DARK MATTER IN THE MILKY WAY

Carlos R. Argüelles

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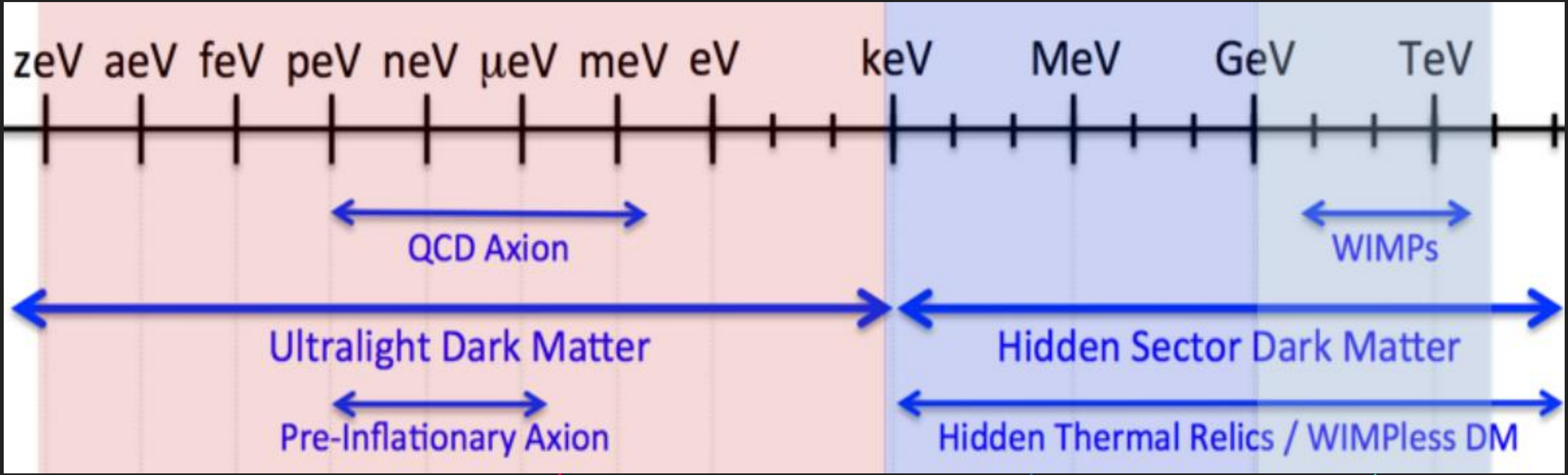
Particle DM paradigm: the nature and mass of the DM candidates?

Adapted from CERN Document server

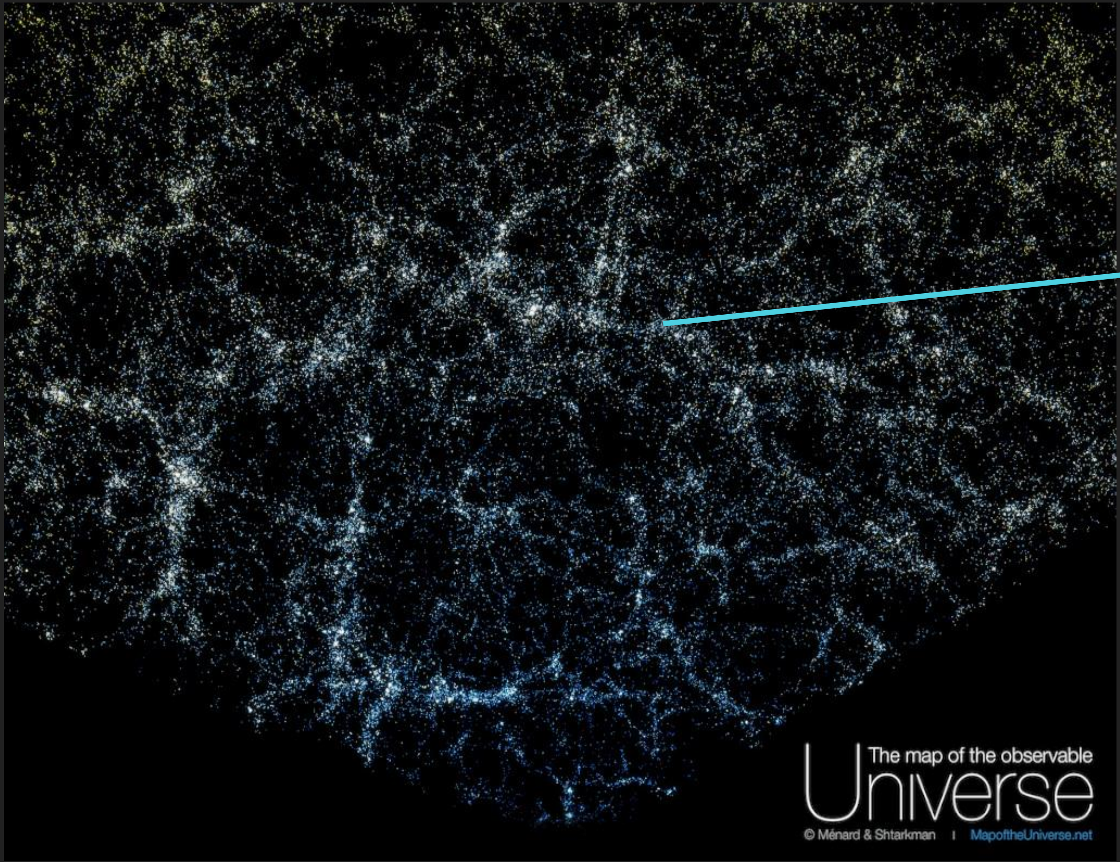


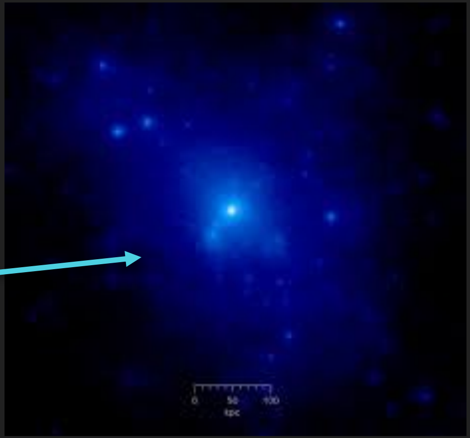
“Wave-like dark matter”

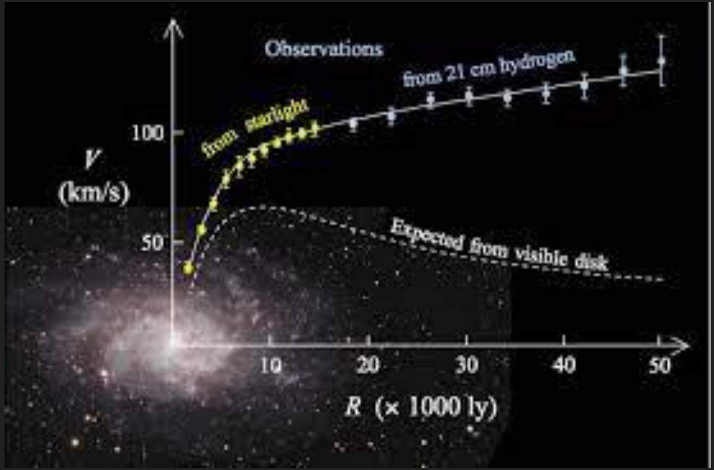
“light dark matter”

“High-mass dark matter”

From large scale structure to DM halo-size structures







However.. important open questions on small scales

- How can we robustly predict the inner shape of the DM halos? → Cored? Cuspy? Universal?

- What about the DM concentration in galactic centers ? → DM spikes? : relevant effects in stellar orbits, etc

- Which is the nature of the supermassive compact objects at galaxy centers ? → Are all BHs ?

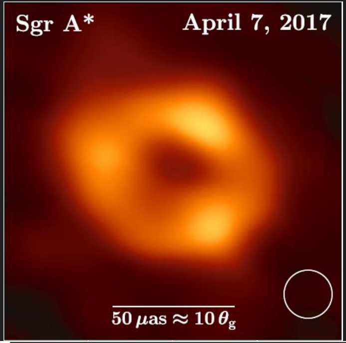
- How massive BHs formed and grow in the high z Universe ? → Mass of initial BH seeds?

- What is the exact distribution of DM in the Milky Way from center to periphery ?

Fermions plus Gravity can provide key insights to all of these questions!

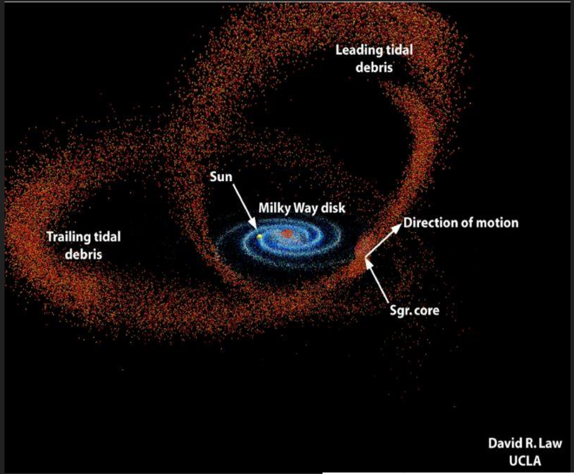
Milky Way observables: from SgrA* to the entire halo

Any underlying DM distribution has to agree with the following set of MW observables, from very center to Galaxy outskirts



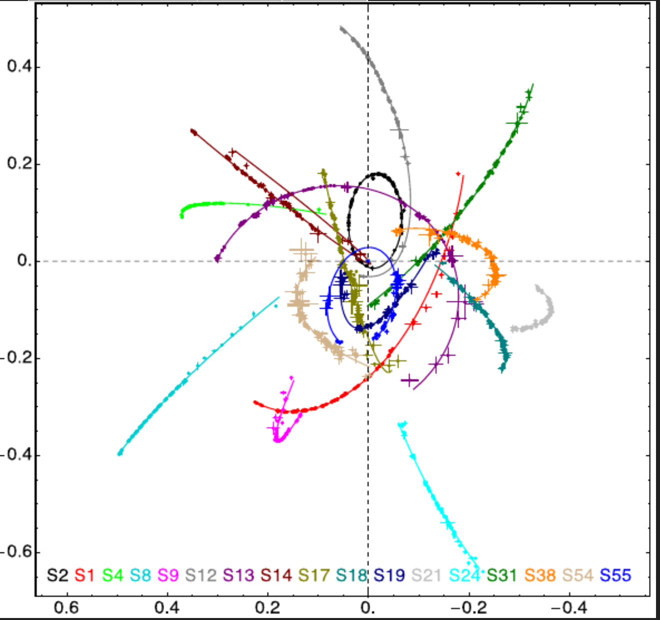
Shadow of SgrA*

EHT collab. ApjL (2022)



Sgr stellar stream

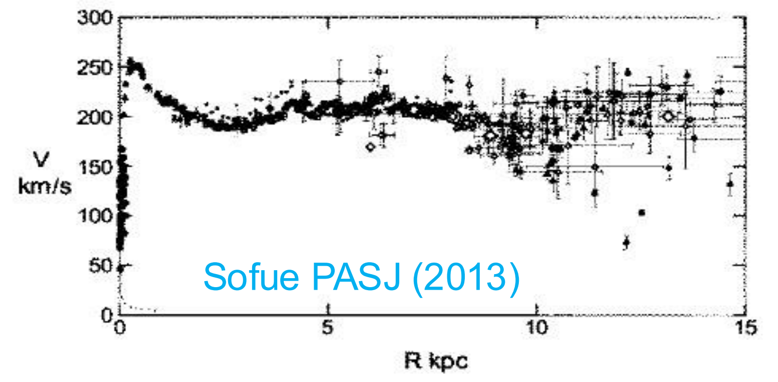
Ibata et al. Apj (2020)



S-cluster stars

Gillessen et al. Apj (2017)

Milky Way rotation curve



Sofue PASJ (2013)

DM halo formation: a statistical mechanics approach

DM halos: an statistical mechanics & thermodynamics approach

Simulations: DM halo formation and overall structure is centered in N-body simulations. Though we still lack a clear understanding on its physical basis.

Statistical mechanics of self-gravitating systems: Maximum entropy principles (MEP) developed in the last decade Pontzen & Governato (2013), Hjorth et al. (2015), Chavanis et al. (2015) lead to DM profiles in good agreement with simulations & observations.

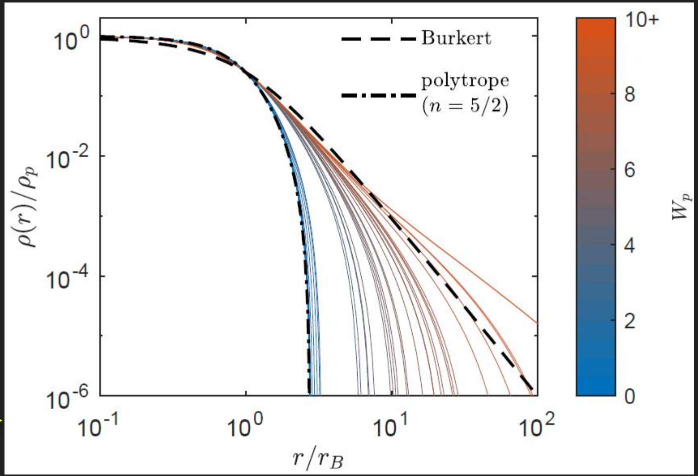
Self-gravitating systems of fermions: MEP approach applied on a kintetic theory couple to gravity, leads to a most likely coarse-grained phase-space distribution of Fermi-Dirac type: Chavanis et al. (1998,2004)

$$\bar{f} = \eta_0 \frac{1 - e^{\beta(\epsilon-\epsilon_m)}}{1 + e^{\beta\epsilon+\alpha}}$$

(Pauli principle)

$$\eta_0 = gm^4/h^3$$

DM halos built out of this DF where compared with observations & simulations Krut, Argüelles et al. Apj (2023)



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 equilibrium equations for Fermi Gas at finite T in hydrostatic equilibrium (i.e. T.O.V), in spherical symmetry Argüelles, Krut, Rueda, Ruffini, PDU (2018)

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

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

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

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

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

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

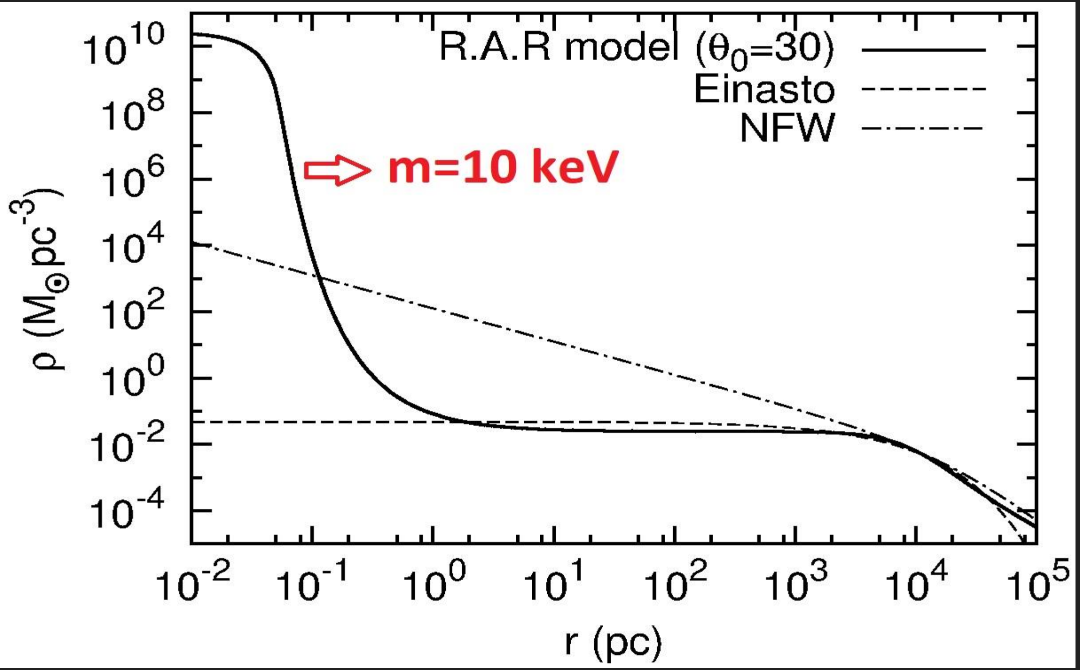
4 free parameters

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

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

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 $\theta_0 > 10$

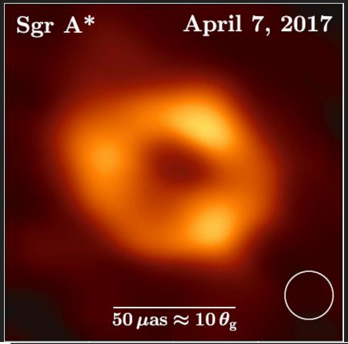
DM profiles depend on the particle mass (see next slides)

The dense central cores, when compact enough, can mimic the space-time signatures of a BH!

The best case study: The Milky Way

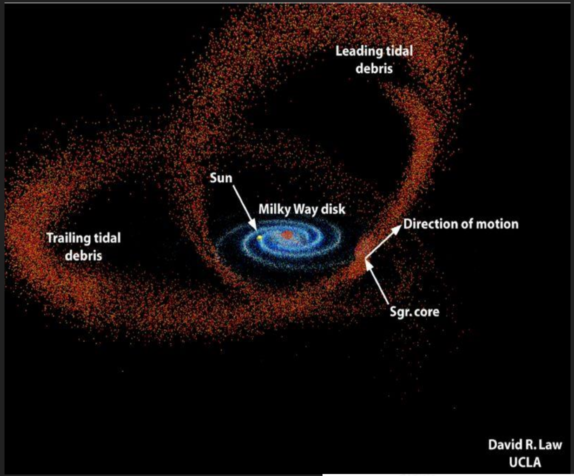
Milky Way observables: from SgrA* to the entire halo

Can a core-halo fermionic DM distribution explain the following set of MW observables without assuming a central BH?



