

Marriage à-la-MOND:

Baryonic dark matter in galaxy clusters and the cooling flow puzzle

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The basic premises of the MOND paradigm

Modified dynamics at low accelerations as an alternative to dark matter

- The appearance of a new acceleration constant in dynamics, a_0
- Standard limit : $a_0 \rightarrow 0$
- MOND limit, $a_0 \rightarrow \infty$: $a_0, G \rightarrow a_0 G$ for pure gravity
[More generally: $(a_0, G, m_i) \rightarrow (Ga_0^2, m_i a_0^{-1})$]

Various theories: modify the Poisson equation; modify Newton's second law;
modify GR

Some immediate consequences

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

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

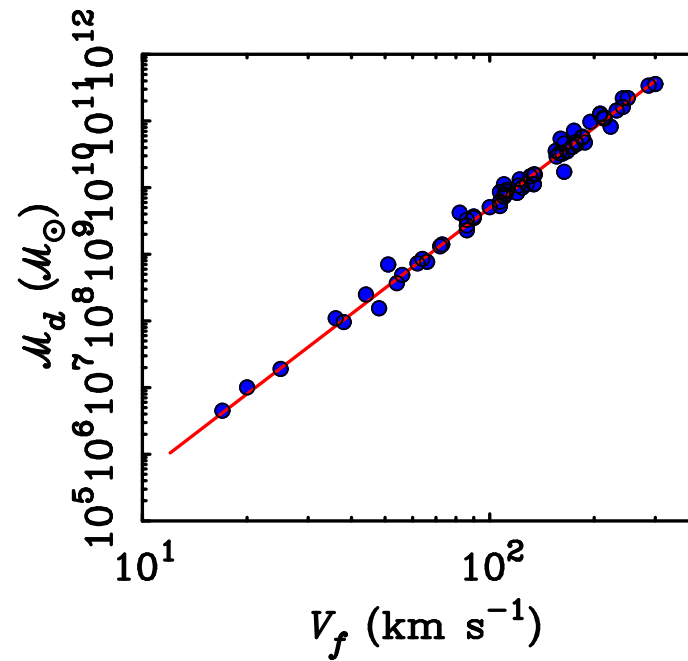
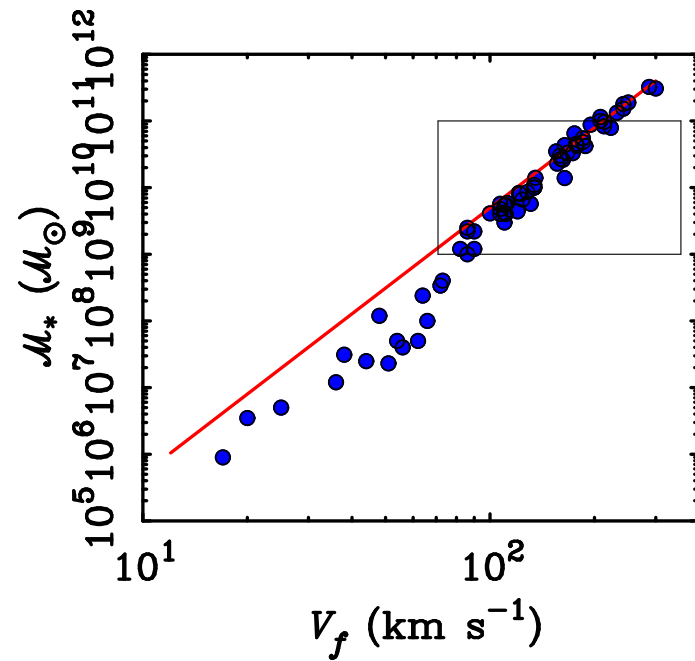
- $a/a_N \approx (a_N/a_0)^{-1/2} \gg 1$
- $a \approx (MGa_0)^{1/2}/R$
- $V(M, R) \approx (MGa_0)^{1/4}$

