Dwarf spheroidal galaxies as degenerate gas of free fermions

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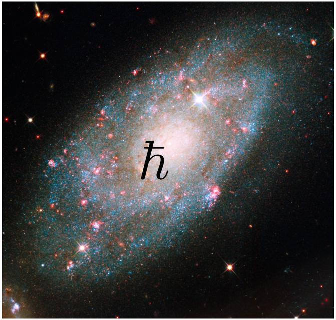

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Hunting the invisible

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Outline

- quantum mechanics and dwarf galaxies
  - a first estimate
  - quantitative analysis
- testing against data
  - velocity dispersion
  - escape velocity
  - free-streaming length
- finite temperature and larger galaxies
- conclusion and outlook

Quantum pressure versus gravity

A first estimate: degenerate spherical configuration of free particles

bosons:

fermions:

$$p \sim \quad h/R \text{ [Heisenberg]}$$

$$P_Q \sim nvp \sim \quad \frac{h^2 \rho}{m^2 R^2}$$

$$P_G \sim \quad \frac{GM^2}{R^4}$$

$$P_Q = P_G \Rightarrow \quad R \sim \frac{h^2}{GMm^2}$$

$$\Rightarrow \quad m \sim 10^{-25} \text{ eV}$$

see also [Sin '94, Harko et al '07/'11, Chavanis '12, Rindler-Daller and Shapiro '12/'14, Davidson '13/'14, ...] (bosons)

and [Vega et al '13/'14] (fermions)

Quantum pressure versus gravity

A first estimate: degenerate spherical configuration of free particles

	bosons:	fermions:
$p \sim$	h/R [Heisenberg]	$N^{1/3}h/R$ [Pauli]
$P_Q \sim nvp \sim$	$\frac{h^2\rho}{m^2R^2}$	$\frac{h^2\rho^{5/3}}{m^{8/3}}$
$P_G \sim$	$\frac{GM^2}{R^4}$	$\frac{GM^2}{R^4}$
$P_Q = P_G \Rightarrow$	$R \sim \frac{h^2}{GMm^2}$	$R \sim \frac{h^2}{GM^{1/3}m^{8/3}}$
$\Rightarrow$	$m \sim 10^{-25}$ eV	$m \sim 20$ eV

fermion w. $m \sim$ eV – keV: DM halo stabilized by quantum pressure?

see also [Sin '94, Harko et al '07/'11, Chavanis '12, Rindler-Daller and Shapiro '12/'14, Davidson '13/'14, ...] (bosons)
and [Vega et al '13/'14] (fermions)

In a bit more detail

Assume degenerate configuration (consistency check later):

$$f_{\mathsf{FD}} = \begin{cases} 1 & p \leq p_F \\ 0 & p > p_F \end{cases} \quad , \qquad \begin{aligned} n &= \int_0^{p_F} 2\, d\Pi_p = \frac{8\pi p_F^3}{3h^3} \\ P_Q &= \int p\, v(p)\, n(p)\, dp \end{aligned}$$

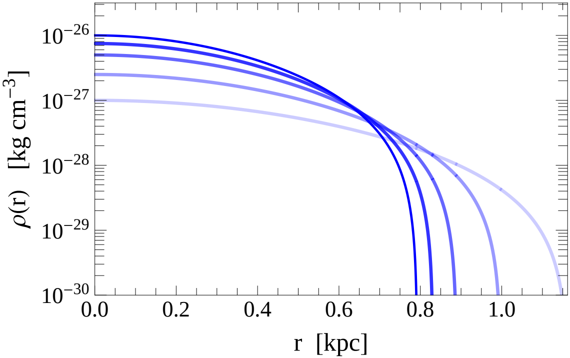
$$\Rightarrow P_Q = \frac{h^2}{5 m_f^{8/3}} \left(\frac{3}{8\pi} \right)^{2/3} \rho^{5/3}$$

hydrostatic equilibrium:

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

density profile $\rho(r)$ depends on two parameters: m_f and ρ_0

Density profile



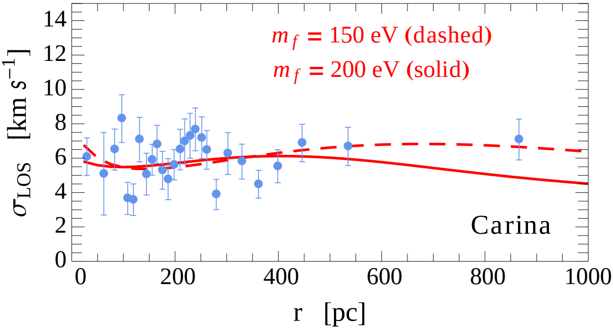
- for $m_f = 200$ eV
- $\rho(r) \to M(r), R, \sigma(r)$..: test vs data
- 'cored' profile

universal cored profile $\to$ can address cusp/core problem

Testing the against data: velocity dispersion

velocity dispersion along the line of sight for the eight bright dwarf galaxies of the Milky Way:

Carina
Draco
Fornax
Leo I
Leo II
Sculptor
Sextans
Ursa Minor



data from [Walker et al '10]. Theory input: $M(r)$ + assumptions on distribution of visible matter: Plummer profile for stellar densities, marginalized over the orbital anisotropy of the stellar component and ρ_0.

$m_f = 150 - 200$ eV provides a good fit to the data

Escape velocity: a lower bound on the DM mass

Fermi velocity is bounded by escape velocity v_∞: [Tremaine, Gunn '79]

$$v_F \sim 8.2 \times 10^{12} \left[\frac{\rho_0}{\text{kg/cm}^3} \left(\frac{\text{eV}}{m_f} \right)^{1/4} \right]^{1/3} \text{km/s} \leq v_\infty^{\text{obs}}(\sigma)$$

$$\Rightarrow m_f \geq 200 \text{ eV} \quad \text{(Leo II)}$$

Note: $v_\infty = \sqrt{\frac{2GM}{R}} \propto m_f^{-4/3} \rightarrow$ for degenerate configuration use v_∞^{obs}, weaker bound on m_f than 'usual' Tremaine-Gunn bound!

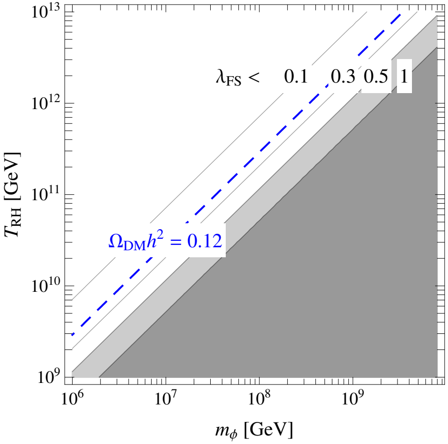
$\Rightarrow$ DM mass fixed to $m_f \simeq 200$ eV

Free-streaming length: cosmological history

simplest setup: inflaton decay $\phi \to f\, f$

- structure formation:
  free-streaming length
  $\lambda_{\text{FS}} = \int \frac{v}{a} dt \overset{!}{<} 0.5$ Mpc
  (suppressed vs case of thermal relic)
- total abundance:
  $\Omega_{\text{DM}} \overset{!}{=} 0.12$

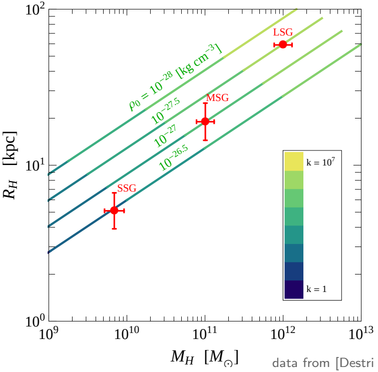
$\Rightarrow Br < 10^{-5}\ , \quad \frac{m_\phi}{T_{\text{RH}}} < 10^{-3}$



correct small scale structure for suitable m_ϕ / T_{RH}

Outlook: finite temperature and larger galaxies

estimate galaxy temperature with Virial theorem
$\Rightarrow T_{\text{Vir}}/T_{\text{crit}}$ increases for larger galaxies
$\Rightarrow$ redo analysis for finite T: $f_{\text{FD}} = \left[1 + \exp\left(\frac{\frac{p^2}{2m_f} + m_f\Phi - \mu}{k_B T}\right)\right]^{-1}$



data from [Destri et al '13]

degeneracy parameter
$k = \exp\left(\frac{m_f\Phi - \mu}{k_B T}\right)$:
$k \to 0$: degenerate FD
$k \to \infty$: Maxwell-Boltzmann

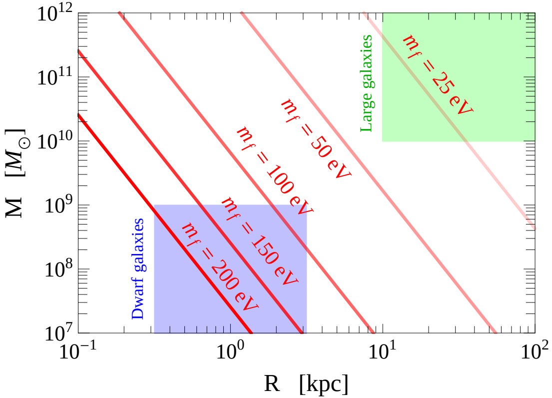
Larger galaxies might correspond to non-generate configurations

