Warm Dark Matter Astrophysics in Agreement with Observations and keV Sterile Neutrinos:

Highlights and Conclusions

of the Chalonge - de Vega Meudon Workshop 2016

In Memoriam Héctor de Vega

Ecole Internationale d'Astrophysique Daniel Chalonge - Héctor de Vega Meudon, CIAS, 15-17 June 2016.

Norma G. Sanchez[(a)], **Sinziana Paduroiu**[(b)], **Peter L. Biermann**[(c,d,e,f)]

[(a)] *LERMA, CNRS UMR 8112, Observatoire de Paris PSL, Sorbonne Universités UPMC Univ Paris 6. 61 Avenue de l'Observatoire, 75014 Paris, France*[*]

[(b)] *Geneva Observatory, University of Geneva, CH-1290 Sauverny, Switzerland*[†] *and*

[(c)] *Max-Planck Institute for Radioastronomy, Auf dem Hügel 69, Bonn, Germany*

[(d)] *Dept. Phys., Karlsruher Institut für technologie, Karlsruhe, Germany*

[(e)] *Dept. of Phys. & Astr., Univ. of Alabama, Tuscaloosa, AL, USA*

[(f)] *Dept. of Phys. & Astr., Univ. of Bonn, Germany*[‡]

(Dated: July 18, 2016)

The mass distribution observed in galaxies is found to be incompatible with the CDM predictions, falsifies the baryonically fine-tuned CDM scenarios and leads to keV Warm Dark Matter (WDM). WDM is a hot topic in galaxies and cosmology and implies novelties in the astrophysical, cosmological, particle and nuclear physics context. WDM research is progressing fast because it essentially *works* naturally reproducing the observations at all scales. A Turning Point operated recently in the Dark Matter research: Warm Dark Matter emerged impressively over Cold Dark Matter (CDM) as the leading Dark Matter candidate. WDM solves naturally the problems of CDM and CDM + baryons. (ΛWDM) provides the same successful large-scale results and CMB results as ΛCDM and agrees with the observations at the galactic and small scales as well. The Chalonge - de Vega Workshop 'Warm Dark Matter in Astrophysics in Agreement with Observations and keV Sterile Neutrinos' addressed the last WDM achievements including its distribution function and equation of state (The Eddington like approach to galaxies), the quantum mechanical framework to galaxy structure reproducing in particular the observed galaxy cores and their sizes, and the properties of dwarf galaxies. This workshop summary puts together astrophysical, cosmological, particle and nuclear WDM, astronomical observations, theory and WDM analytical and numerical frameworks, which reproduce the observations. The Workshop addressed the exciting ongoing theoretical and experimental developments in the search for the leading WDM particle candidate: keV sterile neutrinos. The recent impact of WDM astrophysics, its signatures and constraints with high redshift galaxies, clusters, cosmic recombination, 21 cm line, with or for the JWST, HST, SKA, X-ray astronomy and gravitational lensing were presented. News from KATRIN, ECHo, and ASTRO-H were presented by members of the respective collaborations. Peter L. Biermann, Isabella P. Carucci, Pier-Stefano Corasaniti, Loredana Gastaldo, Anton Huber, Daniel Maier, Nicola Menci, Eloisa Menegoni, Sinziana Paduroiu, Paolo Salucci, Norma G. Sanchez, Matthieu Vivier presented their lectures. A discussion session on the present and future of the Dark Matter research and galaxies allowed new inputs, overall vision, and working plans "*Où va la Science*" ?. The Héctor de Vega medal in the honor of Héctor de Vega was introduced and awarded.

[*]Electronic address: norma.sanchez@obspm.fr

[†]Electronic address: sinziana.paduroiu@unige.ch

[‡]Electronic address: plbiermann@mpifr-bonn.mpg.de

Contents

I. PURPOSE OF THE WORKSHOP, CONTEXT AND INTRODUCTION

This Workshop is the seventh of a Chalonge series in Meudon started with Héctor J. de Vega dedicated to Warm Dark Matter, and this is now the Chalonge - de Vega series. The first WDM Workshop of this series (June 2010) allowed to identify and understand the issues of the serious problems faced by Cold Dark Matter (CDM) and CDM + baryons to reproduce the galactic observations. The 2010 and 2011 Workshops served also to verify and better understand the endless confusion situation in the CDM research, namely the increasing number of cyclic arguments, and ad-hoc mechanisms and recipes introduced in the CDM + baryon galaxy simulations over most of thirty years, in trying to deal with the CDM + baryons small scale crisis: cusped profiles and overabundance of substructures (too many satellites) are predicted by CDM. In contrast, cored profiles and not so overabundant substructures are seen in astronomical observations. The so many galaxy formation and evolution models of CDM + baryons are plagued with ever increasing tailoring or fine-tuning and recipes. Such a type of circular, "never-ending" - increasing and sustained - confusion over the years takes today such research out of the science context. Students and first comers in the subject ask the question: Why then does such research continue ? Why are such WIMP experiments still planned for the future again and again... The answer is not within a pure scientific context. But the real WIMP scientific research is in decline.

On the CDM particle physics side, the situation is no less critical. So far, all the dedicated experimental searches after more than thirty years to find the theoretically proposed CDM particle candidate (WIMP) have repeatedly failed. The CDM indirect searches (invoking CDM annihilation) to explain cosmic ray positron excesses, are in crisis as well, as WIMP annihilation models are plagued with growing tailoring or fine tuning, and in any case, such cosmic rays excesses are well explained and reproduced by natural astrophysical process and sources. The so-called and continuously invoked 'wimp miracle' is nothing but being able to solve one equation with three unknowns (mass, decoupling temperature, and annihilation cross section) within WIMP models theoretically motivated by the SUSY model built twenty five years ago when such models were fashionable.

After more than thirty-five years, and as often in big-sized science, CDM research (CDM+ baryon simulations, direct and indirect WIMP experimental research and model building) has by now its own internal inertia and own organized community, without reproducing the astronomical observations and failing to provide any experimental signal of WIMPs (except signals compatible with experimental noise). Growing CDM + baryon galaxy simulations involve ever increasing large super-computers and large number of people; CDM particle WIMP search involved (and involves) large and long-time planned experiments, huge number of people and huge budgets. One should not to be surprised then if a strategic scientific change has not yet operated in the CDM + baryon research and in the WIMP research, given the way in which the organization operates, although their real scientific situation is of decline.

The New Dark Matter Situation Today and WDM State-Of-The-Art

Warm Dark Matter (WDM) research is progressing fast, the subject is new and WDM essentially works, naturally reproducing the astronomical observations over all scales: small (galactic) and large (cosmological) scales (ΛWDM). Astronomical evidence that Cold Dark Matter (ΛCDM) and its proposed tailored baryonic cures do not work at small scales is staggering.

ΛWDM is a more complete, correct and general theory than ΛCDM, it contains CDM as a limiting case (in the limit of the high mass of the particle), reproduces ΛCDM at large scales and solves all the known problems of CDM at small and intermediate scales.

