Analytical models and N-Body simulations of stellar systems formed by collisionless collapse

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Exploring the Universe

Outline

- Focus on the mechanism of violent relaxation
- Construction of a family of collisionless models (the $f^{(\nu)}$ models)
- Illustration of their properties
- Comparison of the theoretical models with numerical simulations
- Open issues & conclusions

Adopted scenario:violent relaxation[1]

- Violent collapse starting from $2K/|W|<<1$:
  - Efficient core relaxation
  - Radial anisotropy in the outer parts
  - Low sensitivity to details of initial conditions
- It can explain the universality of surface brightness of elliptical galaxies[2]
- What is the underlying distribution function?[3]

[1] Lynden-Bell (1967); [2] van Albada (1982); [3] Bertin & Stiavelli (1984)

Relation with hierarchical merging

- Violent relaxation is important even in CDM structure formation
- We aim at better understanding the simpler monolithic collapse scenario before moving to hierarchical merging
- We focus on this mechanism and, for the moment, we ignore the continuous infall of matter
- Clumpy initial conditions can also simulate aspects of the merger processes

Construction of the $f^{(\nu)}$ models[1,2]

- Extremization of Boltzmann entropy
  - $$S = -\int f \ln f d^3x d^3w$$
- fixing:
  - $$E_{tot} = \tfrac{1}{3} \int E f d^3x d^3w$$
  - $$M = \int f d^3x d^3w$$
  - $$Q = \int J^{\nu} |E|^{-3\nu/4} f\, d^3x d^3w$$

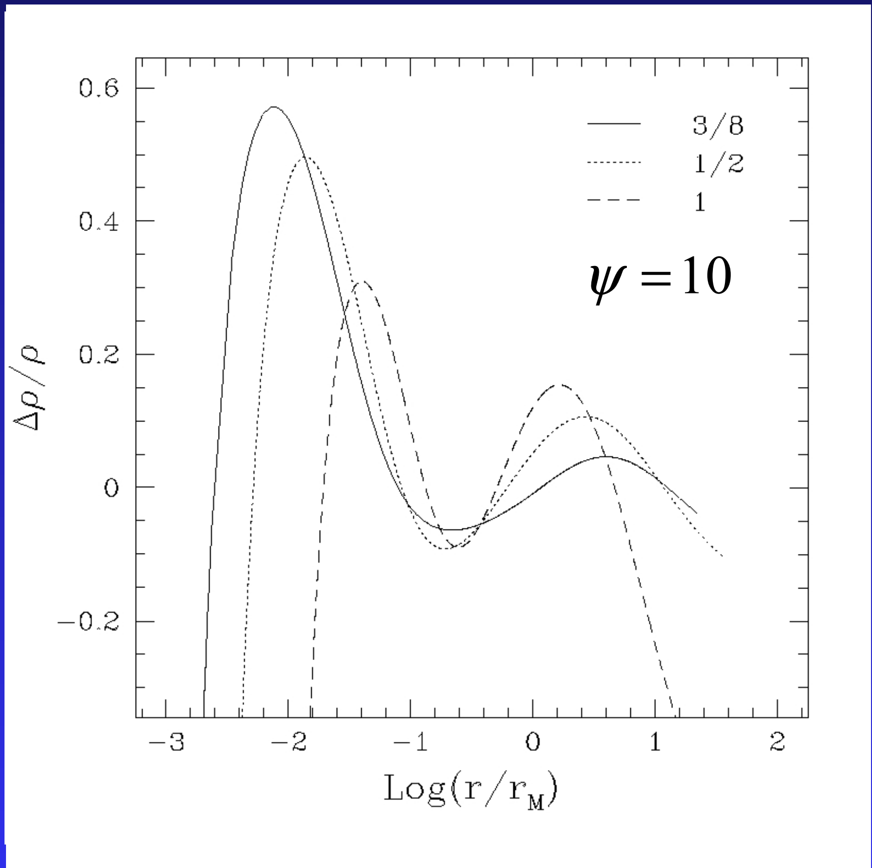
Q keeps into account the physics of incomplete violent relaxation

