Dark Matter fermions: from linear to non-linear structure formation

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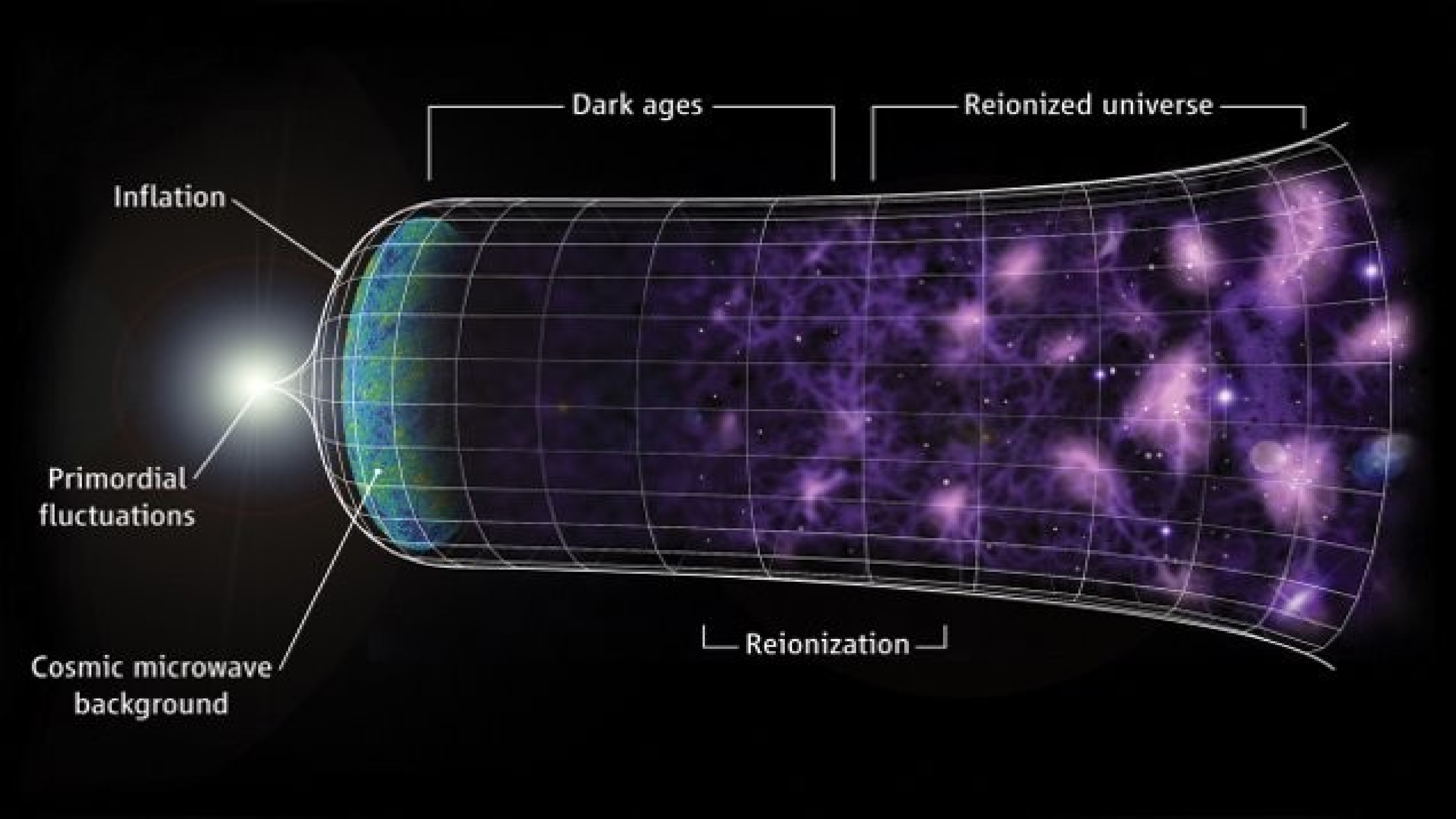
In collaboration with: R. Ruffini, J. A. Rueda, A. Krut, E. A. Becerra-Vergara, R. Yunis

Based on: Argüelles et al., PDU (2018, 2019); **arXiv:1606.07040; arXiv:1810.00405**
Becerra-Vergara, Argüelles, et al., A&A (2020); **arXiv:2007.11478**
Yunis, Argüelles, et al. JCAP (2020); **arXiv:2002.05778**
Argüelles et al. MNRAS (2021); **arXiv:2012.11709**



Dark ages
Reionized universe
Inflation
Primordial fluctuations
Cosmic microwave background
Reionization

Success of the LCDM paradigm on large scales

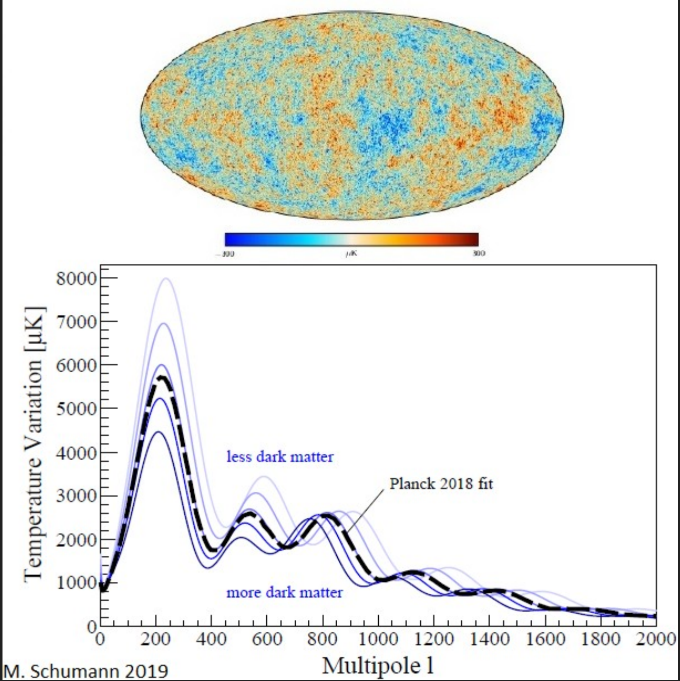
Success of CDM:
Cold, colissionless fluid!

⇩

Astrophysical observations (CMB, BAO, Ly-α forest, local distribution and evolution of galaxies, etc) ranging from horizon scale (∼ 15000 Mpc) to the typical scale between galaxies (1 Mpc) are all consistent with a Universe that was seeded by a scale invariant primordial spectrum, and that is dominated by dark energy ∼ 70% followed by ∼ 25% of Cold Dark Matter (CDM) and only ∼ 5% of baryons plus radiation [Planck Collaboration et al., 2016]; [Vogelsberger et al., 2014]; [Kitaura, Angulo, et al., 2012]

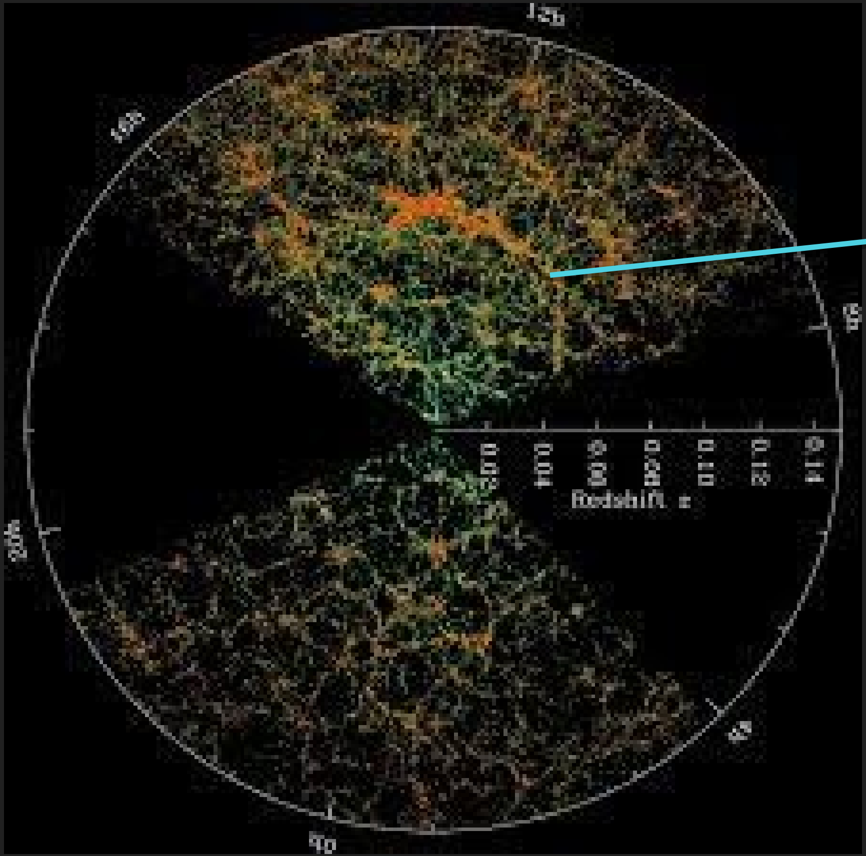
Lambda-CDM Cosmology

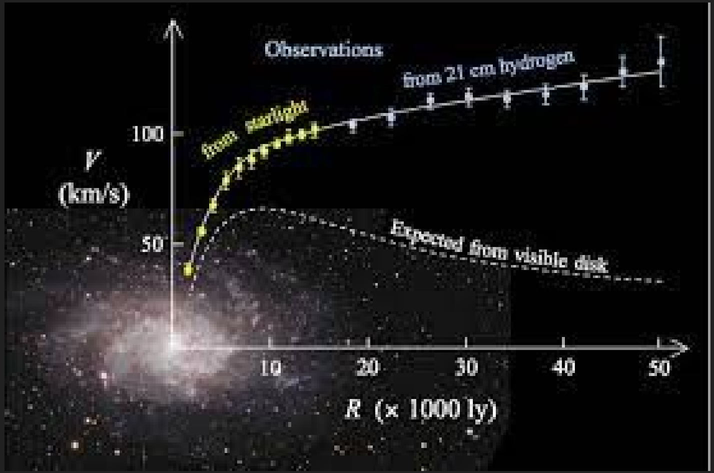
Cosmological perturbation theory
Describes how primordial density perturbations grow into galactic structures due to gravity



