Characterization of black holes with gravitational waves

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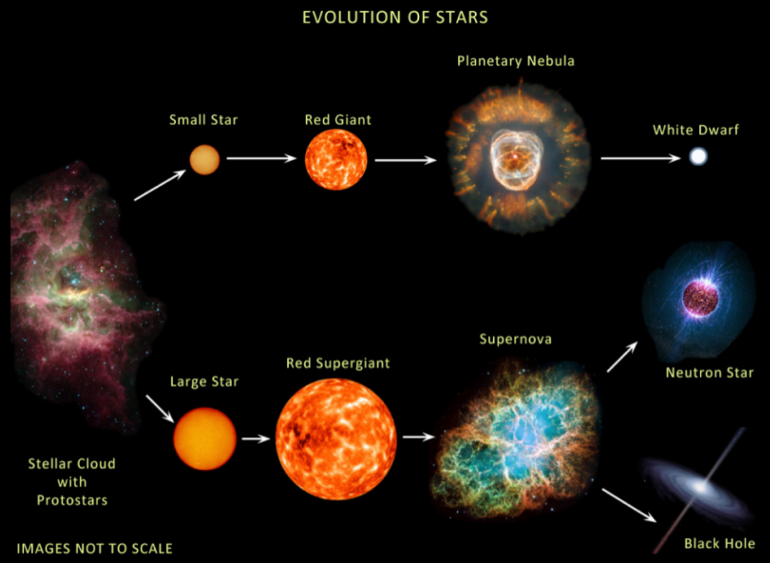
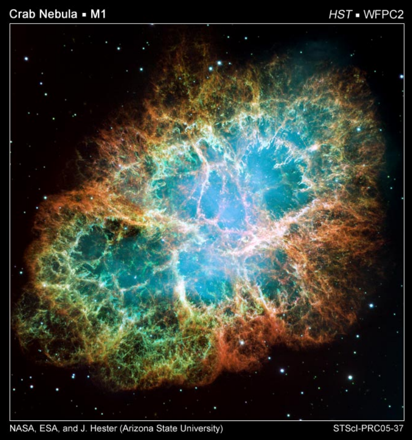
Compact objects

- 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 to metal production?
- What is the maximum mass of a neutron star?

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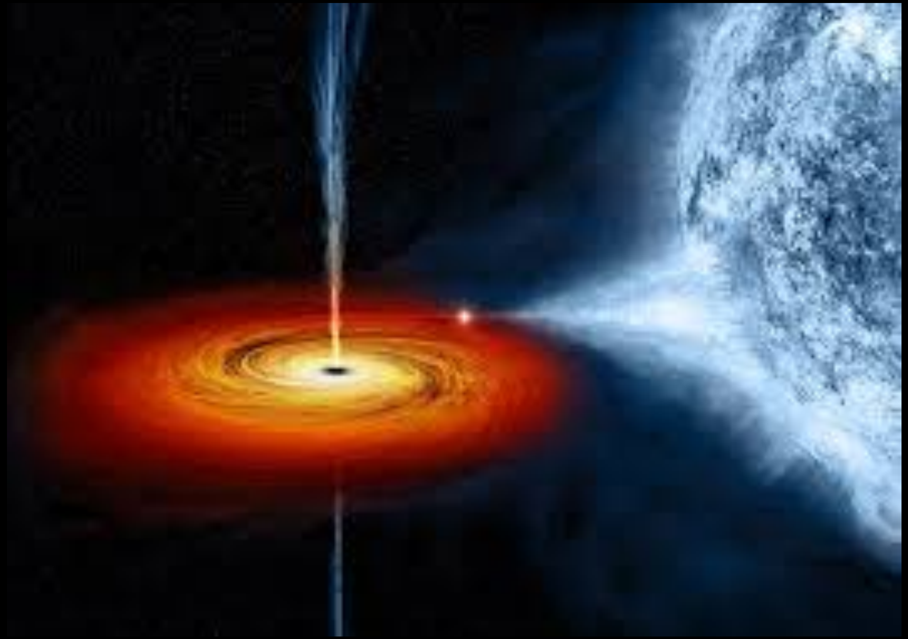
WILL FOCUS ON BLACK HOLES TODAY

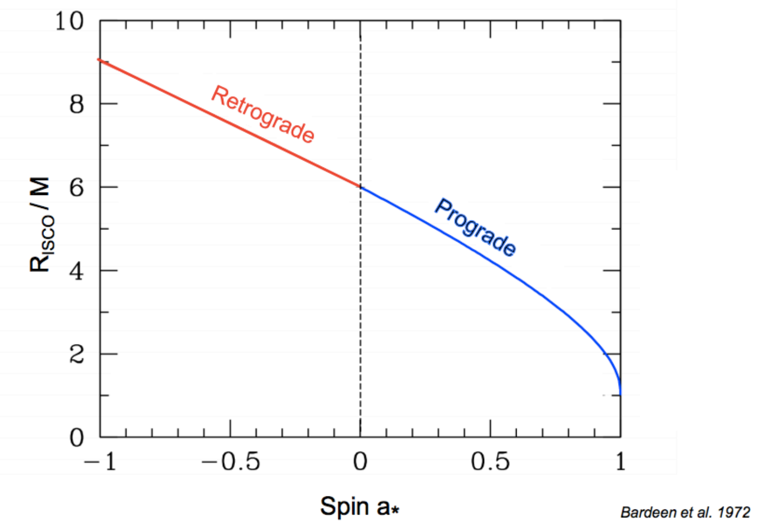
BH spins (with EM)

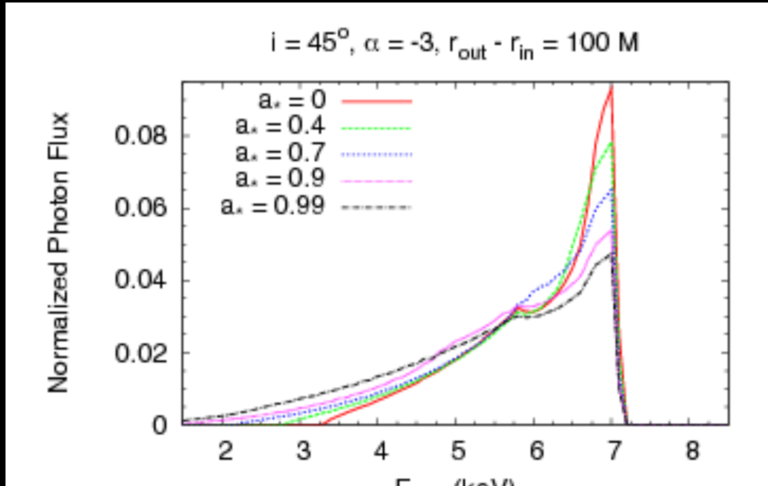
- Traditionally, the spin of black holes has been estimated through its effects on a surrounding disk
- Need an accreting black hole (e.g. in a X-ray binary)



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)





Bambi, 2012

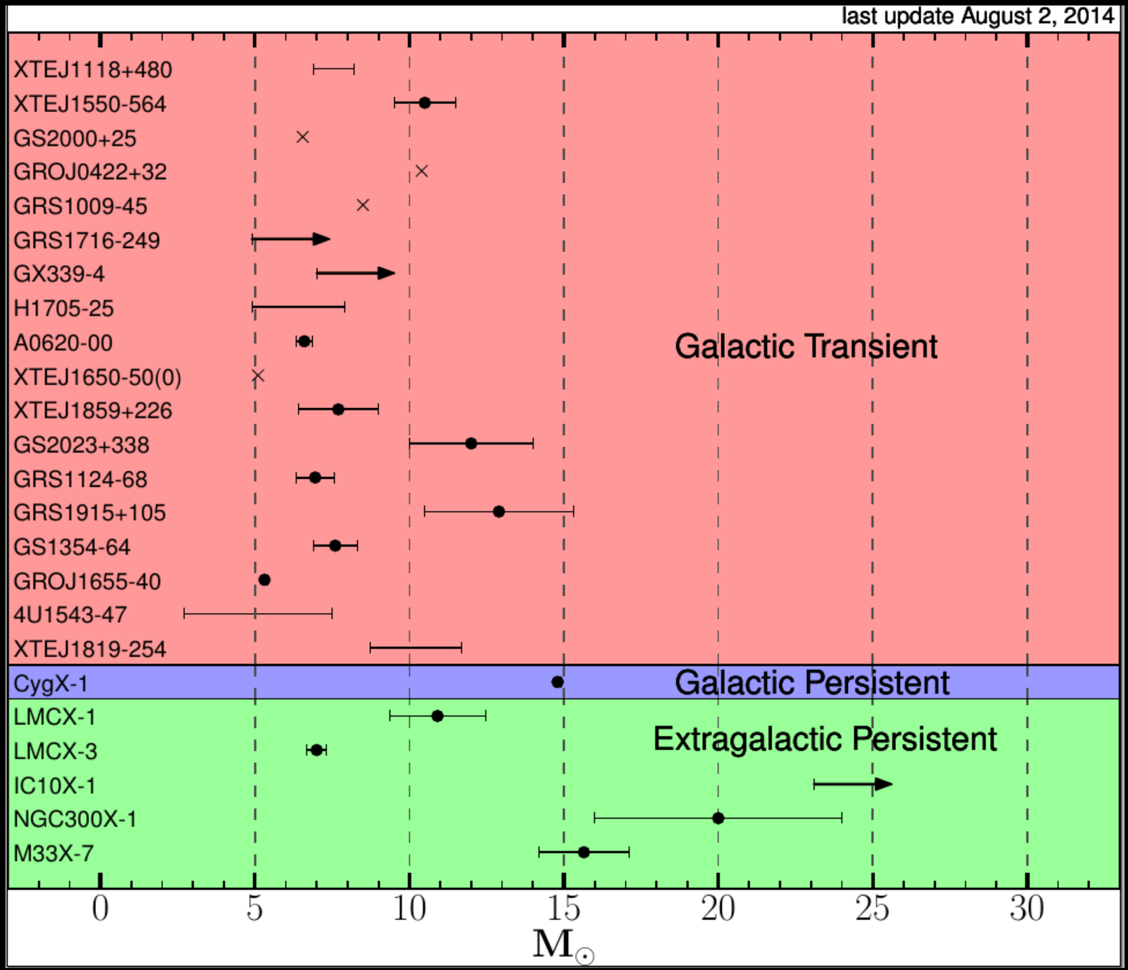
BH spins (with EM)

- 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	✕

BH mass (with EM)

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



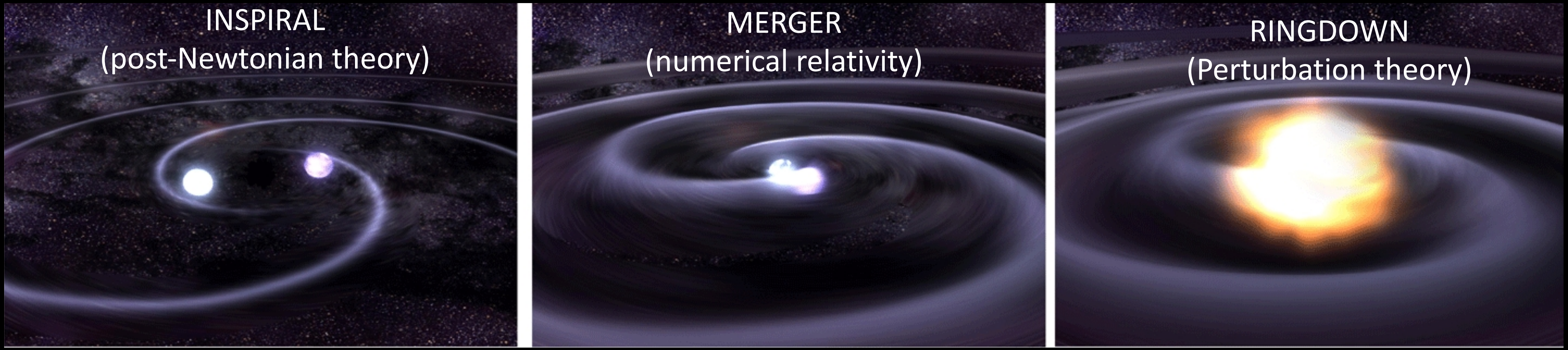
D. Lorimer

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.

Compact Binaries Coalescences

GW emitted by compact binaries are the best understood

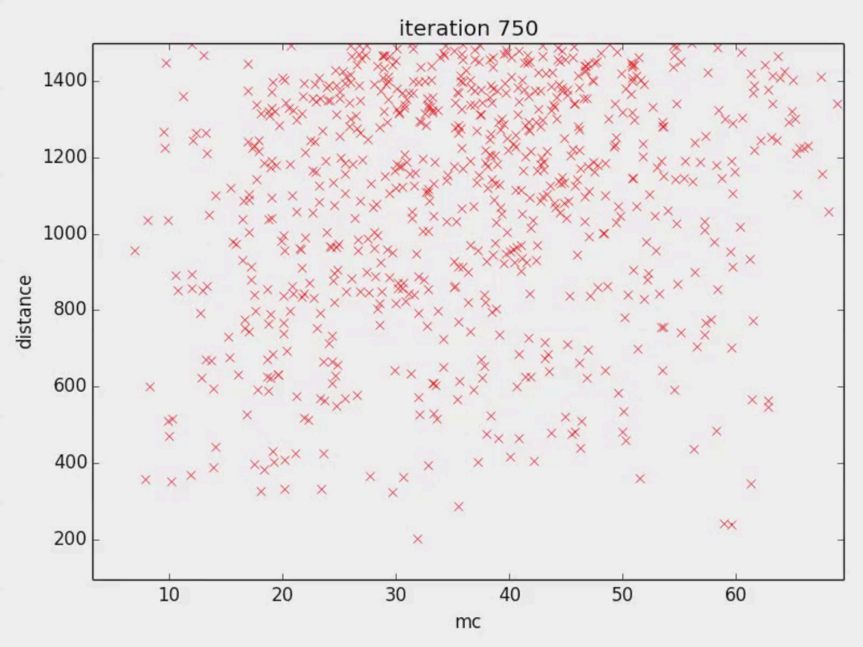


Parameter estimation

- 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)

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

Courtesy of J. Veitch



Mass estimation (with GW)

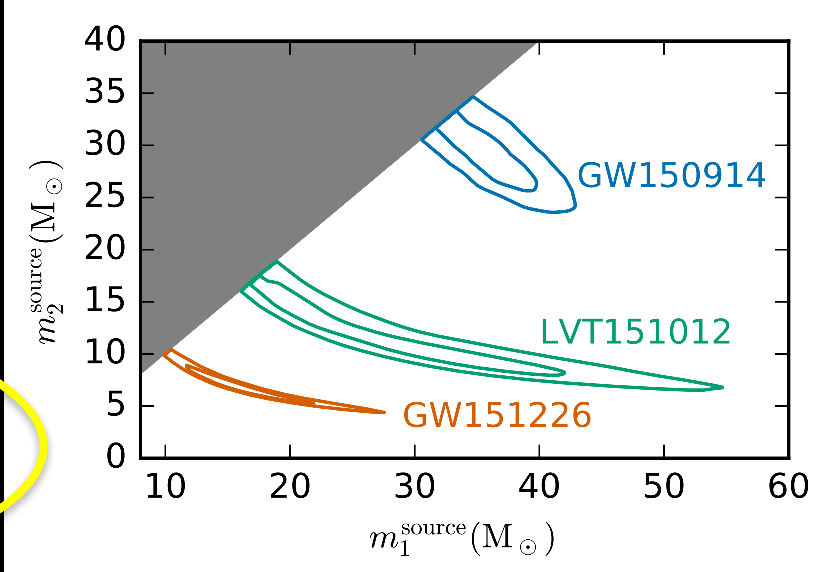
- The masses of the two objects directly affect the phasing evolution of a GW signal
  - Very good at estimating “chirp” mass
  - Worse for component masses
- This is a *direct* measurement, the masses directly affect the amount and frequency of GW emitted

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

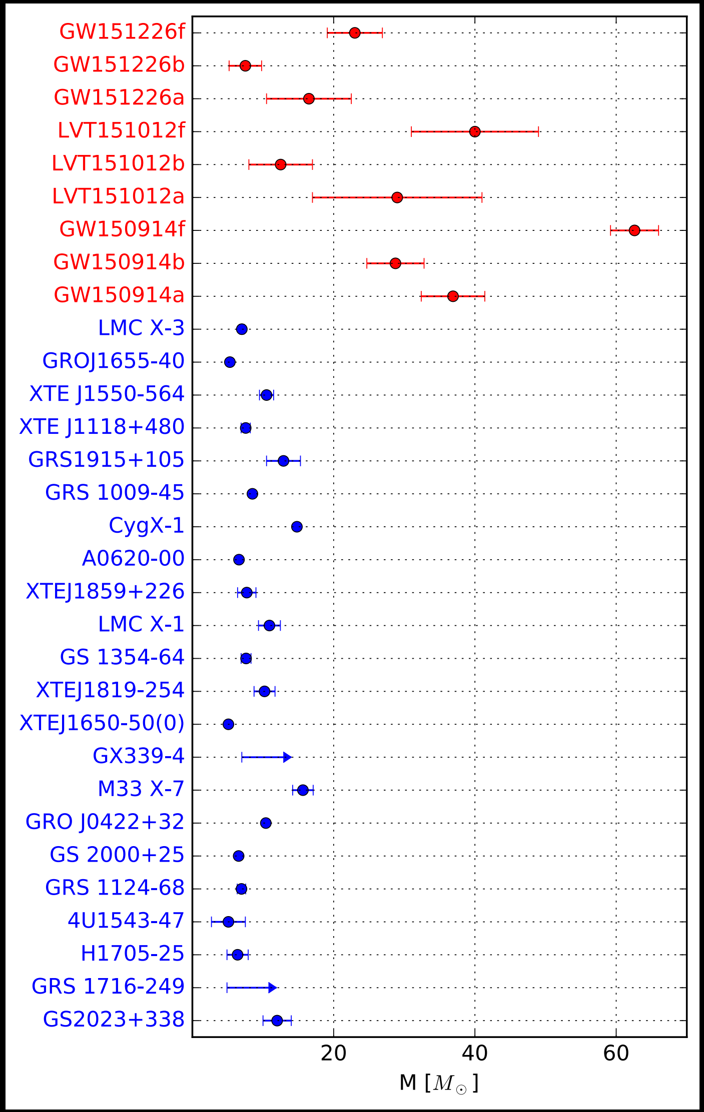
LVC, PRX 6.041015

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate 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 $m_1^{\rm source}/M_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\rm source}/M_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathcal{M}^{\rm source}/M_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$



