Fermionic dark matter on galaxy scales

observations, theory and predictions

A. Krut, C. R. Argüelles, G. Gomez, J. A. Rueda and R. Ruffini

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Outline

- Short introduction

  dark matter and galaxy structures

- Fermionic Dark Matter

  Ruffini-Argüelles-Rueda (RAR)

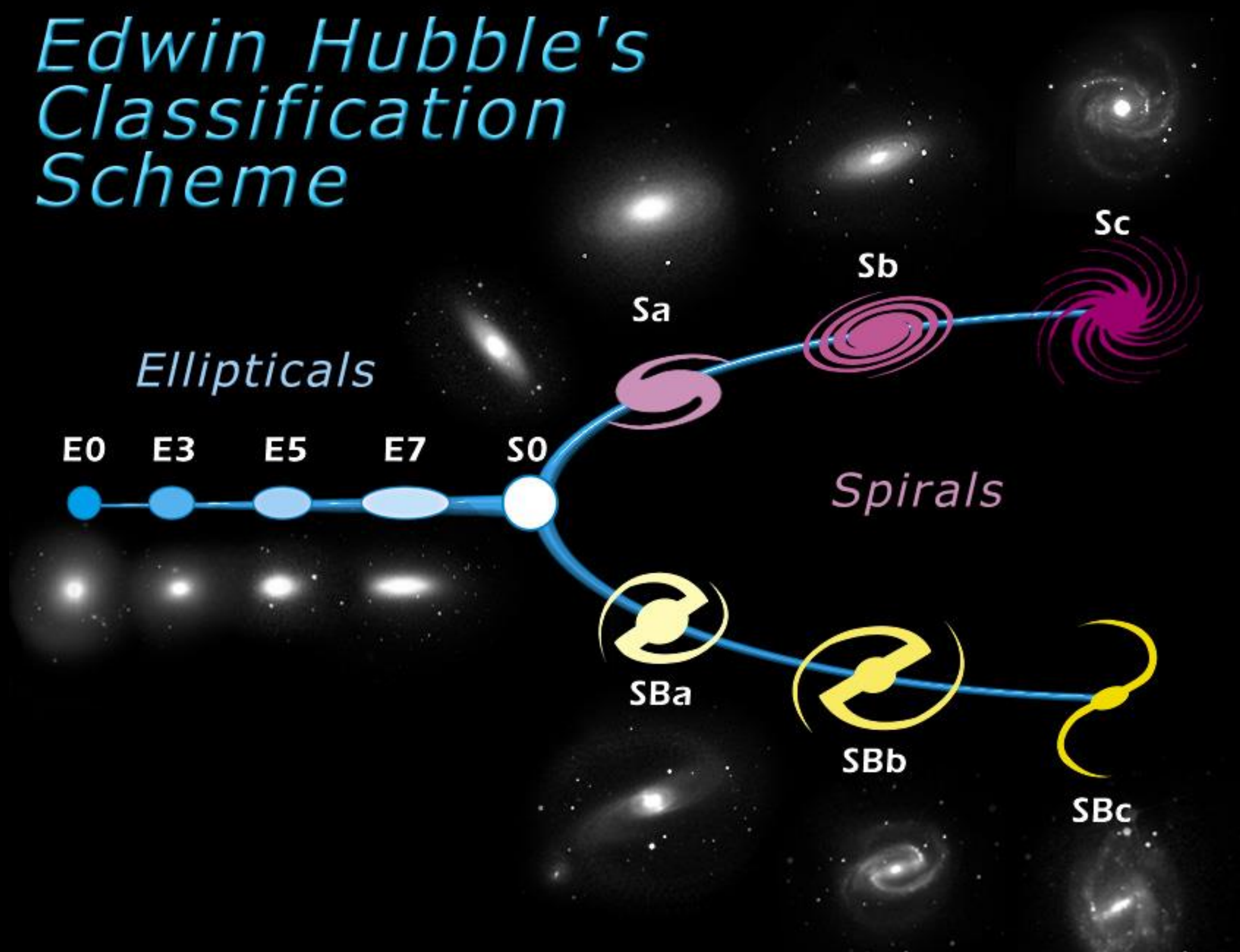
- Results

  predictions for dwarfs to ellipticals

- Conclusion

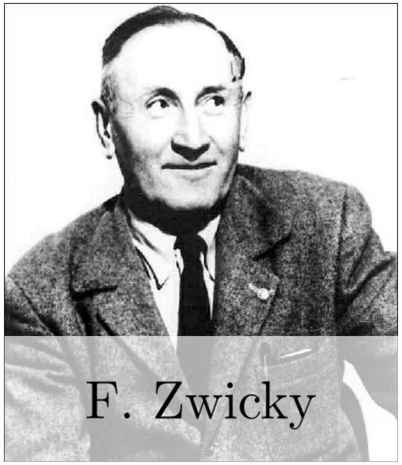
Galaxy Morphology

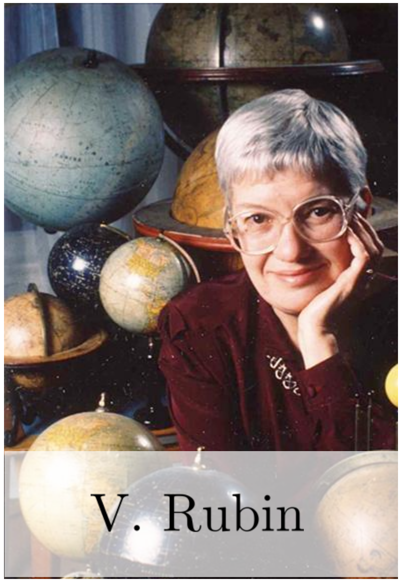
Different types of stallar formations

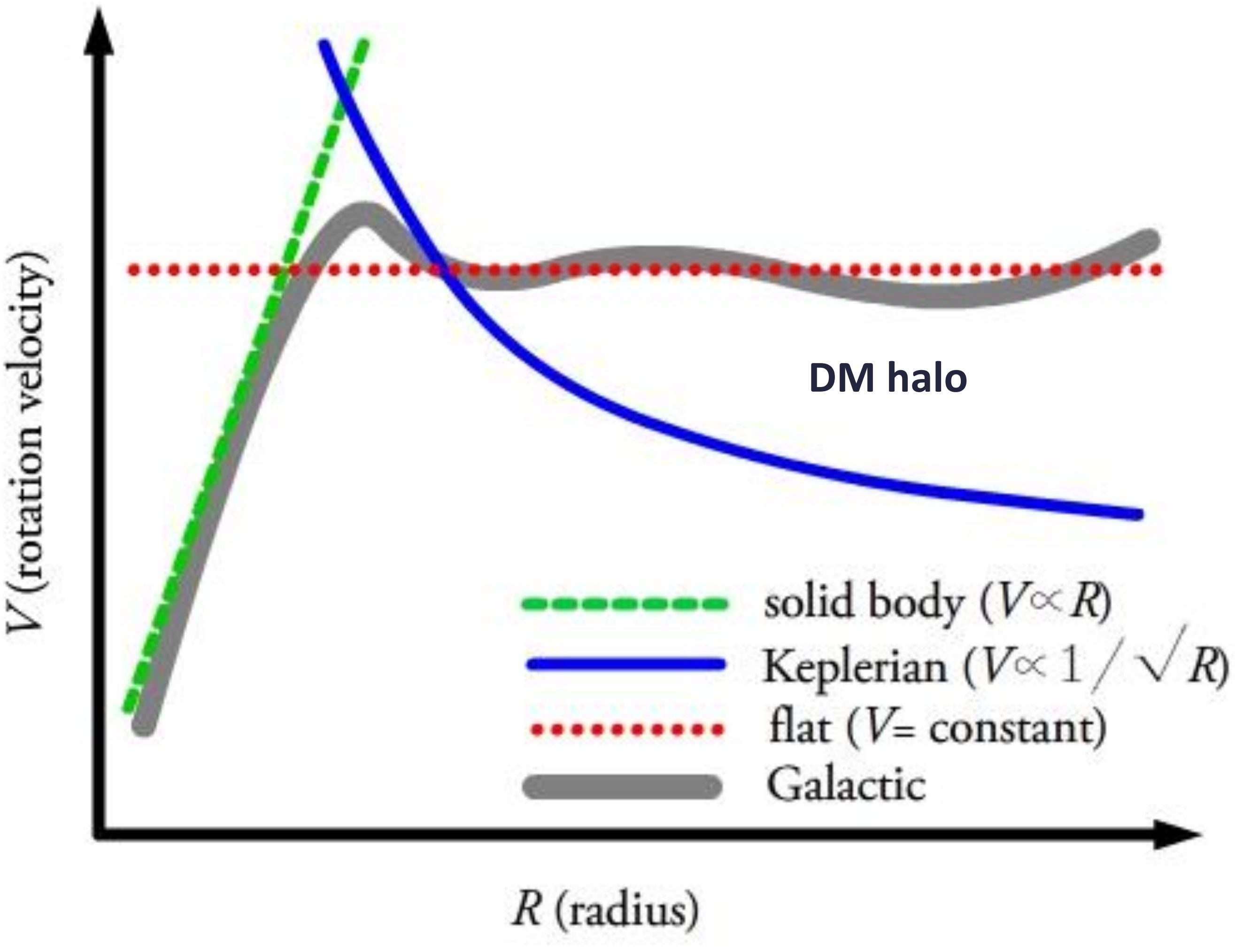


wikipedia.de

More than baryonic matter!?

