Self-gravitating systems of elementary particles as models for DM halos & structure formation

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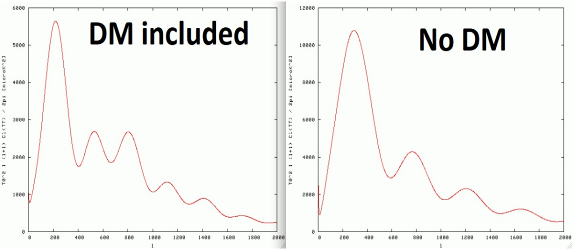
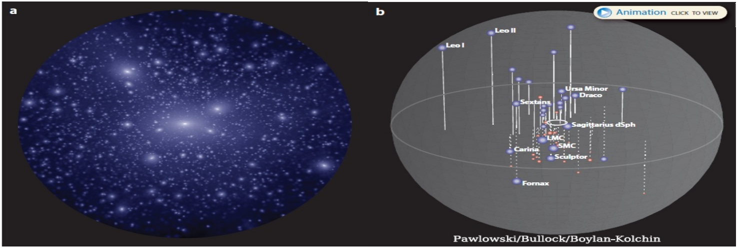
Success of ΛCDM Cosmology

- Astrophysical observations (CMB, BAO, Ly-α forest, local distribution and evolution of galaxies as well as peculiar velocity of local group, etc) ranging from horizon scale ($\sim$ 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 $\sim$ 70% followed by $\sim$ 25% of Cold Dark Matter (CDM) and only $\sim$ 5% of baryons plus radiation [Planck Collaboration et al., 2016]; [Vogelsberger et al., 2014]; [Kitaura, Angulo, et al., 2012]
- Being the most compelling evidence for the existence of CDM the precise features of the CMB

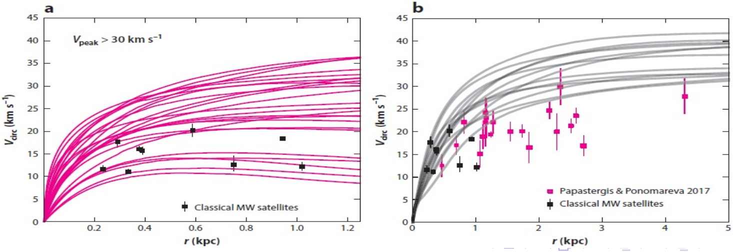


Small-scale challenges to ΛCDM

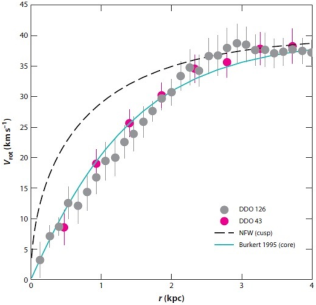
- LOST SATELLITE PROBLEM: possible solution is to argue that galaxy formation becomes increasingly inefficient as DM mass drops



- TOO BIG TO FAIL: large population of predicted (Aquarius-simulations) massive subhalos (with $V_{max} > 30$ km/s) which don't fit the data



- CORE-CUSP PROBLEM: Central regions of DM-dominated galaxies (as inferred from rotation curves) tend to be less cuspy than in LCDM halos



[Oh et al. AJ 2015]

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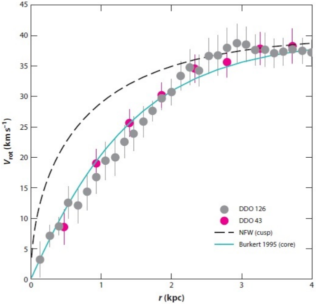
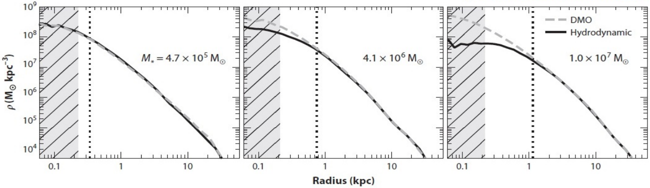


[Oh et al. AJ 2015]

- BARYONIC FEEDBACK becomes inefficient for low (stellar mass M_*) galaxies

[Fitts et al. MNRAS 2017]



Alternatives to ΛCDM

- Different outcomes respect to standard cosmological simulations when dropping one or more assumptions

Cold	→ Warm
Collisionless	→ Self-Interacting DM
DM only	→ DM plus neutrinos
Gaussian IC	→ Primordial NG
GR	→ Modified gravity simulations
Classical particles	→ axion/wave/fussy DM

Self-interacting DM in simulations

- N-body method sample the underlying phase-space distribution with particles

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

Vlasov equation

$$\frac{\mathrm{d}f}{\mathrm{d}t} = \frac{\partial f}{\partial t} + \frac{\partial f}{\partial \mathbf{x}} \cdot \mathbf{v} + \frac{\partial f}{\partial \mathbf{v}} \cdot \left(-\frac{\partial \Phi}{\partial \mathbf{x}}\right) = 0$$

The gravitational potential is related to the mass density via the Poisson equation:

$$\nabla^2 \Phi(\mathbf{x}, t) = 4\pi G \int f(\mathbf{x}, \mathbf{v}, t)\, \mathrm{d}\mathbf{v}$$

$$\ddot{\mathbf{x}}_i = -\nabla_i \Phi(\mathbf{x}_i)$$

$$\Phi(\mathbf{x}) = -G \sum_{j=1}^{N} \frac{m_j}{[(\mathbf{x} - \mathbf{x}_j)^2 + \epsilon^2]}$$

Softening length prevent forces to diverge, which would lead to unrealistic large-angle scattering events.