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)



BH spin (with GW)

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

LVC, PRX 6.041015

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

BH spin (with GW)

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Secondary mass $m_2/\mathrm{M}_\odot$	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	16^{+4}_{-6}	$16^{+5\pm0}_{-6\pm1}$
Final mass $M_f/\mathrm{M}_\odot$	[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}	$13^{+4\pm0}_{-5\pm0}$
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Energy radiated $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$2.98^{+0.55}_{-0.40}$	$3.02^{+0.36}_{-0.36}$	$3.00^{+0.47\pm0.13}_{-0.39\pm0.07}$	$1.02^{+0.09}_{-0.24}$	$0.99^{+0.11}_{-0.17}$	$1.00^{+0.10\pm0.01}_{-0.20\pm0.03}$	$1.48^{+0.39}_{-0.41}$	$1.51^{+0.29}_{-0.44}$	$1.50^{+0.33\pm0.05}_{-0.43\pm0.01}$
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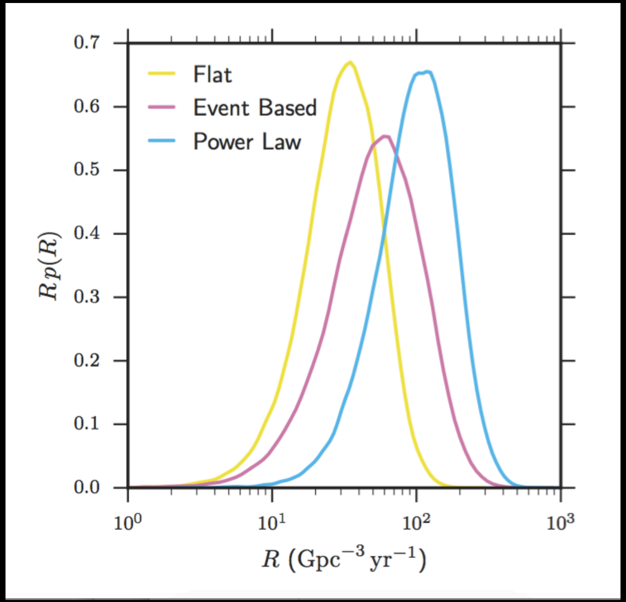
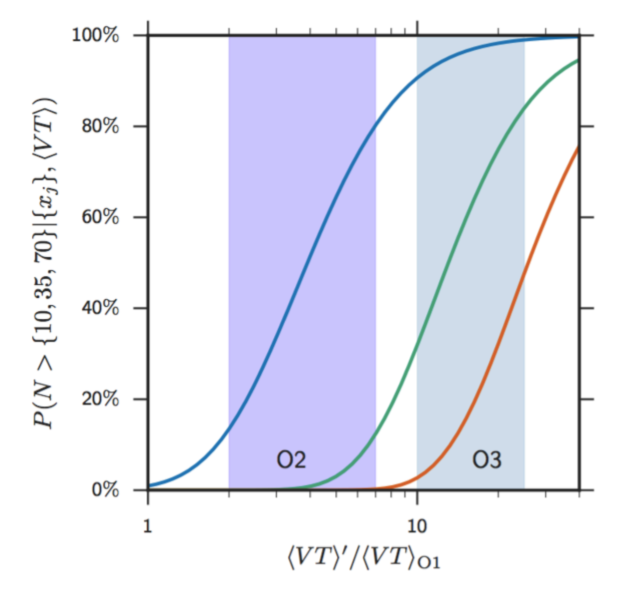
Effective inspiral spin χ_{eff}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Primary spin magnitude a_1	$0.33^{+0.39}_{-0.29}$	$0.30^{+0.54}_{-0.27}$	$0.32^{+0.47\pm0.10}_{-0.29\pm0.01}$	$0.42^{+0.35}_{-0.37}$	$0.55^{+0.35}_{-0.42}$	$0.49^{+0.37\pm0.11}_{-0.42\pm0.07}$	$0.31^{+0.46}_{-0.27}$	$0.31^{+0.50}_{-0.28}$	$0.31^{+0.48\pm0.03}_{-0.28\pm0.00}$
Secondary spin magnitude a_2	$0.62^{+0.35}_{-0.54}$	$0.36^{+0.53}_{-0.33}$	$0.48^{+0.47\pm0.08}_{-0.43\pm0.03}$	$0.51^{+0.44}_{-0.46}$	$0.52^{+0.42}_{-0.47}$	$0.52^{+0.43\pm0.01}_{-0.47\pm0.00}$	$0.49^{+0.45}_{-0.44}$	$0.42^{+0.50}_{-0.38}$	$0.45^{+0.48\pm0.02}_{-0.41\pm0.01}$

RELATIVE SPIN ERRORS CLOSE TO 100%

New kid in town

- The two detections allowed for measurement of the local rate of coalescence
- Tens of BBH per year (LVC, PRX 6.041015)
- How well can their parameters be estimated?

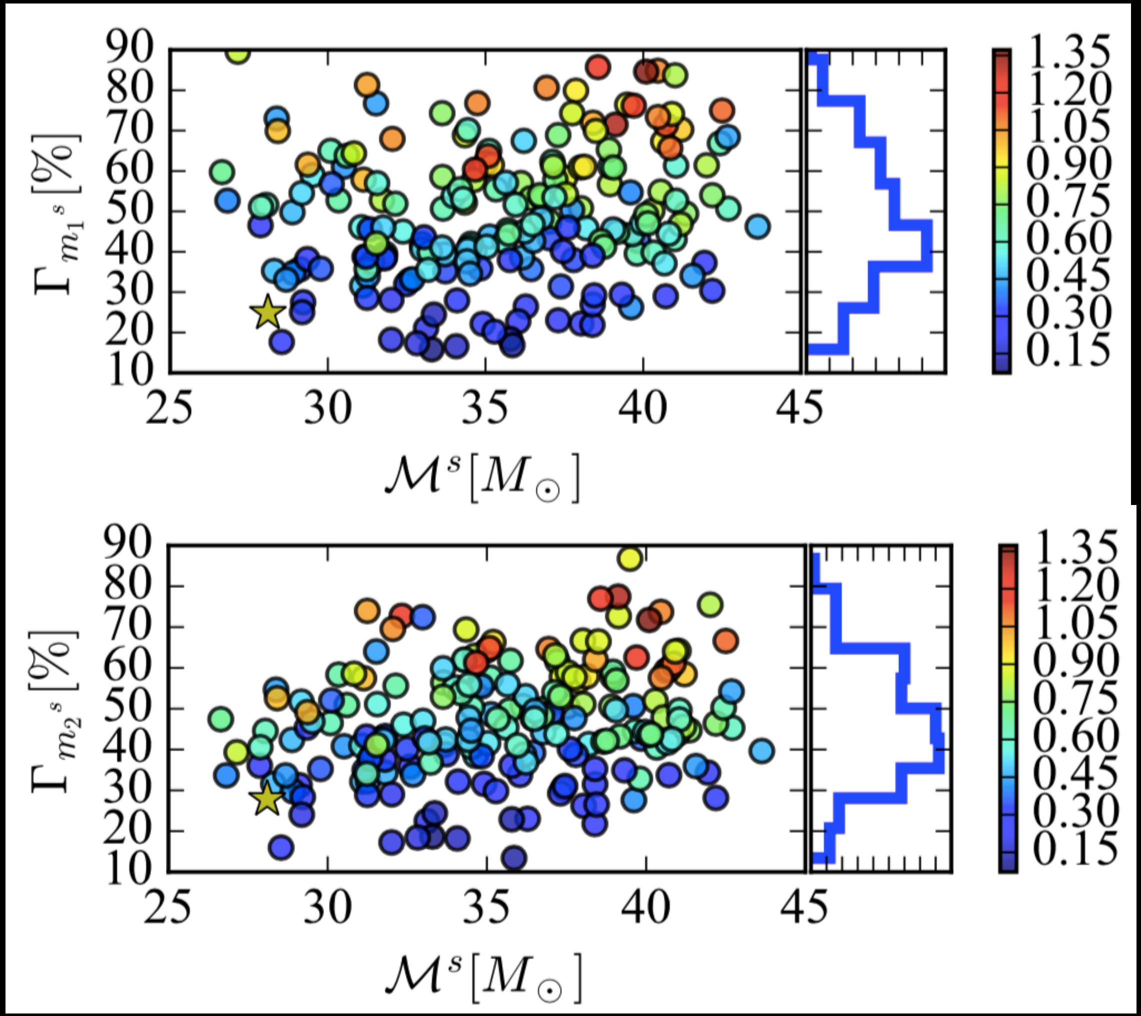




LVC, PRX 6.041015

Masses

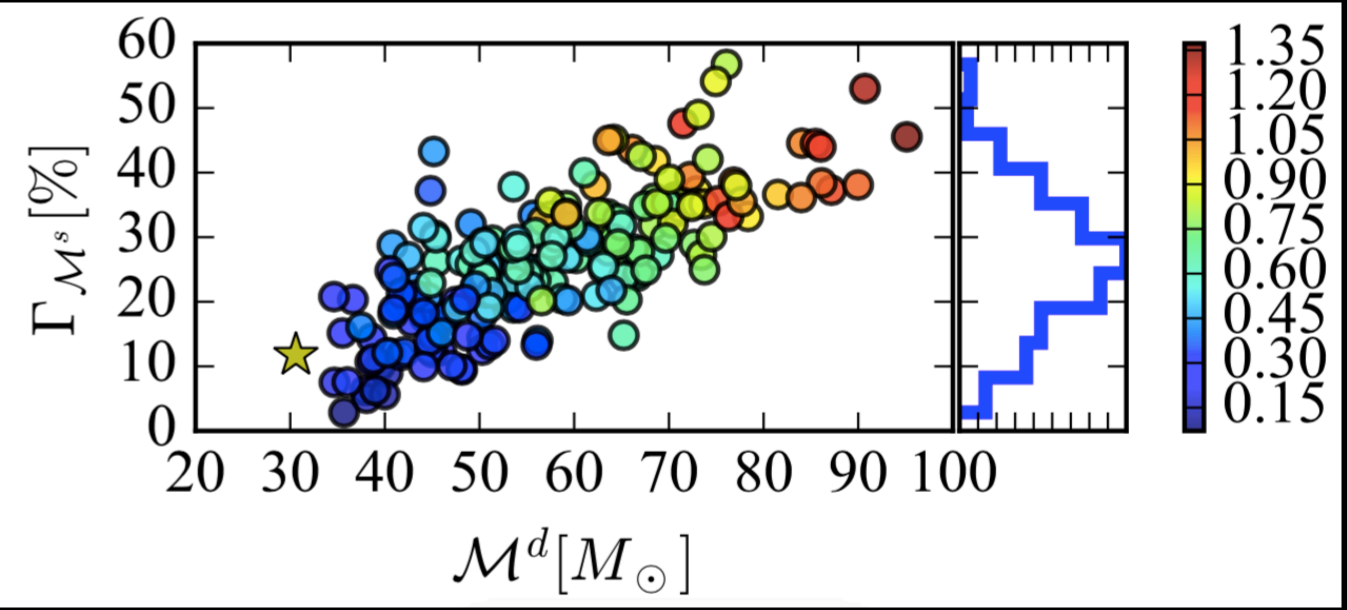
- Component masses will typically be estimated with uncertainties of a few tens of percent
- No apparent correlation with true mass



Vitale+, PRD 95 064053

Mass and redshift

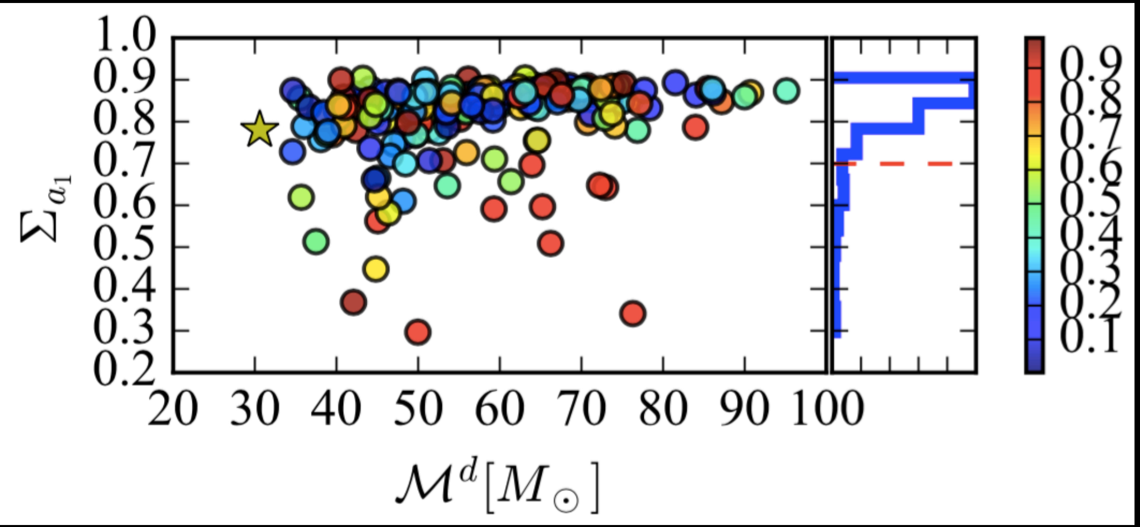
- What we can measure from GW observations is not the true mass, but a redshifted combination: $m^d = (1+z)m^s$
- The detector-frame mass is what sets the evolution of the detected signals

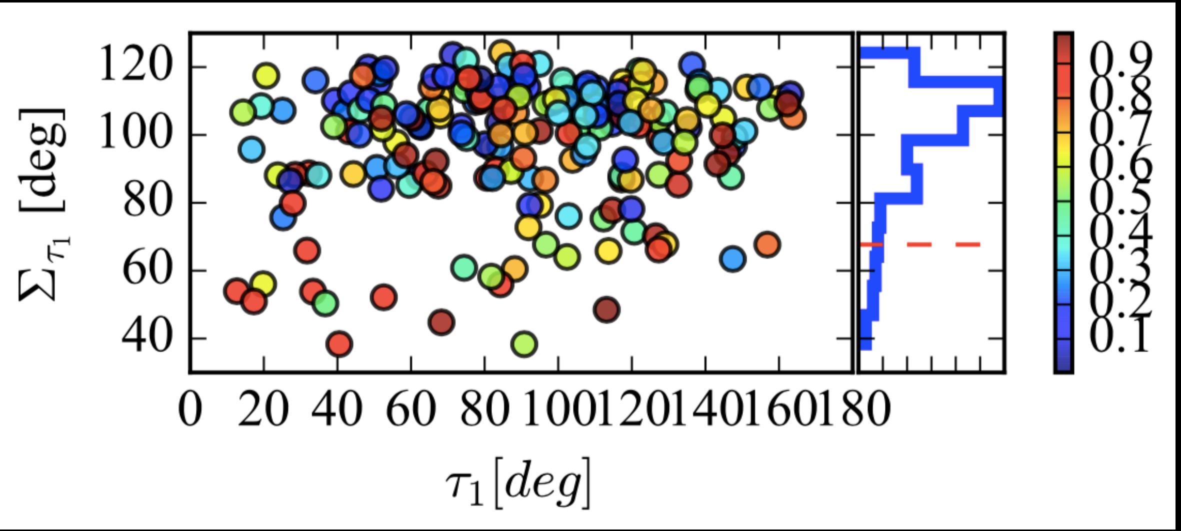


Vitale+, PRD 95 064053

Component spins

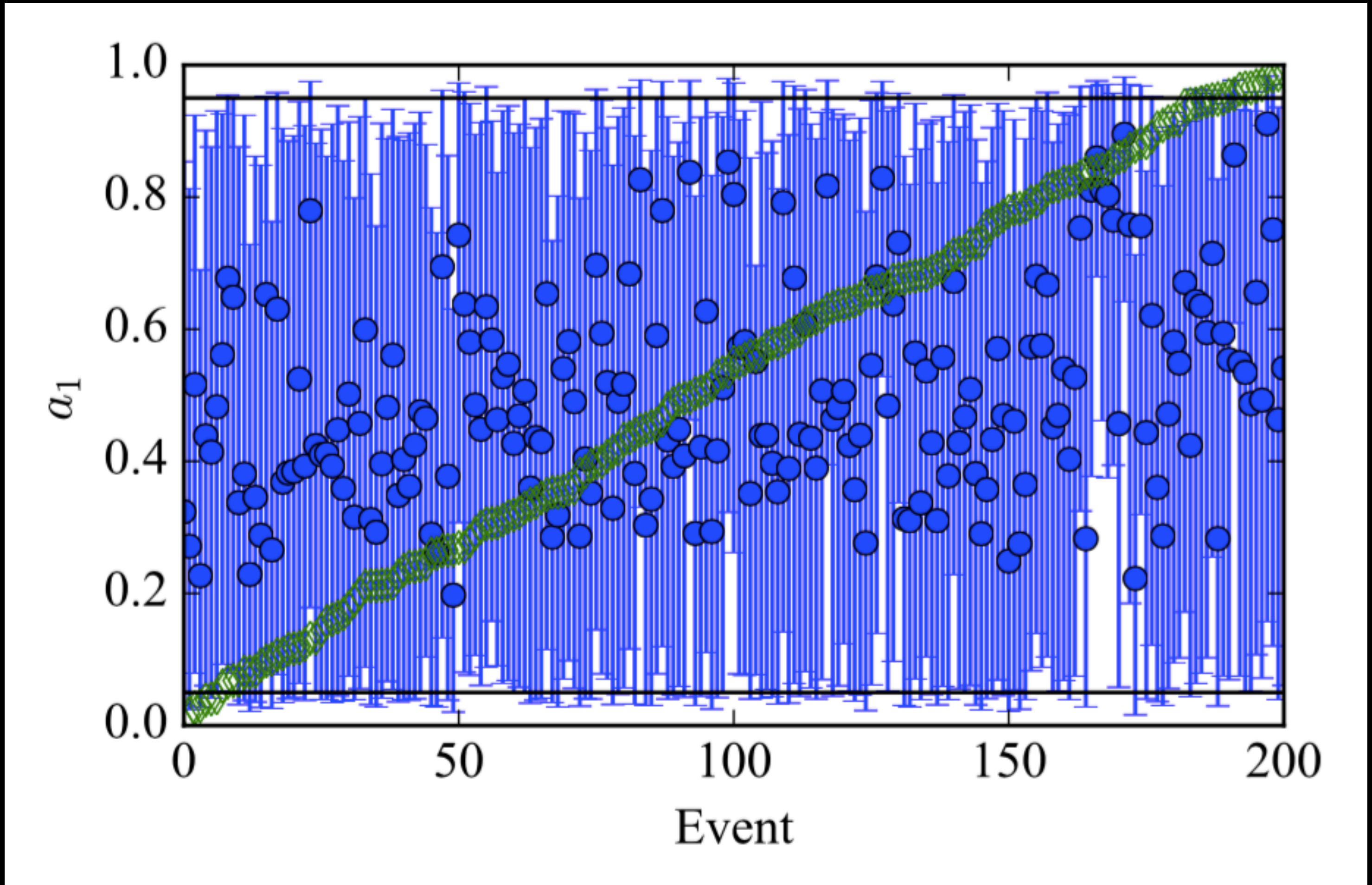
- Both magnitude and orientation are astrophysically interesting
- Component spin magnitude and orientation only seldom measurable
  - For 90% of signals spin magnitude (direction) uncertainty larger than 0.7 (60 degs)