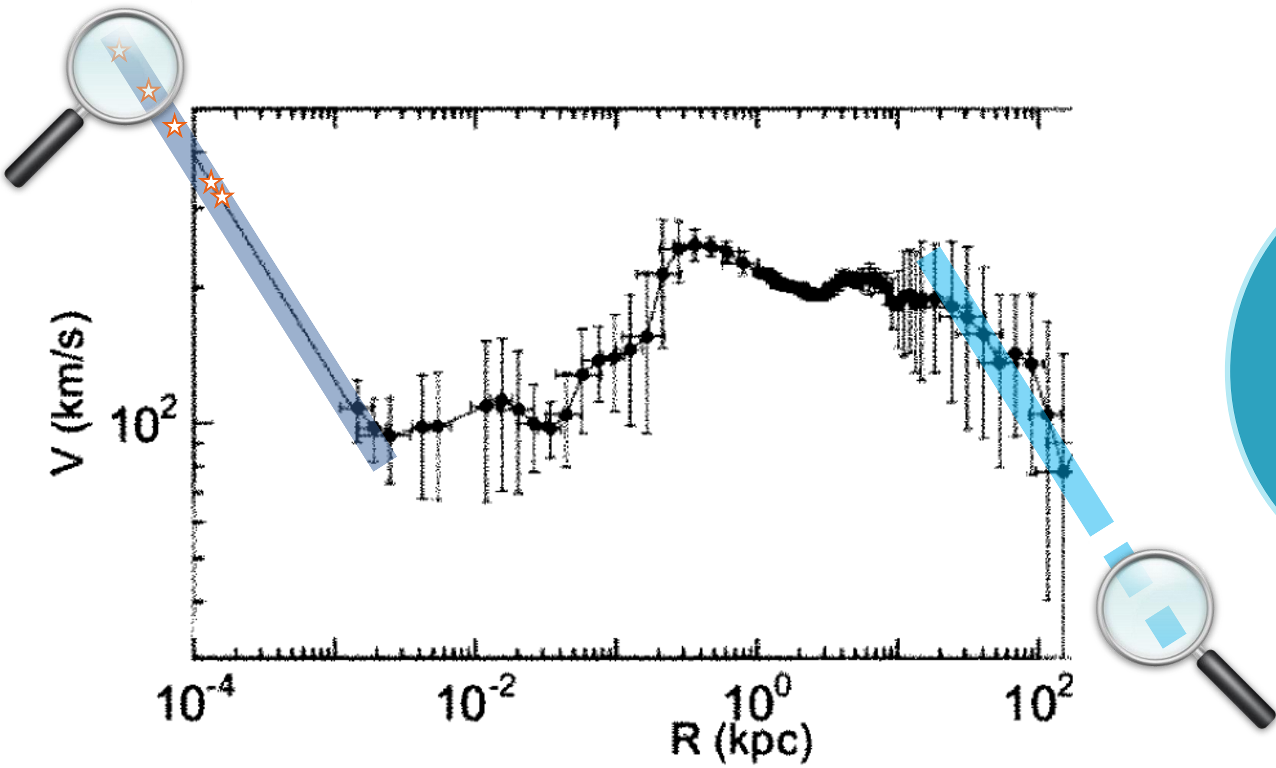


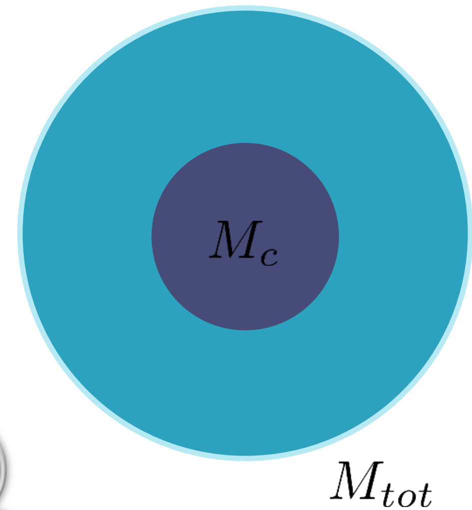




Miky Way rotation curve

Two Keplerian behaviour in rotation curve

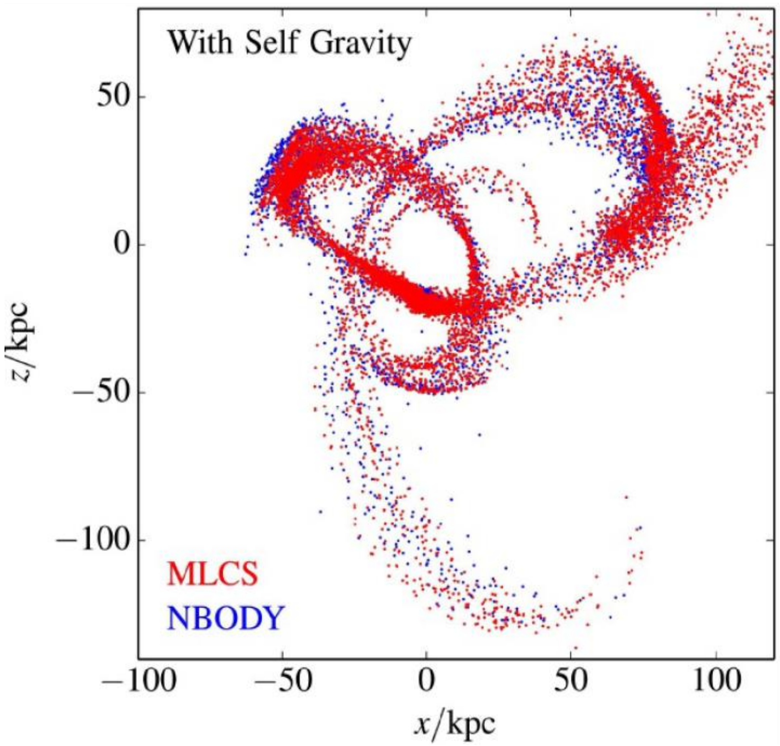


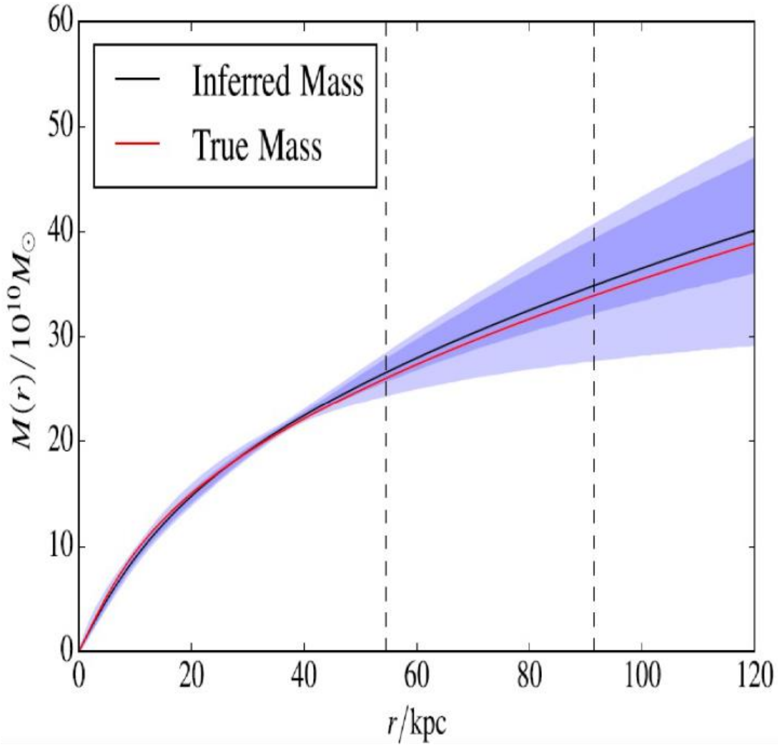


Y. Sofue (PASJ, 2013)

The outer halo

- Outermost satellite galaxies of the MW are excellent total DM tracers
- The Sgr-dwarf satellite with its stream motion of tidally disrupted stars was well observed and well reproduced numerically

