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Takayama, Aug 26th 2016

Characterization of compact objects with gravitational waves

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Takayama, Aug 26th 2016

The dark side of astrophysics

- Over the last few thousand years humanity has used electromagnetic waves to study the universe
- Light has been pivotal to our understanding of the cosmos, stars, planets
  - However light can be easily deflected, absorbed, obscured

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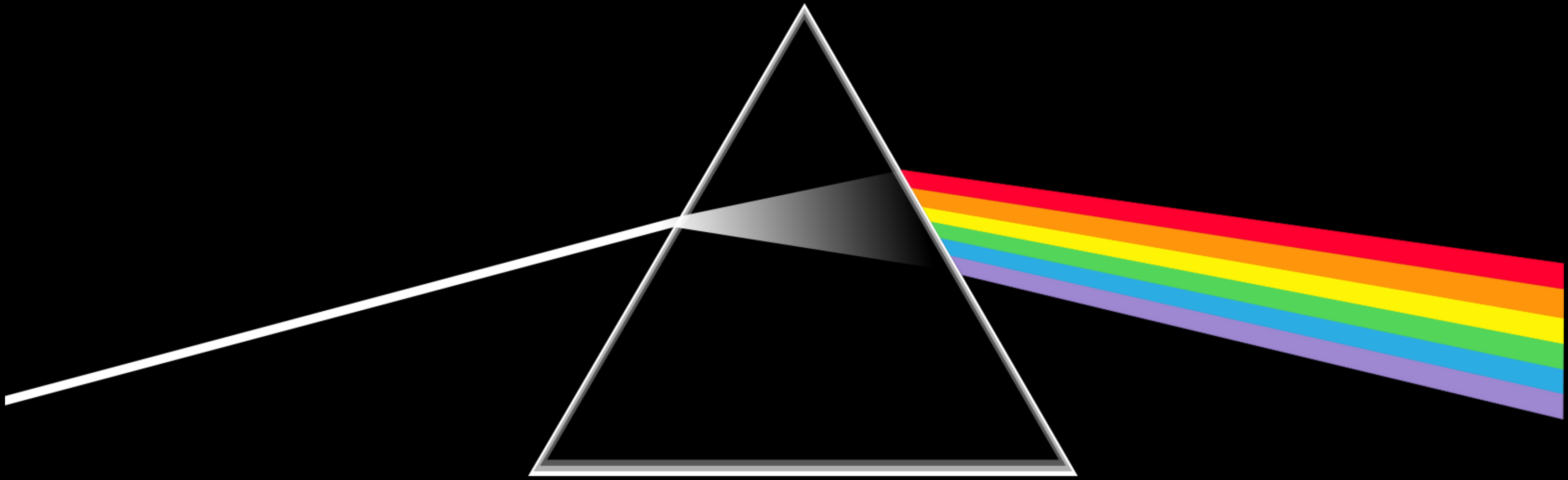
- Over the last few thousand years humanity has used electromagnetic waves to study the universe
- Light has been pivotal to our understanding of the cosmos, stars, planets
  - However light can be easily deflected, absorbed, obscured

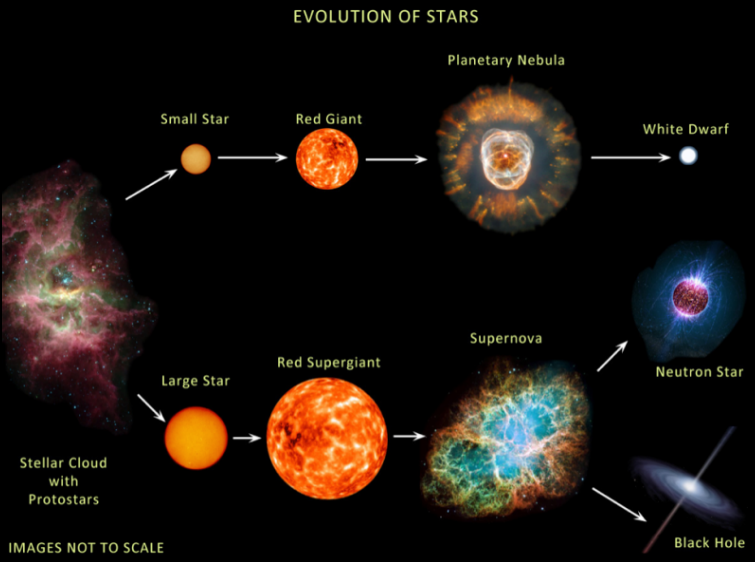
- Now, it’s the time for the dark side

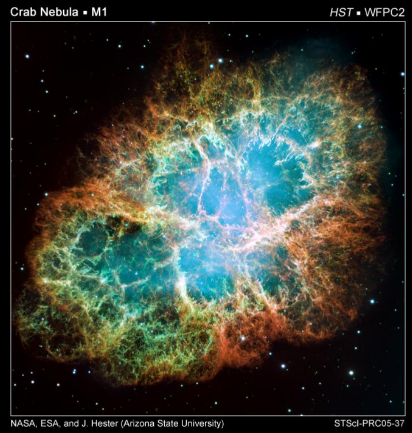
The dark side of astrophysics

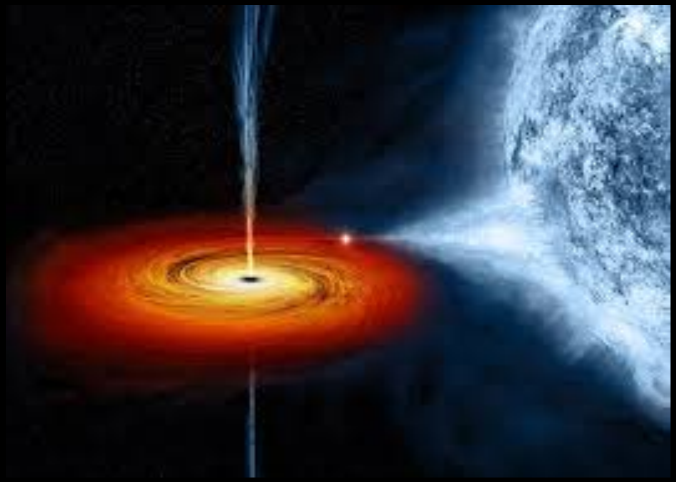


Compact objects

- Compact objects such as neutron stars (NS) and black holes (BH) host some of the most extreme conditions in the universe







Black holes

- Leftovers of massive stars
- Produce extreme gravitational fields
- Does general relativity still hold true near a BH?
- How fast can they spin?
- How big can they get?
- When did the first BHs form?

Neutron stars

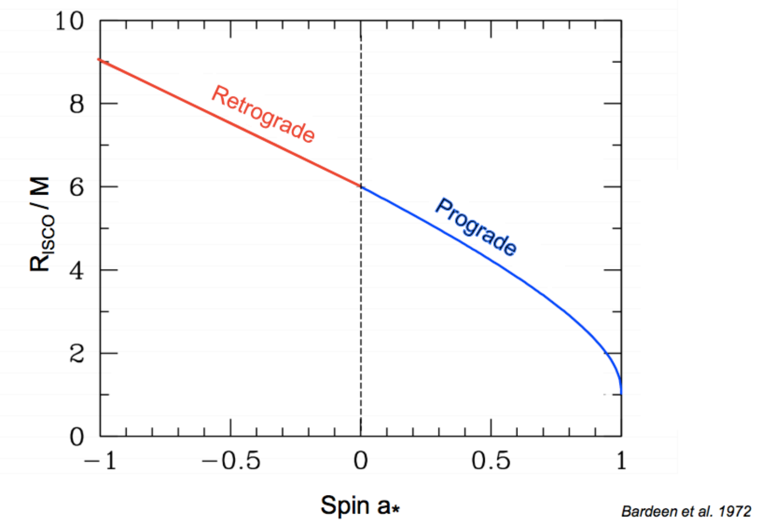
- The most dense objects we can observe
  - A mass of 1.4 $M_\odot$ contained in a sphere with radius of 10 Km
- How does matter behave in these extreme conditions?
- Are neutron stars related to GRBs? And metal production?
- What is the maximum mass of a neutron star?

BH spins (with EM)

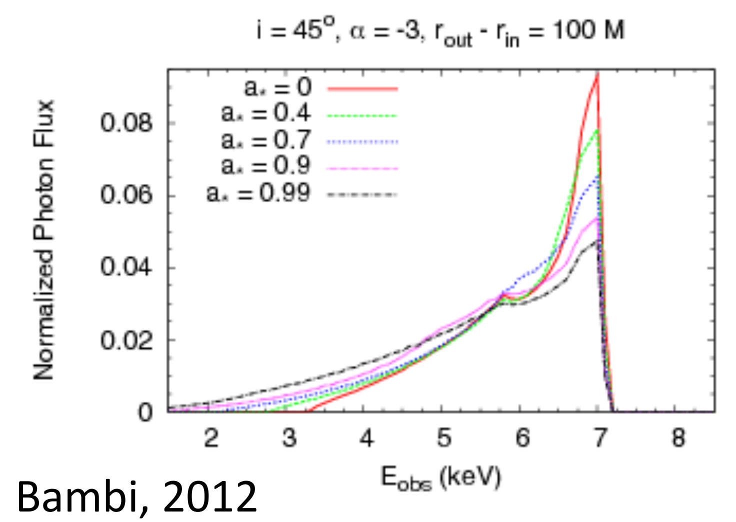
- Traditionally, the spin of black holes has been estimated through its effects on a surrounding disk
- Need an accreting black hole (e.g. in a X-ray binary)

BH spins (with EM)

- If a BH is spinning, the radius of the innermost stable circular orbit will get closer (Continuum fitting)
- If the debris in the disk reflect light, the spectral lines will be distorted by GR effects which depend on the spin (FE-line)



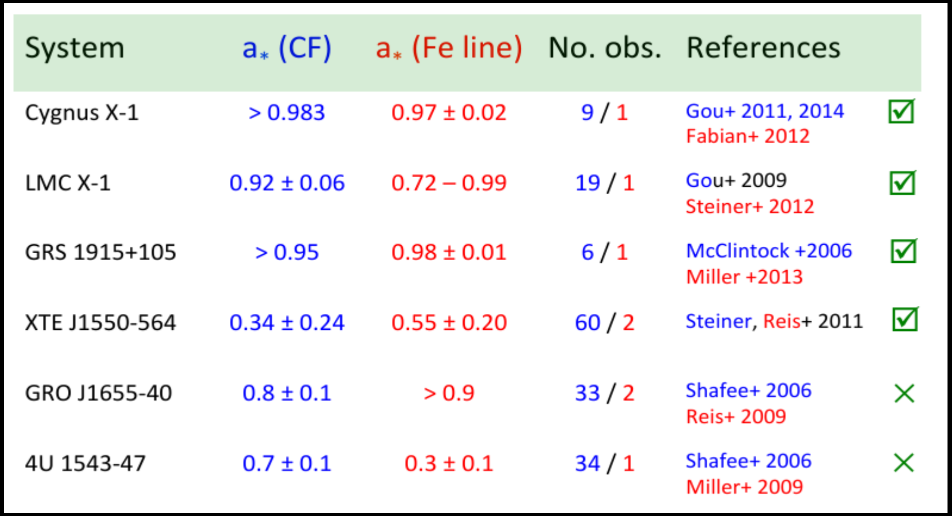
Bardeen et al. 1972



Bambi, 2012

BH spins (with EM)

- Both methods rely on a good understanding of the disk physics and are *indirect* measurement of spin
- Sometime in tension with each other



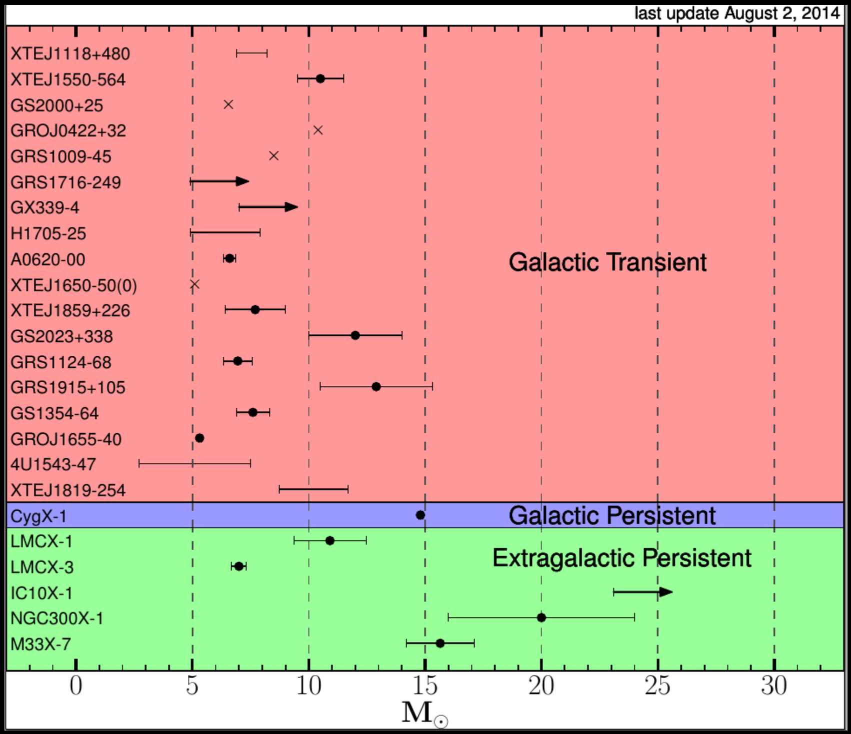
System	a_* (CF)	a_* (Fe line)	No. obs.	References	
Cygnus X-1	> 0.983	0.97 ± 0.02	9 / 1	Gou+ 2011, 2014 Fabian+ 2012	☑
LMC X-1	0.92 ± 0.06	0.72 – 0.99	19 / 1	Gou+ 2009 Steiner+ 2012	☑
GRS 1915+105	> 0.95	0.98 ± 0.01	6 / 1	McClintock +2006 Miller +2013	☑
XTE J1550-564	0.34 ± 0.24	0.55 ± 0.20	60 / 2	Steiner, 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

BH mass (with EM)

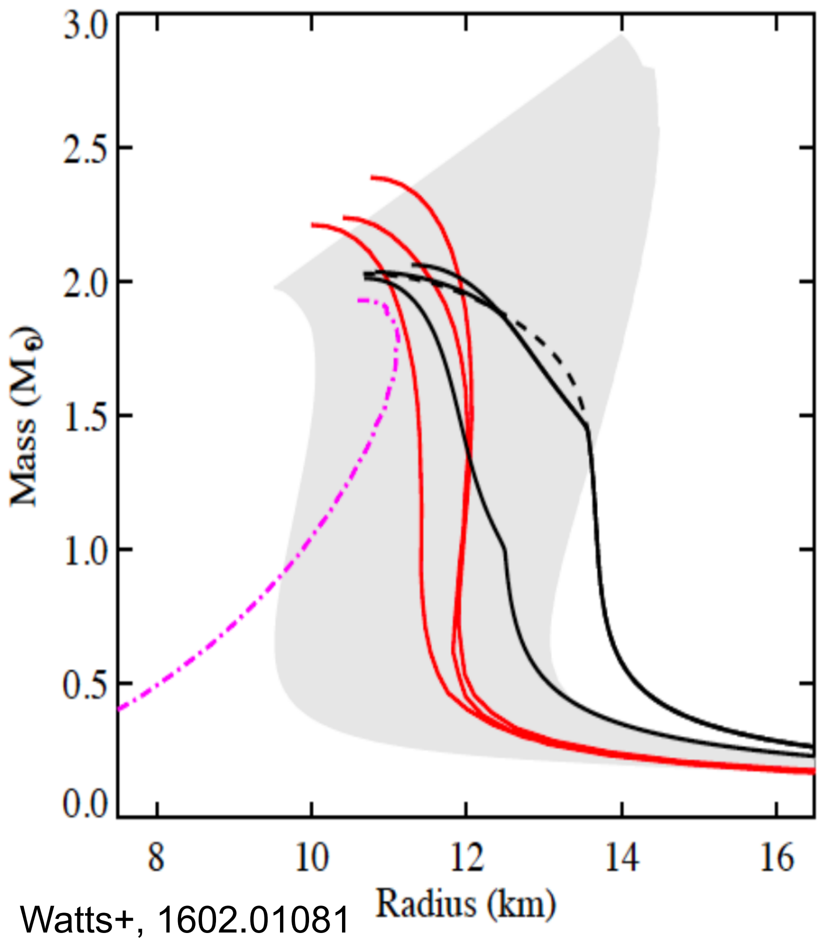
- Also rely on having a luminous companion
- Requires period, radial velocity, inclination, companion mass
- Indirect measurement

D. Lorimer



NS equation of state (with EM)

- The equation of state summarizes how matter behaves in NS
- Boils down to simultaneous measurement of mass and radius
- Possible with EM, but challenging
  - Mass estimates not always reliable
  - Radius estimates non often available and not always reliable
  - NICER to launch 2016, 5% precision



Watts+, 1602.01081

Gravitational waves

- When two compact objects orbit around each other, they emit gravitational waves (GW) that encode all of the system’s properties
- Compact binary systems can thus be used to study BH and NS without the need for light just measuring the GW they emit.

What are they?

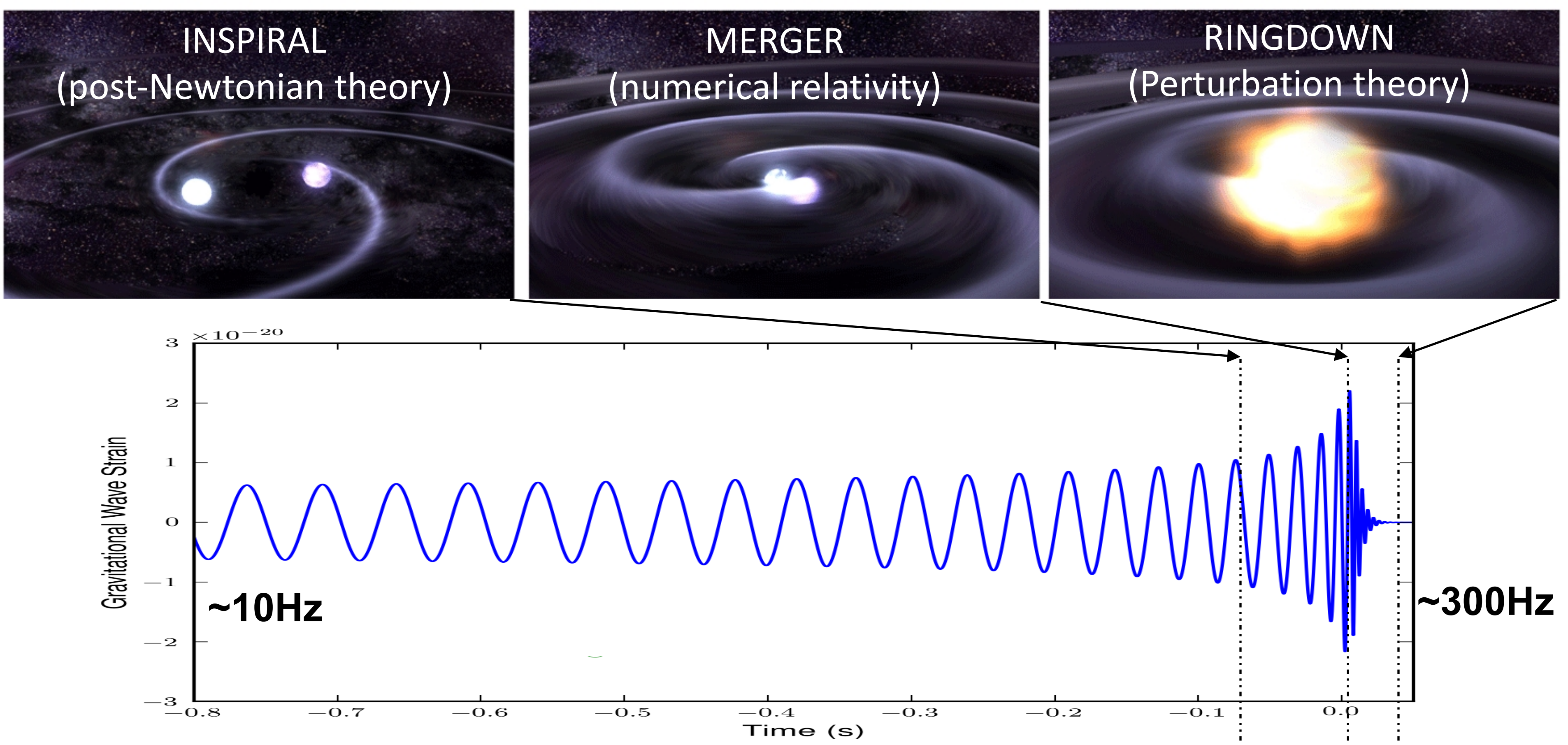
- Gravitational waves are ripples in the space-time continuum, emitted by any system with a non-constant quadrupole moment
- Yes, you can produce gravitational waves too!

