Experiments on Collisions of Electrons or Protons with Hydrogen Atoms or Molecules Shed Light on the Possible Nature of Dark Matter

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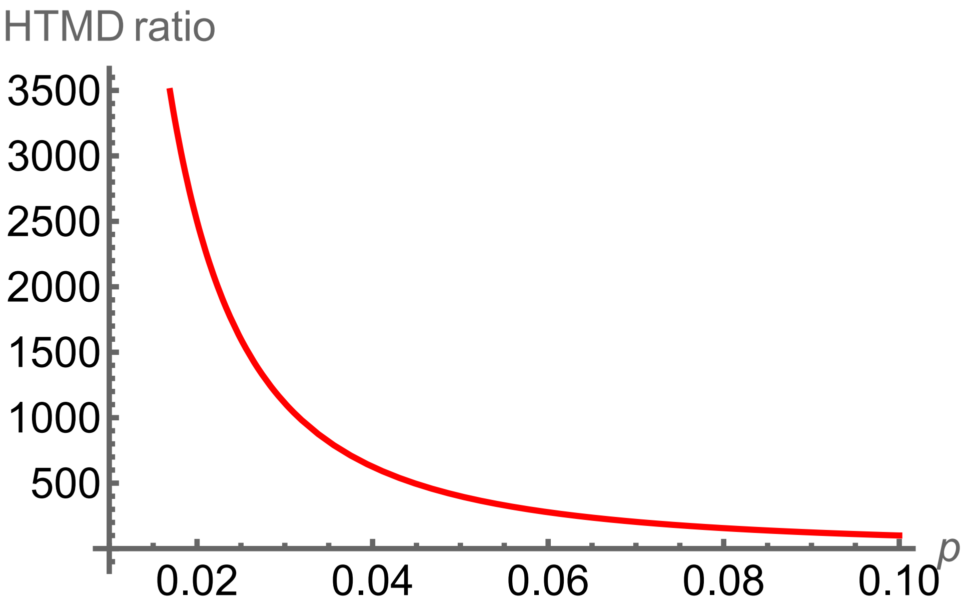
- Analysis of atomic experiments related to the distribution of the linear momentum in the ground state of hydrogen atoms revealed a huge discrepancy.
- Namely, the ratio of the experimental and previous theoretical results was up to *tens of thousands* (J. Phys. B: At. Mol. Opt. Phys. **2001**, *34*, 2235).



- 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 for a great variety of collisional processes between hydrogen atoms and electrons or protons (Gryzinski, 1965).
- The linear momentum p is in units of $m_e c$, where m_e 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 (!)** – in the relevant range of p: $m_e e^2/\hbar < p << m_e c$.

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

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

- This was the motivation behind my *theoretical* results from that paper of 2001 in the JPB.
- 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.
- The radial part $R_{Nk}(r)$ of the coordinate wave functions has the following behavior at small r :

$$R_{Nk}(r) \propto 1/r^{1+s}, \quad s = \pm(k^2 - \alpha^2)^{1/2}. \qquad (1)$$

- Here N is the radial quantum number, α is the fine structure constant, and k is the eigenvalue of the operator

$$K = \beta(2\mathbf{Ls} + 1) \qquad (2)$$

that commutes with the Hamiltonian (β is the Dirac matrix of the rank 4).

- For the ground state ($k = -1$, $N = 0$) Eq. (1) reduces to

$$R_{0,-1}(r) \propto 1/r^{q}, \qquad q = 1 \pm (1 - \alpha^2)^{1/2}. \qquad (3)$$

- So, the 1st solution has only weak singularity: $q \approx \alpha^2/2 \approx 0.000027$ (the “regular” solution, for brevity).
- The 2nd solution is really singular ($q \approx 2$) and is usually rejected (the normalization integral diverges at $r = 0$).

