Probing Structure and History of DM Halos with Gravitational Lensing

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Introduction

- Dark Matter (DM) cosmogony in a couple of slides

  - Initial DM density perturbations grow by gravitational instability, at first kept in check by the cosmic expansion, then enforcing collapse when local gravity prevails (e.g., Peebles 93) .

  - A slightly overdense region expands more slowly than its surroundings, progressively detaches from the Hubble flow, halts, turns around, collapses, and eventually virializes to form a DM halo in equilibrium under self-gravity.

  - Amplitude of more massive perturbations in the density field is smaller, so formation is hierarchical with massive structures forming typically later.

Introduction

- N-body simulations soon confirmed the picture (e.g., White86) and resolved it to a fine detail, adding two important blocks of info (e.g., Springel+06).

- First, the halo growth actually occurs through multiple stochastic merging events with other clumps of sizes comparable (major mergers) or smaller (minor mergers), down to nearly smooth accretion.

- Second, at any stage the density profile in the virialized halos is well described by the NFW (Navarro+97) formula

$$\rho_{DM}(r) = \rho_c \frac{\Delta_{\rm vir}}{3} \frac{c^2 g(c)}{s(1+cs)^2}$$

with small deviations from scale-invariance related to the mild mass-dependence of the concentration parameter c (e.g., Bullock+01).

Introduction

Recent pieces of news

- Intensive high-resolution N-body simulations (Zhao+03, Hoffman+07, Diemand+07) have recently focused on the halo development, with three main outcomes.

- First, the halo growth is recognized to comprise two stages: an early fast collapse including a few violent major mergers building up the halo 'body'; and a later stage of slow accretion, when the body is almost unaffected while the outskirts develop from the inside-out by minor mergers and smooth mass additions.

  The transition is provided by the time when a DM gravitational well attains its maximal depth, or the circular velocity $v_c^2 \equiv GM/R$ its maximum value along an evolutionary track (see Li+07); this also marks the time for the early collapse turmoil to subside.

Introduction

- Second, the ensuing quasi-equilibrium structure is effectively described in terms of the functional

$$K \equiv \sigma_r^2/\rho^{2/3}$$

that combines density and radial velocity dispersion in the form of a DM 'entropy' (*recte* 'adiabat'; see Taylor & Navarro 01 [TN01], Hoffman+07, Ascasibar & Gottloeber 08, Vass+08), formally analogous to the true thermodynamic entropy of a gas in thermal equilibrium.

- Third, the simple powerlaw run

$$K(r) \propto r^\alpha$$

is empirically found to hold in the halo body, with uniform slope around 1.25 (e.g., TN01, Ascasibar+04; Rasia+04, Vass+08). Thus K provides an effective means for recasting in terms of density the pressure $\rho\,\sigma_r^2$ that balances self-gravity for equilibrium.

Two-Stage Development of DM Halos

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- Origin of the entropy slope

- At a zeroth order approximation, the evolutions of the current bounding radius R, of the circular velocity v_c^2, and of the entropy K for a building-up DM halo are obtained in terms its mass and growth rate from the simple scaling laws (see LC09a)

$$R \propto M/\dot{M}^{2/3} \qquad v_c^2 \propto \dot{M}^{2/3} \qquad K \propto R\, M^{1/3}$$

Whence the entropy slope reads

$$\alpha = 1 + \frac{1}{1 + 2\,\epsilon/q}$$

in terms of the inverse growth rate $\epsilon \equiv -\,\mathrm{d}\log(1+z)/\mathrm{d}\log M = q\, M/\dot{M}\, t$

and of the exponent in the time-redshift relation

$$(1+z) \propto t^{-q} \quad \rightarrow \quad q \approx 2/3 \quad z \gtrsim 1; \qquad q \approx 0.8 \quad z \lesssim 0.5$$

Two-Stage Development of DM Halos

- Since $\epsilon \approx 1$ marks the transition from fast collapse to slow accretion, it follows that,

$$\alpha \approx 1.25 \div 1.3$$

depending on whether the transition occurs at z > or < 0.5; the result agrees with the empirical evidence from N-body simulations.

