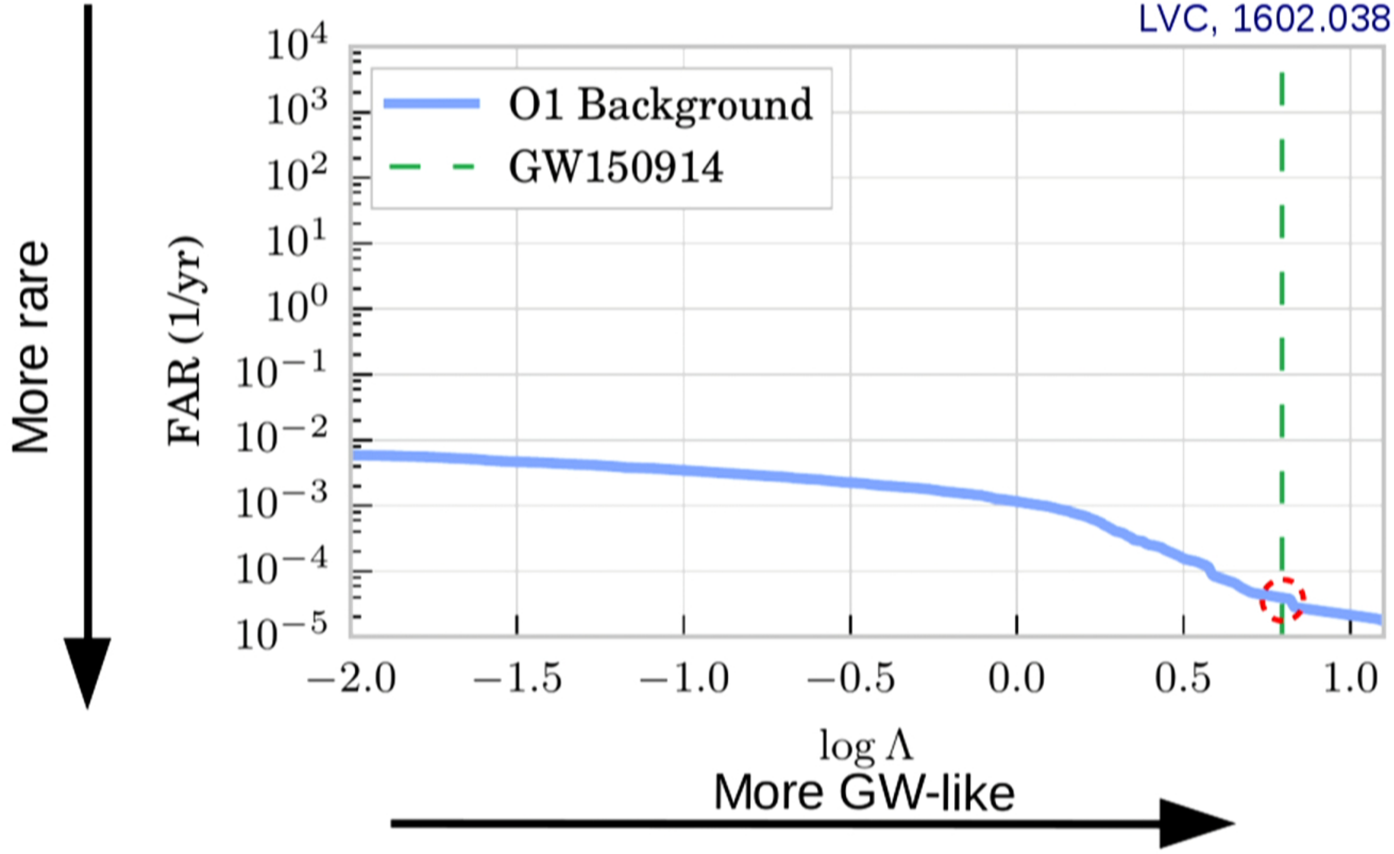
- Search gives a detection statistic for each candidates (foreground)

- Re-run search on time-slided data to form coincidences of noise-triggers

- Do enough time-slided experiments to simulate thousands of years (background)
- Compare detection statistic of candidate(s) with background

oLIB results for GW150914

LVC, 1602.03843

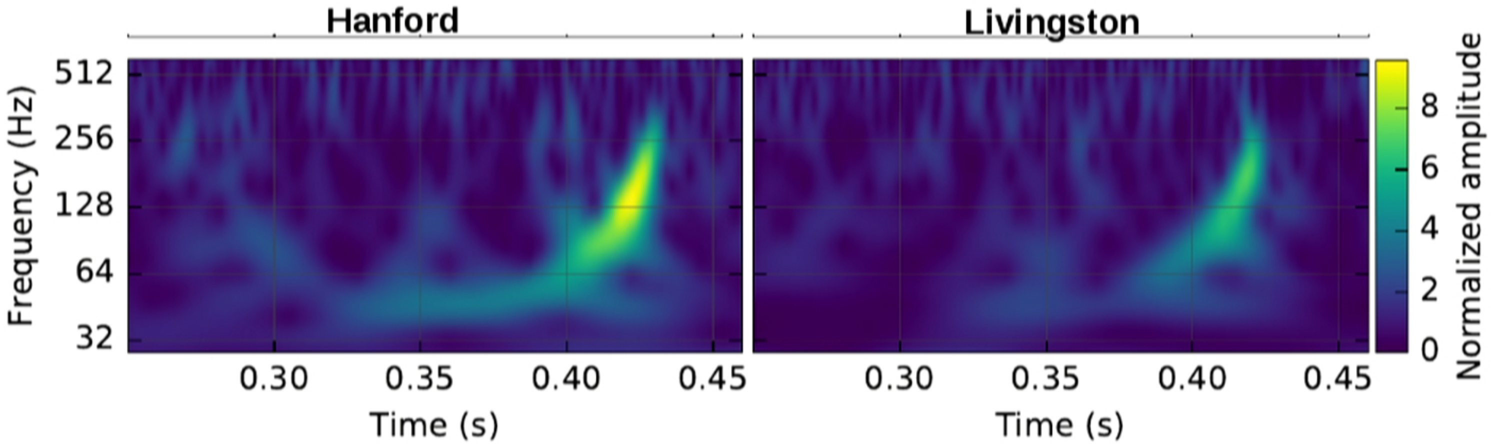


We expect something as significant as GW150914 to only happen once every 27,000 years: 4.6 σ

Prompt detection of GW150914

- GW150914 was first detected by the two low-latency burst algorithms. LVC, 1602.03843
- Minutes latency
- Time-Frequency decomposition showed increasing frequency chirp typical of CBC GW signals

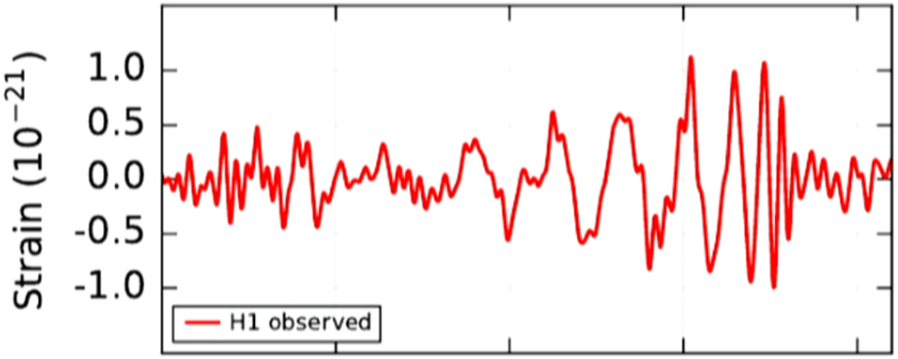
LVC, PRL 116, 061102 (2016).



