Daniel Holz – Lecture 1 Questions

Questions marked in green were answered during the Q&A session. I haven't tried to correct grammar/spelling. Where a slide number was given it is shown.

Q1 (slide 9). What's the difference between LIGO Hanford and Livingston?

There are two LIGO detectors, one in Hanford, Washington and the other in Livingston, Louisiana. They are similar in design, although in O3 the Hanford detector has been slightly less sensitive than the Livingston one. Although they are designed to be sensitive to similar polarizations, because the Earth is round, they have slightly different antenna-power patterns (i.e., they are most sensitive to slightly different parts of the sky).

Q2. If a gravitational wave passes by a nearby black whole as it propagates, how do this BH prerceive it ?

Gravitational waves follow paths/geodesics in spacetime in the same way that photons do. So a nearby BH would cause gravitational lensing of the gravitational waves. Unless the BH is very close (within a few Schwarzschild radii), it won't have significant effects on the gravitational-wave waveform itself.

Q3 (slide 13). In slide 13 is the energy you mention purely gravitational?

Yes, the merger emits more energy in GWs than all the energy in all the starlight in the observable Universe.

Q4. (slide 12). Why in the merger of the two black holes we don't see a downing of the frequency opposite to the incline?

Once the two black holes merge, they result in a bigger black hole. This black hole then "rings down" (it has normal modes, just like a bell). These modes are higher frequency, and damp very quickly. There is some information about ringdown in this paper (and references within).

Q5 (slide 17). Could you explain a little more of how they "removed" the glitch for GW170817 to "see" the data underneath?

See Fig. 2 of this paper. There are different ways to do this. One was to "zero out" the glitch in frequency space (multiply by an inverse Tukey window). A more refined approach was to actually fit the glitch using wavelets, and then subtract it. See references [73] and [75] of the linked paper for more information.

Q6 (slide 12). Can you please explain why energy released in gravitational waves is more than the combined energies of stars?

I discussed this a little more after the lecture. The short version is that the luminosity scales as c^5/G, which is a *huge* number. See, e.g., eq. 19 of this paper.

Q7. Is your instrument sensitive to high altitude thunders ?

Yes, I think so. But this is a better question for Brian Lantz, who is talking this afternoon.

Q8 (slide 18). How is it decided when the "beginning of the chirp" is?

We can characterize the sensitivity of the detectors, and below a certain frequency (~30 Hz) we have very little sensitivity. So the detectable chirp cannot begin before this. The actual chirp has probably been going on for millions, if not billions of years! We just aren't sensitive to it earlier (although *LISA* would be sensitive months to years earlier).

Q9 (slide 19). Can explain again the gap between neutron Star and Black holes?

This is an observational statement. If you look at slide 19, there is a gap between the purple and yellow objects. This has been noticed by observers, and many theorists have tried to explain why it might happen. As LIGO/Virgo continue to operate, they will be able to address whether the gap exists, and if so, what it looks like in detail. See, for example, this paper. Of course, this characterizes the population of black holes *in binaries*, it does not necessarily clarify the general population of isolated black holes.

Q10 (slide 22). any theory explain the 2second of difference between the signals?

See section 5 of this paper for preliminary work and citations. There has been quite a bit of subsequent work (check citations to the paper for a sense of this).

Q11 (slide 26). Since we are describing things in general relativity framework, why do we speak about gravitons? Aren't they associated with some quantum field theory framework which for general relativity we don't yet have

Yes, this is a good point. Since this lecture is associated with SLAC, I took the liberty of using particle physics language. But everything I've talked about is classical general relativity. So when I say "graviton", you can just translate it directly to "gravitational wave".

Q12 (slide 27). How are the velocities of the electromagnetic and of the gravitational waves measured/derived?

We don't measure the absolute velocity; we are only inferring the *relative* velocities between light and gravitational waves. We show that the fractional difference in these velocities is less than 1 part in 1e15.

Q13. How is the black hole mass determined for the x-ray binary black holes?

In an X-ray binary there is a star as well as a black hole. Observations of the star can provide estimates for the stellar mass, orbital period, orbital velocity, inclination, etc.; these can then be used to infer the black hole mass.

Q14 (slide 27). So this means that gravitons--if they exist--travel at the same speed as photons do?

Yes.

Q15 (slide 27). With the constraints on the difference in speed between photons and gravitons, can you use this to constrain the mass of gravitons? And if yes, what is the limit for the mass from this experiment?

Yes, the bound on the mass of the graviton from the time difference was < 9.5e-22 eV/c^2. See this paper for more detail.

