銀河団の弱い重力レンズを用いた重力理論 (MOND) への制限

高橋龍一 (国立天文台)、千葉剛 (日大文理)

MOND (MOdified Newtonian Dynamics : Milgrom 1983)

- It changes equation of motion (EoM) to explain the galactic dynamics without dark matter
- Gravitational sources are only baryonic components (stars and gas)
- It effectively makes gravitational force stronger at galactic and extra-galactic scales
- EoM is changed if acceleration is lower than critical value g_0

$$mg = F$$

$$m g^2 / g_0 = F$$

if $g < g_0 \cong 1 \times 10^{-8}\,\mathrm{cm\,s^{-2}}$

g_0 : constant

Radius where MOND becomes important

$$\frac{M}{r^2} = g_0 \quad \Rightarrow \quad r = \sqrt{M / g_0} \qquad g_0 \cong 1 \times 10^{-8}\,\mathrm{cms}^{-2}$$

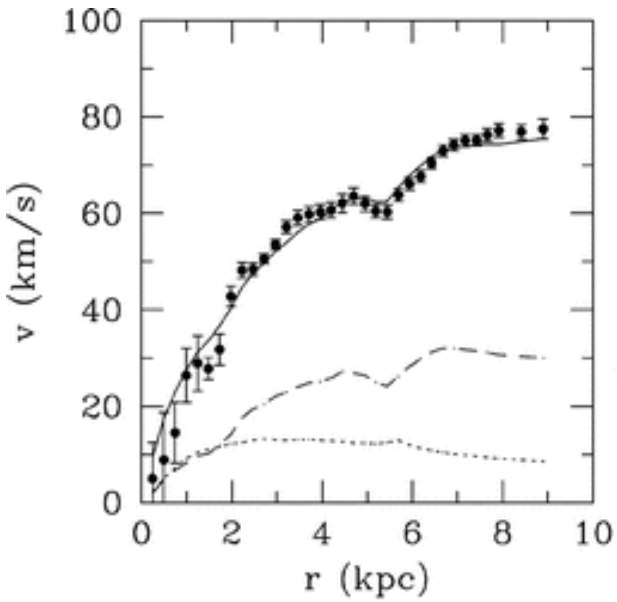
$r \approx 8000\,AU$ **solar system** M_{sun}

$\approx 10\ \mathrm{kpc}$ **galaxy** $10^{11} M_{sun}$

$\approx 400\ \mathrm{kpc}$ **galaxy cluster** $10^{14} M_{sun}$

MOND-gravity regime outside the above radius

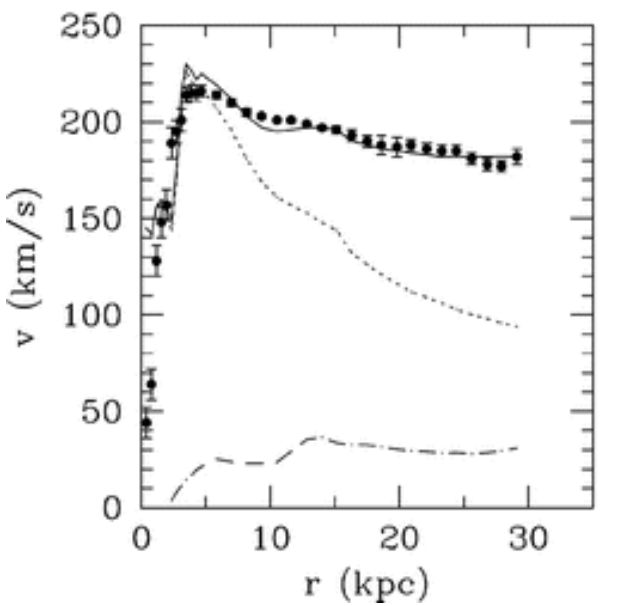
Galactic rotation curves



NGC 1560

$\langle \mu_B \rangle$ = 23.2 mag/arcsec²

$(M/L_B)_{disk}$ = 0.4



NGC 2903

$\langle \mu_B \rangle$ = 20.5 mag/arcsec²

$(M/L_B)_{disk}$ = 1.9

MOND

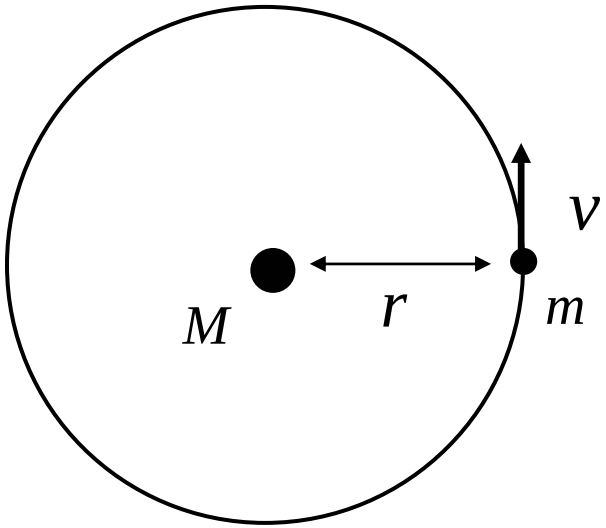
star (Newton)

gas (Newton)

Free parameter is only mass-to-light ratio

(Sanders & McGaugh 2003)

Rotation curve



circular motion

eq. of motion

$$m g^2 / g_0 = F$$

centrifugal force

$$g = \frac{v^2}{r}$$

gravity

$$F = G\frac{mM}{r^2}$$

$$v = \text{const.}$$

(flat rotation curve)

$$v \propto r^{-1/2}$$

(Kepler motion)

$$M \propto L \propto v^4$$

Tully-Fisher relation

Galaxy Clusters (Aguirre et al. 2001; Sanders 2003)

MOND can not explain temperature profiles of clusters

hydrostatic equilibrium

$$dP/dr = -\rho g \qquad \text{with } P = \left(kT/\mu m_p\right)\rho \qquad g = \left[g_0 GM\right]^{1/2}/r \quad \text{for } g < g_0$$

$$\frac{d\ln\rho}{d\ln r} + \frac{d\ln T}{d\ln r} = -\frac{\mu m_p}{kT}\left[g_0 GM\right]^{1/2}$$