- Note that the quantity ϵ enables us to make contact with the classic line of developments (see Fillmore & Goldreich 84, Lu+06) that analytically relate the collapse histories to the shape of the primordial DM perturbations, in the form $\delta M/M \propto M^{-\epsilon}$. From this perspective the above values of α at the transition epoch will apply to the halo body, which precisely corresponds to $\epsilon \approx 1$ for a realistic bell-shaped perturbation.

Two-Stage Development of DM Halos

- The heuristic computation can be checked and refined in terms of the halo average growth histories, obtained from integrating for $M(t)$ the differential equation

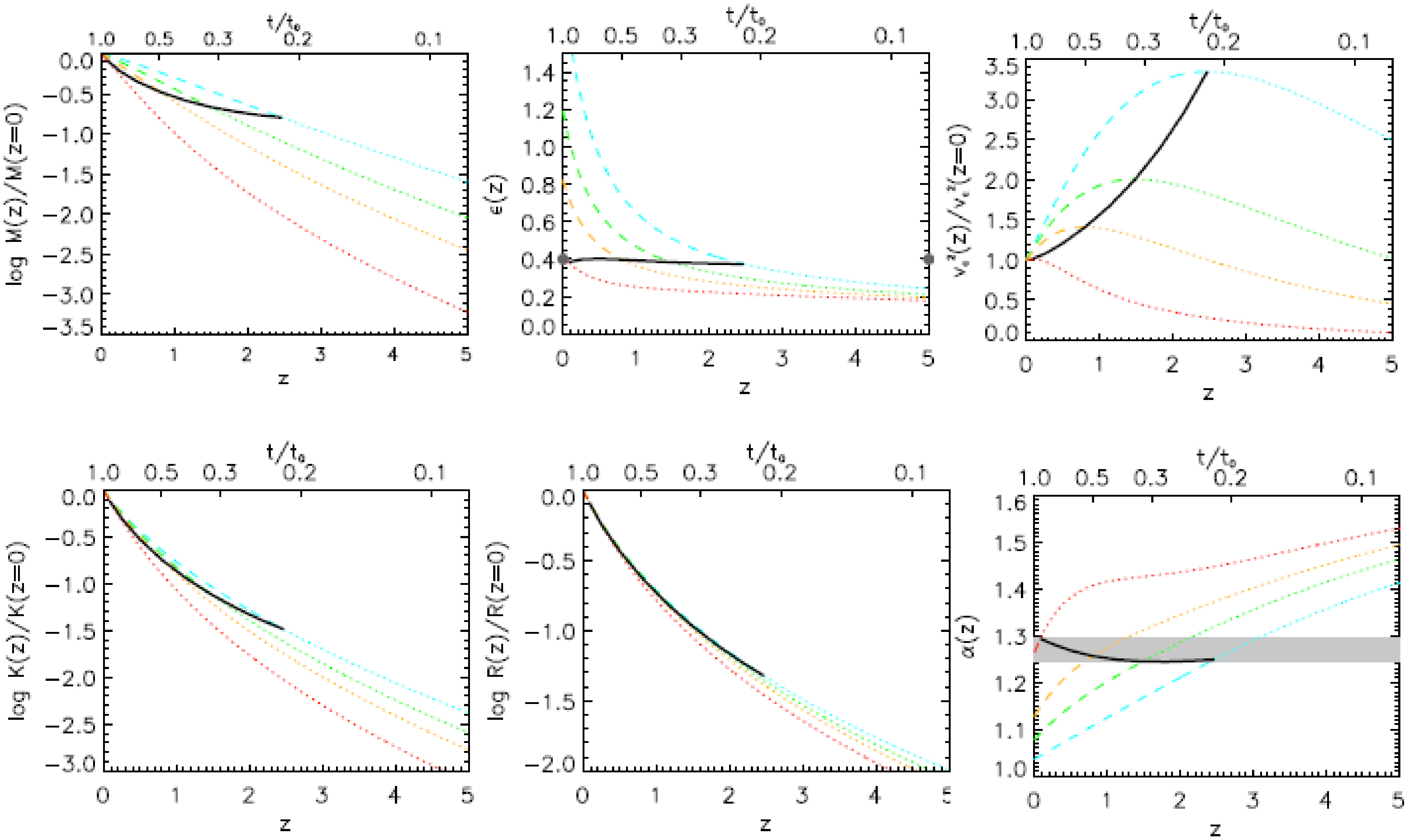
$$\dot{M}(M,t) = \int_0^M dM' \, (M - M') \, \frac{\mathrm{d}^2 P_{M' \to M}}{\mathrm{d}\, M' \mathrm{d}\, t}$$

where the growth kernel under ellipsoidal collapse (see Sheth & Tormen 02, Zhang+08) incorporates the full cosmology, and the detailed cold DM power spectrum.

