Dark Matter
and Galactic Structures

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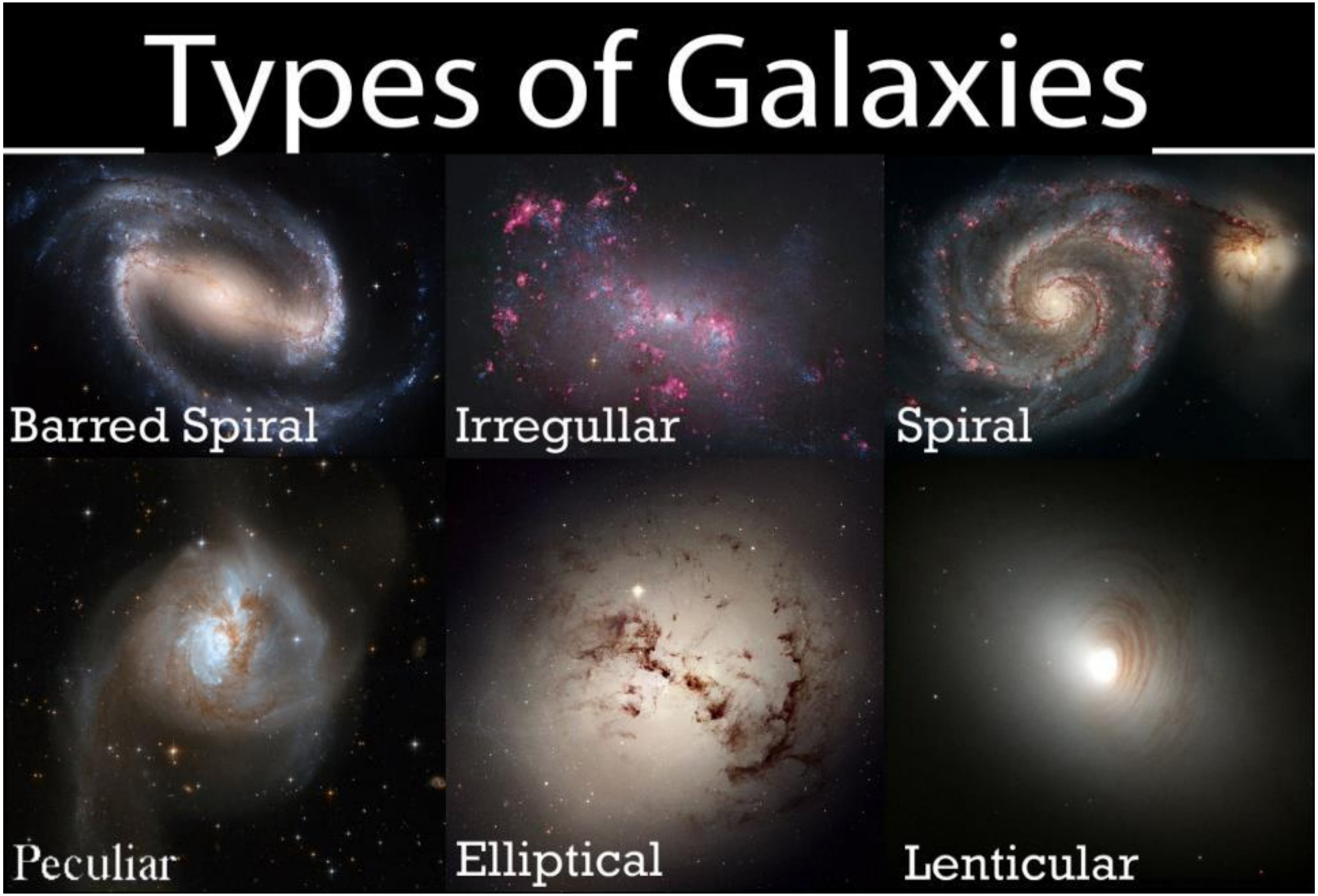
Outline

