MOND phenomenology and galaxy clusters

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The basic premises of the MOND paradigm

- The appearance of a new acceleration constant in dynamics, a_0
- Standard limit ($a_0 \rightarrow 0$): The Newtonian limit
- MOND limit ($a_0 \rightarrow \infty$) : $(a_0,\ G,\ m_i) \rightarrow (Ga_0^2,\ m_i a_0^{-1}\ )$

  $(a_0,\ G) \rightarrow a_0 G$ For pure gravity

Some immediate consequences

$$a \sim \frac{MG}{R^2}\, \nu\left(\frac{MG}{R^2 a_0}\right)$$

$$\nu(x) \approx \begin{cases} 1 & : \quad x \gg 1 \\ x^{-1/2} & : \quad x \ll 1 \end{cases}$$

- $a/a_N \approx (a_N/a_0)^{-1/2} \gg 1$
- $a \approx (MGa_0)^{1/2}/R$
- $V(M,R) \approx (MGa_0)^{1/4}$

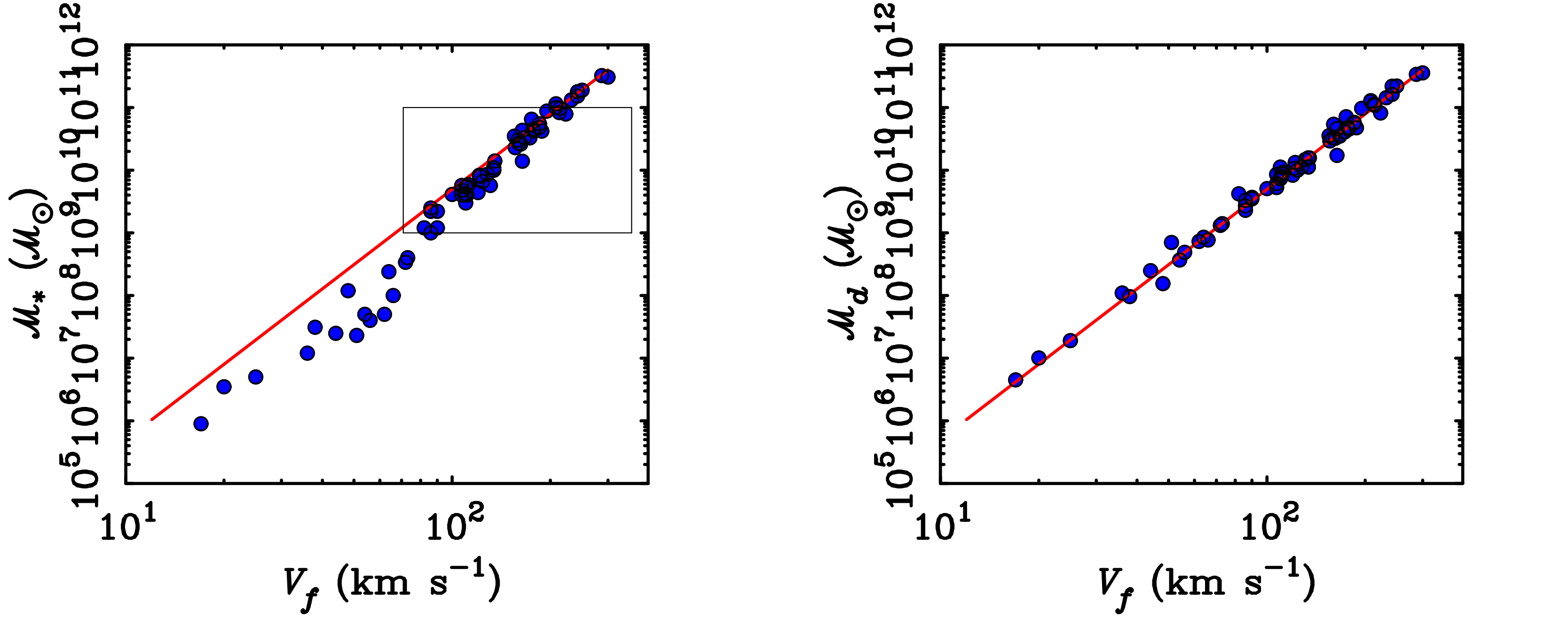
Various theories on these, but generically they give the basic results

