Quantum Mechanics Meets Gravity

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DaMeSyFla: CP Violation 50 years after discovery

SISSA, 23 September 2014

based on:

arXiv:1409.3167 with Valerie Domcke

MOTIVATIONS

- Numerical N-body simulations with cold Dark Matter (DM) do not match observations at small galactic scales

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1) "Cusp/core problem"
2) Bulge-less disk galaxies
3) "Missing satellites problem"
4) "Too big to fail problem"

B. Moore et al., MNRAS, 310, 1147
V. Avila-Reese et al., Astrophys. J., 559, 516
A. V. Maccio et al., MNRAS, 366, 1529
M. Boylan-Kolchin et al., MNRAS, 422, 1203

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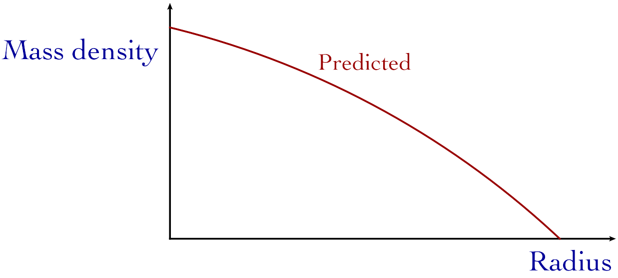

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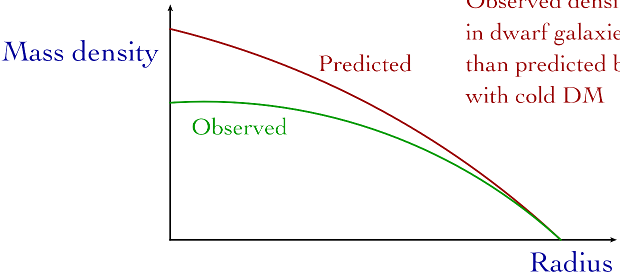

Observed density profiles in dwarf galaxies are shallower than predicted by simulations with cold DM

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- Numerical N-body simulations with cold Dark Matter (DM) do not match observations at small galactic scales

1) "Cusp/core problem"
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→ Include baryons in the simulations

E. Romano-Diaz et al., arXiv:0808.0195

→ Change the cold DM paradigm

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Change the
cold DM paradigm

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Change the cold DM paradigm

↓

It would be extremely interesting to relate the observed properties of galaxies to their DM content rather than to the outcome of a numerical simulation!

MOTIVATIONS

- Numerical N-body simulations with cold Dark Matter (DM) do not match observations at small galactic scales

Change the
cold DM paradigm

- Warm DM — P. Colin, V. Avila-Reese and O. Valenzuela, Astrophys. J., 542, 622; P. Bode, J. P. Ostriker and N. Turok, Astrophys. J., 556, 93
- Self-interacting DM — D. N. Spergel and P. J. Steinhardt, Phys. Rev. Lett., 84, 3760
- DM as a Bose-Einstein condensate (BEC)

S. J. Sin, Phys. Rev. D50, 3650
S. U. Ji and S. J. Sin, Phys. Rev. D50, 3655
C. G. Beohmer and T. Harko, JCAP, 0706, 025

DM as a BEC

i) DM is made of bosons

ii) On galactic scales these bosons are able to form a BEC

iii) In a BEC the temperature is so low that all the bosons are in a single quantum state (the ground state)

DM as a BEC

i) DM is made of bosons

ii) On galactic scales these bosons are able to form a BEC

iii) In a BEC the temperature is so low that all the bosons are in a single quantum state (the ground state)

iv) If there is no thermal pressure, what is the mechanism protecting the system from gravitational collapse ?

