The fascinating Milky Way

Inaugural Lecture by Dr. Amina Helmi

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Summary

The Milky Way is the home of thousands of millions of stars and planets, including our Sun and the Earth. The beauty of the myriads of stars that can be seen on a clear night as a whitish band of light on the sky have always been a source of inspiration and fascination for humankind. For astronomers like myself, in particular, that fascination lies also in deciphering the workings of the Universe through the use of mathematics and the laws of physics.

The Milky Way is fundamental for our understanding of the Universe as a whole, and effectively acts like a Rosetta stone that is used to establish what the Universe is made of and how galaxies in general have formed. It is also fascinating to realize that some of the stars that are close to the Sun now were born in the infant Universe, and are like fossils that have witnessed how the Milky Way grew into what it is today.

The focus of this lecture, and of my own research, is precisely to use stars to reconstruct the history and the characteristics of our home galaxy. In this lecture I will describe what we have learned so far and discuss upcoming research in what is a Golden Era for Galactic Astronomy. In the coming five years the European Space Agency's satellite Gaia will measure the properties of one billion stars in the Milky Way. This unparalleled new dataset will allow us to address the most fundamental questions about our Galaxy's history and dynamics. With the revolutionary new understanding that Gaia promises to deliver, we will obtain unique insights on the process of galaxy formation and on the nature and role of dark matter, two of the most urgent open issues of modern Astrophysics.

A view of La Silla Observatory, showing the ESO 3.6-metre telescope in Chile and with the Milky Way seen overhead in all its magnificence[1].

Leden van het College van Bestuur, zeer geachte aanwezigen

Two of the most important questions in Astrophysics today are: what is the Universe made of? and, how do galaxies form and evolve? An extremely powerful approach to addressing these fundamental questions is to study nearby "representative" systems like the Milky Way. *Only* for the Galaxy and its nearest neighbours can we measure the properties of individual stars like their motions, chemical compositions and ages. Through their motions we can uniquely constrain the nature of the mysterious dark matter, the dominant mass component of the Universe. On the other hand, superb clues of a galaxy's assembly history are encoded in long-lived stars as these retain in their atmospheres a record of their birth environment, and in their motions their dynamical histories. Such stars are thus effectively "fossils". The discovery and interpretation of this "fossil record" has been one of the threads throughout my scientific career: namely to establish *What is the history of our home in the Universe?* Thanks to the recently launched high profile European space mission Gaia and new ground-based facilities this ambitious goal appears to be finally within reach.

Our current understanding of galaxies in the Universe

One of the most spectacular successes in Astrophysics of the past decades has been the opening of new windows to study the formation and evolution of galaxies. These range from deep observations of galaxies over most of the age of the Universe to unprecedented observations of the fossil records of stars in our Galaxy and its neighbors. Furthermore, a cosmological model is now in place that is rather successful in describing the characteristics of the Universe as well as the large-scale distribution and general evolution of galaxies. This is the concordance Λ cold dark matter model. Its fundamental cornerstones are: the Hot Big Bang model (an isotropic and homogeneous Universe that expanded from an initially hot and dense state); the presence of small density fluctuations in the early Universe: the seeds of all the structure we observe today; and, that most of the mass in the Universe is in the form of cold dark matter, and that most of its energy density in the vacuum.

Quite astonishingly we know only the properties of <5% of the mass in the Universe (the atoms we are made of), while the nature of the dominant mass component, the "dark matter" remains elusive. We know of its existence because the motions of stars and gas in galaxies are too large to be only explicable through the mass associated to the light we see, therefore the need to invoke vast amounts of unseen (hence "dark") matter. It is likely that dark matter is constituted by elementary particles that interact with each other only weakly, which is why they are extremely difficult to detect directly in laboratories on Earth (although this is naturally a major enterprise in Particle Physics). Another possibility is that Newton's law of gravity (General Relativity in the weak regime) is incorrect, and that the theory of gravity needs modification.

In the concordance cosmological model, galaxies are embedded in dark matter halos, which grow through mergers in a bottom-up fashion. This hierarchical build up (the smallest halos form first, and then merge to produce larger systems through the action of gravity) is one of the most fundamental characteristics of the cosmological model. Some examples of true relics leftover by mergers are the spectacular streams recently found in the stellar halo of the Milky Way and other nearby galaxies. The discovery and characterization of tidal streams and substructures such as those shown in Figure 1, is of great importance since these are the *only direct* long-lasting probes of the merging history of a galaxy.

