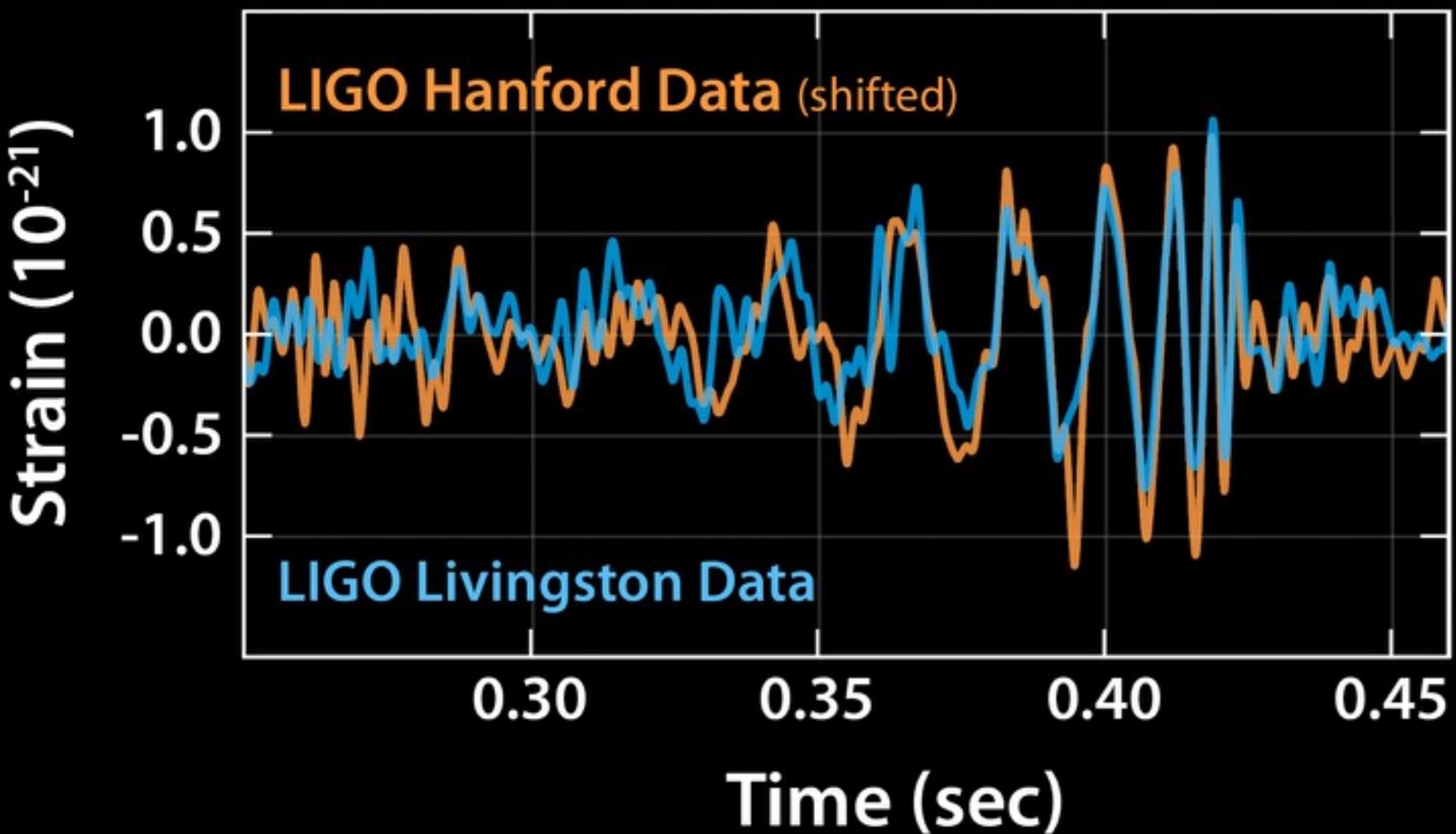
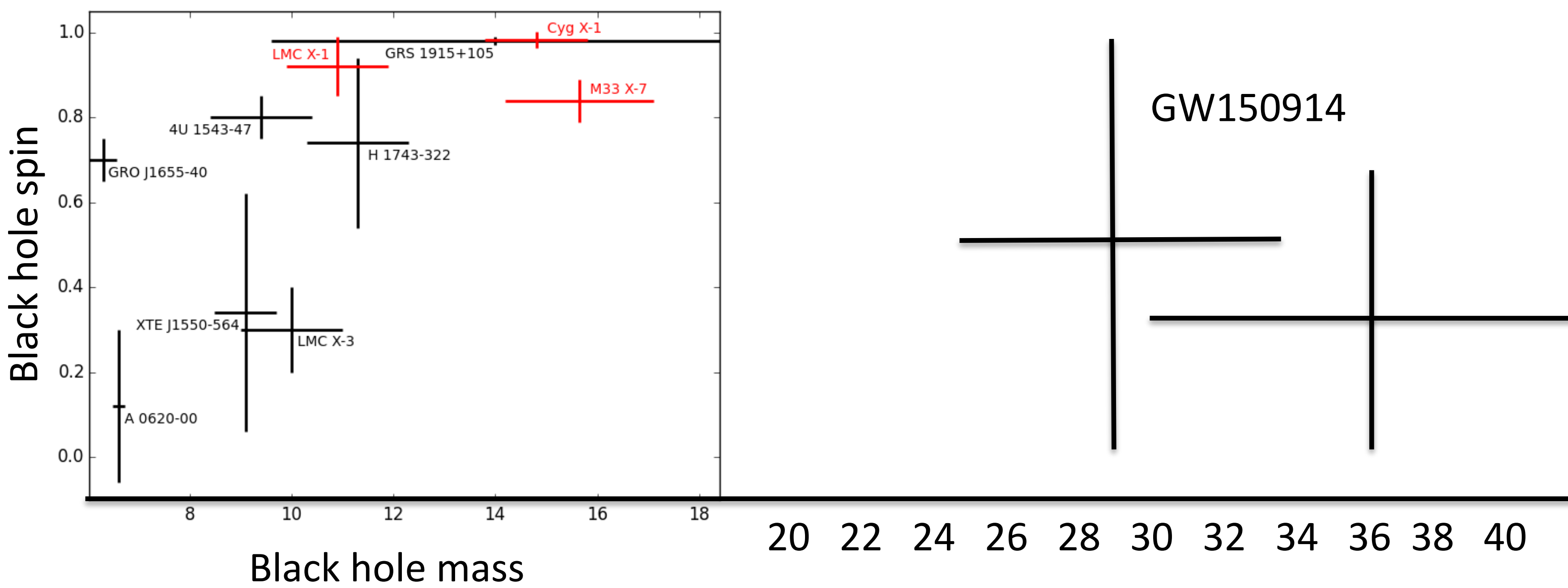
GW150914:
Effects on Near Term Plans

Lisa Barsotti
Stephen Fairhurst
Salvatore Vitale

We did it!


LIGO Hanford Data (shifted)
LIGO Livingston Data
Strain (10-21)
1.0
0.5
0.0
-0.5
-1.0
0.30
0.35
0.40
0.45
Time (sec)

