Phase space density constraints for Warm Dark Matter models

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Why to study "alternative" dark matter models?

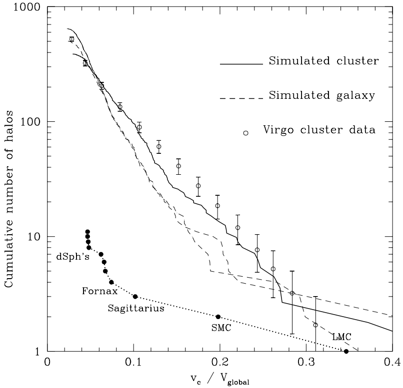
- Cold Dark Matter is made out of heavy, not moving, non-interacting particles
- CDM is very successful on cosmological scales but seems to have issues with subgalactic small scale structures
- Missing Satellites Problem — Klypin et al., Moore et al. 99

  CDM halos host much larger number of satellite galaxies than observed in the Milky Way and Andromeda
- Cusps Problem — Moore 94

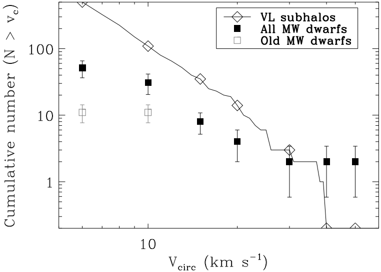
  Matter density profile in CDM halos is way steeper near the center than suggested by observations

Missing Satellites Problem

CDM simulations predict few hundred satellites in a galaxy like ours, whereas only 23 are found so far in the MW



Klypin et.al. 99

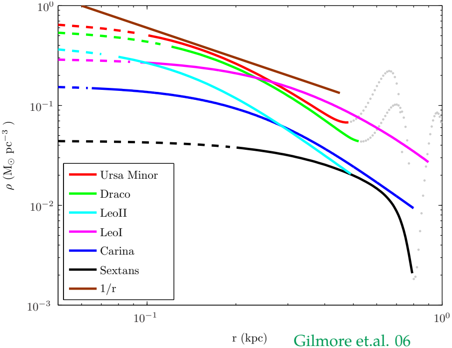


Simon & Geha 07

New surveys are expected to discover some more satellites

Star formation may be not efficient in small halos & they remain dark

Cusps Problem



Gilmore et.al. 06

CDM density follows universal NFW profile with $\rho \sim 1/r$ towards galactic center

Stellar kinematics in local satellites suggest shallow central density profiles

Supernova explosions cause gas blowout from central regions and may substantially reduce central density

Governato et al. 10, 12

"Too big to fail problem": out of 10 biggest CDM subhalos, 8 are too dense to host any known bright MW satellite

M. Boylan-Kolchin et al. 11, 12

Outline

Warm Dark Matter

Phase space density

Gravitino Lightest Supersymmetric Particle dark matter

Sterile neutrino dark matter

What if dark matter is not (quite) cold?

Better simulations (high resolution and astrophysics modeling) still might solve everything

Particle physicist point of view: modifying CDM could positively affect structure formation on subgalactic scales

- Non-negligible velocities of DM particles

  Warm Dark Matter

- Non-negligible self-interaction cross-section

  Collisional/Self Interacting DM

- Non-negligible quantum effects

  Axion BEC, Ultra-light boson/Scalar Field DM

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Conservative point of view: How light can be DM particles? What are the constraints on their velocity distribution if one wants to enjoy all the success of CDM?

Quantifying warmness: free streaming

Naively: Density perturbations do not grow while DM particles are still relativistic. DM streams freely out of potential wells.

Longer modes that enter horizon after DM becomes non-relativistic are unaffected $\Rightarrow$ cut-off for small l / large k

DM becomes non-relativistic when $p \sim m$ or $T_* \sim \left(\frac{T}{p}\right) m$

Cut-off wavelength $\sim$ horizon size: $l_{min,*} \sim H_*^{-1} = \frac{M_{\rm Pl}^*}{T_*^2}$

Present size is

$$l_{min,0} \sim \left(\frac{p}{T}\right) \frac{M_{\rm Pl}^*}{T_0\, m} \sim 70 \text{ kpc} \left(\frac{p}{T}\right) \left(\frac{1 \text{ keV}}{m}\right)$$

