Adiabatic contraction of haloes in scalar field dark matter cosmologies

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FWF
Der Wissenschaftsfonds.

Alternatives to ΛCDM - why?

- Small-scale problems
  - cusp-core
  - missing satellites
  - too-big-too-fail

- Null detection of standard CDM candidates (so far)

Scalar field dark matter

- Forms a Bose-Einstein condensate

Fuzzy dark matter (FDM)

$$m \sim 10^{-22}\ \mathrm{eV}$$

$$\lambda_{\mathrm{dB}} \sim 1\ \mathrm{kpc}$$

SFDM with self-interaction

$$\lambda_{\mathrm{dB}} \ll R_{\mathrm{TF}} \lesssim 1\ \mathrm{kpc}$$

- Governed by Gross-Pitaevskii-Poisson equations

$$i\hbar\frac{\partial\psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\triangle + m\Phi + g|\psi|^2\right)\psi$$

$$\triangle\Phi = 4\pi G m|\psi|^2$$

gravitational potential

coupling constant

$g > 0$ repulsive

$g < 0$ attractive, no suppression of small-scale structure

Hydrodynamic formulation of SFDM

bulk flow velocity

Euler equation
$$\frac{\partial \mathbf{v}}{\partial t} + (\nabla \mathbf{v})\, \mathbf{v} = -\nabla Q - \nabla \Phi - \frac{1}{\rho} \nabla P_{\text{si}}$$

quantum potential

self-interaction pressure

Continuity eq.
$$\frac{\partial \rho}{\partial t} + \nabla(\rho \cdot \mathbf{v}) = 0$$

Two limiting cases from before:

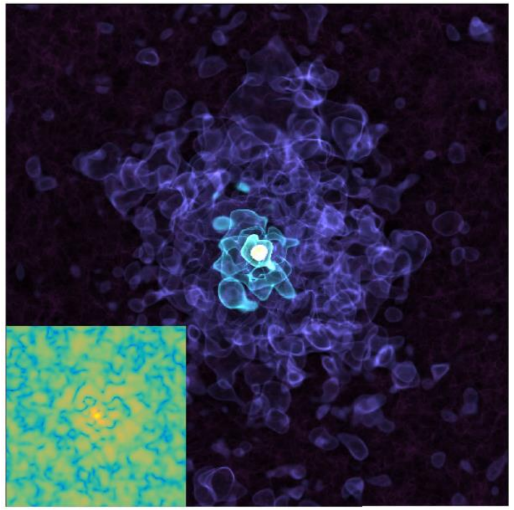
Fuzzy dark matter
(FDM)

$$P_{\text{si}} = 0$$

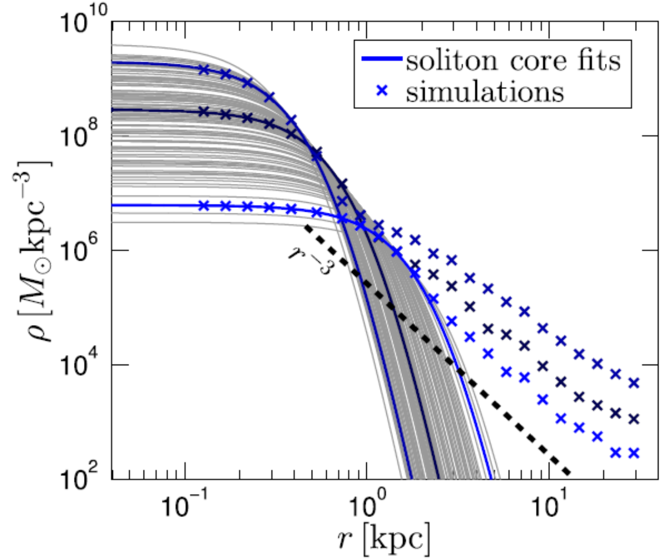
Thomas-Fermi regime
(SFDM-TF)

