Review of Recent Advances on Dark Matter

From the Viewpoint of the Occam Razor Principle

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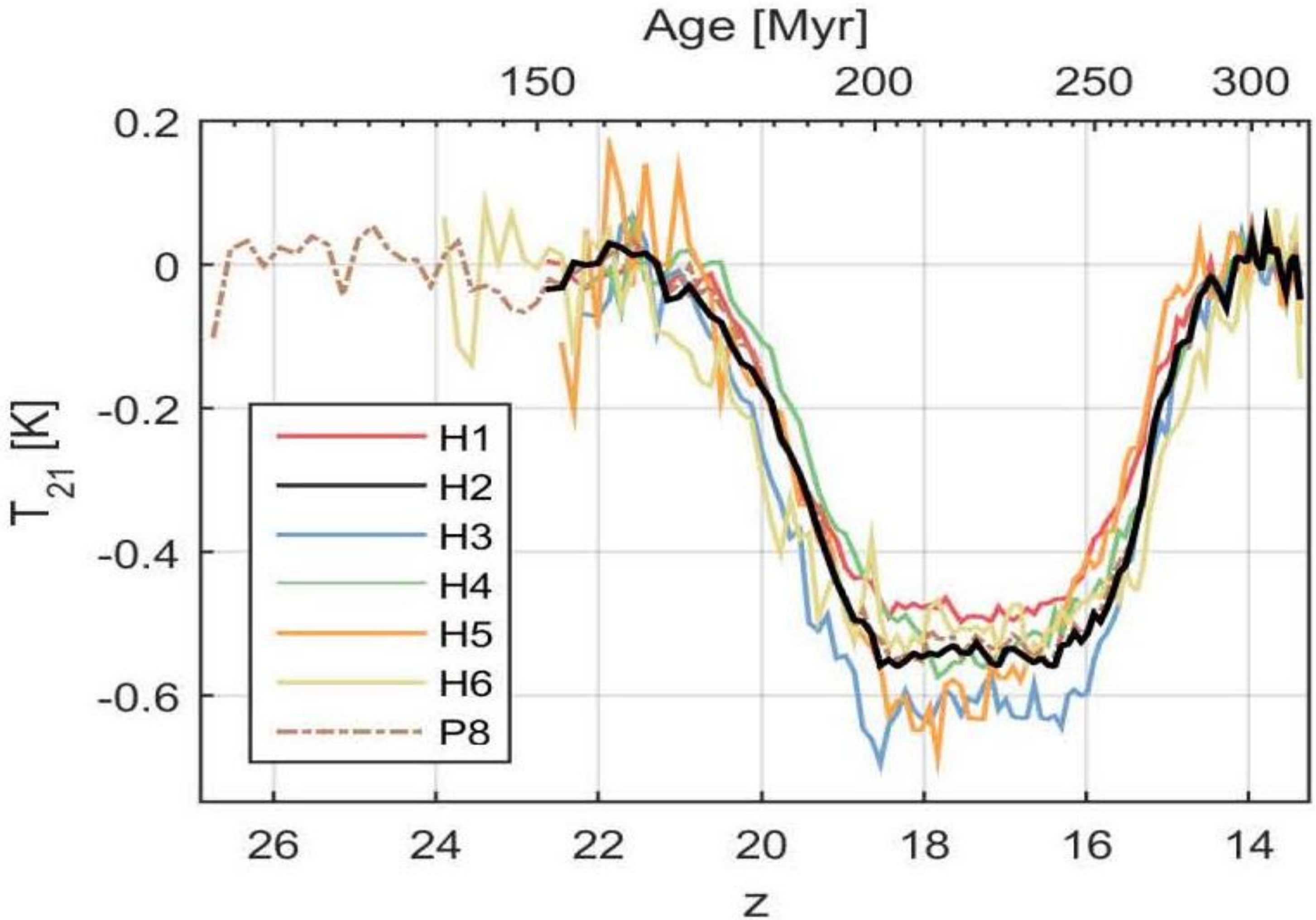
- There are three major types of astrophysical observations that resorted to an unknown matter (called dark matter) for the explanations.
- The first two types are well-known: the flattening of the rotation curves of the galaxies and the gravitational microlensing.
- The third type is relatively new, so let me remind you some details.
- Bowman et al (2018) published a perplexing observation (within the Experiment to Detect the Global Epoch of Reionization Signature (EDGES)) of the redshifted 21 cm spectral line from the early Universe.
- The amplitude of the absorption profile of the 21 cm line, calculated by the standard cosmology, was **by a factor of two smaller** than it was actually observed.
- The consequence of this striking discrepancy was that **the gas temperature** of the hydrogen clouds **was in reality significantly smaller** than predicted by the standard cosmology.