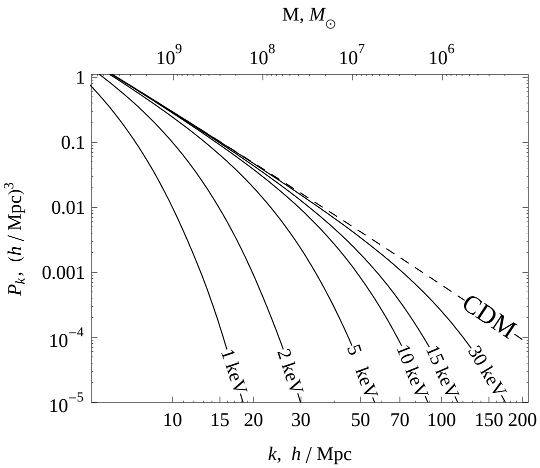
Mass of corresponding compact objects

$$M_{min} \lesssim \rho_{DM} \frac{4\pi}{3} l_{min,0,}^3 \sim 10^9 M_\odot \left(\frac{1 \text{ keV}}{m}\right)^3$$

Cf. dwarf galaxies, $M_{dwarf} \sim 10^8 \div 10^9 M_\odot$

Power spectrum of density perturbations

More precise: To take into account all effects we run Boltzmann simulation and obtained linear power spectrum



Power spectrum of density perturbations $P(k)$ is significantly suppressed in comparison to CDM on the scales $10^{10} \div 10^8 M_\odot$ for $1\ \mathrm{keV} \lesssim m \lesssim 10\ \mathrm{keV}$, respectively.

Phase space density argument

Tremaine & Gunn 79

Initial density of dark matter particles in phase space is (almost) independent of $\vec{x}$ and is given by momentum distribution $f(\vec{p})$

Phase space density characterize dark matter particle model and production mechanism

For fermions maximum value is limited:

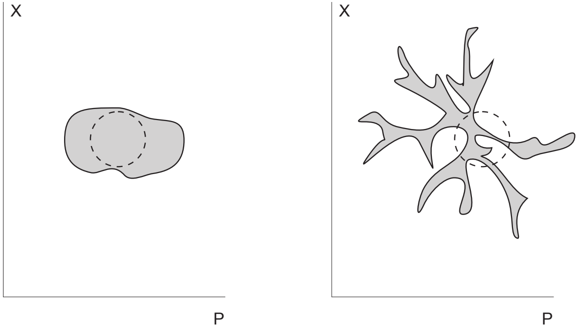
$$f(\vec{p}) \leq \frac{1}{(2\pi)^3} \qquad \text{by Pauli principle}$$

Not more than one particle in quantum unit of phase space volume $\Delta\vec{x} \cdot \Delta\vec{p} = (2\pi\hbar)^3$.

N.B. For thermal distribution $f_{\max} = \frac{1}{2(2\pi)^3}$

Expect maximum phase space density somewhat below $\frac{1}{(2\pi)^3}$

For non-dissipative motion of particles, with gravitational interactions only comoving phase space density is conserved due to Liouvile theorem.



But due to chaotic motion particles tend to penetrate into empty parts of phase space and coarse grained density decreases in time.

The maximum phase space density also decreases in time.

Observation of phase space density

"Poor man's phase space density":

Hogan & Dalcanton 00

$$Q(\vec{x}) = \frac{\rho_{DM}(\vec{x})}{\langle v_{||}^2 \rangle^{3/2}}$$

mass density $\rho_{DM}(\vec{x}) \Longleftrightarrow$ gravitational potential
velocity dispersion $\langle v_{||}^2 \rangle \Longleftrightarrow$ velocities of stars along line of sight

Assume dark matter particles have same velocities as stars (e.g., virialized), we can estimate present phase space density:

$$Q \simeq m^4 \frac{n(\vec{x})}{\langle p^2 \rangle^{3/2}} \simeq m^4 \cdot f_0(\vec{x}, \vec{p})$$

Mass bound from primordial phase space distribution:

$$m^4 f_{\max} > Q_{\max}$$

Observed phase space density of dark halos

- In general, larger objects have smaller phase space density. They experience more severe mixing in the phase space.
- Q ranges from $10^{-13}\,\frac{M_\odot/\text{pc}^3}{(\text{km/s})^3}$ for galaxy clusters to $5\cdot 10^{-3}\,\frac{M_\odot/\text{pc}^3}{(\text{km/s})^3}$ for dwarf satellite galaxies.
- Largest Q is observed in Ultra Compact Dwarfs (Coma Berencies, Leo IV, Canes Venaciti II)

$$Q_{\max} = (3\cdot 10^{-3} \div 2\cdot 10^{-2})\,\frac{M_\odot/\text{pc}^3}{(\text{km/s})^3} \simeq 0.2\ \text{keV}^4$$