Quantum pressure versus Gravity

i) We describe a galaxy as a gas of N DM particles
with mass m
in a spherical halo with total mass M and radius R
with number density $n = \rho/m$

Quantum pressure versus Gravity

	BOSONS	

Quantum pressure versus Gravity

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Momentum	$p \sim \frac{h}{\Delta x} \sim \frac{h}{R}$	

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Quantum pressure versus Gravity

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C. Destri, H. J. de Vega and N. G. Sanchez,
Astropart. Phys. 46, 14

Quantum pressure versus Gravity

	BOSONS	FERMIONS
Momentum	$p \sim \frac{h}{\Delta x} \sim \frac{h}{R}$	$p \sim N^{1/3} \frac{h}{R}$
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Equilibrium	$P_Q \sim P_G$ $\downarrow$ $\frac{h^2 \rho}{m^2 R^2} \sim \frac{GM^2}{R^4}$	$P_Q \sim P_G$ $\downarrow$ $\frac{h^2 \rho^{5/3}}{m^{8/3}} \sim \frac{GM^2}{R^4}$
Size	$R \sim \frac{h^2}{m^2 GM}$ $m \sim 10^{-25}$ eV	$R \sim \frac{h^2}{m^{8/3} GM^{1/3}}$ $m \sim 50$ eV

C. Destri, H. J. de Vega and N. G. Sanchez,
Astropart. Phys. 46, 14

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$\rho \sim M/R^3$

$$\frac{M^{5/3}}{R^5} \sim \frac{M^2}{R^4}$$

See also (in the context of warm DM):
C. Destri, H. J. de Vega and N. G. Sanchez, Astropart. Phys. 46, 14
H. J. de Vega and N. G. Sanchez, arXiv:1301.1864
H. J. de Vega, P. Salucci and N. G. Sanchez, MNRAS, 442, 2717

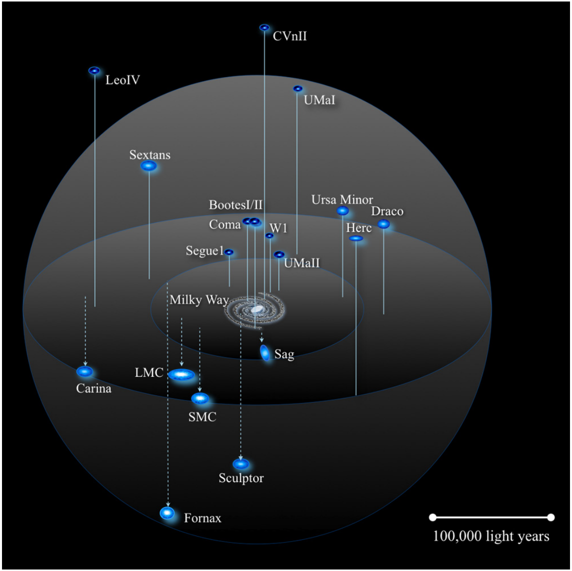
Hypothesis

DM is made of free fermions

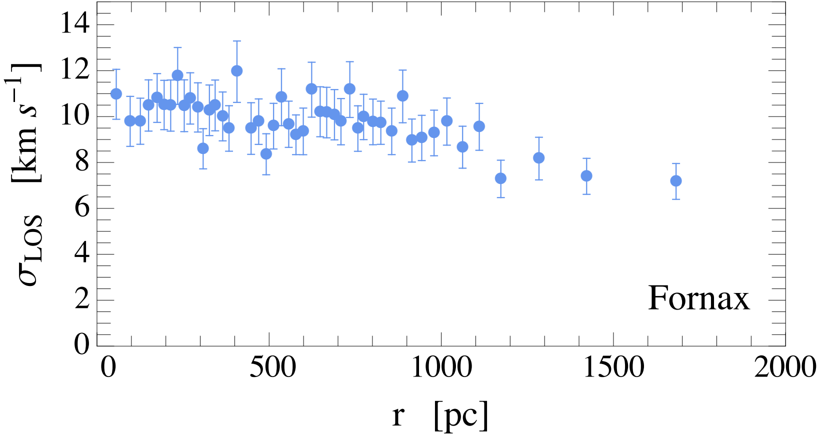
→ Dwarf galaxies correspond to the degenerate limit

→ Large galaxies correspond to the non-degenerate limit

N.B. This picture is supported by the observation that larger galaxies have increasing value of the temperature.