A. The fermionic quantum pressure of WDM ensures the observed small scale structures as the cores of galaxies and their right sizes (including the dwarf galaxies). The Thomas-Fermi Theory naturally takes it into account and produces the correct cored density profiles and their correct sizes. N-body simulations in classical (non-quantum) physics present in the literature do not take into account the fermionic WDM quantum pressure and produce unreliable results at small scales: That is the reason of the "too small core size" problem in classical (non-quantum) N-body WDM simulations present in the literature and the similar dwarf galaxies problem. The WDM simulations to address the core density profiles of the right core size must be quantum simulations or take into account in some effective way the quantum WDM pressure.

B. Two observed quantities crucially constrain the DM nature in an inescapable way independently of the particle physics model: the average DM density ρ and the phase space density Q. The observed values of ρ and Q in galaxies today robustly point to a keV scale DM particle (WDM) and exclude CDM as well as axion Bose-Einstein condensate DM.

C. Lyman alpha bounds on the WDM particle mass apply to specific sterile neutrino models and many sterile neutrino models are available today for which the Lyman alpha bounds are unknown. Therefore, WDM cannot be disfavored in general on the grounds of the Lyman alpha bounds only valid for specific models, as erroneously stated and propagated in the literature. Also, Lyman alpha bounds on the WDM particle mass depends on astrophysical uncertainties and the baryonic modelling.

Astrophysical constraints put the sterile neutrino mass m in the range $1 < \mathrm{m} < 10$ keV. For a dark matter particle decoupling at thermal equilibrium (thermal relic), all evidences point to a 2 keV particle. Remarkably enough, sterile neutrinos decouple out of thermal equilibrium with a primordial power spectrum similar to a 2 keV thermal relic when the sterile neutrino mass is about 7 keV, and therefore, WDM can be formed by 7 keV sterile neutrinos. KATRIN-extensions, ECHo and others experiments could detect such keV sterile neutrinos. It will be a fantastic discovery to detect dark matter in beta decay or in electron capture. Exciting WDM work to perform is ahead of us.

This Workshop addresses the last and fast steps of progress made in Warm Dark Matter Galaxies in Agreement with Observations. In the tradition of the Chalonge - de Vega School, an effort of clarification and synthesis is made by combining in a conceptual framework, theory, analytical, observational and numerical simulation results. The subject is approached in a fourfold way:

(I) Conceptual context: Dark Matter in cosmology and astrophysics: perspective and prospective of the research in the subject: Theory and observations. The emergence of Warm (keV scale) Dark Matter from theory and observations.

(II) Astronomical observations: galaxy structural properties, the universal and non universal properties of galaxies, high quality rotation curves, kinematics, density profiles, gravitational lensing, small and large structures, deep surveys, clusters of galaxies.

(III) Computational framework with the equations of physics. Analytical and numerical frameworks. The new important physical ingredient in galaxy structure: quantum mechanics. Classical (non quantum) numerical simulations with Warm Dark Matter and resulting structures. Results versus observations.

(IV) Experiments and detection: experimental constraints on the DM particle, detection techniques, status of present experiments and results, experiments in development and future prospects.

Topics Covered Included:

- Astrophysical and cosmological observational signatures of Warm Dark Matter, sterile neutrinos and their experimental search.
- Warm (keV scale) dark matter N-body simulations in agreement with observations at large and intermediate scales.
- The phase-space density of dark matter.
- Particle model independent analysis of astrophysical dark matter.
- Baryonic model independent analysis of astrophysical dark matter.

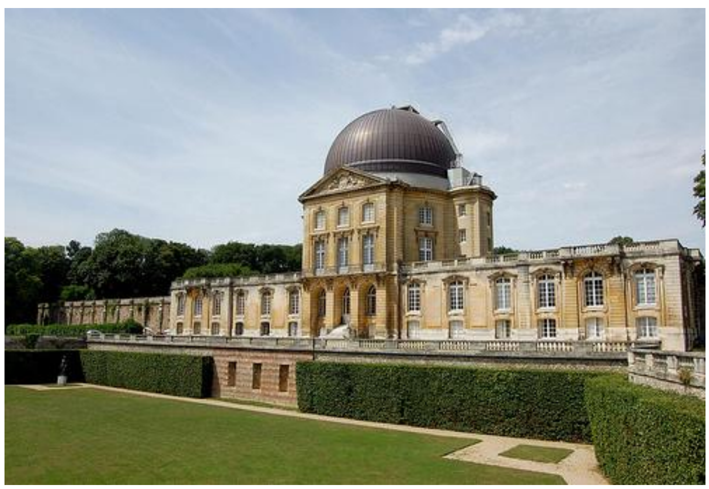
- The radial profiles and the Dark Matter distribution; observed galactic cored DM profiles.
- The keV scale Dark Matter (Warm Dark Matter): Observational and theoretical progress.
- Large and small scale structure formation in agreement with observations at small galactic and at large scales.
- The serious dark matter candidate: Sterile neutrinos at the keV scale.
- Active and sterile neutrinos mass bounds from cosmological data, from astrophysical and X-ray data and from high precision beta decay experiments.
- News on neutrinos and eV scale sterile neutrinos. News from reactor and accelerator experiments on neutrinos and their science implications.
- Signatures and constraints on Warm Dark Matter scenarios from Reionization, 21-cm line, First Galaxies.
- The impact of the mass of the dark matter particle on the small scale structure formation and the choice of the initial conditions.
- The Thomas-Fermi framework to describe the structure and physical states of galaxies in agreement with observations.
- The Eddington like framework to obtain the DM distribution function and the equation of state of galaxies.
- Universal and non-universal profiles. Cored density profiles with WDM core sizes in agreement with observations.
- Supermassive Black Holes : Theory and Observations.

Ecole Internationale Daniel Chalonge - Héctor de Vega

Chalonge de Vega Meudon Workshop 2016

Warm Dark Matter Astrophysics in agreement with observations and keV Sterile neutrinos

Observatoire de Paris, CIAS Château de Meudon,
Meudon campus, 15, 16 and 17 JUNE 2016



All Sessions of the Workshop take place in the historic Castle building (CIAS, Château de Meudon)

Observatoire de Meudon ENTRY: 5 Place Jules Janssen, 92195 Meudon.
Entry for cars: 11 Avenue Marcelin Berthelot, 92195 Meudon

FIG. 1: Poster of the Workshop

II. PROGRAMME AND LECTURERS

- **Peter L. BIERMANN** (MPI-Bonn, Germany & Univ of Alabama, Tuscaloosa, USA) Warm Dark Matter, Supermassive Black Holes and Black Hole Mergers

- **Isabella P. CARUCCI** (SISSA-Astrophysics, Trieste, Italy) Exploiting the 21cm Power Spectrum: Forecasts for SKA on the Warm Dark Matter

- **Pier-Stefano CORASANITI** (CNRS LUTH Observatoire de Paris, Meudon, France) Non-linear Small Scale Structure Formation in Non-standard Cosmologies

- **Anastasia FIALKOV** (Institute for Theory & Computation Harvard University, Cambridge, MA, USA) Warm Dark Matter Astrophysics: Signatures and Constraints on Warm Dark Matter Scenarios from Reionization, 21-cm, First Galaxies