- The resulting evolutionary tracks render the peaked behavior of $v_c^2(t)$ in remarkable agreement with both simulations (e.g., Zhao+03, Diemand+07) and semyanalitic computations based on the simpler EPS theory (e.g., Neistein+06, Li+07).

- The transition redshifts are found to be lower for larger current body masses, as expected in a hierarchical cosmogony; note that all that holds on the average, but considerable variance arises from the stochastic nature of the single growth histories.

Two-Stage Development of DM Halos



Equilibrium Structure of DM Halos

- α-profiles from Jeans Equation

  - The static equilibria of the DM halos obey the classic Jeans equation:

$$\frac{1}{\rho}\frac{\mathrm{d}(\rho\,\sigma_r^2)}{\mathrm{d}r} = -\frac{GM(<r)}{r^2} - \frac{2\beta\,\sigma_r^2}{r}$$

the density profiles $\rho(r)$ can be derived from the values of α on expressing the pressure term as $\rho\,\sigma_r^2 \propto K\,\rho^{5/3} \propto r^{\alpha}\,\rho^{5/3}$, while anisotropy is described in terms of the standard Binney parameter $\beta \equiv 1 - \sigma_\theta^2/\sigma_r^2$ (see Binney 78).

  - In terms of the density slope $\gamma \equiv -\mathrm{d}\log\rho/\mathrm{d}\log r$ Jeans may be recast into the form

$$\gamma = \frac{3}{5}\,(\alpha + \frac{v_c^2}{\sigma_r^2}) + \frac{6}{5}\,\beta\,;$$

when supplemented with the mass definition $M(<r) \equiv 4\pi\int_0^r \mathrm{d}r'\; r'^2\,\rho$ entering v_c^2, this constitutes an integro-differential equation for $\rho(r)$.

