CONICET

A new channel for supermassive black hole formation

Carlos R. Argüelles

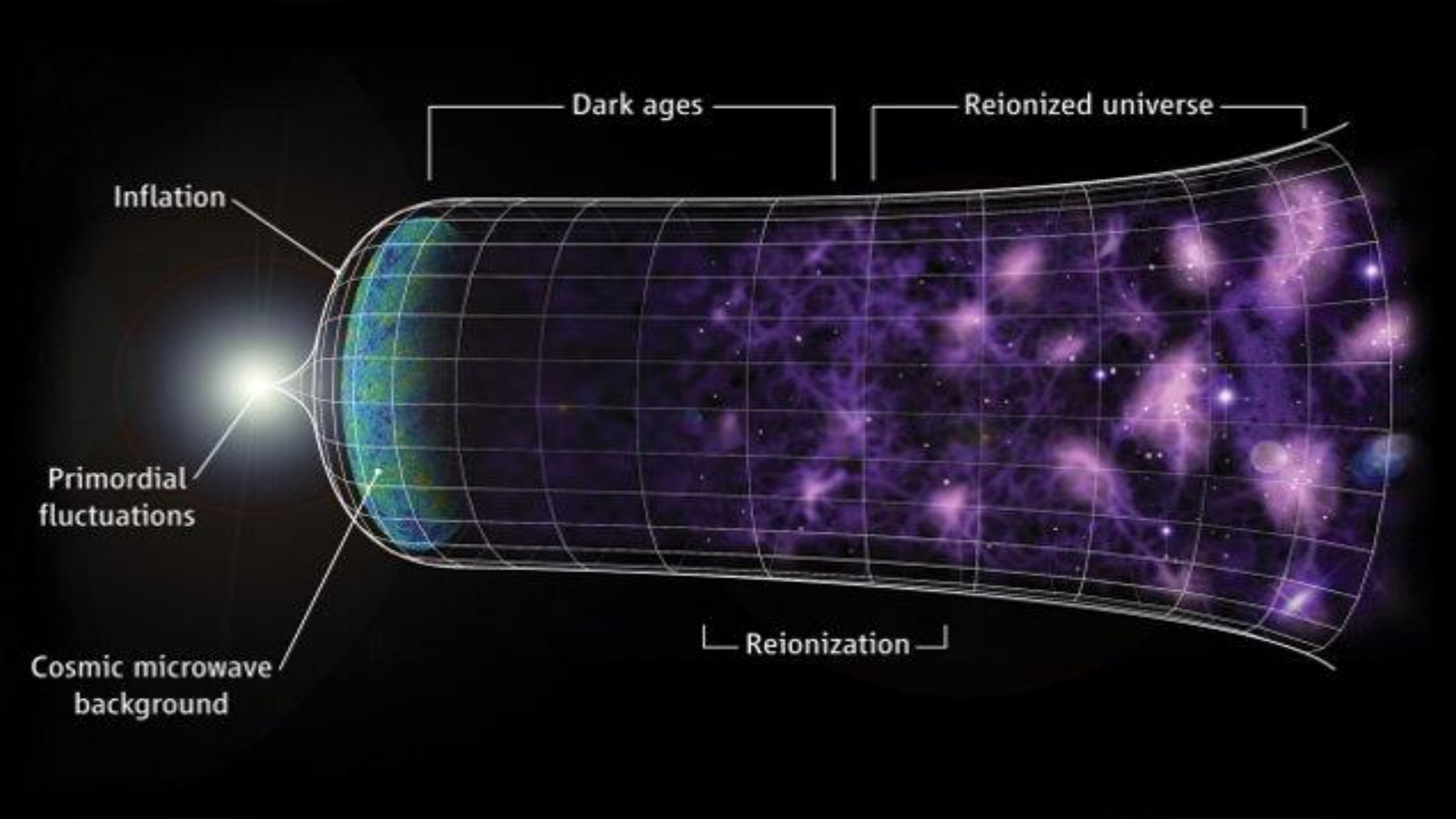
Collaborators: R. Ruffini, J. A. Rueda, A. Krut, E. A. Becerra-Vergara, M. Díaz, R. Yunis, M. Mestre, V. Crespi, K. Boshkayev, J. Uribe-Suárez, P.-H. Chavanis

- **Cosmology 2023 in Miramare– August 28-September 2, SISSA, Italy**

- **BASED ON: Argüelles, Boshkayev, Krut, et al. MNRAS (2023) arXiv:2305.02430**

Argüelles et al. PDU (2018,2019) arXiv:1606.07040; arXiv:1810.00405 & MNRAS (2021) 2012.11709

Becerra-Vergara, Argüelles, et al. A&A (2020) arXiv:2007.11478 & MNRAS Lett (2021) 2105.06301


Dark ages
Reionized universe
Inflation
Primordial fluctuations
Cosmic microwave background
Reionization

DM halo formation from a statistical mechanics approach

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)

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

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

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

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

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

2) Take local average of V-P

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

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

Diffusion current

Maximum Entropy production Pple. Chavanis, MNRAS (1998) Chavanis, (2006)

$$\dot{S} \geq 0$$

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**

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)

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

$$\frac{\mathrm{d}f}{\mathrm{d}t} \equiv \frac{\partial f}{\partial t} + \boldsymbol{v}\frac{\partial f}{\partial \boldsymbol{r}} + \boldsymbol{F}\frac{\partial f}{\partial \boldsymbol{v}} = 0, \longrightarrow \frac{\partial \bar{f}}{\partial t} + \boldsymbol{v}\frac{\partial \bar{f}}{\partial \boldsymbol{r}} + \bar{\boldsymbol{F}}\frac{\partial \bar{f}}{\partial \boldsymbol{v}} = -\frac{\partial J}{\partial \boldsymbol{v}} \quad (1)$$

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

2) Take local average of V-P

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

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

$$F = -\nabla\Phi$$

Diffusion current

- For fermions, the maximum accesible value of the DF is fixed by the Pauli principle $\Rightarrow$

$$\eta_0 = g m^4 / h^3$$

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 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)

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

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

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

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

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

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

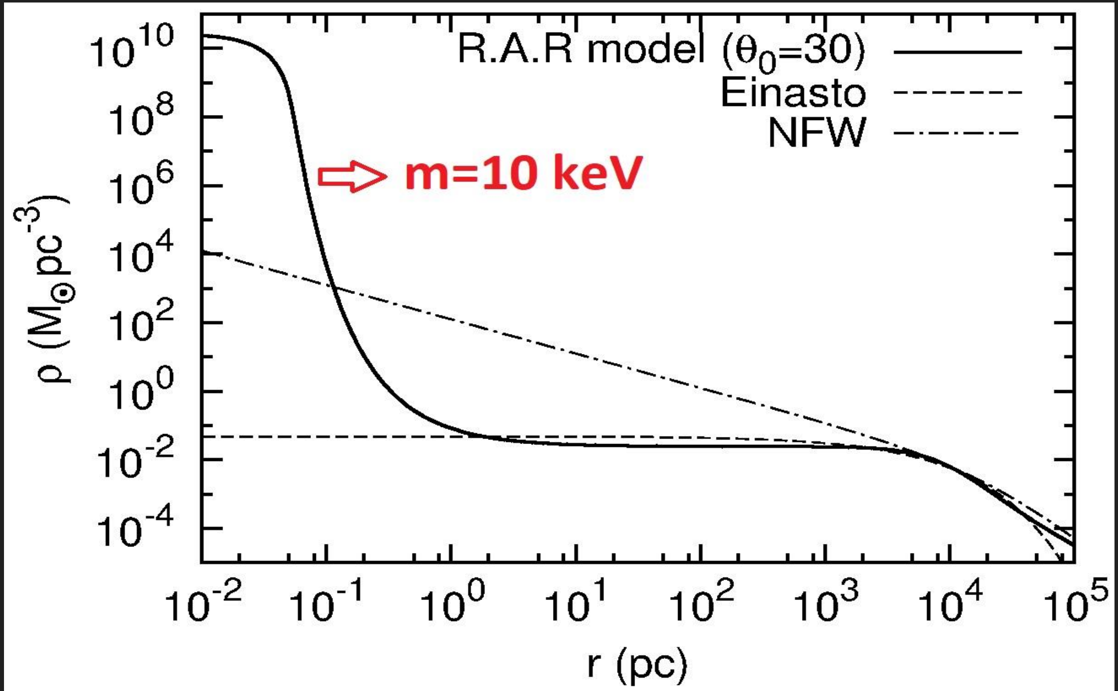
4 free parameters

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)

Thermodynamics of self-gravitating fermions: Stability

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

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

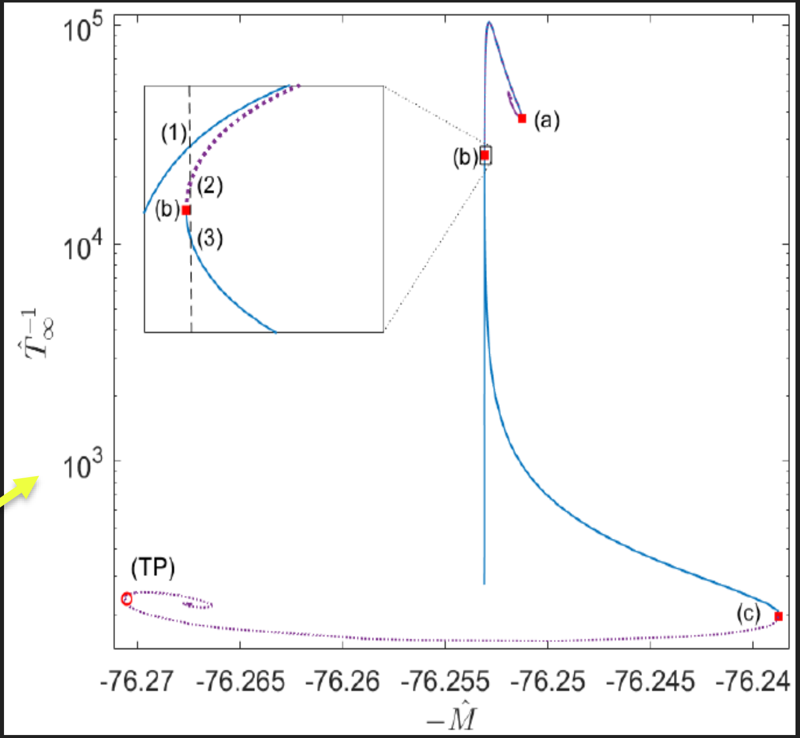
δ^2 S< 0

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)



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

- One should i) calculate the power spectrum P(k) in a given (~10^1 keV) cosmology (CLASS)
  ii) apply the Press-Schechter formalism to obtain $M_{vir} = M(R_{vir})$ at given z_{vir};

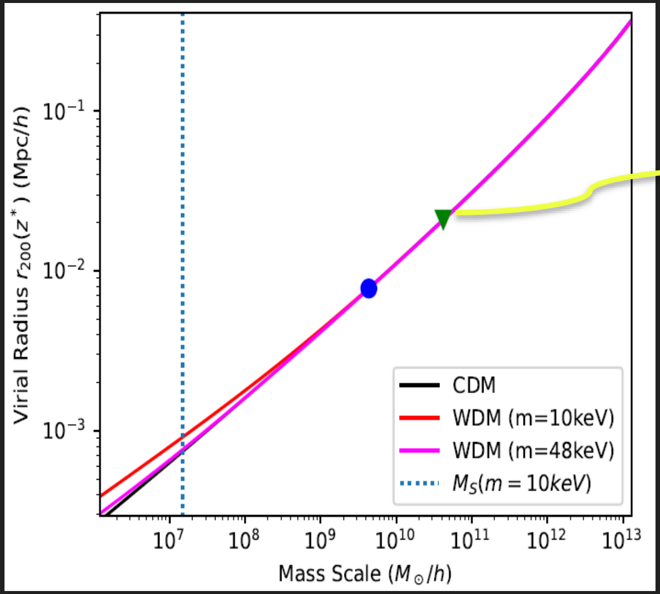
Mass variance

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

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

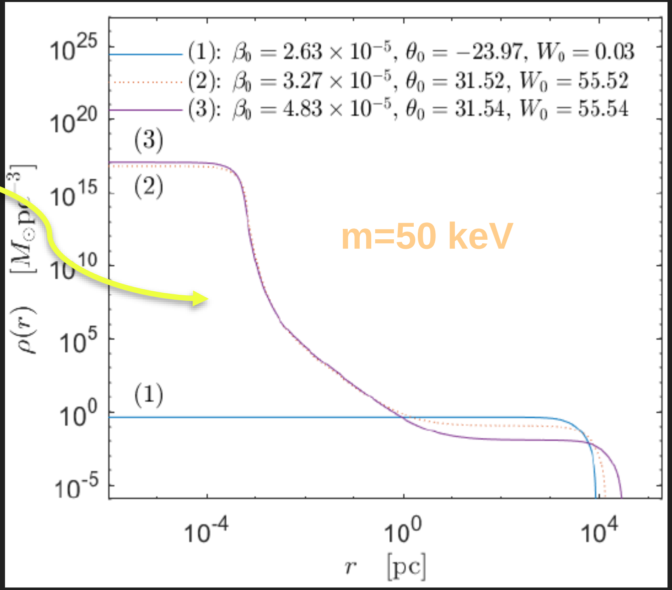
Window *top-hat* function

Critical overdensity (spherical collapse)



M_{vir} = 5.4 x 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

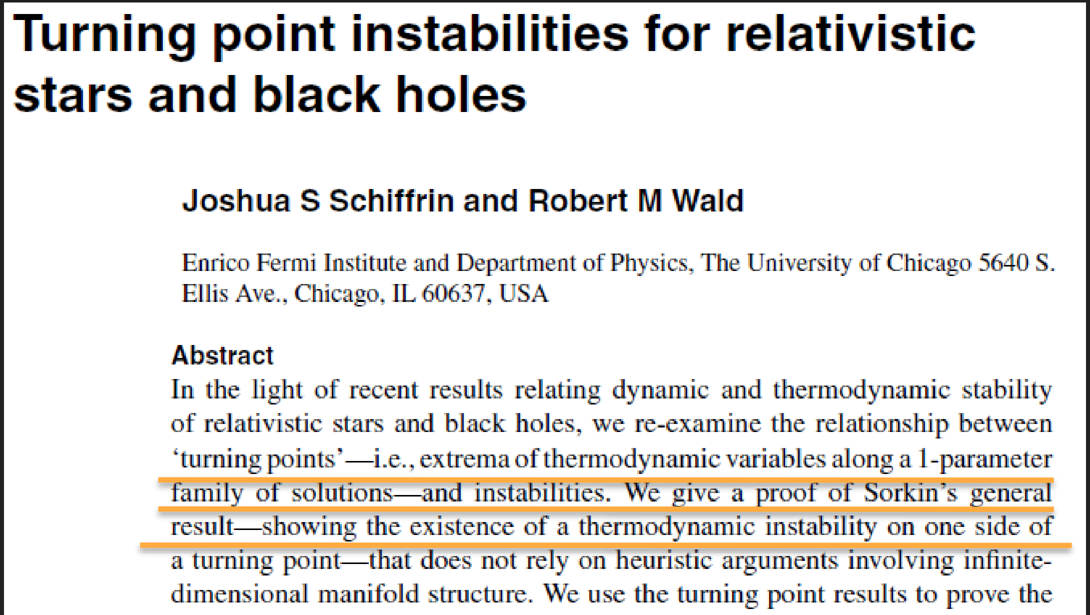


Argüelles et al. MNRAS (2021)