- **Loredana GASTALDO** (Kirchhoff Institute for Physics KIP, Univ Heidelberg, Germany) The Status of the ECHo Experiment for the Investigation of KeV Sterile Neutrinos

- **Anton HUBER** (Karlsruhe Institute of Technology KIT, Karlsruhe, Germany) The Status of the KeV-scale Sterile Neutrino Search with KATRIN

- **Thierry LASSERRE** (CEA, IRFU-Saclay, France) A Status Report on Sterile Neutrino Experiments and the KeV Case

- **Marco LOMBARDI** (Dept. of Physics, University of Milano, Italy) Dark Matter Searches with Gravitational Lensing

- **Daniel MAIER** (Service d'Astrophysique CEA-Saclay, Gif-sur-Yvette, France) ASTRO-H and the Search for KeV Sterile Neutrino Signatures

- **Nicola MENCI** (INAF, Osservatorio di Roma, Roma, Italy) Warm Dark Matter Astrophysics: Galaxy and Star Formation and KeV Sterile Neutrino Mass Constraints

- **Eloisa MENEGONI** (University of Roma I, Rome, Italy) Constraints on Fundamental Physics from CMB Data and Galaxy Clustering

- **Sinziana PADUROIU**, (University of Geneva, Switzerland) Warm Dark Matter Cosmologies: Collapse, Caustics & Cores. Numerical Simulations

- **Paolo SALUCCI** (SISSA-Astrophysics, Trieste, Italy) The Observed Structural Properties of Galaxies and Cored Density Profiles Lead to Warm Dark Matter

- **Norma G. SANCHEZ** (CNRS LERMA Observatoire de Paris, Paris, France) Work with Héctor de Vega on The Structure of Galaxies in KeV Fermionic Warm Dark Matter: Classical and Quantum Regimes

- **Norma G. SANCHEZ** (CNRS LERMA Observatoire de Paris, Paris, France) Galaxy Structure Theory in Agreement with Observations

- **Matthieu VIVIER** (CEA, IRFU-Saclay, France) (Sub)eV Sterile Neutrinos: An Experimental Overview

III. TOPICAL SUMMARY AND HIGHLIGHTS

Conceptual Context and Theoretical Considerations

Dark Matter is the dominant component of galaxies and is an essential ingredient in understanding the formation of galaxies and their properties.

WDM thermal particles with a thermal Fermi-Dirac distribution and a free streaming length corresponding to a mass in the few keV range explain the cosmological structures at all scales: large, intermediate and small scales.

The large scale structure is reproduced by both CDM and WDM in the keV scale simulations, in agreement with the CMB observations. In addition, the free streaming length of WDM particles suppresses the power at small scales, thus preventing a high number of small structures to form - in agreement with observations.

At small scales, at high densities, in the inner halo regions and for the smallest galaxies, the quantum properties of the fermionic WDM become important and quantum calculations (Thomas-Fermi theory of de Vega-Sanchez) give galaxy core sizes, galaxy surface density, phase space density, scaling mass-radius relations, in agreement with observations. Dwarf galaxies, which are dark matter dominated, are supported against gravity by the fermionic quantum pressure of WDM.

Depending on the particle physics model, the mechanism of production, the temperature at decoupling, there are several hypothesized WDM particles, with free streaming length/velocity dispersions corresponding to different masses. In order to give a precise constraint on the WDM particle mass, one needs to distinguish between these models and use the appropriated conversion factor between these masses computed corresponding to the different primordial power spectra. The keV scale is the common meeting point for all WDM particles in general, that means particle masses between 2 and 10 keV. The thermal relic mass is around 2 keV corresponding to the reference or minimal WDM particle mass.

Connecting the physics of warm dark matter particle candidates with some observations, sterile neutrinos may explain the presence of early supermassive black holes distributed along well-contoured semicircles - arcs and early star formation.

Talks by: Norma Sanchez, Peter L. Biermann, Sinziana Paduroiu

Observations

While both ΛWDM and ΛCDM agree with the CMB data and the large scale structure (LSS), only ΛWDM agrees with the small scale structure (SSS), the scale of galaxies. Several properties of galaxies have been discussed and explained in the context of keV WDM models.

The WDM abundance of structures agrees with observations.

The mass distribution observed in galaxies is found to be incompatible with the CDM predictions, falsifies the baryonically fine-tuned CDM scenarios and leads to WDM.

Rotation curves from 3200 galaxies show the presence of cores, not cusps. Using data from I-band photometry and from HI observations, the rotation curves are fitted by the Universal Rotation Curve (URC).

For the first time, data on recent observations of disk dwarfs properties from a sample of 36 objects have been presented: they are another indication of WDM fitted by a generalized URC.

Fermions always provide a non-vanishing pressure of quantum nature. Using the Thomas-Fermi approach, the theoretical rotation curves and density profiles reproduce very well the observational curves for galaxy masses from 5×10^9 to $10^{11} M_\odot$. Thus, gravity and quantum physics - Newton, Fermi and Dirac 'meet' together in galaxies via keV WDM.

This is consistent with the expectations; since the fraction of dark matter over the total mass of galaxies varies from 95% for large dilute galaxies to 99.99% for dwarf compact galaxies, while the baryon fraction can only reach up to 5% in large galaxies.

New results based on the Eddington like approach extended to galaxies show robustly that the self-gravitating DM can thermalize in the inner halo region, despite of being collisionless, due to the gravitational interaction between DM particles, which is important in the inner region. In the outer region, particles are too dilute to thermalize, even if they are virialized. Indeed, the local temperature in the outer region is lower than in the inner region of a halo, where thermalization is achieved. Thermalization has been also linked to ergodicity, the self-gravitating DM gas is an ergodic system.

More constraints on fundamental physics are coming from CMB and galaxy clustering. Planck data improve the constraints on the fine structure constant with respect to those from WMAP-9 by a factor of 5. Analysis of the Planck data limits the variation in the fine structure constant from redshift z=1000 to present day to be less than approximately 0.4%. Dark Energy could be zero at recombination for all we know. Tighter constraints on the fine structure constant and the dark energy density are expected from future experiments, like the Euclid mission.

Talks by: Paolo Salucci, Norma Sanchez, Eloisa Menegoni

Simulations, Modelling and WDM constraints

No CDM simulations can produce pure big disk galaxies; there is no way not to have a bulge in mergers; dwarf population is very different in CDM vs WDM.

Simulations of ΛWDM show distinctive features that can be compared with observations. The free-streaming length of the WDM particles, which gives a suppression of the power on small scales (cut-off in the power spectrum) and a velocity dispersion, has as an immediate obvious effect a lower number of small structures - satellites.

Exploring a wide range of particle velocities, one can see the mechanism of structure formation is a hybrid mechanism of top-down and bottom-up at different scales. While this is obvious with the present resolution in a regime otherwise excluded by different observations (hundreds of eV), to a certain extent this phenomenology is describing the structure formation in the whole regime of warm dark matter.