- The situation changes after allowing for the finite nuclear size.
- For models 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: it cannot be tailored with the corresponding regular solution inside the nucleus.
- In my paper of 2001 in the JPB, I derived a general class of potentials inside the nucleus, for which the singular solution outside the nucleus can be actually tailored with the corresponding regular solution inside the nucleus at the boundary.
- In particular, this class of potentials includes those corresponding to the charge distributions that have a **peak at r = 0.**
- From experiments on the elastic scattering of electrons on protons (see, e.g., Simon et al (1980) and Perkins (1987)), it is known that the charge distribution inside protons does have a **peak at r = 0.**

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

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

- Thus, the regular solution inside the proton can be tailored with the singular solution outside the proton at the boundary.
- So, in my paper of 2001 in JPB, I derived analytically the corresponding wave function.
- As a result, the huge multi-order **discrepancy** between the experimental and theoretical HTMD got **completely eliminated**.
- The reason: for the singular solution outside the proton, a much stronger rise of the coordinate wave function toward the proton at small r translates into a *much slower fall-off* of the wave function in the p-representation for large p (according to the properties of the Fourier transform) than the scaling $\sim 1/p^6$ predicted by Fock (1935).

Oks, *J. Phys. B: At. Mol. Opt. Phys.*, **2001**, *34*, 2235

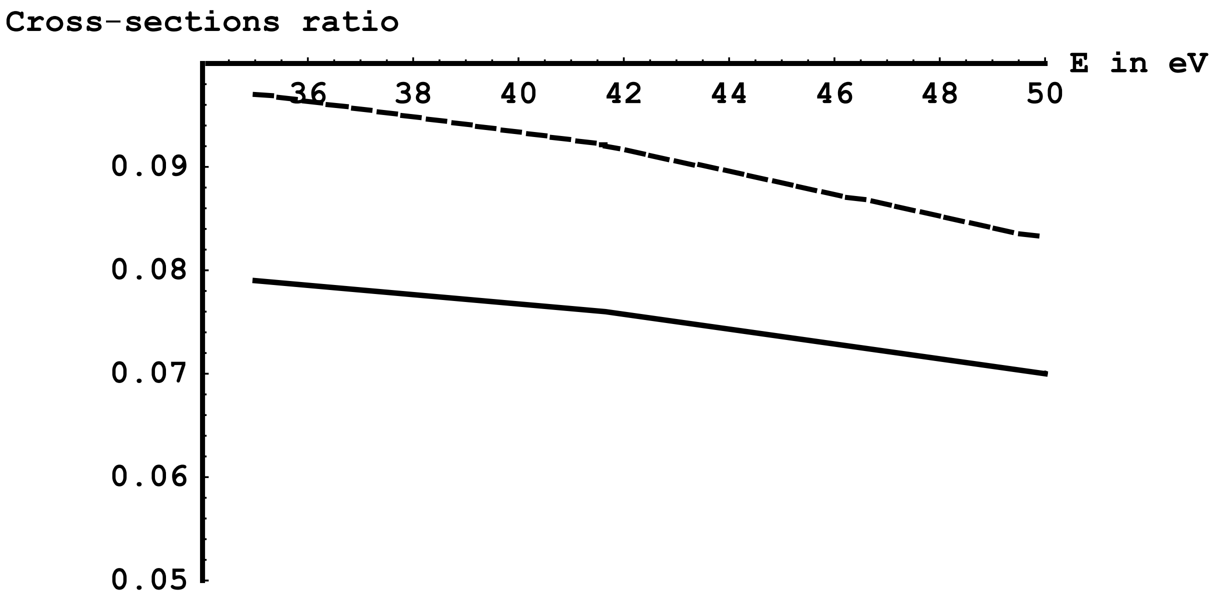
- The corresponding derivation in my paper of 2001in JPB used *only* the fact that in the ground state the eigenvalue of the operator K is

  k = –1.