Compelling evidence for non baryonic matter in the CMB: Need for Dark Matter

From large scale structure to DM halo-size structures





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

$f = f(\mathbf{x}, \mathbf{v}, t)$ mass density of particles in phase-space (x,v)

$$\frac{\mathrm{d}f}{\mathrm{d}t} \equiv \frac{\partial f}{\partial t} + \boldsymbol{v}\frac{\partial f}{\partial \boldsymbol{r}} + \boldsymbol{F}\frac{\partial f}{\partial \boldsymbol{v}} = 0,$$

$$\Delta\Phi = 4\pi G n. \qquad n(\boldsymbol{r}, t) = \int f(\boldsymbol{r}, \boldsymbol{v}, t)\, \mathrm{d}^3\boldsymbol{v}$$

$$\boldsymbol{F} = -\nabla\Phi$$

1) $f = \bar{f} + \tilde{f}$

2) Take local average of V-P

$$\longrightarrow \quad \frac{\partial \bar{f}}{\partial t} + \boldsymbol{v}\frac{\partial \bar{f}}{\partial \boldsymbol{r}} + \bar{\boldsymbol{F}}\frac{\partial \bar{f}}{\partial \boldsymbol{v}} = -\frac{\partial \boldsymbol{J}}{\partial \boldsymbol{v}} \quad (1)$$

$$\boldsymbol{J} = \overline{\tilde{f}\tilde{\boldsymbol{F}}}$$

Diffusion current

$\bar{f}$: coarse-grained; $\tilde{f}$: fine-grained fluctuations

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

$$\dot{E} = \int \boldsymbol{J}\cdot\boldsymbol{v}\, \mathrm{d}^3\boldsymbol{r}\, \mathrm{d}^3\boldsymbol{v} = 0. \qquad \dot{S} = -\int \frac{1}{\bar{f}(\eta_0 - \bar{f})}\frac{\partial \bar{f}}{\partial \boldsymbol{v}}\boldsymbol{J}\, \mathrm{d}^3\boldsymbol{r}\, \mathrm{d}^3\boldsymbol{v} \geq 0.$$

Maximum Entropy production Pple. Chavanis, MNRAS (1998)

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 (Chavanis, MNRAS 1998), **equation (1) is written as a modified Landau-equation, allowing to obtain J** ⟹ $t_{ncoll} << t_{coll}$

$$\frac{d\bar{f}}{d\epsilon} + \beta\eta_0\bar{f} - \beta\bar{f}^2 + J = 0 \xrightarrow{J=cte} \bar{f} = \eta_0 \frac{1 - e^{\beta(\epsilon-\epsilon_m)}}{1 + e^{\beta\epsilon+\alpha}}$$

stationary solution of Fermi-Dirac type including for evaporation: **generalization of Lynden-Bell DF**

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

- For fermions, the maximum accesible value of the DF is fixed by the Pauli principle ⟹ $\eta_0 = gm^4/h^3$

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)

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

$$\frac{d\nu}{d\hat{r}} = \frac{2(\hat{M} + 4\pi\hat{P}\hat{r}^3)}{\hat{r}^2(1 - 2\hat{M}/\hat{r})}$$ → T.O.V

$$\frac{d\theta}{d\hat{r}} = -\frac{1 - \beta_0(\theta - \theta_0)}{\beta_0}\frac{1}{2}\frac{d\nu}{d\hat{r}}$$ → KLEIN

$$\beta(\hat{r}) = \beta_0 e^{\frac{\nu_0 - \nu(\hat{r})}{2}}$$ → TOLMAN

$$W(\hat{r}) = W_0 + \theta(\hat{r}) - \theta_0$$ → E conserv.

$$M(0) = 0; \quad \nu_0 = 0; \quad \theta(0) = \theta_0 > 0; \quad \beta(0) = \beta_0; \quad W(0) = W_0$$

$$\rho(r) = m\frac{2}{h^3}\int f(r,p)\left[1 + \frac{\epsilon(p)}{mc^2}\right] d^3p,$$

$$P(r) = \frac{1}{3}\frac{2}{h^3}\int f(r,p)\left[1 + \frac{\epsilon(p)}{mc^2}\right]^{-1}\left[1 + \frac{\epsilon(p)}{2mc^2}\right]\epsilon\, d^3p$$

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

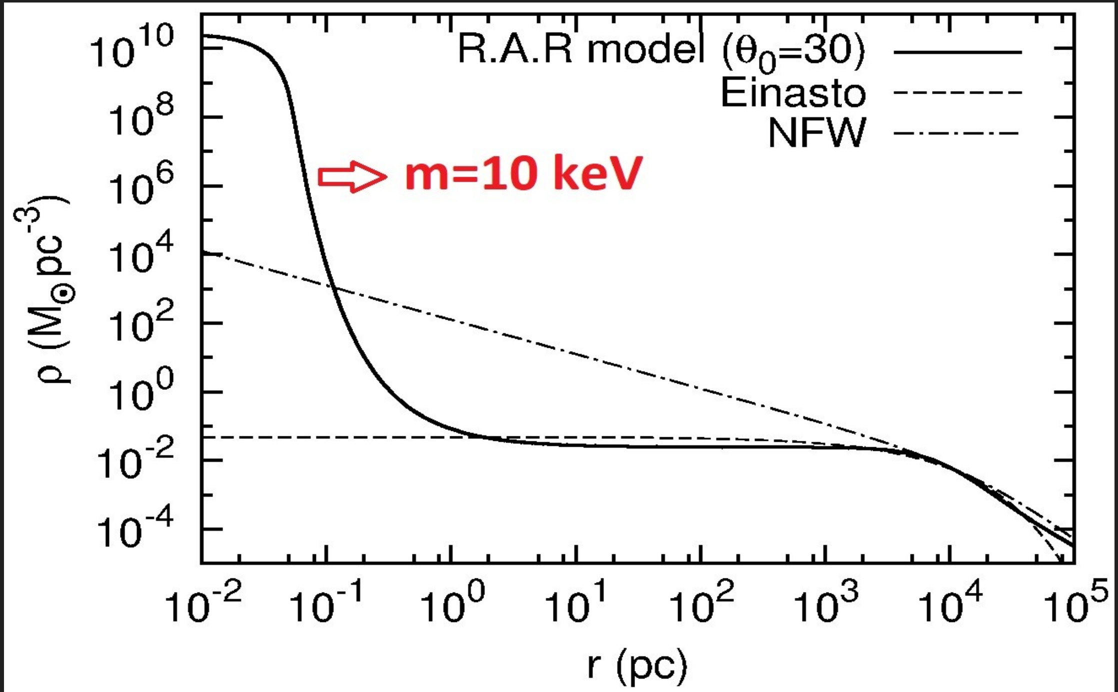
$$\epsilon(p) = \sqrt{c^2p^2 + m^2c^4} - mc^2$$

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

m, $\beta = kT/mc^2$, $\theta = \mu/kT$ and $W = \epsilon_c/kT$

A novel "core – halo" Dark Matter profile for fermions

- The highly non-linear systemd of coupled ODE is solved fulfilling a boundary condition problem in agreement with halo observables Ruffini, Argüelles, Rueda, MNRAS (2015)



Example: Typical spiral halo

Rh ~ 10^4 pc
Mh ~ 10^{11} Mo
:

The dense central core fulfills the 'quantum condition' :

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

DM profiles depend on the particle mass (see next slides)

Stability and lifetime of self-gravitating systems in cosmology

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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On the formation and stability of fermionic dark matter haloes in a cosmological framework

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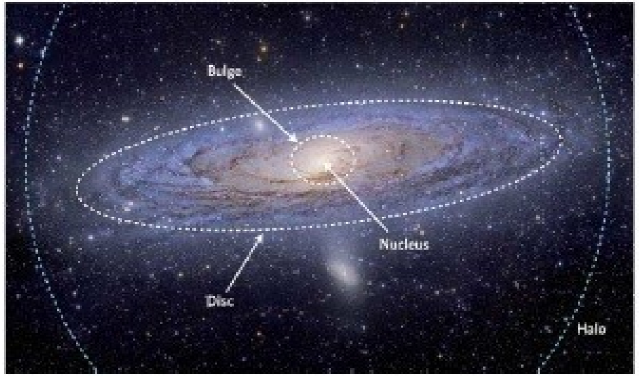
ABSTRACT