$$g = g_N\ \nu(g_N/a_0)$$

Independent galactic Kepler-like laws of galactic dynamics

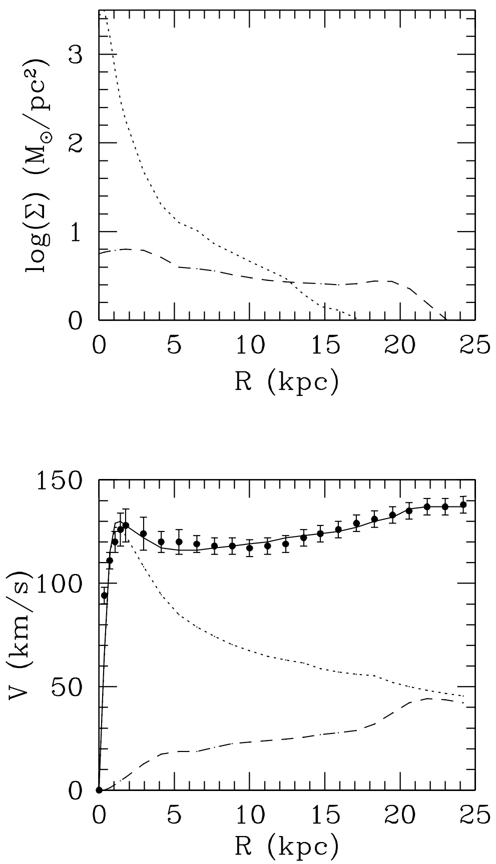
- Asymptotic constancy of orbital velocity: $V(r) \rightarrow V_\infty$
- The mass-velocity relation (baryonic TF relation): $V_\infty^4 = MGa_0$
- $\sigma^4 \sim MGa_0$ relation ("isothermal" spheres, deep MOND virial relation)
- Discrepancy appears always at $V^2/R = a_0$
- Isothermal spheres have surface densities $\bar{\Sigma} \leq a_0/G$
- Added stability of discs with $\bar{\Sigma} \leq a_0/G$
- Disc galaxies have a disc AND a spherical "DM" components
- Negative density of "dark matter" in some locations.

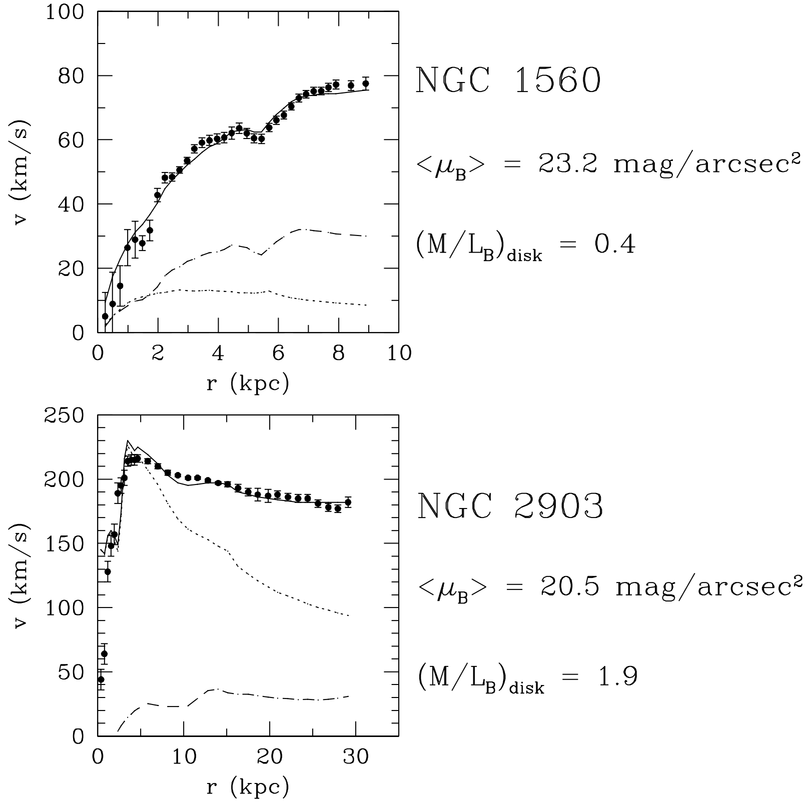
The mass-velocity (baryonic Tully-Fisher) relation



