Geraldine Servant Lecture Questions

Questions marked in green were answered during the Q&A session. Original questions listed without correction for grammar/spelling. Where a slide number was given it is shown.

Q1 Do GWs loose energy as they propagate through spacetime? Thanks!

As GW do not interact, they propagate freely without loosing energy. The energy density of GW produced at time t_* just redshifts as radiation energy density so that \Omega_{GW,0} ~ \Omega_{GW,*}/a^4.

Q2 You have mentioned that energy density for GWs falls off as a^-4, so do gravitational waves have the same equation of state as radiation?

Yes, as stated in answer to Q1 above (gravitons are massless, like photons).

Q3 [slide 11] Would GW produced during left-right phase transition be visible to LISA?

It all depends on the energy scale at which the left-right symmetry is broken. Firstly, the corresponding phase transition should be first-order. Any sufficiently strong (i.e alpha>~0.1, beta/H <~ 10^4) first-order phase transition happening at an energy scale between 10 GeV - 30 TeV is observable at LISA, see 1512.06239 and 1910.13125. The specific model in this paper 1909.02018 about GW from L-R symmetry breaking concludes GW are not observable. Other realisations might lead to a different conclusion.

Q4 [slide 7] Am I right I believe that there is NO one-to-one correspondence between the energy of the Gravitational Waves and the energy scale of the universe that those GWs were produced during?

There is a relation between the observed frequency of GW and the energy scale of the universe when they were produced, see slide 11: f_0 ~ (a_*/a_0) f_* where
f_* \propto H_* \propto \sqrt(\rho_*), rho_* being the energy density of the universe at the time of emission. The proportionality factor depends on the precise production mechanism. It is well-defined in the case of 1st-order phase transitions as the characteristic scale is the size of the bubbles at the time of collisions, which is a fraction of the Horizon size. For cosmic strings, it is more complicated because the signal we observe comes from the superposition of GW which were emitted at different epochs, by loops of different sizes, see discussion in the recent review 1912.02569.

The question mentions “the energy" of GW, one should distinguish the frequency of GW and the energy density in GW at a given frequency, \Omega_{GW}, which is how we characterise the amplitude of the signal for a stochastic background of cosmological origin. That amplitude depends on various aspects of the production mechanism. In the case of 1st-order phase transitions, this amplitude scales as given in slides 21-22, and is not at all related to the energy scale of the universe at the time of emission, it is entirely controlled by the strength of the transition (parameter alpha). For cosmic strings, it is more complicated, see e.g Appendix B of 1912.02569.

Q5 [slide 19] What exactly is the "fluid"?

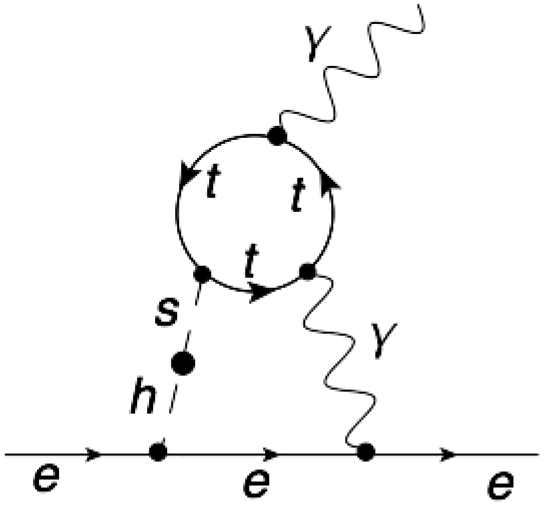
The fluid is the thermal bath constituted by the plasma. In the case of the electroweak phase transition, this is essentially a gas of Standard Model particles. Because all Standard Model particles are massless before electroweak symmetry breaking, all the particles are relativistic at temperatures above ~ 160 GeV and the equation of state is just that of radiation. When bubbles nucleate, expand and eventually collide, this produces non-trivial velocity profiles for this fluid. Part of this kinetic energy goes into GW.

Q6 [slide 17] What do you mean by Higgs bubbles? how does their interaction produce GW?

Higgs bubbles are regions of space where the Higgs field has acquired a background expectation value so that electroweak symmetry is spontaneously broken inside the bubble but not yet outside. Inside the bubbles, Standard Model particles are massive, while they are massless outside. What produces GW are the large velocities (the bubbles expand at nearly the speed of light), once bubbles collide (before there is no breaking of spherical symmetry and no GW are produced). This leads to a non-vanishing anisotropic stress and therefore a source term for GW in the equation of motion (slide 19).

Q7 [slide 32] Could you go into a little more detail on the tension between EDM measurements and EW baryogenesis? Thanks!

Successful EW baryogenesis requires new large sources of CP violation beyond the Standard Model. This typically comes from new couplings between the new scalar field S that is introduced to make the EW phase transition first-order and the Top quark or other new fermions. Because this new scalar field is typically at the electroweak scale, such new CP-violaring coupling will induce an EDM from the mixing between the Higgs field and this new scalar, and a fermionic loop, see attached diagram.



Q8 [slide 36] What does it mean for a potential to be conformal?

This means there is no mass scale in the potential, no quadratic term, only a quartic coupling. If this conformity is slightly broken, a minimum at non-vanishing VEV for the field can develop. Since the potential is rather shallow, this will typically leads to a supercooled phase transition.

Q9 what class of conformal symmetry you talking about?

In a conformal theory there cannot be any dimensional parameter in the lagrangian.
The tree level Lagrangian is scale-invariant, so that the bare mass terms are forbidden, the scalar potential can only contain phi^4 terms.
For a discussion of the underlying transformation laws, see for instance the discussion in 0708.1463.

Q10 [slide 42] Does this graph then show the possibilities that there are many strong colours that we do not observe today?

Yes, in these theories, one introduces a new strongly interacting sector at high energies with new colour degrees of freedom, like a new SU(N) that confines around the TeV scale. At colliders, one would observe new composite states, hadrons and mesons.

Q11 If we have a different source for CP violation, Is the strongly first order phase transition still applicable?

Yes, these are two disconnected aspects. What is required for a strong 1st-order phase transition is typically a new scalar field that mixes with the Higgs, and the strength of the phase transition does not depend much whether there is new CP violation or not. The new CP violation will induce some CP-violating currents in front of the bubble wall once tunnelling has taken place.

Q12 [slide 50] What would the lack of a first-order EW phase transition say about EW baryogenesis?

EW baryogenesis is based on the existence of a first-order EW phase transition. So if we eventually show experimentally that the EW phase transition is a crossover and not first-order, this will rule rule out EW baryogenesis as an explanation of the baryon asymmetry of the universe. We would have to find a way to test leptogenesis.

Q13 How do the HH limits we'll set at the HL-LHC compare with the limits on the Higgs potential that LISA will set?

LHC and LISA provide very different types of information. Only LHC can probe with high precision specific Higgs couplings and test accurately the scalar sector. From LISA we would learn indirectly complementary information on the properties of the effective scalar potential but it would be quite difficult to reconstruct in detail the lagrangian from its observations. On the other hand, LISA

LISA can potentially probe 1st-order phase transitions in the multi 10 TeV range, so point to the existence of new physics at energy scales that cannot be probed by the LHC. Such discoveries could motivate building higher-energy colliders.