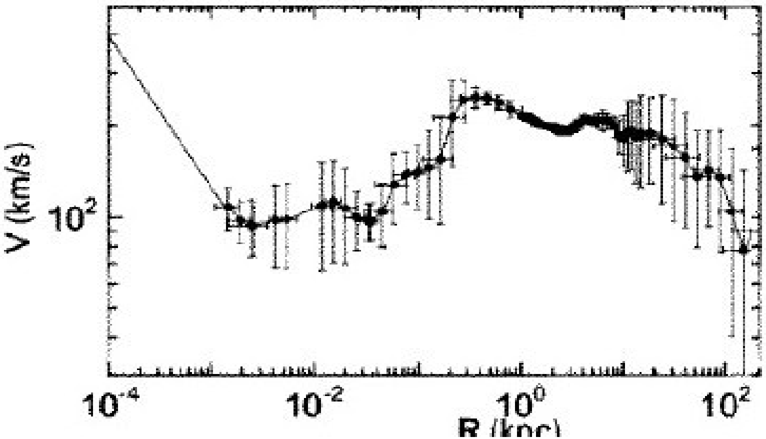
The formation and stability of collisionless self-gravitating systems are long-standing problems, which date back to the work of D. Lynden-Bell on violent relaxation and extends to the issue of virialization of dark matter (DM) haloes. An important prediction of such a relaxation process is that spherical equilibrium states can be described by a Fermi–Dirac phase-space distribution, when the extremization of a coarse-grained entropy is reached. In the case of DM fermions, the most general solution develops a degenerate compact core surrounded by a diluted halo. As shown recently, the latter is able to explain the galaxy rotation curves, while the DM core can mimic the central black hole. A yet open problem is whether these kinds of astrophysical core–halo configurations can form at all, and whether they remain stable within cosmological time-scales. We assess these issues by performing a thermodynamic stability analysis in the microcanonical ensemble for solutions with a given particle number at halo virialization in a cosmological framework. For the first time, we demonstrate that the above core–halo DM profiles are stable (i.e. maxima of entropy) and extremely long-lived. We find the existence of a critical point at the onset of instability of the core–halo solutions, where the fermion-core collapses towards a supermassive black hole. For particle masses in the keV range, the core-collapse can only occur for $M_{\rm vir} \gtrsim 10^9\ {\rm M}_\odot$ starting at $z_{\rm vir} \approx 10$ in the given cosmological framework. Our results prove that DM haloes with a core–halo morphology are a very plausible outcome within non-linear stages of structure formation.

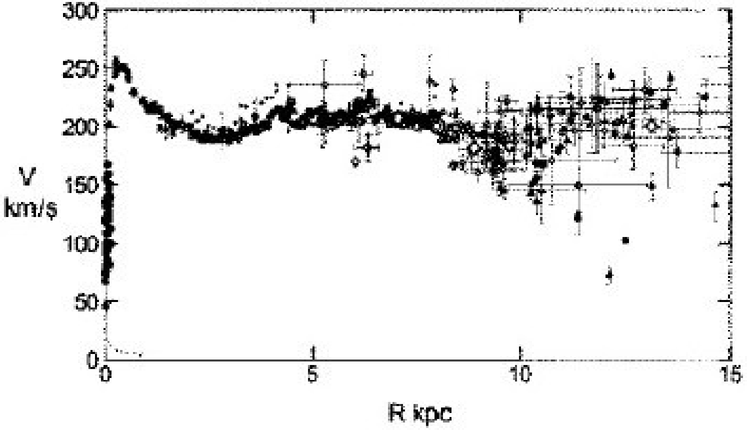
The case of the Milky Way and the Galaxy center

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 $M_h(r = 25kpc) \approx 10^{11} M_\odot$



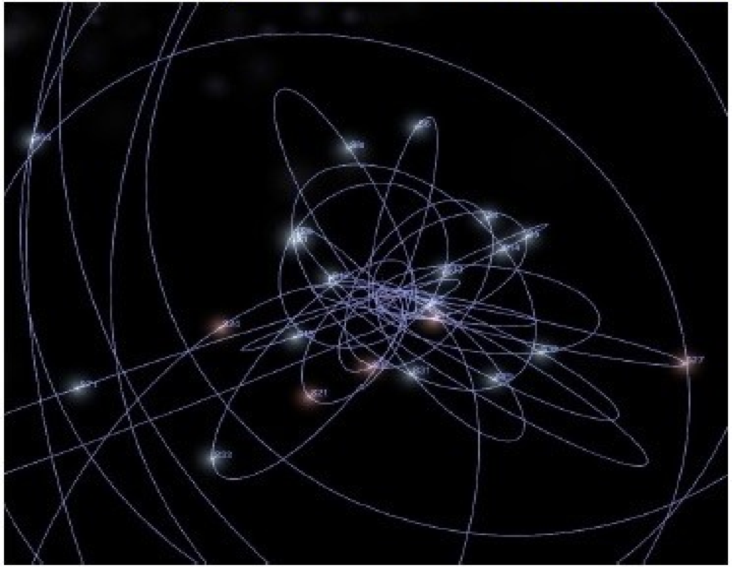


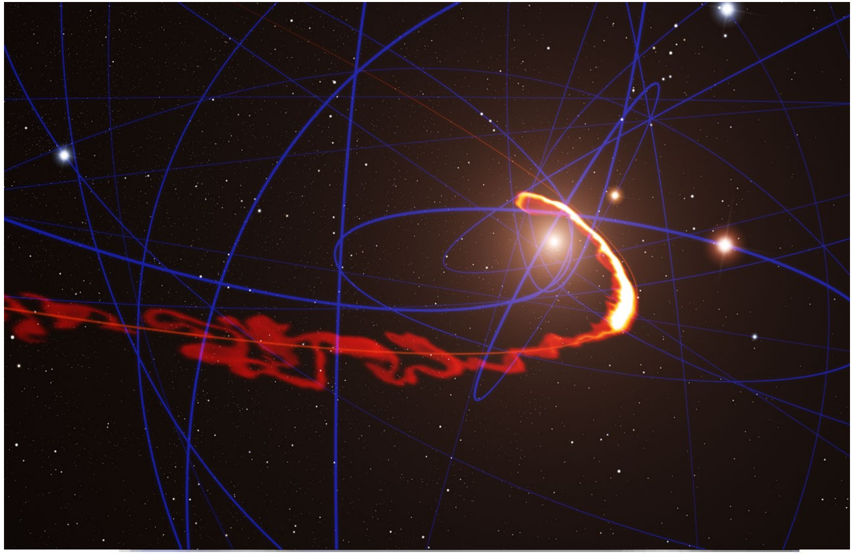


Y. Sofue, (PASJ) (2013)

Milky Way observables. Inside the central **pc:** the S-star cluster

- 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:

$M_c = 4.2 \times 10^6$ Mo Gillessen et al., Apj (2017)

$M(r = 20\ \text{kpc}) = 9 \times 10^{10}$ Mo Sofue, PASJ (2013)

$M(r = 40\ \text{kpc}) = 2 \times 10^{11}$ Mo Gibbons, Belokurov and Evans, MNRAS (2014)

Novel constraints on fermionic dark matter from galactic observables I: The Milky Way