- Go through quadrupole formula and the simplest CBC signal to give an idea of
  - F_GW = 2 F_orbit
  - Distance dependence
  - Mass dependence
  - Expected strain
  - Contraction and stretch in perpendicular directions

$$h_{ij} \propto \frac{4}{D}\left(\frac{\mathcal{M}G}{c^2}\right)^{5/3}\left(\frac{\pi f_{GW}}{c}\right)^{2/3}$$

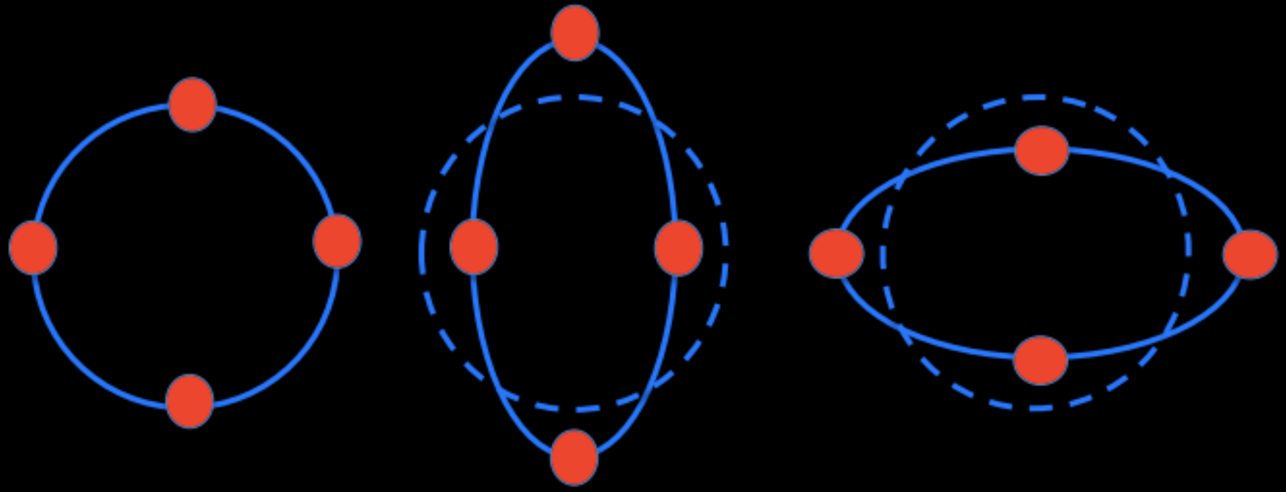
Compact Binaries Coalescences

CBC Gravitational Wave signals are very well understood

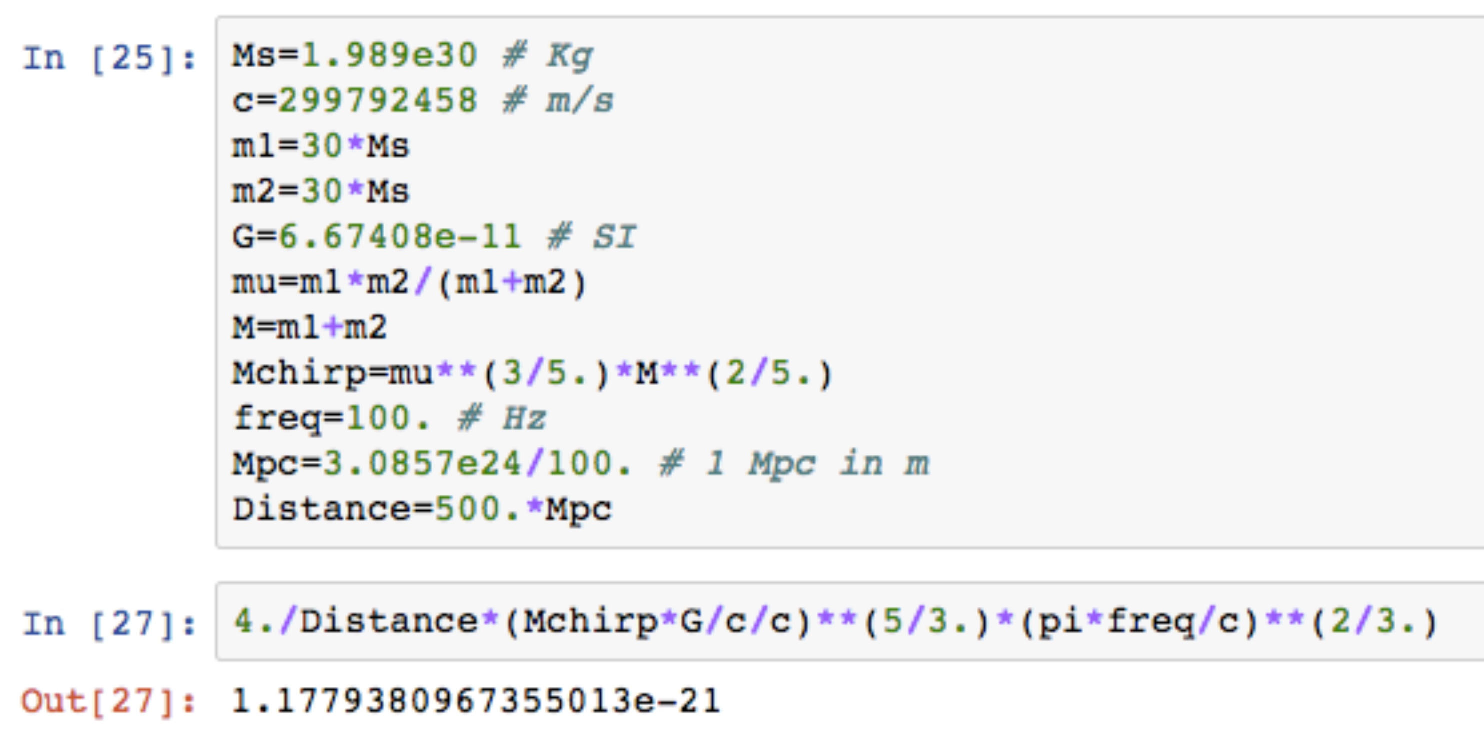


Effect of GW

- While passing through space, GW vary the distance between free floating observers
  - Distances stretch in one direction and squeeze in the perpendicular direction



Order of magnitude estimate



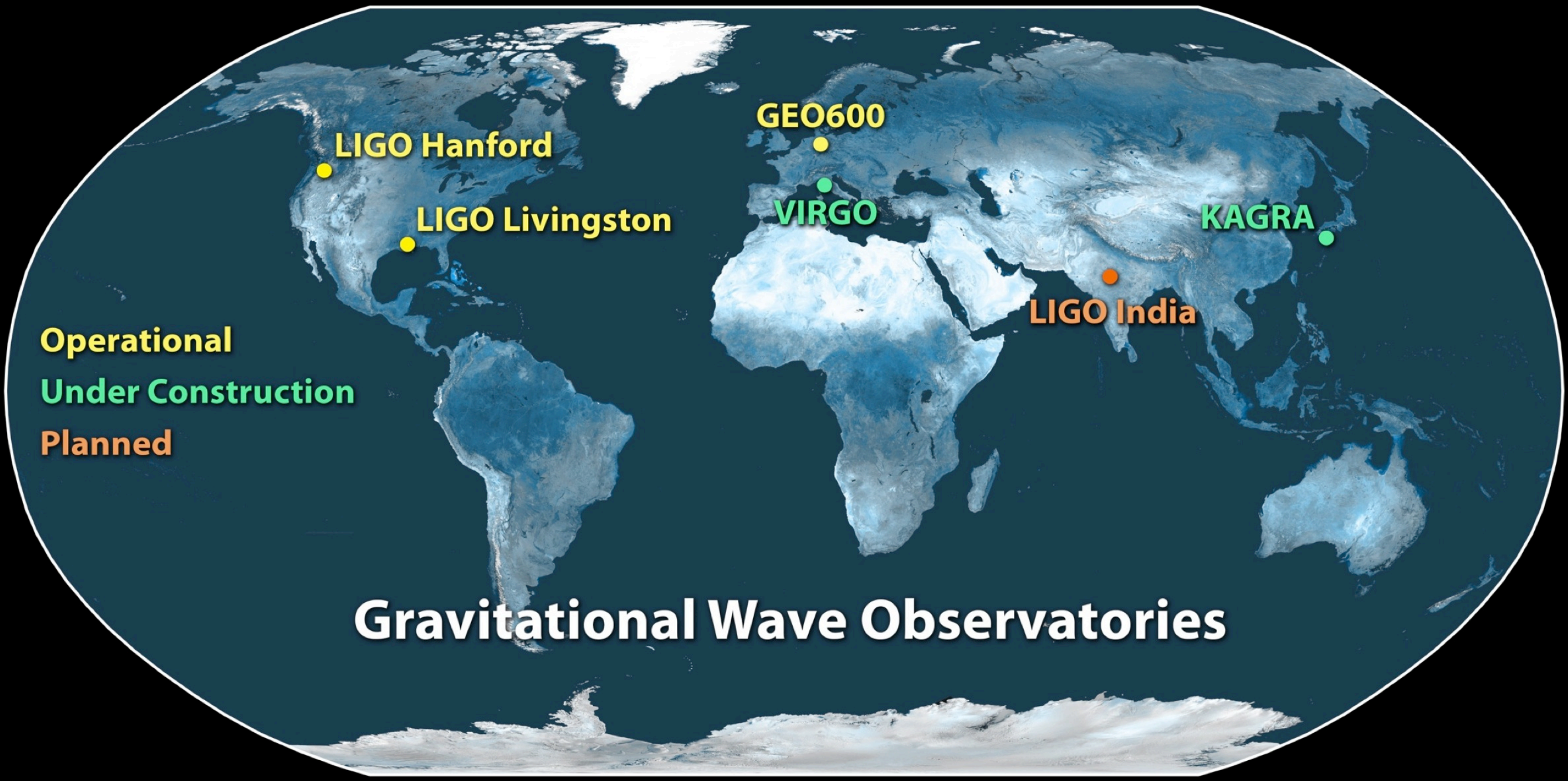
```
In [25]: Ms=1.989e30 # Kg
         c=299792458 # m/s
         m1=30*Ms
         m2=30*Ms
         G=6.67408e-11 # SI
         mu=m1*m2/(m1+m2)
         M=m1+m2
         Mchirp=mu**(3/5.)*M**(2/5.)
         freq=100. # Hz
         Mpc=3.0857e24/100. # 1 Mpc in m
         Distance=500.*Mpc

In [27]: 4./Distance*(Mchirp*G/c/c)**(5/3.)*(pi*freq/c)**(2/3.)

Out[27]: 1.1779380967355013e-21
```

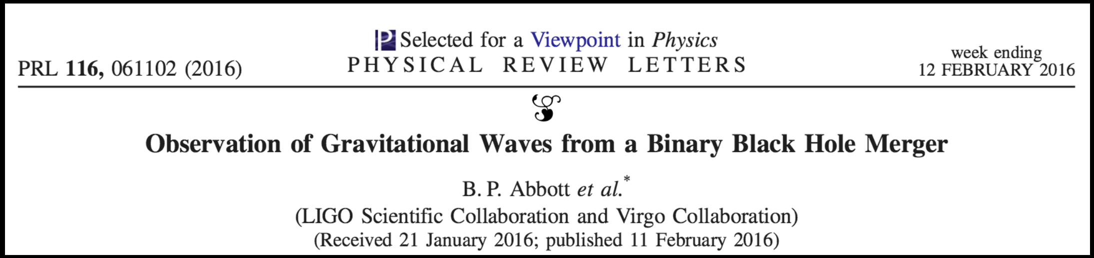
Two $30 M_\odot$ BHs at 500 Mpc would produce a strain (i.e. relative length variation) at Earth of roughly 1 part in 10^{21}

The network of Gravitational Wave detectors



Detections!!

- Advanced LIGO and Virgo detected 2 binary black hole coalescences in their first science run



Selected for a Viewpoint in *Physics*

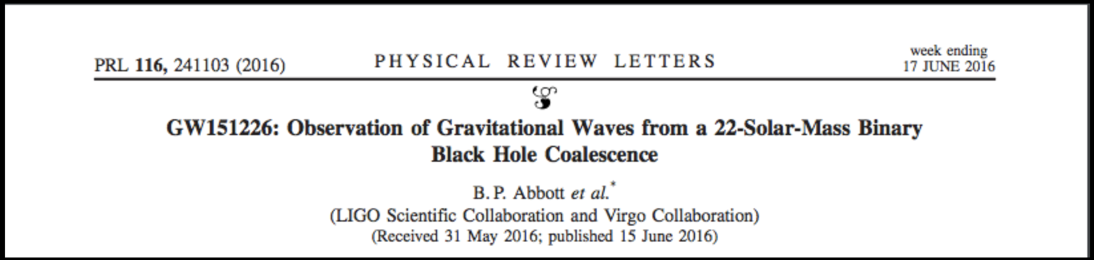
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)



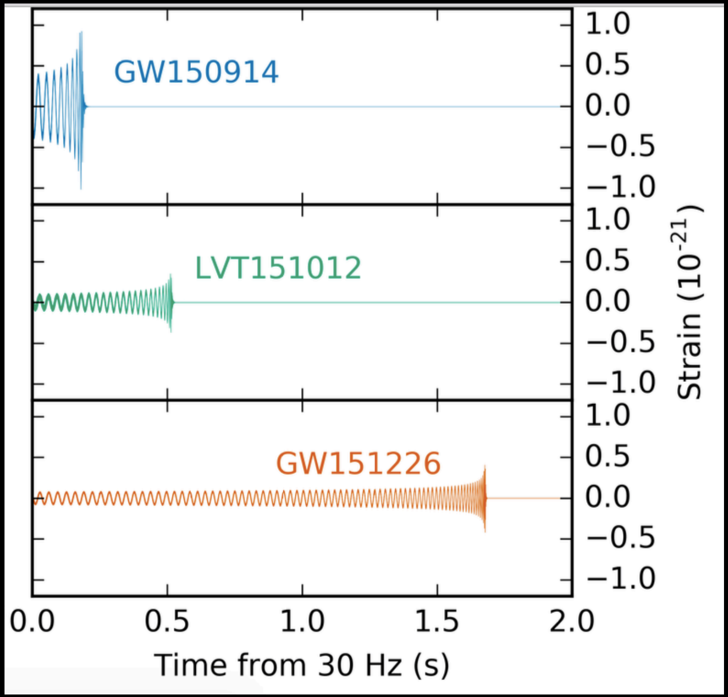
PRL **116,** 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence

B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 31 May 2016; published 15 June 2016)




Prof. RAINER WEISS


CAUTION!
BLACK
HOLES

Parameter estimation

- The (unknown) parameters of a CBC source can be estimated using Bayesian methods
  - Explore a high dimensionality parameter space using stochastic samplings (MCMC, nested sampling)

$$p(\theta|d) \propto p(d|\theta)p(\theta)$$

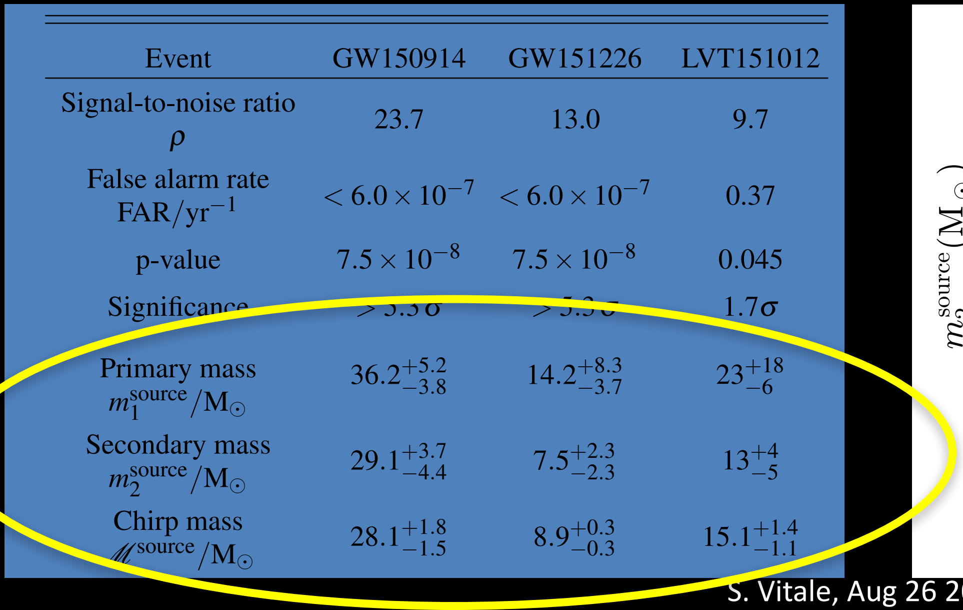
Mass estimation (with GW)

- The masses of the two objects directly affect the phasing evolution of a GW signal
  - Very good at estimating ”chirp” mass
  - Worse for component masses
- This is a *direct* measurement, the masses directly affect the amount and frequency of GW emitted

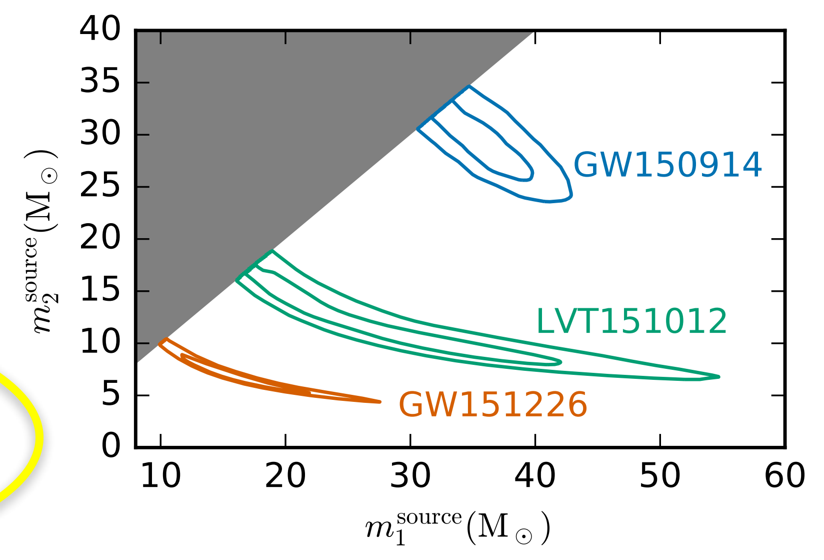
Mass estimation (with GW)

- Typically, longer signals (i.e. lower masses) will lead to better estimation of masses, since we can “follow” the signal for more cycles

LVC, 1606.04856

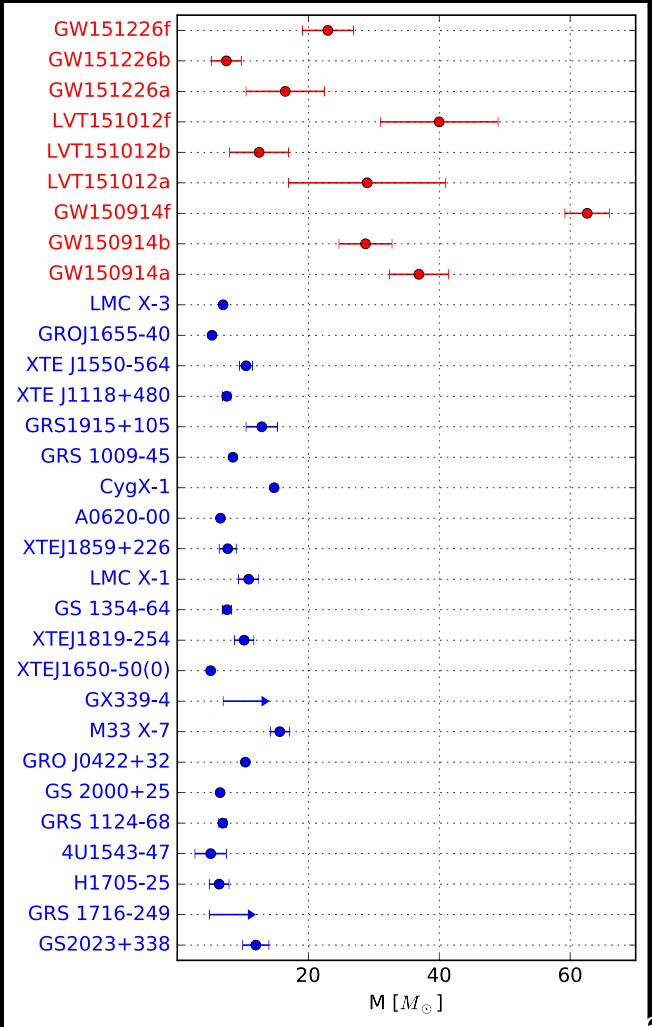


Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate $\mathrm{FAR/yr^{-1}}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\,\sigma$	$> 5.3\,\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$