Vitale+, PRD 95 064053

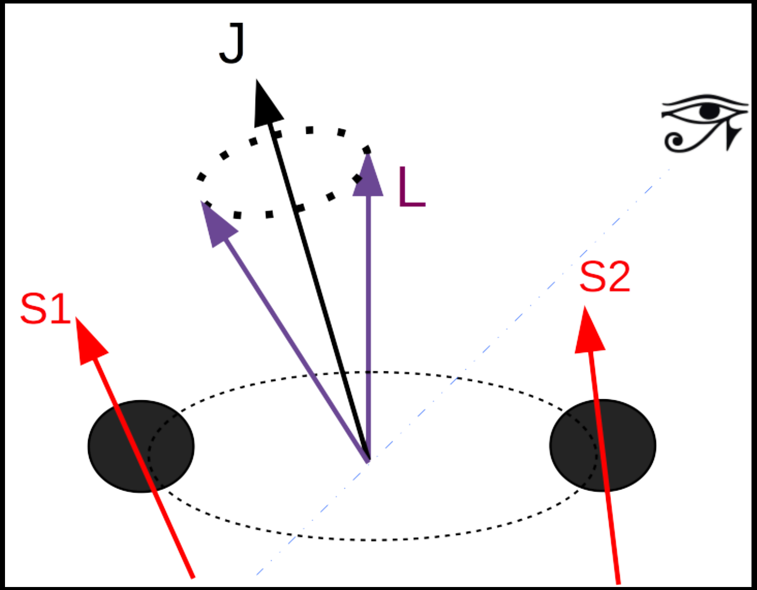
Component spins

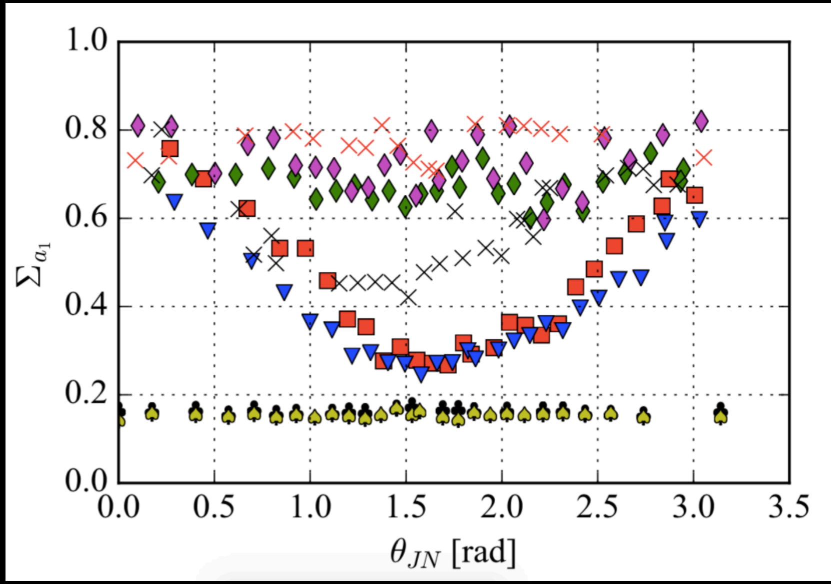


Vitale+, PRD 95 064053

Spin measurement vs orientation

- The orientation of the orbit w.r.t. the line of sight impacts spin measurability
- When there is spin precession, smallest uncertainties for edge-on systems

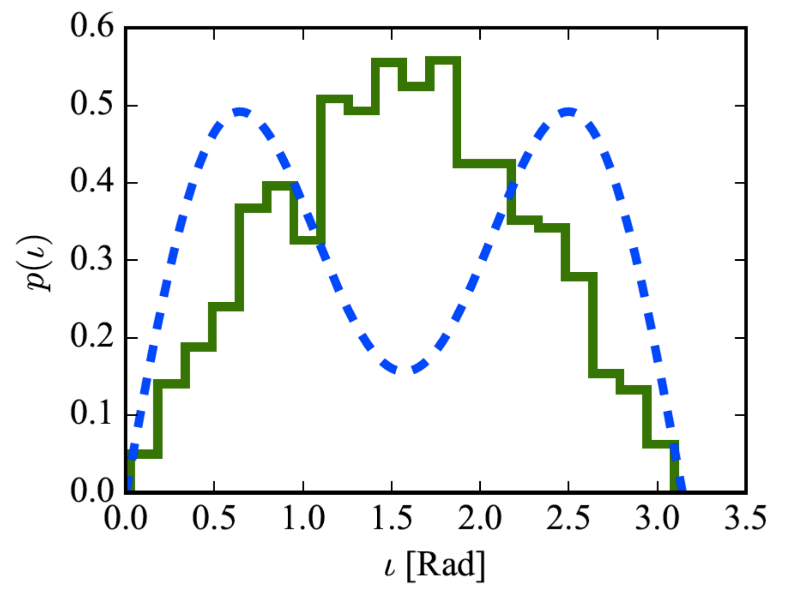




Vitale+, PRD 95 064053, PRL 112 251101

Distribution of orientations

- More GW energy goes along $\pm L$ than perpendicular to it
- With Advanced detectors, most events will be close to face-on or face-off -> little visible precession and larger errors
- (This will change with the next generation of GW detectors)



Vitale, PRD(R) 94 121501

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

CBC and their formation channels

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

Lots of recent studies:

- Rodriguez+ 1609.05916
- Mandel+, MNRAS 458, 2634
- Chatterjee+, 1609.06689
- More!

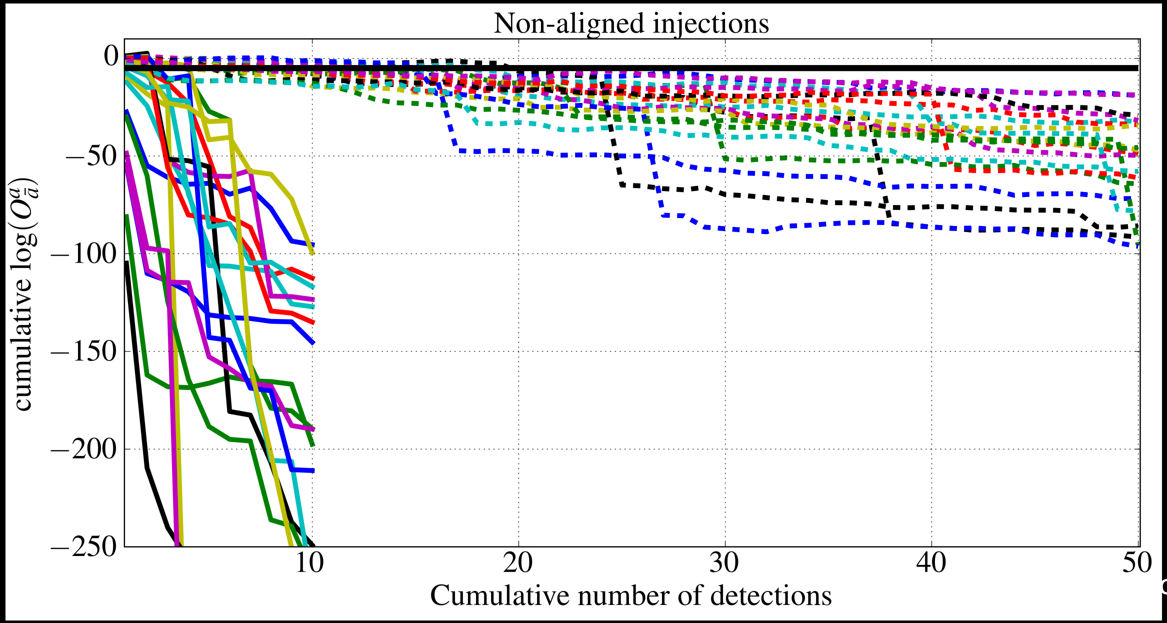
An example: spin alignment

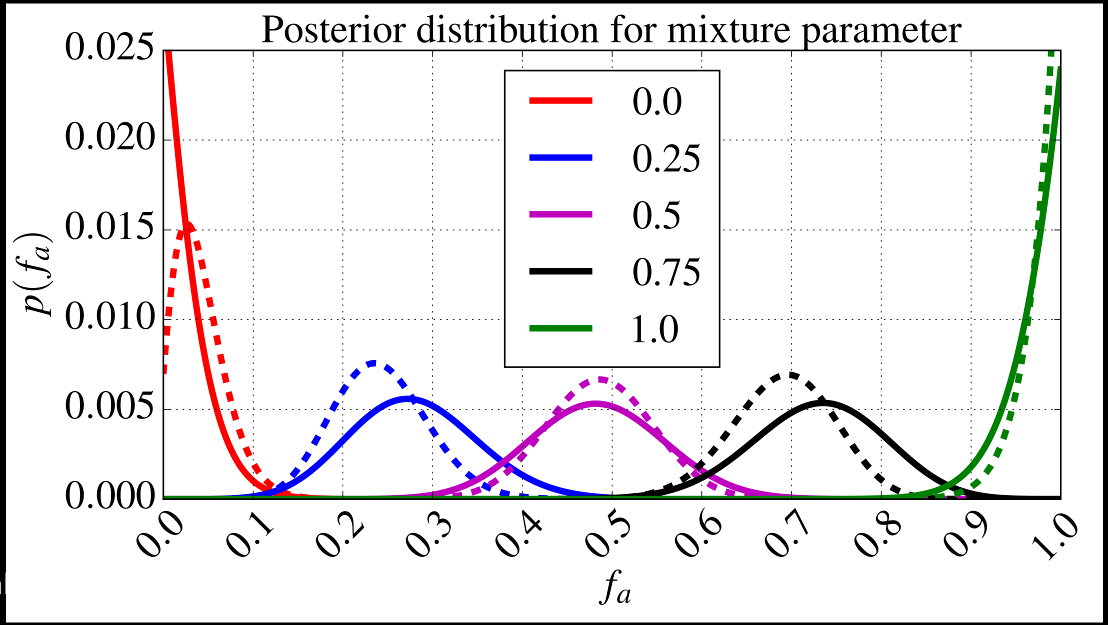
- Most astronomers believe that CBC formed via common envelope will have aligned spins
- We can use Bayesian methods to verify if and how many systems have aligned spins
- Recent studies
  - Stevenson+
  - Farr+

Results

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

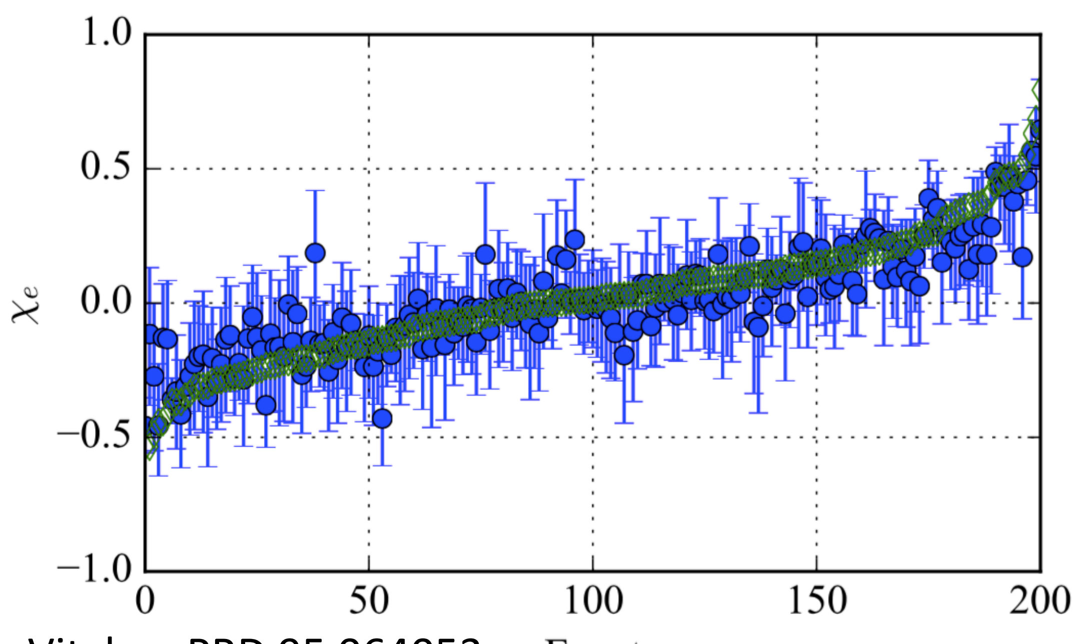
Vitale+, CQG(L) 34 3L1



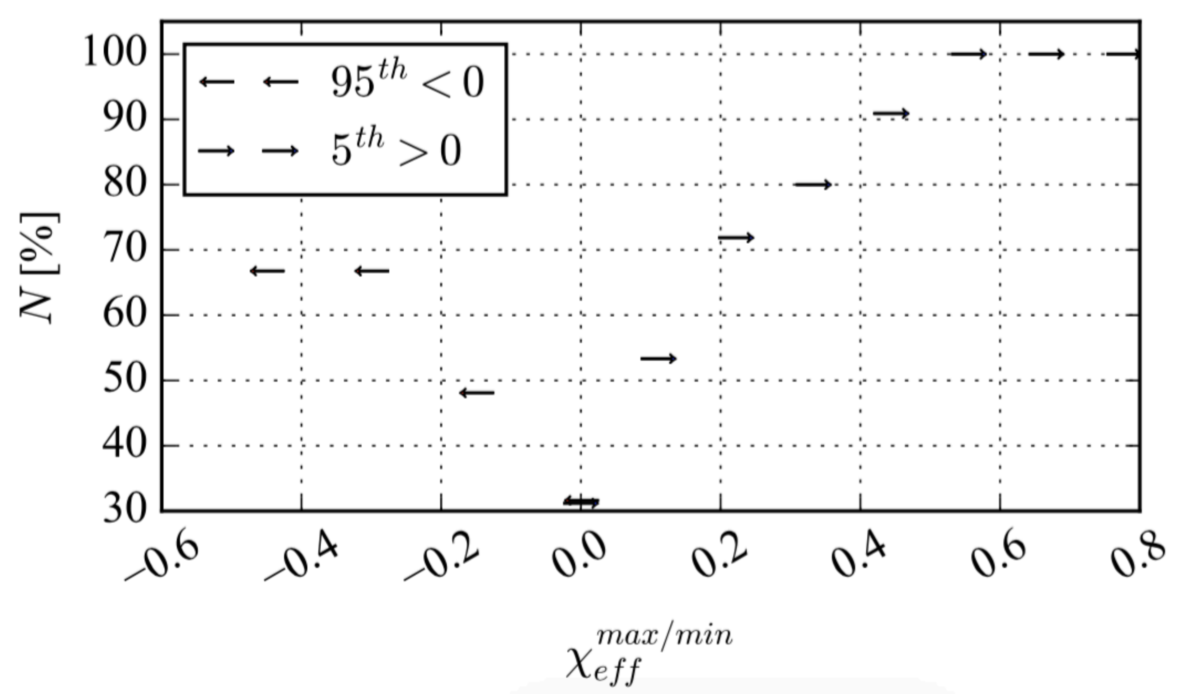


Effective spin

- One can learn something from the projection of the *total* spin along the orbital angular momentum (Rodriguez+ 1609.05916)
- Its sign says something about the formation channel of the CBC