Physics of the Dark Universe 21 (2018) 82–89

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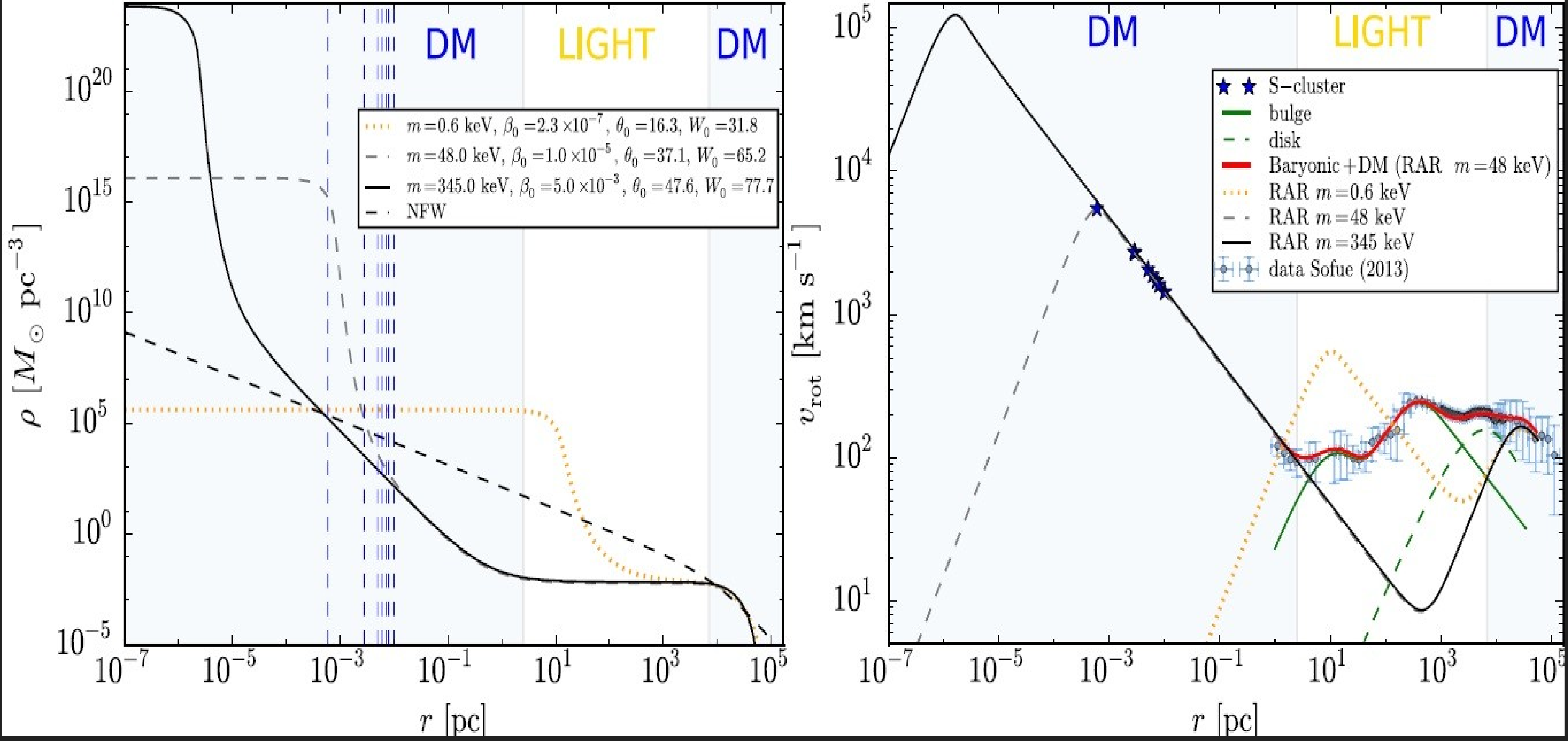
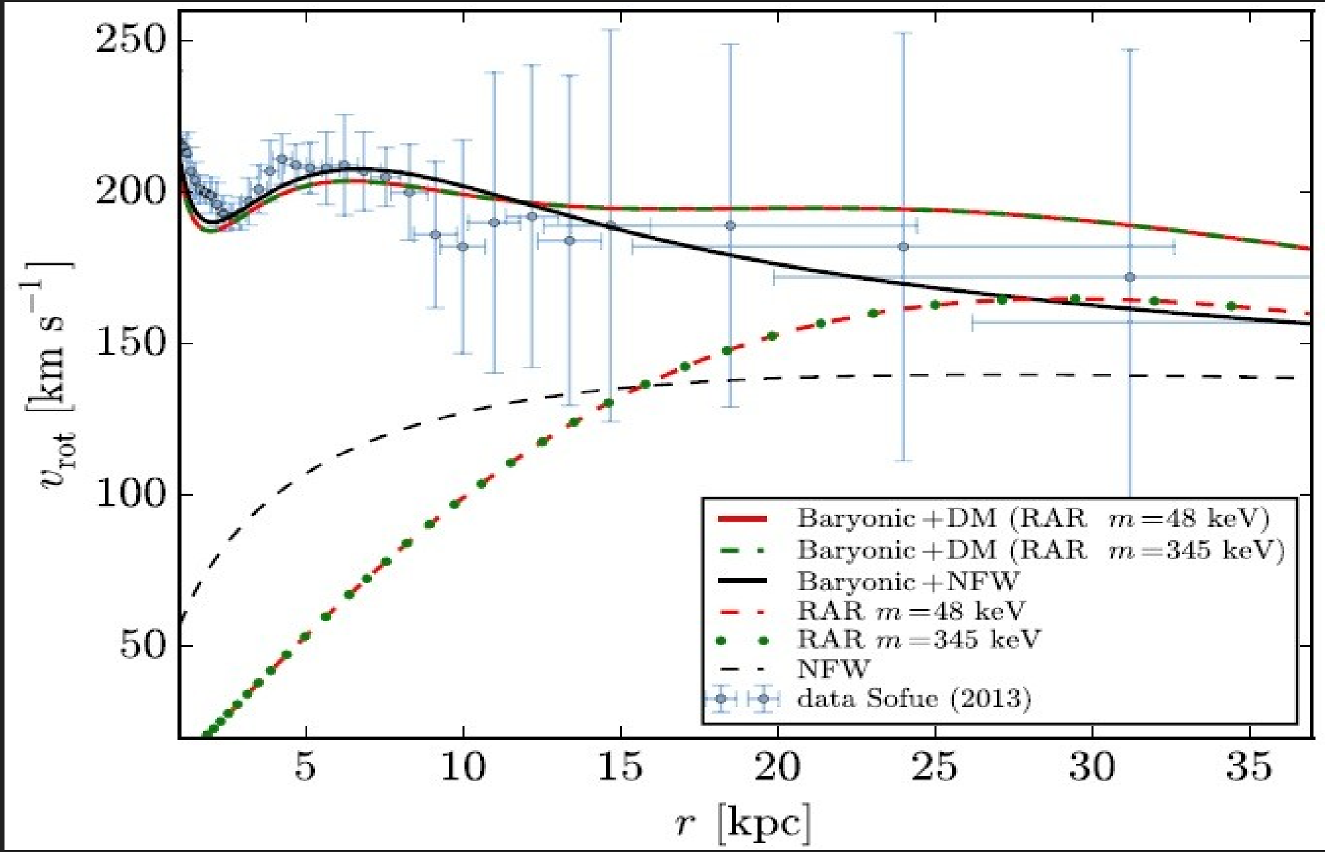


The fermionic halo: excellent fit to the Milky Way rotation curve



Argüelles, Krut, Rueda, Ruffini, PDU (2018)

The DM core: an alternative to the BH paradigm at the SgrA* Galaxy center

A&A 641, A34 (2020)
https://doi.org/10.1051/0004-6361/201935990

Astronomy & Astrophysics

Geodesic motion of S2 and G2 as a test of the fermionic dark matter nature of our Galactic core

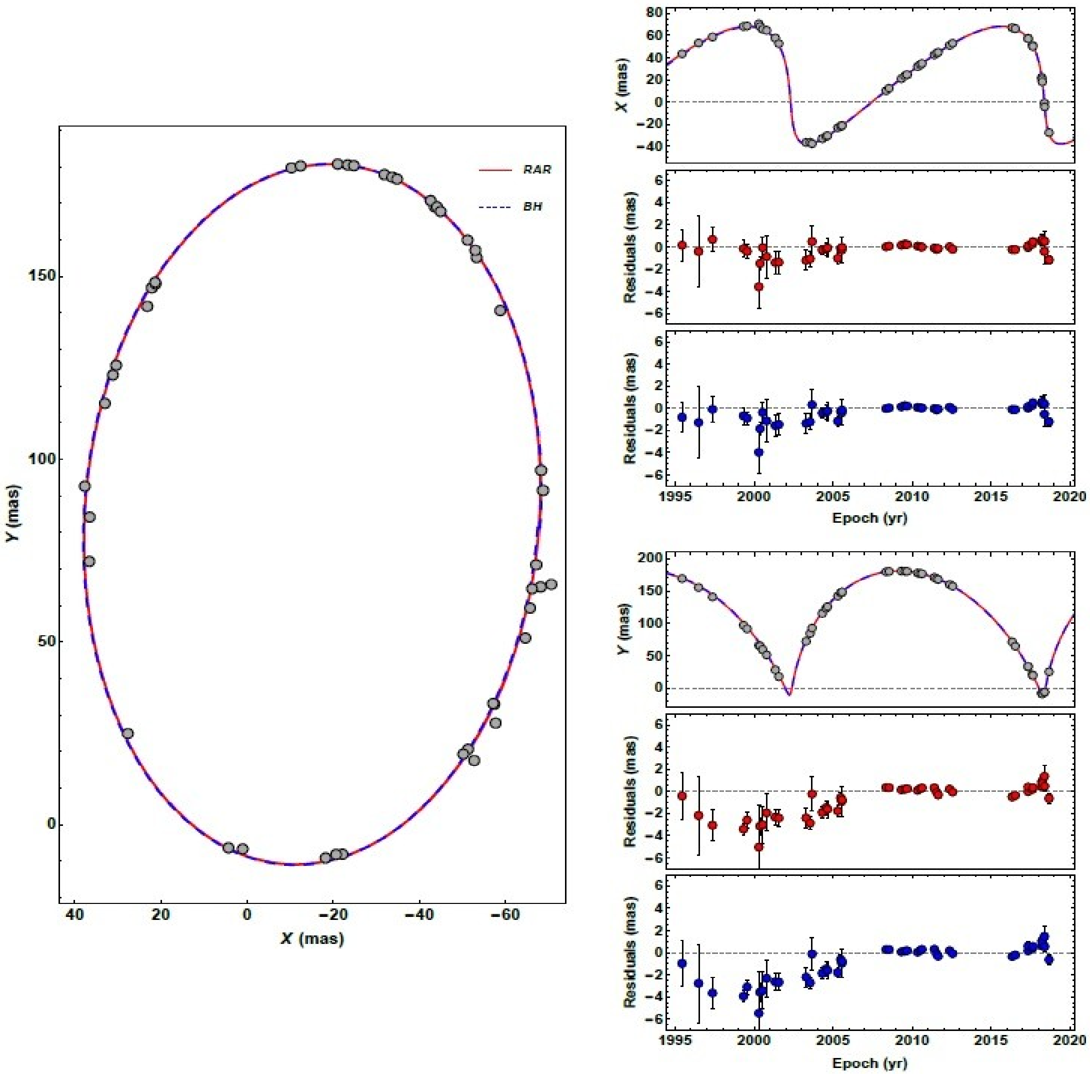
E. A. Becerra-Vergara[1,2,3], C. R. Argüelles[1,2,4], A. Krut[1,2], J. A. Rueda[1,2,5,6,7], and R. Ruffini[1,2,5,6,8]