Bowman et al. *Nature* **2018**, 555, 67.



The absorption signal in the red-shifted 21 cm spectral line, observed by Bowman et al (2018), versus the cosmological red shift.

- Barkana (2018) suggested that some unspecified dark matter collided with the hydrogen gas and made it cooler compared to the standard cosmology.
- He estimated that for fitting the observations by Bowman et al (2018), the mass of these dark matter particles should not exceed 4.3 GeV. (For comparison: hydrogen atoms mass is 0.94 GeV.)
- Thereafter McGaugh (2018) examined the results by Bowman et al (2018) and Barkana (2018) and came to an important conclusion.
- Namely, the observations by Bowman et al (2018) constitute an ***unambiguous proof that dark matter is baryonic***, so that **models introducing non-baryonic nature of dark matter have to be rejected** (because only baryonic dark matter was able to provide an additional cooling to the hydrogen gas).

Barkana, *Nature* **2018**, *555*, 71

McGaugh *Research Notes of the Amer. Astron. Soc.* **2018**, 2, 37

- Before this third type of the astrophysical observations, there was a garden variety of hypotheses on dark matter – at least two dozens or more.
- I covered all of the above hypotheses in my review article of 2021 in the Elsevier journal "New Astronomy Reviews" (93, 101632) and in my review published in 2021 by Nova Science Publishers as a chapter in the book "*Advances in Dark Matter Research*".
- Since I've been given only 17 minutes for this talk, it is impossible to review here all the hypotheses.
- Therefore, as the selection criterion I chose the "Occam razor principle", which dictates that when several theories compete, the one that makes less assumptions has the upper hand (i.e., is the most probable to correspond to reality).
- The overwhelming majority of theories on dark matter either introduce exotic, never discovered experimentally subatomic particles or change the physical laws.
- To the best of my knowledge, there are **only <u>three</u> theories that do not introduce exotic, never discovered experimentally subatomic particles and do not change the existing physical laws.**

1. Self-interaction terms (non-linearities) in the General Relativity (GR) – Deur (2019) *Europ. Phys. J. C 79*, 883.

- The gist of Deur's idea is the following. The Lagrangian of the general relativity contains field self-interaction terms – *similar to the self-interaction terms in quantum chromodynamics* – that become important for very massive systems.
- Their effects are unaccounted for in the studies of galaxies and galaxy clusters since the dynamical studies of these systems rely on Newton's law of gravity.
- Accounting for field self-interaction locally strengthens gravity's binding, thereby making dark matter superfluous.
- Deur expanded the Lagrangian density L_{GR} of the GR in terms of the gravity field φ as

$$L_{GR} = \partial_\alpha \varphi \partial^\alpha \varphi + g\varphi\, \partial_\alpha \varphi \partial^\alpha \varphi + g^2 \varphi^2\, \partial_\alpha \varphi \partial^\alpha \varphi,$$

where g is a coupling of the dimension $1/(\text{energy})^2$, g^2 being proportional to G (the Newton constant).

- The 1st term is Newton's gravity.
- The other terms cause field self-interaction.

- Deur noted that this Lagrangian is similar to the Lagrangian for the gluonic field in quantum chromodynamics (QCD) and that in the QCD the self-interaction terms increase the binding compared to the 1st term.

- Deur showed that accounting for self-interaction **automatically yields flat rotation curves** for disk galaxies.

- Deur's theory should **not** be confused with the hypothesis of a self-interacting dark matter brought up by Spergel & Steinhardt (2000) and further modeled by Loeb & Weiner (2011) and by Yang et al (2020).
- Their hypothesis assumes that dark matter particles interact through an **unknown dark force**.
- Therefore, according to the Occam razor principle, the latter hypothesis is less favorable than Deur's theory.

DISADVANTAGE of Deur's theory:

- it explains only 1 out of the 3 major types of astrophysical observations that resorted to dark matter (the flattening of the rotation curves of the galaxies), but not the other two types.