from McGaugh 2006

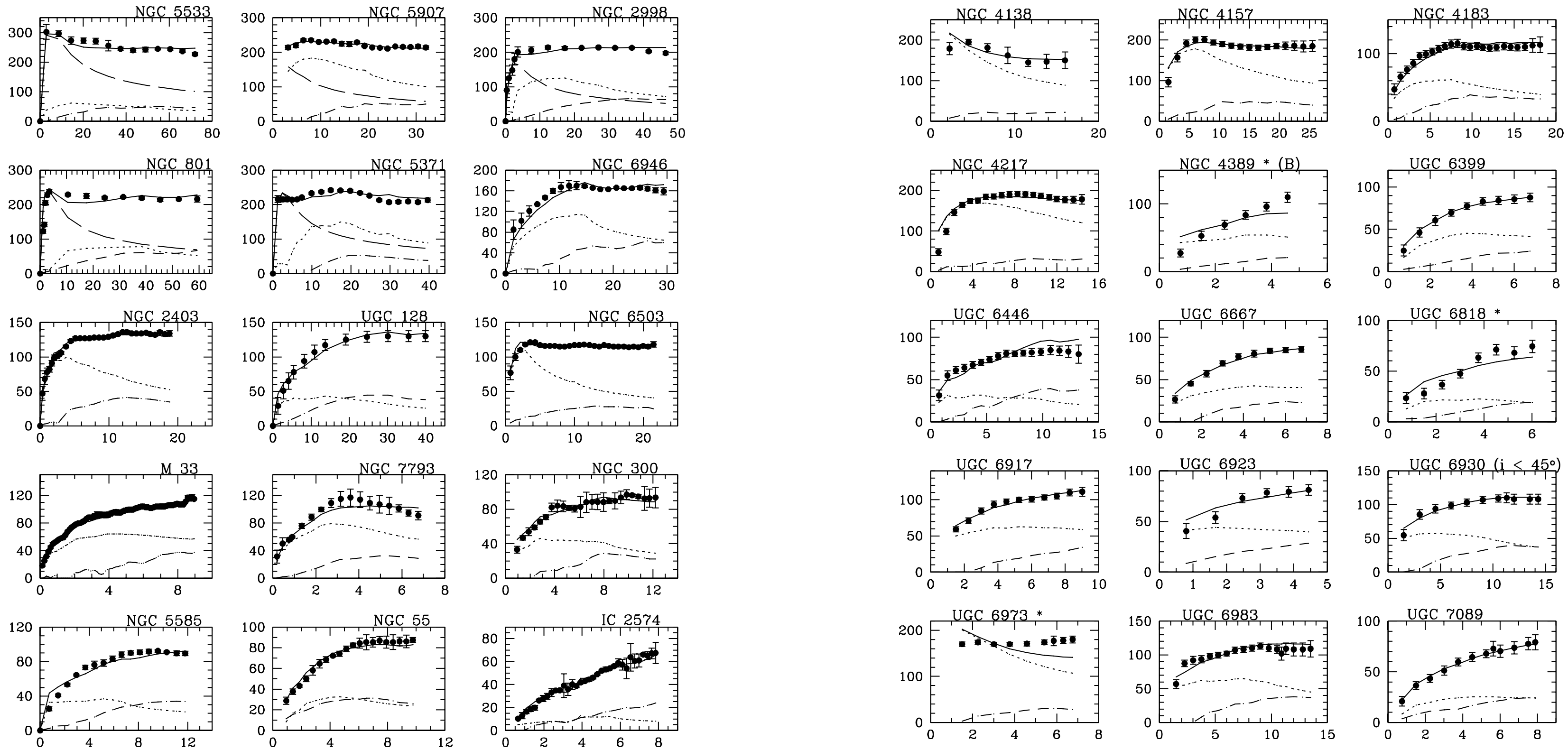
Rotation Curves of Disc Galaxies





Sanders (2005)

Sanders and McGaugh (2002)