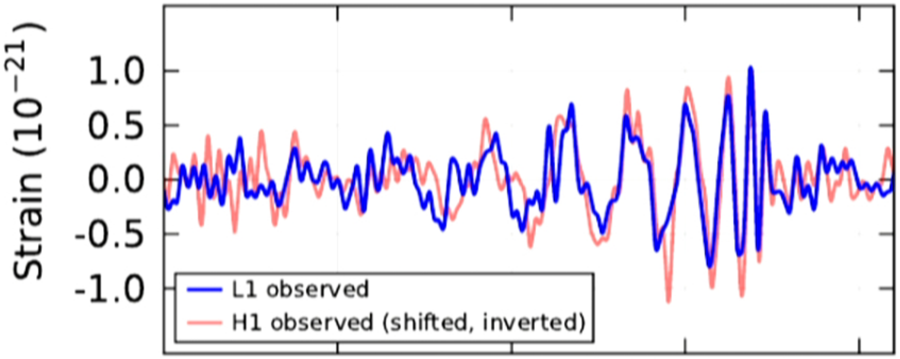
We can actually see it!

LVC, PRL 116, 061102 (2016).

Hanford, Washington (H1)



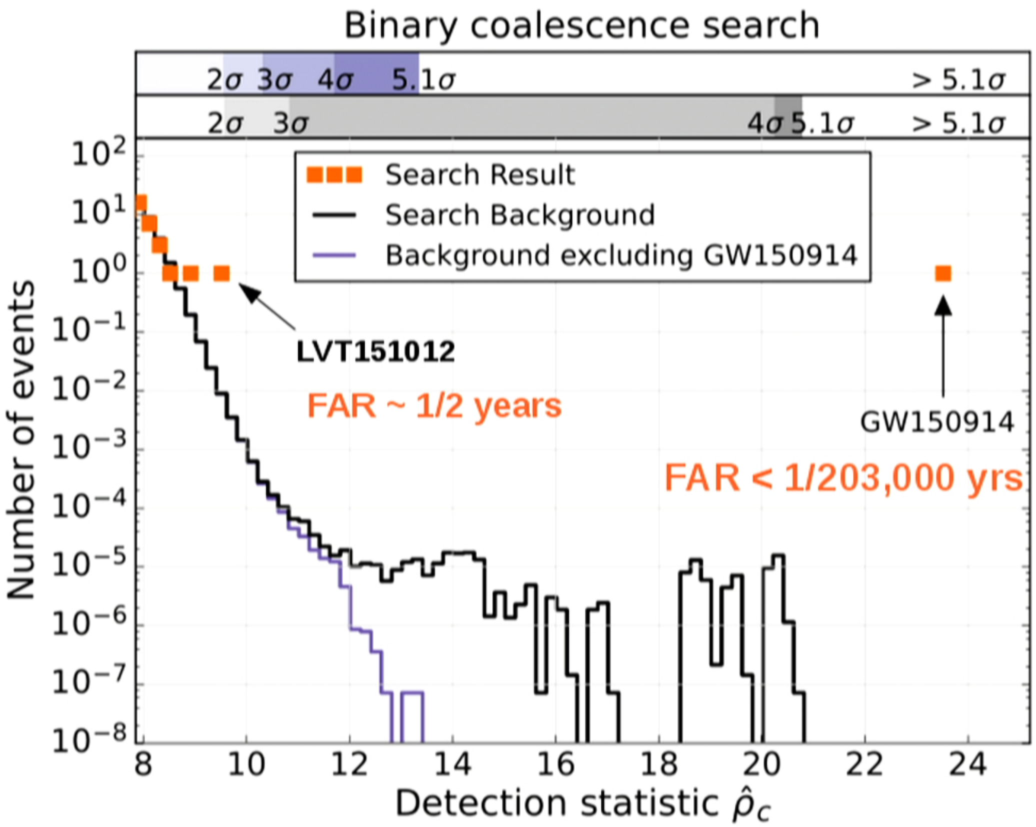
Livingston, Louisiana (L1)



CBC search for GW150914

- Two CBC searches
- Event found with similar significance

LVC, 1602.03839



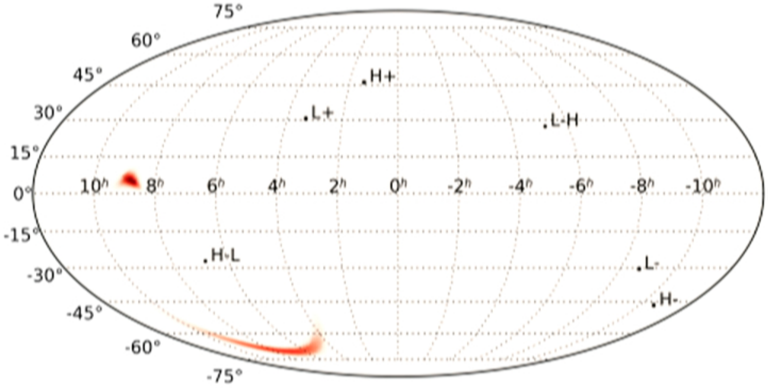
FAR ~ 1/2 years

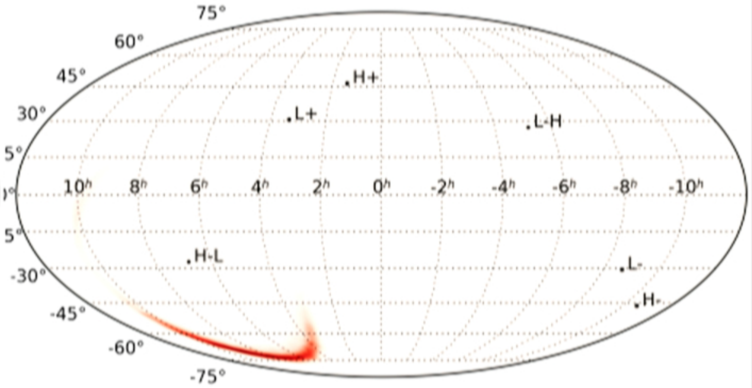
FAR < 1/203,000 yrs

Detection of GW150914 (And hint of second event, LVT151012) used to constrain BBH formation rate: $2-400\, Gpc^{-3}\, yr^{-1}$ (LVC, 1602.03842)

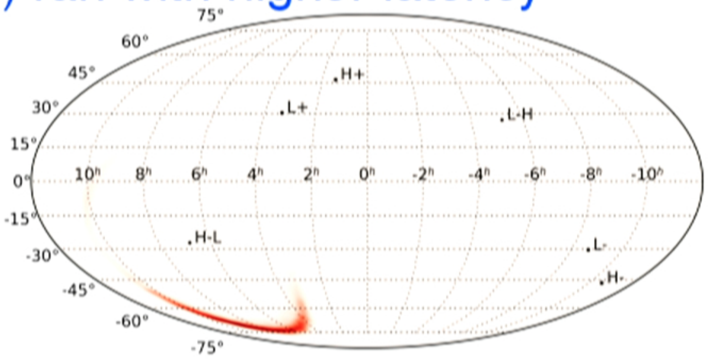
GW150914 – Sky localization

- Sky map generated by burst searches sent to EM facilities after < 48hrs





- CBC targeted parameter estimation (LALInference, Veitch+ PRD 91 042003) ran with higher latency



LVC, 1602.03843


CHICOPEE RACING

CBC and their formation channels

- Measuring masses and spins can help determine channel and environment in which BH and CBC are formed

- Two main formation channels
  - Common envelope evolution
    - Galactic fields
    - Final masses not too different
    - Aligned spins

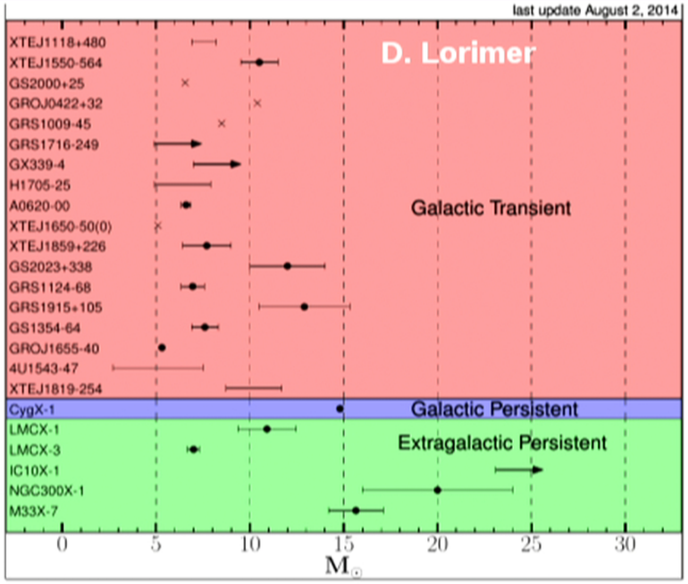
  - Dynamical capture
    - Globular clusters
    - Any mass ratio (?)
    - Misaligned spins