CVnII
LeoIV
UMaI
Sextans
BootesI/II
Ursa Minor
Draco
Coma
W1
Herc
Segue1
UMaII
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax
100,000 light years

M. G. Walker, M. Mateo, E. W. Olszewski, J. Penarrubia, N. W. Evans and G. Gilmore
Astrophys. J., *704*, 1274



Fit of the velocity dispersion

$$v(r) = \sqrt{\frac{M(r)G}{r}}$$

N.B.: these formulae have only an illustrative purpose.
The observed quantity is the projection of the velocity dispersion along the line-of-sight.

Fit of the velocity dispersion

$$v(r) = \sqrt{\frac{M(r)G}{r}}$$

$$M(r) = 4\pi \int_0^r r'^2 \rho(r') dr'$$

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Quantum pressure versus Gravity

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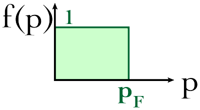

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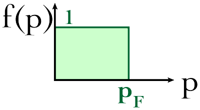

$$P_Q = \frac{8\pi}{3h^3} \int_0^{p_F} \frac{p^4 dp}{(p^2 + m^2)^{1/2}}$$

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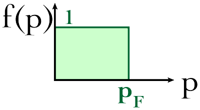


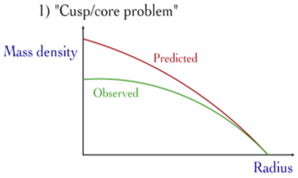
$$P_Q = \frac{8\pi}{3h^3} \int_0^{p_F} \frac{p^4 \, dp}{(p^2 + m^2)^{1/2}}$$

$$\frac{dP_Q}{dr} = - \frac{GM(r)}{r^2} \rho(r)$$

Fit of the velocity dispersion

$$\rho = \rho(m, \rho_0, \mathrm{r})$$

Fit of the velocity dispersion



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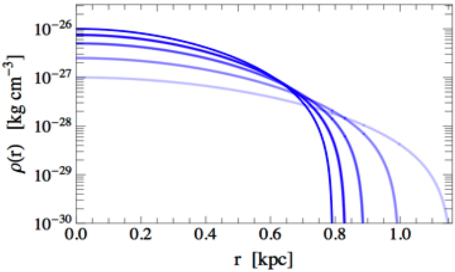
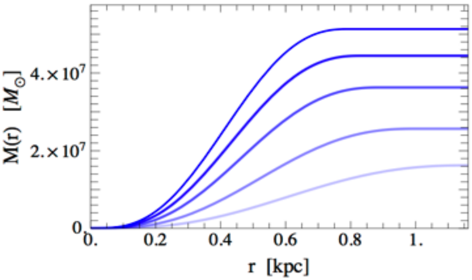
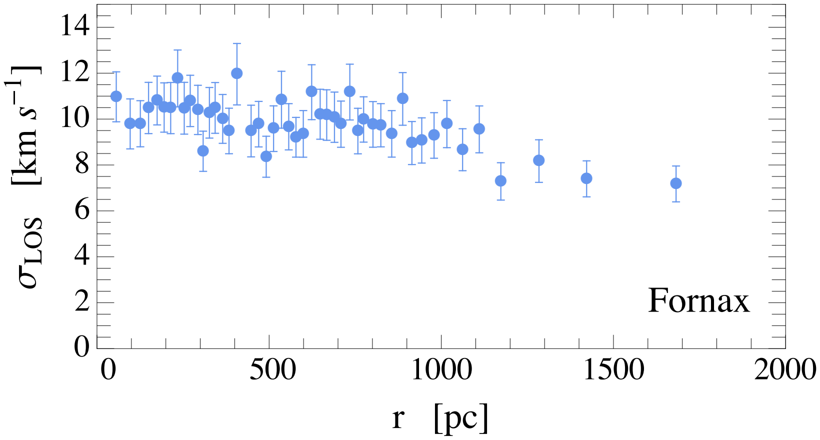
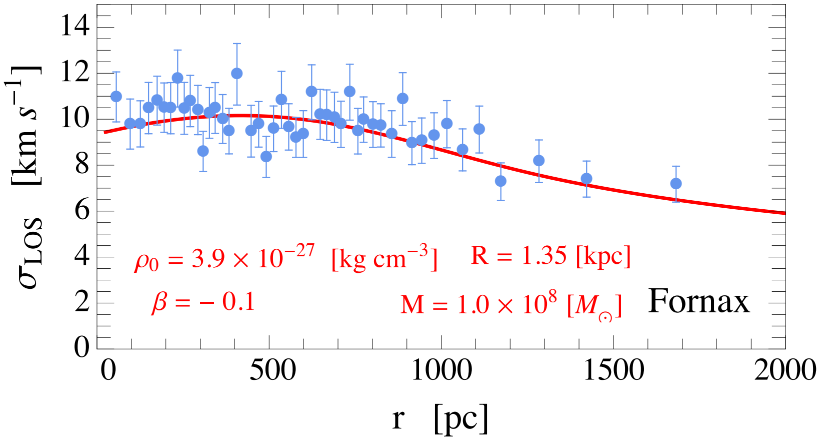