Q16 (slide 32). Are all extra-dimension theories ruled out by this result? Or there are models of extra-dimensions that could still be compatible with this measurement?

These limits only apply to large extra dimensions. If the extra dimensions are curled up into small spaces (compared to the relevant wavelengths), then the GWs and photons would pass right through without noticing that the extra dimensions are there. See also answer to Q36.

Q17 (slide 32). How do the LIGO limits on # of extra dimensions compare with the limits already set on Randal Sundrum gravitons and radions?

As far as I know, these are the first limits on the scale of ~40 Mpc.

Q18 (slide 30). If gravitons can leak into the higher dimensions, can standard model fields do so as well and how would we phenomenologically observe this?

In many popular models (such as Randall-Sundrum), the standard model fields are confined to a brane. If this isn't the case, then those fields would also weaken with distance. It would be difficult to test that in this manner (comparing GW and EM), but direct observations of EM sources would constrain this.

Q19 (slide 50). Why don't we get a redshift for gravitational waves?

There is no absolute scale in classical general relativity. The waveform of a high-mass binary is just a redshifted version of the waveform of a low-mass binary. So just from the waveform, there is no way to infer redshift. However, other information (e.g., using the NS EOS) could imprint itself on the waveform and introduce a preferred scale. Quantum gravity should provide a new scale in GR (the Planck scale), but this isn't something we have any hope of measuring with LIGO sources.

Q20 (slide 48). Are we able to determine the spin information about the merging BH from GW? the resultant BH? If so how? if not, what extra information we are missing?

Yes, LIGO/Virgo provides information about spins as well (primarily the components aligned with the orbital angular momentum). See section V.C of this paper for details.

Q21 (slides 49 – 50). How the amplitude of a GW implies a measure of the source distance? Shouldn't it be also modulated by the meging masses?

By observing the frequency evolution of the waveform we can infer the chirp mass of the binary. This then sets the scale, and the amplitude tells us the distance. There is more information in this article.

Q22 (slide 51). Can you speak more on how standard siren measurements account for peculiar velocities and bulk motions?

This needs to be done using electromagnetic data (e.g., observations of the galaxy distribution near the host galaxy of the source). More detail about the case of GW170817 can be found in this paper.

Q23. What does "calibrated by General Relativity" mean?

The theory of general relativity predicts the form of the GW waveform. So we can measure this, and infer the scale of the binary, and thus its distance. See the answer to Q21 above (and this article).

Q24. How can a measurement of the Hubble constant be made from sources at higher redshifts? Wouldn't it be very complicated as the Hubble law doesn't hold for higher redshifts?

At higher redshifts we measure points on the luminosity distance-redshift curve. This is no longer linear, but is a function of the cosmological parameters. Measuring this curve tells us not only H0, but also the matter and dark energy densities.

Q25 (slide 55). How to distinguish the signals from black hole binaries and those from neutron star binaries? How to determine the signals are from neutron stars rather than some novel stars, like axion stars and boson stars?

To first approximation we can't tell them apart. However, careful inspection of the waveform could provide evidence for tidal effects, which would imply the presence of matter. Very careful measurements of this might even provide information about the matter itself, such as the EOS of neutron stars. This paper, and references therein, discusses some of this.

Q26 (slide 55). What is x axis of slide 55?

The x-axis doesn't represent anything; it's just used to make the picture aesthetically pleasing.

Q27. Can you discuss the benefits we might see in building larger GW telescopes like ELISA, given our current detectors are already so good?

Although our current detectors are amazing, they only detect binary NS mergers out to ~400 Mpc, and black holes out to z~1. Future ground-based detectors might see binary mergers out to much higher redshift, not only providing many more systems, but directly probing the evolution of these systems over cosmic time. Ground-based detectors, such as LIGO and Virgo, are only sensitive to binary systems with component masses up to ~100 msun. To go to higher masses, such as supermassive black holes, you have to go to space. LISA opens up an entirely new window at lower frequency, detecting supermassive black hole mergers to the edge of the Universe.

Q28 (slide 57). What exactly is meant by "absorption feature"?

I was suggesting that the PISN "edge" in the black hole mass distribution is similar to an absorption edge in electromagnetic spectra (e.g., Lyman-break galaxies).

Q29 (slide 55). Why do some of the EM Black Holes only have lower limits on their mass?

This is related to details of how the masses are inferred. For example, in some cases the mass value is degenerate with the inclination of the observed system. Assuming the system is edge-on provides a lower limit, but if the system is closer to face-on the mass could be higher.