Sanders and McGaugh 2002

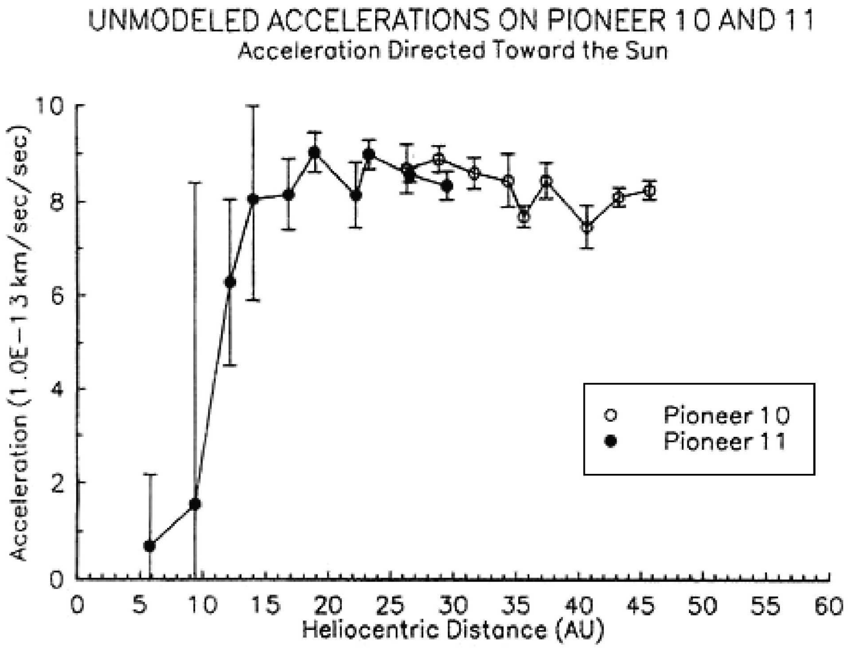
$a_0 =?$

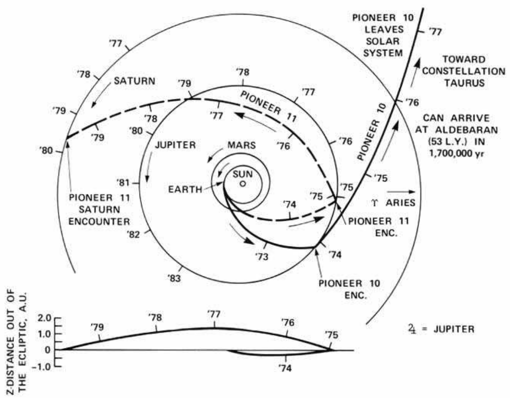
a_0 can be derived in several independent ways:

$$a_0 \approx 1.2 \times 10^{-8} \text{ cm s}^{-2}$$

- $a_0 \approx c\bar{H}_0$
- $a_0 \sim c(\Lambda/3)^{1/2}$

Solar System: the Pioneer Anomaly





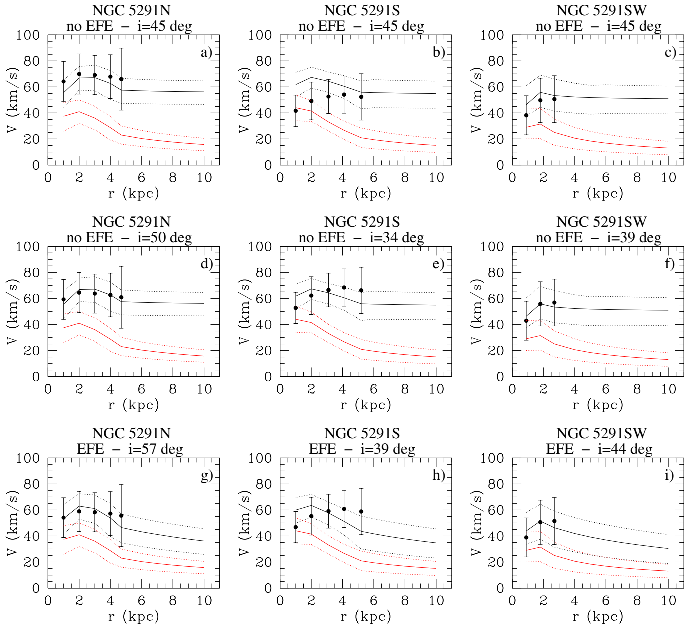
from Anderson et al. 2002

What is behind the phenomenological success of MOND?