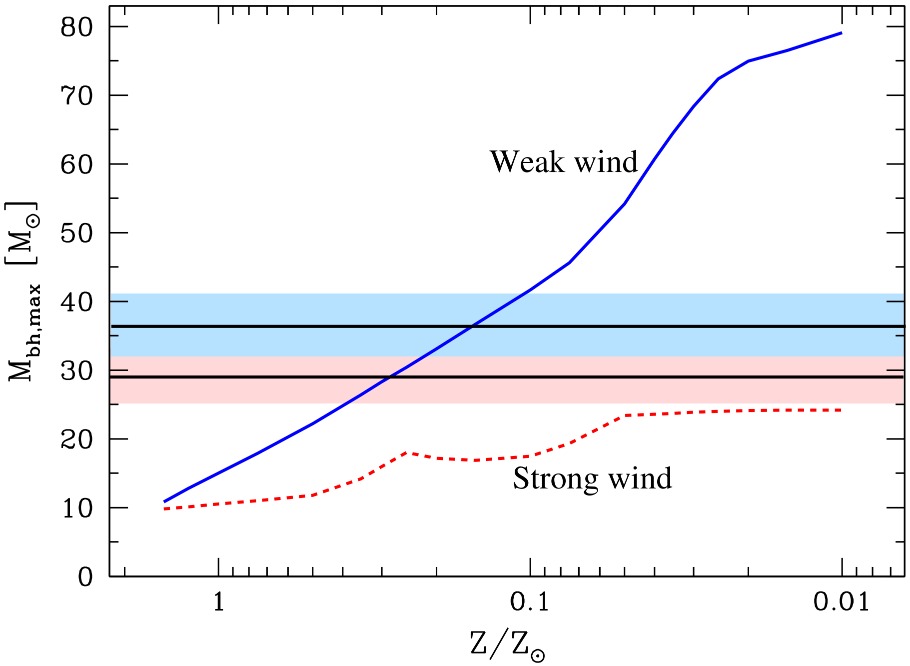
Black hole masses and spins

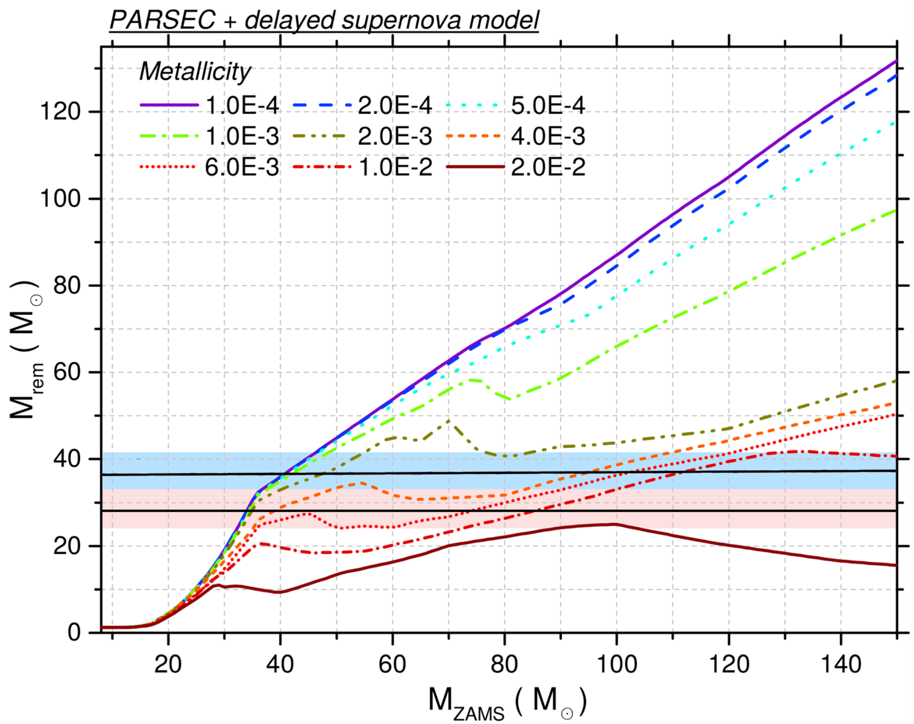


From Nielsen, 2016

Abbott et al, 2016

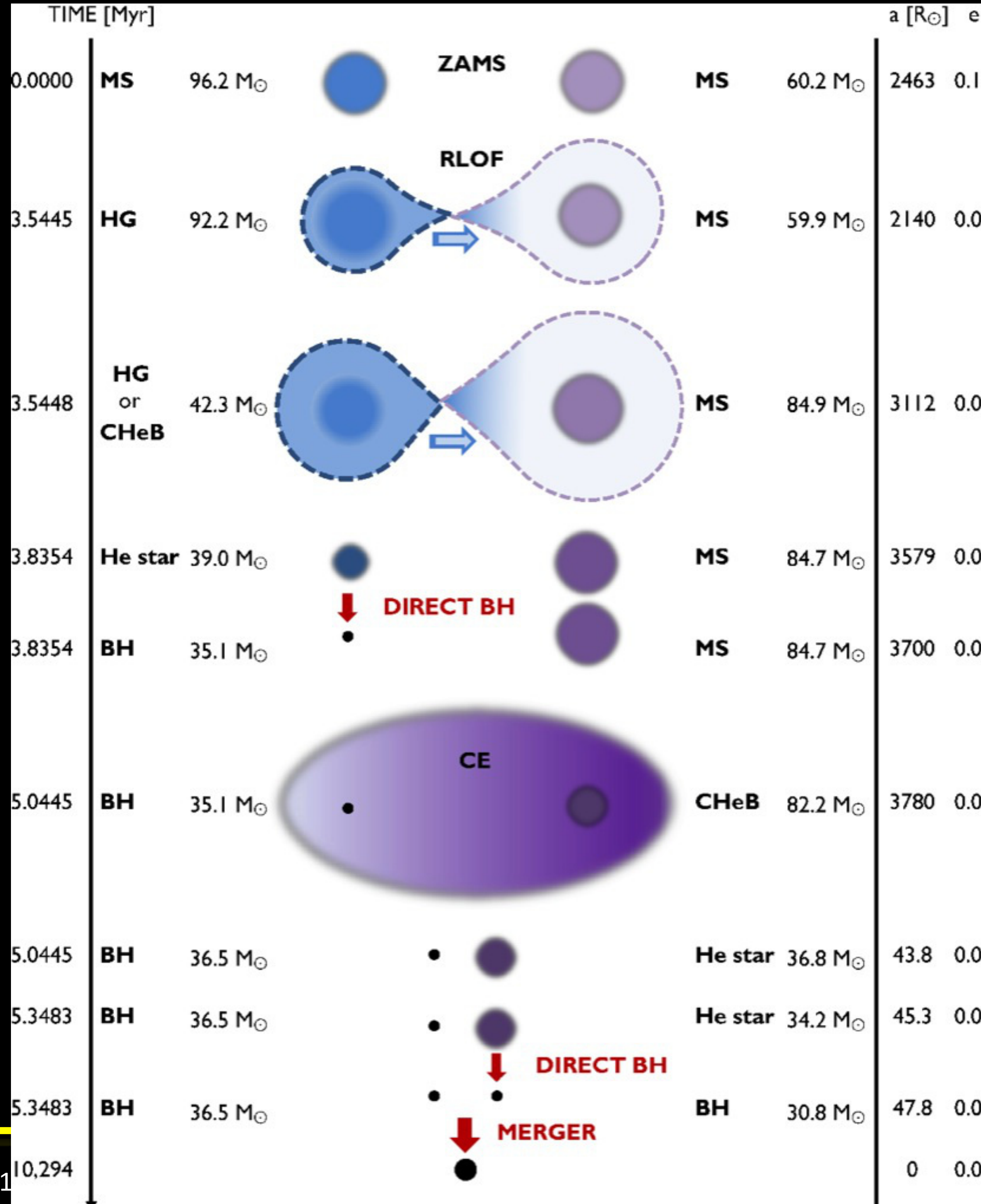
Forming massive black holes





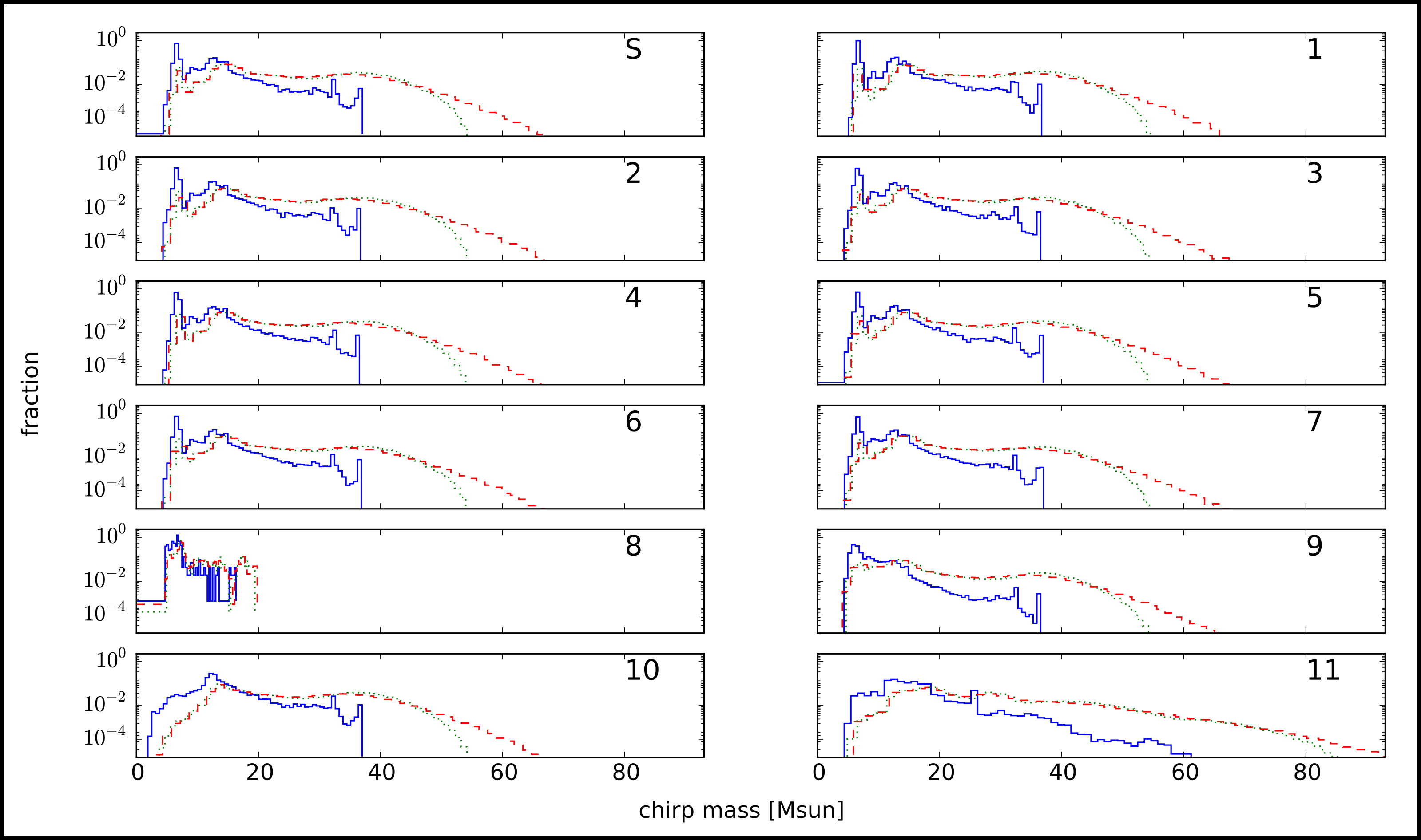
From Abbott et al, ApJL, 2016

A possible evolution scenario



From Belczynski et al 2016

Predicted mass distributions



Models from Dominik et al 2012; figure from Stevenson et al 2015

Differentiating models: After O1

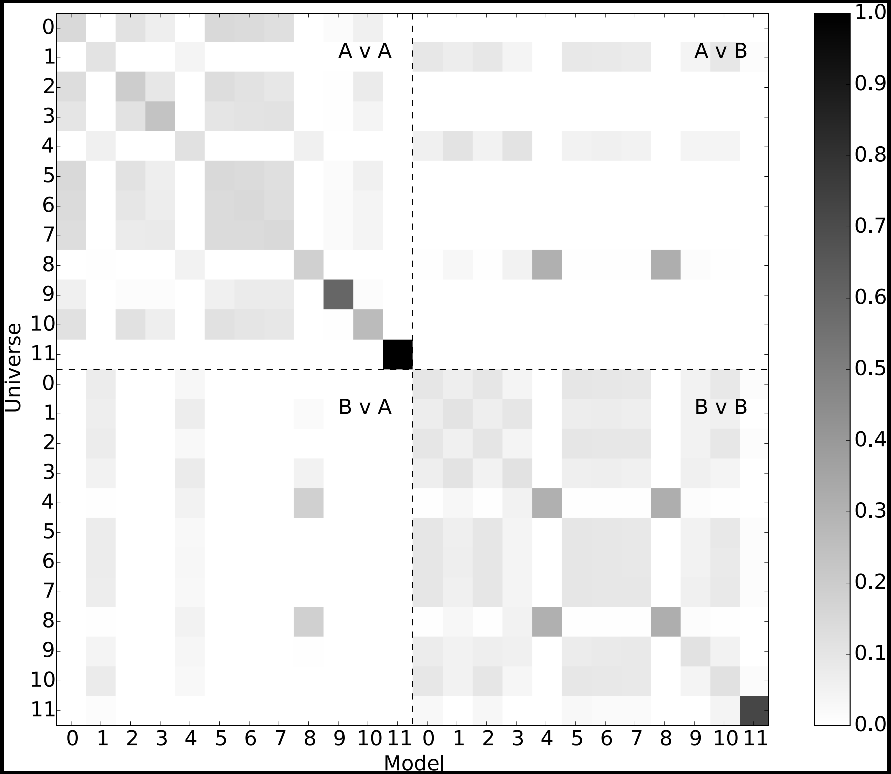
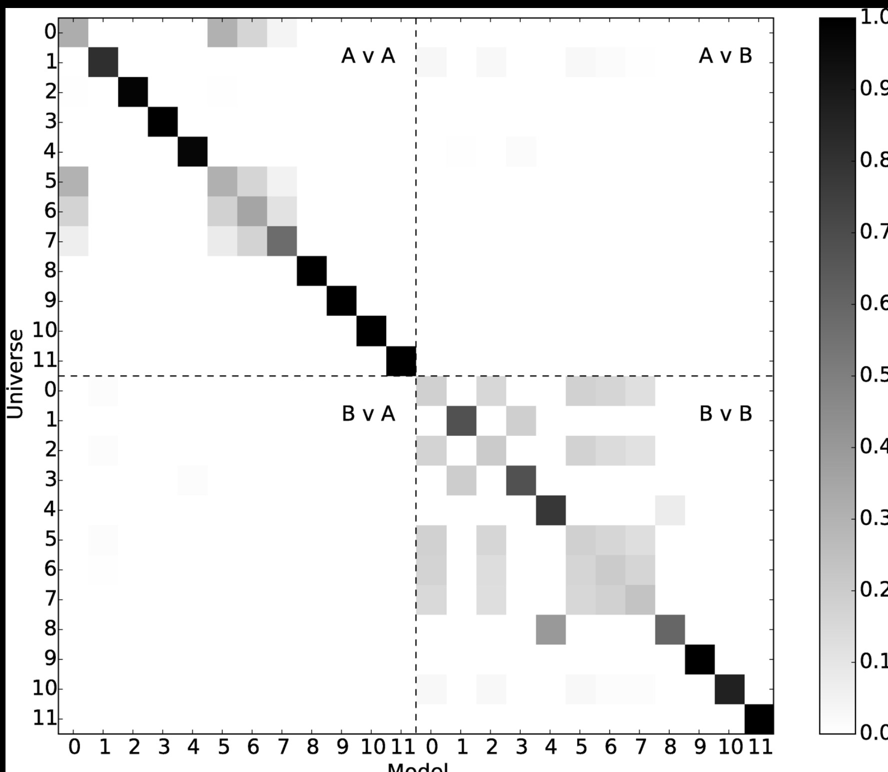


Table 1
Summary of Population Synthesis Models

Model	Physical Difference
Standard	Maximum neutron star mass $= 2.5\,M_{\odot}$, *rapid* supernova engine (Fryer et al. 2012), physically motivated envelope binding energy (Xu & Li 2010), standard kicks $\sigma = 265$ km s^{-1}
Variation 1	Very high, fixed envelope binding energy[a]
Variation 2	High, fixed envelope binding energy[a]
Variation 3	Low, fixed envelope binding energy[a]
Variation 4	Very low, fixed envelope binding energy[a]
Variation 5	Maximum neutron star mass $= 3.0\,M_{\odot}$
Variation 6	Maximum neutron mass $= 2.0\,M_{\odot}$
Variation 7	Reduced kicks $\sigma = 123.5$ km s^{-1}
Variation 8	High black hole kicks, $f_b = 0$
Variation 9	No black hole kicks, $f_b = 1$
Variation 10	*Delayed* supernova engine (Fryer et al. 2012)
Variation 11	Reduced stellar winds by factor of 2

From Stevenson et al 2015

Differentiating models: After O2



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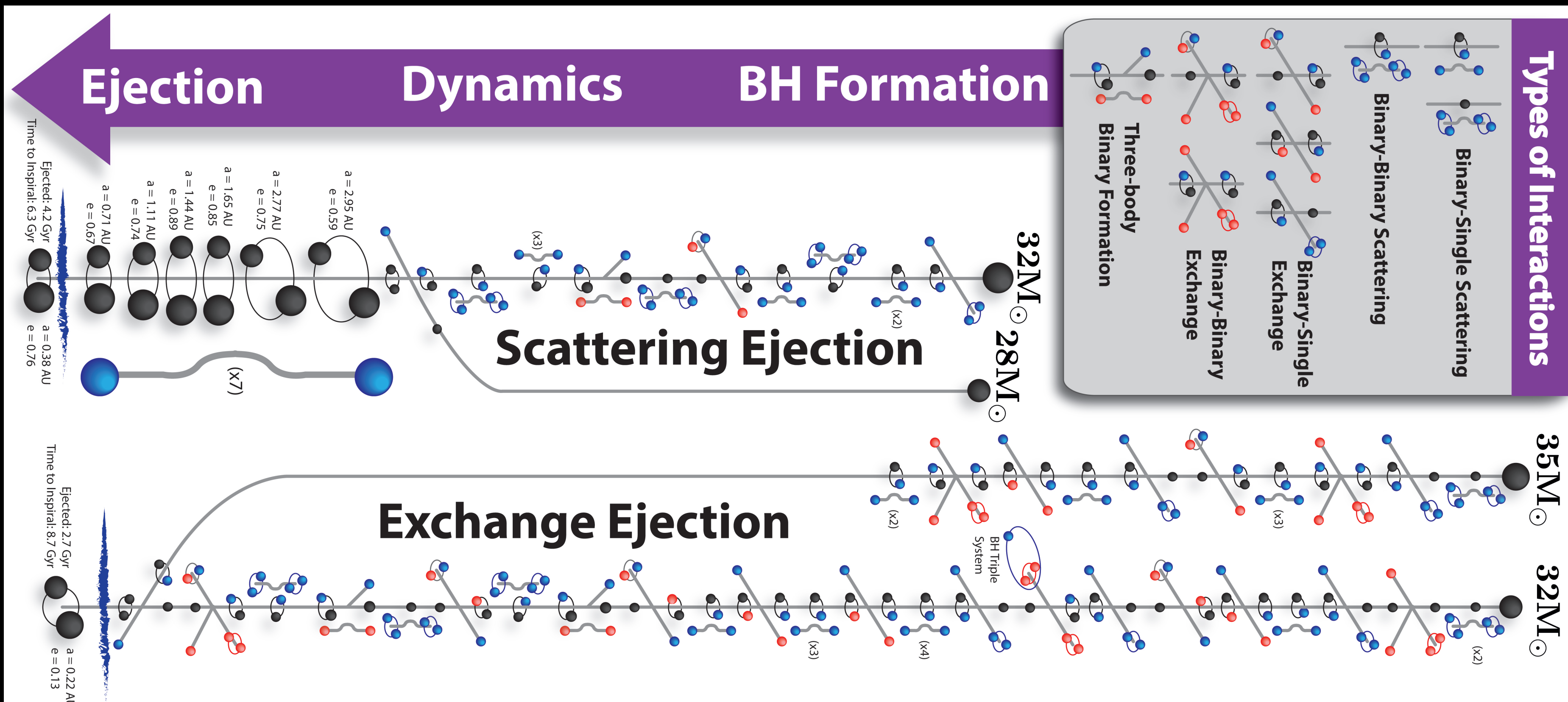
From Stevenson et al 2015

