Cores in Dwarf Galaxies from Fermi Repulsion

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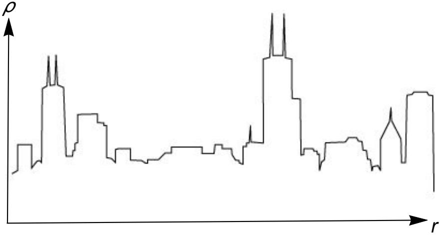

Virtual Institute of Astroparticle physics

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Mainly based on [1611.04590] /w Lisa Randall & Jakub Scholtz

Outline:

Part I: Dark Matter and Dwarf Galaxies

Part II: Quasi-Degenerate Fermi Gases

Part III: Dwarf Galaxies as Quasi-Degenerate Fermi Gases

Part I: Dark Matter and Dwarf Galaxies

Dark Matter and Dwarf Galaxies

Dwarf galaxies are baryon poor, DM dominated, gravitationally bound objects.

Eight 'Classical' Dwarfs:

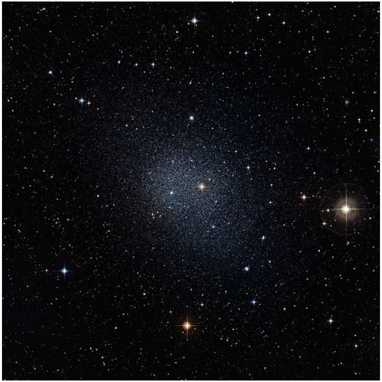
Carina, Draco, Fornax, Leo I, Leo II, Sculptor, Sextans, and Ursa Minor.

These are satellites of the Milky Way.

Dwarf galaxies set **mass bounds** on DM...

They also **present challenges to ΛCDM:**

- Missing satilities problem
- Too big to fail problem
- Core-Cusp problem



Fornax Dwarf Galaxy
Digitized Sky Survey 2

Dark Matter and Dwarf Galaxies

The **Core-Cusp problem** is a conflict between simulation and observation.

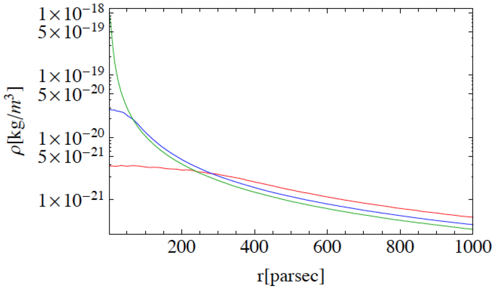
Observations indicate flat (**‘cored’**) density profiles.

ΛCDM simulations of structure formation give sharp (**‘cuspy’**) profiles.

Proposed resolutions are:

- Baryon feedback
  e.g. Pontzen & Governato [1106.0499]
- Dark matter self-interactions
  Spergel & Steinhardt (1999)...
- Warm dark matter
  Dalcanton & Hogan (2000)...
- Degenerate Boson dark matter
  Ji & Sin (1994)... Witten et al. [1610.08297].
- Quasi-degenerate Fermion DM
  Randall, Scholtz, JU [1611.04590]

Related: Destri, Vega, Sanchez [1204.3090]
Domcke & Urbano [1409.3167]
Chavanis, Lemou, Mehats [1409.7840]



Part II: Quasi-Degenerate Fermi Gases

Dark Matter as a Quasi-Degenerate Fermi Gas

Fermion gas is **degenerate** if all quantum states to some energy are filled.