- Short introduction
- Fermionic Dark Matter model
- Milky Way
- Conclusion

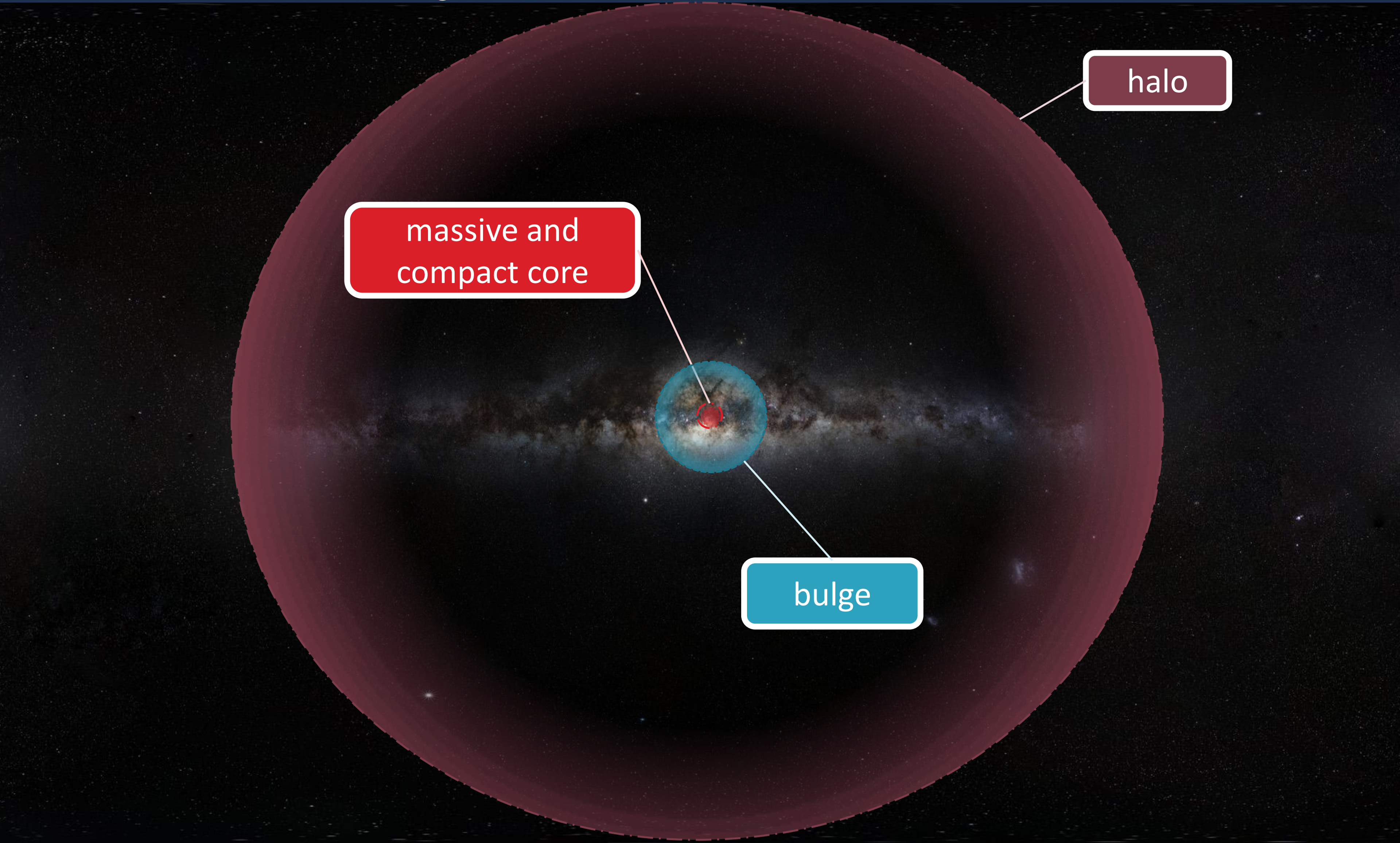
Galaxy Morphology

Different types of stallar formations

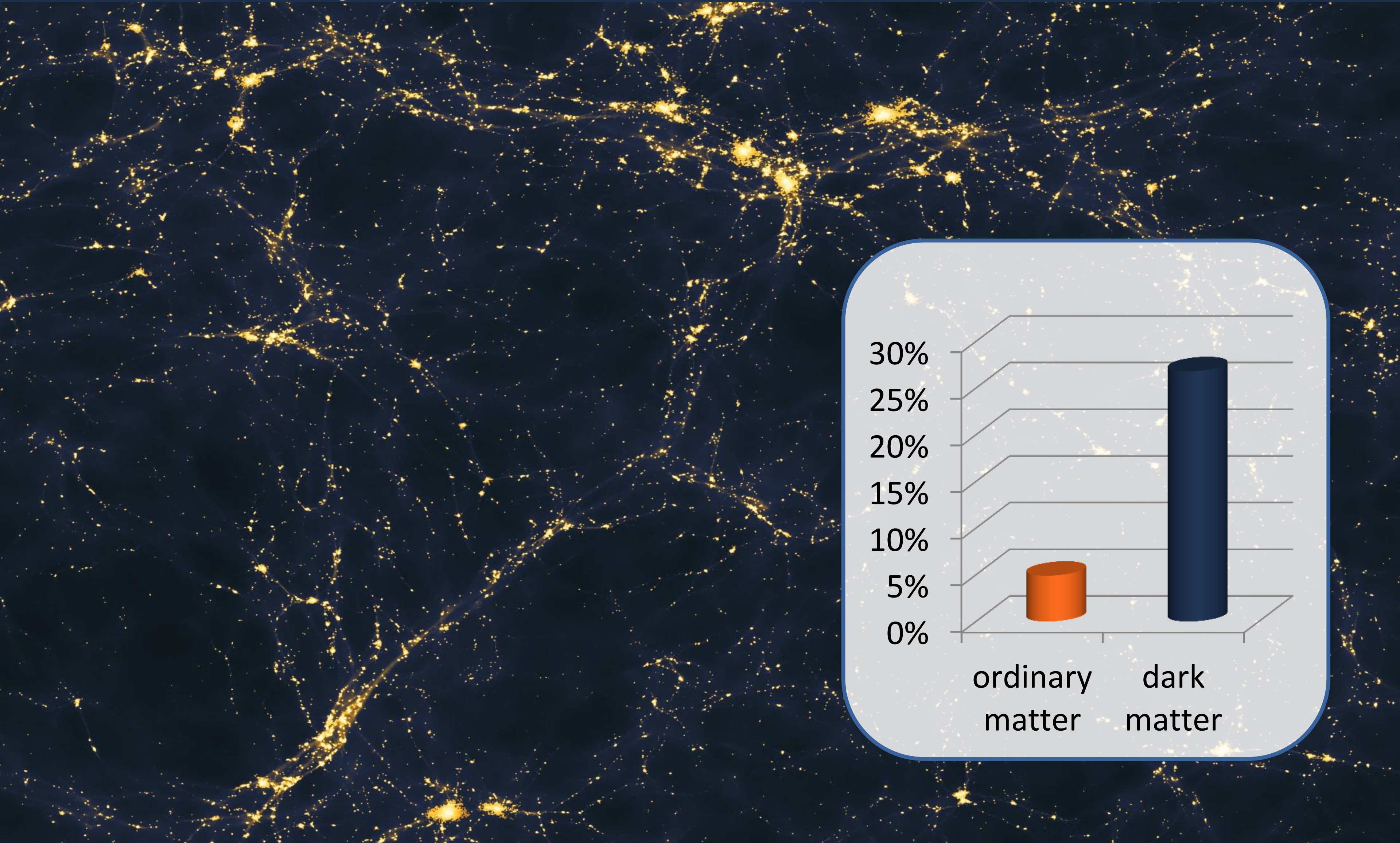


Milky Way

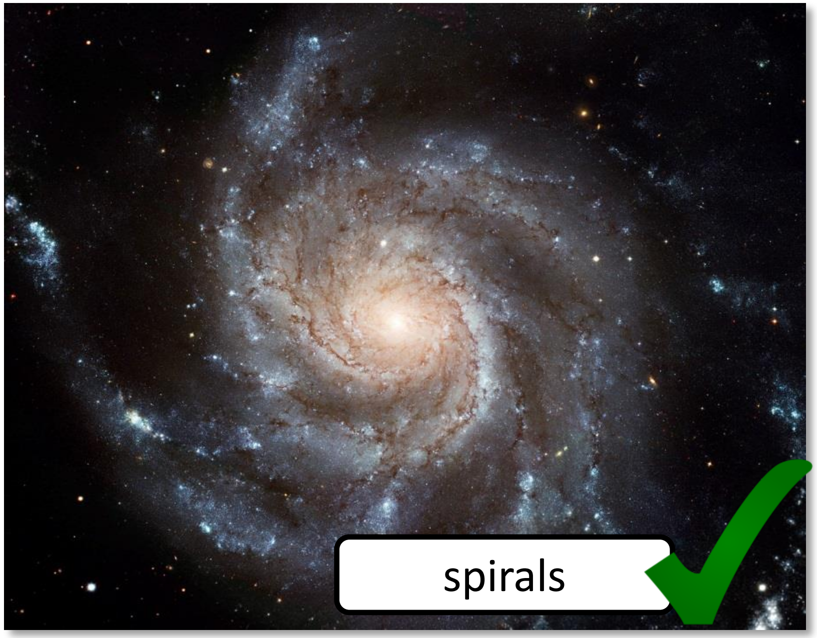
Besides the bulge and disk

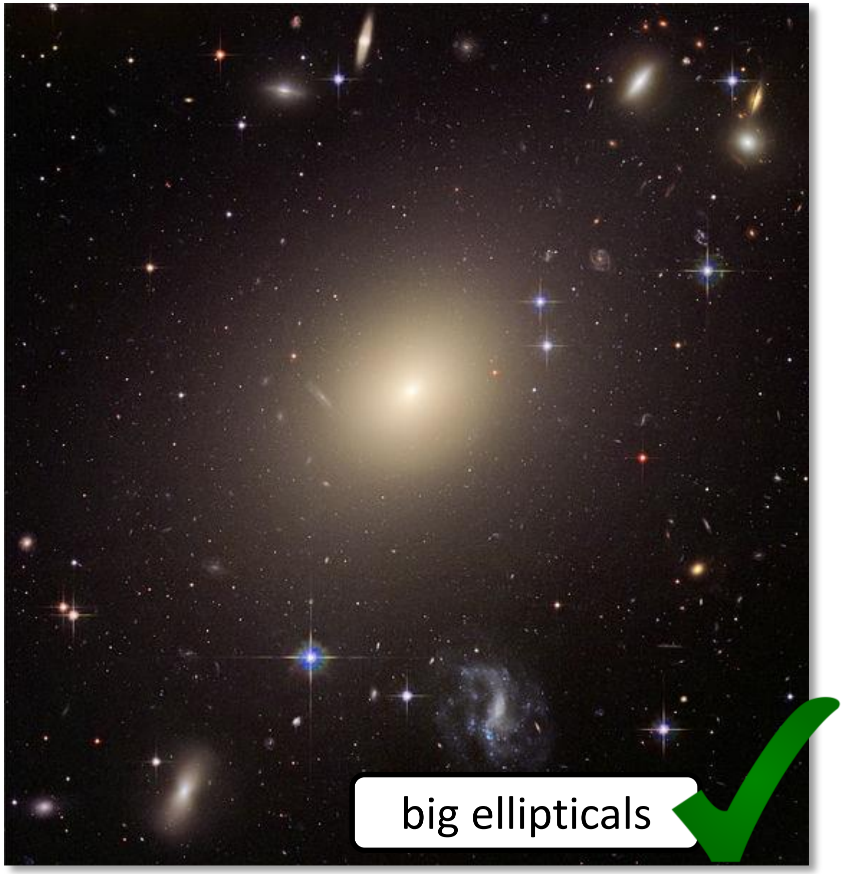


Lambda-CDM



So, where can we find DM?





Dark Matter Candidates

Particle candidates beyond SM

particle mass

GeV/c^2

MeV/c^2

keV/c^2

eV/c^2

meV/c^2

CDM

- MACHOS
- WIMPs

!

WDM

- Sterile Neutrino

HDM

- Neutrinos (ruled out in 80s)

Model assumptions

- Pauli principle (fermions)
- gravitational interaction
- evaporation (neglect inter-galactic medium)
- spherically symmetric

Fermionic DM with Cutoff

phase space density

$$f(r,\epsilon) = \frac{1 - e^{[\epsilon - \varepsilon(r)]/\beta(r)}}{e^{[\epsilon - \alpha(r)]/\beta(r)} + 1}$$

energy $$\epsilon^2 = 1 + \frac{p^2}{mc^2}$$

temperature parameter $$\beta(r) = \frac{k_B T(r)}{mc^2}$$

chemical potential (relativistic)

$$\alpha(r) = 1 + \beta(r)\theta(r)$$

escape energy (relativistic)

$$\varepsilon(r) = 1 + \beta(r)W(r)$$

degeneracy parameter $$\theta(r) = \frac{\mu(r)}{k_B T(r)}$$

cutoff parameter $$W(r) = \frac{E_c(r)}{k_B T(r)}$$

Ruffini R., Stella L., 1983, A&A, 119, 35

Perfect fluid in equilibrium

Statistics

mass density
$$\frac{\rho(r)}{\rho_r} = \frac{4}{\sqrt{\pi}} \int \epsilon^2 \sqrt{\epsilon^2 - 1} f(r,\epsilon) \mathrm{d}\epsilon$$

pressure
$$\frac{P(r)}{\rho_r c^2} = \frac{4}{\sqrt{\pi}} \int (\epsilon^2 - 1)^{3/2} f(r,\epsilon) \mathrm{d}\epsilon$$

$$g_{\mu\nu} = \mathrm{diag}(\mathrm{e}^{\nu(r)}, -\mathrm{e}^{\lambda(r)}, -r^2, -r^2 \sin^2 \vartheta)$$

spherically symmetric

GR

mass
$$\frac{\partial}{\partial r/R} \frac{M(r)}{M} = \frac{r^2}{R^2} \frac{\rho(r)}{\rho_r}$$

metric potential
$$\frac{\partial \nu}{\partial r/R} = \frac{R^2}{r^2} \left[\frac{M(r)}{M} + \frac{r^3}{R^3} \frac{P(r)}{\rho_r c^2} \right] \left[1 - \frac{R}{r} \frac{M(r)}{M} \right]^{-1}$$

Thermodynamic equilibrium

Tolman & Ehrenfest (1930)

$$\beta(r)\mathrm{e}^{\nu(r)/2} = \mathrm{const}$$

Klein (1949)

$$\alpha(r)\mathrm{e}^{\nu(r)/2} = \mathrm{const}$$

conservation of energy

$$\varepsilon(r)\mathrm{e}^{\nu(r)/2} = \mathrm{const}$$

Initial conditions

$$\left.\frac{\partial M}{\partial r}\right|_{r=0} \to \rho_0 \to \{\theta_0, W_0, \beta_0, m\}$$

$$\left.\frac{\partial \nu}{\partial r}\right|_{r=0} \to \{M_0 = 0, \rho_0, P_0\} \to \{\theta_0, W_0, \beta_0, m\}$$