Equilibrium Structure of DM Halos

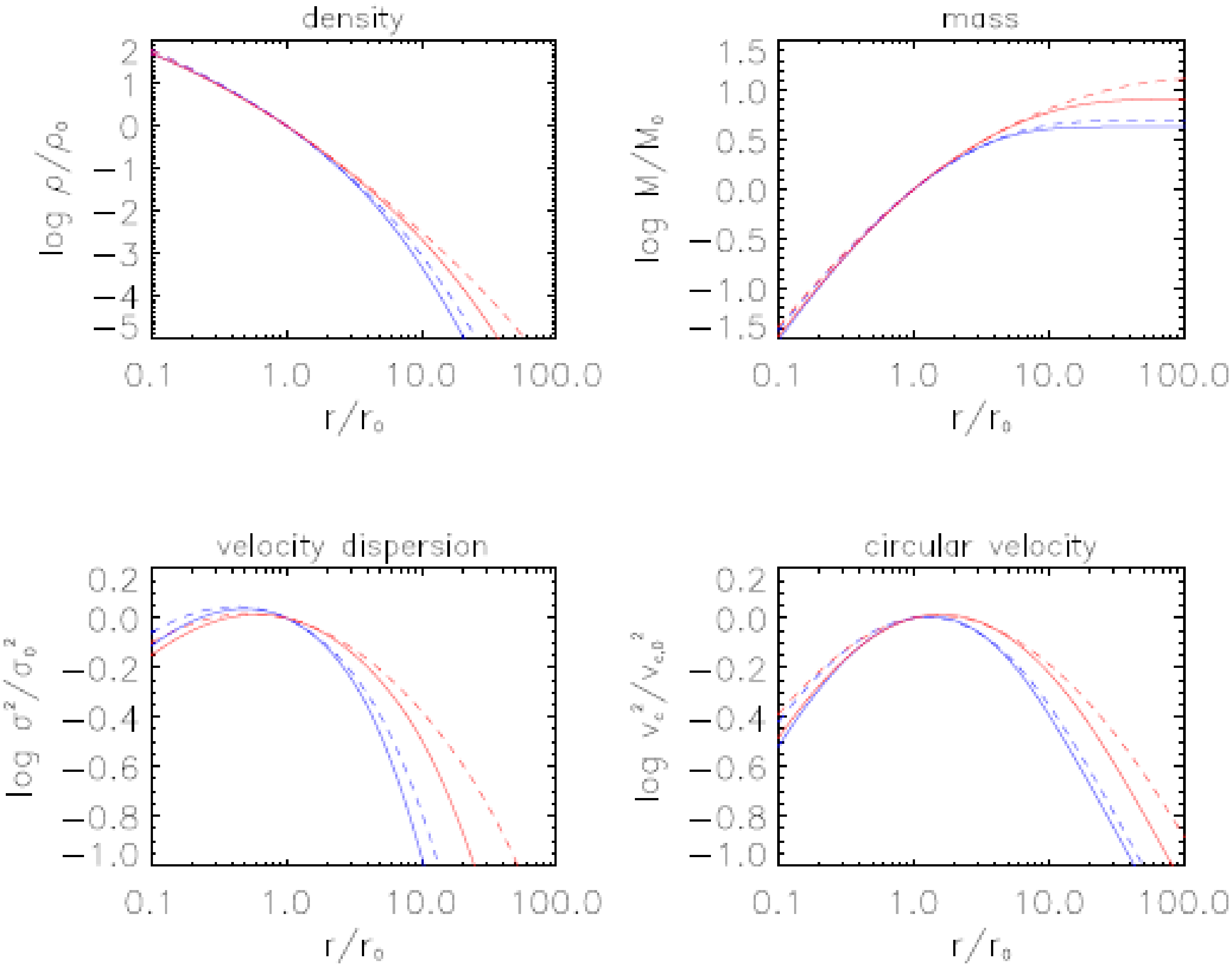
- With $\alpha = \text{const}$ and $\beta = 0$ (meaning isotropy), LC09a studied the solution space of the Jeans Equation, finding that a physical 'α-profile' exists for every $\alpha \lesssim 35/27 = 1.\overline{296}$ this condition guarantees the corresponding density run to be monotonically steepening outwards and with: no central hole, an approximately powerlaw run in the halo body, and an outer cutoff (or a steep powerlaw asymptote) yielding a finite (i.e., definite) total mass. Such a set of solutions include as limiting cases the two prototypes found by TN01 and Dehnen & McLaughin 05.

- Specifically, the central, the body, and the typical outer slopes read in turn:

$$\gamma_a \equiv \frac{3\,\alpha}{5} \qquad \gamma_0 \equiv 6 - 3\,\alpha \qquad \gamma_b \equiv \frac{3\,(1+\alpha)}{2}$$

Compared with the empirical NFW formula, the former is always flatter and the latter steeper even before the final cutoff. The radial range $r > r_{-2}$ where the density profile is steeper than -2 may be specified in terms of the concentration parameter $c \equiv R_v/r_{-2}$ a measure of outskirts' extension, smaller than for NFW.

Equilibrium Structure of DM Halos



Equilibrium Structure of DM Halos

- LC09b extended the α-profiles to anisotropic conditions. It is clear from Jeans that the anisotropy term will steepen the density run for positive β meaning radial dominance, as expected in the outskirts from infalling cold matter. However, tangential components must develop toward the center as supported by N-body simulations (see Austin+05, Hansen & Moore 06). The latter suggest the effective linear approximation

$$\beta(r) \approx \beta(0) + \beta' \left[\gamma(r) - \gamma_a\right]$$

with $\beta(0) \geq -0.1$, $\beta' \approx 0.2$, and the trivial limit $\beta(r) \leq 1$.