For a gas of density ρ of states with mass m this **occurs for**

$$T < T_{\rm Deg} \sim \frac{h^2}{2\pi m}\left(\frac{\rho}{2m}\right)^{\frac{2}{3}}$$

The highest **occupation level** is $p_F = m v_F = h\left(\frac{3}{\pi^2 N_f}\frac{\rho}{m}\right)^{\frac{1}{3}}.$

The corresponding **Fermi pressure** is

$$P_F = \frac{8\pi}{3h^3}\int_0^{p_F} {\rm d}p \left(\frac{p^4}{\sqrt{p^2+m^2}}\right) = \frac{h^2}{5m^{\frac{8}{3}}}\left(\frac{3}{8\pi N_f}\right)^{\frac{2}{3}} \rho^{\frac{5}{3}}$$

Landau & Lifshitz, Vol. 5 (1980)

We can compare this to the **classical pressure**

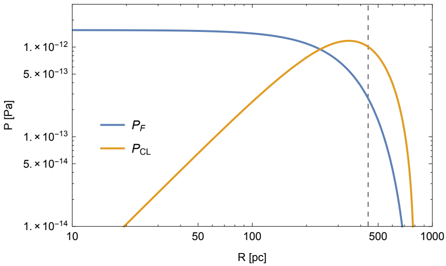
$$P_{\rm cl} = \rho\left(\frac{T}{m}\right) = \frac{GM(R)\rho(R)}{2R}$$

RHS assumes virial temperature distribution: $T(R) = GM(R)m/2R$.

Dark Matter as a Quasi-Degenerate Fermi Gas

Thus at **high density and low temperature** P_F dominates over $P_{\rm cl}$

$$P = \begin{cases} \dfrac{GM(R)\rho(R)}{2R} & T \geq T_{\rm deg} \\ \dfrac{h^2}{5m^{\frac{8}{3}}}\left(\dfrac{3}{8\pi N_f}\right)^{\frac{2}{3}} \rho(R)^{5/3} & T \leq T_{\rm deg} \end{cases}$$



Plot components $P_{\rm cl}$ (YELLOW) and P_F (BLUE) for DM mass $m = 200$ eV and central density $\rho_0 = 10^{-20}$ kg/m^3.

Dark Matter as a Quasi-Degenerate Fermi Gas

The static density profile of a self-gravitating ball of fermions must satisfy

***i)* hydrostatic equilibrium**

$$\frac{\mathrm{d}P}{\mathrm{d}R} = -\left(\frac{GM(R)}{R^2}\right)\rho(R)$$

***ii)* pressure equality**

$$\begin{aligned} P(R) &= P_{\rm cl} + P_F \\ &\approx \frac{GM(R)\rho(R)}{2R} + \frac{h^2}{5m^{\frac{8}{3}}}\left(\frac{3}{8\pi N_f}\right)^{\frac{2}{3}}\rho(R)^{\frac{5}{3}} \end{aligned}$$

***iii)* the continuity condition**

$$M(R) = 4\pi\int_0^R \rho(r)r^2\mathrm{d}r$$

With initial conditions $\rho(0) = \rho_0$, and $M(0) = 0$ this is a closed system.

Dark Matter as a Quasi-Degenerate Fermi Gas

First find sol. with **only Fermi pressure** (i.e. $P_{\rm cl} = 0$), then (i)-(iii) reduce to

$$\frac{h^2}{3m^{\frac{8}{3}}}\left(\frac{3}{8\pi}\right)^{\frac{2}{3}}\frac{\mathrm{d}}{\mathrm{d}R}\left(\frac{R^2}{\rho(R)^{\frac{1}{3}}}\frac{\mathrm{d}\rho(R)}{\mathrm{d}R}\right) = -4\pi G R^2 \rho(R)$$

For **small** R an approximate solution is

$$\rho = \rho_0[1-(R/R_c)^2]$$

For R_c an appropriately chosen scale

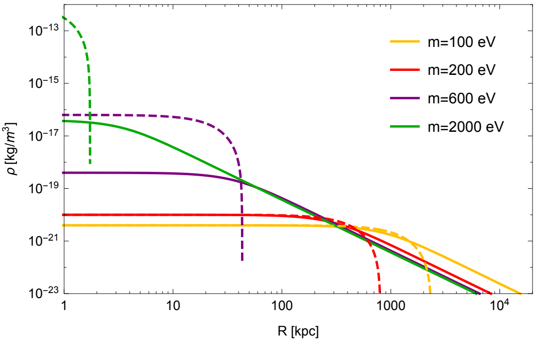
$$R_c^2 = \frac{h^2}{2\pi G m^{\frac{8}{3}}\rho_0^{\frac{1}{3}}}\left(\frac{3}{8\pi N_f}\right)^{\frac{2}{3}}$$

We expect **constant density** core of size R_c as Fermi pressure flattens the expected cusps of density distributions of dwarf galaxies.