$$\{\theta_0, \beta_0, W_0, m\}$$

4 parameters

$$\rho_r = \frac{gm^4}{h^3}[\pi c]^{3/2}$$

$$R^2 = \frac{c^2}{8\pi G\rho_r}$$

$$M = 4\pi R^3 \rho_r$$

scaling factors

Turn off evaporation

Let‘s start slowly

No evaporation

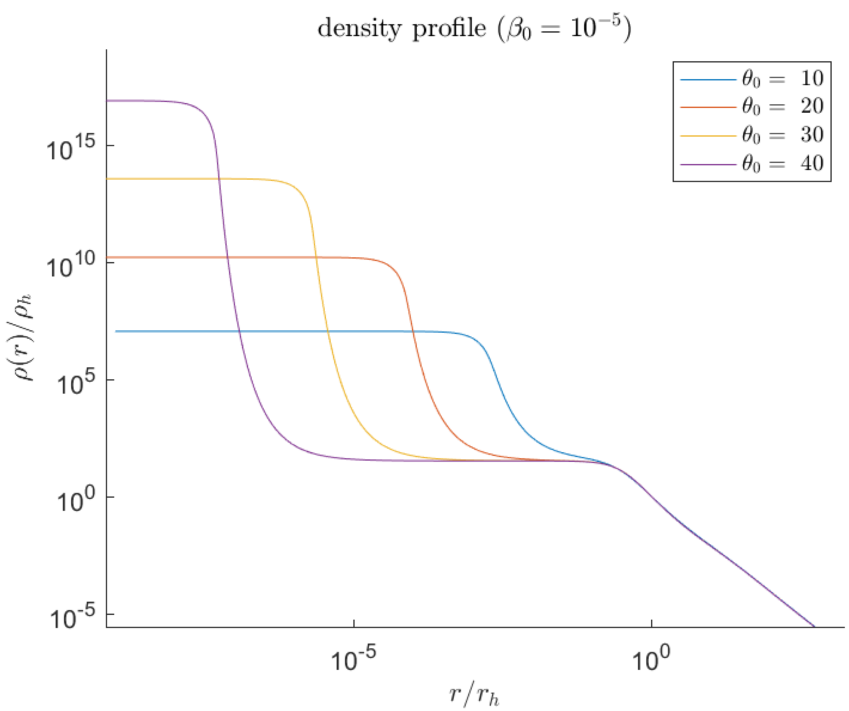
$$W_0 \rightarrow \infty$$

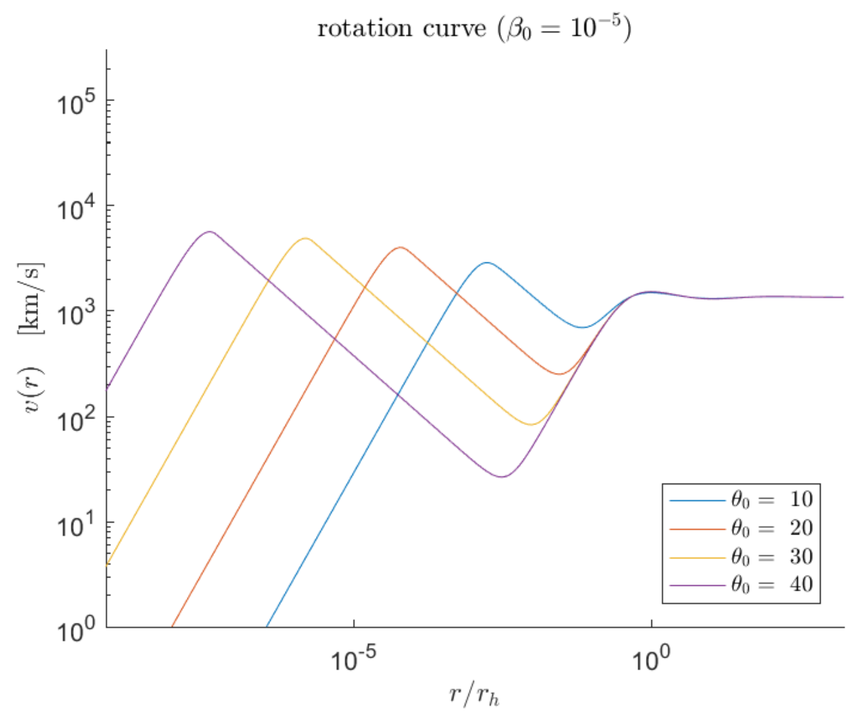
Fermi-Dirac distribution

$$f(r,\epsilon) = \frac{1}{\mathrm{e}^{[\epsilon-\alpha(r)]/\beta(r)} + 1}$$

RAR family

halo-core solutions

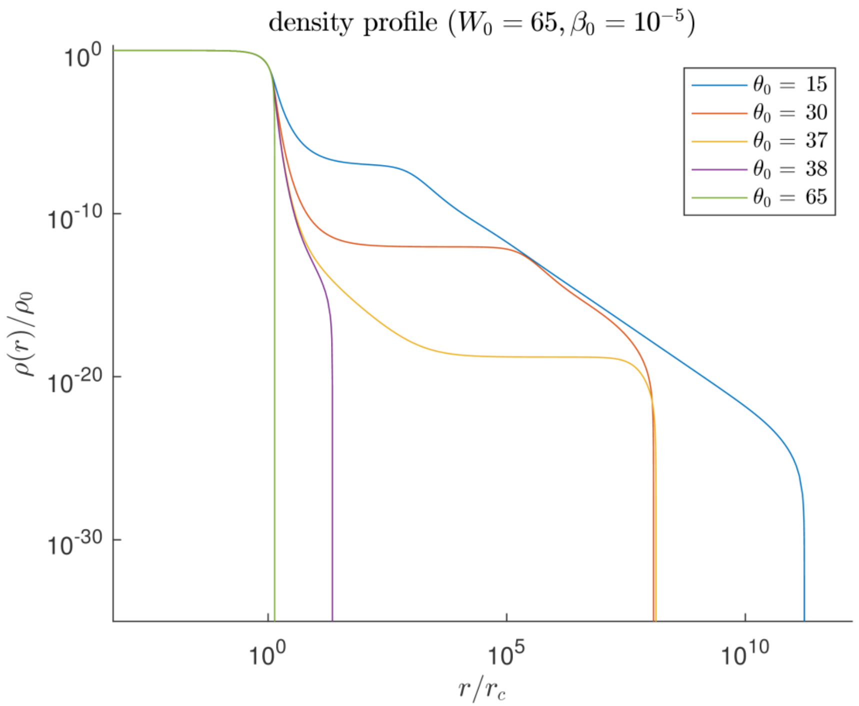


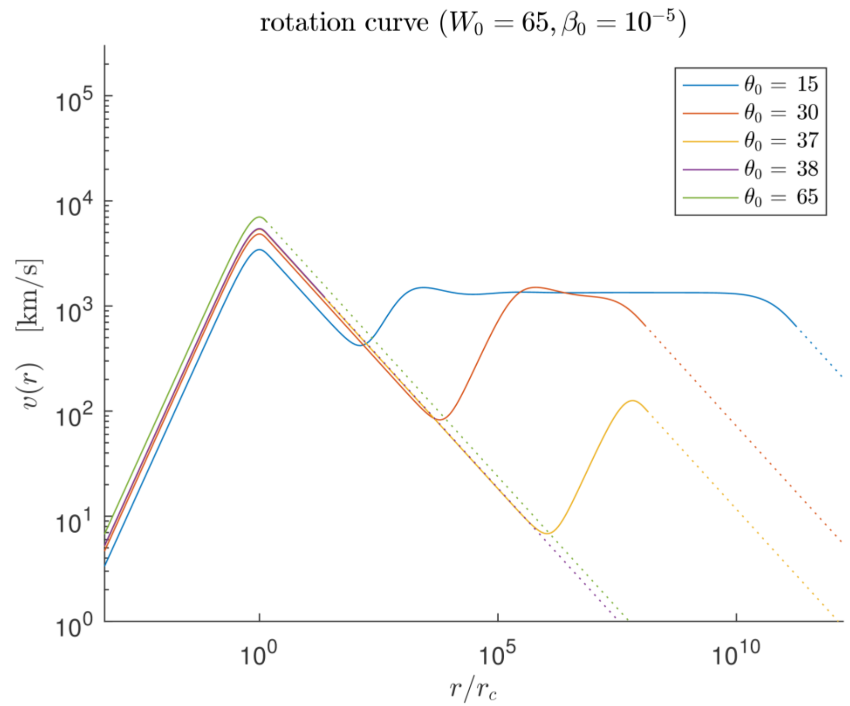


Ruffini R., Argüelles C. R., Rueda J. A., 2015, MNRAS, 451, 622

Turn on evaporation

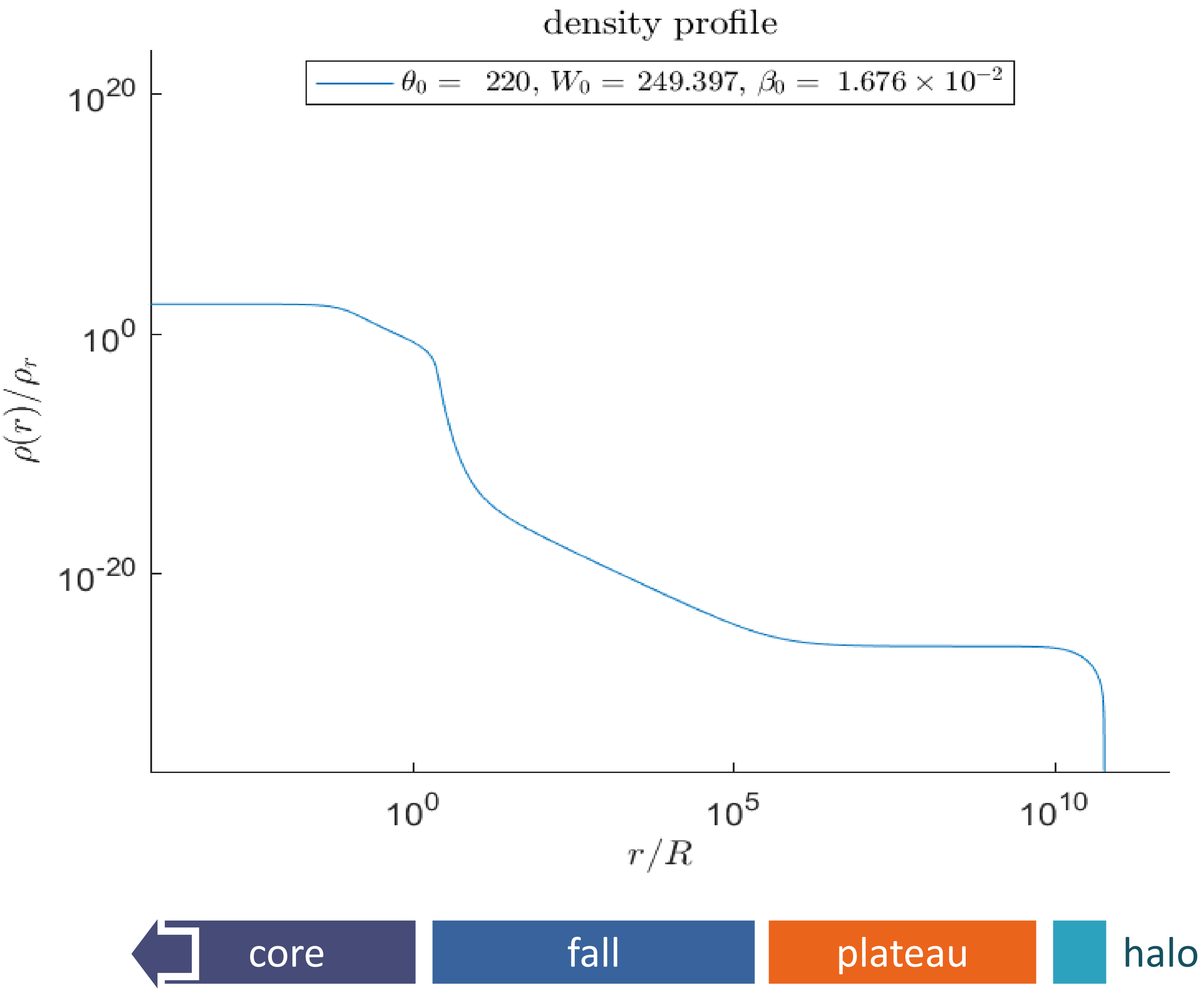
from halo-core solutions to fully degenerate cores