- We find that the corresponding $\rho(r)$ is flattened at the center by a weakly negative β , but is considerably steepened into the outskirts where β grows substantially positive. Specifically, the following simple rules apply: the upper bound to α now reads $35/27 - 4\beta(0)/27$ and the inner slope turns into $\gamma_a = 3\alpha/5 + 6\beta(0)/5$

Probing DM Halos with GL

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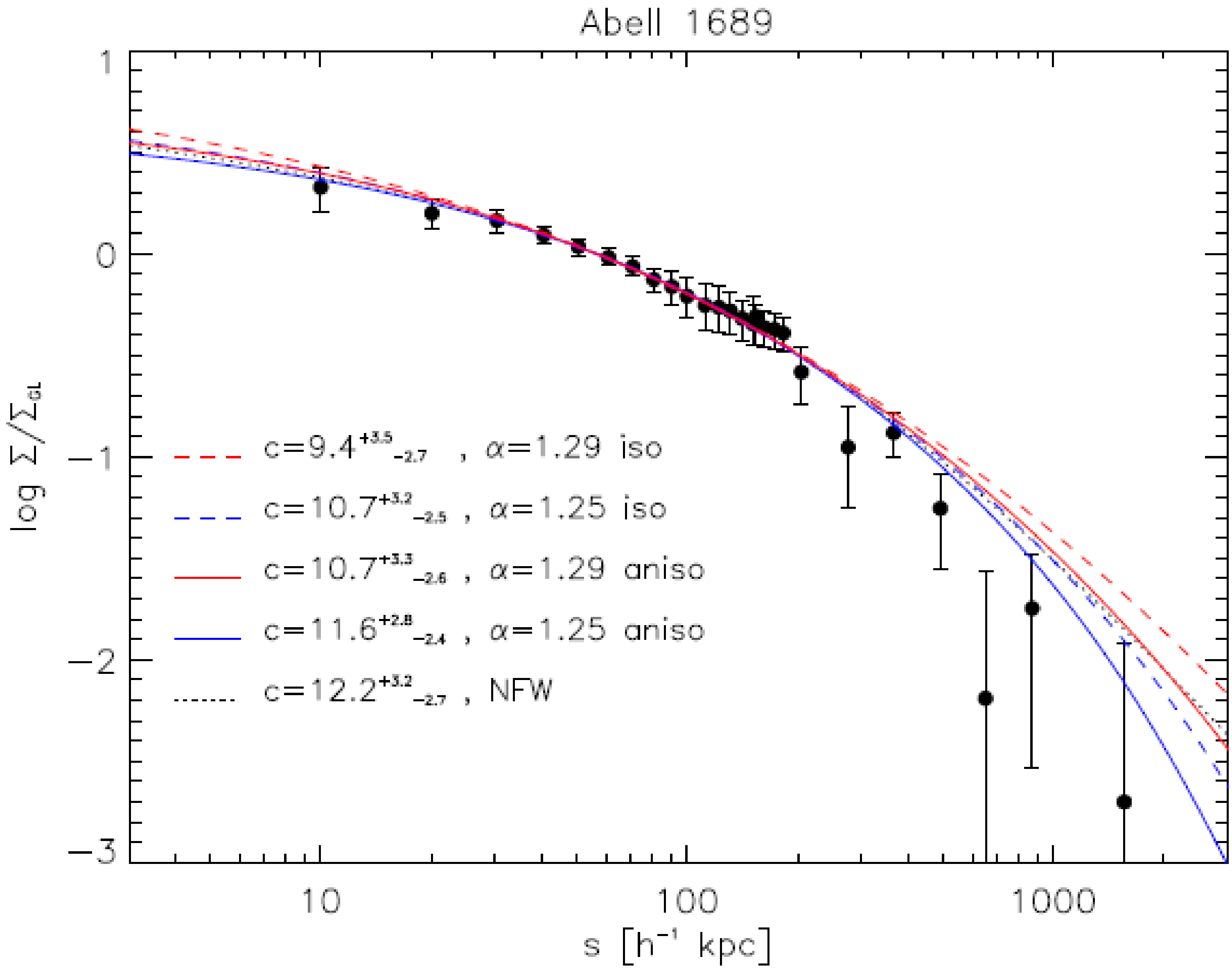
Testing the Halo Structure

- LC09b tested the α-profiles against the recent, extensive gravitational lensing (GL) observations of the cluster A1689 that join strong and weak lensing to cover scales from 0.1 to 2.1 Mpc, the latter being the virial radius of the cluster. The GL data may be recast in terms of projected surface density

$$\Sigma(s) = 2\int_s^{R_v} \mathrm{d}r\, \frac{r\,\rho(r)}{\sqrt{r^2 - s^2}}$$

- The fits of our profiles to the GL data at given α further depend on the concentration c ; it is found that at the minimum χ^2 they require for the α-profiles lower concentrations than NFW, while they perform comparably or better owing to their intrinsically flatter/steeper central/outer structure.