μ : **mean molecular weight**

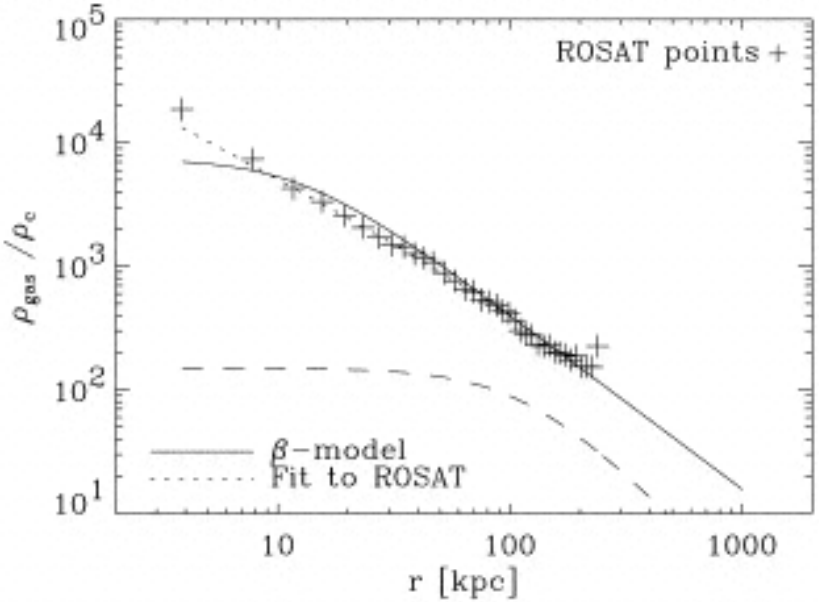
$M(r)$: **mass inside a radius r**

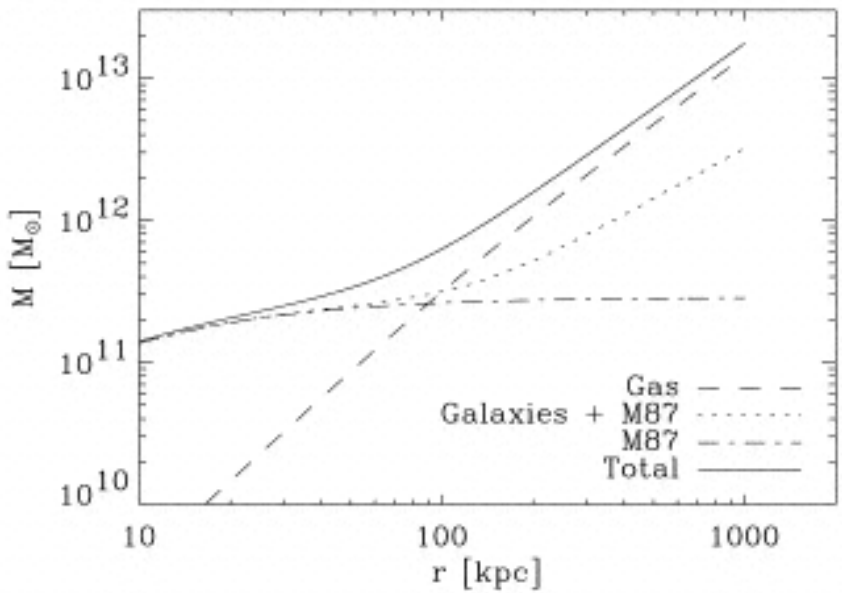
If $\rho(r)$ **and** $T(r)$ **are power law, left hand side is constant**

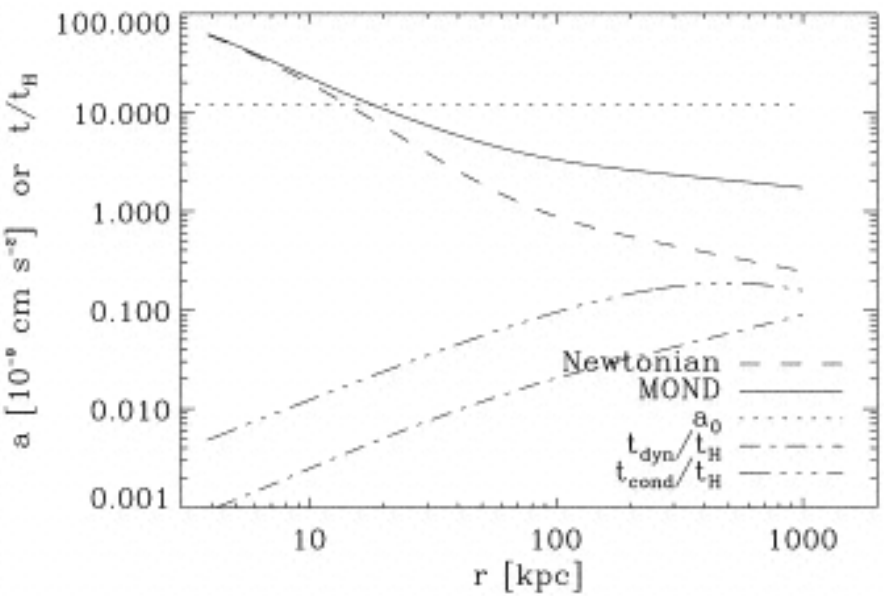
$$T \propto M^{1/2} \quad \Longleftrightarrow \quad \textbf{Isothermal}$$

