# Novel constraints on the phase space of fermionic dark matter in dwarf Galaxies

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# Outline

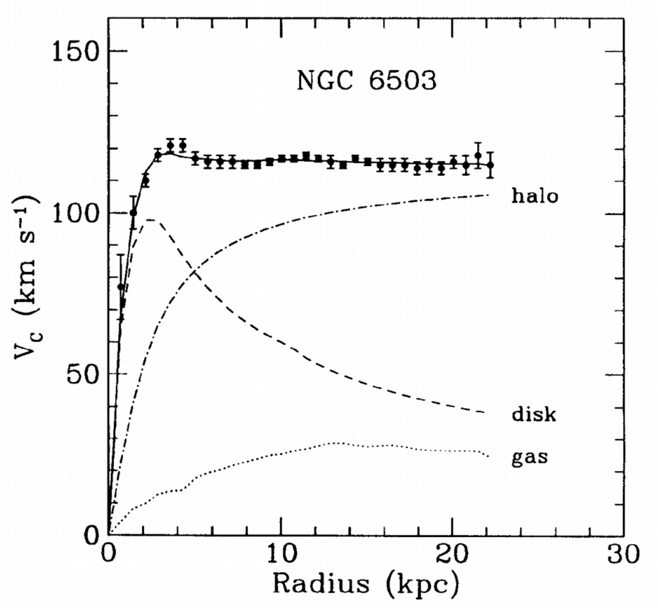
I. Introduction: the need of dark matter in astrophysics and cosmology

II. The fermionic dark matter distribution (MW): The RAR model

III. Some applications to dwarf spheroidal galaxies: Phase space density + velocity dispersion profile

IV. General conclusions and perspectives

# I. Introduction: The need of dark matter



K. G. Begeman et al. MNRAS, 249, 523 (1991)

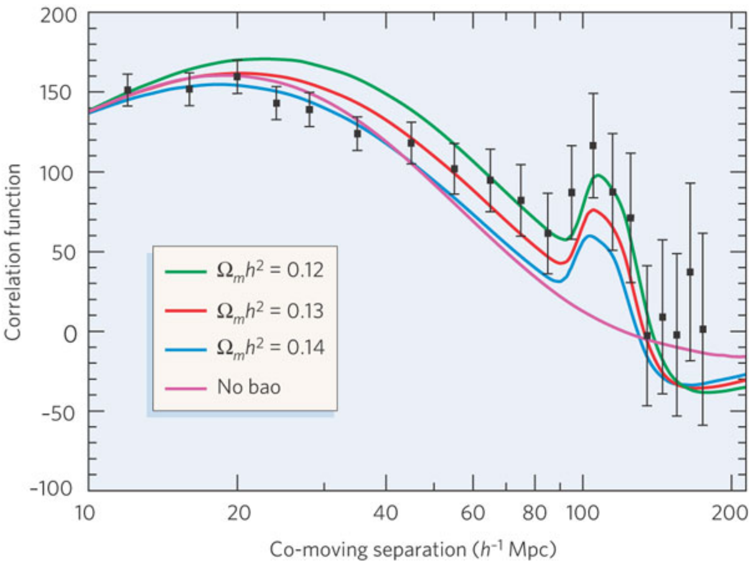


Image credit: Chuck Bennett and Nature.

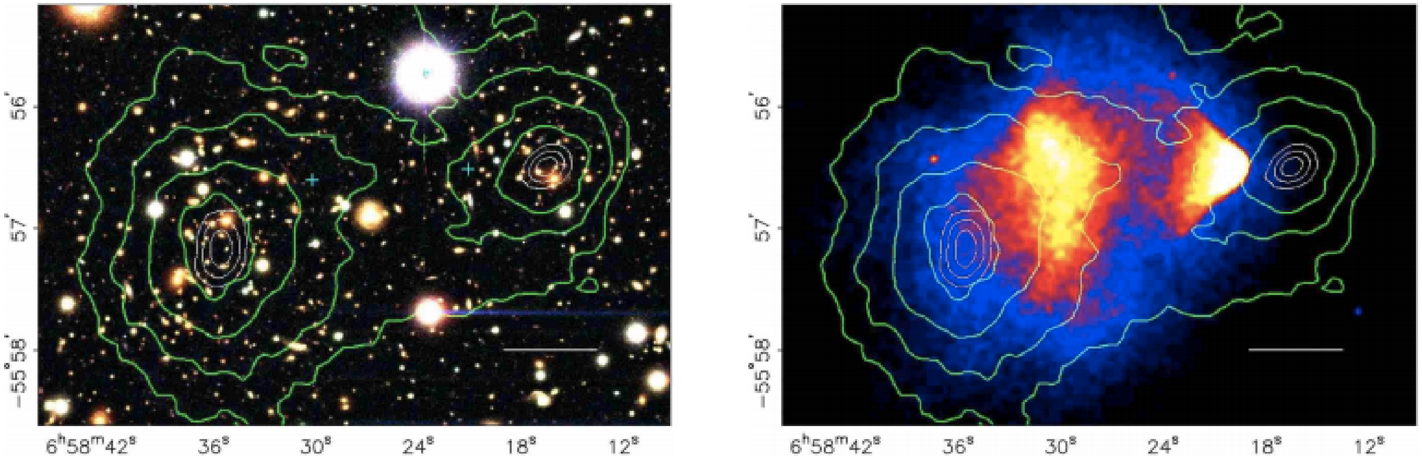


Image Credit: Clowe et. At. Astrophys. J. 648 (2006)

# Dark matter and its alternatives

- Something missing
  - **Dark matter particles**
  - Modify gravity: MOND (TeVeS), *f(R)*
  - MACHOS
  - Primordial black holes

- General classification of DM
  - Hot dark matter (eV fermions)
  - Cold dark matter
  - **Warm dark matter (keV Fermions)**
  - Self-interacting dark matter
  - Scalar field DM: Fuzzy $(\sim 10^{-22}\mathrm{eV})$

- DM particles candidates
  - WIMPS, Axions
  - **Sterile neutrinos**
  - Gravitinos

- DM is expected to be:
  - Non relativistic
  - Non barionic
  - Stable

This work: DM + keV fermions (eg. Sterile neutrinos)

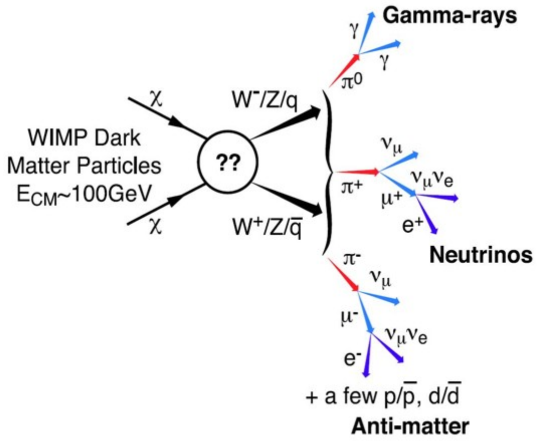
# Astrophysical Constraints

**Rotation curves of galaxies:** Dark matter component is required in order to reproduce data coming from HI.

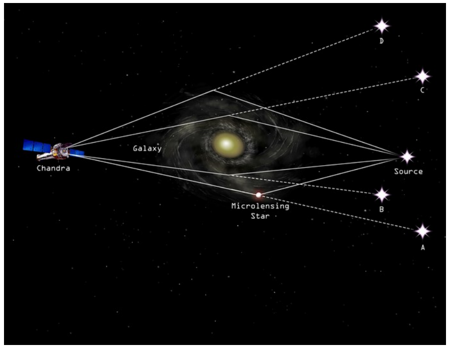
**Distribution of dark matter in galaxies:** One of the best observational test of DM is likely to be in the dark matter distribution of faint dwarf galaxies: Projected velocity dispersion