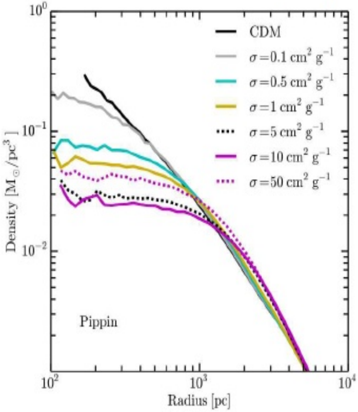
- A cross section for isotropic and elastic scattering among DM particles can modify the small-scale structure

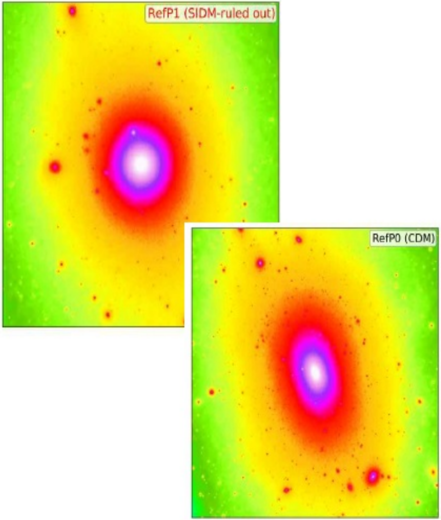
$$\frac{\mathrm{d}f(\mathbf{x}, \mathbf{u}, t)}{\mathrm{d}t} = \Gamma_{in} - \Gamma_{out}$$

$$\Gamma_{out} = f(\mathbf{x}, \mathbf{u}) \int \mathrm{d}\mathbf{u}\, f_v(\mathbf{x}, \mathbf{u}, t) \rho(\mathbf{x}) \frac{\sigma_\chi}{m} |\mathbf{u} - \mathbf{u}_i|$$

- Large cross-section reduces the central density of DM halos and make them rounder

Elbert et al (2015)

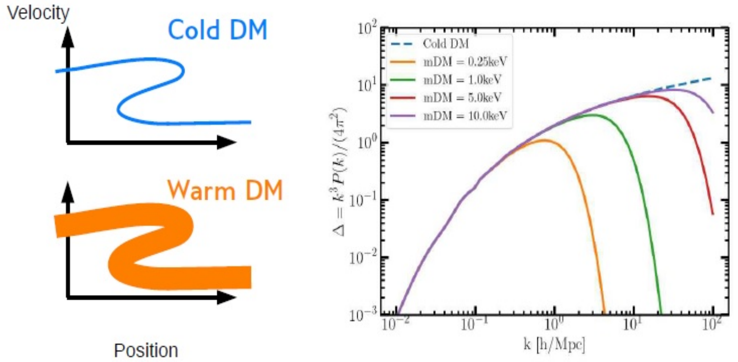




Vogelsberger et al (2012)

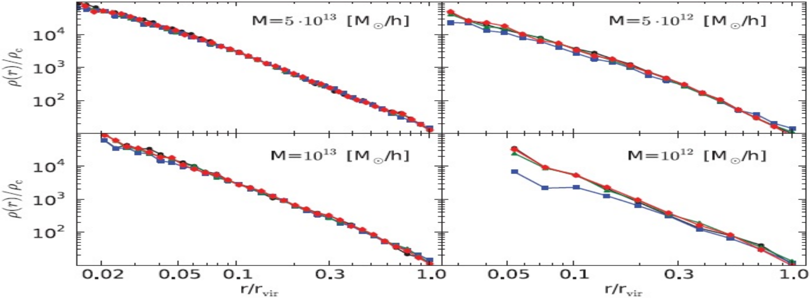
WDM in simulations

- Free streaming of (relativistically decoupled) particles damp primordial density fluctuation below a cutoff scale



- the small spread in velocity-space (respect to CDM) allows N-body simulations to solve WDM similarly as CDM within VLASOV-POISSON, but with a modified initial power spectrum

- Suppression of power below a given scale implies a difference in DM-halo morphology (for BELOW keV particles) [Schneider et al., *MNRAS* 2012]



- Radial distribution of sub-structure (High res. N-body for few keV thermal DM) show that WDM halos

$$M > 5 \times 10^9 M_\odot; \; r > 0.1 r_{\rm vir} \sim 10^1 {\rm kpc} \quad (1)$$

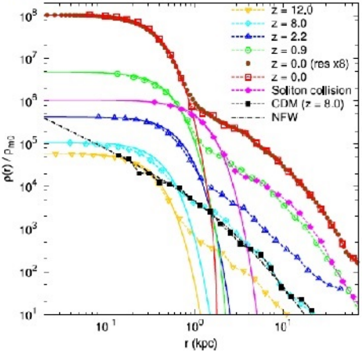
are indistinguishable from CDM halos and well fitted by Einasto profiles ($\alpha \approx 0.6$) [Bose et al., *MNRAS* 2017]

FDM in simulations

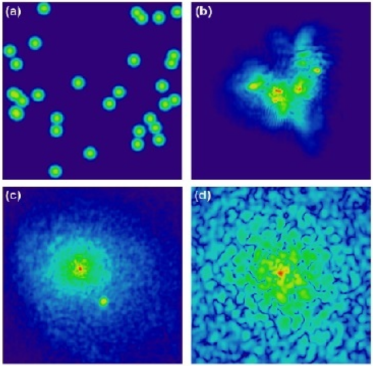
- From VLASOV-POISSON to SCHRÖEDINGER-POISSON

$$\frac{i\hbar}{a^{3/2}}\frac{\partial}{\partial t}(a^{3/2}\Psi) = \left[-\frac{\hbar^2}{2a^2 m_\Phi}\nabla^2 + m\phi_N\right]\Psi \qquad m_\Phi \sim 10^{-22}\mathrm{eV}$$

$$\frac{\nabla^2}{a^2}\phi_N = 4\pi G\,\rho_N \leftarrow \rho_N = \frac{2}{c\lambda_c^2}|\Psi|^2 \qquad \lambda_{db} \sim 10^{16}\mathrm{km}\left(\frac{10^{-4}c}{v}\right)\left(\frac{10^{-22}eV}{cm_\Phi}\right)$$



[Schive et al. (2014)]



Theoretical field descriptions: bosons & fermions.
(A complementary framework to N-body simulations)

Bosons: Ultra-light DM or Fuzzy DM

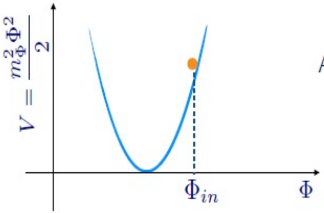
- Main physical motivation for a FDM particle: occurs in QCD-axion

Very light DM with large $n = \rho_{DM}/m_\Phi$

Classical solution to the Klein-Gordon equation $[-\Box + m_\Phi^2]\Phi(\vec{x},t) = 0$

Background: $ds^2 = -dt^2 + a^2\delta_{ij}dx^i dx^j \longrightarrow \ddot{\Phi} + 3H\dot{\Phi} + m_\Phi^2\Phi = 0$, $H = \dot{a}/a$

Initial conditions set by inflation (very homogeneous)