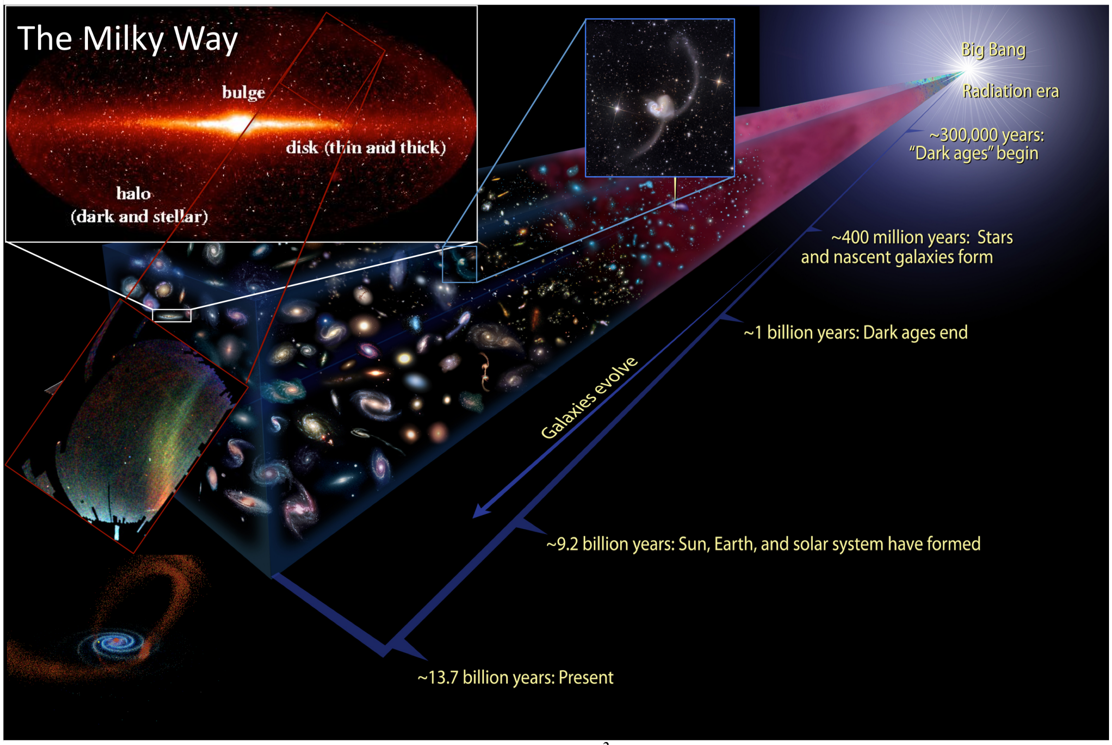

Figure 1. The history of the Universe throughout cosmic time[2]. To explore this history astronomers observe ever more distant galaxies to establish how the galaxy population has assembled through time. On the other hand "Galactic Archaeologists" use long-lived stars as "fossils" to probe the assembly of nearby typical systems like the Milky Way. For example, deep observations of the Milky Way stellar halo have revealed substructures (as shown in the insets) that are leftover debris from mergers our Galaxy has experienced throughout its history[3,4].

The Milky Way in context

The Milky Way contains stars, gas, dust, and the pervasive dark matter, distributed in different components, each with their own characteristics, as shown in the top left inset of Figure 1. These components have different age and chemical element abundance distributions (revealing their place and time of birth), spatial structure (as a consequence of the stars' location at birth), and their constituent stars follow different trajectories (determined by the gravitational forces due to the past and present-day mass distribution). The present-day structure and dynamics of the Milky Way are therefore intimately linked to its assembly and evolution over the age of the Universe.

In the context of the hierarchical paradigm, the progenitors of the Milky Way will have contributed stars, gas and dark matter to the various components of our Galaxy. Stars, in particular, harbor clues to this assembly history. Low-mass stars live for much longer than the present age of the Universe, and retain in their atmospheres a record of the chemical elements of the environment in which they were born. Both the remnants of the very first generations of stars made of nearly pristine gas as well as the subsequent generations containing in their atmospheres the heavy chemical elements returned to the gas by the first stars, may well be present in the Galactic stellar halo, and hence they reveal the physical conditions of the infant Universe. The trajectories of these stars similarly encode their dynamical histories, as exemplified by the tidal tails shown in the insets of Figure 1.

