Beyond MOND: TeVeS and its Tests

(Depeche MOND)

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CTA Seminar
UIUC
March 1, 2006

MOND = MOdified Newtonian Dynamics

TeVeS = Tensor Vector Scalar

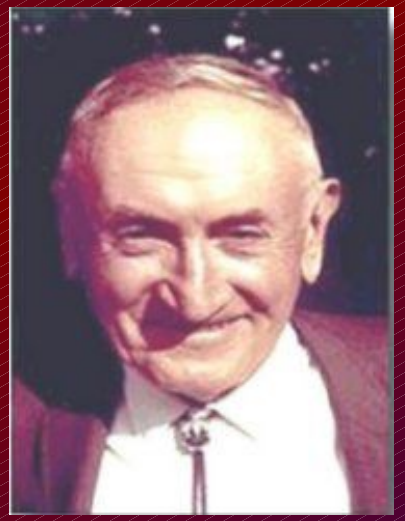
Depeche MOND ~ Depeche Mode = 80's New Wave synth band
("*Update* of MOND" in French)

Outline:

- Why Dark Matter? Why not Dark Matter?
- Where in the Monde did MOND come from?
- What is it good for? Observational successes
- The Journey to TeVeS
- An Intro. to TeVeS
- Consequences of TeVeS
  - La Fin du MOND?
- Conclusion (La fin du talk)

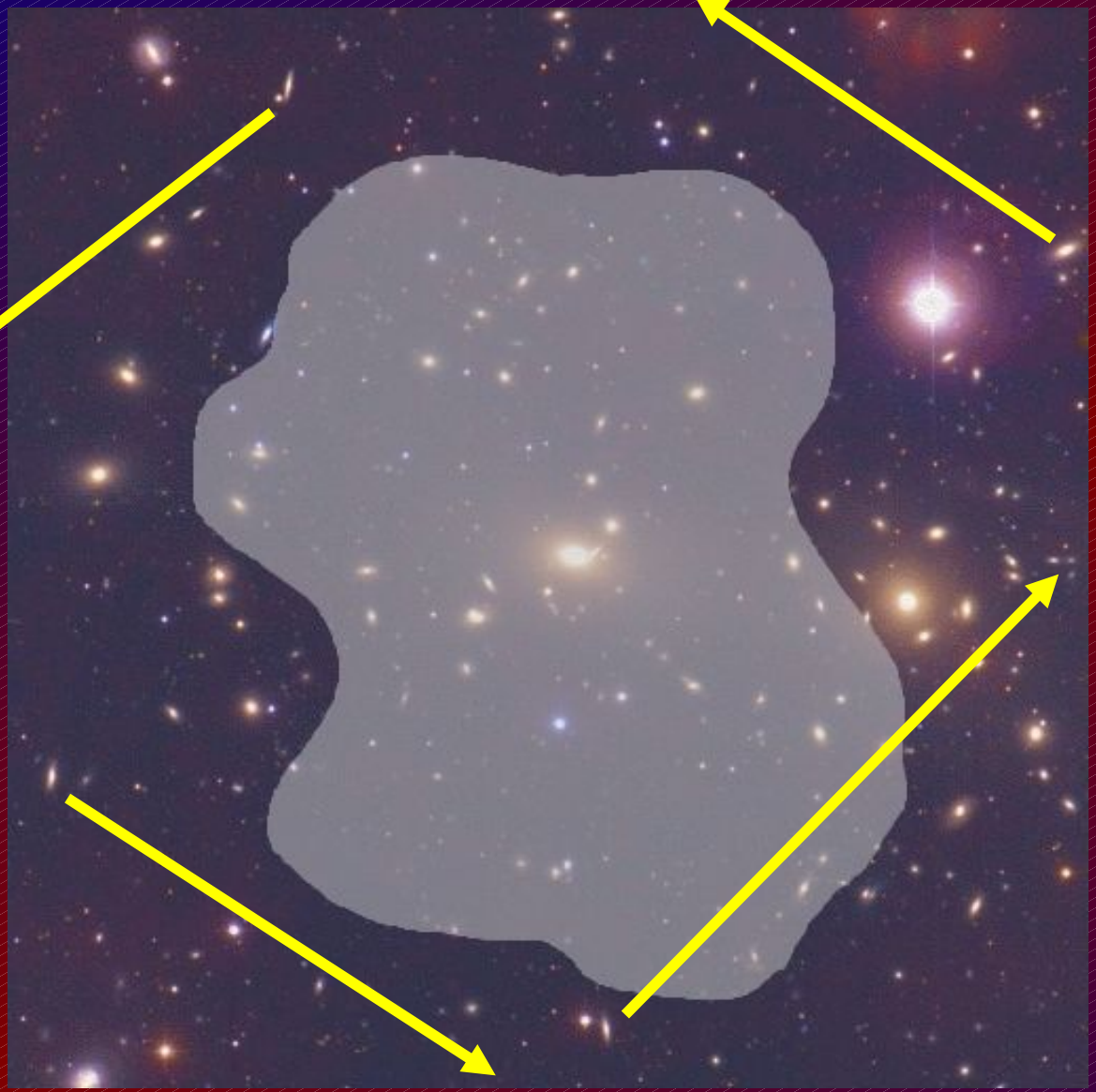
Dark Matter Theory

Coma Cluster
(INAOEP,NOAO,NSF)



Fritz Zwicky

Dark Matter Theory



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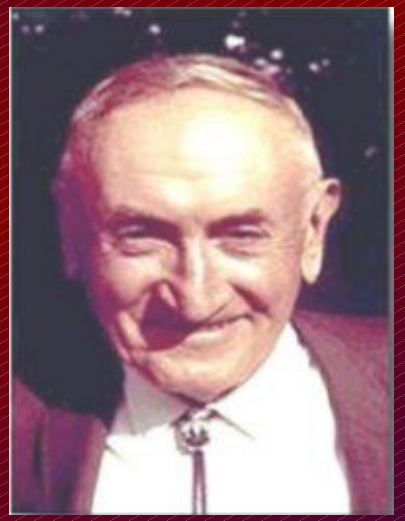
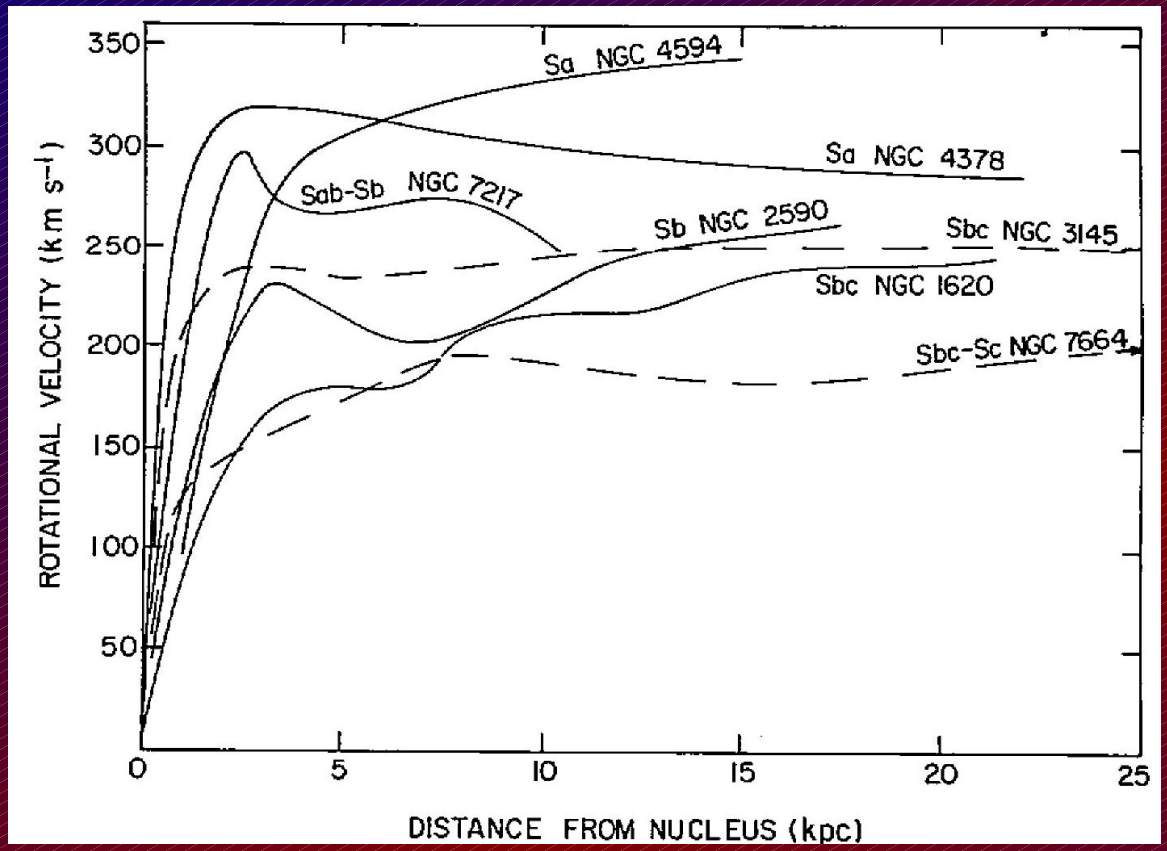