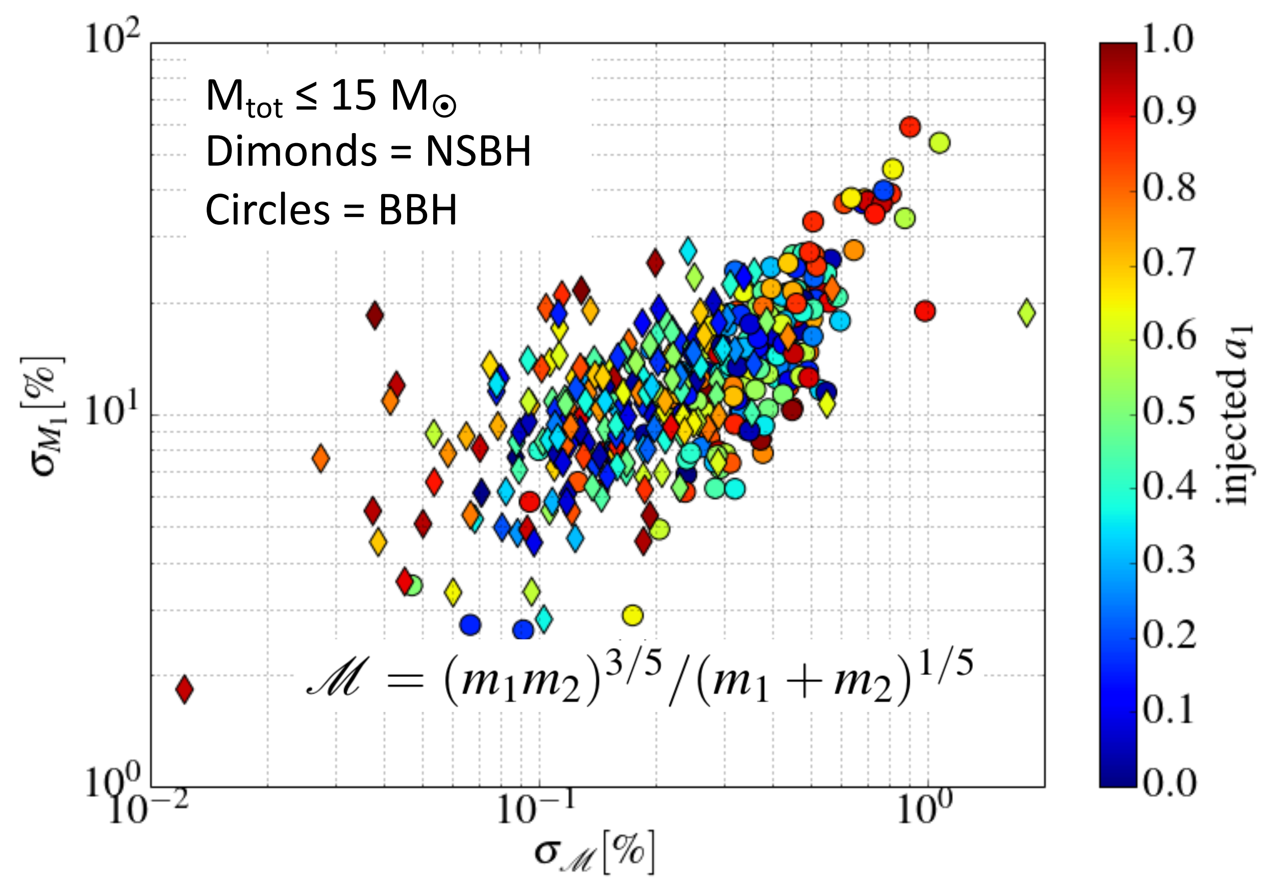
Comparison with EM

- Some of the BHs we discovered had masses significantly larger than what known from the EM
- High masses tell something about metallicity and winds of progenitor stars (LVC, ApjL 818 L22)



S. Vitale, Aug 26 2016

Astrophysical distribution - Masses



$M_{tot} \leq 15\ M_\odot$

Dimonds = NSBH

Circles = BBH

$$\mathcal{M} = (m_1 m_2)^{3/5}/(m_1+m_2)^{1/5}$$

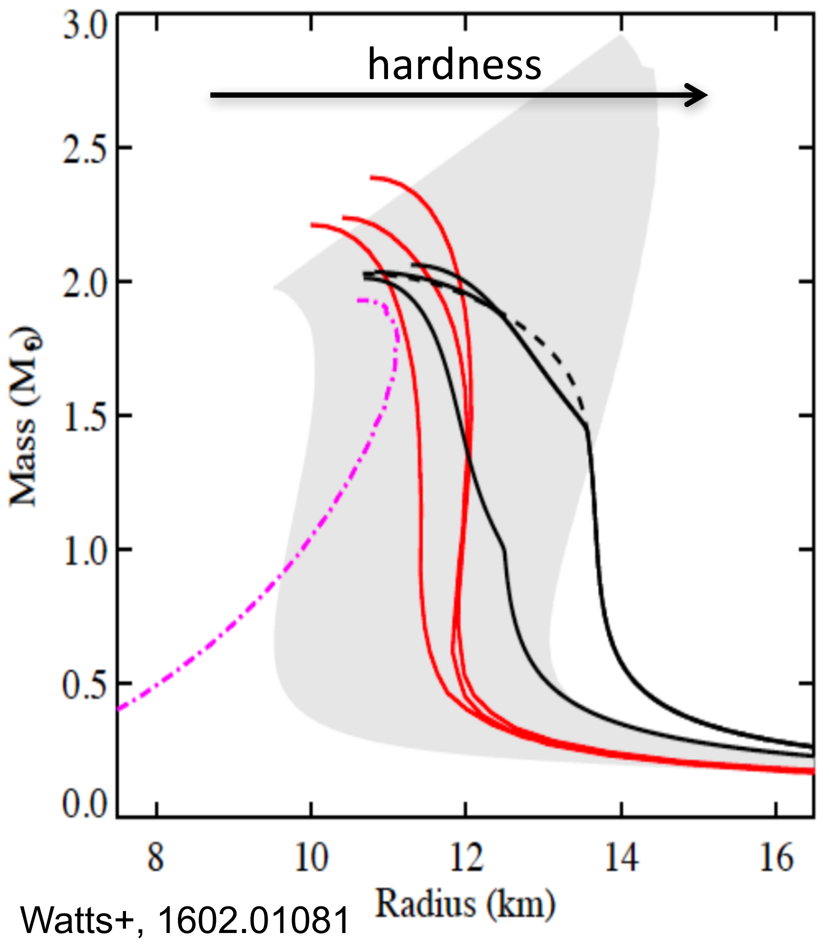
Vitale+ in prep., Vitale+ PRL 112 251101

Population inference

- As more GW will be detected, we will be able to infer the underlying mass distribution of neutron stars and black holes.
- E.g.: Are most NS masses at around 1.35 $M_{\odot}$?
- Two main advantages over EM:
  - Direct measurement
  - Can potentially access many more systems

Neutron Star Equation of State

- Neutron stars host the highest densities in the (visible) universe
- Measuring their equation of state requires joint measurement of radius and mass
- Possible with EM, but challenging
  - Mass estimates not always reliable
  - Radius estimates non often available and not always reliable
  - NICER to launch 2016, 5% precision



Watts+, 1602.01081

Neutron Star Equation of State

- In a CBC, each NS will feel the tidal field of the companion, which induces a quadrupole moment

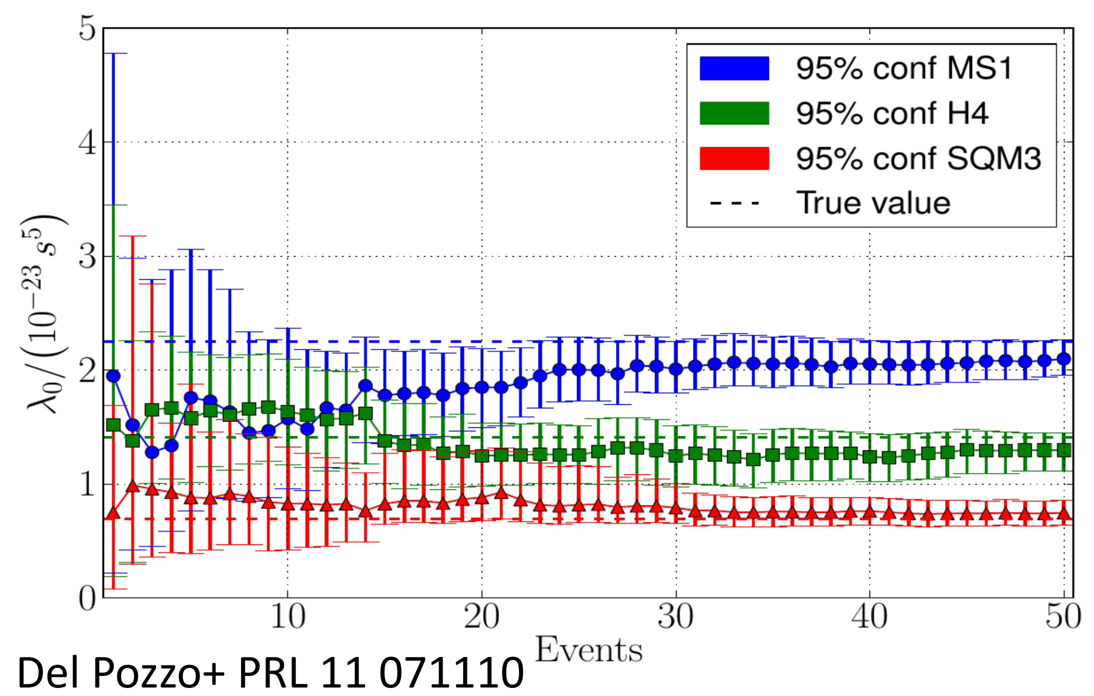
$$\boxed{Q_{ij} = -\lambda(EOS, m)\, T_{ij}}$$

- Known leading and next-to-leading effects on GW phasing
- Early studies considered single events, with contradictory findings (Read+ PRD 79 124033; Hinderer+ PRD 81 123016, many others)
- Markakis+ JPCS 189 012024 considered multiple events but used Fished matrix, unreliable at low signal-to-noise ratios (Vallisneri PRD 77 042001, Vitale+ PRD 84 104020)
- First fully Bayesian approach in 2013 (Del Pozzo+ PRL 11 071110)
- Also see Wade+, and many more.

Neutron Star Equation of State

- Two different avenues:
  - Model selection and EOS ranking
  - Parameter estimation on the tidal deformability
- Both allow to use all events
- Will focus on parameter estimation

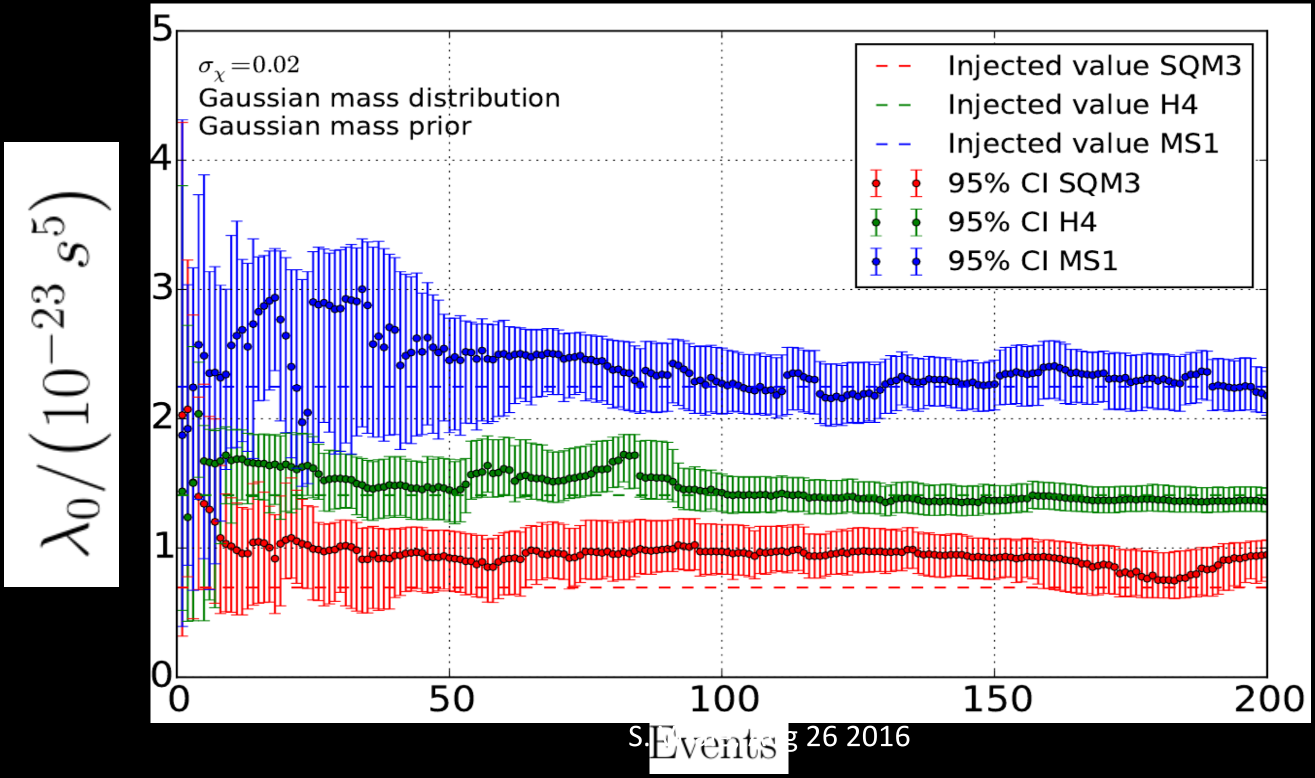
$$\lambda(m) \approx \lambda_0 + \lambda_1\,(m - 1.4M)$$



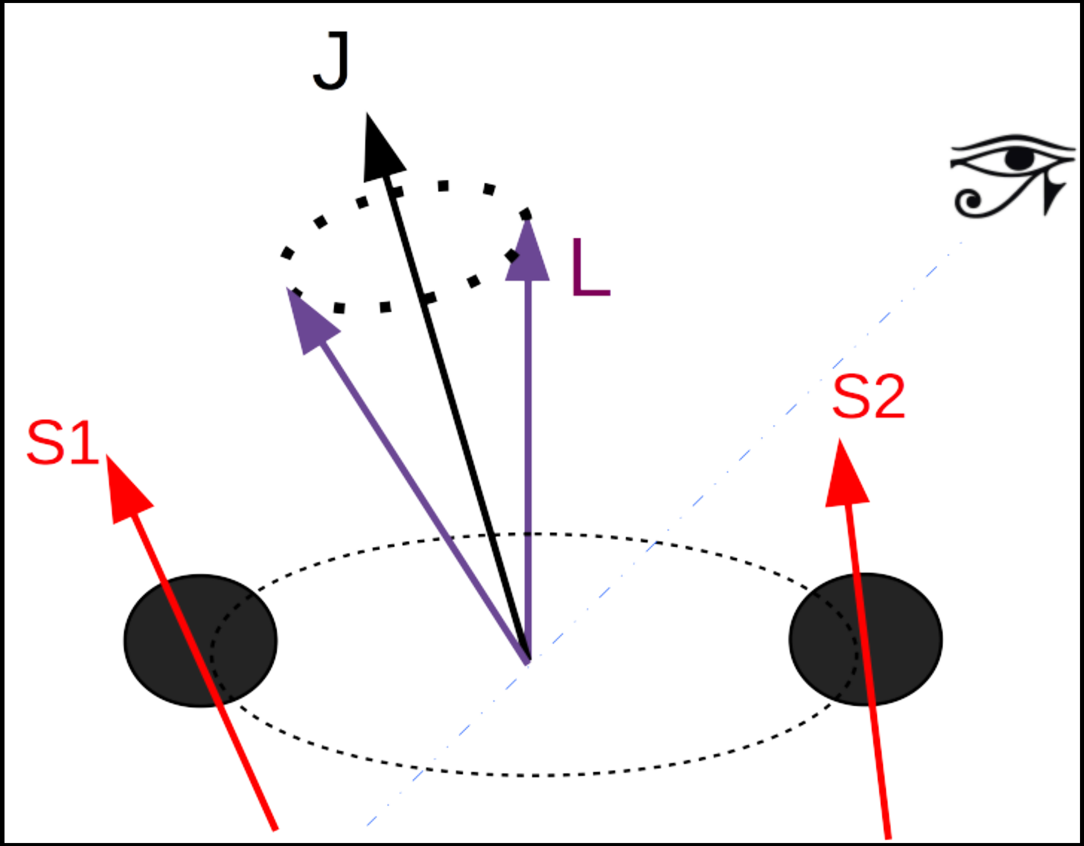
Del Pozzo+ PRL 11 071110

Neutron Star Equation of State

- In Agathos+ PRD 89 082001 we extended the initial study
  - Small neutron star spin
  - More physics (quadrupole-monopole term)
  - Better handling of waveform termination

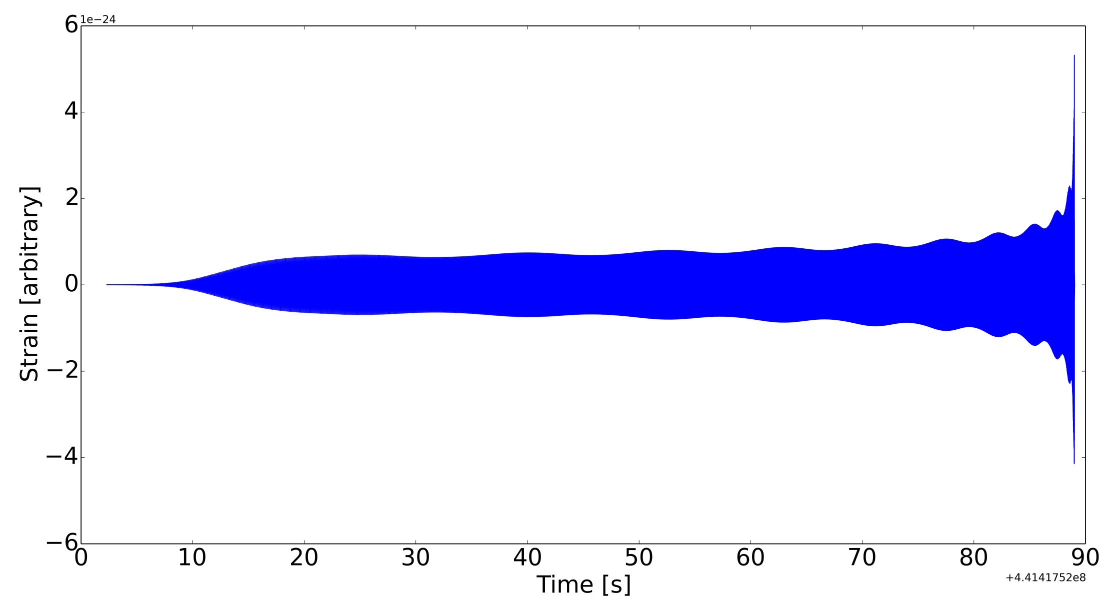


Spins



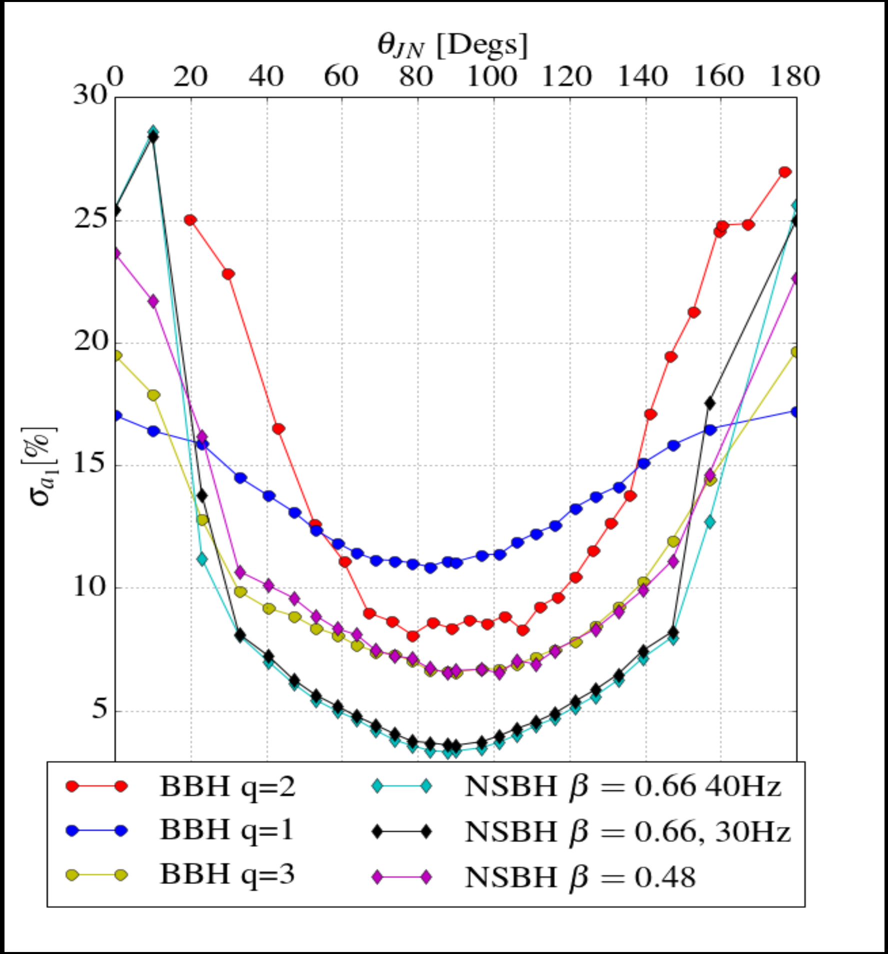
- Spin-Orbit coupling makes the orbit precess
- Waveform gets amplitude and phase modulation
- Rich physics, some degeneracies are reduced
  - Better parameter estimation