Vitale+, PRD 95 064053

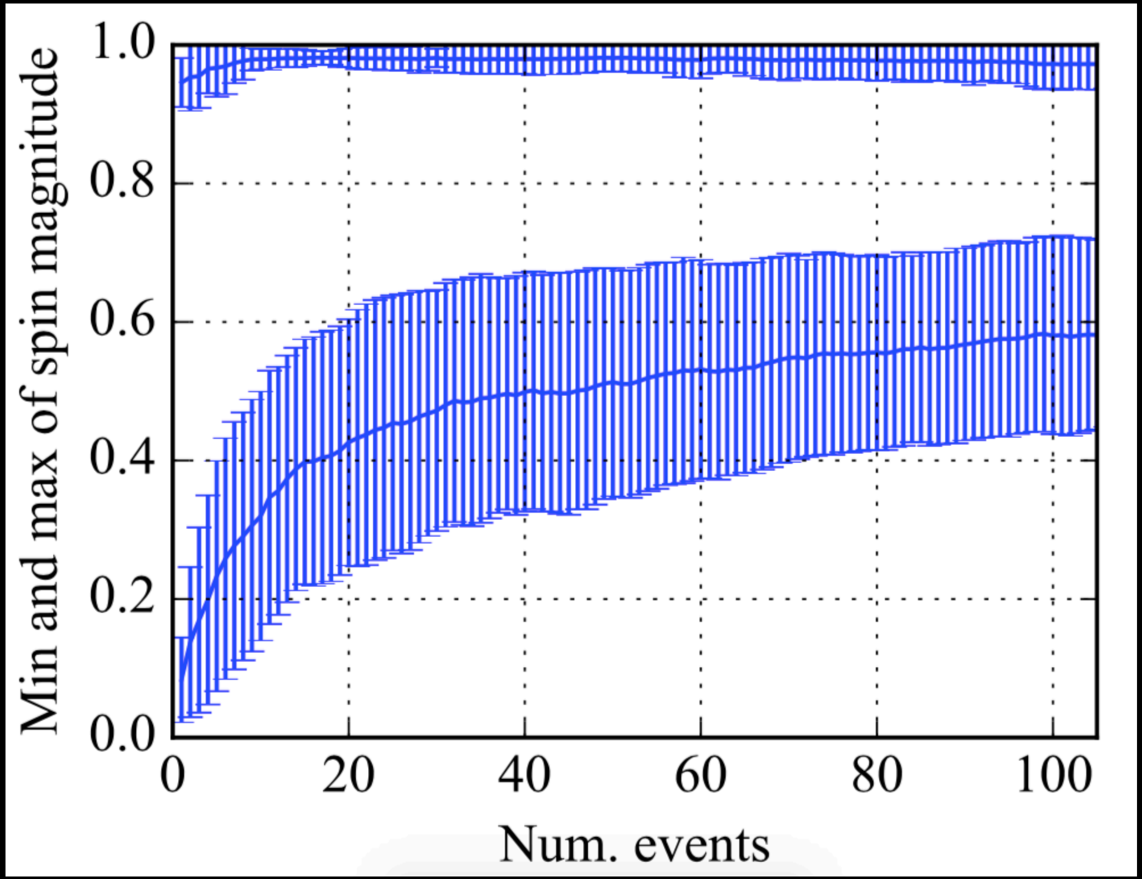


Population inference

- As more GW will be detected, we will be able to infer the underlying mass distribution of neutron stars and black holes.
- Two main advantages over EM:
  - Direct measurement
  - Can potentially access many more systems

An example

- Suppose all BH in the universe have spins in the range [0.7, 1]
- How long would it take to understand that BH do not have negligible spins?
- Use all BBH!
- With a few dozens sources we can confidently exclude small spins
- See also e.g. Mandel+ 1608.08223, Coughlin+ 1503.03179.

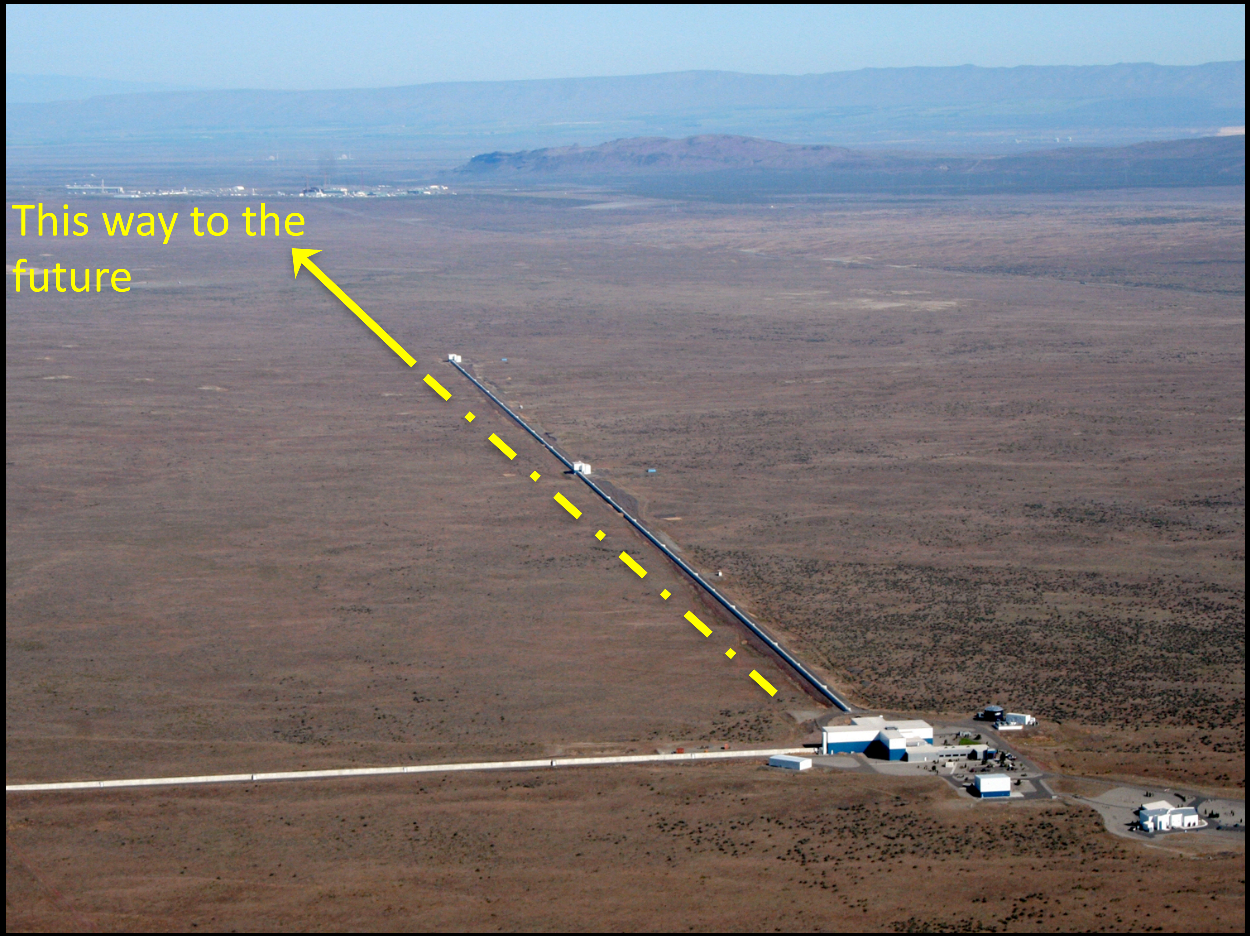


Vitale+, PRD 95 064053

The future

The next generation of GW detectors

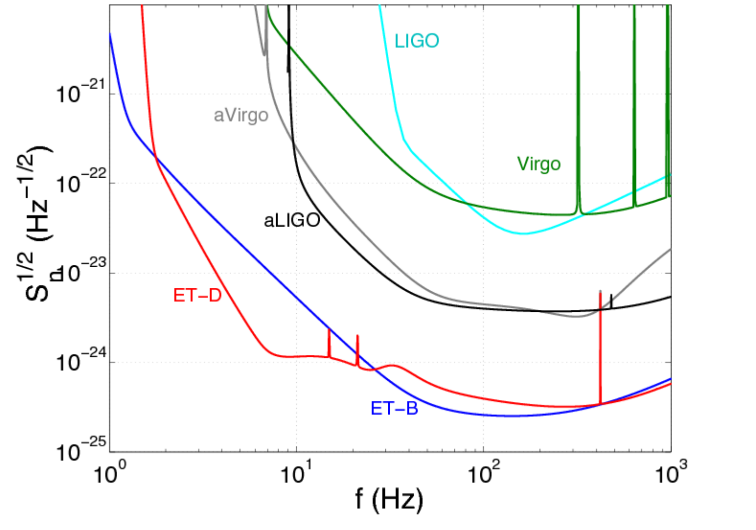
- Realistically, we can gain another factor of ~few over design advanced LIGO using existing facilities
  - A+
  - Voyager (~2.5G)
- Need new facilities for the next big step (3G):
  - Einstein Telescope
  - Cosmic Explorer



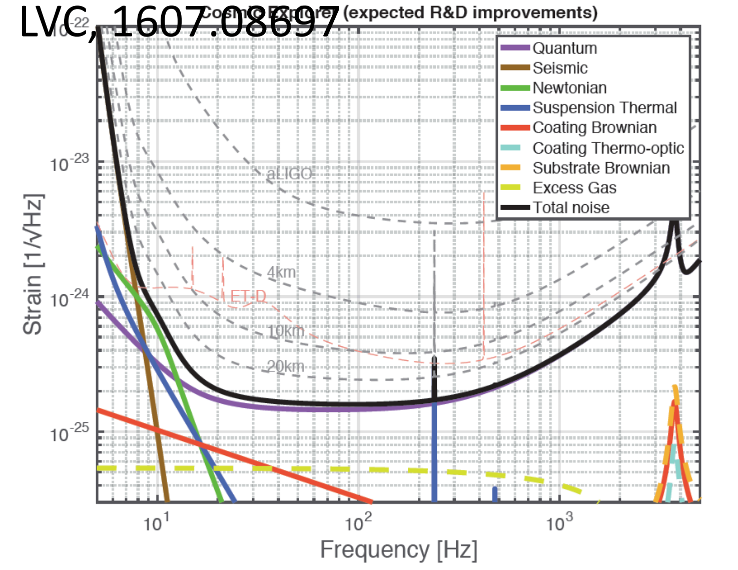
Proposed 3G detectors

- Einstein Telescope
  - 10 Km long arms
  - Triangular shape
  - Underground
  - Sensitivity down to few Hz
- Cosmic Explorer
  - 40 Km long arms
  - L shaped
  - Over ground
  - Sensitivity down to ~8Hz

Regimbau+, PRD 86 122001



LVC, 1607.08697

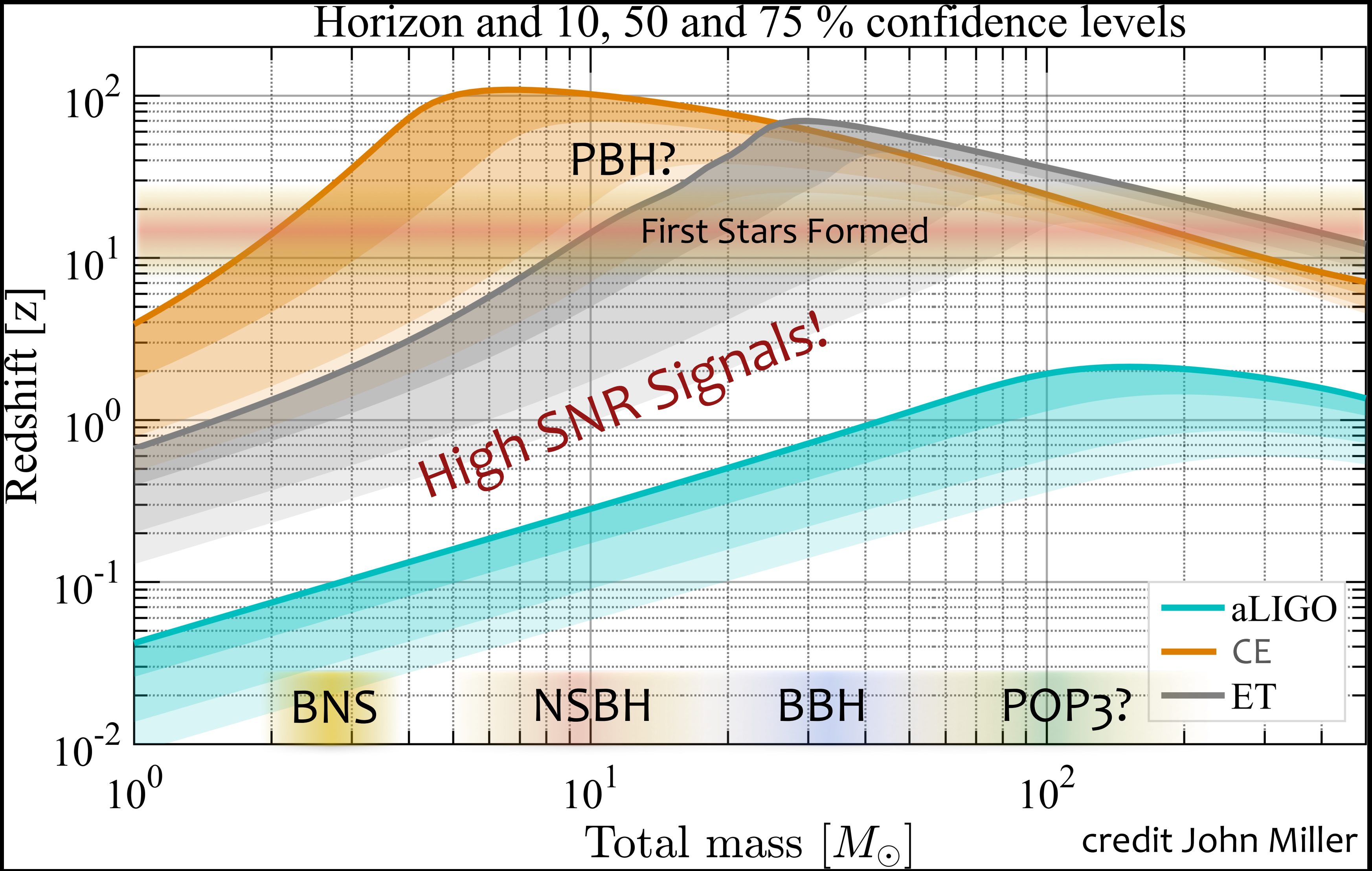


What do we need?

- Requires significant R&D
  - Coating
  - Squeezing
  - Newtonian noise
  - More
- Over a factor of 10 better than Advanced LIGO

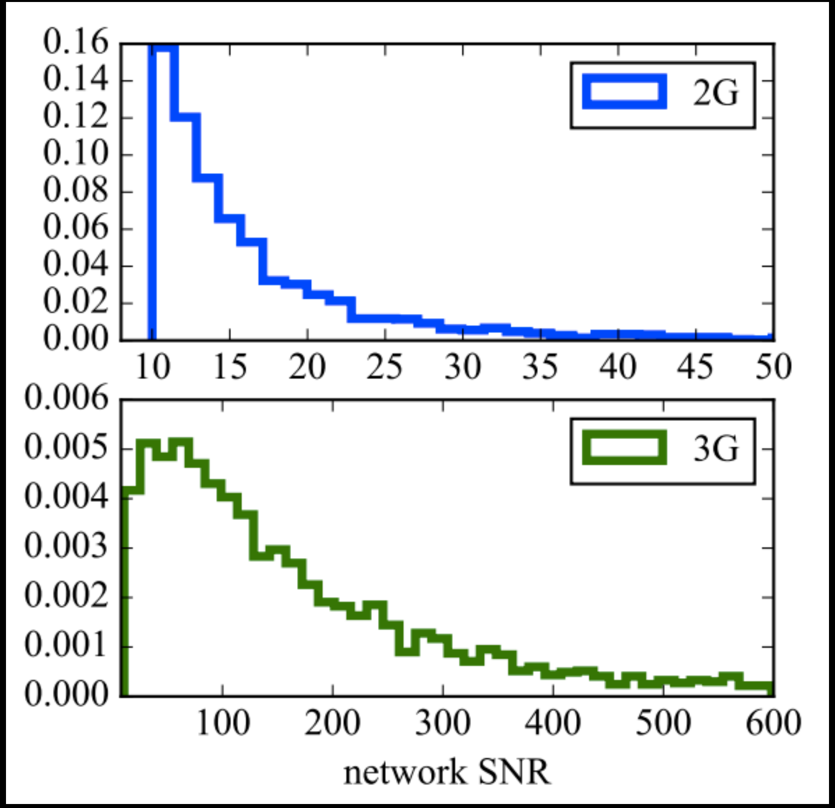
“We can see black holes as far as there are stars in the universe”

- 3G detectors can observe BBH from most of the Universe
- Many loud signals
- Cosmological distances
- How well can BBH be characterized?