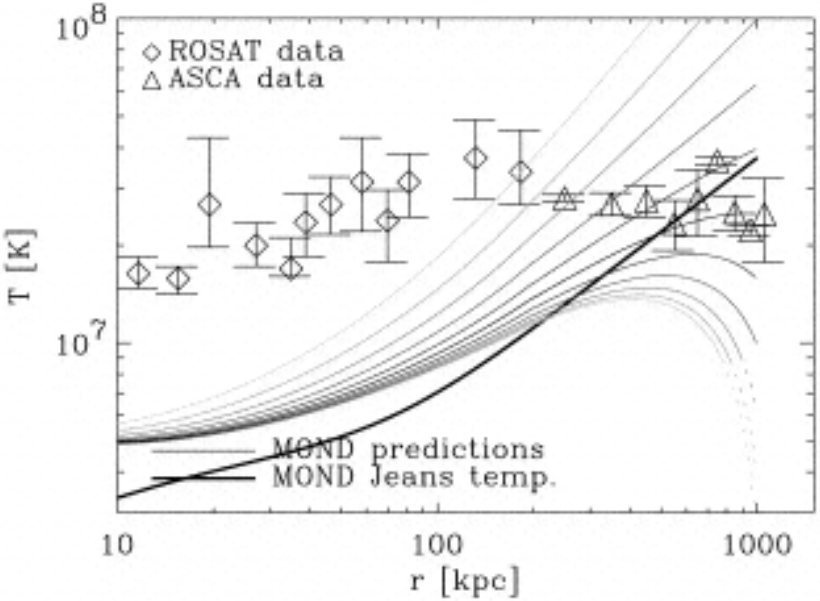
suggested by observations

Virgo Cluster







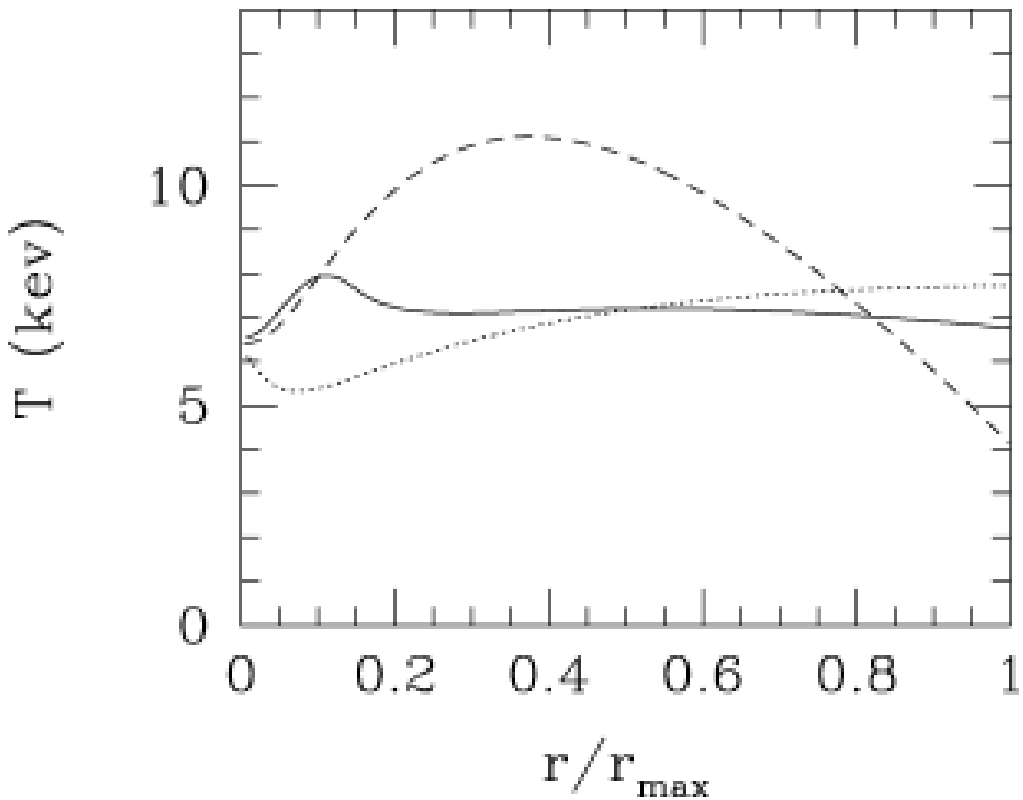


Including dark mass component at center

(Sanders 2003)

$$T \propto M^{1/2} \Longleftrightarrow M = \text{const.}$$ **outside core**

$$\Longrightarrow T = \text{const.}$$



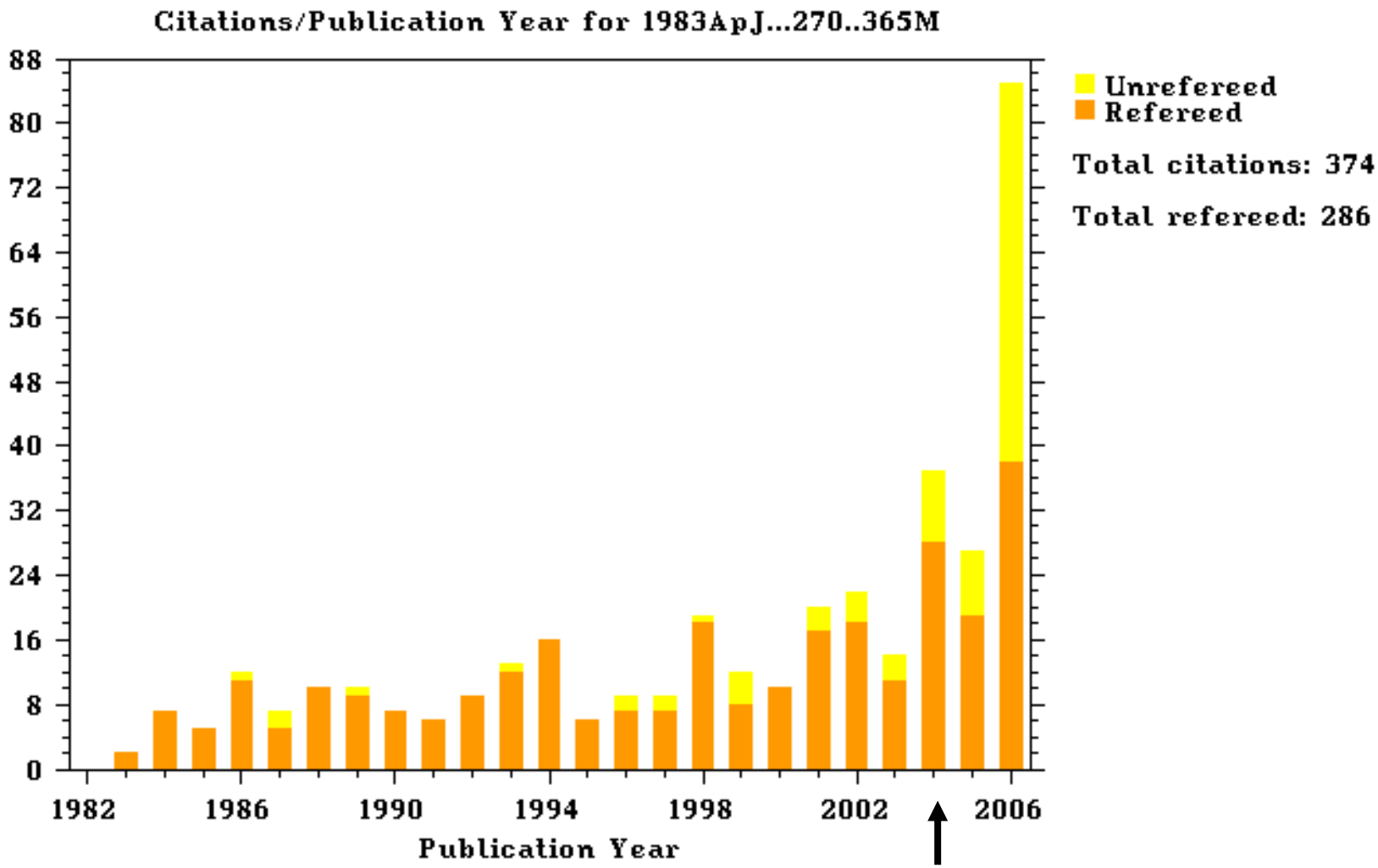
dashed line : only gas component
（isothermal β model）

solid & dotted lines :
including dark halo

Original MOND was modification of Newtonian dynamics

Bekenstein（2004） proposed relativistic MOND. After his work, we can discuss relativistic phenomena such as CMB, large scale structure, gravitational lens.