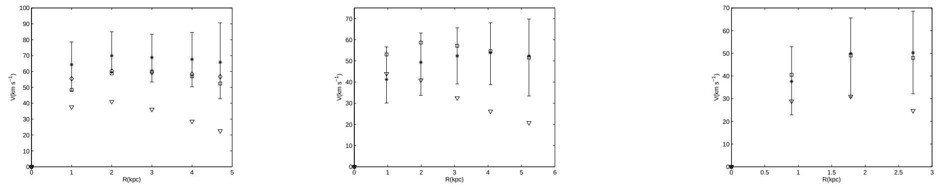
- DM?
  - ▷ DM distribution is determined exactly from that of the baryons.
  - ▷ But DM to baryon ratio varies greatly and also differs from cosmological value.
  - ▷ It is inconceivable that DM will ever explain MOND: for individual galaxies the outcome depends on the unknown history of formation, interactions/mergers, ejection of most baryons, etc..

- New physics?
  - ▷ Cosmological connection?
  - ▷ Nonrelativistic theory?
  - ▷ Relativistic theory: cosmology (only MOND "black hole"); lensing

Example: debris galaxies



Gentile et al. (2007)

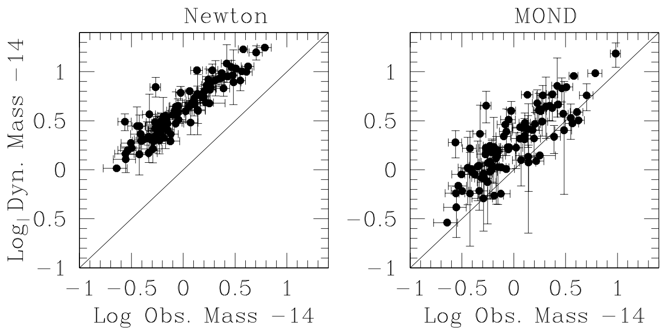


Milgrom (2007)

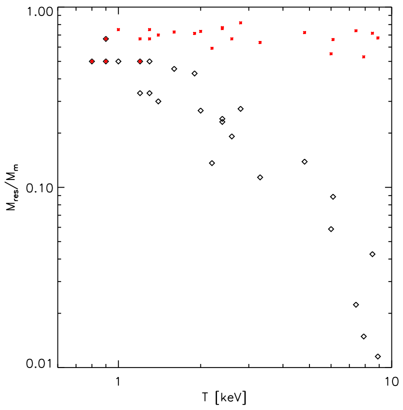
MOND and galaxy clusters

- Early 1990s: MOND does not explain the discrepancy in cluster cores
- Measured acceleration within a few 100 kpc are $> a_0$
- Modify MOND to account for this?

