Title: Cores in Dwarf Galaxies from Fermi Repulsion

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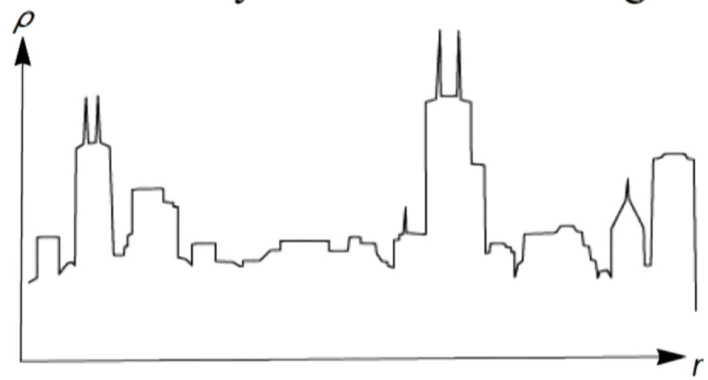
Abstract: <p>Cold dark matter provides a remarkably good description of cosmology and astrophysics. However, observations connected with small scales might be in tension with this framework. In particular, structure formation simulations suggest that the density profiles of dwarf spheroidal galaxies should exhibit cusps, in contrast to observations. I will show that Fermi repulsion can explain the observed cored density profiles in dwarf galaxies for sub-keV fermionic dark matter. While in conventional dark matter scenarios, such sub-keV thermal dark matter would be excluded by free streaming bounds, I will argue that these constraints are ameliorated in models with dark matter at lower temperature than conventional thermal scenarios. Finally, I will outline a class in which the dark matter typically has a lower temperature than the thermal expectation, dubbed Flooded Dark Matter, and discuss aspects of model building.</p>

Cores in Dwarf Galaxies from Fermi Repulsion

James Unwin

University of Illinois at Chicago



Perimeter Institute

January 31, 2017

Work /w Lisa Randall & Jakub Scholtz [1509.08477] & [1611.04590]

Outline:

Part I: Dwarf Galaxies as Degenerate Fermi Gases

Part II: Flooded Dark Matter

Part III: Cores from Flooded Dark Matter

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.

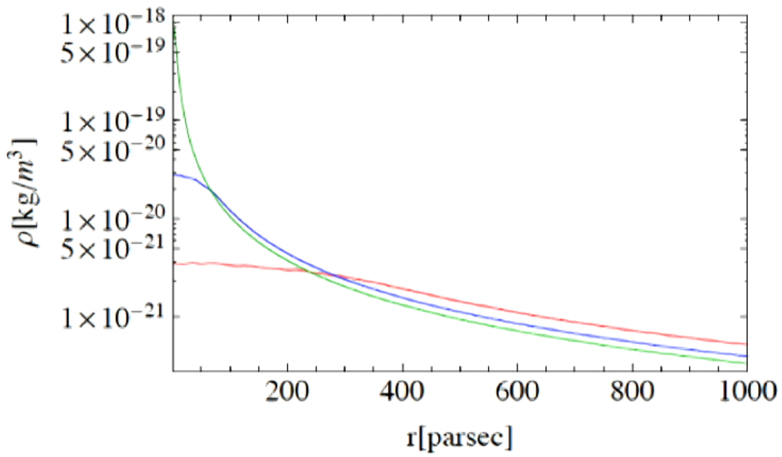
Observations indicate flat (**'cored'**) density profiles.

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]



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 $p_F = mv_F = h\left(\frac{3}{\pi^2 N_f}\frac{\rho}{m}\right)^{\frac{1}{3}}$.

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**

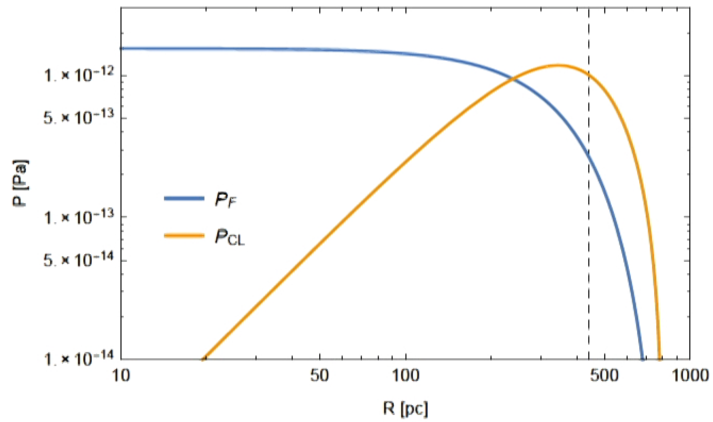
$$P_{\rm cl} = \rho\left(\frac{T}{m}\right) = \frac{GM(R)\rho(R)}{2R}$$