Citation history for Milgrom (1983)



relativistic MOND
by Bekenstein (2004)

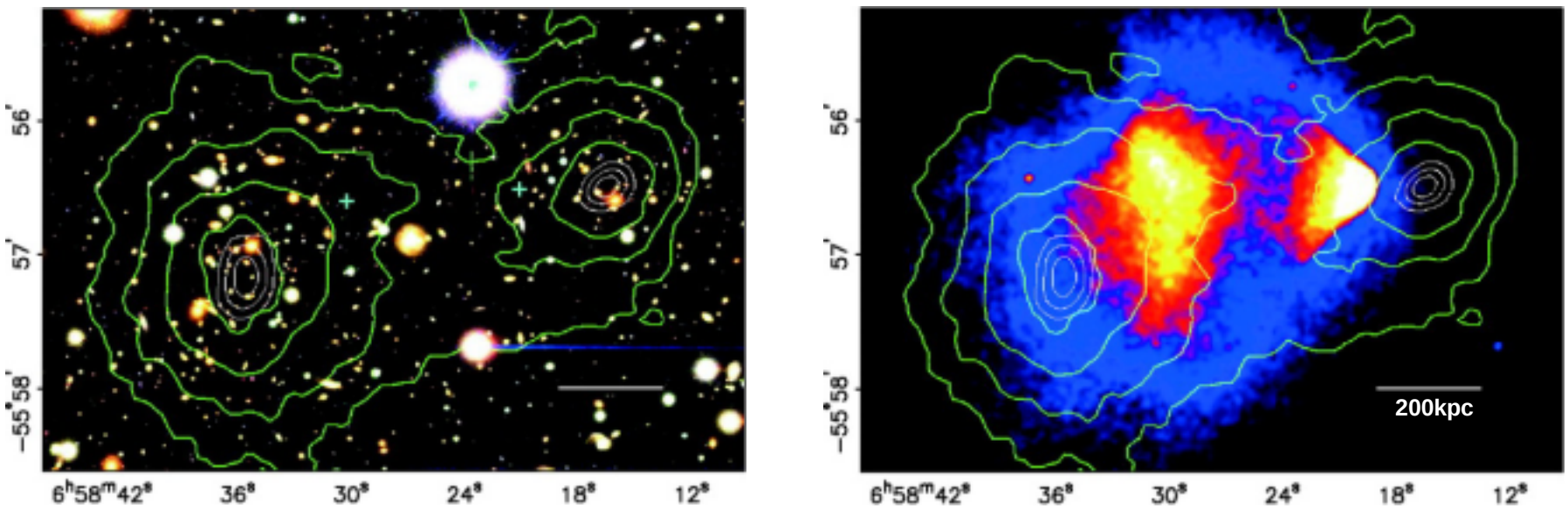
A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER[1]

Douglas Clowe,[2] Maruša Bradač,[3] Anthony H. Gonzalez,[4] Maxim Markevitch,[5,6]
Scott W. Randall,[5] Christine Jones,[5] and Dennis Zaritsky[2]

Received 2006 June 6; accepted 2006 August 3; published 2006 August 30

merging cluster 1E 0657-558

x-ray



green contour : surface density detected by weak lensing

baryonic mass peak ⟺ **total mass peak**

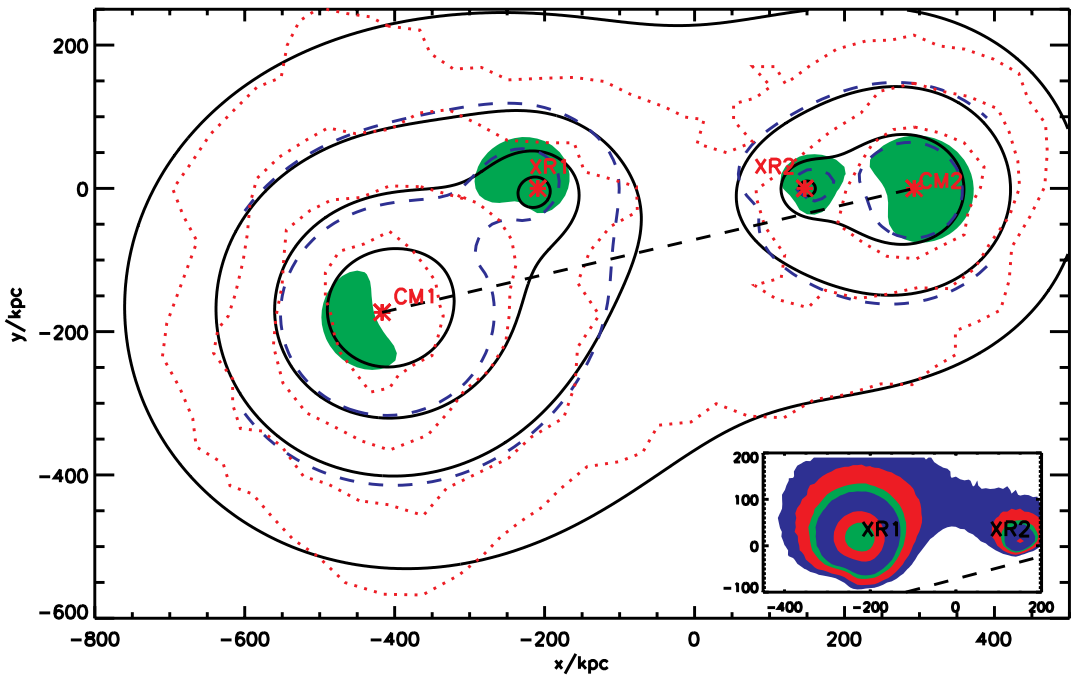
8σ spatial offset

ON THE PROOF OF DARK MATTER, THE LAW OF GRAVITY AND THE MASS OF NEUTRINOS

GARRY W. ANGUS[1], HUANYUAN SHAN[2,1], HONGSHENG ZHAO[1,2], BENOIT FAMAEY[3]