14
12
10
8
6
4
2
0
σ_{LOS} [km s^{-1}]
0
500
1000
1500
2000
r [pc]
Fornax


σ_{LOS} [km s^{-1}]
14
12
10
8
6
4
2
0
0
500
1000
1500
2000
r [pc]
$\rho_0 = 3.9 \times 10^{-27}$ [kg cm^{-3}]
R = 1.35 [kpc]
$\beta = -0.1$
M = 1.0×10^8 [$M_\odot$]
Fornax

Hypothesis

DM is made of free fermions with mass $m \sim 200$ eV

→ Dwarf galaxies correspond to the degenerate limit

→ Large galaxies correspond to the non-degenerate limit

Free-streaming length

DM non-relativistic
at matter-radiation equality
(i.e. cold DM)

$\longrightarrow$ $\lambda_{FS} \ll 0.5$ **Mpc**

Both small and large
density perturbations
are not erased

(actually too many substructures
that we do not observe!)

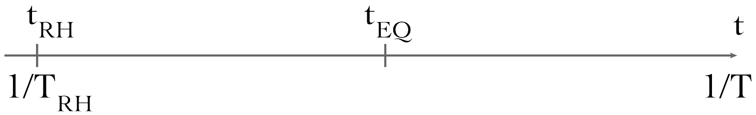
DM ultra-relativistic
at matter-radiation equality
(i.e. SM neutrinos)

$\longrightarrow$ $\lambda_{FS} > 0.5$ **Mpc**

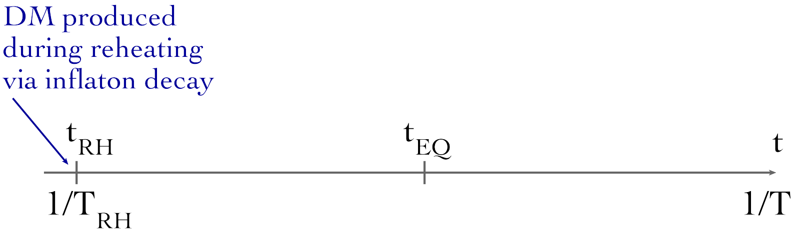
Both small and large
density perturbations
are erased