- Spergel, D.N.; Steinhardt, P.J. Observational evidence for self-Interacting cold dark matter. *Phys. Rev. Lett.* **2000**, 84, 3760.
- Loeb, A.; Weiner, N. Cores in dwarf galaxies from dark matter with a Yukawa potential. *Phys. Rev. Lett.* **2011**, 106, 17132.
- Yang, D.; Yu, H.B.; An, H. Self-interacting dark matter and the origin of ultradiffuse galaxies NGC1052-DF2 and -DF4. *Phys. Rev. Lett.* **2020**, 125, 11110

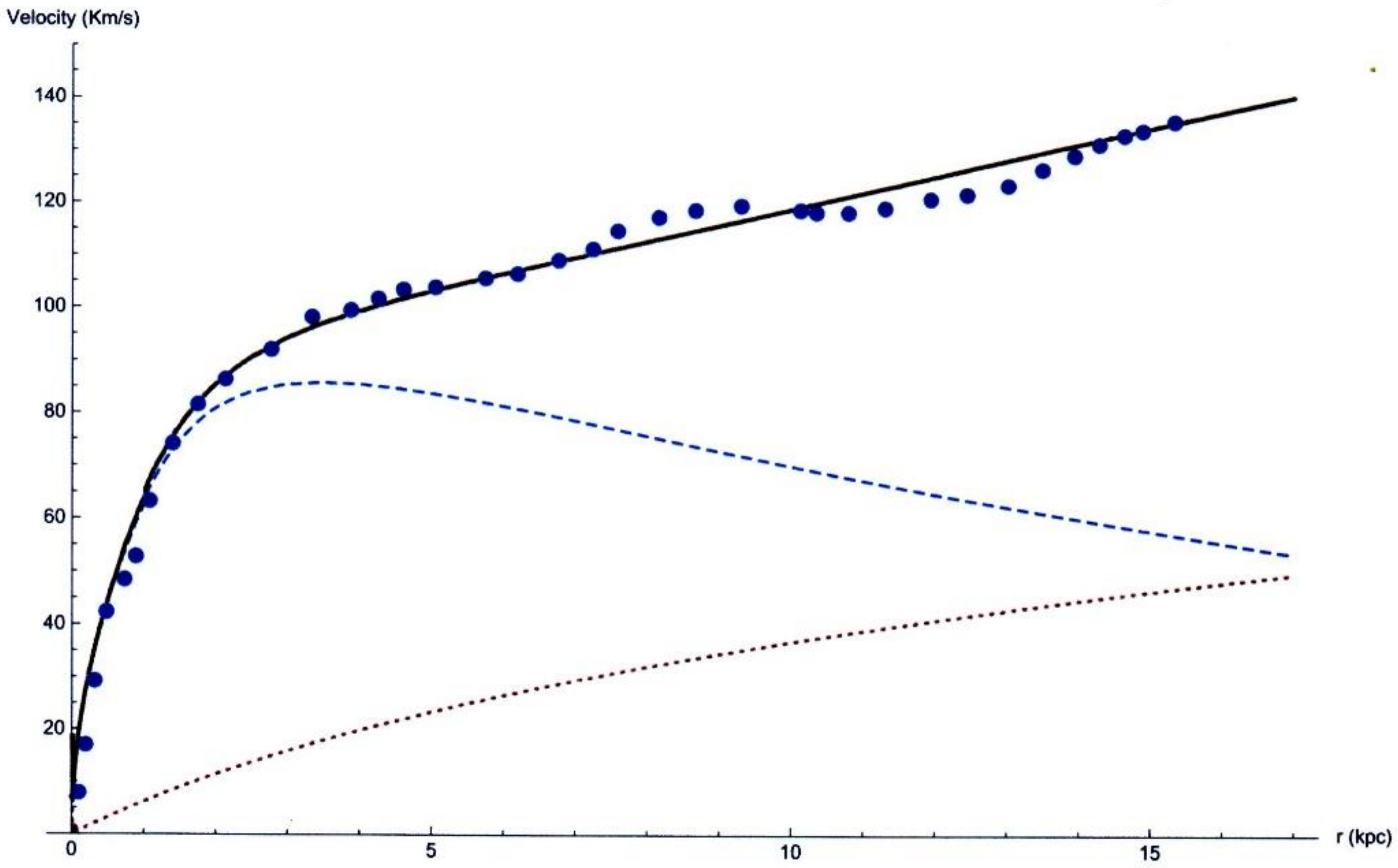
2. Retardation effects–Yahalom (*Symmetry* **2020**, *12*, 1693; **2021**, *13*, 1062)