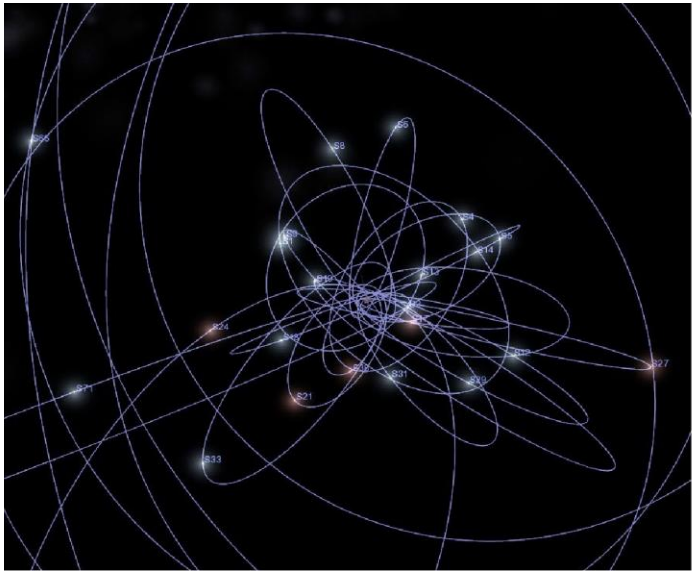


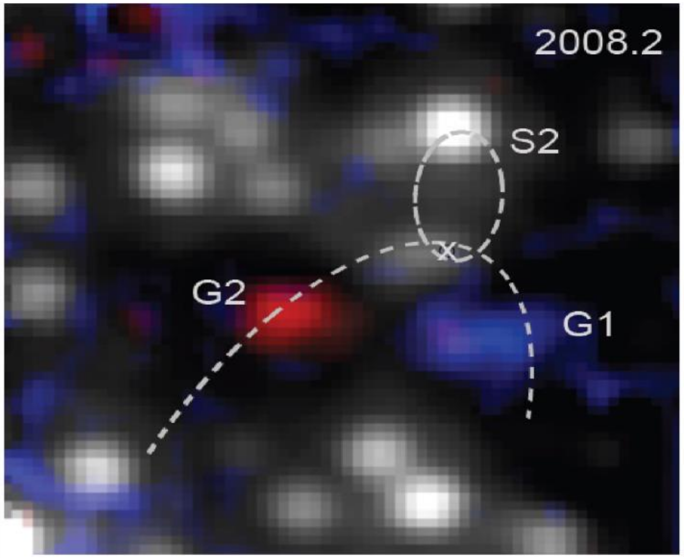


Belokurov et al. (MNRAS) (2014); S. Gibbons et al. (MNRAS) (2014)

The Galactic center

- The central region ($10^{-3}\text{pc} \lesssim r \lesssim 2\text{pc}$) consist of young so-called S-stars and molecular gas
- Stars and gas dynamics are well described by Keplerian law ($v \sim r^{1/2}$)
- A dark compact object ($M \approx 4.2 \times 10^6 M_\odot$) is infered within the smallest pericenter of $r_p(S_2) \approx 6 \times 10^{-4}\text{pc}$

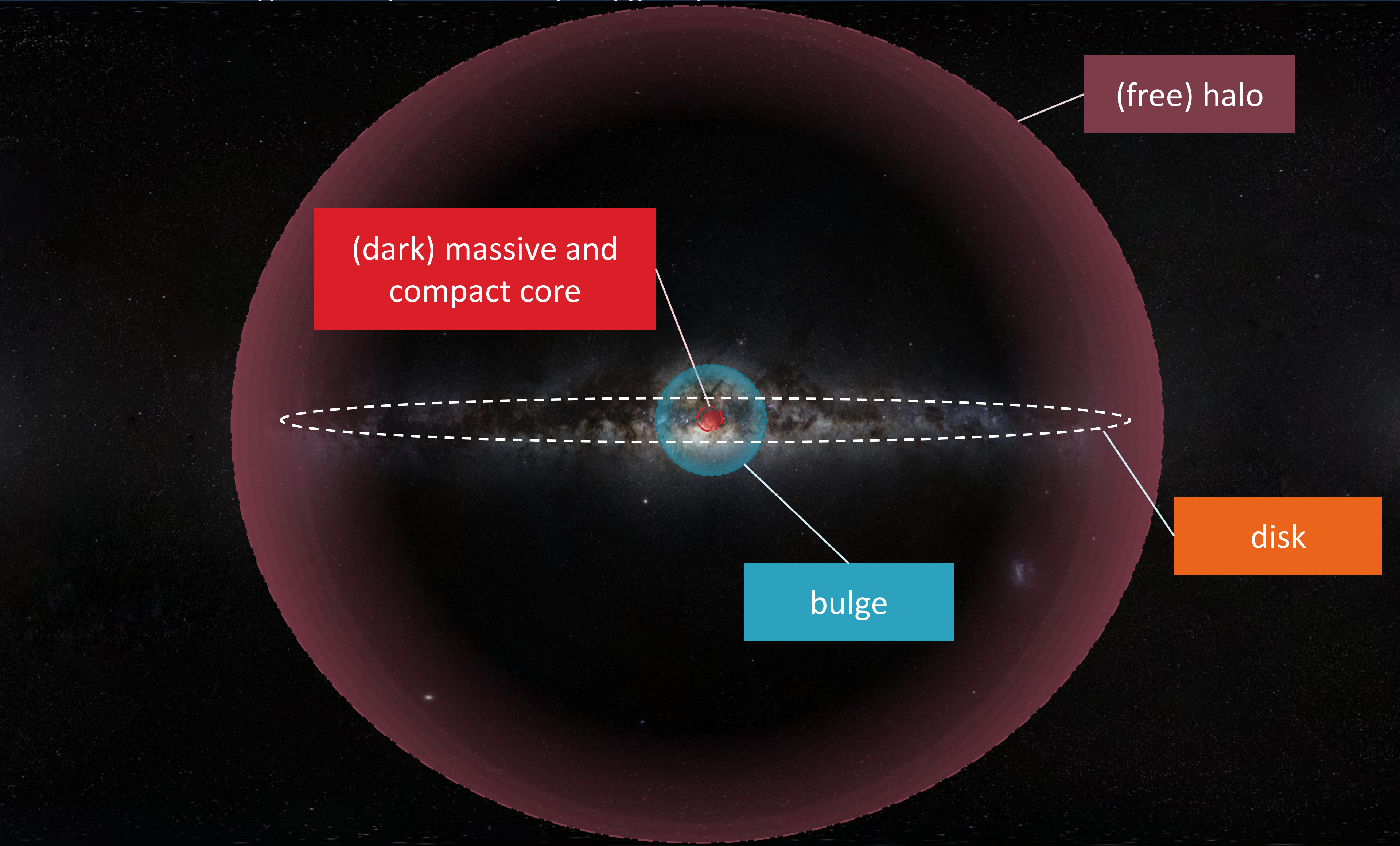




S. Gillessen et al. (Apj) (2015)

Milky Way illustration

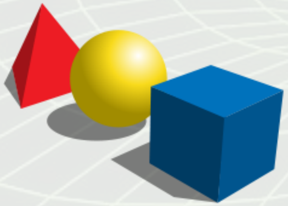
typical components of a (disk) galaxy



Basic Questions

How much of DM exists (in Universe)?
And **where** do we find it?

