Exploring Properties of Dark and Visible Mass Distribution on Different Scales in the Universe

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Dark & Visible Matter

We observed that mass profiles of dark and visible matter in gravitationally bound systems of different scales follow linear correlation on log-log scale

$$\log(\rho_v) \propto \kappa \log(\rho_d),$$

coefficient κ in such correlation appears to be the same for a range of widely different scales

URC analysis for spiral galaxies by Persic and Salucci (1996)
Strong gravitational lensing analysis of CL0024 by Tyson *et al (1998)*

Dark & Visible Matter in Spiral Galaxies

- Persic and Salucci (1996) considered a large number of spiral galaxy RCs, normalized to v_{opt} and r_{opt} and sorted by galaxy luminosities.
- Persic and Salucci shown that such normalized RC in each luminosity group $(-23.5 \le M \le -18.5)$ follow universal profiles (Universal RC).
- Persic & Salucci described URC in terms of simple mass model:
  spherical dark halo + thin exponential stellar disk, i.e.

$$\rho_v(r) \propto I_v(r) \propto \exp(-3.2\, r / r_{opt})$$

Spiral Galaxies Rotation Curves

$$v_{URC}^2(x) \approx v_v^2(x) + v_d^2(x)$$

- Persic & Salucci approximated the visible matter contribution with a fit to the exact solution

$$v_v^2(x) \approx 1.97\,\beta \frac{x^{1.22}}{(x^2 + 0.78^2)^{1.43}},\ x \le 2$$

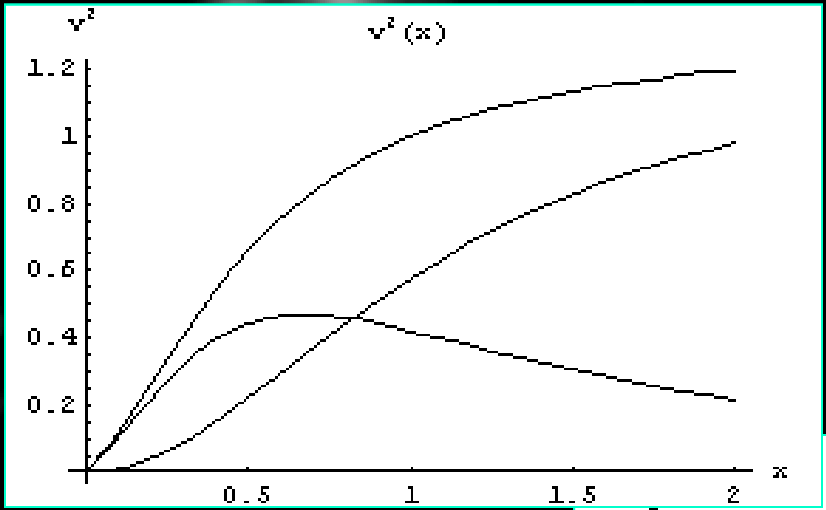
$$v_v^2(x) \approx 0.8615 / x,\ x \ge 2$$

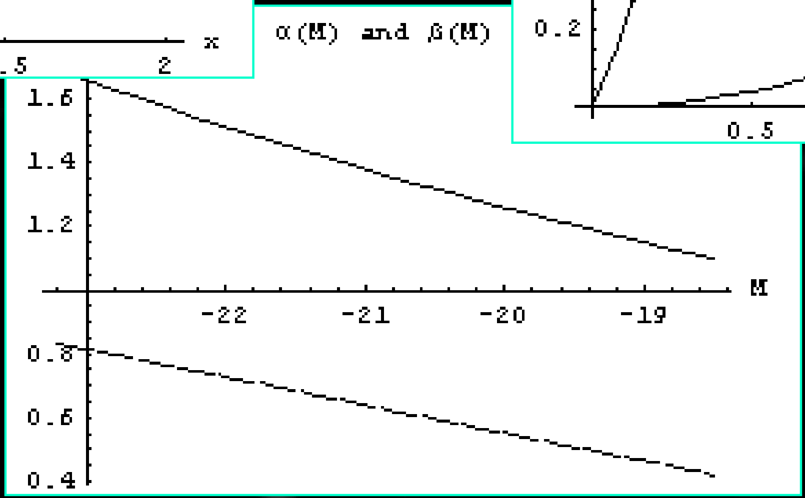
- Spherical dark halo contribution was parameterized by