Fritz Zwicky

$$M_{virial} \sim 400\, M_{lum}$$

DM in Galaxies



Rubin, Ford, Thonnard *ApJL* **225** (1978)

$$v^2 = \frac{G\,M(r)}{r}$$

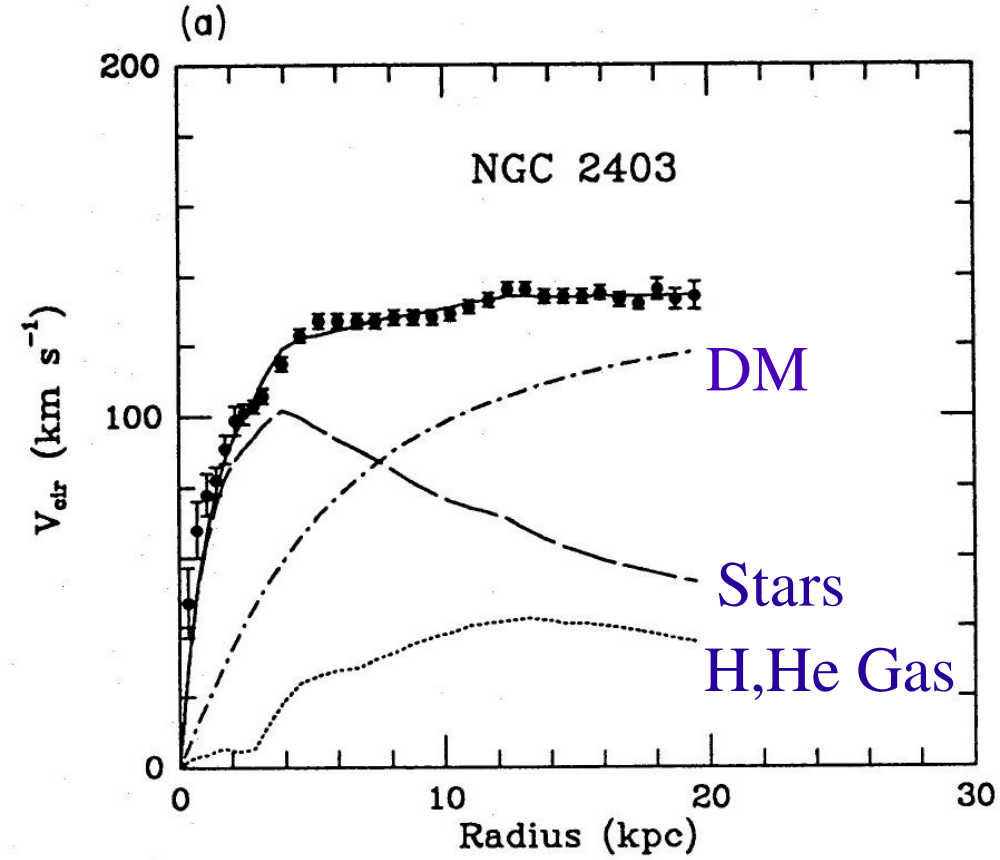
$$\frac{dM}{dr} = 4\pi r^2 \rho = \frac{v^2}{G}$$

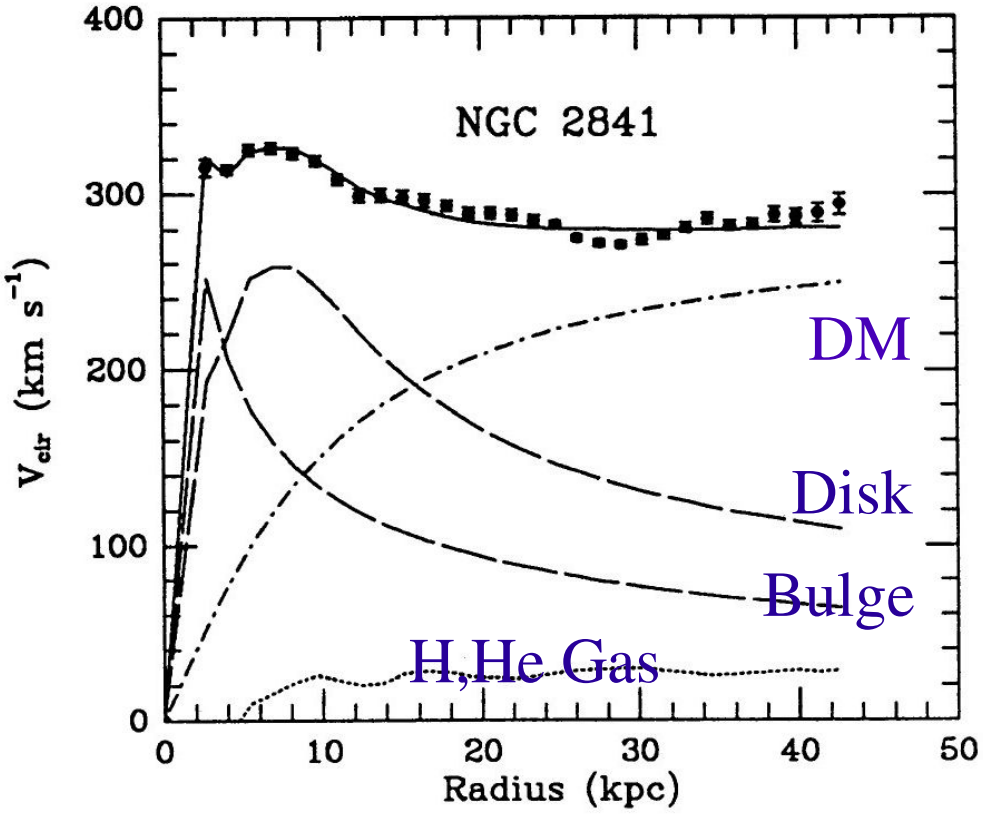
$$\rightarrow \rho \sim r^{-2}$$

But

$$\rho_{lum} \sim r^{-3.5}$$

DM v(r) Models





Begeman, Broeils, Sanders (1991)