- The gist of Yahalom's idea of 2020 is the following.
- Galaxies are huge physical systems with dimensions of many tens of thousands of light years.
- Thus, any change of the mass with time at the galactic center (due to the accretion) will be noticed at the rim only tens of thousands of years later.
- These retardation effects can explain the flattening of the rotation curves of the galaxies without postulating dark matter.
- Yahalom showed that the effective retardation force $\mathbf{F}_{ret}$ is proportional to the 2nd time derivative of the mass M of the system:

$$\mathbf{F}_{ret} = [G/(2c^2)](d^2M/dt^2)\mathbf{r},$$

where **r** is a unit vector.

- He wrote: "*As the galaxy attracts intergalactic gas, its mass becomes larger and therefore dM/dt > 0. However, as the intergalactic gas is depleted, the rate at which the mass is accumulated must decrease and therefore $d^2M/dt^2 < 0$.*"
- If so, then the retardation force is the **attractive** force.



- Plot of the galactic rotation velocity (km/s) versus the distance r(kpc)
- This result for galaxy M33 was obtained assuming a sufficiently large $|d^2M/dt^2| = 9.12 \times 10^{16}$ kg/s^2.

- In the next Yahalom (2021) paper he tried to show how the retardation effects can explain the gravitational microlensing.
- He showed that the retardation effects create an additional force on the light ray in the direction perpendicular to it, usually thought to be caused by some dark matter mass M_{dark}.
- This force can be produced by the retardation effects if (again) $|d^2M/dt^2|$ would be sufficiently high:

$$[r^2/(2c^2)]\ |d^2M/dt^2| \text{ is equivalent to } M_{dark}(r)$$

- Yahalom (2022) emphasized that he did not consider a post-Newtonian approximation, in which matter travels at nearly relativistic speeds.
- He considered the retardation effects and finite propagation speed of the gravitational field in the case of galaxies, where $v/c \sim 10^{-3}$.
- He wrote: "***Every gravitational system, even if it consists of subluminal entities, has a retardation distance, above which retardation cannot be neglected****…The retardation distance is roughly 4.54 kpc for M33; other galaxies of different types have shown similar results*."

DISADVANTAGES of Yahaloms's theory:

- A) it makes an additional assumption of sufficiently large $|d^2M/dt^2| = 9.12 \times 10^{16}$ kg/s^2 (there are no direct measurement of the second temporal derivative of the galactic mass).
- B) it explains only 2 out of the are 3 major types of astrophysical observations that resorted to dark matter (the flattening of the rotation curves of the galaxies and gravitational microlensing), but not the anomalous absorption in the 21 cm line from the early Universe.

3. The Second Flavor of Hydrogen Atoms (SFHA)

- The standard Dirac equation of quantum mechanics for hydrogen atoms has two analytical solutions: 1) a weakly singular at small r; 2) a more strongly singular at small r.
- For models of a point-like nucleus or where the charge distribution inside the nucleus (the proton) is assumed to be either a charged spherical shell or a uniformly charged sphere, the 2nd solution outside the proton is justifiably rejected.
- However, the actual charge distribution inside protons is different from those models: it has a **peak at r = 0**, as known from experiments on the elastic scattering of electrons on protons (see, e.g., Simon et al (1980) and Perkins (1987)).

Simon et al, *Nucl. Phys.* **1980**, *A333*, 381

Perkins, *Introduction to High Energy Physics*; Addison-Wesley: Menlo Park, CA, USA, 1987, Sect. 6.5.

- In papers by Oks (2001, 2020) it was shown analytically that with the allowance for the actual charge distribution inside protons, the 2nd solution outside the proton is legitimate for all states of the zero orbital momentum (*l*=0), which are called the s-states in quantum mechanics.
- This second kind of hydrogen atoms having only the s-states was later called the Second Flavor of Hydrogen Atoms (SFHA) – by analogy with the QCD where up and down quarks are called two flavors.

Oks, *J. Phys. B: At. Mol. Opt. Phys.*, **2001**, *34*, 22352243

Oks, *Research in Astronomy and Astrophysics* **2020**, *20(7)*, 109.