Probing DM Halos with GL



Probing DM Halos with GL

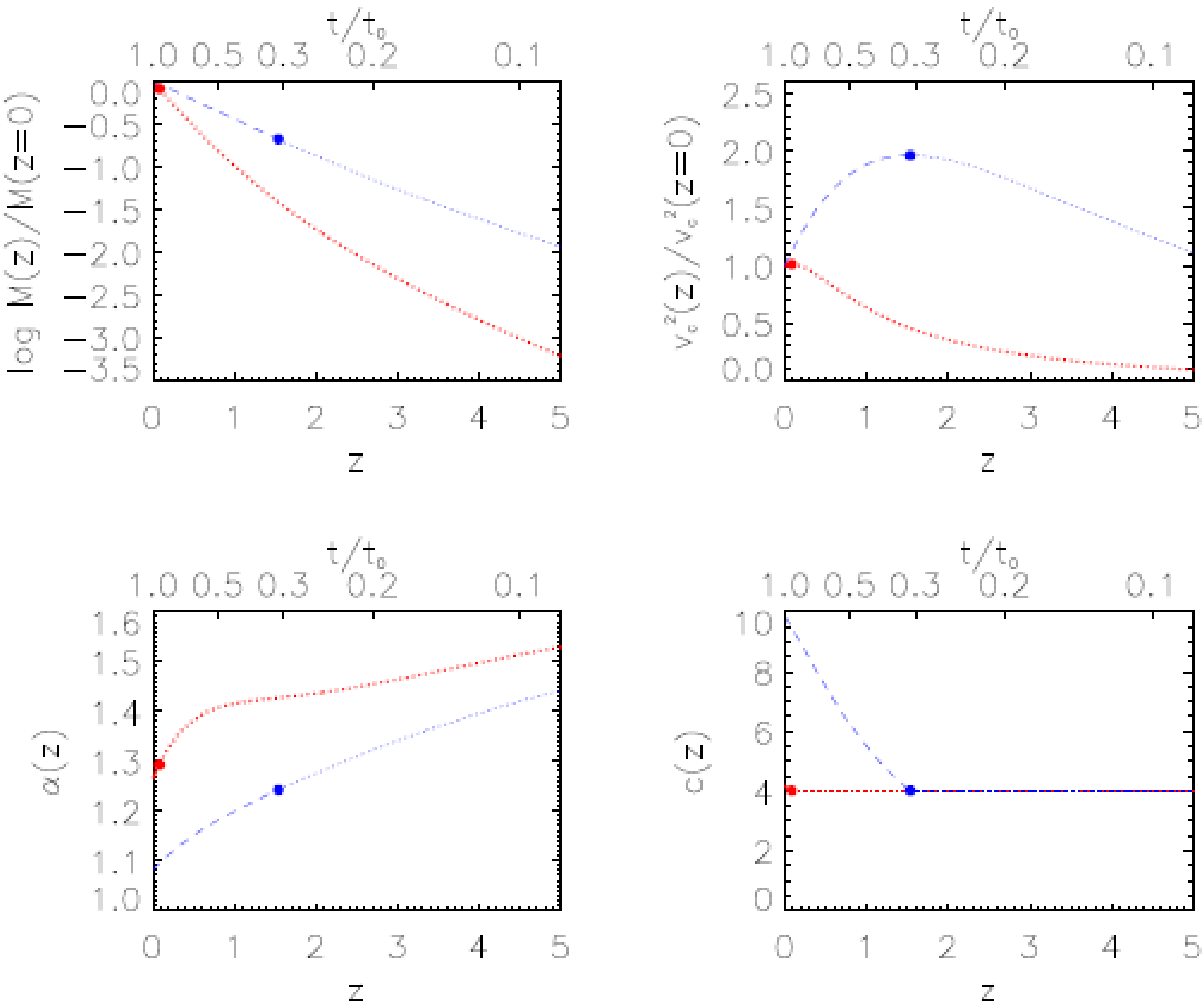
Testing the Halo Development

- Note that balanced fits to the surface density in A1689 require $c \approx 10$ (and even more with NFW); these values are signicantly higher than $c \approx 5$ expected from the average evolutionary history of a massive cluster in the standard ΛCDM cosmogony.