When $H \gg m_\Phi \longrightarrow \Phi \sim \text{constant} \longrightarrow T^\mu_\nu \propto \delta^\mu_\nu$

After $H < m_\Phi \longrightarrow \Phi \sim \Phi_0 \cos(m_\Phi t + \Upsilon)$

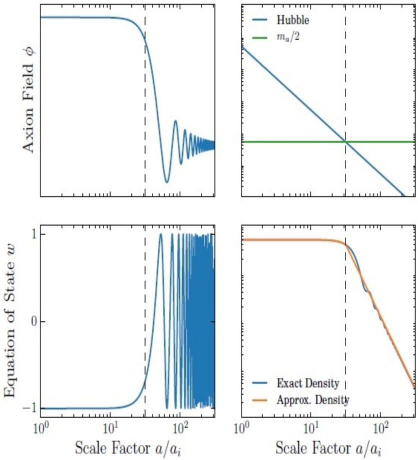
$$T_{\mu\nu} \longrightarrow \rho_{DM} = \frac{m_\Phi^2 \Phi_0^2}{2} + \text{oscillations}$$

$$p_{DM} = -\rho_{DM}\cos(2m_\Phi t + 2\Upsilon)$$

(oscillations are irrelevant on long time scales)

Bosons: Ultra-light DM or Fuzzy DM

- The temperature T_0 at which $\rho_{FDM} \propto a^{-3}$ is 500 eV ($z \sim 10^6$)
- *Evolution* of $\rho(r) = m|\Psi|^2$ from radiation era to matter-radiation equality (at $\sim$ 1 eV) implies $m \sim 10^{-22}$ eV



[Marsh, Phys. Rep 2016]

- SELF-GRAVITY: A large collection of bosons in the same state: described by a classical field Ψ - SCHRÖEDINGER-POISSON ($\rho(r) = m|\Psi|^2$) -

$$-\hbar/2m\nabla^2\Psi + Vm\Psi = mE\Psi \qquad \nabla^2 V = 4\pi G m|\Psi|^2 \tag{2}$$

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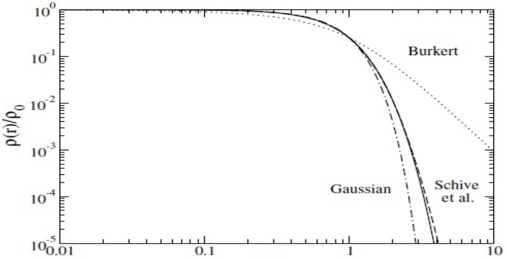
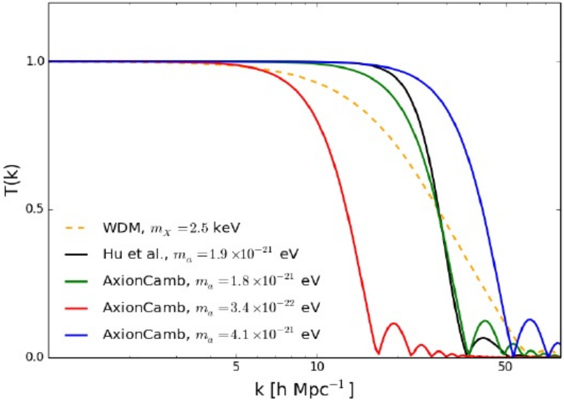
- The lowest eigenstate solution (E_n; $n = 0$) is stable. The nth excited states are unstable and decay to the ground state → Gravitational cooling! [Seidel, *PRL* 1994]; [Schwabe, *PRD* 2016]
- Central density eigenstates: $\rho_c \propto m^3 M^4 \rho_n$. For ($n = 0$) $M \sim 10^9 M_\odot$; $\rho_c \sim 5M_\odot/pc^3 \Rightarrow m \sim 10^{-22}$ eV [Hui, et al. *PRD* 2017]

$$\frac{\lambda_{db}}{2\pi} = \frac{\hbar}{mv} = 1.9\mathrm{kpc}\left(\frac{10^{-22}\mathrm{eV}}{\mathrm{m}}\right)\left(\frac{10\mathrm{kms}^{-1}}{\mathrm{v}}\right)\ \mathrm{de-Broglie\ wavelength} \tag{3}$$

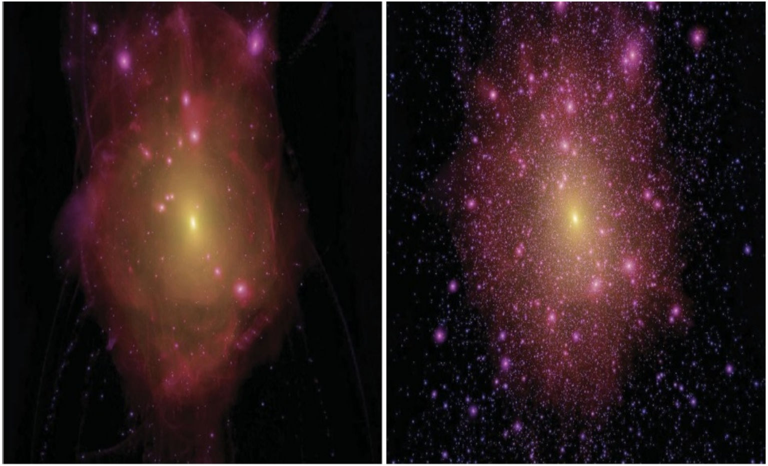


- FDM is unstable ONLY for masses larger than Jeans mass $M_J \sim 10^7 M_\odot (10^{-22}\mathrm{eV/m})^{3/2}$
- The number of CDM sub-halos RISES for M_h below $10^8 M_\odot$, while for FDM halts
- The power spectrum in FDM is SUPPRESSED relative to CDM at small scales
- Ly-α forest offers additional prove of power spectrum: $m_{WDM} > 3.3$ keV translates in $m_{FDM} > 2 \times 10^{-21}$ eV $\Rightarrow$ Tension!! [Hui, et al. *PRD* 2017]



WDM & FDM: Suppression of structure below Mpc

- Matter power spectrum which are cuted-off below given scale produce less amount of substructure and less concentrated [Lovell, et al. *MNRAS* 2012]
- THIS PICTURE: High-res. N-body simulations: $z = 0$; box of 1.5 Mpc side