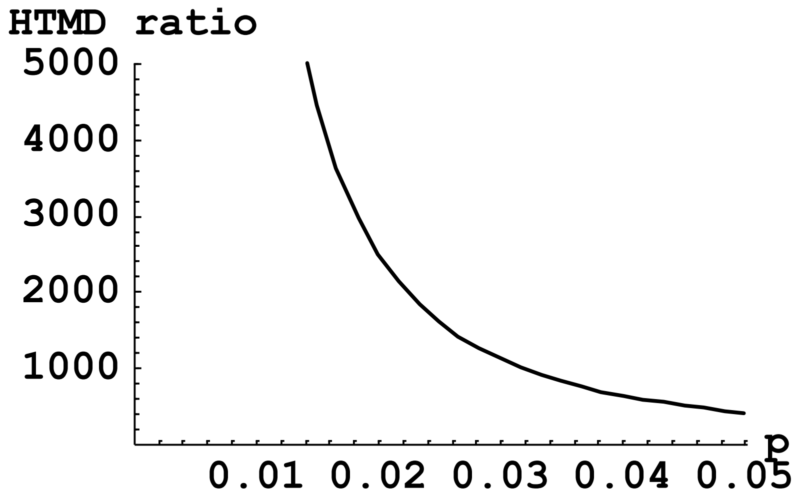
On using the term “flavor”.

- Both the regular and singular solutions of the Dirac equation outside the proton correspond to **the same energy**.
- Since this means **the additional degeneracy**, then according to the fundamental theorem of quantum mechanics, there should be an **additional conserved quantity**.
- In other words: hydrogen atoms have ***two flavors*, differing by the eigenvalue of this additional, new conserved quantity**: hydrogen atoms have *flavor symmetry* (Oks, 2020).
- It is called so **by analogy with quarks that have flavors**: for example, there are up and down quarks.
- For representing this particular quark flavor symmetry, there was assigned an operator of the additional conserved quantity: the isotopic spin I – the operator having two eigenvalues for its z-projection: I_z = 1/2 assigned to the up quark and I_z = –1/2 assigned to the down quark.

Oks, *Atoms* **2020**, 8, 33

- **THE PRIMARY FEATURE of the SFHA**: since the SFHA have only the s-states, then according to the well-known selection rules of quantum mechanics, the **SFHA do not emit or absorb the electromagnetic radiation** (with the exception of the 21 cm line) – **they <u>remain</u> <u>DARK</u>**.

- **More details**: due to the selection rules, all matrix elements (both diagonal and non-diagonal) of the operator **d** of the electric dipole moment are zeros.
- For this reason, the SFHA do not couple not only to the dipole radiation, but also to the quadrupole, octupole, and all higher multipole terms – because they contain linear combinations of various powers of the radius-vector operator **r** of the atomic electron, which yield zeros in all orders of the perturbation theory.
- For the same reason, the SFHA cannot exhibit to multi-photon transitions.
- This is because they consist of several one-photon virtual transitions, each step being controlled by a matrix element of **r**, but all these matrix elements are zeros.
- **THE MOST IMPORTANT: by now the existence of the SFHA is proven in 4 totally different kinds of atomic experiments**, as follows.



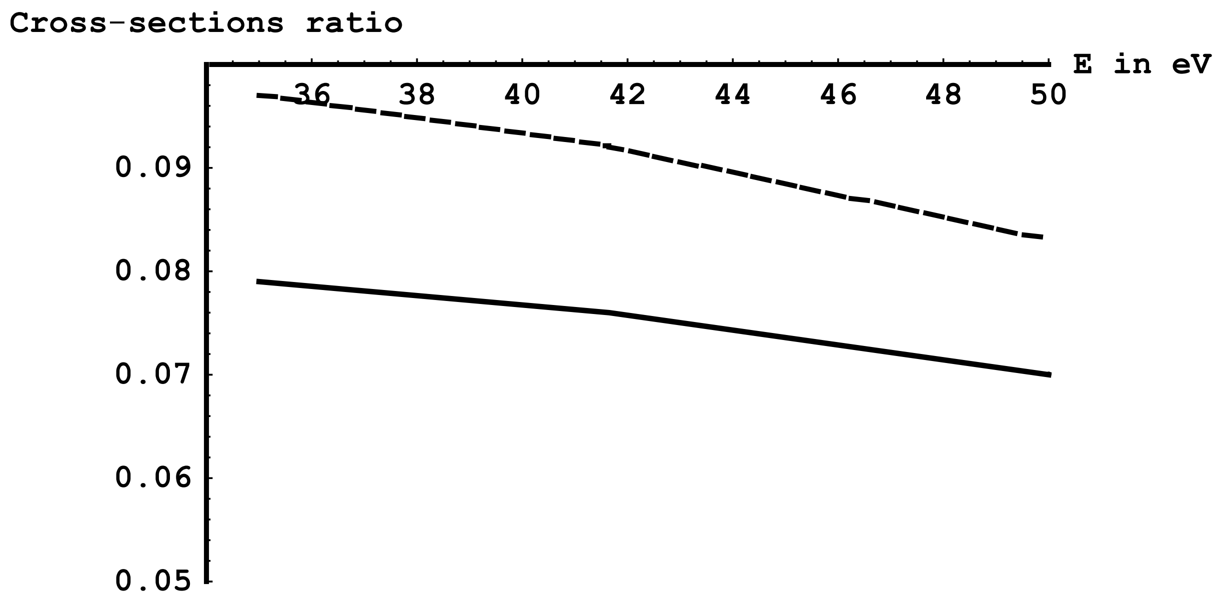
A. Experimental distribution of the linear momentum in the ground state of hydrogen atoms.