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

Independent Kepler-like laws of galactic dynamics

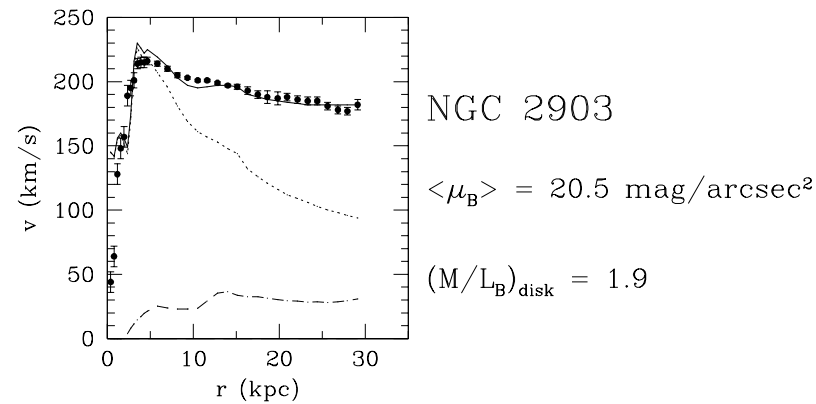
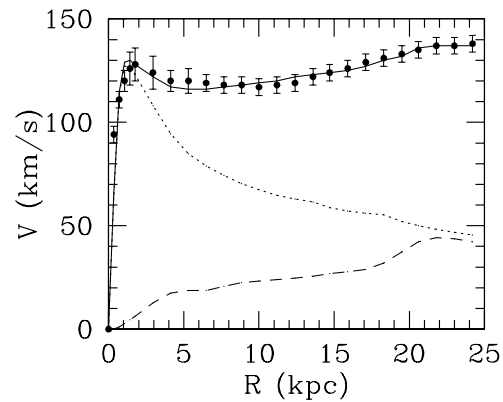
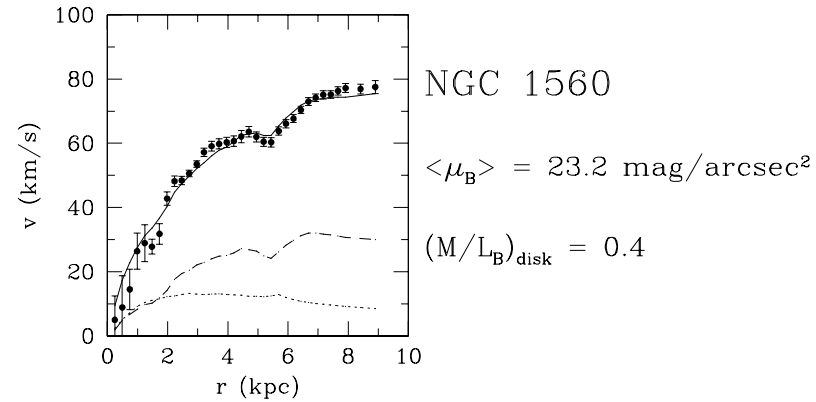
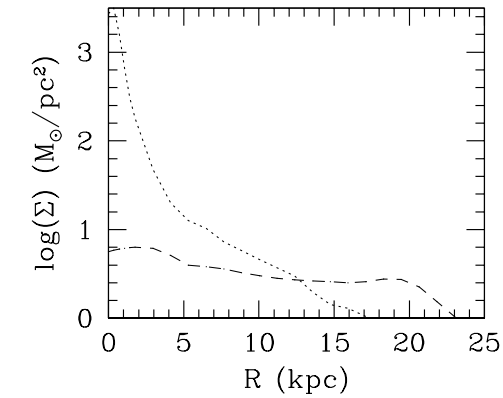
- Asymptotic constancy of orbital velocity: $V(r) \rightarrow V_\infty$
- The mass-velocity relation (baryonic TF relation): $V_\infty^4 = M G a_0$
- $\sigma^4 \sim M G a_0$ relation (“isothermal” spheres, deep MOND virial relation)
- Discrepancy appears always at $V^2/R = a_0$
- Isothermal spheres have 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



