Question 1:

Dear Cheap Astronomy – How exactly does Einstein's physics break down in a black hole.

The idea that a particular branch of physics breaks down in a particular environment is arguably just poor use of language. At best, any physics formula can only model how the real world works. If that physical formula provides predictions that are observed with high accuracy in the real world then it's considered a very successful physics formula.

So for example, Newton's physics provides some fairly successful formulas that operate to a fairly high level of accuracy on Earth, even in fast-moving aircraft. But Einstein's physics is considered to offer even more successful formulas, which produce accurate measurements over a wider range of environments, such as in very fast-moving spacecraft or in strong gravity. For example, early experiments seeking to confirm Einstein's physics found that light passing nearby the Sun is visibly bent in a way that was predicted by Einstein, but not by Newton.

But, no-one says there is a particular point at which Newton's physics breaks down, it just steadily becomes less and less accurate when it's applied in situations where things are moving at extreme speeds or are effected by extreme gravity.

Indeed, the suggestion that anyone's physics breaks down in a black hole is kind of a moot point since you can't measure anything that happens beyond a black hole's event horizon. So, you don't have access to any data that would allow you to test whether your physics formula remains accurate or not.

In any case, Einstein's physics does work in a black hole – at least on a theoretical basis and up to a point. General relativity is geometrical in nature, describing how spacetime curves in the presence of mass-energy densities. And, in the presence the humongous mass-energy density of a black hole, spacetime curves a lot.

But there's black holes and there's black holes. The smallest known black hole is about 4 solar masses and about 24 kilometres in diameter. The biggest known black hole is about 20 billion solar masses and about 68 billion kilometres in diameter, a diameter that is 15 times greater that the diameter of Neptune's orbit around the Sun. So, given how we calculate volume, where spatial dimensions get cubed, it turns out that the nett density of a supermassive black hole is much lower than a stellar mass black hole. Indeed, the nett density of most supermassive black holes is lower than water.

This means that spacetime tightens down very quickly in a stellar black hole, but undergoes much gentler constriction inside a supermassive black hole. Hence, various science communicators have described how you could cross an event horizon of a supermassive black hole before getting spaghettified.

What really bothers everyone about black holes and general relativity is that the geometry predicts that spacetime curvature should constrict right down to a single point, a singularity, at the black hole's centre. This means that any mass or matter at that point exists in a state of infinite density – although really that is just a mathematical quirk brought about by trying to divide something by zero.

If you have a central point with zero volume and that central point contains mass and matter, then the traditional density calculation of density (mass divided by volume) will give you infinite. But infinite isn't a number, it's just a symbol representing neverendingness – so if that's the answer your calculation is delivering, it generally just means your calculation logic is wrong.

So, maybe we should reconsider that matter is really just empty space constrained by forces acting between point-like particles that have no actual volume themselves. So, once you do compress matter right down to its fundamentals, perhaps it really can occupy zero volume. Who knows? And given that everything that happens inside a black hole happens behind an event horizon, it's fair to say that no-one will ever really know.

Question 2:

Dear Cheap Astronomy – What is the temperature of a black hole?

Well, we first have to ask what is temperature? We can feel the heat of something at a distance, because it's pumping out photons. But , the basis of temperature is that temperature reflects the kinetic state of the object you are measuring the temperature of. In other words, the atomic and sub-atomic constituents of a material with a high temperature are vibrating like crazy, while the constituents of that same material with a low temperature are relatively still.

But now consider everything we know about black holes. Firstly, no photons are ever going to come out of them. And if the degenerate matter within is compressed right down and quite possibly locked in a singularity, so it probably won't be vibrating at all, even at a sub-atomic level. And of course, there's time dilation to consider. Even if there was some kind of motion within a black hole, from an external observer's frame of reference, it would take the lifetime of the Universe for that motion to complete. So, putting all those ideas together you might reasonably conclude that black holes have a temperature of zero Kelvin.

This is a conclusion that's drawn from a thought experiment, since you can't take measurements of what's happening inside a black hole. Indeed, this actually relates to what is known as the no-hair principle, which says that once you eliminate any external influences, so you are just left with an isolated black hole, then all you can ever know about that black hole, is its mass, its charge and its motion.

But, concluding that something has a temperature of zero Kelvin does not sit well with most physicists. This isn't possible for any other system, so why should it be possible for a black hole? So, there are other lines of thinking, which essentially put the hair back on black holes. The best-known example of this, and probably the most agreed-on example, is Hawking radiation.

The idea behind Hawking radiation is that the same quantum vacuum fluctuations thought to occur everywhere else in the Universe should also occur adjacent to a black hole event horizon. Such fluctuations involve particles and their anti-particles that appearing momentarily and then annihilating each other so they disappear again without a trace. But near a black hole event horizon, one might go in while the other stays out. And since one half of the pair behind the event horizon means there’s no annihilation outside, the Universe gains a new particle.

And it works out that stellar-sized black hole with tighter event horizon curvatures will produce more Hawking radiation than supermassive black holes – whose event horizons are like vast almost-flat plains in comparison. And this is just because of the surface geometry – there are more paths of escape for a particle produced near a curved surface than for a particle produced near a flat surface.

So, this is the current state of play. If you accept Hawking radiation exists, and not everyone does, then that is the temperature of a black hole. The biggest supermassive black holes should have a temperature of 1.4 times 10-14 Kelvin – which is nought point 0,0,0 and another ten noughts and then a one and a four – which is not that far from zero Kelvin anyway. A stellar mass black hole is more like 6 times 10-8 Kelvin – that is, nought point seven zeros and then a 6. So, even a stellar mass black hole has a temperature that’s still well less than 1 Kelvin, but is a tiny bit warmer than a supermassive black hole.

In fact, no black hole that we know about is warmer than the current background temperature of the Universe – that is, the temperature of the cosmic microwave background, which is approximately 2.7 Kelvin. This means that no black holes that we know about are going to evaporate any time soon.

Even if they aren’t still sucking down new matter, whatever miniscule radiative loss they experience due to Hawking radiation is vastly overwhelmed by the input of photons from the cosmic microwave background. It’s not until the Universe has become so stretched, so that temperature and photon density start approaching zero that any black holes are going to have any chance of evaporating. So, it may be a googolplex or more years from now before our last supermassive black holes finally fade away.