The field of "Galactic archaeology" takes advantage of the "window" that stars provide to probe the processes that have taken place throughout cosmic time and have led to the build up a galaxy like ours. This is a field that has taken off dramatically in the past decade, and which will reach a summit in the coming decade thanks to the recent successful launch of the Gaia satellite, the latest European Space Agency's cornerstone program mission.

A golden era for Galactic Astronomy

Over the next 5 years, Gaia[5] will measure with exquisite accuracy the motions of one billion (1,000,000,000) stars in the whole Galaxy (10,000x more objects and several 100x more precise than its predecessor survey Hipparcos, over a 1,000,000x larger volume) as shown in Figure 2. Accurate positions, distances, and projected motions on the sky (known as proper motions) for stars across the whole sky and out to the edge of the Milky Way halo will become available. To complement this information, very low resolution spectra will be obtained for all these stars to derive their astrophysical properties. Medium resolution spectra will be collected for the brighter stars to measure their motions with respect to us (radial velocities) and some chemical abundances. The survey of Galactic phase-space will be unbiased and complete, and will be of unprecedented detail, quality, and extent. It is currently envisioned that the Gaia mission will have several data releases during its 5 years of operation, with the first one containing full phase-space information for nearly all stars becoming publicly available already in the year 2017.

The scientific impact of the Gaia mission on all areas of Astrophysics will be enormous, ranging from studies of extrasolar planets, through the evolution of stars, to tests of General Relativity. My goal for the next decade is to be at the forefront of harvesting the key science objective of Gaia, namely to unravel the structure, dynamics and assembly history of the Galaxy.

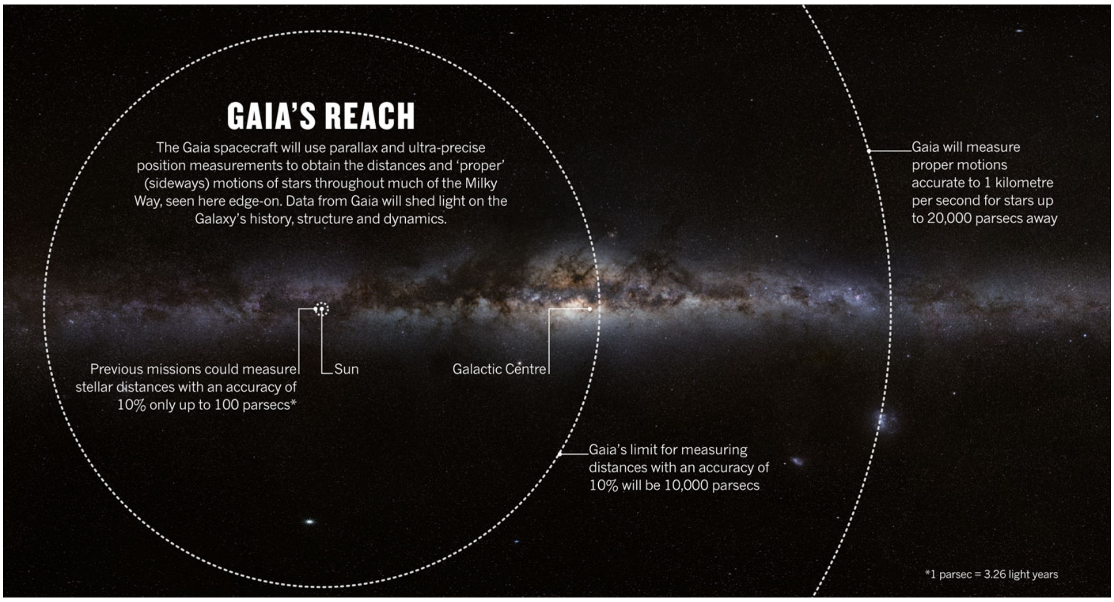

Figure 2: The recently launched Gaia satellite is a transformational European space mission that has started to map the Milky Way in exquisite and unprecedented detail[6]. The catalogue it will produce will remain unsurpassed for decades to come, and its exploitation will address very fundamental questions of modern Astrophysics.

The coming decade: streams and halos

By discovering debris from the merger events the Milky Way has experienced over its lifetime we will be able to derive its assembly history. Galaxies that have merged leave behind long-lasting imprints in the form of streams and substructures (Figure 3, left). These can be identified on the sky, kinematically as moving groups, or as lumps in a space of "conserved quantities" such as energy or angular momenta. Gaia has been designed to detect these features, and it is possible to recover such signatures with sophisticated statistical methods. When detected these features will reveal the building blocks of galaxies back to the beginning of time[7].