- Measuring max BH mass tells about progenitors
  - Metallicity, winds

LIGO

Black holes in X-ray binaries

- Known stellar-mass BH masses and spins come from X-ray binaries
- Mass estimate requires period, radial velocity, inclination
  - Most massive ~15Msun
- Spin estimate done with two methods
  - Fe Line, Continuum fitting
  - Sometimes in tension

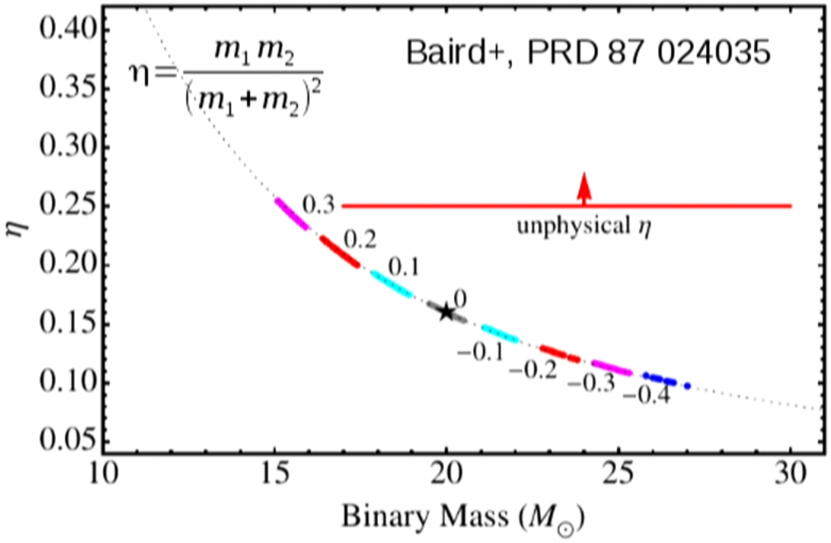


System	a_* (CF)	a_* (Fe line)	No. obs.	References	
Cygnus X-1	> 0.983	0.97 ± 0.02	9 / 1	Gou+ 2011, 2014 Fabian+ 2012	☑
LMC X-1	0.92 ± 0.06	0.72 – 0.99	19 / 1	Gou+ 2009 Steiner+ 2012	☑
GRS 1915+105	> 0.95	0.98 ± 0.01	6 / 1	McClintock +2006 Miller +2013	☑
XTE J1550-564	0.34 ± 0.24	0.55 ± 0.20	60 / 2	Steiner, Reis+ 2011	☑
GRO J1655-40	0.8 ± 0.1	> 0.9	33 / 2	Shafee+ 2006 Reis+ 2009	✗
4U 1543-47	0.7 ± 0.1	0.3 ± 0.1	34 / 1	Shafee+ 2006 Miller+ 2009	✗

J. McClintock

Black hole masses

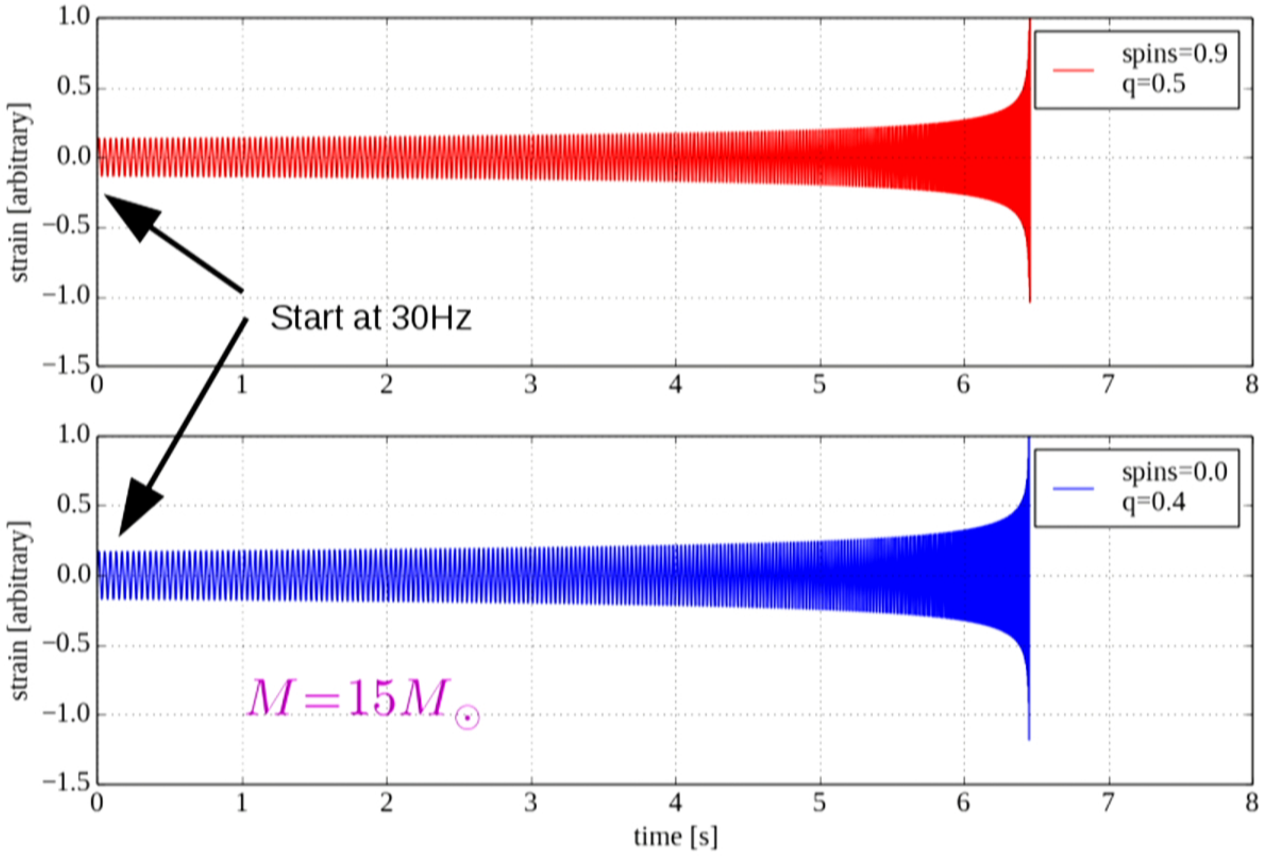
- For BH, we cannot neglect spins
- If spin aligned with orbital angular momentum, significant mass-spin degeneracy



Mass ratio errors above 25-30% (Lynch+, PRD 91 044032)

A change of spin can typically be mimicked by a change of mass ratio (i.e. component masses)