Draft version November 14, 2006

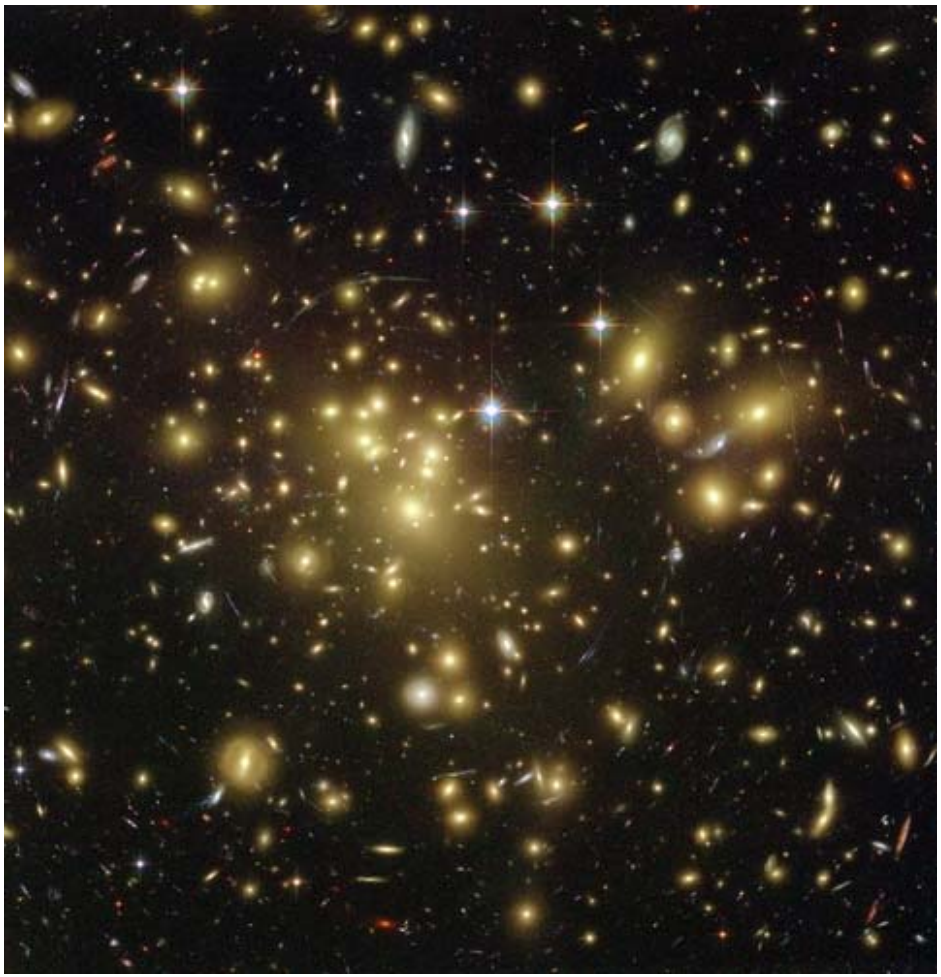
including neutrino dark halo $m_\nu = 2\ \mathrm{eV}$



black lines : convergence (= surface density) map in MOND
red dotted lines : observation
green region : neutrino halo

DM to baryon mass ratio is 2.4

Weak Lensing in Cluster



cluster A1689

shear of background galaxies

↓

gravitational potential of cluster

Weak Lensing in MOND

MOND radius

$$\frac{M}{r^2} = g_0 \qquad g_0 \cong 1\times 10^{-8}\,\mathrm{cms}^{-2}$$

$$r_M = \sqrt{M/g_0} \approx 400\,\mathrm{kpc}$$

cluster $10^{14} M_{sun}$

MOND-gravity regime outside this radius

comparable

$\approx$

Einstein radius

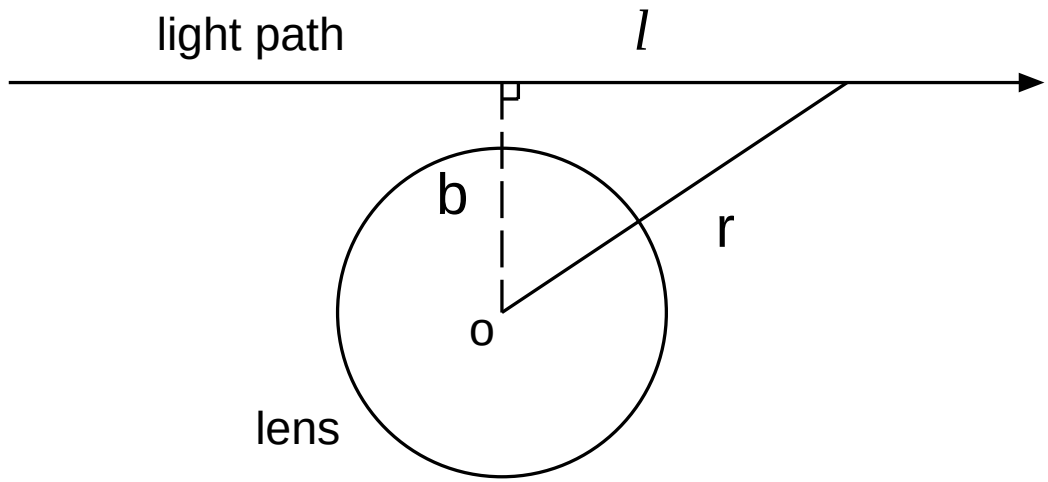
$$r_E \approx \sqrt{M/H_0}$$

since $g_0 \approx H_0$

Weak lensing provides important method to prove which MOND is valid or not

deflection angle

$$\alpha = 2b\int dl\,\frac{g(r)}{r}$$



$g = g_N$ *for* $g_N > g_0$

$= \sqrt{g_0 g_N}$ *for* $g_N < g_0$

M (<r) : lens mass inside a radius r

$$g_N(r) = \frac{M(<r)}{r^2}$$

(Bekenstein 2004; Zhao et al. 2006)