[1] Stiavelli & Bertin (1987); [2] Bertin & Trenti (2003)

$$f^{(\nu)} = A \exp(-aE - d\, J^{\nu} \Big/ |E|^{3\nu/4}) \cdot \theta(-E)$$

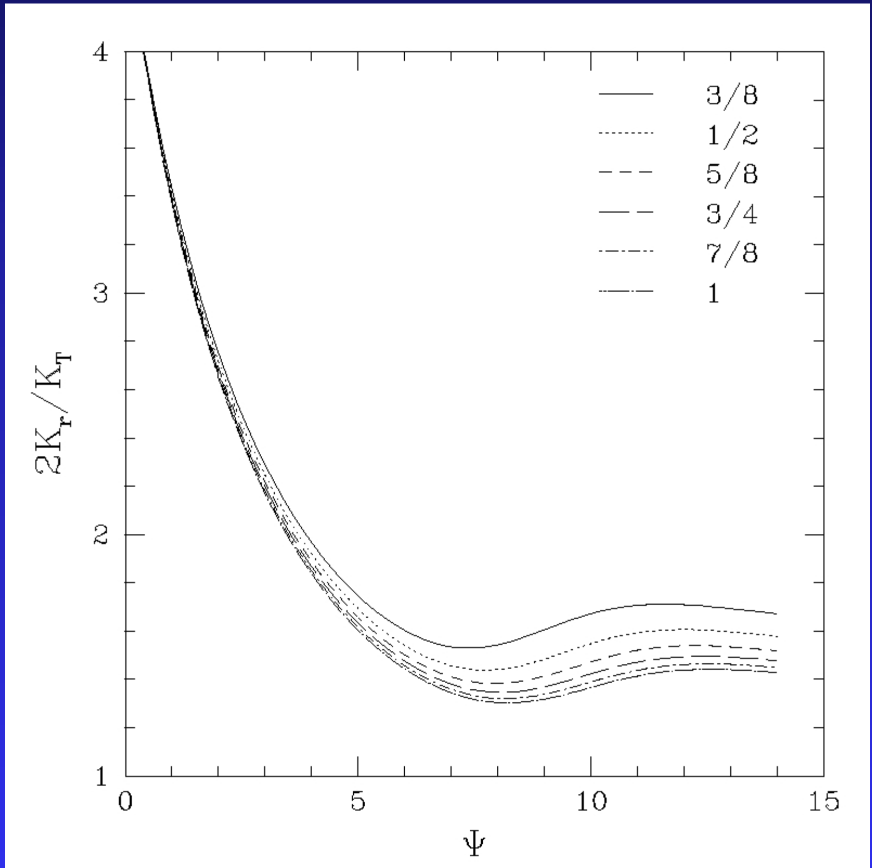
- A,*a*,*d*,*v* are real positive constants giving 2 scales and 2 dimensionless parameters (ν and Ψ=-$a\Phi(0)$)
- The non-truncated models are built by taking a vanishing *f* for E>0
- Self consistent solutions are constructed from the Poisson equation

The density profile



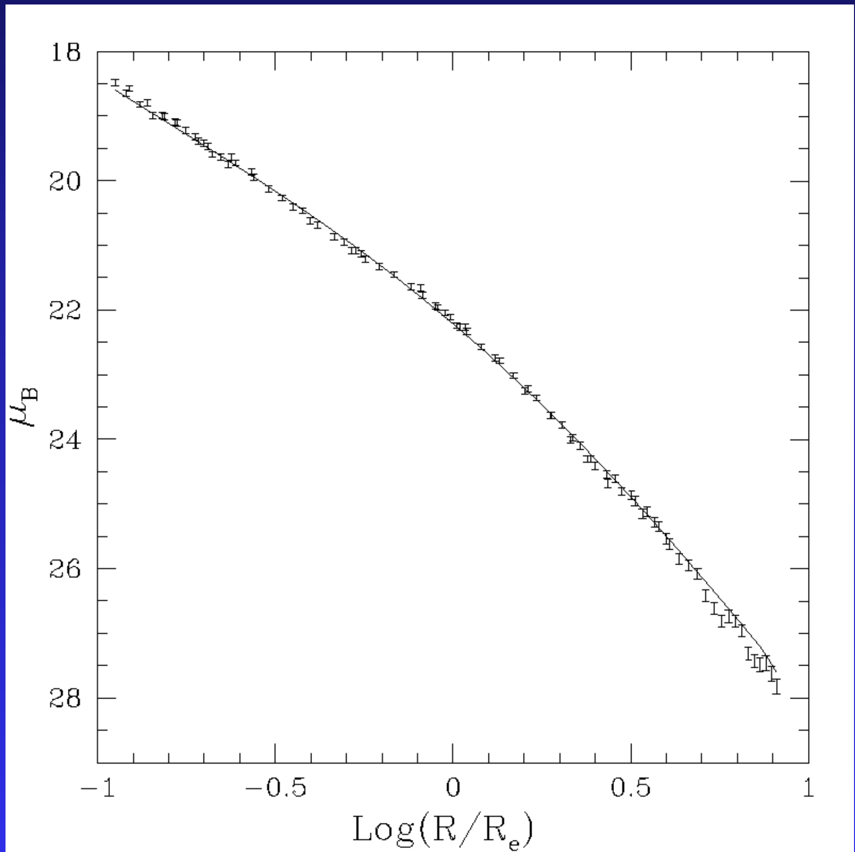
- $(\nu;\psi)$: parameters of the model
- Universal behavior:
  - $1/r^4$ at large radii
  - $1/r^2$ in the the central regions but with flat core
- Small residuals from Jaffe profile for concentrated models
- Projected profile well fitted by $R^{1/n}$ with $n \approx 4$