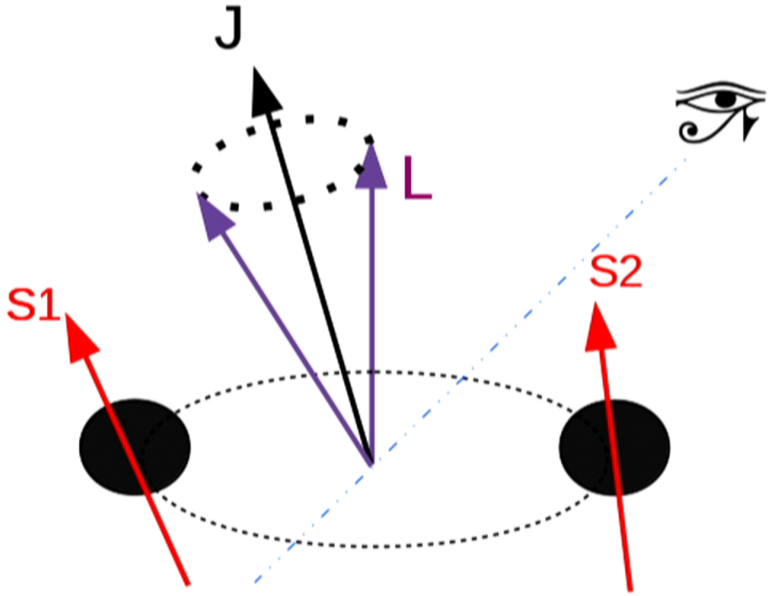
Aligned-spin mass-spin degeneracy



Start at 30Hz

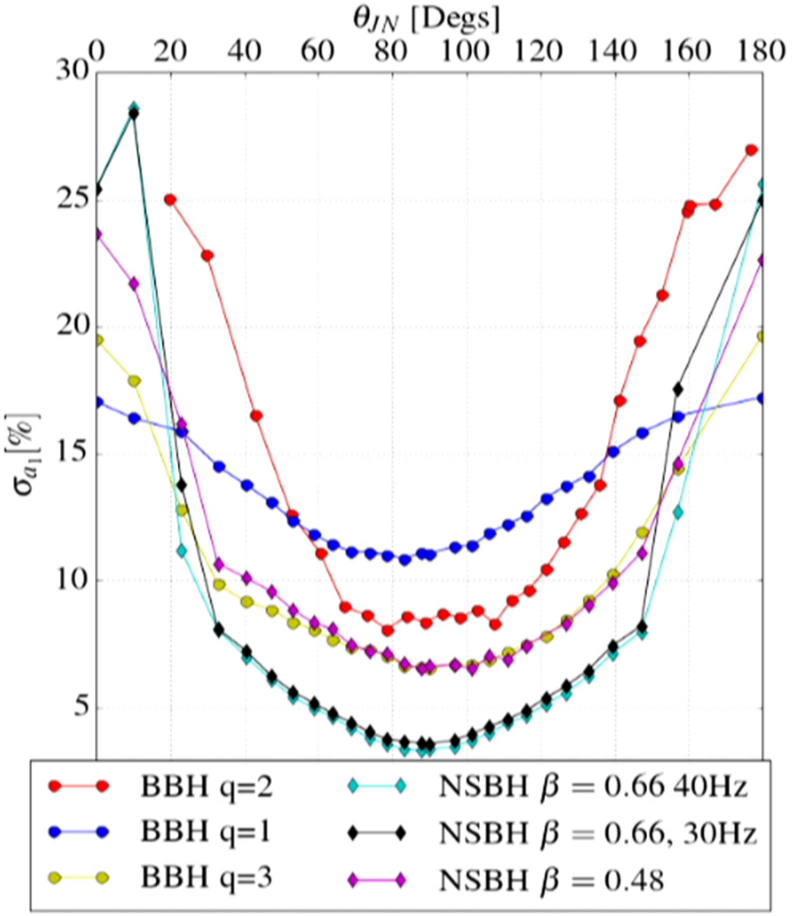
$M = 15 M_\odot$

Precessing spins



- Spin-Orbit coupling makes the orbit precess
- Richer physics, some degeneracies are reduced
- WF gets amplitude and phase modulation
- Spin-Spin coupling

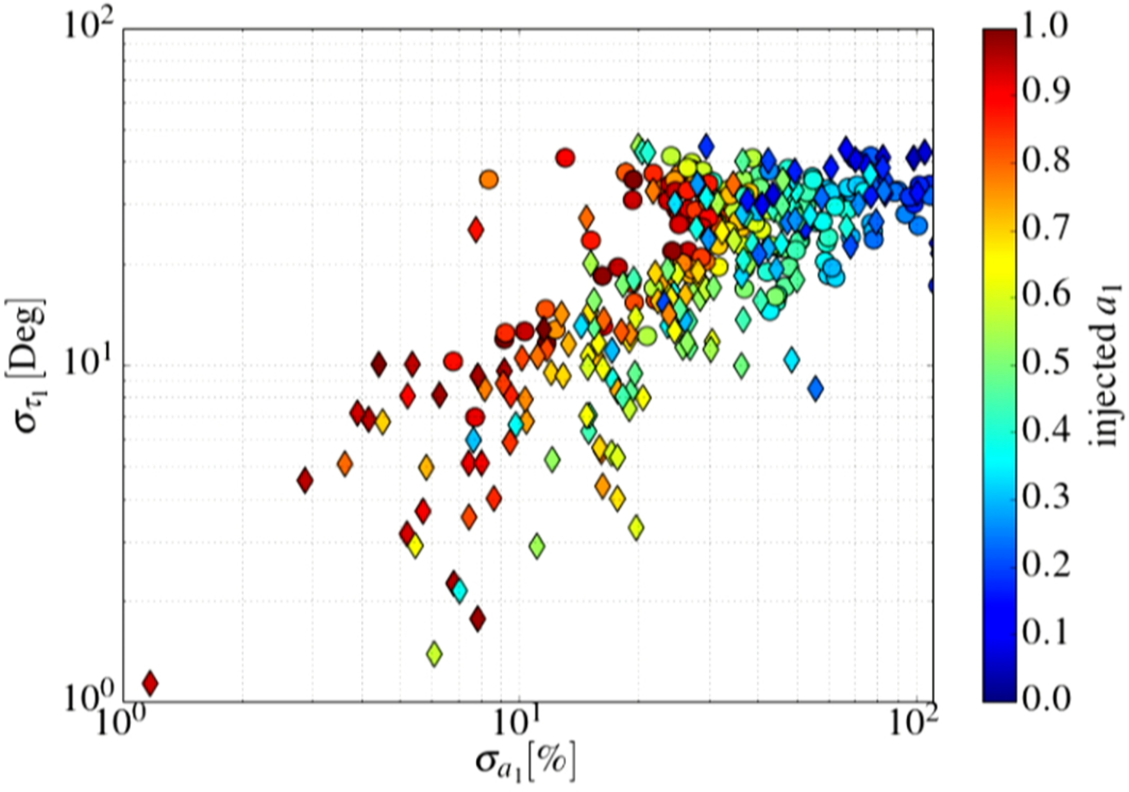
Effects of orbital orientation



- Spin estimation strongly affected by orientation
- Spin errors at their minimum if system seen “edge-on”
- Much less likely to detect than “face-on”

Vitale+, in prep., Vitale+ PRL 112 251101

Astrophysical distribution - spin



M_tot <15 Msun

Diamonds = NSBH
Circles = BBH

Vitale+ in prep., Vitale+ PRL 112 251101

Estimates for GW150914

- Parameter estimation is obtained running stochastic samplers to explore the full parameter space (Veitch+ PRD 91 042003)

$$p(\vec{\theta}|d)=\frac{p(d|\vec{\theta})\,p(\vec{\theta})}{p(d)}$$

- Used two waveform families to check WF systematics.
  - One fully precessing spin and one spin-aligned
  - Results highly compatible.
- Used two independent samplers
  - Identical results
- Instrumental calibration errors taken into account (Vitale+ PRD 85, 064034, LVC 1602.03840)
- Assumed general relativity is correct (more later)