Dynamical formation

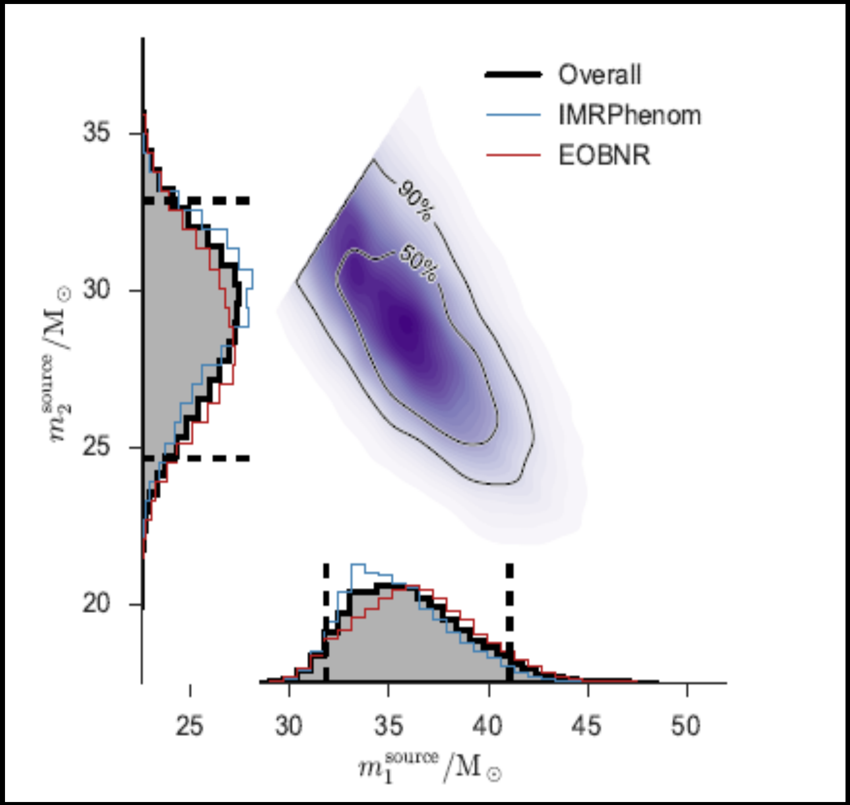


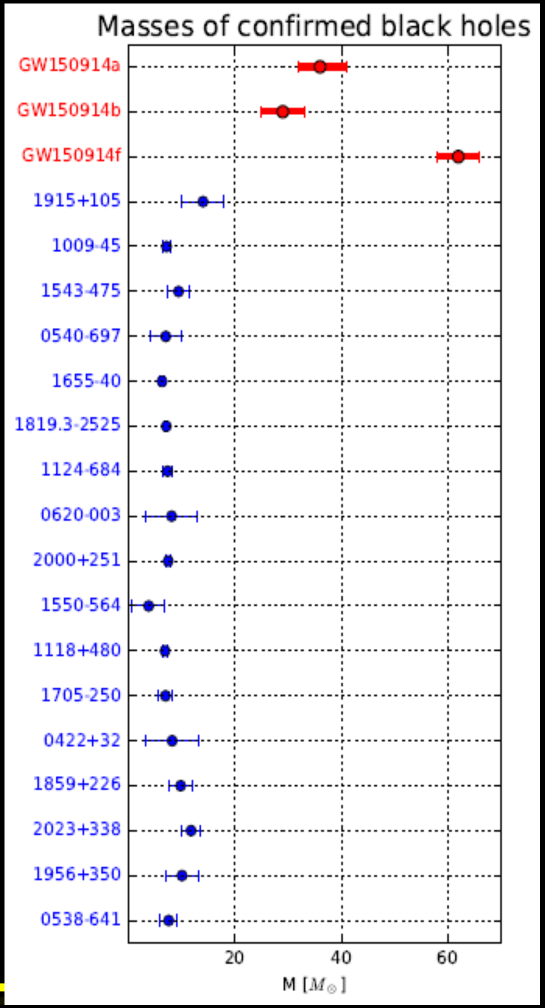
From Rodriguez et at 2016

The Message - I

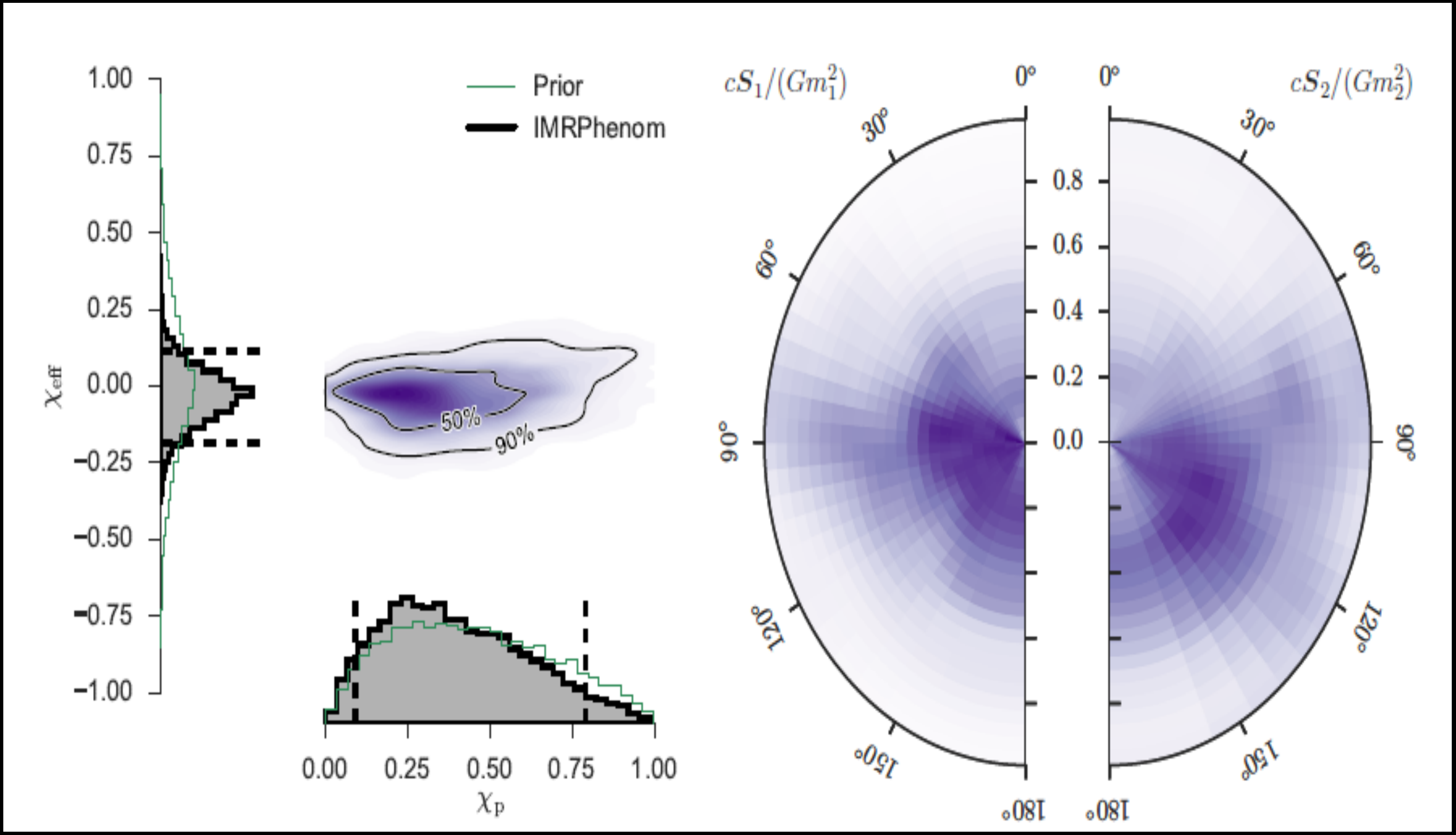
- Future observations will reveal the mass and spin distribution of black holes in binaries
- Provides a new way to probe formation and evolution of massive stars in binary systems
  - Common envelope
  - Stellar winds
  - Supernovae and black hole kicks
  - …
- Or, the models may not fit the observations

Review of GW150914's parameters: MASSES

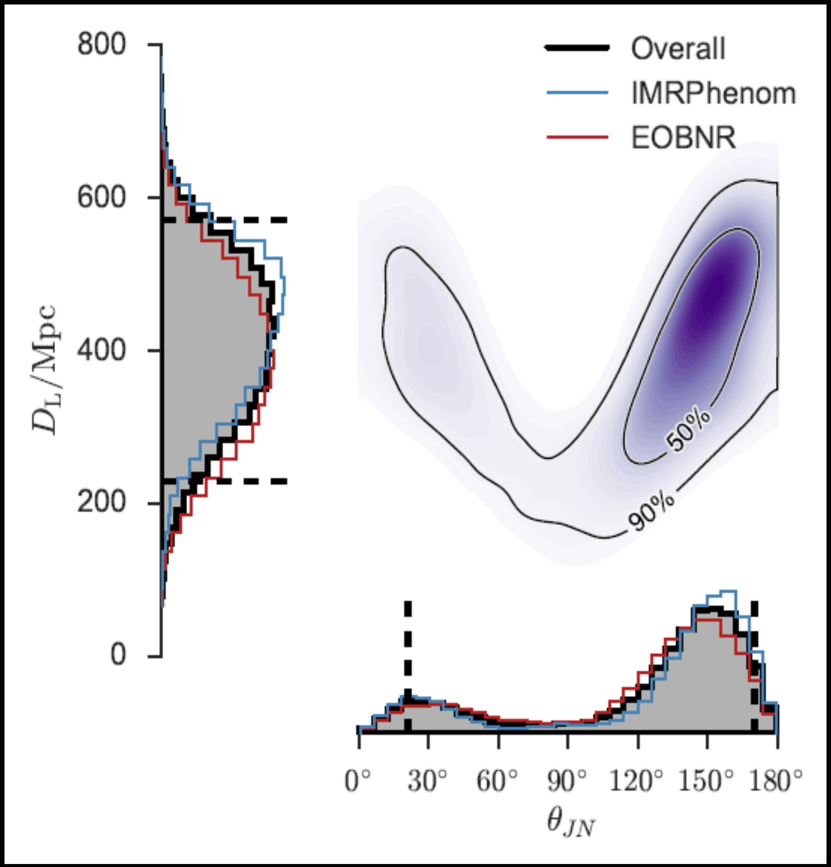




Review of GW150914's parameters: SPINS



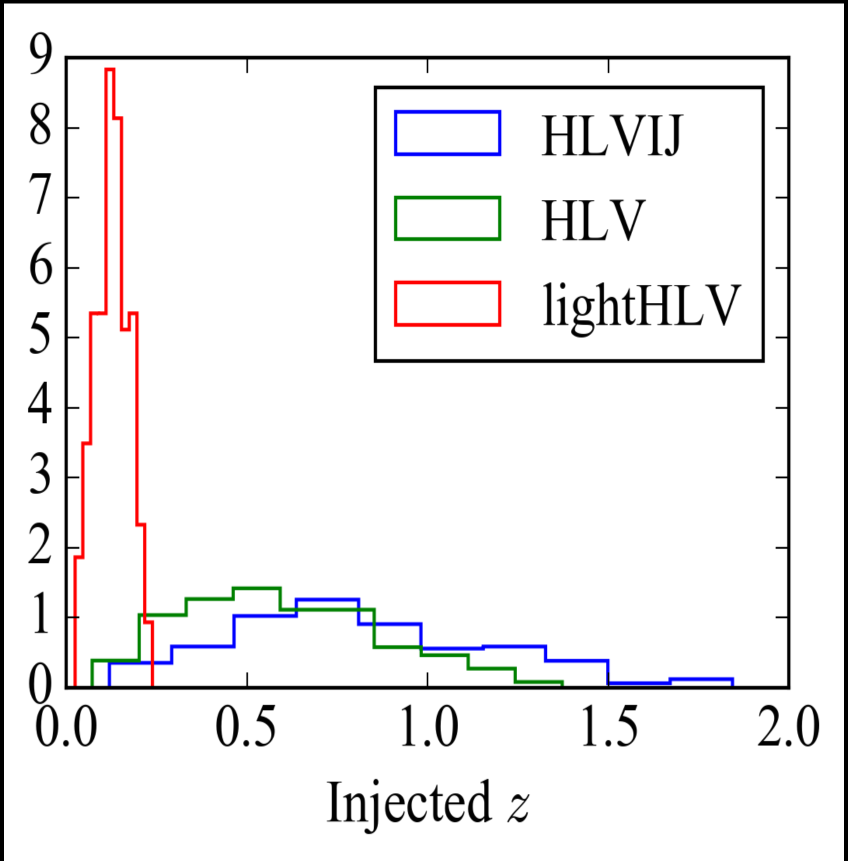
Review of GW150914's parameters: DISTANCE



Moving forward

- Were the uncertainties in the estimates of GW150914's parameters "typical"?
- Simulated populations of heavy BBH, uniform in commoving volume, and estimated parameters with HLV (design) and HLVIJ.

