Queen Mary
University of London

The Dawn of FIMP Dark Matter

Tommi Tenkanen
in collaboration with
N. Bernal, M. Heikinheimo, K. Tuominen, and V. Vaskonen

Queen Mary University of London

Talk based on arXiv: 1706.07442

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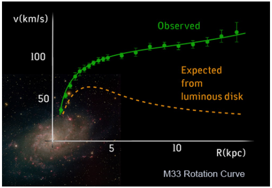
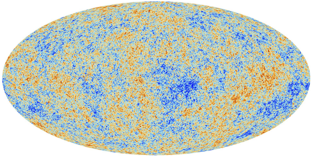
E-mail: t.tenkanen@qmul.ac.uk

Why do we think dark matter exist?

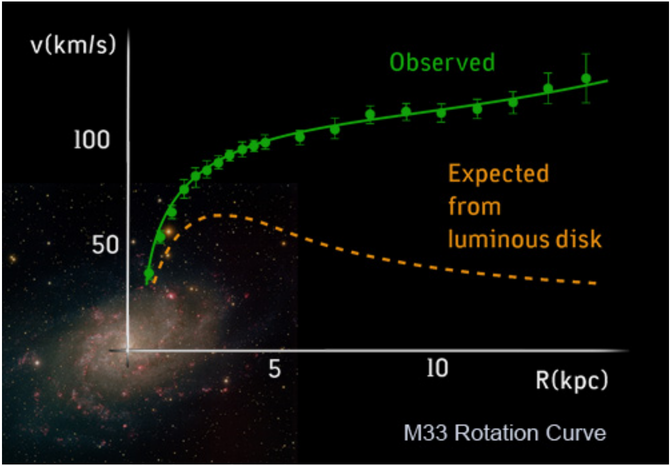
Evidence for Dark Matter

- Overwhelming evidence for the existence of dark matter: rotational velocity curves of galaxies, Bullet Cluster, gravitational lensing, acoustic peaks in the Cosmic Microwave Background (CMB) radiation spectrum...

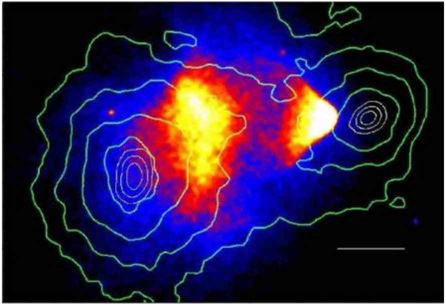




Rotational velocity curves of galaxies

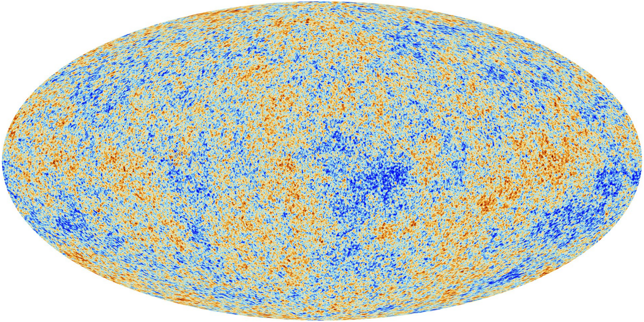


Bullet cluster(s), gravitational lensing



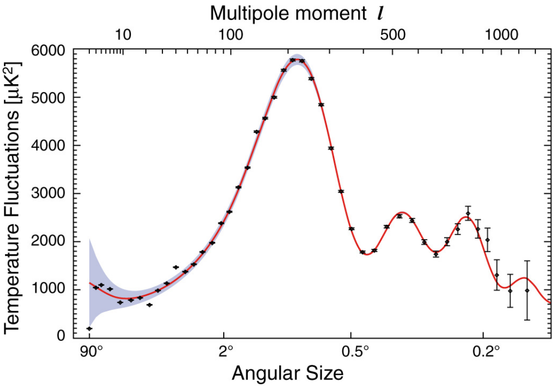
Cosmic Microwave Background (CMB) radiation

- The "first light" from $t = 380000$ y; the afterglow of the Big Bang era



Cosmic Microwave Background (CMB) radiation

- The observed peak structure of temperature fluctuations shows that dark matter cannot constitute of ordinary matter
- The peak structure cannot be explained by modified gravity theories



What is dark matter?