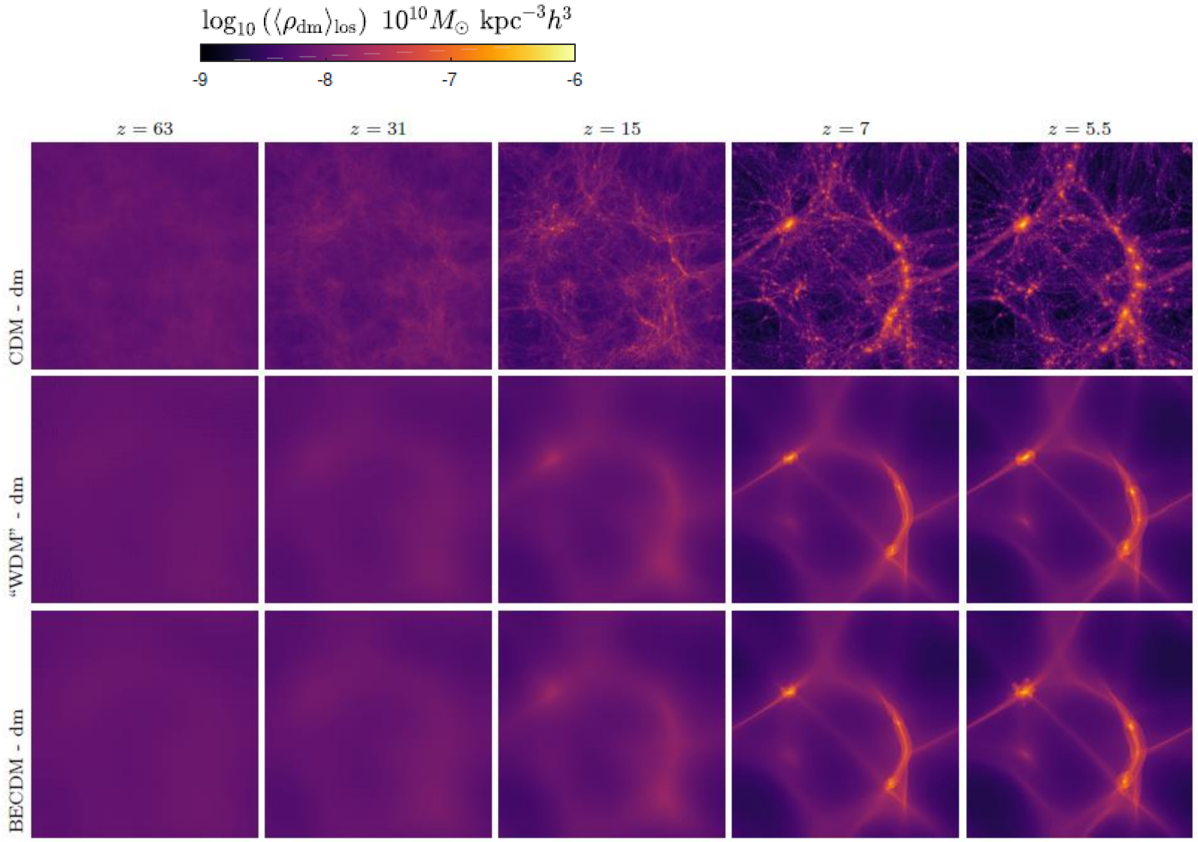
strong self-interaction

FDM: Haloes & large-scale structure



Mocz et al. 2017;
arXiv:1705:05845





Mocz et al. 2019; arXiv:1911.05746

SFDM-TF haloes

- Spherical, non-linear collapse reveals core-envelope structure
- Hydrostatic case modelled by

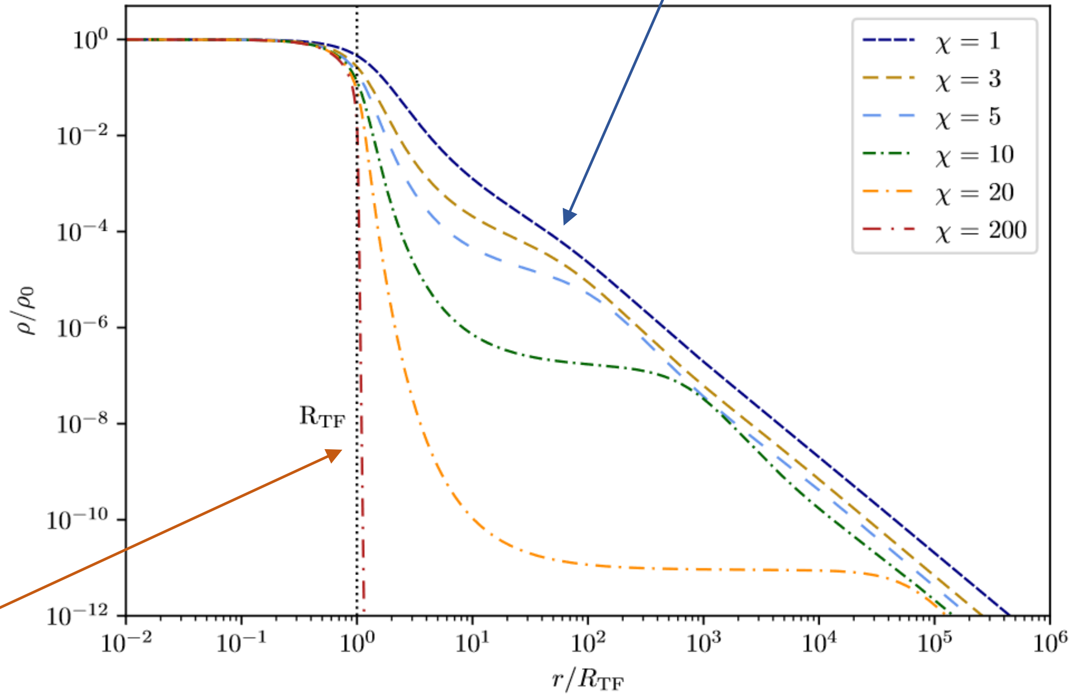
$$\frac{1}{\xi^2}\frac{d}{d\xi}\left(\xi^2\frac{d\psi}{d\xi}+\chi\xi^2 e^{-\psi}\frac{d\psi}{d\xi}\right)=e^{-\psi}$$