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

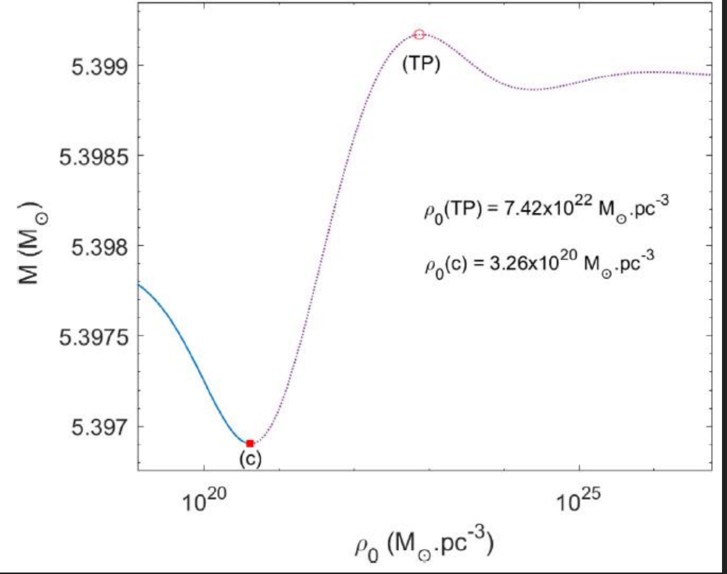
Joshua S Schiffrin and Robert M Wald

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

Argüelles et al. MNRAS (2021)

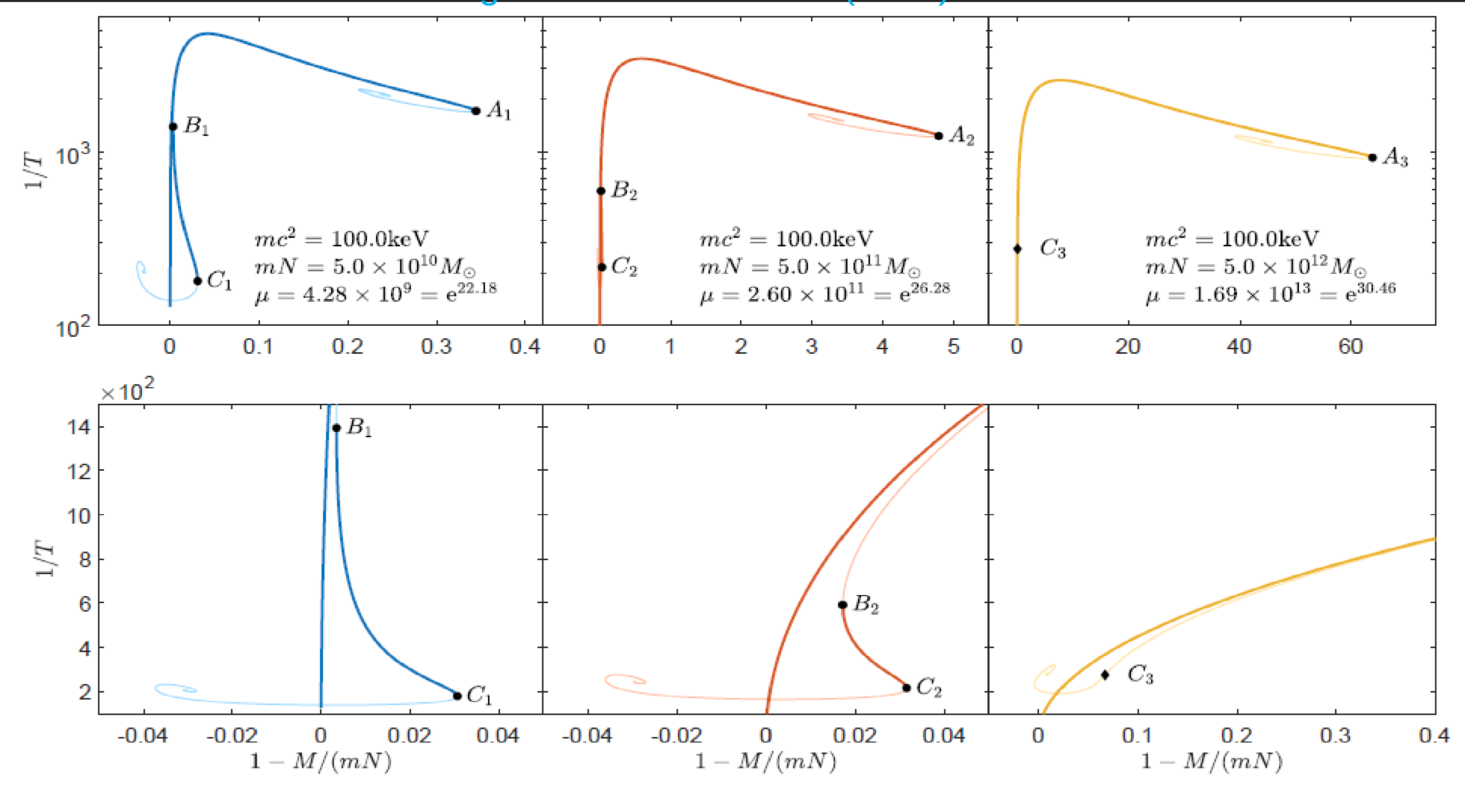


Phenomenology I: A new channel for SMBH formation

Stability analysis of fermionic halos in GR: M_vir = 5x10^(10) – 5x10^(12) M⊙

- Critical solutions (at **C_i**) fulfill with the boundary conditions from Cosmology at halo-formation **(M_vir; r_s)**
- Stable Branch core-halo solutions correspond to B-C (The larger M the shorter the stable-branch up to M*)

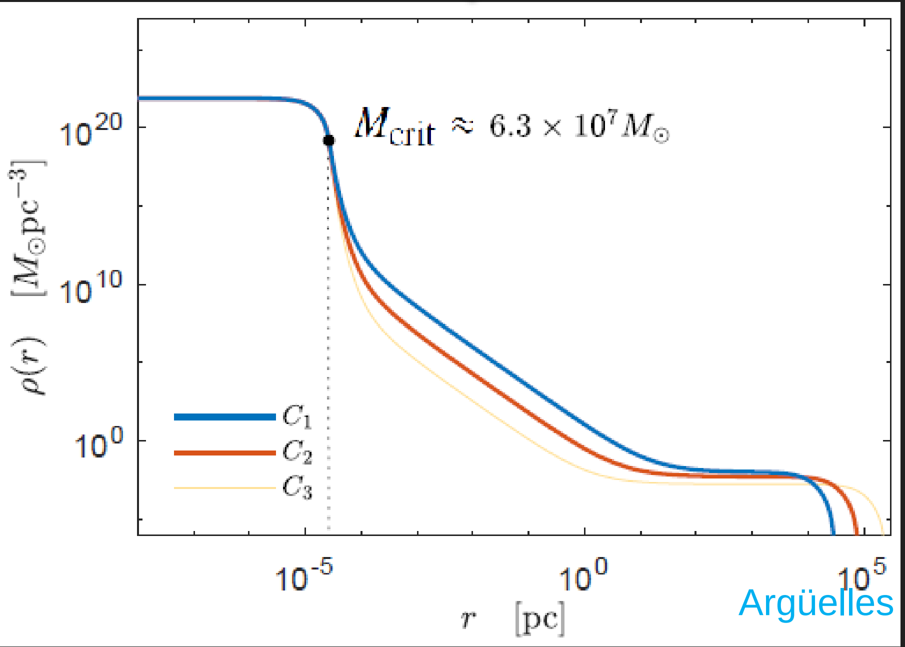
Argüelles et al. MNRAS (2023)

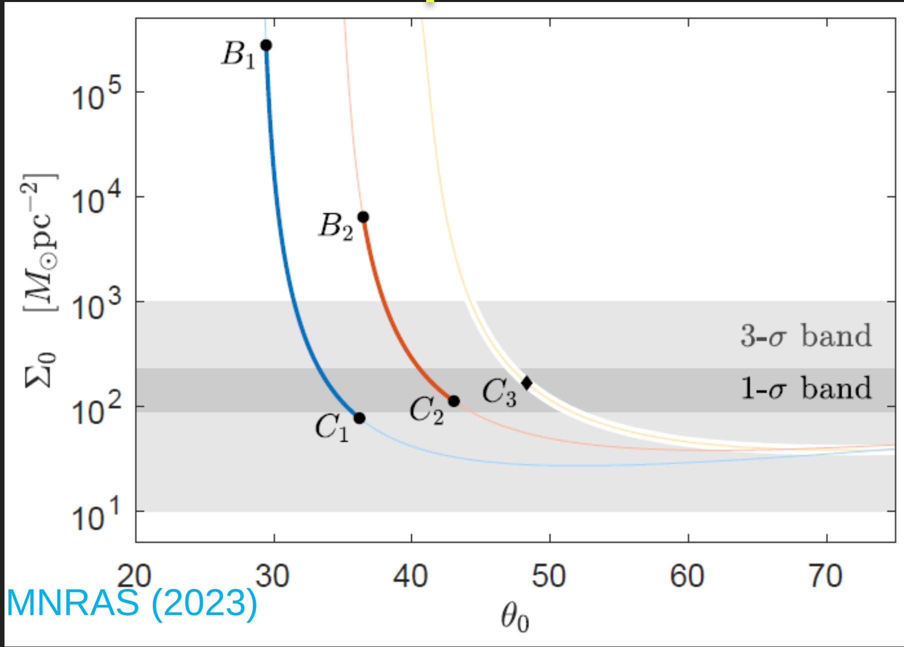


- It does exist solutions of Einstein equations for self-gravitating systems of (neutral) fermions which gives hints to: (i) the mass of the DM particles; (ii) the formation of SMBH at the center of active galaxies; (iii) the phenomenology and stability of DM halos

Critical solutions (at **C_i**) fulfill with the boundary conditions at halo-formation **(M_vir; r_s)**

Critical solutions fulfilling with the observational DM-Surface-density relation, Σo ρ_o r_o = 190 MΘ/pc^2
Donato, Gentile, Salucci et al. MNRAS (2009)





Argüelles et al. MNRAS (2023)

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

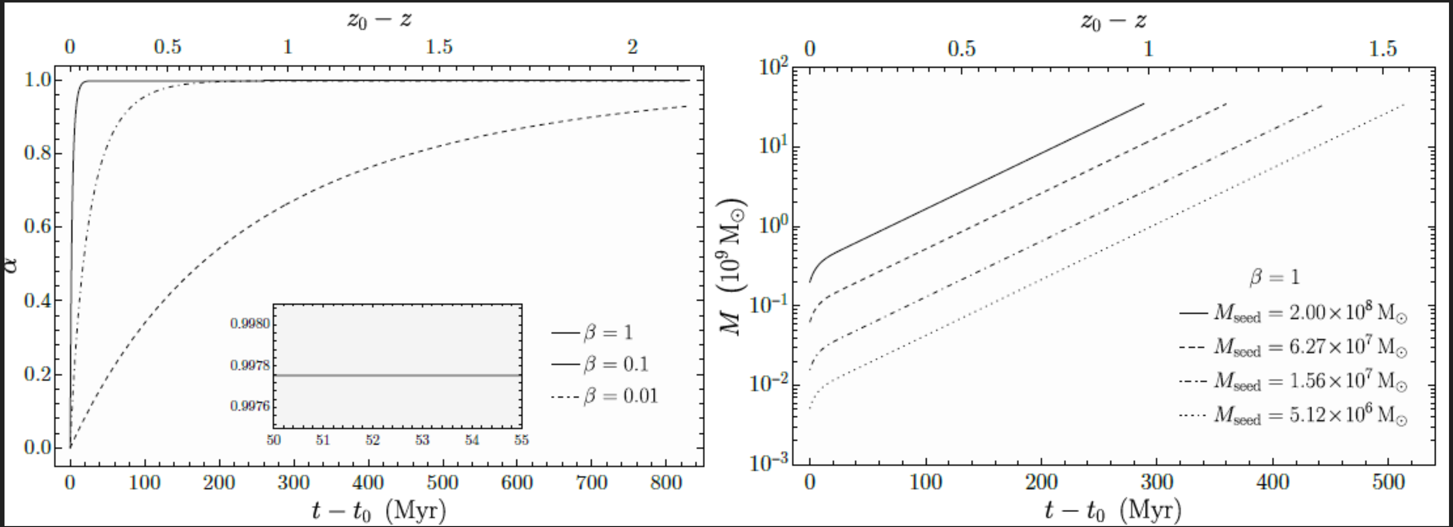
. We compute, in a Kerr metric, the evolution of mass and angular momentum of the BH using a geodesic general relativistic disc accretion model Argüelles et al. MNRAS (2023)

. 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

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

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

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

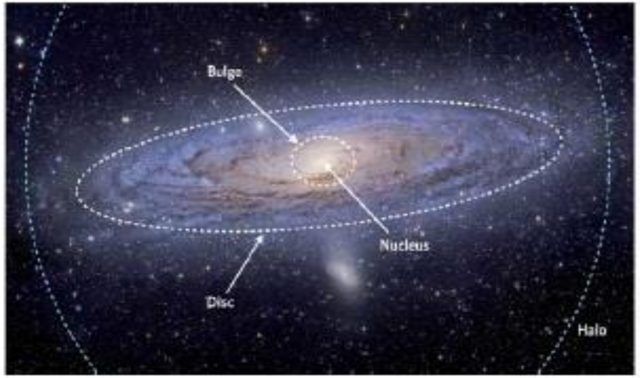


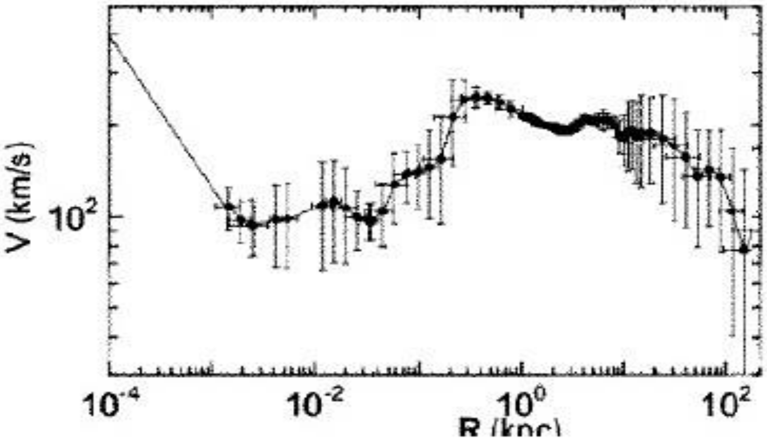
This BH-seeds are larger tan typical baryonic-sedes (e.g. Pop. III stars), and can grow up to 10^9 – 10^(10) M⊙ in a fraction of 1st Gyr of the life of the Universe without invoking unrealistic accretion rates !