Gilmore et al. 07

- N.B. Globular clusters have Q up to $30\,\frac{M_\odot/\text{pc}^3}{(\text{km/s})^3}$ but do not contain any DM $\Rightarrow Q_{\max}$ estimates the largest dark matter phase space density

Mass lower bound

Decreasing of the maximum phase space density implies a lower bound on DM particle mass:

$$Q_{\max} \simeq 0.2\ \mathrm{keV}^4 \lesssim f_{\max} \cdot m^4 \simeq \frac{\#}{(2\pi)^3} \cdot m^4$$

Collisionless dark matter with thermal-like initial distribution could form observed dark halos only if

$$m \gtrsim 1\ \mathrm{keV}$$

If maximum observed Q indeed estimates the largest phase space density of DM particles ever achieved, then

$$m \sim 1 \div 10\ \mathrm{keV}$$

N.B. Q depends on mass very strongy. For 100 GeV WIMP the phase space density has to be diluted by a large factor $\sim 10^{24}$ during nonlinear evolution.

Warm Dark Matter candidates

There is a couple of keV scale particles which can serve as WDM:

- Gravitino as the Lightest Supersymmetric Particle
  e.g. theories with low SUSY breaking scale
- Sterile neutrino
  e.g. νMSM by M. Shaposhikov et al.
  Provides also a lot of "bonuses", from baryon asymmetry to pulsar kicks.

Gravitino as Dark Matter particle

Spin 3/2 fermion in supergravity theories. Mass $m_{3/2} \simeq F/M_{\rm Pl}$ depends on the SUSY breaking scale and can be quite light

Can be the Lightest Supersymmetric Particle $\Longrightarrow$ Stable

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In the Universe gravitino is produced in two ways:

- Decays of all heavier superparticles Moroi et al. 93

$$\Omega^{\rm dec}_{3/2} \approx 0.2 \cdot \left(\frac{1 \text{ keV}}{m_{3/2}}\right) \left(\frac{M}{150 \text{ GeV}}\right)^3$$

  Need very light superpartners: $M \approx 100 \div 300$ GeV

- Scatterings of the heavier superparticles in primordial plasma Moroi et. al. 93; Boltz et. al. 01; Pradler 07; Rychkov & Strumia 07

$$\Omega^{\rm sc}_{3/2} \approx 0.2 \cdot \left(\frac{1 \text{ keV}}{m_{3/2}}\right) \left(\frac{M}{200 \text{ GeV}}\right)^2 \left(\frac{T_R}{1 \text{ TeV}}\right)$$

  Need very low reheating temperature: T_R in TeV range

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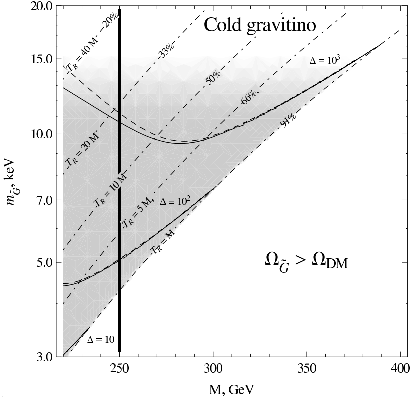
Two representative scenarios:

All superpartners mass are of the same order M

Excluded by LHC



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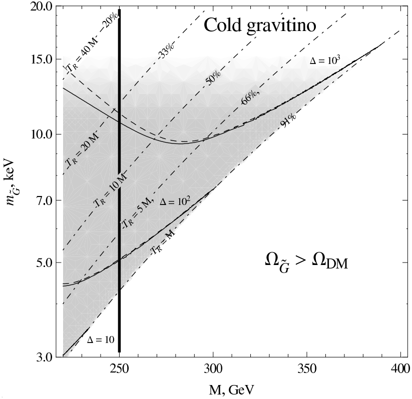
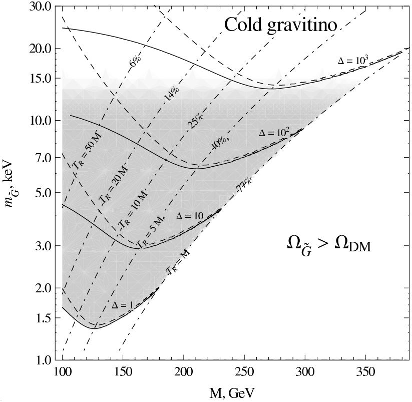