What have we learned?

- Dark matter affects structures at all scales (both temporal and spatial)
- Modified gravity theories cannot provide a plausible explanation for all aforementioned phenomena $\Rightarrow$ dark matter seems to consists of new particles (or compact objects)

How much there is dark matter?

- Observations of the CMB and large scale structure of the universe show that the matter content of the universe constitutes of dark matter, $\Omega_{\rm CDM} \simeq 0.26$, and "baryonic" matter, $\Omega_{\rm b} \simeq 0.05$.

- The rest of the total energy density, $1 - \Omega_{\rm CDM} - \Omega_{\rm b} = \Omega_{\Lambda} \simeq 0.69$, is dark energy (we have no idea what it is)

Properties of dark matter

- Dark matter must be stable or very long-lived, $t_{\rm dec} \gtrsim 10^{26}$ s
- Dark matter must be cold, i.e. non-relativistic (otherwise it spoils structure formation)
- Observations of the CMB show that the universe was radiation-dominated at the time of big bang nucleosynthesis at $t \simeq 1$ s, and matter overcame at $t_{\rm eq} = 50,000$ y $\Rightarrow$ a strict constraint for any DM model

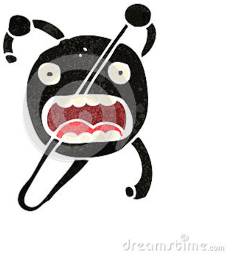
"Dark" matter?

- Dark matter is not dark but transparent

- Of course, one can ask how "dark" dark matter is, i.e. how strongly it interacts with photons $\Rightarrow$ should be measured

What is dark matter?

- What is the correct explanation for the invisible matter content observed in the universe? Does the dark matter particle exist? Or are there many dark matter particles?



What is dark matter?

- Are they WIMPs, FIMPs, SIMPs, GIMPs, PIDMs, WISPs, ALPs, Wimpzillas, sterile neutrinos, moduli fields, MACHOs, or primordial black holes?
- Or, should gravity be modified?
- How can we tell which model is the correct one (if any)?

How to observe dark matter?

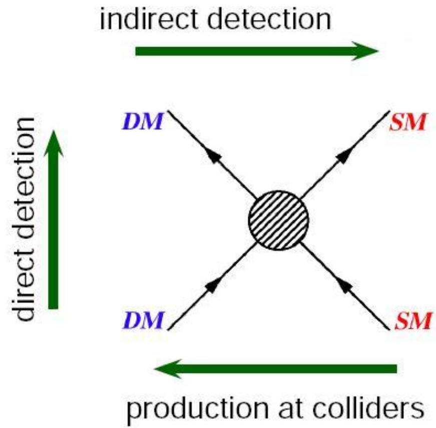
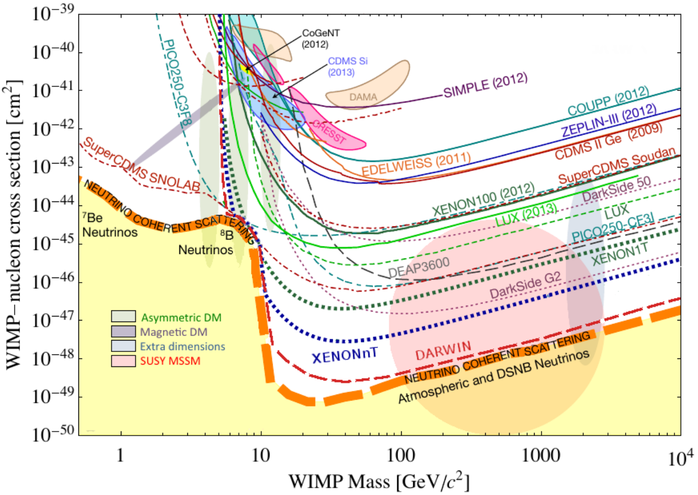


Image credit: Max-Planck-Institut Für Kernphysik – Cheers!

