

## CAST for not so Dummies

I have decided to write a document about CAST during the training sessions I was doing for the new CERN guides. I know from experience that, when you become a guide, even if you join 1-2 visits with an experienced guide, it is not quite enough to get a good feeling of each experiment in detail. Although, as guides we do not have to know everything in a great detail, it is always good to know “fun facts” about experiments, with which you can stimulate the interest in the visitors, and make them go back to their homes with higher desire to learn. This very document will try to serve this purpose, it will give “fun facts” and important things of the CAST, which I think can be told to visitors by guides. I aim to have a light, easy to read guide for everyone including physicists to administrative people or artists. I called it “CAST for not so Dummies”, I was gonna name it “CAST for Dummies” but then thought, if you are at CERN, you can't be dummy!

CAST stands for CERN Axion Solar Telescope. As the name says, it is a telescope at CERN looking for a particle called [axion](#), which should be coming from the Sun. The first question is of course what is an axion? It is a hypothetical particle, which means it is not known if it exists or not, but we have a physical motivation that it does. The very short version is this:

*“There is a problem in our theory, to solve this problem we can propose an extension to our theory, a new mechanism, and result of this mechanism is a particle called axion. If we observe the particle, it will prove our theory, and will solve one of the standing problems in physics. Furthermore axion can be a solution to dark matter problem.”*

And here is the long version: Feynman has this great analogy for nature and physics. Physics is like watching a game of chess, and trying to understand the rules. All we do is trying to write a “Chess Rule Book”, which in the case of particle physics is the [Standard Model](#). Technology increase your ability to see different parts of the chess board. Initially you can see some corners of the chess board, and guess the different type of particles(like pawn, bishop) and how they interact with each other, how they move. Lets say you watch for long time and start to get confident in the rules you are decoding, but one day, you see something so strange, your rule book fails to explain it. Then one has to change the rules , or make little adjustments to extend them to cover the particular weird case.

Axion comes from a similar story. We have 4 types of interactions in the universe. In [weak interactions](#), CP(charge-parity) is not a symmetry: meaning if you replace all the particles with their antiparticles, and take the mirror image of the system, the physics becomes slightly different. This is what we call “[CP Violation](#)”. It is important because it can give hints on why there is a lot of matter in the universe, and very little anti-matter. Lets summarize: *In the weak interactions CP symmetry is violated.* Physics of [strong interactions](#) in theory also allow violation of CP, but it is not observed. Not observing something you expect to observe is somehow a problem in physics. Think that you have an model, and in your model you have a non-zero

term(CP violation term in Strong Interactions). But all the measurements you make tell you that this term is zero, or extremely small, beyond your measurement sensitivity. This can be a coincidence, but physicists do not like coincidences! So we want to explain why this term is zero. [Skivie](#) has a great analogy to understand this. The answer to the Strong CP problem comes from Peccei and Quinn, they propose a mechanism, that explain why we do not observe CP violation in strong interactions. They show that CP violation term in our equation is not a constant, but instead a dynamic variable, and after some energy scale, this term becomes 0. There is a result of the mechanism they propose, there should be a new particle: axion. The name is given by Franz Wilczek, who used the name of a detergent brand, saying “this will clean a problem in Standard Model”. Steven Weinberg suggested the name “Higglet”(well, axion can be thought as a smaller celebrity compared to Higgs, so Higglet was also a nice name) but axion became the official name of the particle.