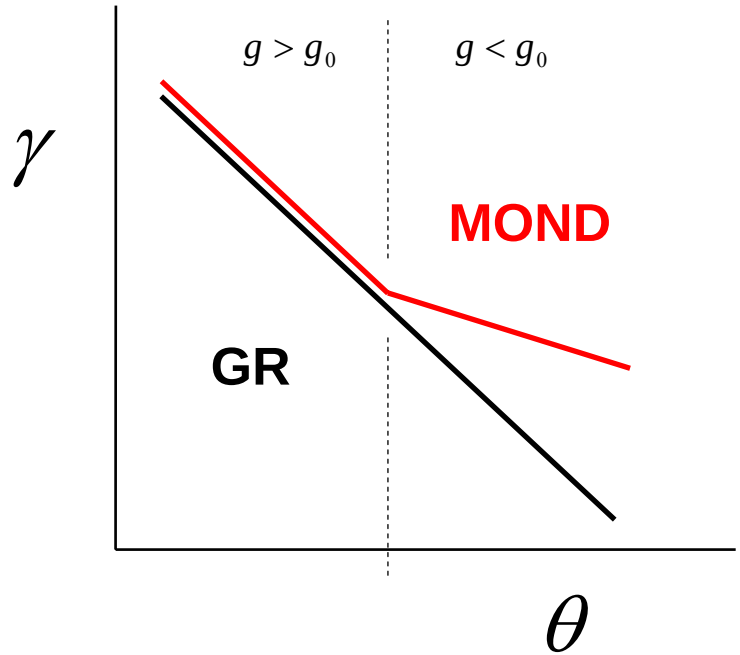
shear γ & convergence κ

lens mass

$$M(<r) \propto r^{p} \quad \text{with} \quad p \geq 0$$

$$\gamma \propto \kappa \propto \theta^{p-2} \qquad for\ g > g_0$$

$$\propto \theta^{p/2-1} \qquad for\ g < g_0$$



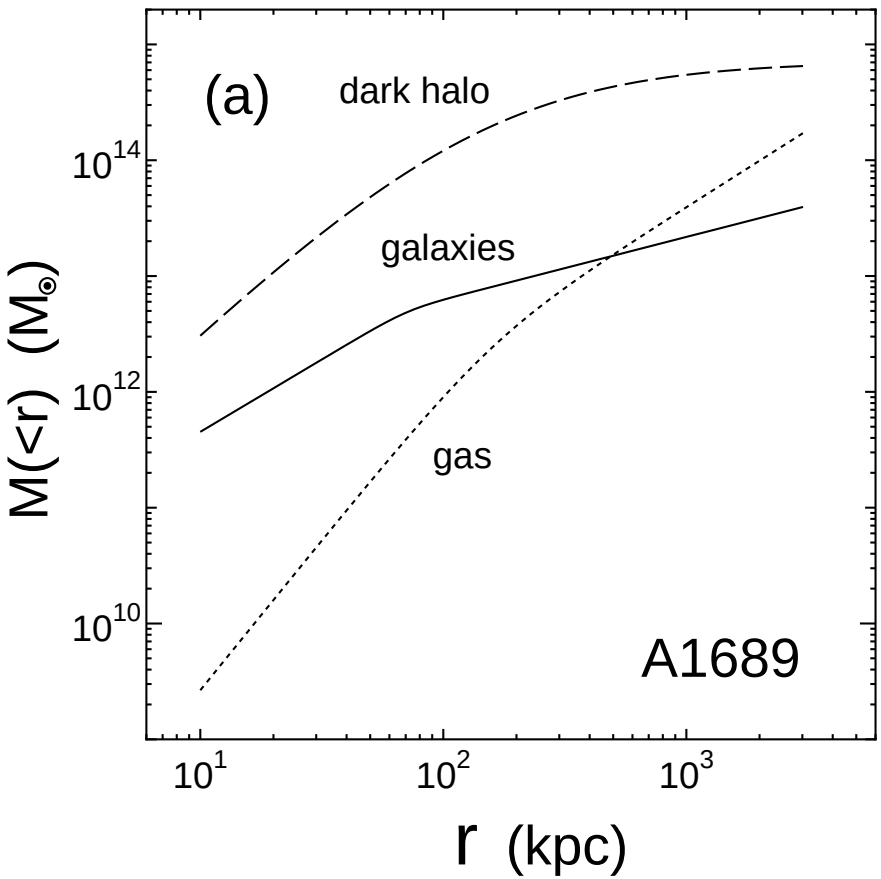
θ：angle from cluster center

slope in MOND is shallower than that in GR

Because gravitational force in MOND decreases slowly

Cluster A1689

mass profile



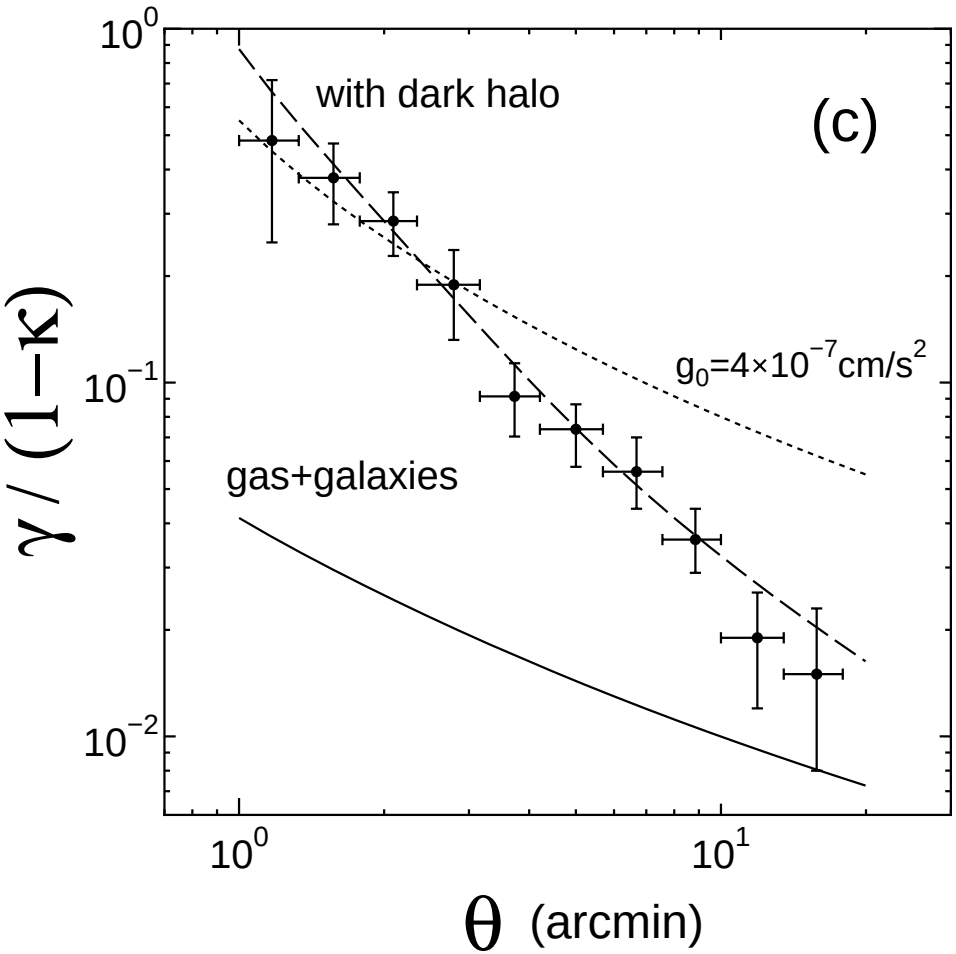
galaxies ← **mass-to-light ratio** $8\,(M/L)_{SUN}$ **(Zekser et al. 2006)**

gas ← **X-ray obs.** **(Andersson & Madejski 2004)**

dark halo ← **need to fit shear data** **(Hernquist profile)**

We calculate shear using above mass profile, and compare observational data

reduced shear $\gamma/(1-\kappa)$ (Broadhurst et al. 2005)



solid line : MOND prediction

(gravitational sources are galaxies & gas)