Gaia's census of streams can also be used to establish the distribution of dark matter in the Milky Way. Stream stars follow nearly parallel trajectories thereby mapping the gravitational field in which they move. Therefore, they are ideally suited to test cosmological predictions on the distribution of dark matter in galaxies as well as alternative theories of gravity (Figure 3, right).

There is no other galaxy in the Universe for which this suite of very direct fundamental tests of the cosmological model can be made, and we are uniquely placed at this point in time to exploit the fascinatingly vast Gaia catalogue of stars to unveil the secrets of the Universe.

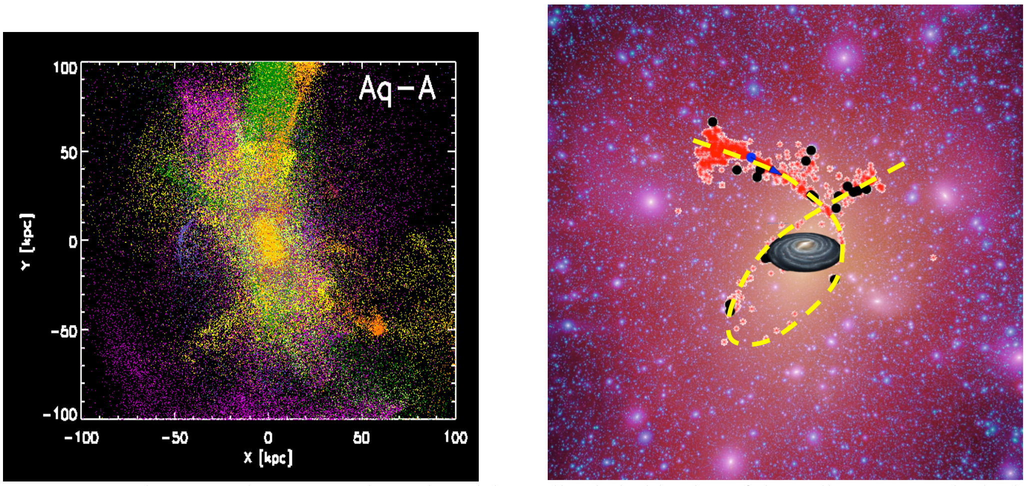

Figure 3. In the concordance cosmological model a stellar halo like that of the Milky Way may be built via mergers of smaller galaxies. In the left panel, a numerical simulation is depicted where their debris from such galaxies is indicated with different colours. In such a halo distant stars are spatially clumped, while those nearby may be moving together through space in streams, or be clumped in integrals of motion space requiring sophisticated methods for their recovery. The different colours in this panel indicate different merger events. Thin stellar streams, such as that depicted on the right panel, are ideal to characterize the gravitational potential of the Milky Way. Our Galaxy is thought to be embedded in an elongated dark matter halo, and to be surrounded by thousands of dark matter ("invisible") clumps as shown here. Gaia will detect hundreds of such streams, whose characterization will allow us to pin-down the nature of the mysterious dark matter, as well as to recover the history of the Galaxy.

Fascination for science

The great majority of us look at the heavens on a clear night and stare with great awe at the Milky Way and pictures of astronomical objects can often take our breath away. It is part of human nature to experience this fascination and curiosity and to ask fundamental questions such as what our place in the Universe is, what our origins are, or to wonder about life in other planets, or more generally about the meaning of life.

At this point in time we live in a society that is strongly driven by economy, and even funding agencies require scientists to measure the impact of their research in monetary or economic terms. This measure is too restrictive given the many facets of a human being. For example, what is the (monetary) value of a scientist that appears on TV explaining global warming? What is the value of a child's amazement after visiting a planetarium[8]? What will be the societal impact of discovering life in another planet? How much is it worth to try and understand how relationships between people function? "It is certainly questionable to state that the value of every research outcome can be quantified and measured"[9].

Furthermore in this modern era immediate return for investment (be it an sms, e-mail, or a science project) seems to be the only possible, or at least the preferred, path. We know also as a society that immediate satisfaction does not lead to long-lasting development. So it is not clear why to require this from the scientific enterprise should be acceptable. Often the application of the knowledge that scientists acquire as they perform research comes much later and in unexpected ways. Let us not forget that "good things take time".