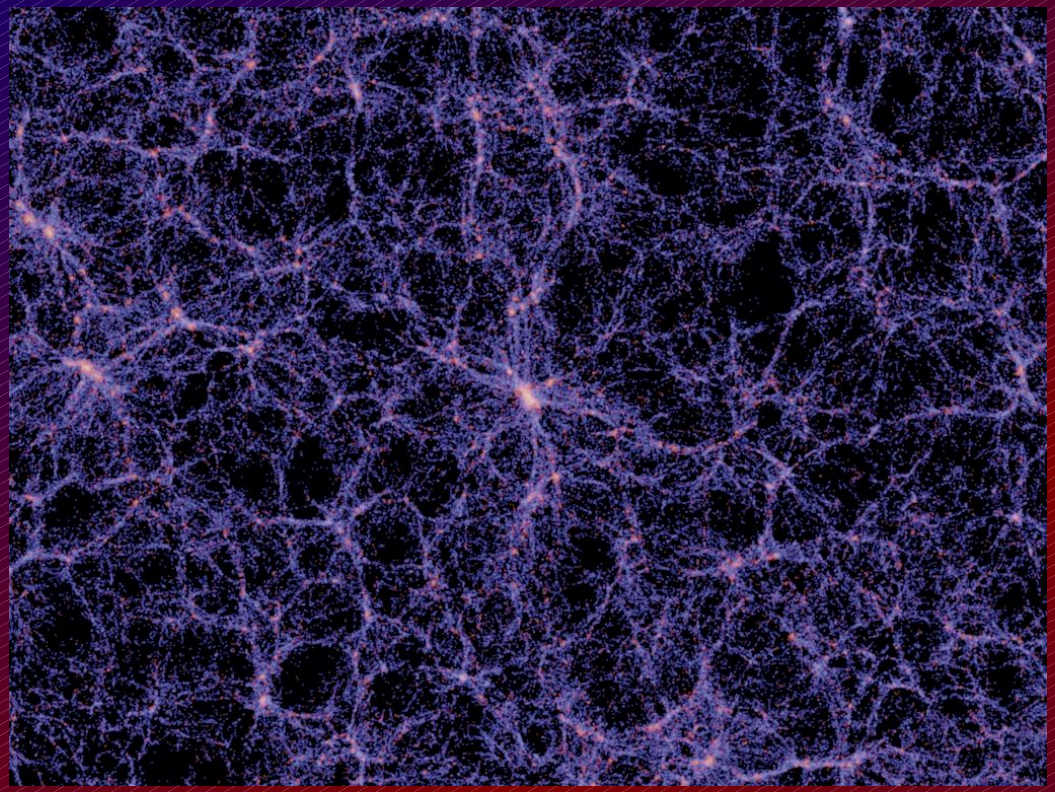
$$\frac{M}{L} \rightarrow \rho_{lum}$$

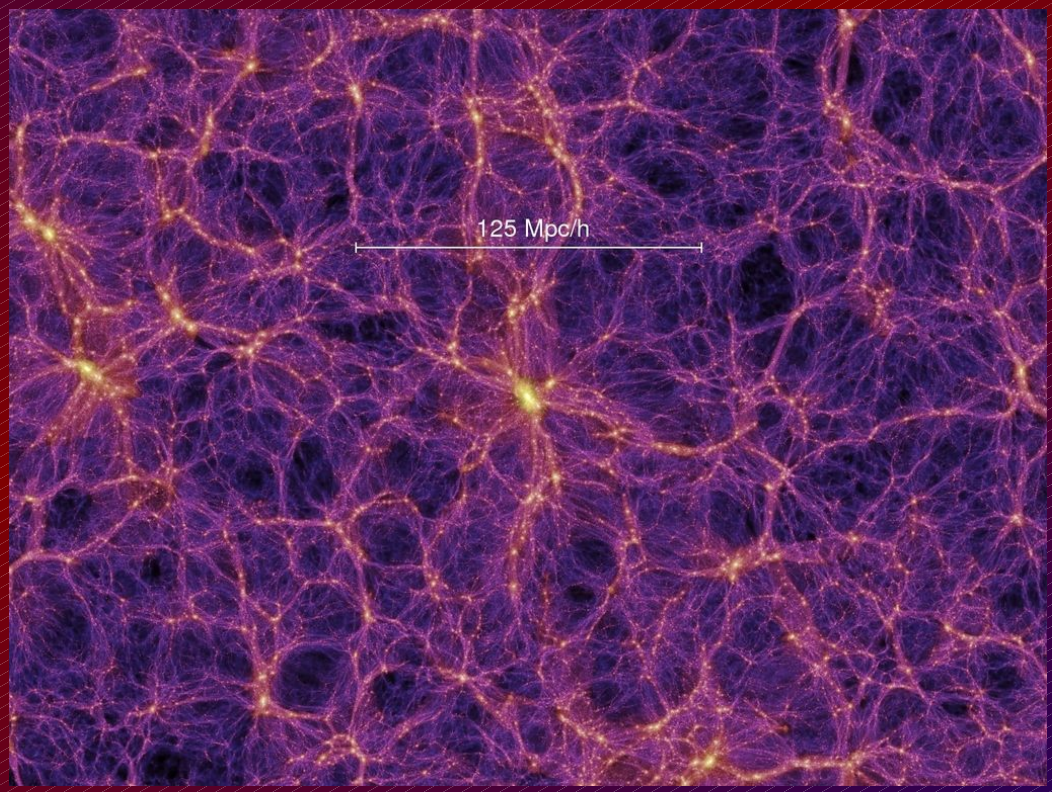
$$\rho_{DM}(r) = \frac{\rho_0}{1+\left(\frac{r}{r_0}\right)^2}$$

Clustering

Luminous Matter

Dark Matter





Millennium Simulation

http://www.mpa-garching.mpg.de/galform/millennium/

Dark Matter Candidates:

- MACHOs (MAssive Compact Halo Objects)
  - BHs, red dwarfs, brown dwarfs, ...
- WIMPs (Weakly Interacting Massive Particles)
  - Neutrinos, neutralinos, other SUSY particles
- Where are all the dwarf galaxies?
  - Missing a few orders of magnitude in number
  - Maybe we can't see them?
- No Central DM Cusp
  - Maybe feedback, DM self-annihilation??

MOdified Newtonian Dynamics

M. Milgrom

Milgrom (1983):

$$\frac{v^2}{r} = \frac{G\,M(r)}{r^2}$$

MOdified Newtonian Dynamics

M. Milgrom

Milgrom (1983):

$$\frac{v^2}{r} = \frac{G M(r)}{r^2}$$

- Fundamental acceleration scale a_0 not length scale
- Newtonian Dyn. for $a > a_0$, MOND for $a < a_0$

$$\vec{g}\,\mu\left(\frac{|\vec{g}|}{a_0}\right) = \vec{g}_N$$

MOND $g \ll a_0 \rightarrow \mu(x \ll 1) \simeq x$

$$\rightarrow g \simeq \sqrt{g_N a_0} \sim r^{-1}$$

Newt. $g \gg a_0 \rightarrow \mu(x \gg 1) \simeq 1 \rightarrow g \simeq g_N$

MOND and Missing Mass Problem

In the MOND regime:

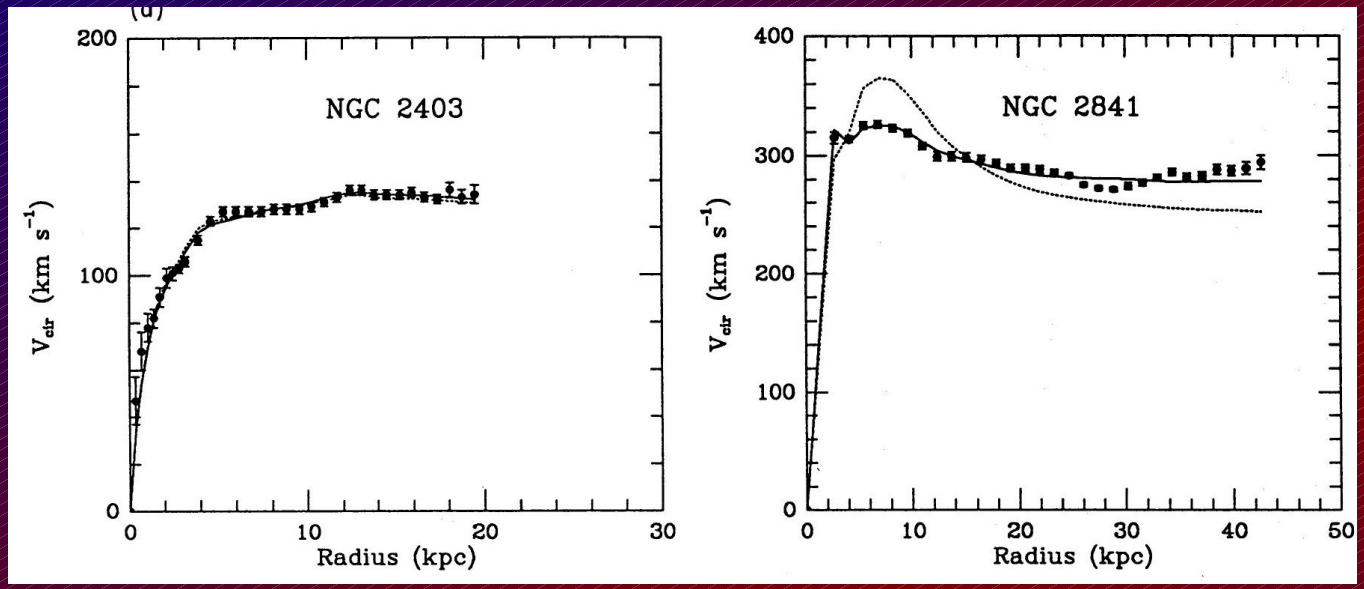
$$g \ll a_0 \;\rightarrow\; g = \sqrt{g_N a_0} \;\rightarrow\; g = \frac{\sqrt{G M a_0}}{r}$$

$$\rightarrow\; \frac{v^2}{r} = \frac{\sqrt{G M a_0}}{r} \;\rightarrow\; v^4 = G M a_0 = const.$$

Tully-Fisher:

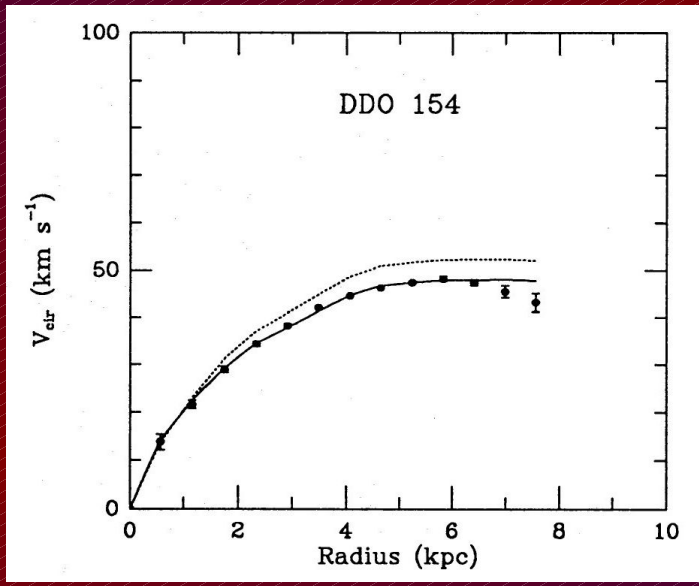
$$M \propto L \;\rightarrow\; L \propto v^4 / a_0$$