Dark Matter as a Quasi-Degenerate Fermi Gas

The **full solution** with $P_{\rm cl} \neq 0$ is an example of a Lane-Emden equation.

We **plot solutions** for different DM masses. These are **constant for $R \to 0$**.



Showing **degenerate** ($P_{\rm cl} = 0$) as dashed and **quasi-degenerate** as solid.

Take the central densities ρ_0 such that they reproduce $M_{1/2}$ for **Fornax**.

Part III: Dwarf Galaxies as Quasi Degenerate Fermi Gases

Fitting to Observations

How to **define core radius** R_c at which transition to constant density?

- Recall from **static solution**:

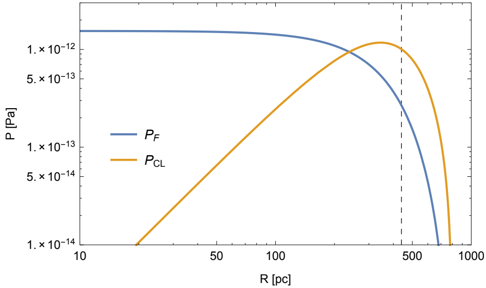
$$R_c^2 = \frac{h^2}{2\pi G m^{\frac{8}{3}} \rho_0^{\frac{1}{3}}} \left(\frac{3}{8\pi N_f} \right)^{\frac{2}{3}}$$

- Can define R_P at which

$$P_{\rm cl} = P_F$$

- Or define R_* on the **slope** of the density distribution:

$$\left. \frac{\mathrm{d}\log\rho}{\mathrm{d}\log R} \right|_{R_*} = -\frac{3}{2}$$



Up to small factors **these coincide**: $R_c \simeq R_* \simeq R_P$. Only one relevant scale.

We use R_* to allow direct comparisons to the Literature.

Fitting to Observations

With core radius R_c defined we can **compare to observations**.

Best measured dwarf galaxy core radius is **Fornax**:

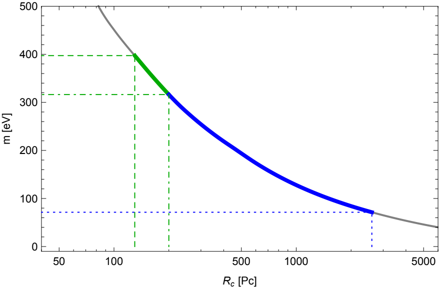
$$R_c^{\text{Fornax}} = 1^{+0.8}_{-0.4} \text{ kpc} .$$

Amorisco et al [1210.3157]

Amorisco et al fit using Burkert profile.

Different fits allow $R_c^{\text{Fornax}} \gtrsim 130$ pc.

See paper for details.



We **plot R_c for Fornax** treating the DM as quasi-degenerate Fermi gas.

Observe the requirement that $R_c \lesssim 2.6$ kpc give **mass limit** (95% CL)

$$m \gtrsim 70 \text{ eV}$$

This is the most **conservative limit** on the mass of fermion DM.

Fitting to Observations

Intriguingly, large & dwarf galaxies **obey scaling** $\langle \rho_0 R_c \rangle = 75^{+85}_{-45}\ M_\odot\ \mathrm{pc}^{-2}$

Burkert [1501.06604]

Recall for quasi-degenerate Fermi gas, the **static solution** is

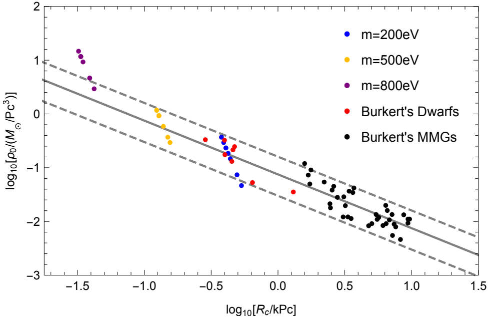
$$R_c^2 = \xi_1^2 \frac{h^2}{2\pi G m^{\frac{8}{3}} \rho_0^{\frac{1}{3}}} \left(\frac{3}{8\pi N_f} \right)^{\frac{2}{3}}$$