For example, the instruments and telescopes necessary to carry out astronomical research require years, and most often decades, of development from conception to construction and commissioning. For example, the Gaia mission was conceived in the 1990's, and launched only in 2013, i.e. approx 20 years of investment, and it will take at least another 10 years to fully exploit its dataset. At the moment, also two new multi-object spectrographs, WEAVE and 4most, are being constructed for follow-up and complementary studies, and expected to become online at the end of this decade. These are major European investments to capitalize on the Gaia mission, and to maximize the scientific return to the European community.

To pursue science, we need substantial investment and intellectual freedom. We need to explore the quest for understanding why things work the way they do as much as the quest for applicability of our findings (see Figure 4). Pasteur is a great example of a scientist who wanted to know why people became ill, and then used this knowledge to develop a vaccine. But is Pasteur greater than Bohr, who developed the model of the atom and led quantum theory, which is at the basis of very many discoveries and technological developments later on?

The value of the scientific enterprise cannot be restricted to direct economic profit. It relates to being human, to the search for truths, for understanding of the world and the people around us. Only then can we profit truly as a society of the knowledge that we have, and the abilities and true innovative potential. New knowledge does generally not come from an economic need, while on the contrary the world profits economically from freely generated ideas (see again Figure 4). We need freedom to generate true, revolutionary innovation on the short and long-term. But also because if the goal is for science to provide a higher quality of human life, then we need to consider all aspects of what makes us human.

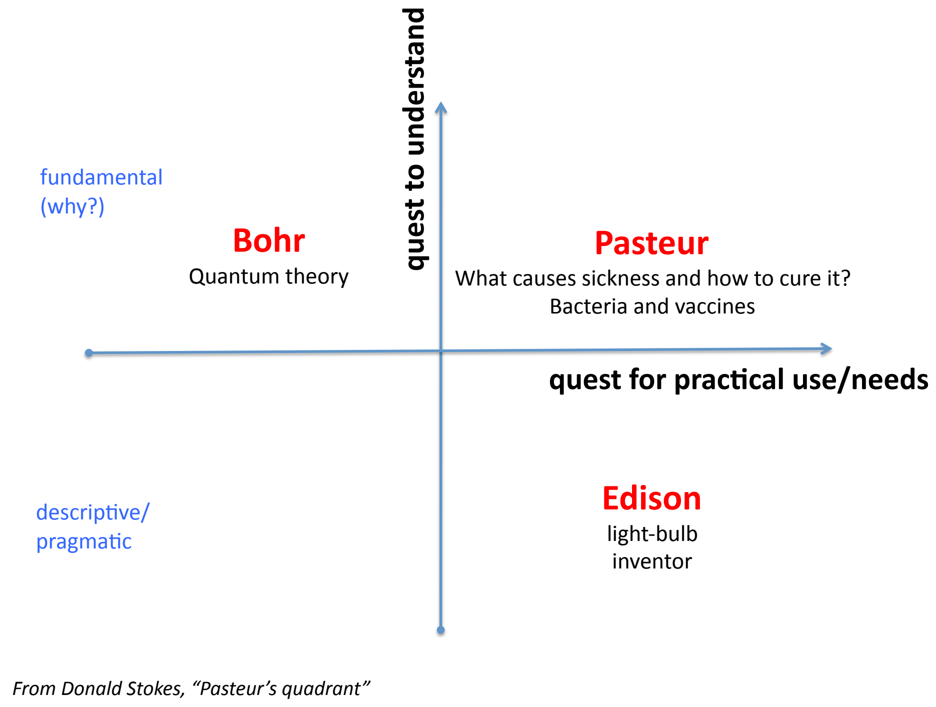

Figure 4. Schematic drawing of the different ways to carry out research, be it driven by the quest to understand or by practical needs, as described by Stokes in "Pasteur's quadrant"[10]. This scheme shows that Pasteur carried out fundamental research to understand what causes sickness, and this knowledge led him to develop a vaccine. This is what most funding agencies currently seem to prefer. However, Bohr was as great a scientist as Pasteur, but the impact of his research was not immediate but of fundamental/theoretical nature at the time. His model of the structure of atoms led to the development of quantum theory. The long-term impact of that research is almost immeasurable, as it is the basis of innumerable discoveries and technological developments that have taken place since then.

Fascination for science has no gender

The first time I recall being truly fascinated by Astronomy was in primary school, when a teacher taught me that it was possible to understand the seasons and the workings of the Solar System by reasoning. The realization that the mysteries and beauty of the heavens could be explained using the subjects that I liked the most in school (namely mathematics and physics), led me later on to choose Astronomy as a career.