Fermions: WDM & keV particles

- Fermions with self-gravity DO ADMIT a perfect fluid approximation basically due to the Pauli exclusion pple. [Ruffini, *Phis.Rev* 1969]
- Challenge: Solve the Einstein equations for hydrostatic equilibrium (T.O.V: i.e. perfect fluid) of a thermal and semi-degenerate fermion gas (spherical symmetry)

$$\frac{dM}{dr} = 4\pi r^2 \rho,$$
$$\frac{dP}{dr} = -\frac{1}{2}\frac{d\nu}{dr}(c^2\rho + P), \qquad \frac{d\nu}{dr} = \frac{2G}{c^2}\frac{M + 4\pi r^3 P/c^2}{r^2[1 - 2GM/(c^2 r)]}$$

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

$$f(r,p) = \frac{1}{e^{\frac{\epsilon(p)-\mu(r)}{kT(r)}} + 1}, \qquad \epsilon(p) = \sqrt{c^2p^2 + m^2c^4} - mc^2$$

Theory: Thermodynamics and Statistical physics

- COLLISIONLESS RELAXATION: described by the VLASOV-POISSON equation

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi(\mathbf{r},t)\frac{\partial f}{\partial \mathbf{v}} = 0 \qquad \triangle\Phi = 4\pi G\int f d^3\mathbf{v}$$

- Main collisionless mechanisms: phase mixing & violent relaxation. Defined over macroscopic (averaged) states: $f \to \bar{f}$
- VIOLENT RELAXATION [Lynden Bell, *MNRAS* 1967]: the total energy of the bodies is NOT conserved

$$\frac{dE}{dt} = \frac{\partial\Phi}{\partial t}\Big|_{r(t)}$$

- COLLISIONLESS RELAXATION TIME proper of violently changing Φ is the Dynamical time $t_D \ll t_R \to$ Relaxation in galaxies can be approached without the need for collisions
- (Macroscopic) Maximization entropy principle at fixed total mass and energy (η is a phase-space patch or macrocell)

$$S = \int \rho(\mathbf{r},\mathbf{v},\eta)\ln\rho(\mathbf{r},\mathbf{v},\eta)d\eta d^3\mathbf{r}d^3\mathbf{v} \qquad \bar{f}(\mathbf{r},\mathbf{v}) = \int \rho(\mathbf{r},\mathbf{v},\eta)\eta d\eta$$

$$\delta S = 0 \Rightarrow \bar{f} = \frac{1}{e^{\beta[\epsilon(p)-\alpha]}+1}$$

- Dimensionless form of the diff. eqtns. $\rightarrow$ Necessary step $\hat{r} = r/\chi$, $\chi \propto m^{-2}$

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

$$\frac{d\theta}{d\hat{r}} = -\frac{1-\beta_0(\theta-\theta_0)}{\beta_0}\frac{\hat{M}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}/\hat{r})}, \tag{5}$$

$$\frac{d\nu}{d\hat{r}} = \frac{\hat{M}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}/\hat{r})}, \tag{6}$$

$$\beta(r) = \beta_0 e^{-\frac{\nu(r)+\nu_0}{2}} . \tag{7}$$

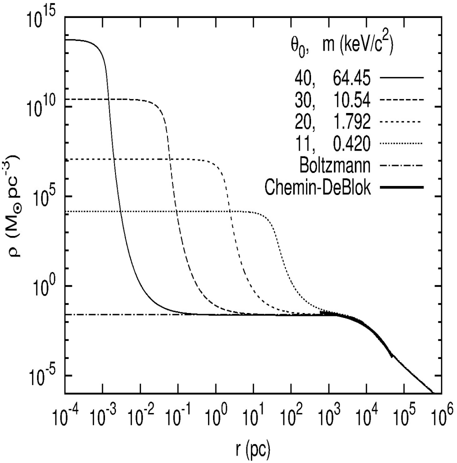
- Free parameters: $\beta = kT/mc^2$, $\theta = \mu/kT$ and m
- Initial condition problem:

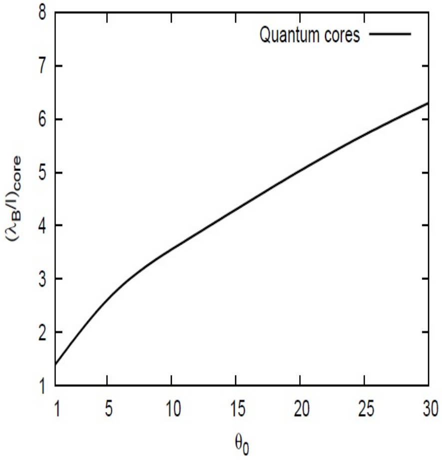
$$M(0) = 0; \quad \nu_0 = 0; \quad \theta(0) = \theta_0 > 0; \quad \beta(0) = \beta_0; \tag{8}$$

- DM halo observables typical of spiral galaxies (boundary conditions):

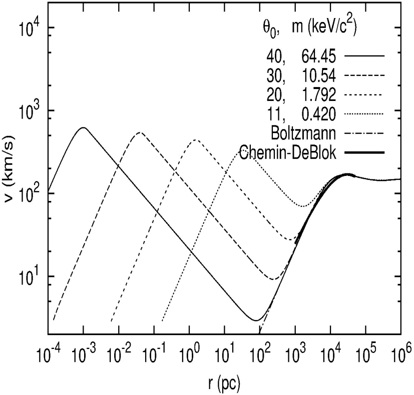
$$r_h = 25\,\mathrm{Kpc};\ \mathrm{v_h} = 168\,\mathrm{km/s};\ \mathrm{M_h} = 1.6\times 10^{11}\mathrm{M}_\odot \tag{9}$$

- $\beta_0 = kT/mc^2 \propto v_h$ quite independently of θ_0;
- $\rho(r)$ solutions for a wide range of free parameters (θ_0, m), for given HALO boundary conditions inferred from observables





