Warm Dark Matter and Large Scale Structure of the Universe

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Motivation

- ΛCDM cosmology is consistent with a plethora of observations.
- In particular, the observed Large Scale Structure (LSS) of galaxies, clusters etc. can be explained by the growth of primordial perturbations in the dark matter (DM) density.
- The compatibility of theory and observation is remarkable, except for discrepancies at relatively small scales $\lesssim 1\text{Mpc}$.
- These problems may be solved by assuming DM to be warm instead of cold.

Outline

1) Small scale problems

2) Solution via warm dark matter

3) Warm dark matter candidates

4) Observational constraints

Core-cusp problem

- Simulations of structure formation with cold dark matter (CDM) predict a steep density profile of the form $\rho \propto r^{-\alpha}$, $\alpha \sim 1$, in galaxy cores.
- This seems to be inconsistent with the observed flat density distribution in galaxy cores.
- Various astrophysical processes have been proposed and improved simulations used to explain this difference but the situation remains inconclusive.

[Primack; 2009; arXiv:0909.2247]

Satellite abundance problem

- ~ 1000 DM subhalos have been predicted for the Local Group while only ~ 10 satellite galaxies have been detected.
- One explanation would be that some of the galaxies in the subhalos are too faint to be observable.
- The reason for this might be suppression of star formation.

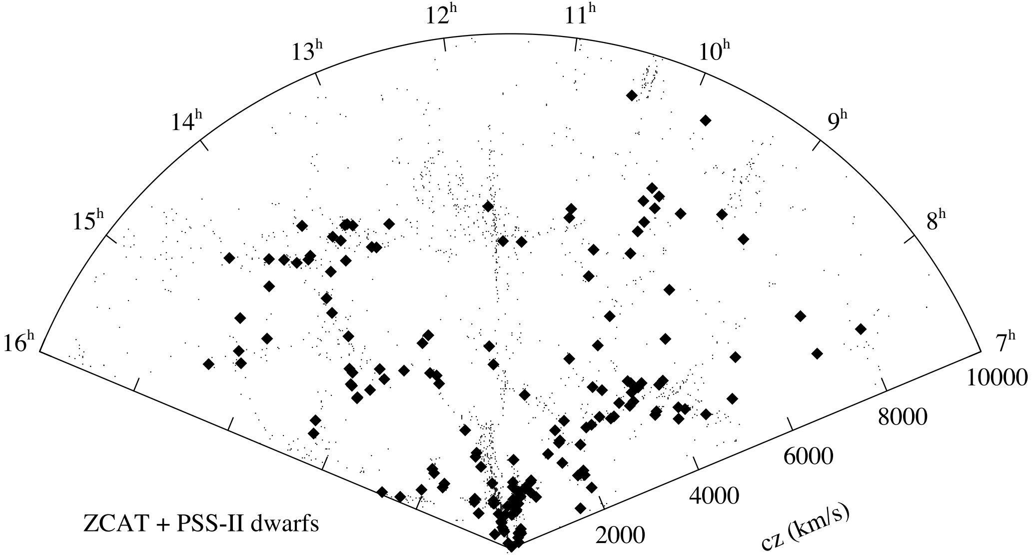
[Primack; 2009; arXiv:0909.2247]

Galaxy abundance in mini-voids

- Similarly to the satellite problem, the abundance of dwarf galaxies in mini-voids predicted by simulations is larger than observed.
- Most of the dwarf galaxies are located near the larger and brighter galaxies (see picture on next slide).
- This seems to be incompatible with hierarchical structure formation, i.e. small bound systems formed first, as predicted by CDM.

[Primack; 2009; arXiv:0909.2247]

Galaxy abundance in mini-voids



Summary of small scale problems

- All the above problems arise on scales $\lesssim 1\text{Mpc}$.
- It is therefore tempting to think of a common origin for these observation instead of a variety of astrophysical effects.
- The idea: Find a mechanism that suppresses structure formation at small scales.

Brief review of structure formation

- We start with an initial density distribution with small deviations from the average value in the radiation dominated era. (These initial conditions may be provided by primordial quantum fluctuations which get amplified during inflation.)
- During radiation domination perturbations on sub-horizon scales are essentially frozen.
- Only after matter-radiation-equality (EQ) can these perturbations grow effectively, first linearly and then non-linearly, to build stars, galaxies etc.

Free streaming

- Consider only perturbations in the DM energy density.
- Since DM is weakly interacting it decouples from radiation already during radiation domination, i.e. before EQ.
- From this moment on the DM particles move freely on geodesics in the expanding spacetime.
- This free streaming suppresses perturbations on scales smaller than the free streaming length λ_{FS} as long as these do not grow, i.e. before EQ. This is exactly what we are looking for.

Free streaming length

The comoving free streaming length is

$$\lambda_{\mathrm{FS}} = \int_0^{t_{\mathrm{EQ}}} \frac{v(t)}{a(t)} \mathrm{d}t,$$

where v is the physical velocity of the particle.