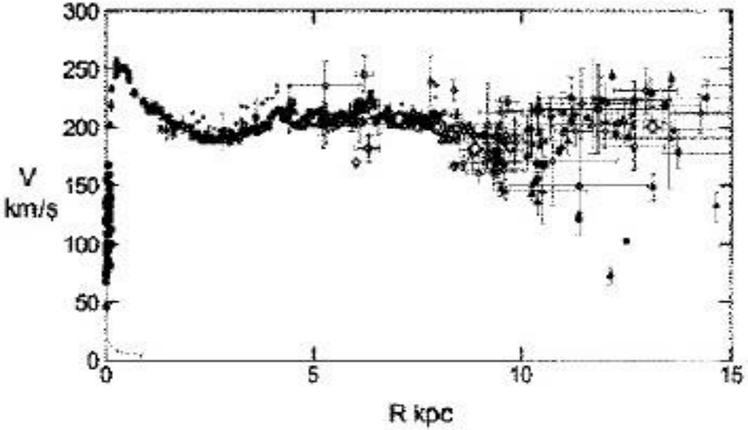
Phenomenology II - Below critical core-halo solutions:
The Milky Way (Rotation Curve and S-stars)

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



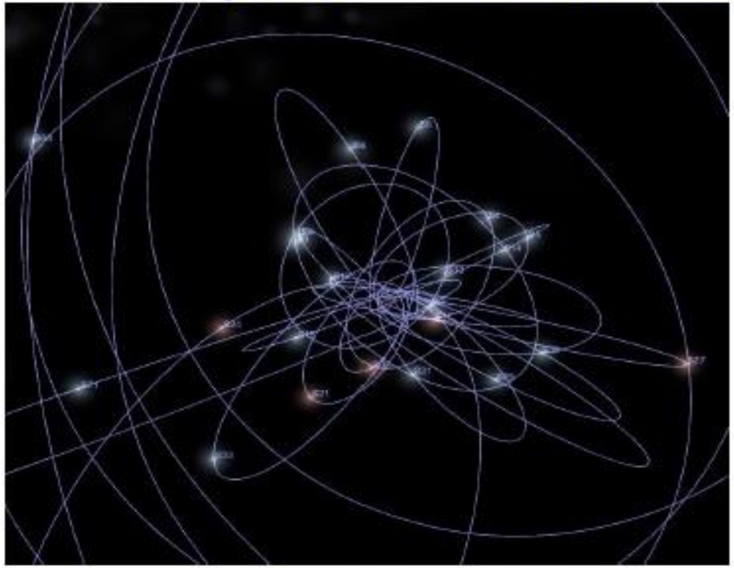


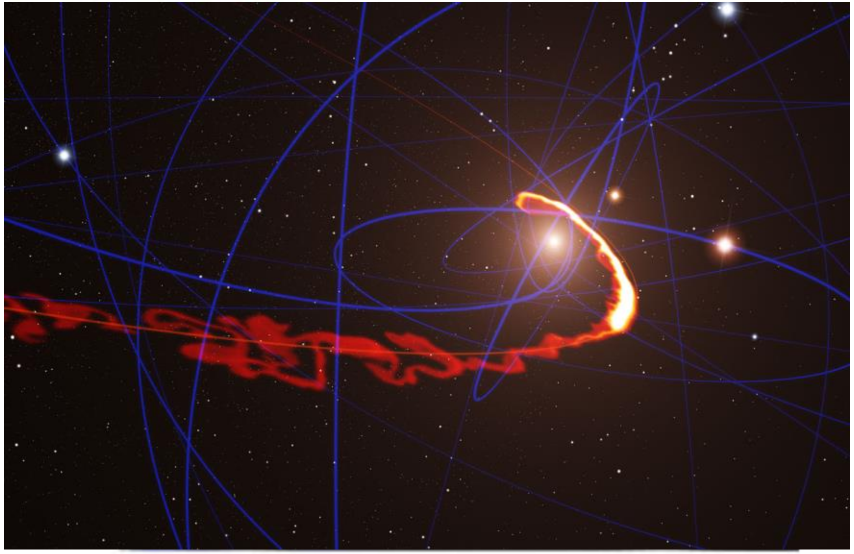


Y. Sofue, (PASJ) (2013)

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)

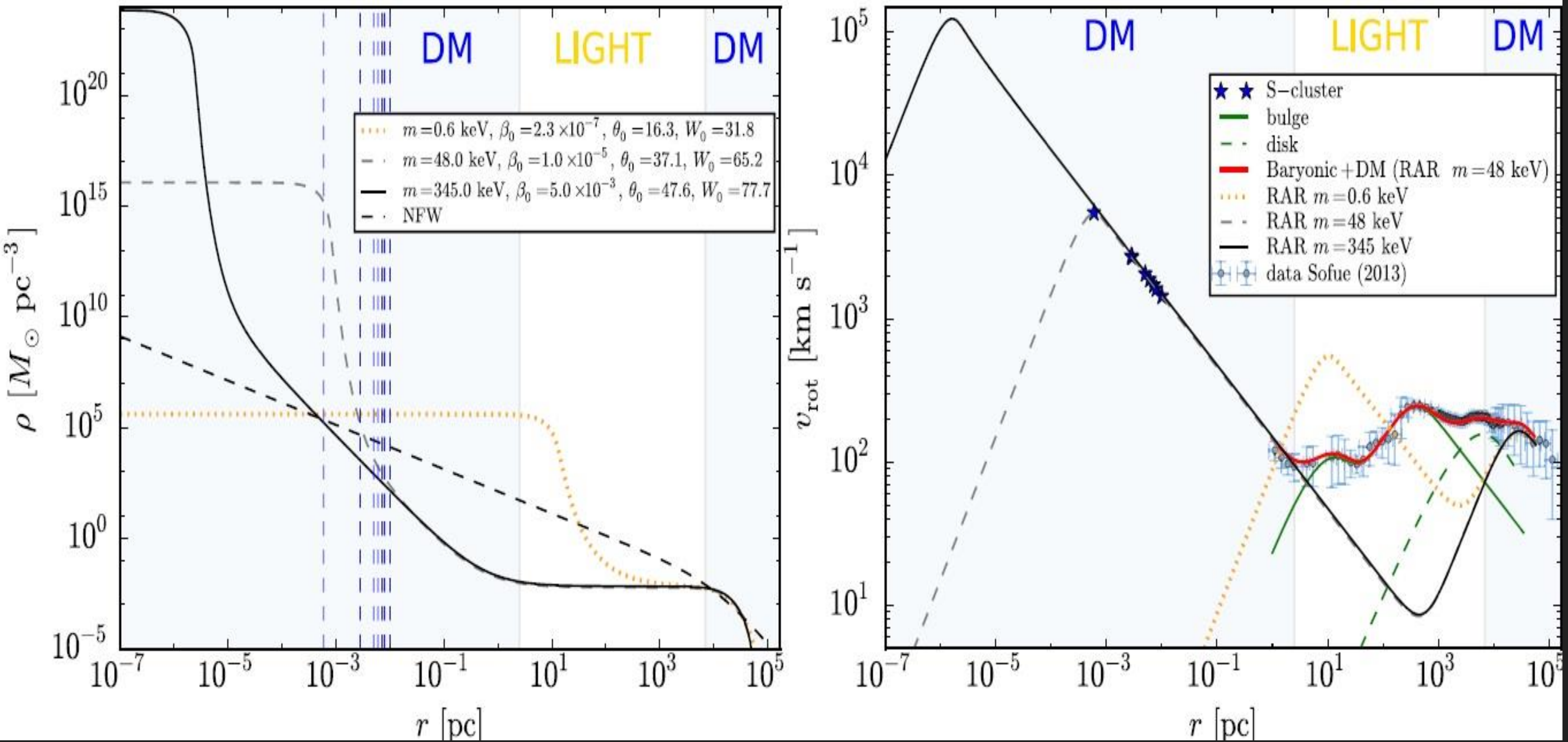
$M(r = 20\ \mathrm{kpc}) = 9 \times 10^{10}$ Mo Sofue, PASJ (2013)

$M(r = 40\ \mathrm{kpc}) = 2 \times 10^{11}$ 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

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



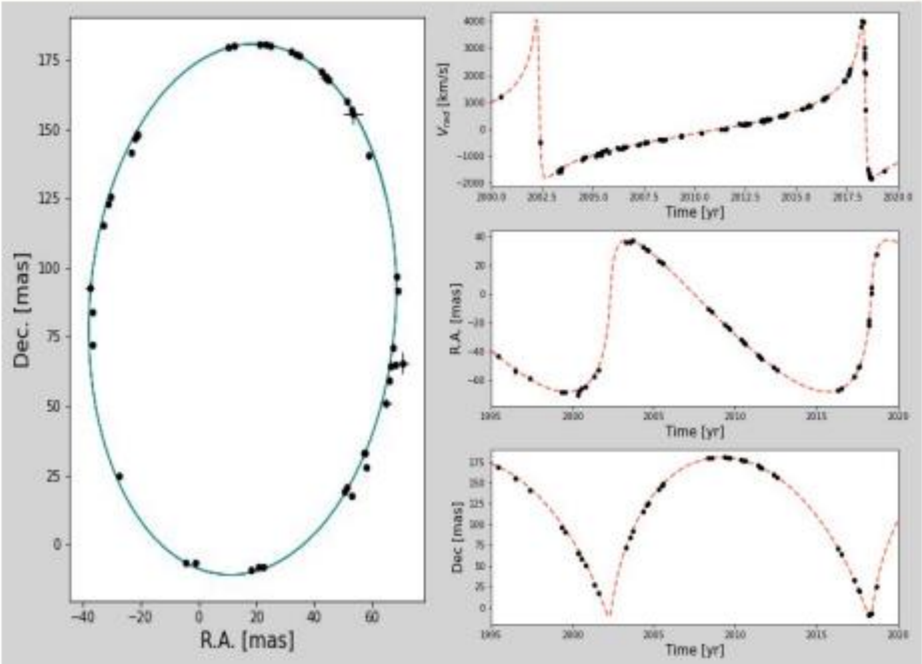
Phenomenology II: The S2-star at the Milky Way Center

CCAD Centro de Computación de Alto Desempeño

S2 star

RAR - mc² = 100 keV

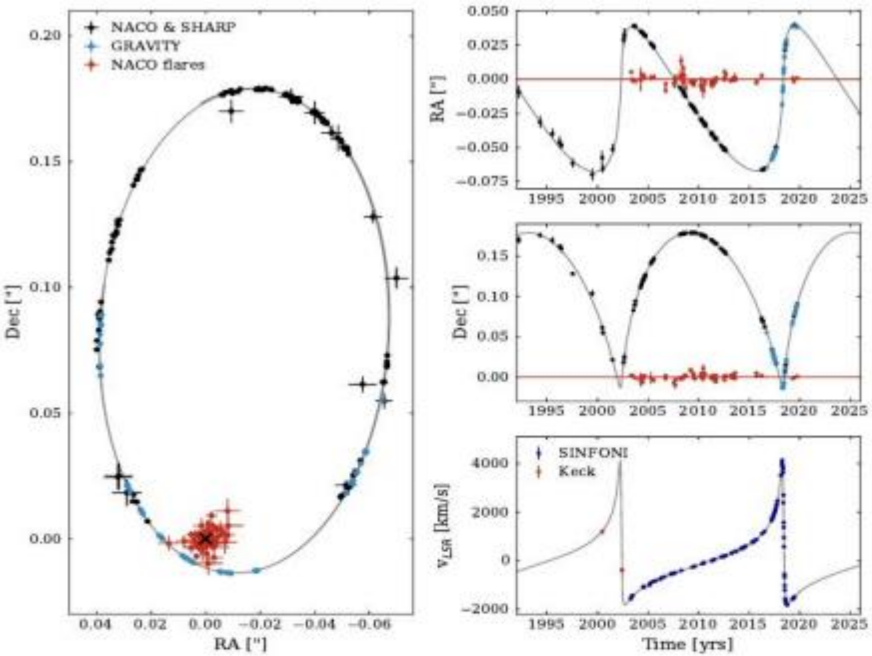
e	a [arcsec]	T [yr]	ω [°]	i [°]	Ω [°]	t_p [yr]	Δϕ [min/rev]
0.886	0.125	16.05	66.4	134.4	227.9	2018.38	11.8