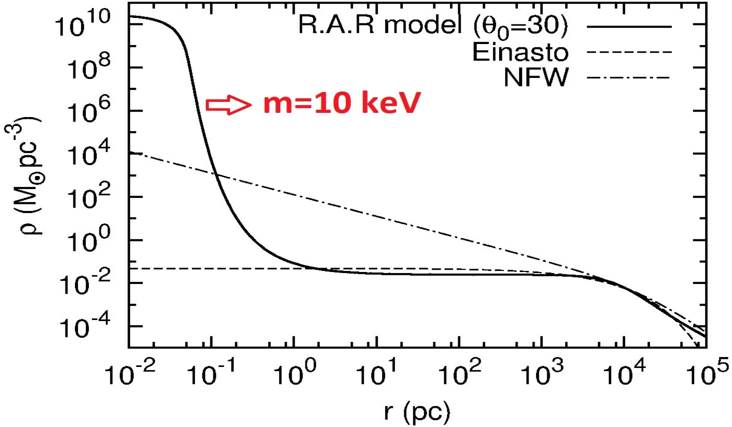
- RAR ROTATION CURVES for fixed boundary conditions
- m is mainly sensitive to the Core
- For $m \sim 10\text{keV}/c^2 \rightarrow M_c \sim 10^6 M_\odot$ (SgrA* candidate)



θ_0	$m(keV/c^2)$	$r_c(pc)$	$M_c(M_\odot)$
11	0.420	3.3×10^1	8.5×10^8
25	4.323	2.5×10^{-1}	1.4×10^7
30	10.540	4.0×10^{-2}	2.7×10^6
40	64.450	1.0×10^{-3}	8.9×10^4
58.4	2.0×10^3	9.3×10^{-7}	1.2×10^2
98.5	3.2×10^6	3.2×10^{-13}	7.2×10^{-5}

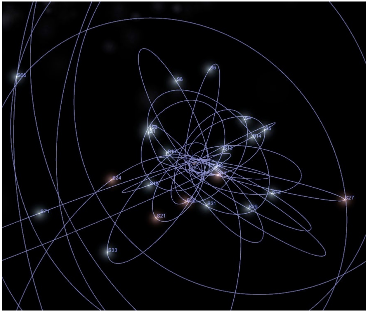
Fermions: WDM & keV particles

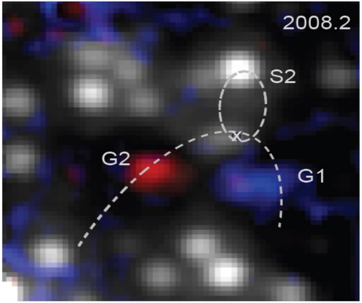
- General solutions: Novel CORE-HALO fermionic profiles which *depend* on the particle mass. Central dense core fulfills 'quantum condition' $\lambda_{db} > 3l_{core}$ [Ruffini, C. R. A, Rueda *MNRAS* 2015]



The S-stellar cluster & central gas

- 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

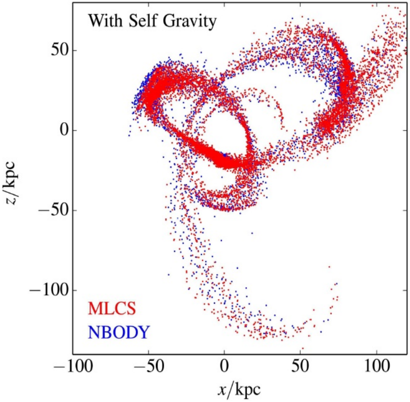


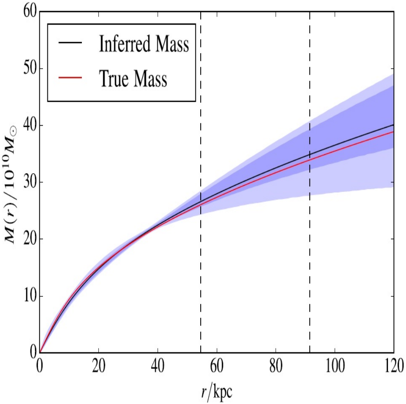


Observations implies $M_c \approx 4.2 \times 10^6 M_\odot$ within the smallest pericenter $r_{p(S2)} \approx 6 \times 10^{-4}$ pc

The outermost DM halo constraints: Sgr-dwarf

- The outermost satellite galaxies of the MW are excellent total DM tracers
- The Sgr-dwarf satellite with its stream motion of tidally disrupted stars was well observed and well reproduced numerically *Belokurov et al. (MNRAS) (2014)*, *S. Gibbons et al. (MNRAS) (2014)*





Extended RAR model

- Objective: solve in the more general way the relativistic equations for hydrostatic equilibrium of a thermal and semi-degenerate fermion gas including for escape of particles

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

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

The parametric equation of state (EOS) of the fermion gas is

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

- The problem is treated in a spherically symmetric metric

$$ds^2 = e^{\nu}c^2dt^2 - e^{\lambda}dr^2 - r^2d\theta^2 - r^2\sin^2\theta d\phi^2,$$

Theory: Thermodynamics and Statistical physics

- DM halo formation: COLLISIONLESS RELAXATION & ESCAPE OF PARTICLES → generalized Fokker-Planck equation for fermions P.H. Chavanis, *Physica A* (2004)

$$\frac{\partial f}{\partial t} + \mathbf{v}\frac{\partial f}{\partial \mathbf{r}} - \nabla\Phi(\mathbf{r},t)\frac{\partial f}{\partial \mathbf{v}} = \frac{\partial}{\partial \mathbf{v}}\mathbf{J}_f \qquad \triangle\Phi = 4\pi G\int f d^3\mathbf{v}$$

- Stationary solutions of the form $f = f(\epsilon)$ ($f(\epsilon_c) = 0$, $\epsilon_c = v^2/2 + \Phi$) can be found, satisfying the H-theorem for an arbitrary functional

$$S = -\int C(f) d^3\mathbf{r} d^3\mathbf{v}$$

- The generalized Kinetic equation has a thermodynamical structure (corresponding to a canonical description in the case of KRAMERS)
- If $C(f)$ is the Boltzmann Entropy functional

$$f(\epsilon) = A(\exp[-\beta(\epsilon)] - \exp[-\beta(\epsilon_c)]) \qquad \textbf{classical} \quad \text{particles}$$

- If $C(f)$ is the Fermi-Dirac Entropy functional

$$f(\epsilon) = \frac{1 - e^{\beta(\epsilon-\epsilon_c)}}{e^{\beta(\epsilon-\mu)} + 1} \qquad \textbf{quantum} \quad \text{or} \quad \textbf{classical} \quad \text{particles}$$

Theory: The RAR model

- The Einstein equations can be written can be written in the form of Tolman and Oppenheimer and Volkoff

$$\begin{aligned} \frac{dM}{dr} &= 4\pi r^2 \rho, \\ \frac{dP}{dr} &= -\frac{1}{2}\frac{d\nu}{dr}(c^2\rho + P), \quad \frac{d\nu}{dr} = \frac{2G}{c^2}\frac{M + 4\pi r^3 P/c^2}{r^2[1 - 2GM/(c^2 r)]} \end{aligned}$$