Shadow of SgrA*

EHT collab. ApjL (2022)



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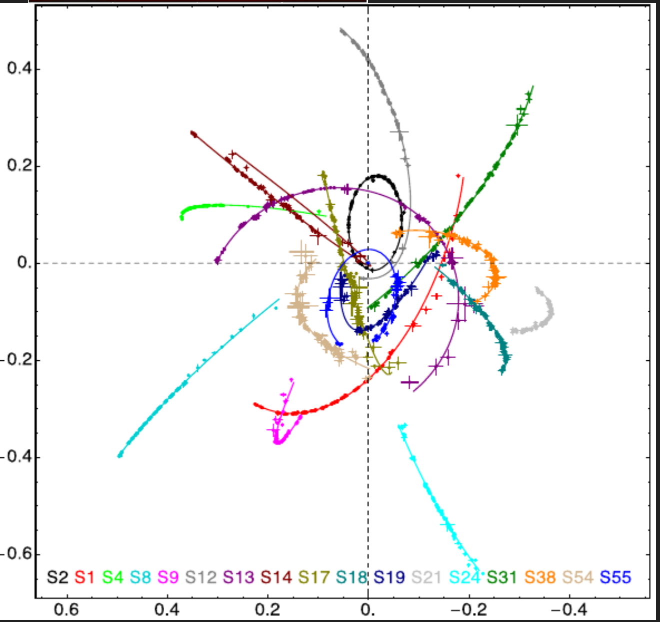

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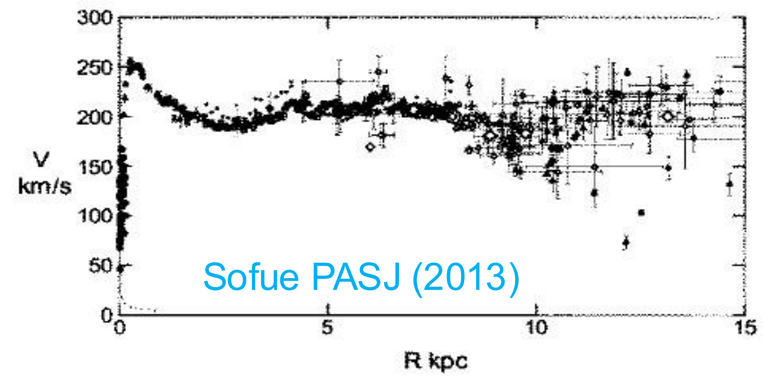
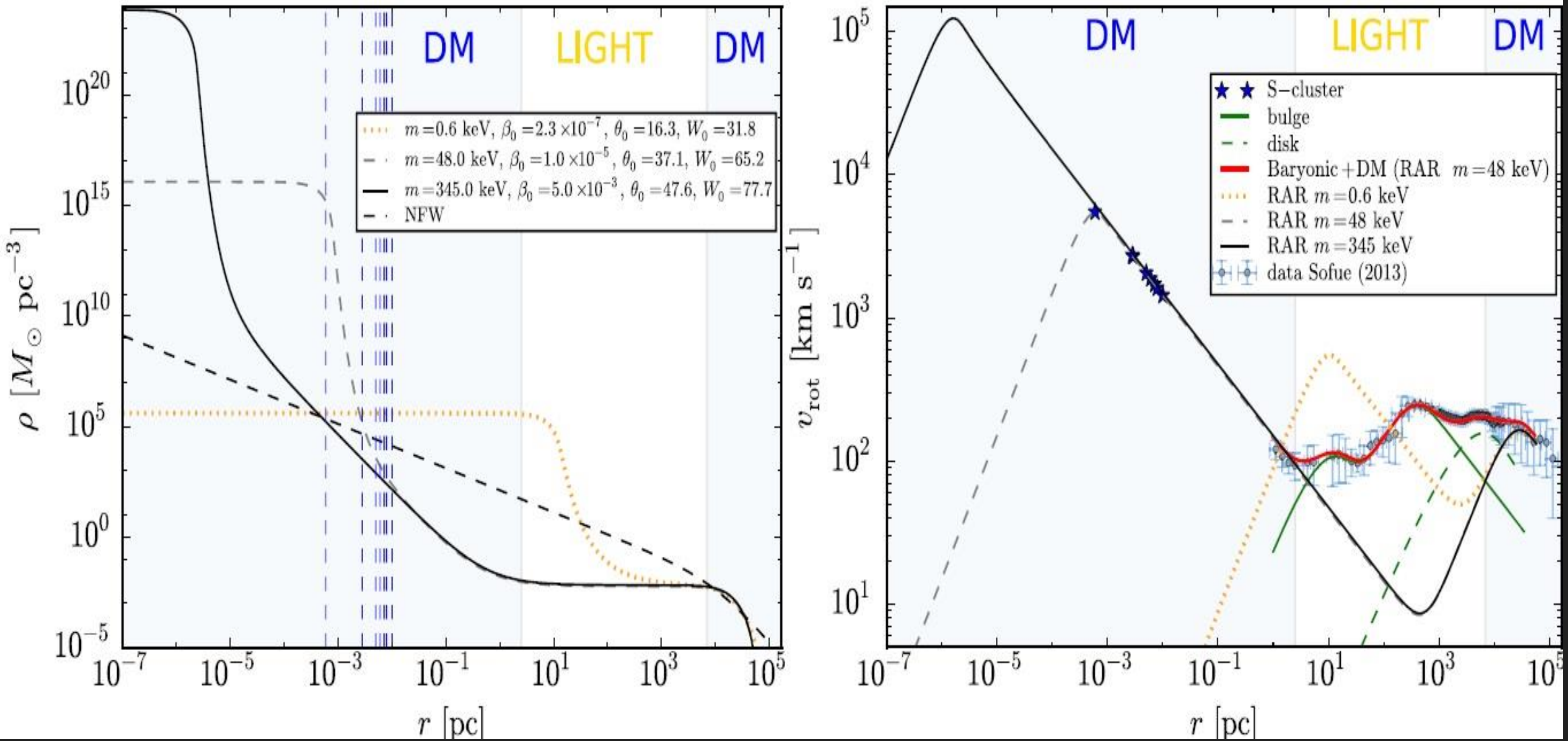


Sofue PASJ (2013)

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

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

C.R. Argüelles [a,b,*], A. Krut [b,c,d], J.A. Rueda [b,c,e], R. Ruffini [b,c,e]



Any alternative model to the central BH scenario MUST explain: (Data: VLT, Keck I – II Gemini North, Subaru, GRAVITY, EHT)

- The multiyear accurate astrometric data of S2-star around SgrA*, including the relativistic redshift and periapsis precession GRAVITY collab. (2018,2020); Do et al., Science (2019)

- The currently available data of the orbit (and redshift) of the G2 object, Plewa et al. Apj (2017); Gillessen et al. Apj (2019); Peiβker et al. (2020,2021)

- The multiyear accurate astrometric data of the 17 best resolved S-stars around SgrA*, Gillessen et al. Apj (2017)

- The shadow of SgrA* and ring-like image of the lensed photons The EHT collab. ApjL (2022)

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]

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **505,** L64–L68 (2021) https://doi.org/10.1093/mnrasl/slab051
Advance Access publication 2021 May 20

Hinting a dark matter nature of Sgr A∗ via the S-stars

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Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS **511,** L35–L39 (2022) https://doi.org/10.1093/mnrasl/slab126
Advance Access publication 2021 December 14

What does lie at the Milky Way centre? Insights from the S2-star orbit precession

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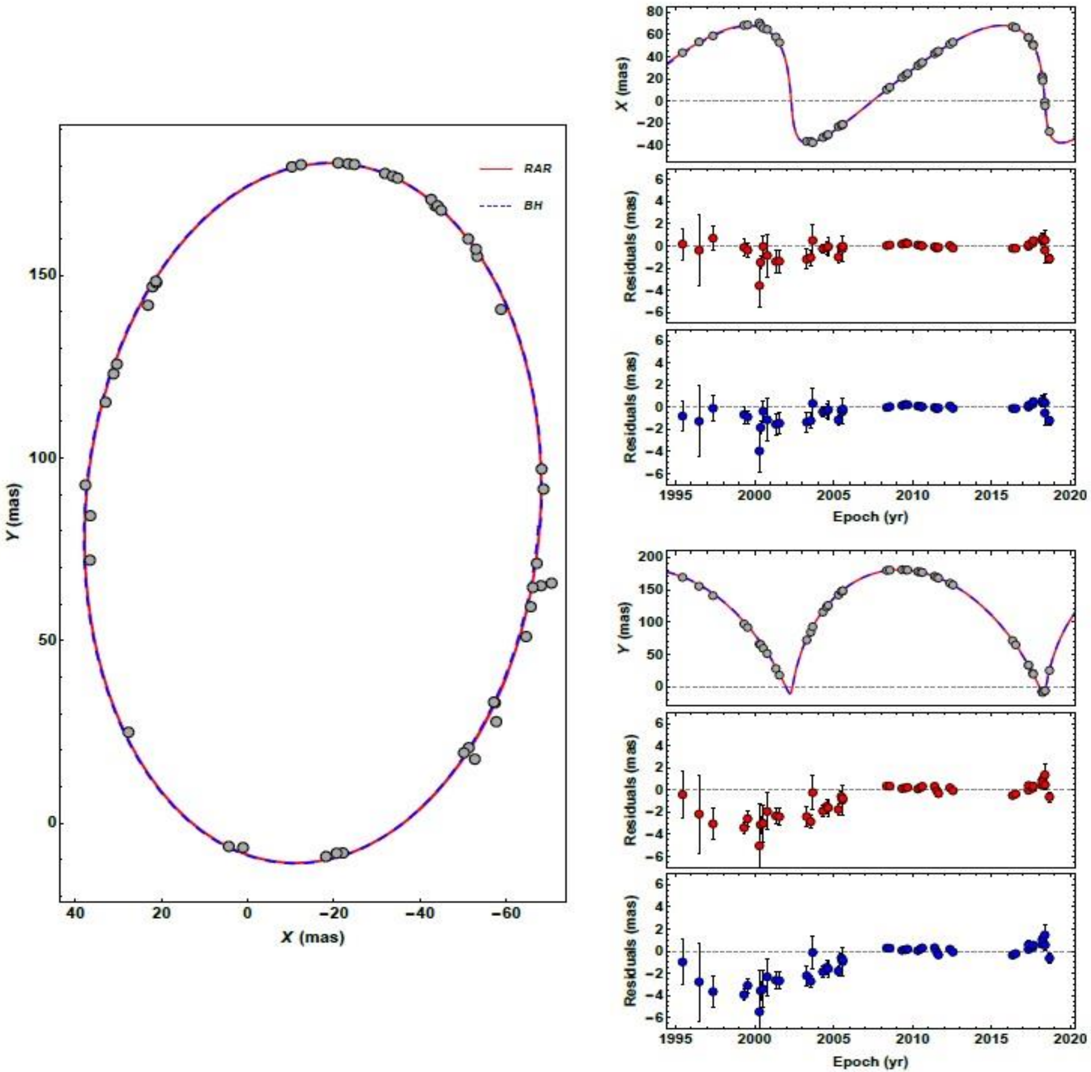
J. A. Rueda[2,3,6,7★] and R. Ruffini[2,3,6,7]



THEORETICAL and OBSERVED orbit of S2 around SgrA* (observations from Do et al (2019))

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:

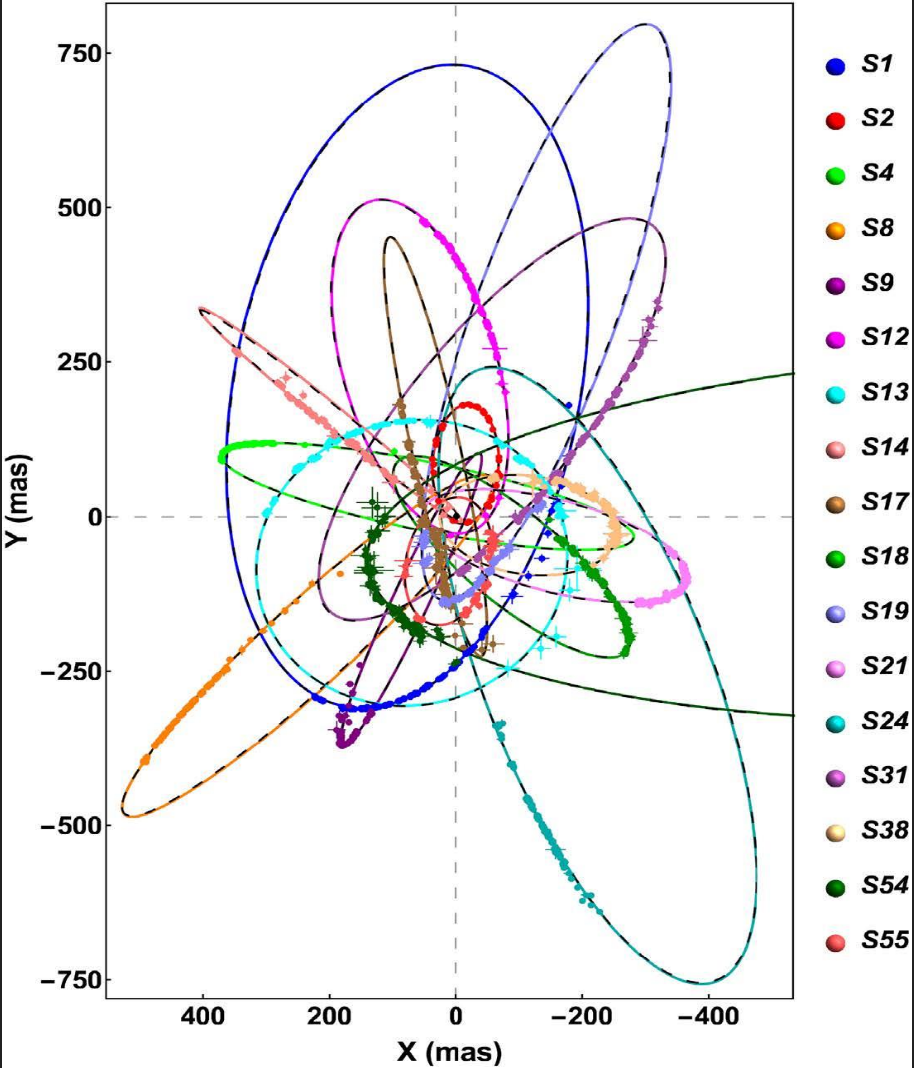
1) Schwarzschild BH of 4.07×10^6 Mo

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

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

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

Becerra-Vergara, Argüelles, et al. A&A (2020)



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

Gillessen et al. Apj (2017)

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

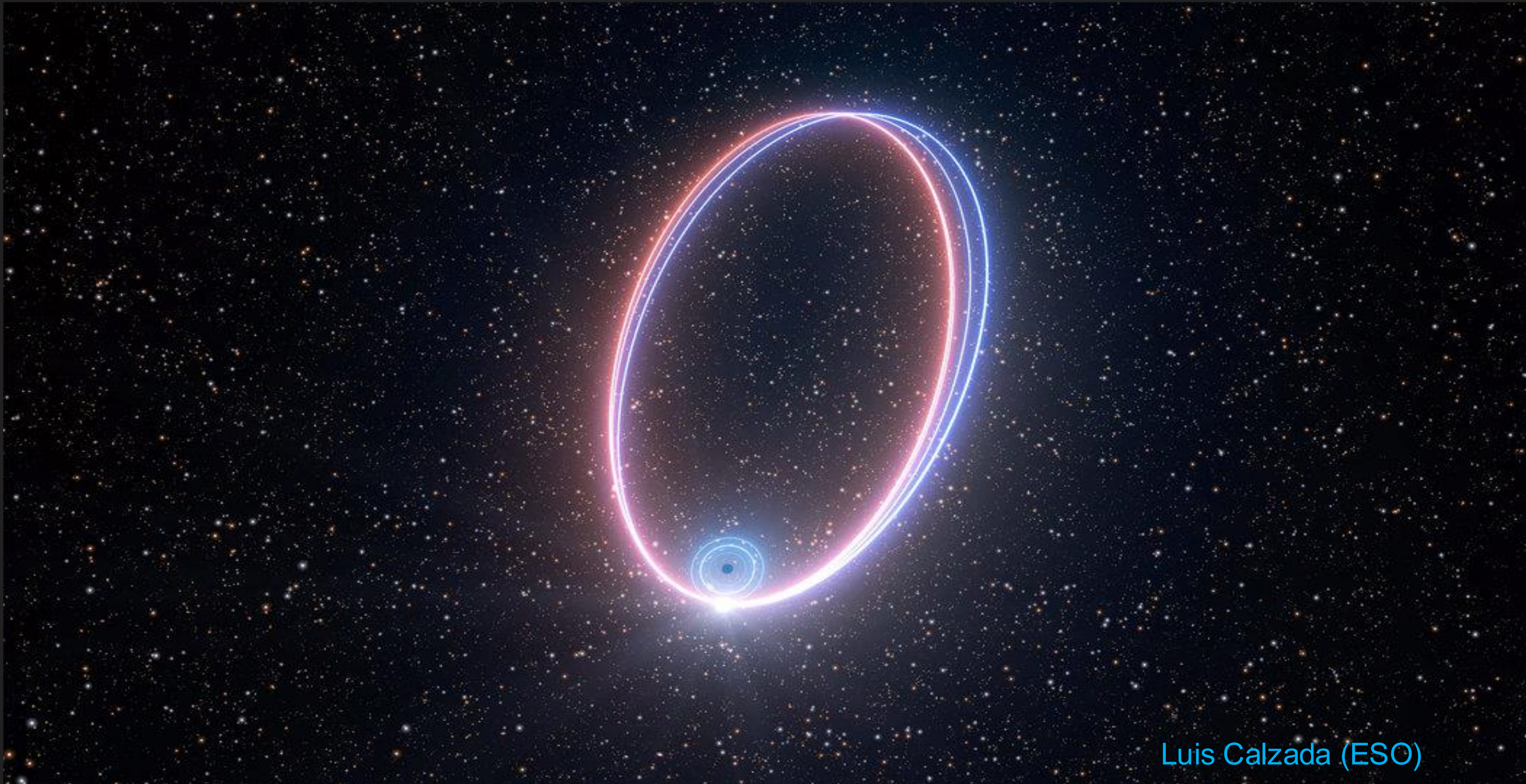
$$\langle \bar{\chi}^2 \rangle_{BH} = 1.6$$

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

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

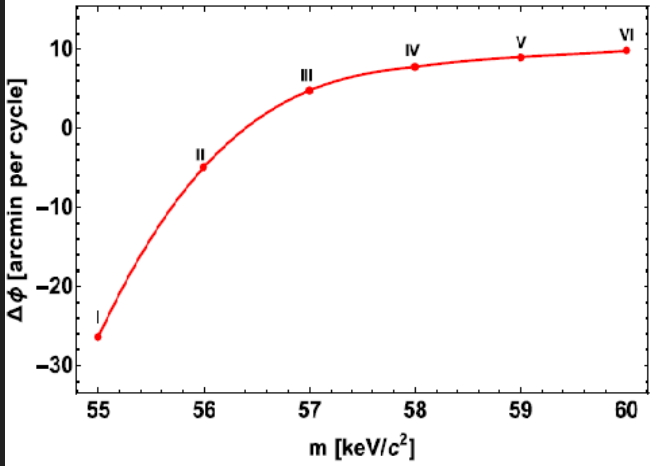
Becerra-Vergara, Argüelles, et al. MNRAS Lett (2021)

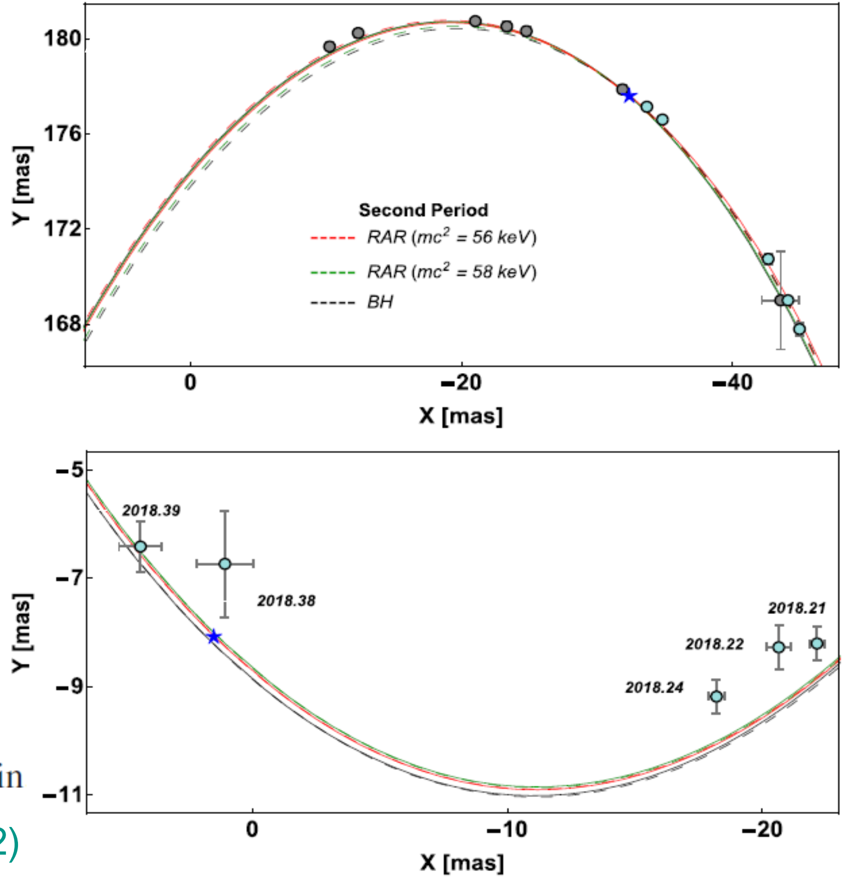
Testing the DM-core alternative with the S-2 star precession