It is clearly smaller than data.

dotted line：40×g0

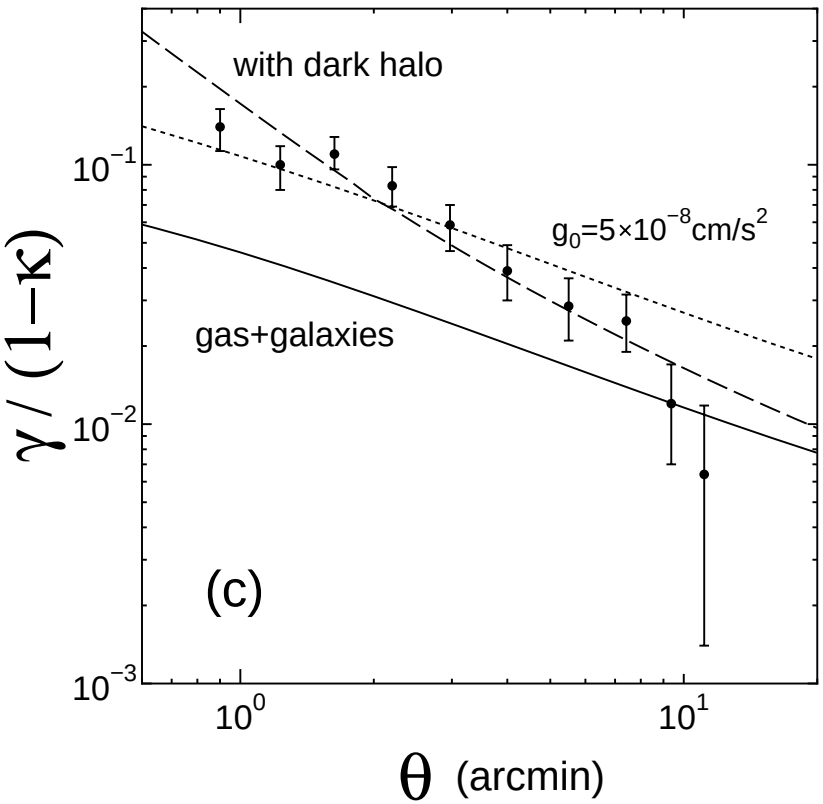
too shallow to fit data

dashed line：including dark halo

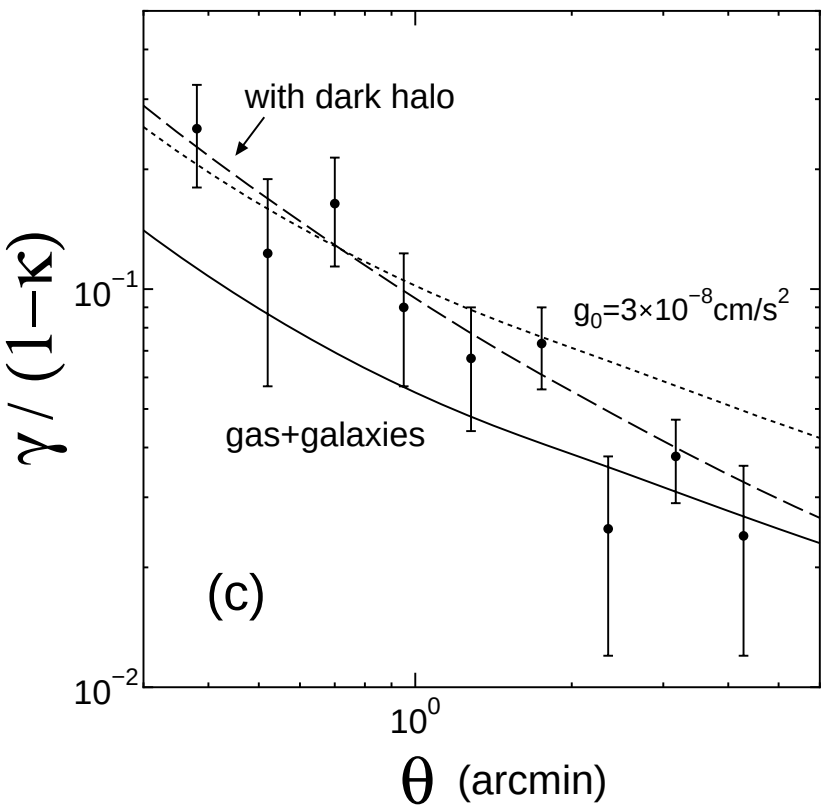
➡ **Dark halo is needed in MOND**

Other Clusters

CL0024+1654



CL1358+6245



● Conclusion

- **MOND cannot explain weak lensing data irrespective of g_0.**