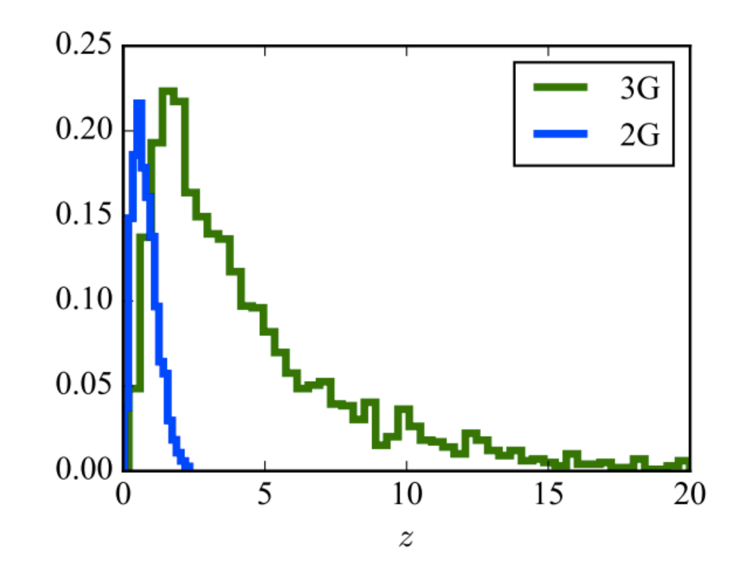


Loud and clear

- BBH detected by 3G detectors will typically be loud
- Their inclination angle distribution will be isotropic
- Most events from redshift of a few



BBH with component masses in range [6,100]M

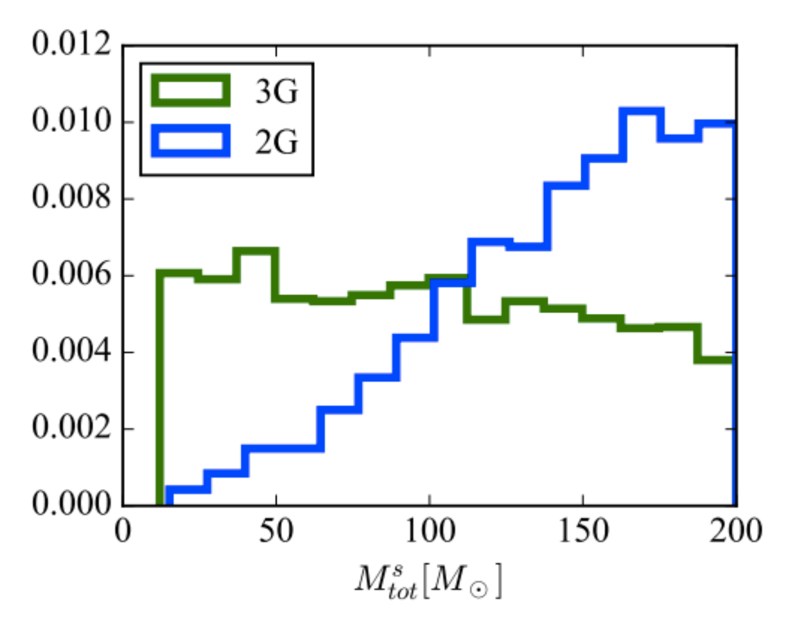


Vitale, PRD(R) 94 121501

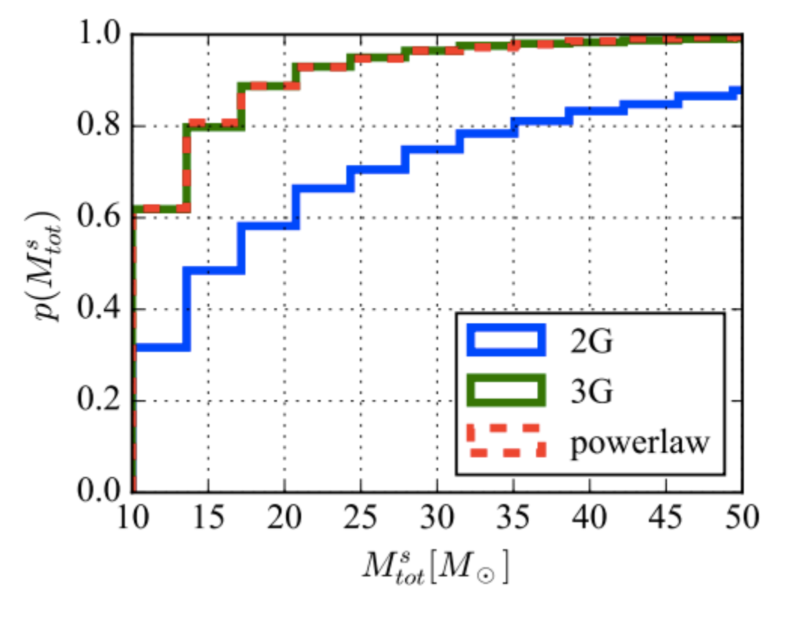
Mass selection bias

- 2G detectors have a selection bias for high mass events
- Resolved by 3G detectors

Vitale, PRD(R) 94 121501



Flat distribution of Mtotal



Power law distribution (O1 BBH)

Why a network?

- For advanced detectors
  - Sky localization
  - Recognize glitches
  - Increase network duty cycle
- For A+, Voyager, ET, CE
  - All of the abovementioned
  - Mass estimation!! (Through luminosity distance and cosmology)

$$m^s = \frac{m^{det}}{1+z}$$

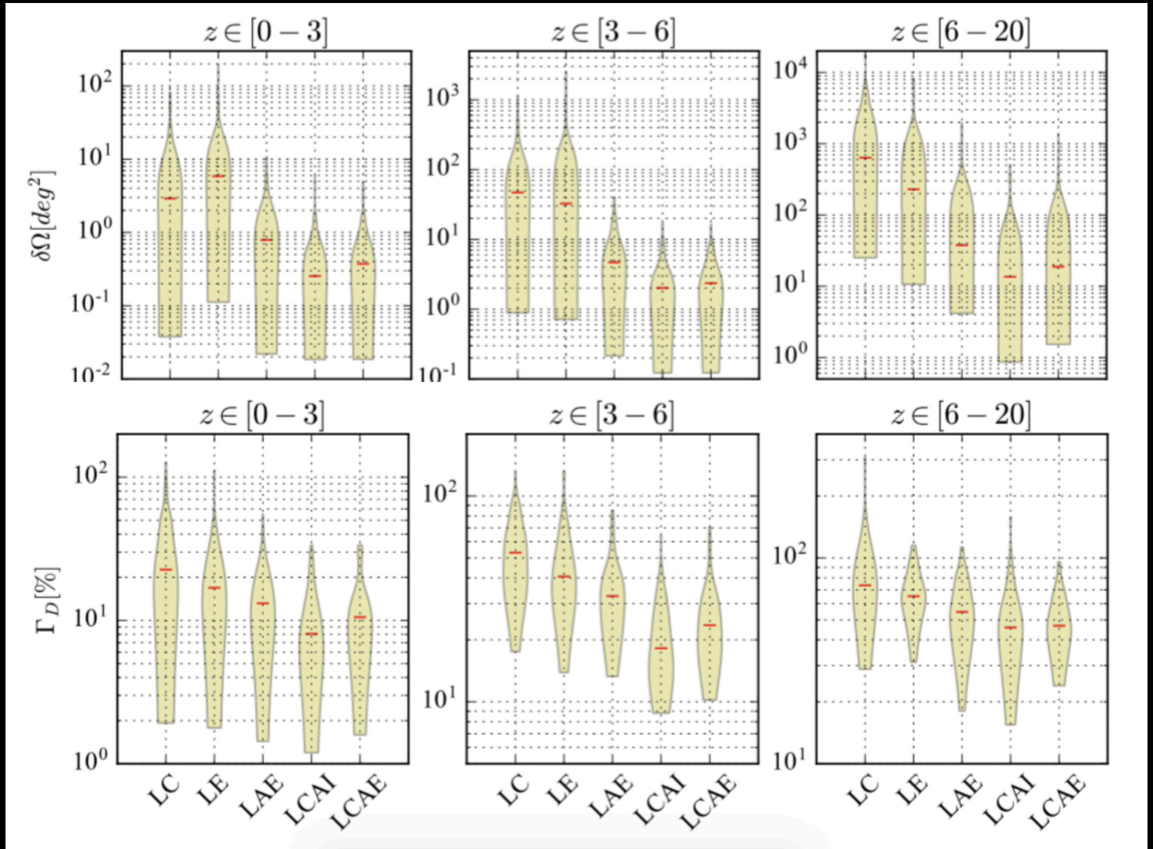
	Longitude	Latitude	Orientation	Type
L	-1.58	0.533	2.83	CE
C	1.82	0.67	1.57	CE
I	1.34	0.34	0.57	CE
E	0.182	0.76	0.34	ET
A	2.02	-0.55	0	CE

Extrinsic parameters

- With 3G detectors, distance estimation is needed to measure intrinsic masses -> need more than 2 instruments!

Sky location

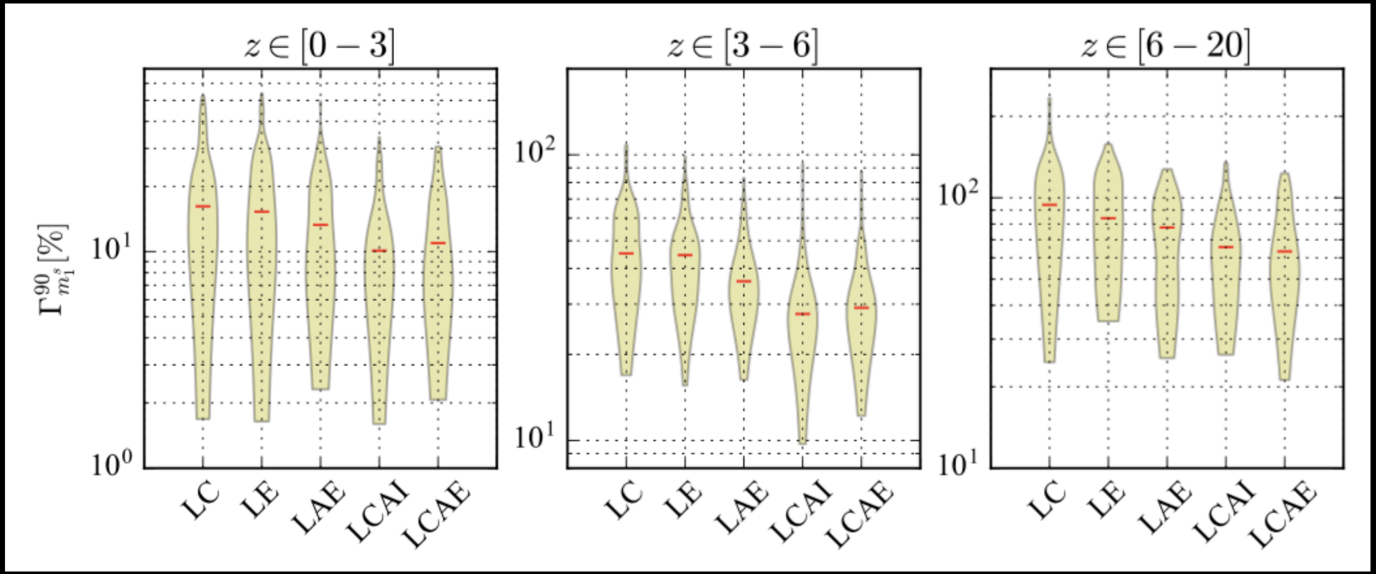
Luminosity Distance



Vitale+, PRD 95 064052

Masses

- Especially at large redshifts, having more than 2 sites is important to measure component masses
- Uncertainties of [few-10]% for z<3
- Factor 1.5-2 better with 4 IFOs w.r.t. 2 IFOs

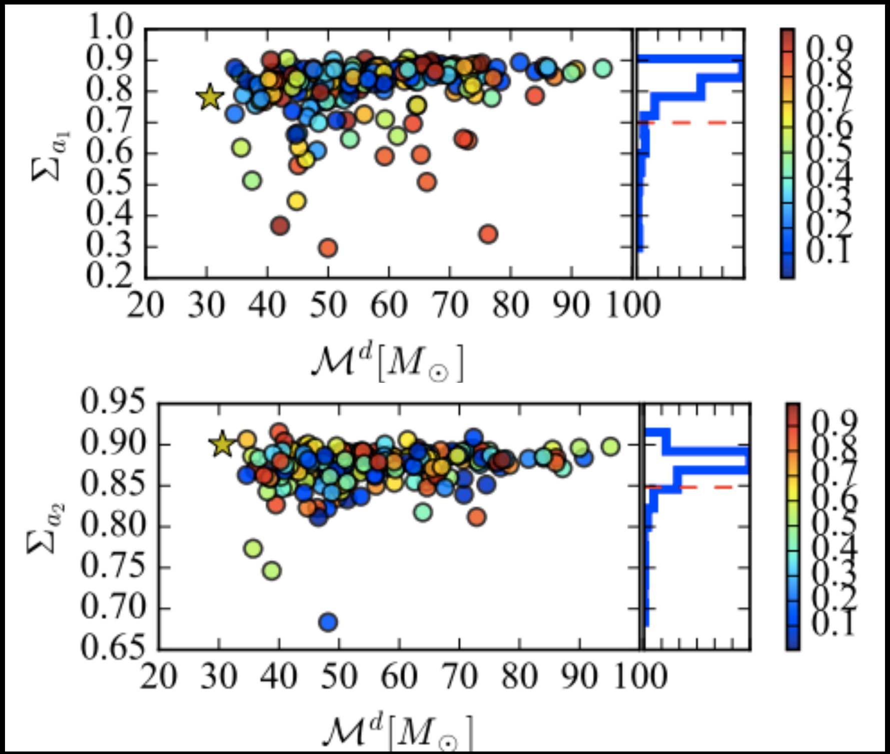


Vitale+, PRD 95 064052

Spins

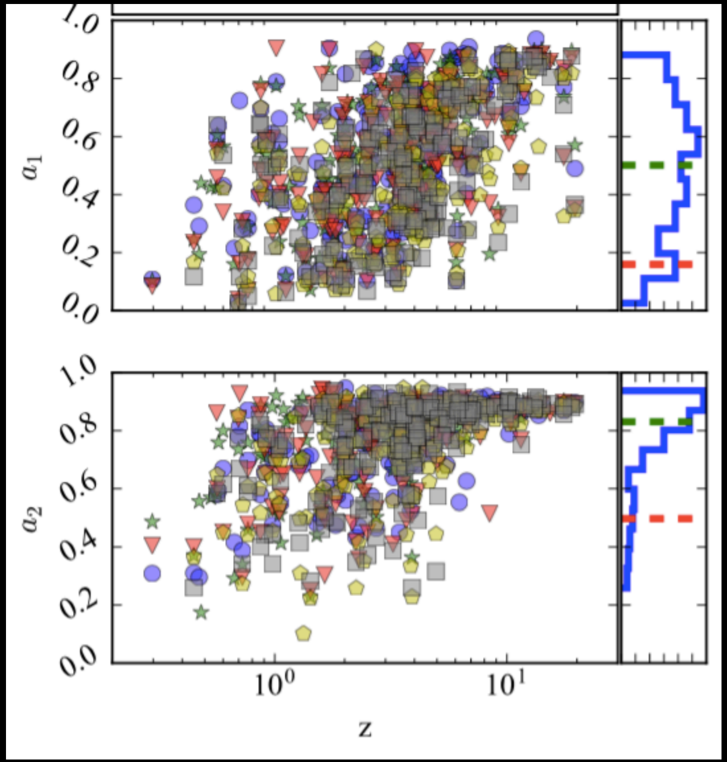
- Due to larger SNR and isotropic orbital orientation, 3G will get much better spin estimation than 2G

2G



Vitale+, PRD 95 064053

3G



Vitale+, PRD 95 064052

Facing reality

- Would like to have two (or more!) 3G detectors
- Funding or timelines might in fact result in only 1 3G detector to be online, at least for a while

- We might have
  - 1 3G
  - 1 or more detectors from previous generations

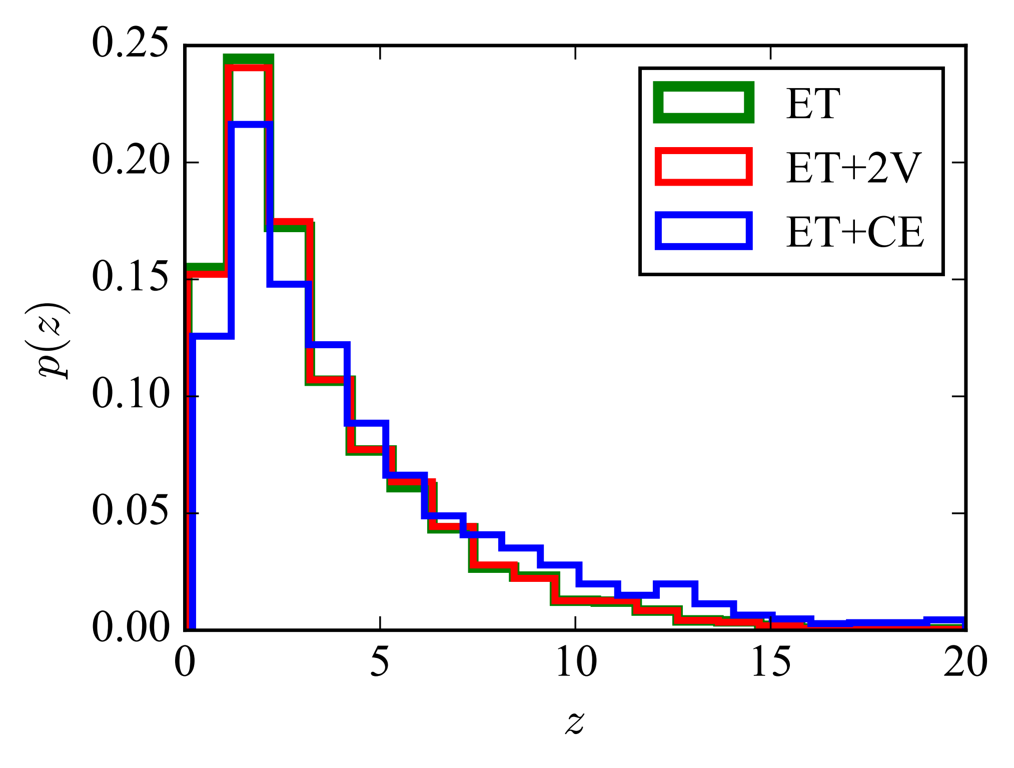
Heterogeneous networks

- Does it make sense to have 3G running with previous generations detectors?