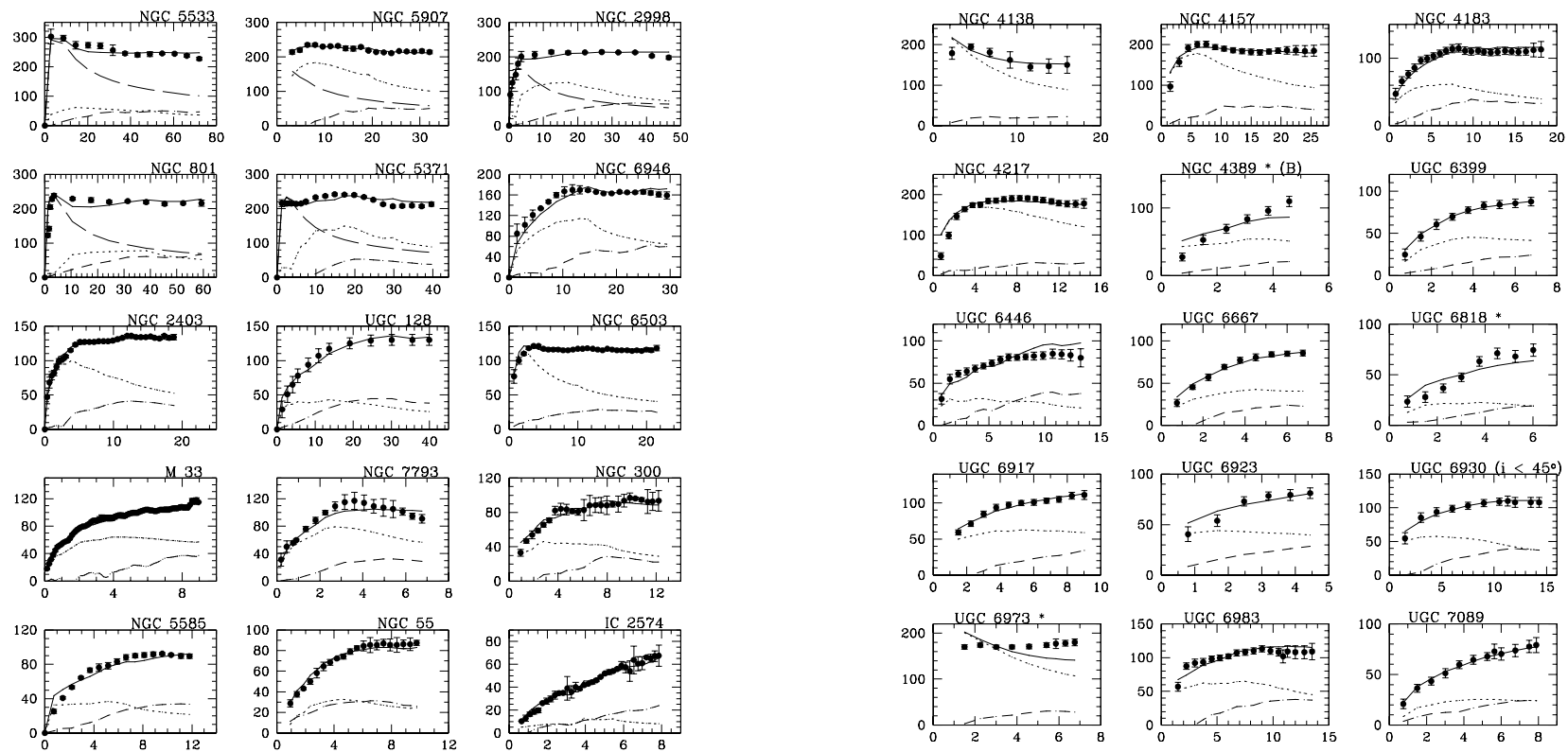
from McGaugh 2006

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:

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

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

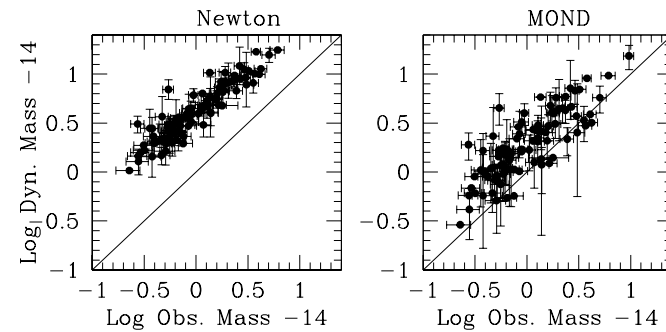
What is behind the phenomenological success of MOND?