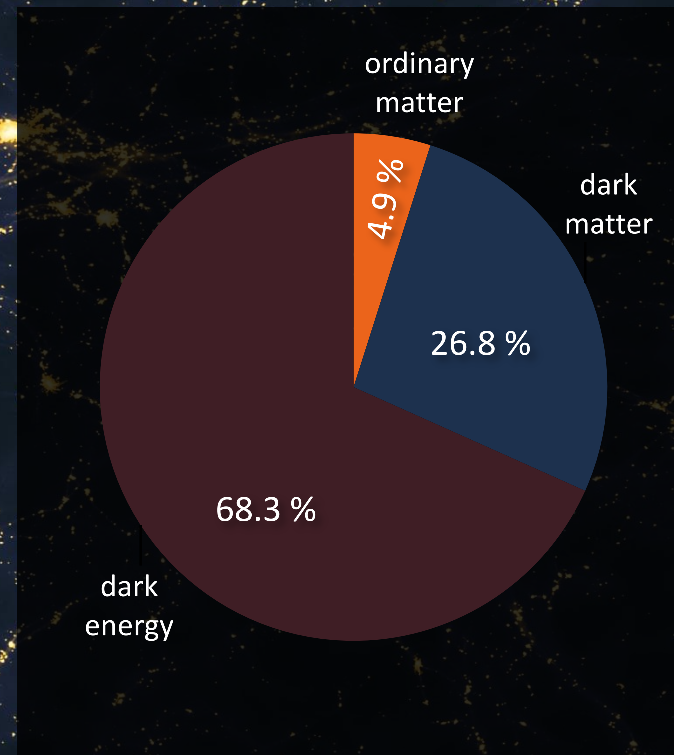
How does DM affect *structures*?



What is DM?

Lambda-CDM

- ΛCDM reproduces very well the Large Structure of Universe
- But few problems on smaller scales remain



> 10 Mpc

big ellipticals

spirals

dwarf galaxies

Dark Matter candidates

particle mass

GeV/c^2

MeV/c^2

keV/c^2

eV/c^2

meV/c^2

CDM

- WIMPs
  weakly interacting massive particles

!

WDM

- Sterile Neutrino
  most promising candidate

HDM

- Neutrinos
  ruled out in 80s

Fermionic DM with Cutoff

Self-gravitating system of massive fermions in spherical symmetry

collisionless relaxation
& escape of particles

phase space density

$$f(r,\epsilon) = \frac{1 - e^{[\epsilon - \varepsilon(r)]/\beta(r)}}{e^{[\epsilon - \alpha(r)]/\beta(r)} + 1}$$

with $1 \leq \epsilon \leq \varepsilon(r)$

energy $$\epsilon^2 = 1 + \frac{p^2}{mc^2}$$

temperature parameter

$$\beta(r) = \frac{k_B T(r)}{mc^2}$$

chemical potential (relativistic)

$$\alpha(r) = 1 + \beta(r)\theta(r)$$

escape energy (relativistic)

$$\varepsilon(r) = 1 + \beta(r) W(r)$$

degeneracy parameter $$\theta(r) = \frac{\mu(r)}{k_B T(r)}$$

cutoff parameter $$W(r) = \frac{E_c(r)}{k_B T(r)}$$

Ruffini R., Stella L., 1983, A&A, 119, 35
Merafina M., Ruffini R., 1989, A&A, 221, 4
Ruffini R., Argüelles C. R., Rueda J. A., 2015, MNRAS, 451, 622

Perfect fluid in equilibrium

$$g^{\mu\nu} = \mathrm{diag}(\mathrm{e}^{\nu(r)}, -\mathrm{e}^{\lambda(r)}, -r^2, -r^2 \sin^2\vartheta)$$

spherically symmetric

GR

metric potential
$$\frac{\partial \nu}{\partial r/R} = \frac{R^2}{r^2}\left[\frac{M(r)}{M} + \frac{r^3}{R^3}\frac{P(r)}{\rho c^2}\right]\left[1 - \frac{R}{r}\frac{M(r)}{M}\right]^{-1}$$

mass
$$\frac{\partial}{\partial r/R}\frac{M(r)}{M} = \frac{r^2}{R^2}\frac{\rho(r)}{\rho}$$

TOV approach

Statistics

mass density
$$\frac{\rho(r)}{\rho} = \frac{4}{\sqrt{\pi}}\int \epsilon^2\sqrt{\epsilon^2 - 1} f(r,\epsilon)\mathrm{d}\epsilon$$

pressure
$$\frac{P(r)}{\rho c^2} = \frac{4}{3\sqrt{\pi}}\int (\epsilon^2 - 1)^{3/2} f(r,\epsilon)\mathrm{d}\epsilon$$

EOS needed!

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EOS needed!

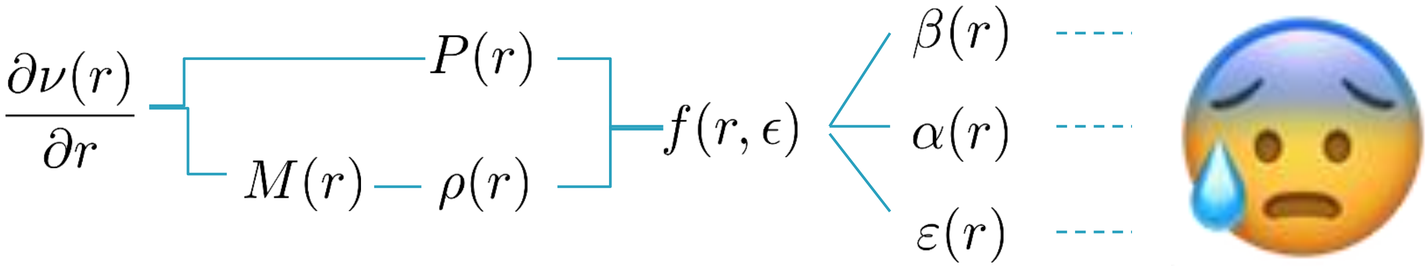
Thermodynamic equilibrium

$$\frac{\partial \nu(r)}{\partial r} \quad P(r),\; M(r) - \rho(r) \quad f(r,\epsilon) \quad \beta(r),\; \alpha(r),\; \varepsilon(r)$$

conservation of energy along a geodesic

Tolman & Ehrenfest (1930)	Klein (1949)	Merafina, Ruffini (1989)
$\beta(r)\mathrm{e}^{\nu(r)/2} = \mathrm{const}$	$\alpha(r)\mathrm{e}^{\nu(r)/2} = \mathrm{const}$	$\varepsilon(r)\mathrm{e}^{\nu(r)/2} = \mathrm{const}$

Thermodynamic equilibrium



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dim-less initial conditions

boundary condition

focus on the galactic center without BH!

$$\left.\frac{\partial M}{\partial r}\right|_{r=0} = 0 \rightarrow M_0 = 0$$

$$\left.\frac{\partial \nu}{\partial r}\right|_{r=0} = 0 \rightarrow \{\beta_0, \theta_0, W_0\}$$

unit system

eliminate constant particle mass from equations

$$\rho = \frac{g m^4}{h^3}[\pi c]^{3/2} \quad \sim m^4$$

$$R = \left[\frac{c^2}{8\pi G \rho}\right]^{1/2} \quad \sim m^{-2}$$

$$M = 4\pi R^3 \rho \quad \sim m^{-2}$$

$$\{m, \beta_0, \theta_0, W_0\}$$

4 parameters

Milky Way fit

constraints form core, halo and entire galaxy

- boundary condition: r_h, $M_h = M(r_h)$, $M_{tot} = M(r_b)$ and $M_c = M(r_c)$ where r_c is core radius (of degenerate core), r_h is halo radius and r_b is boundary radius

observation

core	halo	total
$M_c = 4.2 \times 10^6 M_\odot$	$M_h = 9 \times 10^{10} M_\odot$ $r_h = 20\text{kpc}$	$M_{tot} = 2.4 \times 10^{11} M_\odot$

R. Ruffini et al. (MNRAS, 2015), C. R. Argüelles et al. (MNRAS-submitted) 1606.07040 (2017)

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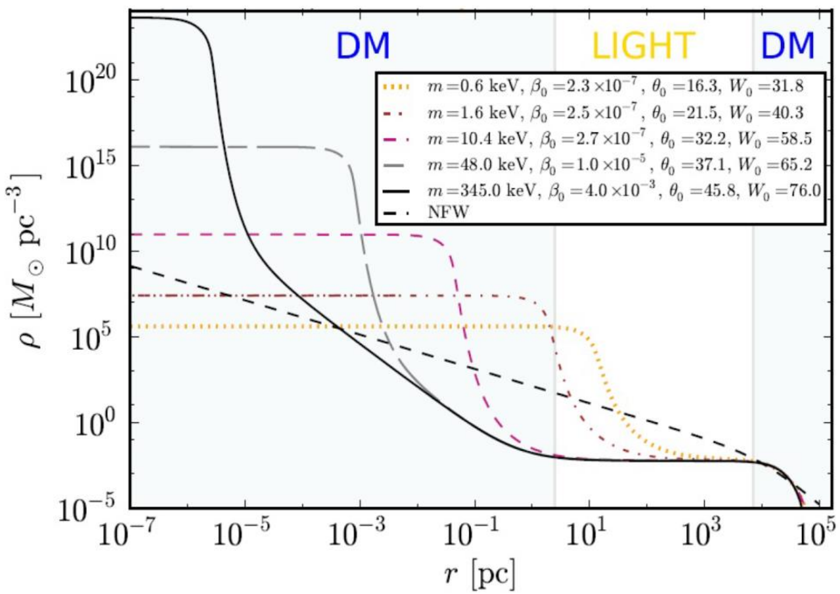