- Therefore, actually the corresponding derivation is valid not just for the ground state, but for any state of hydrogen atoms characterized by the quantum number k = –1.
- Those are S-states (*l* = 0), specifically $^2S_{1/2}$ states.
- So, both the regular exterior solution and the singular exterior solution are legitimate not only for the ground state $1^2S_{1/2}$, but also for the states $2^2S_{1/2}$, $3^2S_{1/2}$, and so on, i.e., for the states $n^2S_{1/2}$, where n = N + |k| = N + 1 is the principal quantum number (n = 1, 2, 3, …).
- Both the regular exterior solution corresponding to $q = 1 – (1 – \alpha^2)^{1/2}$ and the singular exterior solution corresponding to $q = 1 + (1 – \alpha^2)^{1/2}$ are legitimate also for the *l* = 0 states of the *continuous* spectrum.
- All of these additional results were presented in my paper of 2020 in *Research in Astronomy and Astrophysics* (**2020**, *20(7)*, 109) published by the British IOP Publishing, where I applied these results to solving one of the dark matter puzzles.

- This second kind of hydrogen atoms having only the s-states was later called the Second Flavor of Hydrogen Atoms (SFHA). Here is why:
- 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, *Atoms* **2020**, 8, 33).
- 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.

- Thus, the elimination of the huge multi-order discrepancy between the theoretical and experimental distributions of the linear momentum in the ground state of hydrogen atoms constituted the first experimental evidence of the existence of the SFHA – since no alternative explanation was ever provided.
- Below I briefly present three additional experimental evidences from three *different* kinds of atomic experiments.



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 (because it was measured directly, without applying the electric field), as I wrote in the paper in the Swiss journal *Foundations* (**2022**, *2*, 541).
- In that paper, I showed that the discrepancy between the experiments and the theory **can be eliminated if in the experimental hydrogen gas, SFHA were present in *the share ~ 40%*.**
- No alternative explanation was ever provided.

- The third evidence relates to **experiments on the electron impact excitation of hydrogen *molecules***
- I studied works on the excitation of the first two stable excited electronic *triplet* states of H_2: the state c $^3\Pi_u$ and the state a $^3\Sigma_g^+$.
- The reason for the choice: the singlet states can get populated both by the direct excitation and by exchange between the incident electron and one of the molecular electrons. The triplet states can get populated only by the exchange, so that the *corresponding theory is simpler for the triplet states*.
- I found that even the most advanced calculations - by the convergent close-coupling (CCC) method with the total number of states equal to 491 (Zammit et al, *Phys. Rev. A* **2017**, *95*, 022708) **underestimate** the experimental cross-sections (by Wrkich et al, *J. Phys. B* **2002**, *35*, 4695 and by Mason-Newell, *J. Phys. B* **1986**, *19*, L587) by **at least a factor of two (!)**.

- In my other paper in *Foundations* (**2022**, *2*, 697) I showed that if in some hydrogen molecules one or both atoms would be the SFHA, then the above very significant discrepancy could be eliminated.
- This is because for such “unusual” H_2 molecules, the corresponding theoretical cross-section is by a factor of three greater than for the usual H_2 molecules. Here is why:
- Zammit et al (*Phys. Rev. A* **2017**, *95*, 022708) provided theoretical results not only for the convergent close-coupling method involving 491 states, but also for the CCC involving lesser number of states.
- It showed that the decrease of the number of states involved in their calculations yields significantly greater excitation cross-sections than CCC(491).
- This is because the less the number of states, the less are the interference effects.

- This is the case for **the “unusual” (SFHA containing) H_2 molecules: they have significantly lesser number of states** (only the s-states) compared to the usual H_2 molecules.
- Therefore, for such “unusual” H_2 molecules, the corresponding theoretical cross-section is by a factor of three greater than for the usual H_2 molecules.
- I estimated that for eliminating that factor of two discrepancy between the experiment and the theory, the unusual hydrogen molecules should be present in the experimental gas in the share of ~ 30%.
- No alternative explanation was ever provided.

- For the lack of time, I only briefly mention the fourth experimental evidence of the existence of the SFHA: from **experiments on the charge exchange between hydrogen atoms and low energy protons**
- The experimental cross-sections (Fite et al, *Proc. Royal Soc.* **1962**, *A268,* 527) are noticeably greater than the theoretical ones by Dalgarno-Yadaf, *Proc. Phys. Soc. (London)* **1953**, *A66*, 173).
- Again, this discrepancy can be eliminated if the SFHA was present in the experimental gas (Oks, *Foundations* **2021**, *1,* 265).
- The reason: the cross-section of the charge exchange with low energy protons is larger for the SFHA than for the usual hydrogen atoms.