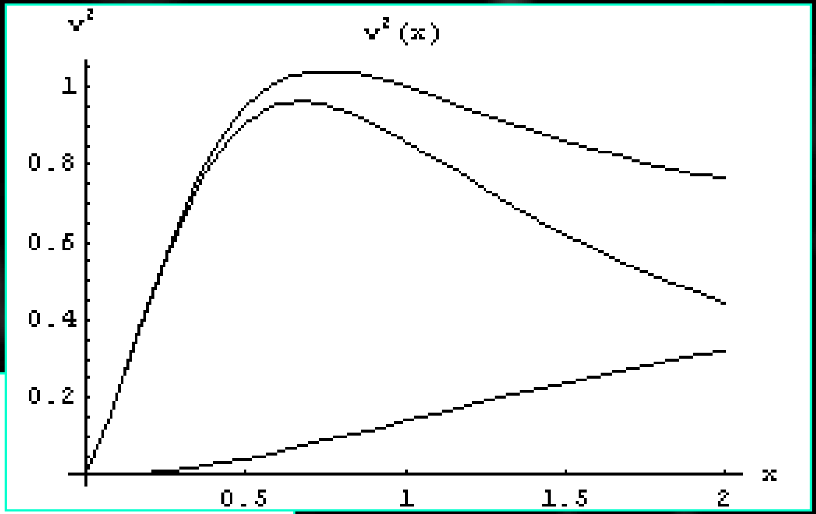
$$v_d^2(x) \approx (1-\beta)(1+\alpha^2)\frac{x^2}{x^2+\alpha^2}$$

Spiral Galaxies Rotation Curves

Examples of *Universal Rotation Curves*







Visible Matter in Spiral Galaxies

For visible matter:

We noticed that visible mass profile in this model is well described with i*sothermal Boltzmann distribution*…

$$\rho_v(r) \approx \exp[-\beta\,\Phi(r)] = \exp[-\frac{\mu_v}{T}\Phi(r)]$$

…temperature T is about 10^5-10^6 K, consistent with actual temperature of interstellar gas in the Galaxy

Visible Matter in Spiral Galaxies

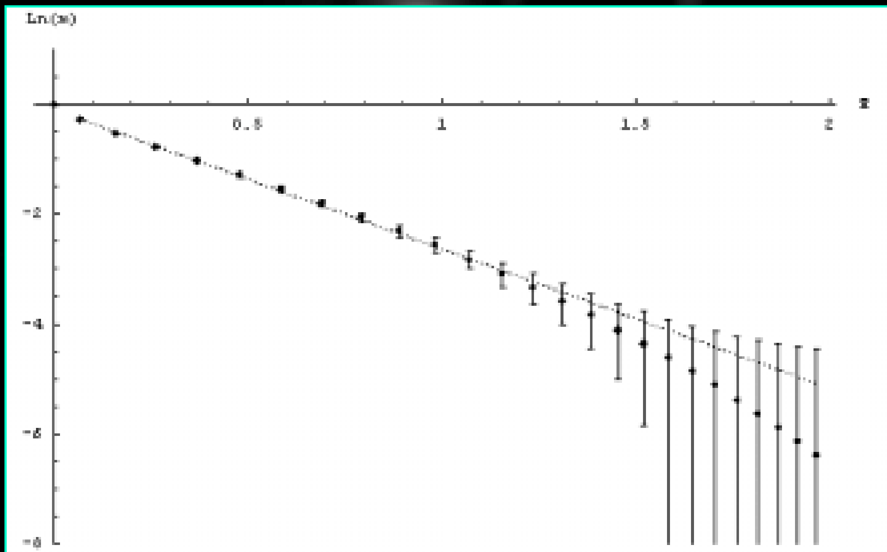
- Note, URCs encode actual gravitational potential throughout the stellar disk via