We can split the integral in a part where the particle is relativistic and another where it is non-relativistic:

$$\lambda_{\mathrm{FS}} \approx \int_0^{t_{\mathrm{NR}}} \frac{1}{a(t)} \mathrm{d}t + \int_{t_{\mathrm{NR}}}^{t_{\mathrm{EQ}}} \frac{v(t)}{a(t)} \mathrm{d}t$$

Free streaming length

During radiation domination we have $a(t) \propto \sqrt{t}$ and the velocity is redshifted according to $v(t) \propto a(t)^{-1}$.

This implies $a(t) = a_{\mathrm{NR}} \sqrt{t/t_{\mathrm{NR}}}$ and hence

$$\begin{aligned} \lambda_{\mathrm{FS}} &\approx 2 \frac{t_{\mathrm{NR}}}{a_{\mathrm{NR}}} + \int_{t_{\mathrm{NR}}}^{t_{\mathrm{EQ}}} \frac{a_{\mathrm{NR}}}{a(t)^2} \mathrm{d}t \\ &= \frac{t_{\mathrm{NR}}}{a_{\mathrm{NR}}} \left(2 + \ln \left(\frac{t_{\mathrm{EQ}}}{t_{\mathrm{NR}}} \right) \right) . \end{aligned}$$

By increasing t_{NR} we can make λ_{FS} larger!

Cold, warm, and hot dark matter

- CDM corresponds to the particles being non-relativistic already at the time of decoupling, $t_{\mathrm{NR}} = t_{\mathrm{dec}}$.
- This DM seems to have the problems discussed in the beginning.
- The other extreme, hot DM, has $t_{\mathrm{NR}} = t_{\mathrm{EQ}}$ and leads to structure formation incompatible with observation (top-down).
- Warm DM means to have t_{NR} somewhere in between.
- This can be achieved by increasing the mass of DM compared to CDM while keeping interaction strengths constant. (Changing both parameters is of course also possible.)

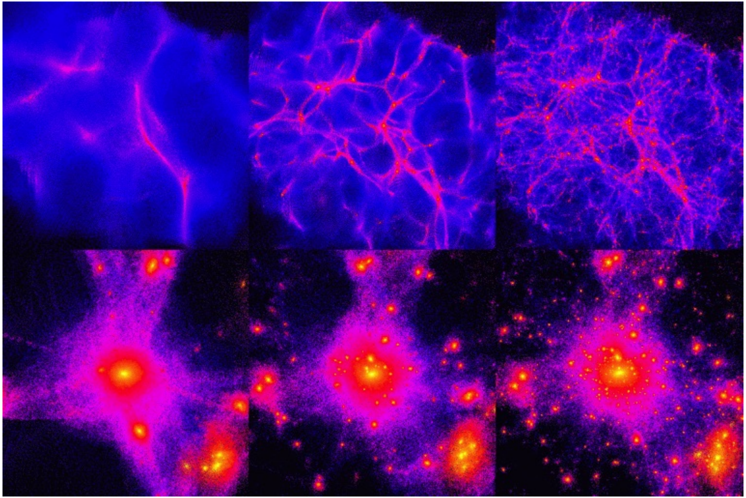
Simulations of warm dark matter

Simulations of warm dark matter with masses 175eV, 350eV and 1.5keV have, among others, the following characteristics when compared to CDM:

- Halo core densities are lowered and smoothed.
- Overall number of low mass halos is reduced.
- Number of low mass satellite halos in high mass halos is suppressed.
- Voids are almost empty of small halos.
- Low mass halos are formed late in a top down process.

[Bode, Ostriker, Turok; 2001; arXiv:astro-ph/0010389]

Simulations of warm dark matter



[Credit: Ben Moore, University of Zürich]

Warm dark matter candidates

Sterile neutrinos:

- Only gravitational interaction - not charged under SM gauge groups (sterile)
- Usually right-handed chirality
- Yukawa interactions gives mixing with ordinary neutrinos (possible detection)
- For GUTs (e.g. SO(10)) they could in principle also have gauge interactions, but these gauge bosons are very heavy, i.e. interaction is heavily suppressed.
- Mass could be generated from a see-saw mechanism.

Warm dark matter candidates

Gravitino

- Spin 3/2 superpartner of graviton
- Must be stable - i.e. in models it should be the Lighest supersymmetric particle (LSP) (keV)

Current constraints

Measurements from the Lyman-α forest (Absorption spectra from quasars caused by hydrogen gas) gives 2σ lower limits:

- $m_{\mathrm{WDM}} > 4\,\mathrm{keV}$
- $m_{\nu\mathrm{s}} > 28\,\mathrm{keV}$

[Viel, Becker, Bolton, Haehnelt, Rauch, Sargent; 2007; arXiv:astro-ph/0709.0131]

The Euclid satellite can improve this by gravitational lensing because it not only relies on the visible baryons. From the weak lensing power spectrum a new constraint will be around:

- $m_{\mathrm{WDM}} > 2\,\mathrm{keV}$

[Markovic, Bridle, Slosar, Weller; 2010; arXiv:astro-ph/1009.0218]

Thank you!