Anisotropy content:



- $\alpha(r) = 2 - \langle w_T^2 \rangle / \langle w_r^2 \rangle$
- Anisotropy already significant @ r_M
- Low Ψ part of the sequence is unstable against radial orbit instability (if $2K_r/K_T > 1.7$)

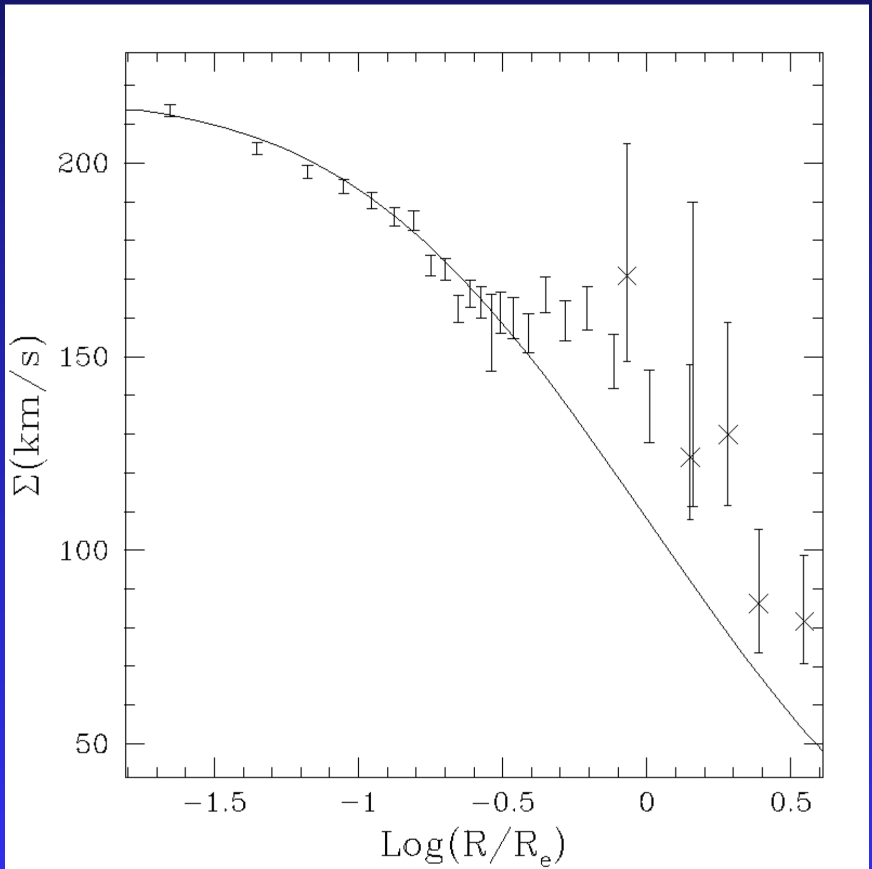
An example: NGC3379



- E1 prototype[1] of $R^{1/4}$
- Low dark matter content[2]
- We attempt a combined photometric[1] and kinematic[3] fit for the galaxy
- Constant M/L assumed
- Best fit with (1/2;9.4)