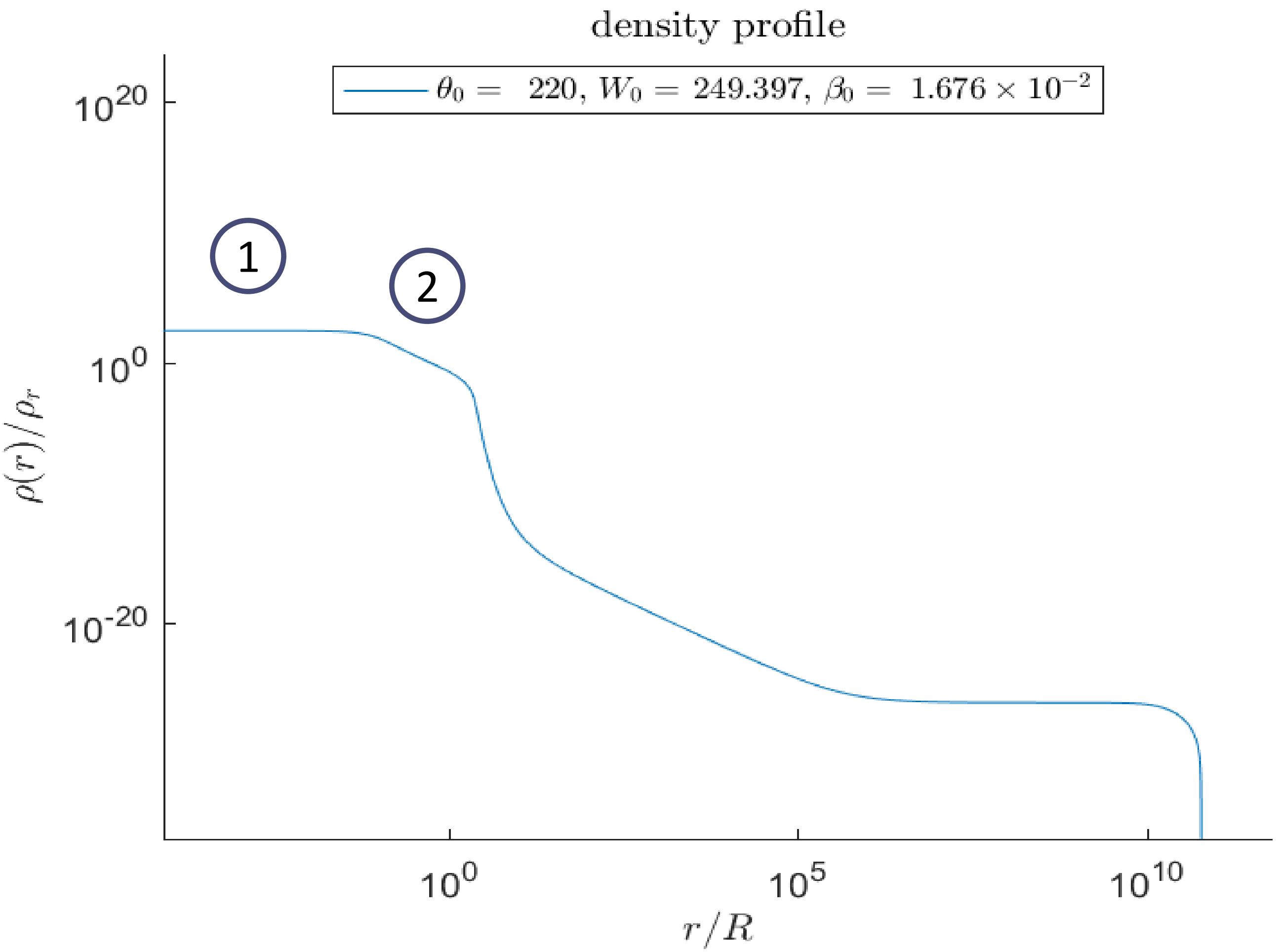
(most) general profile

regimes in density profile



(most) general profile

regimes in density profile - core

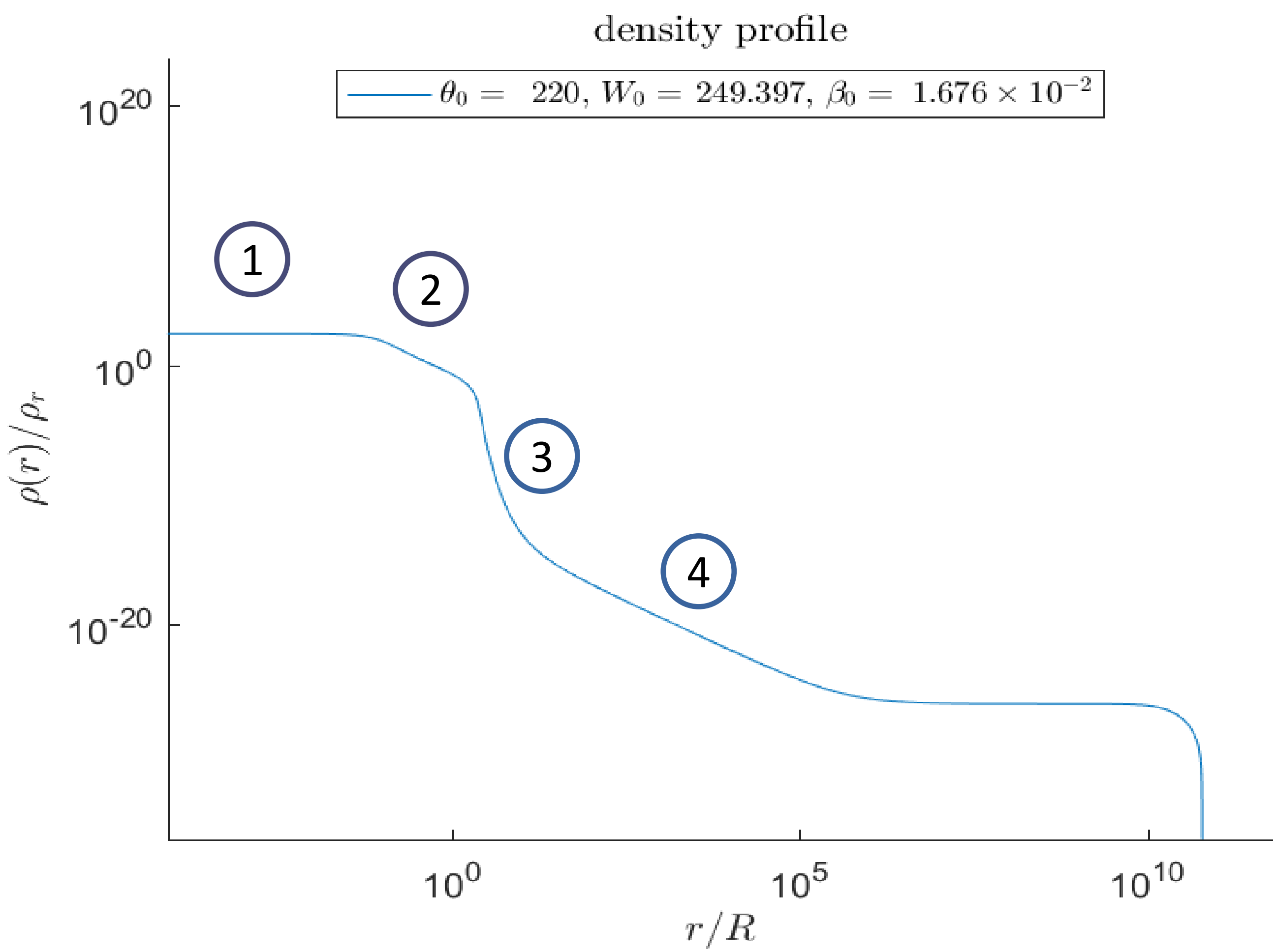


(1) uniform core

(2) core shell

core | fall | plateau | halo

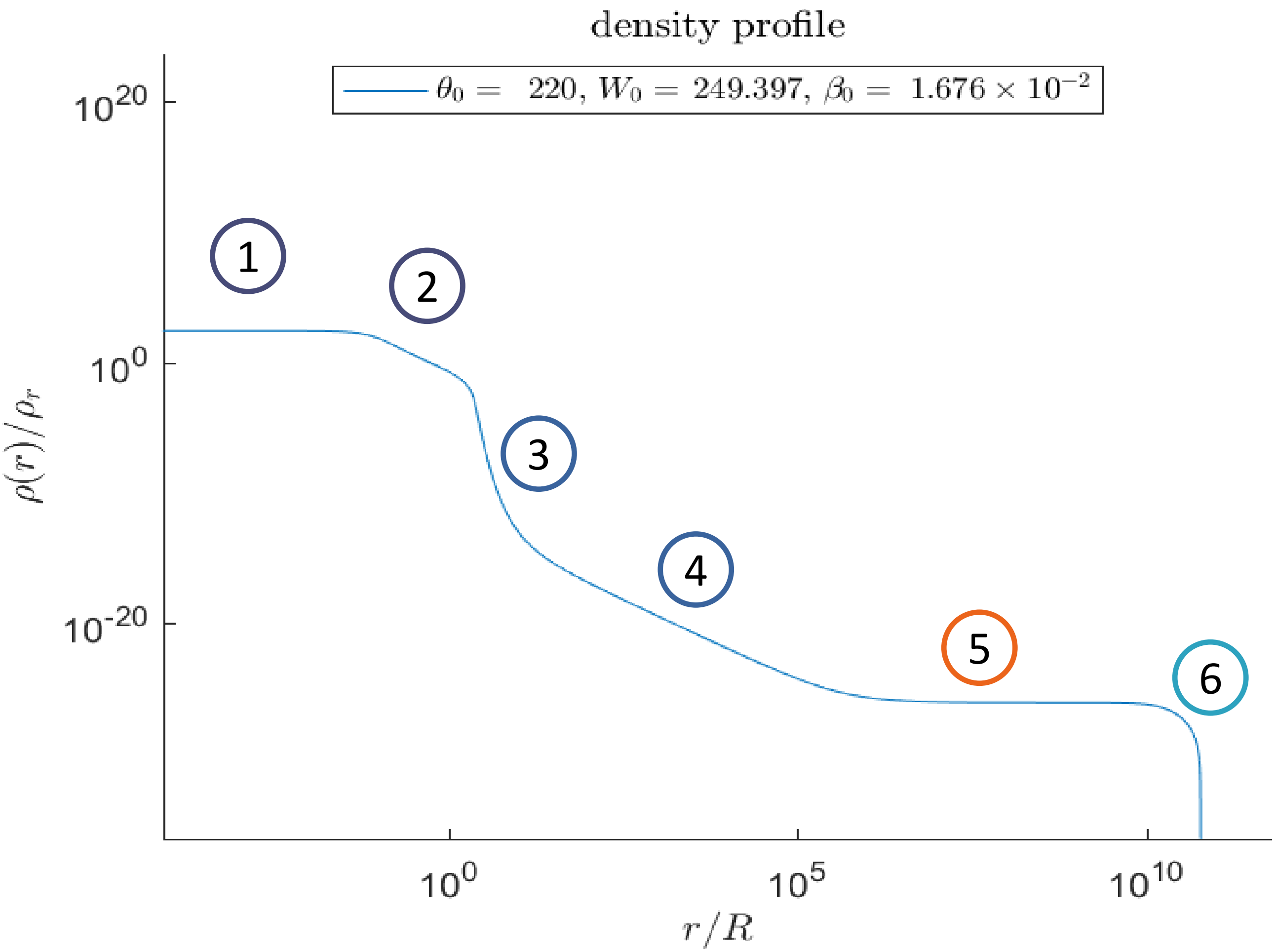
(most) general profile



1. uniform core
2. core shell
3. steep fall
4. evaporation *pull*

(most) general profile

regimes in density profile – plateau and halo

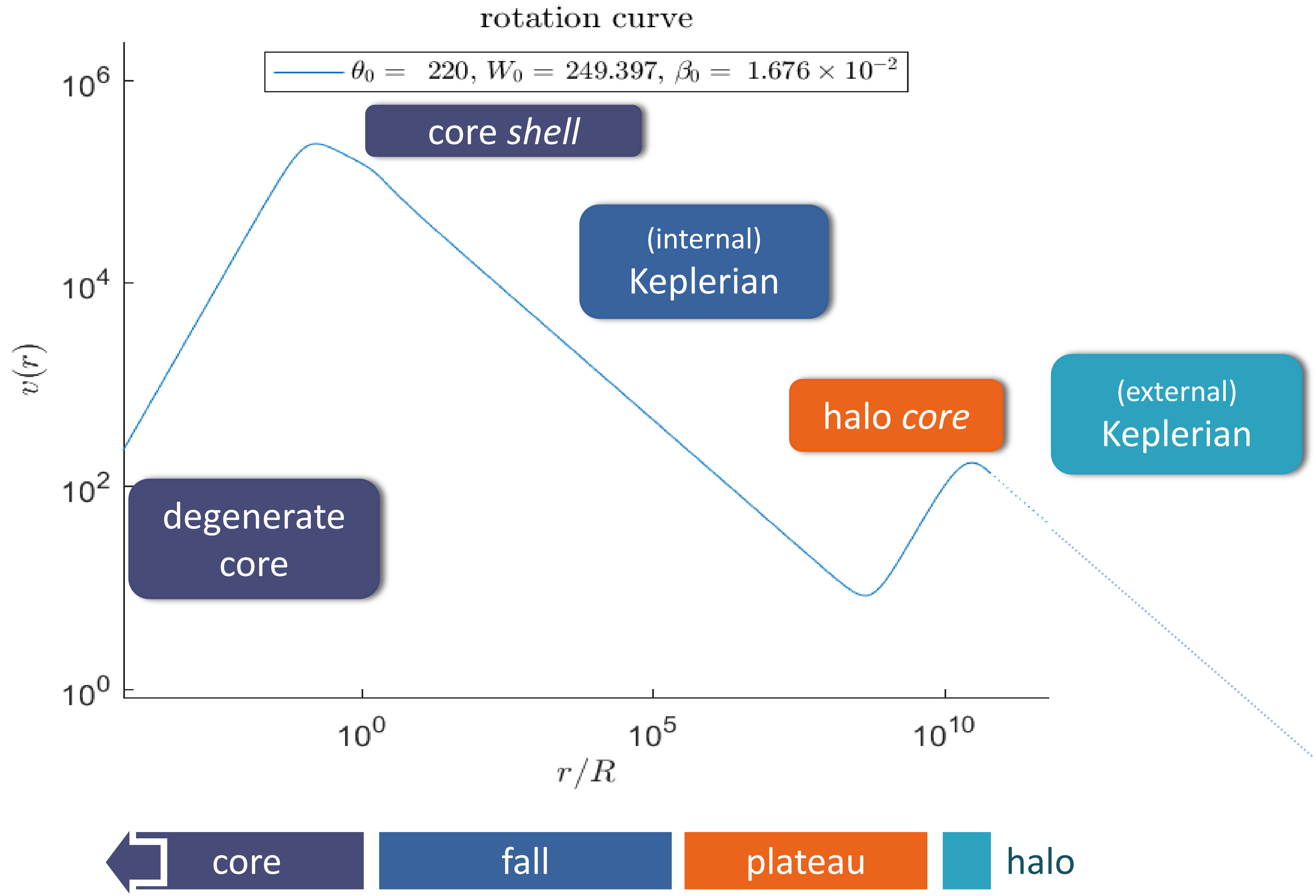


1. uniform core
2. core shell
3. steep fall
4. evaporation *pull*
5. plateau
6. free halo with cutoff

core | fall | plateau | halo

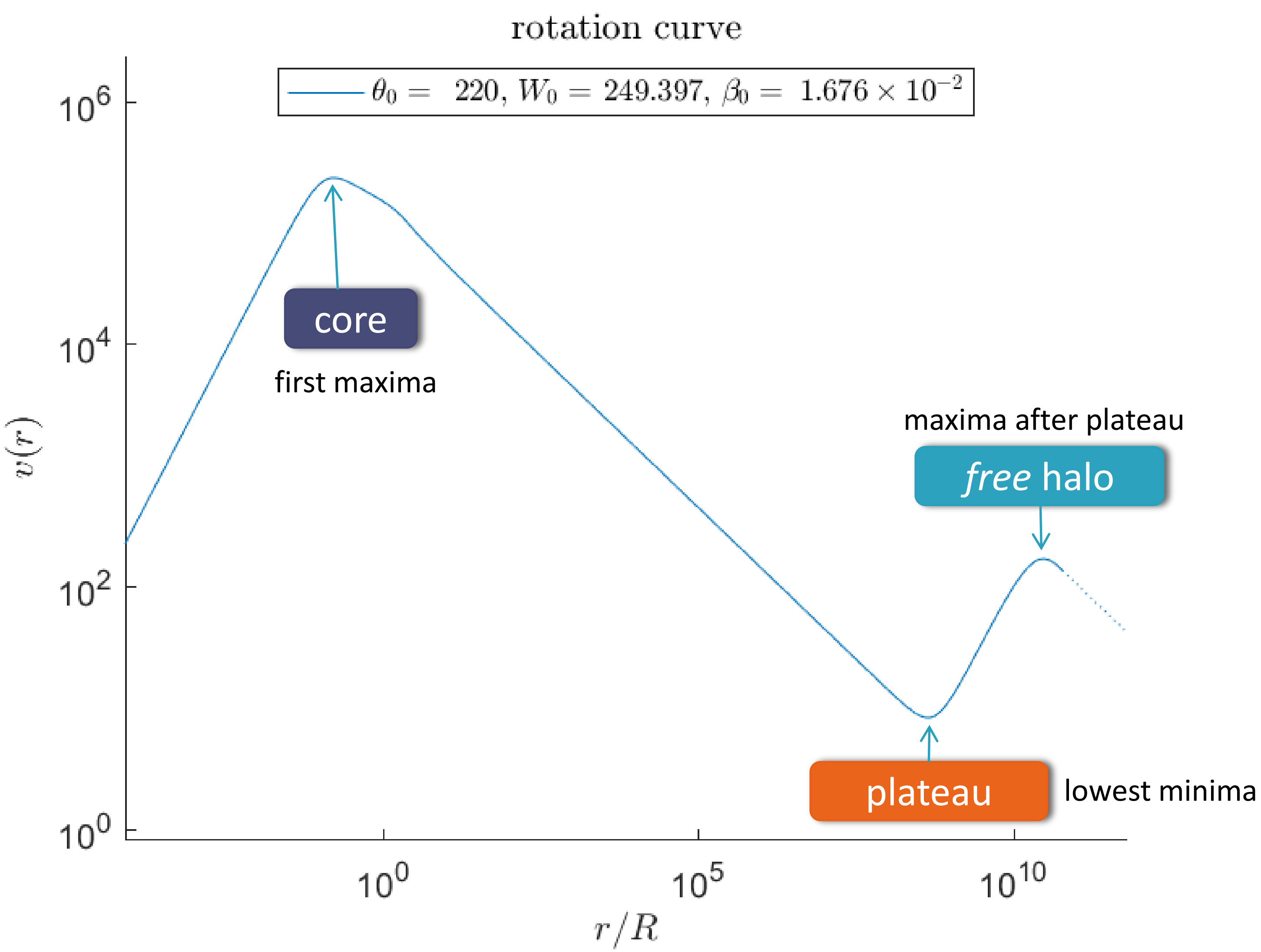
(most) general profile

less regimes in rotation curve



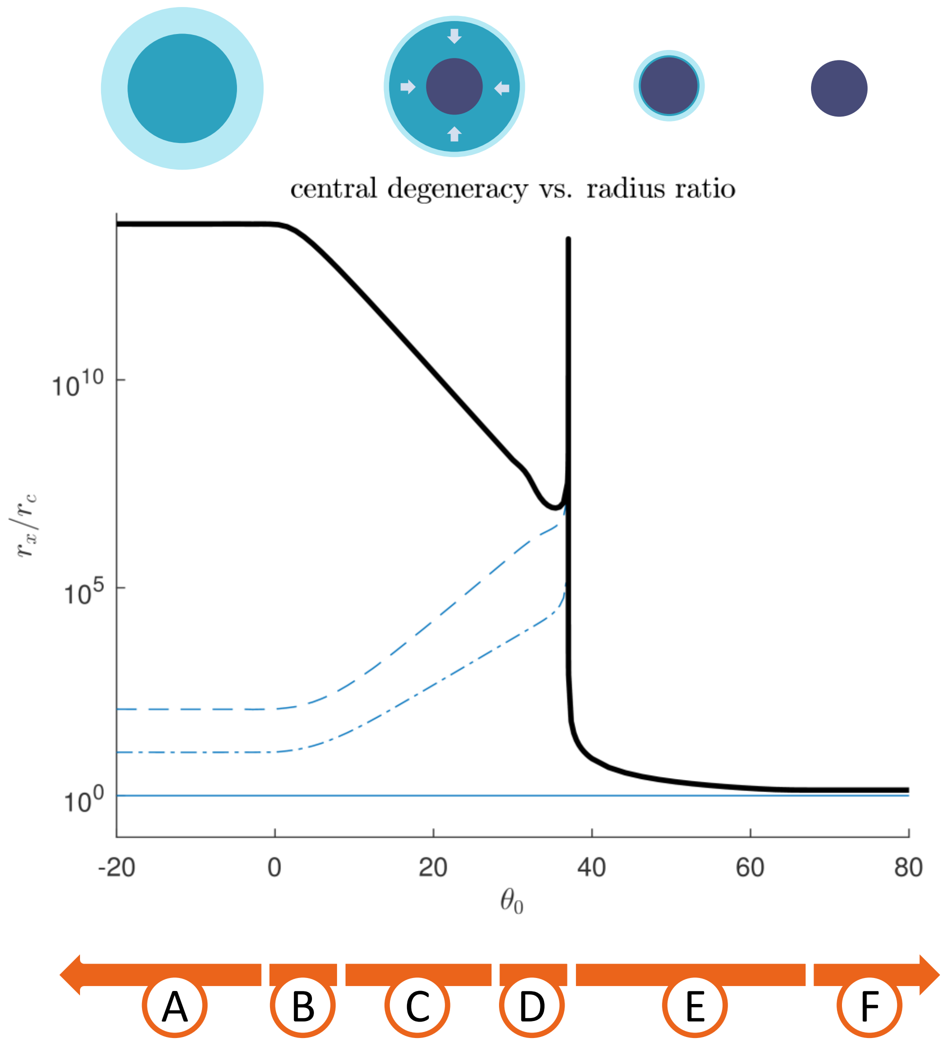
Core, Plateau and free Halo

defined by extrema in the rotation curve



Various regimes

For varying central degeneracy (temperature and cutoff parameter are fixed)