Luis Calzada (ESO)

Testing the DM-core alternative with the S-2 star precession





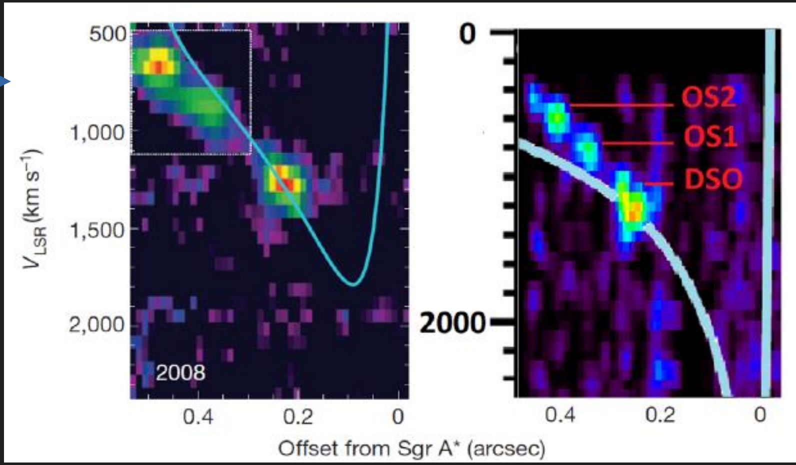
$$\Delta\phi_{\rm BH} = 6\pi G M_{\rm BH}/[c^2 a(1-e^2)] \approx 12\,\text{arcmin}$$

Argüelles et al. MNRAS Lett. (2022)

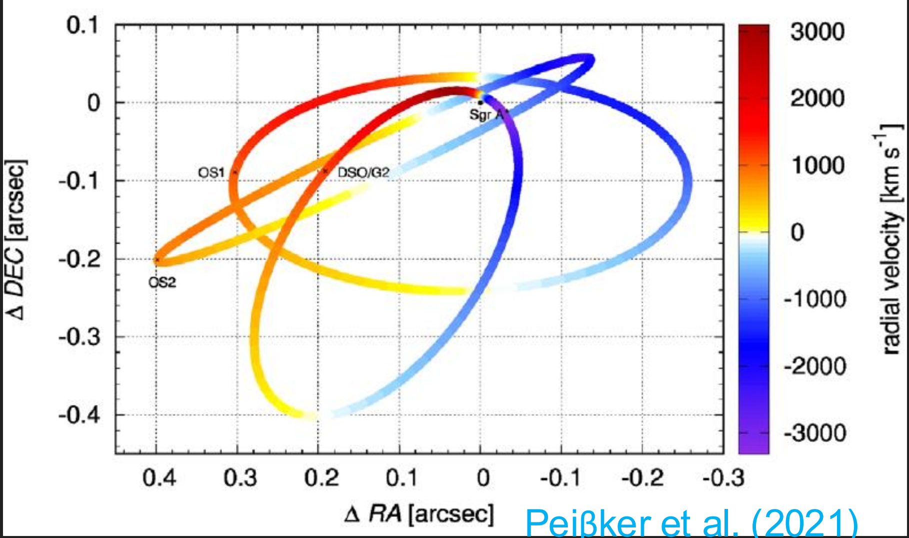
The head of G2/DSO object: a gaseous cloud or a dust enshrouded star ?

- The predicted flaring event and expected tidal dissolution of G2 at about pericenter passage in 2014.3 was not observed -e.g. Witzel et al. (2014)-

- A consensus is reached about the nature of G2: a dust-enshrouded young stellar object Peiβker et al. (2021)



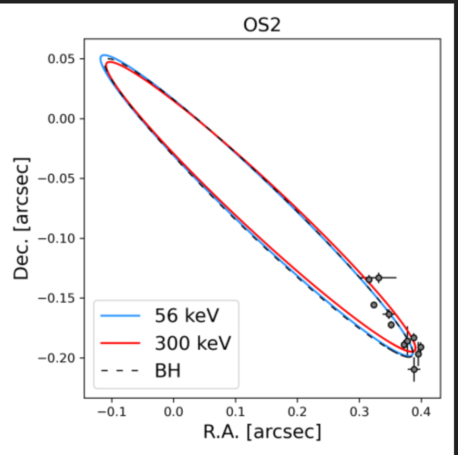
- The tail emission of the G2/DSO object consist of two Compact sources with different orbital elements

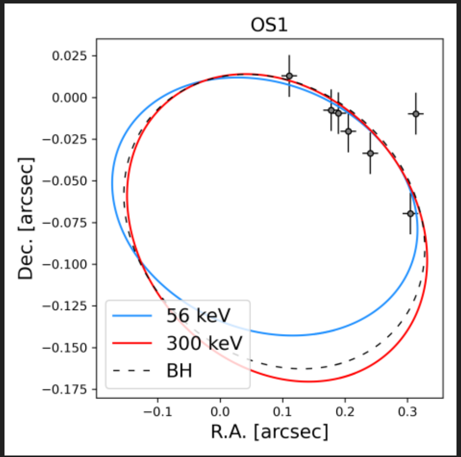


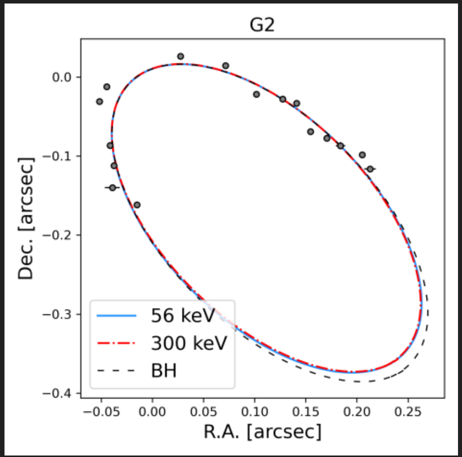
Peiβker et al. (2021)

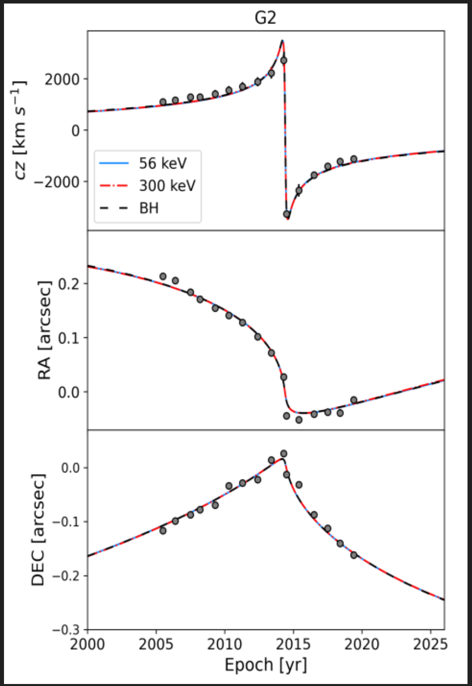
- Can the core-halo fermionic model explain the motions of these objects for the same potential than solved for the S-2 star?

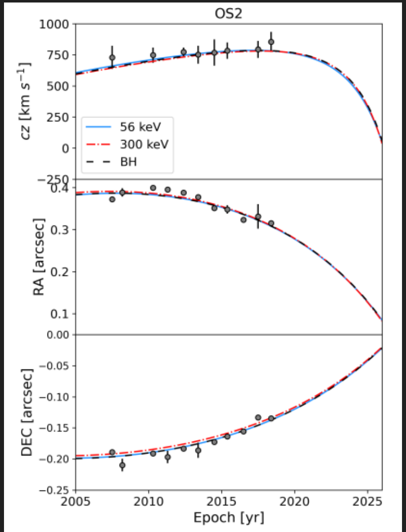
The fermionic model can explain the new data of the G2/DSO object !

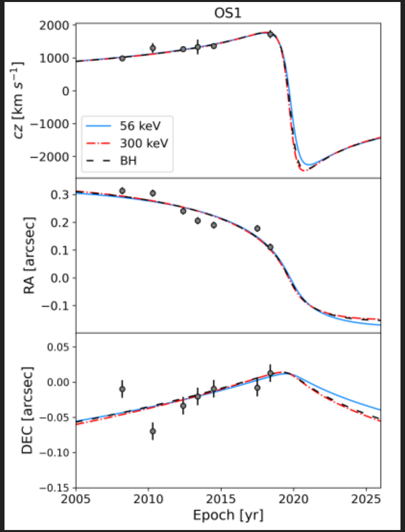






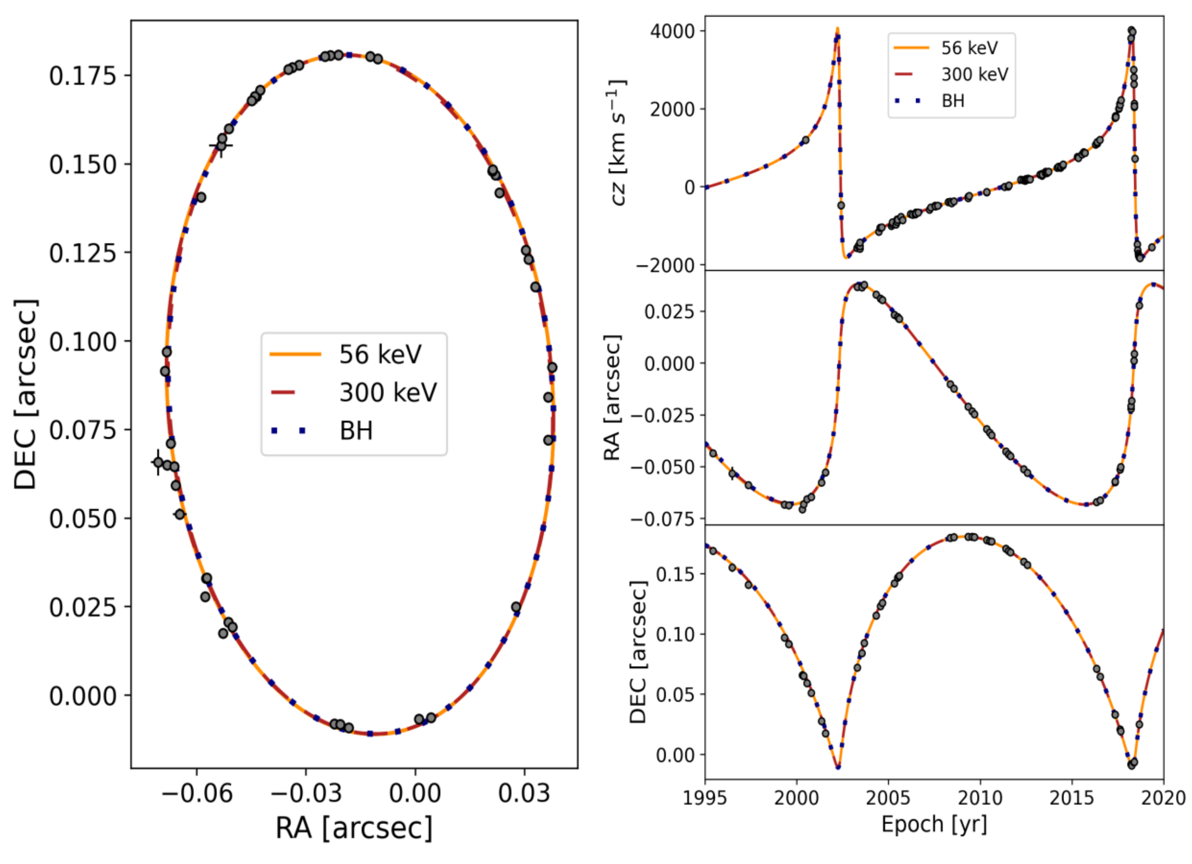




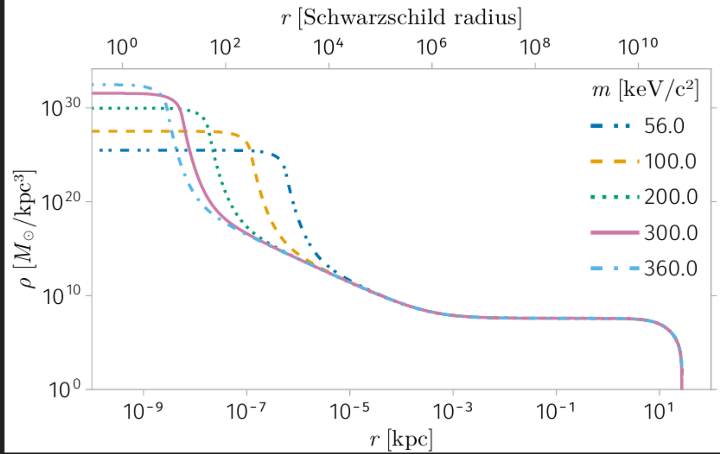


Best fits:	56 keV	300 keV	BH
G2	69.59	68.78	68.71
OS1	51.36	53.28	52.31
OS2	114.06	117.50	116.13

S-2 star: new results from MCMC for higher particle masses



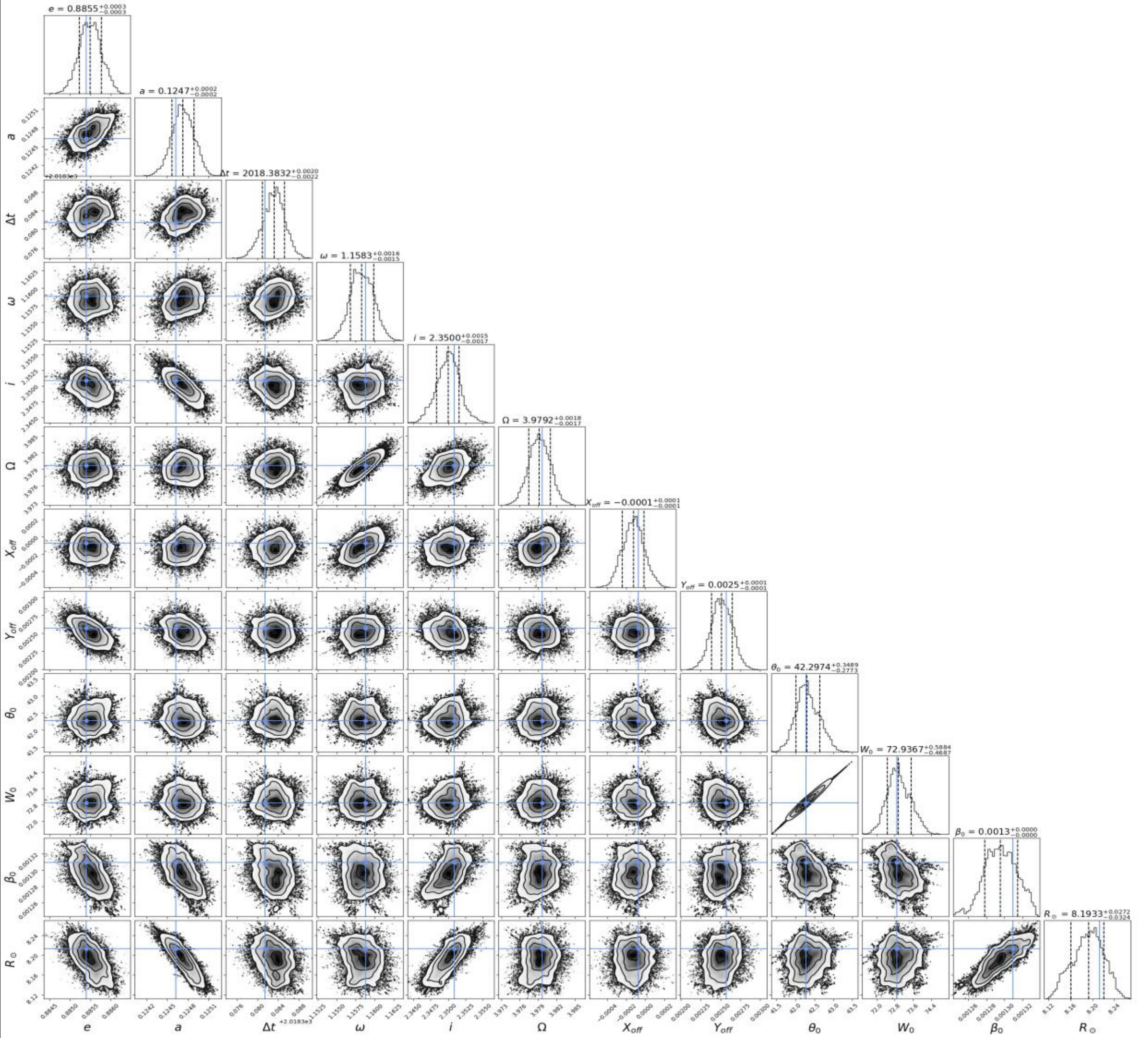
For fixed Milky Way halo inferred from observables, it exist different core-compacities all the way to the critical mass of collapse into a BH



Crespi, Argüelles, Becerra-Vergara, et al. (In preparation)

See Becerra-Vergara et al A&A (2020) & Argüelles et al MNRAS Lett (2022) confirming observed relativistic effects

Posteriors of the S2-star orbital parameters + RAR model param. determined from a MCMC method within a core-halo solution (m=300 keV)



Crespi, Argüelles, Becerra-Vergara et al. (In preparation)

Best fit RAR model parameters:

θo=42.279

Wo=72.895

βo=1.309x10^(-3)

Orbital elements are below 1% with respect to the BH results

Disc accretion onto dark matter fermion cores

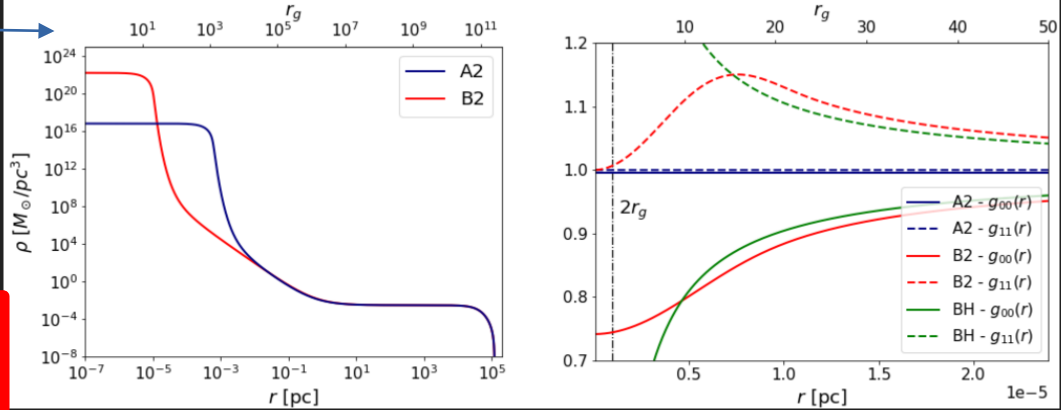
Disc accretion for horizonless dark compact objects: the fermion core

- We study accretion flow and associated emission using generalized "α-discs" onto the DM-core
  Millauro, Argüelles et al. A&A (2024)

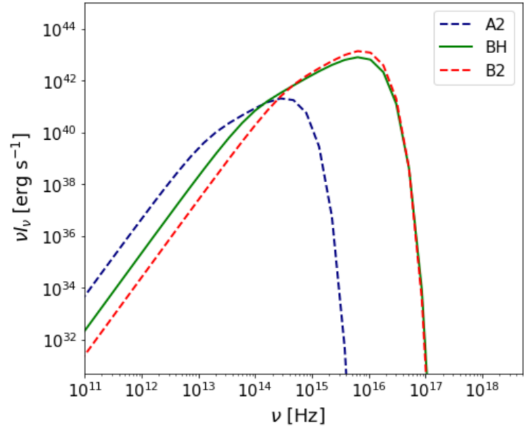
Fermionic DM profiles of active galaxies

Example: Mc=10^7 Mo; M=10^{12} Mo

Solution A2 → m=50 keV
Solution B2 → m=200 keV



Emitted flux: it always exist a DM-core comapcity such that the flux is indistinguishable from that of BH of the same mass as the core