And λ is related to the mass M through

$$e^{-\lambda} = 1 - \frac{2GM}{c^2 r}.$$

- The thermodynamic equilibrium conditions within GR (Klein conditions) together to energy conservation along a geodetic G. Ingrosso, *A&A* (1992)

$$\begin{aligned} e^{\nu/2} T &= \text{constant}, \\ e^{\nu/2}(\mu + mc^2) &= \text{constant}, \\ e^{\nu/2}(\epsilon + mc^2) &= \text{constant}. \end{aligned}$$

Theory: The RAR model

- Dimensionless form of the diff. eqtns. → Necessary step
  $\hat{r} = r/\chi$, $\chi \propto m^{-2}$

$$\frac{d\hat{M}}{d\hat{r}} = 4\pi \hat{r}^2 \hat{\rho},$$
$$\frac{d\theta}{d\hat{r}} = -\frac{1-\beta_0(\theta-\theta_0)}{\beta_0} \frac{\hat{M}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}/\hat{r})},$$
$$\frac{d\nu}{d\hat{r}} = \frac{\hat{M}+4\pi\hat{P}\hat{r}^3}{\hat{r}^2(1-2\hat{M}/\hat{r})},$$
$$\beta(r) = \beta_0 e^{-\frac{\nu(r)+\nu_0}{2}}$$
$$W(r) = W_0 + \theta(r) - \theta_0$$

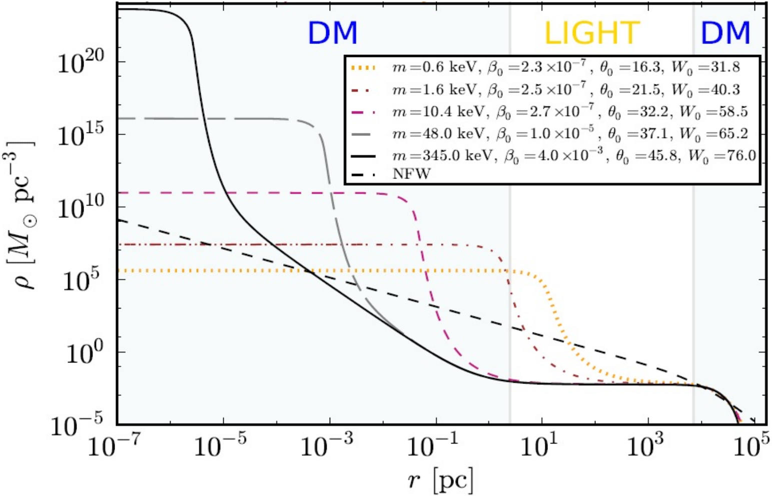
- Free parameters: m, $\beta = kT/mc^2$, $\theta = \mu/kT$ and W$= \epsilon_c/kT$

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

- Initial condition problem: Solved for different m such that $M(r)$ satisfy the required observations

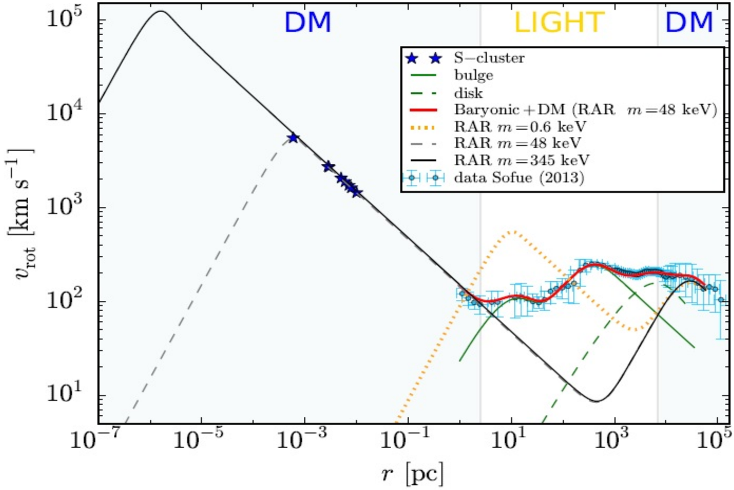
Fermions: WDM: keV-ish DM

- Extended RAR theory including for escape of particles provide new solutions allowing for more compact quantum cores [C. R. A, et al. *PDU* (2018) 1606.07040]

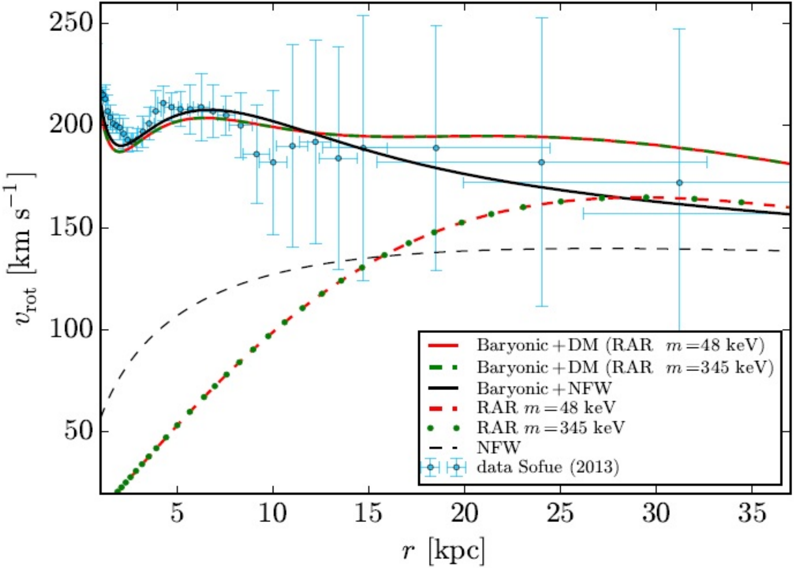


Fermions: WDM: keV-ish DM

- Extension of the RAR profiles including for escape of particles provides excellent fits to the MW rotation curve [C. R. A, et al. *PDU* (2018) 1606.07040]