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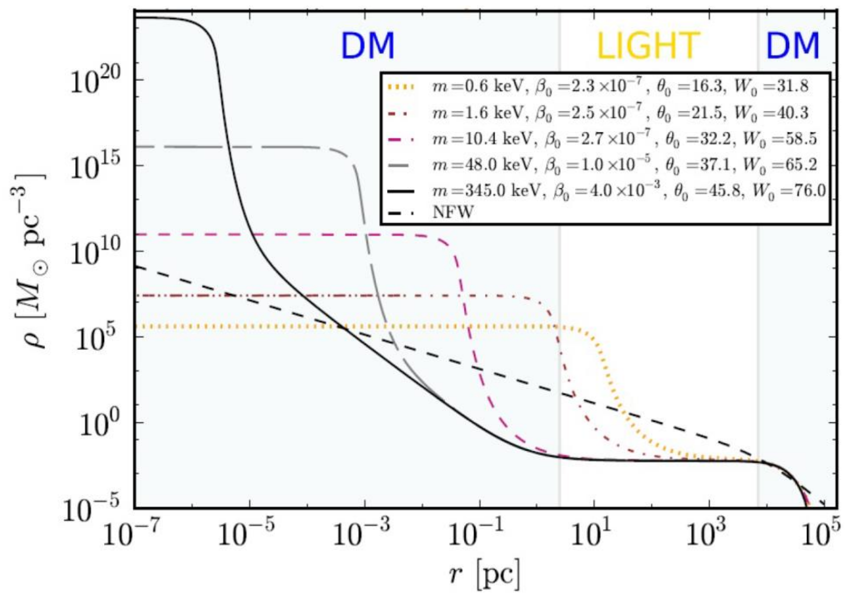

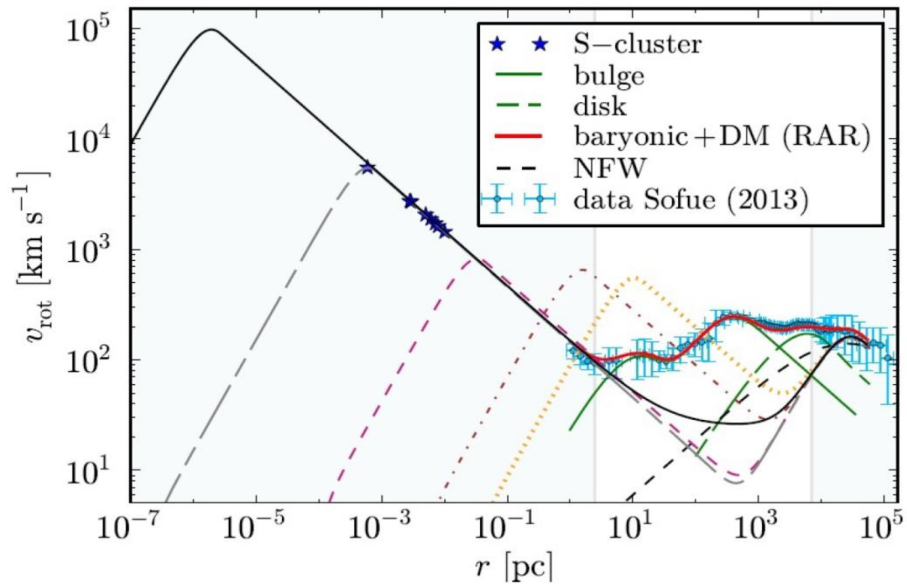

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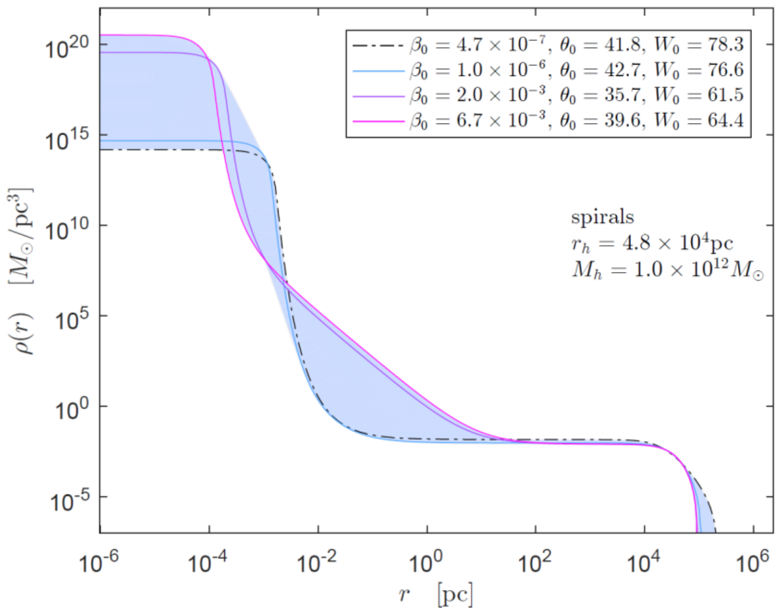
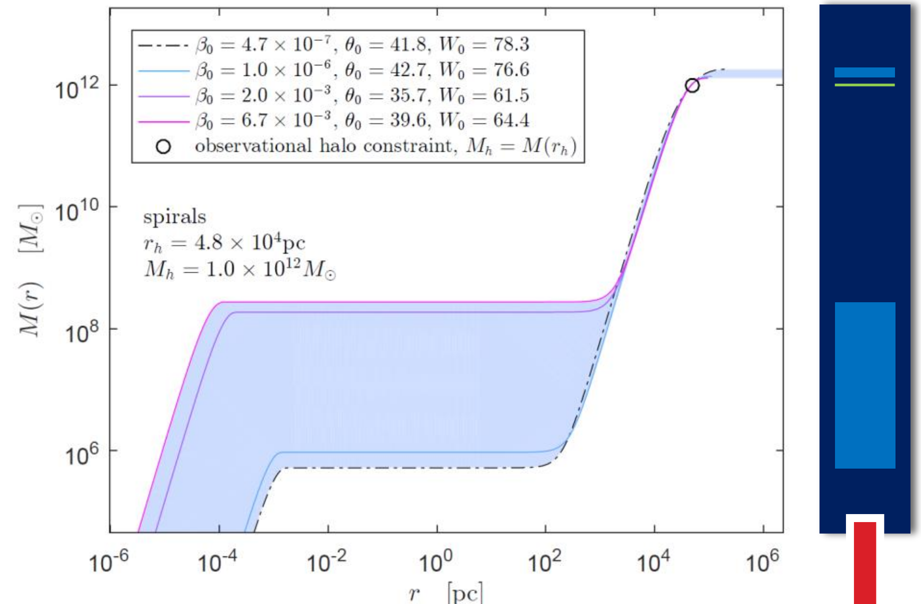
Typical Seyfert-like spirals

- The case of $m = 48$ keV fermionic dark matter
- Observationally-given boundary condition: $r_h = 48$ kpc and $M_h = 1 \times 10^{12} M_\odot$