- The cross-section for the resonant charge exchange is (roughly) inversely proportional to the square of the ionization potential U_{ioniz} from the particular atomic state.
- **For the usual hydrogen atoms, U_{ioniz} increases due to the Stark shift** by the field of the incoming proton.
- However, **the energy levels of the SFHA do not shift in the electric field (no Stark effect) – because of the selection rules for the s-states.**
- No alternative explanation was ever provided.

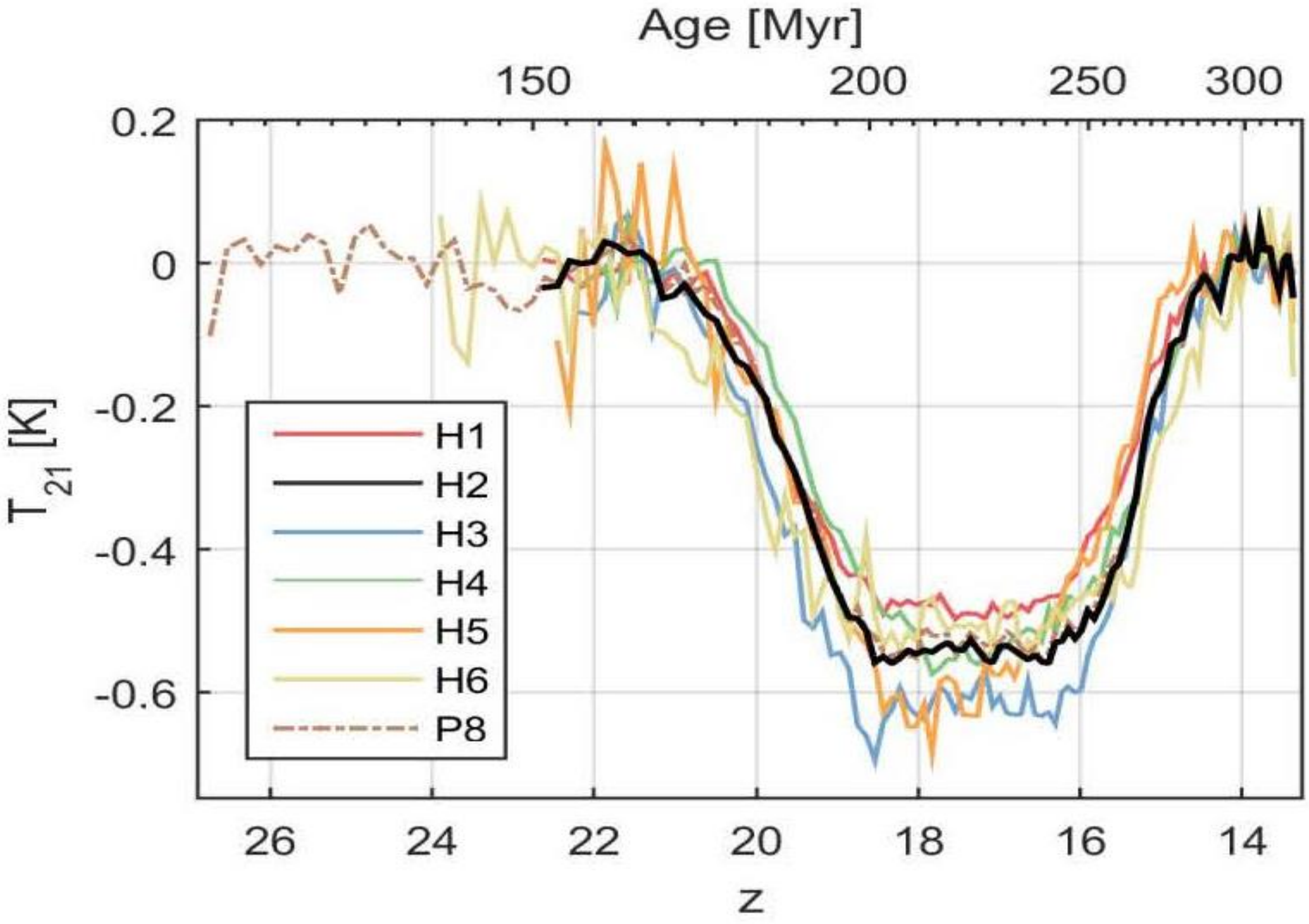
- **THE PRIMARY FEATURE of the SFHA**: since the SFHA have only the s-states, then according to the well-known selection rules of quantum mechanics, the **SFHA do not emit or absorb the electromagnetic radiation** (with the exception of the 21 cm line) – **they remain DARK**.