$$\beta_0 = 10^{-5}, W_0 = 65$$

(A) **diluted regime**
diluted core with halo

(B) **semi-degenerate transition**
core becomes more degenerate

(C) **degenerate regime (with halo)**
surface radius is decreasing

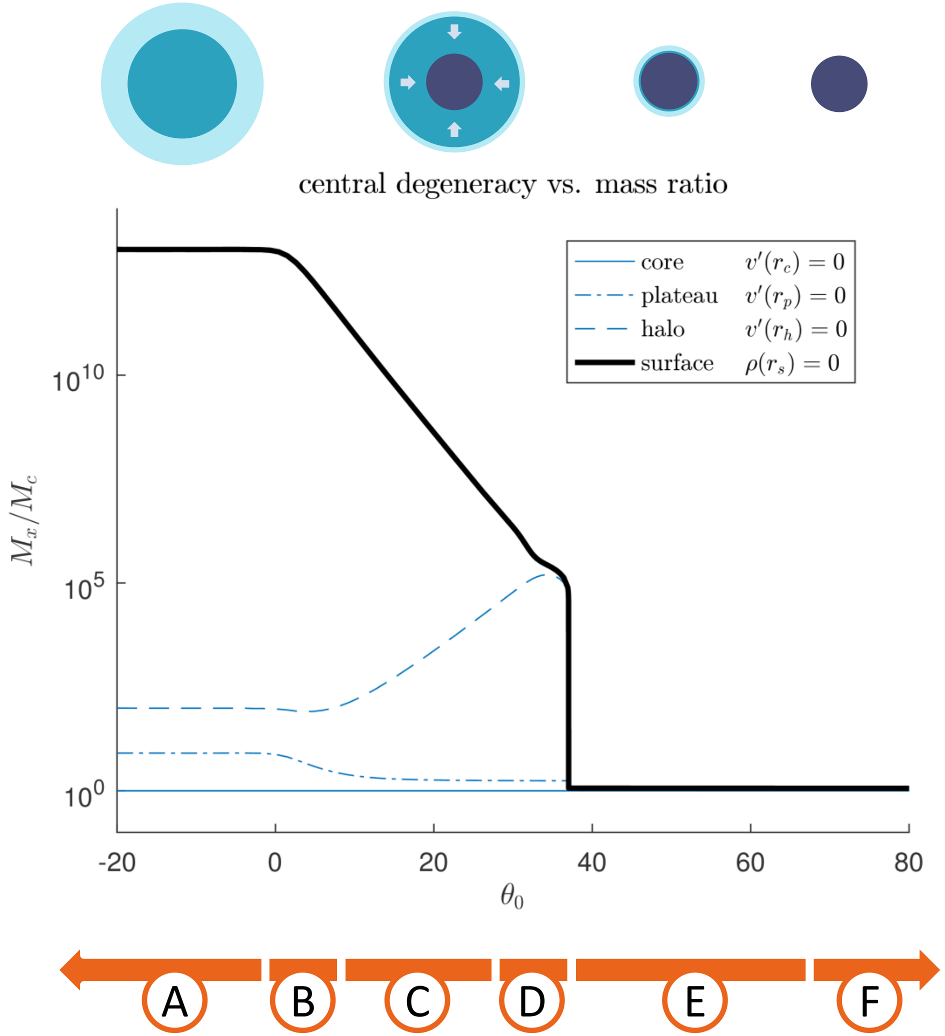
(D) **critical regime**
surface effects appear

(E) **degenerate regime (no halo)**
halo evaporated

(F) **fully degenerate core**

Various regimes

For varying central degeneracy (temperature and cutoff parameter are fixed)



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  diluted core with halo
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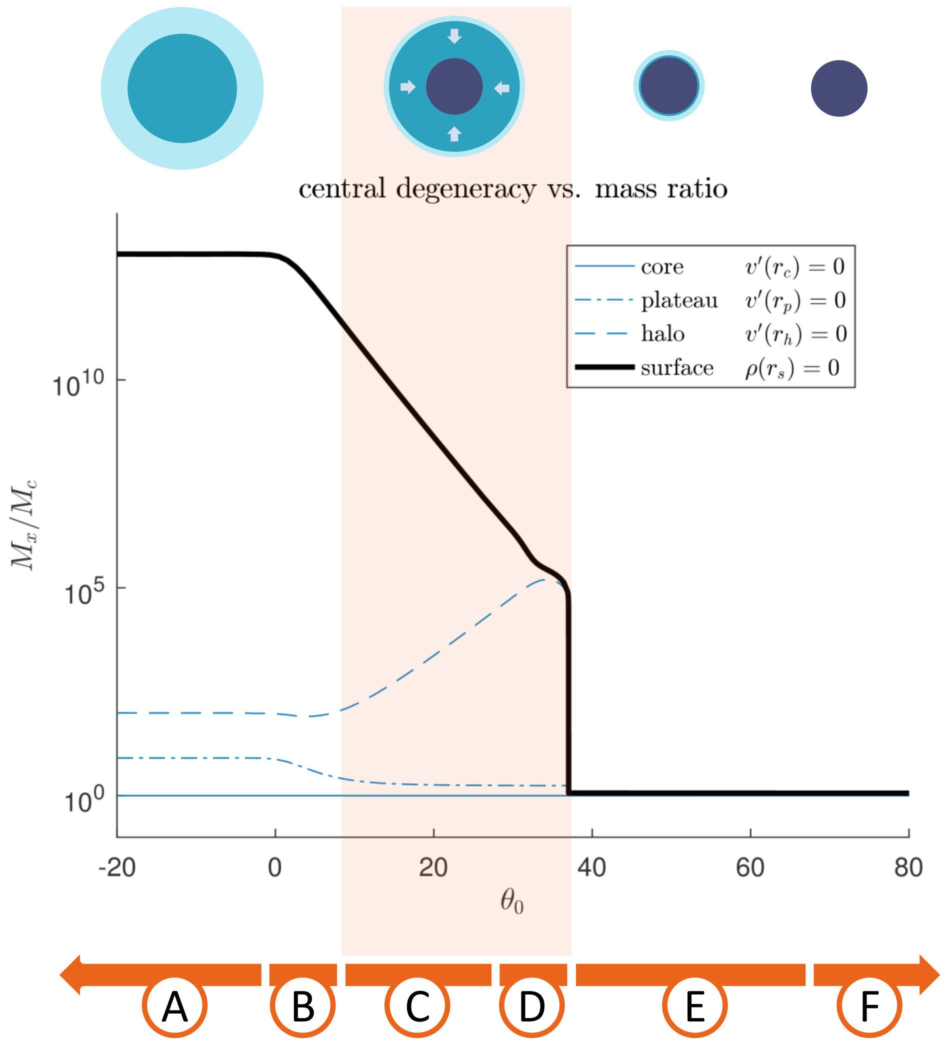
  surface radius is decreasing
- (D) **critical regime**
  surface effects appear
- (E) **degenerate regime (no halo)**
  halo evaporated
- (F) **fully degenerate core**

Focus regimes with halo

For varying central degeneracy (temperature and cutoff parameter are fixed)

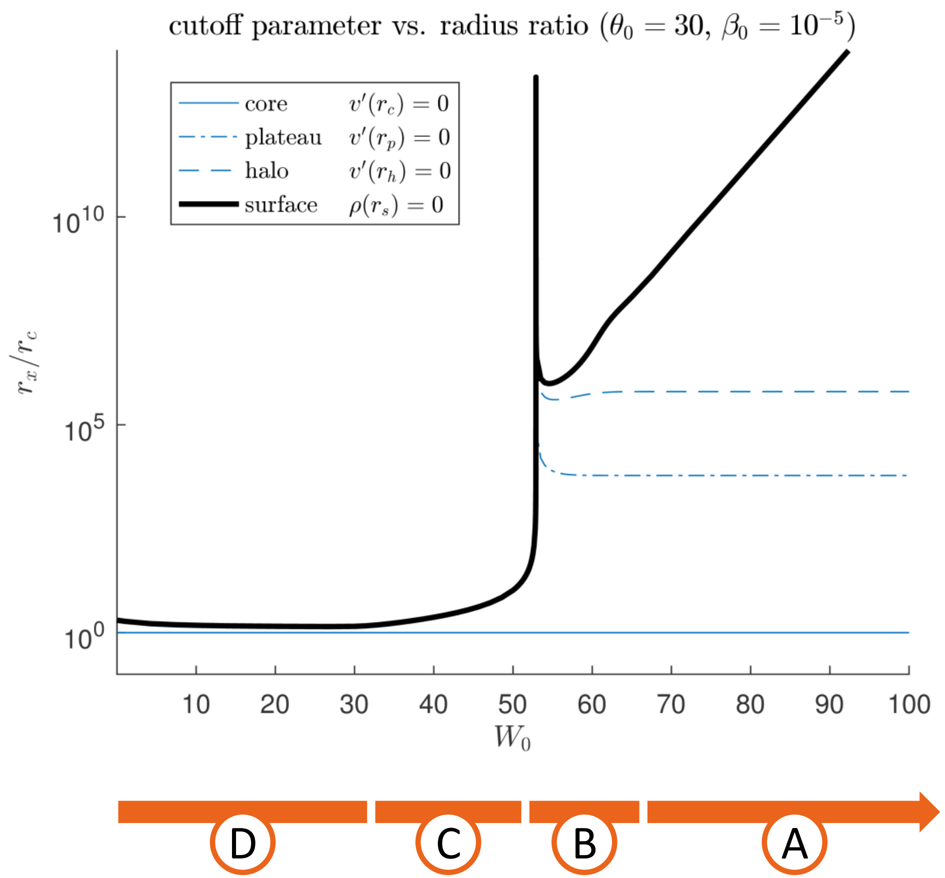


$$\beta_0 = 10^{-5}, W_0 = 65$$

- A — diluted regime
  diluted core with halo
- B — semi-degenerate transition
  a degenerate core forms
- C — degenerate regime (with halo)
  surface radius is decreasing
- D — critical regime
  surface effects appear
- E — degenerate regime (no halo)
  halo evaporated
- F — fully degenerate core

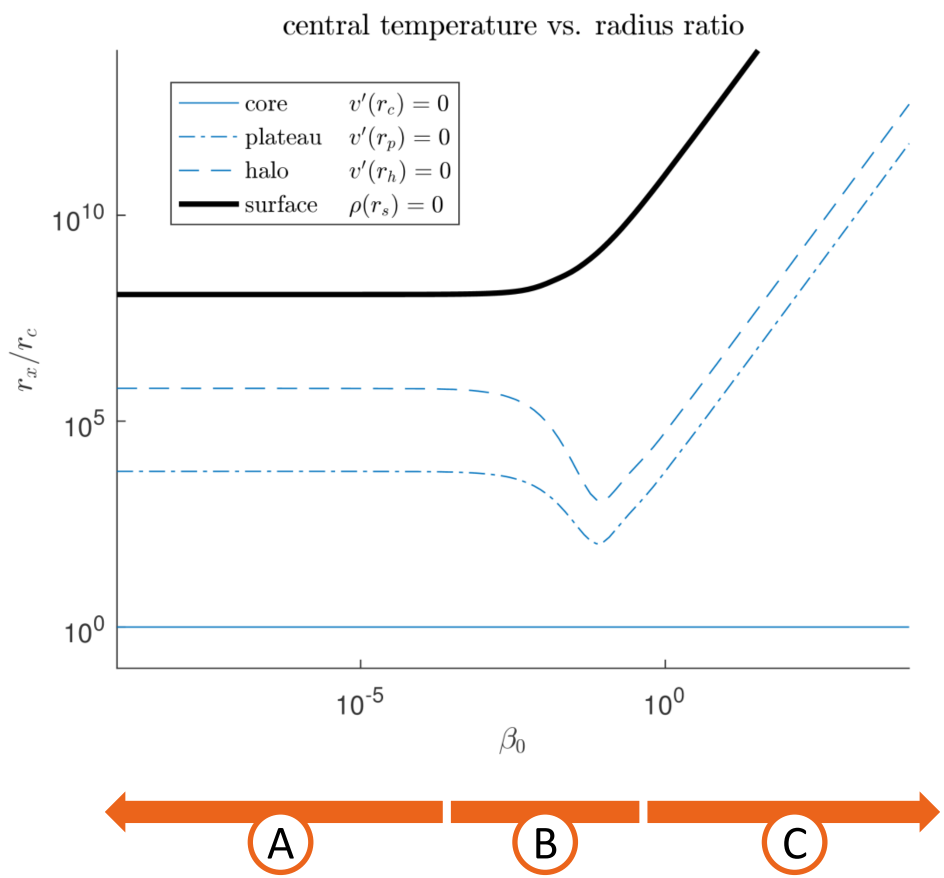
Vary evaporation

$$\theta_0 = 30, \beta_0 = 10^{-5}$$



- (A) **weak evaporation** — *finite mass distribution*
- (B) **critical evaporation** — *surface effects appear*
- (C) **strong evaporation** — *evaporation of the halo*
- (D) **disruptive evaporation** — *fully degenerate core*