Search for dark matter



Self-interacting dark matter

- Problems related to small scale structure (galaxies, clusters) formation have been suggested to be explained by self-interacting DM with $\sigma_{\rm DM}/m_{\rm DM} \simeq \mathcal{O}(1){\rm cm}^2/{\rm g}$
- Astrophysical observations provide an upper bound on DM self-interactions $\sigma_{\rm DM}/m_{\rm DM} \lesssim 1{\rm cm}^2/{\rm g}$

Production of Dark Matter

A simple example: the Higgs portal

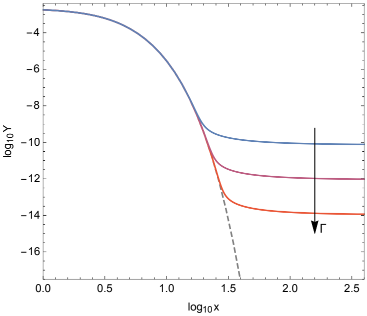
- The scalar sector of the model is specified by the potential

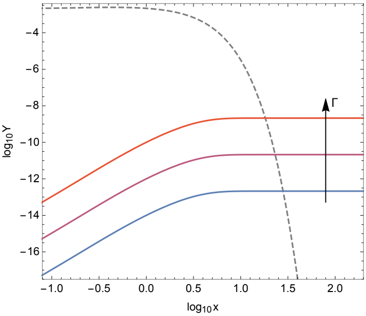
$$V(\Phi, s) = \mu_{\rm h}^2 \Phi^\dagger \Phi + \lambda_{\rm h} (\Phi^\dagger \Phi)^2 + \frac{1}{2}\mu_{\rm s}^2 s^2 + \frac{\lambda}{4} s^4 + \frac{y}{2} \Phi^\dagger \Phi s^2$$

- Here Φ and s are, respectively, the usual Standard Model Higgs doublet and a real singlet scalar
- The coupling between Φ and s acts as a portal between the Standard Model and an unknown Hidden Sector (the so-called Higgs portal)
- How was the observed DM abundance produced?

Dark Matter production mechanisms

- There are basically two mechanisms for dark matter production: freeze-out and freeze-in





The Freeze-Out

- Dark matter was initially in thermal equilibrium with the SM particles. This requires a rather strong coupling, $y \simeq 0.1$.
- May lead to a WIMP miracle: thermal relic with a weak scale cross-section and a mass $m_s \sim \mathcal{O}(10^2)$ GeV gives the correct relic abundance.
- Starts to be very constrained by experiments

Frozen-in Dark Matter

- Requires $y \lesssim 10^{-7}$, or otherwise the hidden sector thermalizes with the SM (this is sometimes called a FIMP scenario)
- Can be sensitive to initial conditions
- Almost impossible to test by colliders and direct detection experiments but can be tested especially by cosmological and astrophysical observations

Review of freeze-in scenarios

- Out now! See arXiv: 1706.07442

The Dawn of FIMP Dark Matter: A Review of Models and Constraints

Nicolás Bernal,[a,b] Matti Heikinheimo,[c] Tommi Tenkanen,[d] Kimmo Tuominen[c] and Ville Vaskonen[e]

A plethora of models

- One can introduce a sterile neutrino ψ

$$\mathcal{L}_{\rm Hidden} = \bar{\psi}(i\partial\!\!\!/ - m_{\psi})\psi + igs\bar{\psi}\gamma_5\psi$$

  or promote the "dark Higgs" s to be a complex doublet of a hidden $SU(2)$ symmetry, and so on

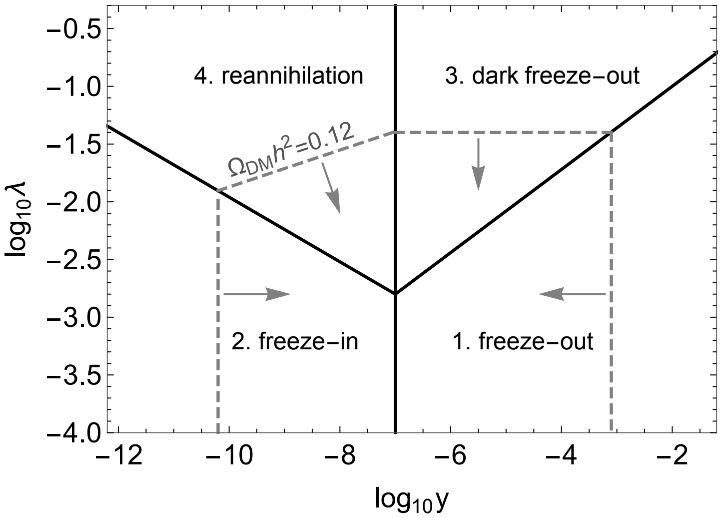
- Either the scalar s, the fermion ψ, the vector A_{μ}, or many of them simultaneously, can play the role of dark matter

- Other portals: the vector portal $B^{\mu\nu}$, the lepton portal $\Phi^{\dagger}L$ ...