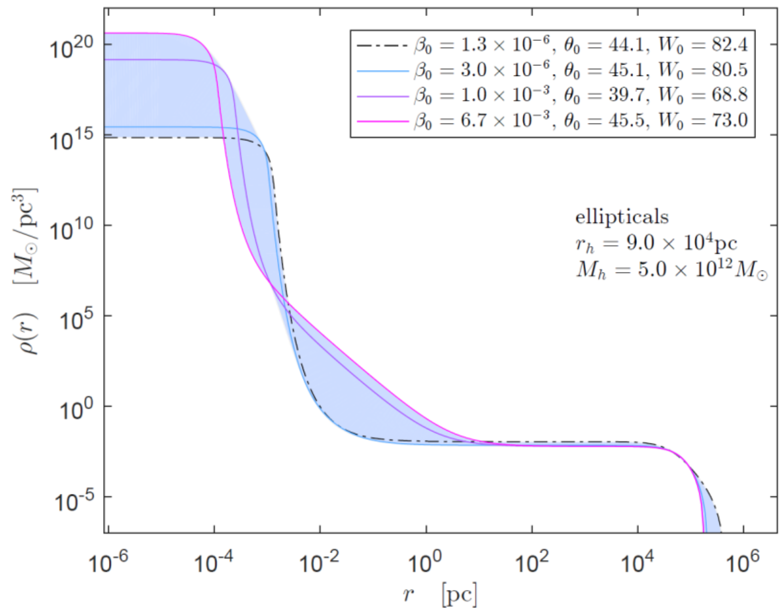


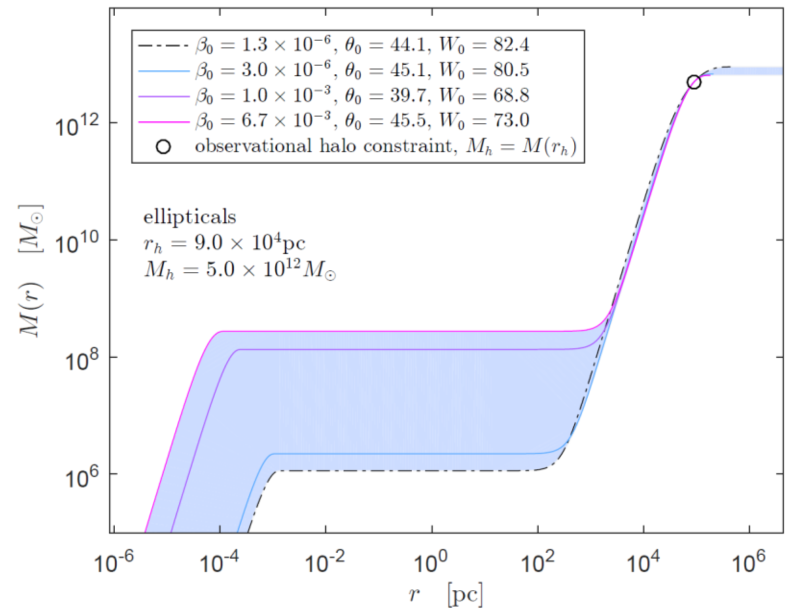
prediction

core	**total**
$M_c \in (4 \times 10^5, 2 \times 10^8) M_\odot$	$M_{tot} \in (1, 2) \times 10^{12} M_\odot$

Typical normal ellipticals

- The case of $m = 48$ keV fermionic dark matter
- Observationally-given boundary condition: $r_h = 90$ kpc and $M_h = 5 \times 10^{12} M_\odot$





prediction

core

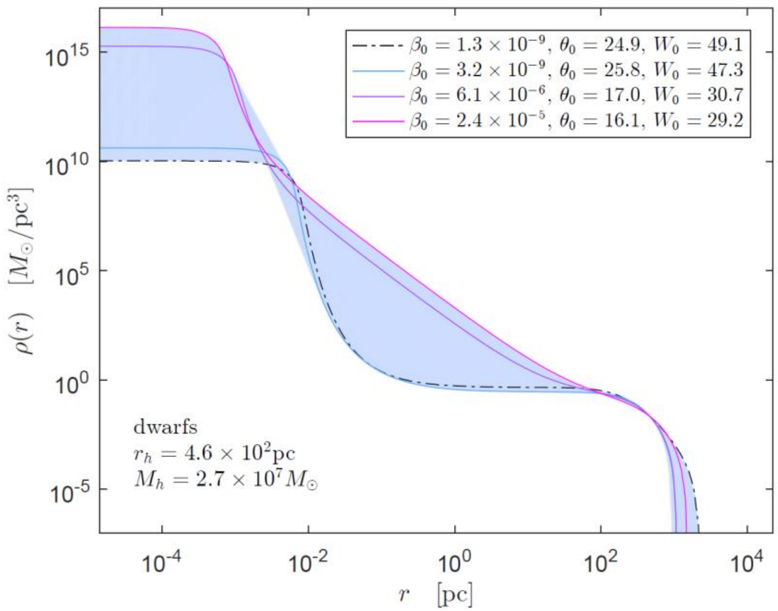
$M_c \in (1 \times 10^6, 2 \times 10^8) M_\odot$

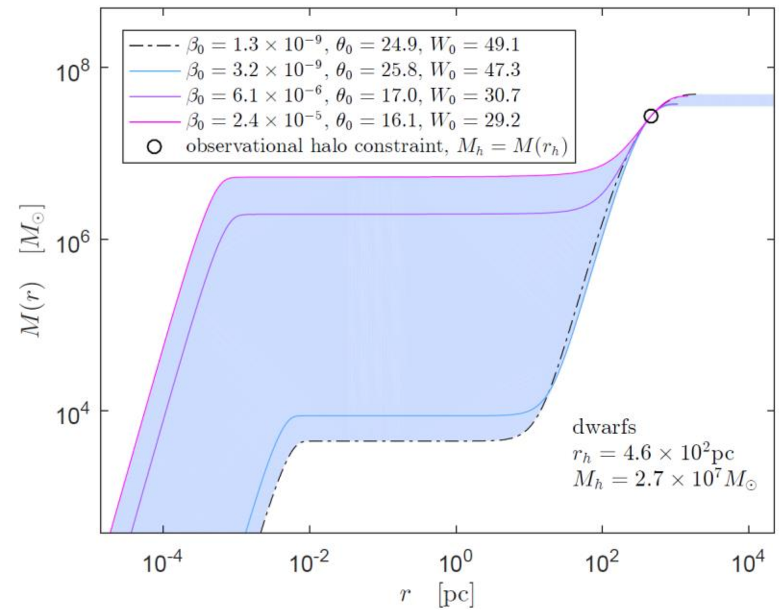
total

$M_{tot} \in (6, 9) \times 10^{12} M_\odot$

Typical dwarf spheroidals

- The case of $m = 48$ keV fermionic dark matter
- Observationally-given boundary condition: $r_h = 0.46$ kpc and $M_h = 2.7 \times 10^7 M_\odot$





prediction

core

$M_c \in (3 \times 10^3, 4 \times 10^6) M_\odot$

total

$M_{tot} \in (3, 5) \times 10^7 M_\odot$

Prediction confirmed!

The Astrophysical Journal, 839:72 (15pp), 2017 April 20 https://doi.org/10.3847/1538-4357/aa6972

CrossMark

Detection of Supermassive Black Holes in Two Virgo Ultracompact Dwarf Galaxies

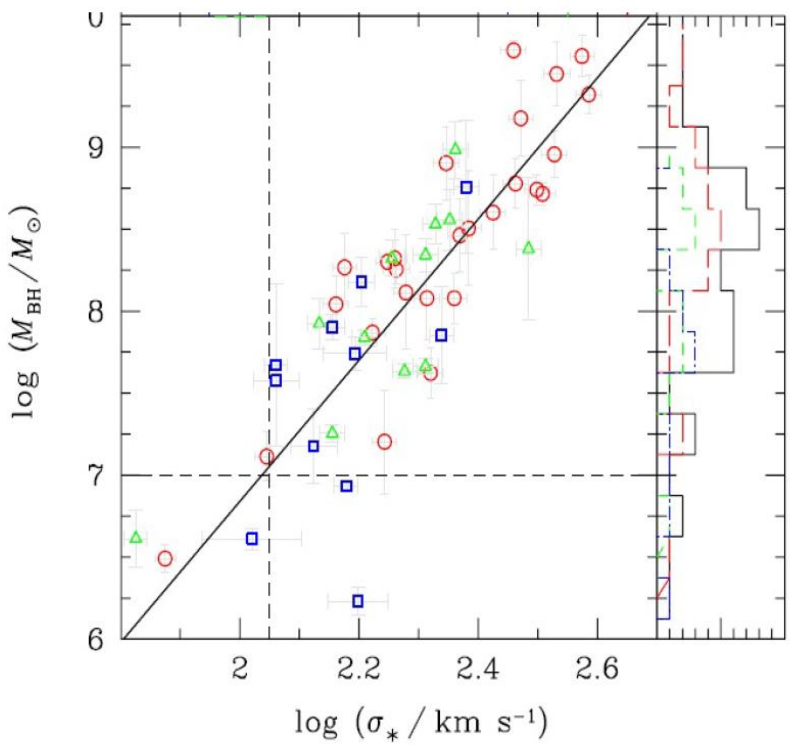
Christopher P. Ahn[1], Anil C. Seth[1], Mark den Brok[2], Jay Strader[3], Holger Baumgardt[4], Remco van den Bosch[5], Igor Chilingarian[6,7], Matthias Frank[8], Michael Hilker[9], Richard McDermid[10], Steffen Mieske[9], Aaron J. Romanowsky[11,12], Lee Spitler[10,13,14], Jean Brodie[12,15], Nadine Neumayer[5], and Jonelle L. Walsh[16]