Gluinos and squarks heavier than T_R, never existed in cosmic plasma



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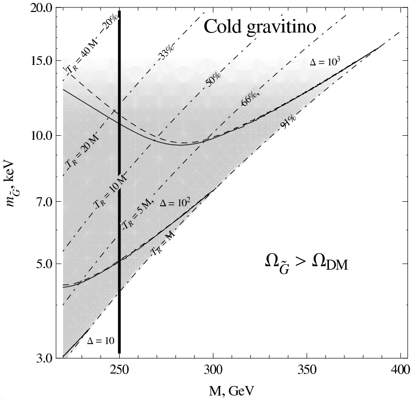

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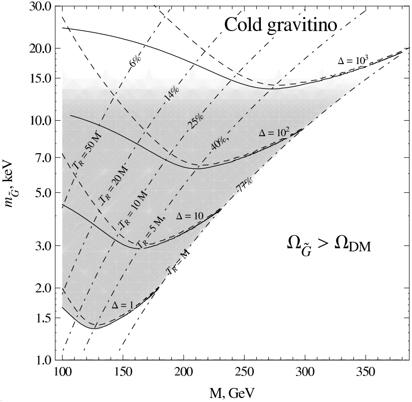

By now gravitino WDM is almost excluded by the LHC SUSY search results

Sterile neutrino as Dark Matter particle

Much more freedom in model building ⇒ Cosmology very much depends on the model

Simplest production mechanism is via mixing with active ν
Dodelson & Widrow 94

Primordial distribution has almost thermal shape

$$f(p) \simeq \frac{g_\nu}{(2\pi)^3} \frac{\beta}{e^{p/T}+1}$$

Normalization is determined by the mixing angle $\beta \propto \sin^2\theta$

If sterile neutrino account for all dark matter $\Omega_\nu \approx 0.2$

$$\beta \simeq 10^{-2} \left(\frac{1\ \mathrm{keV}}{m_\nu}\right)$$

Knowing maximum of distribution function one can apply phase space bound

$$m_\nu^4 \cdot f_{\max} = \left(\frac{m_\nu}{1\ \mathrm{keV}}\right)^3 \cdot 10^{-2}\ \mathrm{keV}^4 > Q_{\max} \Longleftrightarrow m_\nu \gtrsim 5.7\ \mathrm{keV}$$

Lyman-α spectra of distant quasars give completely independent but comparable limit on the sterile neutrino DM mass $m_\nu \gtrsim (5.6 \div 28)$ keV

Abazajan 06; Seljak et al. 06; Viel et al. 08

The same mixing angle determines the decay rate in $\gamma + \nu_L$ Non-observation of the corresponding X-ray line puts the bound $\beta < 2.5 \cdot 10^{-3} \Longleftrightarrow m_\nu \lesssim 4$ keV

Boyarsky et. al.; Riemen-Sorensen et.al.; Watson et.al.; Abazajan et.al. 06

Sterile neutrino dark matter produced via the active-sterile mixing is ruled out

Other production mechanisms available

To conclude:

- There are issues in modeling the structure formation in CDM on subgalactic scales
- Phase space density constraint allows to check whether DM is cold enough knowing its momentum distribution
- DM particles with thermal-like distributions have to be heavier than ≈ 1 keV
  If heavier than 30 keV $\Rightarrow$ indistinguishable from CDM
- WDM scenarios usually involve non-standard particle physics and/or cosmology

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Thank You!

Free streaming

Free streaming length at radiation-matter equality (beginning of rapid growth of perturbations),

$$l_{\text{fs}}(t_{\text{eq}}) \sim v \cdot t_{\text{eq}} = \frac{p}{T}\frac{T_{\text{eq}}t_{\text{eq}}}{m}$$

Present size (for relativistic thermal-like distribution at decoupling with $\frac{p}{T} \simeq 3$)

$$l_0 \sim 200\ \text{kpc} \cdot \frac{1\ \text{keV}}{m}$$

Perturbations at smaller scales are suppressed.
Mass of less abundant objects

$$M \lesssim \rho_{DM} \cdot \frac{4}{3}\pi l_0^3 \sim 10^9 M_\odot \cdot \left(\frac{1\ \text{keV}}{m}\right)^3$$

Cf. dwarf galaxies, $M_{dwarf} \sim 10^8 \div 10^9 M_\odot$.