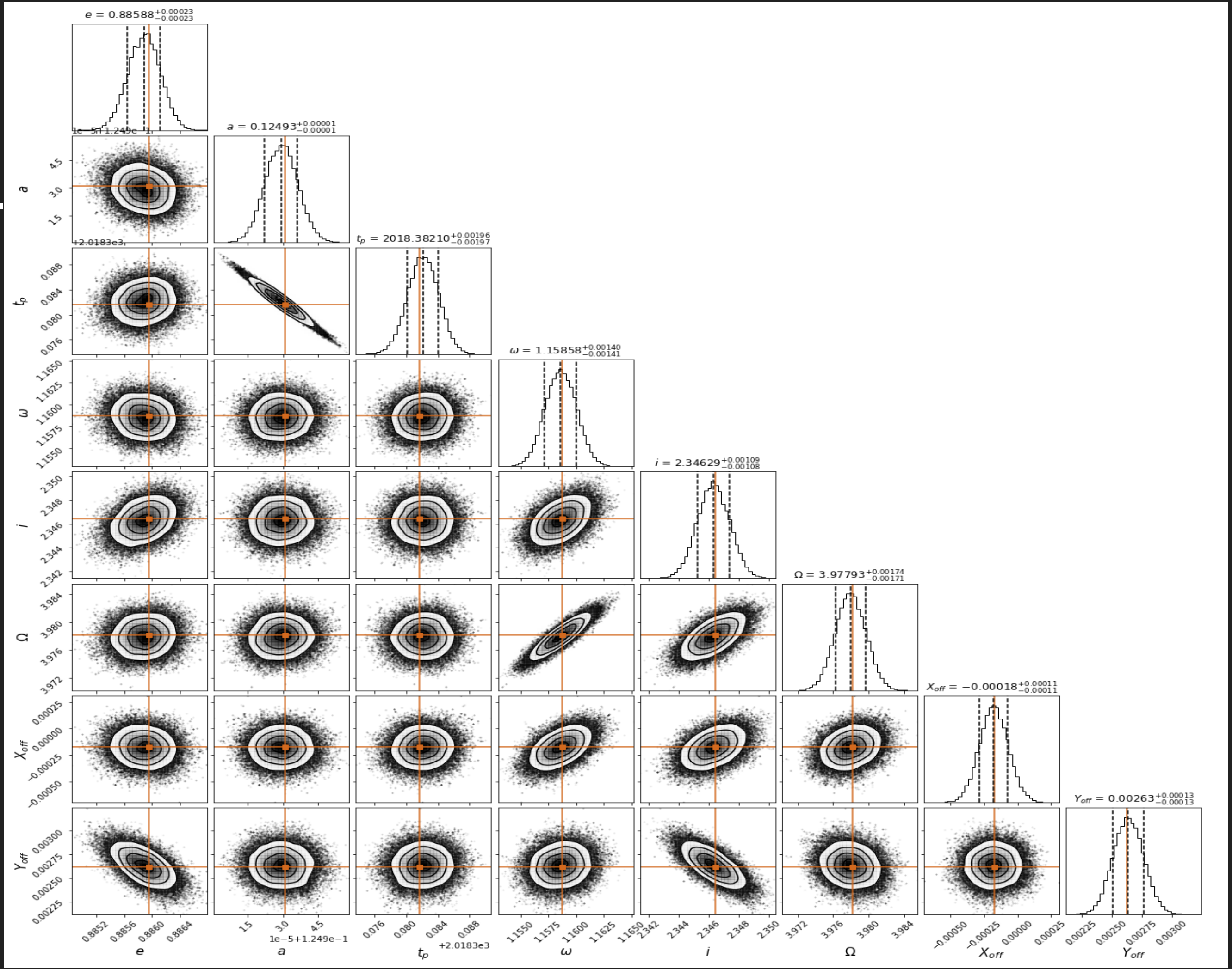
Gravity Collaboration 2020

BH - M_{BH} = 4.26 x 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

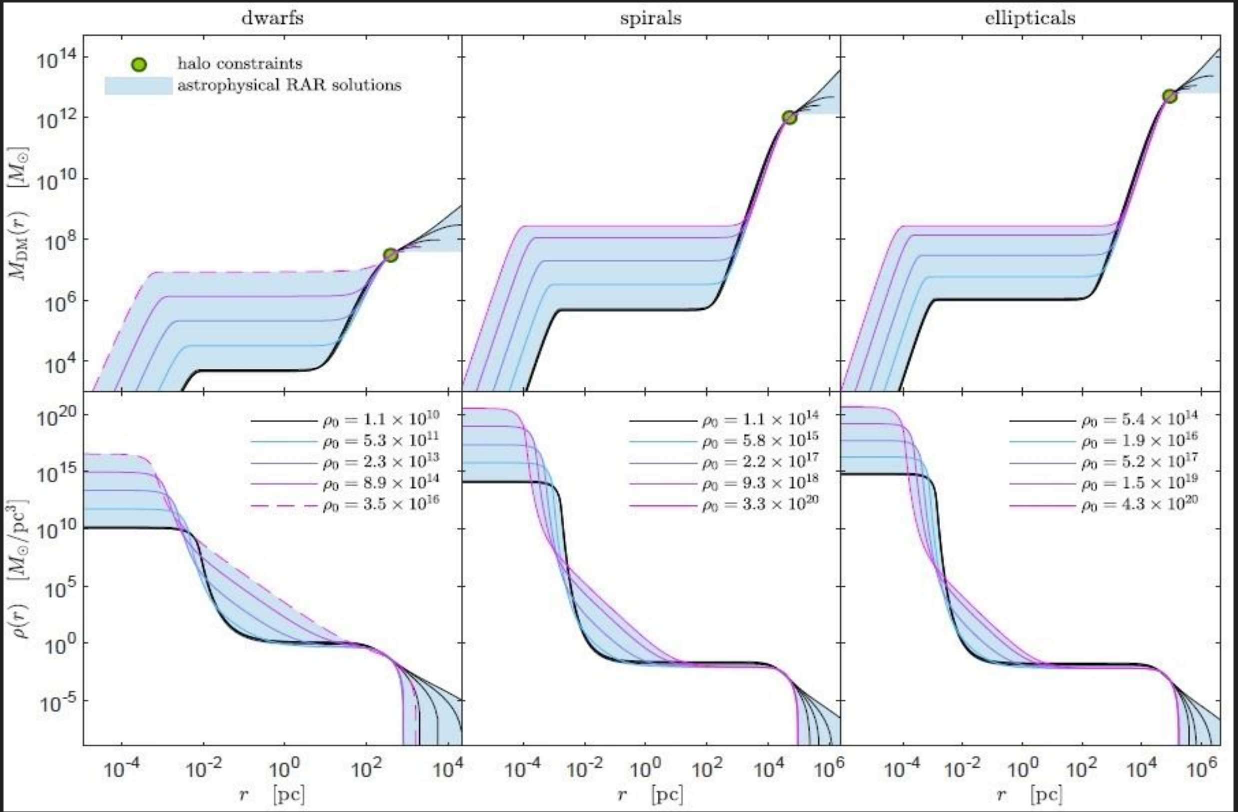


- Posteriors of the S2-star orbital parameters determined from a Monte-Carlo Markov-Chain method within a core-halo non-criritcal solution (m=100 keV)



Fermionic core-halo profiles: From dwarf to elliptical galaxies

- 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

$$r_{h(d)} = 400\ \mathrm{pc}$$
$$M_{h(d)} = 3\times10^7\ M_\odot$$

SPIRALS: sample of nearby disk galaxies from THINGS

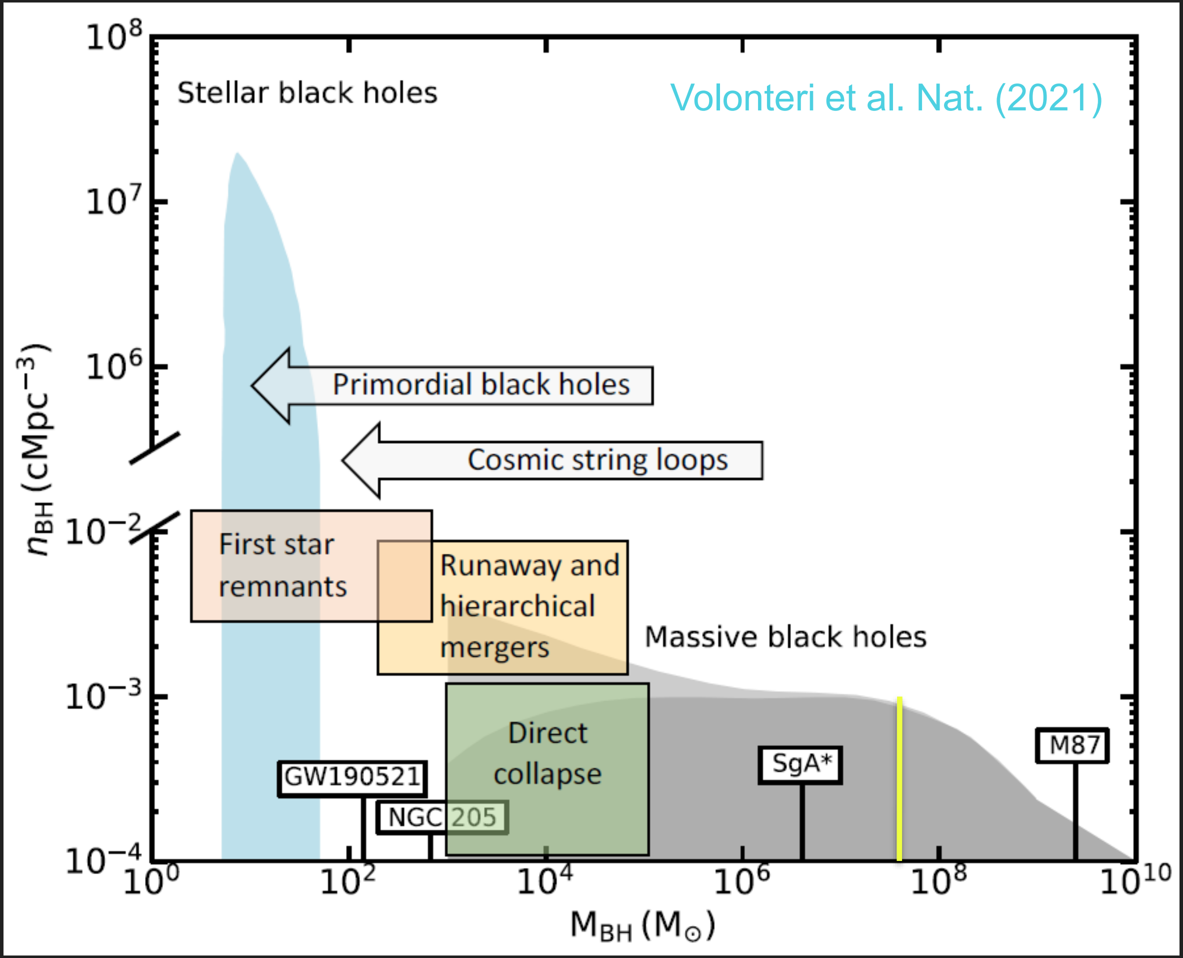
$$r_{h(s)} = 50\ \mathrm{kpc}$$
$$M_{h(s)} = 1\times10^{12}\ M_\odot$$

ELLIPTICALS: sample analyzed via weak lensing

$$r_{h(e)} = 90\ \mathrm{kpc}$$
$$M_{h(e)} = 5\times10^{12}\ M_\odot$$

Discussion: standard SMBH formation channels

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)

Back up slides

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)

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

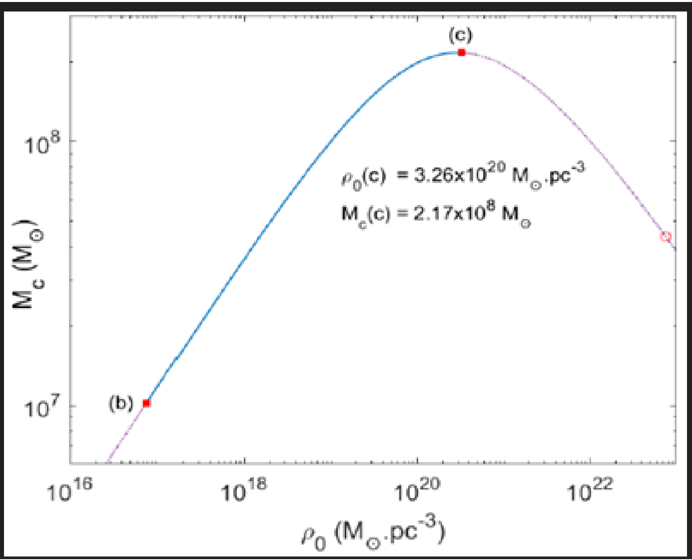
Turning point instabilities for relativistic stars and black holes

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

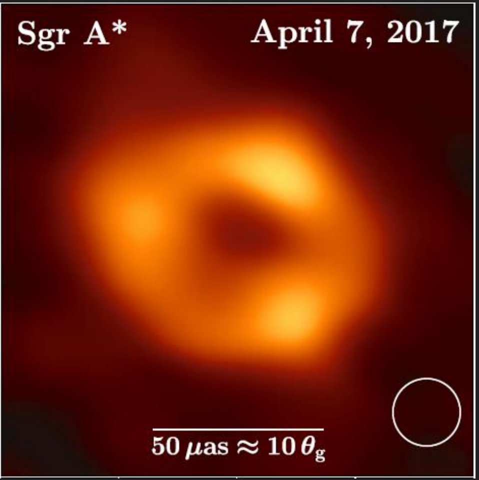
Abstract

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



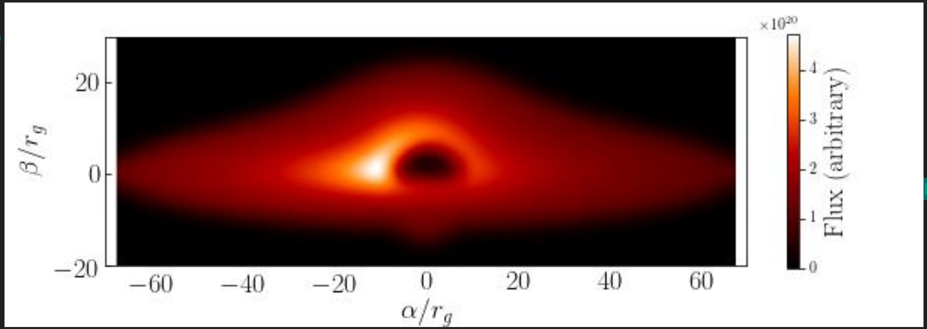
The shadow of SgrA*

How does this DM model stands with the recent EHT results on SgrA*?



EHT collaboration, ApjL (2022)

- 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)
- Does exist any fermion-core compact enough to deflect light in a similar fashion tan the BH ? YES !
  Solution prior to core-collapse has a maximal light deflection at 5 Rg !

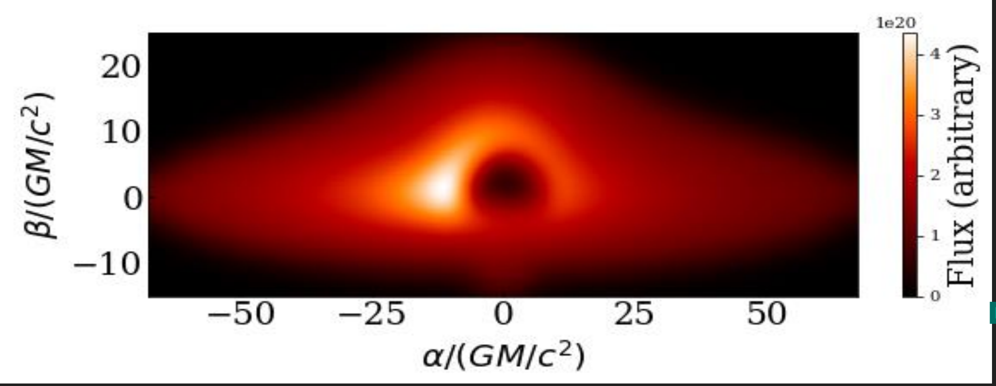


Pelle, Argüelles, et al (In prep.)

Done with a GR ray-tracing code: ***Skylight***
Pelle, Reula, et al., MNRAS (2022)

- DM fermion-cores (not yet collapsed) can develope light-images similar to the BH case, with a **shadow feature** !

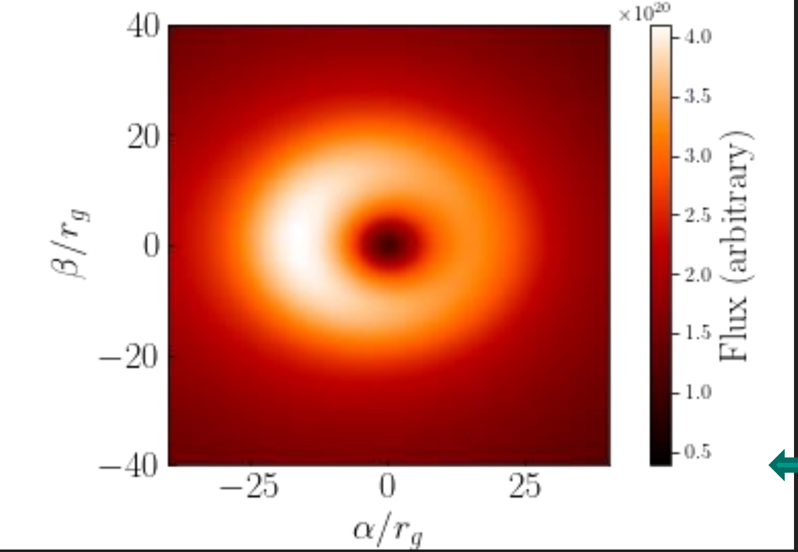
How does the RAR model stands with the recent EHT results on SgrA*?