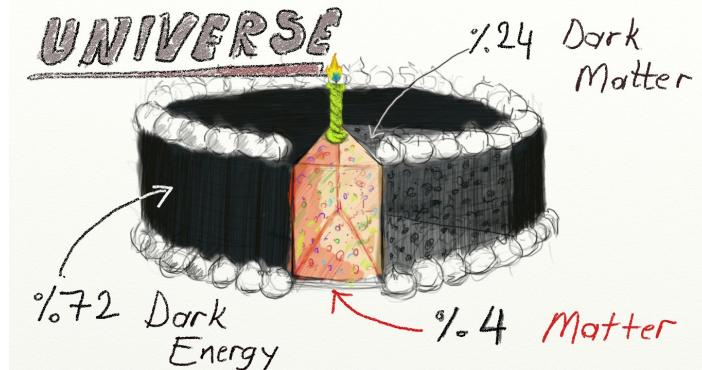
From the way we builds a model, we can predict properties of the particles that are in the model. This is how we know what Higgs is like, and what Axion should be like. Axion is a very light, and weakly interacting particle. When I say weakly interacting, what I mean is that it is a ghost, it passes through us, it passes through walls, it passes through planets. The concept of touching as we know is simply electrons not wanting to get close to each other, due to their interactions. So if you don't interact, you will pass through stuff, like a guy who doesn't want to interact with anyone in an office, so he can pass through the long corridor and go directly to his desk. With this analogy, photon would be a cheerful socially active office person(yes sometimes they are also annoying).

I should put a big BUT here. Although it pass through stuff, it has some types of interactions where it can be converted into something else. When an axion pass through a transverse magnetic or electric field, it can be converted into a photon(This is called Primakoff effect). Similarly if a photon passes through a magnetic or electric field, it can be converted into an axion, with the same probability. The shy office guy loves chocolate chip cookies. If you offer him cookies while he passes, he may stop to eat some, and with all that chocolate load, he'll be converted into a more cheerful guy, who now likes to interact!

But since it weakly interacts, only a tiny tiny percentage of axions will be converted to photons, even if you have a really high field. To have even 1 photon in the end, you'll need to send many many axions in the magnetic/electric field.

I'll open a parenthesis and tell you another reason that makes axion important. It is a candidate for [dark matter](#). What is dark matter: It is something that has mass and is affected from gravitation, but it hardly interacts with any particle via the 3 other forces. In total it has 6 times more mass compared to matter we can see(galaxies, planets, everything). We know dark matter is there by observing how matter behaves, but our instruments do not see it directly(yet!). Axion fits to this schema perfectly. So finding axions, will solve two problems in physics(Strong

## CP problem and Dark Matter)



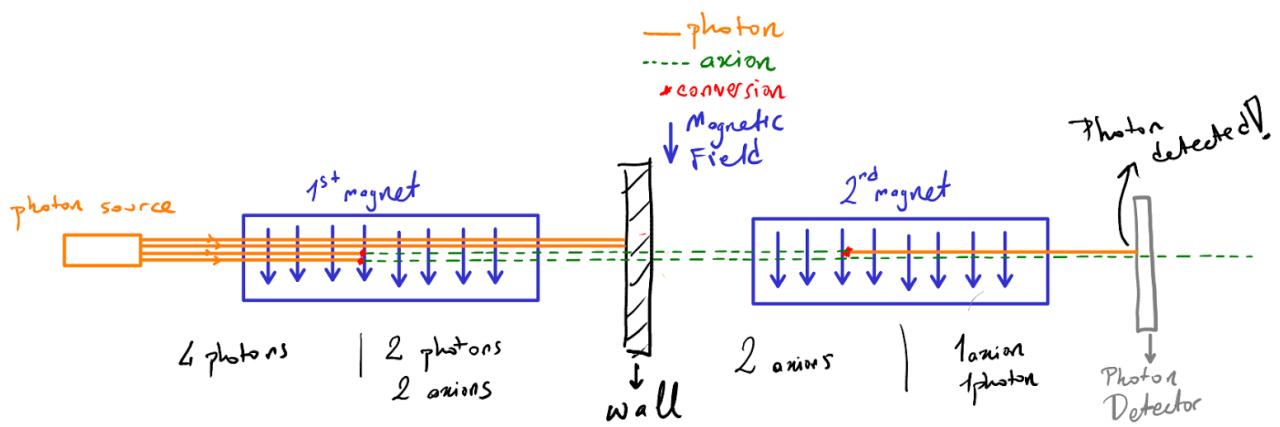
Drawing by Fırat Yılmaz

The probability of axion-photon conversion depends on following things.