Estimates for GW150914

- High probability for ~"face-away" orientation
  - Eventual precession effects reduced
  - Only loos
  - al spins.
- Large ma
  happen in
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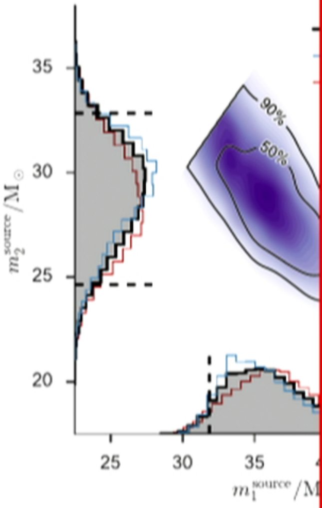
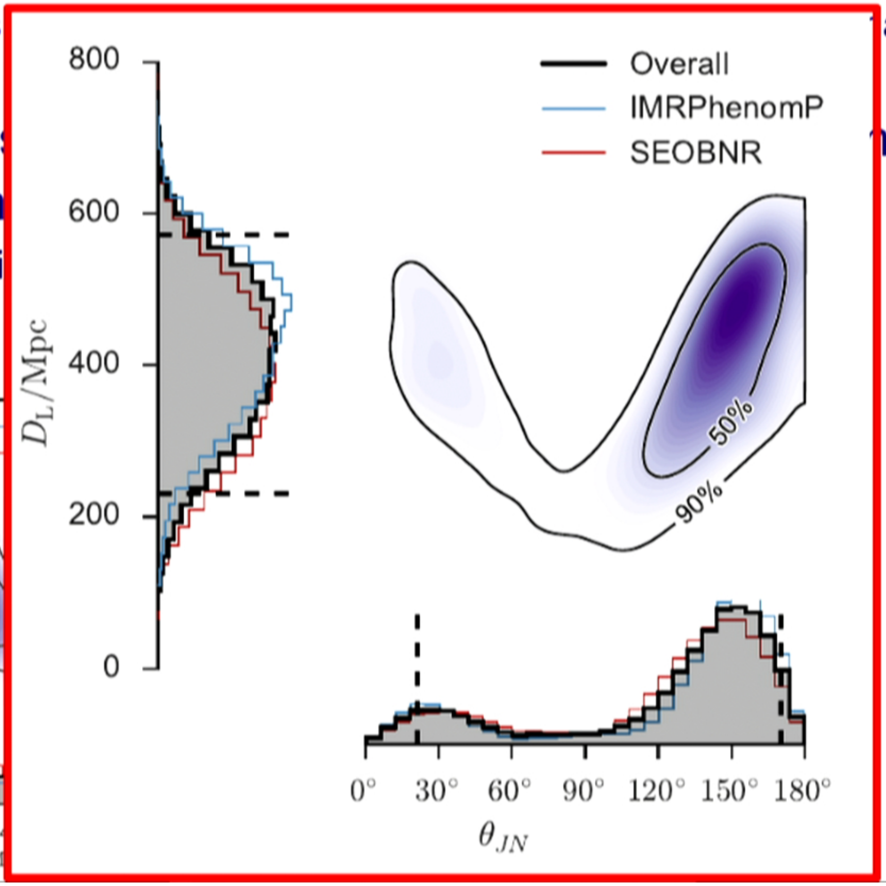
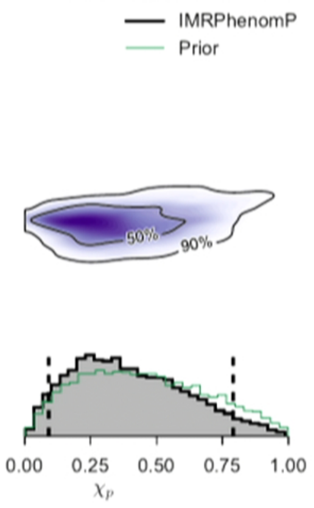
  - Mass esti
    mass
  - ~8% for chirp





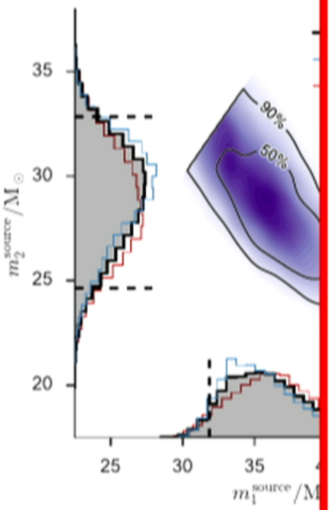
LVC 1602.03840

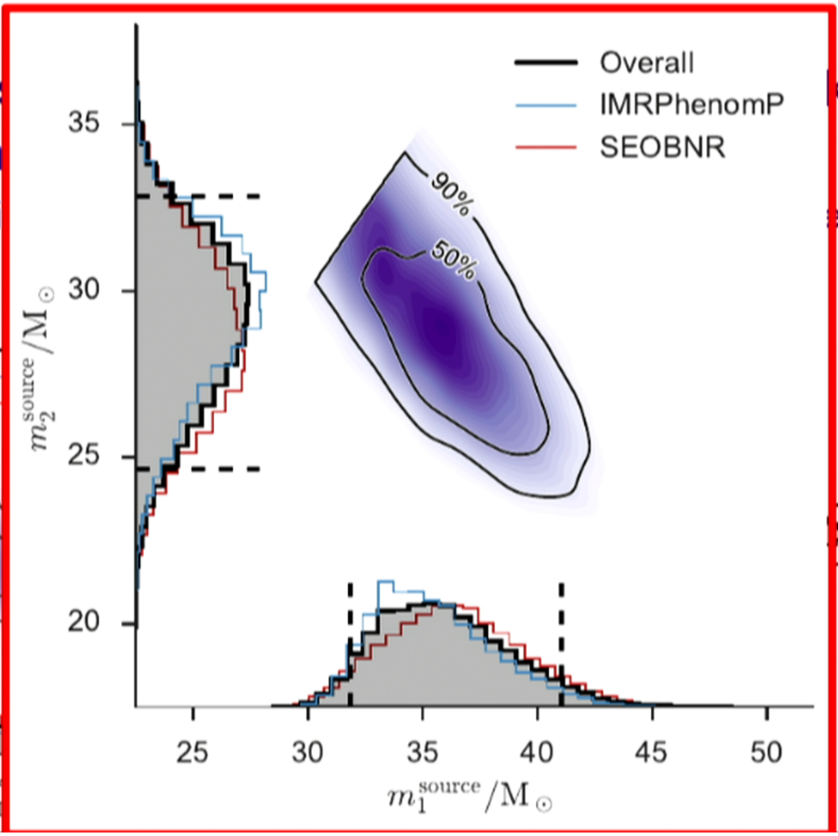


Estimates for GW150914

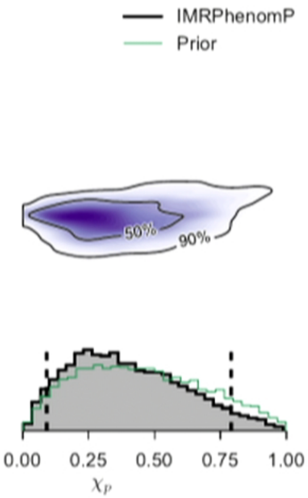
- High probability for ~"face-away" orientation
    - Eventual precession effects reduced
    - Only loose constraints on spins: |a1|< 0.7, |a2|<0.9. No maximal spins.