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

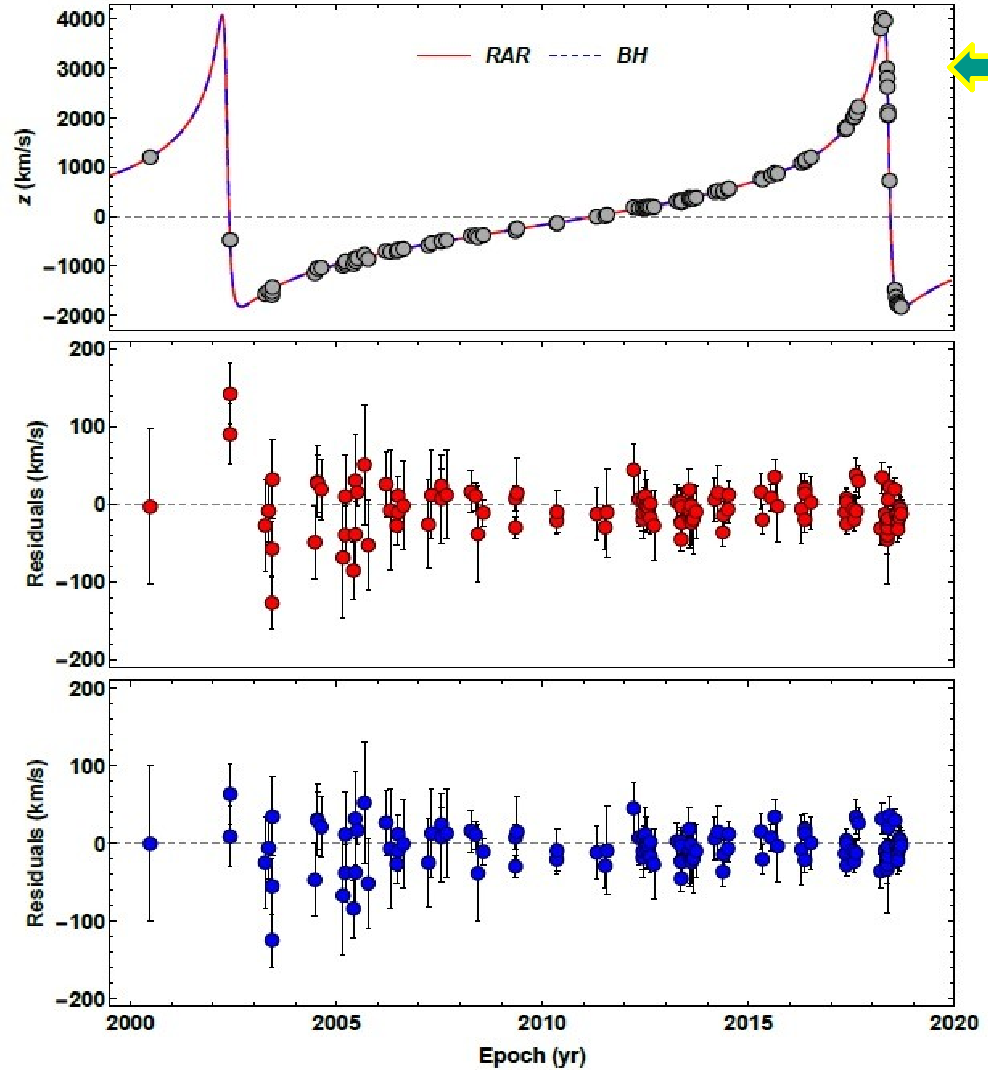
THEORETICAL MODELS: calculated by solving the e.o.m of a test particle in the gravitational field of:

1) Schwarzschild BH of 4.07 x 10^6 Mo

$$\langle \bar{\chi}^2 \rangle_{BH} = 3.3586$$

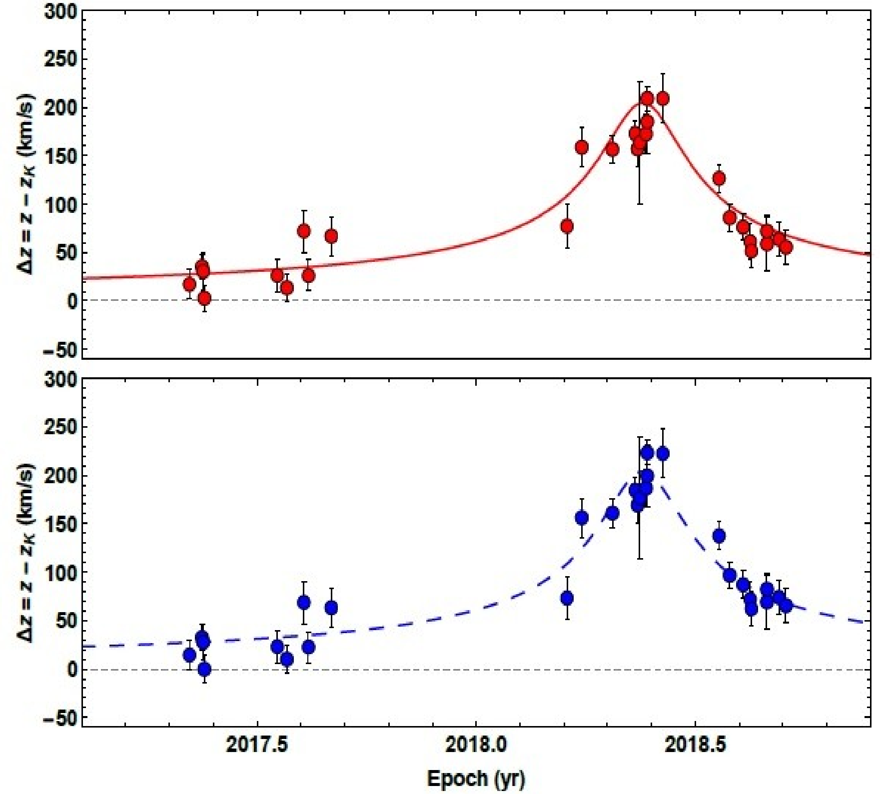
2) Fermionic DM distribution with Mc = 3.5 x 10^6 Mo (fermion mass m= 56 keV)

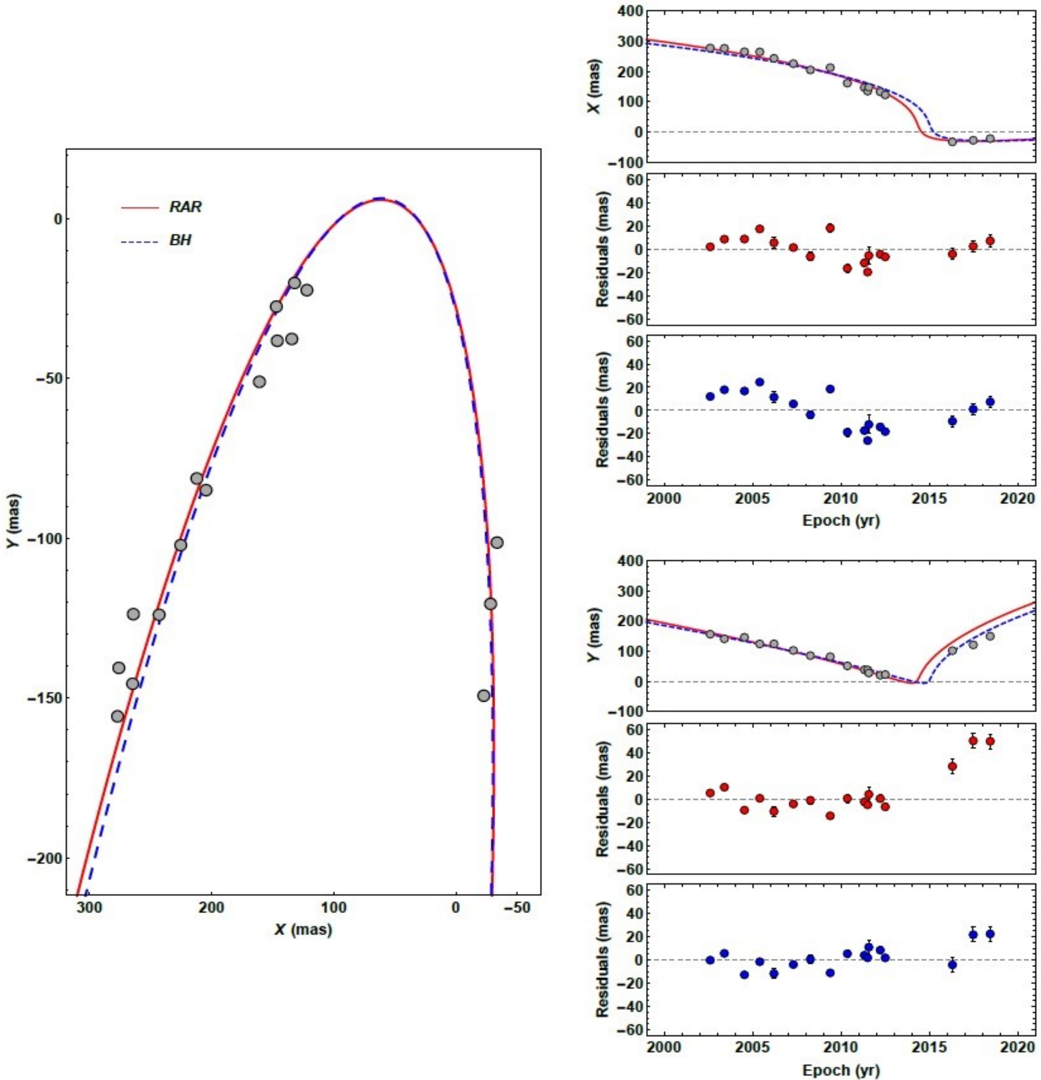
$$\langle \bar{\chi}^2 \rangle_{RAR} = 3.0725$$