with $\xi = \dfrac{r}{r_0}$, $\quad \chi = \left(\dfrac{R_{\rm TF}}{\pi r_0}\right)^2$

characteristic radius of isothermal sphere

radius of polytropic core

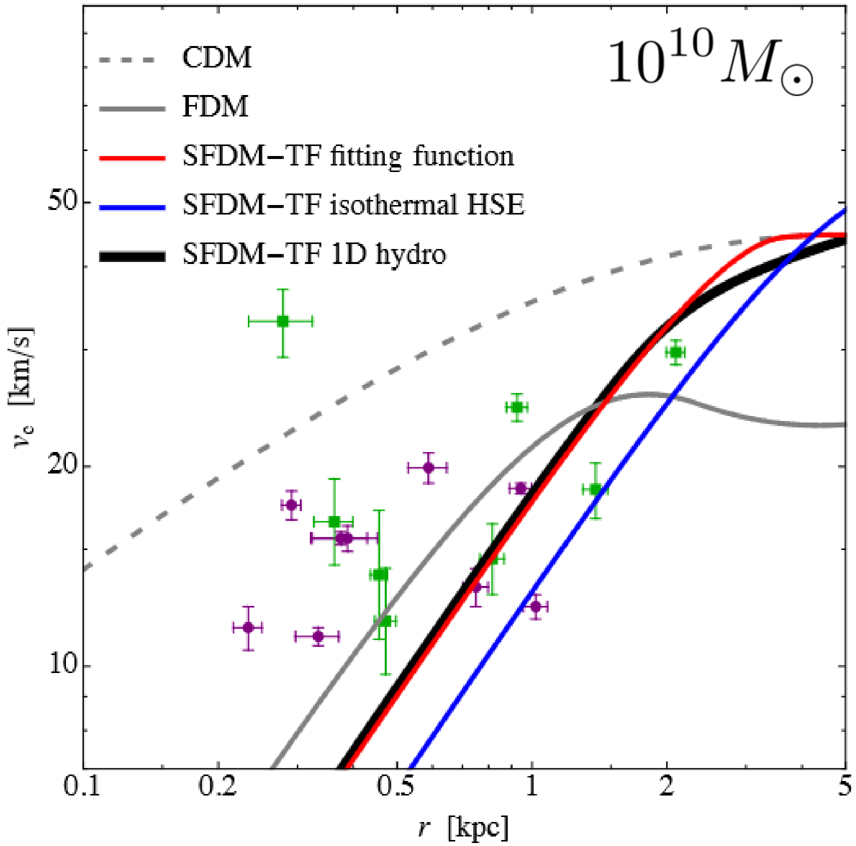
isothermal envelope with characteristic radius r_0