**Galaxy satellites around the MW:** Missing problem and too big to fail

**Gamma-ray excess:** indirect dark matter searches by surveying a wide variety of astrophysical sources and probing astrophysical processes that could reveal clues to the nature of dark matter



**Strong lensing in galaxies: deflection of light due to the mass distribution**



# II. The fermionic DM distribution: **The RAR model**

- For self-gravitating fermions the equation of state reads

$$\rho = \frac{g}{h^3} m \int_0^{\epsilon_c} f_c(p) \left(1 + \frac{\epsilon(p)}{mc^2}\right) d^3p,$$

$$p = \frac{2}{3}\frac{g}{h^3} \int_0^{\epsilon_c} f_c(p) \frac{1+\epsilon(p)/2mc^2}{1+\epsilon(p)/mc^2} d^3p,$$

- The phase space distribution function including the energy cutoff is defined as follows:

$$f_c(p) = \begin{cases} \frac{1-e^{(\epsilon-\epsilon_c)/kT}}{e^{(\epsilon-\mu)/kT}} & \epsilon \leqslant \epsilon_c, \\ 0 & \epsilon > \epsilon_c, \end{cases}$$

$$\epsilon = \sqrt{c^2p^2 + m^2c^4} - mc^2.$$

- The spherically symmetric space-time is described by the metric

$$g_{\mu\nu} = diag(e^{\nu}, -e^{\lambda}, -r^2, -r^2 sin^2\phi),$$

# The Einstein equations

- **The Einstein equations** can be written as

$$\frac{d\nu}{d\hat{r}} = 2\frac{\hat{M}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}/\hat{r})},$$

$$\frac{d\theta}{d\hat{r}} = -\frac{1-\beta_0(\theta-\theta_0)}{\beta_0}\frac{\hat{M}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}/\hat{r})},$$

$$\frac{d\hat{M}}{d\hat{r}} = 4\pi\hat{r}^2\hat{\rho},$$

- Thermodynamic equilibrium conditions and energy conservation

$$e^{\nu/2}T = const.,$$

$$e^{\nu/2}(\mu+mc^2) = const.,$$

$$e^{\nu/2}(\epsilon+mc^2) = const.$$

- **The model parameters** are defined as

$$\beta = kT/mc^2 \quad \theta = \mu/kT, \quad W = \epsilon_c/kT.$$

**There is a particle mass dependent in this prescription!**

# The DM distribution in the Milky-Way

- Initial condition values

$$M(0) = 0, \quad \nu(0) = 0, \quad \theta(0) = \theta_0, \quad \beta(0) = \beta_0, \quad W(0) = W_0.$$

- boundary **halo conditions:**

$$\nu(r = r_b) = \nu_b, \quad \beta(r = r_b) = \beta_b, \quad W(r = r_b) = 0.$$

$$M_h = 9 \times 10^{10}\ M_\odot, \quad r_h = 20\ \text{kpc}.$$

**DM halo + Compact object**

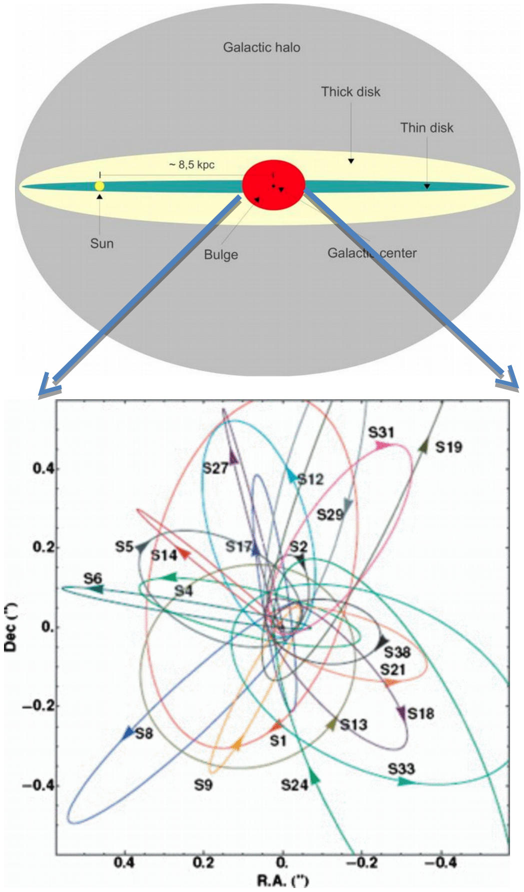
- Rotation curve: **DM distribution**

$$v_T = \sqrt{v_b^2(r) + v_d^2(r) + v_{DM}^2(r)}.$$

- **Central compact object:** S-star cluster dynamic

$$M_c = 4.2 \times 10^6\ M_\odot,$$

$$r_p \simeq 0.58\ \text{mpc}.$$



# Astrophyscial constraints from the MW

Main results of Argüelles et. al. (2016)

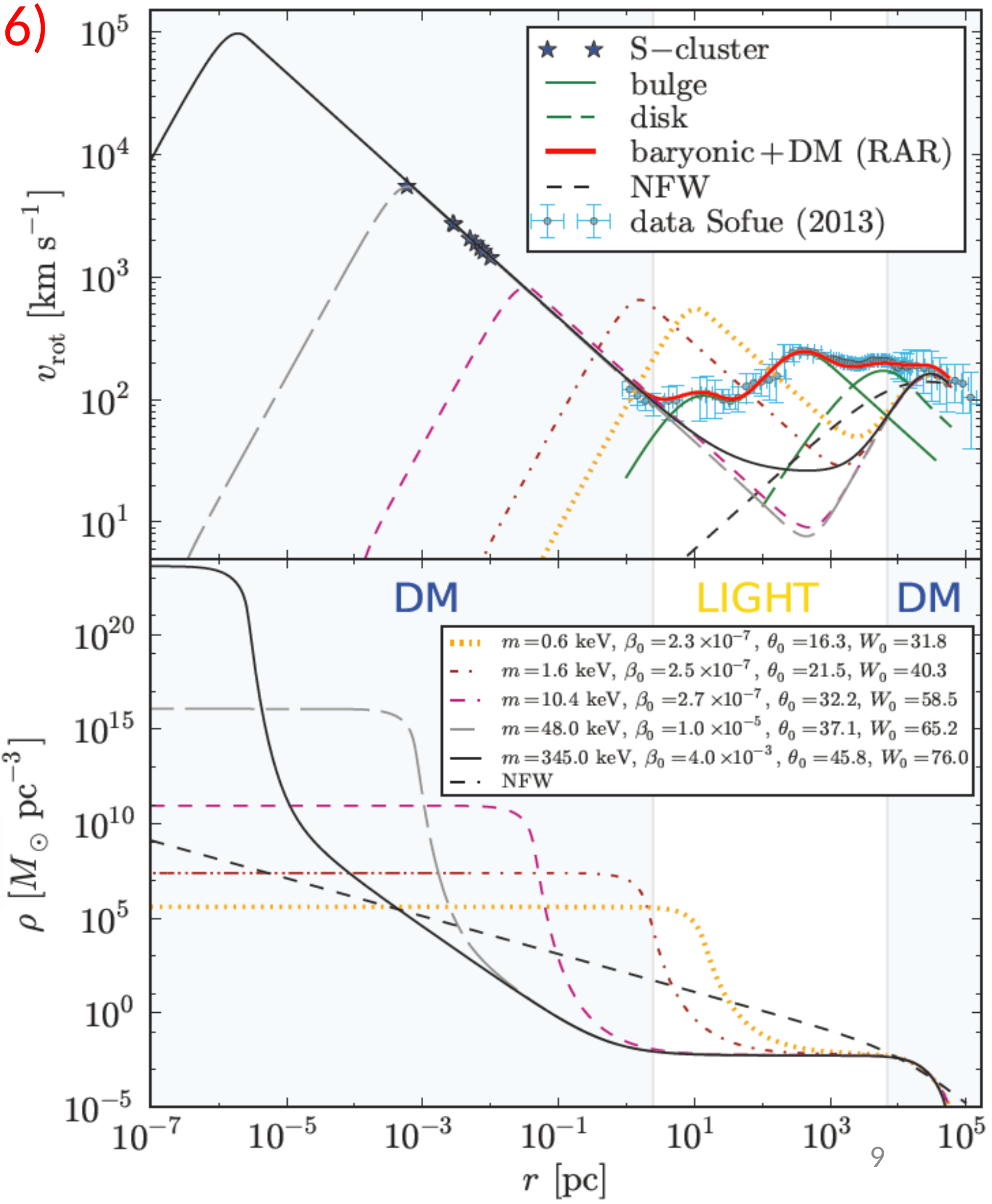
- The RAR model:
  - Central quantum core
  - Dilute (Boltzmanian) halo