This implies a **scaling relationship**:

$$\rho_0 R_c^6 m_{\rm DM}^8 \sim \text{constant.}$$

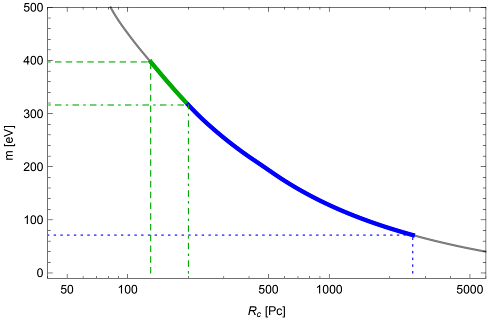
Correlation between R_c and ρ_0 of the eight Classical Dwarfs.

DM masses for realistic cores **accommodates Burket scaling**.



Fitting to Observations

Coming back to Fornax. Sufficiently large cores requires light fermion DM:



But **free streaming bounds** (Lyman-α) on thermal dark matter require

$$m_{\rm DM} \gtrsim 3 \text{ keV}$$

Baur, et al. [1512.01981]

Thus v. light fermions DM consistent with large cores **can't be thermal**...

Bounds from free streaming

DM relativistic for $T^{(\mathrm{DM})} \gtrsim m_{\mathrm{DM}}$. Note it can be $T \neq T^{\mathrm{DM}}$.

Relativistic DM erases the primordial density perturbations.

Existence of **dwarf galaxies** implies perturbations of $l_{\mathrm{limit}} \sim 0.1$ Mpc.

Density perturbation of size l_p erased if $l_p \ll l_F$, thus **limit** $l_F > l_{\mathrm{limit}}$.

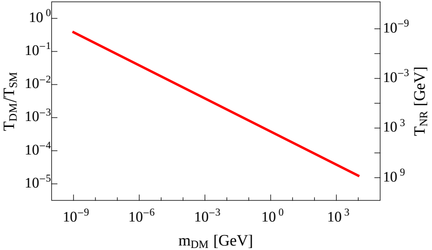
$$l_F = \Big[1 + z(T_{\mathrm{NR}})\Big] l_H(T_{\mathrm{NR}}) \simeq \Big[1 + z(T_{\mathrm{NR}})\Big] \frac{M_{\mathrm{Pl}}}{T_{\mathrm{NR}}^2} ,$$

$[1 + z(T_{\mathrm{NR}})] \simeq T_{\mathrm{NR}}/T_0$ is redshift when DM is non-relativistic ($T_0 \approx 2.7\mathrm{K}$)

$$\Rightarrow \qquad l_F = \frac{M_{\mathrm{Pl}}}{T_0} \frac{1}{T_{\mathrm{NR}}} \simeq \frac{M_{\mathrm{Pl}}}{T_0} \left(\frac{1}{T(T^{\mathrm{DM}} = m_{\mathrm{DM}})} \right) .$$

For $T = T^{\mathrm{DM}}$ then $l_F > l_{\mathrm{limit}} \sim 0.1$ Mpc **implies** $m_{\mathrm{DM}} \gtrsim 1$ **keV.**

Relaxing the free streaming constraints by decoupling



As SM dof regenerated via decays it becomes **warmer than hidden sector**

$$T_{DM}/T_{SM} \simeq \left(\frac{s_{DM}}{s_{SM}}\right)^{1/3} \simeq \left(\frac{m_{DM}\Omega_B}{\Delta m_p \Omega_{DM}}\right)^{1/3}$$

This means **DM nonrelativistic earlier**, and bounds on the free streaming length are weakened compared to thermal relic:

$$\sim 3 \text{ keV} \;\rightarrow\; \sim 500 \text{ eV}$$

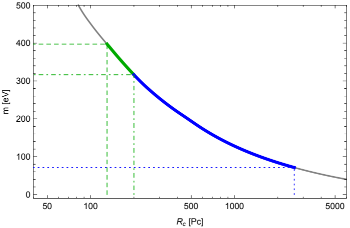
An Example is **Flooded Dark Matter**.