Q30 (slide 60). There are 2 hold out points in primordial black hole parameter space we still haven't ruled out yet with GW detectors. Do these remain because we can't reach these masses with current detectors, or for a more fundamental reason?

I'm not sure I understand this question. Is it referring to the spin distribution plot on slide #60, or some other plot? Regardless, yes, because ground-based detectors have a limited frequency sensitivity range (~10 Hz to a few kHz), they are sensitive to BHs in the range ~1--100 Msun. Anything significantly above or below this cannot be detected by LIGO/Virgo.

Q31 (slide 60). Why is it expected that BHs would be spinning at a~0.7?

BHs that are created from the merger of smaller black holes end up spinning at a~0.7. This is because the black holes can't shed the significant orbital angular momentum of the binary, so the resulting angular momentum ends up in the spin of the final black holes. This is discussed in some detail in this paper.

Q32 (slide 56). a lack of observation of mergers higher than 100 solar masses indicates something about "direct collapse" to forming larger black holes?

Yes, the idea is that some black holes form from “failed supernova”, where the star ends up collapsing on itself. Fig. 1 of this paper is very informative.

Q33. It seems we know gravitational *waves* exist, leading me to wonder. When and how do you recon we might discover the graviton, and why has it been so hard to find?

Because gravity couples so weakly, it is very hard to come up with a way to measure the effect of a single graviton. In fact, Freeman Dyson argued that gravitons were not, in principle, detectable: the detector would collapse into a black hole before the measurement could be completed! There is still a lot of activity on this topic, but all of it theoretical. I am not aware of any proposed experiment, even for the very distant future, that would detect a single graviton.

Q34. Is there a possibility that the detection of the 2019 binary neutron stars could actually be black holes? Their masses were unusually higher and light was not detected for this merger

Yes, this is a possibility. We have not measured tidal effects in the waveform, so from a gravitational-wave perspective all we know is the masses. These are very suggestive of neutron stars, but certainly not definitive.

Q35. The heavier black holes detected by LIGO from very far in the redshift are also very old. How confident are we about saying that they are of astrophysical origin and not primordial?

All black holes are identical (they have no hair; the only features are mass, spin, and charge), so there’s no way to know for sure how they were made just by looking at them. So, certainly, the black holes LIGO is seeing might be primordial. However, there are lots of reasons to think that astrophysical processes would naturally make black holes just like the ones which LIGO is seeing (see, e.g., this paper written before the first detections). The primordial explanations are generally more fine tuned (at least, in my opinion). Measuring the full mass distribution and evolution will help distinguish these formation explanations.

Q36. As you said Gravitons and Photons travels through same Universe , does it mean String Theory is wrong?

The work I talked about constrains large extra dimensions (large compared to the wavelength of the light and the gravitational waves). In string theory, the extra dimensions are generally compactified to tiny dimensions, and so these constraints don’t apply. In some “string inspired” theories, such as Randall-Sundrum, the extra dimensions are large, and it is these that we constrain.

Q37. How does the presence of Dark Matter effects the measurement of Hubble Constant using Gravitational Waves?

Dark matter isn’t expected to change the waveform, and therefore doesn’t change the general application of standard sirens. This is because, to have an effect, the mass in dark matter in the region of the black holes would have to be comparable to the black hole mass. It is difficult to see how this could be possible (in general, the binary will clear out all nearby matter). One could worry about other effects of dark matter, such as the peculiar velocity or bulk motion effects I discussed. These would need to be constrained through electromagnetic observations.

Q38. Are neutron star mergers detectable in Cosmological simulations which track structure formation? If yes, can this be used to predict what kind of galaxies would host these mergers?

Yes, this is exactly the sort of thing discussed in the paper I mentioned on slides 41--45. We placed neutron star mergers in a cosmological simulation. At present, the binary systems are placed according to some prescription; it is not possible to run a cosmological simulation while simultaneously resolving such small scales that one can also directly simulate the formation of compact binaries.

Q39. What are expected/hoped for discoveries/clarifications from the addition of new GW detectors? LISA. TianQin. DECIGO. LISA Pathfinder. Others?

These detectors are all space-based, which means they are sensitive to lower frequencies. This means they will be able to detect supermassive black holes (a population which is inaccessible to LIGO/Virgo). Those black holes are thought to play key roles in galaxy formation and evolution, and tracking them across cosmic time would be fascinating. These detectors will also find many binary white dwarfs (at large separations), as well as some stellar mass binaries (perhaps months to years before they merge in the LIGO/Virgo detectors!). See also my answer to Q27.