Spinning Waveforms w/ precession



- **However**, the amount of modulation visible in the *detector frame* also depends on the orientation
- Face-on CBC → Less modulation

Effects of Orbital Orientation

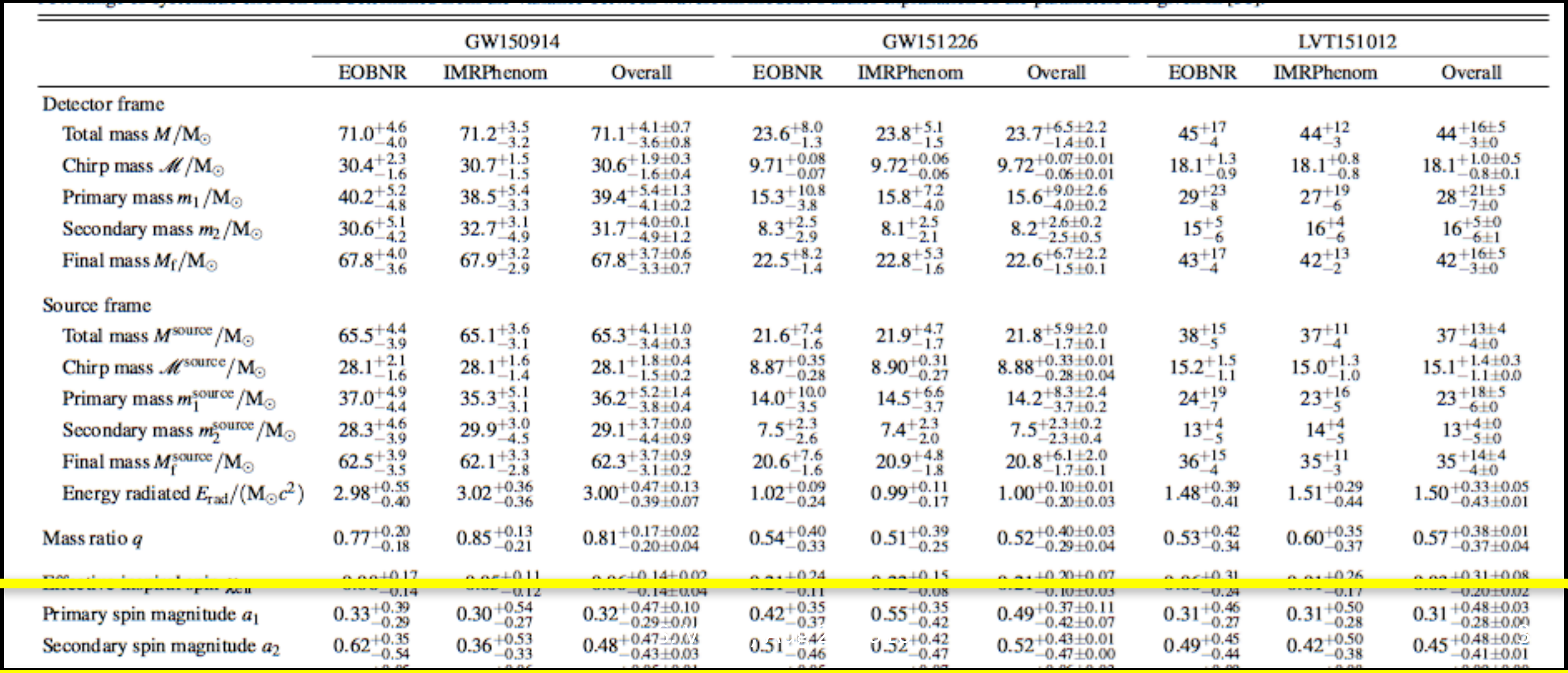


- Spin estimation strongly affected by orientation
- Spin errors minimum if system seen “edge-on”
- Less likely to detect than “face-on”

BH spin (with GW)

- Spins enter the waveform at higher PN orders
- They are harder to measure than mass parameters

LVC, 1606.04856

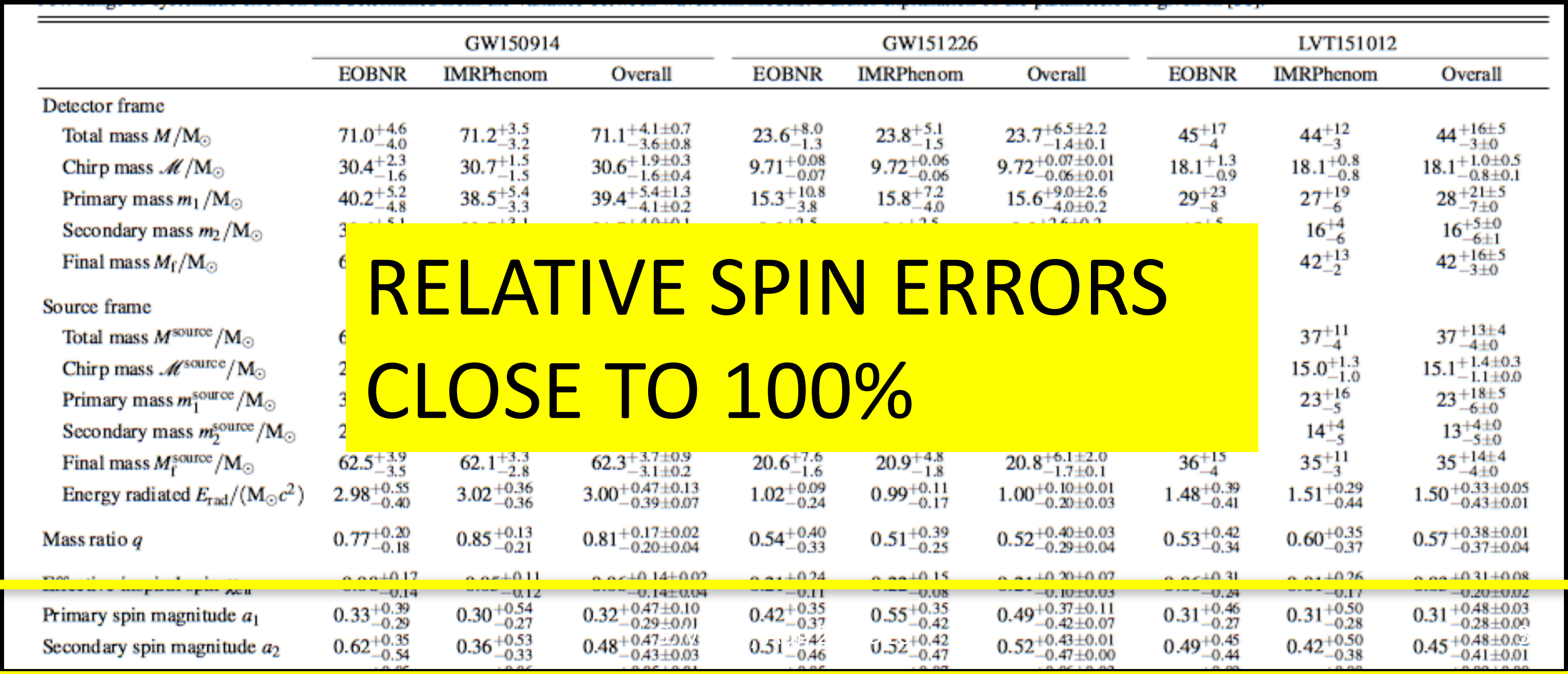


	GW150914			GW151226			LVT151012		
	EOBNR	IMRPhenom	Overall	EOBNR	IMRPhenom	Overall	EOBNR	IMRPhenom	Overall
Detector frame									
Total mass $M/\mathrm{M}_\odot$	$71.0^{+4.6}_{-4.0}$	$71.2^{+3.5}_{-3.2}$	$71.1^{+4.1\pm0.7}_{-3.6\pm0.8}$	$23.6^{+8.0}_{-1.3}$	$23.8^{+5.1}_{-1.5}$	$23.7^{+6.5\pm2.2}_{-1.4\pm0.1}$	45^{+17}_{-4}	44^{+12}_{-3}	$44^{+16\pm5}_{-3\pm0}$
Chirp mass $\mathcal{M}/\mathrm{M}_\odot$	$30.4^{+2.3}_{-1.6}$	$30.7^{+1.5}_{-1.5}$	$30.6^{+1.9\pm0.3}_{-1.6\pm0.4}$	$9.71^{+0.08}_{-0.07}$	$9.72^{+0.06}_{-0.06}$	$9.72^{+0.07\pm0.01}_{-0.06\pm0.01}$	$18.1^{+1.3}_{-0.9}$	$18.1^{+0.8}_{-0.8}$	$18.1^{+1.0\pm0.5}_{-0.8\pm0.1}$
Primary mass $m_1/\mathrm{M}_\odot$	$40.2^{+5.2}_{-4.8}$	$38.5^{+5.4}_{-3.3}$	$39.4^{+5.4\pm1.3}_{-4.1\pm0.2}$	$15.3^{+10.8}_{-3.8}$	$15.8^{+7.2}_{-4.0}$	$15.6^{+9.0\pm2.6}_{-4.0\pm0.2}$	29^{+23}_{-8}	27^{+19}_{-6}	$28^{+21\pm5}_{-7\pm0}$
Secondary mass $m_2/\mathrm{M}_\odot$	$30.6^{+5.1}_{-4.2}$	$32.7^{+3.1}_{-4.9}$	$31.7^{+4.0\pm0.1}_{-4.9\pm1.2}$	$8.3^{+2.5}_{-2.9}$	$8.1^{+2.5}_{-2.1}$	$8.2^{+2.6\pm0.2}_{-2.5\pm0.5}$	15^{+5}_{-6}	16^{+4}_{-6}	$16^{+5\pm0}_{-6\pm1}$
Final mass $M_\mathrm{f}/\mathrm{M}_\odot$	$67.8^{+4.0}_{-3.6}$	$67.9^{+3.2}_{-2.9}$	$67.8^{+3.7\pm0.6}_{-3.3\pm0.7}$	$22.5^{+8.2}_{-1.4}$	$22.8^{+5.3}_{-1.6}$	$22.6^{+6.7\pm2.2}_{-1.5\pm0.1}$	43^{+17}_{-4}	42^{+13}_{-2}	$42^{+16\pm5}_{-3\pm0}$
Source frame									
Total mass $M^\mathrm{source}/\mathrm{M}_\odot$	$65.5^{+4.4}_{-3.9}$	$65.1^{+3.6}_{-3.1}$	$65.3^{+4.1\pm1.0}_{-3.4\pm0.3}$	$21.6^{+7.4}_{-1.6}$	$21.9^{+4.7}_{-1.7}$	$21.8^{+5.9\pm2.0}_{-1.7\pm0.1}$	38^{+15}_{-5}	37^{+11}_{-4}	$37^{+13\pm4}_{-4\pm0}$
Chirp mass $\mathcal{M}^\mathrm{source}/\mathrm{M}_\odot$	$28.1^{+2.1}_{-1.6}$	$28.1^{+1.6}_{-1.4}$	$28.1^{+1.8\pm0.4}_{-1.5\pm0.2}$	$8.87^{+0.35}_{-0.28}$	$8.90^{+0.31}_{-0.27}$	$8.88^{+0.33\pm0.01}_{-0.28\pm0.04}$	$15.2^{+1.5}_{-1.1}$	$15.0^{+1.3}_{-1.0}$	$15.1^{+1.4\pm0.3}_{-1.1\pm0.0}$
Primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$	$37.0^{+4.9}_{-4.4}$	$35.3^{+5.1}_{-3.1}$	$36.2^{+5.2\pm1.4}_{-3.8\pm0.4}$	$14.0^{+10.0}_{-3.5}$	$14.5^{+6.6}_{-3.7}$	$14.2^{+8.3\pm2.4}_{-3.7\pm0.2}$	24^{+19}_{-7}	23^{+16}_{-5}	$23^{+18\pm5}_{-6\pm0}$
Secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$	$28.3^{+4.6}_{-3.9}$	$29.9^{+3.0}_{-4.5}$	$29.1^{+3.7\pm0.0}_{-4.4\pm0.9}$	$7.5^{+2.3}_{-2.6}$	$7.4^{+2.3}_{-2.0}$	$7.5^{+2.3\pm0.2}_{-2.3\pm0.4}$	13^{+4}_{-5}	14^{+4}_{-5}	$13^{+4\pm0}_{-5\pm0}$
Final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$	$62.5^{+3.9}_{-3.5}$	$62.1^{+3.3}_{-2.8}$	$62.3^{+3.7\pm0.9}_{-3.1\pm0.2}$	$20.6^{+7.6}_{-1.6}$	$20.9^{+4.8}_{-1.8}$	$20.8^{+6.1\pm2.0}_{-1.7\pm0.1}$	36^{+15}_{-4}	35^{+11}_{-3}	$35^{+14\pm4}_{-4\pm0}$
Energy radiated $E_\mathrm{rad}/(\mathrm{M}_\odot c^2)$	$2.98^{+0.55}_{-0.40}$	$3.02^{+0.36}_{-0.36}$	$3.00^{+0.47\pm0.13}_{-0.39\pm0.07}$	$1.02^{+0.09}_{-0.24}$	$0.99^{+0.11}_{-0.17}$	$1.00^{+0.10\pm0.01}_{-0.20\pm0.03}$	$1.48^{+0.39}_{-0.41}$	$1.51^{+0.29}_{-0.44}$	$1.50^{+0.33\pm0.05}_{-0.43\pm0.01}$
Mass ratio q	$0.77^{+0.20}_{-0.18}$	$0.85^{+0.13}_{-0.21}$	$0.81^{+0.17\pm0.02}_{-0.20\pm0.04}$	$0.54^{+0.40}_{-0.33}$	$0.51^{+0.39}_{-0.25}$	$0.52^{+0.40\pm0.03}_{-0.29\pm0.04}$	$0.53^{+0.42}_{-0.34}$	$0.60^{+0.35}_{-0.37}$	$0.57^{+0.38\pm0.01}_{-0.37\pm0.04}$
Effective inspiral spin χ_eff	[illegible]$^{+0.17}_{-0.14}$	[illegible]$^{+0.11}_{-0.12}$	[illegible]$^{+0.14\pm0.02}_{-0.14\pm0.04}$	[illegible]$^{+0.24}_{-0.11}$	[illegible]$^{+0.15}_{-0.08}$	[illegible]$^{+0.20\pm0.07}_{-0.10\pm0.03}$	[illegible]$^{+0.31}_{-0.24}$	[illegible]$^{+0.26}_{-0.17}$	[illegible]$^{+0.31\pm0.08}_{-0.20\pm0.02}$
Primary spin magnitude a_1	$0.33^{+0.39}_{-0.29}$	$0.30^{+0.54}_{-0.27}$	$0.32^{+0.47\pm0.10}_{-0.29\pm0.01}$	$0.42^{+0.35}_{-0.37}$	$0.55^{+0.35}_{-0.42}$	$0.49^{+0.37\pm0.11}_{-0.42\pm0.07}$	$0.31^{+0.46}_{-0.27}$	$0.31^{+0.50}_{-0.28}$	$0.31^{+0.48\pm0.03}_{-0.28\pm0.00}$
Secondary spin magnitude a_2	$0.62^{+0.35}_{-0.54}$	$0.36^{+0.53}_{-0.33}$	$0.48^{+0.47\pm\text{[illegible]}}_{-0.43\pm0.03}$	$0.51^{+0.44}_{-0.46}$	$0.52^{+0.42}_{-0.47}$	$0.52^{+0.43\pm0.01}_{-0.47\pm0.00}$	$0.49^{+0.45}_{-0.44}$	$0.42^{+0.50}_{-0.38}$	$0.45^{+0.48\pm\text{[illegible]}}_{-0.41\pm0.01}$

BH spin (with GW)

- Spins enter the waveform at higher PN orders
- They are harder to measure than mass parameters