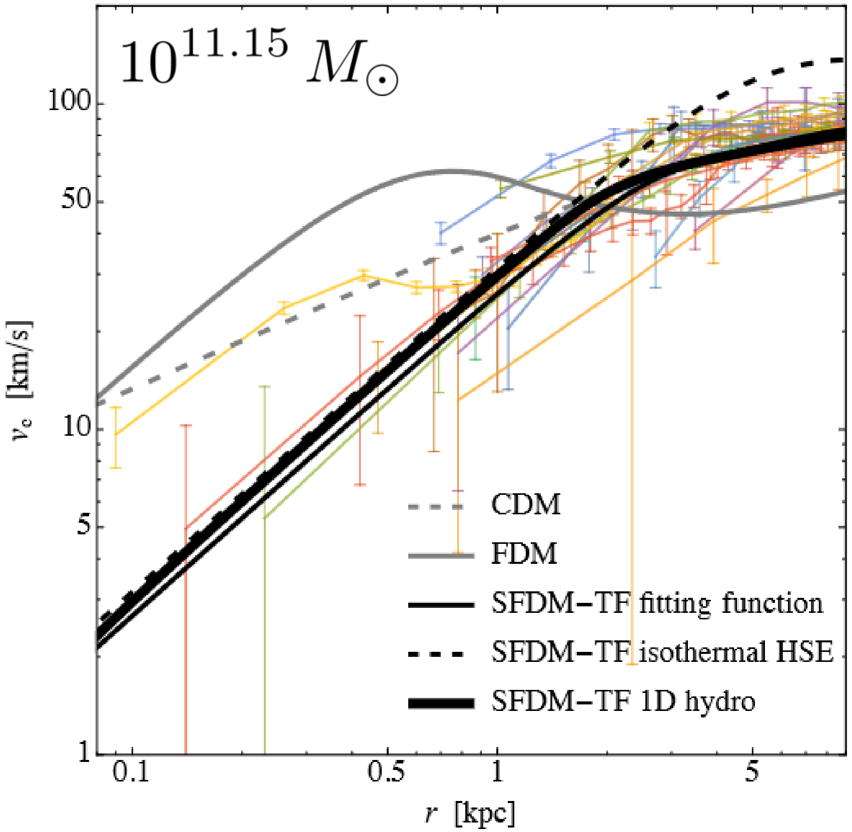
Dawoodbhoy, Shapiro & Rindler-Daller, 2021; arXiv:2104.07043

SFDM-TF & small-scale problems

Dawoodbhoy, Shapiro & Rindler-Daller, 2021; arXiv:2104.07043



too-big-to-fail problem



cusp-core problem

$c_{\rm NFW} = 20$
for CDM

$mc^2 = 0.8 \cdot 10^{-22}$ eV
for FDM

$R_{\rm TF} = 4$ kpc
for SFDM-TF

SFDM-TF can solve both problems at once!

SFDM-TF: Adding baryons

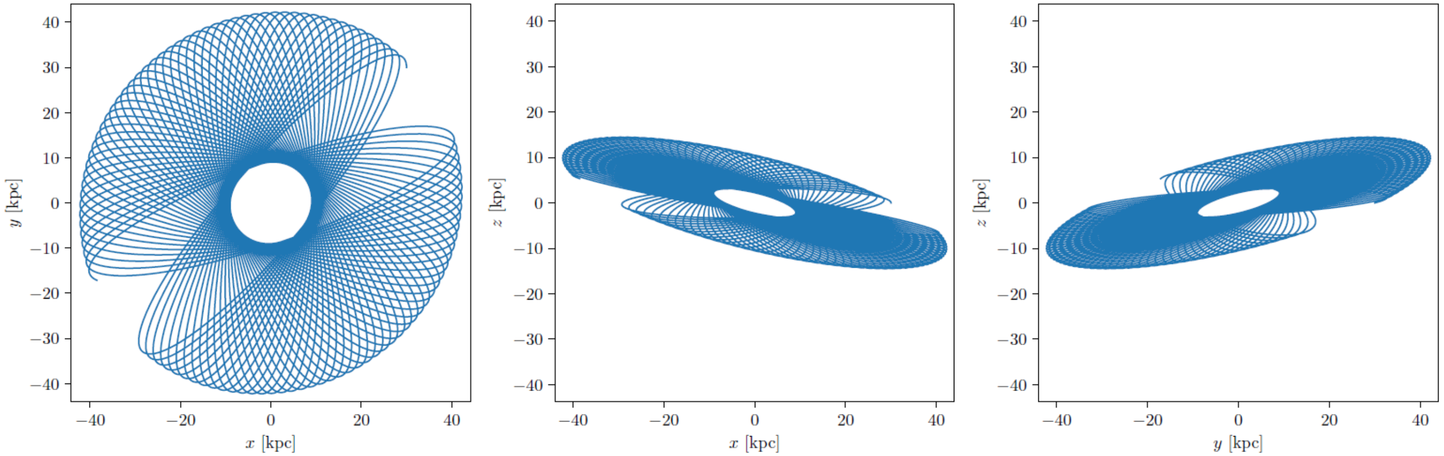
- Analyze adiabatic contraction for this model from first principles

  - Thorough analysis of underlying Quantum-Hamilton-Jacobi framework

  - Probe dark matter particle orbits in such haloes

  - Calculate impact of AC with various core radii of $R_{\mathrm{TF}} \sim 0.1 - 1 \text{ kpc}$