Vary central temperature

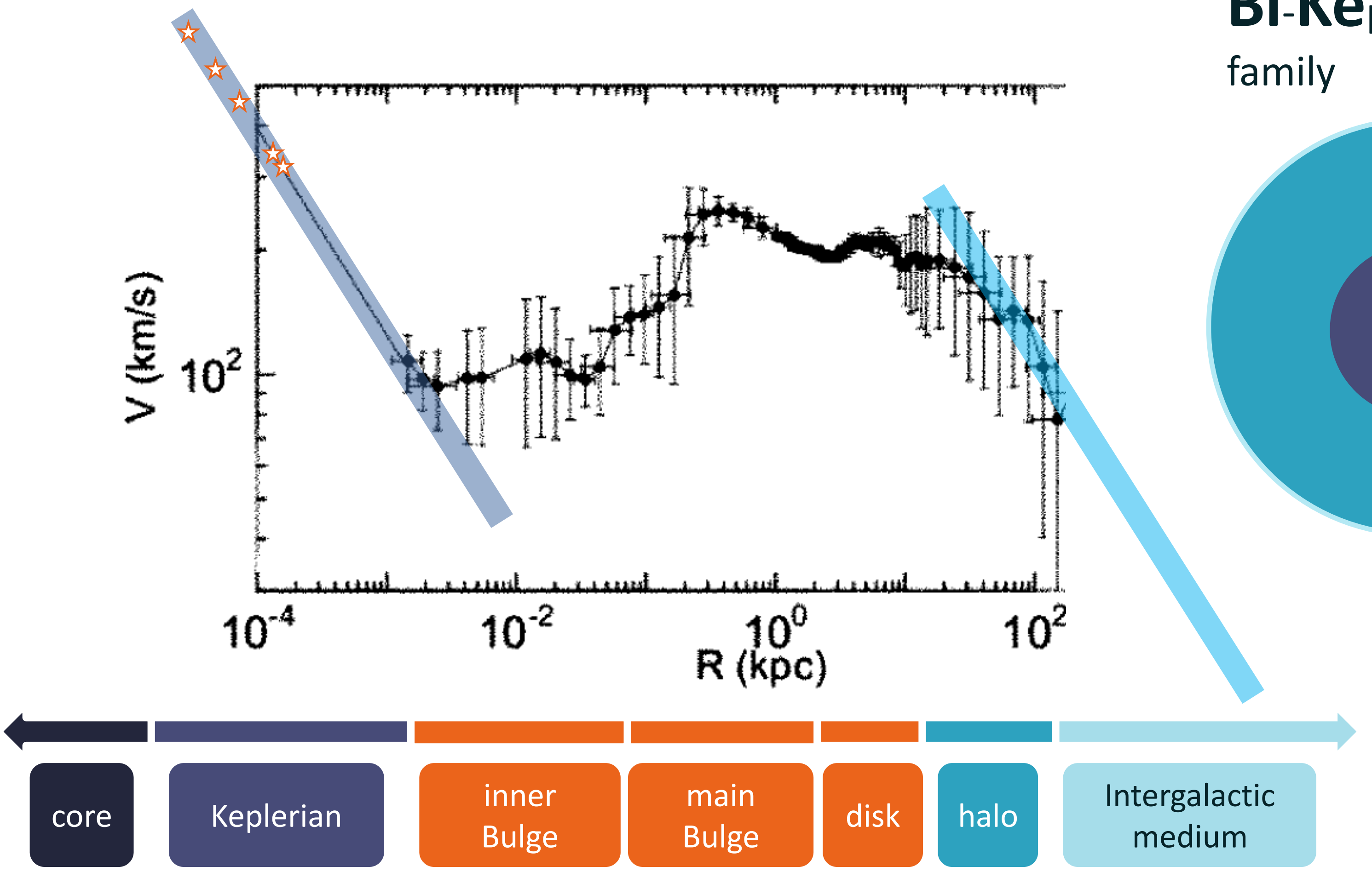


$$\theta_0 = 30, W_0 = 65$$

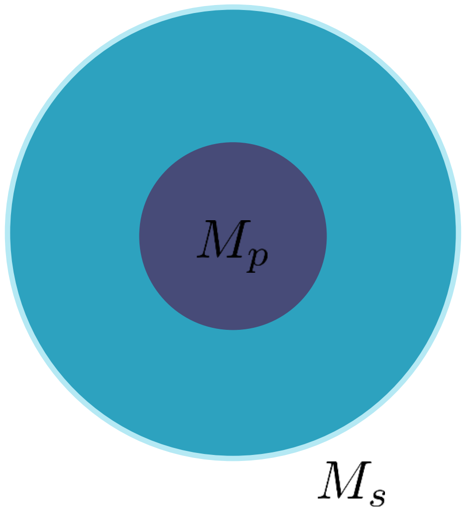
- (A) low temperatures
  temperature invariance
- (B) moderate temperature
  thermal effects appear
- (C) high temperature
  blow up by thermal pressure

BiKe model in MW

Two Keplerian behaviour in rotation curve



Bi-**Ke**plerian family



BiKe model

1. $M_p = M_p(\theta_0, \beta_0, W_0, m)$

   $M_s = M_s(\theta_0, \beta_0, W_0, m)$

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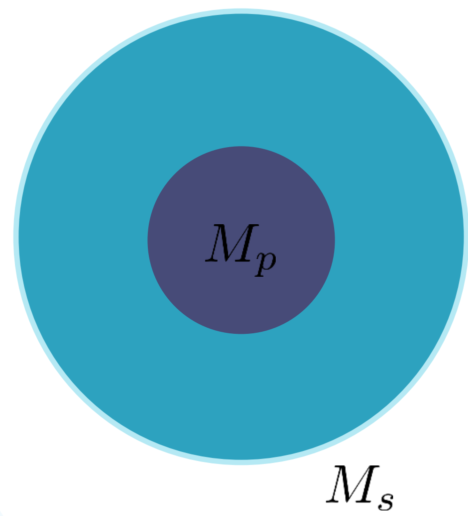
2. $m = m(r_p)$ from observations

↓

$$\{\theta_0, M_s, M_p, r_p\}$$

Bi-**Ke**plerian family



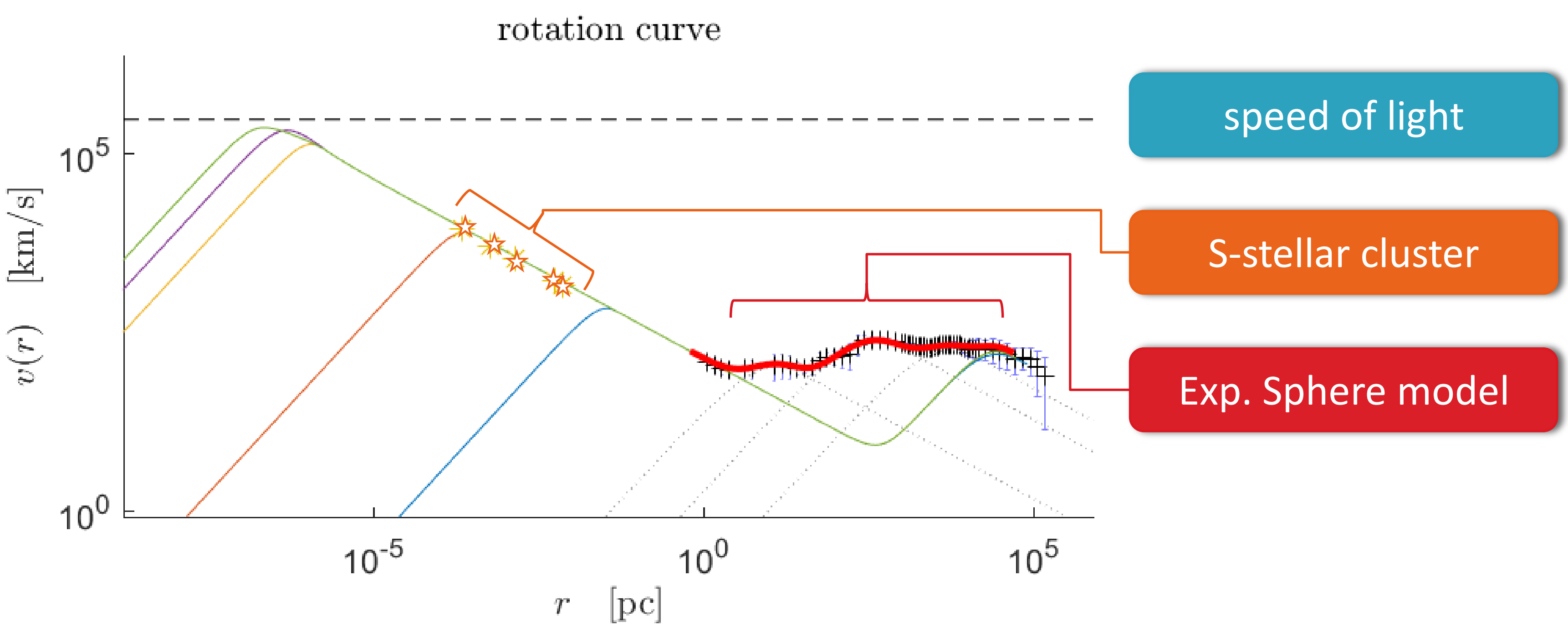
BiKe family in Milky Way

different degenerate cores for same halo

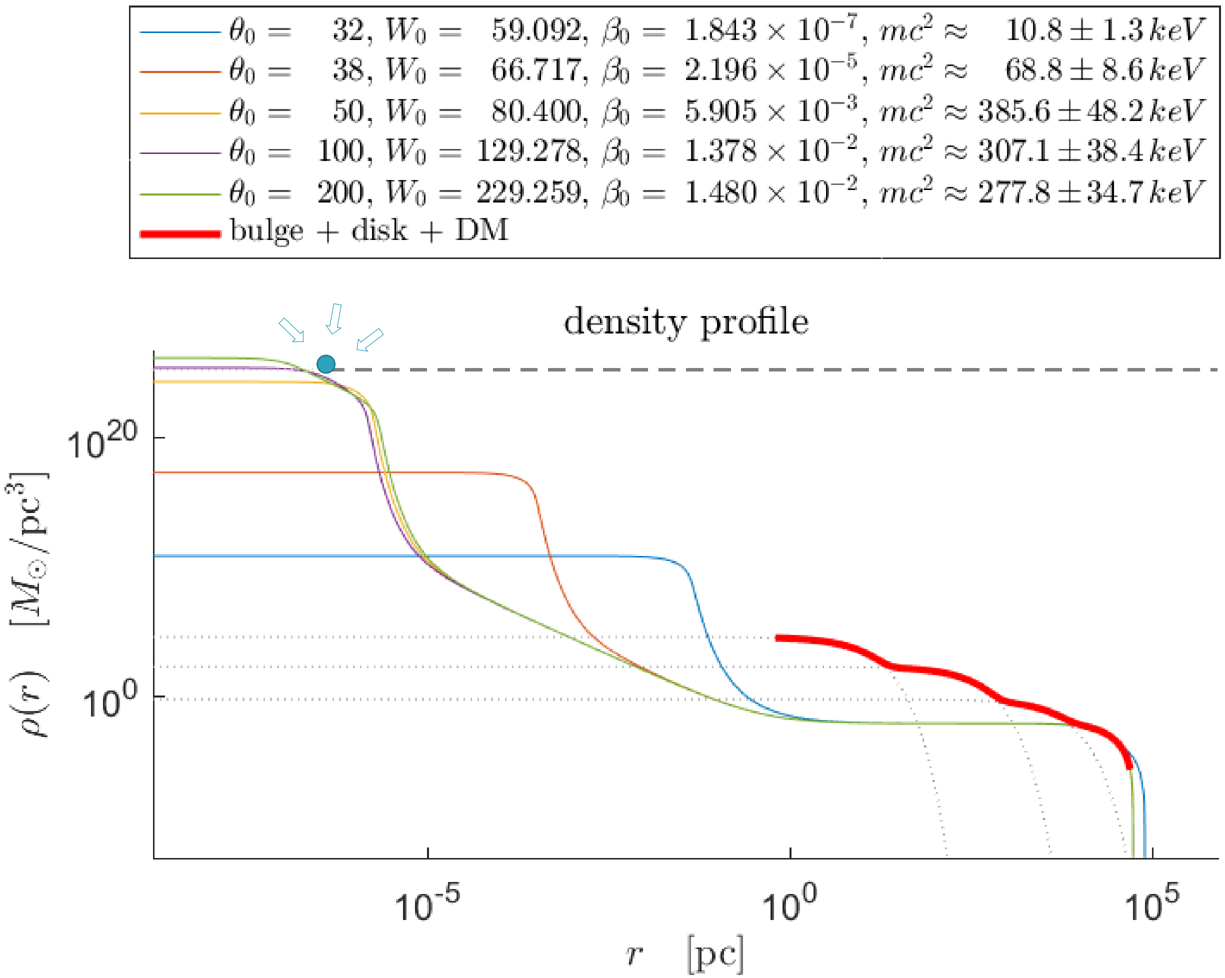
- $\theta_0 = 32,\ W_0 = 59.092,\ \beta_0 = 1.843 \times 10^{-7},\ mc^2 \approx 10.8 \pm 1.3\,keV$
- $\theta_0 = 38,\ W_0 = 66.717,\ \beta_0 = 2.196 \times 10^{-5},\ mc^2 \approx 68.8 \pm 8.6\,keV$
- $\theta_0 = 50,\ W_0 = 80.400,\ \beta_0 = 5.905 \times 10^{-3},\ mc^2 \approx 385.6 \pm 48.2\,keV$
- $\theta_0 = 100,\ W_0 = 129.278,\ \beta_0 = 1.378 \times 10^{-2},\ mc^2 \approx 307.1 \pm 38.4\,keV$
- $\theta_0 = 200,\ W_0 = 229.259,\ \beta_0 = 1.480 \times 10^{-2},\ mc^2 \approx 277.8 \pm 34.7\,keV$
- bulge + disk + DM