- 3G-2G. Factor >10 difference. 2G are of no help
- 3G-A+. Factor ~>5 difference. A+ probably of no help
- 3G-Voyager: Voyager might help for sky localization (not detection/range)

- Will focus on BBHs (with full Bayesian parameter estimation)

Range



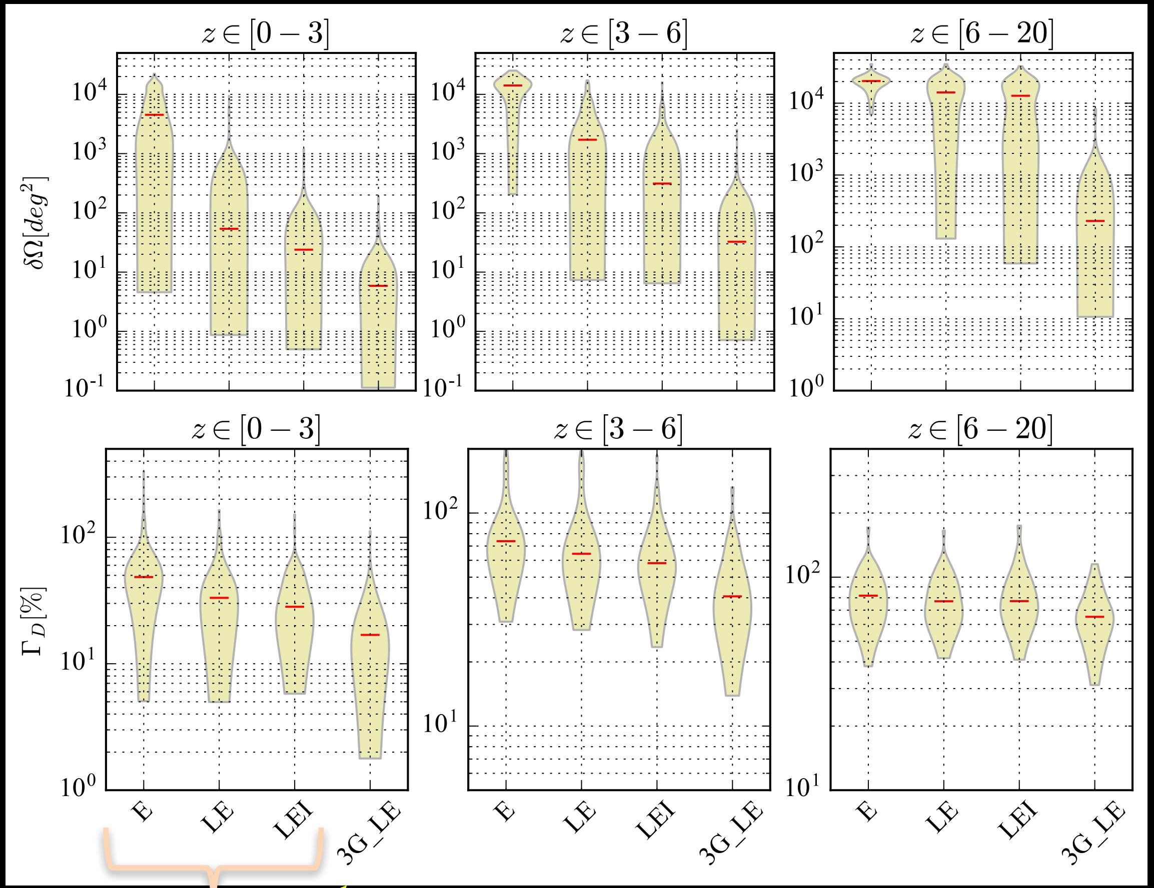
- Considered population of BBH with component masses in the range [6,100] M
- Uniform in com. vol.
- As long as at least 1 ET detector is included, BBH are detected up to redshift of ~15
- Adding Voyager won't change much
- Adding a CE pushes the typical detection farther away

Extrinsic parameters (2.5G+3G)

- Adding a Voyager significantly improves sky localization - factor ~100
- Will check, but probably similar conclusion will hold for BNS
- However with only 1 3G will rarely have localizations better than 1deg2
- Marginal improvement in distance estimation

Sky location

Luminosity Distance



PRELIMINARY

1 ET (+ Voyager(s))

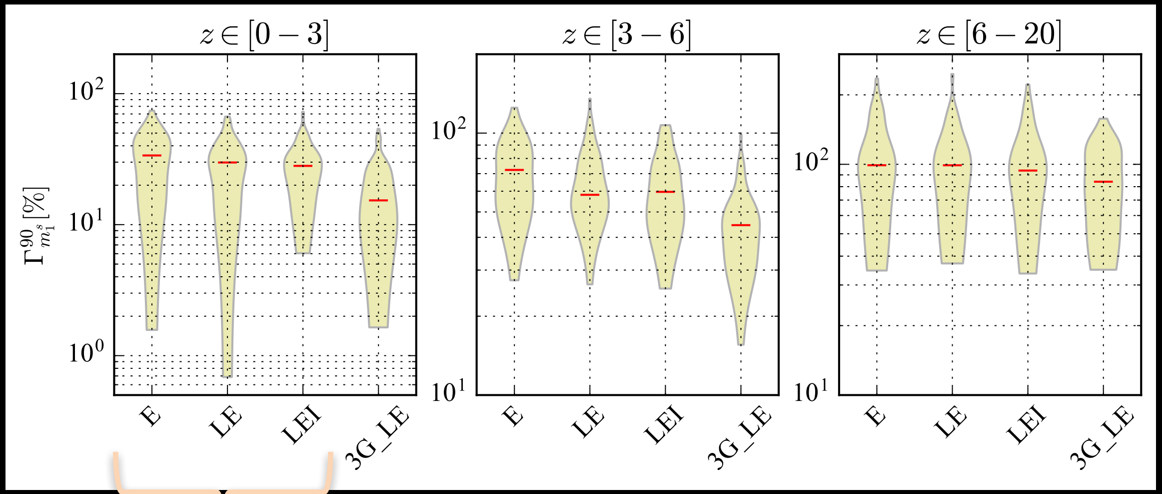
3G only

Source frame masses (2.5G+3G)

- Adding a Voyager does **not** improve estimation of component masses

- A factor of ~2 to be gained by adding a second 3G detector

Component mass



PRELIMINARY

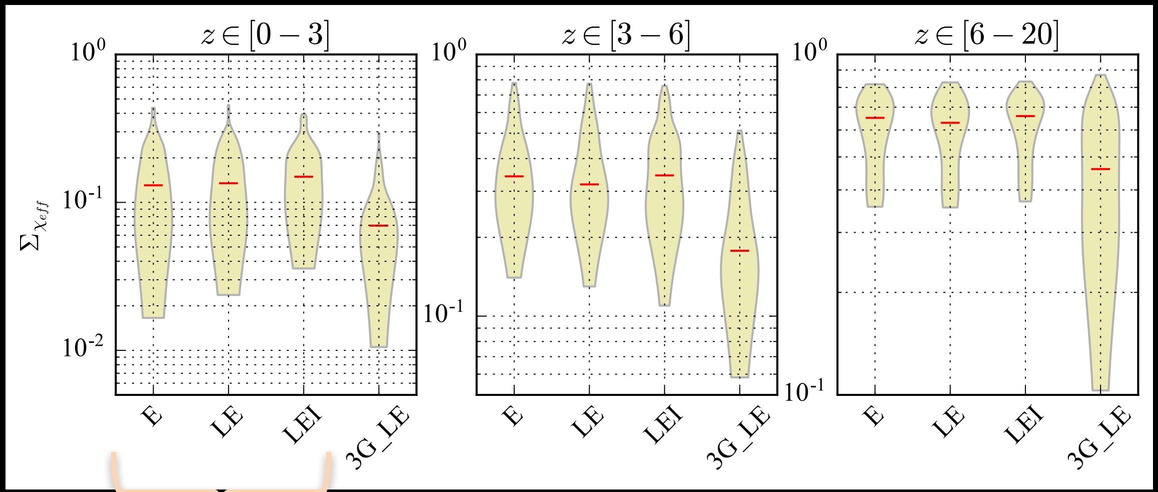
1 ET (+ Voyager(s))

3G only

Spins (2.5G+3G)

- Adding a Voyager does **not** improve estimation of component spins
- Two (or more) 3G detectors would do better at measuring spins (more SNR, more visible precession)

Component spins



PRELIMINARY

1 ET (+ Voyager(s))

3G only

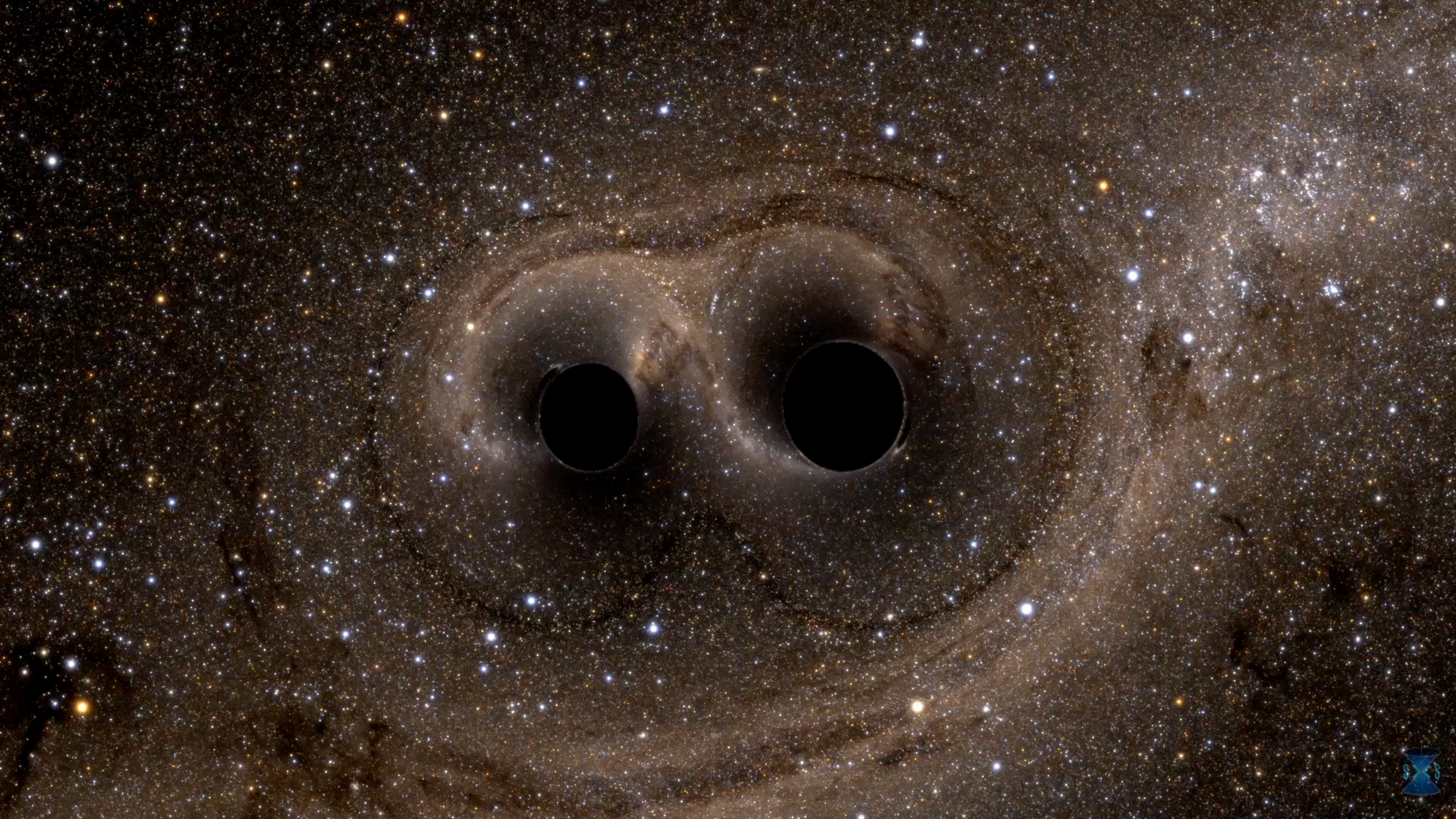
Conclusions

- Advanced detectors will reveal a wealth of BBH signals in the next few years
  - Characterization of BH mass and spins
  - Formation channels
  - Cosmology
  - Tests of general relativity
- Should soon detect neutron stars
  - Equation of state
  - Electromagnetic counterparts
- Unknown sources!

Conclusions

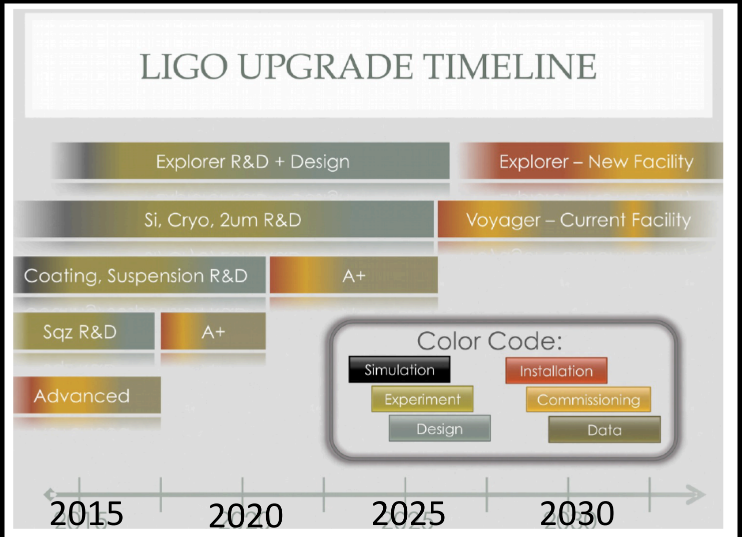
- Advanced detectors will explore the universe up to z~1
- The next generation will open a whole new scenario
  - BBH can be detected as far as there are stars
  - >>Thousands of sources per year
  - Loud signals
  - Precise characterization and precise tests of GR
  - High probability of detected rare or exotic events (e.g. supernovae)

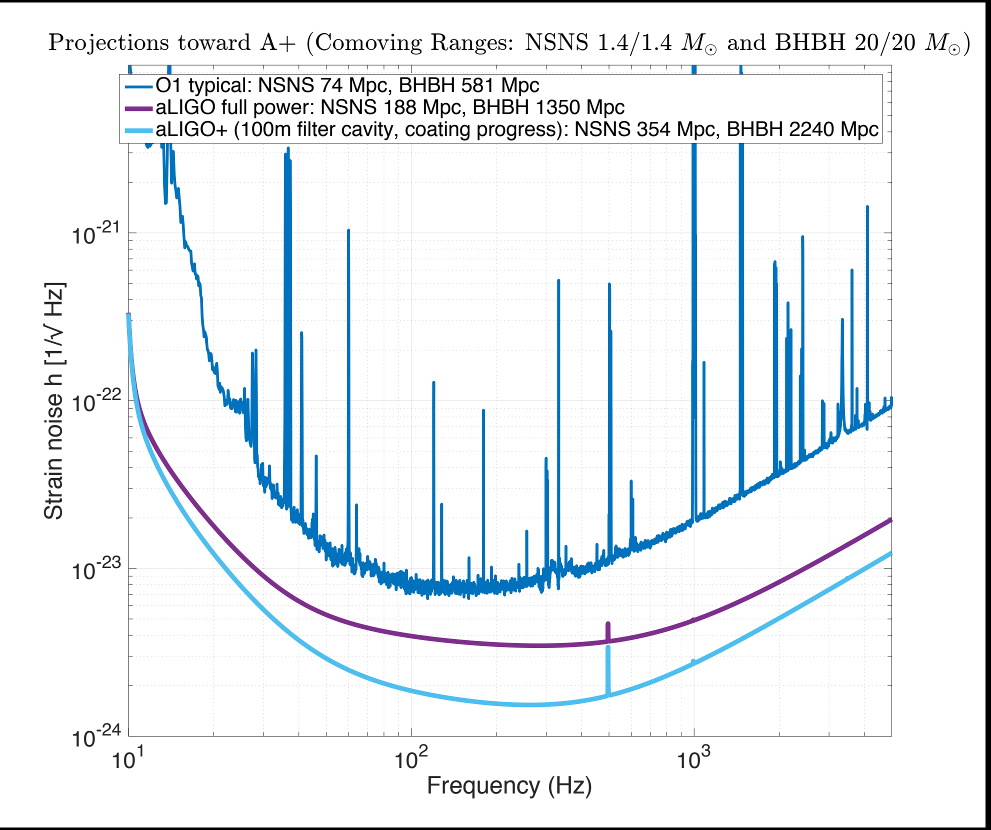
The end



Making advanced LIGO better: A+

- Squeezing and coating required R&D required to increase the sensitivity beyond aLIGO
- Could be implemented before design sensitivity is reached