Orbits

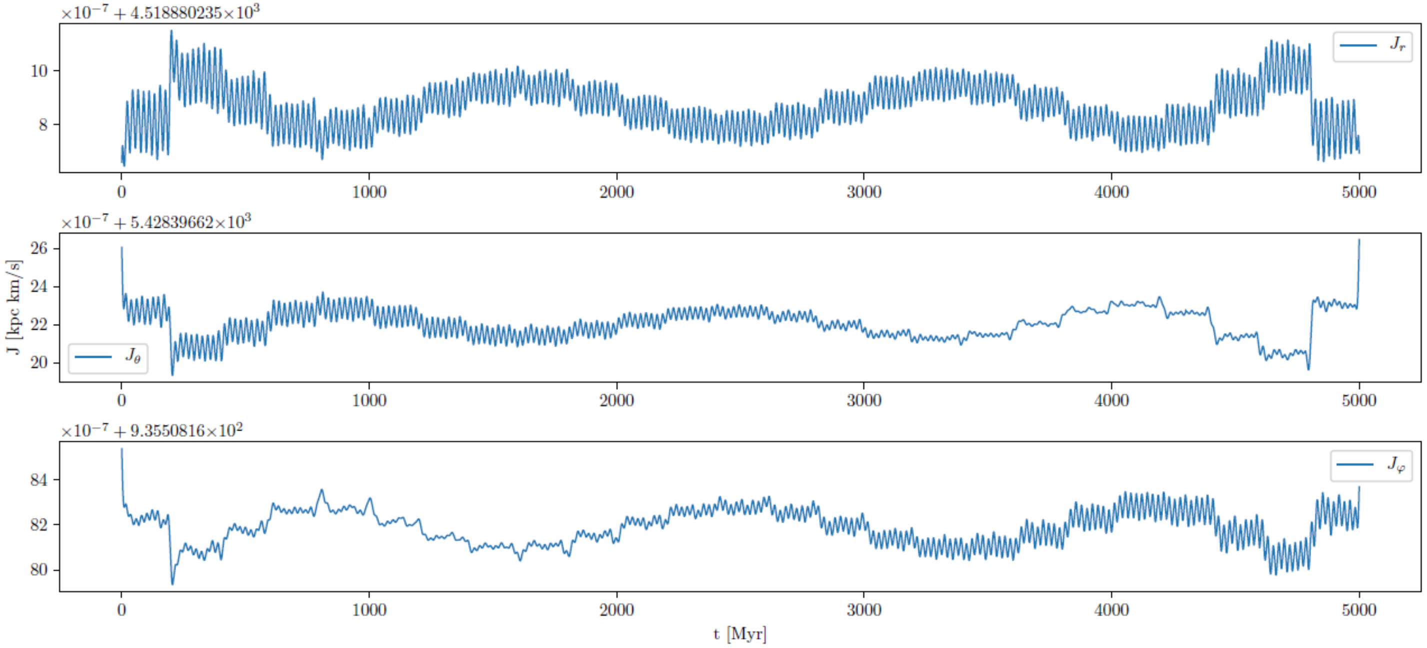


- From GP equation one can derive a Quantum-Hamilton-Jacobi equation
- Solve this QHJE for action integrals numerically with e.g. Python package **gala**

$$J_r = \frac{1}{2\pi} \int dr \sqrt{2m(E - \Phi) - g\rho - \frac{L^2}{r^2}}$$

$$J_\theta = \frac{1}{2\pi} \int d\theta \sqrt{L^2 - \frac{L_z^2}{\sin^2 \theta}}$$

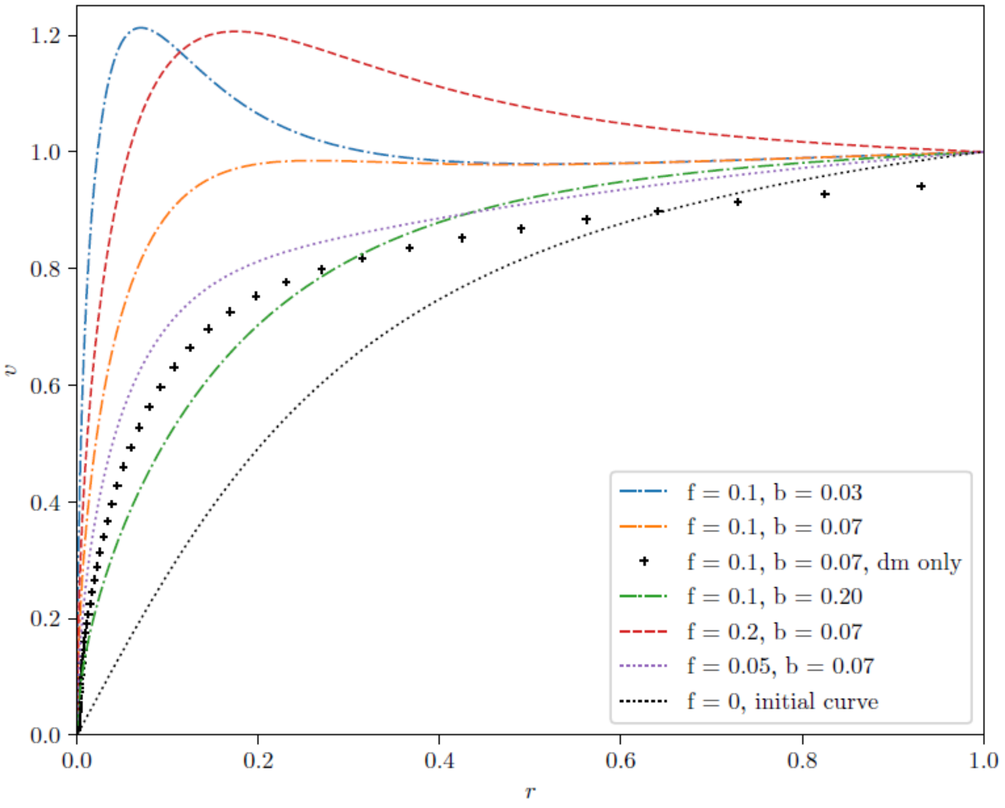
$$J_\varphi = \frac{1}{2\pi} \int d\varphi L_z = L_z$$