- Large ma k holes to happen in
    - Mass esti s, ~8% for chirp mass





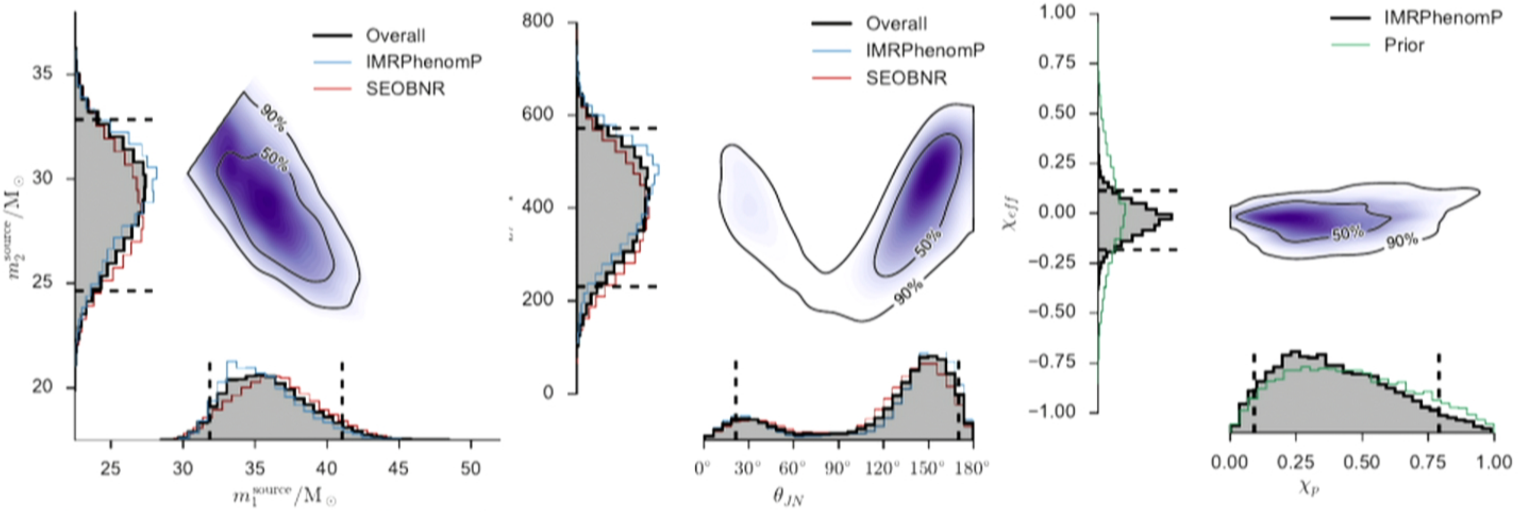
LVC 1602.03840



Estimates for GW150914

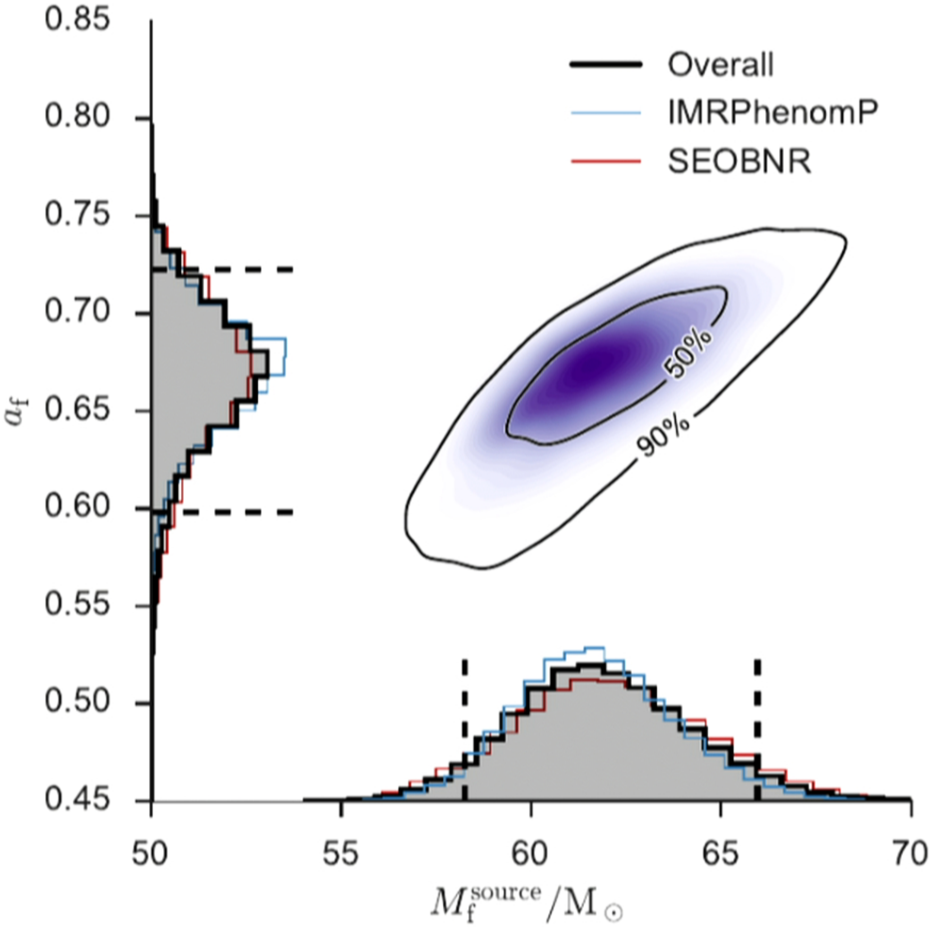
- High probability for ~"face-away" orientation
  - Eventual precession effects reduced
  - Only loose constraints on spins: |a1|< 0.7, |a2|<0.9. No maximal spins.

- Large mass caused the merger of the two black holes to happen in the LIGO band
  - Mass estimation of the order of ~15% for component masses, ~8% for chirp mass



LVC 1602.03840

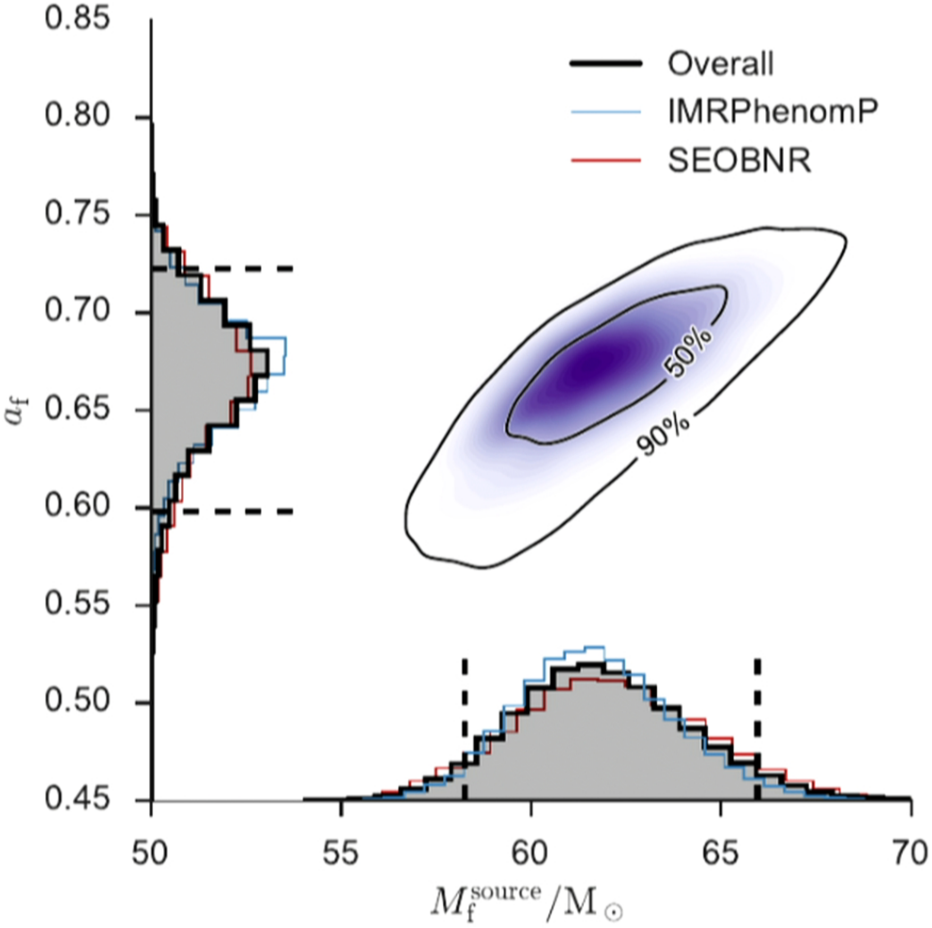
Estimates for GW150914



- Assuming GR is right, we can also calculate the mass and spin of the final black hole (using NR)
- 3 Msun radiated away with GW
- Surface of horizons
  - BH1 ~ 1.6e5 Km2
  - BH2 ~ 1.0e5 Km2
  - Final BH ~4.4e5 Km2