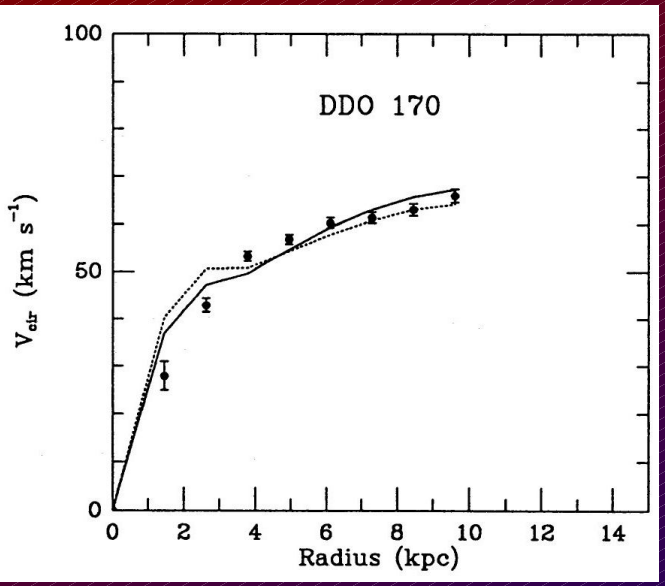
MOND and Rotation Curves



$$a_0 = 1.2\,x\,10^{-8}\,cm/s^2$$

$$\mu(x) = \frac{x}{\sqrt{1+x^2}}$$

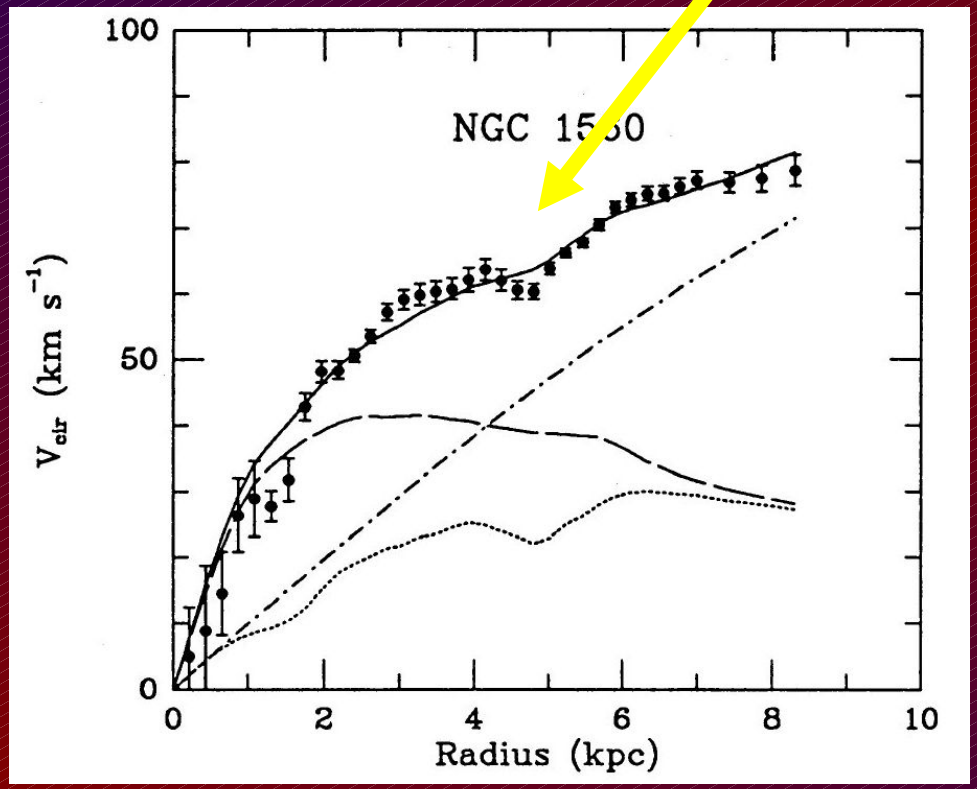


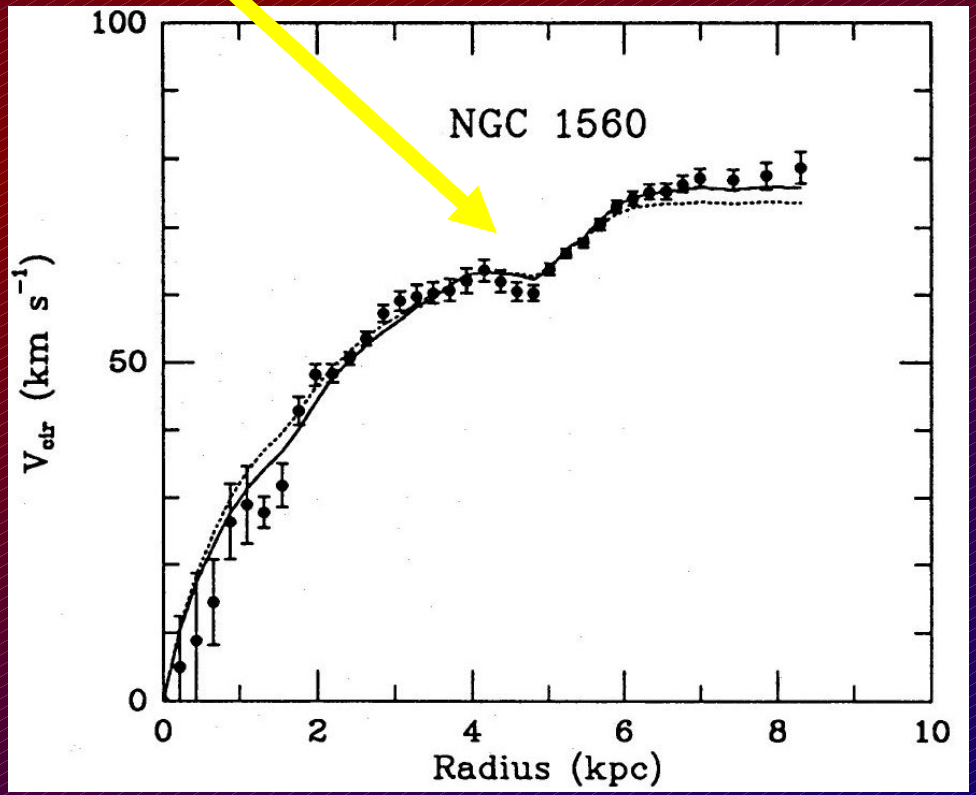


Dotted: fit M/L

Solid: fit M/L, R

MOND and Rotation Curves



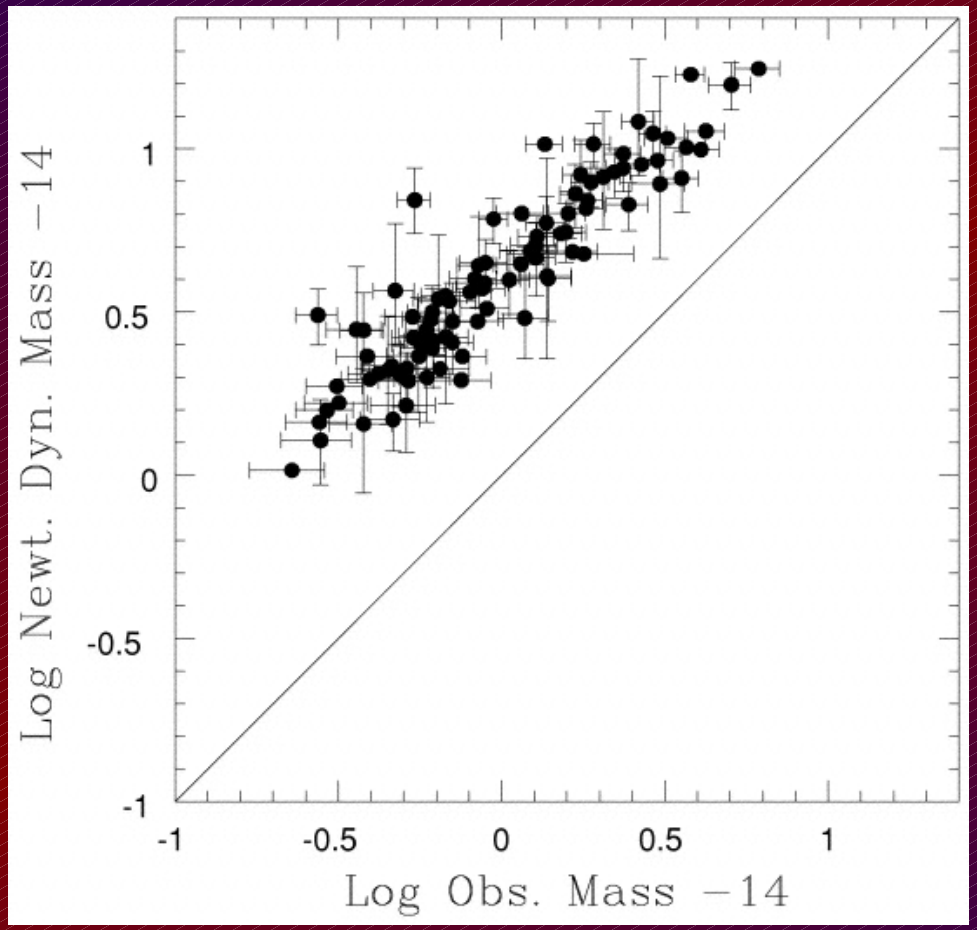


MOND & Galaxy Clusters