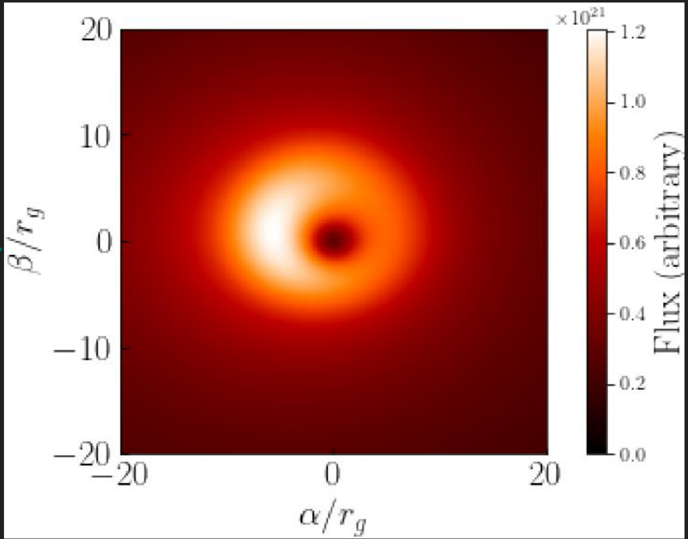
- Blurred (Gaussian filter) monochromatic Image (λ=1.3 mm) caused by light rays coming from an accretion disk (S&S) onto the stable DM core, seen by a far observer

Edge-on view

Face-on view



m=378 keV/c^2



m=300 keV/c^2

Pelle, Argüelles, et al (In preparation)

Phenomenology II:

different galaxy types, and galaxy relations

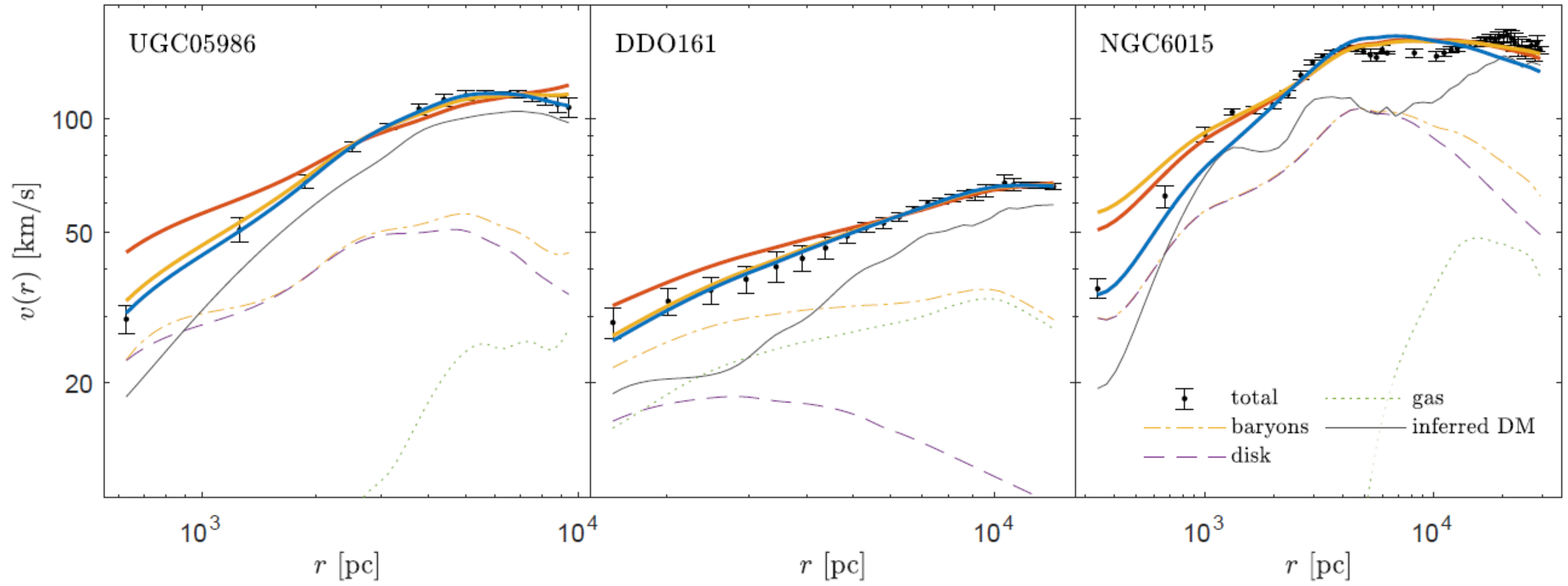
Testing the RAR model with the SPARC data-set of 120 disk galaxies

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

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

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

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

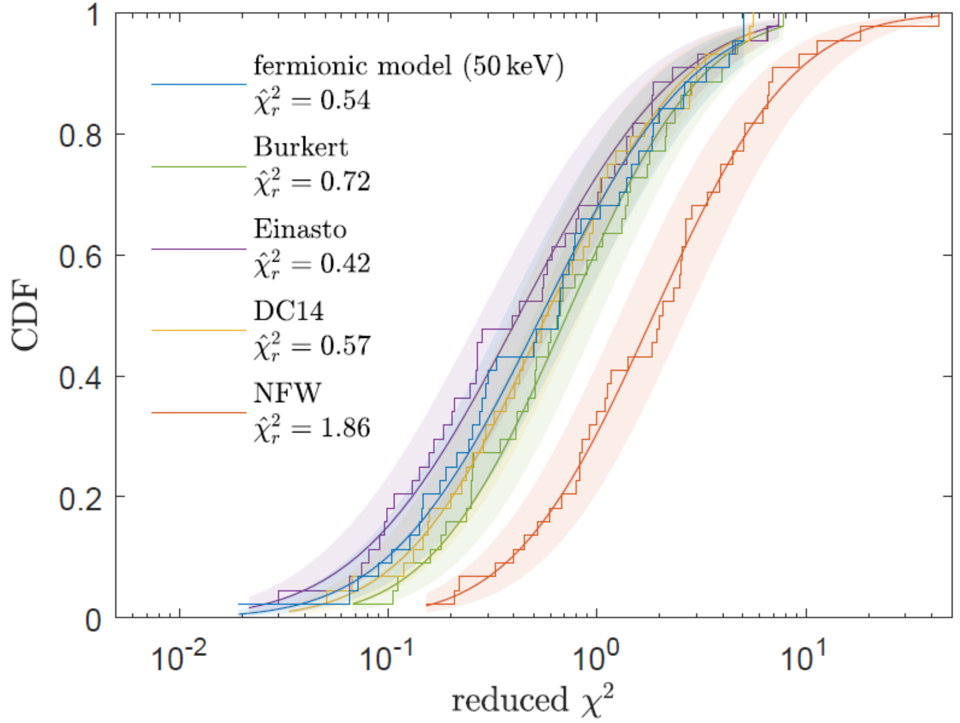


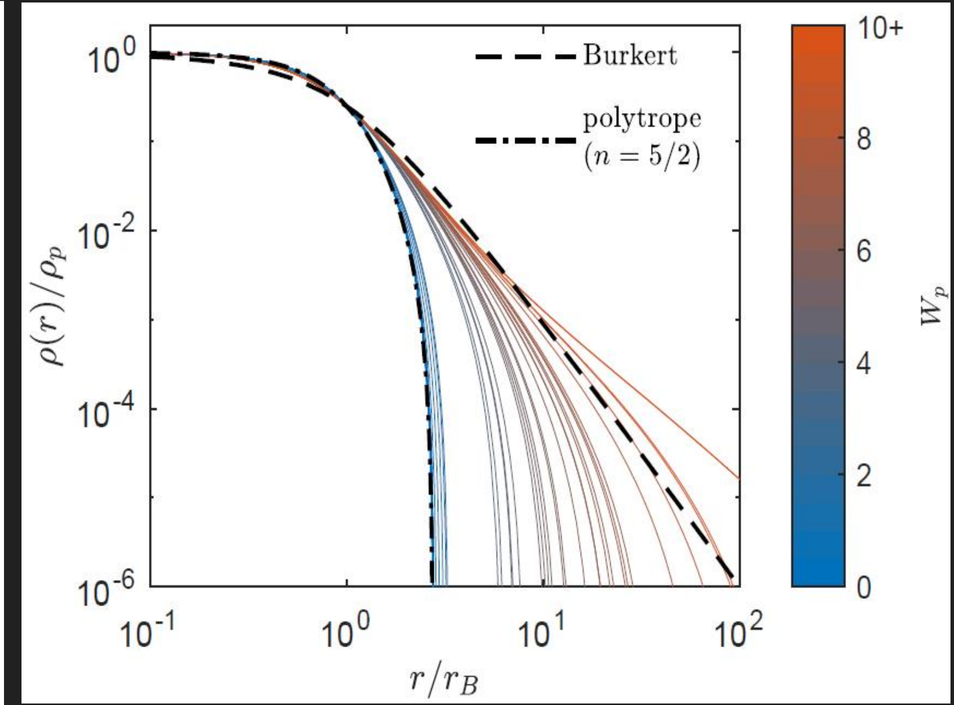
Krut, Argüelles, Chavanis, Rueda, Ruffini, Apj (2023)

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

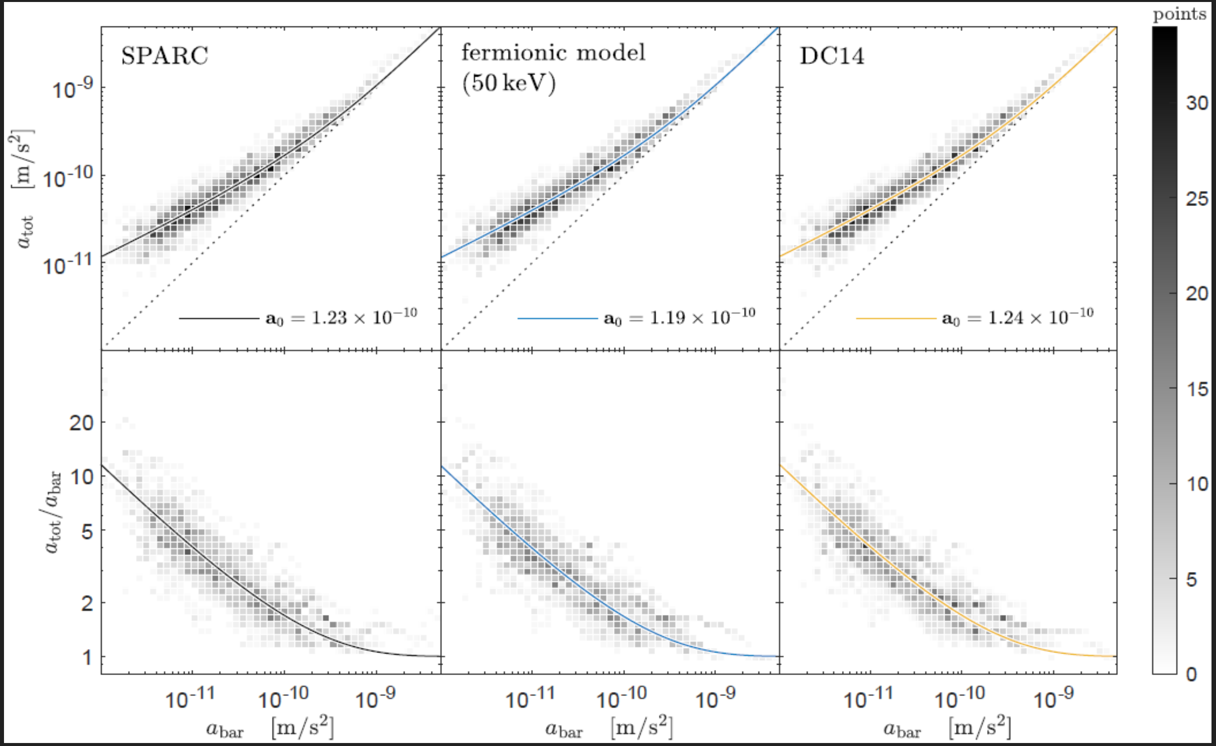




Krut, Argüelles, Chavanis, Rueda, Ruffini, Apj (2023)

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 (submitted 2022)

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

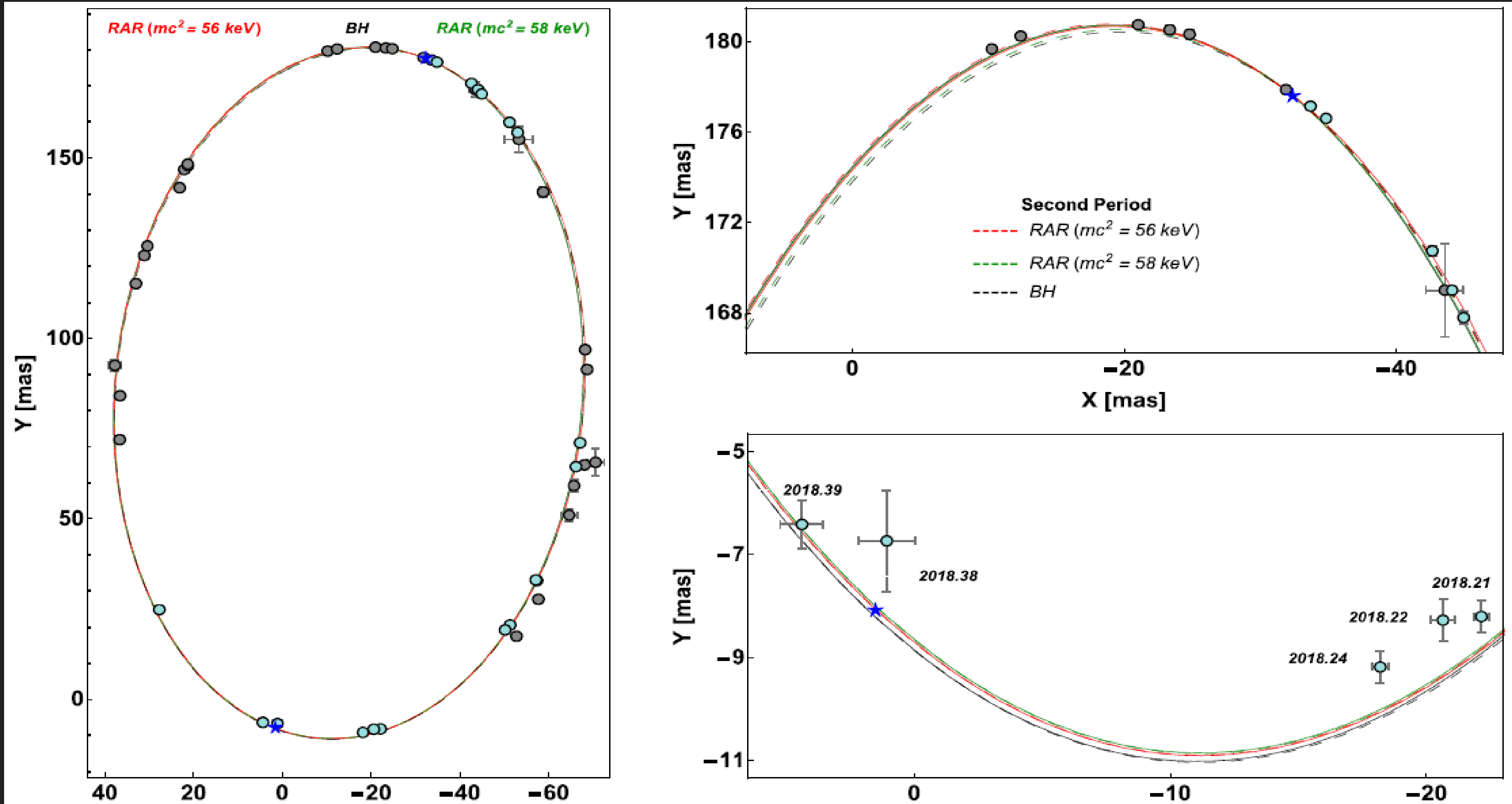
C. R. Argüelles,[1,2,3★] M. F. Mestre,[1,4] E. A. Becerra-Vergara,[2,3,5★] V. Crespi,[1] A. Krut,[2,3] J. A. Rueda[2,3,6,7★] and R. Ruffini[2,3,6,7]

[1] *Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque, B1900FWA La Plata, Argentina*
[2] *ICRANet, Piazza della Repubblica 10, I-65122 Pescara, Italy*
[3] *ICRA, Dipartimento di Fisica, Sapienza Università di Roma, P.le Aldo Moro 5, I-00185 Rome, Italy*
[4] *Instituto de Astrofísica de La Plata, UNLP & CONICET, Paseo del Bosque, B1900FWA La Plata, Argentina*
[5] *GIRG, Escuela de Física, Universidad Industrial de Santander, Bucaramanga 680002, Colombia*
[6] *ICRANet-Ferrara, Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara, Via Saragat 1, I-44122 Ferrara, Italy*
[7] *INAF, Istituto de Astrofisica e Planetologia Spaziali, Via Fosso del Cavaliere 100, I-00133 Rome, Italy*