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 $P_{\rm cl}$

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



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

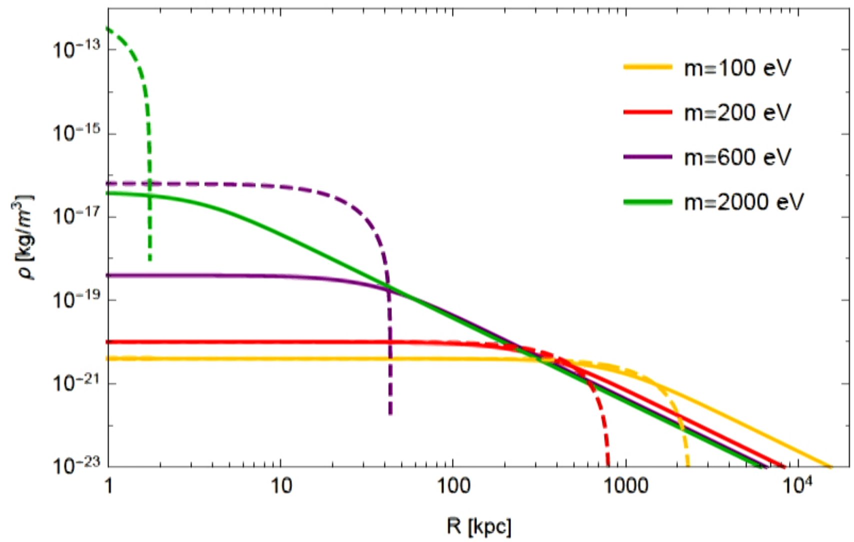
$$R_c^2 = \frac{h^2}{2\pi G m^{\frac{8}{3}}\rho_0^{\frac{1}{3}}}\left(\frac{3}{8\pi N_f}\right)^{\frac{2}{3}}$$

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**.

Fitting to Observations

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

- Recall from **static solution**:

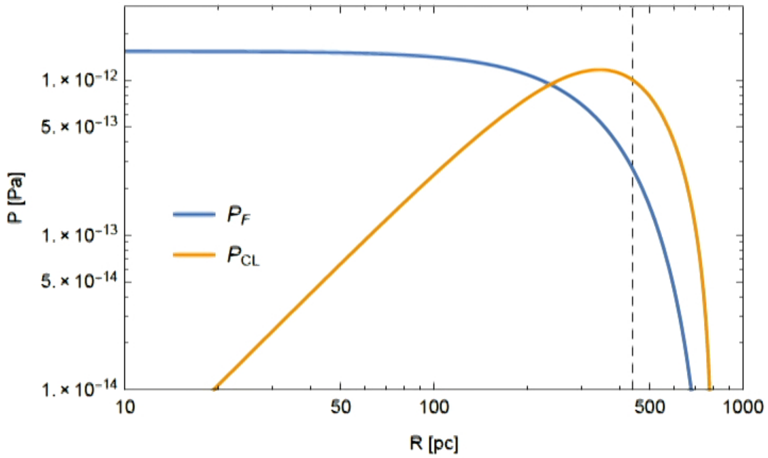
$$R_c^2 = \frac{h^2}{2\pi G m^{\frac{8}{3}} \rho_0^{\frac{1}{3}}} \left(\frac{3}{8\pi N_f}\right)^{\frac{2}{3}}$$

- 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**:

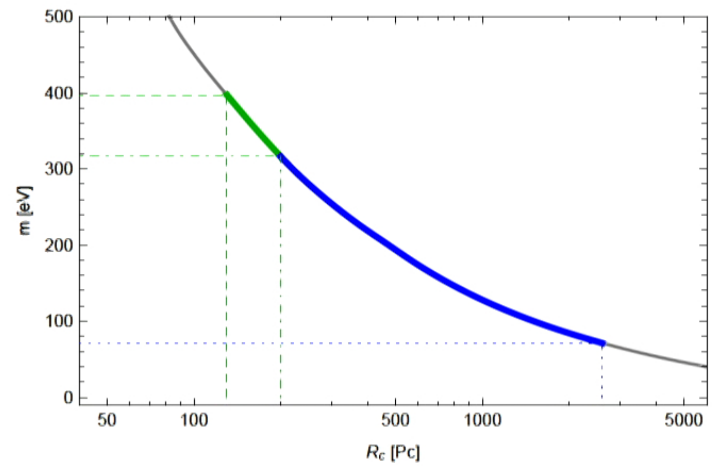
$$R_c^{\text{Fornax}} = 1^{+0.8}_{-0.4}\ \text{kpc}\ .$$

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

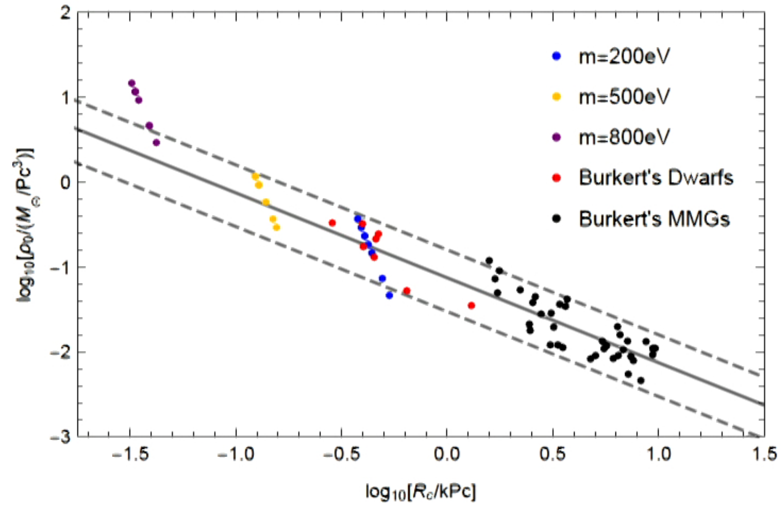
$$R_c^2 = \xi_1^2 \frac{h^2}{2\pi G m^{\frac{8}{3}} \rho_0^{\frac{1}{3}}} \left(\frac{3}{8\pi N_f}\right)^{\frac{2}{3}}$$

This implies a **scaling relationship**:

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

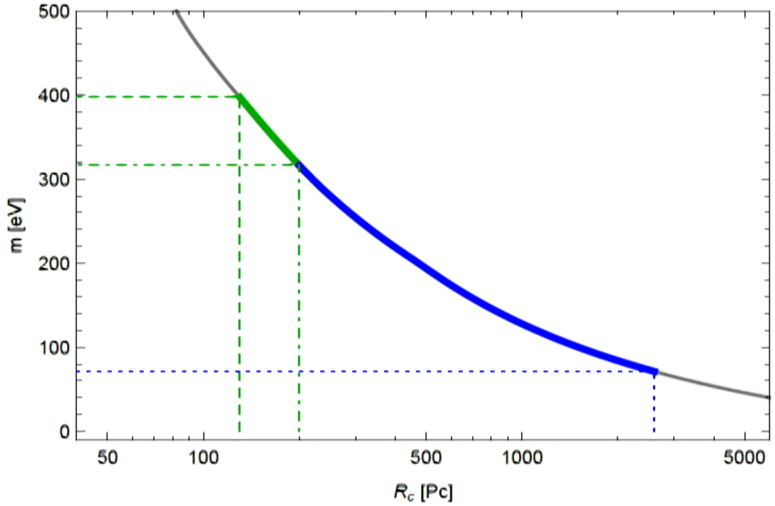
Correlation between R_c and ρ_0 of the eight Classical Dwarfs.

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

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

Baur, et al. [1512.01981]

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

Part II: Flooded Dark Matter

Different Motivation: Democratic Reheating

- Typically thought that **inflation occurred** in the early universe.
- **Democratic** inflaton decay is a fairly natural expectation.
- If there are **many sectors** it is surprising that at late time Standard Model has considerable fraction of energy and dominates entropy.
- Moreover, without a large **entropy injection** into the Standard Model, dark sectors would typically contribute too much entropy.
- **Ask:** what is required to match the present Universe given a democratically decaying inflaton?
- Suppose Standard Model reheated by **late decay** of heavy state Φ, whereas DM comes from a hidden sector primordial abundance.

