Fermionic Dark Matter Profiles

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Outline of the Presentation

● Self-gravitating fermions as Dark Matter in galaxies
  ○ DM halo formation: collisionless relaxation and coarse-grained Entropy maximum
  ○ DM halos as equilibrium systems of self-gravitating fermions
  ○ A novel "dense core – diluted halo" Dark Matter profile for fermions

● The case of the Milky Way and the Galaxy center
  ○ The DM fermion-core: an alternative to the BH paradigm at the Galaxy center
  ○ The fermionic halo: excellent fit to the Milky Way rotation curve

● Universality of the fermionic DM profiles
  ○ A paradigm shift in the formation and nature of the galactic centers?
  ○ From dwarfs, to ellipticals to galaxy clusters

● Conclusions
  ○ Scope and open questions
Self-gravitating fermions as Dark Matter in galaxies
DM halo formation: collisionless relaxation & coarse-grained Entropy maximum

- DM as a collisionless particle system described by a mean-field Vlasov-Poisson equation

\[ f = f(x, v, t) \quad \text{mass density of particles in phase-space } (x,v) \]

\[
\frac{df}{dt} = \frac{\partial f}{\partial t} + v \frac{\partial f}{\partial r} + F \frac{\partial f}{\partial v} = 0, \quad 1) \quad f = \bar{f} + \tilde{f} \\
\Delta \Phi = 4 \pi G n. \quad n(r, t) = \int f(r, v, t) \, d^3 v \]

\[ F = -\nabla \Phi \]

\[ \bar{f}: \text{coarse-grained; } \tilde{f}: \text{fine-grained fluctuations} \]

- Ask J to fulfill macroscopic constraints: 1st and 2nd laws of thermodynamics

\[ E = \int J \cdot v \, d^3 r \, d^3 v = 0. \]

\[ S = -\int \frac{1}{f(\eta_0 - f)} \frac{\partial f}{\partial v} J \, d^3 r \, d^3 v \geq 0. \]

Collisionless relaxation and Fermi-Dirac phase space distributions

- During its evolution the system maximizes its rate of entropy creation while satisfying the constraints fulfilled by the dynamics: **Maximum Entropy Production Principle (MEPP)**

- Applying the **MEPP + quasi-linear theory (Severne & Luwell 1980)**, equation (1) is written as a modified Landau-equation, allowing to obtain \( J \)

\[
\frac{d\tilde{f}}{d\epsilon} + \beta \eta_0 \tilde{f} - \beta \tilde{f}^2 + J = 0
\]

\( J = \text{cte} \)

\[
\tilde{f} = \frac{\eta_0}{1 + e^{\beta(\epsilon - \epsilon_m)}}
\]


- Lynden-Bell's violent relaxation mechanism: **extended** in Kull et al., Apj (1996) for indistinguishable particles (e.g. neutrinos)

- For fermions, the maximum accessible value of the DF is fixed by the Pauli principle

\[
\eta_0 = \frac{g m^4}{\hbar^3}
\]
DM halos as equilibrium systems of self-gravitating fermions

- Fermions under self-gravity DO ADMIT a perfect fluid approximation
  Ruffini & Bonazzola, Phys. Rev. (1969) - by solving Einstein Dirac equations -

- We solve Einstein equations for a semi-degenerate gas of fermions in hydrostatic equilibrium (i.e. T.O.V), in spherical symmetry Argüelles, Krut, Rueda, Ruffini, PDU (2018)

\[
\frac{d\hat{M}}{d\hat{r}} = 4\pi\hat{r}^2 \hat{\rho}
\]
\[
\frac{d\nu}{d\hat{r}} = \frac{2(\hat{M} + 4\pi\hat{P}\hat{r}^3)}{\hat{r}^2(1 - 2\hat{M}/\hat{r})}
\]
\[
\frac{d\theta}{d\hat{r}} = -\frac{1 - \beta_0(\theta - \theta_0)}{\beta_0} \frac{1}{2} \frac{d\nu}{d\hat{r}}
\]
\[
\beta(\hat{r}) = \beta_0 e^{\frac{\nu_0 - \nu(\hat{r})}{2}}
\]
\[
W(\hat{r}) = W_0 + \theta(\hat{r}) - \theta_0
\]

\[
\rho(r) = \frac{m^2}{h^3} \int f(r, p) \left[ 1 + \frac{\epsilon(p)}{mc^2} \right] d^3p,
\]
\[
P(r) = \frac{1}{3} \frac{2}{h^3} \int f(r, p) \left[ 1 + \frac{\epsilon(p)}{mc^2} \right]^{-1} \left[ 1 + \frac{\epsilon(p)}{2mc^2} \right] \epsilon d^3p
\]
\[
f(r, p) = \begin{cases} 
\frac{1 - e^{(\epsilon - \epsilon_c)/kT}}{e^{(\epsilon - \mu)/kT} + 1}, & \epsilon \leq \epsilon_c \\
0, & \epsilon > \epsilon_c
\end{cases}
\]
\[
\epsilon(p) = \sqrt{c^2 p^2 + m^2 c^4} - mc^2
\]