ABSTRACT

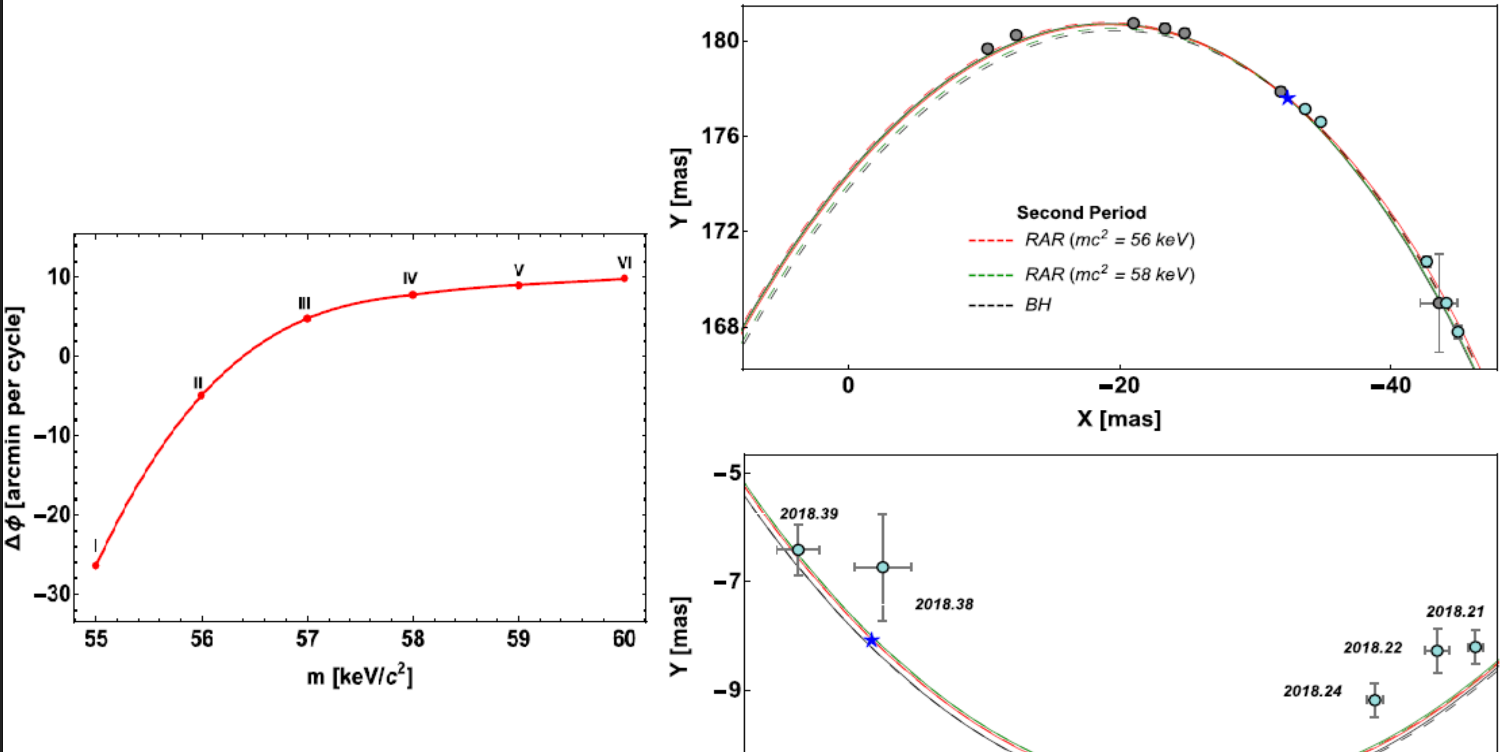
It has been recently demonstrated that both, a classical Schwarzschild black hole (BH), and a dense concentration of self-gravitating fermionic dark matter (DM) placed at the Galaxy centre, can explain the precise astrometric data (positions and radial velocities) of the S-stars orbiting Sgr A∗. This 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



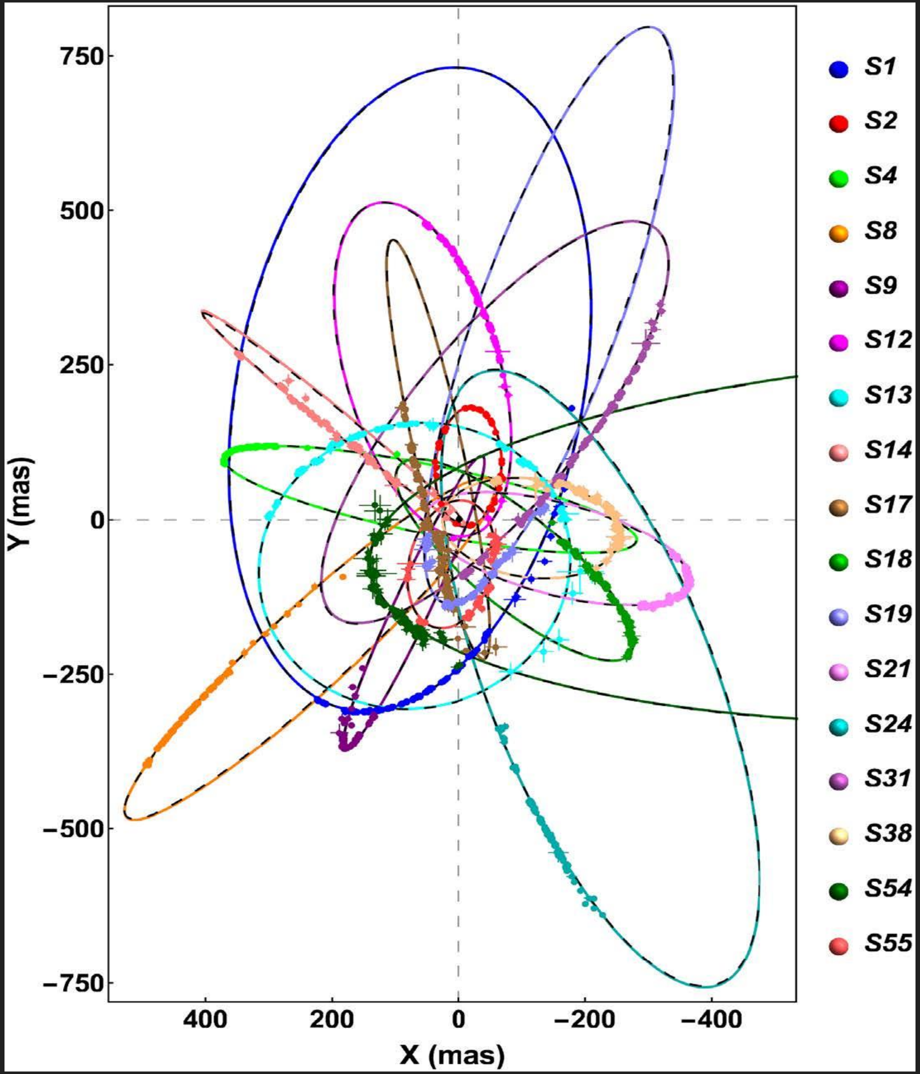
Argüelles et al. MNRAS Lett. (2022)

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)



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

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

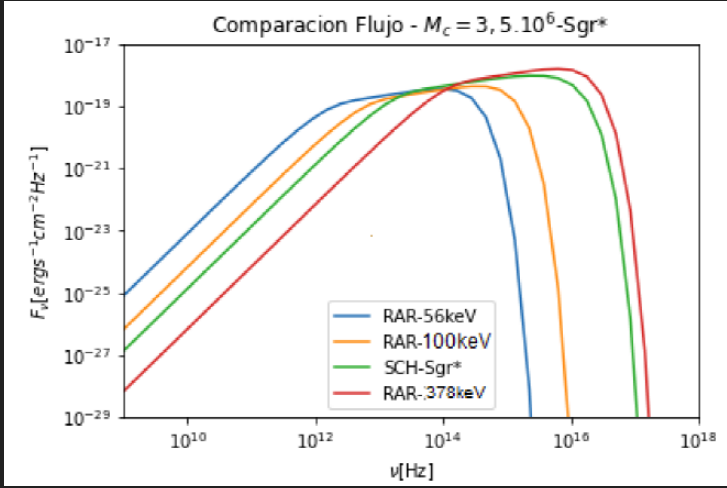
2) Fermionic DM distribution with Mc = 3.5 x 10^6 Mo (fermion mass m= 56 keV)

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

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

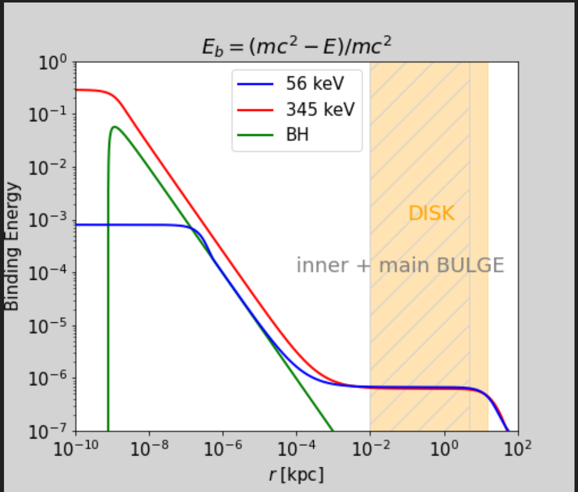
Disc accretion for horizonless dark compact objects: the fermion core

- Emmited flux for different fermion-core compacities (i.e. different DM particle masses) compared with the BH case →
The case of a Milky Way –like galaxy (shown as example)



Efficiency of energy extraction from the central object

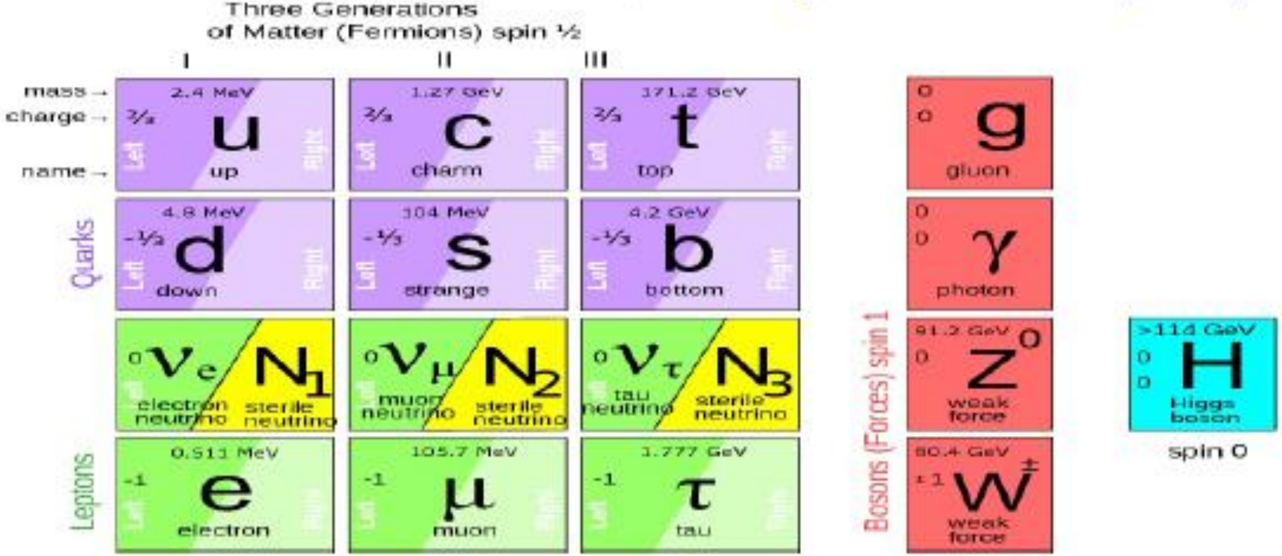
$$E_{binding} = \frac{m - E_c}{m} = 1 - \sqrt{A(r)\left(1 + \frac{r_c A'(r_c)}{2A(r_c) - r_c A'(r_c)}\right)}.$$



- The fermion core is transparent and therefore the disc can eneter inside the core, where the efficiency saturates

mc^2[keV]	R_{in}[kpc]	Efficiency [%]
56	$3,58 \cdot 10^{-8}$	0.07
100	$7,57 \cdot 10^{-9}$	0.37
378	$1,01 \cdot 10^{-10}$	28.5

- 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!

$$\mathcal{L} = \mathcal{L}_{SM} + i\nu_R \partial_\mu \gamma^\mu \nu_R - g\,\bar{L}\nu_R \phi - M/2\bar{\nu}_R^c \nu_R \qquad (2)$$

- 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-interacting right handed neutrinos in RAR - halos

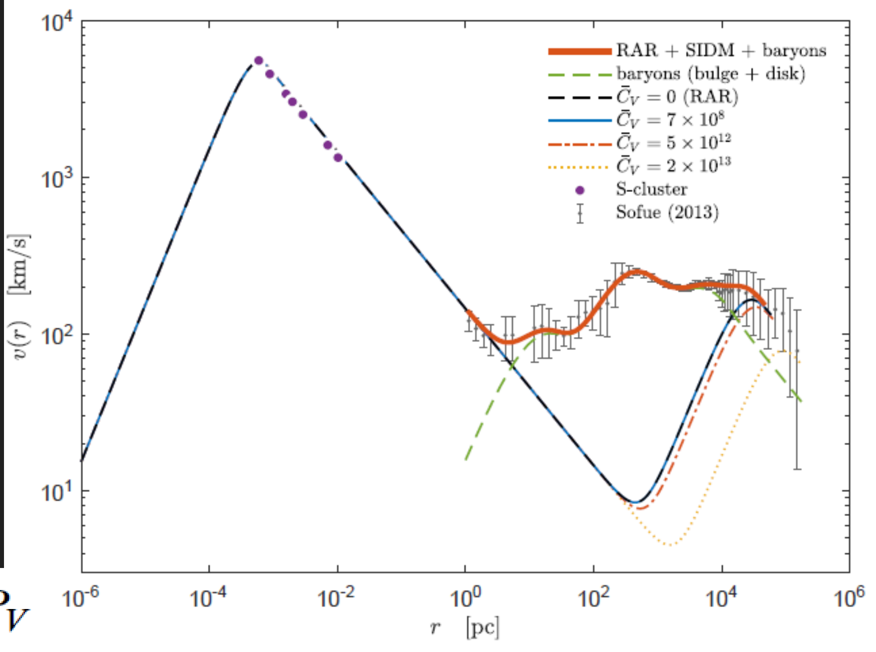
- The Higgs portal term in the Lagrangian is neglected given the bulk of sterile neutrinos live longer than the age of the Universe

$$\mathcal{L}_{N_{R1}} = i\overline{N}_{R1}\gamma^{\mu}\nabla_{\mu}N_{R1} - \frac{1}{2}m\overline{N^{c}}_{R1}N_{R1},$$

$$\mathcal{L}_{V} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_{V}^{2}V_{\mu}V^{\mu},$$

$$\mathcal{L}_{I} = -g_{V}V_{\mu}J_{V}^{\mu} = -g_{V}V_{\mu}\overline{N}_{R1}\gamma^{\mu}N_{R1},$$

$$\mathcal{L}_{GR} = -\frac{R}{16\pi G},$$



- We work in the Relativistic Mean Field theory approx. fields are replaced by their mean values in its ground state .