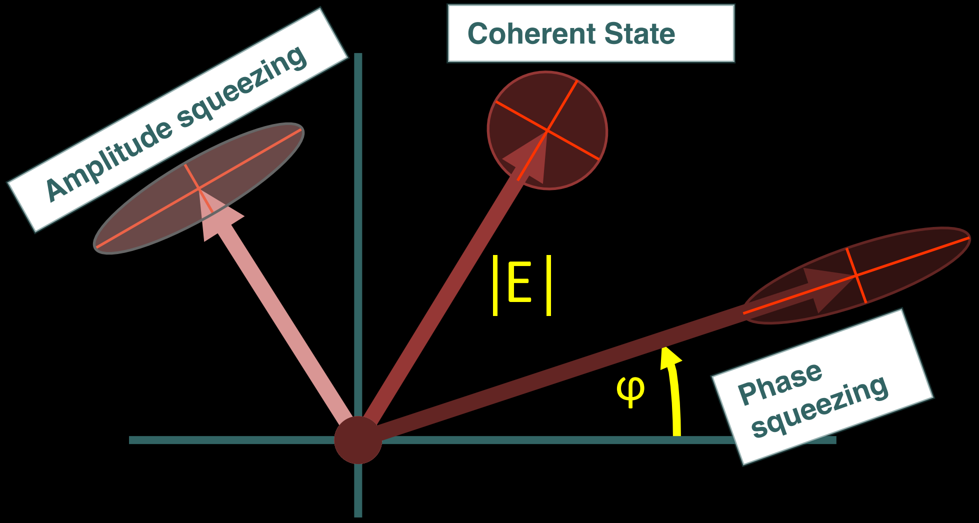


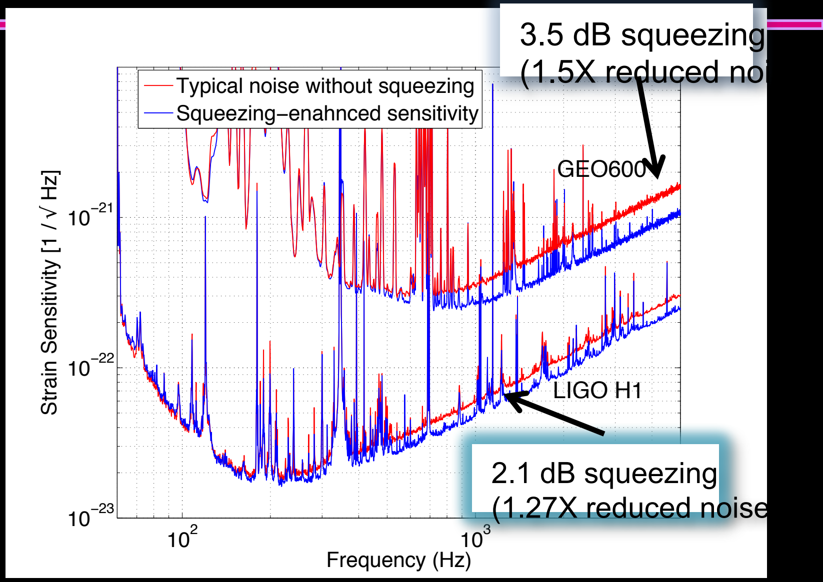


J. Miller , G1601807

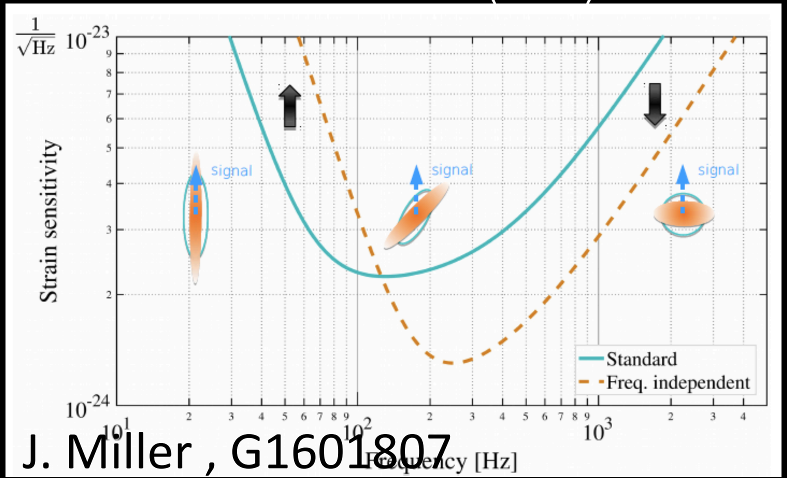
Quantum squeezing

- Demonstrated at Geo and LIGO
- Reduces shot noise (i.e. f>~200 Hz)
- Could be included already in O3





LVC, Nature Physics, 7, 962 (2011)
Nature Photonics 7 613 (2013)

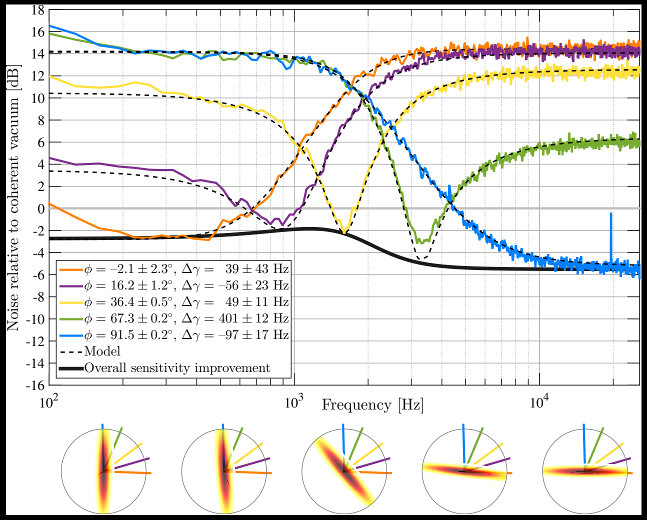


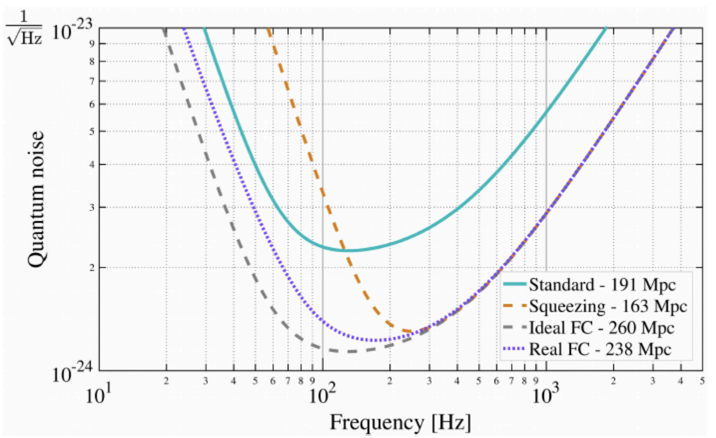
J. Miller , G1601807

Squeezing with filter cavity

- In its simpler implementation, squeezing improves high frequency at expense of low frequency (tens of Hz)
  - But these are the frequencies we care most for BBH!
- Squeezing with filter cavity
  - Rotates error ellipse in freq-dependent way
  - Improves both low and high frequencies

Oelker, et al PRL 116, 041102 (2016).





J. Miller , G1601807

The textbook definition

- Gravitational waves are ripples in the space-time continuum, emitted by any system with a non-constant quadrupole moment

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}\,, \qquad |h_{\mu\nu}| \ll 1$$

$$\Box \bar{h}_{\mu\nu} = -\frac{16\pi G}{c^4} T_{\mu\nu}$$

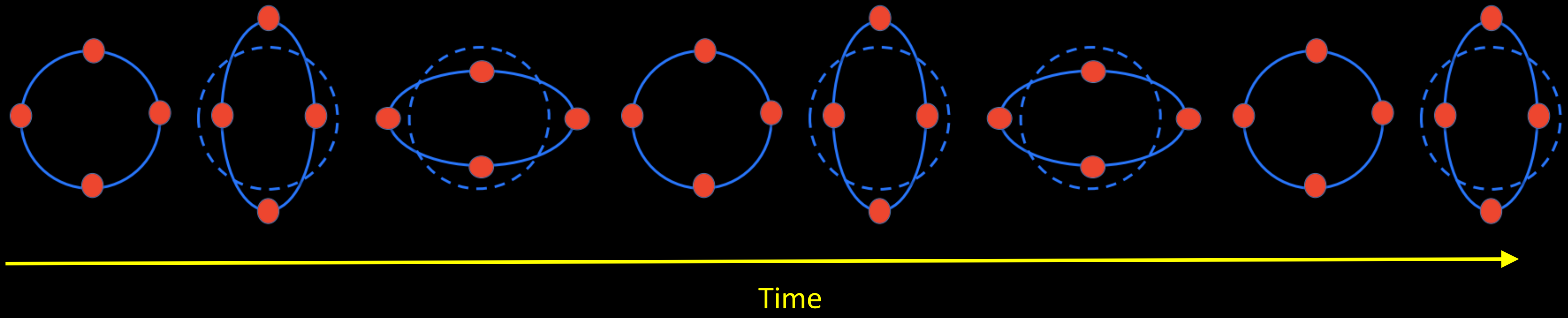
$$\left[h_{ij}^{T}(t, \mathbf{x})\right]_{\text{quad}} = \frac{1}{r} \frac{2G}{c^4} \ddot{Q}_{ij}^{\text{TT}}(t - r/c)$$

The textbook definition

- Gravitational waves are ripples in the space-time continuum, emitted by any system with a non-constant quadrupole moment

Effect of GWs

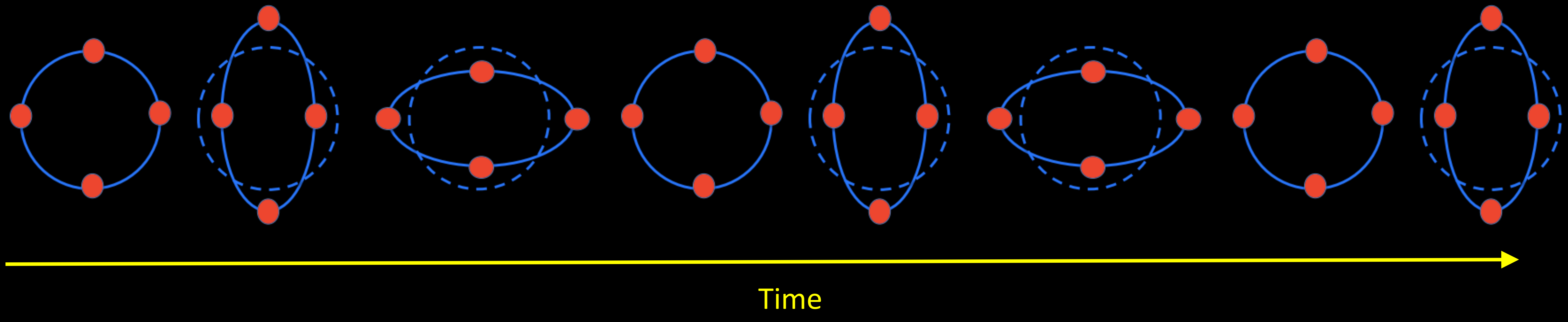
- While passing through space, GWs vary the distance between free floating observers
  - Distances stretch in one direction and squeeze in the perpendicular direction



Effect of GWs

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

EASY! 🙂



Order of magnitude estimate

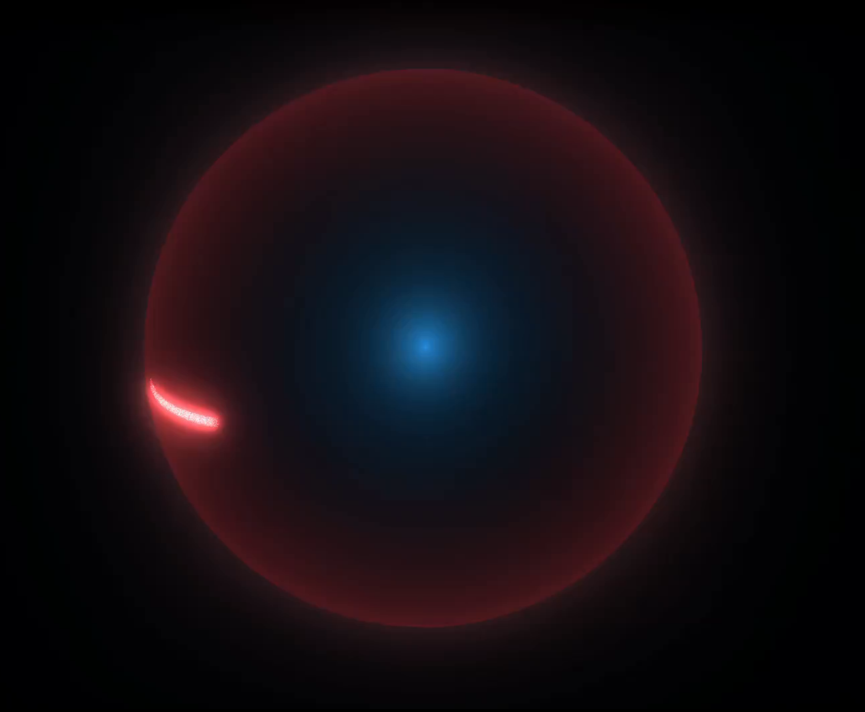
$$h_{ij} \propto \frac{4}{D}\left(\frac{\mathcal{M}G}{c^2}\right)^{5/3}\left(\frac{\pi f_{GW}}{c}\right)^{2/3}$$

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

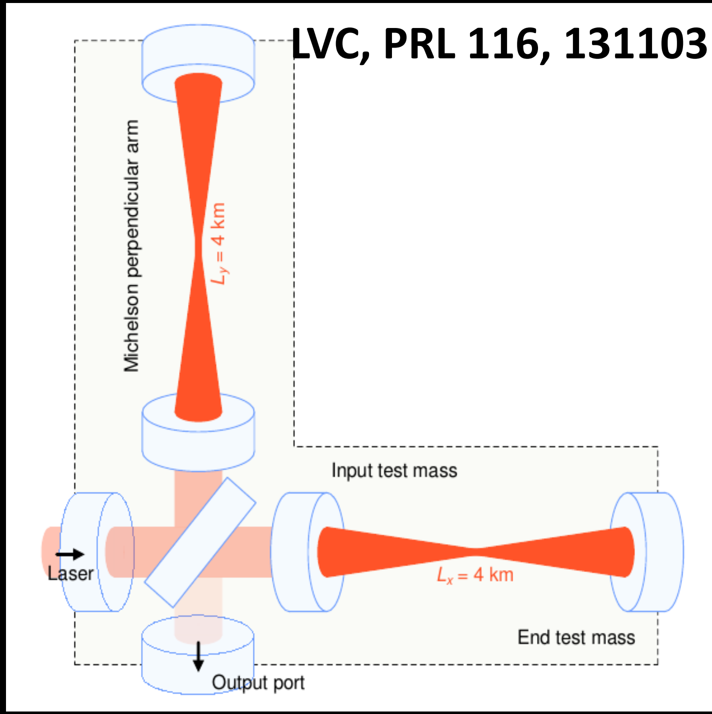
Order of magnitude estimate

- A typical source would produce a strain (i.e. relative length variation) at Earth of roughly 1 part in 10^{21}



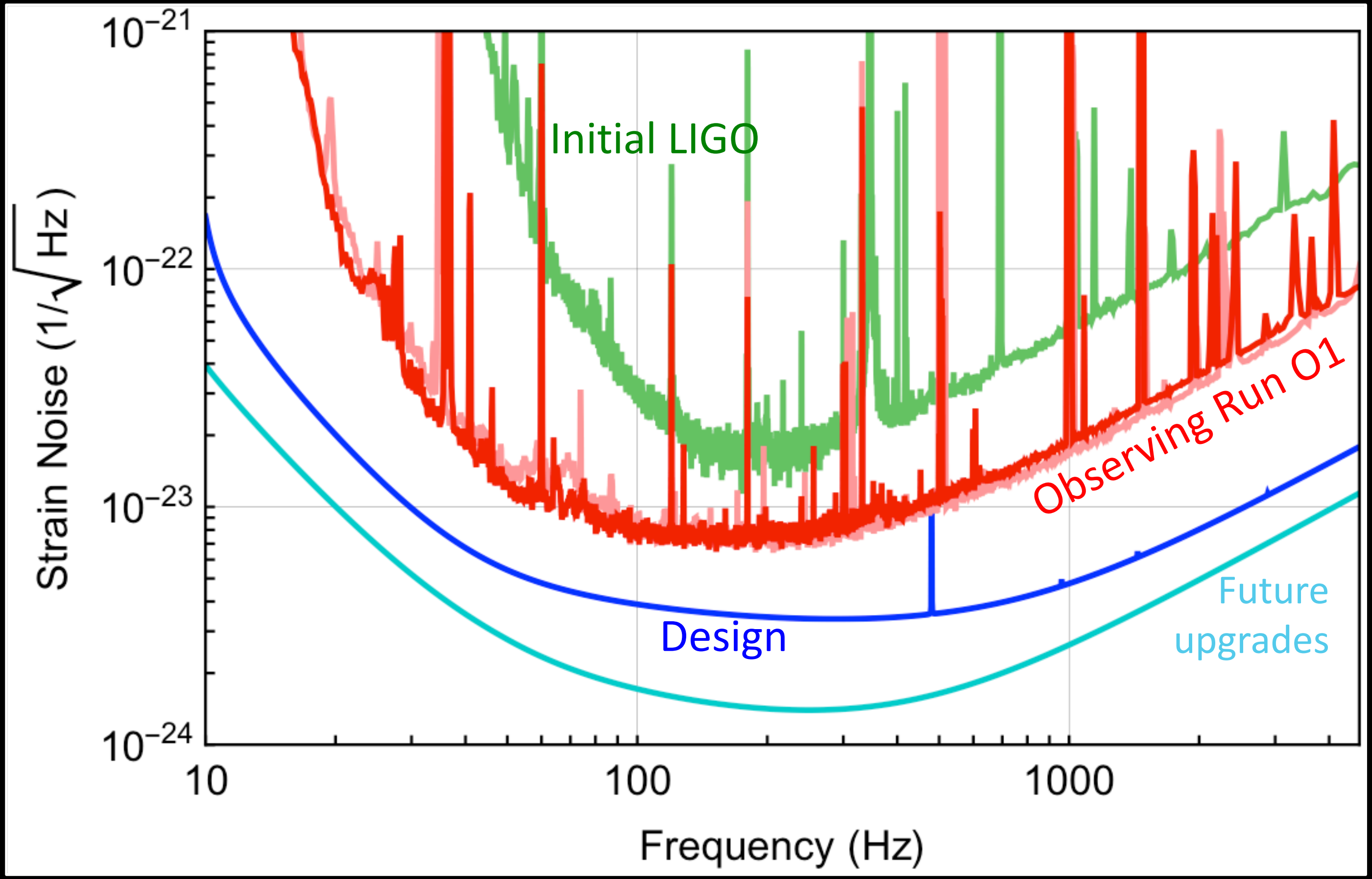
LIGO

- 4-Kilometer long arms interferometers
- If gravitational waves pass through, they change length of the arms and interference condition