High resolution warm dark matter halos exhibit caustics and shells, which are permanent structures in real space and phase space. As expected, their size and density depends on the velocity of the particle.

Some technical difficulties are encountered when simulating WDM particles. The artificial mass segregation, which results in the formation of spurious halos is hard to overcome. However, using several structural properties of halos like the spin (spurious halos have large spin) and halos dynamical state - virialization, helps to distinguish the spurious halos and to eliminate them from the studied samples and mass functions.

In WDM the star formation rate appears higher as compared to CDM, at $10^9\,M_\odot$ it could be a factor of 100 which depends on the DM particle mass, consistent too with results by Biermann & Kusenko (2006).

Using hydrodynamical simulations in the few keV range, the impact of WDM on the 21cm intensity mapping in the post-ionization era (z=3-5) has been investigated. For a 3 - 4 keV WDM thermal mass, a 20 - 40 % suppression of low mass halos of order $10^9 M_\odot$ is found (including photo-ionization, self-shielding and molecular Hydrogen). This implies an increase of power in HI and hence, the 21cm power spectra, testable with the SKA forecasts.

WDM Semi-analytic models are less expensive tools. A Monte Carlo realization of collapse and merging histories links the physics of baryons to the DM halos through scaling laws and allows a fast spanning of parameter space and even though they do not contain spatial information, they confirm general constraints on the properties of WDM.
The tightest constraints to date on the WDM particle masses *independent of the baryonic physics* come from the abundance of ultra-faint lensed galaxies of z = 6 galaxies using the recently measured UV luminosity functions in the Hubble Frontier Fields, which yield: m > 2.1 keV at 3 σ, m > 2.4 keV at 2 σ (thermal). This sets $m_{sterile} > 6.1$ keV for Shi-Fuller model and firmly rules out Dodelson-Widrow mechanism (in the case of the 3.5 keV line).

Talks by: Sinziana Paduroiu, Pier-Stefano Corasaniti, Isabella P. Carucci, Nicola Menci

Detection and Experiments

Members of different collaborations have presented current experiments, the setups, results from analyzing the data and future prospects.

For the eV sterile neutrino range, an experimental overview has emphasized the uncertainties and anomalies in results from LSND and MiniBooNE (FNAL) experiments, reactor neutrinos, and the Gallium anomaly, and the solutions proposed for future neutrino experiments. In the present framework, there is no full consistency in fitting all anomalies, but they are suggestive for sterile neutrinos.

The ^{163}Ho Electron Capture experiment (ECHo) is designed to investigate the electron neutrino mass in the sub-eV range, giving an upper limit of 10 eV, by analyzing the calorimetrically measured energy spectrum following the electron capture process of ^{163}Ho. In investigating the existence of keV sterile neutrinos, the presence of resonances complicates the analysis, but preliminary tests on how the keV sterile neutrino would affect the electron capture spectrum have been done and presented, electrons and photons of the excited state of the isotope are observed. Other isotopes are also proposed to study.

The main goal of the KATRIN experiment is to measure the neutrino mass, but the setup can be modified to detect the imprint of a keV scale sterile neutrino. Two planned measurements will be performed, the first one in 2017. A new detector system, TRISTAN is currently in development. Three years of KATRIN will get close to the DM limit in a m_s - $\sin^2\theta$ diagram; systematics are critical and recent developments were presented.

The ASTRO-H International X-ray satellite was designed to acquire data for new insights on large scale structure, matter in strong gravitational fields, cosmic rays acceleration and dark matter. Simulations demonstrate that ASTRO-H could have been very good. After it was launched this year successfully, the satellite broke down and it cannot be recovered. Still, it was possible for the satellite to collect 38 days of data (instead of 3 years) on the Perseus cluster. These data will be analyzed and will be made available. Plans to take profit of the capabilities achieved in the Astro-H instruments should be pursued, in particular, for the search of the potential keV sterile neutrino decay emission lines.

Talks by: Mathieu Vivier, Loredana Gastaldo, Anton Huber, Daniel Maier

IV. CONCLUSIONS

The evidence for keV dark matter particles, commonly referred to as Warm Dark Matter (WDM) is originally derived from galaxies; and galaxies still provide the strongest quantitative argument (Norma Sanchez). The structure of small disk galaxies (Paolo Salucci) and the number counts of small galaxies at very high redshifts (Nicola Menci) provide strong constraints now: The thermal equivalent of the WDM particle is between about 2 and 3 keV, and correspondingly higher for, e.g., the Shi-Fuller mechanism (a factor of about 2.5 higher). Other evidence does show evidence for very early strong star formation, supporting the predictions (Peter L. Biermann) made for the effect of sterile neutrinos (Pier Stefano Corasaniti). Cosmological simulations now give predictions (Sinziana Paduroiu), that show caustic structure possibly making observation tests for X-rays challenging. Other simulations on what neutral Hydrogen observations with high spatial resolution might see were also explored (Isabella Paola Carucci), and the prediction is that WDM and CDM universes would look very different. The hopes for the ASTRO-H satellite X-ray mission were severely curtailed, as just a month of data rather than three years are available now (Daniel Maier). The existing MWBG fluctuation data (Planck) permit the parameters of fundamental constants of nature such as the fine-structure constant to be strongly constrained (Eloisa Menegoni). Many of the existing neutrino experiments suggest anomalies (M. Vivier for Thierry Lasserre) are present, but do not lend themselves to an easy solution. Future dedicated experiments such as ECHo (Loredana Gastaldo) and KATRIN (Anton Huber) may allow the parameter range for a postulated sterile neutrino to be seriously restricted, but this is expected to take many years of work. In conclusion, the strongest push comes from observations of galaxies at high redshift, and predictions of what we might detect at yet higher redshifts; the allowed range of the WDM particle mass is more restricted than ever before.

Sessions lasted for three full days in the beautiful Meudon campus of Observatoire de Paris, where CIAS 'Centre International d'Ateliers Scientifiques' is located. All sessions took place in the historic Chateau building, (built in 1706 by the great architect Jules-Hardouin Mansart in orders by King Louis XIV for his son the Grand Dauphin).

The meeting was open to all scientists interested in the subject. All sessions were plenary followed by discussions. The format of the Meeting was intended to allow easy and fruitful mutual contact and communication. Large time was devoted to discussions. All informations about the meeting are displayed at:

http://www.chalonge.obspm.fr/Cias_Meudon2016.html

The presentations by the lecturers are available on line (in .pdf format) in 'Programme and Lecturers' at:

http://www.chalonge.obspm.fr/Programme_CIAS2016.html

V. A NEW MEDAL: THE HÉCTOR DE VEGA MEDAL

In the honor of Héctor de Vega, the Scientist and the Human Person, a Medal with his portrait and his name was created, coined and edited: The Héctor de Vega Medal.

Science with a great intellectual exigency and a human face.