$$\rho = \rho_C + \rho_V, \quad P = P_C + P_V$$

$$\rho_V = P_V = 1/2 C_V n^2$$

$$C_V = g_V^2/m_V^2$$

Yunis, Argüelles, Mavromatos, Moliné, et al. PDU (2020)

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

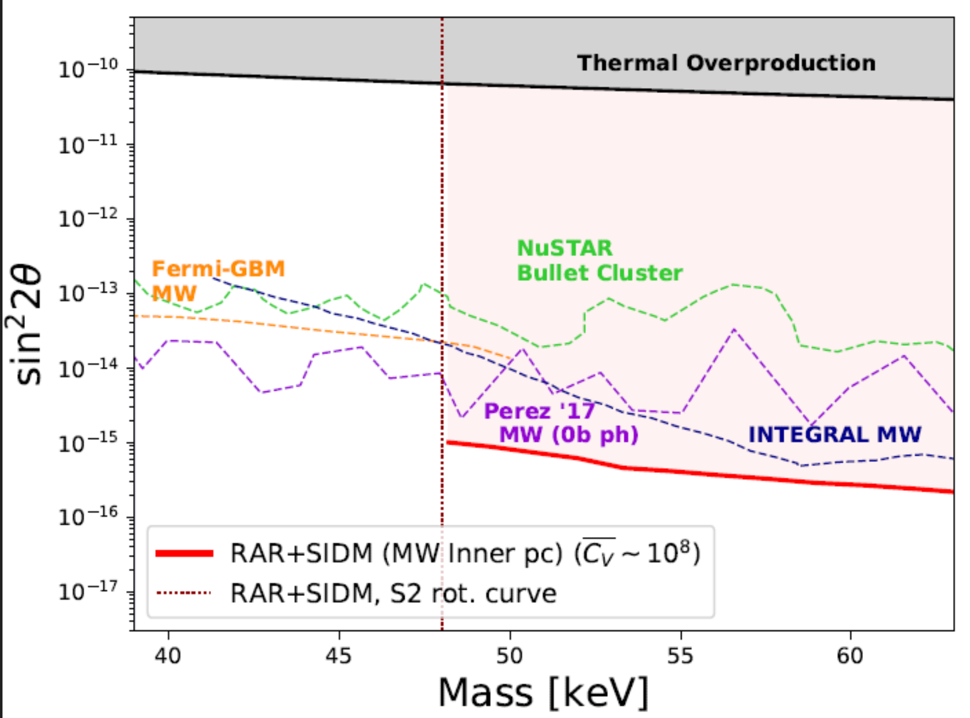
- The cross section constraints from colliding galaxy clusters D. Harvey et al. Science (2015)

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

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

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

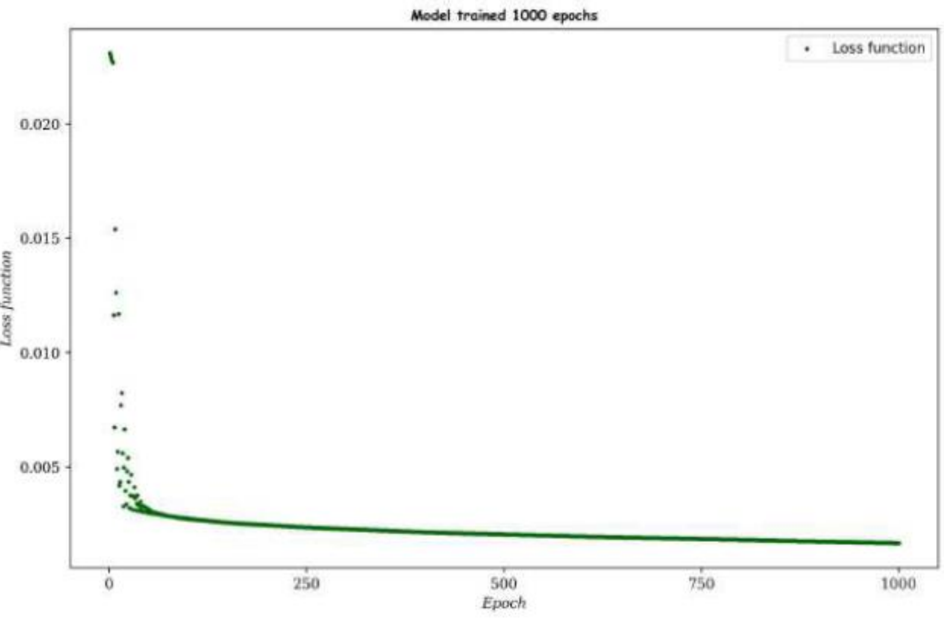
$$\overline{C}_V \equiv \left(\frac{g_V}{m_V}\right)^2 G_{\mathrm{F}}^{-1} \in (2.6\times10^8, 7\times10^8),$$

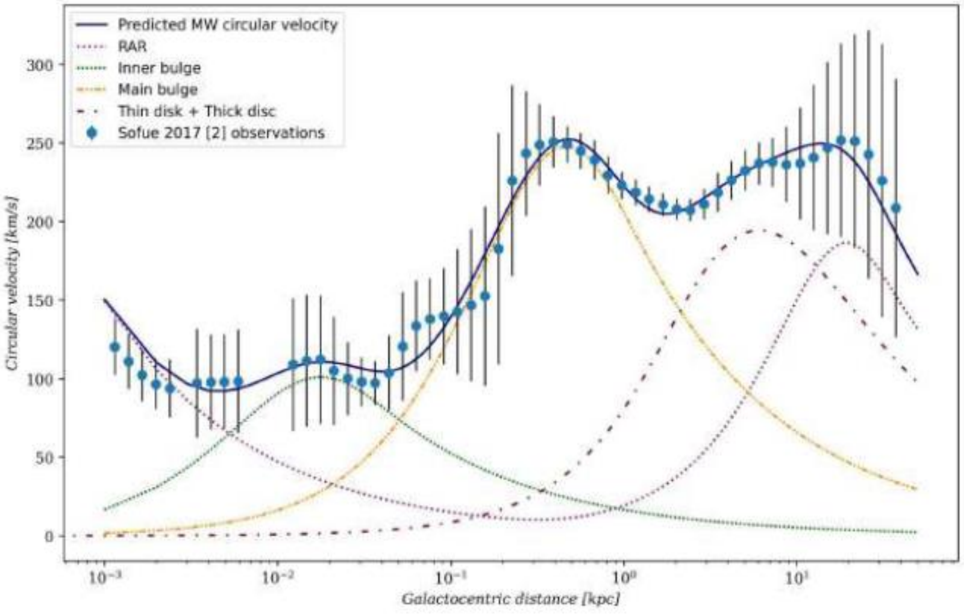


NuMSM parameter-space is relaxed by an additional production channel of s-neutrinos via the Vµ decay (lowering the bounds on interaction angle) Yunis, Argüelles, Mavromatos, et al. PDU (2020)

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

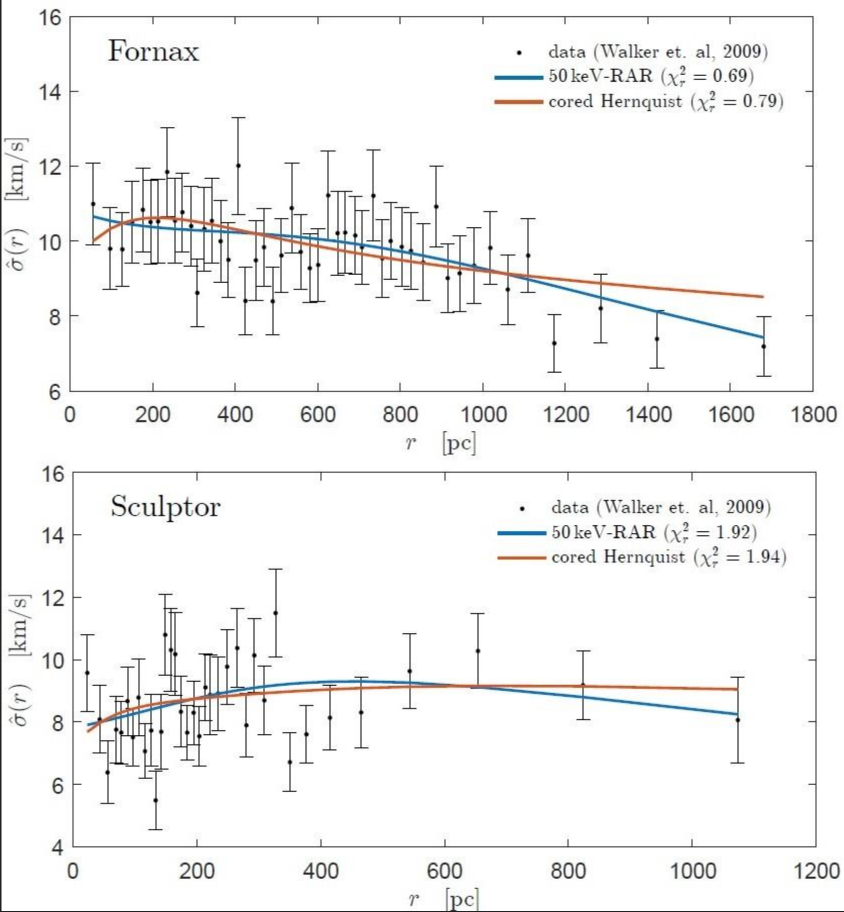
- We use machine learning tools (grdient descent, through **PyTorch**) to fit the observed Milky Way RC: Very useful to test semi-analitical models for DM (such as RAR, or Fuzzy DM) : can include **> 10** free parameters (Baryonic + DM), minimizing the Loss-function in few hs time

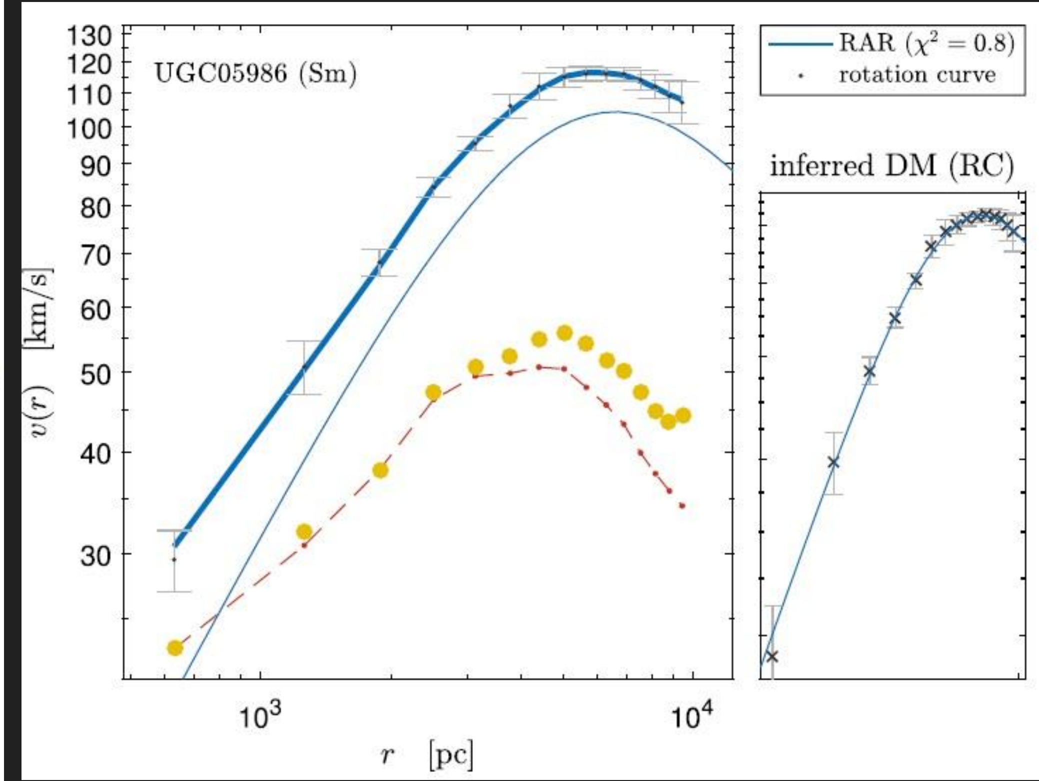




Collazo, Argüelles & Mestre, http://fof.oac.uncor.edu/2022/posters/ (2022)

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

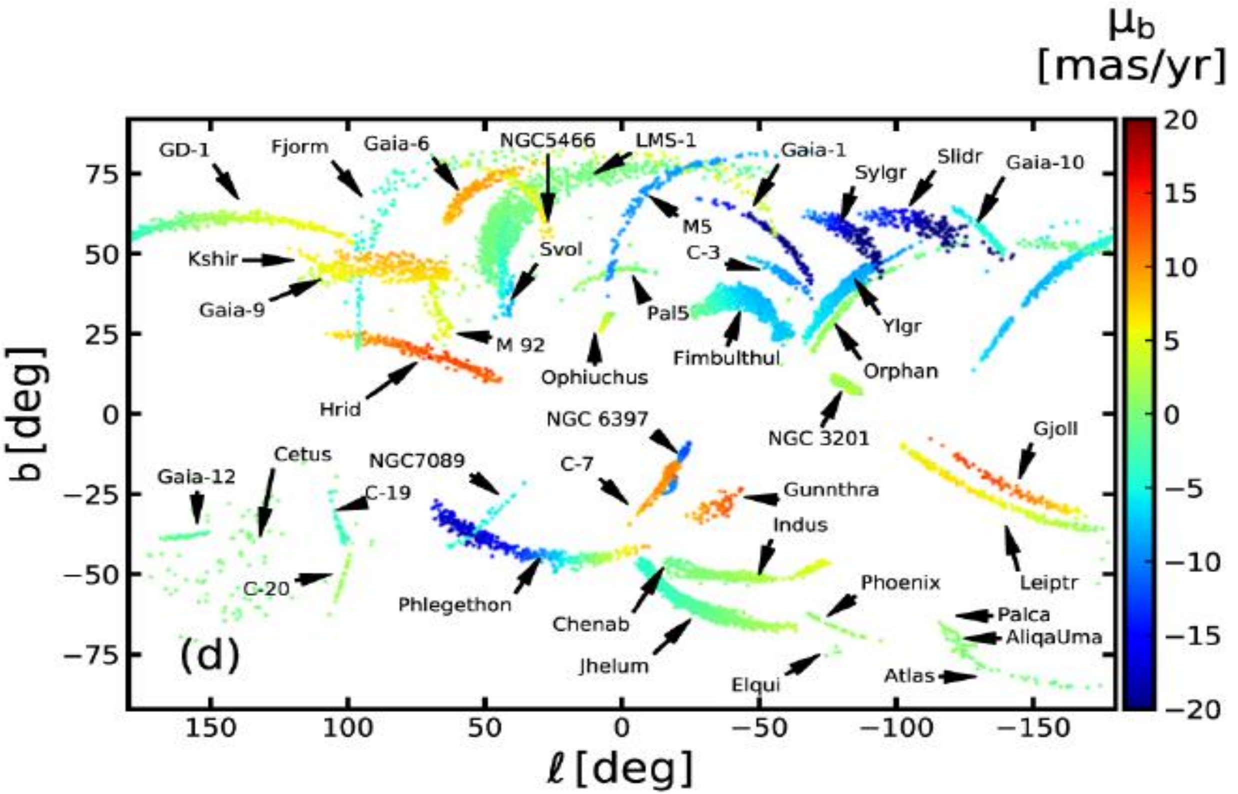




Applications: Galactic Scales (Stellar-Stream tracers)