[1] de Vacouleurs & Capaccioli (1979);[2] Saglia et al. (1992);[3] Romanowsky et al. (2003)

NGC3379: velocity dispersion[1,2]



- Use of planetary nebulae as kinematical tracers
- Good representation of the kinematics with (1/2;9.4)
- Implied M/L_B=4.7
- Low DM content is confirmed

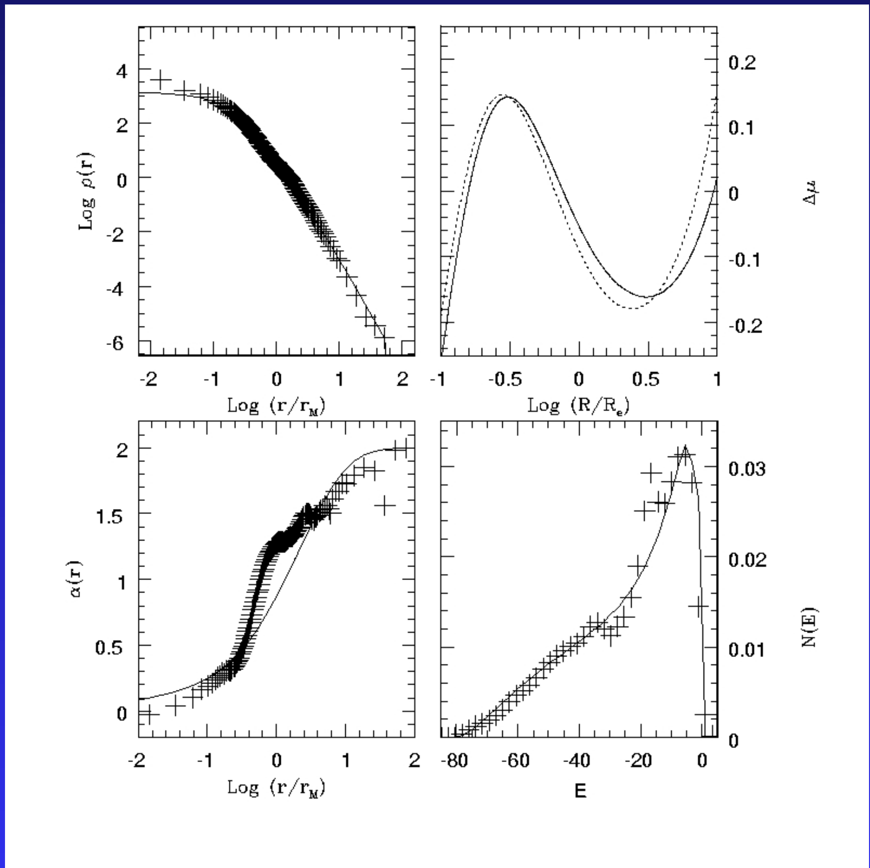
[1] Statler & Smecker-Hane (1999);[2] Romanowsky et al. (2003)

Comparison with simulations

- We use an improved version of van Albada collisionless N-body code[1,2]
- Clumpy initial conditions: $2K/|W| \leq 0.3$ & approximate spherical symmetry (with $N \approx 10^6$)
- Final, quasi equilibrium, state compared to the $f^{(\nu)}$ models
- Fit of the density and anisotropy profiles
- Comparison at the level of phase space (E,J^2)