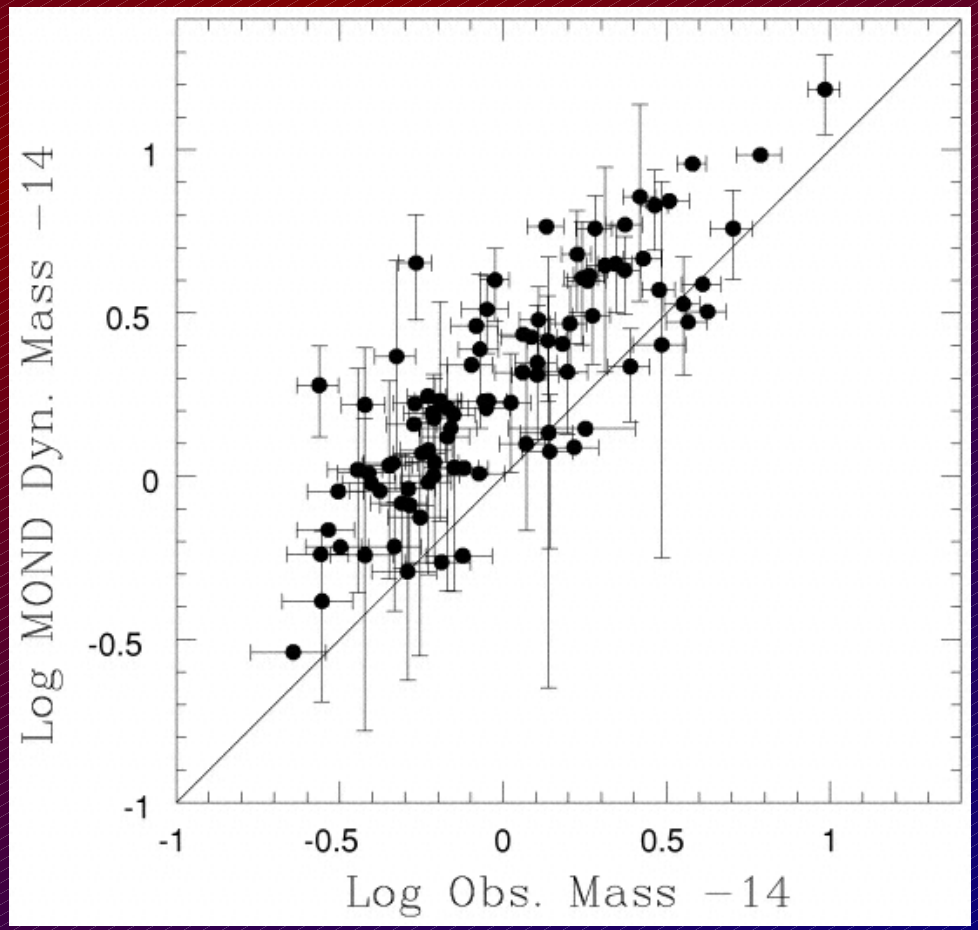
$$M_N = -\frac{r_{out}}{G}\left(\frac{kT}{m}\right)\left(\frac{d\ln\rho}{d\ln r}+\frac{d\ln T}{d\ln r}\right)$$

$$M_{MOND} = \frac{M_N}{\sqrt{1+\left(a_0/a\right)^2}}$$

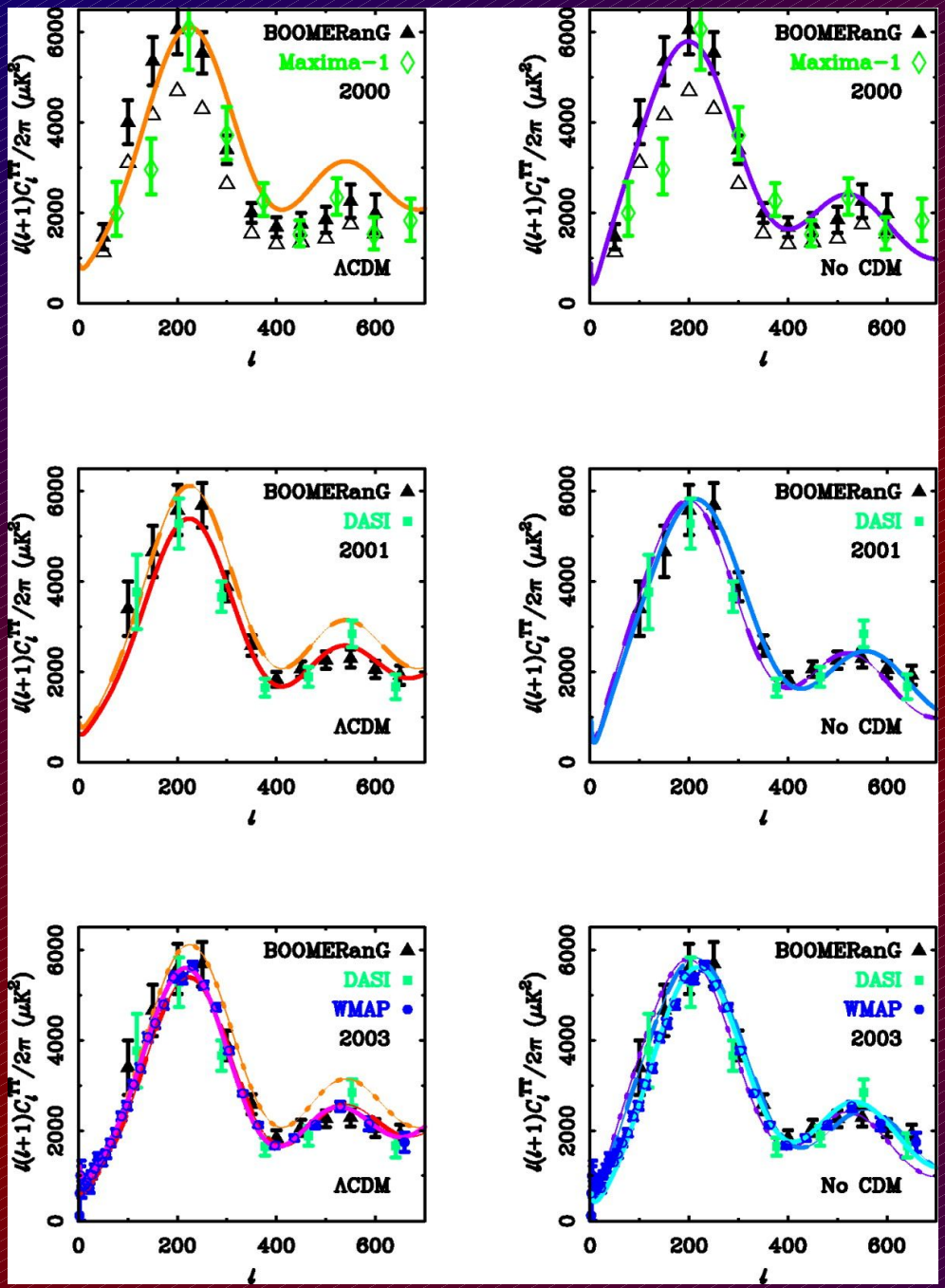
Newtonian



MOND



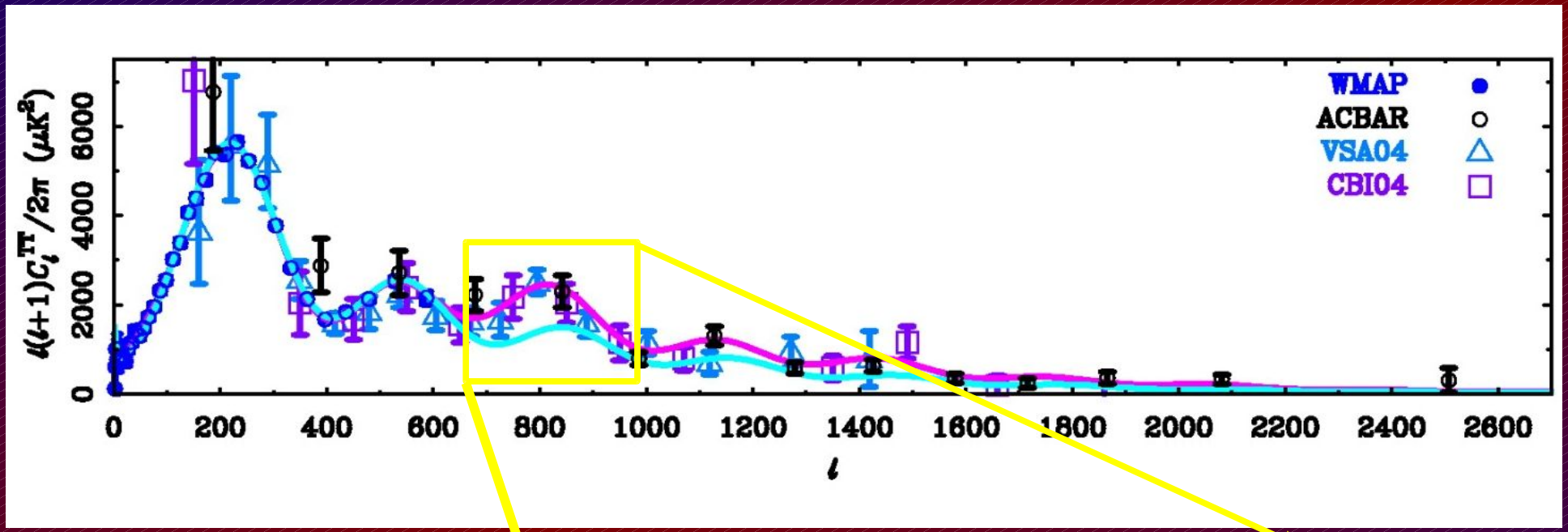
MOND & Cosmology



McGaugh (2004):