Distribution of redshifts

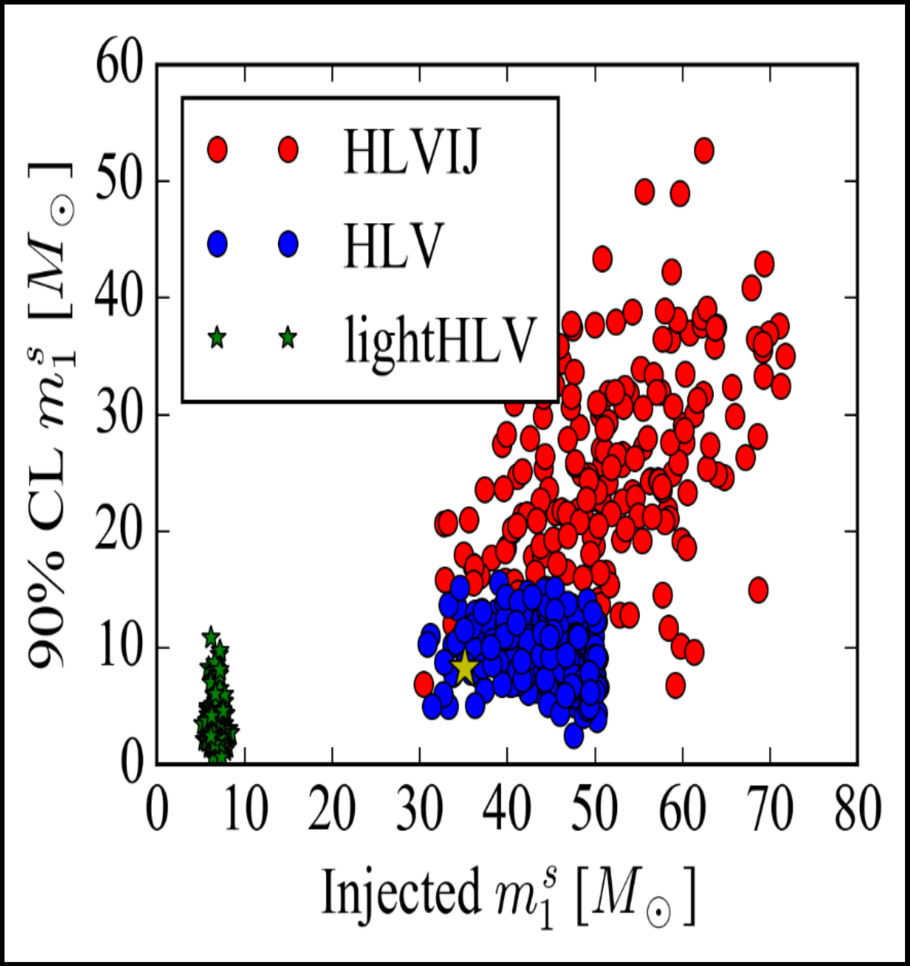


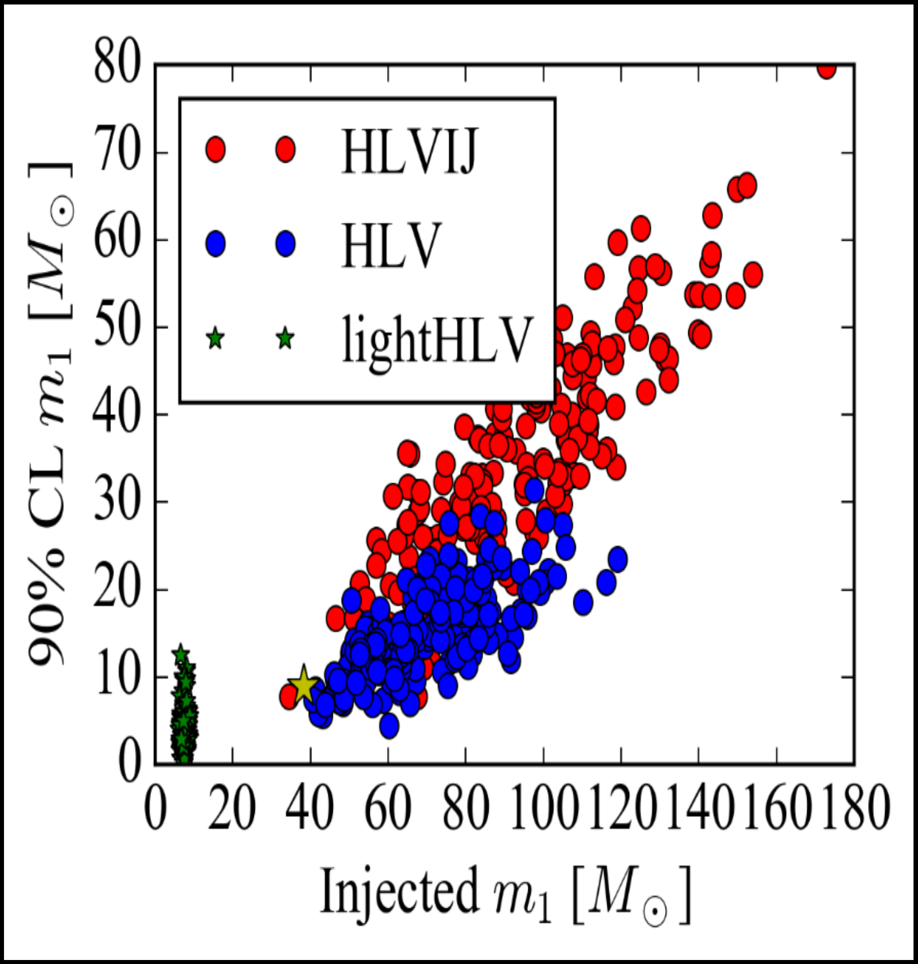
- Light BBH (≤15Mtot) will probe the nearby universe
- Heavy (≤100Mtot) from z~1
  - Higher as more interferometers are added
- Detectable sources lie in the range z ≤ 2
  - Need even more than 5 IFOs to explore large cosmological distances
  - … or 3G instruments

Mass estimates

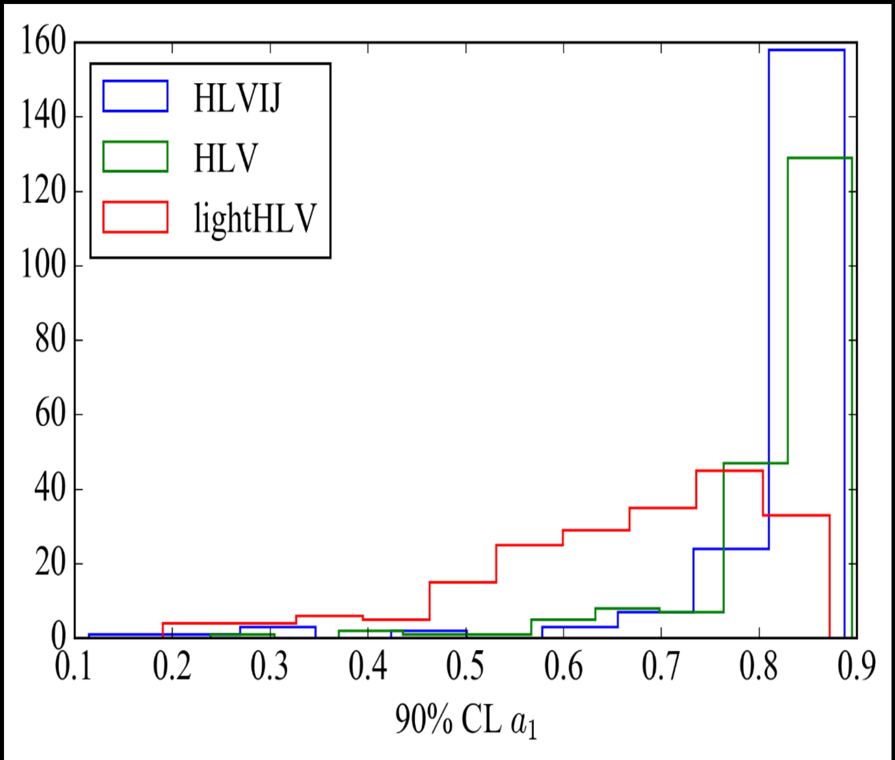
SOURCE FRAME

DETECTOR FRAME





Spin estimates



- Distribution of 90% confidence interval for estimation of spin magnitude shows
  - Very large uncertainties for most events
  - Occasionally, small uncertainties for events with large spins and favorable orientations
- The situation might be better for lower masses due to more cycles in band
  - Not immediate from this plot, since for the light BBH I had used SpinTaylorT4, which might have led to slightly smaller errors

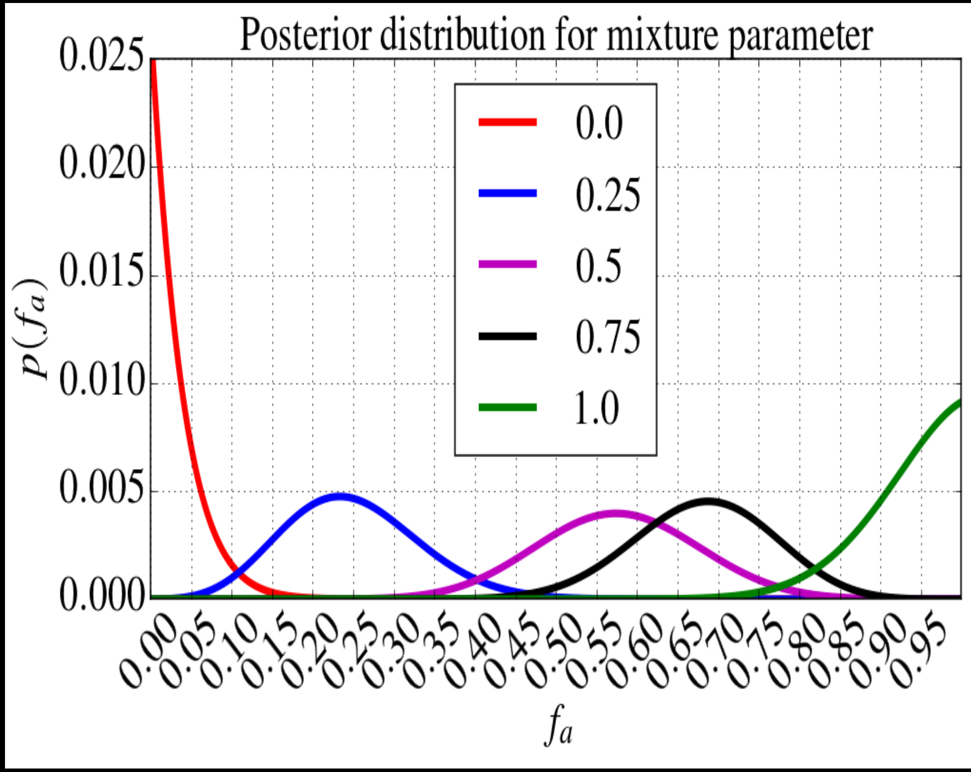
Formation channels

- The two most likely formation patterns for BBH (and CBCs in general) are:
  - *Common envelope*: the two objects were in a binary system from the very beginning.
  - *Dynamical capture*: the two objects were born independently, then met and formed a bound system.
- Astrophysically interesting to understand which one happens more often

- Each channel results in a quite different expected spin distribution, in particular spin orientation:
  - Common envelope systems are expected to have spins along the orbital angular momentum
  - Dynamical capture systems should have randomly oriented spins

Formation channels

- Formed catalog of 200 heavy BBH for which a given fraction has spins aligned with the orbit (i.e. came from common envelope)
- We will be able to calculate the fraction with good accuracy.
- 200 heavy BBH could be detected in as little as 1-2 years of operation of 2G IFOs.

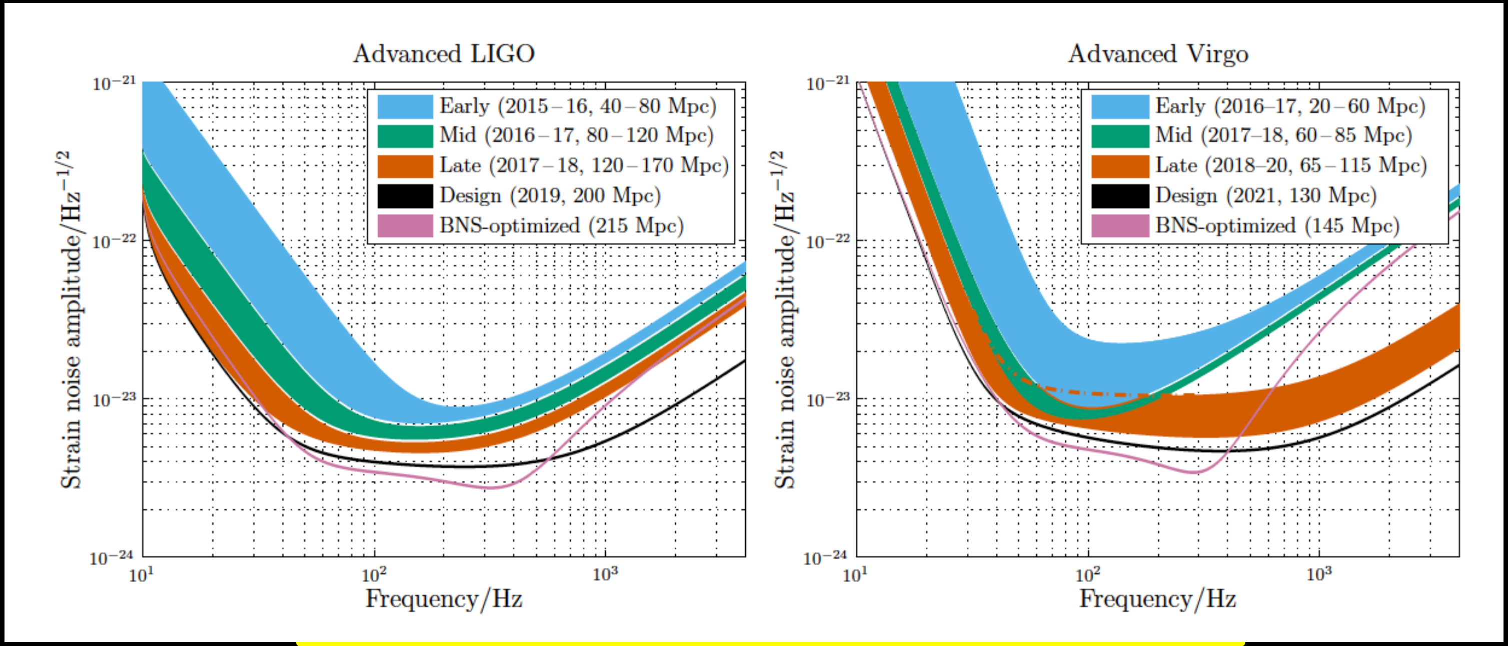


The Message - II

- Future observations will reveal the mass and spin distribution of black holes in binaries
- Uncertainties of GW150914 are typical for sources in the same mass range
  - Spin is poorly constrained
  - For a fixed SNR, mass and spin uncertainties will not improve as more detectors are added

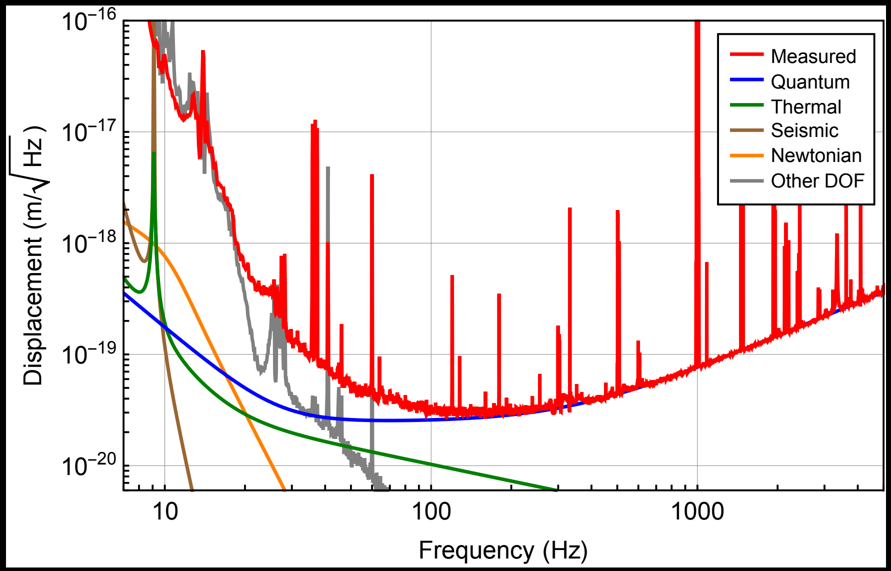
Some questions for the near term (next few years, no major upgrades)

- Can we optimize advanced detectors sensitivity to see more black holes?
- What about high frequency sensitivity?