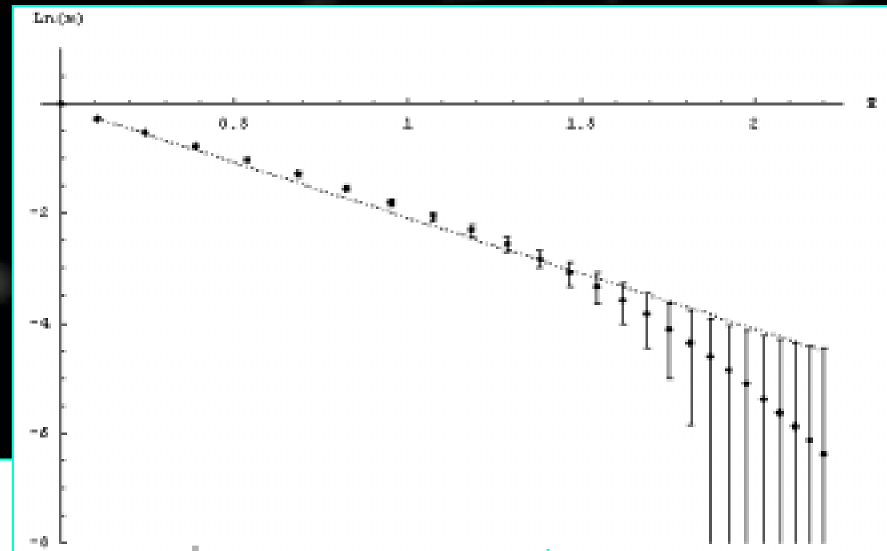
$$\frac{d\Phi(r)}{dr} = \frac{v_{URC}^2(r)}{r}$$

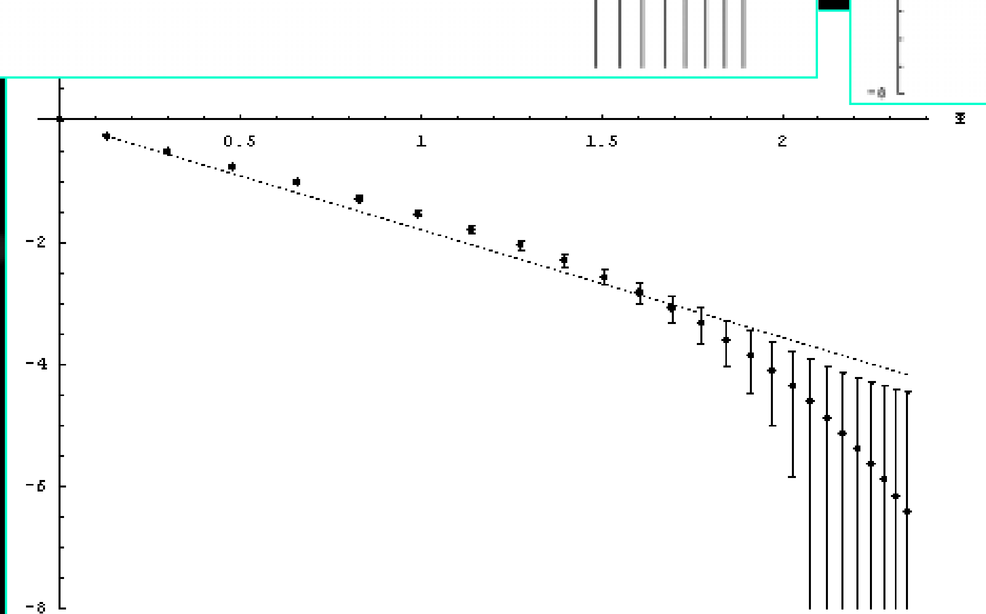
- We will be interested in relation between

$$\log[\rho_v(r)] \text{ vs. } \Phi(r) \approx \int_0^r dr' v_{URC}^2(r')/r'$$

Visible Matter in Spiral Galaxies







M	*β*
-18.5	2.52-2.55
-21.5	1.85-2.03
-23.5	1.56-1.76

Dark Matter in Spiral Galaxies

For dark matter:

- It turns out that for larger r $\log(\rho_v)$ and $\log(\rho_d)$ show linear correlation.
- URCs are not particularly sensitive to behavior of dark halo at small distances.
- URC can be fit perfectly well with exponential profile for the spherical dark halo

$$\rho_d(r) \approx \exp(-a\,r / r_{opt})$$

remember

$$\rho_v(r) \approx \exp(-3.2\,r / r_{opt})$$

Dark vs. Visible Matter in Spiral Galaxies

Best fits for different galaxies' absolute magnitudes M

$$\kappa \log \rho_d(r) \approx \log \rho_v(r)$$

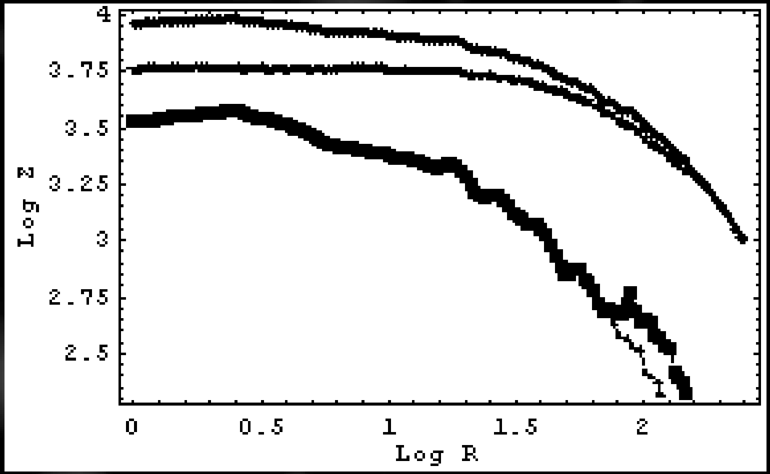
$$\kappa \approx 3.2/a \approx 2.5 - 4.1$$

M	β	*visible*	*dark: a*	κ
-18.5	2.52-2.55	3.2	1.28	2.50
-21.5	1.85-2.03	3.2	0.97	3.31
-23.5	1.56-1.76	3.2	0.78	4.11

Dark vs. Visible Matter in galaxy clusters

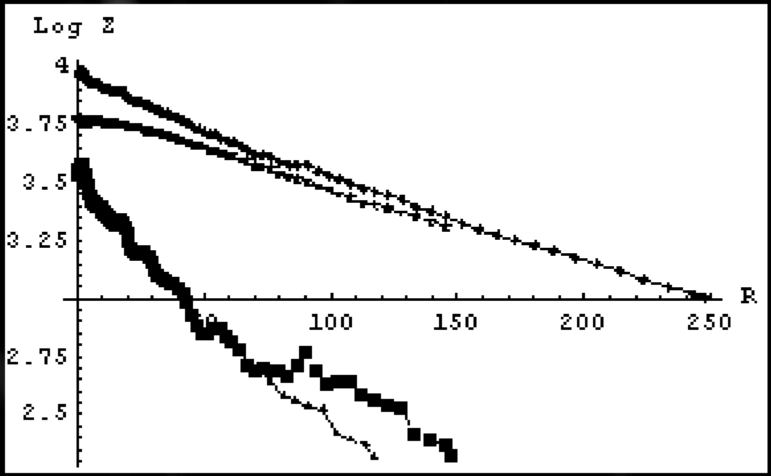
- Tyson *et al* published analysis of Hubble telescope images of strong gravitational lensing in galaxy cluster CL0024 (1998).
- Detailed mass maps and radial-averaged projected mass profiles were presented for total and visible masses.
- The study was concentrated on soft core of dark mass distribution in the cluster.

Dark vs. Visible Matter in galaxy clusters



radial profiles were originally presented on log-log scale for *total* and *visible* mass