- **Dark matter halo is needed in MOND.**

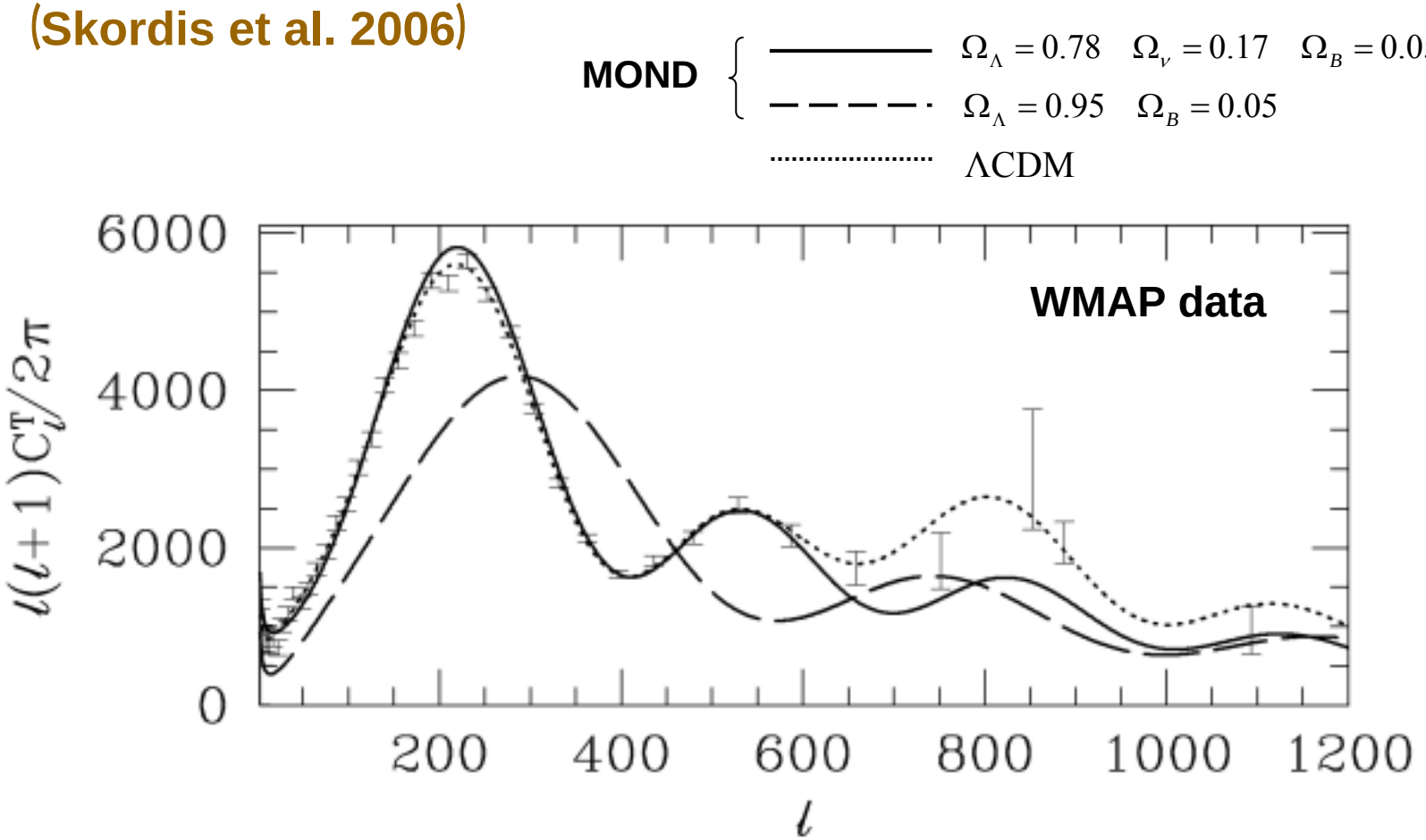
- **Above results are consistent with previous studies.**

(Aguirre, Schaye & Quanaert 2001; Sanders 2003)

CMB

バリオンのみだと Silk damping で小スケールの揺らぎが抑えられる

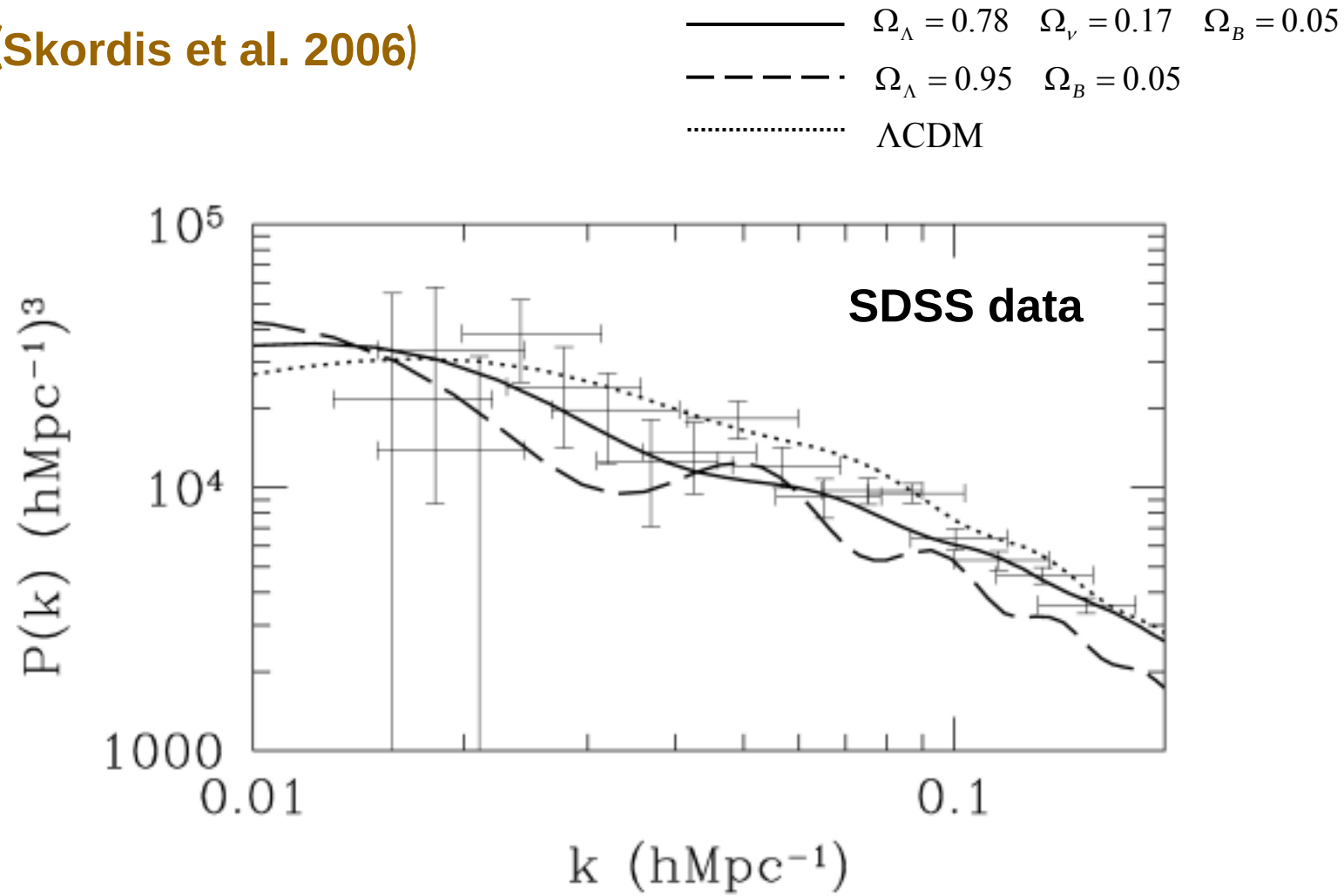
(Skordis et al. 2006)



MOND は WMAP の結果を再現できる

大規模構造

(Skordis et al. 2006)



MOND は power spectrum も再現