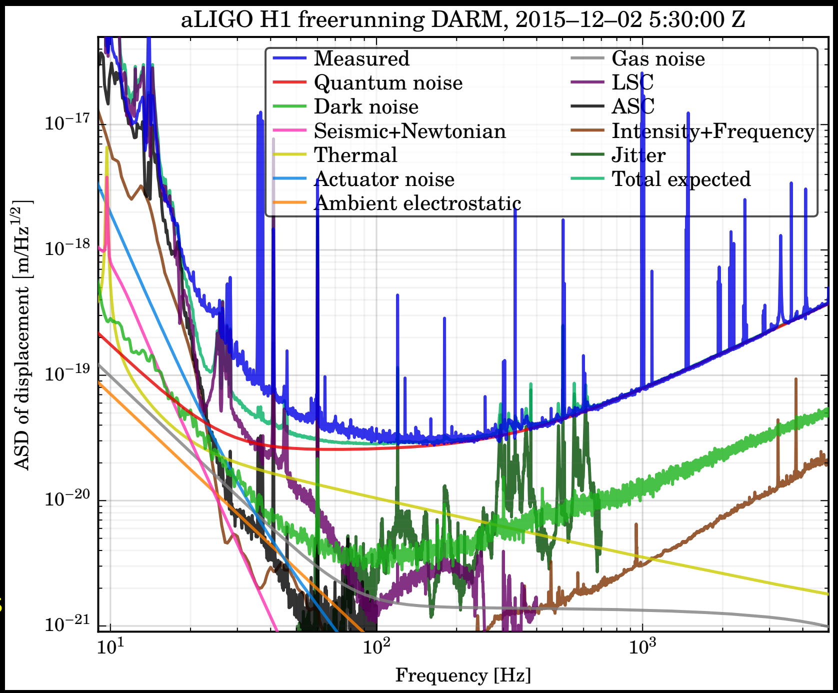
O1 aLIGO Sensitivity

H1 sensitivity during O1



GW150914: The Advanced LIGO Detectors in the Era of First Discoveries
http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.131103

H1 noise budget (credit: Evan Hall)



- A factor of ~2 excess of noise at low frequency
- Obviously understanding and fixing this excess of noise is the 1st thing in the to-do-list

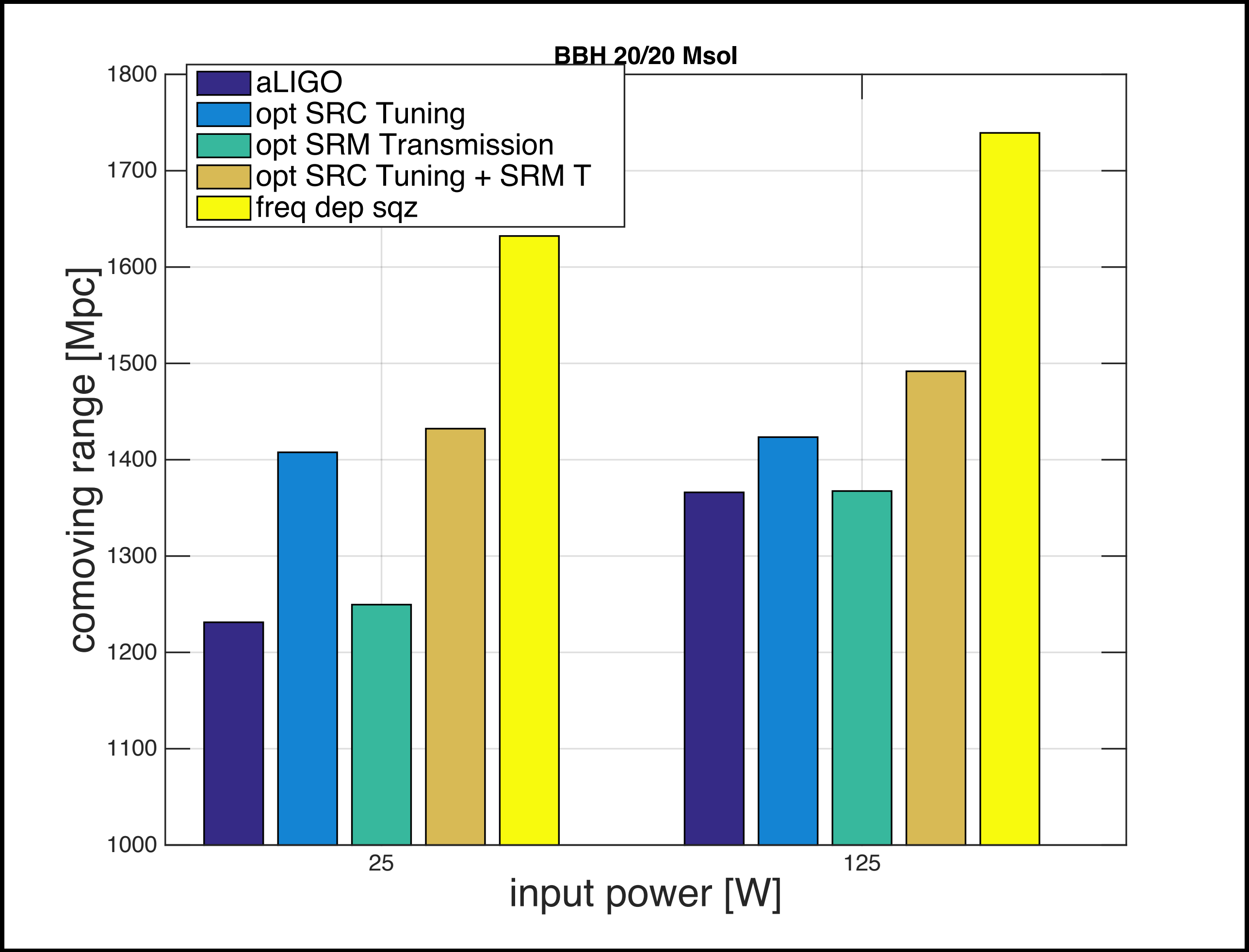
Shaping quantum noise

- (Power)
- Signal Recycling Mirror transmission
- Signal Recycling Cavity tuning
- Squeezing (here optimal frequency dependent)

Note: aLIGO curve used for this analysis

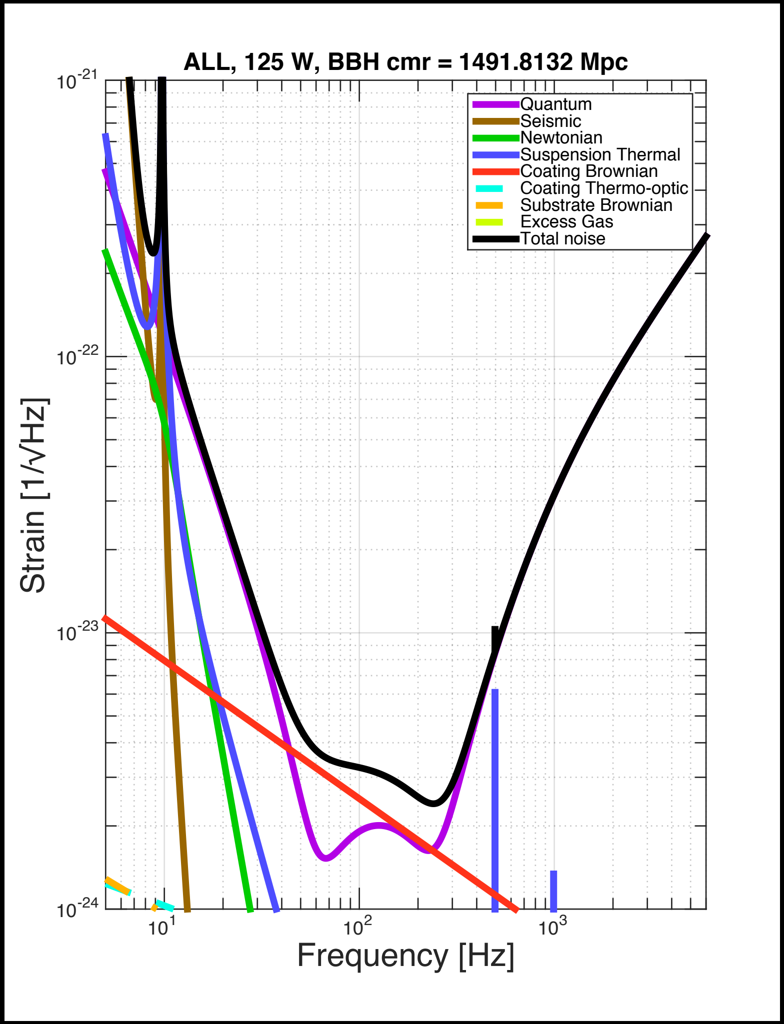
Configuration optimization comparison (by Jamie Rollins)

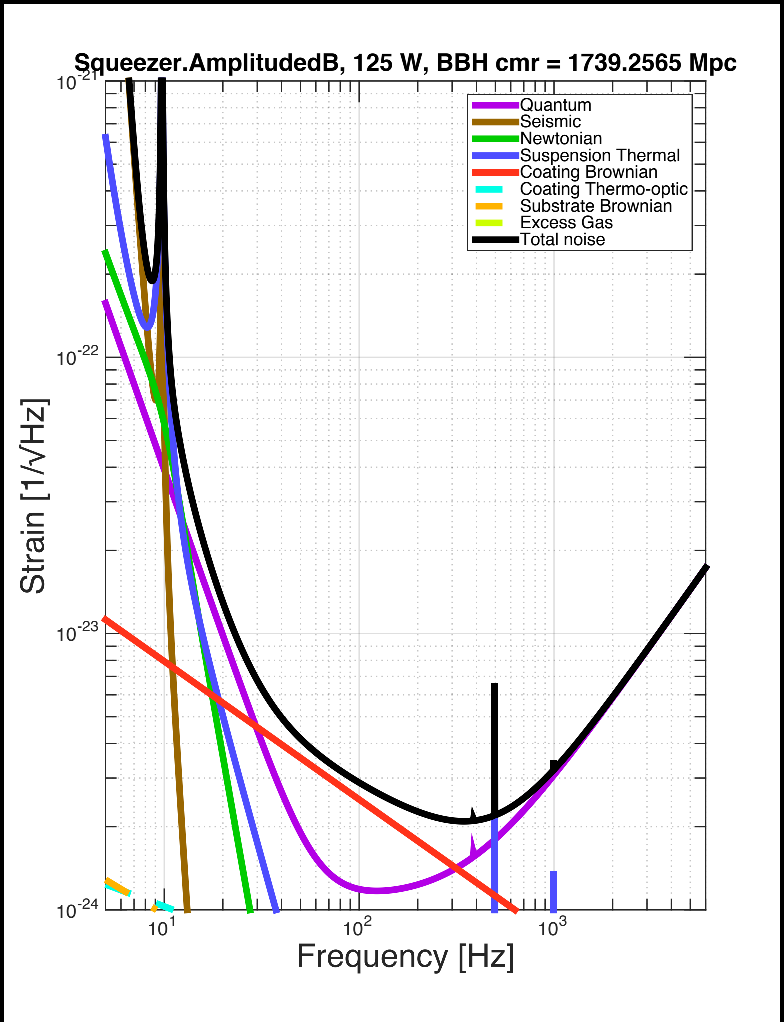
Inspiral Range with Cosmology
by John Miller
LIGO-T1500491
(in gwinc svn)



Example curves @ full power:

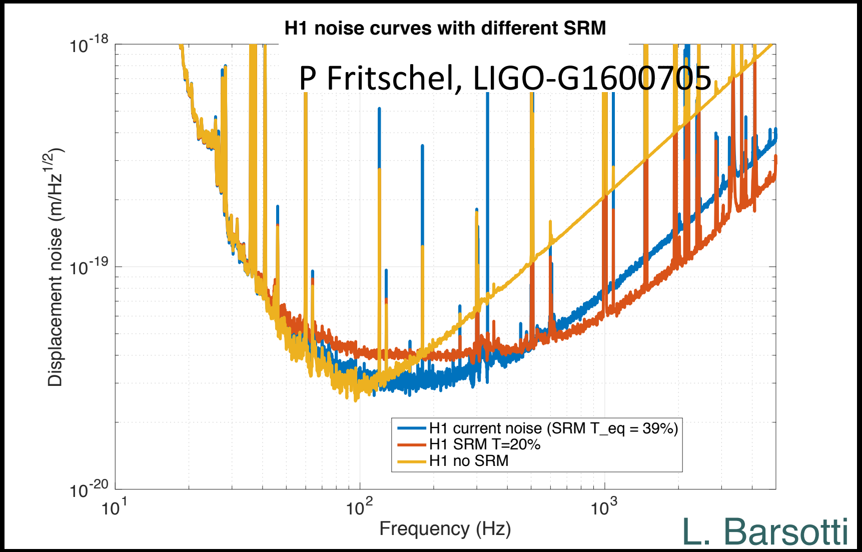
Optimized (Tuning/SRM T) vs Squeezing

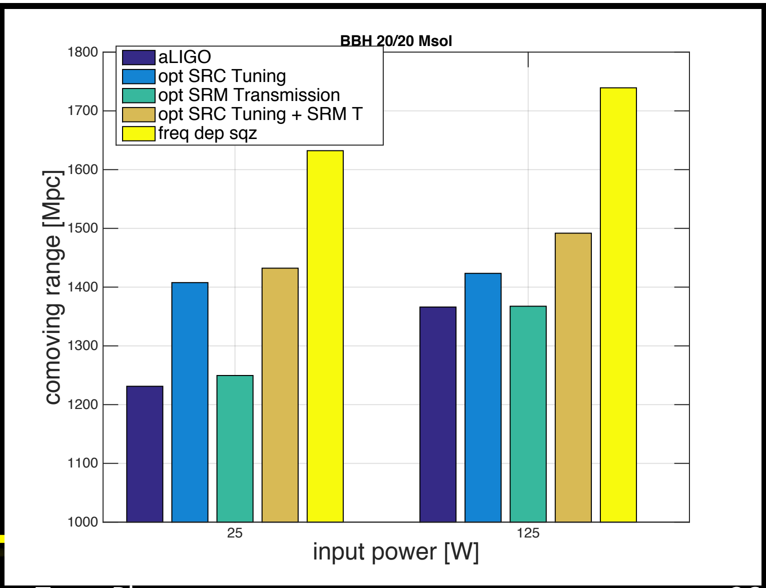




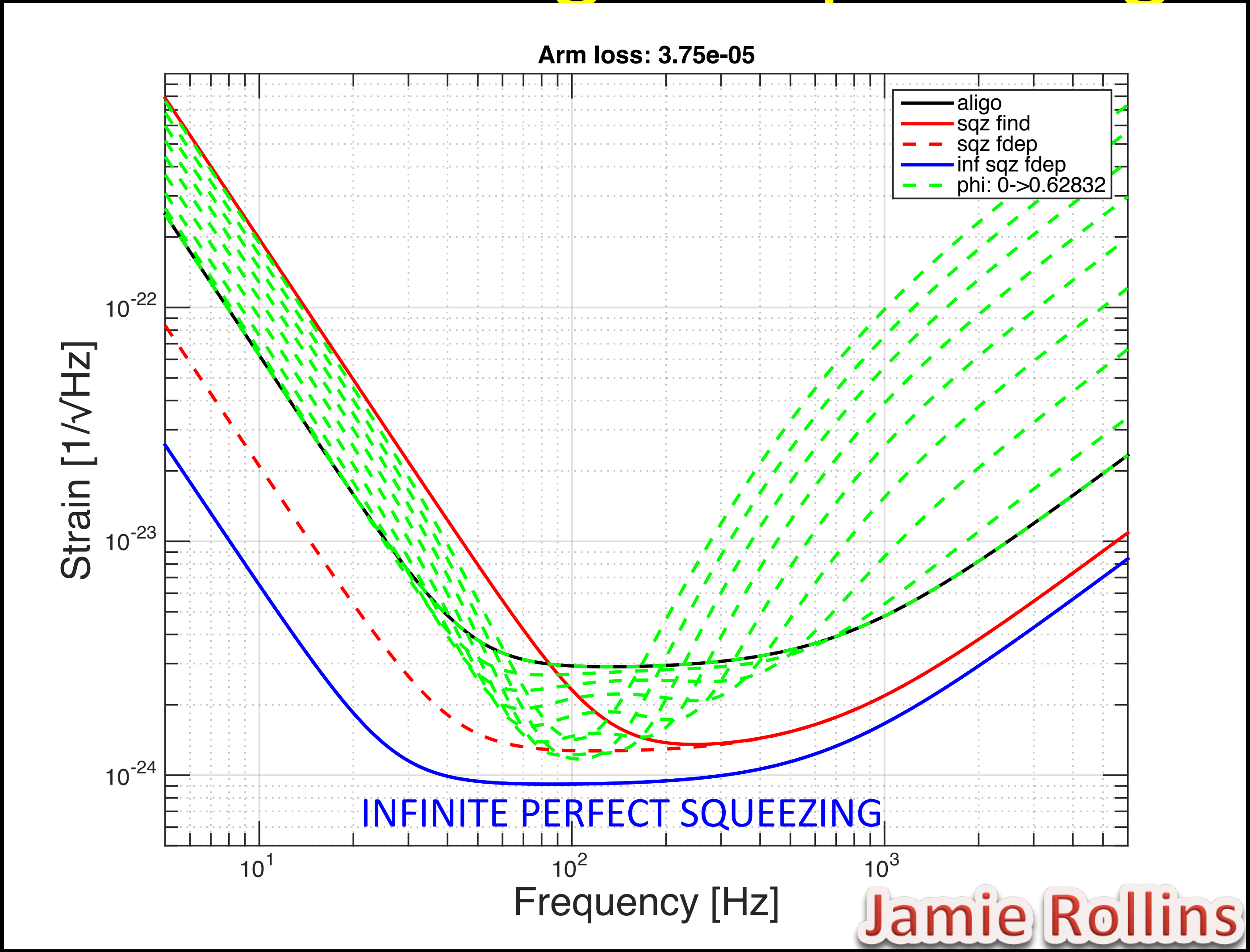
What this optimization tells us

- Current SRM transmission is already optimized for BBH
- Signal Recycling Cavity tuning helps over design curve (especially at low power)
- Squeezing helps more

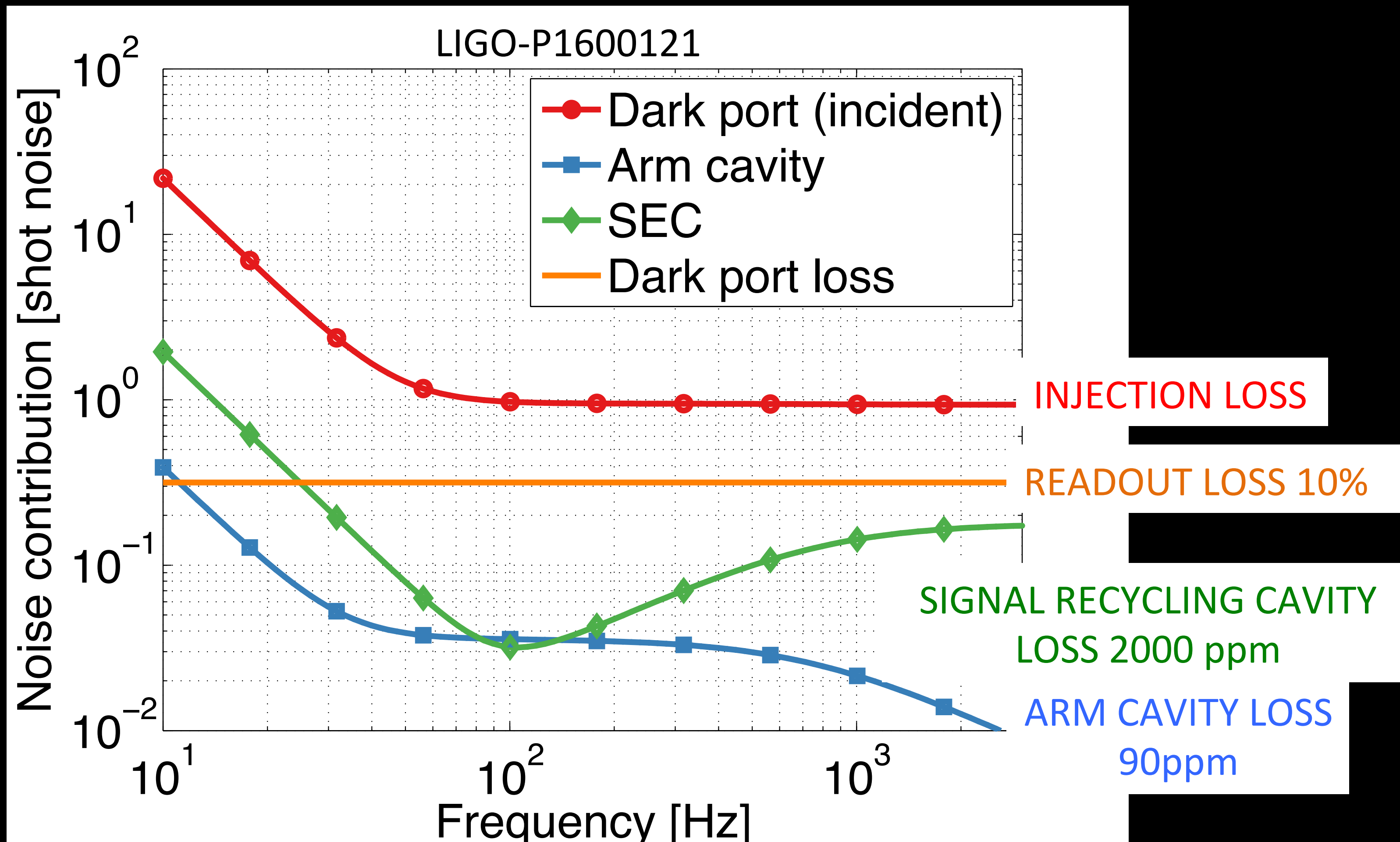




SRC Tuning vs Squeezing

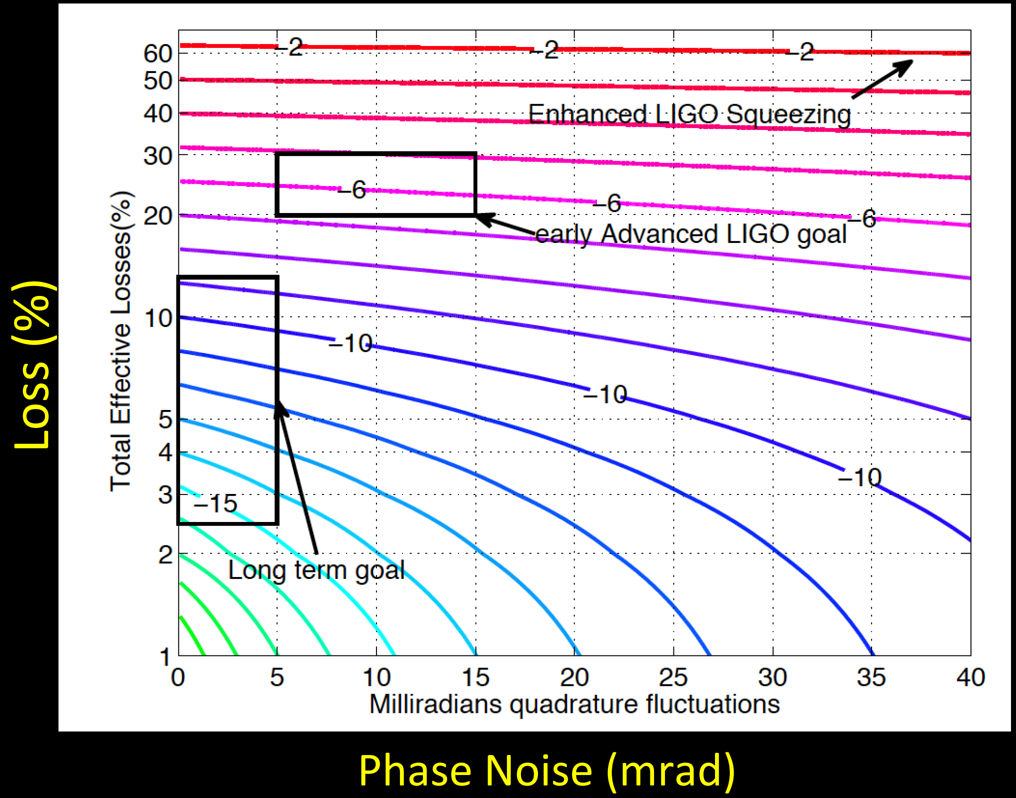


Illuminating Plot (by Jan Harms) to understand quantum noise



10 dB of high frequency squeezing doesn't seem impossible anymore

Dwyer et al. Optics Express (2013)



Phase noise of the squeezing source became negligible: ~1.5 mrad of phase noise
E. Oelker et al. (LIGO-P1600074, accepted in Optica)

Measured QE of photodetector ~0.5%
H. Vahlbruch et al. LIGO-P1600153

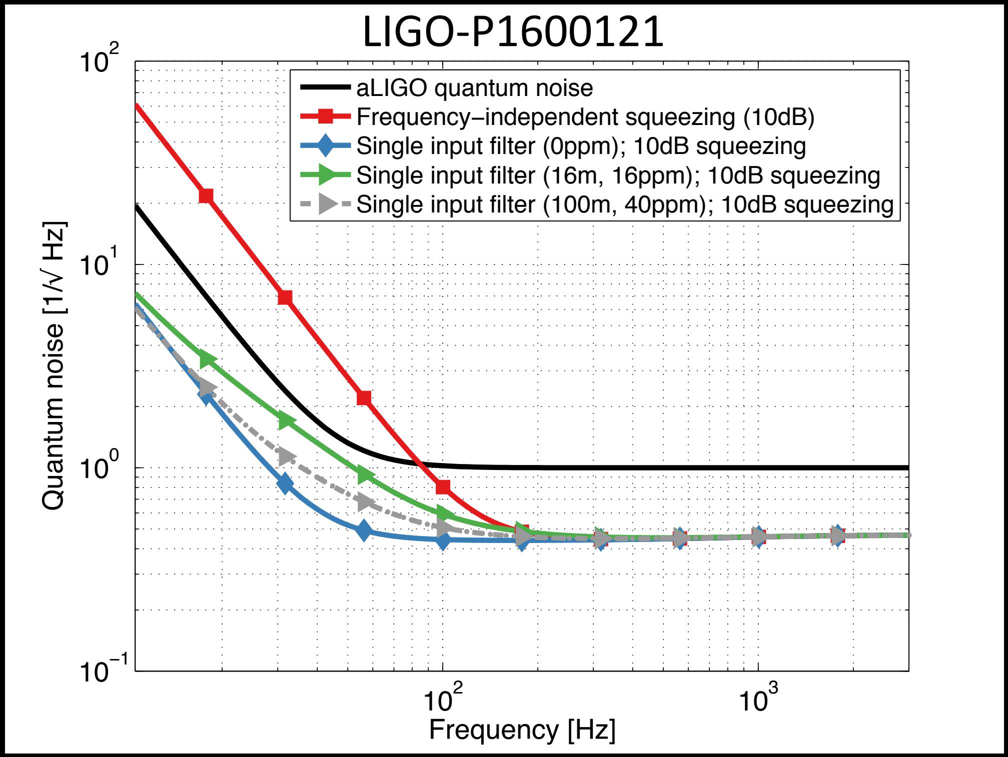
Efforts on going to understand and reduce mode matching loss (Lisa's talk on Wed)

Faraday loss (single pass)

- aLIGO: ~3% (Koji Arai – it was 4%)
- GEO: ~2%
- Florida design, target <0.5% G1600068

Quantum noise @ low frequency

- Determined by filter cavity loss/length; mode matching to the filter cavity also important → see Eleonora's talk on Wed
- Bottom line: quantum noise reduction with squeezing could look something like this:

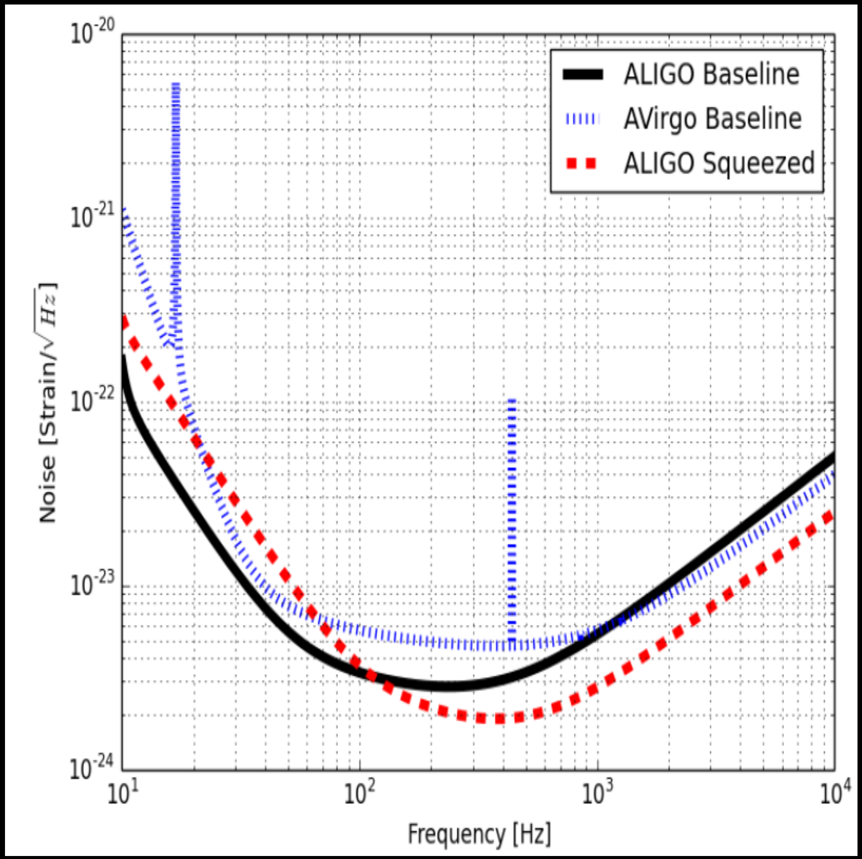


The Message - III

- It seems that the ~2020 aLIGO curve will have frequency dependent squeezing, no SRC tuning, most likely same high(ish) SRM transmission
- Up to a factor of 2-3 improvement at high frequency is doable (6-10 dB squeezing), as long as we continue to work on reducing loss
- Low frequency quantum noise reduction -- more on Eleonora's talk on Wed → goal is 6-10 dB BROADBAND quantum enhancement