1. [Coupling constant](#). It defines how probable the conversion is. If coupling constant is too high, axions and photons would be frequently converted into each other in electric/magnetic fields. Since this doesn't happen, we know it must be quite low. What we try to find is how low it is.
2. Strength and length of the magnetic/ electric field. If you have a stronger field or a longer source, it is more likely that the conversion will occur. So if the coupling constant is too low, to see photons being converted from axions, for instance you'll need really long magnets with strong magnetic fields. More cookies you put around the office, more likely the shy office guy will stop to eat them.

In theory, the recipe is simple, find some axions, pass them through a strong magnetic field, and you'll have photons, which are easy to detect. (Our eyes for instance are great photon detectors). But wait! Where do I find axions? If I can't see them, if I don't even know they are real, how do I know if there are axions coming to my direction?

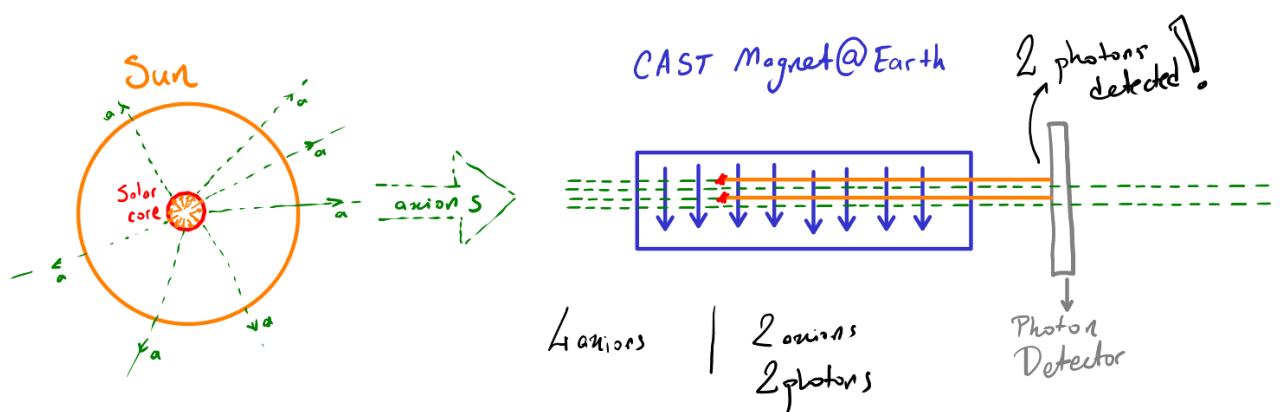
Well, firstly you can try creating them yourself. For instance if you send a strong photon beam into a magnet, and some will be converted into axions. After that you can place a thick wall that will stop all the photons, and only axion will pass through. Then after the wall you can put another magnet, which will convert some of the axions into photons and you can detect the photons! If I detect any photons, I can claim they are regenerated photons that was converted into axions in the first magnet.



For instance, you send 4 photons into a magnet, 2 are converted to axions. The photons that are not converted will hit the wall and stop, while axions will pass through the wall. In the second magnet lets say one of axions are converted back into photon. While the other axion pass through the detector undetected, photon will be detected. Of course, in reality the probability of conversion is really low, 50% of the photons are not converted into axions.

Second option would be finding an axion source from the space. This is what CAST does. Sun, is the closest photon source for us. It's not the biggest or strongest star, but since it is quite close to us, it is the brightest source. Axions are emitted from the Sun with the following mechanism: In the core of the Sun the x-ray photons are emitted due to temperature which is 10 Million degrees Kelvin. These photons normally make a lot of collisions and most can not go out of the Sun in long time. But where axions are emitted in the solar core, there are also very high electric fields, when photons are passing from these fields, some of them should be converted to axions! These axion go out of the Sun easily and reach the Earth since they interact very weakly with matter. We can say that, there is a constant flux of axions coming from the Sun to the Earth.

When axions come to the Earth, if we do not do anything they will just pass through the Earth. To see axions we use a LHC magnet and try to convert them back to photons, because as said earlier, photons are easy to detect.