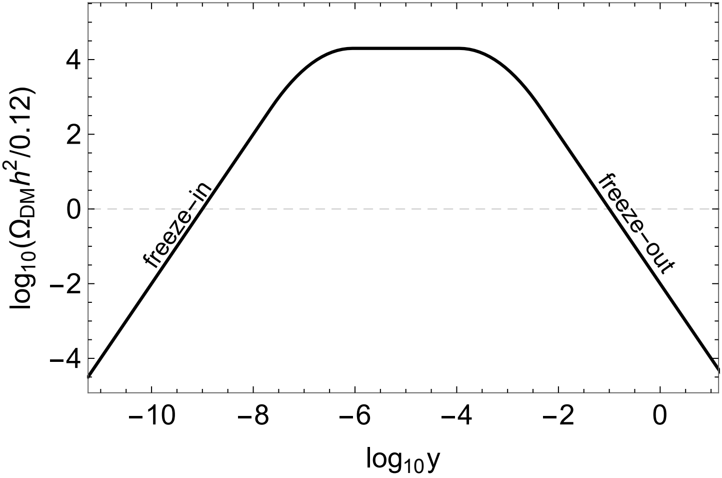
- Other models include supersymmetric particles, (pseudo-)Goldstone bosons, massive gravitons, ...

Thermal History of Dark Matter

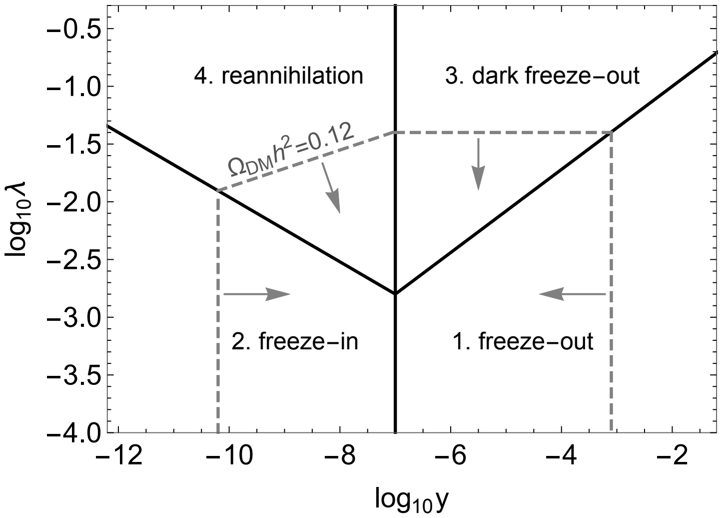
Thermal History of Dark Matter: a phase diagram



Thermal History of Dark Matter: a volcano diagram



Thermal History of Dark Matter: a phase diagram

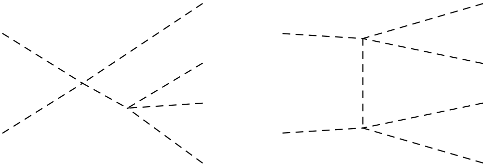


Thermal history of the Hidden Sector

- An initial population of DM is produced through Higgs decays $h \to ss$ at $T \sim m_{\rm h}$. In the standard freeze-in scenario, this is also the final abundance.
- However, if number-changing interactions (such as $2 \to 4$ annihilations in the simplest real scalar case) in the hidden sector are fast, they will lead to thermalization of the hidden sector
- This reduces the average momentum (temperature) of DM particles and increases their number density until thermal equilibrium is reached

Dark Freeze-out

- The $2 \leftrightarrow 4$ interactions maintain thermal equilibrium until the $4 \to 2$ interaction rate drops below the Hubble rate and the number density freezes out