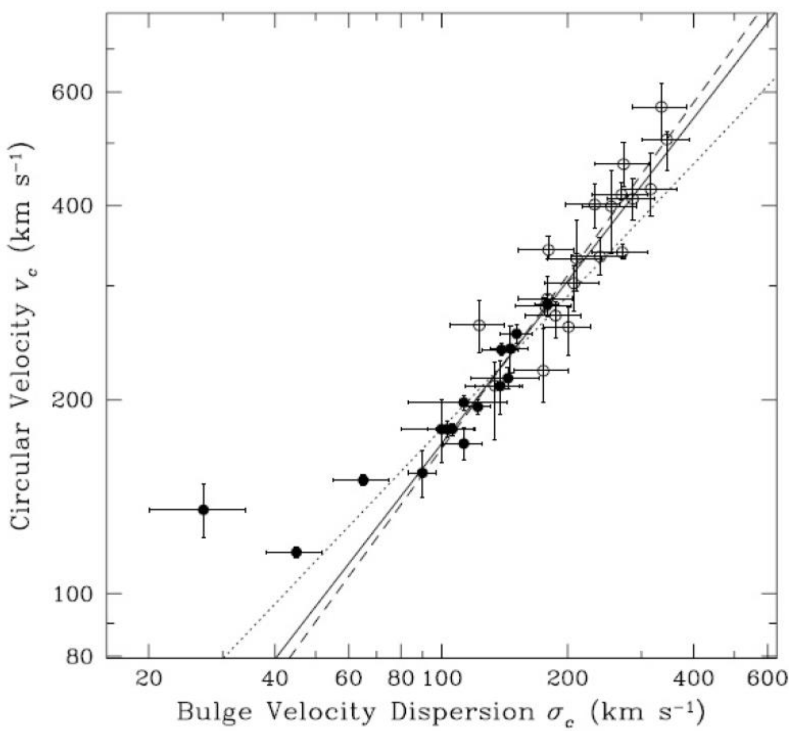
Abstract

We present the detection of supermassive black holes (BHs) in two Virgo ultracompact dwarf galaxies (UCDs), VUCD3 and M59cO. We use adaptive optics assisted data from the Gemini/NIFS instrument to derive radial velocity dispersion profiles for both objects. Mass models for the two UCDs are created using multi-band *Hubble Space Telescope* imaging, including the modeling of mild color gradients seen in both objects. We then find a best-fit stellar mass-to-light ratio (M/L) and BH mass by combining the kinematic data and the deprojected stellar mass profile using Jeans Anisotropic Models. Assuming axisymmetric isotropic Jeans models, we detect BHs in both objects with masses of $4.4^{+2.5}_{-3.0} \times 10^6\ M_\odot$ in VUCD3 and $5.8^{+2.5}_{-2.8} \times 10^6\ M_\odot$ in M59cO (3σ uncertainties). The BH mass is degenerate with the anisotropy parameter, β_z; for the data to be consistent with no BH requires $\beta_z = 0.4$ and $\beta_z = 0.6$ for VUCD3 and M59cO, respectively. Comparing these values with nuclear star clusters shows that, while it is possible that these UCDs are highly radially anisotropic, it seems unlikely. These detections constitute the second and third UCDs known to host supermassive BHs. They both have a high fraction of their total mass in their BH; ~13% for VUCD3 and ~18% for M59cO. They also have low best-fit stellar M/Ls, supporting the proposed scenario that most massive UCDs host high-mass fraction BHs. The properties of the BHs and UCDs are consistent with both objects being the tidally stripped remnants of ~$10^9\ M_\odot$ galaxies.

Galaxy universal correlations

- $\log(M_{\rm BH}/M_\odot) \approx 8.12 + 4.24\log(\sigma_*/[200{\rm km/s}])$
  K. Gültekin et al. (Apj) 2009
- $\log(v_{\rm circ}) \approx 0.84\log(\sigma_*) + 0.55$
  L. Ferrarese (Apj) 2002; Kormendy et al. (Nature) 2011