- Fermion mass constraints:

$m < 10\ \mathrm{keV},$ ✗

$10\ keV \lesssim m \lesssim 48\ \mathrm{keV},$ DM ✓

$48\ keV \lesssim m \lesssim 345\ \mathrm{keV},$ DM+CO ✓



# Quantum core alternative to the BH paradigm?

- The RAR model predicts: Arguelles et. at. (2016)

  Dwarfs: $M_h = 2.7 \times 10^7 \ M_\odot, \quad r_h = 4.6 \times 10^2 \ \mathrm{pc},$

  Ellipticals: $M_h = 5 \times 10^{12} \ M_\odot, \quad r_h = 9 \times 10^4 \ \mathrm{pc}.$

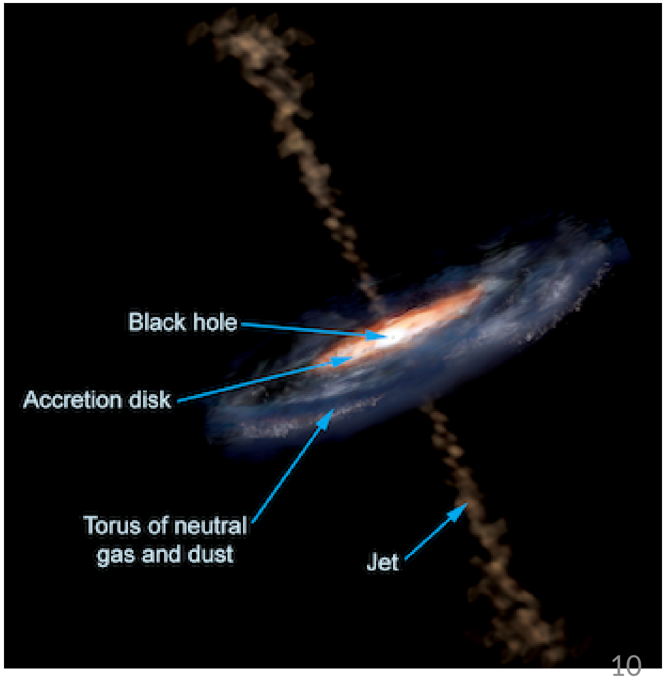
  $m \sim 50 \ keV : \quad M_c \in (3.8 \times 10^3 M_\odot, 2.2 \times 10^8 M_\odot).$

- **Empirical correlations** for galaxies: $M_\bullet - M_{DM}, \quad M_\bullet - \sigma * .$

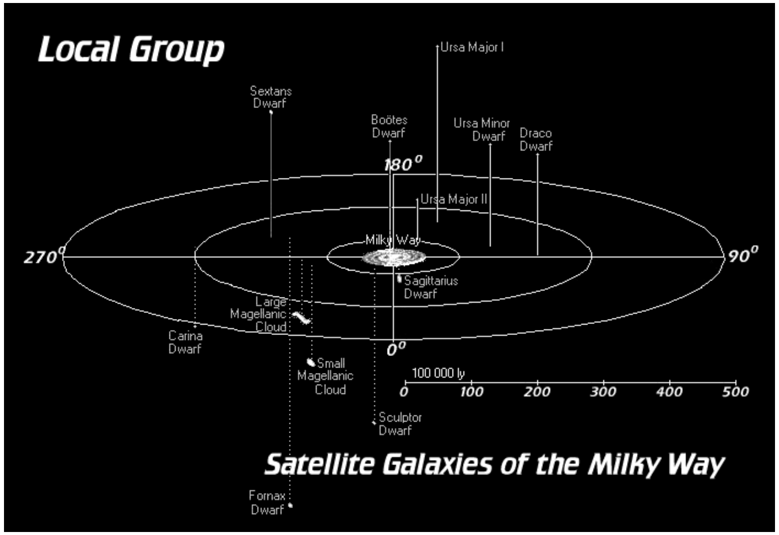
- Compact core alternative: galaxies without active galactic nuclei (**AGN**)