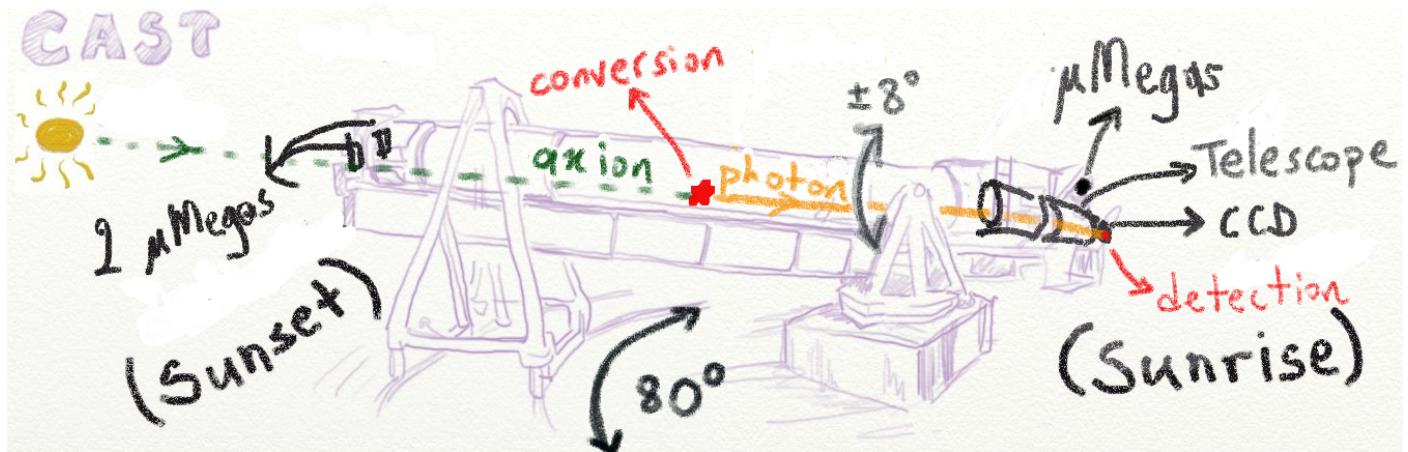


Lets say in the solar core, some of many photons are converted to axions, and 4 of them came into our magnet. Axions enter the magnet pass through first detectors, since they don't interact. In the magnetic field, 2 of this 4 axions are converted back into photons. This 2 photons will be detected by my detector, while axions will pass through it. Again, in reality the probability of conversion is really low, 50% of the axions are not converted into photons in the magnet.

The CAST magnet is a LHC prototype test magnet. It has 2 bores(pipes) which are designed for protons to travel in different directions. In both ends of both bores we have detectors. Magnet is sitting on a mechanism that can move +8 degrees vertically, and 100 degrees horizontally. Every morning, when the Sun rises, we align the magnet to the Sun and track it while its rising. During the sunset we do the same from the other side.



The detectors that are close to sunrise(east) are called "sunset detectors", while the ones close to sunset(west) are called "sunrise detectors". During the sunrise, axions come from the sun, pass through the building walls, pass through sunset detectors and go in the magnet. Inside they are subject to the 8.8Tesla magnetic field. The ones that are converted to photons(if any) are detected by sunrise detectors. In the evening the opposite happens. Both at sunrise and sunset, CAST magnet can watch the Sun for 1.5 hours. This is because of mechanical limitations of the magnet, if we had a more flexible system, we could have watched the Sun 24 hours, even when we don't see it physically in the sky. The CAST magnet's tracking movement looks like [something like this](#). Note that this is a fast forwarded video of a 1.5 hour long movement.



Example of a morning tracking during sunrise. The axions that come from the sun enter the magnet passing through sunset detectors, and if the ones that are converted to photons they will be detected in sunrise detectors.

Drawing by Fırat Yılmaz

To prevent detection of the photons coming from outside the magnet, we shield the detectors as much as possible. We want the only photons that are detected, to be the ones that are converted from axions who entered the magnet. One can think each detector as a camera, that is looking into the pipe. They should not see anything that comes from outside. They should only see photons that come from inside the magnet bore, and when they do, we will know these are the photons that were axions when they entered the magnet.