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

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

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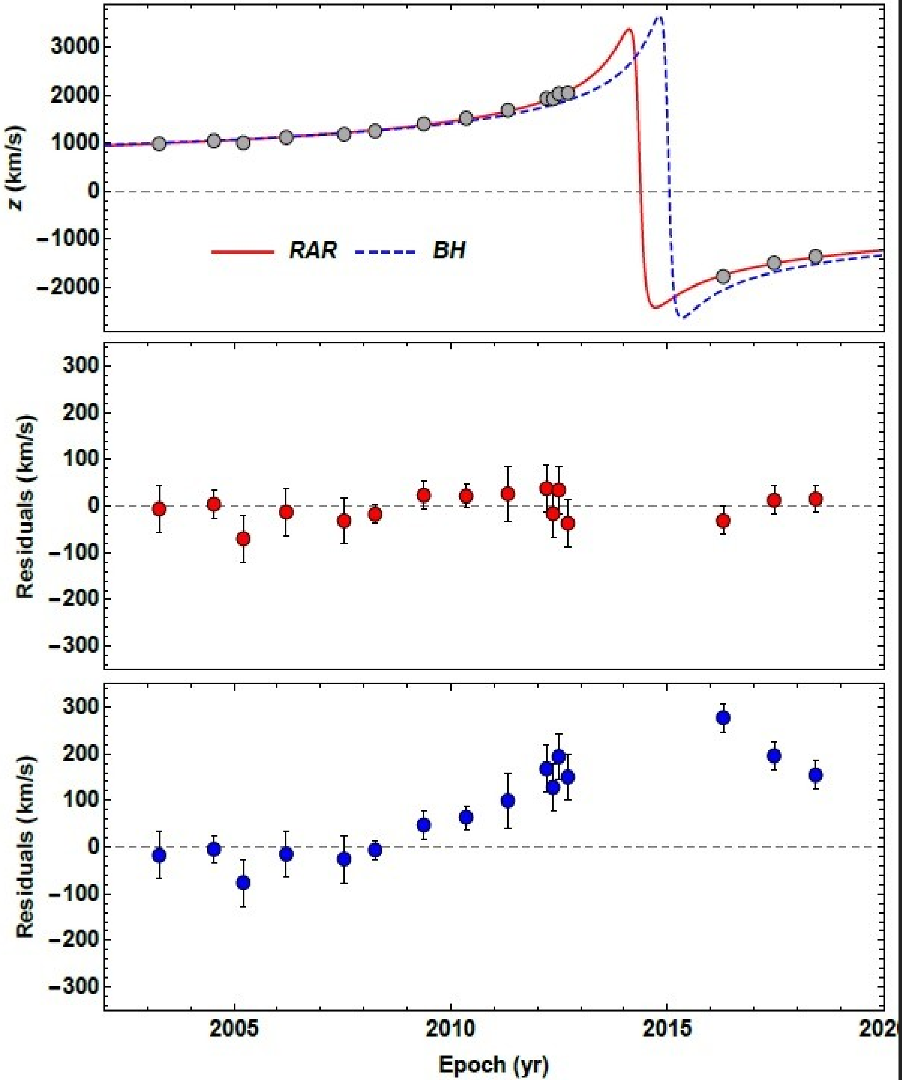
2) Fermionic DM distribution with Mc = 3.5×10^6 Mo (fermion mass m= 56 keV)



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

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

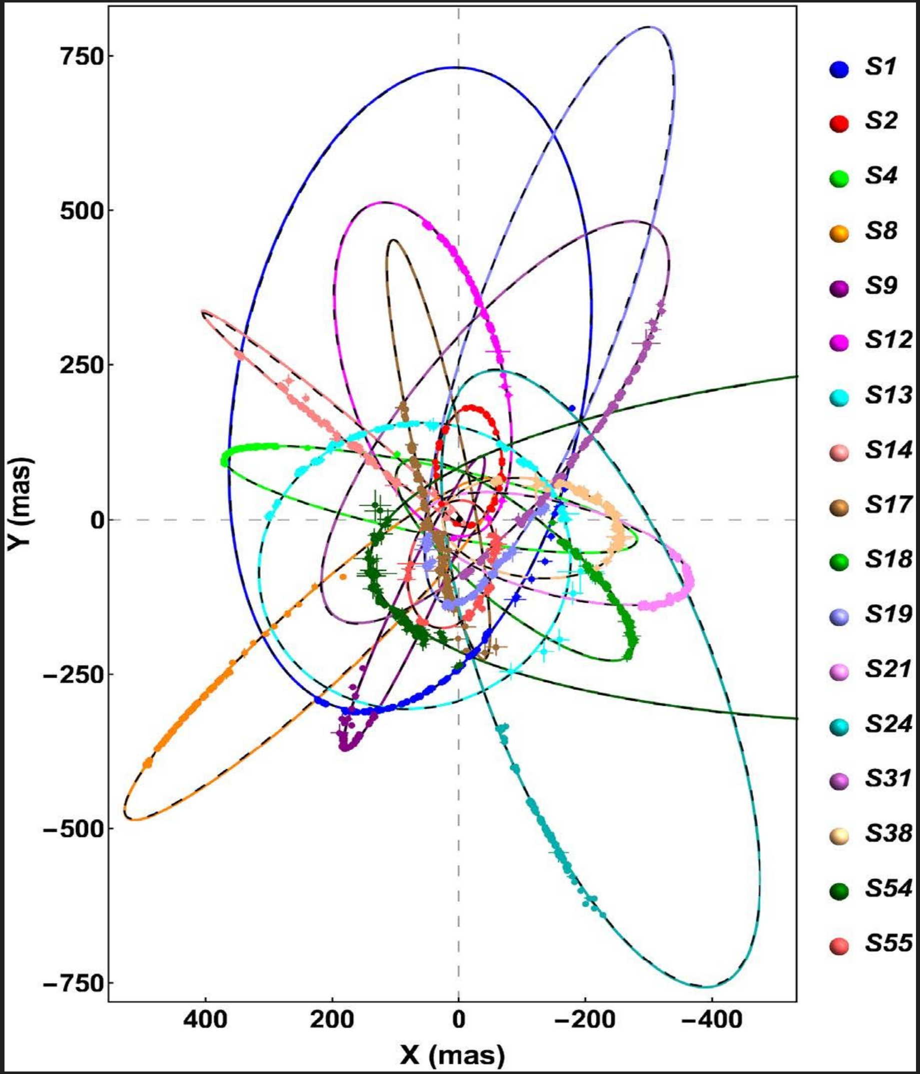
THEORETICAL MODELS: calculated by solving the e.o.m of a test particle in the gravitational field of:

1) Schwarzschild BH of 4.07 x 10^6 Mo

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

2) Fermionic DM distribution with Mc = 3.5 x 10^6 Mo (fermion mass m= 56 keV)

$$\bar{\chi}^2_{z\ \mathrm{RAR}} = 0.9960$$



THEORETICAL and OBSERVED 17 best-resolved S-star orbits around SgrA*

THEORETICAL MODELS: calculated by solving the geodesic equation of a test particle in the gravitaitonal field of:

1) Schwarzschild BH of 4.07 x 10^6 Mo

$\langle \bar{\chi}^2 \rangle_{RAR}$ **= 1.5**

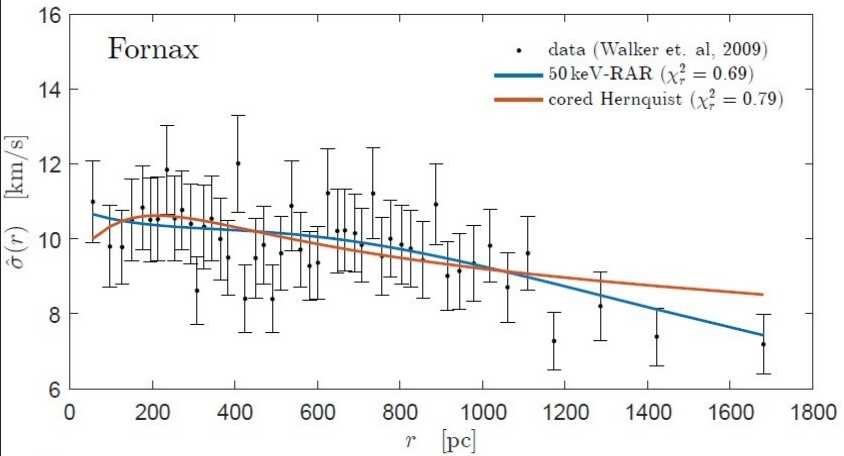
2) Fermionic DM distribution with Mc = 3.5 x 10^6 Mo (fermion mass m= 56 keV)