- 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

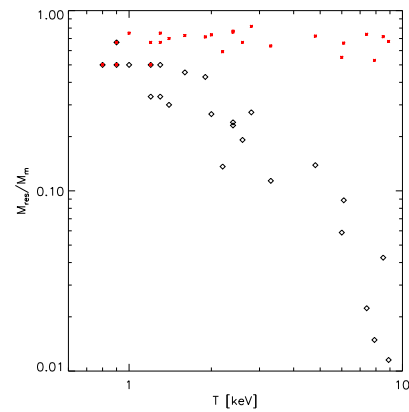
MOND and galaxy clusters

- 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

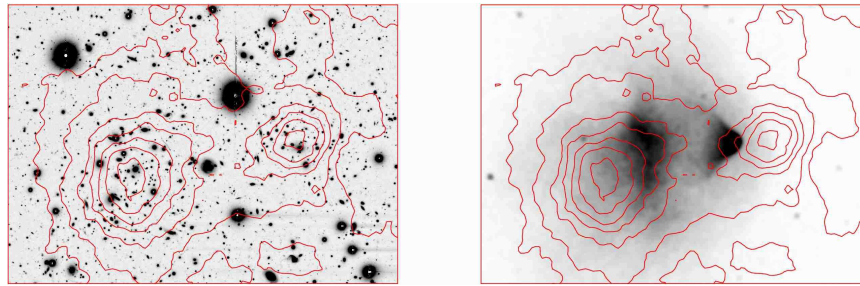


Sanders 1999



Angus et al. 2007

The bullet cluster



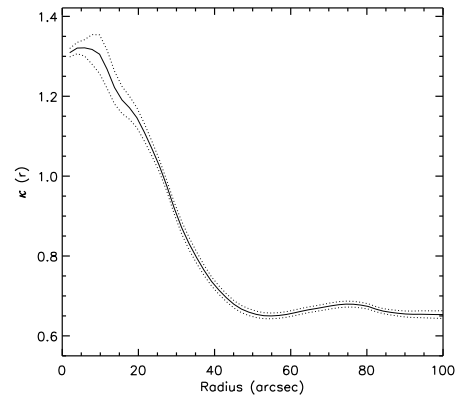
Clowe et al. 2006

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

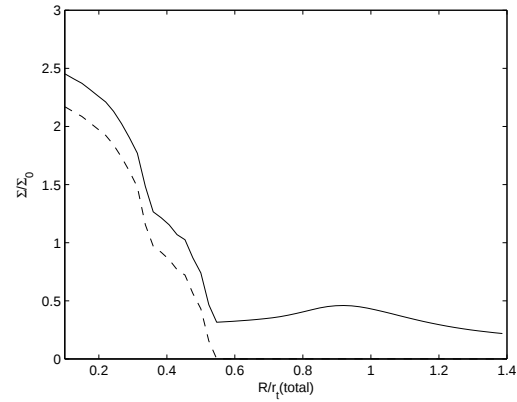
BDM is largely non-dissipational

The high-relative-velocity problem

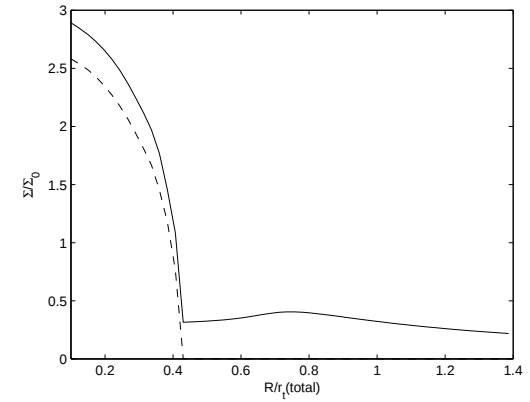
The “ring” cluster (CI 0024+17)



Jee et al. (2007)



Milgrom & Sanders (2007)

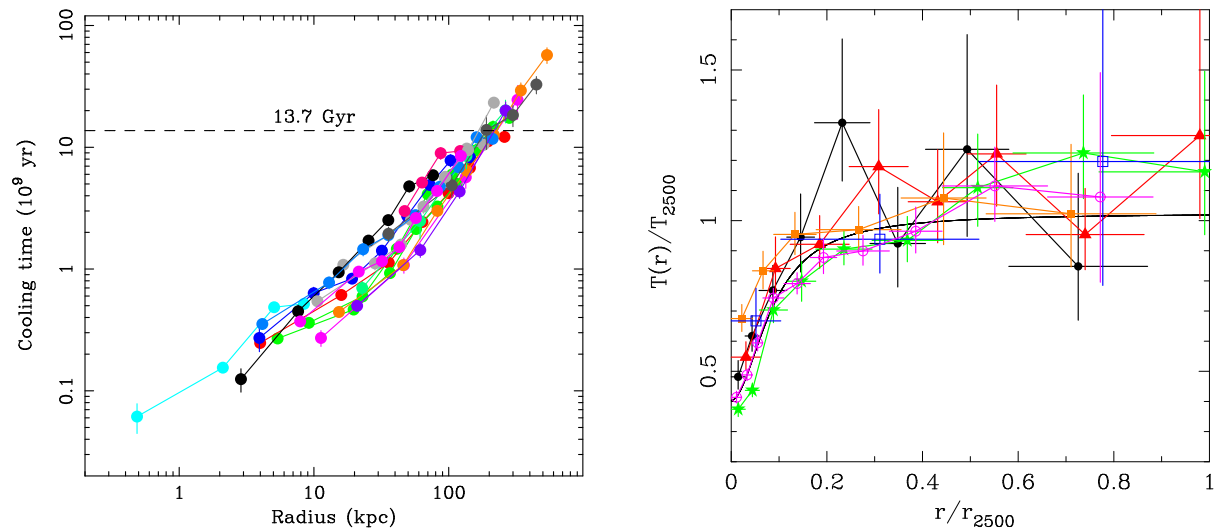


How does it work?

- 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 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 Λ CDM, it implies baryons as DM, which might be effective
- Requires much less DM hence releasing constraints 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

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:

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

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

Support of cloudlets? Magnetic? hydrostatic:

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

Observed effects

- Lensing
- Discrete flashes