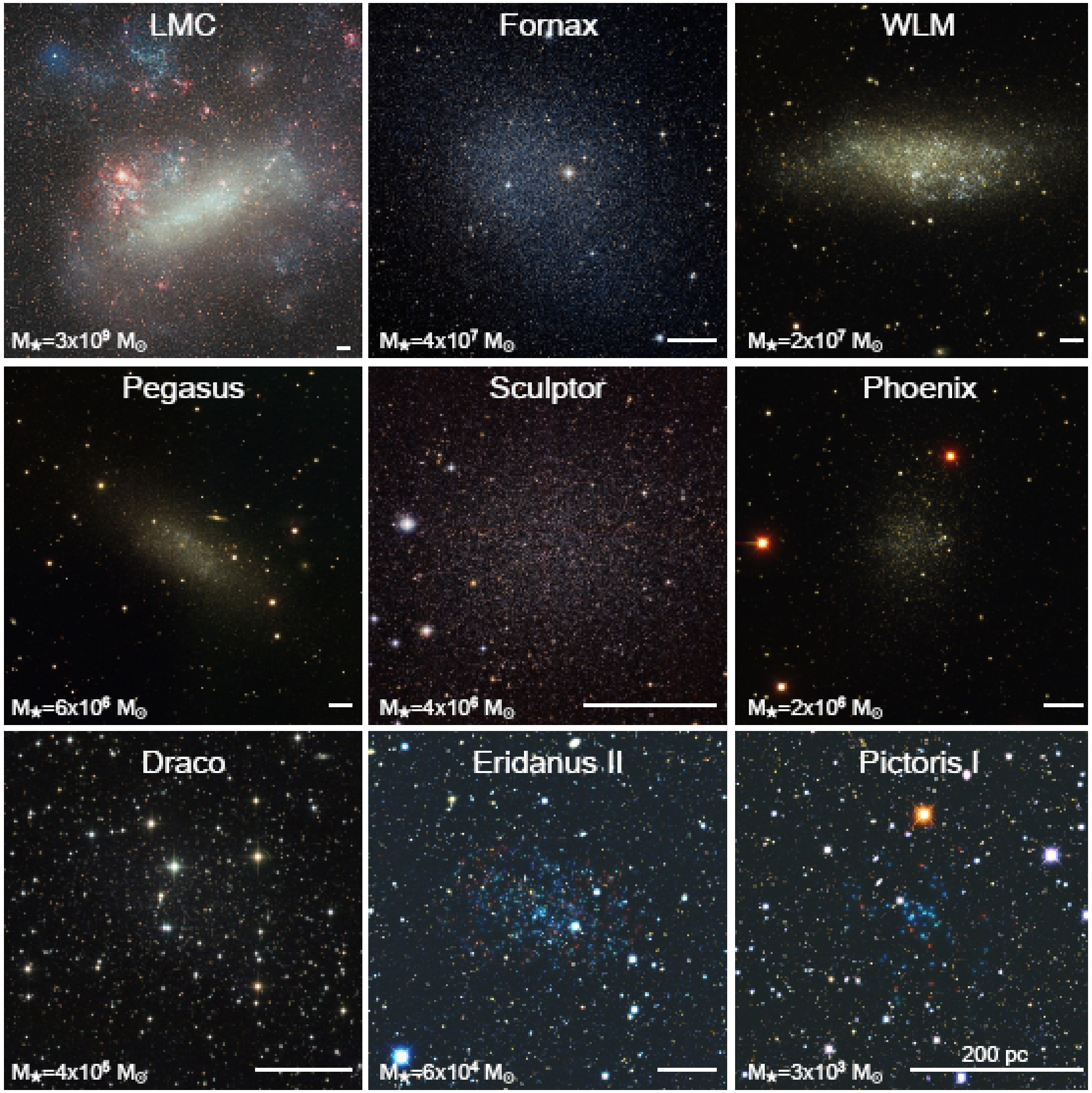
- **SMBH:** $10^{9-10} M_\odot$

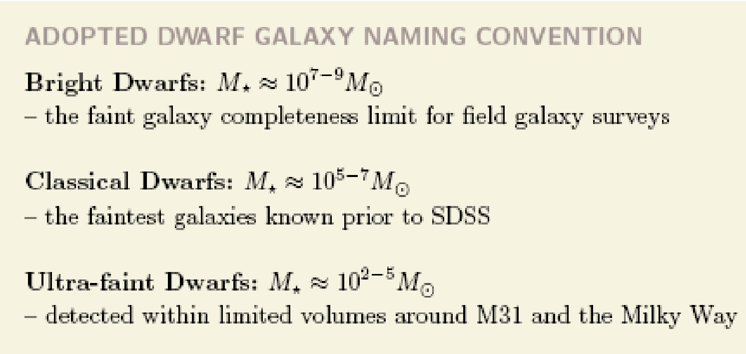
  BH-seed formation: Collapse+accretion



# III. Some applications to dwarf galaxies







ADOPTED DWARF GALAXY NAMING CONVENTION

**Bright Dwarfs:** $M_\star \approx 10^{7-9} M_\odot$
– the faint galaxy completeness limit for field galaxy surveys

**Classical Dwarfs:** $M_\star \approx 10^{5-7} M_\odot$
– the faintest galaxies known prior to SDSS

**Ultra-faint Dwarfs:** $M_\star \approx 10^{2-5} M_\odot$
– detected within limited volumes around M31 and the Milky Way

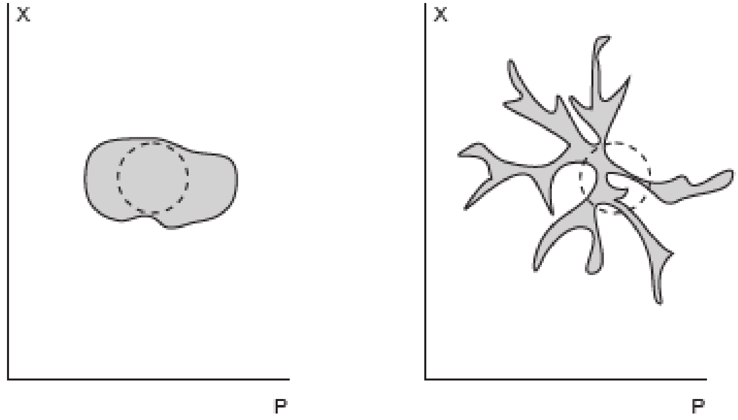
Bullock (2017)

# Phase space density

## 1. The phase space density:

- Colisionless disipationless dynamics can only lead to the decrease of the coarse-grained phase-space density

Liouville Theorem



$$Q_i \geq Q_f.$$

- The smaller is the DM mass – the bigger is the number of particles in a given DM-dominated object.

- Objects with highest phase-space density: dwarf spheroidal galaxies

Image Credit: ESO

# Phase space density approaches

- Tremaine–Gunn bound: $Q^{obs} < Q^{prim}. \longrightarrow m_{TG}^4 \geq \frac{9(2\pi\hbar)^3}{(2\pi)^{5/2} g G \sigma r_0^2}.$

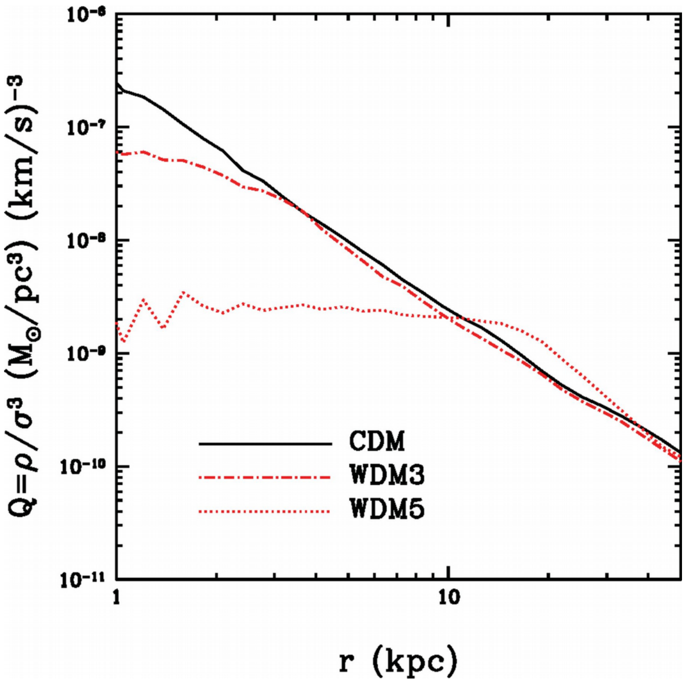
It uses a singular isothermal sphere

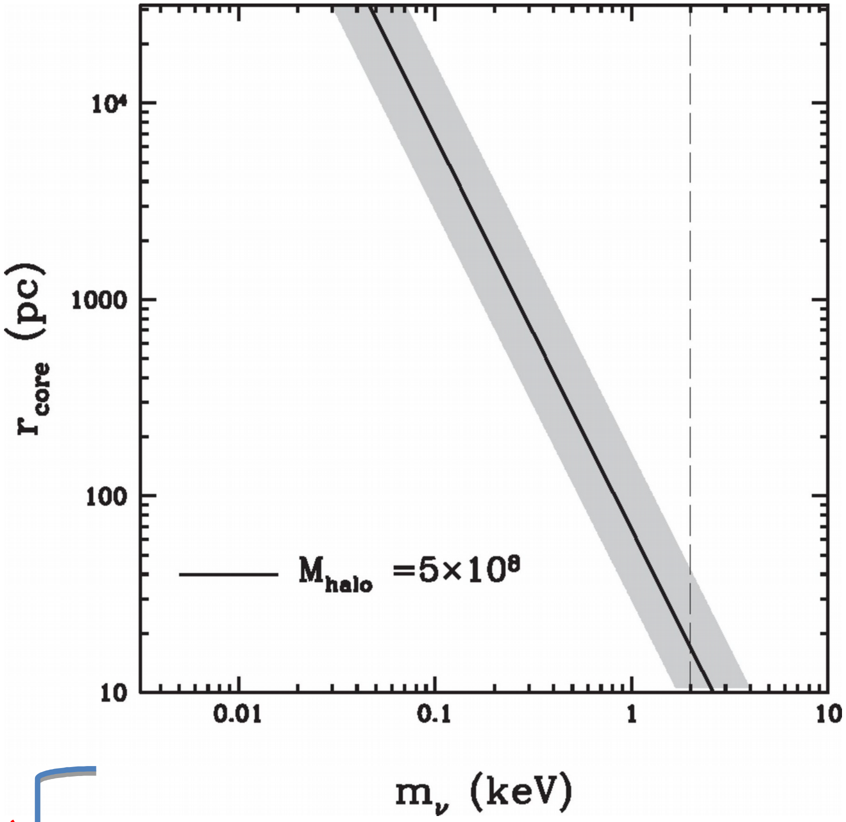
$Q^{obs}$ → *m=?* → For the RAR model the fermion mass is constrained directly from the observed PSD.