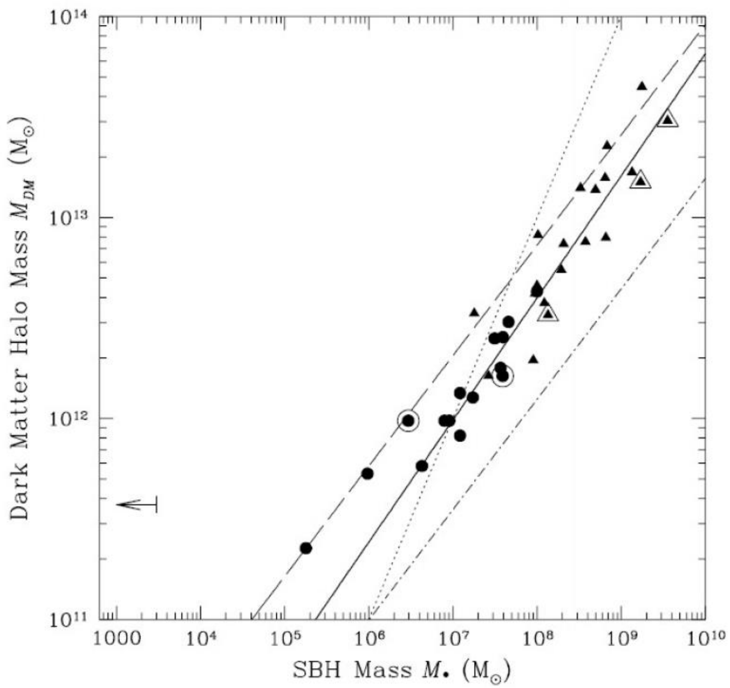




The core-halo correlation

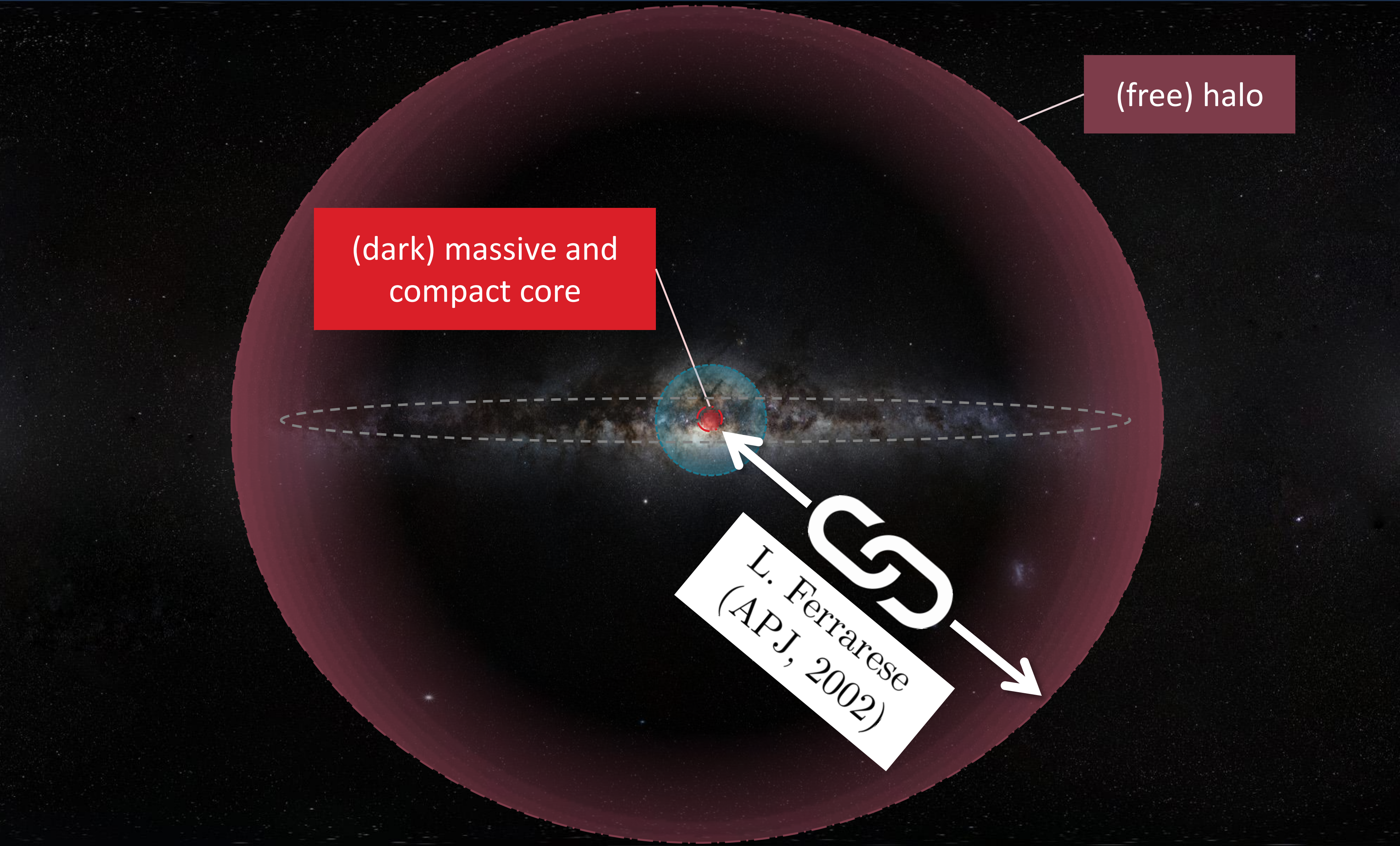
and RAR predictions

- By transitivity between the $M_{\rm BH}$-σ_* and σ_*-$v_{\rm circ}$ correlations by Ferrarese '02, she found in 2002 the $M_{\rm BH}$-$M_{\rm DM}$ correlation L. Ferrarese (APJ, 2002)



Core-halo connection

a fundamental relation



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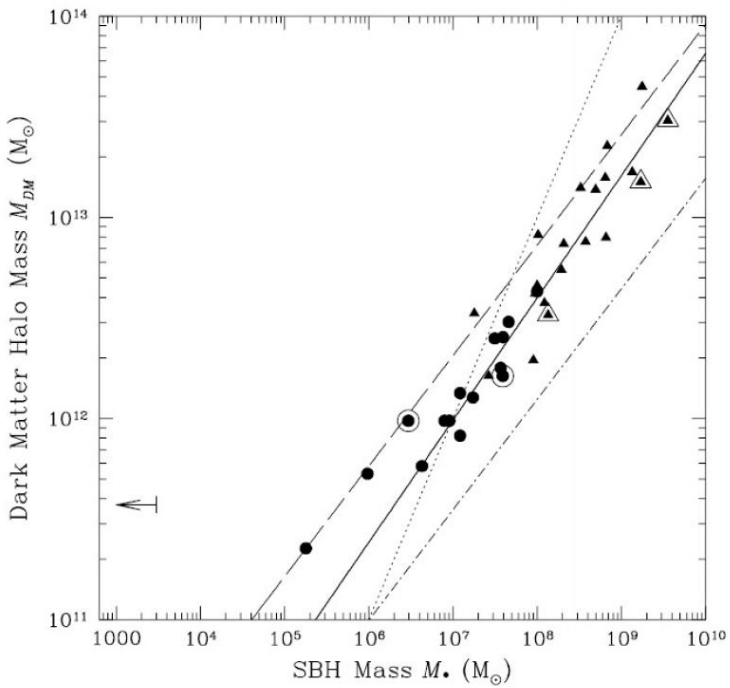
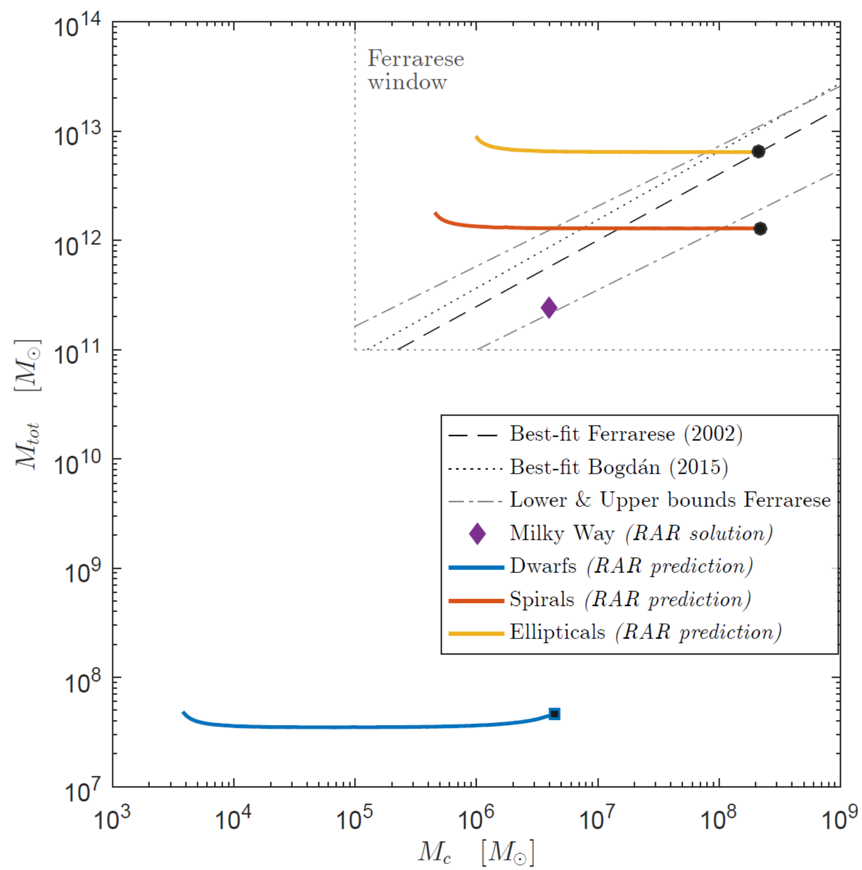




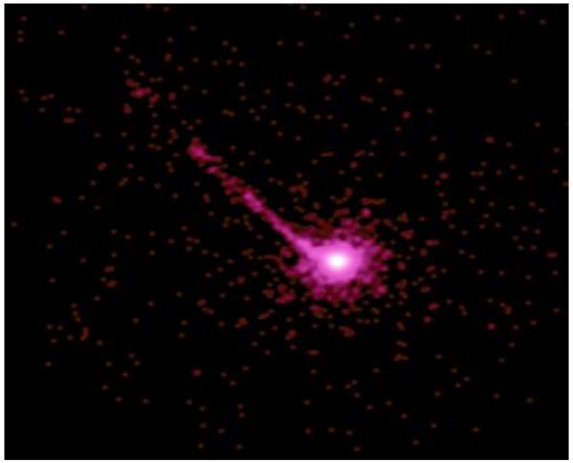
Normal and active galaxies

normal galaxies

no active nuclei nor jets ($M_c \sim 10^{6-7} M_\odot$)

active galaxies

yes, active nuclei and jets ($M_c \sim 10^{9-10} M_\odot$)



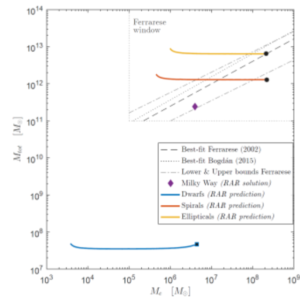
Summary

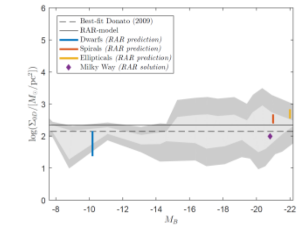
- A continuous distribution of $\sim 10^1 - 10^2$keV fermions can be an alternative to the black hole scenario in SgrA* and being at the same time in agreement with the Milky Way DM halo without spoiling the baryonic (bulge and disk) components

- The RAR model is able to fulfill the observed properties of galaxies, such as the $M_{\rm BH}$-$M_{\rm DM}$ relation and the $\Sigma_{0D} \approx$ constant universal law, for a unique DM fermionic mass

- For $m \sim 50$keV/c^2 with massive fermionic quantum cores reaching a M_c^{cr} mass, it exists the interesting possibility that the less massive (not-yet collapsed) cores of $M_c \sim 10^{6-8} M_\odot$ explain the less-active galaxies; while the more massive cores of M_c^{cr} plus subsequent more violent baryonic accretion would explain the most massive SMBHs with associated jets
$\rightarrow$ **the latter requieres more work to be done**

- High precision strong lensing meassurements, as the expected EHT observations, may unveil the nature of SgrA* in the Galactic center and distinguish between a BH and a dense DM core
$\rightarrow$ **first results expected in early 2018...**





EventHorizonTelescope

Thank you