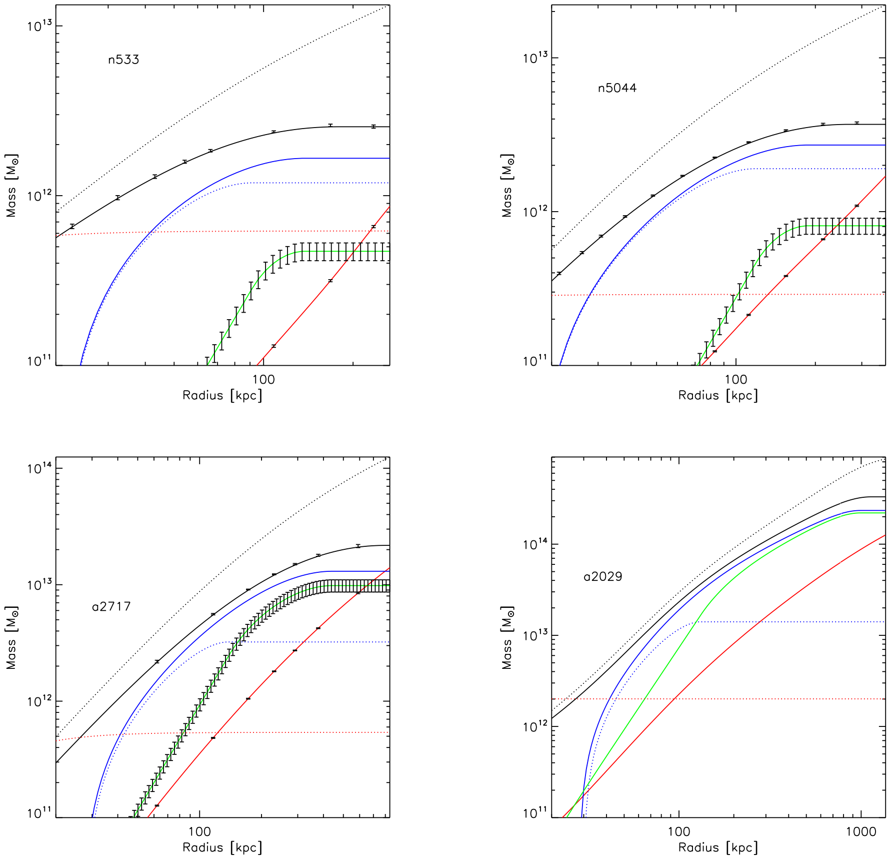
BDM in clusters according to MOND



Sanders 1999



Angus et al. 2007

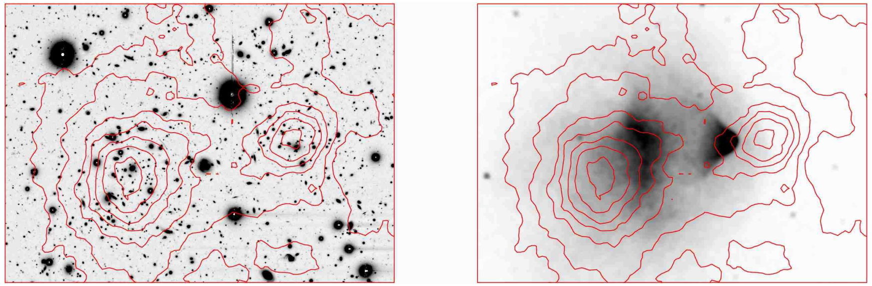


Angus et al. 2007

Candidates: neutrinos; BDM (MACHOS, massive BHs, cold-gas clouds)

Total amount needed-contributes little to the total NS baryon density

The bullet cluster



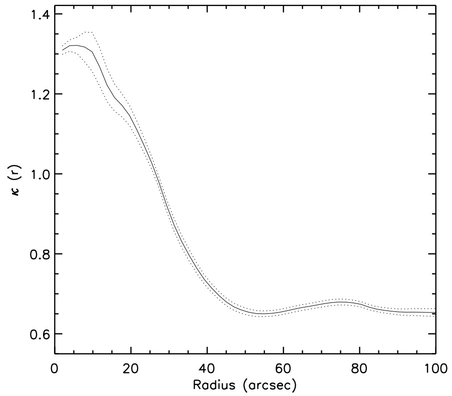
Clowe et al. 2006

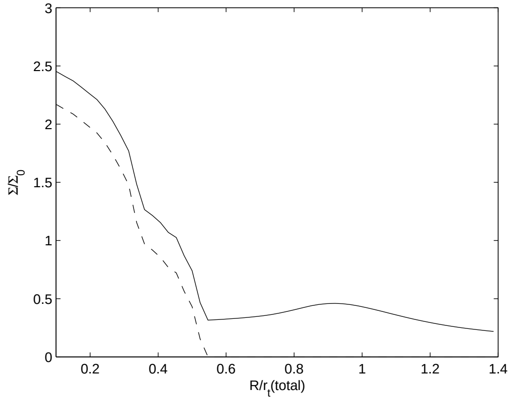
Results expected from what we know on isolated clusters (Angus et al. 2006)

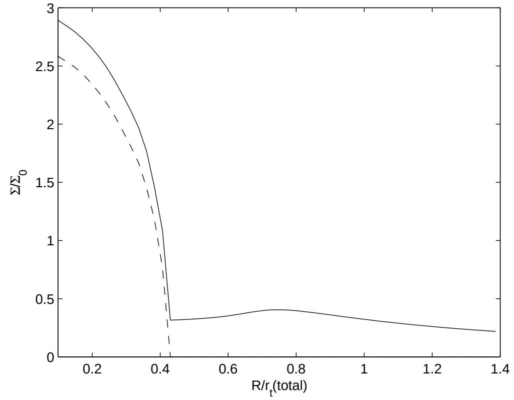
BDM is largely non-dissipational

The high-relative-velocity problem

The "ring" cluster (Cl 0024+17)



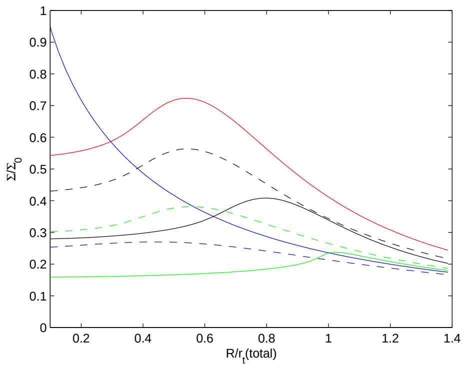




Jee et al. (2007)