N.B.
This picture is true if DM is thermally produced

DM from inflaton decay

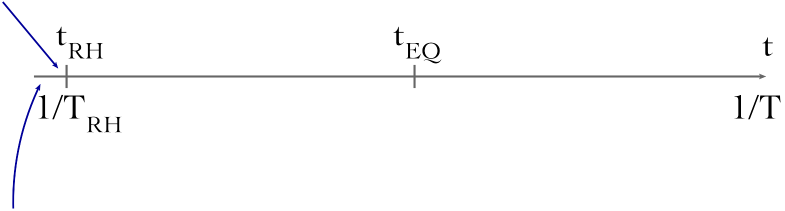


DM from inflaton decay



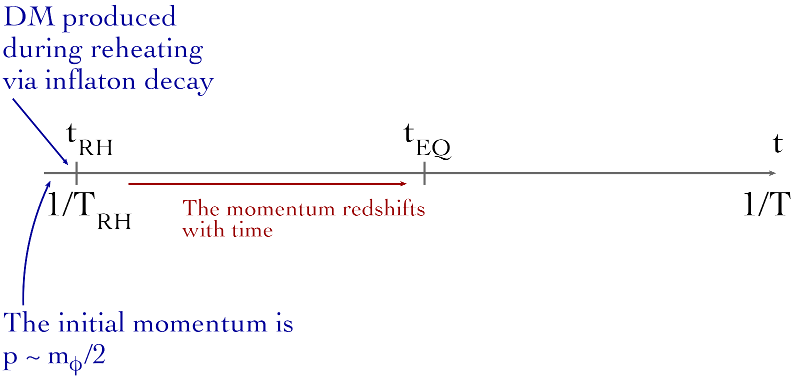
DM from inflaton decay

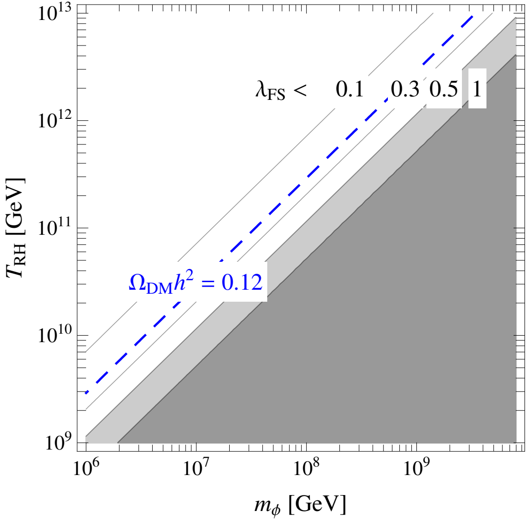
DM produced
during reheating
via inflaton decay



The initial momentum is
$p \sim m_\phi/2$

DM from inflaton decay




10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
T_{RH} [GeV]
$\lambda_{FS} <$ 0.1 0.3 0.5 1
$\Omega_{DM}h^2 = 0.12$
10^6
10^7
10^8
10^9
m_ϕ [GeV]

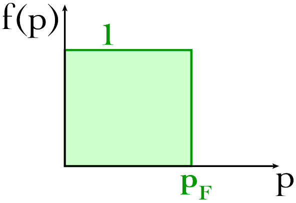
Model

DM is made of free fermions with mass $m \sim 200$ eV produced non-thermally via inflaton decay

→ Dwarf galaxies correspond to the degenerate limit

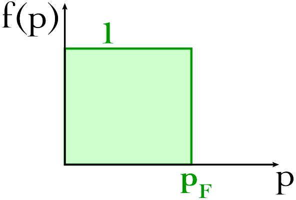
→ Large galaxies correspond to the non-degenerate limit