- The figure above shows the ratio of the theoretical High-energy Tail of the linear Momentum Distribution (HTMD), calculated by Fock (1935), to the actual HTMD deduced from the analysis of atomic experiments (Gryzinski, 1965).
- The linear momentum p is in units of mc, where m is the electron mass and c is the speed of light.
- It is seen that the relative discrepancy between the theory and experiments can reach many orders of magnitude: **3 or 4 orders of magnitude (!)**.

Fock, *Z. Physik* **1935**, *98*, 145

Gryzinski, *Phys. Rev.* **1965**, 138, A336

- The problem with the wave function in the momentum representation φ(p) at large p indicates the problem with the coordinate wave function ψ(r) at small r – according to the properties of the Fourier transform, by which ψ(r) and φ(p) are related.
- The engagement of the SFHA **completely eliminated this really huge discrepancy** – due to the totally different behavior of ψ(r) at small r (and thus of φ(p) at large p) for the SFHA (Oks, 2001).
- No alternative explanation ever provided.



B. Experiments on the electron impact excitation of hydrogen atoms

- The figure above presents the comparison of the experimental (Callaway and McDowell (1983)) and theoretical (Whelan et al (1987)) ratio of the cross-section σ_{2s} of the excitation of the state 2s to the cross-section σ_{2p} of the excitation of the state 2p.
- The theoretical ratio (dashed line) is systematically higher than the experimental ratio (solid line) by about 20% - far beyond the experimental error margins of 9%.

Callaway & McDowell, *Comments At. Mol. Phys.* **1983**, *13*, 19

Whelan et al, *J. Phys. B: At. Mol. Phys.* **1987**, *20*, 1587

- The experimental cross-section σ_{2s} for the excitation to the 2s state was determined by using the quenching technique: by applying **an electric field that mixes the state 2s with the state 2p** and then observing the emission of the Lyman-alpha line from the state 2p to the ground state.
- The central point is the following. In the mixture of the SFHA with the usual hydrogen atoms, both the SFHA and the usual hydrogen atoms can be excited to the 2s state.
- However, after applying the electric field, the mixing of the 2s and 2p states (followed by the emission of the Lyman-alpha line) occurs only for the usual hydrogen atoms.
- This is because the SFHA has only the s-states, so that they do not contribute to the observed Lyman-alpha signal.
- **Therefore, measurements of the cross-section $\boldsymbol{\sigma_{2s}}$ in this way, should underestimate this cross-section** compared to its actual value, while the cross-section σ_{2p} should not be affected by the presence of the SFHA (Oks, 2022a).

Oks, *Foundations* **2022a**, *2*, 541

- In Oks (2022a) paper it was shown that the discrepancy between the experiments and the theory **can be eliminated if in the experimental hydrogen gas, both the usual hydrogen atoms and the SFHA were present in about equal shares.**
- No alternative explanation ever provided.

Oks, *Foundations* **2022a**, *2*, 541

C. Experiments on the electron impact excitation of hydrogen molecules

- There is a discrepancy by **at least of a factor of two** between the experimental and theoretical cross-sections, and it can be eliminated if the SFHA was present in the experimental gas (Oks, 2022b).
- No alternative explanation ever provided.