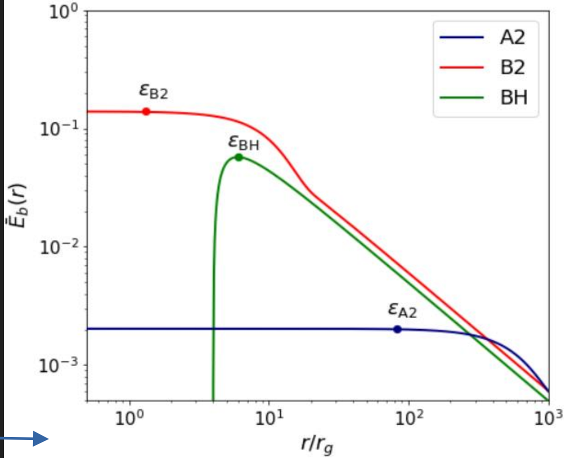


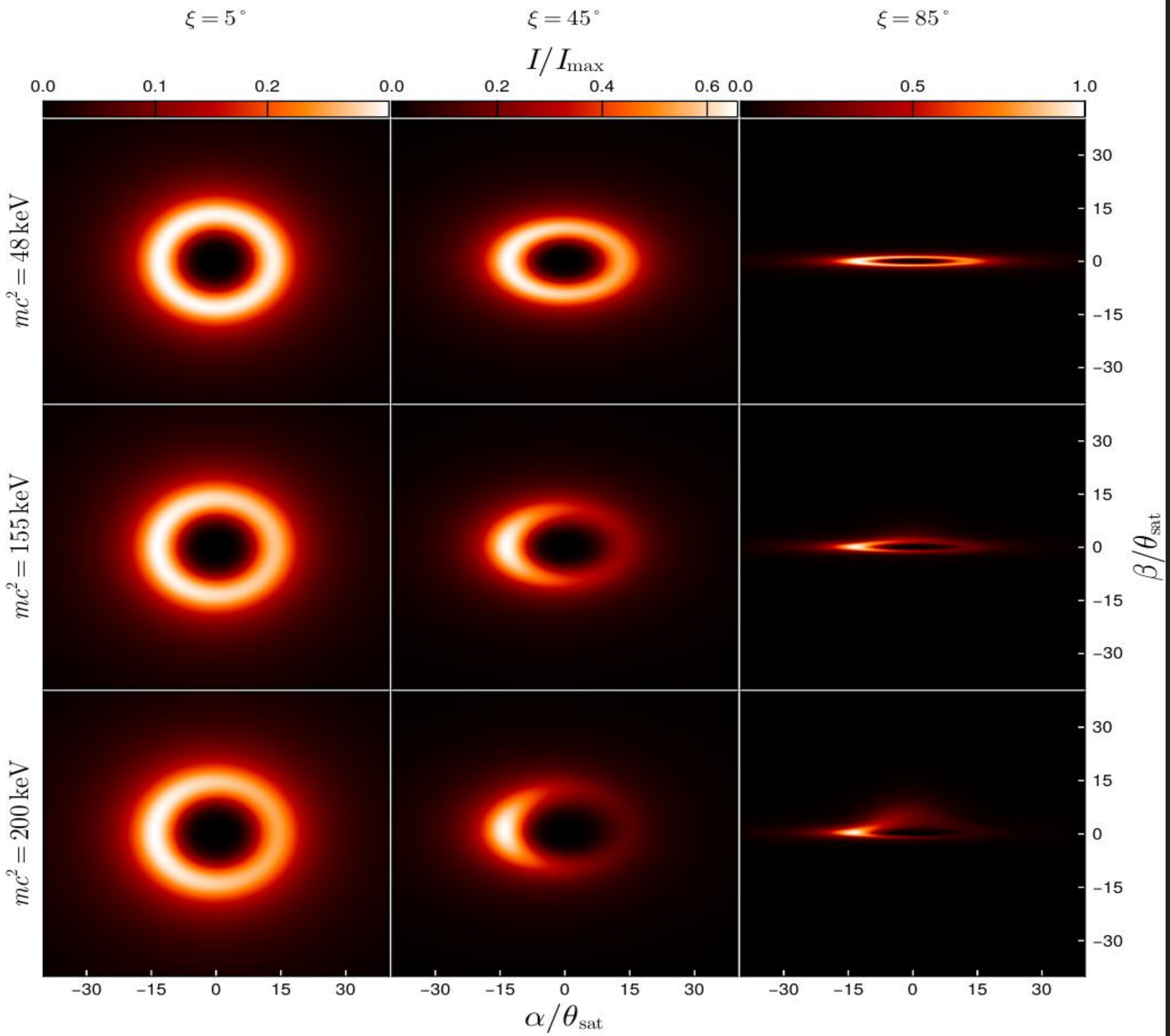
- Geometrically thin & optically thick disc with angular speed ~ Keplerian

$$\Omega = \left(\frac{GM(r)}{r^3}\right)^{1/2}$$

Efficiency of energy extraction from the central object

$$\bar{E}_b(r) = 1 - \sqrt{g_{00}(r)\left(1 + \frac{r g'_{00}(r)}{2g_{00}(r) - r g'_{00}(r)}\right)}$$





The disc cast a shadow surrounded by a ring-like feature of the lensed photons resembling what expected in the BH scenario
Pelle, Argüelles, et al. (2024) MNRAS

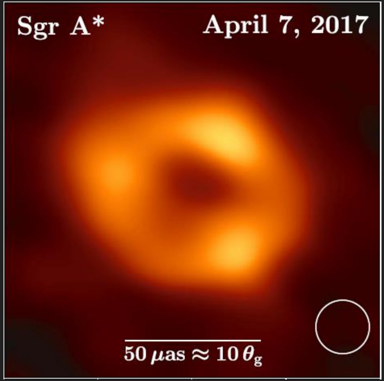
- Absence of ISCO in femrion-core solutions: matter can enter inside the 'transparent' core

- Absence of photon ring: the most compact (i.e. critical) highly degenrate solution has Rc ≥ 8 Mc

- Maximum photon deflection angle is ~ 3/10 π

m (keV)	M_c ($M_\odot$)	r_g (cm)	r_c (r_g)	$r_{\rm sat}$ (r_g)	$\theta_{\rm sat}$ (as)[4]
48	1×10^7	1.48×10^{12}	947	78.8	7.71
155	1×10^7	1.48×10^{12}	36.7	3.09	0.30
200	1×10^7	1.48×10^{12}	15.5	1.37	0.13

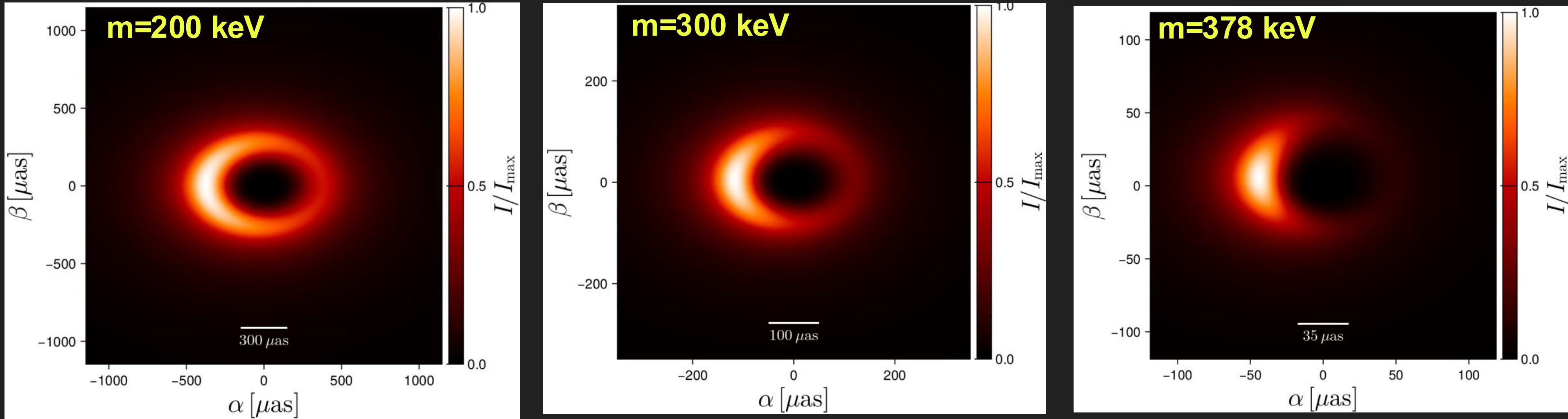
Can the fermion core cast a shadow feature like in the BH scenario?



- The EHT analysis support an image dominated by a bright thick ring with diameter of 52 μas ~ 10 Rg/D (Rg=GM/c^2) The EHT collaboration ApjL (2022)

- Compact DM fermion-cores of ~4x10^6 Mo can develope images similar to the BH case, with a **shadow feature and NO photon ring !** Pelle, Argüelles, Vieyro, et al. MNRAS (2024)

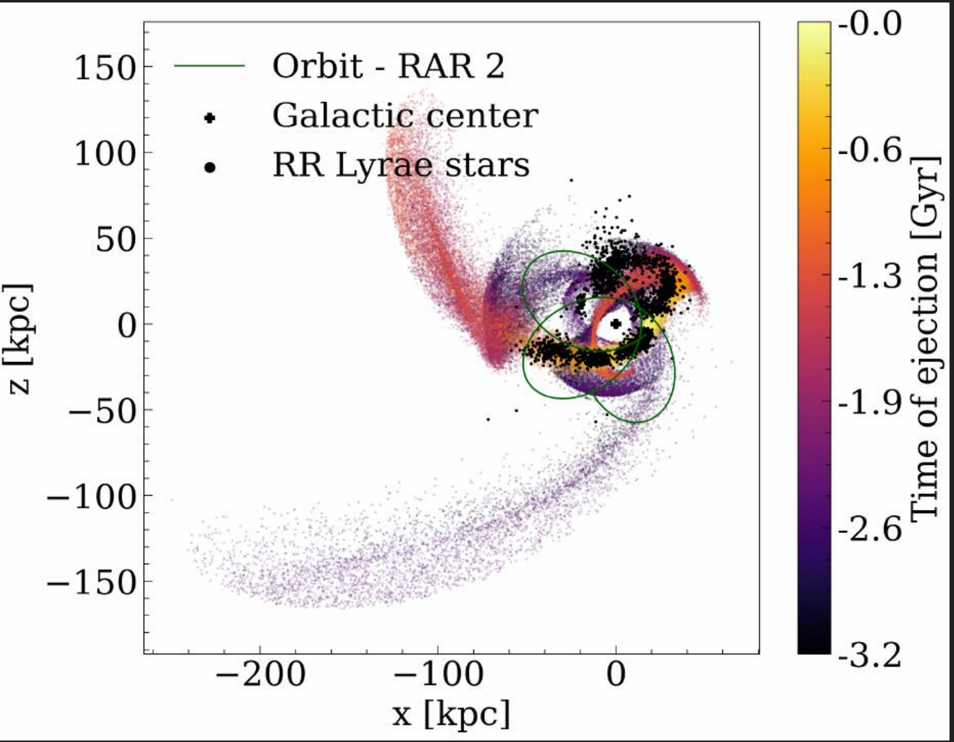
Full relativistic ray-tracing techniche done for a Milky Way-like case



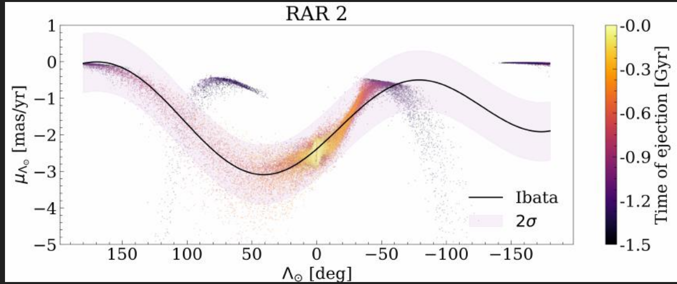
DM in the Galactic outskirts: different tracers

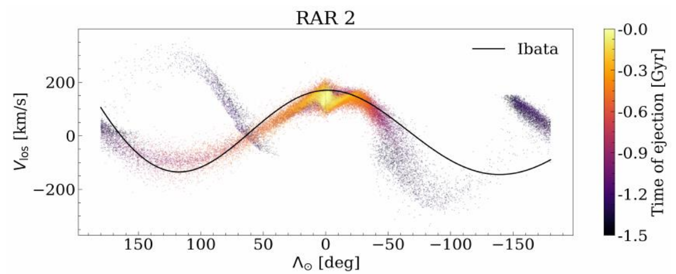
Milky Way observables: stellar streams using GAIA DR2-data

The fermionic core-halo model reproduces the main (6D) features Ibata et al. Apj (2020) of stelllar streams and simultaneously provides a good alternative to the BH scenario (GD-1 Mestre et al. A&A (2024) and Sgr stream Collazo, Mestre & Argüelles A&A (2025) in press)



The offset through the end of the leading arm can be explained by adding the LMC



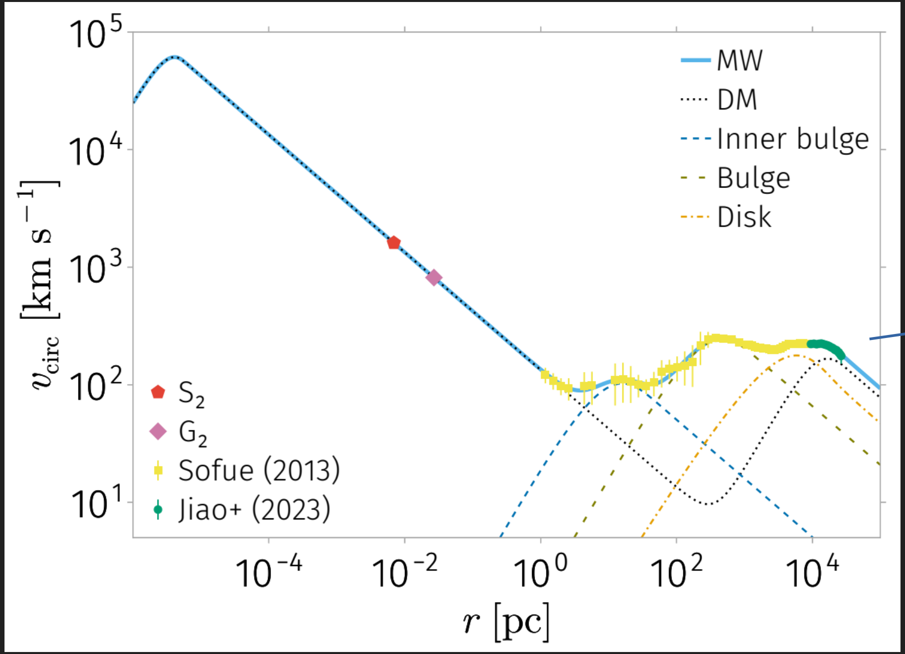


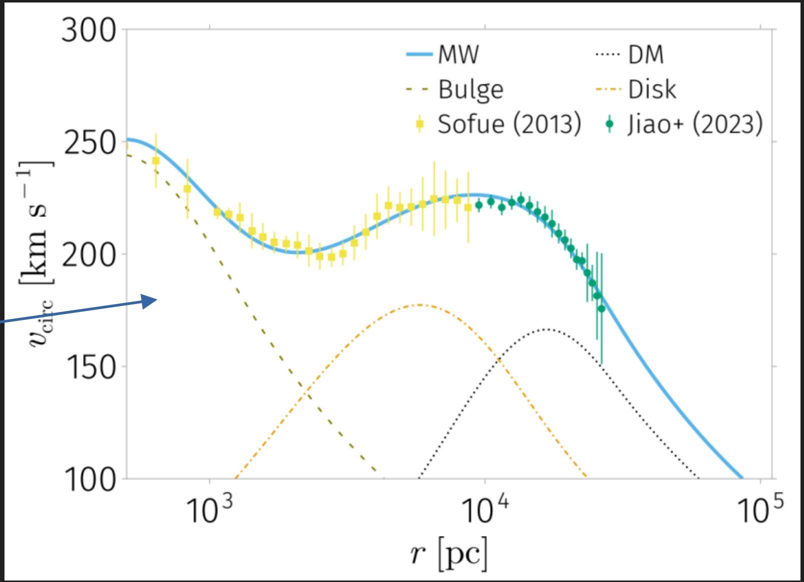
The predicted total mass of the Galaxy ~ 3×10^{11} Mo & sharp decay of the RC agrees with GAIA DR3 results!!

Milky Way observables: S-2 star G2 object & GAIA DR3- RC data

The same fermionic core-halo solutions which explains the S2 & G2 orbits & produce shadow-like features (m=300 keV), simulatneously explain the outer GAIA-DR3 rotation curve (RC) data !

Crespi, Argüelles, Becerra-Vergara, Mestre, Peissker, Rueda & Rufini (In prep. 2025)





Krut, Argüelles & Cavanis, arXiv: 2503.10870

For m > 190 keV, such Milky Way solutions are STABLE (& long-lived) in cosmology!

Conclusions

- The DM halo region of fermionic profiles is of “cored” nature in better agreement with observations than traditional CDM cuspy ones

- RAR profiles develop a dense, compact & supermassive core (lacking a hard surface) which can mimic the space-time signatures of a massive BH, or eventually collapse into one

- Compact enough DM cores (e.g. m~300 keV) can explain tracers of the Milky Way’s gravitational potential from center (Shadow-like, S-G stars) all the way to outer halo scales (GAIA DR2 & DR3 data)

- The fermionic model may provide a natural explanation for the connection between massive BHs and surrounding halos

- The model provides insights into the nature & mass of the DM particle (sub-MeV) to be found in the laboratory

Back up slides

On halos scales: Testing the model with 120 disk galaxies (SPARC)