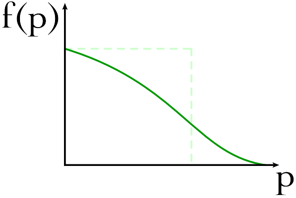
Degenerate vs. non-degenerate FD distribution



$$\rho = \rho(m, \rho_0, r)$$

Degenerate vs. non-degenerate FD distribution





$$\rho = \rho(m, \rho_0, r)$$

$$\rho = \rho(m, \rho_0, r\ ;\ k)$$

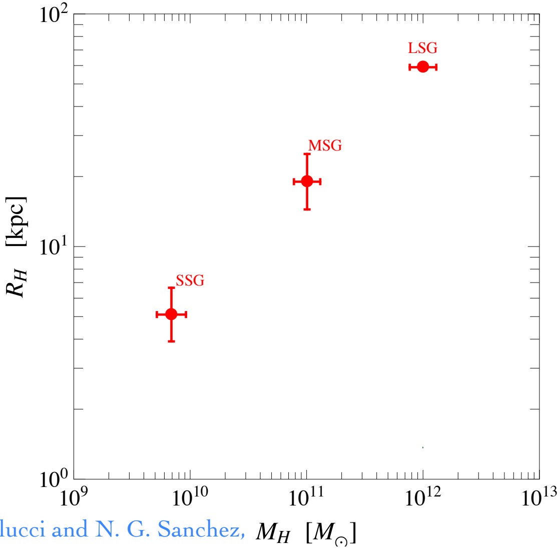
Degenerate vs. non-degenerate FD distribution

$$\rho = \rho(m, \rho_0, \mathrm{r}\,;\, \mathrm{k})$$

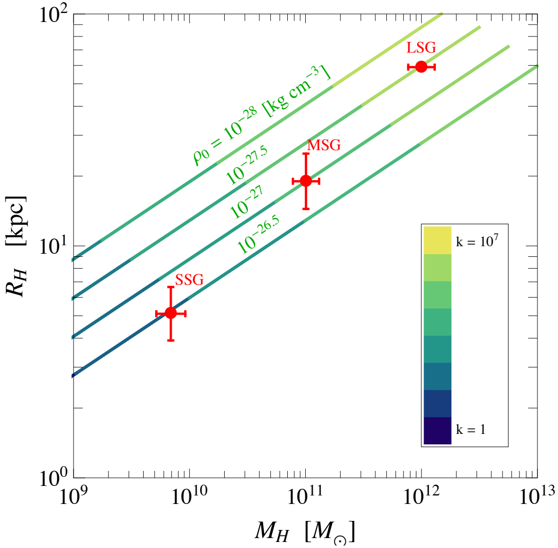
$$\downarrow$$

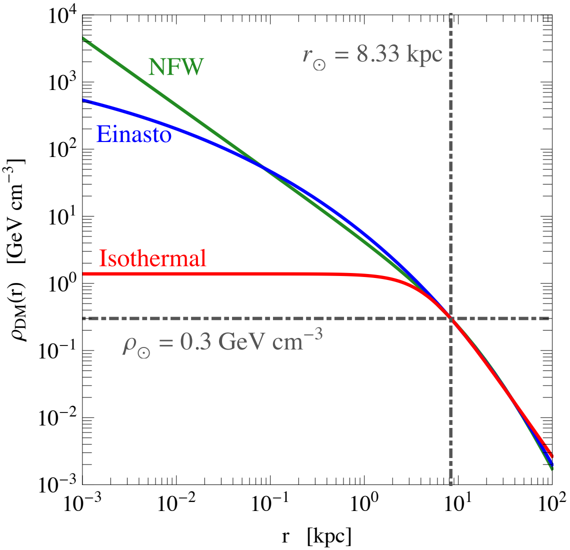
$$\mathrm{R_H}: \ \rho(\mathrm{r} = \mathrm{R_H}) = \rho_0/4$$