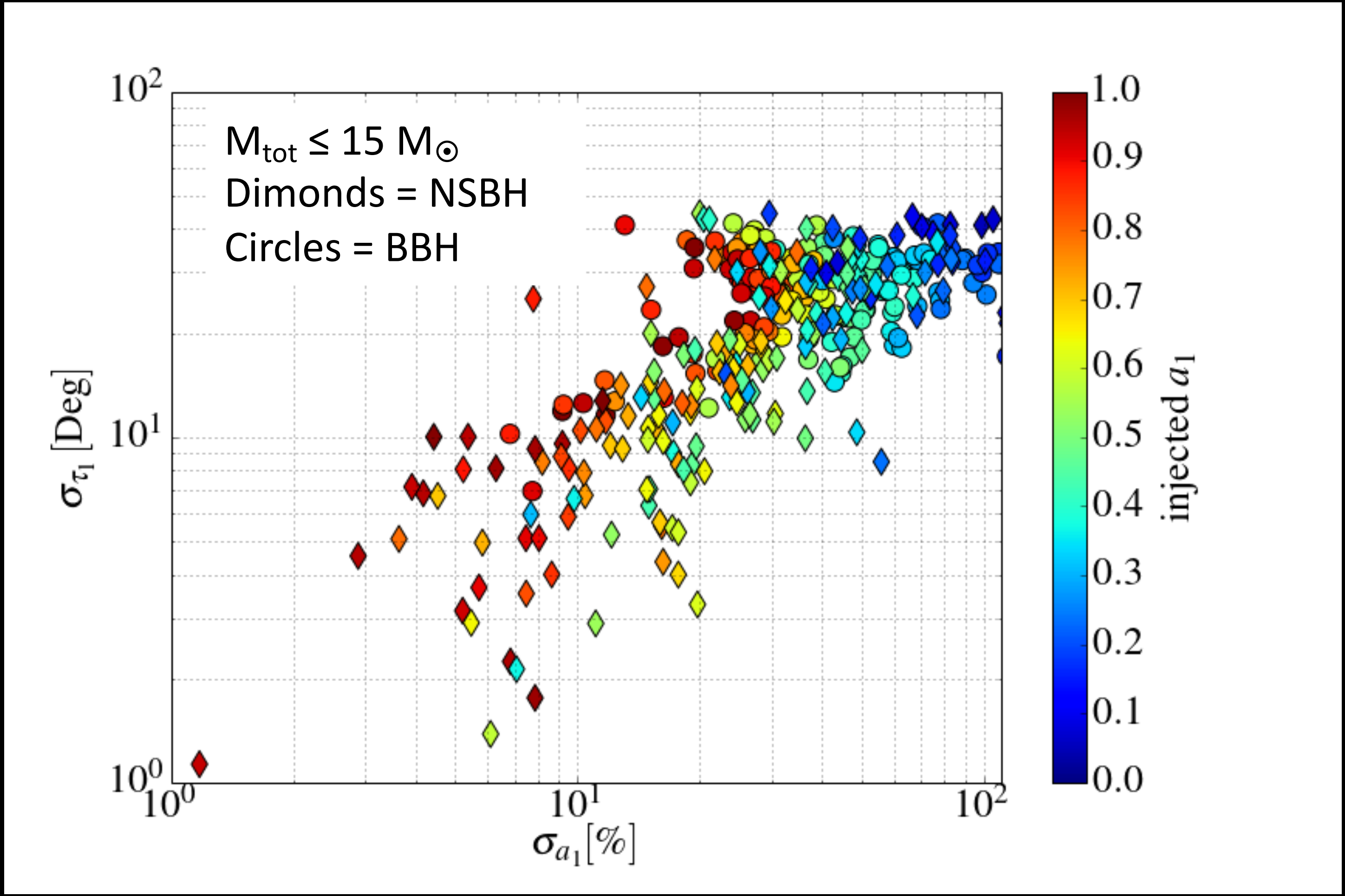
LVC, 1606.04856



	GW150914			GW151226			LVT151012		
	EOBNR	IMRPhenom	Overall	EOBNR	IMRPhenom	Overall	EOBNR	IMRPhenom	Overall
Detector frame									
Total mass $M/\mathrm{M}_\odot$	$71.0^{+4.6}_{-4.0}$	$71.2^{+3.5}_{-3.2}$	$71.1^{+4.1\pm0.7}_{-3.6\pm0.8}$	$23.6^{+8.0}_{-1.3}$	$23.8^{+5.1}_{-1.5}$	$23.7^{+6.5\pm2.2}_{-1.4\pm0.1}$	45^{+17}_{-4}	44^{+12}_{-3}	$44^{+16\pm5}_{-3\pm0}$
Chirp mass $\mathscr{M}/\mathrm{M}_\odot$	$30.4^{+2.3}_{-1.6}$	$30.7^{+1.5}_{-1.5}$	$30.6^{+1.9\pm0.3}_{-1.6\pm0.4}$	$9.71^{+0.08}_{-0.07}$	$9.72^{+0.06}_{-0.06}$	$9.72^{+0.07\pm0.01}_{-0.06\pm0.01}$	$18.1^{+1.3}_{-0.9}$	$18.1^{+0.8}_{-0.8}$	$18.1^{+1.0\pm0.5}_{-0.8\pm0.1}$
Primary mass $m_1/\mathrm{M}_\odot$	$40.2^{+5.2}_{-4.8}$	$38.5^{+5.4}_{-3.3}$	$39.4^{+5.4\pm1.3}_{-4.1\pm0.2}$	$15.3^{+10.8}_{-3.8}$	$15.8^{+7.2}_{-4.0}$	$15.6^{+9.0\pm2.6}_{-4.0\pm0.2}$	29^{+23}_{-8}	27^{+19}_{-6}	$28^{+21\pm5}_{-7\pm0}$
Secondary mass $m_2/\mathrm{M}_\odot$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16^{+4}_{-6}	$16^{+5\pm0}_{-6\pm1}$
Final mass $M_\mathrm{f}/\mathrm{M}_\odot$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	42^{+13}_{-2}	$42^{+16\pm5}_{-3\pm0}$
Source frame									
Total mass $M^\mathrm{source}/\mathrm{M}_\odot$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	37^{+11}_{-4}	$37^{+13\pm4}_{-4\pm0}$
Chirp mass $\mathscr{M}^\mathrm{source}/\mathrm{M}_\odot$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	$15.0^{+1.3}_{-1.0}$	$15.1^{+1.4\pm0.3}_{-1.1\pm0.0}$
Primary mass $m_1^\mathrm{source}/\mathrm{M}_\odot$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	23^{+16}_{-5}	$23^{+18\pm5}_{-6\pm0}$
Secondary mass $m_2^\mathrm{source}/\mathrm{M}_\odot$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	14^{+4}_{-5}	$13^{+4\pm0}_{-5\pm0}$
Final mass $M_\mathrm{f}^\mathrm{source}/\mathrm{M}_\odot$	$62.5^{+3.9}_{-3.5}$	$62.1^{+3.3}_{-2.8}$	$62.3^{+3.7\pm0.9}_{-3.1\pm0.2}$	$20.6^{+7.6}_{-1.6}$	$20.9^{+4.8}_{-1.8}$	$20.8^{+6.1\pm2.0}_{-1.7\pm0.1}$	36^{+15}_{-4}	35^{+11}_{-3}	$35^{+14\pm4}_{-4\pm0}$
Energy radiated $E_\mathrm{rad}/(\mathrm{M}_\odot c^2)$	$2.98^{+0.55}_{-0.40}$	$3.02^{+0.36}_{-0.36}$	$3.00^{+0.47\pm0.13}_{-0.39\pm0.07}$	$1.02^{+0.09}_{-0.24}$	$0.99^{+0.11}_{-0.17}$	$1.00^{+0.10\pm0.01}_{-0.20\pm0.03}$	$1.48^{+0.39}_{-0.41}$	$1.51^{+0.29}_{-0.44}$	$1.50^{+0.33\pm0.05}_{-0.43\pm0.01}$
Mass ratio q	$0.77^{+0.20}_{-0.18}$	$0.85^{+0.13}_{-0.21}$	$0.81^{+0.17\pm0.02}_{-0.20\pm0.04}$	$0.54^{+0.40}_{-0.33}$	$0.51^{+0.39}_{-0.25}$	$0.52^{+0.40\pm0.03}_{-0.29\pm0.04}$	$0.53^{+0.42}_{-0.34}$	$0.60^{+0.35}_{-0.37}$	$0.57^{+0.38\pm0.01}_{-0.37\pm0.04}$
Effective inspiral spin χ_eff	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Primary spin magnitude a_1	$0.33^{+0.39}_{-0.29}$	$0.30^{+0.54}_{-0.27}$	$0.32^{+0.47\pm0.10}_{-0.29\pm0.01}$	$0.42^{+0.35}_{-0.37}$	$0.55^{+0.35}_{-0.42}$	$0.49^{+0.37\pm0.11}_{-0.42\pm0.07}$	$0.31^{+0.46}_{-0.27}$	$0.31^{+0.50}_{-0.28}$	$0.31^{+0.48\pm0.03}_{-0.28\pm0.00}$
Secondary spin magnitude a_2	$0.62^{+0.35}_{-0.54}$	$0.36^{+0.53}_{-0.33}$	$0.48^{+0.47\pm\text{[illegible]}}_{-0.43\pm0.03}$	$0.51^{\text{[illegible]}}_{-0.46}$	$0.52^{+0.42}_{-0.47}$	$0.52^{+0.43\pm0.01}_{-0.47\pm0.00}$	$0.49^{+0.45}_{-0.44}$	$0.42^{+0.50}_{-0.38}$	$0.45^{+0.48\pm\text{[illegible]}}_{-0.41\pm0.01}$

RELATIVE SPIN ERRORS CLOSE TO 100%

Astrophysical distribution - Spin



Vitale+ in prep., Vitale+ PRL 112 251101

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

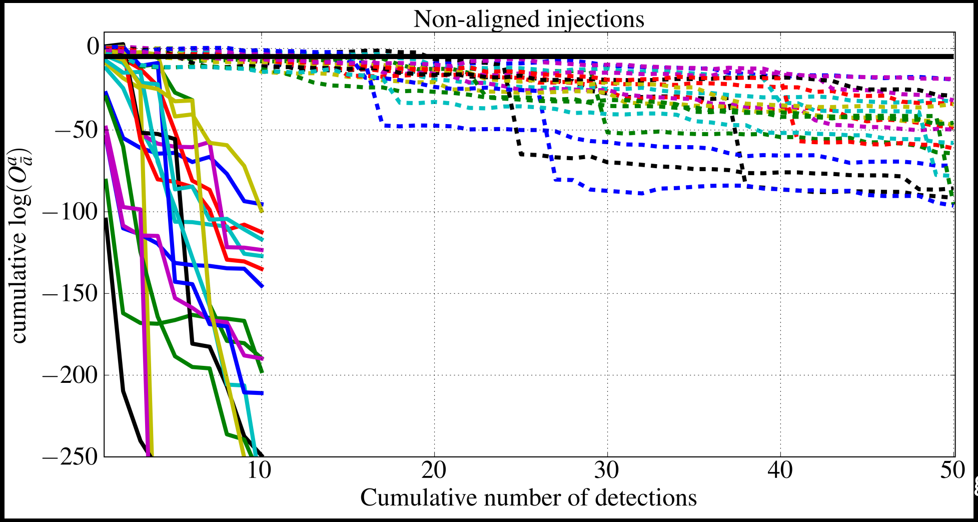
An example: spin alignment

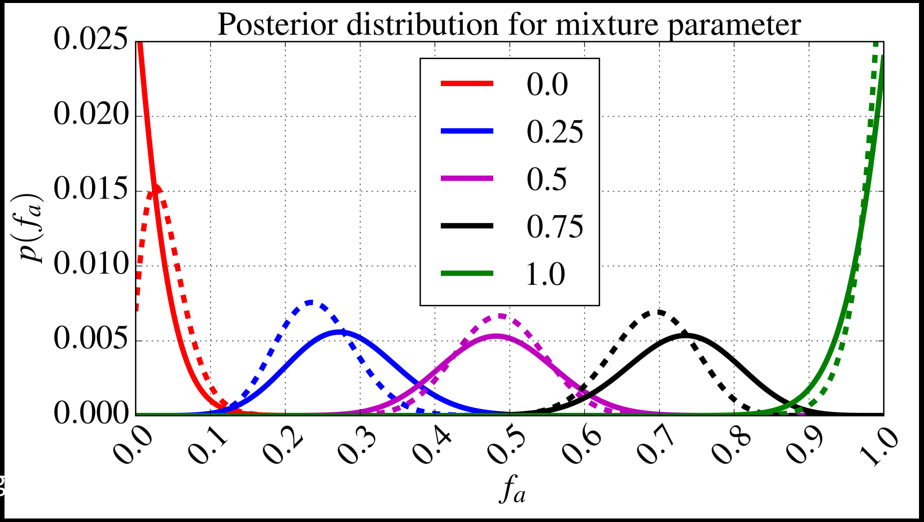
- Most astronomers believe that CBC formed via common envelope will have aligned spins (Gerosa+, many others)
- We can use Bayesian methods to verify if and how many systems have aligned spins

- If time allows, show how to obtain the posterior distribution of f_a

Results

- 100 NSBH (dashed) and 200 BBH
- Astrophysical distribution
- Can measure the fraction of aligned systems with uncertainties of ~15-20%


Non-aligned injections


Posterior distribution for mixture parameter

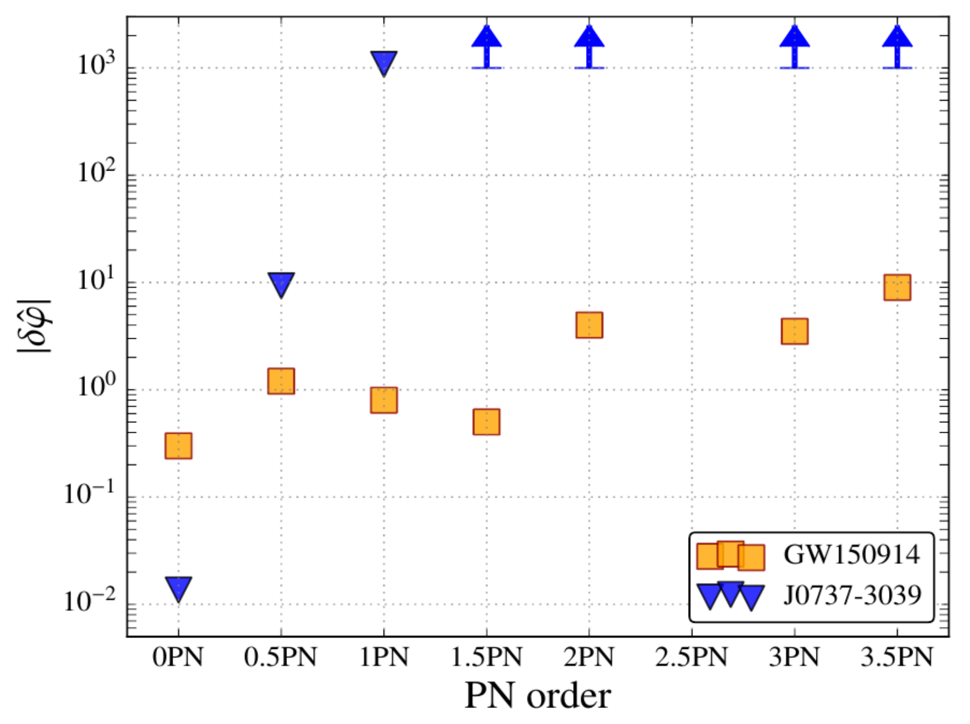
Strong field tests of General Relativity

- GWs represent our first chance to test general relativity in its strong-field dynamical regime
- Double pulsar J0737-3039 has
  - Masses ~ $M_\odot$
  - Speeds ~ 1e-3 c
  - Derivative orbital period ~ 1e-12
- GW150914
  - Few to tens of $M_\odot$
  - Relative speed ~ 0.5 c
  - Derivative orbital period ~ 1

Strong field tests of General Relativity

- There is a large number of alternative theories of gravity that we will be able to test using gravitational waves
  - Massive graviton
  - Brans-Dicke
  - Many more!
- But the real theory of gravity might not have been proposed yet. Need unmodeled tests
  - Post-Netwonian phasing tests
  - TIGER

GR tests with GW150914: phasing



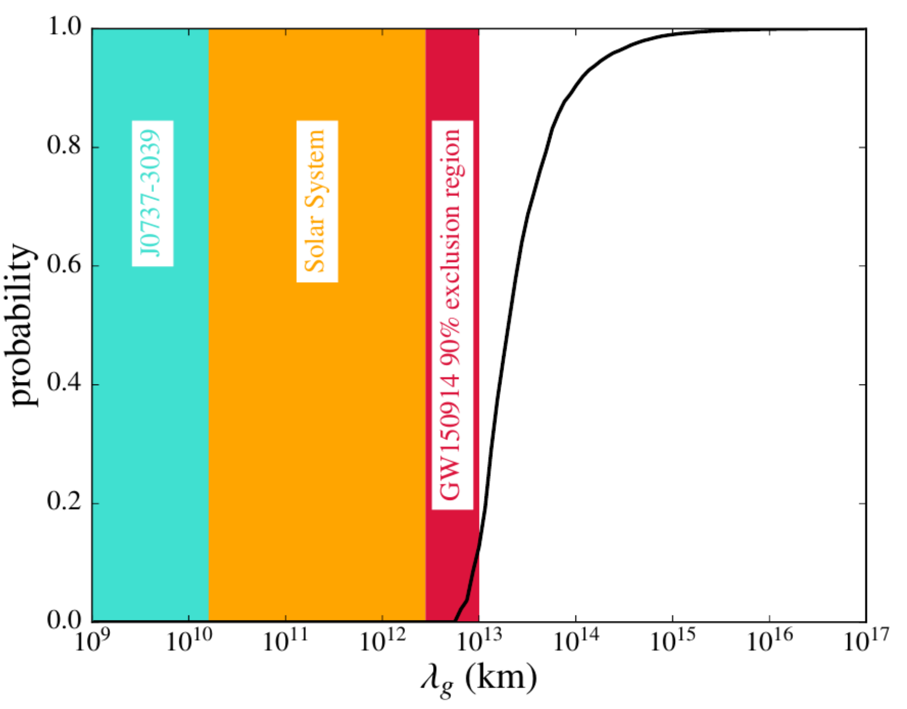
LVC PRL 116, 221101 & 1606.04856

- Post Newtonian expansion of GW phase has coefficients known within GR

$$\psi(f) \sim \sum \varphi_k (\pi M f)^{\frac{k-5}{3}}$$

- Can put upper limit on how different from GR they can be
  - Using double pulsar
  - Using GW150914
- Double pulsar already beaten at 0.5PN

GR tests with GW150914: massive graviton



LVC PRL 116, 221101

- A full self-consistent theory 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)

✓ 3 orders of magnitude better than double pulsar

✓ Factor of 3 better than solar system

✓ Some model dependent tests do better

$$m_g \leq 1.2 \times 10^{-22}\ \mathrm{eV/c^2}$$

TIGER

- Test Infrastructure for General Relativity
- Look for generic deviations in an unmodeled fashion
- Based on Bayesian model selection, combine evidence from all detected events
- Does not rely on “golden events” (i.e.: high signal-to-noise ratio)
- Extensively tested on BNS (Li+ PRD 85 082003 , Agathos+ PRD 89 082001)
- In development for BBH

TIGER

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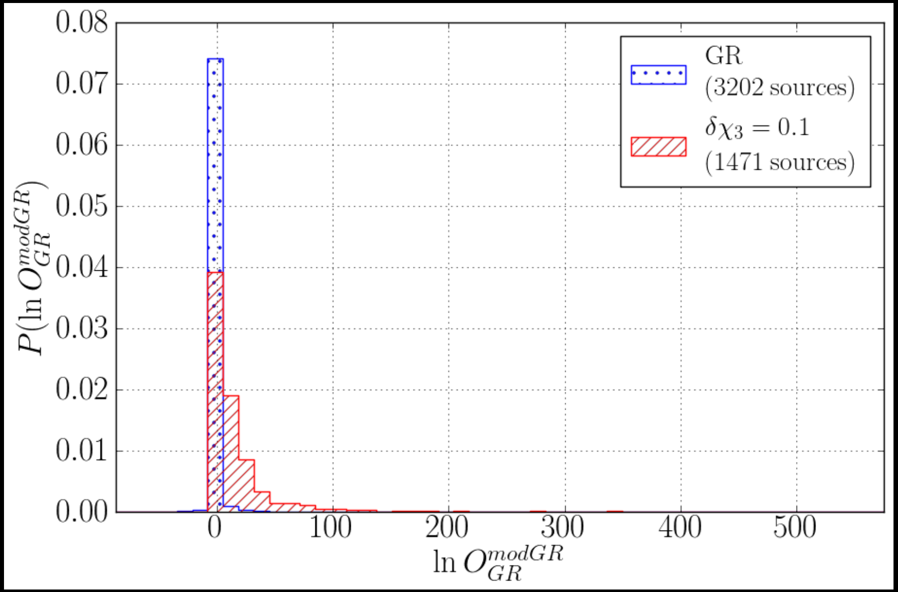
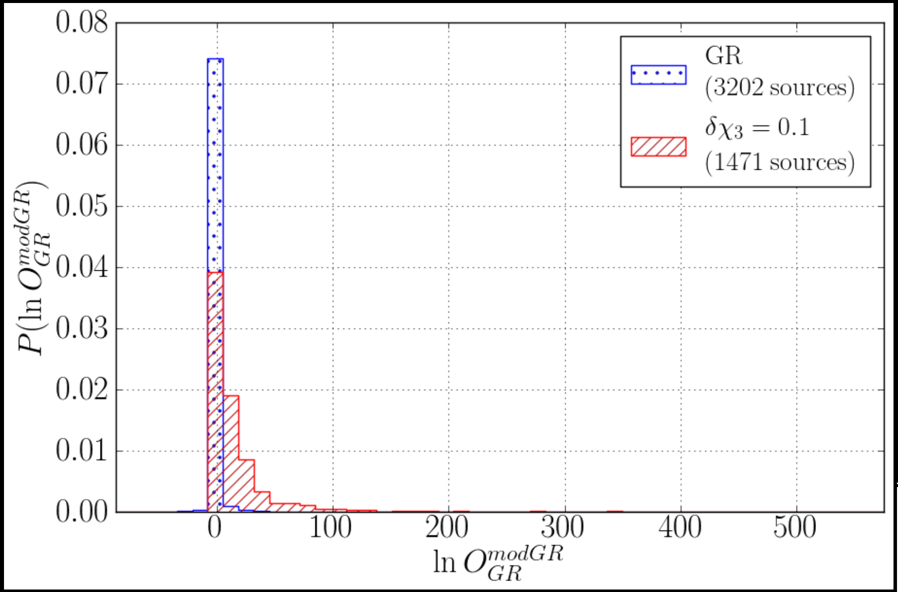
- Extensively tested on BNS (Li+ PRD 85 082003 , Agathos+ PRD 89 082001)
- In development for BBH
- Define two models “GR is correct” vs “GR is not correct”
  - “GR is not correct” is true if any post Newtonian or phenomenological phase parameters deviates from its GR value
- Calculate Bayesian odds (ratio of probabilities)
- Each detection contributes to odds
- Good efficiency after few tens of BNS

TIGER BNS example

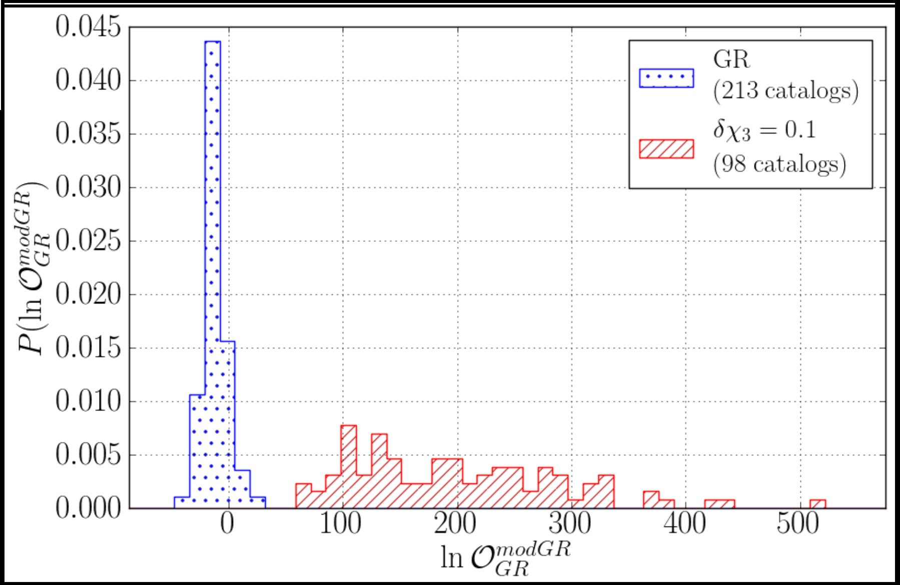


Singe BNS source

TIGER BNS example



Singe BNS source



Catalogs of BNS sources

Cosmography with GWs

- Gravitational waves provide direct measurement of *luminosity distance*
- If the *redshift* of the source can be estimated in some other way one can measure cosmological parameters.

$$D_L(z) = \begin{cases} \frac{(1+z)}{\sqrt{\Omega_k}} \sinh[\sqrt{\Omega_k} \int_0^z \frac{dz'}{H(z')}] & \text{for} \quad \Omega_k > 0 \\ (1+z) \int_0^z \frac{dz'}{H(z')} & \text{for} \quad \Omega_k = 0 \\ \frac{(1+z)}{\sqrt{|\Omega_k|}} \sin[\sqrt{|\Omega_k|} \int_0^z \frac{dz'}{H(z')}] & \text{for} \quad \Omega_k < 0 \end{cases}$$

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda E(z, w(z))}$$

How to measure the redshift?