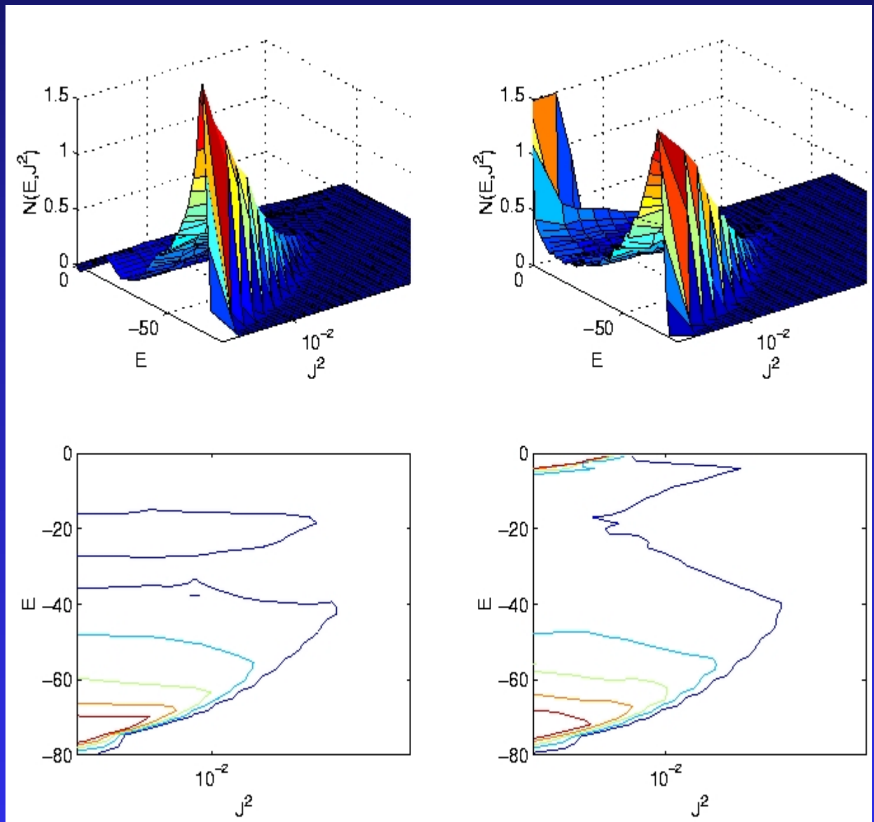
[1] van Albada (1982) ; [2] Trenti & Bertin (2004) in preparation

Some results I



- Clumpy initial conditions
- -2K/W≈0.1 & N=800K
- Final state: E2/E3
- Best fit with (1/2;6.4) with fixed scales
- Density profile reproduced over 10 orders of magnitude!
- Projected density: $R^{1/4}$
- Close match in single particle energy distribution

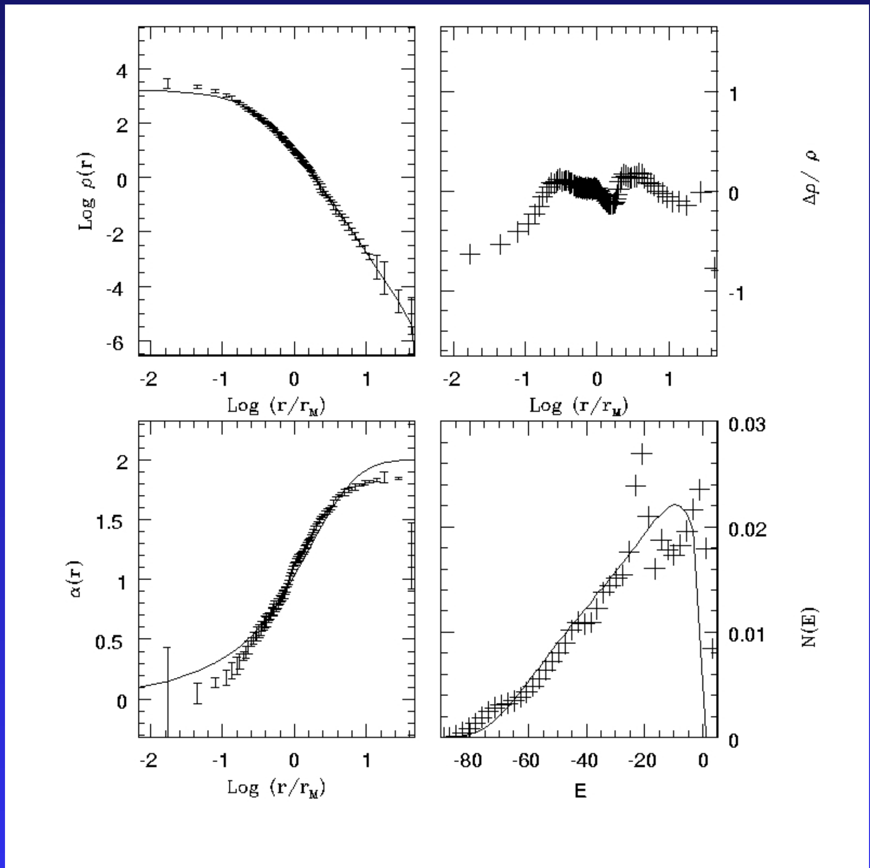
Comparison @ Phase space (E,J^2)