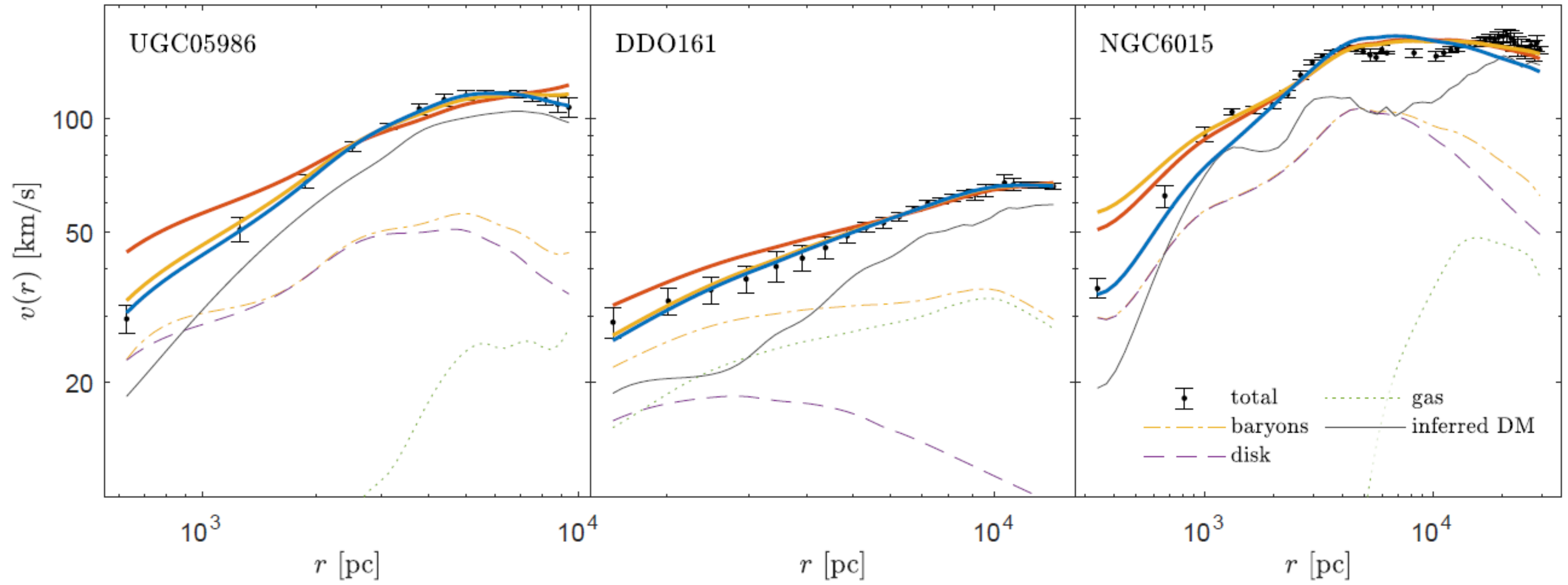
(Blue): Fermionic DM; (Yellow): gNFW; (Red): NFW

$$V_{\rm bar}^2 = \Upsilon_{\rm b} V_{\rm b}^2 + \Upsilon_{\rm d} V_{\rm d}^2 + V_{\rm g}^2$$

$$V_{\rm DM}^2 = V_{\rm tot}^2 - V_{\rm bar}^2$$

→

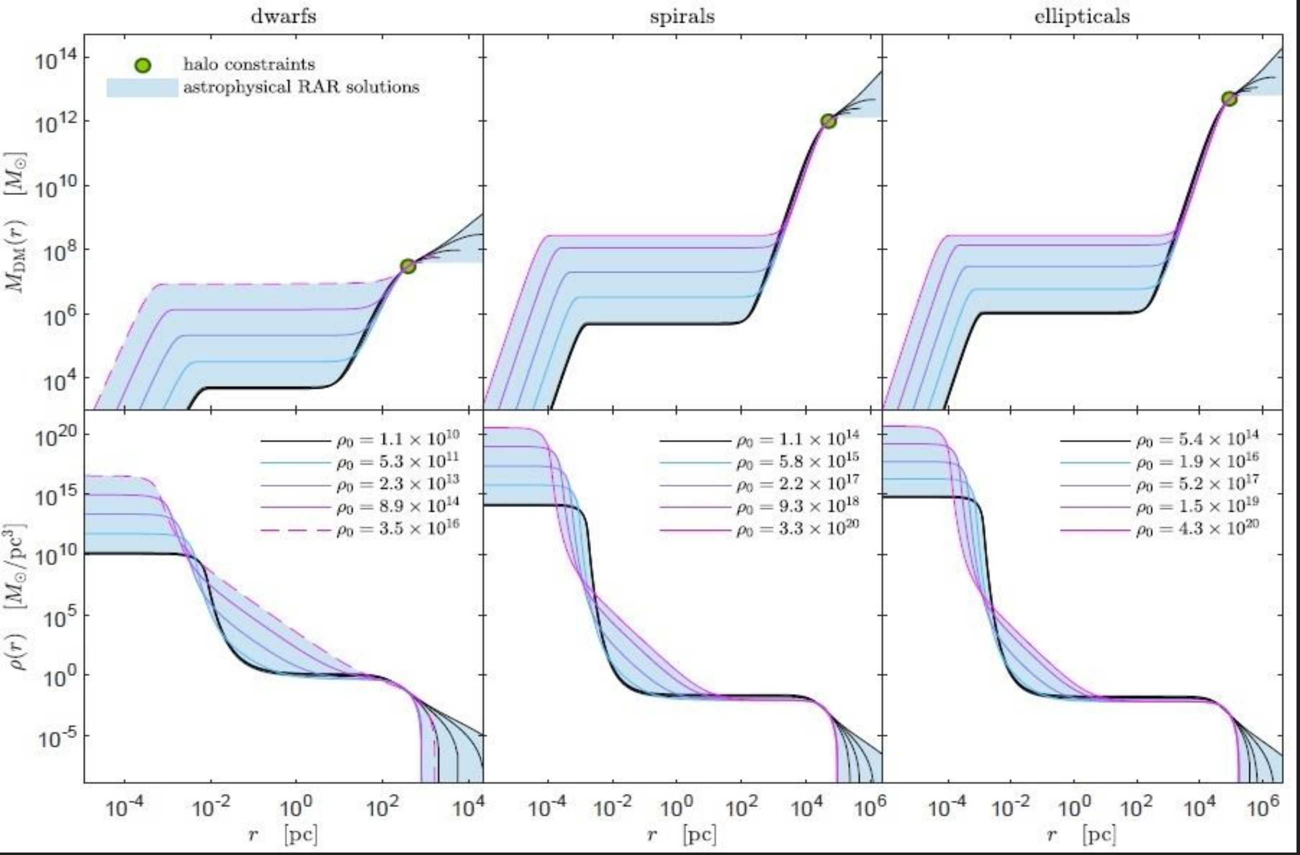
$$\chi^2(\boldsymbol{p}) = \sum_{i=1}^{N} \left[\frac{V_i - v(r_i, \boldsymbol{p})}{\Delta V_i} \right]^2$$



Krut, Argüelles, Chavanis, Rueda, Ruffini, Apj (2023)

On core & halo scales: fermionic profiles from dwarf to elliptical galaxies

- The fermionic model can be applied to any galaxy type, 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

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

SPIRALS: sample of nearby disk galaxies from THINGS

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

ELLIPTICALS: analyzed via weak lensing

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

CCAD Centro de Computación de Alto Desempeño

S2 star

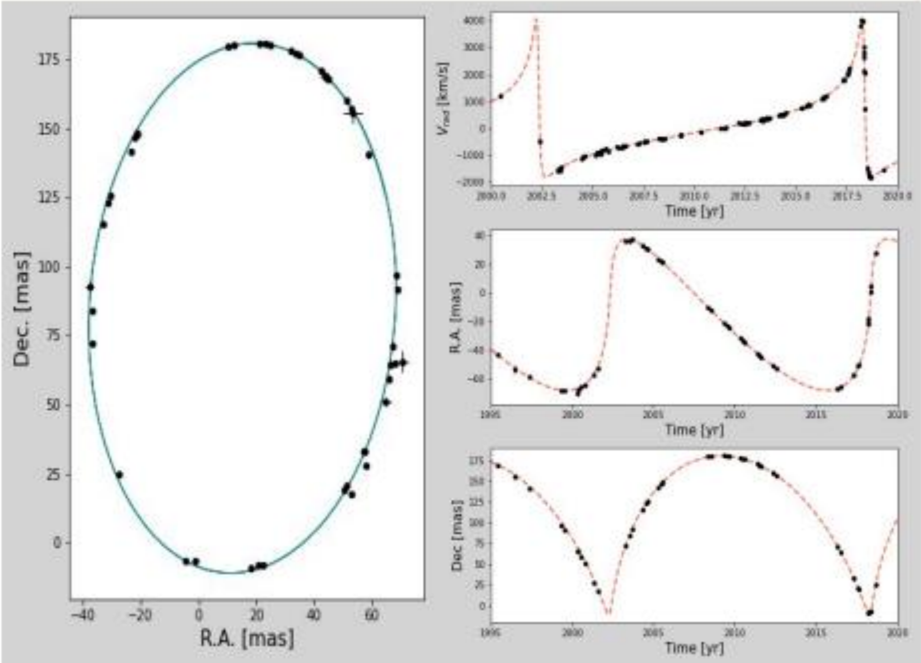
RAR - mc^2 = 100 keV

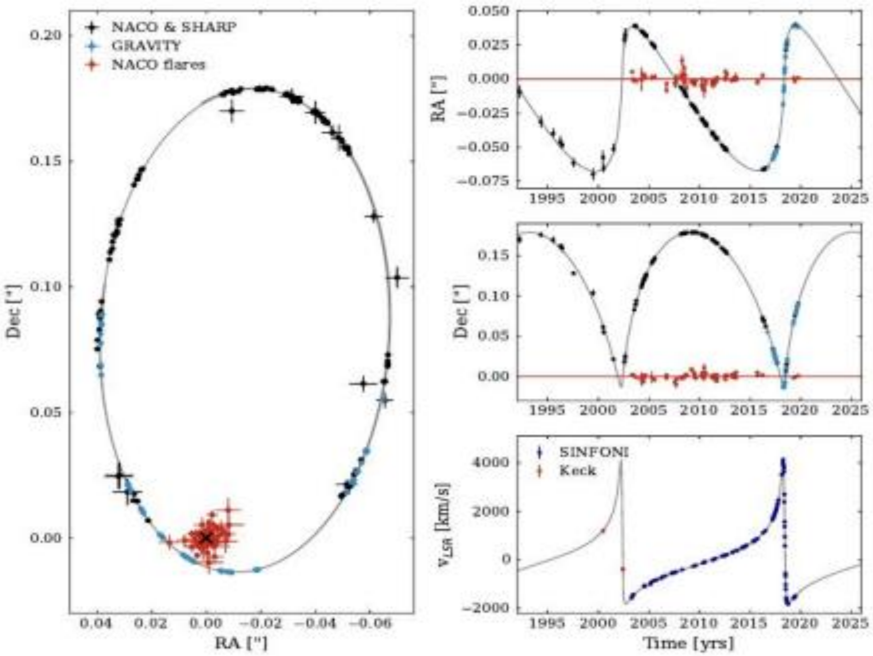
e	*a* [arcsec]	T [yr]	ω [°]	*i* [°]	Ω [°]	t_p [yr]	Δϕ [min/rev]
0.886	0.125	16.05	66.4	134.4	227.9	2018.38	11.8

Gravity Collaboration 2020

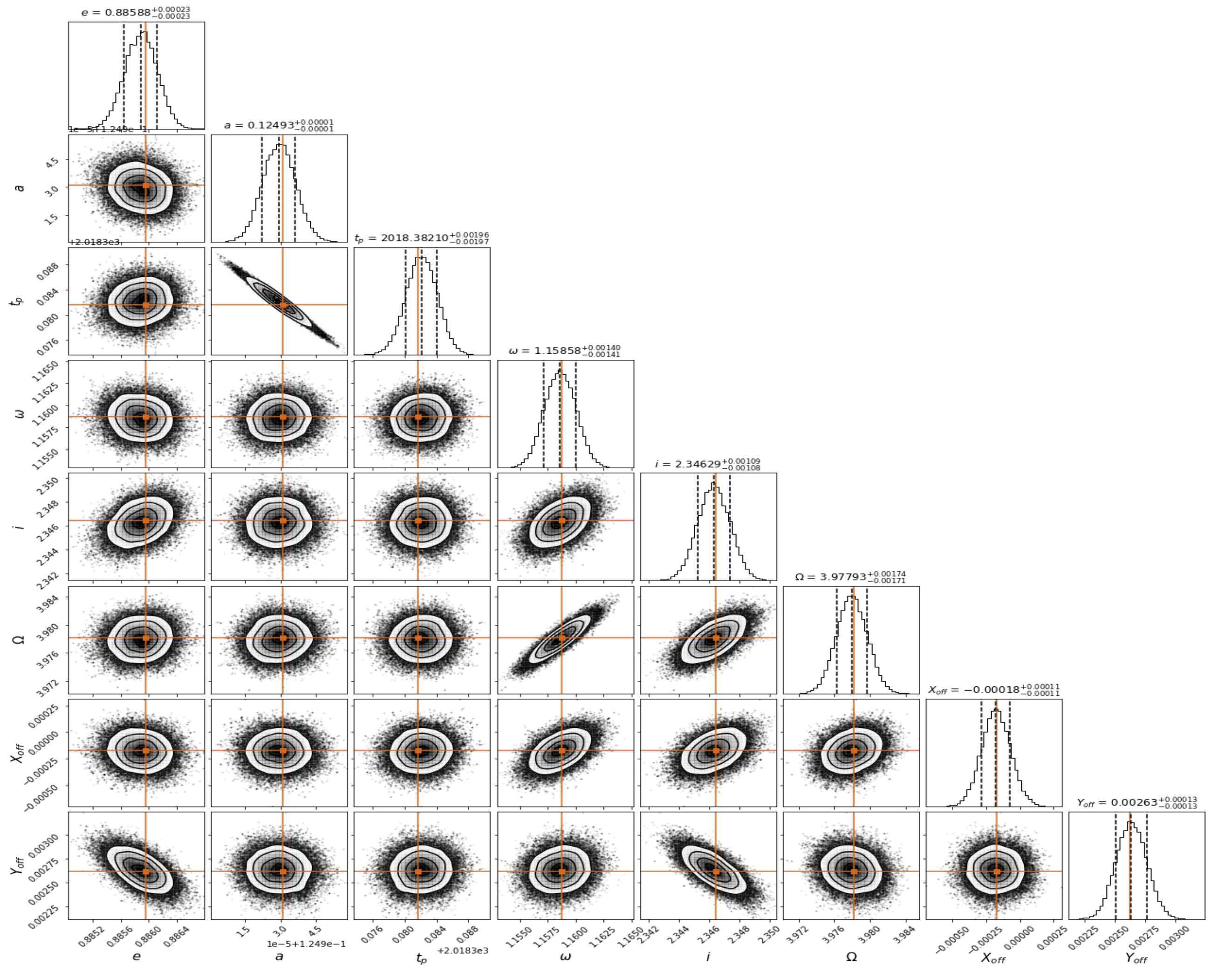
BH - $M_{BH} = 4.26 \times 10^6 M_{\odot}$

e	*a* [arcsec]	T [yr]	ω [°]	*i* [°]	Ω [°]	t_p [yr]	Δϕ [min/rev]
0.885	0.125	16.05	66.26	134.6	228.2	2018.38	12.1





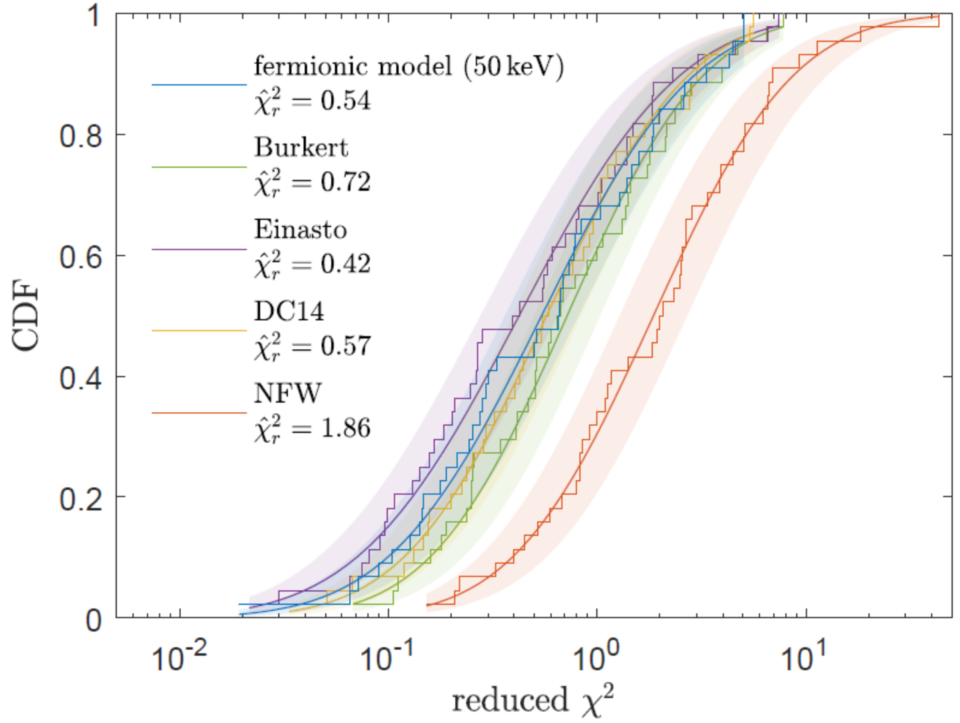
- **Posteriors of the S2-star orbital parameters determined from a Monte-Carlo Markov-Chain method within a core-halo non-criritcal solution (m=100 keV)**

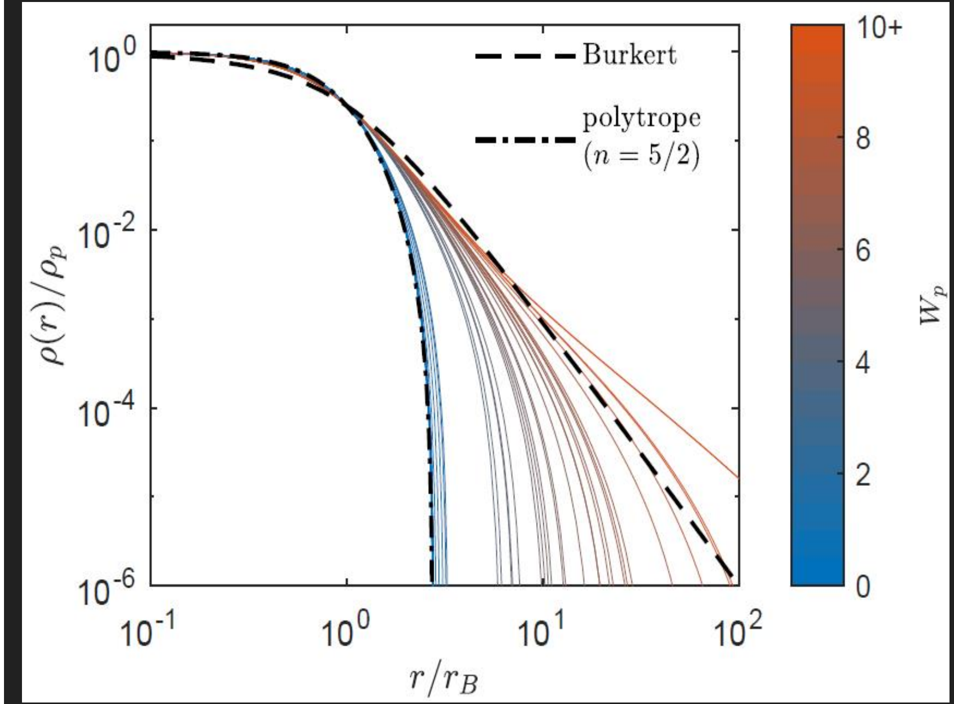


Testing the RAR model with the SPARC data-set of 120 disk galaxies

- RAR profiles which best-fit SPARC galaxies can develope halo shapes similar to Burkert

- Cuspy (NFW) DM profiles are clearly disfavoured w.r.t cored profiles by the SPARC RCs

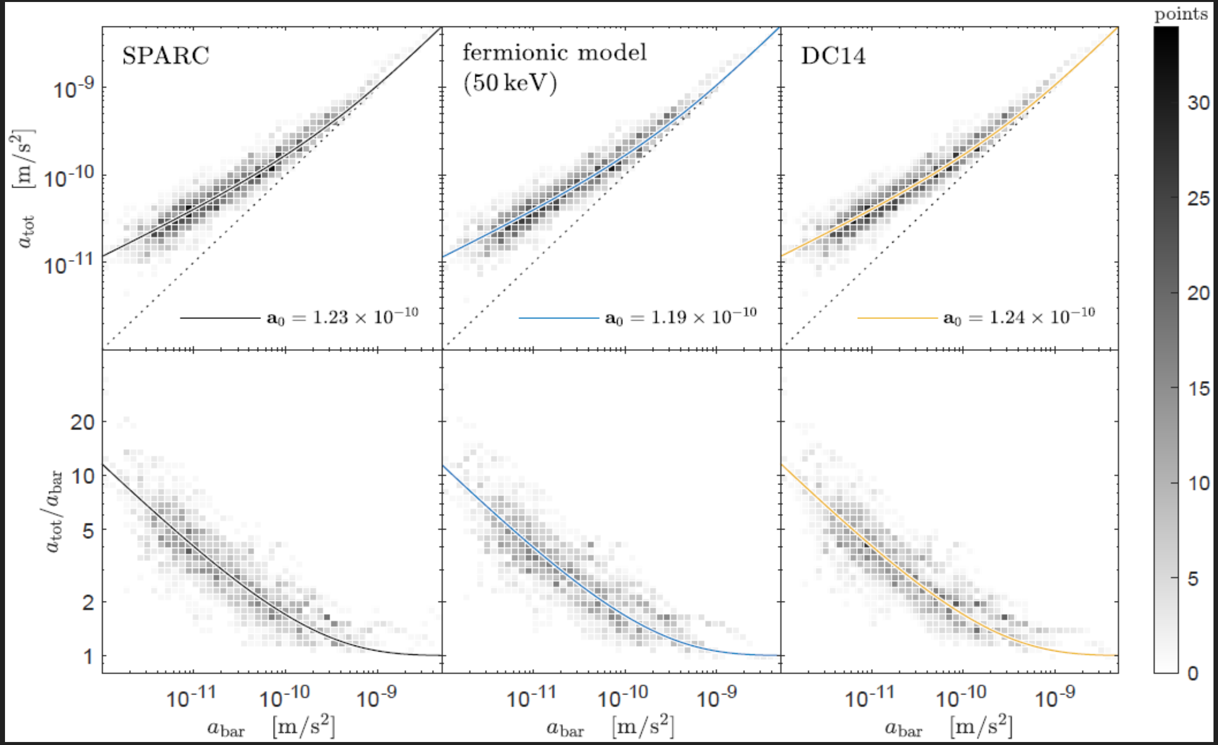




Krut, Argüelles, Chavanis, Rueda, Ruffini, Apj (2023)