(Randall, Scholtz, JU [1509.08477]).

Cores from Decoupled Dark Matter

Recall Fornax core radius is $R_c^{\rm Fornax} = 1^{+0.8}_{-0.4}$ kpc.

Amorisco et al [1210.3157]



Preferred mass range is **70 eV – 400 eV.**

For DM to **match relic density** requires:

$$T_{\rm DM}/T_{\rm SM} \simeq \left(\frac{s_{\rm DM}}{s_{\rm SM}}\right)^{1/3} \simeq \left(\frac{m_{\rm DM}\Omega_B}{\Delta m_p \Omega_{\rm DM}}\right)^{1/3}$$

Can't make dark sector arbitrary colder, so free streaming bound remains:

$$m_{\rm FDM} \gtrsim 470 \text{ eV}$$

Dark Matter with thermal distribution:

$$s_{\rm DM} \sim T_{\rm DM}^3$$

can't quite give sufficiently large cores.

What is needed to reproduce observable Cores?

- The core-size of dwarfs is extracted via a **fit to specific profile** (e.g. Burkert). Different profile choice could favour a smaller core size.

- **Baryon feedback** could enhance smaller cores, allowing heavier DM.

- Momentum distribution **skewed** to lower energies

Extreme example: **axion** (produced non-relativistically).

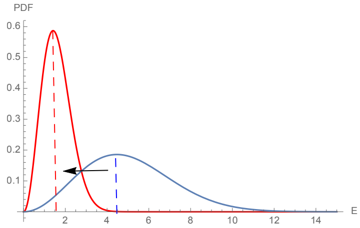
More reasonable examples:

- Resonantly produced **sterile neutrinos**

Shi, Fuller [astro-ph/9810076]

- **Preheating** (non-perturbative inflaton energy transfer)

Kofman, Linde, Starobinsky [hep-ph/9704452]



Summary

Dwarf Galaxies as Degenerate Fermi Gases:

- **Core-Cusp problem** could be hint that DM is not ΛCDM.
- DM mass range to match observed cores R_c: **70 eV – 400 eV**.
- Note, requires non-thermal fermion dark matter.
- **Baryon feedback** could enhance smaller cores, allowing heavier DM.
- **Correlations** between R_c and ρ_0 in different dwarfs.
- (Quasi)-degenerate Fermi gas is essentially **DM neutron star**.

Thank you.

Back-up: Chandrasekhar limit

Note, no risk of cores collapsing to **black holes**. Solving the Lane-Emden equation in the ultra-relativistic limit one obtains the Chandrasekhar bound

$$M_{\rm Ch} = 8\pi^2\sqrt{6}\omega_3^0 \frac{M_{\rm Pl}^3}{m^2} = 5\times 10^{18}\left(\frac{\rm eV}{m}\right)^2 M_\odot ~,$$

where $\omega_3^0 \approx 2.018$ is a numerical constant. Domcke & Urbano [1409.3167]

Degenerate Fermi core collapses to black hole if **mass exceeds** $M_c > M_{\rm Ch}$.

The mass enclosed in the core is

$$M_c \sim \rho_0 R_a^3 \sim \frac{M_{\rm Pl}^3\sqrt{\rho_0}}{m^4}\left(\frac{3}{\pi N_f}\right) ~,$$

Dwarf galaxy central density is typically $\rho_0 \sim 10^{-20}{\rm kg/m}^3$, thus risk only for

$$m \lesssim \rho_0^{1/4} \approx 0.1 \text{ eV} ~.$$

For **neutron star** $m \sim 1$ GeV and $\rho_0 \sim 10^{17}{\rm kg/m}^3$, thus $M_C \sim M_{\rm Ch} \sim 3M_\odot$.