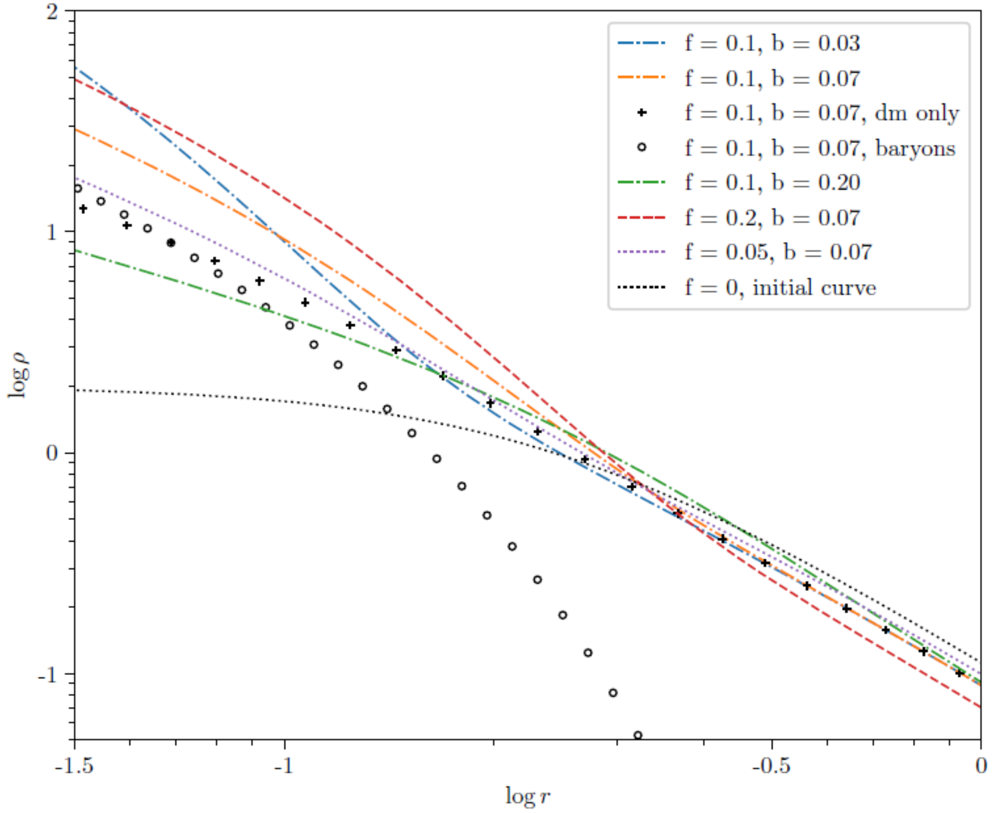
Adiabatic contraction

$$\underbrace{r_f\left[M_b(r_f)+M_{\mathrm{dm}}(r_f)\right]}_{\text{final}} = \underbrace{r_i M_i(r_i)}_{\text{initial}} = r_i\,\frac{M_{\mathrm{dm}}(r_f)}{1-f}$$