The RAR model explains the Radial Acceleration Relation and the BTFR

Radial Acceleration Relation: Non linear correlation between the radial acceleration caused by the total matter, and the one generated by the baryons only: **Valid at any resolved galaxy radii !**



$$a_{tot} = \frac{a_{bar}}{1 - e^{-\sqrt{a_{bar}/a_0}}}$$

These acceleration relations DO NOT imply of any new physics (i.e. MOND), and can be reproduced by the LCDM, and by the fermionic halos obtained from a MEP

Krut, Argüelles, Chavanis, Rueda, Ruffini, Apj (2023)

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

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What does lie at the Milky Way centre? Insights from the S2-star orbit precession

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J. A. Rueda[2,3,6,7★] and R. Ruffini[2,3,6,7]

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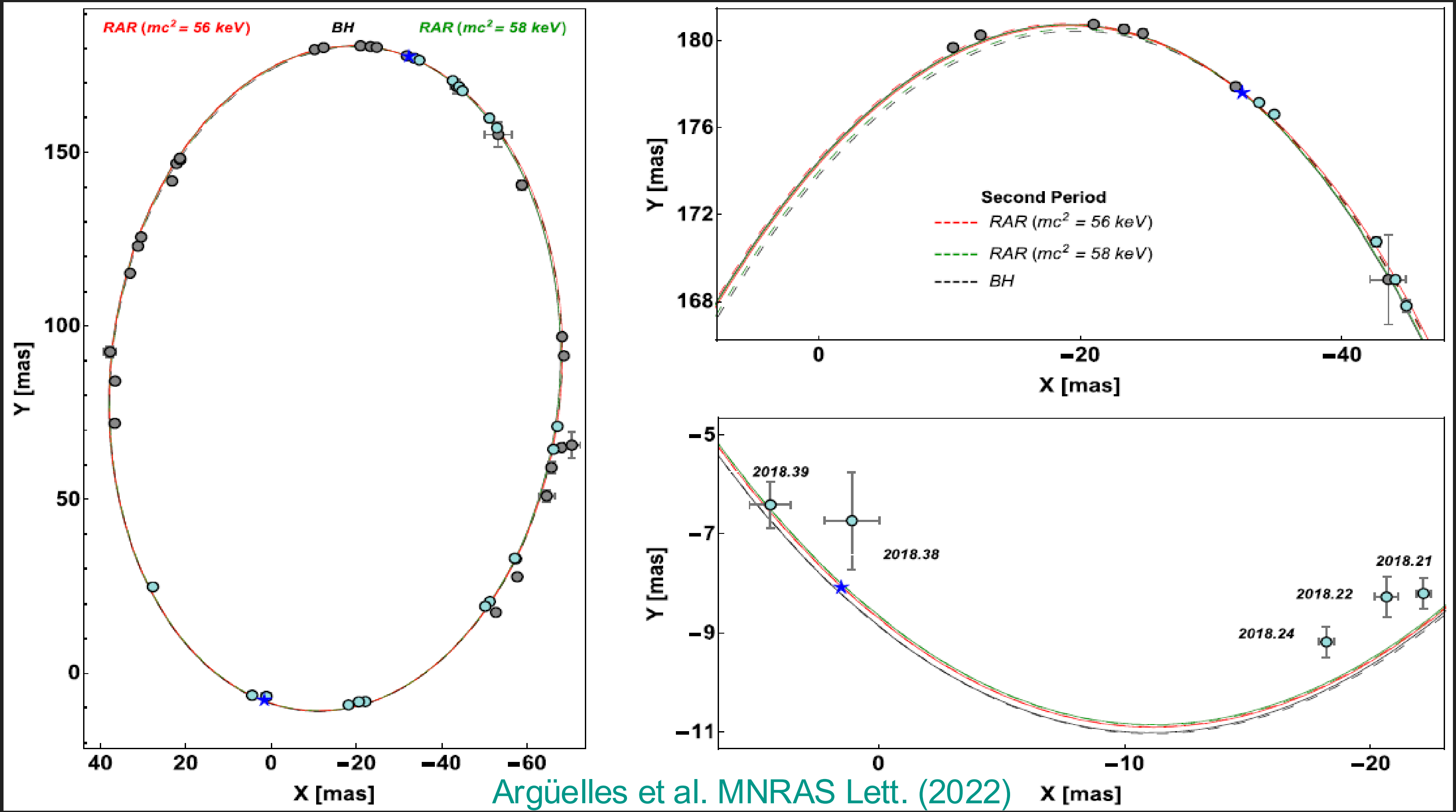
ABSTRACT

It has been recently demonstrated that both, a classical Schwarzschild black hole (BH), and a dense concentration of self-gravitating fermionic dark matter (DM) placed at the Galaxy centre, can explain the precise astrometric data (positions and radial velocities) of the S-stars orbiting Sgr A∗. This result encompasses the 17 best resolved S-stars, and includes the test of general relativistic effects such as the gravitational redshift in the S2-star. In addition, the DM model features another remarkable result: The dense core of fermions is the central region of a continuous density distribution of DM whose diluted halo explains the Galactic rotation curve. In this Letter, we complement the above findings by analysing in both models the relativistic periapsis precession of the S2-star orbit. While the Schwarzschild BH scenario predicts a unique prograde precession for S2, in the DM scenario, it can be either retrograde or prograde, depending on the amount of DM mass enclosed within the S2 orbit, which, in turn, is a function of the DM fermion mass. We show that all the current and publicly available data of S2 cannot discriminate between the two models, but upcoming S2 astrometry close to next apocentre passage could potentially establish if Sgr A∗ is governed by a classical BH or by a quantum DM system.

Testing the DM-core alternative to the BH with the S-2 star precession



Argüelles et al. MNRAS Lett. (2022)

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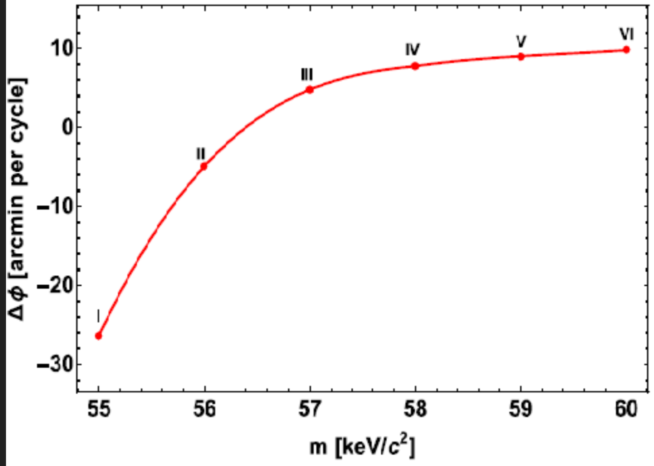
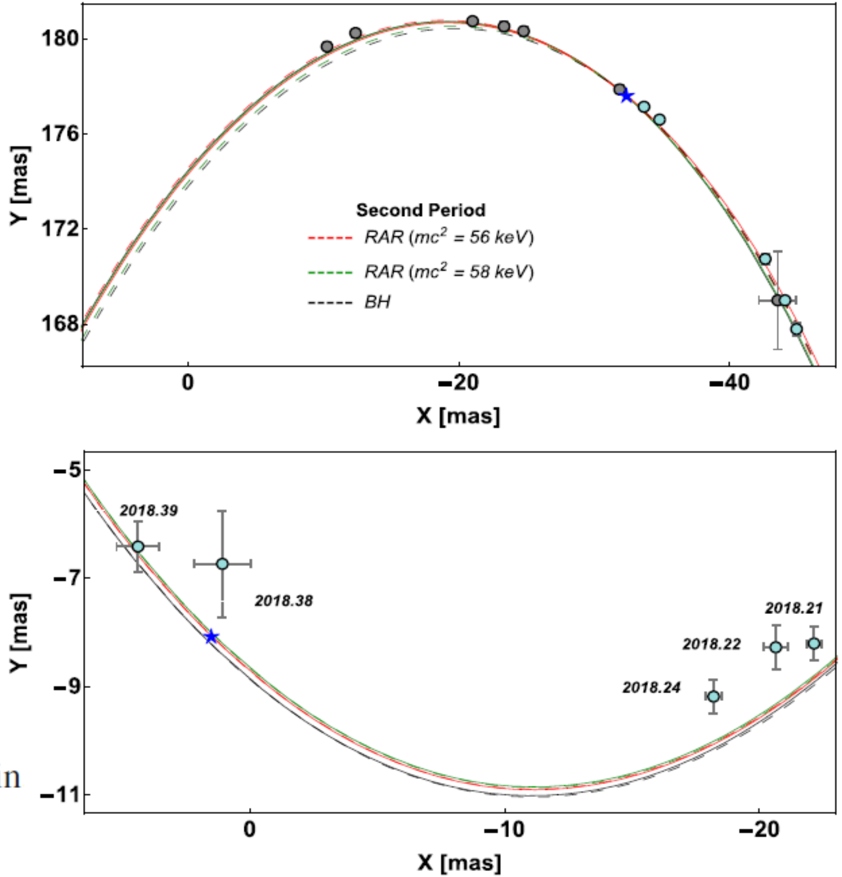


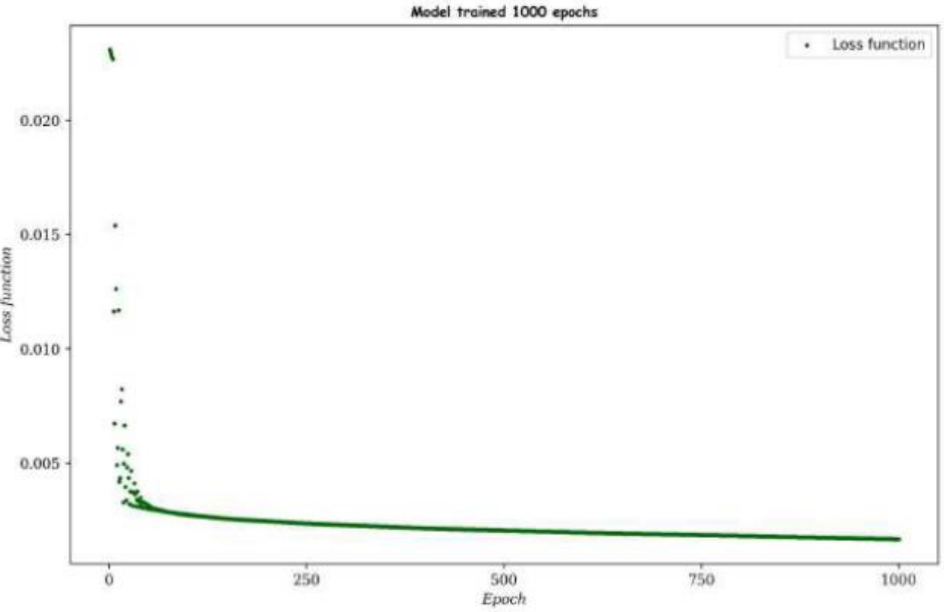


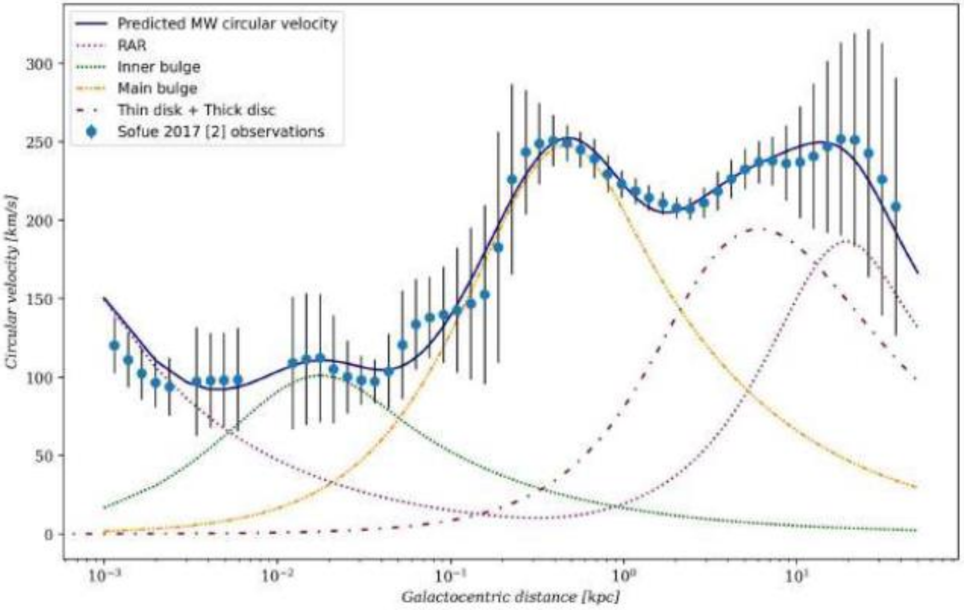
$$\Delta\phi_{\rm BH} = 6\pi G M_{\rm BH}/[c^2 a(1-e^2)] \approx 12\,\text{arcmin}$$

Argüelles et al. MNRAS Lett. (2022)

Rotation Curve fitting using state-of-the-art Machine Learning

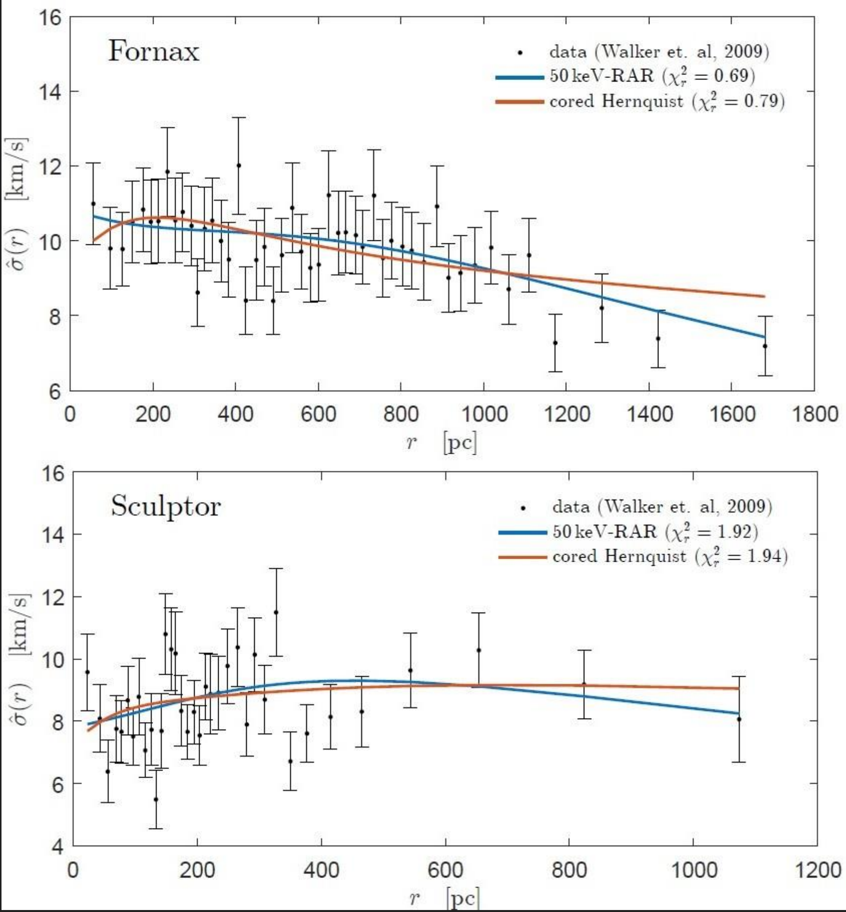
- We use machine learning tools (grdient descent, through **PyTorch**) to fit the observed Milky Way RC: Very useful to test semi-analitical models for DM (such as RAR, or Fuzzy DM) : can include **> 10** free parameters (Baryonic + DM), minimizing the Loss-function in few hs time

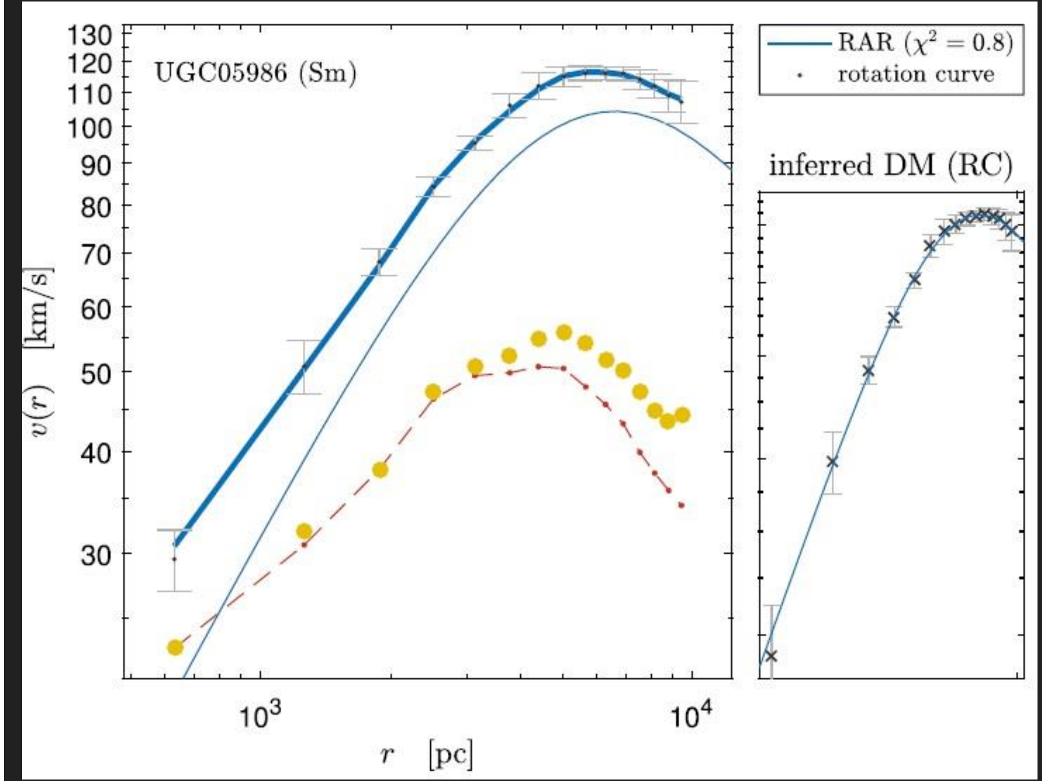




Collazo, Argüelles & Mestre, http://fof.oac.uncor.edu/2022/posters/ (2022)