- To explain this, with our semyanalitic approach to halo development we compute variant histories biased toward early times, in particular the one associated with the `main progenitor' that constitutes the main branch in a merging tree.

- Compared with the average, this history features a higher transition redshift $z_t \approx 1.5$ (vs. $z_t \approx 0.2$), a less massive body with $M \approx 2 \times 10^{14}\, M_\odot$ (vs. $M \approx 10^{15}\, M_\odot$), an entropy slope $\alpha \approx 1.25$ (vs. $\alpha \approx 1.3$), and currently extended outskirts (vs. nearly none). The result is a higher concentration $c \simeq 4\,(1+z_t) \approx 10$ (vs. $c \approx 5$). The occurrence of such biased halos relative to the average is found to be 1 : 8.

Probing DM Halos with GL



Discussion

- The halos produced by strongly biased histories also provide sharp GL data; in fact, observations of strong GL tend to focus on cases with centrally concentrated profiles that produce conspicuously large Einstein rings (see Broadhurst & Barkana 08), while observations of weak GL require extended outskirts for affecting numerous background galaxies.

- The latter data are not very constraining yet in view of their considerable uncertainties and possible systematics, but they are progressing by improved control over the redshift distribution of the background galaxies, and over the detailed 3-D structure of the cluster (see Limousin+07; Medezinski+07; Umetsu & Broadhurst 08). Whence we expect progressively sharper evidence for the physical profiles.

Discussion

- The present interpretation of meaning and occurrence of high concentrations invites sampling more clusters with X-ray data through the Bremss emission from the intracluster plasma (ICP). Cavaliere+09 show that in the outskirsts both a steep temperature decline and a flat slope of the ICP adiabat $k(r) \equiv k_B T/n^{2/3}$ highlight a high DM concentration; info inferred from GL and X-ray data for A1689 appears to be consistent.

- DM annichilation signal from Galactic center. We are working on that...

- Finally, we address the case for cold DM. From $\sigma_r^2(r) \propto \rho^{2/3}(r)\, K(r) \propto r^{\alpha-2\gamma(r)/3}$, we expect that cold DM halos will be marked by $\sigma_r^2(r)$ falling down from its radial peak not only (if weakly) toward the center, but also into the outskirts. The latter behavior may be directly tested in clusters with optical observations of galaxy velocities.

Conclusions

- To sum up, the DM halo pattern comprises related time and space behaviors. As to time, in the framework of ΛCDM cosmogony we find a two-stage development comprised of an early violent collapse of the body followed by a slow, inside-out growth of the outskirts.
- As to space, we derive physical α–profiles, which feature density runs $\rho(r)$ with central slopes intrinsically flatter, and outer ones intrinsically steeper (to yield a definite mass) relative to the NFW rendition of ealy N-body data. We find this run to be stable with, or even sharpened by anisotropy.
- Then we test the halo structure and development through GL observations. The physical α–profiles straighforwardly fit the recent GL data, specifically in the well sampled case of A1689. The present, preliminary analysis requires a halo with non-standard concentration c~10, that we find still consistent with a two-stage development moderately biased toward an early transition redshift.