Cosmic history

Denote the scale factor Φ becomes nonrelativistic by $a = a_0$ and define

$$R^{(i)} \equiv R(a_i) \equiv \frac{\rho_{\rm DM}(a_i)}{\rho_\Phi(a_i)} \, .$$

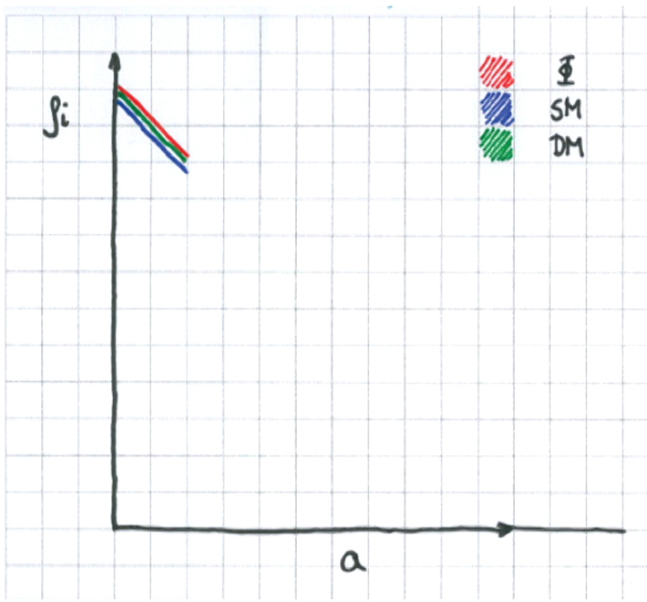
Assuming democratic inflaton decay

$$R^{(0)} \equiv R(a_0) \simeq 1 \, .$$

Also track **other populations**:

$$R^{(0)}_{\rm SM} \equiv \frac{\rho_{\rm SM}(a_0)}{\rho_\Phi(a_0)}; \qquad R^{(0)}_{\rm DS} \equiv \frac{\rho_{\rm DS}(a_0)}{\rho_\Phi(a_0)} \, .$$

nb. Use FRW scale factor a to track time.



Cosmic history

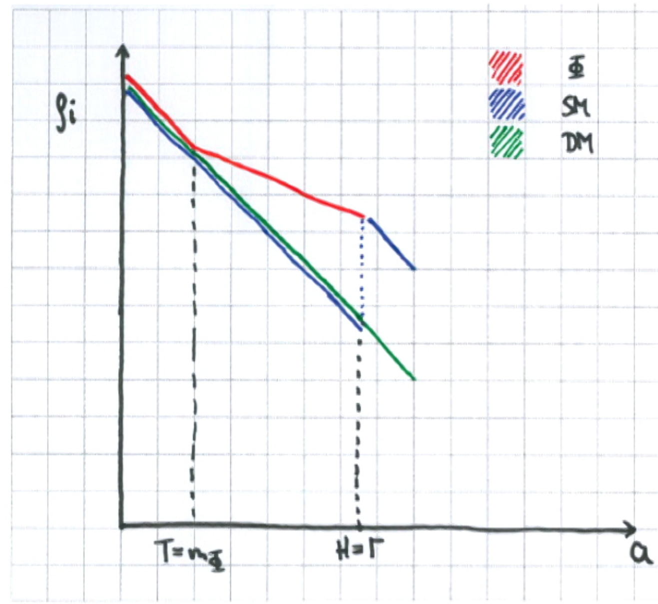
Heavy state decays at $H \simeq \Gamma$ and repopulates the Standard Model.

At the time of the Φ decay

$$\left(\frac{a_0}{a_\Gamma}\right)^3 \simeq \frac{\Gamma^2 M_{\rm Pl}^2}{m_\Phi^4}$$

The **ratio of energy densities** at the time of the Φ decay

$$R^{(\Gamma)} = R^{(0)}\left(\frac{a_0}{a_\Gamma}\right) \simeq R^{(0)}\left[\frac{\Gamma^2 M_{\rm Pl}^2}{m_\Phi^4}\right]^{1/3} .$$



Cosmic history

Dark matter must become non-relativistic and also baryogenesis must occur.