But, the experimental physics does not always work with perfect ideal conditions that we are taught in high school or even in university. In reality [The cows are not spherical](#). There is something called *background*.

We said we track the Sun for 1.5 hours with the sunrise detectors. For the rest of the day, detectors keep working but take background data. So lets say, during 1.5 hours, I observed 15 photons(10 photons/hour). Does it mean that I saw the axion? Not necessarily. I should also check how many photons I saw while I was NOT watching the sun. If I observed 205 photons during 20 hours of background(around 10 photons/hour), then I saw same rate of photons during tracking and background runs, and I can't claim I saw axions. One may ask, where did the photons come while we were not watching the sun? They are results of "non-perfectness" of our systems. Although we shield the detectors, so that x-ray photons can not enter, some other particles like muons(a heavy electron-like particle that is hard to stop with shielding), or gamma rays(more energetic photons) can enter, interact with some part of the system(for instance the pipework) and create x-ray photons. Furthermore, each material can have a radioactivity(normally we don't tell it to non-physicists, so they don't freak out.). Some materials can emit photons or other particles(such as alpha or beta particles), and these may also be seen by our detectors. For instance, all lead contain a radioactive isotope  $^{210}\text{Pb}$ , that emit radiation. That's why experiments like CAST prefer to use ancient Roman lead, as the radioactive part has disappeared through decays(Thanks Roman empire, you are contributing to

modern physics!).

Since we watch the Sun only for 1.5 hours with each detector each day, we know that anything that comes outside of this 1.5 hours is not possibly axions, and are called *background*. Think it as sound. Lets say your roommate is listening to music. This is your background sound. It is always there, and has a constant characteristic assuming that it is same kind of music all the time and not switching from Vivaldi to Iron Maiden. And lets say you are trying to prove a hypothetical instrument called church bell. You know that if it exists, you should hear it every hour for 2 minutes, with some characteristics. If the church is close enough, and the music volume is low enough, every hour you'll hear the bell. Your ears, which are great detectors for sound waves, will see a difference in the incoming sounds for this 2 minutes. Background music is still there, but with an addition of a ringing sound. You see that to be able to hear church bell (detect signal), you need to have your music volume down(low background) and church close enough(high axion flux + high axion to photon conversion). Also, if your background is really distinct from expected signal, you have better chance. For instance if your background sound is a bass gitar solo from Paul McCartney, and your expected signal is the church bell, you won't have much problem hearing it. But if your roommate likes experimental music and is listening to a crazy piece made of mixture of church bell sounds(I'm sure someone has made it), you'll not hear or distinguish the church bell you are expecting.(If I get little technical with the last analogy, we have better chance of detecting axions, if our background is low especially in the energy range of solar axions: 1-10 keV.) But in the end, low background is the key thing, lower the background sound, better the chance you will hear your signal. Then one may say, "Why don't I ask my roommate to turn the music off?". Yes, that's exactly what we are trying to do with detectors: we want zero background. I have to tell, we managed to decrease our background sound to much lower than when we first started. We believe that in some time, we'll be able to make it so low that we almost don't hear it.

In the experiment we have 4 detectors, 2 at each ends of each bores. Three of these are MicroMEGAs(Micro Mesh Gaseous structure) detectors, which are gaseous detectors, and one is CCD(Charge-Coupled Device) which is similar to chips used in digital cameras. The CCD is placed after a x-ray telescope, which focuses all the photons that come parallel to the beamline, to a 3 mm diameter spot on the chip. This has an advantage, everything that is detected outside this area is definitely not a photon coming from axions(we are aligned to the Sun and all axions from the Sun move parallel to the magnet bore).

We have been running CAST in 2 different phases.

1. Vacuum phase: Inside the magnet, we had vacuum, i.e. there are almost no particles in the magnet.
2. Gas phase: Inside the magnet, there is a gas, and the pressure is 0 to 100 mbars.  
Everyday we added little more gas.