- **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 multipoles 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 multi-photon transitions.
- This is because multi-photon transitions consist of several one-photon virtual transitions, each step being controlled by a matrix element of **r**, but all these matrix elements are zeros.

How the discovery of the SFHA can shed light on the possible nature of dark matter

- 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**. (I am just conveying his conclusion; I present my view at the end of the talk.)

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

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

- 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 decouple from the Cosmic Microwave Background radiation (CMB) much earlier (because of having only the s-states) than the usual hydrogen atoms.
- Because of this, the SFHA **cool down faster** than the usual hydrogen atoms (that decouple from the CMB much later). Here is why:

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

- Let us denote by a(t) the value of the expansion parameter of the Universe.
- As the SFHA decouple from the CMB, their kinetic gas temperature $T_{K,S}$ decreases proportional to $1/a^2$
- In distinction, the CMB temperature decreases slower: proportional to 1/a.
- Therefore, **at the time when the usual hydrogen atoms decouple from the CMB, their kinetic gas temperature is greater than for the SFHA**.
- Therefore, **the spin temperature (that controls the intensity of the absorption signal in the 21 cm line) is lower for the SFHA than for the usual hydrogen atoms.**
- In that paper of 2020, 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

- The explanation based on the SFHA seems to be more specific and natural than adopting a possible cooling of baryons either by unspecified dark matter particles, as in paper by Barkana (2018), or by some exotic dark matter particles of the charge of the million times smaller than the electron charge, as in paper by Muñoz & Loeb (2018) and Liu et al (2018).
- Besides, Liu et al (2019) estimated that if there are charged dark matter particles, they can only constitute ~ 10^{-8} of the total dark matter energy density.
- The most important: exotic dark matter particles of the charge of the million times smaller than the electron charge were never discovered experimentally, while the existence of the SFHA is evidenced by 4 different types of atomic/molecular experiments.
- **The "Occam razor principle"** dictates that **when several theories compete, the one that makes less assumptions has the upper hand** (i.e., **it is the most probable to correspond to reality**).
- Thus, the Occam razor principle favors the **existing** SFHA as as explanation of the observed anomalous absorption in the 21 cm line.

Muñoz & Loeb, 2018, Nature 557, 684

Liu et al, 2019, Phys. Rev. D, 100, 123011

- Also, our explanation does not require an additional **hypothetical** radio background suggested by Feng & Holder (2018), Ewall-Wice et al (2018), Fialkov & Barkana (2019), and Reis, Fialkov & Barkana (2020).
- In distinction, the existence of the SFHA is evidenced by 4 different types of atomic/molecular experiments.
- **Important: the theory of the SFHA is based on the standard quantum mechanics (the Dirac equation). It does not go beyond the Standard Model and does not resort to changing the physical laws.**
- So, again: the Occam razor principle favors the **existing** SFHA as as the explanation of the observed anomalous absorption in the 21 cm line.