Ontario: ~1e6 Km2

Estimates for GW150914



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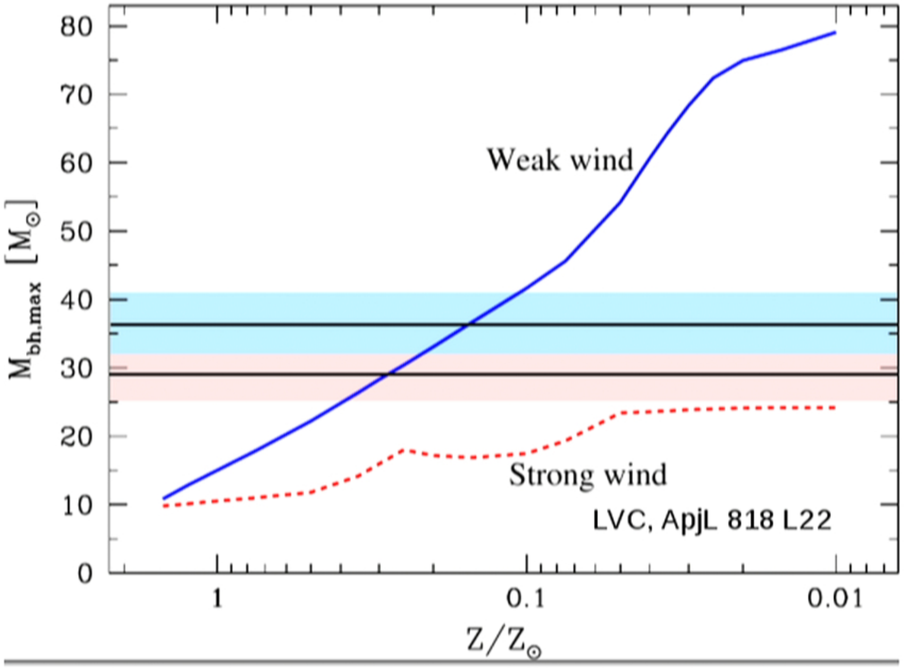
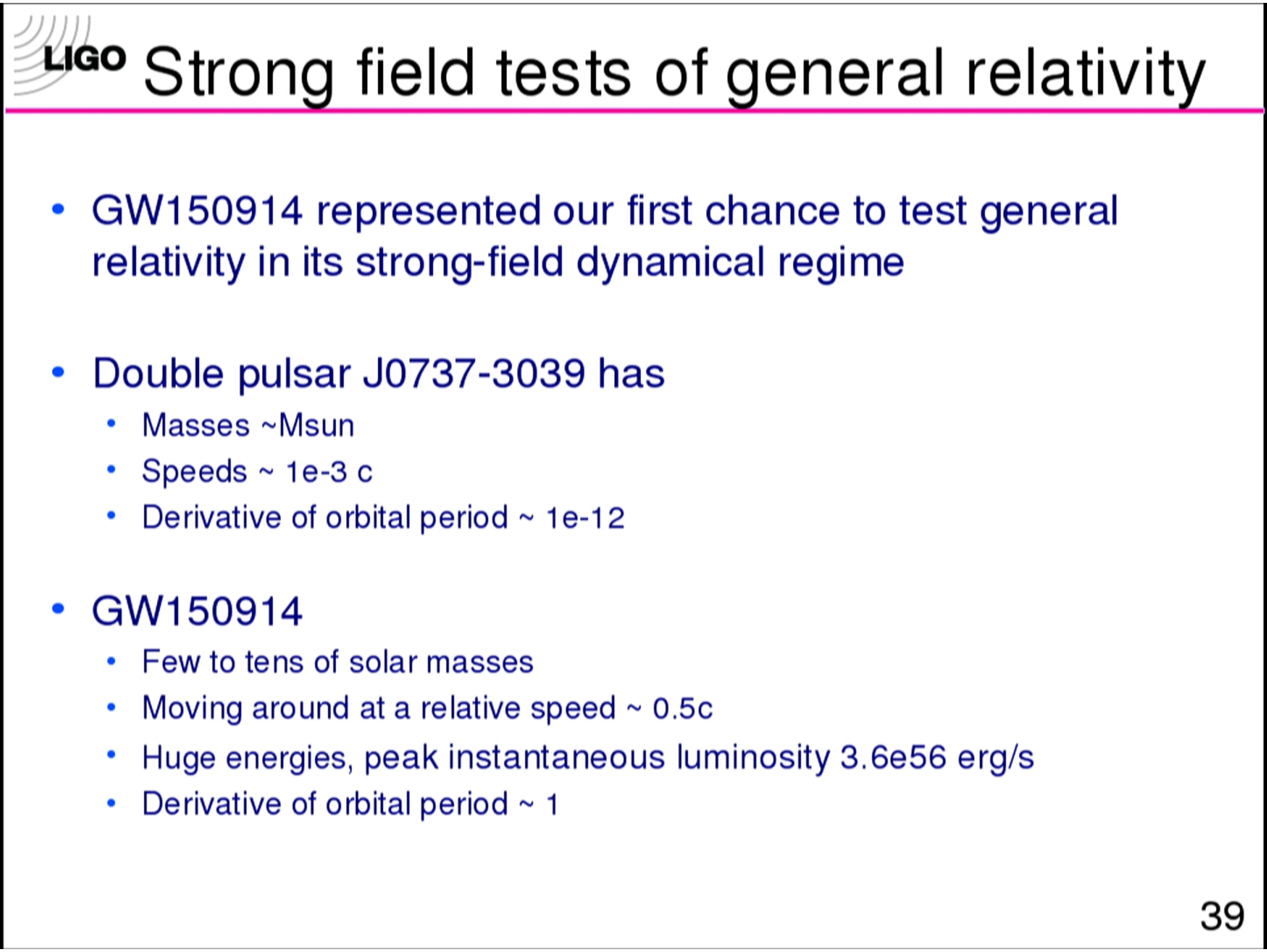
Ontario: ~1e6 Km2

Astrophysical implications

- Component masses puts a constraint on the metallicity of the progenitors



- Strong wind models disfavored (cannot build up 30Msun BHs)
- Weak wind model OK if metallicity <~ 0.5 Zsun



Strong field tests of general relativity

- GW150914 represented our first chance to test general relativity in its strong-field dynamical regime

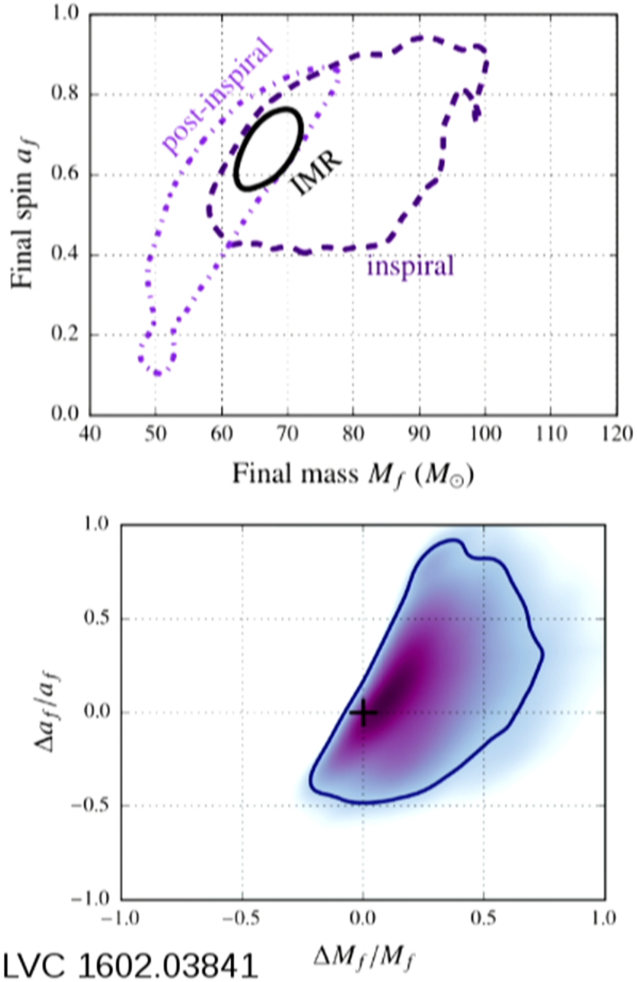
- Double pulsar J0737-3039 has
  - Masses ~Msun
  - Speeds ~ 1e-3 c
  - Derivative of orbital period ~ 1e-12

- GW150914
  - Few to tens of solar masses
  - Moving around at a relative speed ~ 0.5c
  - Huge energies, peak instantaneous luminosity 3.6e56 erg/s
  - Derivative of orbital period ~ 1

GR tests with GWs

- Within LIGO-Virgo, coordinated effort started in 2011
- Rich literature for space, ground and pulsars
- Mostly focused on testing some specific non-GR theory
- Would also need a generic test that will work for unknown deviations from general relativity (Li+ PRD 85 082003 , Agathos+ 89 082001)

