INTRODUCTION

Ok, this is the overview of the content of the lectures.

First of all, I would liek to know where you come from, i.e. if there is anyone form the astronomy department.

Since my background, I have a Ms in Astrophysics and Comsology, and a PhD in particle physics, I try to put more emphasis on the connection between the Astro and the Particle aspects of what I am going to show you, since the two things are really connected. You will see that to understand what is really going on in the Universe out there, and you know that we talk about the Universe we are not only going around in space and observe a certain direction, but we are also observing phenomena and objects back in time, since light takes a finite amount of time to propagate form a certain point to us, so that means that we see now something that might have happend billions years ago.

Now the big question is, how do I study the universe?

You have seen in Prof Wulz lectrues that there are two basic ways to explore the universe, namely radiation in whatever wavelenght or frequency, and particles.

I will stress the concept of Multimessenger astronomy, which turned popular again since a few years after the discovery of the first gravitational wave, but you have actually already seen it in the last lecture when talking about neutrinos and the solar problem. If you remember, the calculation made by Bachall about the total flux of neutrinos was not matched by the experimental observation. So they could see less neutrinos that the predicted number, and the solution to the puzzle was that both the theory prediction AND the observed number observed by experiment were right. Simply there was an additional aspect to add, i.e. the oscillations of neutrinos. So that the number of electron neutrinos, the only family that could be seen in the homestake experiment, was decreasing during the travel from the Sun to Earth.

I will talk about this again later today, but this was just to introduce the concept that basically I have an astropysical problem, in this case the nucelar fusion inside the Sun. I have a model that tells me how Hidroge atoms combines to give me Helium, produce energy and photons to stabilize the star against the gravitational collapse and at the same time neutrinso are produced. Thanks to the observation of both photons AND neutrinos, so two different types of messengers, I can get the proper picture of what happens there, and confirm the model of nuclear fusion plus find out that neutrinos oscillate (thanks to the SNO expeirment, then Kamiokande and so on).

And this is what I hope to do during this lectures: I will introduce you some problems in astrophysics or cosmology, and will try to see how to use the information from different messengers or experiments to try to solve the puzzles. In practise we will talk a bit about black holes, events of merging of black holes or neutron starts, and the very big problem of dark matter in the universe.

Again, the topic is huge. In order to understand deeply all of this, which by the way I dont myself, I just know some stuff here and there, you have to know about litterally everything, from stellar astrophysics to stellar population, to galaxy formation and evolution, to AGNs so active galactic nuclei, gamma ray bursts, particles, cosmology etc.

So it would take forever basically, so I will focus on key points and try to give you a self consistent and compact explanation of a few interesting cases.

By the way, I consider these topics really fascinating so in case you have questions, even general, you can of course ask me whenever you like and hopefully I knwo the answer, but yeah as I was saying it is really difficult to know all of this in detail. Mostly you specialize in a tiny part of it, and then smart people get together and work on a project but each focussing on a particular aspect.

I see some PhDs students here working in particle and searches for exotic particles at the Large Hadron Collider that I am sure are expert in the filed of particles there at the LHC but maybe have no idea about propagation of cosmic rays in the galaxies or dwarf spheroidal galaxies.

**GW**

So, lets get started with gravitational waves.

It is really the hot topic in astronomy and astrophysics, and I would say also in general theoretical and experimental physics since, after the discovery of the Higgs boson in 2012, we don‘t have really something to be super excited about at least in particle and astroparticle physics.

Just to introduce the topic, I can say that Gws are again another proof that Einstein was right and the theory of general relativity holds pretty well, and all the predictions that you can make out of it seem to be consistent with observation.

Gws are important becouse they offer an independent way ob observing the universe and the astrophysical processes that happen there beside the use of electromagnetic waves (light or X rays or Gammas or radio or infrared) and cosmic rays.

With GW you can probably go even more back in time so closer and close to the instant of the Big Bang, so the moment where the Universe was born as described by the accepted standard model of comslogy, which described the birth and evolution of the universe (we will see it next time briefly).

So they are a very powerful method to investigate many aspects and phenomena out there in the cosmos, and they could even be the ONLY way to study some of them.

One thing that you always hear about these Gws is that they were one of the first prediction of general relativity by Einstein . It is quite true, in the sense that Einsteins and other people started calculating stuff right after the publication fo the paper, however it took a lot of years, around 50 or so, to establish the proper cauclations and to derive a proper waveform (so to predict correctly the amplitude and frequency of the GW originating from a certain system of masses).

I personally think that GR is the hardest topic I have ever encountered in my study career, so it is no surprising at all that it took so much time to calculate it.

Anyway, a crucial step forward was the discovery of a binary system where two neutron stars orbiatte around each other, called Hulse-Taylor system where these two are the guys who discovered the system during their PhDs and won later in 1993 a nobel prize. { I didnt discover anything during my PhD }

This was very important because the analysis of this system confirmed a prediction of GW: essentially, if I have such system, I expect the emission of gravitational waves, and since they carry away energy, the system slows down. All this measurements are actually performed with the Arecibo radio telescope, which is situated in

Hulse-Taylor binary system

Well before the discovery of gravitational waves by the Ligo and Virgo collaborations, around 30 years ago, there was another experimental proof of the existence of gravitational waves. Now, to be honest, to me the evidence was still indirect, but the authors of the original paper, dated back in the 1970s, claimed to have found the first evidence of the existence of gravitational radiation according to Einstein’s theory of general relativity.

This system is a binary system, composed by two neutron stars, that orbitate around a common centre of mass. The mass of the two stars are very similar, and this is absolutely expected for pulsars or neutron stars since they all have a common origin meaning that they are the remnants of Supernovae explosions.

I am sure you heard about Supernovae, they are one of the most energetic events in the space, I will talk about it a bit later if I still have some time left, since they are a diamond mine for astrophysics studies, both from pure astronomy so whatever band of observations (infrared, optical, xrays, gamma rays), purely astroparticles physics since basically they produce a very hot and dense plasma so highly ionized gas of elements that then decay since they are unstable, and they basically produce all the elements heavier than Iron that you find in the universe (parenthesis: elements up to Lithium and possibly some slightly heavier are produced during baryogenesis which is a phase of the Big Bang; heavier elements up to Iron can be produced by massive stars during their life cycle through nuclear fusion processes, everything heavier is produced during Supernovae explosions or in terrestrial laboratories). So to come back to cosmic rays, this shock wave of highly ionized plasma of nuclei of different chemical elements are injected in the space and produce highly energetic cosmic rays that are most likely what then we observe with the various detectors you now know very well. Plus: one other extremely important particle which actually gives the information of what really happens during the various phases of the stars evolution that are neutrinos. Always remember that neutrinos are really the real-time messengers of what happens inside the stars or during the Supernovae explosions, thanks to the fact that their interaction rate is so negligible that they come straight to Earth (plus they are neutral so they are not deflected by the galactic magnetic field). Finally, we will see that SNe are a source of gravitational waves, not yet detected or let’s say that we have no news about this topic from Ligo and Virgo so maybe they are working on possible GW from SNe explosions. So SNe explosions and in general star evolution was my favourite course that’s why I am so passionate about this topic, hope you are also, and if not you don’t pass the exam :-)

Now back to this binary system with two neutron stars, of which one is a pulsar. Pulsars are a very important type of neutron stars that emit a huge load of radiation, in particular in the radio band. Again to be more precise, the most favored model of pulsars indicates as rapidly spinning neutron stars as the possible objects that creates the peculiar emission in the radio band that we observe with radiotelescopes.

KAGRA = Kamioka gravitational waves detector