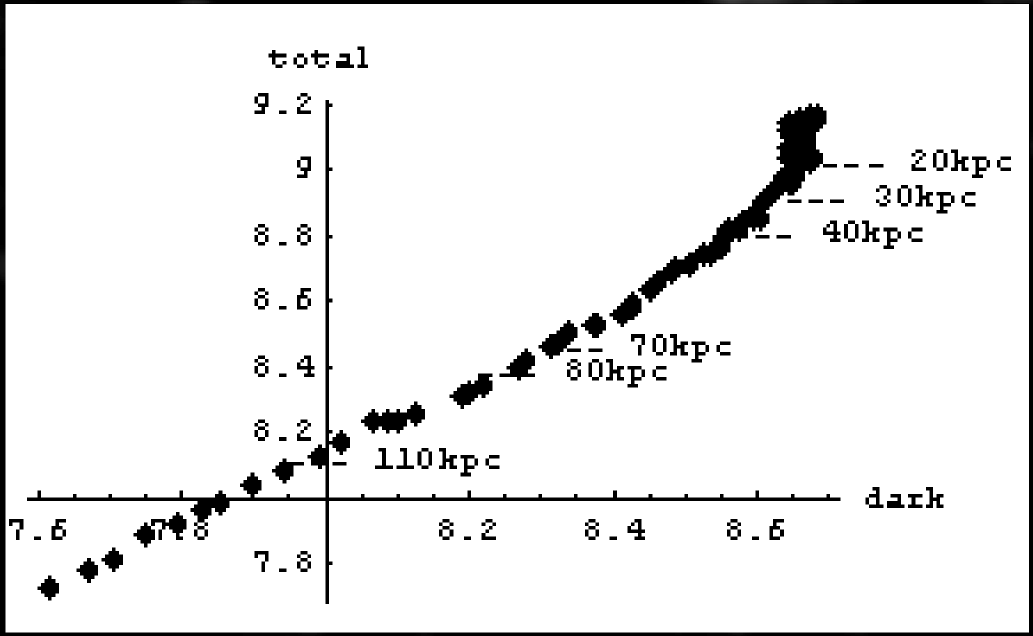
if profiles were re-plotted on log-lin scale, one would observe exponential fall-off



visible mass profile has anomalous flat region at about 100kpc

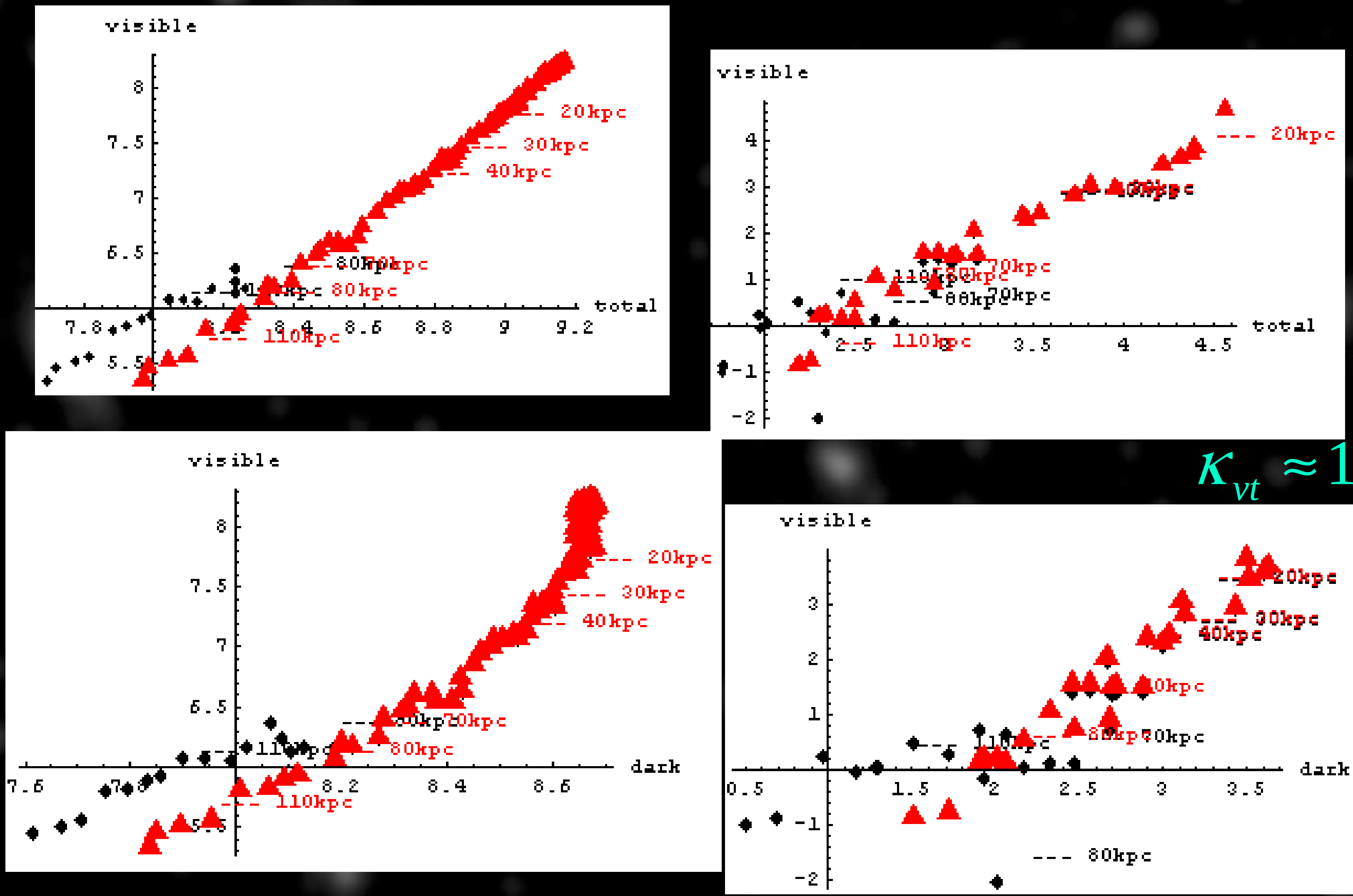
Dark vs. Visible Matter in galaxy clusters