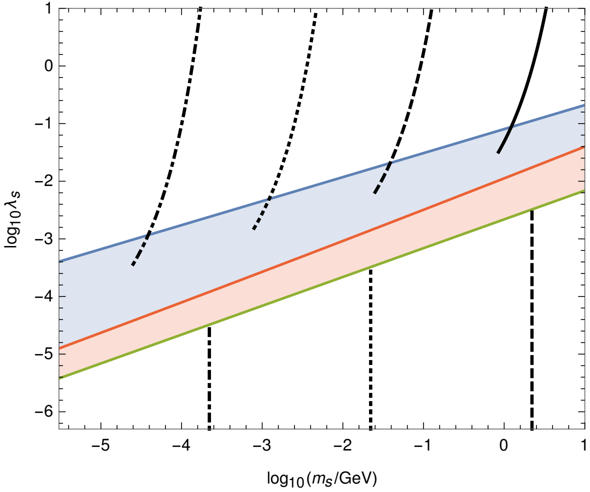


Examples of number-changing interactions.

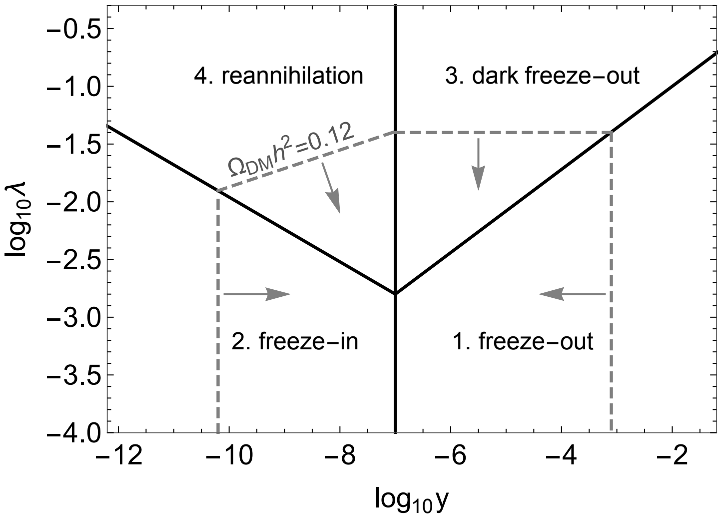
- This mechanism is referred to as dark freeze-out

Dark Freeze-out

- Three regimes: thermal case (dark freeze-out, above red line), non-thermal case (the standard freeze-in, below the green line), no solution at all (red region)

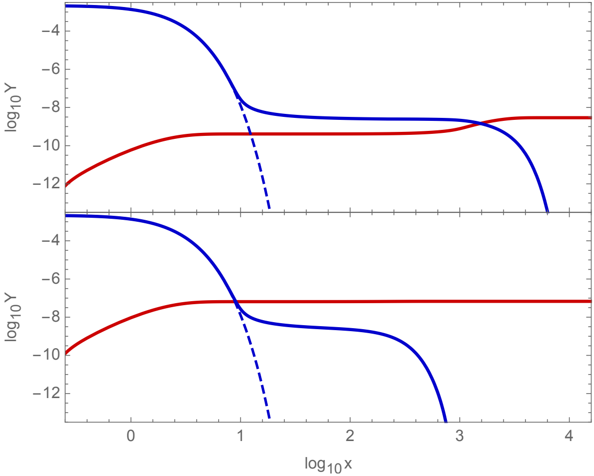


Thermal History of Dark Matter: a phase diagram



Hidden Sector dynamics

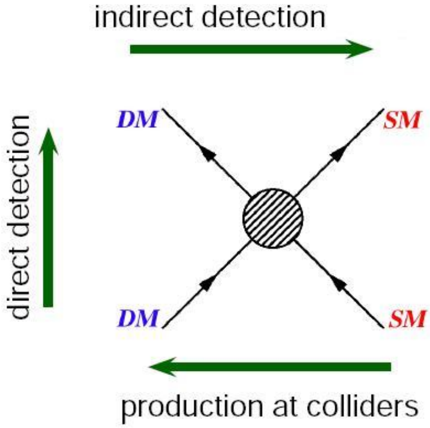
- Similar results can be derived for other fields in the hidden sector, including e.g. sterile neutrino or vector DM



- See more: Heikinheimo et al., arXiv:1604.02401 (sterile neutrinos), 1704.05359 (sterile neutrinos and vectors)