!

$$M_s = 2.3 \times 10^{11}\, M_\odot$$
$$M_p = 4.2 \times 10^{6}\, M_\odot$$
$$r_p = 0.4 \pm 0.1\,\mathrm{kpc}$$



BiKe family in Milky Way



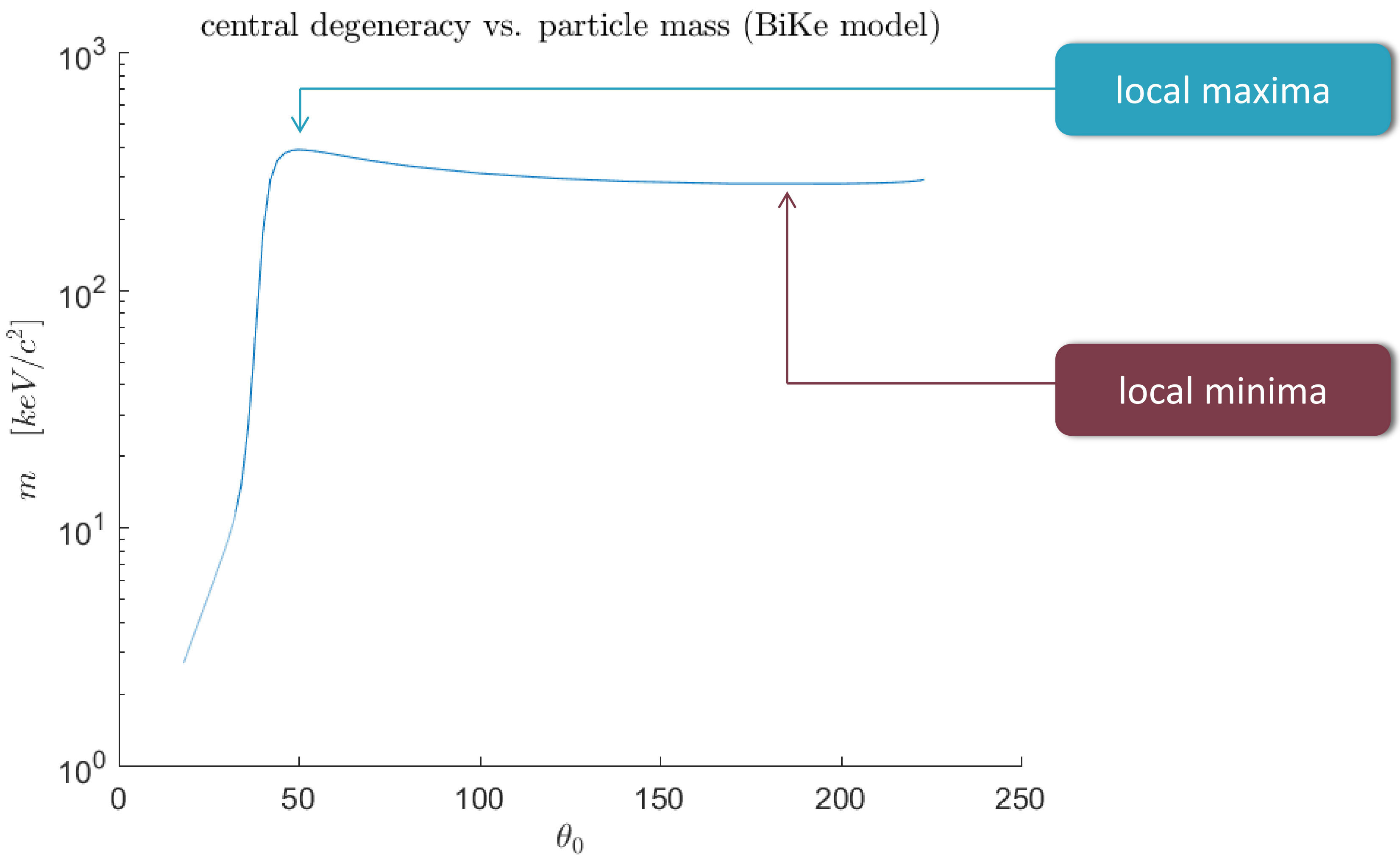
$$M_s = 2.3 \times 10^{11}\ M_\odot$$
$$M_p = 4.2 \times 10^{6}\ M_\odot$$
$$r_p = 0.4 \pm 0.1\ \mathrm{kpc}$$