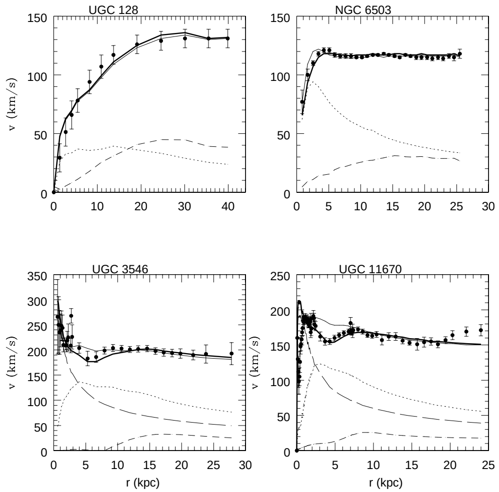
Milgrom & Sanders (2007)

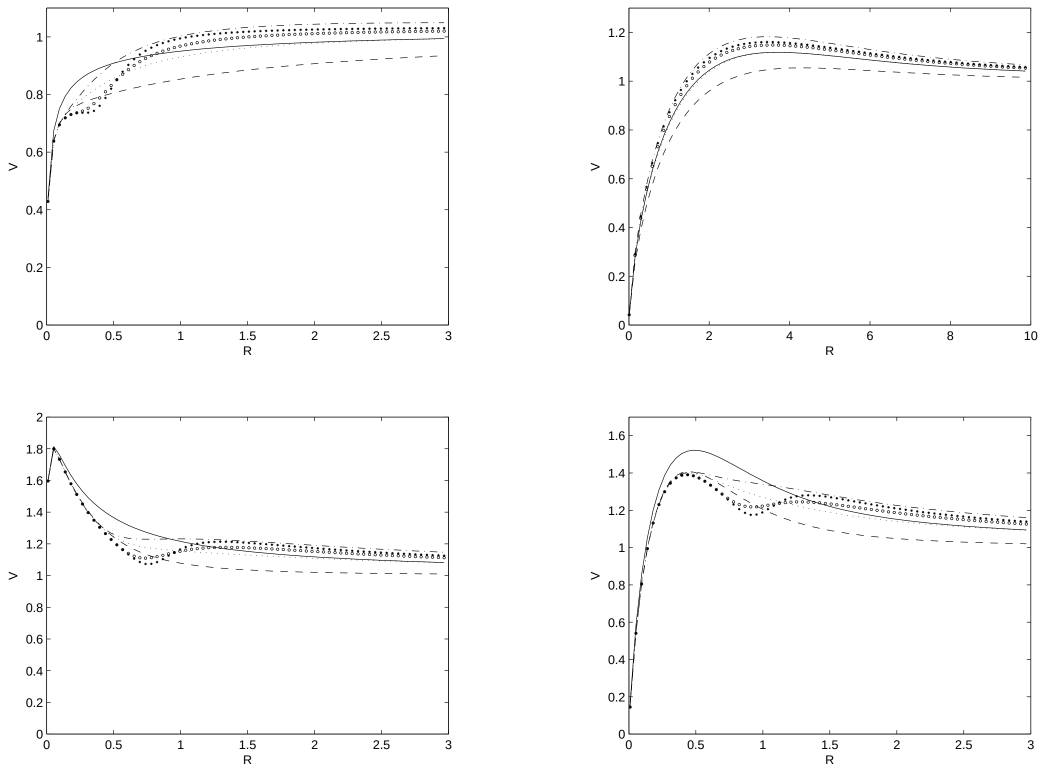
How does it work?



- MOND defines the transition radius $r_t \equiv (MG/a_0)^{1/2}$.
- Analog to $r_G = MG/c^2$
- Spherical mass: for $R_{mass} < r_t$ a peak appears, generically
- Other configurations
- MOND also defines a universal surface density $\Sigma_0 \equiv a_0/G$

The analog feature in galaxies?