It never occurred to me then that as a girl I should be less able to fulfill this ambition of mine. As children we all have such dreams and ambitions and it seems to me that gender only starts to play a role when the environment in which we grow up preferentially nurtures or stimulates some of our choices and abilities, or to the contrary it hinders or censors their development. It is intriguing that in a country like Argentina, where I grew up, in the specific cases of mathematics or astronomy, about half of the university lecturers are female (as are most of the teachers in high school). It then comes a surprise that in a progressive society like the Dutch one, or more generally in northern Europe, so few girls decide to follow a study in science. Please take a look around you at this very moment and become aware of this gender bias.

Role models are clearly missing currently but as important perhaps are the subtle messages that we all convey, often completely unaware of their impact. Women (and girls) tend to be more insecure and as a consequence experience more strongly a set back, especially in the younger years (during primary and secondary school). Overcoming those insecurities is a major hurdle, and those who know me a little, know also I am still struggling. To be successful, "confidence matters as much as competence"[11].

In recent years, it has been argued that one of the reasons fewer women reach powerful positions, is that in societies with a high welfare standard, women have the choice of working part-time or not at all. However, this argument does not explain the dearth of female professors in Dutch universities. Even if in the Netherlands 23% of all women work full time (and 77% of all men), of all full professors only 10% are female, evidencing again a meager and disproportionate fraction of the working population[12].

Fortunately the University of Groningen has a progressive policy and has instituted the very prestigious and successful Rosalind Franklin Fellowship to attract talented female researchers that eventually become full professors, a program that has been emulated by many other universities across the Netherlands. And whether a coincidence or not, I have been lucky enough to have a very balanced research group over the past decade, where the female-to-male ratio was 50/50. But these are only the first steps. We need to move to a situation in which everybody can see that diversity and the multiple female-skills and talents, besides their brain power, can only be beneficial for science and research. It should not be difficult to realize how much there is to be gained by having a balance in the work-floor, just as there is a natural balance out there in the world.

Let me give you a final example of how this bias was overcome in the world of music, where even the 1970s, many orchestras were male dominated. Thanks to "blind auditions", where the musician would perform out of sight, behind a screen, an increase of 50% has been observed in success rate. Today, these blind auditions are standard for many orchestras[13]. Can we find something similar for scientists?

Let us not forget that the Universe is there for all of us to admire and explore, independently of age, gender or race. And with that, I conclude.
Ik heb gezegd.

Acknowledgements

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References

1. Image obtained from http://www.eso.org/public/images/uhd_img4262p_bt_cc/
2. Background illustration obtained from STScI site, http://www.stsci.edu/~inr/thisweek1/2008/thisweek231.html
3. Belokurov, V., Zucker, D.B., Evans, N.W., et al. 2006, ApJ, 642, L137
4. Law, D.R., & Majewski, S.R. 2010, ApJ, 714, 229
5. For more information, see http://sci.esa.int/gaia/
6. Image obtained from http://www.nature.com/news/astrometry-europe-s-star-power-1.13859, picture credit to S. Brunier/ESO; Graphic Source: ESA
7. Helmi, A., 2000, "*The formation of the Galactic halo*", PhD Thesis University of Leiden
8. See http://www.studereninleiden.nl/actueel/bericht/mobiel-planetarium-voor-basis-en-middelbaar-onderwijs/
9. See Robeyns, I. 2013, de Jonge Akademie, http://www.dejongeakademie.nl/nl/columns/wetenschapsbeleid/minister-bussemaker-beperk-wetenschap-niet-tot
10. Stokes D. E., 1997, "*Pasteur's Quadrant – Basic Science and Technological Innovation*", Brookings Institution Press; also Dudley J., 2013, "*Defending Basic Research*", Nature Photonics 7, 338
11. Julia King, 2014, The Guardian, http://www.theguardian.com/women-in-leadership/women-leadership-blog/2014/oct/20/women-science-engineering-under-representation?CMP=new_1194
12. Meijer, J. 2014, based on statistics by the CBS, http://www.lnvh.nl/site/Worth-reading/Links/reactie-van-joke-meijer-op-artikel-barbara-baarsma-nrc-30092009.
13. Goldin, C. & Rouse, C.: 2000, Orchestrating Impartiality: The Impact of "Blind" Auditions on Female Musicians. The American Economic Review 90, 4