D. Experiments on the charge exchange between hydrogen atoms and protons

- There is a similar discrepancy between the experimental and theoretical cross-sections, and it can be eliminated if the SFHA was present in the experimental gas (Oks, 2021).
- No alternative explanation ever provided.

Oks, *Foundations* **2022b**, *2*, 697

Oks, *Atoms* **2021**, *9*, 41; *Foundations* **2021**, *1*, 265

Now – about the SFHA as the candidate for dark matter.

- The anomalous absorption in the 21 cm line from the early Universe indicates that the gas temperature of the hydrogen clouds was significantly smaller than predicted by the standard cosmology.
- What if the unspecified baryonic dark matter, proposed by Barkana (2018) as the cooling agent, was actually the SFHA?
- The SFHA do not couple to the electromagnetic radiation **except for the radiative transitions between the two hyperfine sublevels of the ground state corresponding to the same 21 cm wavelength** as for usual hydrogen atoms.
- In Oks (2020) paper in Research in Astronomy and Astrophysics it was explained that in the course of the Universe expansion, the SFHA being decoupled from the Cosmic Microwave Background radiation (CMB), **cool down faster** than the usual hydrogen atoms (that decouple from the CMB much later).
- Therefore, **their spin temperature (that controls the intensity of the absorption signal in the 21 cm line) is lower**.
- In that paper it was shown that this explains the observed anomalous absorption in the 21 cm line both **qualitatively and quantitatively**.

Oks, *Research in Astronomy and Astrophysics* **2020**, *20*, 109

- Besides, there is another astrophysical observational puzzle that can be explained with the help of the SFHA.
- Recently the Dark Energy Survey (DES) team created the most detailed map of the distribution of dark matter in the Universe.
- Unexpectedly, the distribution turned out to be by few percent smoother, less clumpy than followed from the Einstein's gravity (Jeffrey et al 2021).
- This outcome prompted calls for new physical laws.

Jeffrey et al, *Monthly Notices of the Royal Astronomical Society* **2021**, *505(3)*, 4626

- A relatively simple model, explaining this observational puzzle *without resorting to any new physical laws*, was presented in Oks (2021) paper in Research in Astronomy and Astrophysics.
- It showed that if dark matter is represented by the SFHA, then in a small part of the ensemble of the SFHA, gravitationally interacting pairs of the SFHA can form; no electromagnetic interaction.
- These pairs would gradually lose the energy and the atoms within the pair would approach each other, but then quantum effects would stop this "clumping".
- It was shown that this mechanism explains the above observational puzzle both **qualitatively and quantitatively**.

Oks, *Research in Astronomy and Astrophysics* **2021**, *10*, 241

SUMMARY

- The overwhelming majority of theories on dark matter either introduce exotic, never discovered experimentally subatomic particles or change the physical laws, except the above three theories, which are therefore preferable from the viewpoint of the Occam razor principle.
- **Deur's theory (self-interaction in GR): Great theory!**

DISADVANTAGE: it explains only 1 out of the 3 major types of astrophysical observations that resorted to dark matter (the flattening of the rotation curves of the galaxies), but not the other two types.

- **Yahalom's theory (retardation effects in GR): Great theory!**

DISADVANTAGES:

- A) it makes an additional assumption of sufficiently large $|d^2M/dt^2| = 9.12 \times 10^{16}$ kg/s^2 (there are no direct measurement of the second temporal derivative of the galactic mass). This is a minus from the viewpoint of the Occam razor principle.
- B) it explains only 2 out of the are 3 major types of astrophysical observations that resorted to dark matter (the flattening of the rotation curves of the galaxies and gravitational microlensing), but not the anomalous absorption in the 21 cm line from the early Universe.

Second Flavor of Hydrogen Atoms (SFHA):

ADVANTAGES:

- A. The existence of the SFHA is confirmed by four different kinds of atomic experiments. So, **the SFHA does exist**.
- B. It does not go beyond the Standard Model.
- C. It is based on the standard quantum mechanics, namely on the Dirac equation – without any change to the physical laws.
- D. It explains all 3 major types of astrophysical observations that resorted to dark matter, including the anomalous absorption of the 21 cm spectral line from the early Universe. It also explains why the observed distribution of dark matter is smoother than expected from the Einstein's gravity.

Thank you for your attention

Gracias por su atención