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

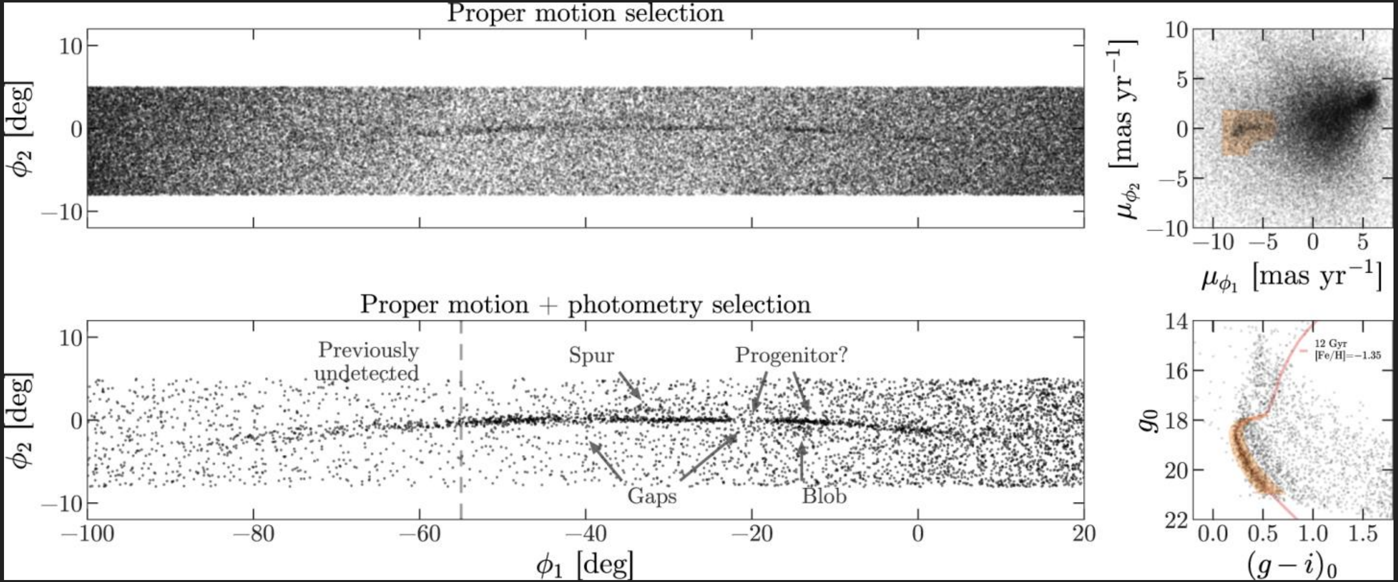




Applications: Galactic Scales (Stellar-Stream tracers)

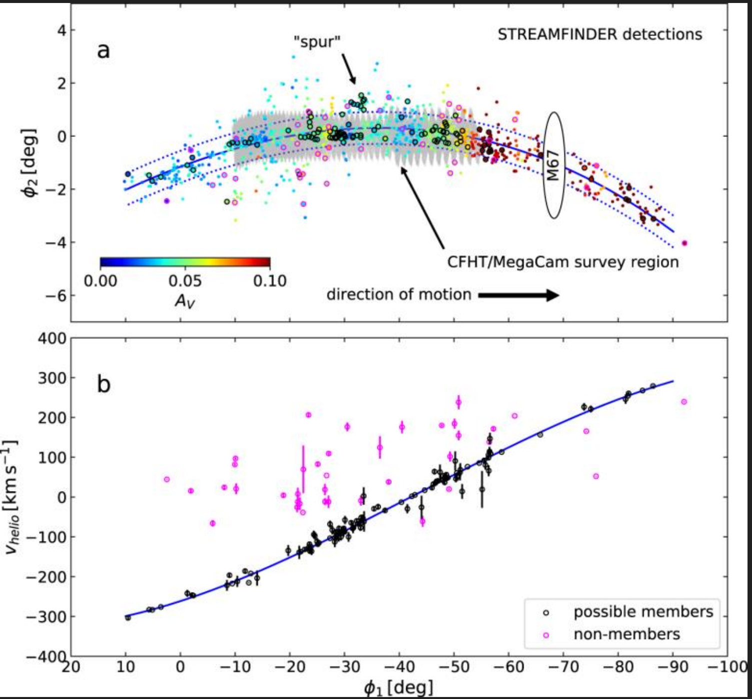
Constraining the fermionic DM model with the GD-1 stream

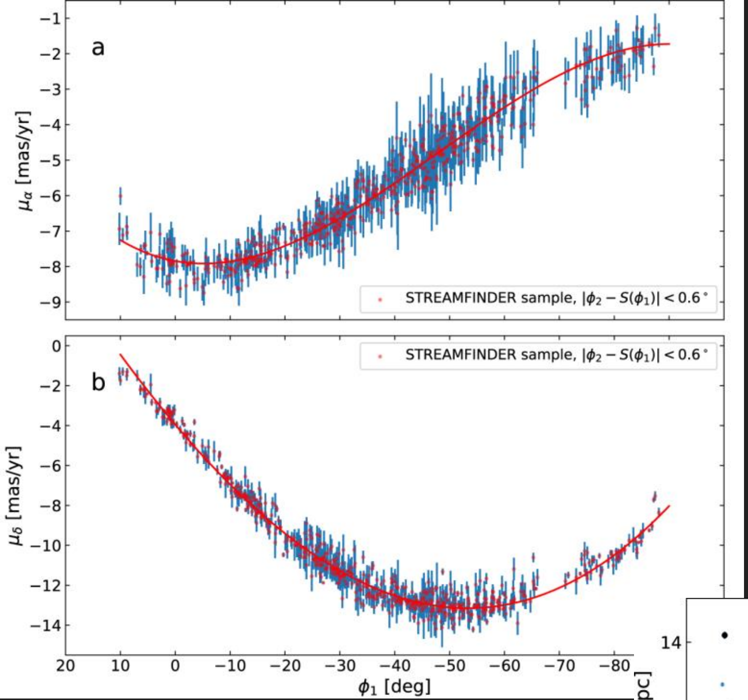
- A cold stream (GD-1) travelling through the halo (shown in self-coordinates along the stream) Price-Whelan & Bonaca, Apj (2018)



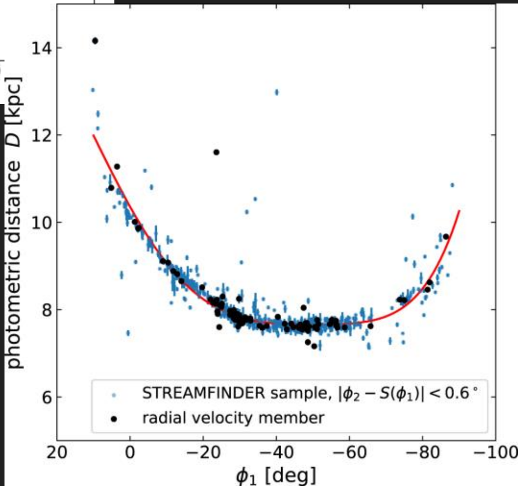
- Can the Gd-1observables be explained for a Milky Way composed of baryons + fermionic DM model ?

GD-1 observables





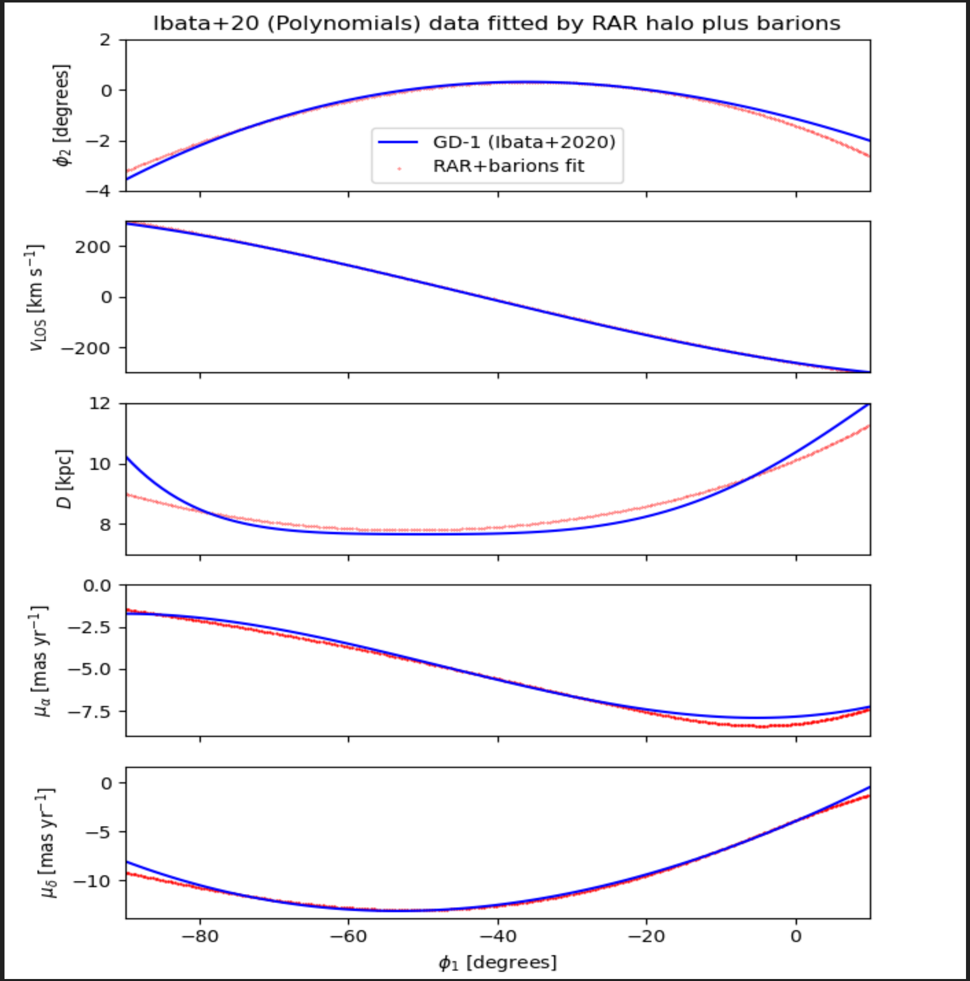
Ibata, et al. Apj (2020)



STREAMFINDER (Gaia DR2): 811 star candidate members;

Cross correlation with spectroscopy: 156 stars in RV sample

Best-fit RAR model parameters to GD-1



Full model: Galaxy potential + GD-1 stream

Galaxy potential: RAR(θ_0, W_0) + Baryons (fixed)

(m and β_0 fixed to fulfill Mc=M_(SgrA*) in agreement with S-stars)

GD-1 stream: Orbit (IC) (6 parameters)

We find a best fit parmeters

Θ_0=36.2; W_0=63.6

In Good agreement with overall rotation curve (independent tracer!)

Mestre, Argüelles, et al. A&A (2024)

Applications: Cosmological Scales (non linear regime)

On the growth of supermassive black holes formed from the gravitational collapse of fermionic dark matter cores

C. R. Argüelles,[1,2,3]★ K. Boshkayev,[4,5]† A. Krut,[1] G. Nurbakhyt,[4] J. A. Rueda,[1,2,6,7,8]‡ R. Ruffini,[1,2,9]§ J. D. Uribe-Suárez,[2,10]¶ and R. Yunis[2]

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Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

Observations support the idea that supermassive black holes (SMBHs) power the emission at the center of active galaxies. However, contrary to stellar-mass BHs, there is a poor understanding of their origin and physical formation channel. In this article, we propose a new process of SMBH formation in the early Universe that is not associated with baryonic matter (massive stars) or primordial cosmology. In this novel approach, SMBH seeds originate from the gravitational collapse of fermionic dense dark matter (DM) cores that arise at the center of DM halos as they form. We show that such a DM formation channel can occur before star formation, leading to heavier BH seeds than standard baryonic channels. The SMBH seeds subsequently grow by accretion. We compute the evolution of the mass and angular momentum of the BH using a geodesic general relativistic disk accretion model. We show that these SMBH seeds grow to $\sim 10^9 - 10^{10}\,M_\odot$ in the first Gyr of the lifetime of the Universe without invoking unrealistic (or fine-tuned) accretion rates.

Key words: galaxies: nuclei — quasars: supermassive black holes — galaxies: formation — galaxies: structure — galaxies: high-redshift — dark matter

How a self-gravitating system of collisionless fermions reaches the steady state?

- Dynamically stability - i.e having f(r,p) solution- DOES NOT necessarily imply thermodynamic stability (Some dynamically stable solutions are more likely in Nature than others)

- To find dynamically and thermodynamicaly stable configurations of fermions in GR, we need solutions that maximize the global entropy

$$S = \int_0^R s(r) e^{\lambda/2} 4\pi r^2 \mathrm{d}r$$

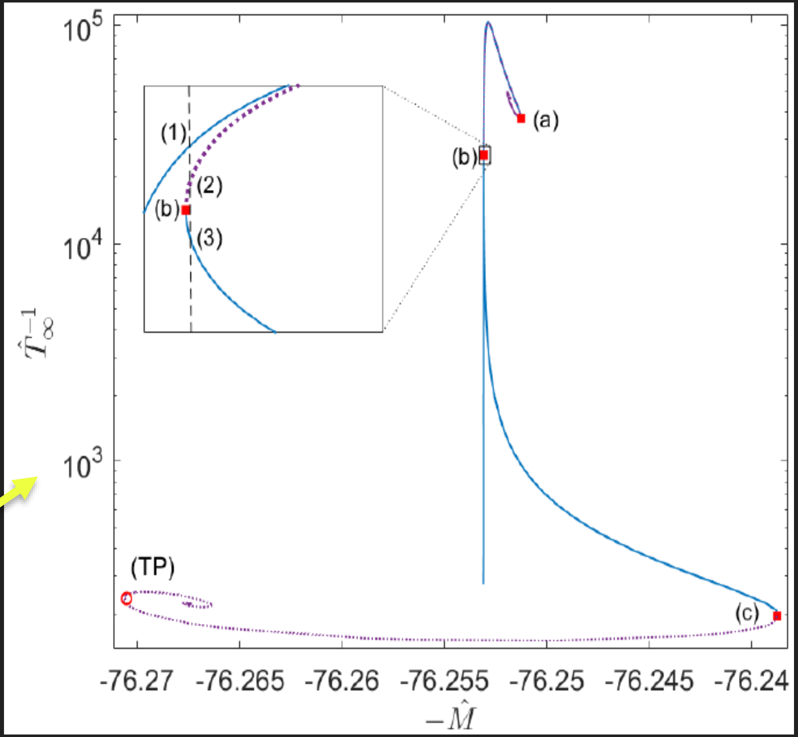
δ^2 S< 0

Gibbs-Duhem →

$$s(r) = \frac{P(r) + \rho(r) - \mu(r) n(r)}{T(r)}$$

- Stability problem can be solved via the Katz criterion J. Katz, MNRAS (1978) : relies only in the derivatives of the caloric curve (E vs. $1/T_\infty$)

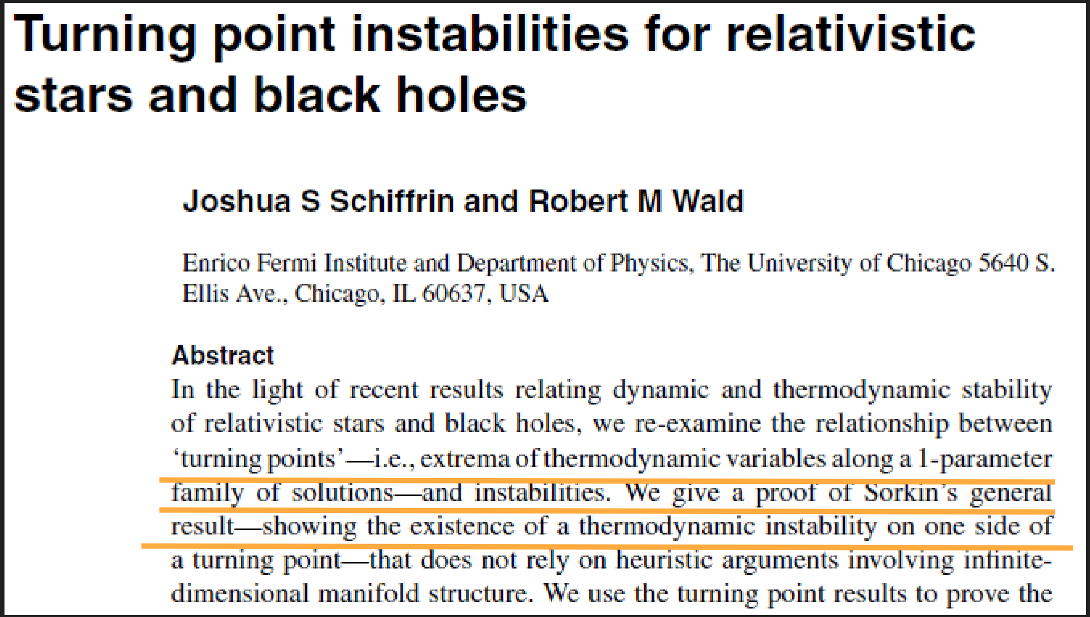
- Series of equilibrium along the caloric curve for fixed N and μ. The case of typical DM halos of M ~ 5 x 10^{10} Mo Argüelles et al. MNRAS (2021)



Turning point instability & last stable configuration

- Hystorically, the gravitational collapse of a degenerate (and relativistic) `star' was understood in terms of the onset of a thermodynamic instabiliy at a Turning-Point (TP), e.g. at $dM/d\rho_0 = 0$
- However TPs don't provide a necessary condition for thermodynamic instability: the onset of instability can occur prior to the TP (or even without its existence) Schiffrin & Wald (2014)

For our case we have:



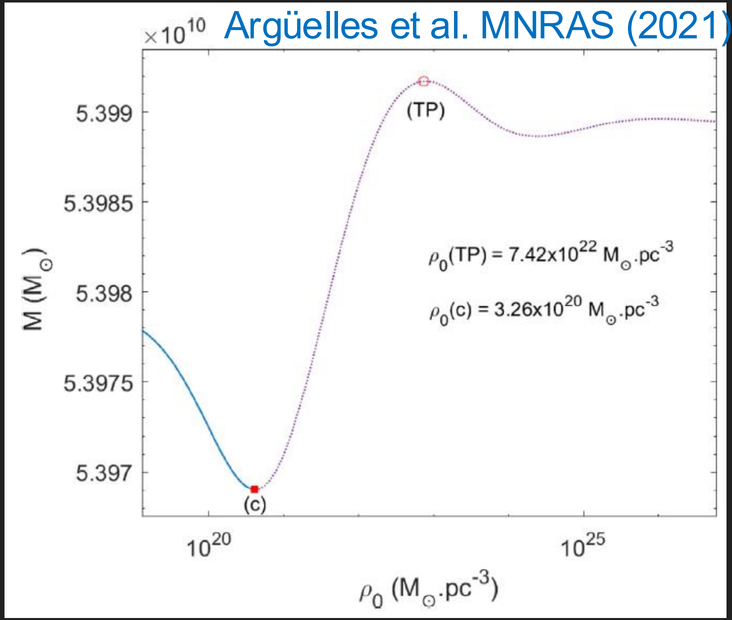
Turning point instabilities for relativistic stars and black holes

Joshua S Schiffrin and Robert M Wald

Enrico Fermi Institute and Department of Physics, The University of Chicago 5640 S. Ellis Ave., Chicago, IL 60637, USA

Abstract

In the light of recent results relating dynamic and thermodynamic stability of relativistic stars and black holes, we re-examine the relationship between 'turning points'—i.e., extrema of thermodynamic variables along a 1-parameter family of solutions—and instabilities. We give a proof of Sorkin's general result—showing the existence of a thermodynamic instability on one side of a turning point—that does not rely on heuristic arguments involving infinite-dimensional manifold structure. We use the turning point results to prove the



How do we obtain realistic DM halos in cosmology via this method ?