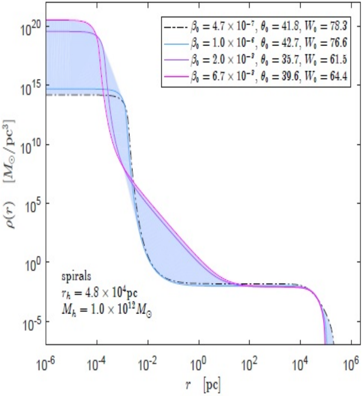


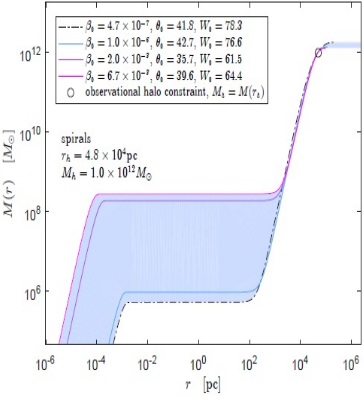
- [C. R. A et al. *PDU* (2018) 1606.07040]



Typical Seyfert-like Spirals

- THE CASE OF $m = 48$ keV FERMIONIC DARK MATTER
- Observationally-inferred boundary condition at r_h: $M_h(r_h = 48 \text{ kpc}) = 1 \times 10^{12} M_{\odot}$

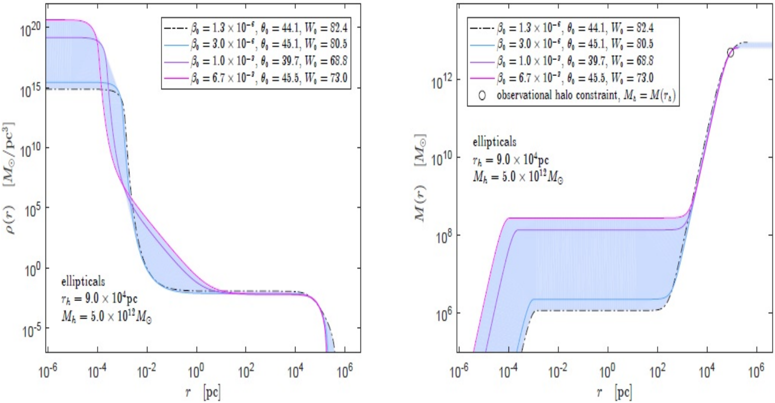




- PREDICTED: $M_c \in (4 \times 10^5, 2 \times 10^8) M_{\odot}$; $M_{tot} \in (1 \times 10^{12}, 2 \times 10^{12}) M_{\odot}$ [C. R. A et al. (2018) 1606.07040]

Typical normal Ellipticals

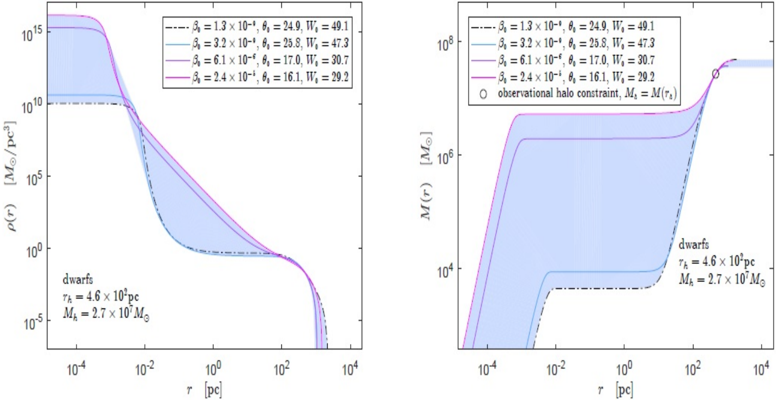
- THE CASE OF $m = 48$ keV FERMIONIC DARK MATTER
- Observationally-inferred boundary condition at r_h: $M_h(r_h = 90\text{ kpc}) = 5\times10^{12} M_\odot$



- PREDICTED: $M_c \in (1\times10^6, 2\times10^8)M_\odot$; $M_{tot} \in (6\times10^{12}, 9\times10^{12})M_\odot$ [C. R. A et al. (2018) 1606.07040]

Typical Dwarf Spheroidals

- THE CASE OF $m = 48$ keV FERMIONIC DARK MATTER
- Observationally-inferred boundary condition at r_h: $M_h(r_h = 0.4 \text{ kpc}) = 3 \times 10^7 M_\odot$



- PREDICTED: $M_c \in (3 \times 10^3, 4 \times 10^6) M_\odot$; $M_{tot} \in (3 \times 10^7, 5 \times 10^7) M_\odot$ [C. R. A et al. (2018) 1606.07040]

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Detection of Supermassive Black Holes in Two Virgo Ultracompact Dwarf Galaxies

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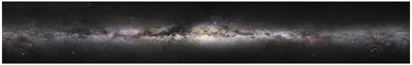
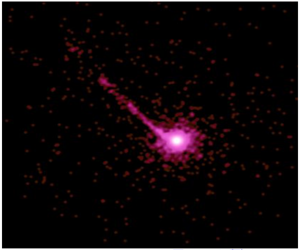
Abstract

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

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



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

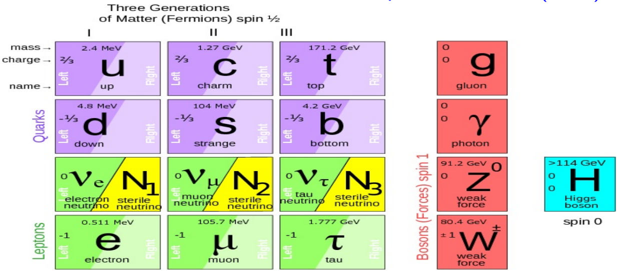


CONSTRAINTS ON PARTICLE PHYSICS BEYOND SM

- Coupling with Higgs provides (through SSB mechanism) the Quark, Lepton (e,μ,τ) and gauge boson - mass generation

$$\mathcal{L}_\psi \propto -m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L) \qquad BUT \ \ in \ \ SM \ \nexists \ \nu_R \tag{10}$$

- 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!

$$\mathcal{L} = \mathcal{L}_{SM} + i\nu_R\partial_\mu\gamma^\mu\nu_R - g\,\bar{L}\nu_R\phi - M/2\bar{\nu}_R^c\nu_R \tag{11}$$

- Coupling with Higgs provides (through SSB mechanism) the Quark, Lepton (e,μ,τ) and gauge boson - mass generation