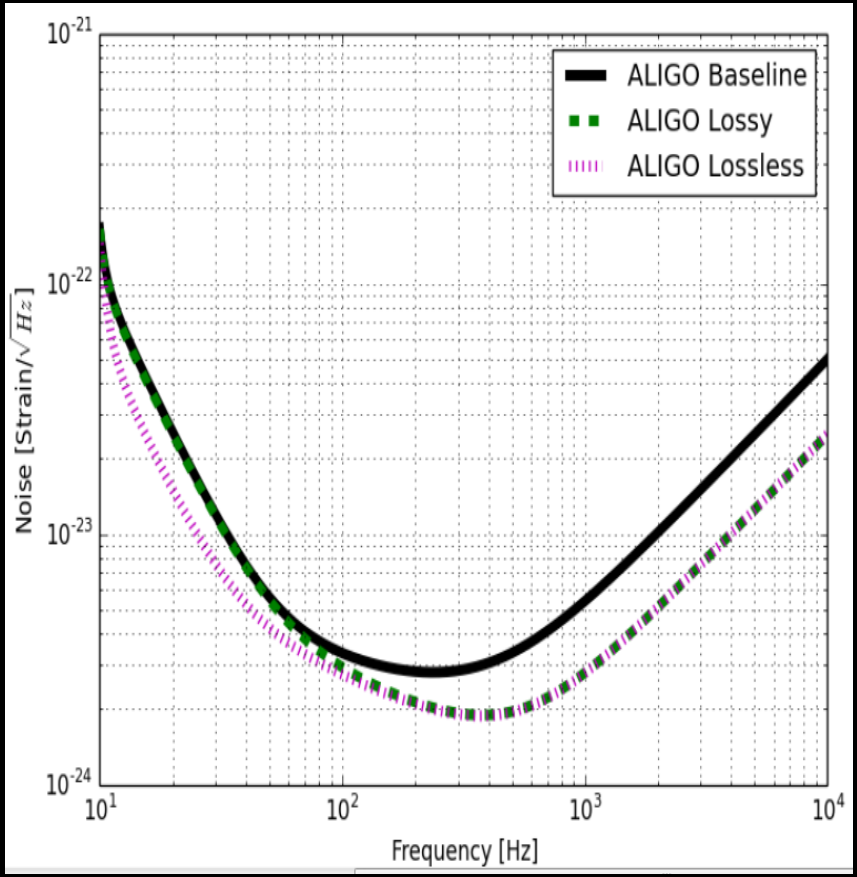
Impact on parameter estimation: squeezing w/o filter cavity

- In Lynch+ 2014 we considered the impact of squeezing on parameter estimation for binary neutron star and stellar mass black holes
- For the BSN, the extra SNR at high frequency is nearly exactly compensated for by the loss at low frequency
  - Better estimation of sky position and tidal parameters (Equation of state)
- For higher mass systems, loss of SNR and fewer detections
- Squeezing with filter cavity harmful if heavy BBH will be the primary science target



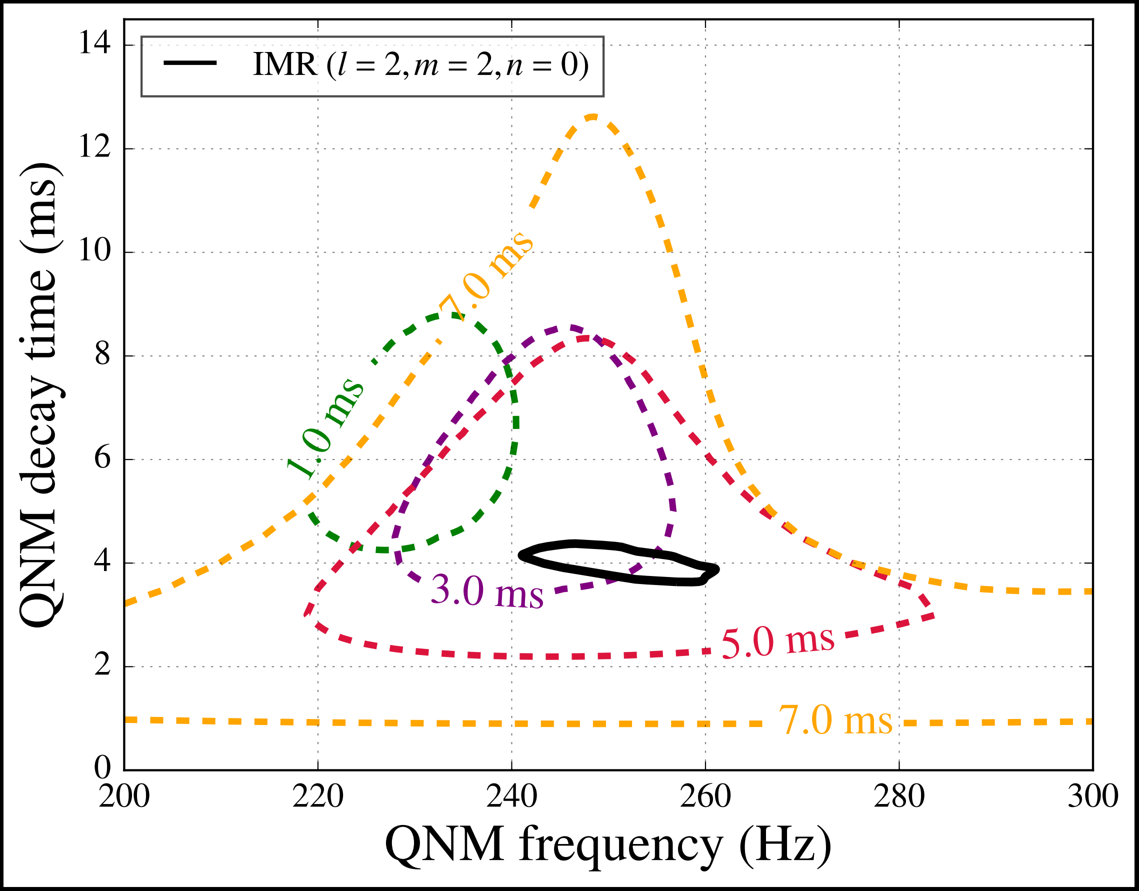
Impact on parameter estimation: squeezing with filter cavity

- As we said, it improves performances at all frequencies → increase number of detections
- What happens to the average event, depends on sensitivity of the network



Merger Physics: GW150914

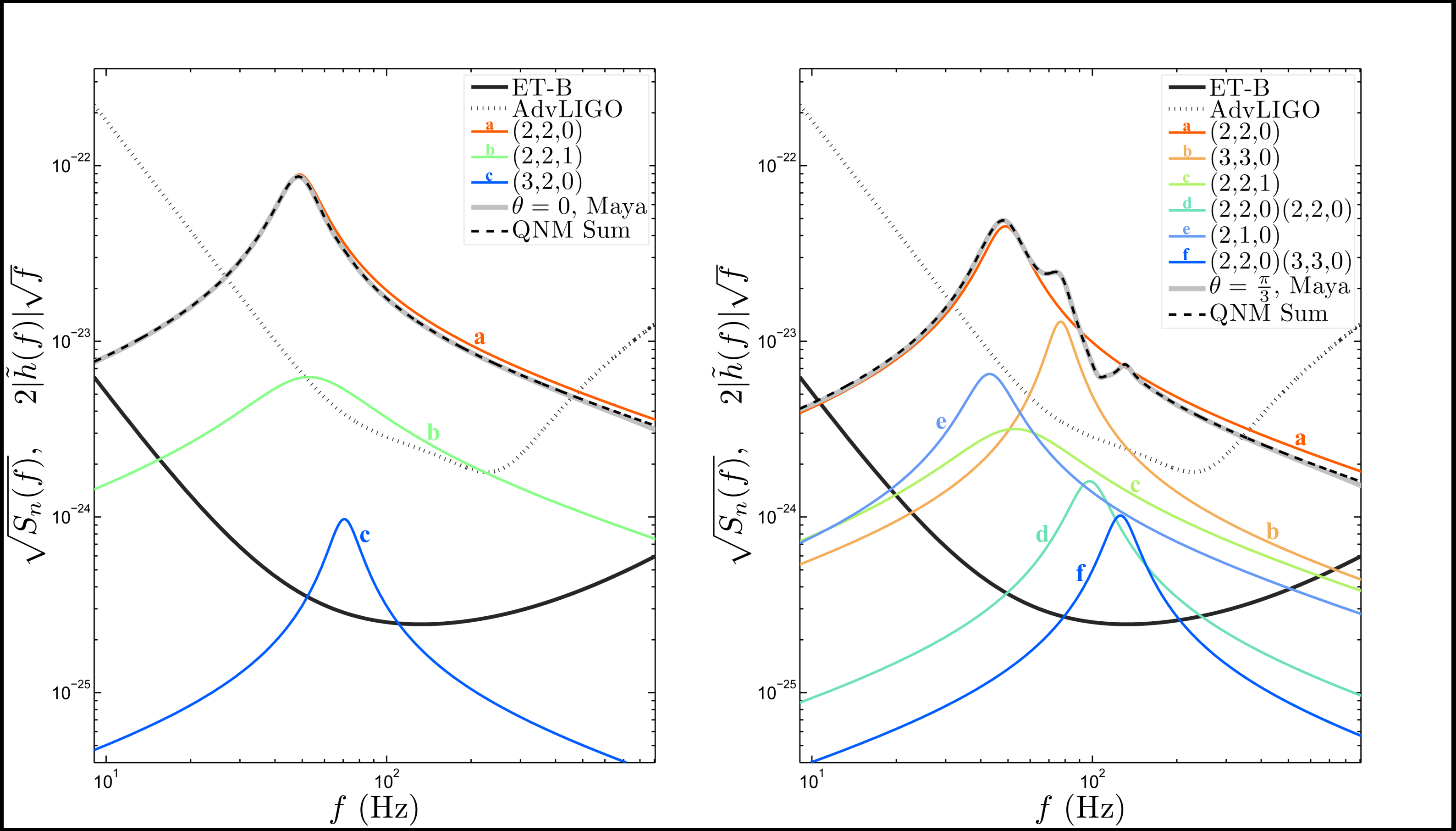
- Ringdown fit with an exponential decay
- SNR of 7 from 3ms after merger
- No identification of other modes