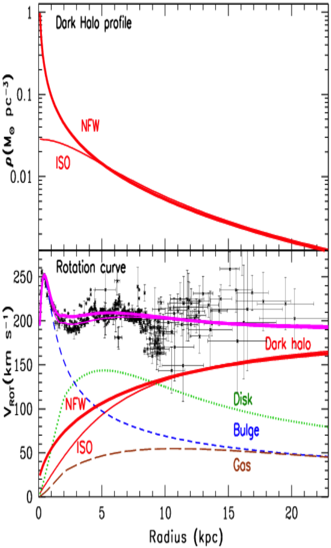
$$\mathrm{M_H}$$

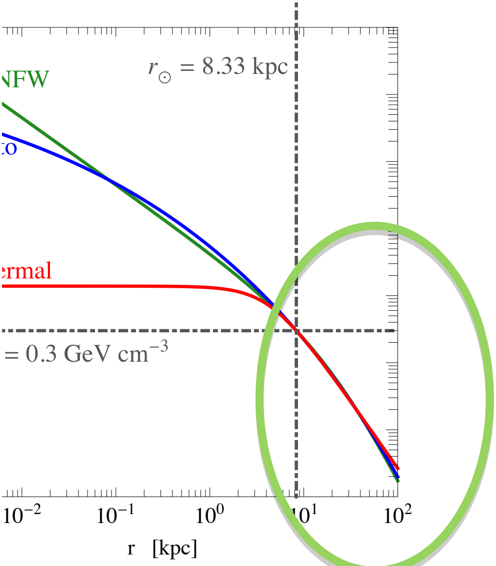


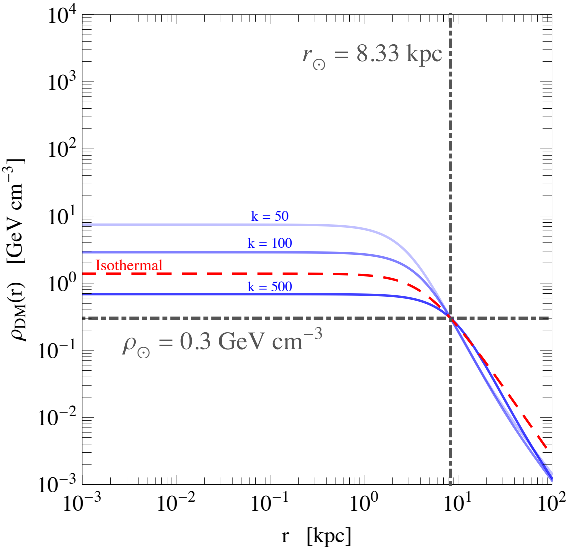
From
H. J. de Vega, P. Salucci and N. G. Sanchez,
MNRAS, 442, 2717


$\rho_0 = 10^{-28}$ [kg cm^{-3}]
$10^{-27.5}$
10^{-27}
$10^{-26.5}$
LSG
MSG
SSG
k = 10^7
k = 1
R_H [kpc]
M_H [$M_\odot$]
10^0
10^1
10^2
10^9
10^{10}
10^{11}
10^{12}
10^{13}


NFW
Einasto
Isothermal
$r_\odot$ = 8.33 kpc
$\rho_\odot$ = 0.3 GeV cm^{-3}
ρ_{DM}(r) [GeV cm^{-3}]
r [kpc]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2


Dark Halo profile
NFW
ISO
ρ(M⊙ pc⁻³)
1
0.1
0.01
Rotation curve
Dark halo
NFW
ISO
Disk
Bulge
Gas
V_ROT (km s⁻¹)
250
200
150
100
50
0
0
5
10
15
20
Radius (kpc)


r⊙ = 8.33 kpc
NFW
o
ermal
= 0.3 GeV cm⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
r [kpc]


$r_\odot$ = 8.33 kpc
k = 50
k = 100
Isothermal
k = 500
$\rho_\odot$ = 0.3 GeV cm^{-3}
$\rho_{DM}(r)$ [GeV cm^{-3}]
r [kpc]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2

Conclusions

- We proposed a model in which DM is made of free fermions with mass ~200 eV
- Dwarf spheroidal galaxies correspond to the degenerate limit of the gas
- Large galaxies correspond to the non-degenerate limit
- Connection with inflation physics
- The model can be tested against astrophysical data