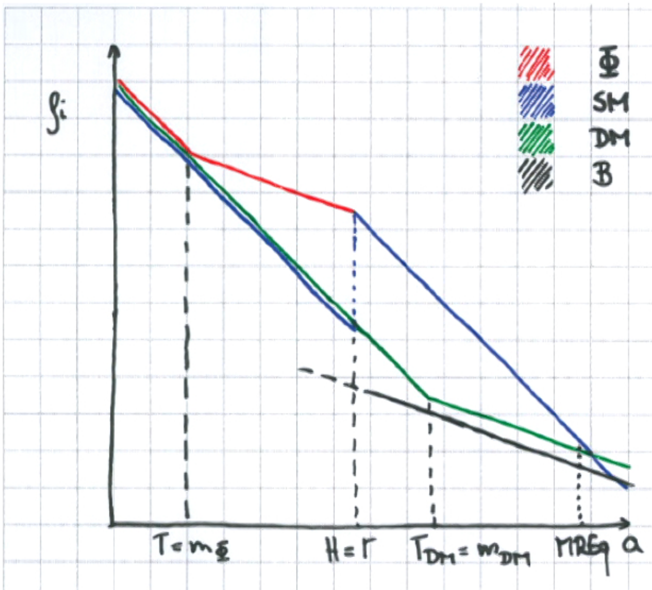
Assuming evolution only due to expansion the ratio is unchanged after a_Γ

$$R^{(\Gamma)} \simeq \left(\frac{s_{\rm DM}^{(\Gamma)}}{s_{\rm SM}^{(\Gamma)}}\right)^{4/3} = \left(\frac{s_{\rm DM}^{(\infty)}}{s_{\rm SM}^{(\infty)}}\right)^{4/3} .$$

Can be expressed in **observed quantities**

$$\frac{s_{\rm DM}^{(\infty)}}{s_{\rm SM}^{(\infty)}} \simeq \Delta \frac{n_{\rm DM}}{n_B} \simeq \Delta \frac{\Omega_{\rm DM}}{\Omega_B}\frac{m_p}{m_{\rm DM}},$$

where $\Delta = n_B/s_{\rm SM} = 0.88 \times 10^{-10}$.



Primordial relic dark matter

We have that:

$$R^{(\Gamma)} \simeq R^{(0)} \left[\frac{\Gamma^2 M_{\rm Pl}^2}{m_\Phi^4}\right]^{1/3} \qquad \text{and} \qquad R^{(\Gamma)} \simeq \Delta \frac{\Omega_{\rm DM}}{\Omega_B} \frac{m_p}{m_{\rm DM}} .$$

Thus the decay rate required to match the observed **DM relic density**:

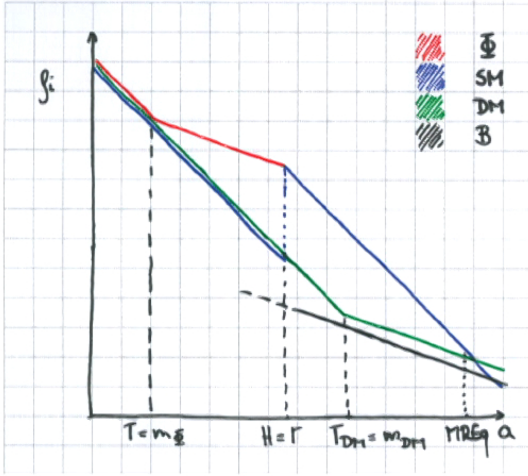
$$\Gamma \simeq \frac{m_\Phi^2}{M_{\rm Pl}} \left(\Delta \frac{\Omega_{\rm DM}}{\Omega_B} \frac{m_B}{m_X}\right)^2$$

SM reheat temperature due to Φ decay

$$T_{\rm RH} \simeq \sqrt{\Gamma M_{\rm Pl}} \simeq m_\Phi \Delta \frac{\Omega_{\rm DM}}{\Omega_B} \frac{m_B}{m_{\rm DM}}$$

Competition between requirement:

- phenomenologically high $T_{\rm RH}$
- and small Γ to dilute DM

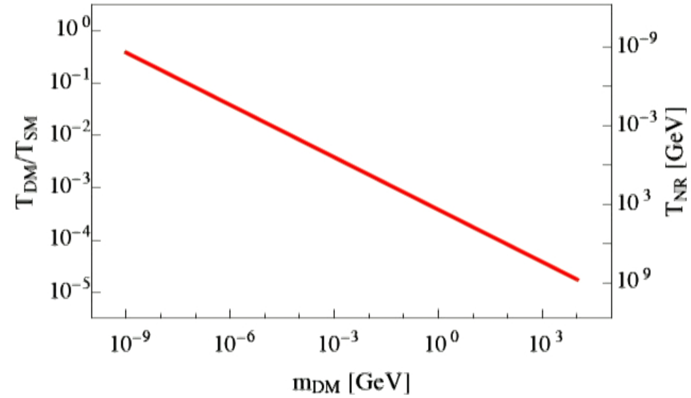


Constraining the parameter space

Successful models must satisfy the following general criteria:

- The **DM relic density** matches the value observed today.
- The Standard Model reheat temperature is well above **BBN**.
- **Baryogenesis** should occur (may place bounds on $T_{\rm RH}$).
- A **thermal bath** of Φ is generated after inflation which implies a limit on the mass $m_\Phi \sim \rho_\Phi^{1/4}(a_0) \lesssim 10^{16}$ GeV.
- DM should be **'warm'/'cold'**.

Relaxation of free streaming constraints



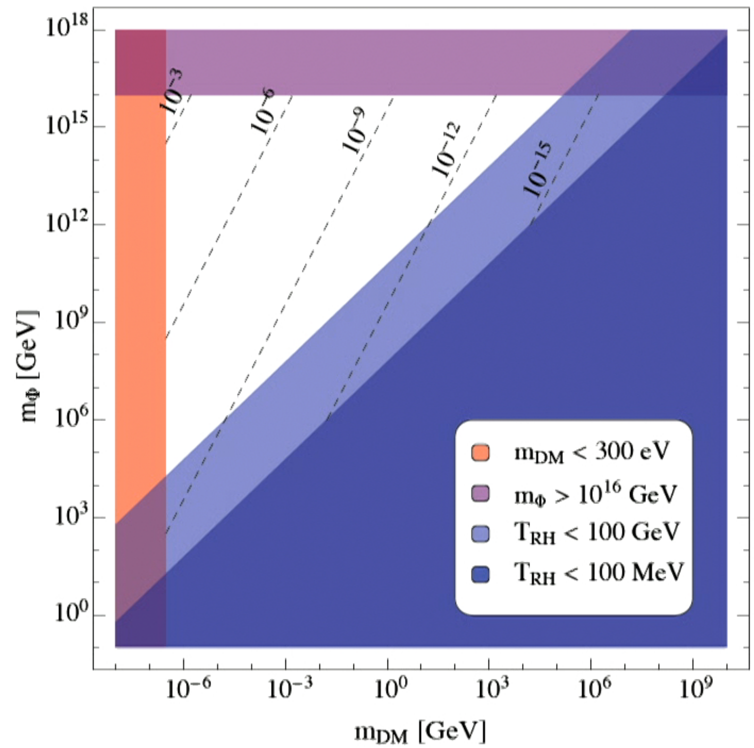
As SM dof regenerated via decays it becomes **warmer than hidden sector**

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

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

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

Constraining the parameter space



Contours of κ, defined $\Gamma = \kappa^2 m_\Phi / 8\pi$.