- If the CBC produces an EM counterpart (e.g. GRB) (Schutz, Nature 1986)
- If one knows the NS EOS (Read & Messenger PRL 108 091101, Del Pozzo+ 1506.0659)
- If the post-merger signal is observed (Messenger+ PRX 4, 041004)
- If the true distribution of NS masses is known (Taylor & Gair PRD 86, 023502)
- Even if no EM is found, but there is a reliable galaxy catalog (Del Pozzo PRD 86 043011)

Second vs third generation of GW detectors

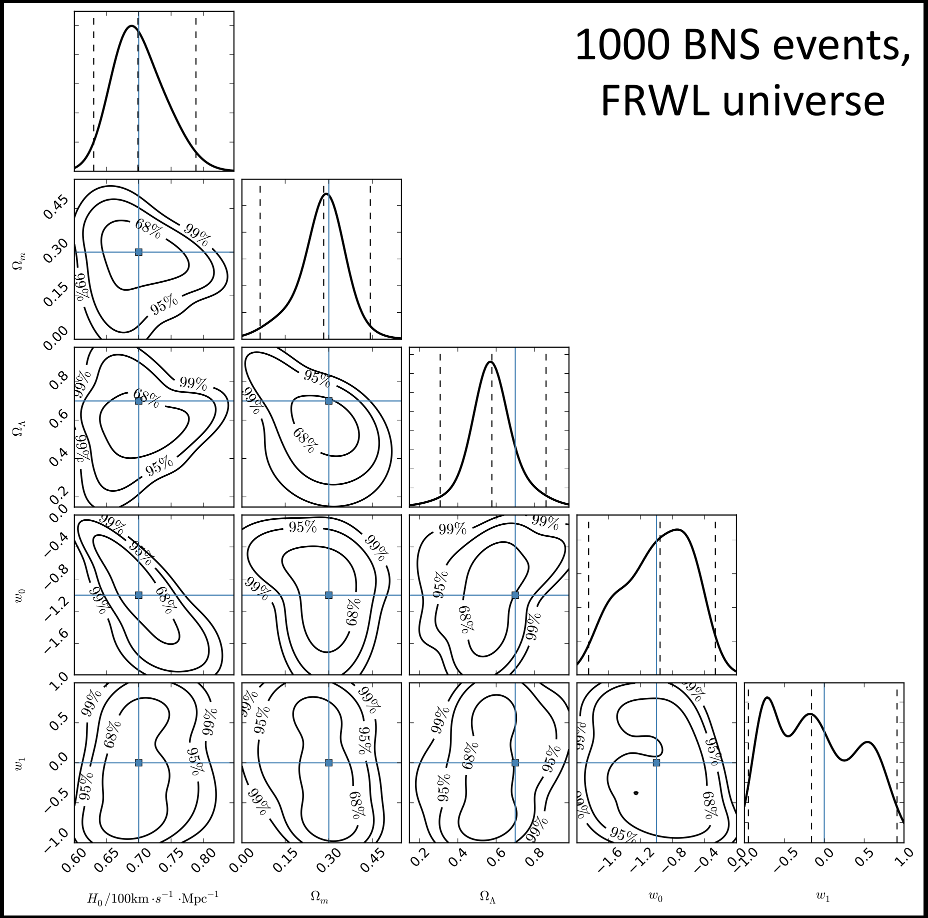
- Measuring cosmological parameters might have to wait the for the next generation of GW detectors, when thousands of detections will be made each year.
- Having thousands of events increases the chance of EM counterpart
- … and allows for populations studies

An example: cosmology with EOS

- Del Pozzo+ (1506.0659) explores how well cosmological parameters can be estimated if the NS EOS is known.
- Thousands of BNS assuming different cosmologies
- Third generation GW detectors (Einstein telescope)

An example: cosmology with EOS

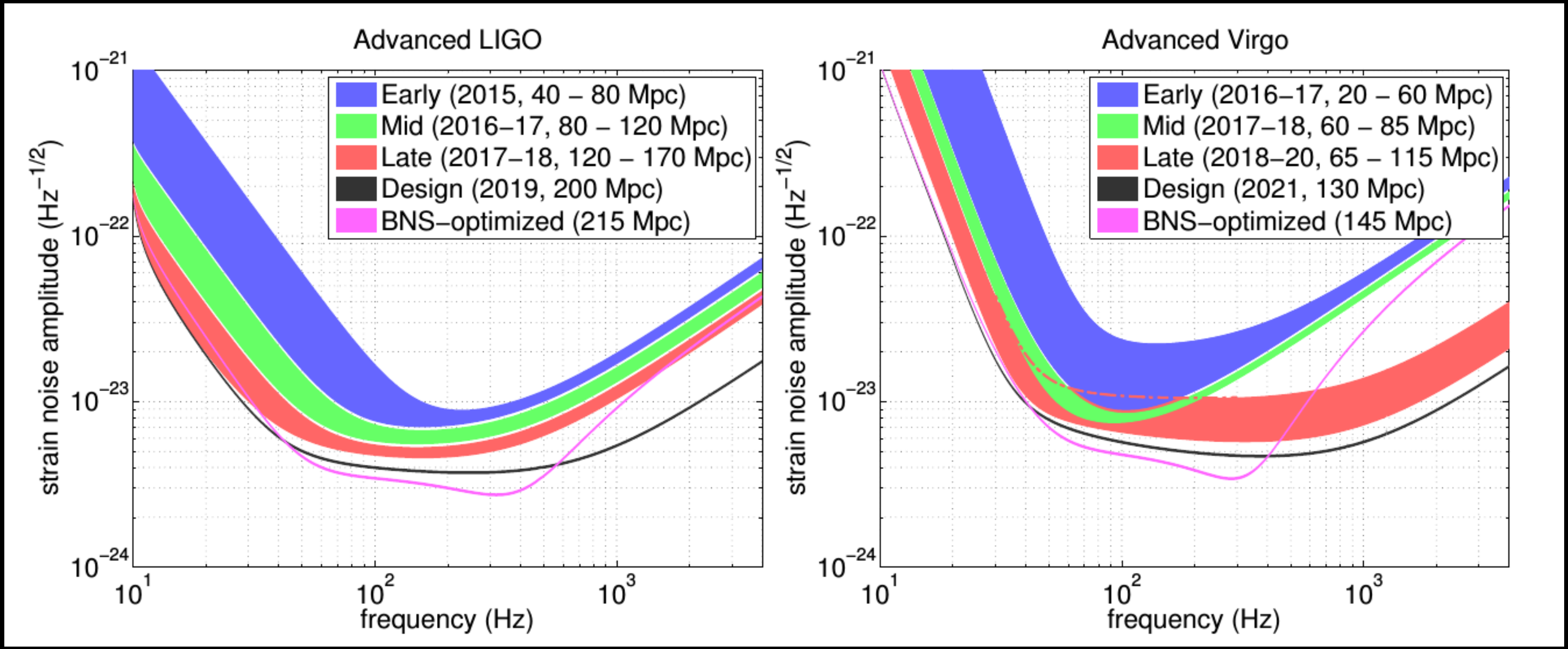
- Hubble constant measurable with precision of ~10% with 1000 sources
- Λ_m and Λ_k factor of >10 worse than Planck
  - These become comparable to Planck with more sources
- DE parameters (w's) precision comparable to Planck with 1000 sources
  - Can improve EM measurement with more detections



1000 BNS events, FRWL universe

1506.0659

Advanced LIGO not at design sensitivity yet: more detections coming soon!



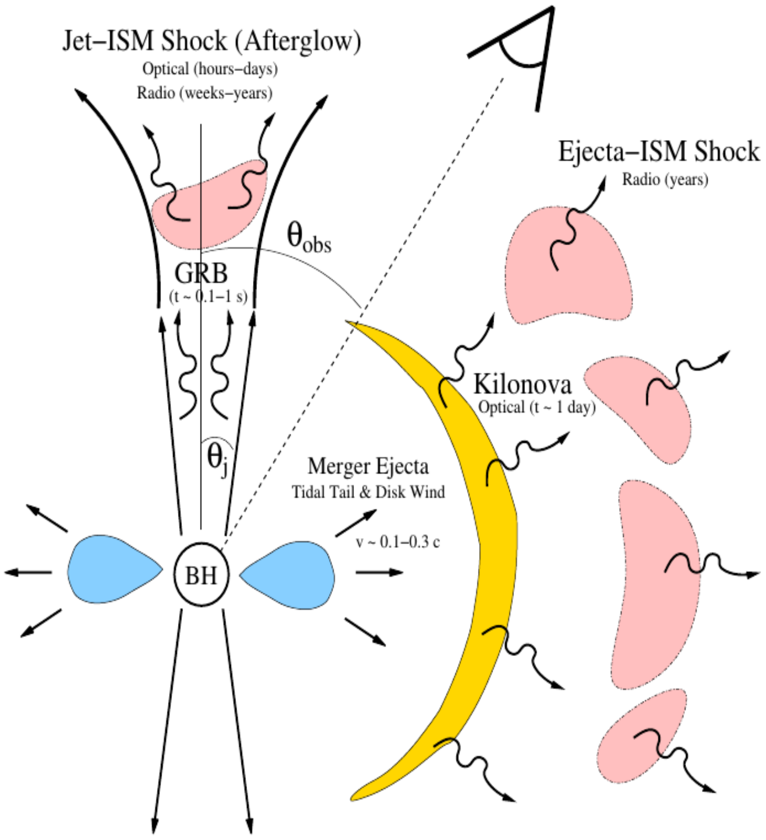
LVC Liv. Rev. Rel 19, 1

- Next Science Runs:
  - 2015: 2 BBH event
  - 2016 - 2017: 5-10 significant BBH events, ~2 BNS
  - 2017-2018 : 10-30 significant BBH events, ~10 BNS
  - 2019: > 50 significant BBH events, ~20 BNS

Thank you!

GW – Electromagnetic connection

- CBC containing neutron stars are expected to be bright in the EM band
  - Progenitors of short GRBs?
  - Rich variety of frequencies and timescales
- Core collapse supernovae are believed to power long GRBs
- And are BBH luminous??

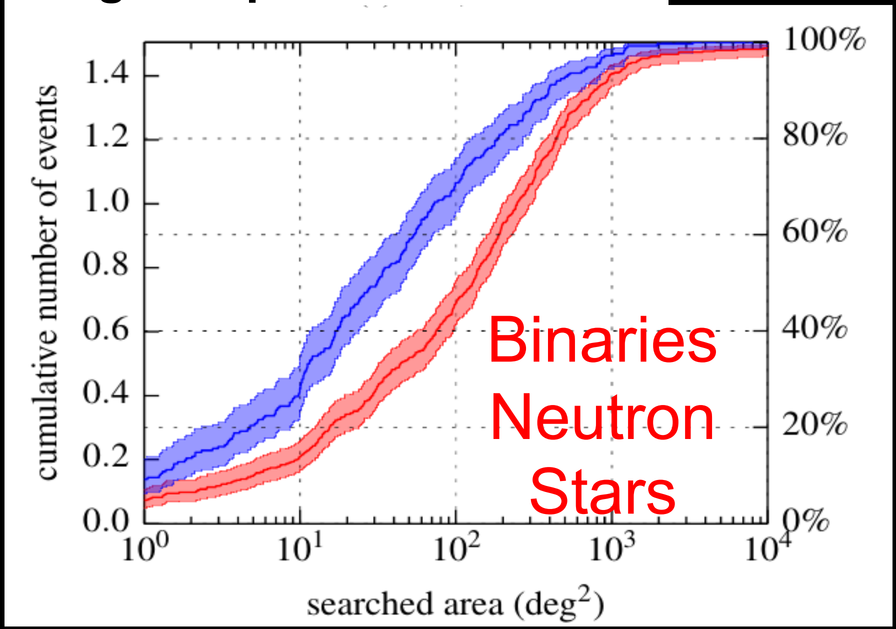


Metzger, Berger

GW – Electromagnetic connection

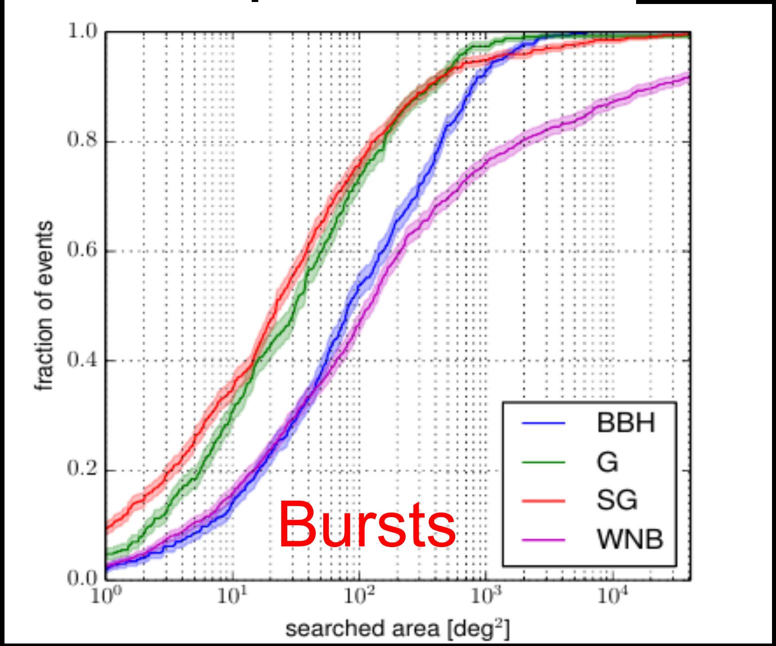
- Challenges: searches need to be fast and precise; typical latencies few minutes
- Sky error areas from GW data are large, especially with only 2-3 detectors on-line
- Median searched areas ≤ 100 deg^2 in the next science run with Virgo on-line
- Not strongly dependent on model

Singer+ ApJ 795 105



Binaries Neutron Stars

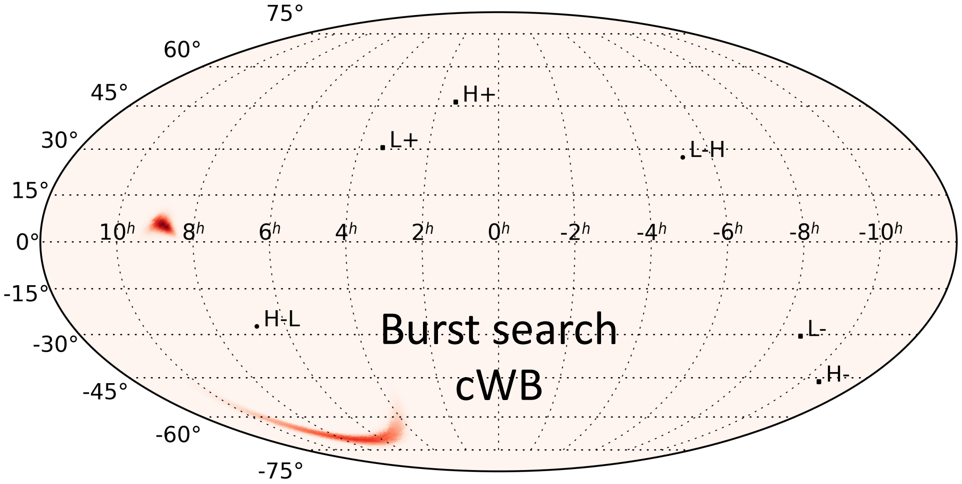
Essick+ ApJ 800 81

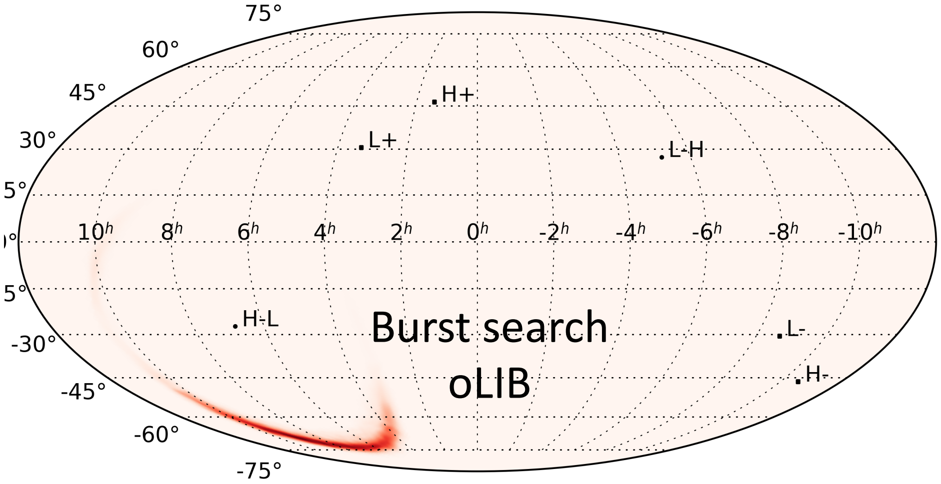


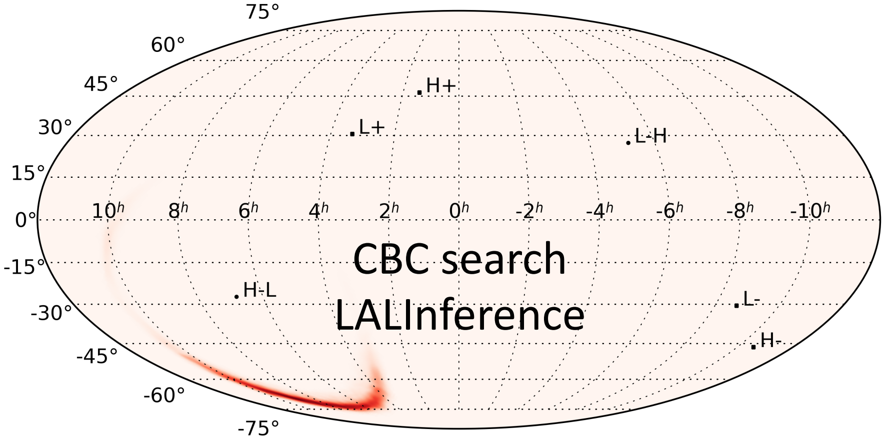
Bursts

GW150914-Sky Localization

Sky maps generated by burst searches and shared with EM partners within 48 hours


Burst search cWB


Burst search oLIB


CBC search LALInference

LVC, 1602.03843

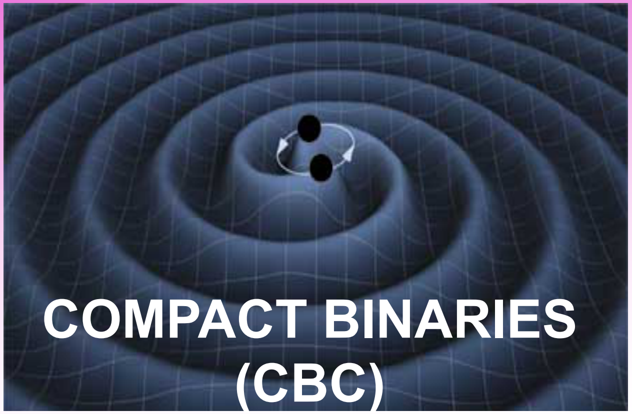
CBC targeted parameter estimation (LALInference, Veitch+ PRD 91 042003) ran with higher latency

Multi-band

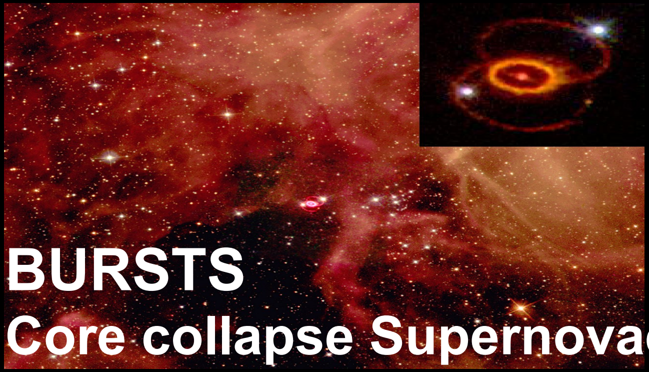
- Sesana (PRL 116, 231102) noticed that if eLISA were online, it would have detected GW150914 a few years ago
  - Pre-merger alert
  - Much smaller sky areas and telescopes ready in advance
- Benefit even if BBH are not luminous! Vitale (PRL 117, 051102) showed that BH spins can be measured a factor 2 better for those joint detections.