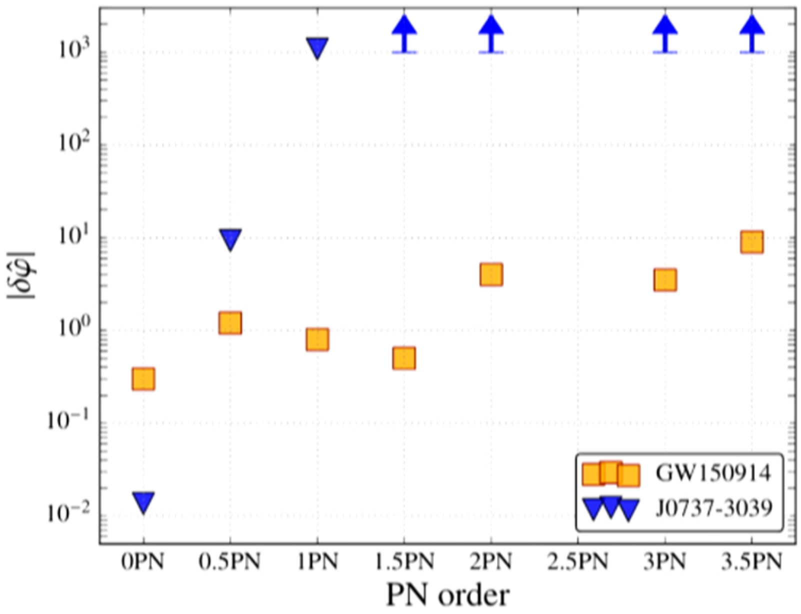
GR tests with GW150914: remnant BH



- Within GR the mass and spins of the remnant BH are uniquely determined by the mass and spins of initial BHs
- Predict final mass and spins from inspiral (i.e. initial BHs) and compare with actual value calculated directly form post inspiral (remnant BH)
- Results fully compatible with GR

LVC 1602.03841

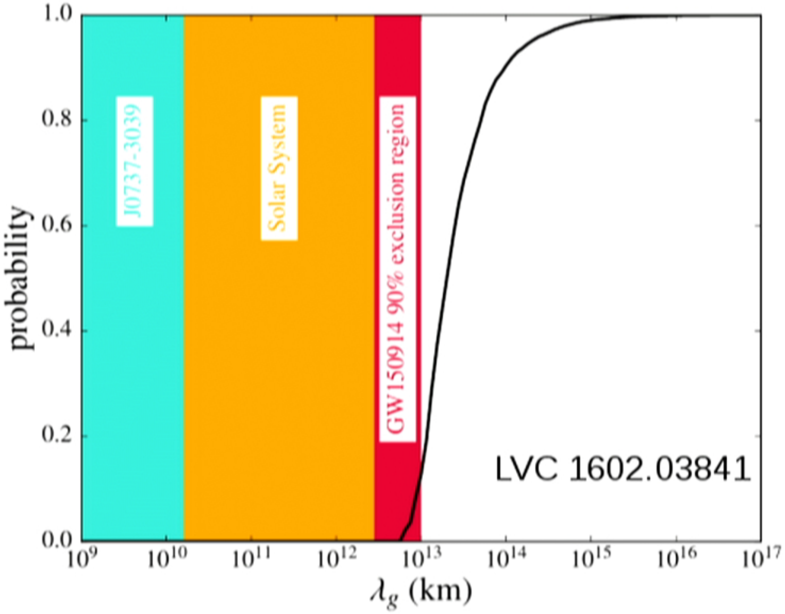
GR tests with GW150914: Phasing



Yunes, Hughes, 1007.1995
LVC 1602.03841

- The double pulsar has allowed for low-order Post Newtonian tests of GR
- We allowed each PN term in turn to deviate from its GR value and put bound
- Double pulsar already beaten at 0.5PN

GR tests with GW150914: massive graviton



- 3 orders magnitude better than double pulsar
- Factor of 3 better than solar system
- Some model dependent tests do better

$$m_g < 1.2\times10^{-22}\, eV/c^2$$

- A full self-consistent of gravitational field mediated by massive particle is not yet available
- However, just modifying the dispersion relation one can calculate extra phasing term for GW phase (Will, PRD 57 2061)


asing term
ill, PRD 57
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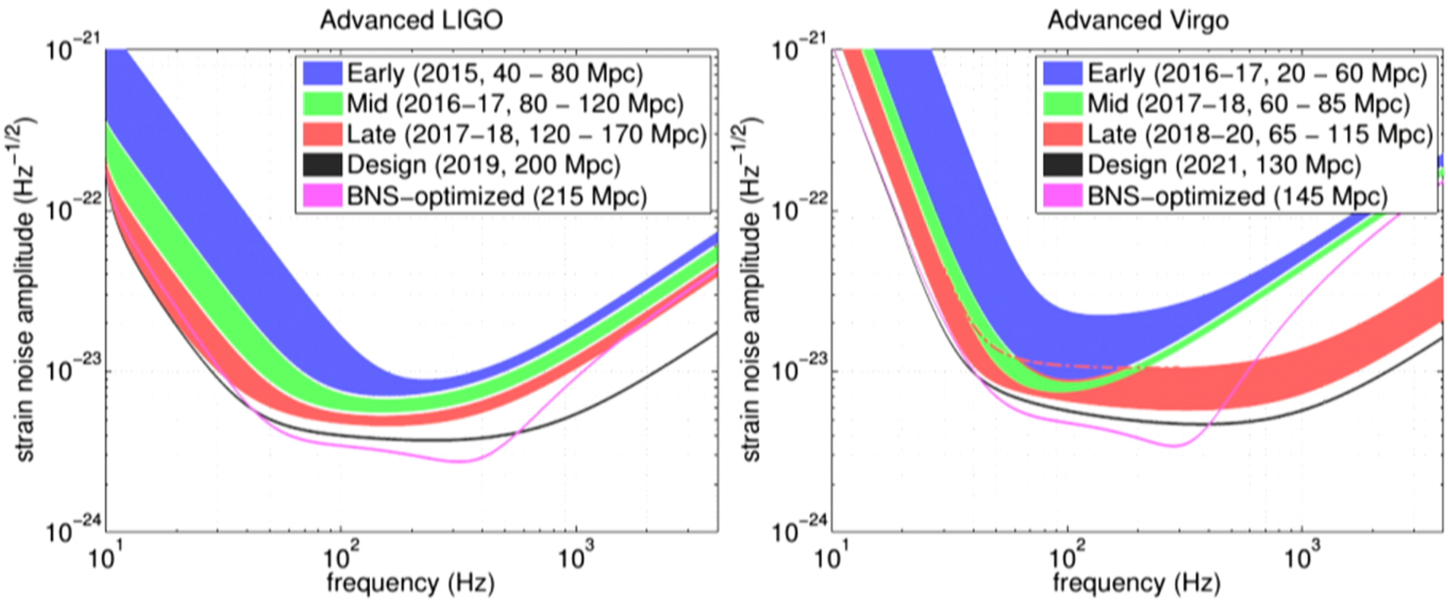
Schedule and sensitivity



LVC Liv.Rev.Rel 19, 1

Expected science runs:

- 2015 - 3 months, LIGO only (40-80 Mpc) ⟵ O1, DONE
- 2016-17 – 6 months, LIGO (80-120 Mpc) + Virgo (20-60 Mpc)
- 2017-18 – 9 months, LIGO (120-170 Mpc) + Virgo (60-85 Mpc)
- 2019, LIGO (200 Mpc) + Virgo (65-130 Mpc)

Conclusions – 5 year goals

- GW150914 is only the first step to GW astronomy

- More binary black holes detections will lead to
  - Understanding of BH mass and spin distributions, formation channels
  - Checks of GR is its strong field regime
  - Precise idea of BBH formation rates, rates(z) ?

- Will probably detect binary neutron stars
  - Joint EM-GW discovery: progenitors, environment, opening angle, ...
  - Rank equations of state
  - Maximum mass of neutron star?
  - Hubble constant (10% level)

- Never stop listening!
  - Gravitational waves bursts from SNe, other violent events, unknown sources