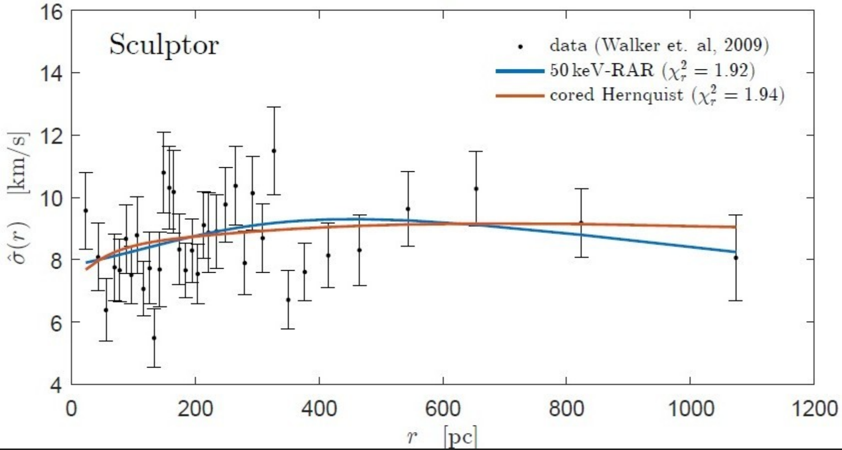
$\langle \bar{\chi}^2 \rangle_{BH}$ **= 1.6**

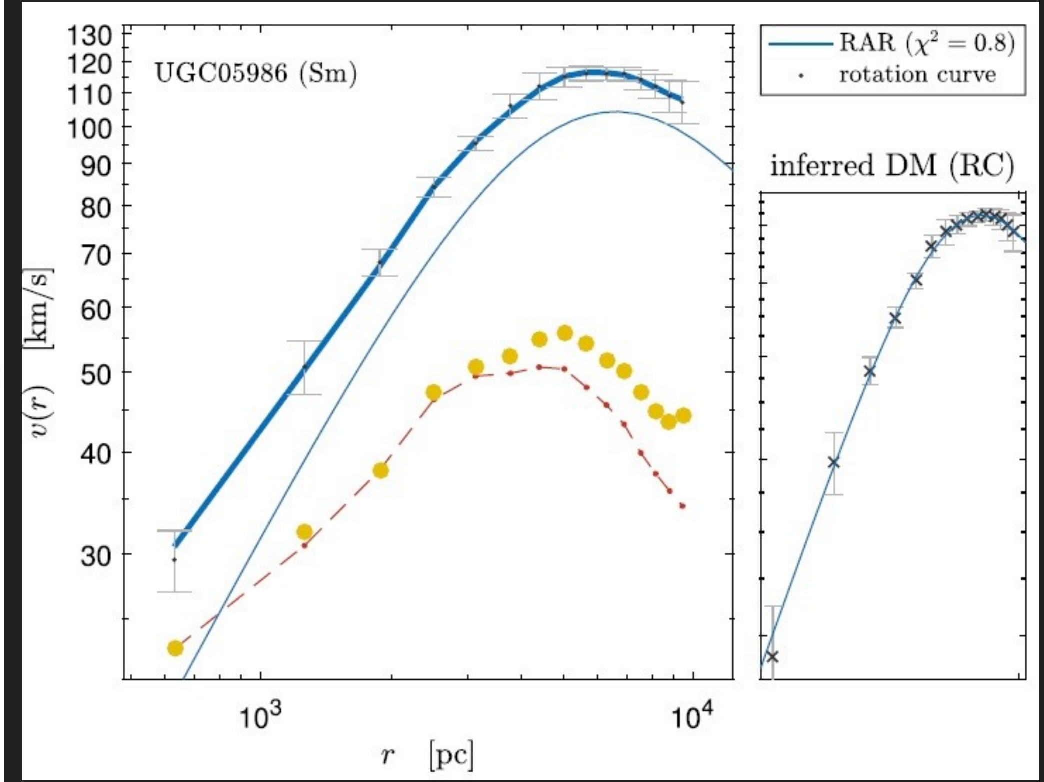
Becerra-Vergara, Argüelles, et al. MNRAS Lett (2021)

Universality of the fermionic DM profiles: from dwarf to elliptical galaxies

L.o.S dispersion velocity data and high resolution rotation curves in disk galaxies are well reproduced by the model



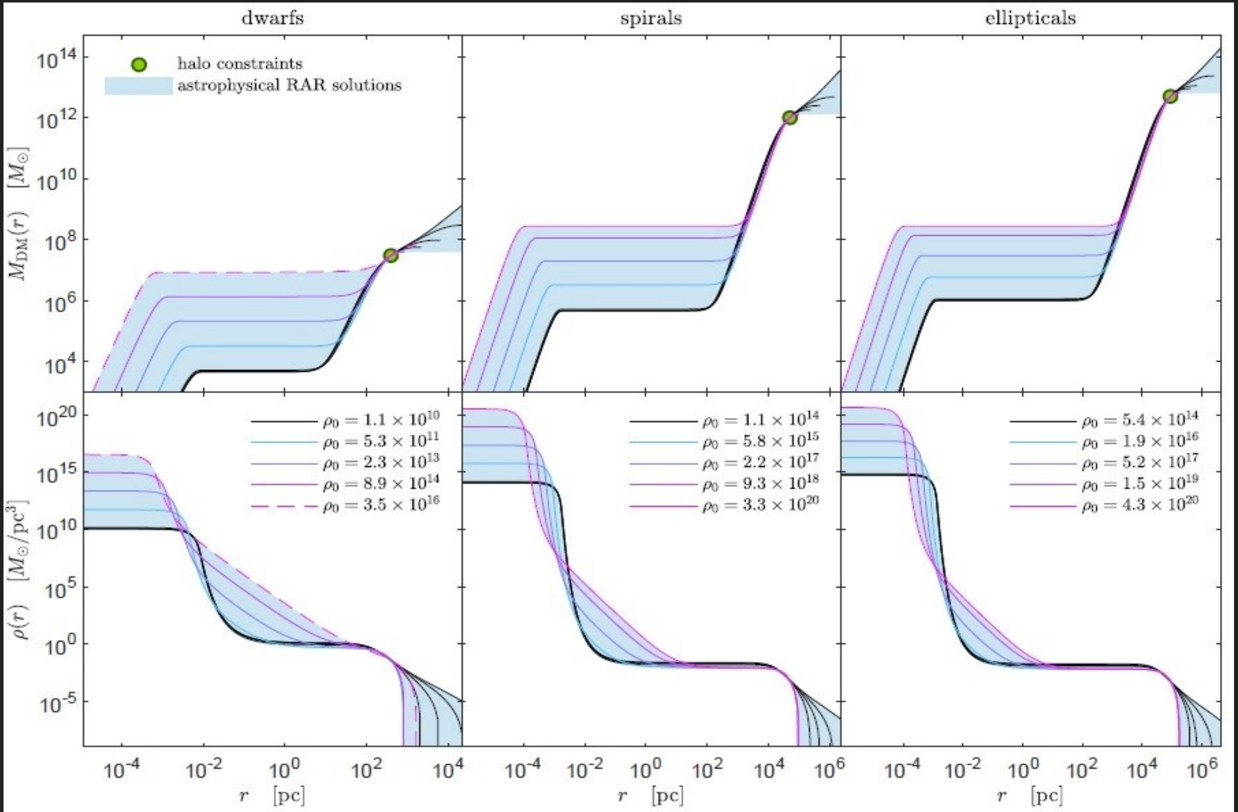




Argüelles, Krut, Rueda, Ruffini, PDU (2019)

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 ~ 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

$$r_{h(\rm d)} = 400 \text{ pc}$$
$$M_{h(\rm d)} = 3 \times 10^7 \text{ M}_\odot$$

SPIRALS: sample of nearby disk galaxies from THINGS

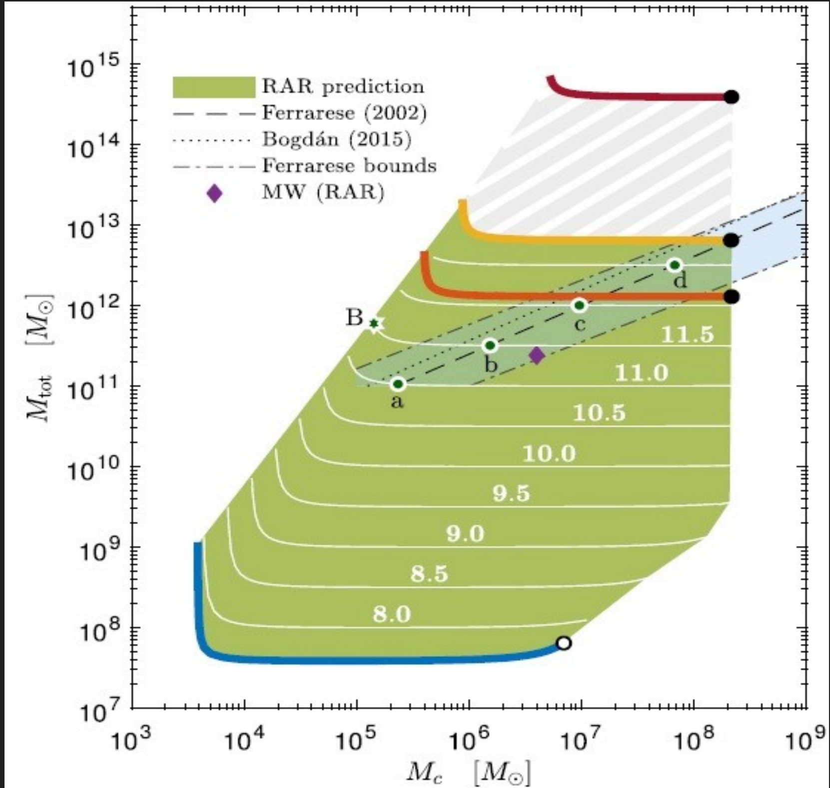
$$r_{h(\rm s)} = 50 \text{ kpc}$$
$$M_{h(\rm s)} = 1 \times 10^{12} \text{ M}_\odot$$