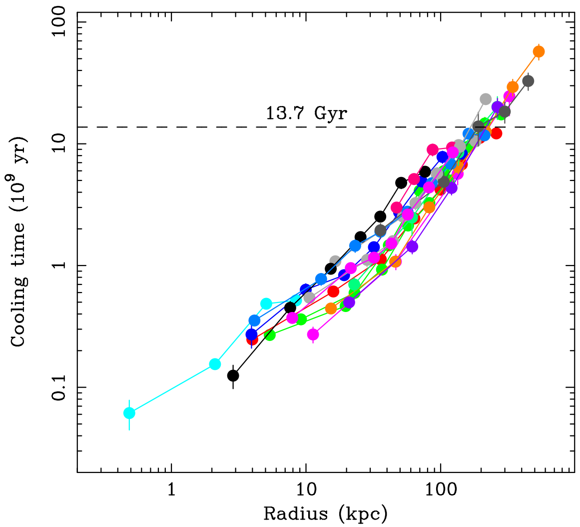


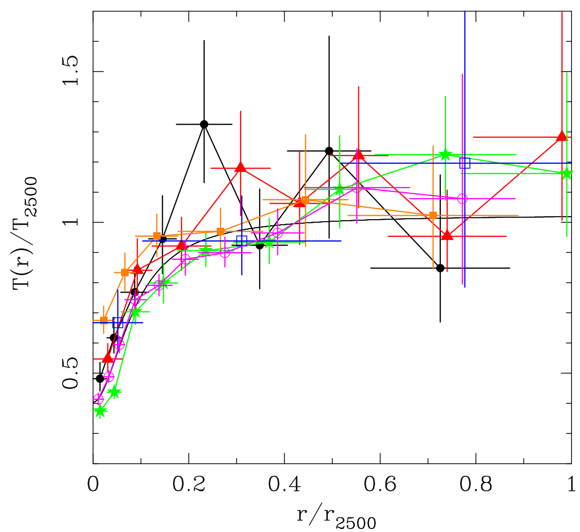


V
R
0 0.2 0.4 0.6 0.8 1
0 0.5 1 1.5 2 2.5 3
V
R
0 0.2 0.4 0.6 0.8 1 1.2
0 2 4 6 8 10
V
R
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2
0 0.5 1 1.5 2 2.5 3
V
R
0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6
0 0.5 1 1.5 2 2.5 3

The cooling-flow conundrum

The puzzle: no signs of cooling (lines, mass deposits)





Peterson and fabian 2006

Heating is required

Desiderata:

- Smoothly distributed across the core and doesn't vary much with time.
- Heating rate depends on position through the square of some density, hinging always on two body interactions.
- Naturally gives a core temperature that is a fraction of the virial temperature of the cluster.

Present preferred candidate is AGN heating

DM is not deemed relevant as it is supposed to be made of weakly interacting particles

MOND and the CF problem

Doesn't enter the gasdynamics but forces a new outlook on the role of baryons:

- As opposed to WI CDM, it implies baryons as DM, which might be effective
- Requires much less DM hence releasing constrains on BDM from clusters.
- This BDM is not required in galaxies hence is not subject to many constraints we have on BDM

Possible candidates and mechanisms:

- Supermassive BHs dynamical friction
- Cold dense gas clouds

Properties of such heating comply with the desiderata listed above

- An amply sufficient energy reservoir.
- Smoothly distributed across the core and doesn't vary much with time
- Heating goes like the square of some density
- Core temperature that is a fraction of the virial temperature
- Cool clouds could be the source of the hot gas itself.

Heating by gas clouds

Considered extensively during the nineties (but with more stringent constraints from galaxies and cluster, which are now relaxed). Fell into disfavor as THE DM

Σ of clouds is constrained:

$$\dot{E}_B/\dot{E}_c \sim \eta(M_{hidden}/M_{gas})(T_{hidden}/T_{gas})(\tau_{cool}/\tau_{cross})(\Sigma_{total}/\Sigma_{cloud})$$

$$\Sigma \sim 10^4 \eta \Sigma_B \sim \cdot 10^3 \eta M_{B,13} R_2^{-2} gr\ cm^{-2}$$

Support of cloudlets? Magnetic? hydrostatic:

$$r \sim 10^{13} T_{10} \eta^{-1} M_{B,13}^{-1} R_2^2\ cm; \qquad M = 10^{-4} T_{10}^2 \eta^{-1} M_{B,13}^{-1} R_2^2 M_\odot$$

Observed effects

- Lensing
- Discrete flashes