From Abbott et al, PRL, 2016

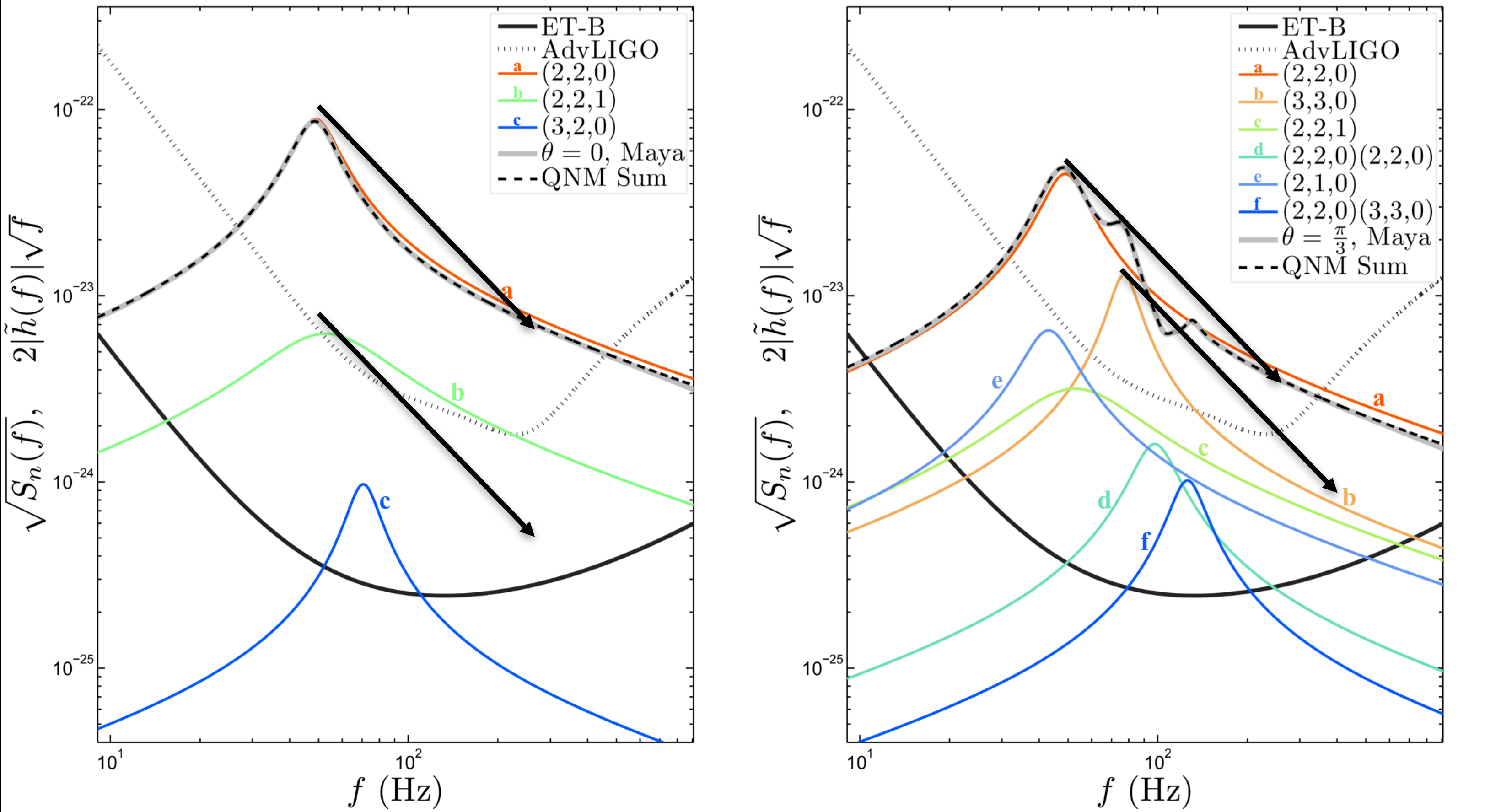
Observing higher modes and overtones

350 Msun binary @ 100 Mpc; From London et al 2014.



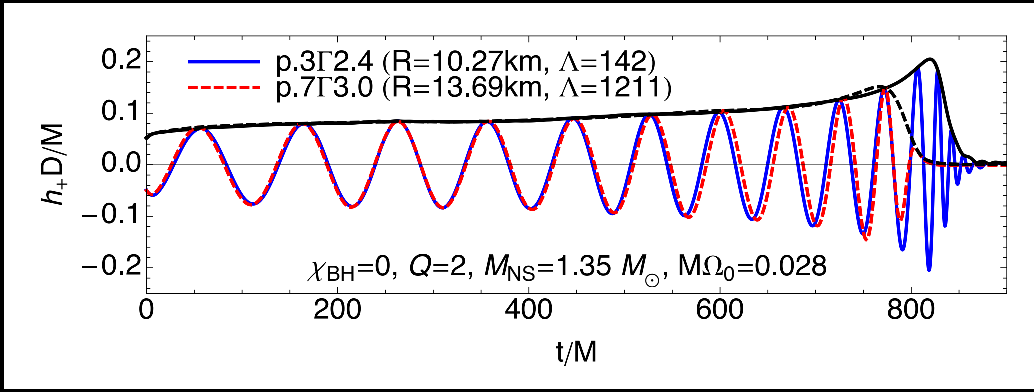
Observing higher modes and overtones

Arrows indicate peaks for 60 Msun @ 400 Mpc

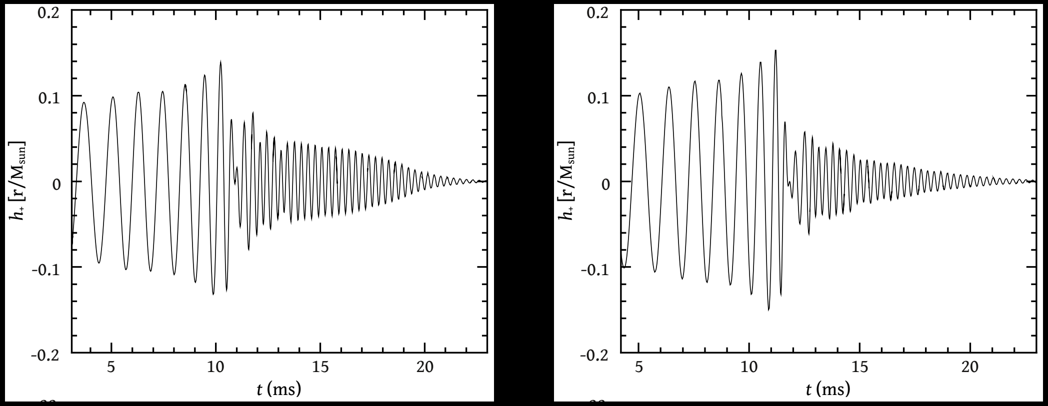


Merger Physics: BNS & NSBH

- NS structure can effect BNS and NSBH waveforms
- High rate of BBH does not imply high rate of BNS/NSBH
- Effects are typically SNR~1 at 100 Mpc



NSBH where NS is or is not disrupted, from Lackey et al 2014



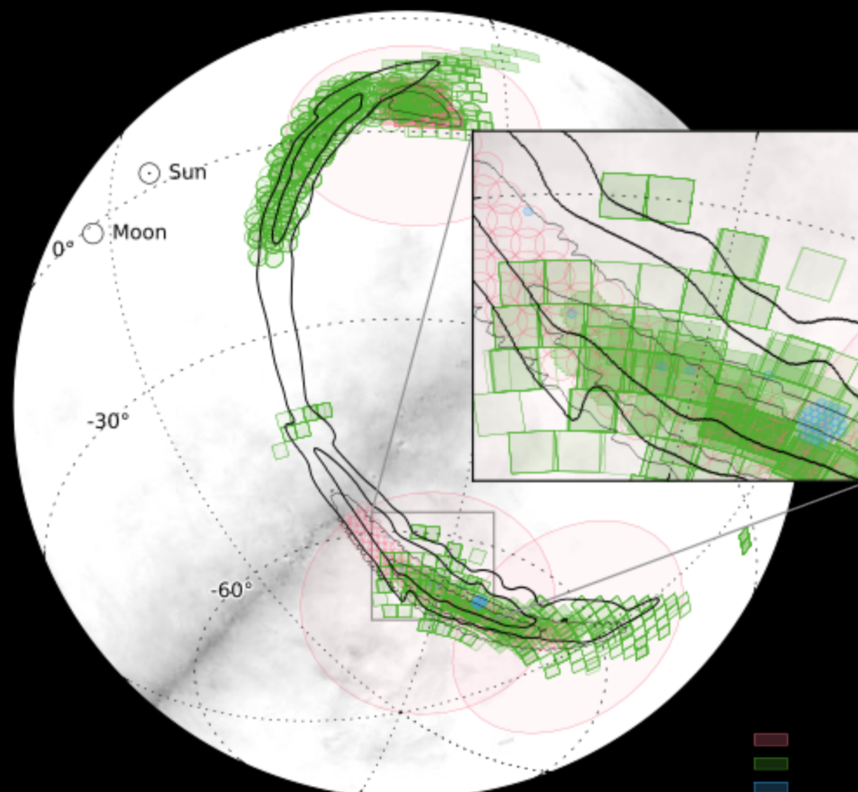
BNS post-merger oscillations, from Stergiolas, 2011

The Message - IV

- Improved high frequency can give insights into merger physics:
  - BBH: multiple ringdown modes
  - NSBH: tidal disruption
  - BNS: post-merger oscillations
- Likely only for the closest/loudest of systems.

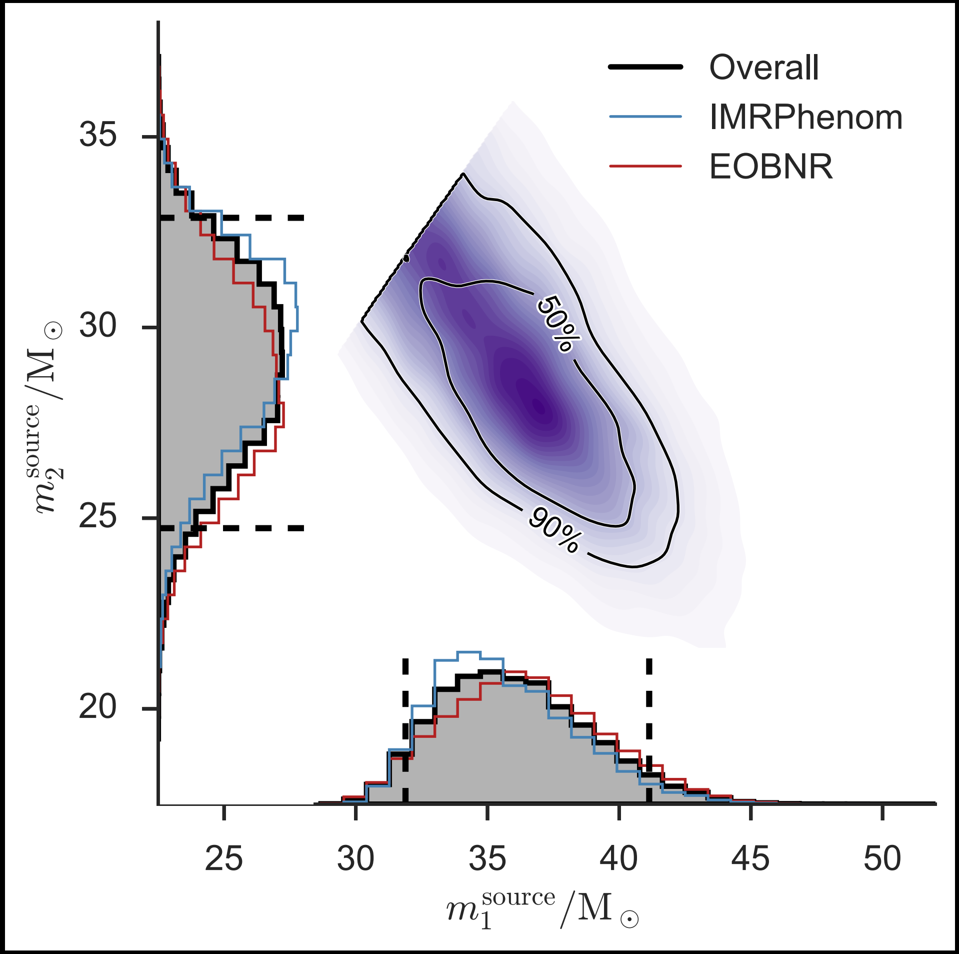
Networks & Localization

- Usual motivation is for EM follow-up
- May not be relevant for BBH



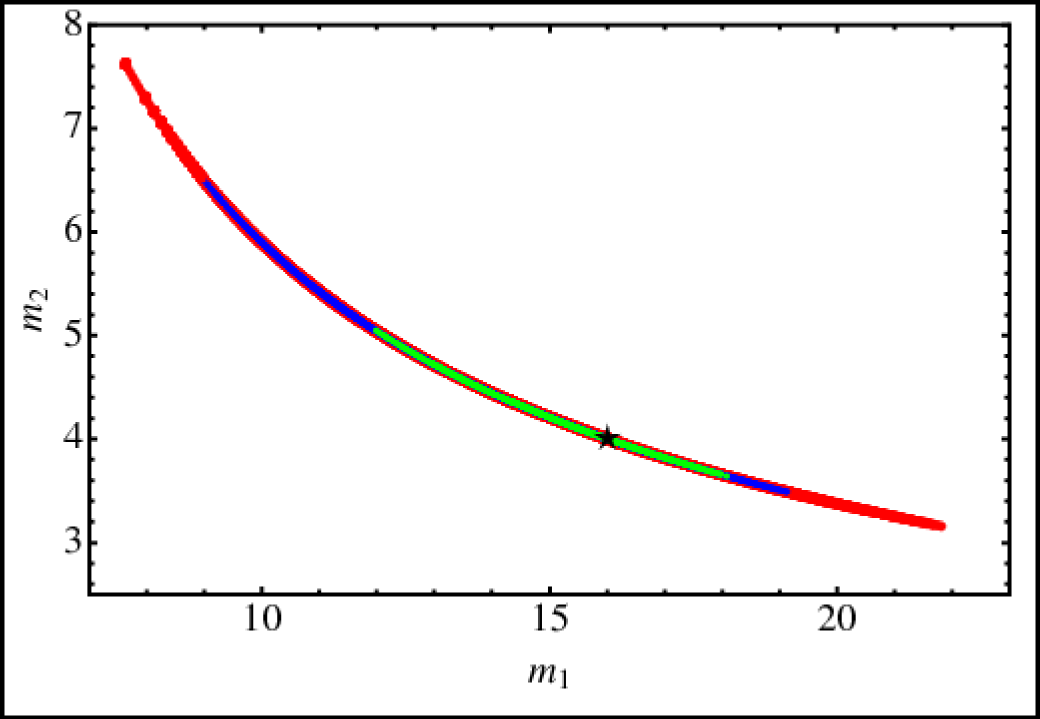
Networks & Localization

- Uncertainty in distance affects mass estimates through redshift
- About a 3% effect for GW150914



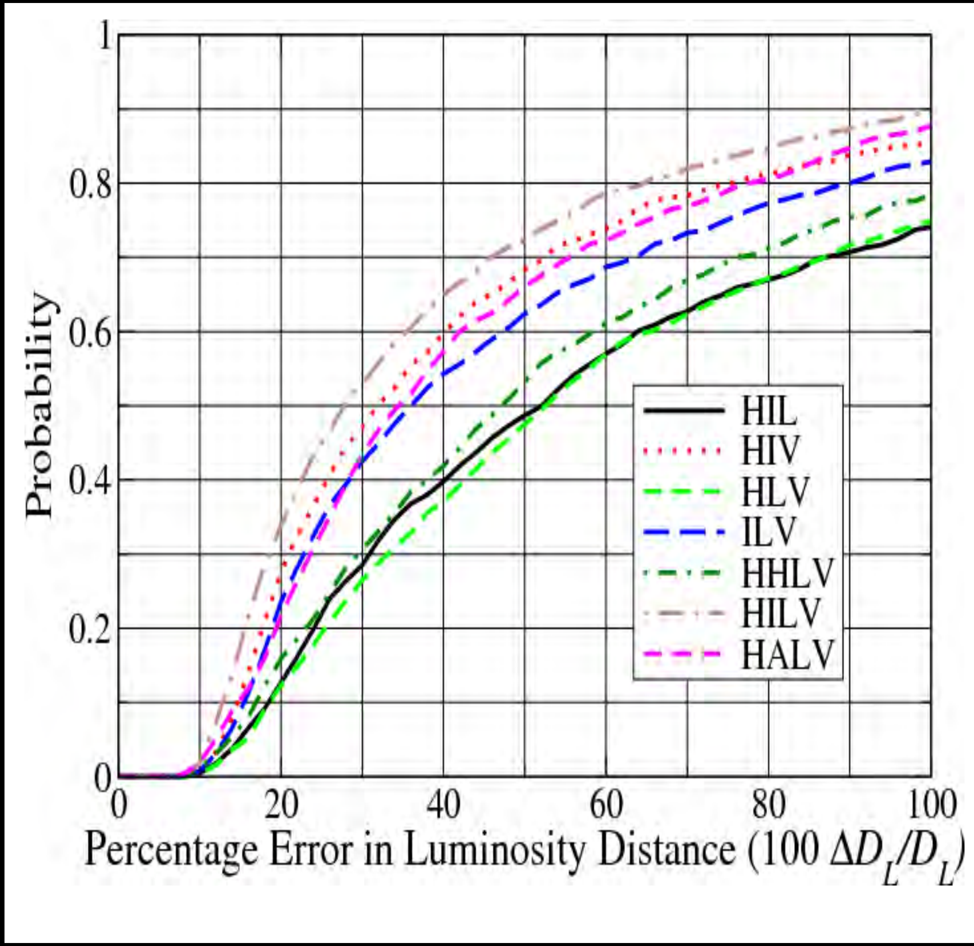
Mass estimates

- Fractional mass uncertainty scales with absolute redshift uncertainty: δM/M ~ δz
- Likely to be dominant error on chirp mass for lighter systems seen by only aLIGO



Importance of a network

- Localizations go from hundreds to tens of square degrees
- Distance:
  - Localization: fixes detector response
  - 2 polarizations: restrict orientation



The Message - V

- Localization matters for black hole binaries
- Network detection gives significant improvement in position and distance measurements
- Likely to be limiting factor in mass estimate for BBH.

The final message: what can/can not do with a 2G network

	Sky Localization	Spin Estimation	Mass Estimation	Distances	Cosmology	Merger Physics
BNS	2GNet	2G	2G	2GNet	>2G	>2G
NS-BH	2GNet	2G	2G	2GNet	>2G	>2G
Light BBH	2GNet	2G	2G	2GNet	>2G	>2G
Heavy BBH	2GNet	>2G	2G	2GNet	2G	2G?