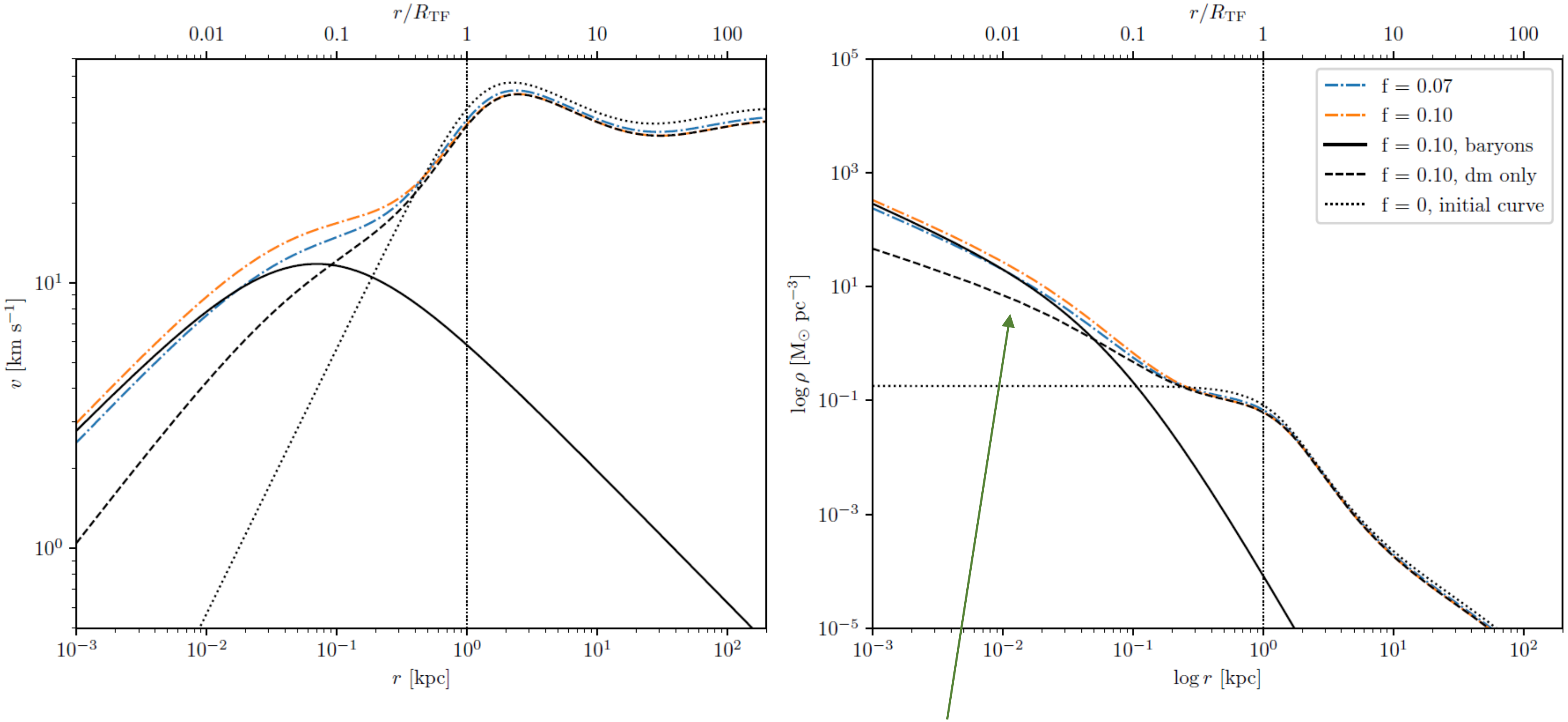
baryon fraction



Blumenthal et al. 1986 recreated



Results



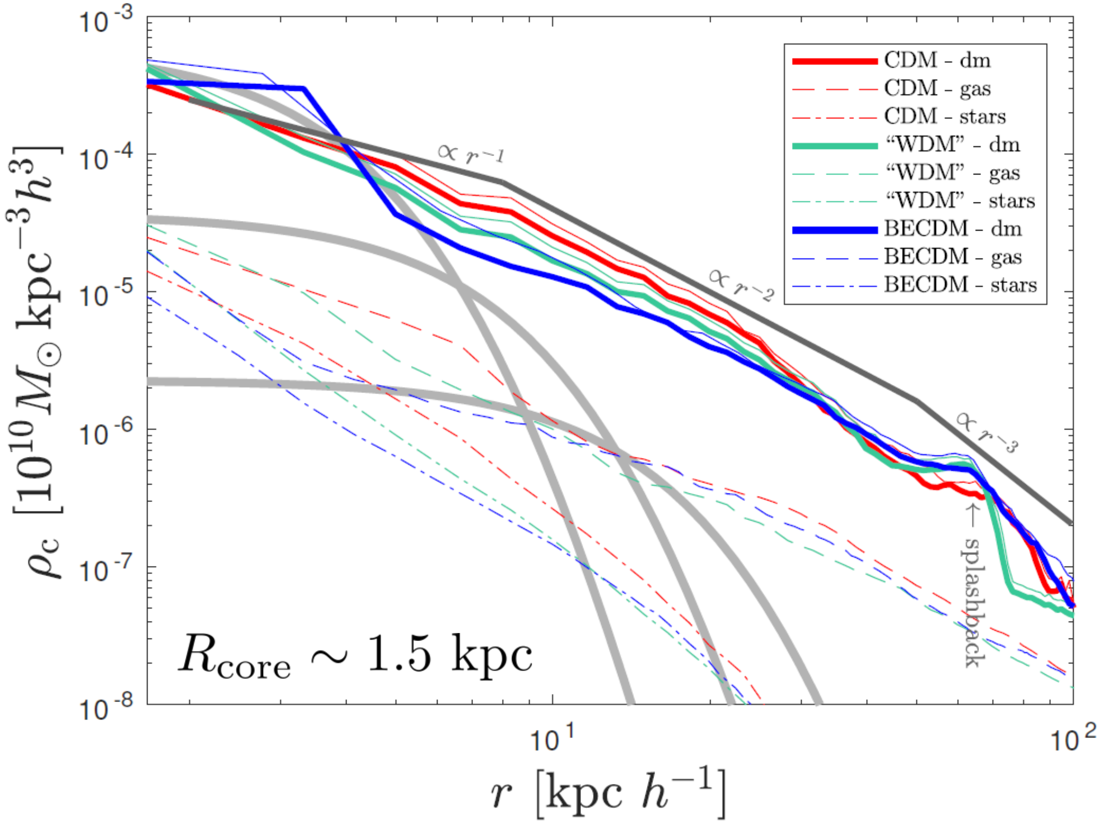
denser core regions due
to baryons

Comparison to FDM

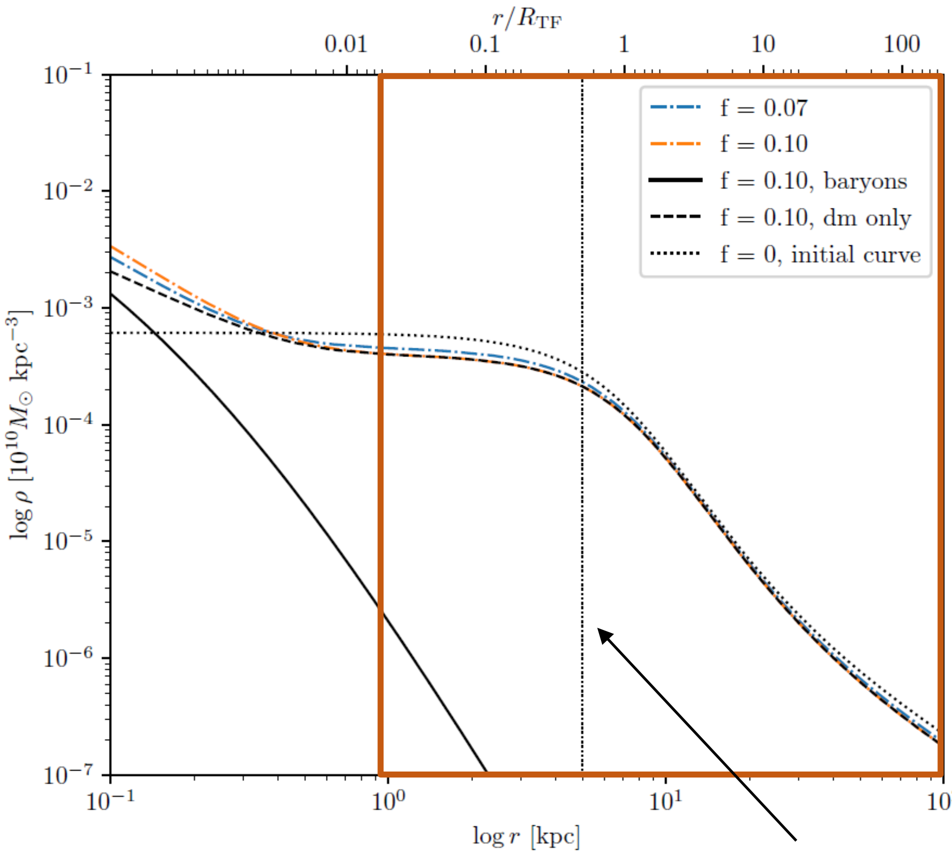
Density profiles for $M_{200} = 8.2 \cdot 10^9\ M_\odot, R_{200} = 42$ kpc

Mocz et al. 2019;
arXiv:1911.05746

FDM
halo 1



SFDM-TF



$R_{\rm TF} = 4$ kpc

Conclusion

- Regular orbits possible in SFDM-TF regime
- Our calculation confirms that the central density profiles of SFDM halos steepen in the presence of baryons
- Outlook: Comparison of DM models with baryons & calculation of adiabatic contraction for fuzzy dark matter