Free parameters (evaluated at the center, r=0)

\[m, \beta = kT/mc^2, \theta = \mu/kT \text{ and } W = \epsilon_c/kT\]

\[M(0) = 0; \ \nu_0 = 0; \ \theta(0) = \theta_0 > 0; \ \beta(0) = \beta_0; \ W(0) = W_0\]
A novel "dense core – diluted halo" Dark Matter profile for fermions

• The integro-differential system of equations is solved fulfilling a specific boundary condition problem in agreement with halo observables Ruffini, Argüelles, Rueda, MNRAS (2015)

Example: Typical spiral halo

$R_h \sim 10^4 \text{kpc}$
$M_h \sim 10^{11} \text{Mo}$

The dense central core fulfills the 'quantum condition':

$(\lambda_B > 3l_c)$ satisfied for $\theta_0 > 10$

DM profiles depend on the particle mass (see next)
The case of the Milky Way and the Galaxy center
Milky Way observables: from central parsec to outer halo

- central pc governed by a dark compact object of mass $M_c \sim 4 \times 10^6 M_\odot$
- central kpc governed by an inner and main spheroidal Bulge
- central 10 kpc governed by a flat disk
- outer region governed by a DM spherical halo with $M_h(r = 25kpc) \approx 10^{11} M_\odot$

The central $10^{-3}$ pc $\lesssim r \lesssim 2$ pc consist in young S-stars and molecular gas obeying a Keplerian law ($v \propto r^{-1/2}$).

The observational near-IR technics were developed in S. Gillessen et al. (Apj) (2009) and in S. Gillessen et al. (Apj) (2015) for S-stars and gas cloud G2.

Observations implies $M_c \approx 4.2 \times 10^6 M_\odot$ within $r_{p(S2)} \approx 6 \times 10^{-4}$ pc.
Fermionic 'core – halo' profiles: can their overall gravitational potential explain the Milky Way rotation curve as well as the S-star dynamics without the central BH hypothesis?

Hint: Need to solve the former boundary condition problem searching for a set of free R.A.R parameters able to fulfill:

\[ M_c = 4.2 \times 10^6 \text{ Mo} \quad \text{Gillessen et al., Apj (2017)} \]
\[ M(r = 20 \text{kpc}) = 9 \times 10^{10} \text{ Mo} \quad \text{Sofue, PASJ (2013)} \]
\[ M(r = 40 \text{kpc}) = 2 \times 10^{11} \text{ Mo} \quad \text{Gibbons, Belokurov and Evans, MNRAS (2014)} \]
Novel constraints on fermionic dark matter from galactic observables
I: The Milky Way

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**Graph and Diagram**

- **DM**
- **LIGHT**
- **DM**

**Equations and Data**

- $m = 0.6 \text{ keV}, \beta_0 = 2.3 \times 10^{-7}, \theta_0 = 16.3, W_0 = 31.8$
- $m = 48.0 \text{ keV}, \beta_0 = 1.0 \times 10^{-5}, \theta_0 = 37.1, W_0 = 65.2$
- $m = 345.0 \text{ keV}, \beta_0 = 5.0 \times 10^{-3}, \theta_0 = 47.6, W_0 = 77.7$
- NFW

**Legend**

- **S-cluster**
- bulge
- disk
- Baryonic + DM (RAR $m = 48 \text{ keV}$)
- RAR $m = 0.6 \text{ keV}$
- RAR $m = 48 \text{ keV}$
- RAR $m = 345 \text{ keV}$
- data Sofue (2013)

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$r [\text{pc}]$ vs. $\rho [M_\odot \text{pc}^{-3}]$ and $v_{\text{rot}} [\text{km s}^{-1}]$.
The fermionic halo: excellent fit to the Milky Way rotation curve
Any alternative model to the central BH scenario MUST explain: (Data: VLT, Keck I – II Gemini North, Subaru)

- The multiyear accurate astrometric data of S2-star around SgrA*, including the relativistic redshift. GRAVITY collab. (2018); Do et al., Science (2019)

- The currently available data on the orbit and redshift of the G2 object, Plewa et al. Apj (2017); Gillessen et al. Apj (2019);

- The G2 post-pericenter passage deceleration (explained by a drag force in the BH scenario)
THEORETICAL and OBSERVED orbit of S2 around SgrA*  

Red : R.A.R model  

Blue : BH model  

THEORETICAL MODELS: calculated by solving the e.o.m of a test particle in the gravitational field of:

1) Schwarzschild BH of  $4.07 \times 10^6$ Mo

\[ \langle \tilde{\chi}^2 \rangle_{BH} = 3.3586 \]