- One should i) calculate the power spectrum P(k) in a given (~10¹ keV) cosmology (CLASS)
  ii) apply the Press-Schechter formalism to obtain $M_{vir} = M(R_{vir})$ at given z_{vir};

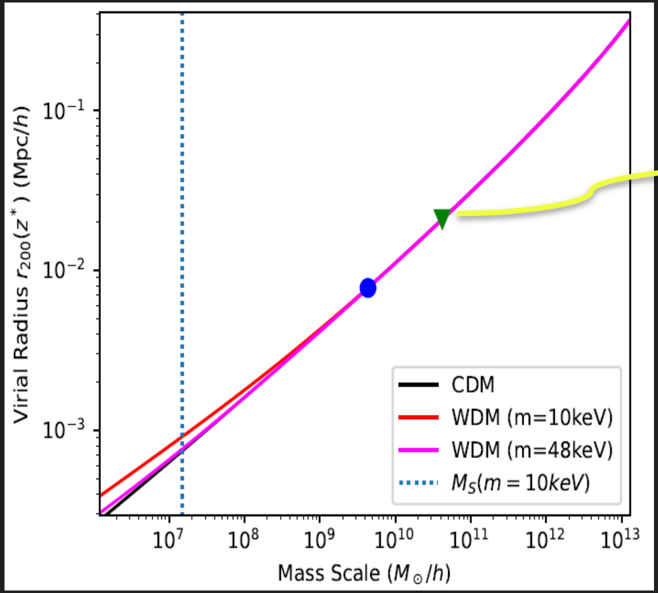
Mass variance →

$$\sigma^2(M) = \frac{1}{2\pi^2}\int_0^\infty P(k)W^2(k,R)k^2\mathrm{d}k$$

Window *top-hat* function

$$\sigma(M^*) = \delta_c(t)$$

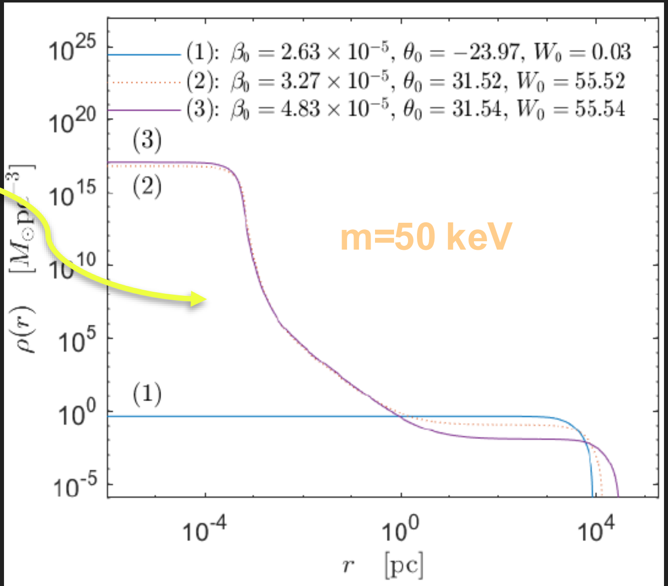
Critical overdensity (spherical collapse)



$M_{vir} = 5.4 \times 10^{10}$ Mo

iii) Use the stable family of solutions obtained at violent relaxation (i.e. valid at z_{vir}), in agreement with avobe virial constraints

Argüelles et al. MNRAS (2021)



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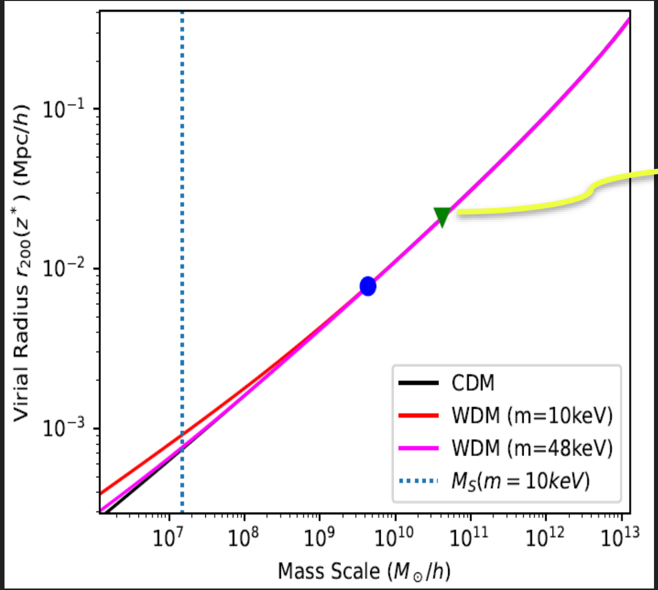

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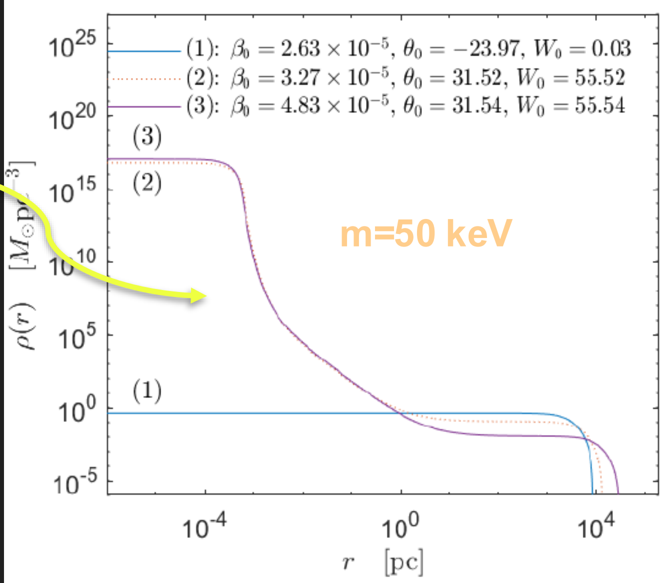

Argüelles et al. MNRAS (2021)

Novel SMBH formation scenario from DM core-collapse

This solution 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)

The degeneracy pressure of the DM core cannot support its own weight and undergo a core-collapse towards a SMBH-seed from DM ! (i.e. without the need of barionic matter)

Argüelles et al. MNRAS (2021)

$$M_{\rm crit} \approx 0.384\frac{m_{\rm Pl}^3}{m^2} \approx 6.274\times10^9\left(\frac{10\ {\rm keV}}{mc^2}\right)^2 M_\odot$$

Turning point instabilities for relativistic stars and black holes

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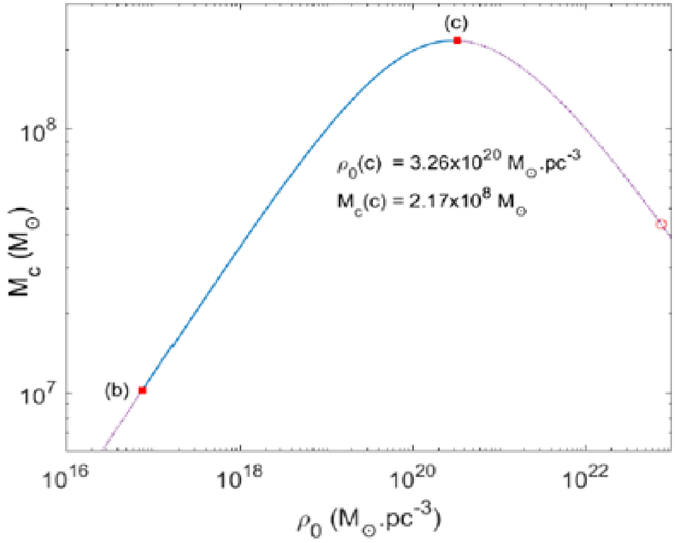


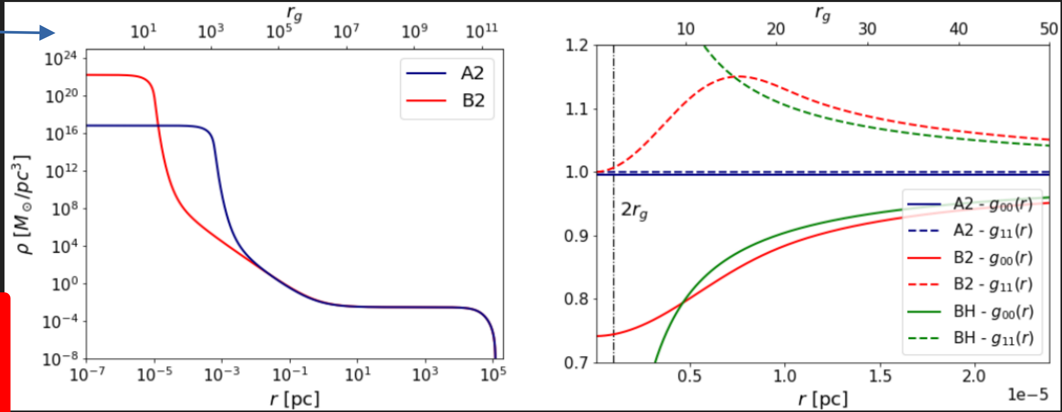
Disc accretion for horizonless dark compact objects: the fermion core

- We study accretion flow and associated emission using generalized "α-discs" onto the DM-core
  Millauro, Argüelles et al. A&A (2024)

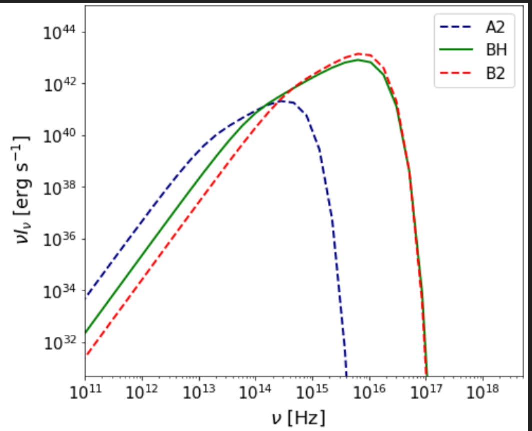
Fermionic DM profiles of active galaxies

Example: Mc=10^7 Mo; M=10^{12} Mo

Solution A2 → m=50 keV
Solution B2 → m=200 keV



Emitted flux: it always exist a DM-core comapcity such that the flux is indistinguishable from that of BH of the same mass as the core

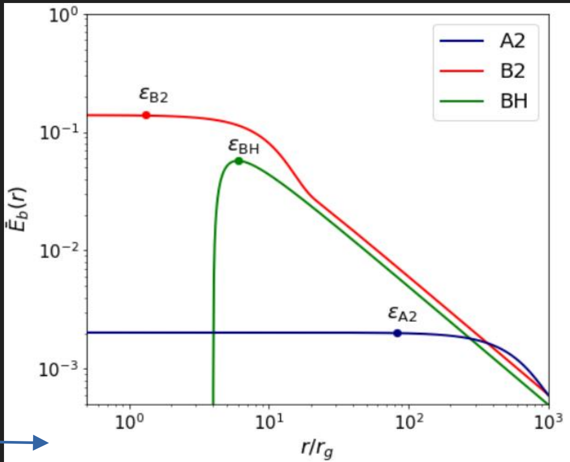


- Geometrically thin & optically thick disc with angular speed ~ Keplerian

$$\Omega = \left(\frac{GM(r)}{r^3}\right)^{1/2}$$

Efficiency of energy extraction from the central object

$$\bar{E}_b(r) = 1 - \sqrt{g_{00}(r)\left(1 + \frac{r g'_{00}(r)}{2g_{00}(r) - r g'_{00}(r)}\right)}$$



Growth of SMBH seeds formed from the gravitational collapse of DM cores

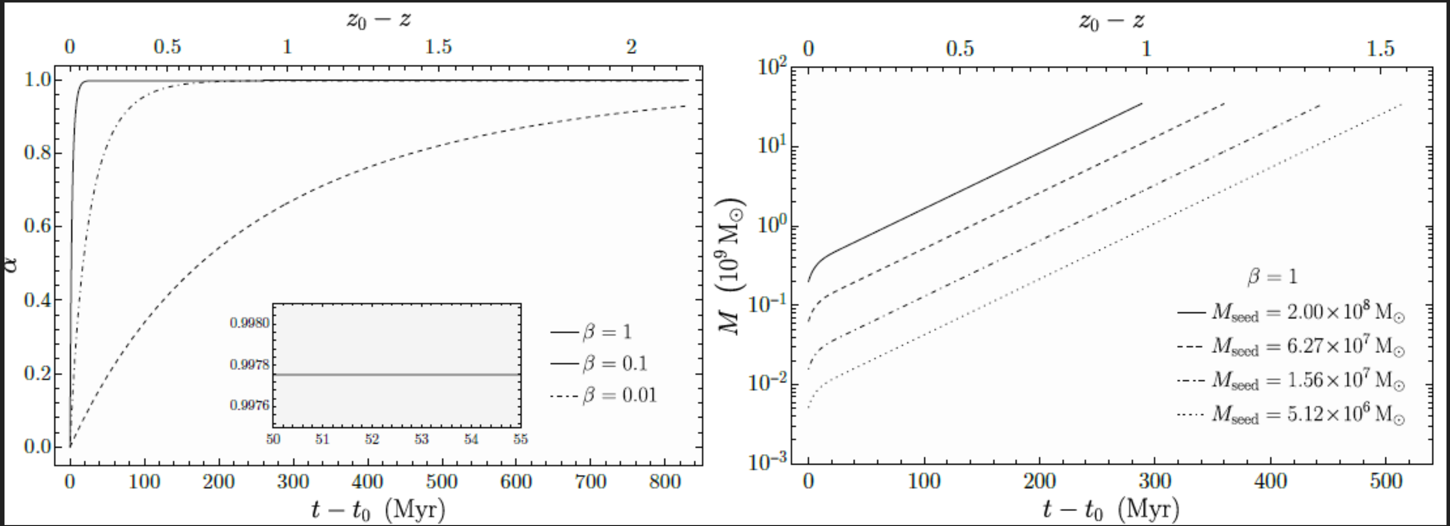
. We compute, in a Kerr metric, the evolution of mass and angular momentum of the BH using a geodesic general relativistic disc accretion model Argüelles et al. MNRAS (2023)

. The rate at which the rest-mass dm flows inward through the local balance between gravitational acceleratoin and radiation pressure (along z-axis) is calculated

$$\dot{M} = \dot{M}_{\rm matter} + \dot{M}_{\rm rad}$$
$$\dot{J} = \dot{J}_{\rm matter} + \dot{J}_{\rm rad}$$

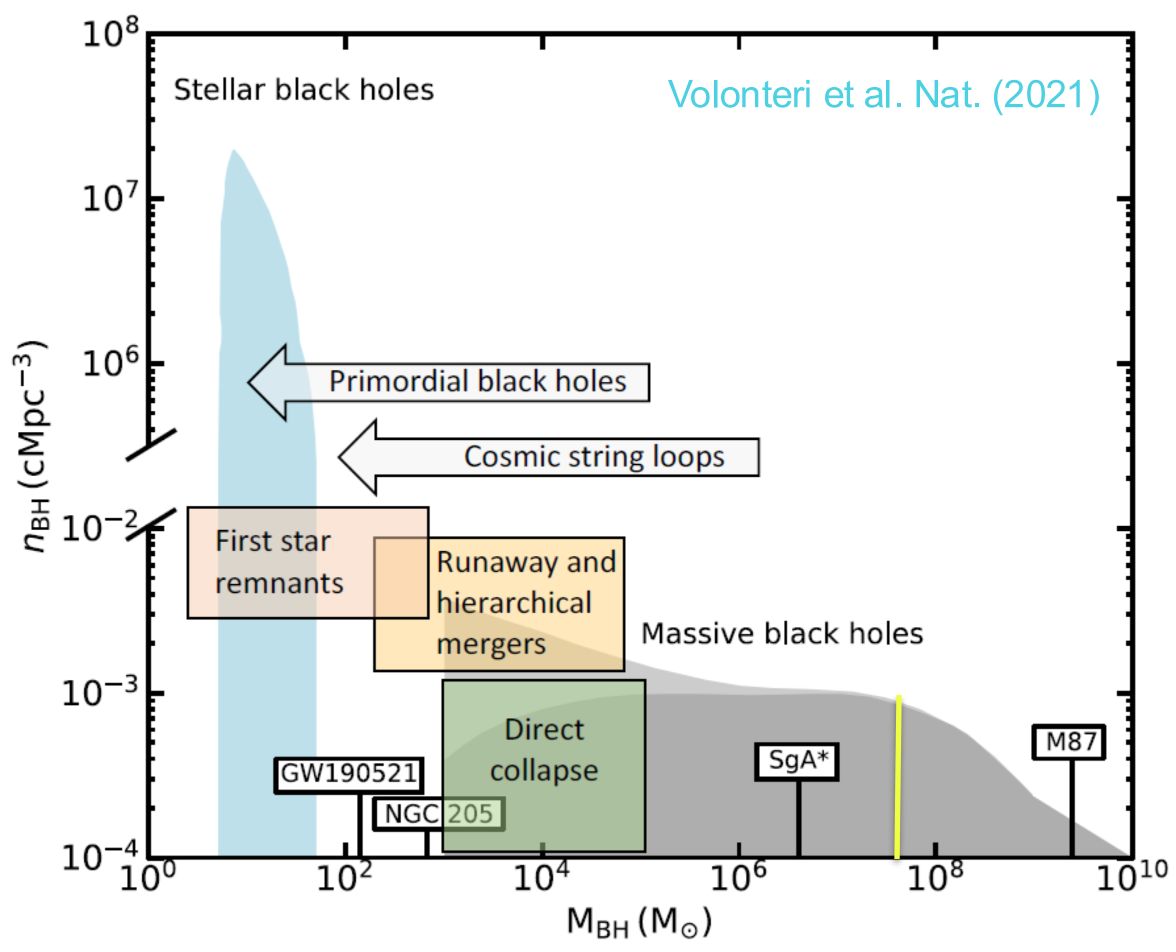
$$\dot{M}_{\rm matter} = \epsilon_0\, \dot{m}$$
$$\dot{J}_{\rm matter} = l_0\, \dot{m}$$

$$\dot{m} \equiv \beta\, \dot{m}_{\rm crit} = \frac{8\pi\beta M}{3\kappa \max\left\{\frac{f(x,\alpha)}{x^2}\right\}}$$



This BH-seeds are larger tan typical baryonic-sedes (e.g. Pop. III stars), and can grow up to 10^9 – 10^(10) M⊙ in a fraction of 1st Gyr of the life of the Universe without invoking unrealistic accretion rates !

Different Massive BH formation channels: Baryonic & Early Universe channels



(I) Baryonic channels:

- **Pop. III stars** (1st stars remnants)
- **Direct collapse of gas clouds**
- **Runnaway collisions in star clusters**

(II) Early Universe channels:
(poorly constrained epochs)

- **Topological defects** (cosmic strings, domain walls)

(III) DM channels:

- **Fermionic DM core-collapse**
- **SIDM (grav. catastrophe)**

Success of the LCDM paradigm on large scales

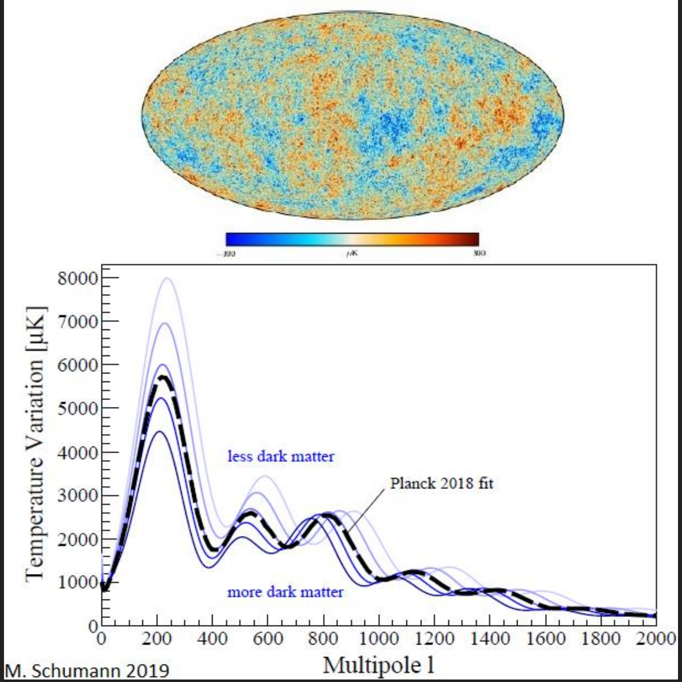
Success of CDM:
Cold, colissionless self-gravitating system

⇩

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