Stellar streams in the Galaxy: key tracers of the gravitational potential

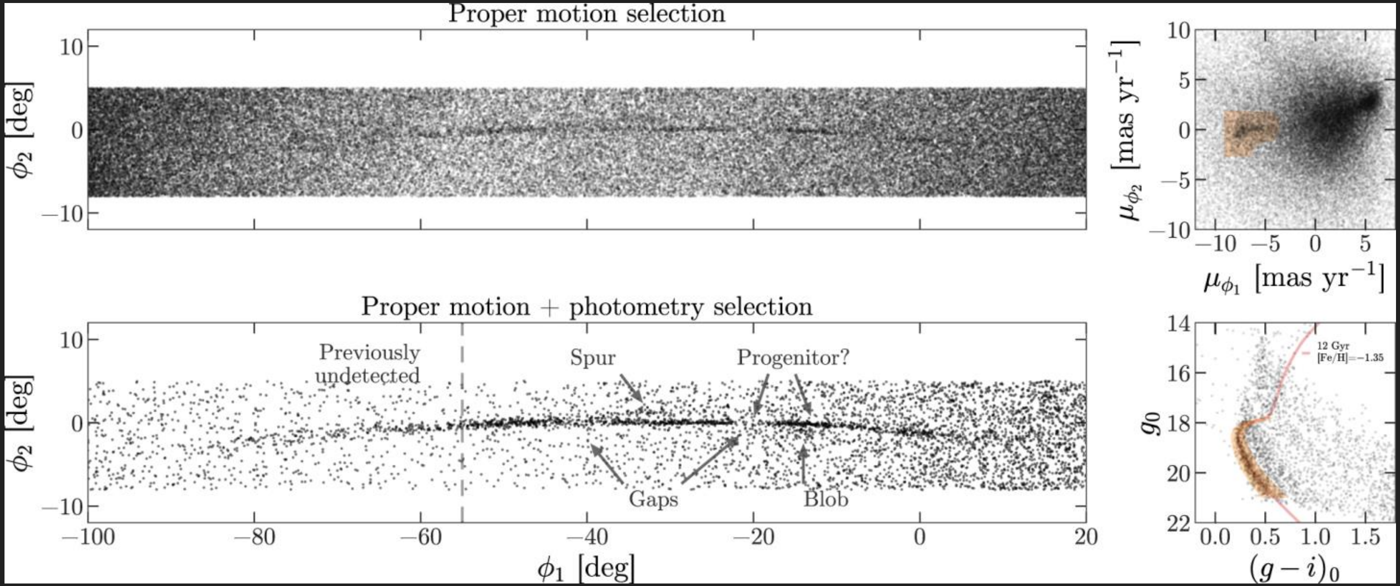
41 stellar streams comprising 9192 Gaia EDR3 stars



Malhan, Ibata, et al. Apj (2022)

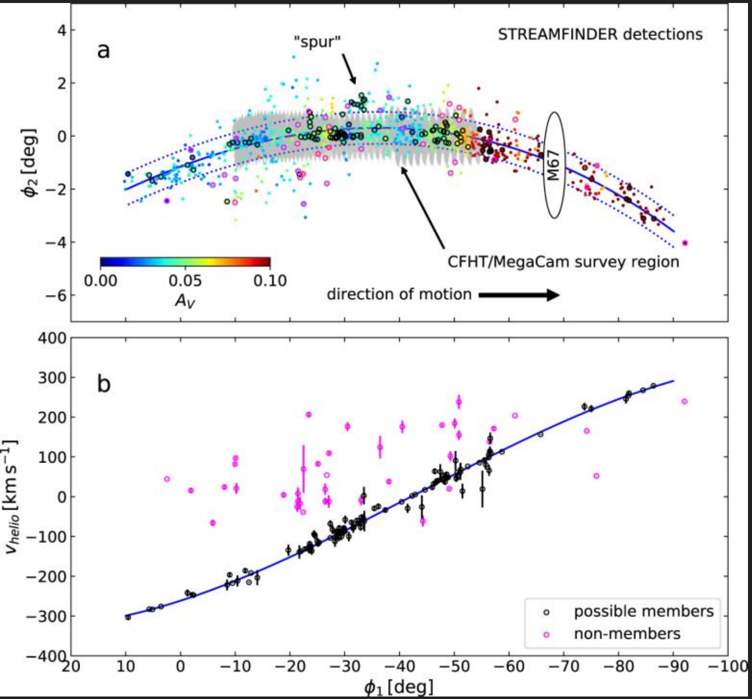
Constraining the fermionic DM model with the GD-1 stream

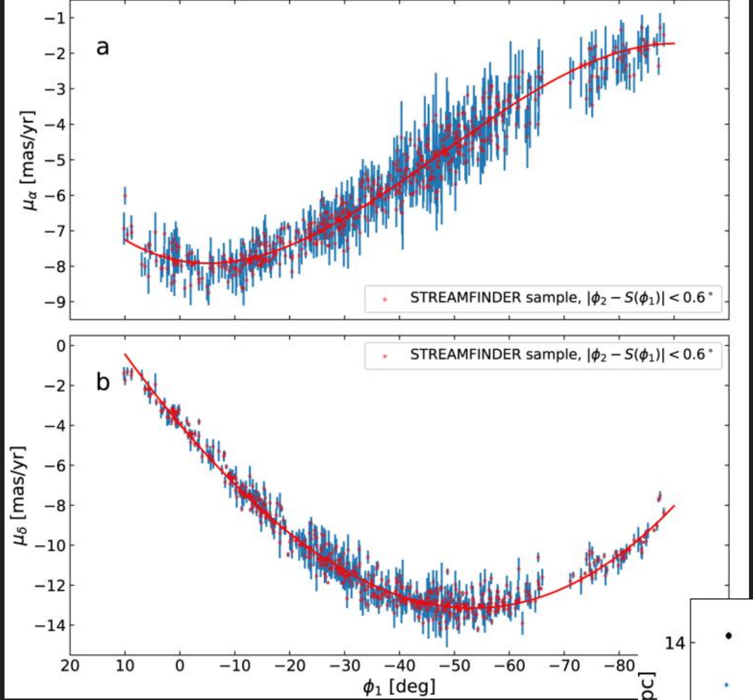
- A cold stream (GD-1) travelling through the halo (shown in self-coordinates along the stream) Price-Whelan & Bonaca, Apj (2018)

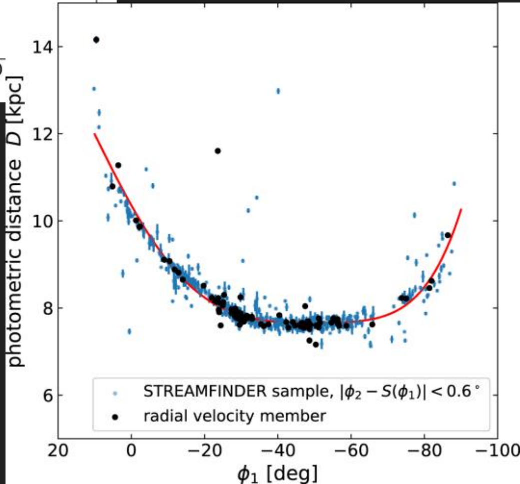


- Can the Gd-1observables be explained for a Milky Way composed of baryons + fermionic DM model ?

GD-1 observables





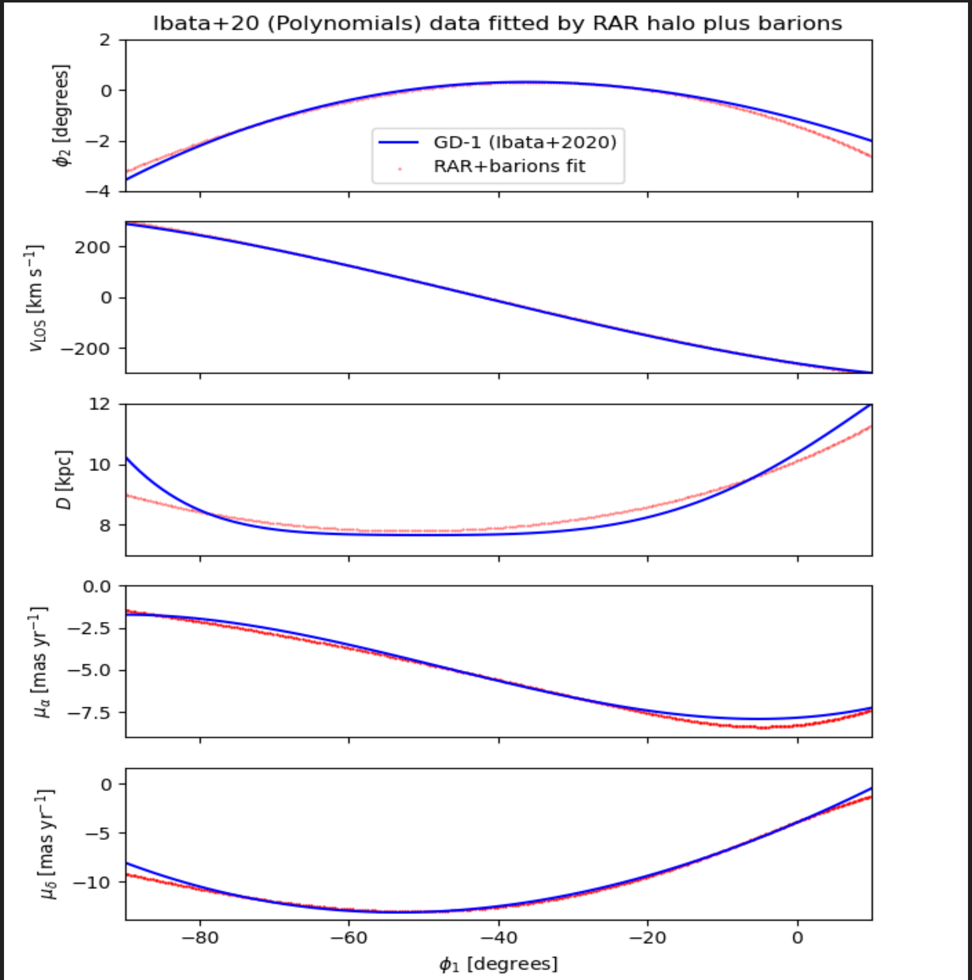


Ibata, et al. Apj (2020)

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

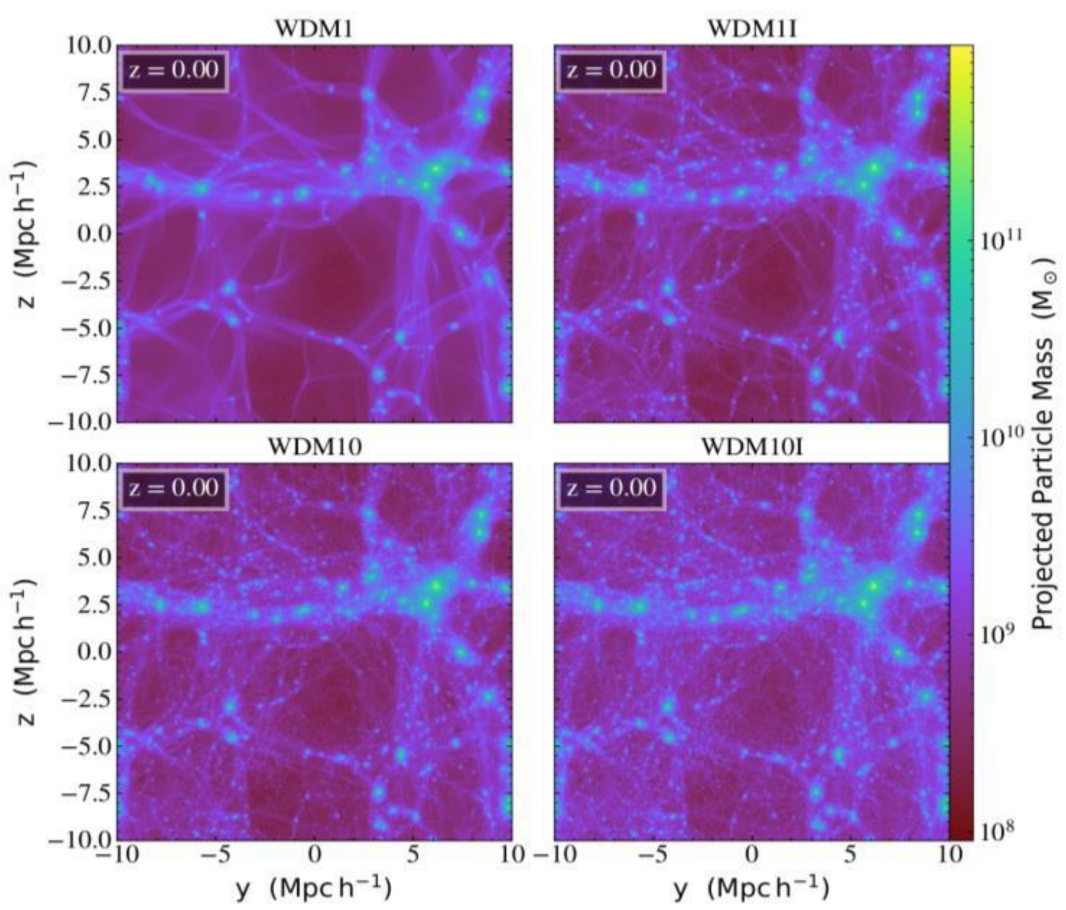
Θ_0=36.2; W_0=63.6

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

Mestre, Argüelles, et al. (In preparation)

Applications: Cosmological Scales (non linear regime)

N-body simulations in SI-WDM cosmologies (Gadget-4)



4 cosmologies (z=0), corresponding to different Power Spectrums within a SI-WDM model: (Box size: 20 Mpc/h; N=512^3 particles, softening length: 1 kpc)

WDM1: m=1 keV

WDM1 I : m=1 keV (C_v ≠ 0)

WDM10: m=10 keV

WDM10 I: m=10 keV (C_v ≠ 0)

Stahl, Yunis, Argüelles, et al. (In preparation)

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]

[1]*Instituto de Astrofísica de La Plata, UNLP-CONICET, Paseo del Bosque s/n B1900FWA La Plata, Argentina*
[2]*ICRANet, Piazza della Repubblica 10, I-65122 Pescara, Italy*
[3]*ICRA, Dipartimento di Fisica, Sapienza Università di Roma, Piazzale Aldo Moro 5, I-00185 Roma, Italy*
[4]*NNLOT, Department of Theoretical and Nuclear Physics, Al-Farabi Kazakh National University, Almaty 050040, Kazakhstan*
[5]*International University of Information Technology, Manas st. 34/1, 050040 Almaty, Kazakhstan.*
[6]*ICRANet-Ferrara, Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara, Via Saragat 1, I-44122 Ferrara, Italy*
[7]*Dipartimento di Fisica e Scienze della Terra, Università degli Studi di Ferrara, Via Saragat 1, I-44122 Ferrara, Italy*
[8]*INAF, Istituto di Astrofisica e Planetologia Spaziali, Via Fosso del Cavaliere 100, I-00133 Rome, Italy*
[9]*INAF, Viale del Parco Mellini 84, I-00136 Rome, Italy*
[10]*Facultad de Ciencias Básicas, Universidad Santiago de Cali, Campus Pampalinda, Calle 5 No. 6200, 760035 Santiago de Cali, Colombia*

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