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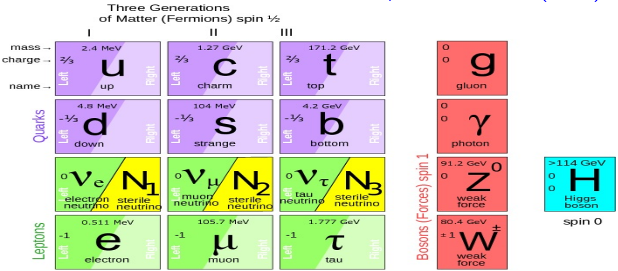

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- A Lagrangian extension including for self-interactions $\mathcal{L}_I$ under self-gravity was analyzed C. Argüelles, N. Mavromatos, et al. *JCAP* (2016) 1502.00136

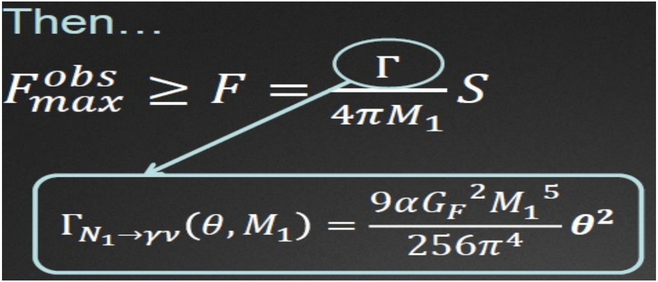
$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{\nu_R} + \mathcal{L}_V - g_V V_\mu J^\mu$$

Indirect ν_s detection from GC

- Sterile neutrino Decay channel: $N_1 \to \nu_\alpha + \gamma$

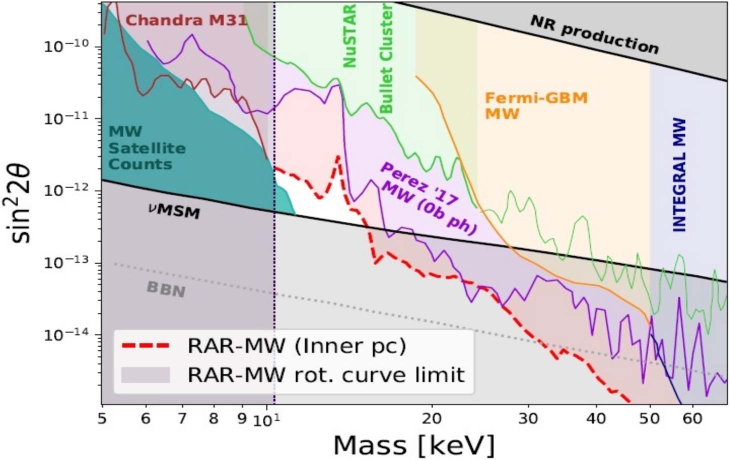
$$f = \frac{\Gamma_\gamma}{4\pi M_{N_1}} \int d\Omega \int dx \rho_{DM}(x) = \frac{\Gamma_\gamma}{4\pi M_{N_1}} S_{DM}$$

- DM density profile assumption (i.e. RAR model) $\to \rho_{DM} \equiv \rho_{DM}(m_s)$



Indirect ν_s detection from GC

- DM halos in terms of self-gravitating neutral fermions can put constraints on particular DM models such as νMSM [R. Yunis, C.R.A. et al., (2018) 1810.05756]



Conclusions

- Relaxed systems of self-gravitating bosons/fermions arising from *stationary solutions* of Schröedinger-Piosson/ Vlasov-Poisson provide novel core-halo profiles which may offer insights to non-linear structure formation on small scales
- Non-interacting FDM - $m_{FDM} \sim 1 - 10 \times 10^{-22}$ eV - or WDM (semi-degenerate) fermions $m_{WDM} \sim 10 - 100$ keV may provide solutions to the challenges faced by ΛCDM on scales below 10 kpc or so
- Standard FDM models are in tension with Ly-α forest data and (ruled out!) by galaxy scaling relations such as $\rho_c \propto r_c^{-1}$ [Deng et al., *PRD* 2018] (Interacting FDM is needed!)
- Virialized WDM within the RAR model for semi-degenerate fermions (above 10-keV) is in line with Ly-α and galaxy rotation curves & scaling-relations data sets [C.R.A. et al., (2018) 1810.00405]

THANK YOU! QUESTIONS?

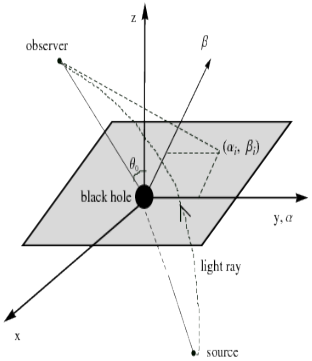
Strong lensing around SgrA*: RAR-core Vs. BH

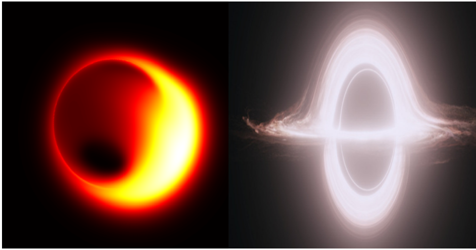
- Deflection angle $\hat{\alpha}(r_0)$ in the Relativistic Regime

$$\hat{\alpha}(r_0) = 2\int_{r_0}^{\infty} \frac{e^{\lambda/2} dr}{\sqrt{(r^4/b^2)e^{-\nu} - r^2}} - \pi .$$

$$b = r_0 \exp\left[-\nu(r_0/2)\right] \quad \text{impact parameter.}$$

- For Schwarschild BH the deflection angle can reach $\hat{\alpha} > 3/2\pi$ (i.e relat. images)





Strong lensing around SgrA*: RAR-core Vs. BH

- RAR-core: At $r \sim 10^{-5}$ pc strong lensing effects arises: Einstein ring at $r \sim 4\,R_s$ L. G. Gómez, C. R. Argüelles, V. Perlick, J. A. Rueda, R. Ruffini, PRD (2016)
- DM RAR cores do not show a photon sphere ($\hat{\alpha}(r_0) < 1$), i.e. they do not cast a shadow as the BH does!
- The EHT expect angular resolution of $\sim 30\mu$arcsec (angular diameter θ of BH shadow $\sim 50\mu$arcsec $\sim 6R_s$)