- Hogan and Dacalton averaged PSD: $Q \equiv \frac{\rho}{\langle v^2 \rangle^{3/2}},$

$$Q = \frac{g m^4}{(2\pi\hbar)^3} \underbrace{\frac{\left[\int f(p) d^3 p\right]^{5/2}}{\left[\int f(p) p^2 d^3 p\right]^{3/2}}}_{q} = \frac{g m^4}{(2\pi\hbar)^3} q;$$

# Fermionic phase space density





- Expected core size in dSph MW galaxies: a hundred pc (Walker 2009)
- Lyman-alpha forest constraint: m>5.3 keV (Irsic et al. 2017)
- Large scale structure: m>2 keV

Catch 22 problem for WDM: “if you want a large core you won’t get the galaxy, if you get the galaxy it won’t have a large core.” Macciò et al. (2013).

# Some applications to dwarf spheroidal galaxies

## 2. The projected velocity dispersion

Jean Equation:

$$\frac{1}{\nu}\frac{d}{dr}(\nu\bar{v_r^2}) + 2\frac{\beta\bar{v_r^2}}{r} = -G\frac{M(r)}{r^2}.$$

Stellar distribution:

- Plummer profile

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

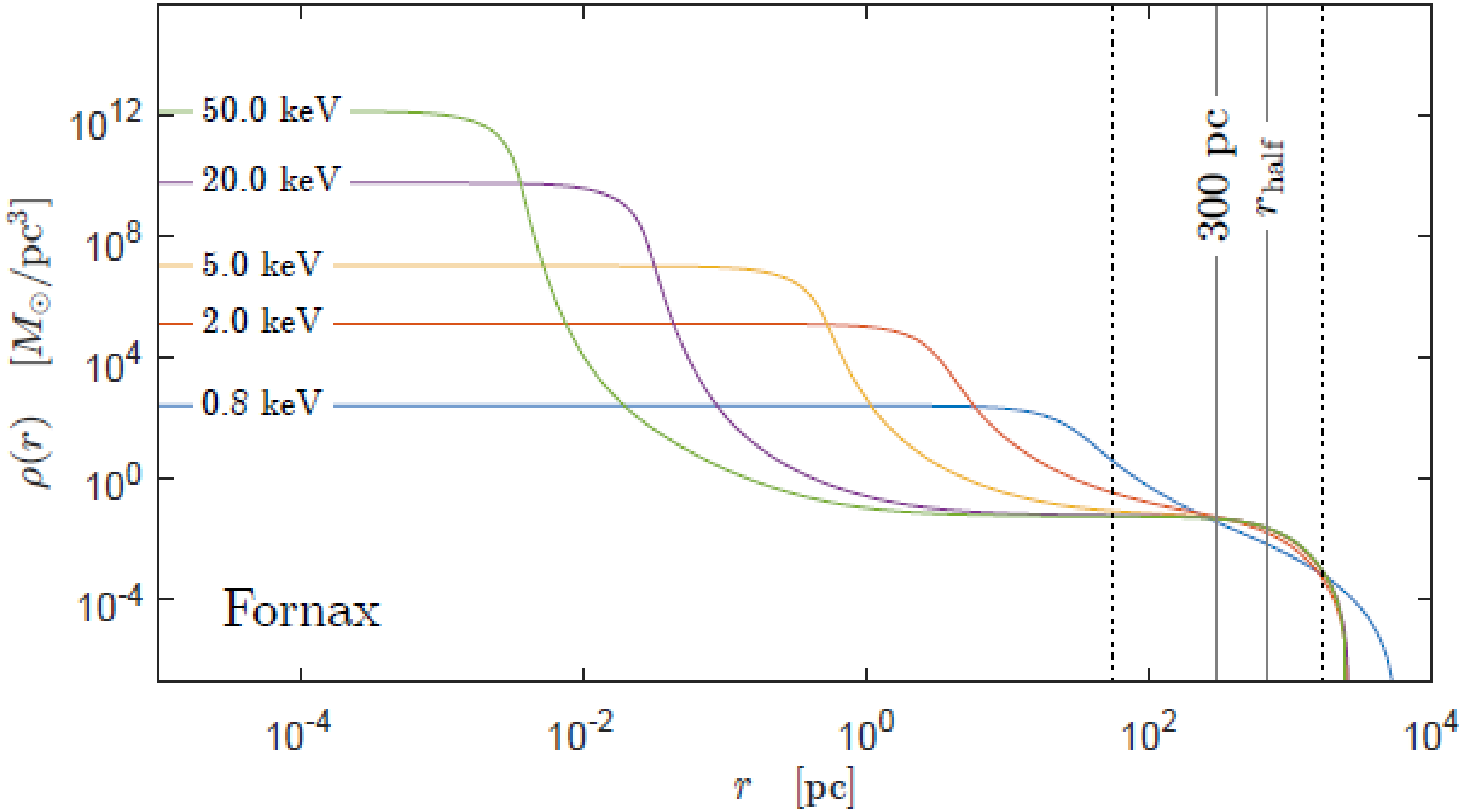
$$\nu(r) = \frac{3L}{4\pi r_{\rm half}^3}\frac{1}{[1+(r/r_{\rm half})^2]^{5/2}}.$$