If you have vacuum or gas, you have different results and you are sensitive to different axions. In a magnetic field in vacuum, one is most sensitive to axions with low mass. So if the axion has a

mass higher than a specific value(0.02eV) the conversion probability is quite low in vacuum. Instead of vacuum, if we have a gas, then the conversion probability is high only if axions are within a narrow mass range. Lets give an example. In vacuum, axions will be converted into photons only if their mass is less than 0.02eV. Instead if I have 6mbar of Helium gas, they will be converted into photons if their mass is between (0.255eV - 0.265 eV). You can think this as follows: Axions can be converted to photon(or vice versa) only if they have almost the same mass. In reality photons never have mass. But we can look from a different angle and say they have mass. We know that in vacuum photons travel with speed of light, and in a medium, it travels with less speed depending on the refractive index of the medium. This can be thought as photon has mass when not in vacuum. We call this effective mass. As you increase the pressure in the magnet, the photon becomes slower, effective mass increases, and we become sensitive to axions with higher mass, which is equal to this effective mass.

In CAST, we first used Helium gas, then we had to use a special isotope of Helium with 1 neutron ( $^3\text{He}$ ). Reason is that magnet has to be extremely cold(less than  $-273^\circ$ ) to be superconducting, and helium becomes liquid after some pressure so we needed a gas that can be still gas in higher pressures.

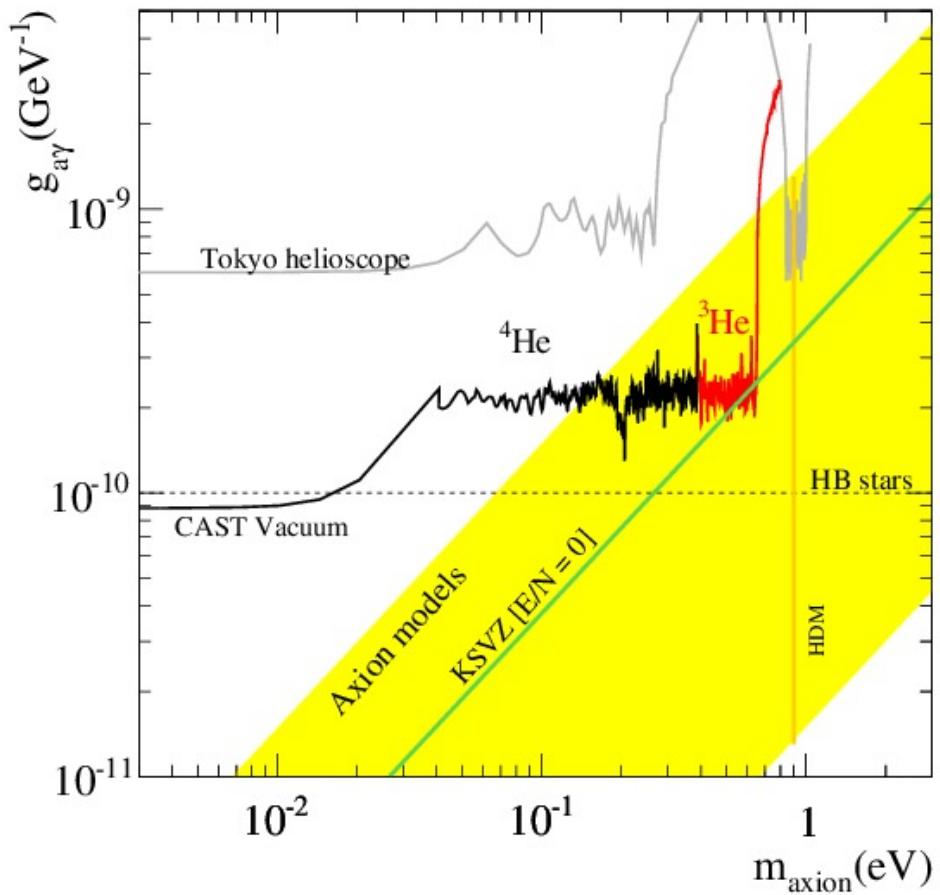
Finally lets take a look at what CAST achieved. Did we find axions? No. Does it mean this experiment failed? No again. In CAST, we try to prove existence of axions, but if we can't we impose some limits and tell what could be the properties of axions, and exclude some possibilities. Axions are being probed by many different experiments, and although we are in competition to find the axion and provide the strictest limits, we are also working in a collaborative way. Each experiment excludes some possibilities, and we are narrowing down the circle in our search for the fugitive particle.