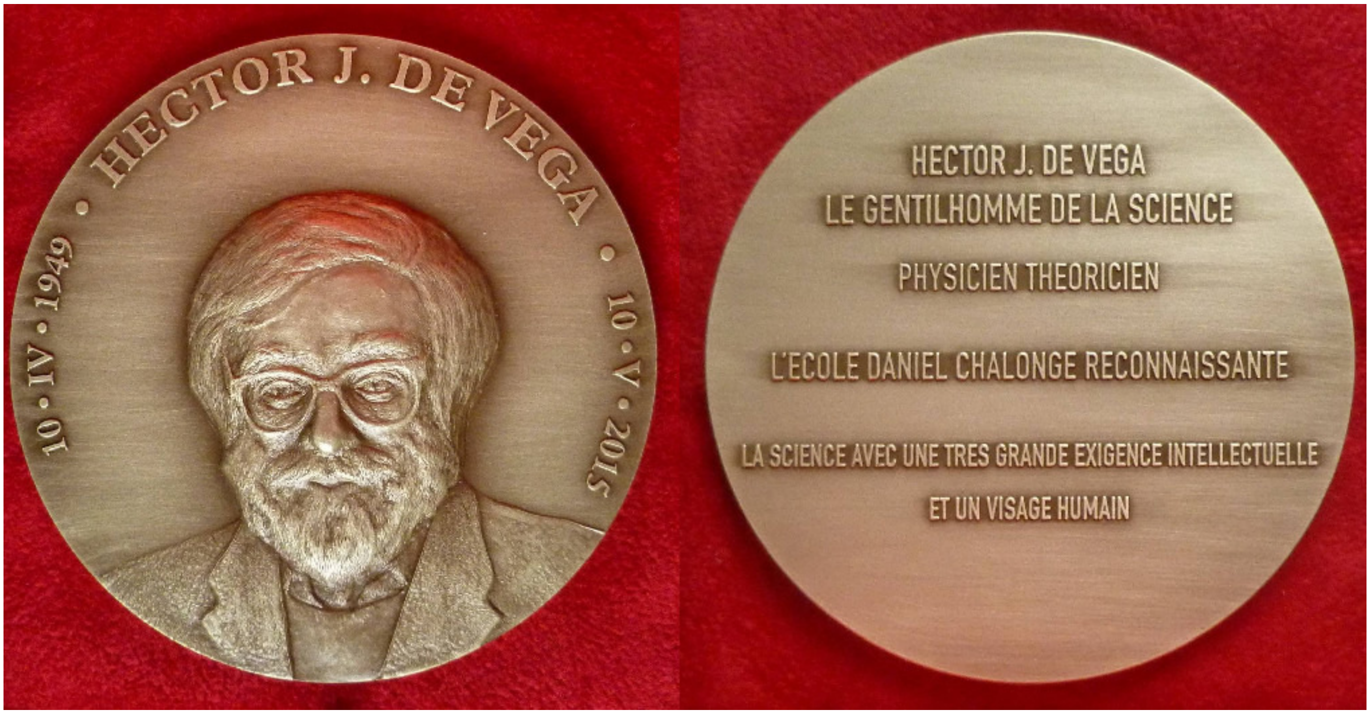


FIG. 2: **The Héctor de Vega Medal**

The first side of the medal shows the name, dates and an artistic engravure of Héctor de Vega's portrait inspired by the outstanding picture taken by Nadia Charbit Blumenfeld. In the reverse side of the Medal the following text is engraved in french:

Hector J. de Vega Le Gentilhomme de la Science Physicien Theoricien L'Ecole Daniel Chalonge Reconnaissante La Science avec une Tres Grande Exigeance Intellectuelle et un Visage Humain.

Hector J. de Vega The Gentleman of Science Theoretical Physicist The Chalonge School Science with Great Intellectual Exigency and a Human Face.

The announcement of the Medal took place during the Opening of the Programme Héctor de Vega of the Year 2016 (Session of Scientific Culture - Last News of the Universe - 26 March 2016).

The first Medal was presented during the Autumn Session of Scientific Culture - Last News of the Universe - 26 March 2016 to Dr. Alba ZANINI (INFN Turin, physicist, Ambassador of the city of Turin for Science and Culture and Ambassador of the Chalonge- de Vega School).

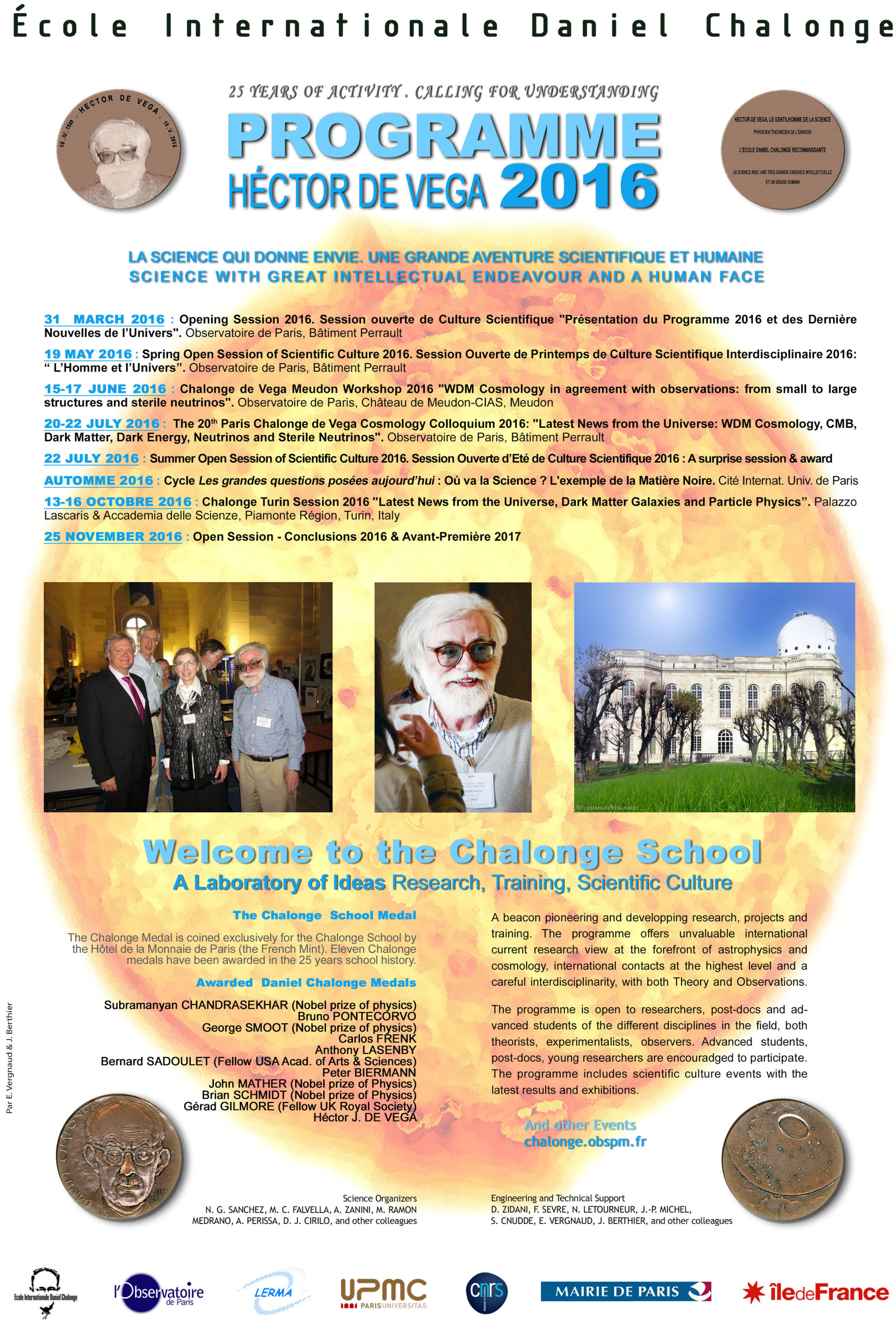
The second Medal was presented during the Spring Interdisciplinary Session "The Human and the Universe" 19 May 2016 to Dr. Nadia CHARBIT BLUMENFELD (Medical doctor, BLUMENFELD's Family, grandfather Erwin photographer, father Henry physicist Saclay, mother Kathleen photographer), author of the photo portrait of Héctor from which the portrait of the Medal was engraved.