Mass profile of DM

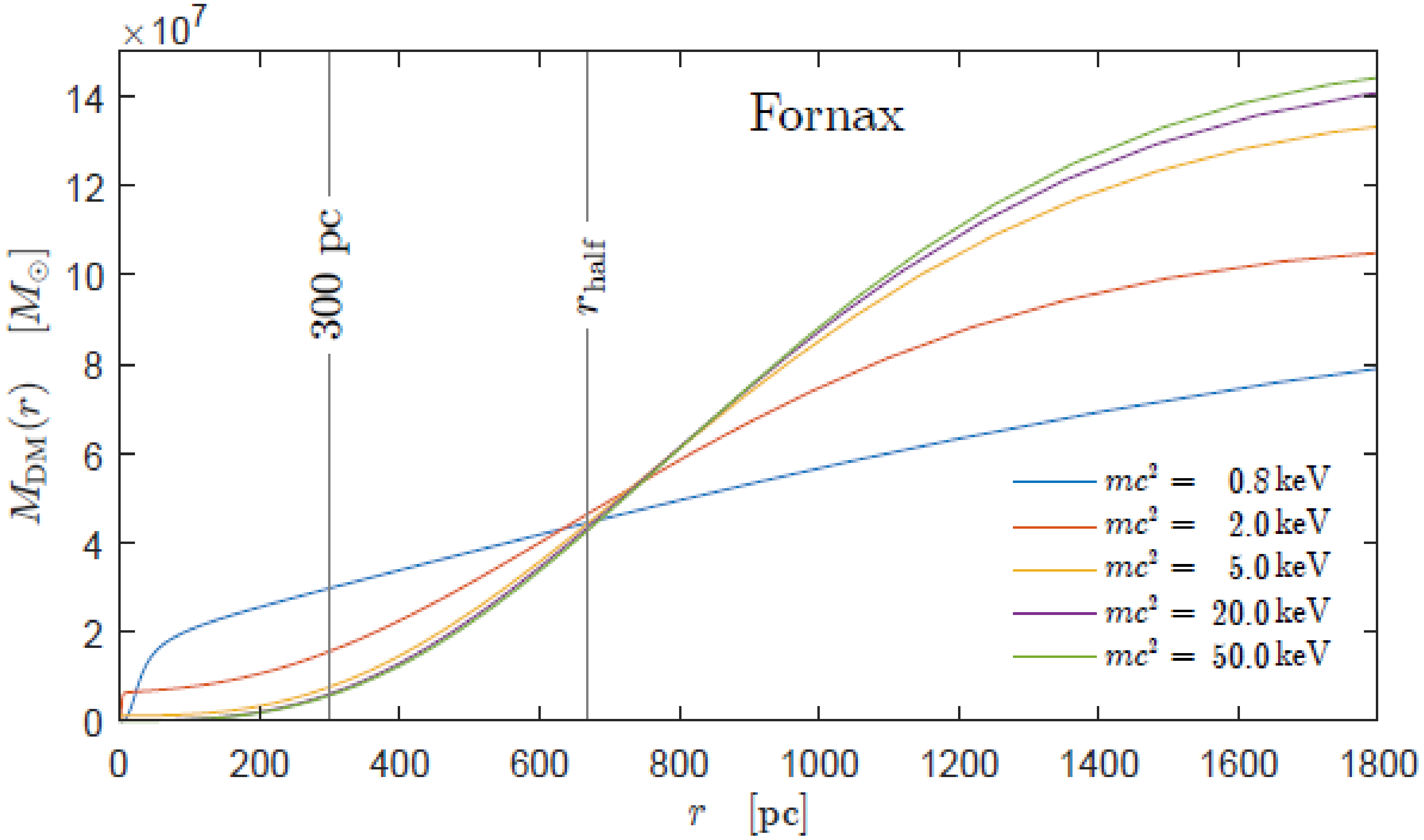
- The RAR model
- Hernquist (Cored)
- Pseudo isothermal

$$\sigma_{LOS}^2(R) = \frac{2}{I(R)}\int_R^\infty \left(1-\beta\frac{R^2}{r^2}\right)\frac{\nu\bar{v_r^2}r}{\sqrt{r^2-R^2}}dr.$$

# The density profile



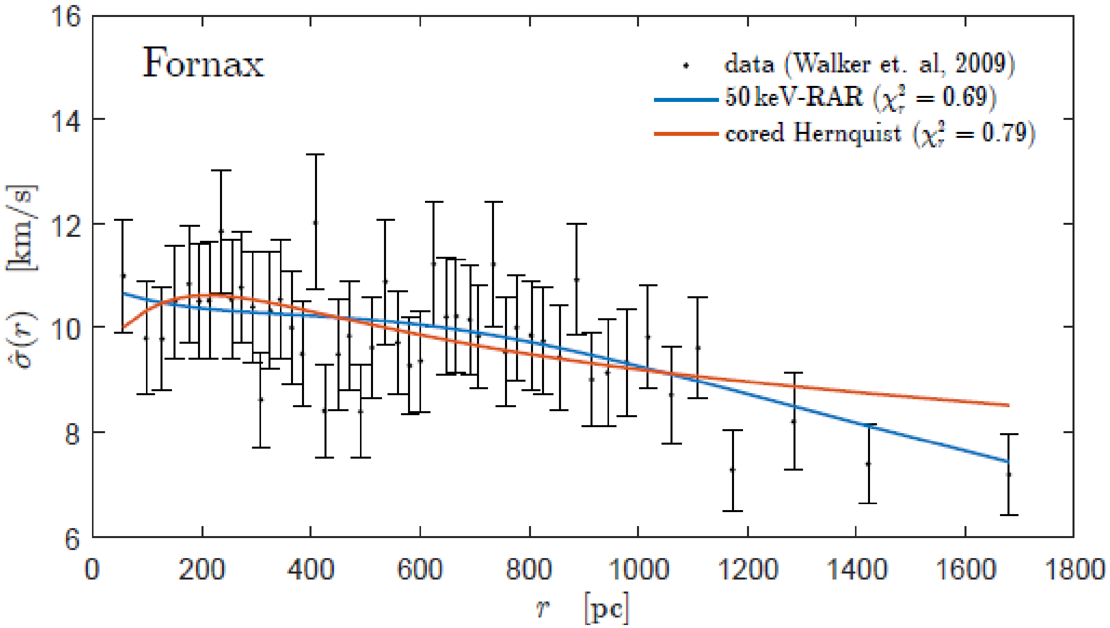
# The mass distribution

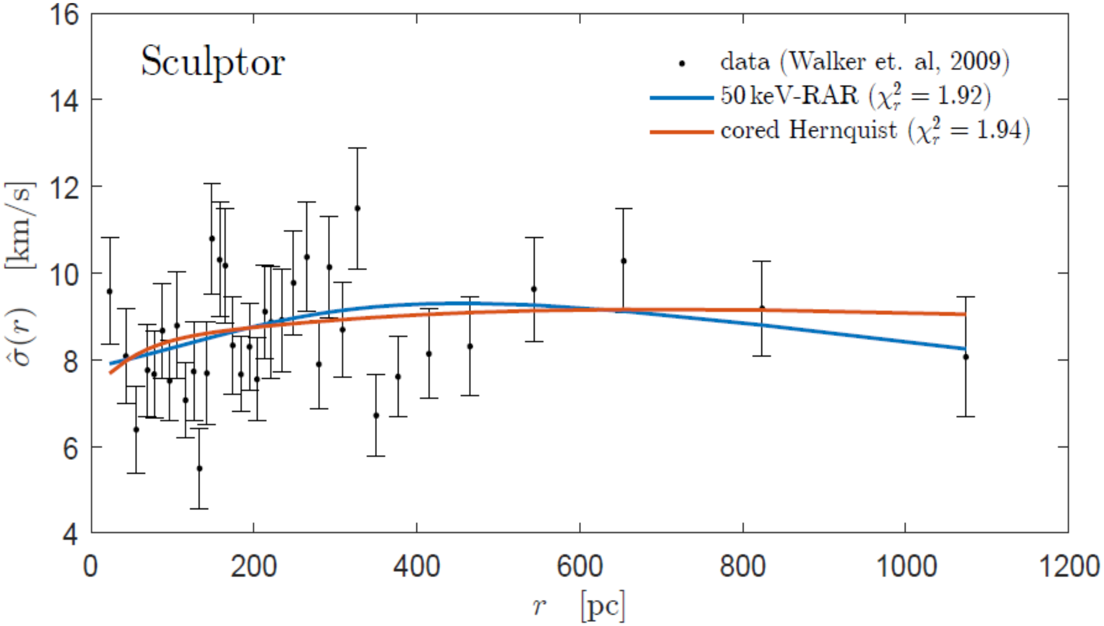


Walker et al. (2009)