ELLIPTICALS: sample analyzed via weak lensi

$$r_{h(\rm e)} = 90 \text{ kpc}$$
$$M_{h(\rm e)} = 5 \times 10^{12} \text{ M}_\odot$$

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 (Mc ~ 10^4 Mo for dwarfs), up to super massive BHs (Mc ~ 10^8 Mo for Seyfert and elliptical galaxies) Argüelles, Krut, Rueda, Ruffini, PDU (2019)



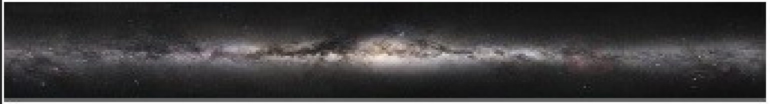
The degeneracy-pressure-supported DM cores, become gravitationally unstable when reaching the critical mass, collapsing to a super massive BH

For m~50 keV $M_c^{cr} \sim 2 \times 10^8 \, M_\odot$

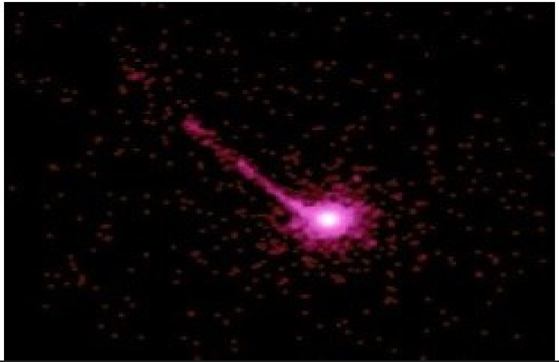
May provide initial seed for the formation of observed SMBHs in active galaxies such as M87
(without the need of unrealistic super – Eddington accretion rates)

A paradigm shift in the formation and nature of the galactic centers?

- Normal Galaxies → NO Active Nuclei NOR Jets ($M_c \sim 10^{6-7} M_\odot$)



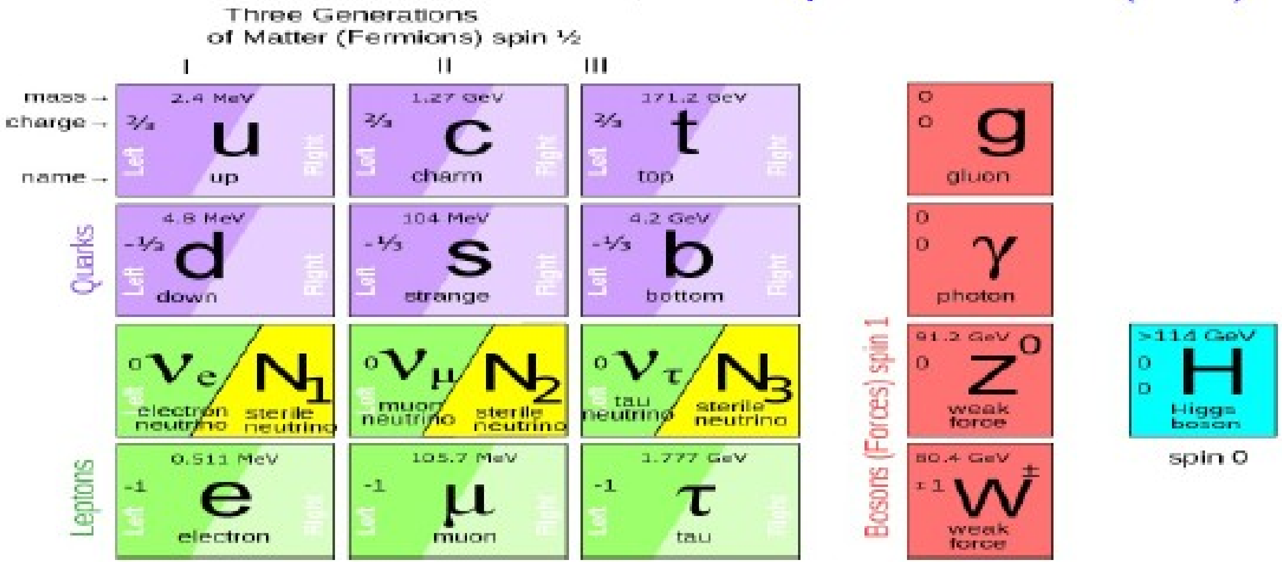
- Active Galaxies → YES Active Nuclei AND Jet emission ($M_{\rm BH} \sim 10^{9-10} M_\odot$)



THANK YOU !

The particle nature of the keV-ish fermions?

- Minimal extension of SM (νMSM) adding 3 right-handed STERILE ($Q_{SM} = 0$) neutrinos T. Asaka, S. Blanchet, M. Shaposhnikov *PLB* (2005) 0503065



- Group-invariance in νMSM model: SU(3)xSU(2)xU(1) remains unchanged!

$$\mathcal{L} = \mathcal{L}_{SM} + i\nu_R \partial_\mu \gamma^\mu \nu_R - g\,\bar{L}\nu_R \phi - M/2\bar{\nu}^c_R \nu_R \tag{2}$$

- A Lagrangian extension including for self-interactions $\mathcal{L}_I$ under self-gravity was analyzed C. Argüelles, N. Mavromatos, et al. *JCAP* (2016) 1502.00136

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{\nu_R} + \mathcal{L}_V - g_V V_\mu J^\mu$$

Effects of self-interactions in particle physics (nuMSM) constraints

- The cross section constraints from colliding galaxy clusters D. Harvey et al. Science (2015)

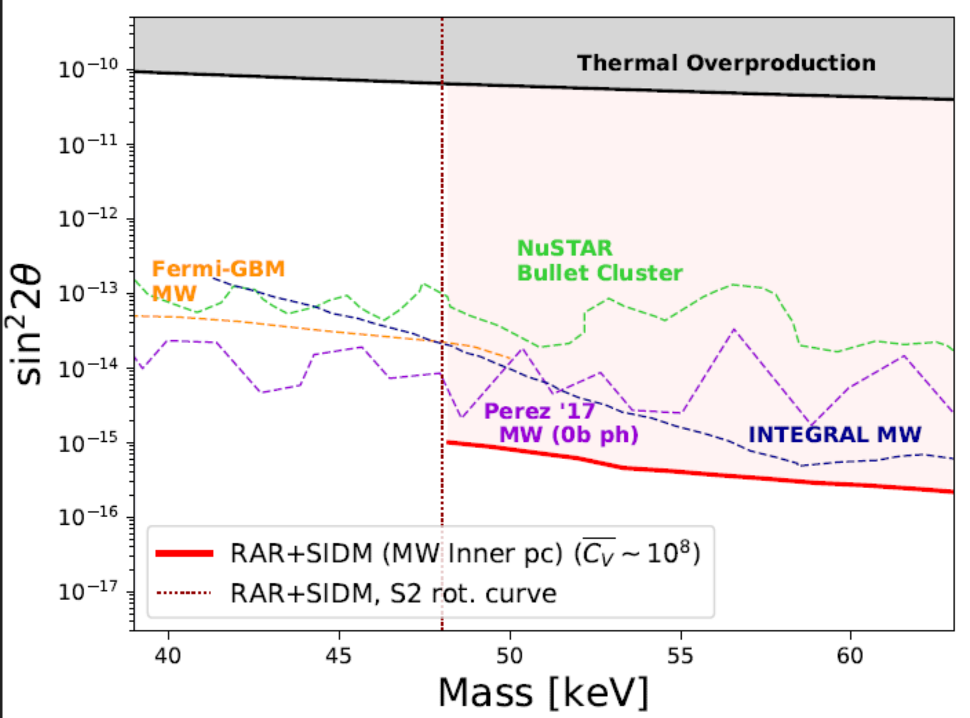
$$0.1 \leq \frac{\sigma_{\rm SIDM}/m}{{\rm cm}^2\,{\rm g}^{-1}} \leq 0.47$$

- Theoretical corss-section for the SI sterile neutrinos Argüelles, et al. JCAP (2016)

$$\sigma^{\rm tot}_{\rm core} \approx \frac{(g_V/m_V)^4}{4^3\pi} 29 m^2$$

⇓

$$\overline{C}_V \equiv \left(\frac{g_V}{m_V}\right)^2 G_F^{-1} \in (2.6\times 10^8, 7\times 10^8),$$



NuMSM parameter-space is relaxed by an additional production channel of s-neutrinos via the Vμ decay (lowering the bounds on interaction angle) Yunis, Argüelles, Mavromatos, et al. PDU (2020)