The third Medal was presented during the Chalonge Meudon Workshop 2016 to Peter L. BIERMANN (MPI Bonn and Tuscaloosa, astrophysicist)

Next presentations will follow on different occasions and meetings.

Next meeting: The 20th Paris Cosmology Colloquium Chalonge - de Vega, 20-22 July 2016

VI. PROGRAMME HÉCTOR DE VEGA 2016



VII. LIVE MINUTES OF THE WORKSHOP BY PETER BIERMANN

June 15: Norma Sanchez greets everybody, comments on the strikes that make it difficult for people to get here.

PLB: comments after my talk from Paolo Salucci on the LF of QSOs, and from Norma Sanchez about growing BHs from DM directly (as we did with Faustin Munyaneza); also a comment by Pier Stefano Corasaniti, saying that there is evidence observationally about very early star formation in the universe; argument about activity rate of active SMBHs; Norma Sanchez prefers the direct growth of SMBHs; however, the agglomeration of massive stars requires near-zero heavy element abundance, so can be tested.

Norma Sanchez (results obtained with Héctor de Vega before 2015): DM particles freeze out at decoupling, about $T_d \simeq 100$ GeV; defining keV scale as between 1 and 10 keV; other arguments show that the thermal equivalent mass must be between 2 and 4 keV; structures in the Universum such as galaxies and clusters of galaxies grow out of small primordial quantum fluctuations; WDM cuts the fluctuation spectrum at $73\,\mathrm{kpc}(\mathrm{keV}/\mathrm{m_s})^{1.45}$; defines a transfer fct going from CDM to WDM; e.g., thermal FD particle 2.5 keV, Dodelson-Widrow 9.67 keV, Shi-Fuller 6.38 keV, and νMSM 4.75 keV; all analogous; for small scales quantum effects are necessary to explain galaxies; she repeats that compact dwarf galaxies are quantum objects for WDM; $Q = \rho/v^3$, phase density; thermal relic mass limited to about 4 keV, from halo mass versus galaxy halo radius; also phase density Q versus galaxy halo mass; mentions the universal rotation curve by Paolo Salucci (URC) with proper scaling "collapses" into a common curve for $r/r_h \sim 2$; uses also the Burkert profile; mentions 1401.0726 Héctor de Vega + Norma Sanchez, and 1401.1214; PRD 77, 043518 (2008); suggests that simulations will be necessary for $Q/m^4 < 0.1$.

Sinziana Paduroiu: CDM versus WDM: she emphasizes that no CDM simulations can produce pure big disk galaxies; there is no way not to have a bulge in mergers; dwarf population very different in CDM vs WDM; mentions Bode, Turok, and Ostriker 2001; Viel et al. 2005; most WDM simulations just cut the power-spectrum, and do not worry about initial velocities; runs through the argument that the Bode et al. case to correspond to 1000 degrees of freedom; discusses the starting conditions with thermal or non-thermal velocities; she used 3 keV, matching the latest arguments by Norma Sanchez and Nicola Menci; shows some movies of structure formation in WDM, illustrating both top-down and bottom-up mechanisms; she keeps mentioning the quantum pressure for compact galaxies; mentions the dependencies of phase density Q on the parameters in the simulations; in the discussion Paolo Salucci mentions that in M87 they found a core radius of about 150 kpc; S.P. says, that kind of thing is difficult in DM only N-body simulations; P.S. says that M87 has about $10^{14}\,M_\odot$; mentions that someone else has determined a cored distribution of the globular cluster system around M87.

Matthieu Vivier (prepared with Thierry Lasserre): Sterile neutrino experiments and the keV case; runs through the standard case for neutrino physics, including the recent Nobel prizes; then focuses on neutrino anomalies, or "new" oscillations? i) LSND anomaly, anomaly on the electron anti-neutrino rate; anti-electron-neutrino excess detected; one interpretation is a 4th neutrino state; one option is to extend the standard model by another one or two more neutrinos; they would have to be sterile neutrinos; M. Shaposhnikov 2005 Phys.L.B. 620, 15, model to explain all properties; one neutrino is then around 10 keV, and two others with GeV; ii) MiniBooNe (FNAL) anomaly: they run in both neutrino and anti-neutrino mode: MiniBooNe was not conclusive checking the LSND anomaly; they found at lower energy an excess; iii) reactor neutrinos: found more neutrinos than expected after improved predictions; iv) the Gallium neutrino anomaly: deficit observed; also suggests a new sterile state; no-oscillation hypothesis disfavored at > 99.9 % C.L. (> 3 sigma level); describes new reactor experiments as well as experiments where the neutrino sources are brought to detectors; most recent results from NUCIFER are all consistent with predictions; summary: no full consistency in fitting all anomalies, and consistency experiments.

Anton Huber: KATRIN experiment; extension to measuring the keV-scale sterile neutrino; three years of KATRIN will get close to the DM limit in a m_s - $\sin^2\theta$ diagram; however, systematics are critical; he cites Norma Sanchez, who argues that a phase space limit is $m_s > 1.86$ keV; then the X-ray limits versus the assumption, that all DM is just one particle, the sterile neutrino, suggests about 3 keV; allowing for all systematics allows a limit of $5\,10^{-7}$ in $\sin^2\theta$ at the "best" case mass of about 10 keV; several papers by S. Mertens et al.; one systematic problem is back-scattered energetic electrons in keV range; another is due to very high energy electrons (enough energy to just pass through); results in reflection and trapping of electrons; solved via a regular external magnetic field; detector problems, backscattering, charge sharing, pile-up (work by Kai Dolde); two measurements, one 7 days pre-KATRIN, and then in five years, a post-KATRIN stage; he says that KATRIN will determine the neutrino mass if it is 300 meV, and get an upper limit if it is at or below 200 meV.