| Galaxy | $M_{half}$ $\times 10^7$ $[M_\odot]$ | $M_{half}^{RAR}$ $\times 10^7$ $[M_\odot]$ | $\bar{\rho}$ $[{\rm M_\odot\ pc^{-3}}]$ | $\bar{\rho}^{RAR}$ $[{\rm M_\odot\ pc^{-3}}]$ | $M_{300}$ $\times 10^7$ $[M_\odot]$ | $M_{300}^{RAR}$ $\times 10^7$ $[M_\odot]$ | $M_{last}$ $\times 10^7$ $[M_\odot]$ | $M_{last}^{RAR}$ $\times 10^7$ $[M_\odot]$ | $V_{max}$ $[km\ s^{-1}]$ | $V_{max}^{RAR}$ $[km\ s^{-1}]$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Fornax | $5.3 \pm 0.9$ | 3.86 | $4.2 \pm 0.7 \times 10^{-2}$ | $2.82 \times 10^{-2}$ | $0.7^{+0.2}_{-0.2}$ | 0.66 | $12.8^{+2.2}_{-5.6}$ | 13.2 | $18^{+5}_{-3}$ | 19.36 |
| Sculptor | $1.3 \pm 0.4$ | 0.98 | $1.7 \pm 0.5 \times 10^{-1}$ | $1.33 \times 10^{-1}$ | $1.3^{+0.2}_{-0.2}$ | 1.35 | $10.0^{+3.2}_{-5.0}$ | 9.55 | $\geq 15$ | 18.27 |

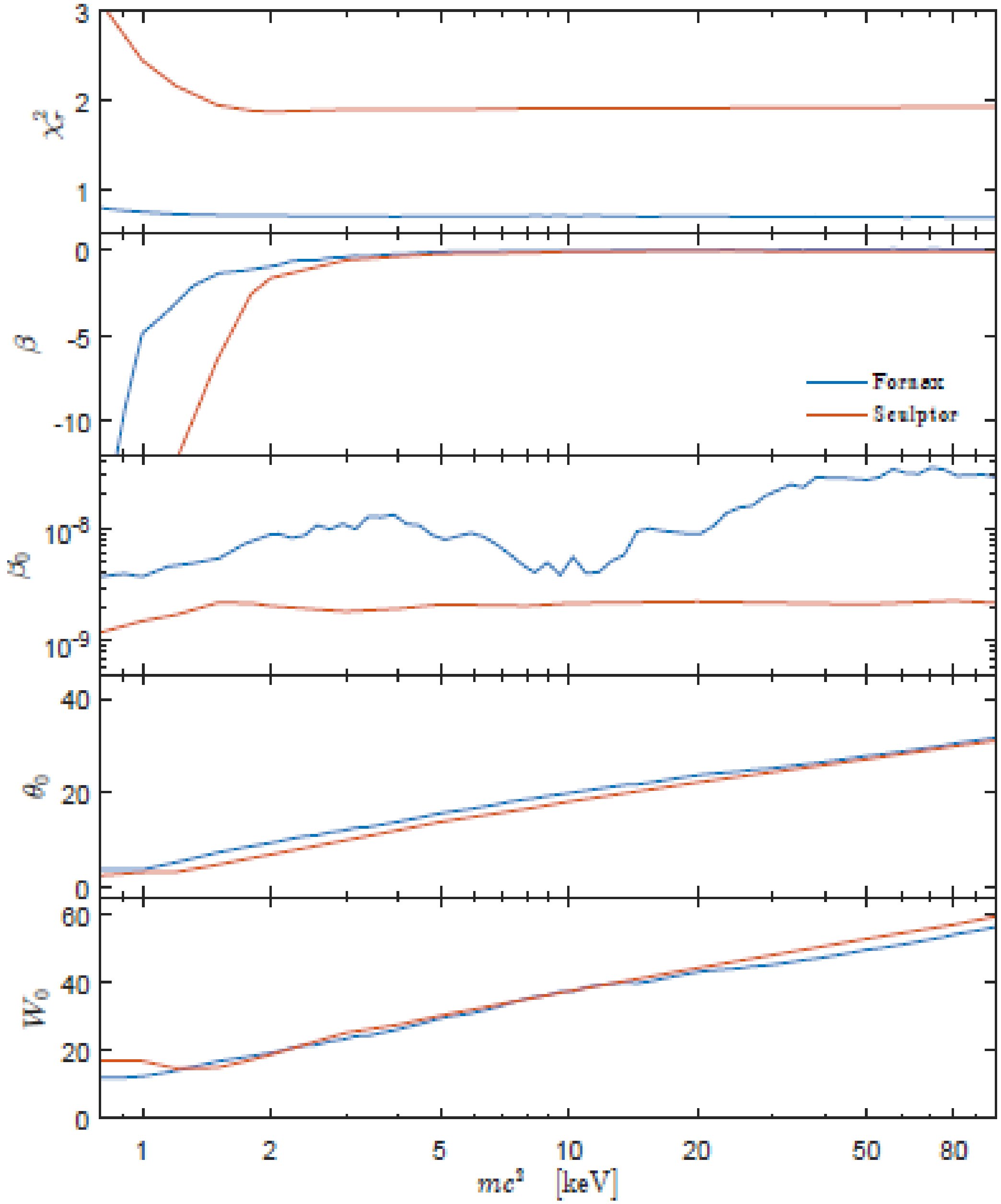
# LOS Velocity dispersion





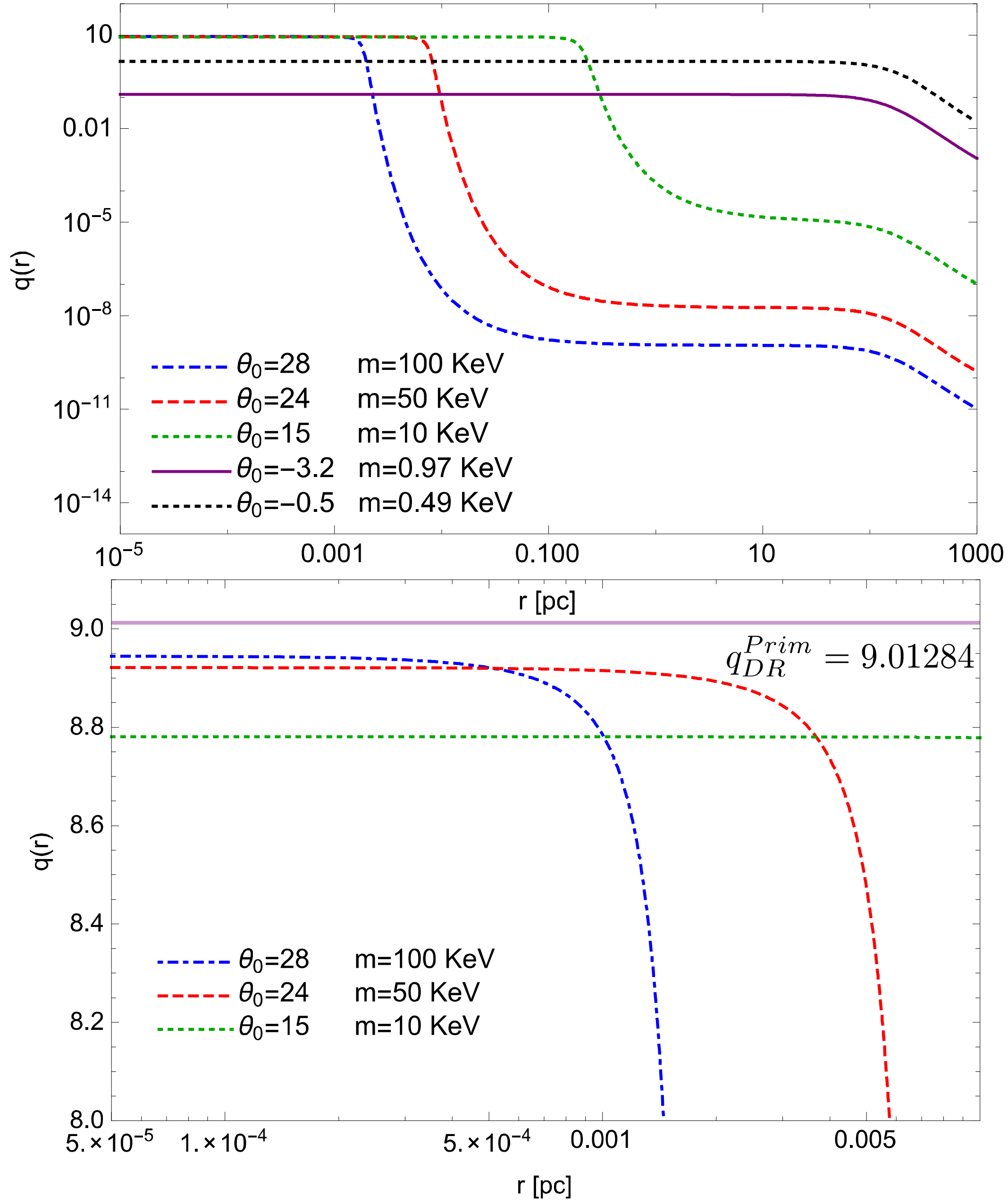
$$\chi^2(\boldsymbol{p}) = \sum_{i=1}^{N} \left[ \frac{\hat{\sigma}_i - \hat{\sigma}(r_i, \boldsymbol{p})}{\Delta \hat{\sigma}_i} \right]^2$$