Gravitational Wave Sources

TRANSIENT

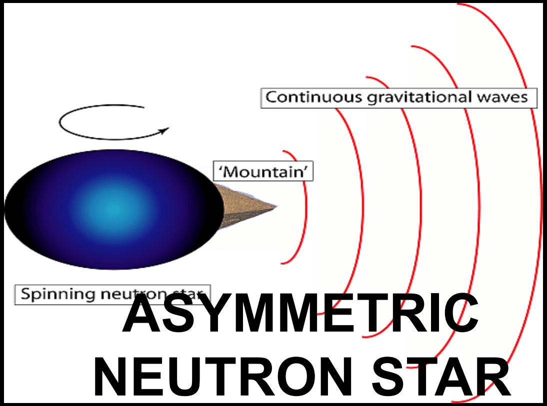


COMPACT BINARIES (CBC)

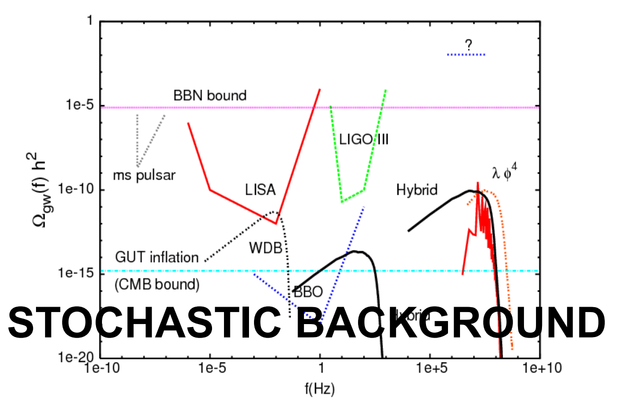


BURSTS
Core collapse Supernovae

PERSISTENT



ASYMMETRIC NEUTRON STAR



STOCHASTIC BACKGROUND

MATCH FILTER

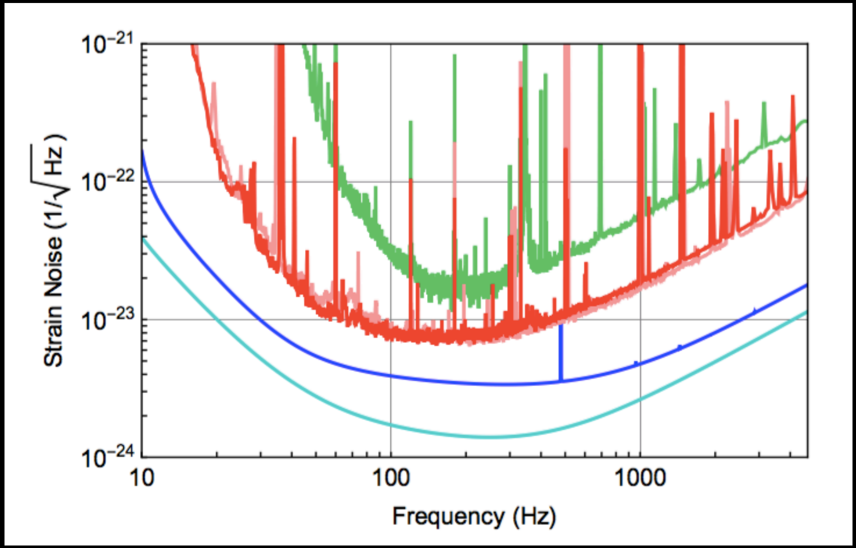
UNMODELED

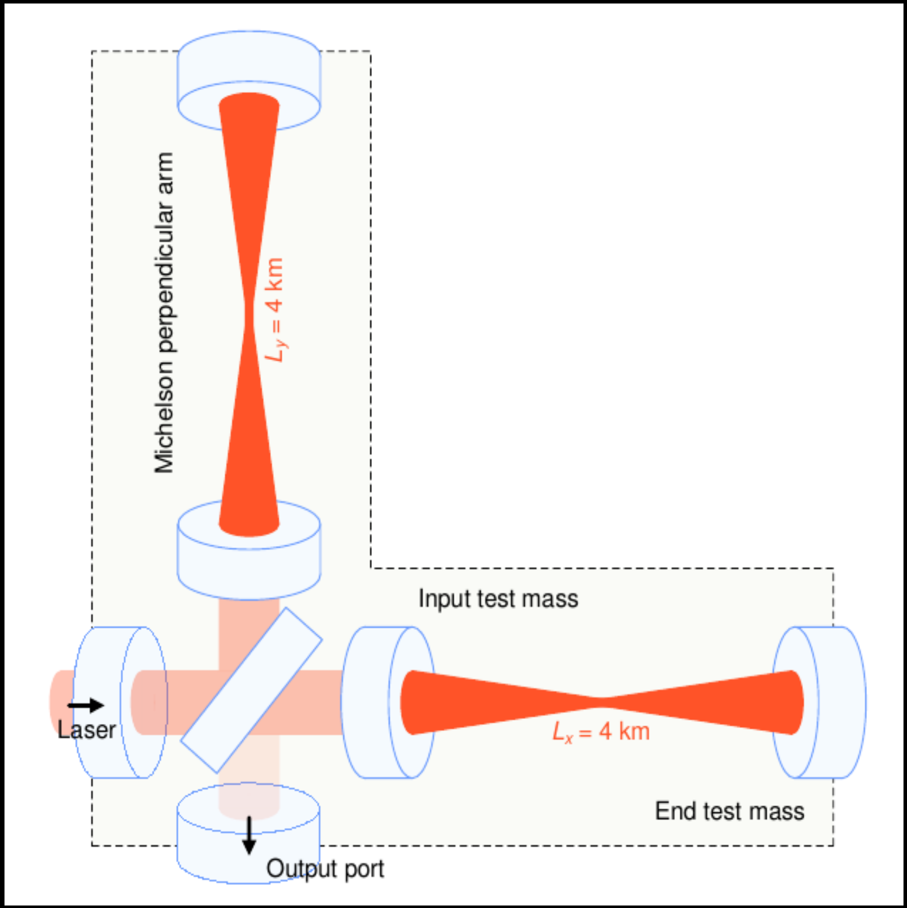
How to detect them?

- We basically need to be able to measure the distance between objects *very* well
- I mean really well:
  If the masses are 4km apart, you must be able to monitor their distance to 10^-18 meters
- Use lasers!

Ground based GW detectors

- Use laser interferometry to measure small differential length variations

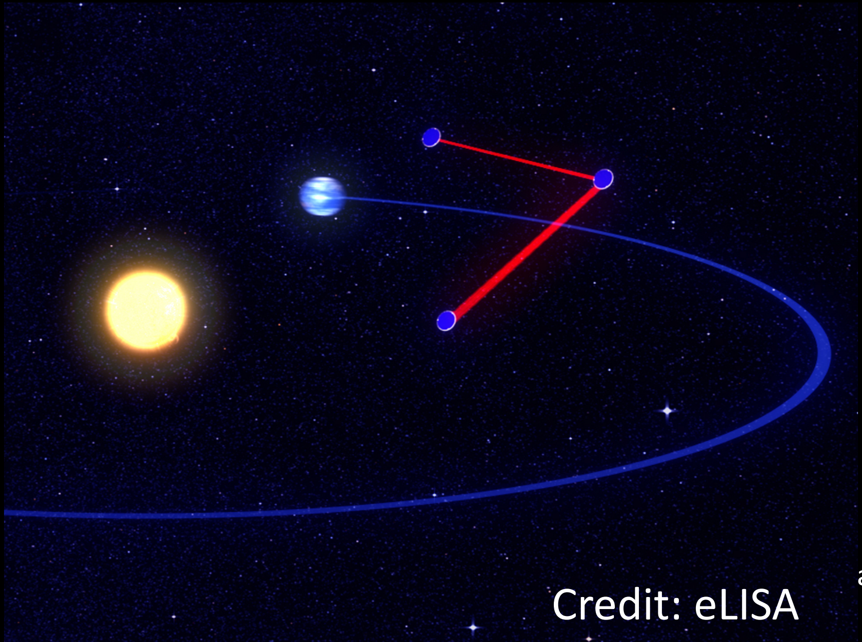


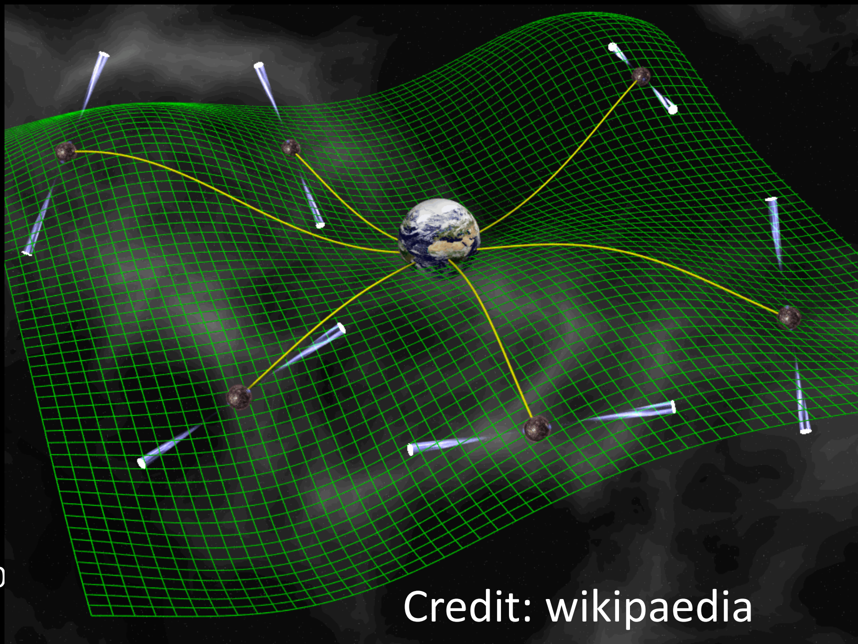


LVC, 1602.03838

Space based GW detectors

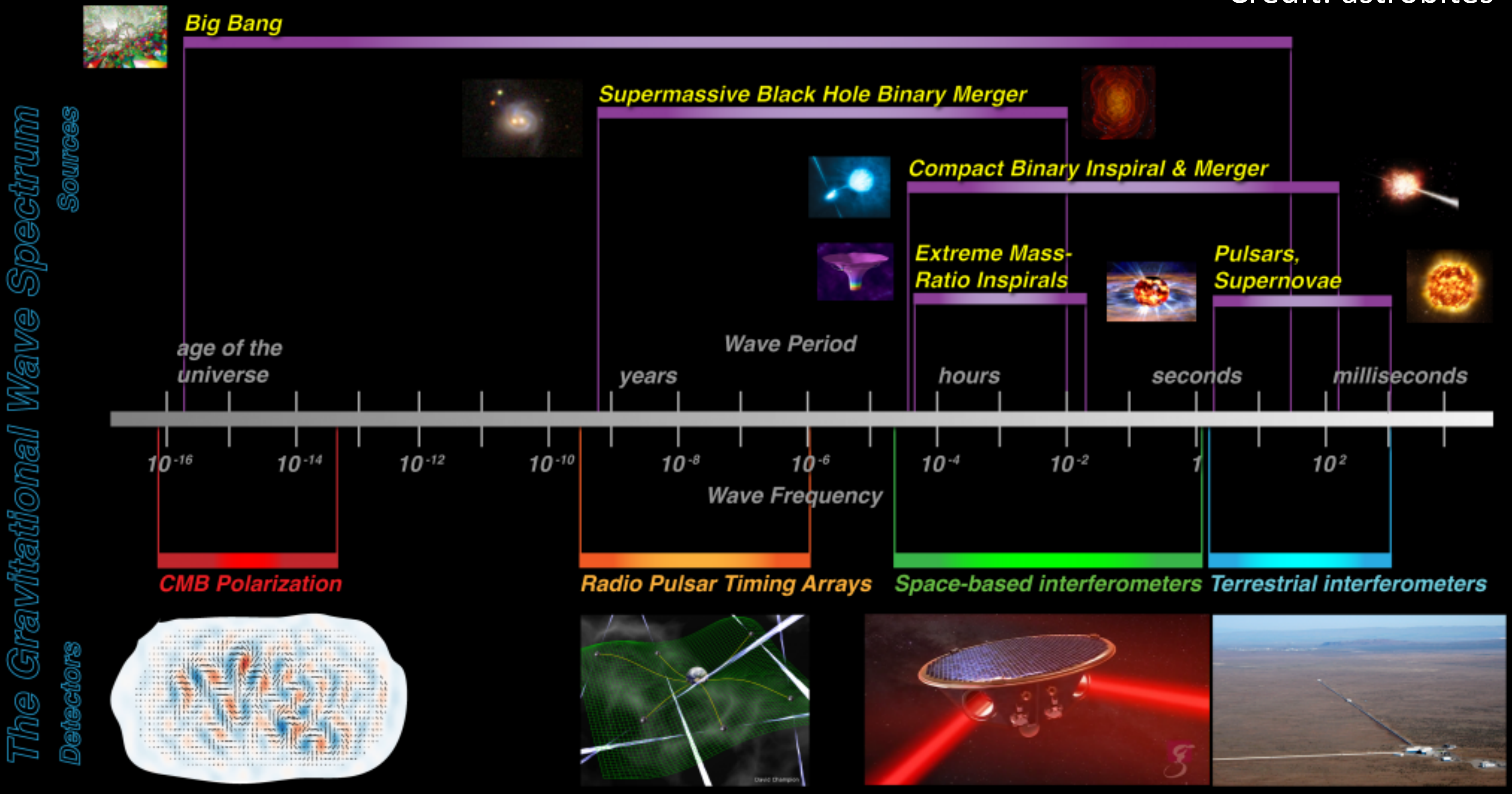
- eLISA
  - Interferometry in space
  - Targets more massive objects than LIGO
  - Launch > 2030
- Pulsar timing array
  - Use pulses time-travel as a clock
  - Targets supermassive BH


Credit: eLISA


Credit: wikipaedia

The GW spectrum

Credit: astrobites



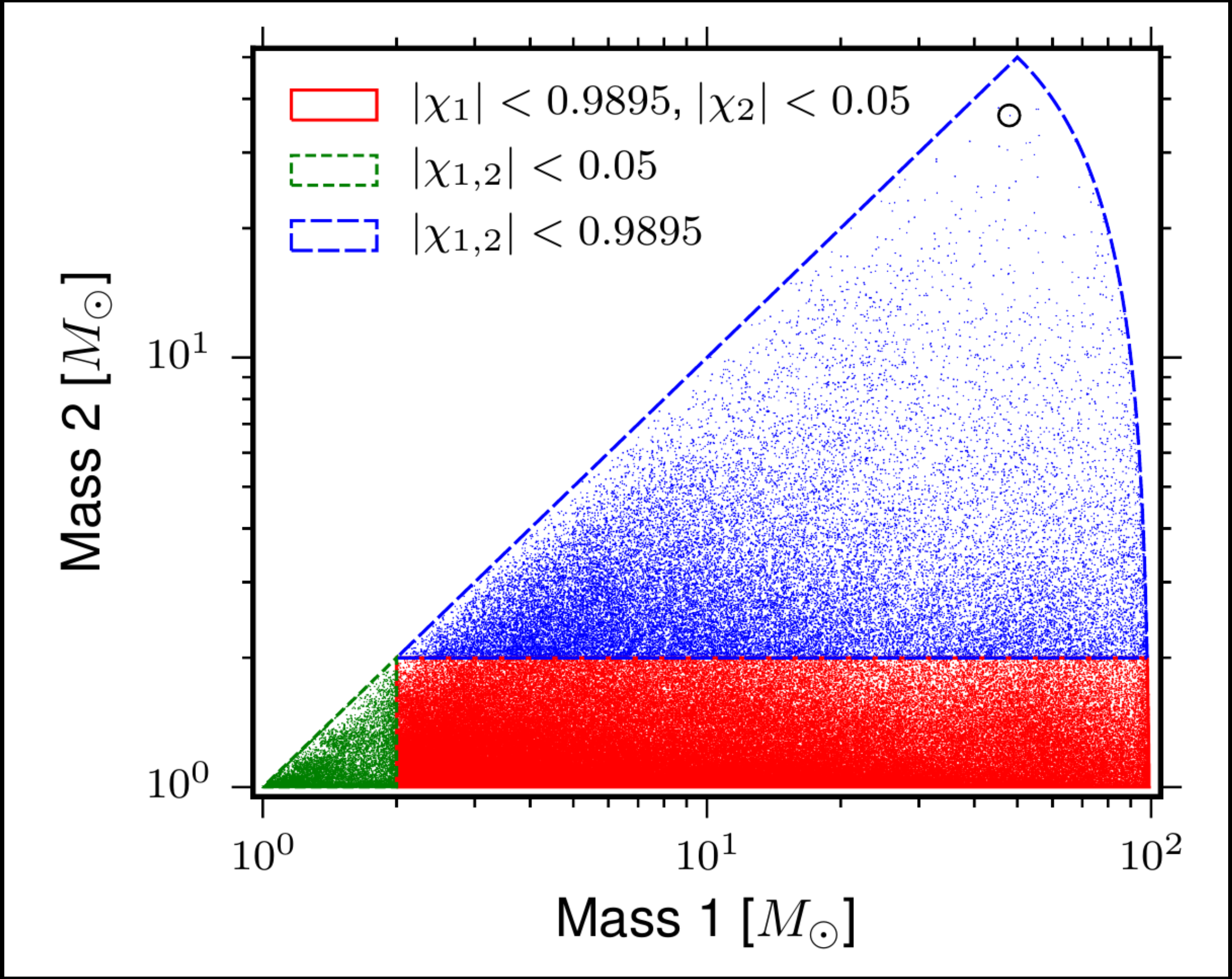
In the next five years…

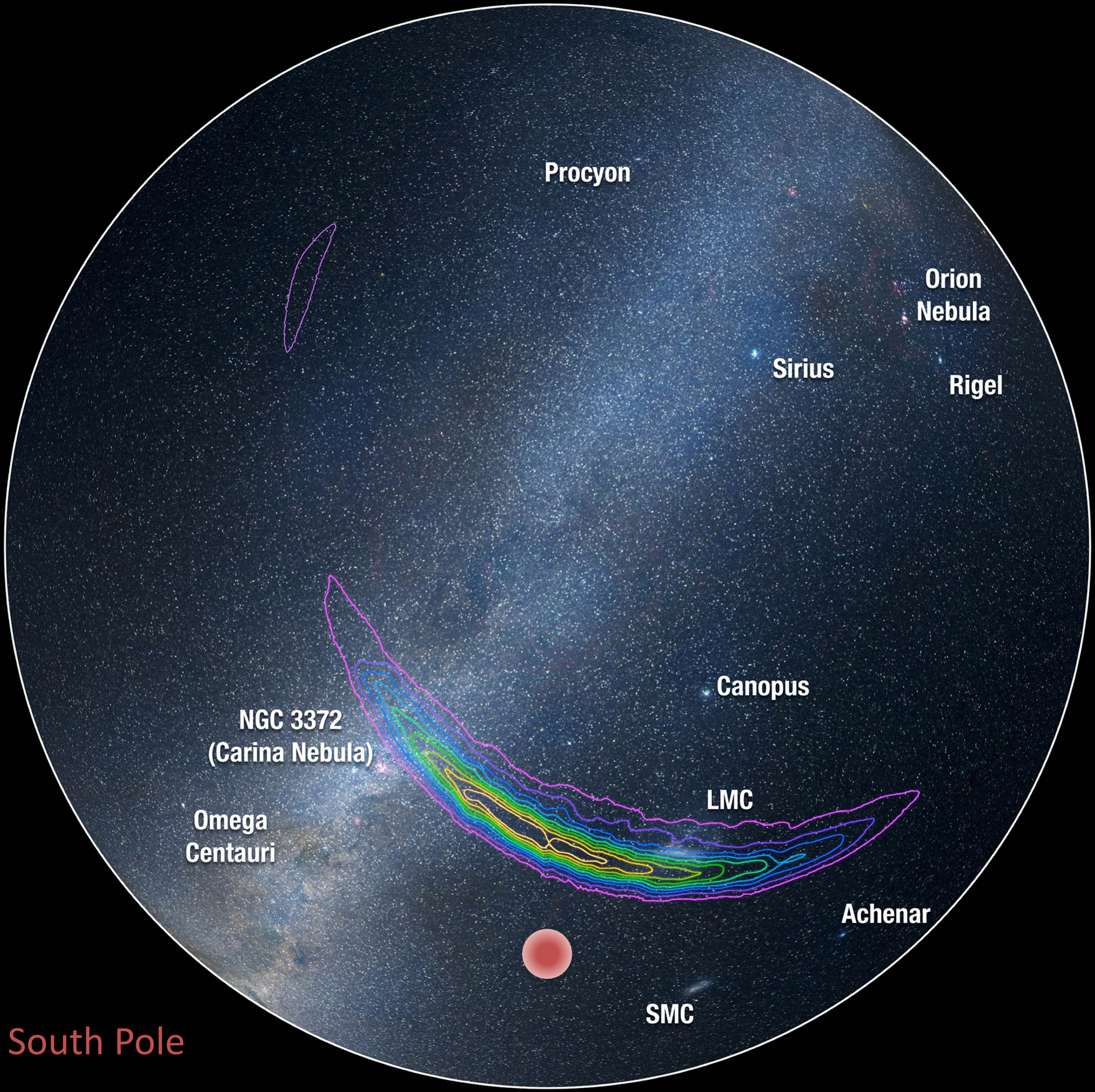
- More binary black holes detection will lead to:
  - Understanding of black hole mass and spin distributions, formation channels
  - Tests of General Relativity in its strong field regime
- We will probably detect binary neutron stars
  - Joint Electromagnetic/Gravitational Wave discovery: progenitors, environment, opening angle,..
  - Rank equations of state
  - Maximum mass of neutron star?
- We will never stop listening!
  - Gravitational wave bursts from supernovae, other violent events, unknown sources