- Baryon density matches primordial H,He,Li abundances
- Mass of neutrino ~ 1 eV

MOND & Cosmology



AQUADratic Lagrangian (AQUAL)

Bekenstein & Milgrom (1984):

Newtonian: $$L_N = -\rho\phi_N + (8\pi G)^{-1}(\nabla\phi_N)^2$$

AQUAL: $$L = -\rho\phi + (8\pi G)^{-1} a_0^2 F\left[\frac{(\nabla\phi_N)^2}{a_0^2}\right]$$

$$F(x \ll 1) \propto x^{3/2}\ ,\ F(x \gg 1) \propto x \qquad \mu = F'(x)$$

$$\nabla.\left[\mu(|\nabla\phi|/a_0)\nabla\phi\right] = 4\pi G\rho = \nabla\phi_N$$

$$\mu(g/a_0)\vec{g} = \vec{g}_N + \nabla\times\vec{h} = \vec{g}_N + O(1/r^3)$$

Relativistic AQUAL (RAQUAL)

Bekenstein & Milgrom (1984):

$$\tilde{g}_{ab} = e^{2\psi} g_{ab} \qquad L = L_g + L_m + L_\psi$$

$$L_g = -\tilde{R} e^{-2\psi} + \psi_{,a}\psi^{,a} \qquad L_\psi = -F\left(\psi_{,a}\psi^{,a}\right)$$

Two Problems:

1) Superluminal ψ waves!

2) Predicts no gravitational lensing!

Bekenstein (1988): Phase Coupled Gravity, still bad w/ lensing

Disformal Metric Theories

Bekenstein (1992):

$$\tilde{g}_{ab} = e^{-2\psi}\left(A g_{ab} + B \psi_{,a} \psi_{,b}\right)$$

$B<0$: Light deflection + Acausal light and GW's

$B>0$: NO Light deflection + Causal light and GW's

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$B>0$: NO Light deflection + Causal light and GW's

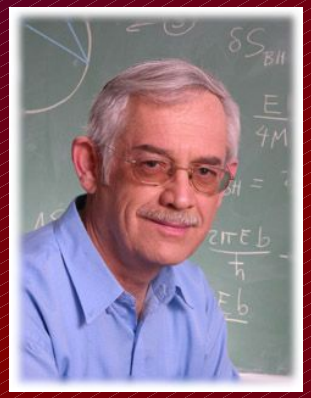
Sanders (1997):

$$\tilde{g}_{ab} = e^{-2\psi} g_{ab} - 2 U_a U_b \sinh(2\psi)$$

$$U_a U^a = -1$$

- "Stretches/Shrinks" Einstein metric ortho./para. to U_a
- Selects preferred frame

TeVeS



Bekenstein (2004): $\tilde{g}_{ab} = e^{-2\psi} g_{ab} - 2U_a U_b \sinh(2\psi)$

$$L = L_t + L_v + L_s + L_m$$

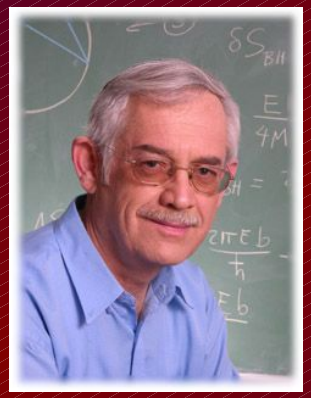
Tensor: $L_t = L_{GR} = R\sqrt{-g}$

Vector: $L_v = -KU^{[a,b]}U_{[a,b]} + \lambda\left(U^a U_a + 1\right)$

Scalar: $L_s = -\sigma^2\left(g^{ab} - U^a U^b\right)\phi_{,a}\phi_{,b} + \frac{G\sigma^4}{2l^2}F(kG\sigma^2)$

Matter: $L_m = L_m(\tilde{g}_{ab}, \ldots)$

TeVeS



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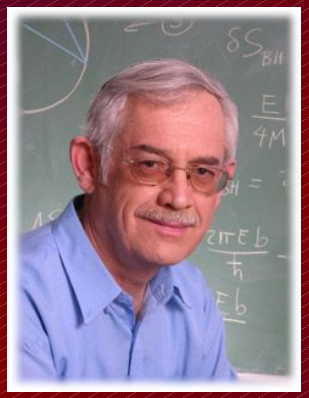
$$k, K, l, F$$

TeVeS



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Matter: $L_m = L_m(\tilde{g}_{ab}, \ldots)$

$0 \quad \infty$

k, K, l, F

More TeVeS Equations

$$G_{ab} = 8\pi G\left[\tilde{T}_{ab} + \left(1 - e^{-4\phi}\right) U^c \tilde{T}_{c(a} U_{b)} + \tau_{ab}\right] + \Theta_{ab}$$

$$\tau_{ab} = \sigma^2\left(\phi_{,a}\phi_{,b} + \ldots + F + \ldots\ldots\right)$$

$$\Theta_{ab} = K\left(g^{cd} U_{[c,a]} U_{[d,b]} - \frac{1}{4} U^{a,b} U_{a,b}\right) - \lambda U_a U_b$$

Non-Relativistic Limit

$$\dot{\phi} \to 0 \quad , \quad |\phi| \ll 1 \quad , \quad g_{ab} \to \text{Minkowski}$$

$$g_{tt} = -\left(1+2V\right)+O(V^2)$$

$$U_a = -\left[1+V+O(V^2)\right]\delta^t{}_a$$

$$\tilde{g}_{tt} \simeq -\left(1+2V+2\phi\right)$$

$$\nabla\left[\mu\left(kl^2\left(\nabla\phi\right)^2\right)\nabla\phi\right] = kG\tilde{\rho}$$

$$a_0 \sim \frac{1}{kl^2}$$

RAQUAL: $\nabla.\left[\mu\left(|\nabla\phi|/a_0\right)\nabla\phi\right] = 4\pi G\rho$

TeVeS Tidbits

- TeVeS --> MOND
- Bekenstein (2004): scalar, vector and tensor perturbations are individually causal for $\phi > 0$
- PPN :