critical density of Galactic Nucleus

$$\rho_{cr} = \frac{M_p}{\frac{4}{3}\pi r_S^3}$$

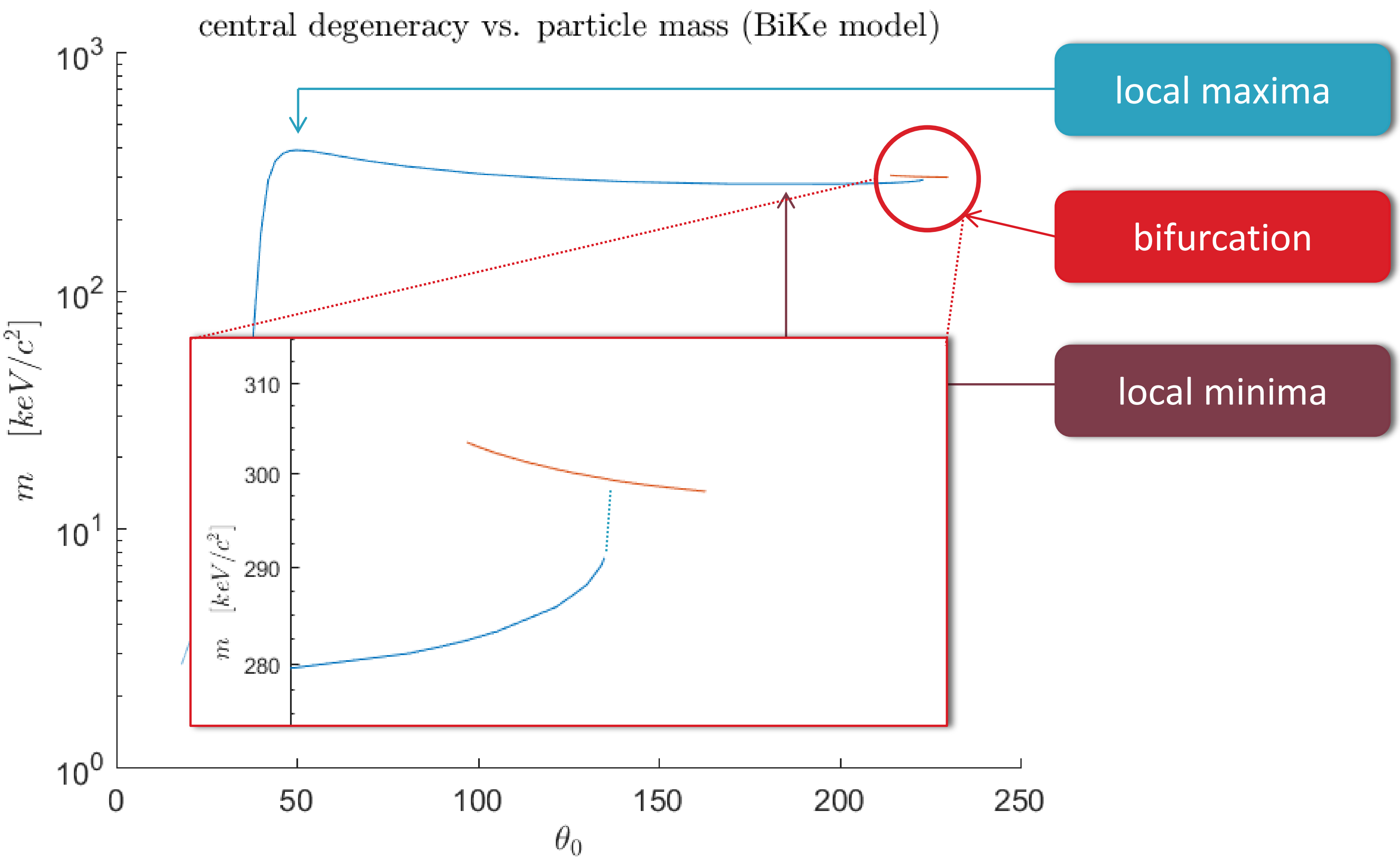
BiKe family analysis

Extrema in parameter space



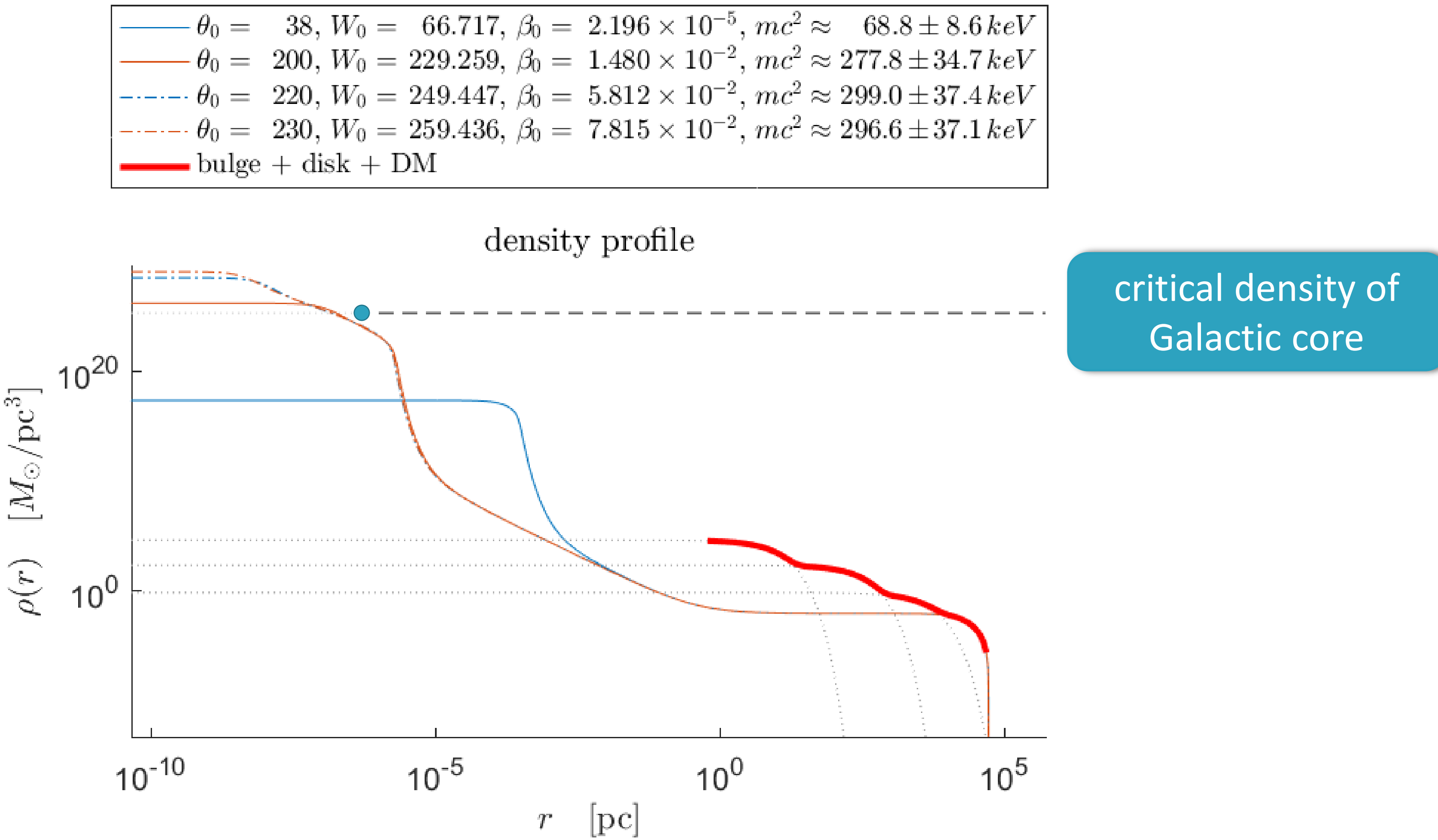
BiKe family analysis

Bifurkation in parameter space

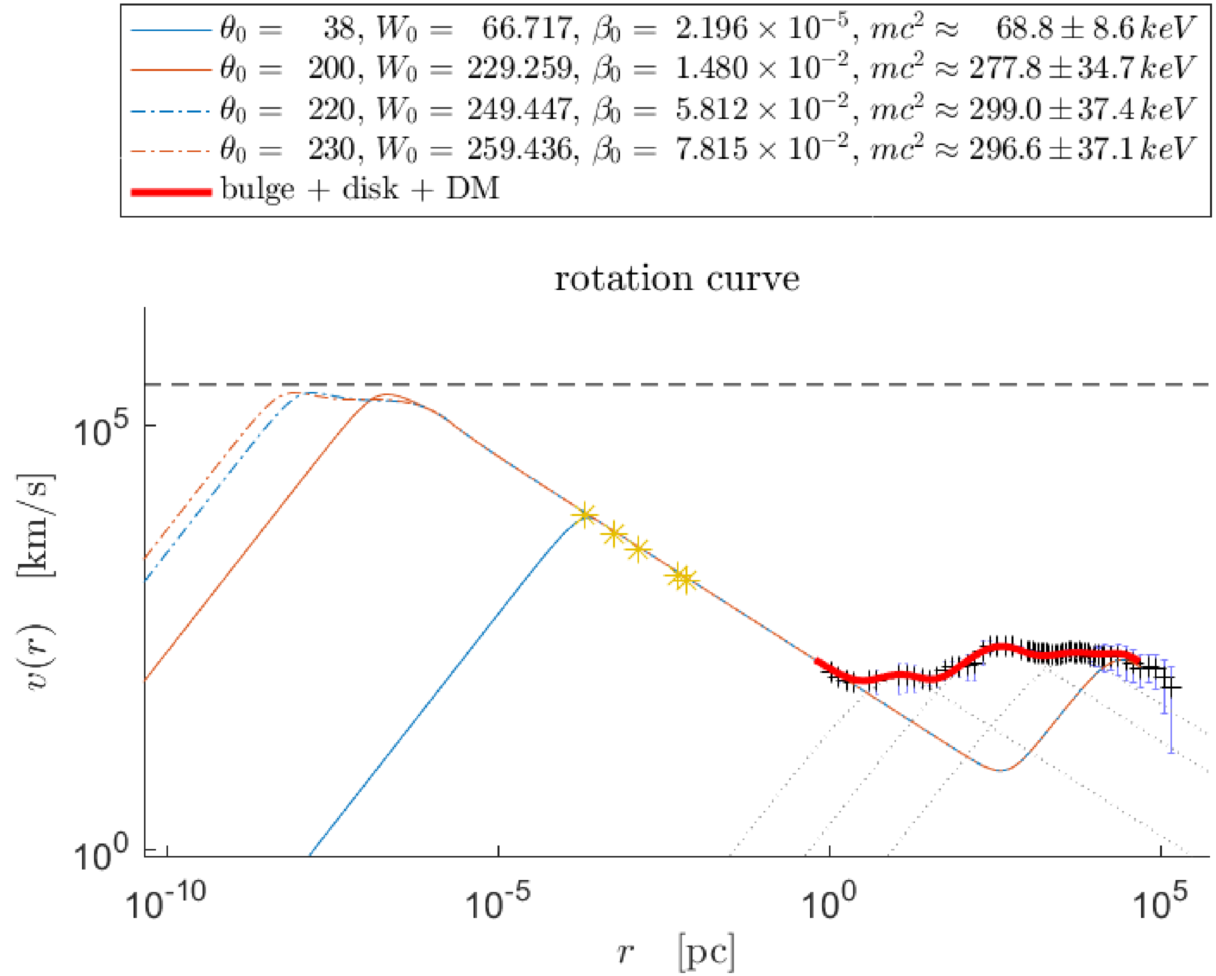


Alternative Core

density profile



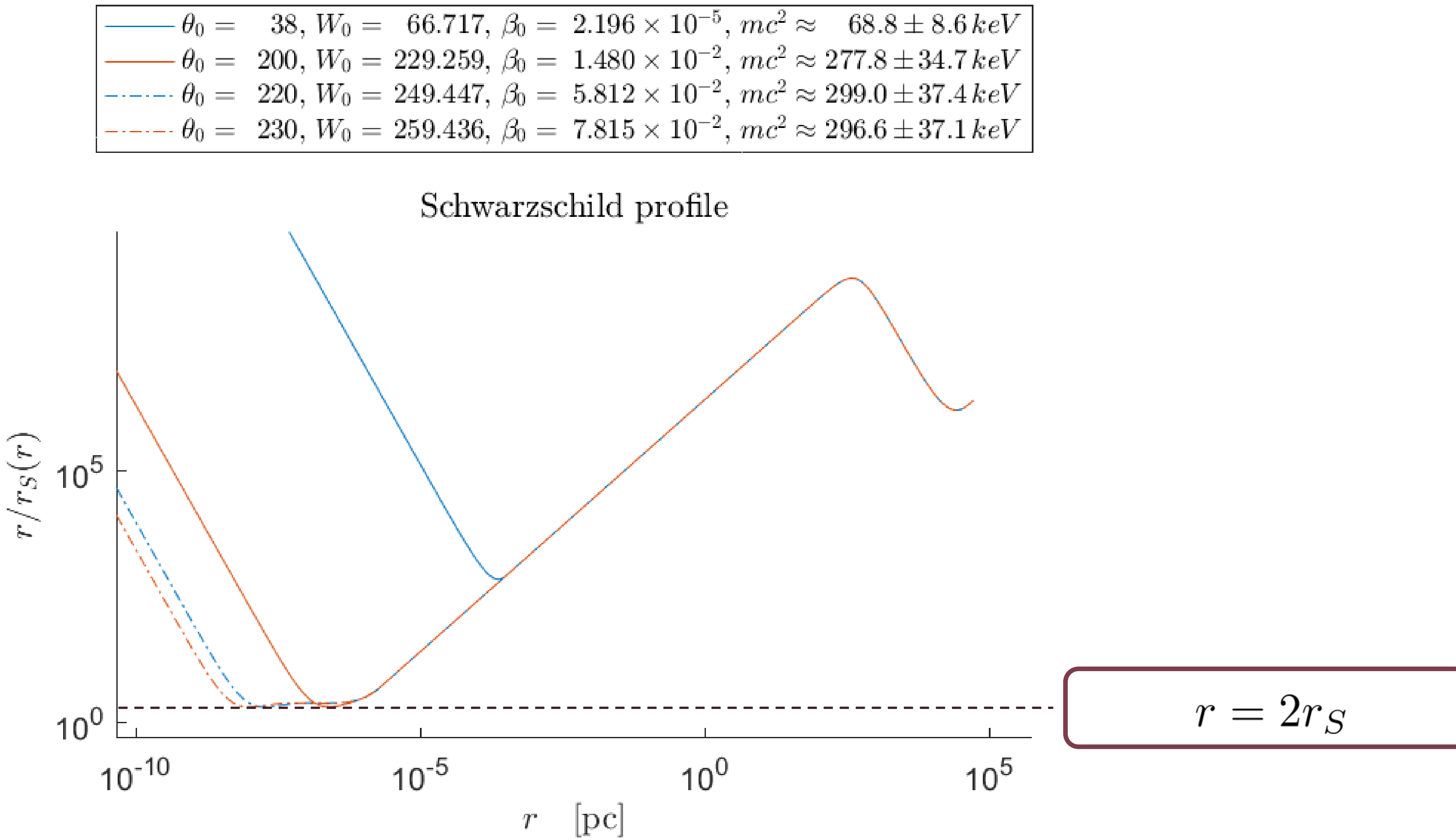
Alternative Core



speed of light

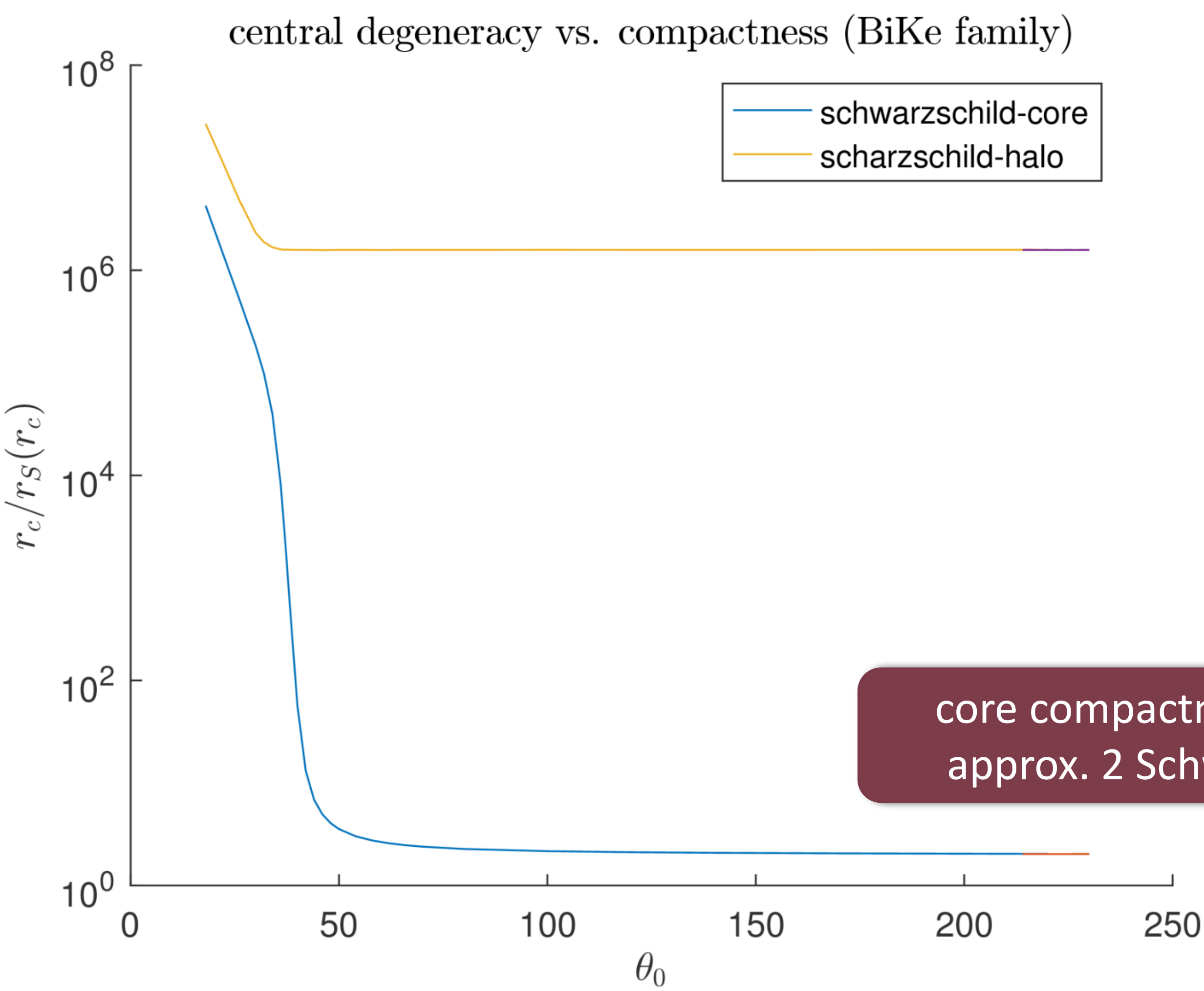
Compactness

Two Schwarzschild radii



Compactness

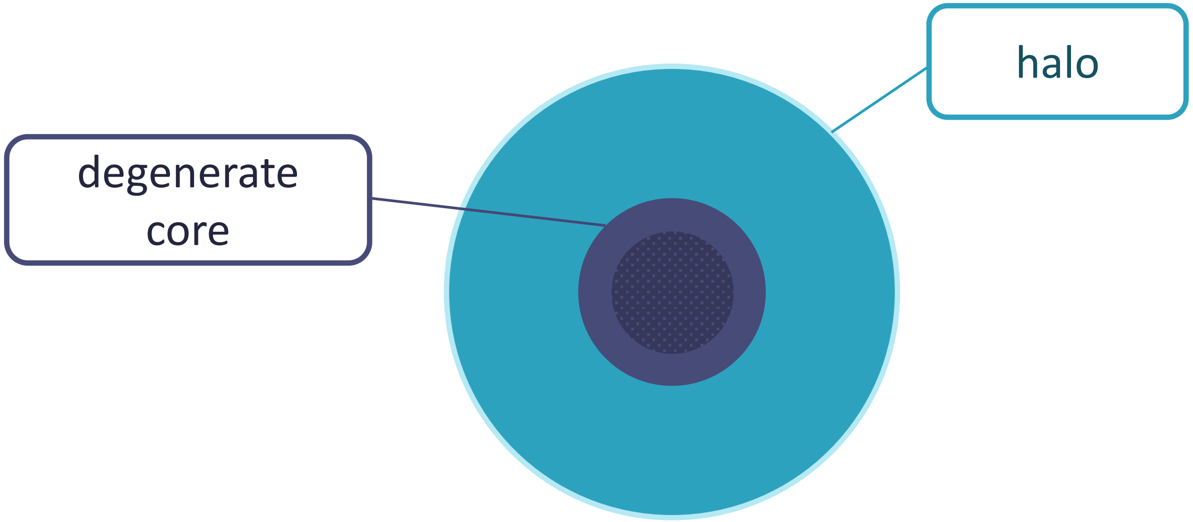
Two Schwarzschild radii



core compactness coverges to approx. 2 Schwarzschild radii

Summary

- Idealized DM model explains main characteristics of a galaxy (core and halo)
- Bike family in the relativistic approach prevents the gravitational collaps
- Inferred particle mass bounded to $m \in [60, 425]\mathrm{keV}/c^2$ (from MW)



Thank you