More science with early upgrades to Advanced LIGO (10 years)

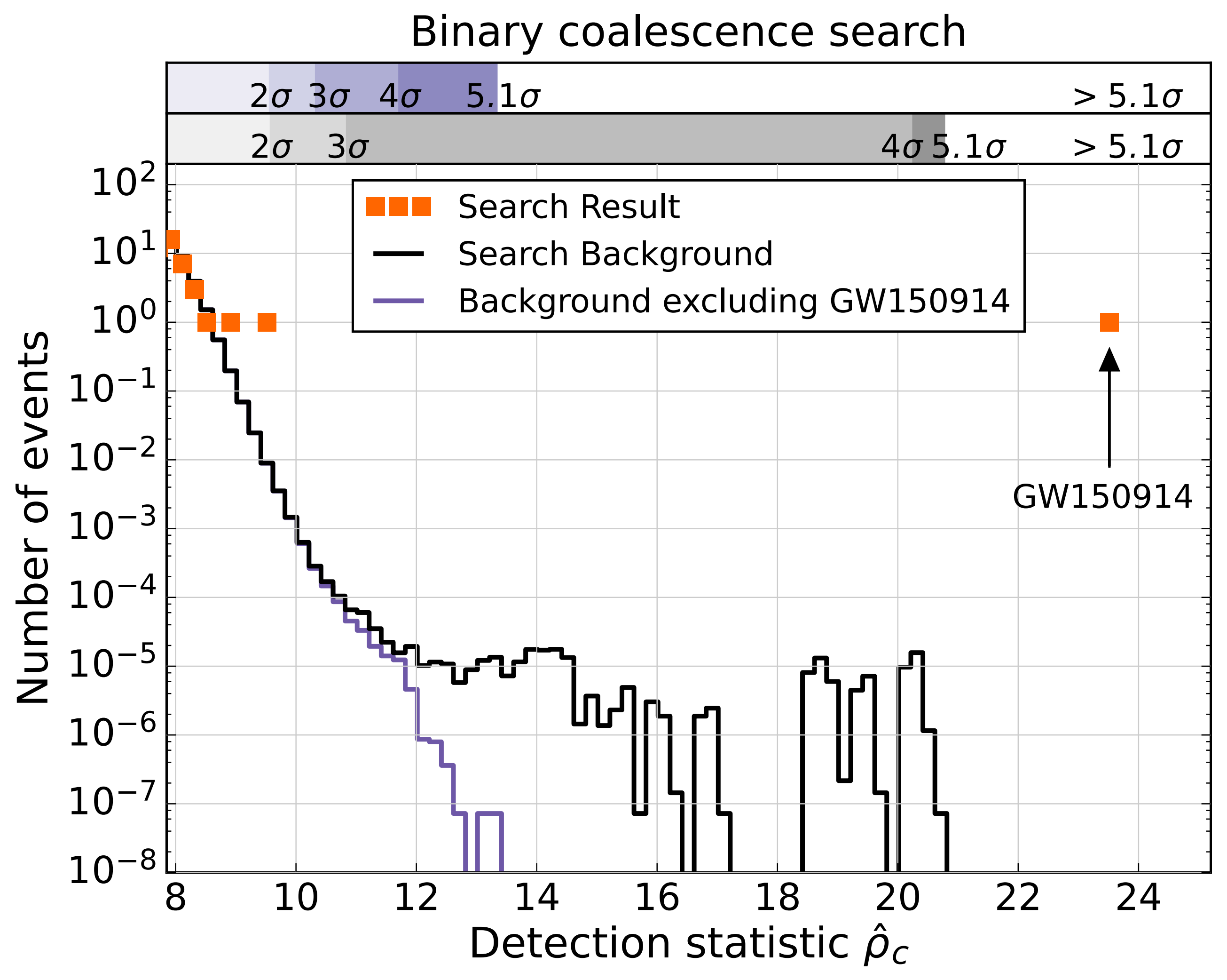
- Early upgrades envisioned beyond Advanced LIGO, larger science output (Miller+ PRD 91 062005):
  - Squeezed states of light can improve both high and low frequencies, improving sky localization, measurements of neutron star tidal deformability (Lynch+ PRD 91 044032)
  - Coating and beam size can improve sweet spot sensitivity

    → more detections
  - Suspensions and heavier masses affect < 50 Hz region:
    → higher SNR and parameter estimation for BBH
- Overall up to a factor of 2 in reach, ~ 8 in volume
- Evolving science goals

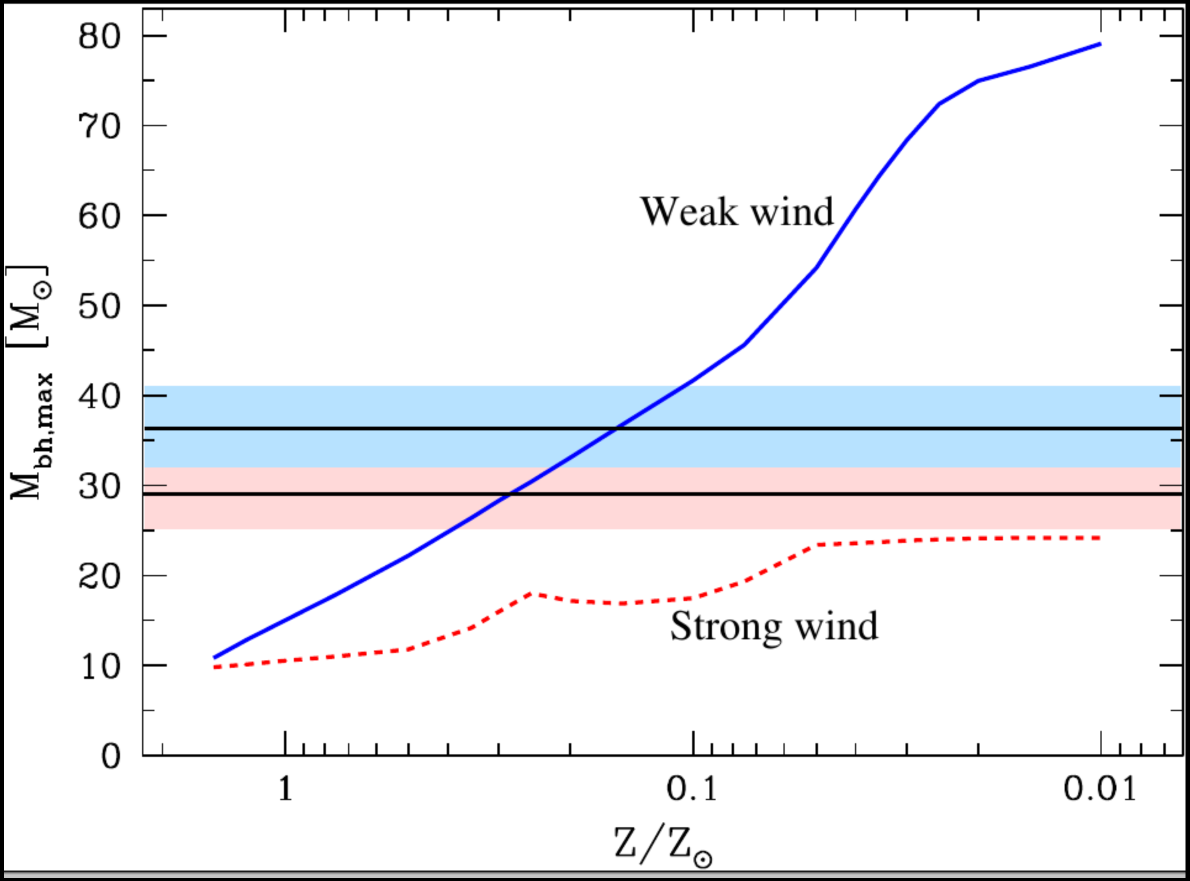

$|\chi_1| < 0.9895, |\chi_2| < 0.05$
$|\chi_{1,2}| < 0.05$
$|\chi_{1,2}| < 0.9895$
10^1
10^0
Mass 2 $[M_\odot]$
10^0
10^1
10^2
Mass 1 $[M_\odot]$


Procyon
Orion Nebula
Sirius
Rigel
Canopus
NGC 3372 (Carina Nebula)
LMC
Omega Centauri
Achenar
SMC

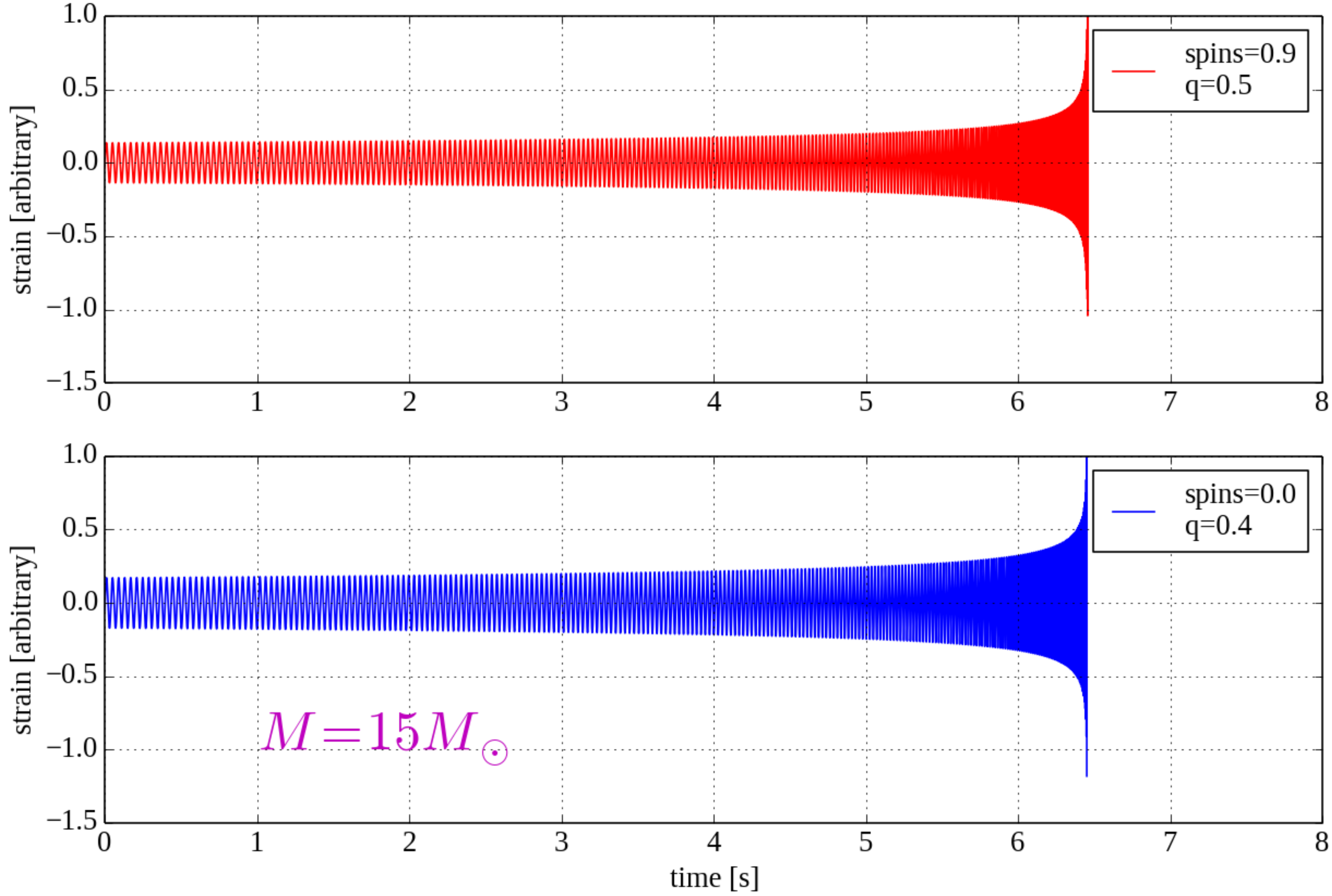
South Pole


Binary coalescence search
2σ 3σ 4σ 5.1σ
> 5.1σ
2σ 3σ
4σ 5.1σ
> 5.1σ
Search Result
Search Background
Background excluding GW150914
GW150914
Number of events
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
8
10
12
14
16
18
20
22
24
Detection statistic $\hat{\rho}_c$

Astrophysical implications

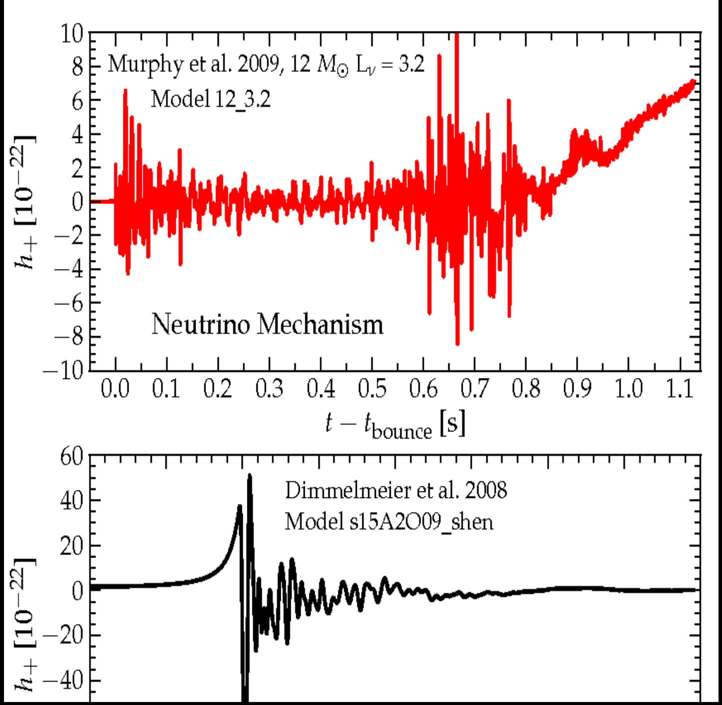


Aligned-spin mass-spin degeneracy



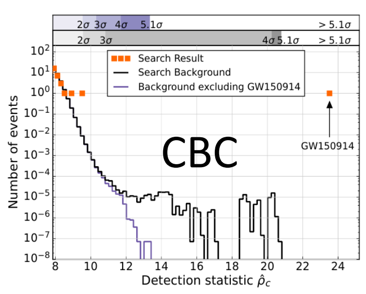
Unmodeled Sources

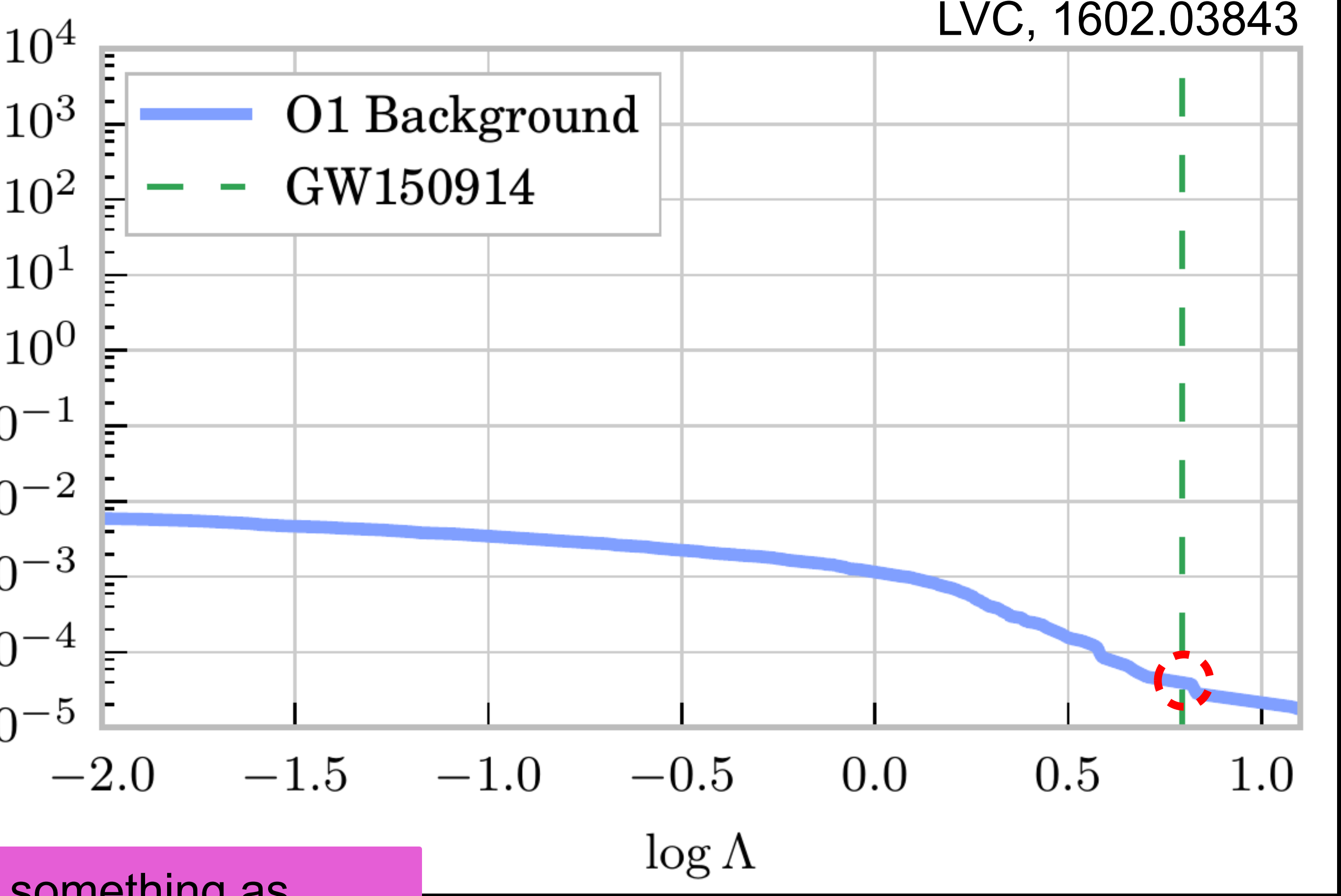
- Any violent astrophysical or cosmological phenomenon
  - Core collapse supernovae
  - Cosmic strings
  - Post-merger signals from hypermassive neutron stars
  - Something unexpected
- Uncertain or no knwledge of gravitational wave signal morphology
- Less advertised, but not less interesting than CBCs
  - Also, high mass binary black holes escaped CBC net



Logue+, PRD 86 044023

oLIB results for GW150914





LVC, 1602.03843

More rare

More GW-like

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