2) Fermionic DM distribution with $M_c = 3.5 \times 10^6$ Mo (fermion mass $m = 56$ keV)

\[ \langle \tilde{\chi}^2 \rangle_{RAR} = 3.0725 \]
THEORETICAL and OBSERVED line of sight radial velocity (i.e. z) of S2 around SgrA*

Redshift excess (w.r.t Keplerian Zk)
THEORETICAL and OBSERVED orbit of G2 around SgrA*

Red : R.A.R model  Blue : BH model

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THEORETICAL and OBSERVED line of sight radial velocity (i.e. $z$) of G2 around SgrA*

Red: R.A.R model  Blue: BH model

THEORETICAL MODELS: calculated by solving the e.o.m of a test particle in the gravitational field of:

1) Schwarzschild BH of $4.07 \times 10^6$ Mo

$$\bar{\chi}^2_{z_{BH}} = 26.3927$$

2) Fermionic DM distribution with $M_c = 3.5 \times 10^6$ Mo (fermion mass $m = 56$ keV)

$$\bar{\chi}^2_{z_{RAR}} = 0.9960$$
Universality of the fermionic DM profiles
From dwarf to elliptical to galaxy clusters

- The same fermionic model can be applied to other galaxy types, from dwarf, to ellipticals, to galaxy clusters Argüelles, Krut, Rueda, Ruffini, PDU (2019)

For \( m \approx 50 \) keV we make a full coverage of free parameters of the theory, for realistic boundary conditions inferred from observables:

**DWARFS:** eight best resolved MW satellites

\[
\begin{align*}
\rho_{h(d)} &= 400 \text{ pc} \\
M_{h(d)} &= 3 \times 10^7 M_\odot
\end{align*}
\]

**SPIRALS:** sample of nearby disk galaxies from THINGS

\[
\begin{align*}
\rho_{h(s)} &= 50 \text{ kpc} \\
M_{h(s)} &= 1 \times 10^{12} M_\odot
\end{align*}
\]

**ELLIPTICALS:** sample analyzed via weak lensing

\[
\begin{align*}
\rho_{h(e)} &= 90 \text{ kpc} \\
M_{h(e)} &= 5 \times 10^{12} M_\odot
\end{align*}
\]
Universal galaxy relations: from dwarf to elliptical to galaxy clusters

- The model has PREDICTIVE power: the central DM core-masses provides alternatives either to intermediate-mass BHs \( (M_c \sim 10^4 M_\odot \text{ for dwarfs}) \), up to super massive BHs \( (M_c \sim 10^8 M_\odot \text{ for Seyfert and elliptical galaxies}) \) [Argüelles, Krut, Rueda, Ruffini, PDU (2019)]

The degeneracy-pressure-supported DM cores, become gravitationally unstable when reaching the critical mass, collapsing to a super massive BH

\[ M_c^{\text{cr}} \sim 2 \times 10^8 M_\odot \]

For \( m \sim 50 \text{ keV} \)

May provide initial seed for the formation of observed SMBHs in active galaxies such as M87 (without the need of unrealistic super – Eddington accretion rates)
A paradigm shift in the formation and nature of the galactic centers?

- Normal Galaxies → NO Active Nuclei NOR Jets \((M_c \sim 10^6-7M_\odot)\)
- Active Galaxies → YES Active Nuclei AND Jet emission \((M_{BH} \sim 10^9-10M_\odot)\)
Conclusions
Conclusions: open questions & scope

- The main mechanism behind DM halo formation is **collisionless violent relaxation**: leads to a most likely coarse-grained phase-space DF of Fermi-Dirac type which can lead to fermionic 'core-halo' (quasi) relaxed structures where all baryonic matter stably reside

Open questions:
- Why Nature selects this kind of morphologies instead of Boltzmannian (diluted Fermi) ones?
  **Hints**: Long-liveness of profiles, Thermodynamic stability
- How is this picture modified when accounting for (realistic) incomplete violent relaxation?
  **Hints**: Only modify the outer DM halo tail, underlying physics of central region remain valid

- Such 'core-halo' systems of 50 keV fermions -accounting for Pauli-principle and escape of particle effects- can **explain the galaxy rotation curves while provide an alternative to the central BH in normal galaxies**. The critical DM cores offer a seed for ~$10^9$ Mo SMBH formation

Open questions:
- The Nature of such 50 keV fermions?, Which SM extension can account for such particles?
  **Hints**: Right handed neutrinos with dark sector interactions (e.g. Yunis, Argüelles, et al. PDU (2020))
- Features (and accretion) of luminous matter in the presence of this dense-DM fermion cores?
  **Hints**: GR simulations including for hydrodynamics; Study strong lensing around dark central objects Gómez, Argüelles, et al., PRD (2016)
THANK YOU!