These mass profiles, if plotted one vs. another on log-log scale, show prominent linear correlation



$$\kappa_{td} \approx 1.15 - 1.90$$

Dark vs. Visible Matter in galaxy clusters



$$\kappa_{vt} \approx 1.40 - 2.25$$

$$\kappa_{vd} \approx 2.10 - 4.40$$

Dark vs. Visible Matter in galaxy clusters

correlation coefficient for visible and dark matter is in the range

$$\kappa \approx 2.1 - 4.4$$

…remember κ obtained for spiral galaxies

$$\kappa \approx 2.5 - 4.2$$

Dark vs. Visible Matter

Note that log-log-linear correlation is expected in case of thermal or dynamical equilibrium:

- Isothermal Boltzmann distribution

$$\log(\rho_{v,d}(r)) \approx -\mu_{v,d} / T_{v,d} \cdot \Phi(r)$$

- Dynamical Equilibrium distribution

$$\log(\rho_{v,d}(r)) \approx -\log(T_{v,d}(r)) - \mu_{v,d} \int \frac{d\Phi(r)}{T_{v,d}(r)}$$

coefficient κ *associated with* $\kappa_{vd} \approx \mu_v / \mu_d \cdot T_d / T_v$

Dark vs. Visible Matter

What one would expect:

- In galaxy clusters κ should be slightly larger than 1:
  - gravitational heating results in similar mass profiles: $\kappa \approx 1$;
  - further radiative cooling of visible component gives: $\kappa \geq 1$;
  - typical cooling time is much larger than the age of the universe ($t_{cool} >> t_{cluster}$).
- In spiral galaxies κ should be much larger than 1 $\kappa >> 1$:
  - significant cooling of visible component thought necessary for formation of the stellar disk.
- κ is not expected to stay the same for different systems:
  - κ is determined by final cooling/heating interplay in particular system.

Dark vs. Visible Matter

- ***Our current views about dark matter and structures evolution/formation does not explain observed correlation.***
- Explanations:
  - Coincidence (?)
  - Underlying feature of structure formation (?)
  - General property of gravitational dynamics (?)
  - Dark-visible matter thermal equilibrium at certain scale (?)
- May indicate substantial nongravitational interaction between dark and visible matter
- May indicate mass of dark matter particles about 2-4 times smaller than that of visible matter

$$\mu_d \approx \frac{1}{\kappa_{vd}} \mu_v \approx 200 - 1000 MeV$$

Dark vs. Visible Matter

Uncertainties shall be mentioned:

- Measurements of RC of spiral galaxies are numerous, but their separation is ambiguous; Moreover, formation and dynamics of spiral galaxies is not well understood
- Gravitational lensing in galaxy clusters are cleaner measurements, but studies comparing total and visible masses are rare;
  Moreover, resolution and error in mass profiles is still very bad

Dark vs. Visible Matter

Further research directions:

- Experimental
  - Larger survey of gravitational lensing in galaxy clusters with emphasis on dark vs. visible matter distribution is highly desirable
- Theoretical
  - Study of the role of gravity in and as the source for thermalization is interesting
  - Better understanding of galaxy cluster and spiral galaxy dynamics and evolution is important