For axions there are 2 unknowns.

1. Their mass
2. Their coupling constant

When we don't observe axions, we can calculate for each mass, what is the maximum coupling constant axions may have. Combining the result for all masses give us the *exclusion plot*.

One should read the exclusion plot as follows: For each mass, find the coupling constant that corresponds to it on the blue line. If axions had this particular mass, and coupling constant was higher than this value, my experiment would detect the axion. Since I did not detect anything, I exclude the possibility that coupling constant is higher. That's why it is called an exclusion plot.



**The Exclusion Plot:** The black and red lines are the result of cast, while grey one is results of other helioscope.  
The yellow band is the theoretically favored axion models, meaning that we expect axion to have mass and coupling constant in this band.

In the end, we haven't found our dear particle. It is possible that CAST, or another type of experiment, or the next axion Helioscope [IAZO](#) will observe it. Let's hope for the best!

I've added some common questions and answered them. If you have more questions or think some parts are unclear, please send it to [cenk.yildiz@cern.ch](mailto:cenk.yildiz@cern.ch). I want this document to be *rolling*. As I receive input from people, I'll improve it in time.

**Q: A question that comes to mind is “So what?”. Even if we find axions, how will it affect humanity? Is it worth the money we spend for this? Will time travel or teleportation be**

**possible if we find axions?**

A: Even if you won't be able to make a time machine or teleportation just because you found axion, it will be something that show us we understood the universe better. Understanding it gives us power to manipulate it.

**Q: What if axions are coming from other directions and converted to photons in the magnet while you are not watching the sun, how can you call these photons background?**

A: It is possible, it may be that there is an axion flux everywhere in all directions, and if so they would be entering the magnet all the time, and some can be converted. This is true, but we are focused on solar axions, so other axions that enter the magnet and create a photon would do that anytime, and would not create a difference when we are watching the sun. If we go back to our church bell analogy, my background would be the music + a faint constant ringing (non-solar axions), and still I would distinguish the church bell since it should only be heard during specific times. Furthermore, when we are not tracking the sun, we sometimes turn off the magnetic field, and sometimes keep it on. If there was a constant axion to photon conversion in the magnet, it would disappear when we turn off our magnetic field(since axions are only converted when there is a field) and number of photons we observe would be less when we have the field off. In fact there are experiments called "Haloscope Experiments" that try to convert axions that are coming from the [galactic halo](#). (see: [ADMX](#))

**Q: What if axions are converted back into photons in the sun and gets trapped, or what if axions that are converted to photons in the magnet are converted back into axions before reaching the detector?**

A: It is possible, but really unlikely, so essentially it doesn't affect our calculations. Lets assume that in our magnet the probability of conversion from axion to photon is 1/1000, so 1 of every 1000 axions will be converted into photons. For this photon to be converted back into axion you again have 1/1000 chance(in fact you even have less chance, since the photon will travel less distance in the magnet). You can see that probability of an axion to be converted into photon, then back into axion is less than:

$$\frac{1}{1000} \times \frac{1}{1000} = \frac{1}{1000000}$$

In reality the probabilities are much much lower than 1/1000, so the probability of double conversion becomes even less.

Cenk Yildiz  
Geneve, February 2013

**References:**

[PDG Axion Review](#) - A scientific source for summary of axion theory, searches and limits

[Pooldable Analogy to Axion Physics](#)

[www.cern.ch/cast/publications](http://www.cern.ch/cast/publications) - Publications of CAST experiment.

[Firat's presentation](#) - Presentation of a CAST Summer Student, source of some drawings in this document.