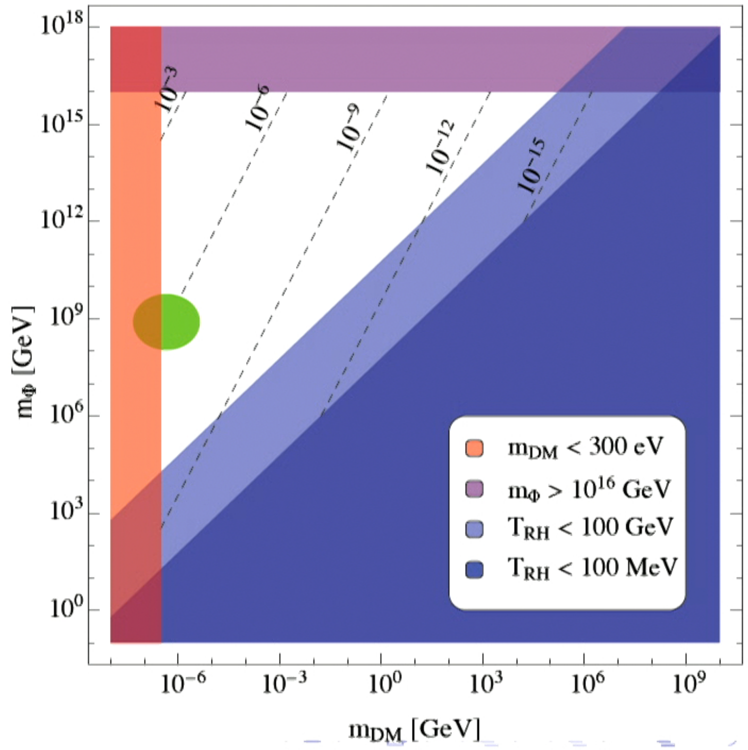
Entropy injection from RH neutrino decay

The RH neutrinos plays the role of Φ, its decays reheat the SM sector.

Consider neutrinos **seesaw mechanism** and we identify $\Phi \equiv N$

$$\mathcal{L}_\nu = y_{ij} H \bar{L}_i N_j + M_{ij} N_i N_j \ .$$

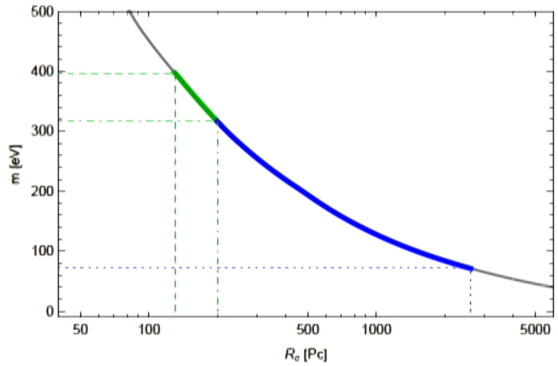
- Suppose yukawas mirror leptons: $y^i_\nu \sim y^i_l$.
- Matching $m_\nu \sim 0.1$ eV implies **Majorana mass** $M \sim 10^9$ GeV.
- **For** N_3 have $y^3_\nu \sim y_e \sim 10^{-6}$.
- Parameters give **ideal** Γ for both DM relic density and high $T_{\rm RH}$.
- Baryogensis can proceed through **nonthermal leptogenesis**.
- Predicts one v. light neutrino: $m_{\nu_1} \ll m_{\nu_2}, m_{\nu_3}$.



Cores from Flooded 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:

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

Simplest Flooded Dark Matter models doesn't quite give sufficiently large cores to match observations...

Actually true for any thermal DM scenario.

What is needed for Cores from Flooded Dark Matter?

- 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).

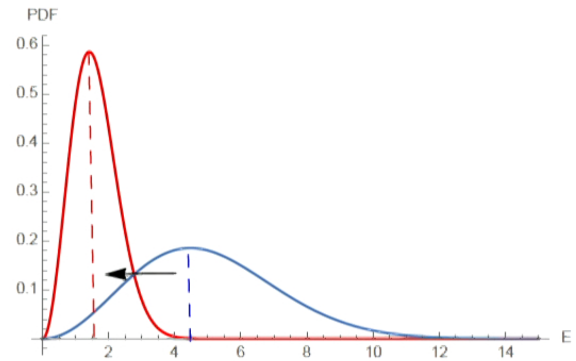
More reasonable examples:

- Resonantly produced **sterile neutrinos**

Shi, Fuller [astro-ph/9810076]

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

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



Summary

Part I: 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.
- (Quasi)-degenerate Fermi gas is essentially **DM neutron star**.

Part II: Flooded Dark Matter

- **Entropy injection** to SM floods primordial DM and sets relic density.
- **Lifetime of Φ** essentially determines $\Omega_{\rm DM}/\Omega_B$.
- **Weakens Lyman-α** bound to $m_{\rm DM} \gtrsim 500$ eV.
- Avoids the perturbative **unitarity bound**: $m_{\rm DM} \lesssim 100$ TeV.

Griest & Kamionkowski PRL 64, 615

Related: Bramante & JU [1701.05859]

Thank you!