Observational properties

Collider, direct and indirect detection signatures



Direct detection

- By construction, the coupling must be so feeble that the DM particle never reaches thermal equilibrium with the visible sector $\Rightarrow$ FIMPs are inherently very difficult to test
- Light DM has to have a large number density in order to match the measured DM abundance $\Rightarrow$ enhances the detection rates
- Multiple experimental setups have been suggested for the detection of elastic and inelastic scatterings of DM in the mass range from keV to MeV

Indirect detection

- Indirect detection signals can result from decay or annihilation processes of DM particles
- The feeble couplings can result in very long lifetimes $\Rightarrow$ decaying DM can be naturally embedded in the freeze-in paradigm
- The X-ray and γ-ray observatories provide a powerful and independent probe of light DM (the 3.5 keV line, the GeV excess from the galactic center...)

Collider signatures

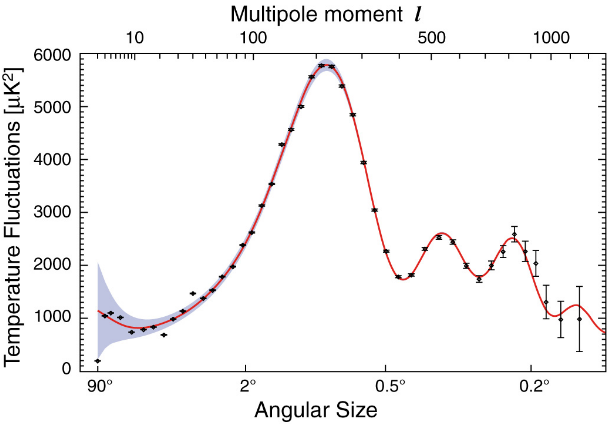
- Collider experiments are typically not sensitive to freeze-in models, due to the small production cross section
- However, appearance of particles with macroscopic lifetimes is possible
- Results to "displaced signatures": tracks appearing away from the collision axis, long-lived particles decaying in the calorimeter, or disappearing tracks

Astrophysical signatures

- Small scale structure vs. the cold DM paradigm?
- Frozen-in DM can be strongly self-interacting and its momentum distribution may not be thermal $\Rightarrow$ FIMP DM can suppress structure formation similar to warm DM and alleviate the "DM crisis on small scales"
- Important: this does not depend on the coupling between the dark and visible sectors

Cosmological signatures

- Frozen-in DM is non-thermal
  ⇒ FIMP DM remains sensitive to primordial initial conditions
  ⇒ non-observation of DM isocurvature in CMB places constraints on FIMP properties



Testing FIMPs with primordial physics

- "Standard Model with a real singlet scalar and inflation", Enqvist, Nurmi, TT, K. Tuominen (arXiv: 1407.0659)
- "Inflationary Imprints on Dark Matter", Nurmi, TT, K. Tuominen (arXiv: 1506.04048)
- "Isocurvature Constraints on Portal Couplings", Kainulainen, Nurmi, TT, K. Tuominen, V. Vaskonen (arXiv: 1601.07733)
- "Observational Constraints on Decoupled Hidden Sectors", M. Heikinheimo, TT, K. Tuominen, V. Vaskonen (arXiv: 1604.02401)

Other aspects of FIMPs

- Could the SM sector be reheated by an inverted freeze-in? Yes!
  ⇒ "Reheating the Standard Model from a Hidden Sector",
  TT, V. Vaskonen (arXiv: 1606.00192)

- Could a FIMP drive inflation? Yes!
  ⇒ "Feebly Interacting Dark Matter Particle as the Inflaton", TT
  (arXiv: 1607.01379)

- What if there is more structure in the hidden sector?
  ⇒ "WIMP miracle of the second kind", M. Heikinheimo, TT, K. Tuominen,
  arXiv: 1704.05359

Conclusions and Outlook

Conclusions

- The nature of dark matter is still unknown
- The FIMP framework provides for a compelling alternative to the standard WIMP paradigm
- Cosmological and astrophysical observations provide a valuable resource on testing different dark matter models

Where to go from here?

- Continue searches for WIMPs, FIMPs, and other DM candidates (LHC, direct and indirect detection)
- Measure the properties of the CMB more accurately (isocurvature, non-gaussianity, primordial tensor modes)
- Calculate detailed predictions for structure formation in microphysical models of DM $\Rightarrow$ effective theory of structure formation and increasingly accurate observations of it provide new means to solve the DM enigma