# LOS Velocity dispersion



$$\chi^2(\boldsymbol{p}) = \sum_{i=1}^{N} \left[ \frac{\hat{\sigma}_i - \hat{\sigma}(r_i, \boldsymbol{p})}{\Delta\hat{\sigma}_i} \right]^2$$

# Phase space density for Sculptor



- One-halo length scale:

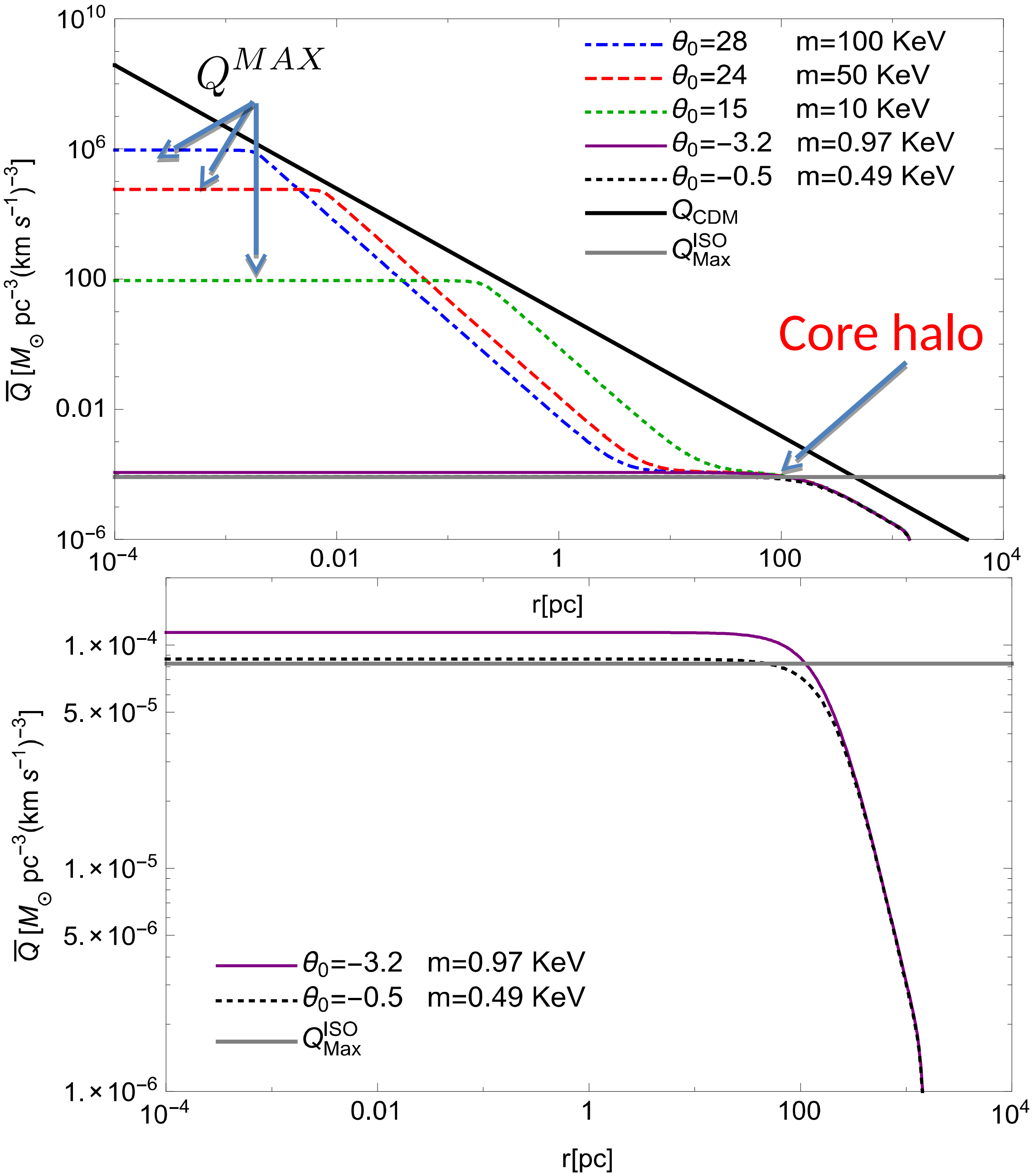
$$M_h = 2.7 \times 10^7 M_\odot,$$
$$r_h = 460\ \mathrm{pc},$$
$$\sigma = 10.1\ \mathrm{kms}^{-1}.$$

- Maximal PSD:

| $q_{max}^{RAR}$ | $\theta_0$ | m[keV] |
|---|---|---|
| 8.94 | 28.4 | 100 |
| 8.92 | 24.5 | 50 |
| 8.78 | 15.2 | 10 |

Liouville's theorem ✝

# Observed phase space density for Sculptor



- Averaged PSD

$$\bar{Q}(r) = \frac{1}{4/3\pi r^3}\int_0^r 4\pi r\prime^2 Q(r\prime)dr\prime.$$

- Cusp LCDM

$$Q_{CDM}(r) = Q_h(r/r_h)^{-\beta},$$
$$\beta \simeq 1.9 - 2.$$

- Estimated values

$$Q^{ISO}_{Max} \approx 8.44\times10^{-5}[M_\odot\mathrm{pc}^{-3}(\mathrm{kms}^{-1})^{-3}].$$

$$\bar{Q} \approx 6.55\times10^{-5}[M_\odot\mathrm{pc}^{-3}(\mathrm{kms}^{-1})^{-3}].$$

# Conclusions and perpectives

- It was computed the PSD of dSph galaxies with a **m> 10 keV** being in agreement with:
  1. One-halo length scale
  2. Core halo structure
  3. PSD Conservation (Liouville’s theorem)
  4. Observed PSD in dSph MW galaxies
  5. Lower mass bound set by Lyman-alpha forest (m>5.3 keV)
  6. The projected velocity dispersion profile
- The fermion mass was inferred by observations and **NOT** from PSD arguments.
- There is not ***Catch 22 problem*** within the RAR model.
- Put the RAR model in the context of structure formation: missing satellite problem.
- Consider further kinematical data of dwarf galaxies of the local group.