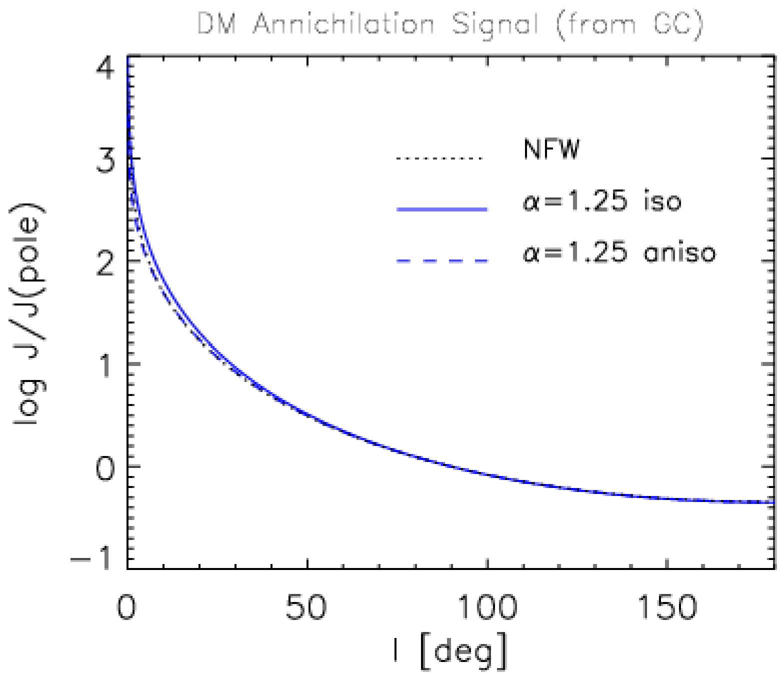
Conclusions

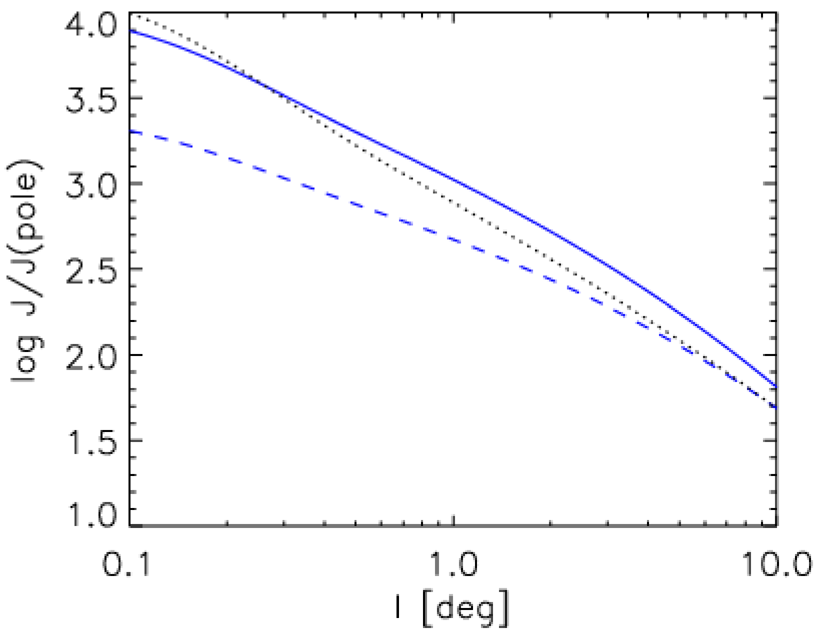
- My DM - related papers:

  - ***Lapi, A.**, & Cavaliere, A. 2009, ApJL, submitted [LC09b]*
  - ***Lapi, A.**, & Cavaliere, A. 2009, ApJ, in press [LC09a]*
  - *Cavaliere, A., **Lapi, A.**, & Fusco-Femiano, R. 2009, submitted*
  - *Salucci, P., Swinbank, A.M., **Lapi, A.**, Yegorova, I., Bower, R.G., Smail, I., & Smith, G.P. 2007, MNRAS, 382, 652*
  - *Salucci, P., **Lapi, A.**, Tonini, C., Gentile, G., Yegorova, I., & Klein, U. 2007, MNRAS, 378, 41*
  - *Tonini, C., **Lapi, A.**, & Salucci, P. 2006, ApJ, 649, 591*
  - *Tonini, C., **Lapi, A.**, Shankar, F., & Salucci, P. 2006, 638, L13*

That's all.
Thank you for the attention!

Bonus Slide...


DM Annichilation Signal (from GC)
NFW
α=1.25 iso
α=1.25 aniso
log J/J(pole)
l [deg]
4
3
2
1
0
−1
0
50
100
150


log J/J(pole)
l [deg]
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.1
1.0
10.0