Feng & Holder, 2018, Astrophys. J., 858, L17

Ewall-Wice et al, 2018, Astrophys. J., 868, 63

Fialkov & Barkana, 2019, Phys. Rev. Lett., 121, 011101

Reis, Fialkov & Barkana, 2020, MNRAS, 499, 5993

- 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

- **Our model does not involve new physics**. It deals with the dynamics of a system consisting of a large number of **gravitating neutral particles** not interacting electromagnetically, whose mass is equal to the mass of hydrogen atoms.
- The central point of the model is a **partial inhibition of the gravitation for a relatively small subsystem** of the entire system – due to quantum effects.
- Our estimate of the percentage of the pairs of particles, exhibiting the inhibition of the gravitational interaction and thus the inhibition of the unlimited "clumping", is $\gtrsim 2.5\%$.
- This agrees with the percentage observed by the DES team: the few percent more smooth, less clumpy distribution of dark matter compared to the prediction of the general relativity.
- The **most viable candidate for the dark matter particles in this model is the SFHA** that has only S-states and therefore does not couple to the electromagnetic radiation, so that the SFHA is practically dark.

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

SUMMARY

1. The theoretical discovery of the SFHA was based on the standard Dirac equation of quantum mechanics without any change of physical laws.
2. The existence of the SFHA is confirmed by four different kinds of atomic experiments. So, **the SFHA does exist**.
3. This discovery does **not** go beyond the Standard Model.
4. 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.
5. It also explains why the observed distribution of dark matter is smoother than expected from the Einstein's gravity.

- There are several **final notes**, as follows.
- First, the SFHA is the candidate not necessarily for **all** dark matter.
- In other words, the SFHA could represent only a *part of dark matter*, so that not each and every astrophysical observation (beyond the three major observations discussed above) has to be explained by the SFHA: just as any of other theories of dark matter does **not** explain **all** astrophysical observations.
- It is well possible that the effects assigned to dark matter in different types of astrophysical observations do not have one universal cause, i.e., **there is no one universal type of "dark matter"**.
- For more details I refer to my recent review in "New Astronomy Reviews" (Elsevier journal) published in **2023**, *96*, 101573.

- This situation would not be unique.
- For example, explaining a huge energy release during relatively short period of time in the most powerful solar flares required the hypothesis of the anomalous resistivity of the flare plasmas – the anomalous resistivity caused by the development of a Low-frequency Electrostatic Plasma Turbulence (LEPT).
- **The development of the LEPT in the most powerful solar flares was then confirmed in observations by the spectroscopic diagnostic** (Koval & Oks, 1983).
- However, explaining less powerful solar flares did not require the LEPT hypothesis and the LEPT in such flares was not detected spectroscopically.

Koval & Oks, 1983, *Bull. Crimean Astrophys. Observatory* 67, 78.

- Second, there are galaxies that seem not having dark matter – see, e.g., Gibney (2022).
- If these galaxies still cause gravitational microlensing, this can be explained, e.g., by Yahalom theory (2021) based on the retardation effects in general relativity or perhaps by another theory not developed yet.
- Once again, none of the existing theories has to explain each and every astrophysical observation because dark matter could be a *multi-faceted phenomenon*.

Gibney, 2022, *Nature*, *News* 19 May

Yahalom, 2021, *Symmetry* 13, 1062

- The following parable (fable) seems to be in order.
- “A group of blind men heard that **a strange animal, called an elephant**, had been brought to the town, but none of them were aware of its shape and form. Out of curiosity, they said: "*We must inspect and know it* ***by touch***, of which we are capable". So, they sought it out, and when they found the animal, they started touching it. The first person, whose hand landed on the trunk, said, "This animal is like a thick snake". For another one whose hand reached its ear, the animal seemed like a kind of fan. As for another person, whose hand was upon its leg, said, the elephant is a pillar like a tree-trunk. The blind man who placed his hand upon its side said the elephant, "is a wall". Another who felt its tail, described the animal as a rope. The last felt its tusk, stating the elephant is like a spear.”

- Let us hope that in the near future, the bits and pieces of the astrophysical observations of the unknown substance will be combined into a more comprehensive understanding **what is this multifaceted “elephant” called dark matter.**

Thank you for your attention

ご清聴ありがとうございました