LVC, PRL 116, 131103

Advanced LIGO performance in the first science run

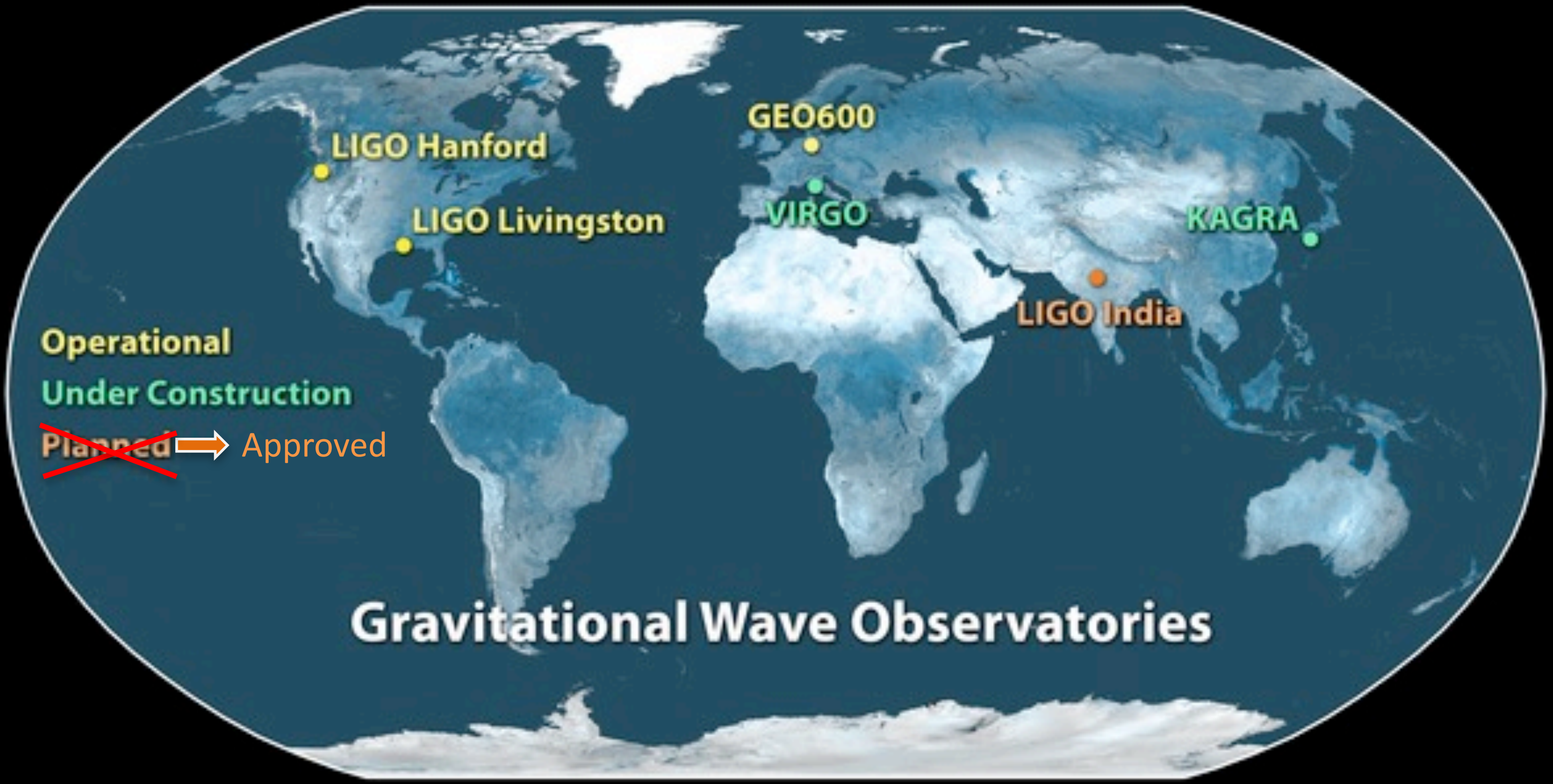


LVC, PRL 116, 131103

Binary neutron star inspiral range: **70-80 Mpc**

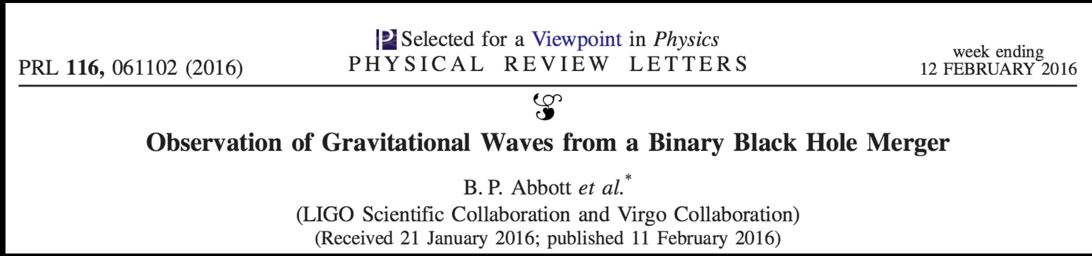
The Global Network

More detectors are needed to provide better source localization and polarization information



Detections!!

- Advanced LIGO detected 2 binary black hole coalescences in its first science run


Selected for a Viewpoint in *Physics*

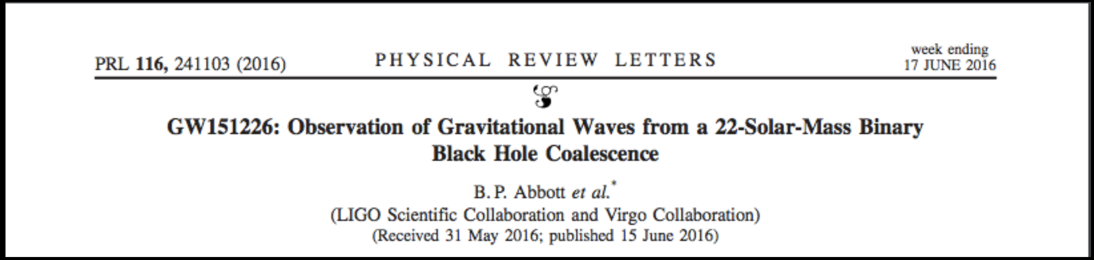
PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

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)

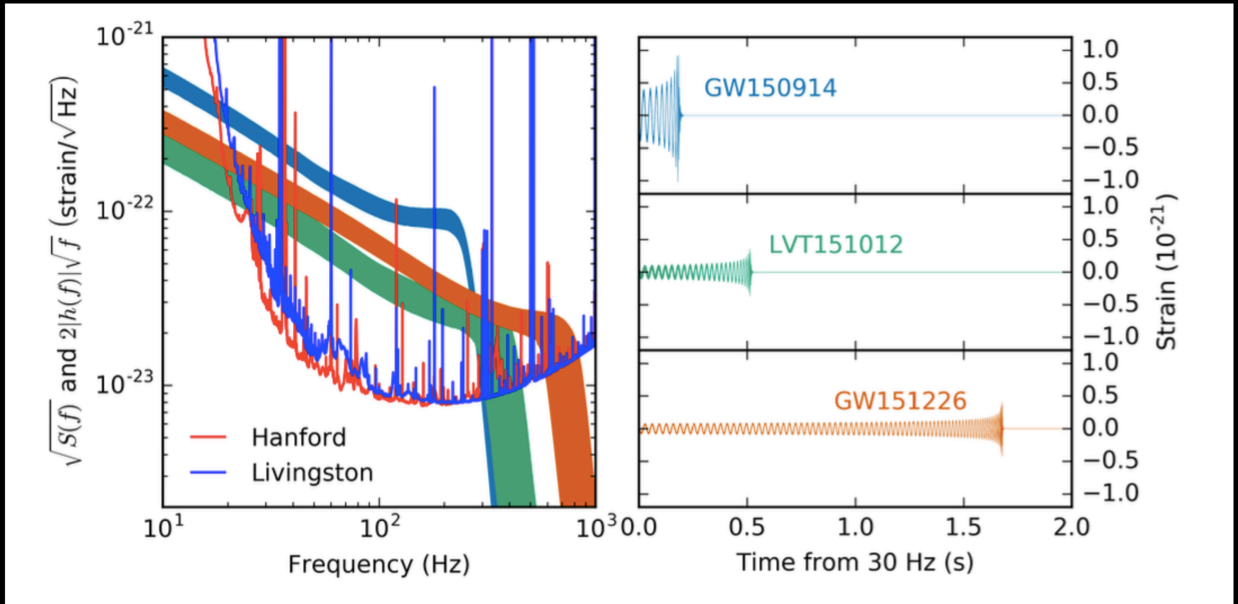

PRL **116,** 241103 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

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)



LVC, PRX 6.041015

BREAKING NEWS

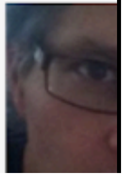
Gravitational waves are real, say physicists, proving Einstein's theory to be true.

Thursday, February 11, 2016   Edition: **U.S. & World** | Regional

Meryl Streep   Beyoncé KKK   Deer hunters   'Bloody mess'   Trumpism

Formation of a binary star merger. (NASA)

Video



Cosmic breakthrough: Physi detect Einstein's gravitation

The detection, which came from the violent m black holes in deep space, is being hailed as c key prediction of Albert Einstein's General The

By Joel Achenbach and Rachel Feltman · 57 minu

- **Brief history of gravity, gravitational wa**

President Obama
@POTUS
Follow

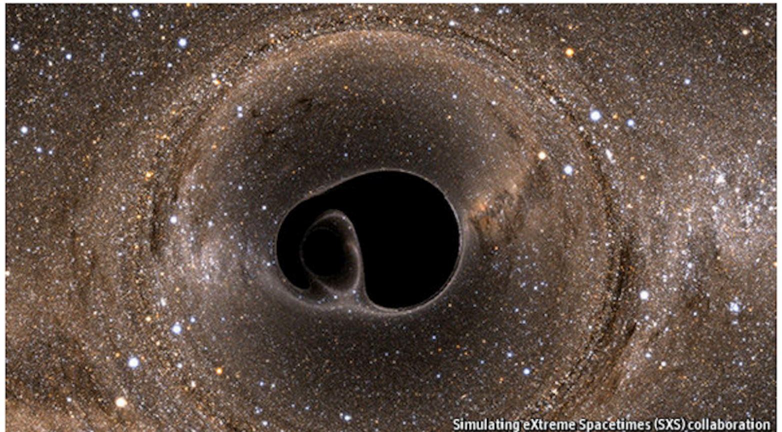
Einstein was right! Congrats to @NSF and @LIGO on detecting gravitational waves - a huge breakthrough in how we understand the universe.

Merger and acquisition

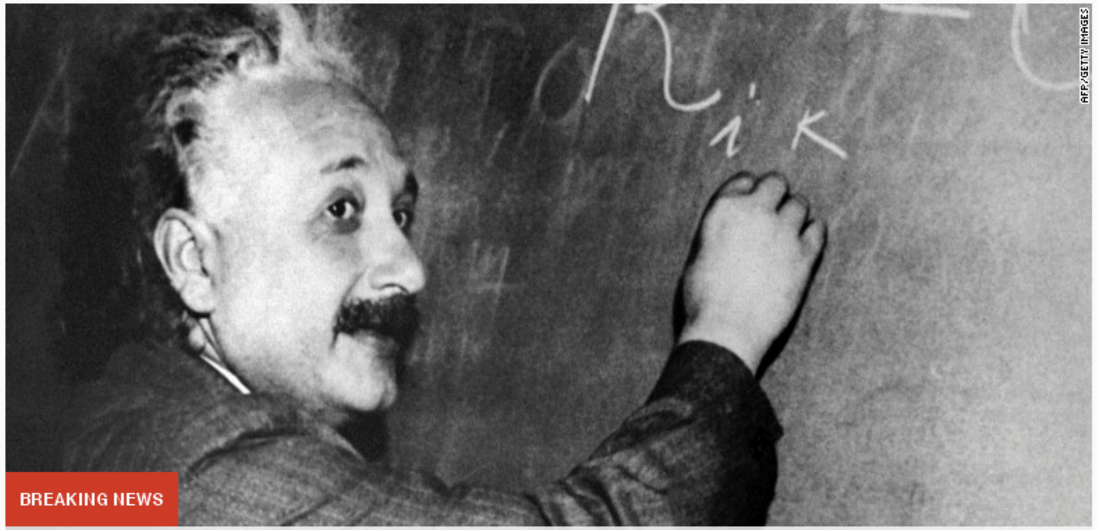
Gravitational waves have been detected for the first time

Signs of black holes merging arrive a century after Albert Einstein predicted them

Feb 13th 2016 | From the print edition   Timekeeper   Like 3.1K   Tweet

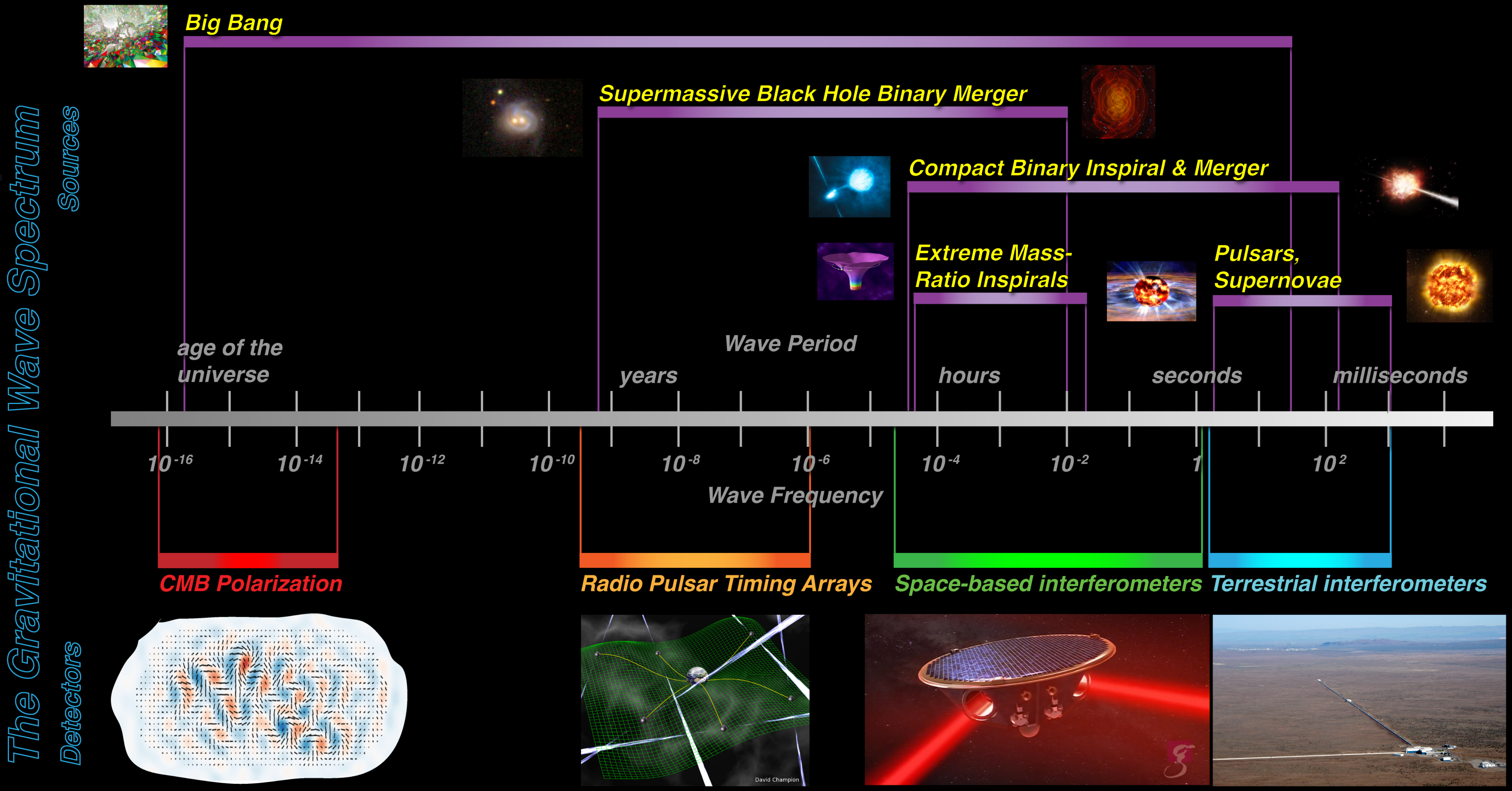


Einstein was right



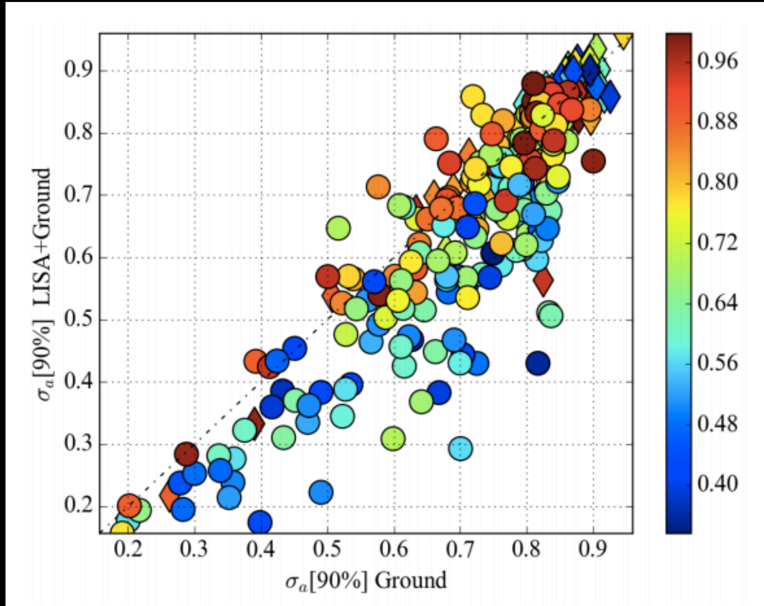
'We're opening a window on the universe,' says physicist

Einstein's special mark on universe


The Gravitational Wave Spectrum
Sources
Detectors
Big Bang
Supermassive Black Hole Binary Merger
Compact Binary Inspiral & Merger
Extreme Mass-Ratio Inspirals
Pulsars, Supernovae
Wave Period
age of the universe
years
hours
seconds
milliseconds
10-16
10-14
10-12
10-10
10-8
10-6
10-4
10-2
1
102
Wave Frequency
CMB Polarization
Radio Pulsar Timing Arrays
Space-based interferometers
Terrestrial interferometers
David Champion

Multibanding

- Events such as GW150914 could be detected by both LISA and (later) ground based detectors (Sesana, PRL **116**, 231102)
  - Possibility of pre-merger alerts
- Can use LISA information as prior information for LIGO (Vitale, PRL **117**, 051102)



Vitale, PRL **117**, 051102