Jun 16:

Eloisa Menegoni (Roma): Constraints on fundamental physics from CMB data and galaxy clustering: starts with discovery of MBWBG; explains the derivation of C_l; shows the success of the simple model fit to the Planck data; primary anisotropies are due to i) gravity (Sachs-Wolfe-effect), ii) adiabatic density perturbations, and iii) Doppler effect, from velocity perturbations; the resulting visibility function is connected to the fine-structure constant α; rate of scattering $\dot{\tau} = n_e \sigma_T c$ ...; recombination; see Avelino et al. 2001 PRD 64, 103505; changing the fine structure constant changes the redshift of recombination pretty significantly; there is "cosmic degeneracy" between the Hubble constant and the fine structure constant; Menegoni et al. 2009 PRD 80, 08/302, 0909.3584; using also HST data reduces the allowed error range in a plot of H_0 versus α; Planck gave a very much reduced error budget as compared to WMAP9, so the data confirm that α is at its canonical value; also degeneracy between the fine structure constant and the equation of state of DE; using CMB + HST + SN-Ia, then both α and w are reasonable, $\alpha/alpha_0 = 0.996 \pm 0.009$, and w very close to -1; Calabrese, Menegoni et al. 2011 PRD 84, 023518; find no insight really from early DE models; Euclid will help, to be launched 2020; 0501174 Cole et al.; then talks about clustering; summary: the fine structure constant may have varied by less than 0.4 % from recombination to today; she confirms that DE could be zero at recombination for all we know; Norma Sanchez emphasizes in discussion that the values of H_0 from Planck should be taken with caution.

Daniel Maier (Saclay): ASTRO-H and the search for the keV sterile neutrino; he says that ASTRO-H is broken beyond repair; they have data on the Perseus cluster from the satellite for the first 38 days (instead of the planned 3 yrs); these data will be published in a few weeks; describes the satellite, very many instruments, with an extended optical bench for the hard X-rays; explains the detectors; temperature stability is 2 μK in orbit, mostly due to CRs, since on the ground the stability was 0.4 μK; lots of technology; Paolo Salucci mentions that we now know the distribution of DM in the Galactic Center region better than in galaxy clusters, at the worst just as good; shows a plot of the expected signal, and the Milky Way is best, but forgot the galaxy M31 and also the best dwarfs (Paolo Salucci states this); shows simulations which demonstrate that ASTRO-H could have been very good; all data taken during the check-out phase were not expected to be used for science, but now they have to be used; in emergency mode the Solar Array Paddles and the Extended Optical Bench separated from the satellite; incorrect rotation modes also in safe mode; a publication is coming on the possible 3.5 keV line; a second paper will discuss the velocity field of the gas in Perseus; he then says that it would be relatively easy to build the satellite again, but he is not sure the funding exists; so a more optimistic view than what was expressed at the Vulcano meeting; he mentioned that a number of Japanese satellites had serious failures, ASTRO-H is not the first; long discussion about the options i) to build another satellite, and ii) reanalyze the existing data.

Nicola Menci (Roma): WDM astrophysics, galaxy and star formation: $M_{freestream} = 10^{15.6} M_{\odot} (m_s/30eV)^{-2} - >$ keV scale as well; feedback can bring models back to reality; however, critical issues remain, such as at high redshift; Guo et al. 2011; it also suppresses the L/M ratio in small galaxies, see Brook & Di Cintio; Papastergis et al. 2011, 2015; argues for delay of star formation in WDM models, but of course ignores the ionization and extra cooling; the fraction of quiescent galaxies is far too high in CDM models; in WDM models that fraction is much closer to reality; uses CDM Somerville, CDM de Lucia, and his own models; $m_s = 2.9\, m_x$ for ..; $m_x > 4$ keV indistinguishable from CDM in terms of galaxy formation; the most powerful probe is the formation of high redshift galaxies; using clusters as lenses one can reach galaxies a factor of 10 - 20 fainter using HST; Alavi et al. 2015; $->$ deepest LF ever measured; Livermore et al. 2016 even deeper; 164 galaxies at redshift 6 and beyond; reaching quite large densities; NM and NM et al. 2016; give number density of galaxies $->$ 3 keV; NM et al. 2016b; Alavi et al. 2015, Parsa et al. 2015, Livermore et al. 2016; Merle 2016; he plots comoving density, and finds galaxies with a density beyond 1 Mpc^{-3}; Marsch et al. 2015; Schive et al. 2016; he says after questioning, that the lower limit is 2.1 keV for a thermal relic; Norma Sanchez emphasizes that an upper limit is 4 keV for the thermal relic mass from the abundance of small galaxies; so the window is now 2.1 (3 sigma) to 4 keV; apparently their paper is out today; assuming the Shi-Fuller mechanism allows then a real mass which is larger: At coffee Nicola Menci says that UV is strongly obscured, and the corresponding less obscured X-rays are an important test; he was not certain whether these models used the mass function of the quiescent BHs and not just the active BHs; he also said that there is a "massive seed theory"; in the competition between accretion, and making new BHs, the mass function can be modified obviously.

Pier Stefano Corasaniti (Meudon): Non-linear structure formation in non-standard cosmologies; Pontzen & Governato 2014, Klypin et al. 1999; Boylan-Kolchin et al. 2012; Hahn, Abel, Kaehler 2013, Agarwal & Corasaniti .. 2015 ; spurious halo contamination; so he proposed (A & C '15) a physical criterion; he uses the spin parameter of halos; in spin parameter $J/(2^{1/2} MVR) = \lambda'$; in terms of this spin parameter all have spuriously high spin; also spurious non-sphericity; virial condition as well violated for spurious halos; most spurious halos are low mass; so eliminating all spurious halos recovers log-normality in all these three measures, spin, non-sphericity, and viriality; cleaning up gives better mass function; Atek et al. 2015 LF at high redshift, Bouwens et al. 2015,..; points out problems with UV LF due to extinction; they use a conversion to star formation rate; Mashian,.. Loeb 2015; then using matching on star formation densities; in WDM higher star formation rate as compared to CDM; at $10^9\, M_{\odot}$ a factor of 100 possibly; this depends on the DM particle mass; upon questioning he says, that only from my lecture did he realize that there is a mechanism to have star formation really early; later he talked a lot about how to relate the SMBH density (Caramete & PLB 2010) to the density which he determines for small galaxies at high redshift; he showed comoving densities up to about $10^{+0.5}\, Mpc^{-3}$. PLB comment: the SMBH original density is higher than 10^{-2} Mpc^{-3}, using growth by merging gives about 10^{-1} Mpc^{-3}, so a fair fraction of all small galaxies must produce a SMBH originally; and to explain the great arc many of the original SMBHs must merge in 5 or 6 binary generations to produce what we observe.