Conclusion and outlook

- A degenerate gas of fermions with $m_f \simeq 200$ eV yields a good fit to the dwarf galaxy data
  - velocity dispersion
  - escape velocity
  - free-streaming length
- Larger galaxies might be obtained in finite temperature limit
- Can address cusp/core and missing satellite problem
- Open questions: larger galaxies? structure formation?

backup slides

Mass-radius relation



- ρ_0 eliminated
- dwarf galaxies: DM dominated compact objects
- larger galaxies: finite T (later)

see also [Vega, Sanchez '13]

focus on dwarf galaxies and $m_f \sim 150 - 200$ eV

Observations: surface density $\Sigma_0 \equiv R_H \rho_0 = 141^{+81}_{-52} M_\odot/pc^2$ independent of galaxy luminosity [Donato et al '09]

Predictions from non-degenerate Fermi model:
$\Sigma_0 \simeq 238\, M_\odot/pc^2$ (SSG),
$\Sigma_0 \simeq 280\, M_\odot/pc^2$ (MSG),
$\Sigma_0 \simeq 275\, M_\odot/pc^2$ (LSG).

$\Rightarrow$ given the precision of R_H, this looks promising

Fit to the velocity dispersion

projected velocity dispersion along the line-of-sight: see e.g. [Walker et al '10]

$$\sigma^2_{\rm LOS}(R) = \frac{2G}{I(R)} \int_R^\infty \nu(r') M(r') (r')^{2\beta-2} F(\beta, R, r') dr' \ ,$$

where

$$F(\beta, R, r') \equiv \int_R^{r'} \left(1 - \beta \frac{R^2}{r^2}\right) \frac{r^{-2\beta+1}}{\sqrt{r^2 - R^2}} dr \ .$$

We adopt the Plummer profile for the projected stellar density

$$I(R) = \frac{L}{\pi r_{\rm half}^2} \frac{1}{[1 + (R/r_{\rm half})^2]^2} \ ,$$

where L is the total luminosity and $r_{\rm half}$ the half-light radius.
$\rightarrow$ 3-dimensional stellar density

$$\nu(r) = -\frac{1}{\pi} \int_r^\infty \frac{dI}{dr} \frac{dR}{\sqrt{R^2 - r^2}} = \frac{3L}{4\pi r_{\rm half}^3} \frac{1}{[1 + (r/r_{\rm half})^2]^{5/2}} \ .$$

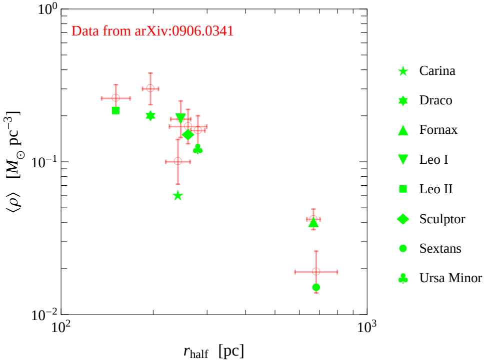
A criterion for degeneracy

A rough estimate:

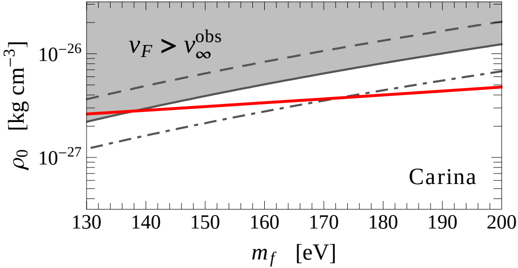
		dwarf galaxies	larger galaxies
critical temperature:	$T_c \sim T_F = \frac{p_F^2}{2 m_f k_B}$	$\sim 10^{-3}$ K	$\sim 10^{-4}$ K
Virial theorem:	$T_{\mathsf{Vir}} \sim \frac{G M m_f}{R k_B}$	$\sim 10^{-3}$ K	$\sim 10^{-1}$ K

$\Rightarrow$ redo analysis for finite T: $f_{\mathsf{FD}} = \left[1 + \exp\left(\frac{\frac{p^2}{2m_f} + m_f \Phi - \mu}{k_B T} \right) \right]^{-1}$

Mean density within half-light radius



Escape velocity



$\Rightarrow$ DM mass fixed to $m_f \simeq 200$ eV