Simulation (1/2;6.4) $f^{(v)}$

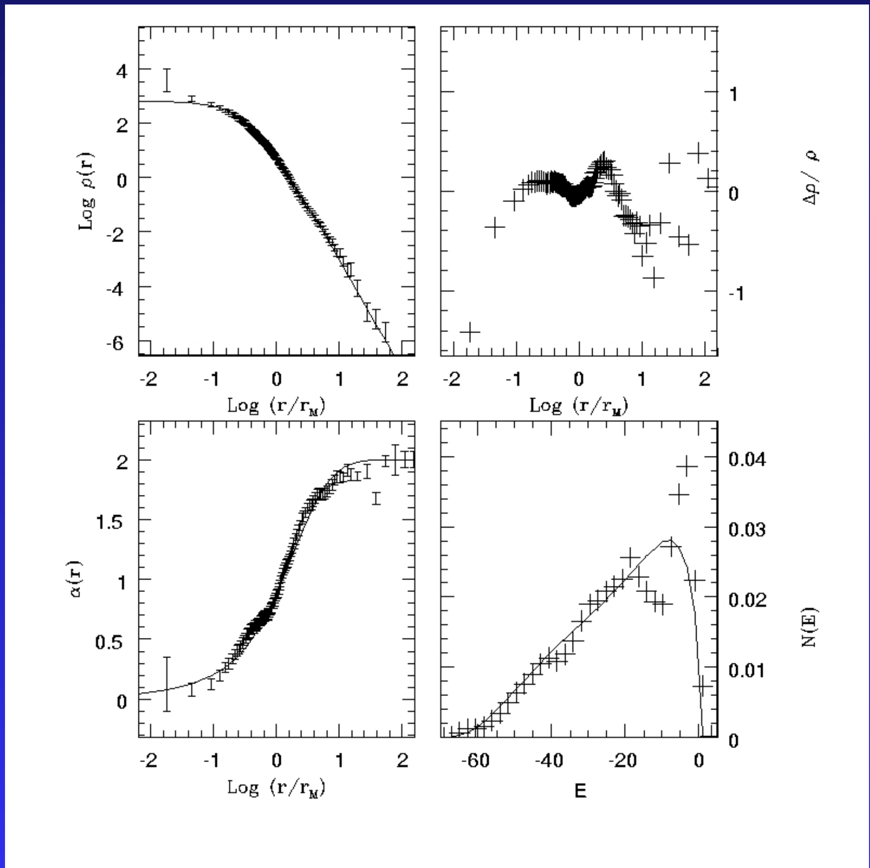
- Best fit model identified with previous fit
- Overall excellent for strongly bound stars
- At the origin, the singularity of the models does not appear in the product of the simulations

Some results II



- N=800K in 20 clumps
- 2K/|W|=0.05
- Best fit: (1/2;4.6)
- $2K_r/K_T$ =1.83
  - Marginal instability!
  - The simulation product is significantly non spherical (≈E3/E4)

Some results III



- N=800K in 20 clumps
- 2K/|W|=0.23
- Best fit: (5/8;5.4)
- $2K_r/K_T$ =1.66

General trends

- Density profile for $r>r_M$ is universal for all the simulations
- Projected density profile well fitted by the $R^{1/n}$ law with $3<n<5$
- Final state is moderately tri-axial (up to E3)
- Anisotropy content and central concentration are correlated with initial $2K/|W|$
- End products are close to marginal stability with respect to the radial orbit instability

The third conserved quantity *Q*

- The $f^{(\nu)}$ family was obtained extremizing the Boltzmann entropy
- *Q* was introduced to keep into account the physics of incomplete violent relaxation
- From the fits it appears that, *a posteriori*, the *Q* Ansatz is justified for $\nu \approx 1/2$
- Work is in progress to test the conservation of *Q* directly

Conclusions

- The $f^{(\nu)}$ models represent an appealing family with:
  - Realistic properties (e.g. fit of NGC3379)
  - A straightforward statistical mechanics derivation
- The $f^{(\nu)}$ models capture key features of violent relaxation simulations:
  - Density fitted over 10 orders of magnitude
  - Anisotropy profile well represented