Loredana Gastaldo (U. HD): ECHo experiment to measure keV sterile neutrino $^{163}_{67}$Ho; uses Penning trap; she says that she observes electrons and photons of the excited state of this isotope after that it is hit by a sterile neutrino; statistics at end point of decay spectrum only a few 10^{-13} of all events; the basic system is to measure the normal neutrinos; Gastaldo et al. NIMA 711, 150 (2013), Ranitzsch et al. 1409.0071; Faessler et al. JPhysG 42, 015108 (2015), PRC 91, 045505 (2015), PRC 91, 064302 (2015); Rujula et al. 1510.054462; Robertson et al. PRC 91, 035504 (2015); problems with higher order excitations; now move on to sterile neutrinos; Filianin et al. 1402.4400; mass of sterile neutrino distance from kink to end-point of decay spectrum; 1602.04816; identification of sterile neutrino signatures could be limited by the complex structure of the ^{163}Ho spectrum! Filianin et al. JPhysG 41, 095004 (2014), other Electron Capture (EC) isotopes; ^{123}Te, ^{157}Tb, ^{163}Ho, ^{179}Ta, ^{193}Pt, ^{235}Np; these other EC candidates can measure other masses of sterile neutrinos.

Jun 17:

Isabella Paola Carucci (SISSA, Trieste): Exploring the 21cm power spectrum forecasts for SKA on WDM: she starts with the Current Power spectrum extending it with the Lyman α forest from Tegmark et al 2004; Lyman α constrains the scales larger then 300 kpc; she says we need to look for damped Lyman α systems from galaxies; then use "intensity mapping", not focusing on any one source, just map what you see; initially about a degree resolution; use simulations, study CDM and WDM; for 3 to 4 keV WDM particle (thermal equivalent) mass they find a 20 - 40 % suppression of low mass halos, of order $10^9 M_\odot$; Bagla 2010, and Dave 2013, connected to halos, and the other based just on "particles"; uses photo-ionization, self-shielding, and molecular Hydrogen; the simulations show much smoother structures for WDM; huge differences in WDM structures; reduction of power in the matter power spectra results in an increase of power in the terms of the HI and hence the 21cm power spectra; the effect is quite drastic; she tests the HI modelling using the HI column density distribution, Noterdaeme 2012, and Zafar 2013.

Paolo Salucci (SISSA): Observed structural properties of galaxies and cored density profiles lead to WDM; for the first time presents data on disks in dwarf galaxies; argues against a WIMP particle; Sinziana Paduroiu asks him about where all the DM is, and he answers that integrating the galaxy mass function, multiplying with the proper proportion of DM, gives 80 % of all DM; clusters of galaxies give the rest 20 %; disks have exponential profile (Freeman 1970); M33 has truncation at 4 exponential scales, NGC300 at 10 exponential scales; at low luminosity almost linear rotation curve. High luminosity galaxies have a rapid rise of V_{rot} and then a flat rotation curve; introduces his "Universal Rotation Curve (URC)"; mentions paper with Hector de Vega and Norma Sanchez in MNRAS 2014/15; smallest galaxies most numerous, more DM dominated, densest objects, first born, immune to baryonic physics arguments in CDM; states dSph complex dynamics, dwS simple disk; updates nearby galaxy catalogue by Karachentsev et al.; looking for dwarf disks he ends up with 36 objects; doubly normalizes the RC, in radius and in velocity; this normalization is very important; most extreme is UGC4483; stellar mass is proportional to light in K-band; states that the compactness of the luminous matter depends on the compactness of the DM; this RC he calls DDURC, and then the scatter is very small; new relation between baryonic mass and total mass, an extension of the old relation; these small galaxies do not follow the URC, but again lie on a “fundamental plane”, so seen in projection, lie on a line in a cube of concentration, mass and length scale; he can make a similar argument with mass, concentration and central density; in the URC he needs to add another parameter, the concentration; he ends by saying that these dwarf disks do not contribute much to the WDM discussions; he says upon questioning that the total mass of these dwarf disks is larger than the dwarf spheroidals.

Norma Sanchez (Paris): WDM: She emphasizes that the nature of DM is critical for the understanding of galaxies and galaxy formation; on large scales CDM and WDM coincide; she summarizes “CMB data confirm the ΛWDM model on large scales”; then adds the new point of quantum mechanics in galaxies; Newton + Fermi + Dirac meet so-to-speak in galaxies via keV WDM; she argues against MOND; keV WDM solves the core/cusp problem, the satellite problem, the non-observation of WIMPs, DM-annihilation, axions, DM bosons; Destri, Hector de Vega, & Norma Sanchez New Astronomy 2013, Hector de Vega & Norma Sanchez PRD 2013, Hector de Vega, Salucci, & Norma Sanchez MNRAS 442, 2717 (2014), Norma Sanchez IJMP 2016; uses minimal mass of dwarf galaxies −> minimum mass of DM particle, of 1.91 keV; mentions that the fraction of baryons even in large galaxies reaches only 5 %; shows from the work with Paolo Salucci the URC; very similar to the Burkert profile; $M_{min} = 3 \cdot 10^4 M_\odot (2\,\mathrm{keV}/m_s)^{16/5}$ for galaxies, in the extreme limit; this applies to the smallest and most compact galaxies; emphasizes that cusped density profiles produce distribution functions which are divergent at the center; in the outside region of halos temperature is lower, since virialization starts before thermalization; Harvey et al. Science 2015: collisions between clusters show that self-interaction between DM particles is extremely limited; result cross-section divided by mass < 0.47 cm^2/g; DM verified at 7.6 σ; needs DM to be Fermionic; including Shi-Fuller DM is between 2 and 9 keV; just thermal case mass between 2 and 4 keV; she points to sterile neutrinos, but says that many possibilities exist in particle physics; Norma Sanchez + 2015 suggests that SMBHs are the limit, so argues that SMBHs grow from Fermionic DM.

Special General discussion session: In the discussion Norma Sanchez states that in the work with Héctor they found direct solutions in a degenerate configuration including a SMBH as a proper solution, she calls a rich family of solutions, as a direct extension of the degenerate cores in galaxies, then also finding no SMBHs in small galaxies; Nicola Menci says that with low efficiency accretion one can yield SMBHs from accretion; I mention the work by Jan van Paradijs about super-Eddington accretion; Nicola Menci says that at $z > 1$ CDM simulations give too many AGN, and calls it a crisis; by more than one order of magnitude at $z > 5$; comment then to Nicola Menci that Giant Radio Galaxies show that the efficiency overall is quite high in BH accretion; analysis on the subject DM and galaxies through the 25 years of intense activity of the school versus the clarification in cosmology i.e. CMB for instance as done from COBE and WMAP, which established the Standard cosmological model with inflation; Nicola Menci suggests an optimistic view of the situation of the field, after Norma Sanchez points out the inertia, in the DM research in general, not for WDM of course which is going fast! saying "from 40 years" and more (from the times of Chalonge and Szicky); Paolo Salucci voices optimism; I also agree mentioning CR physics.

Héctor de Vega medal; she also mentions the previous two presentations of the Medal; mentions Poincare wrote about GWs, he called them "ondes gravifiques", with a number of important papers from 1902 to 1906.

***

We thank all again, both lecturers and participants, for having contributed so much to this exciting meeting and look forward to seeing you again in the next Workshop of this series.

We thank the CIAS Observatoire de Paris for its support and all those who contributed so efficiently to the successful organization of this meeting, particularly Nicole Letourneur, Djilali Zidani, Sylvain Cnudde, Jean-Pierre Michel, Emmanuel Vergnaud and Jerome Berthier.