$$\beta, \gamma = 1$$

--> Light deflection/ranging = GR

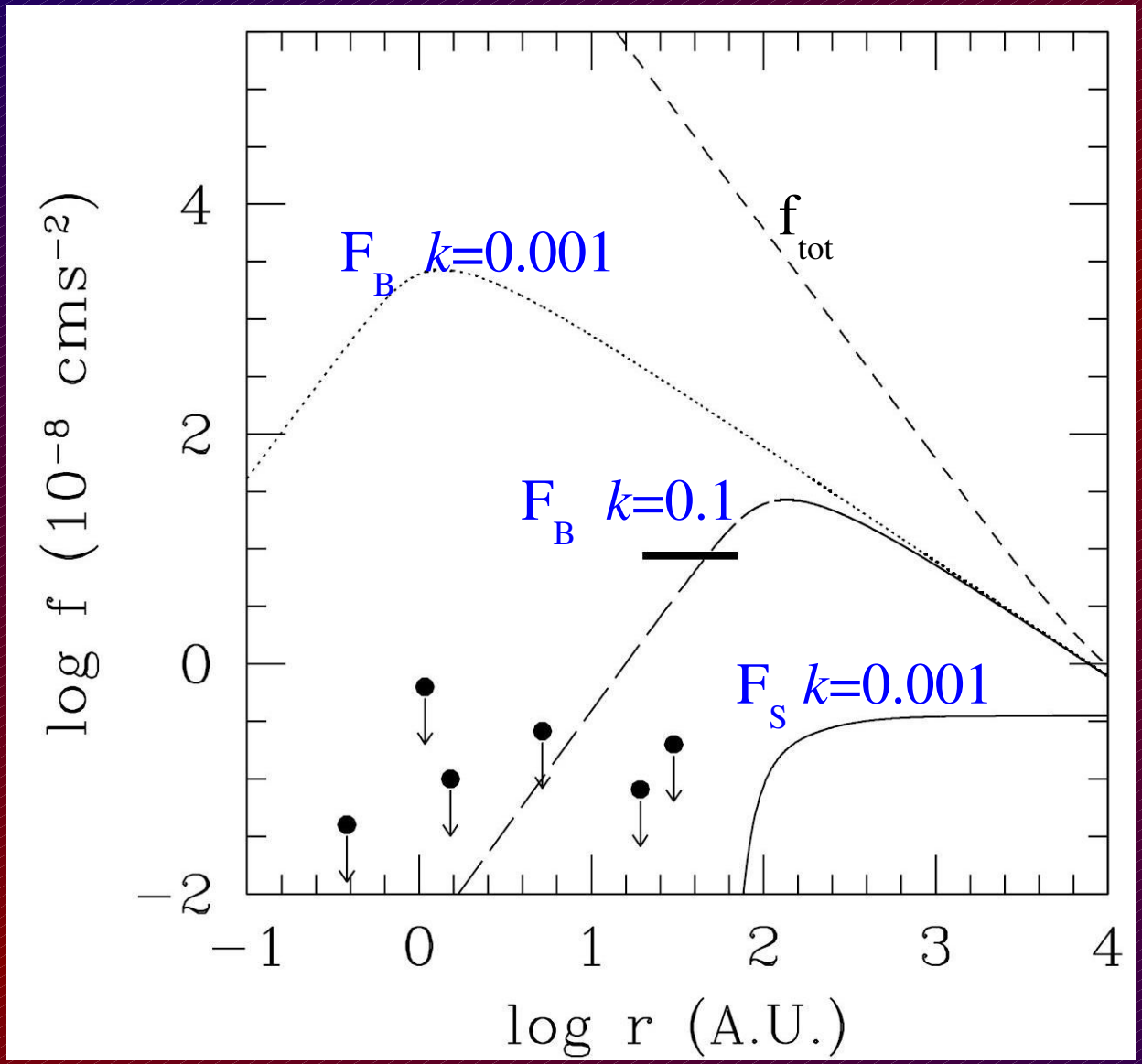
--> Perihelion precession = GR

- Still need to calculate other PPN parameters

$$\alpha_{1,2,3} \rightarrow$$ Preferred frame effects

TeVeS & the Solar System

Sanders astro-ph/0602161



$$\Delta\Omega_p = -a_p\sqrt{\frac{a\left(1-e^2\right)}{G\,M_{sun}}}$$

Mercury:

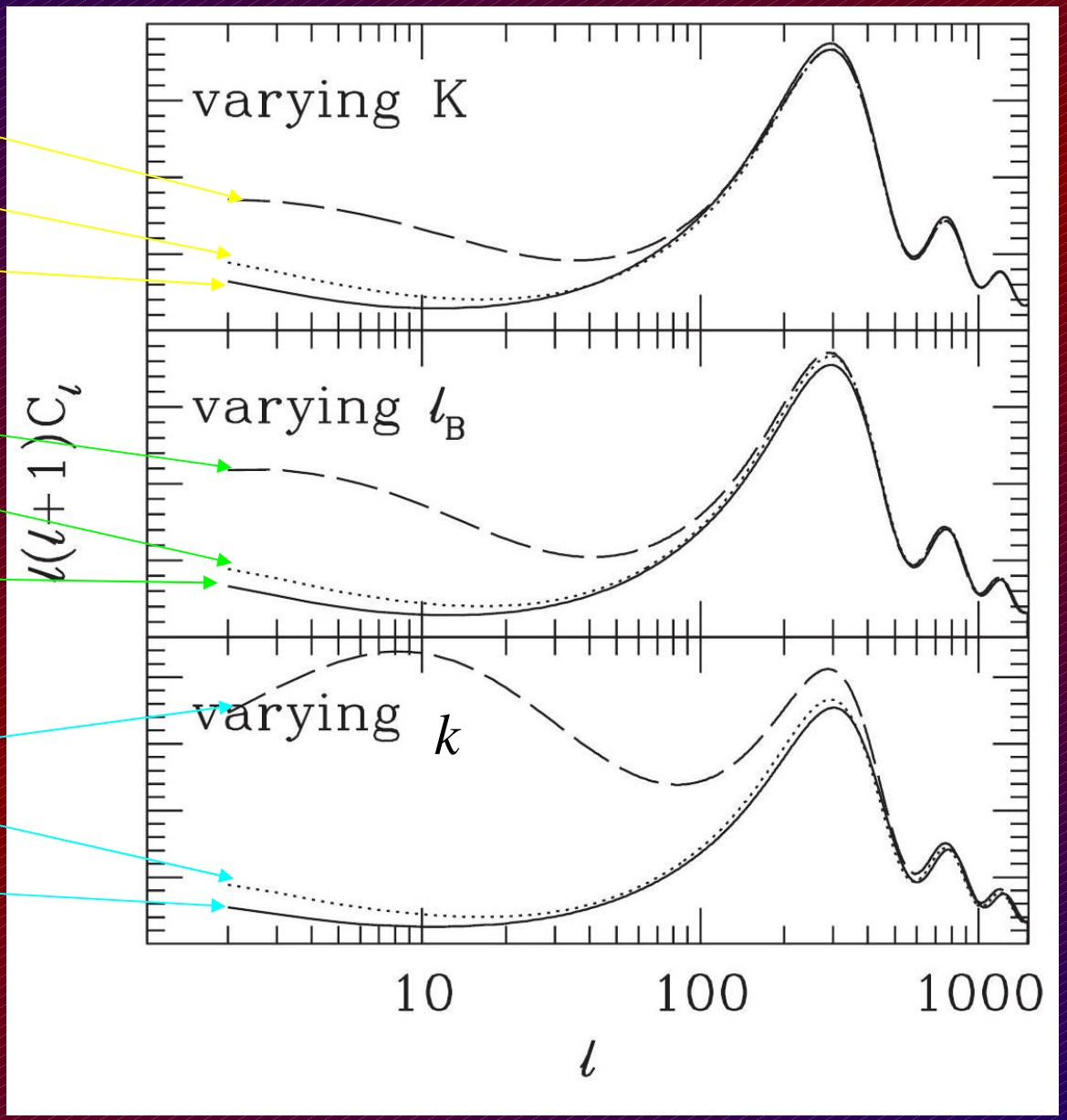
$$\Delta\Omega_p < 0.05''/century$$

$$\rightarrow\ a_p < 4\times10^{-10}\,cm/s^2$$

$$\Delta M_{sun} = a_p\left(r_2^2 - r_1^2\right)$$

$$\frac{\Delta M_{sun}}{M_{sun}} = \frac{\Delta P}{2P} + \frac{3\Delta r}{2r}$$

TeVeS & CMB



0.08
K = 0.1
1

10 Mpc
l = 100 Mpc
1000 Mpc

0.16
k = 0.12
0.025

l = 100 Mpc
k = 0.12

K = 0.1
k = 0.12

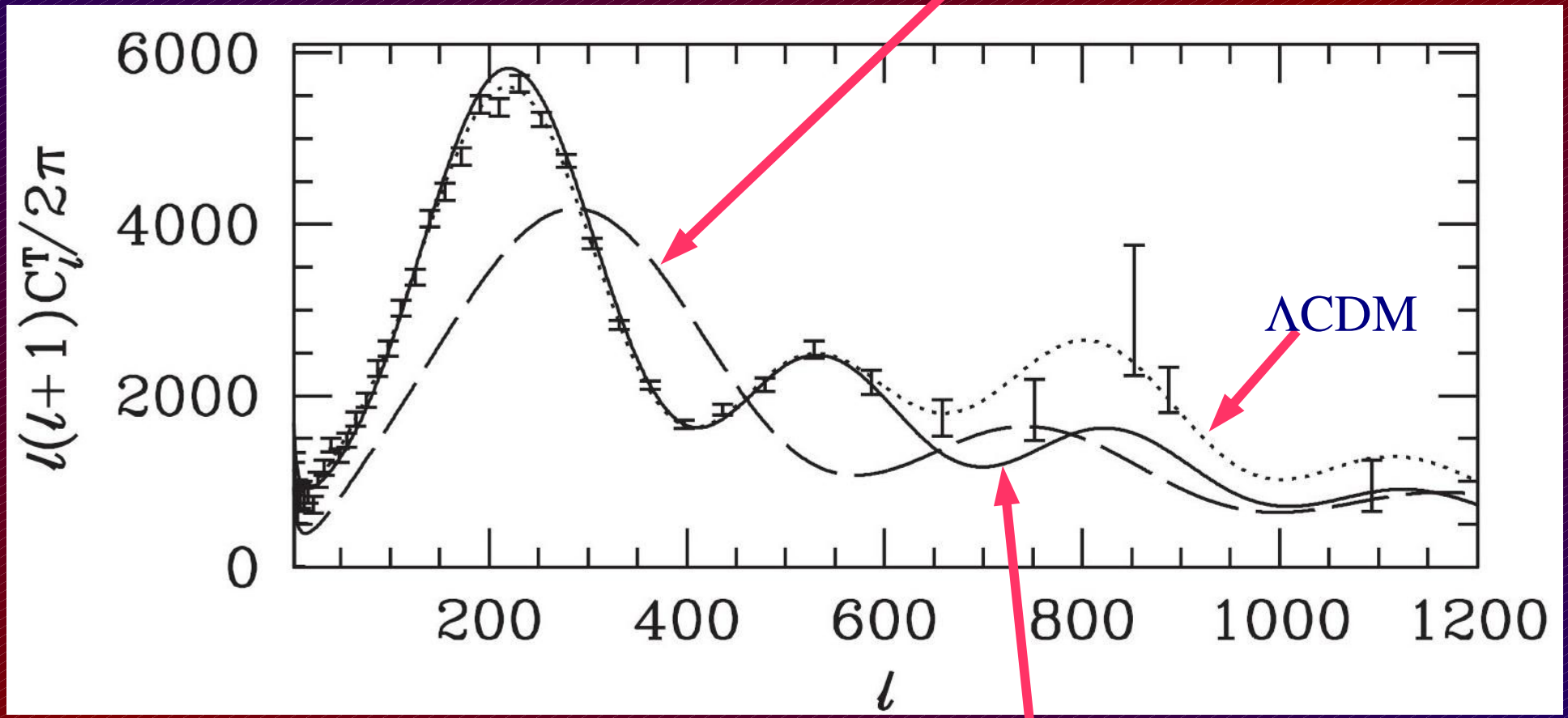
K = 0.1
l = 100 Mpc

Skordis et al. (2006)

TeVeS & CMB

$a_0 = 4.2 \times 10^{-8}\, cm/s^2$

$\Omega_\Lambda = 0.95$, $\Omega_B = 0.05$



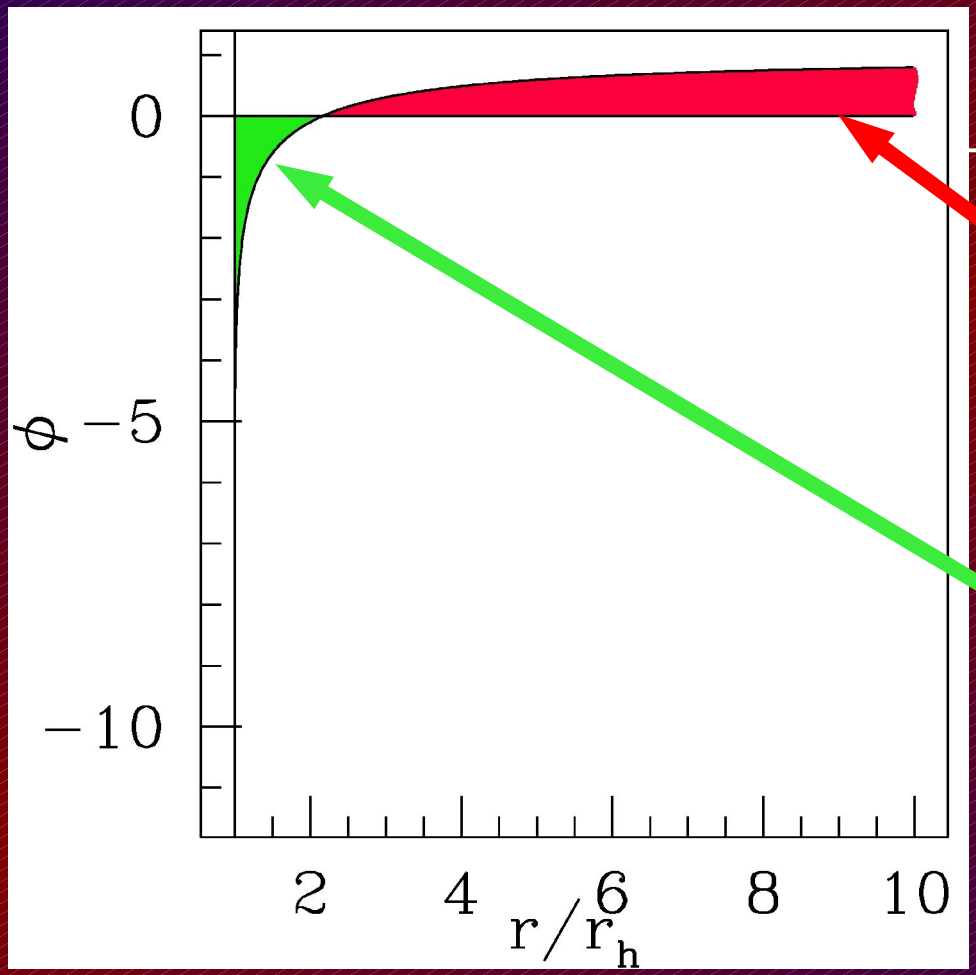
Skordis et al. (2006)

$\Omega_\Lambda = 0.78$, $\Omega_\nu = 0.17$, $\Omega_B = 0.05$, $m_\nu \sim 2\,eV$

TeVeS & BH's

Giannios PRD 71 (2005): Spherically Symmetric Static TeVeS Solutions

$$U^r = 0 \;,\; U^t \neq 0 \;\rightarrow\; \tilde{g}_{ab} = \text{Schwarzschild}$$



$$\rightarrow\; \phi(r) = \phi_0 + C \ln\left(\frac{r - r_h}{r + r_h}\right)$$

Causal Perturbations

$\phi > 0$

Acausal Perturbations

$\phi < 0$

TeVeS & BH's

Giannios PRD 71 (2005): Spherically Symmetric Static TeVeS Solutions

$$U^r \neq 0 \;,\; U^t \neq 0 \qquad k, K, \phi_c \ll 1$$

$$\gamma = 1$$

$$\beta = 1 + \frac{k}{8\pi} + \frac{K}{4} + \phi_c \left(3 + \frac{k}{\pi K} \pm \sqrt{\frac{2k}{\pi K} + 5} \right)$$

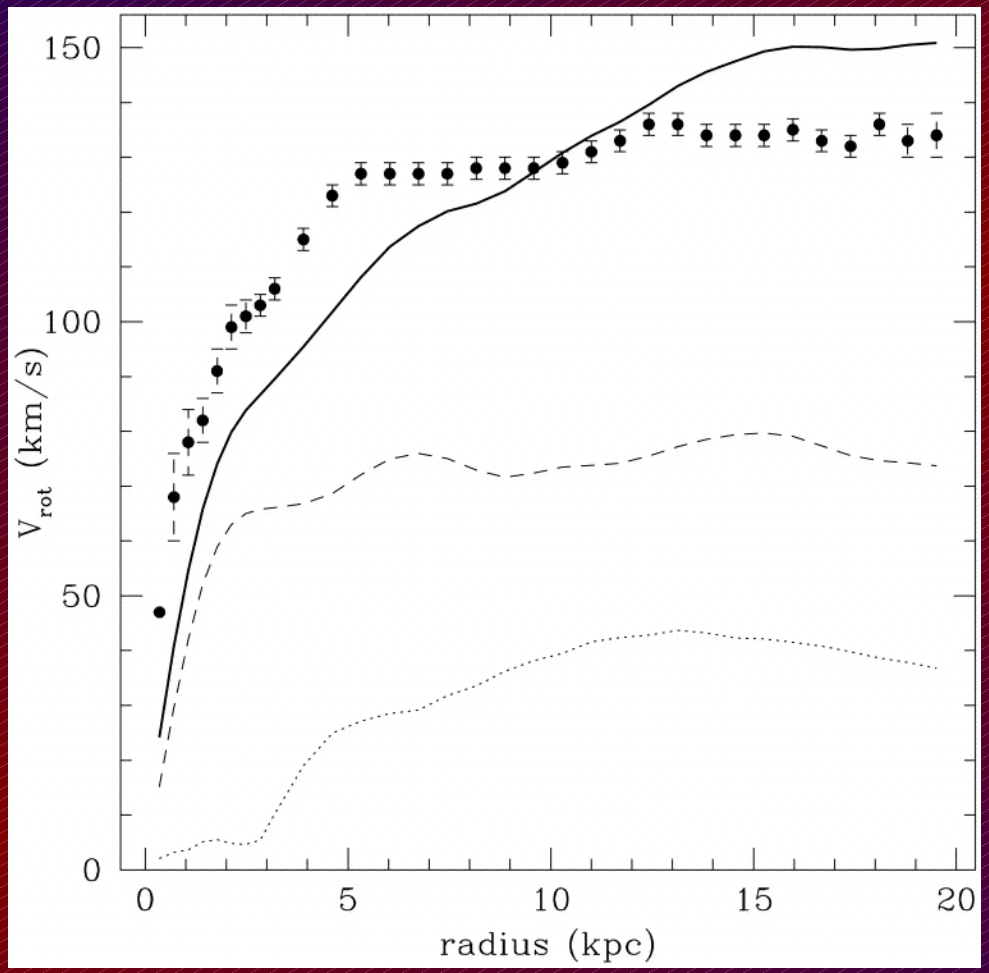
--> lunar laser ranging : $\beta - 1 < 10^{-4}$

Summary

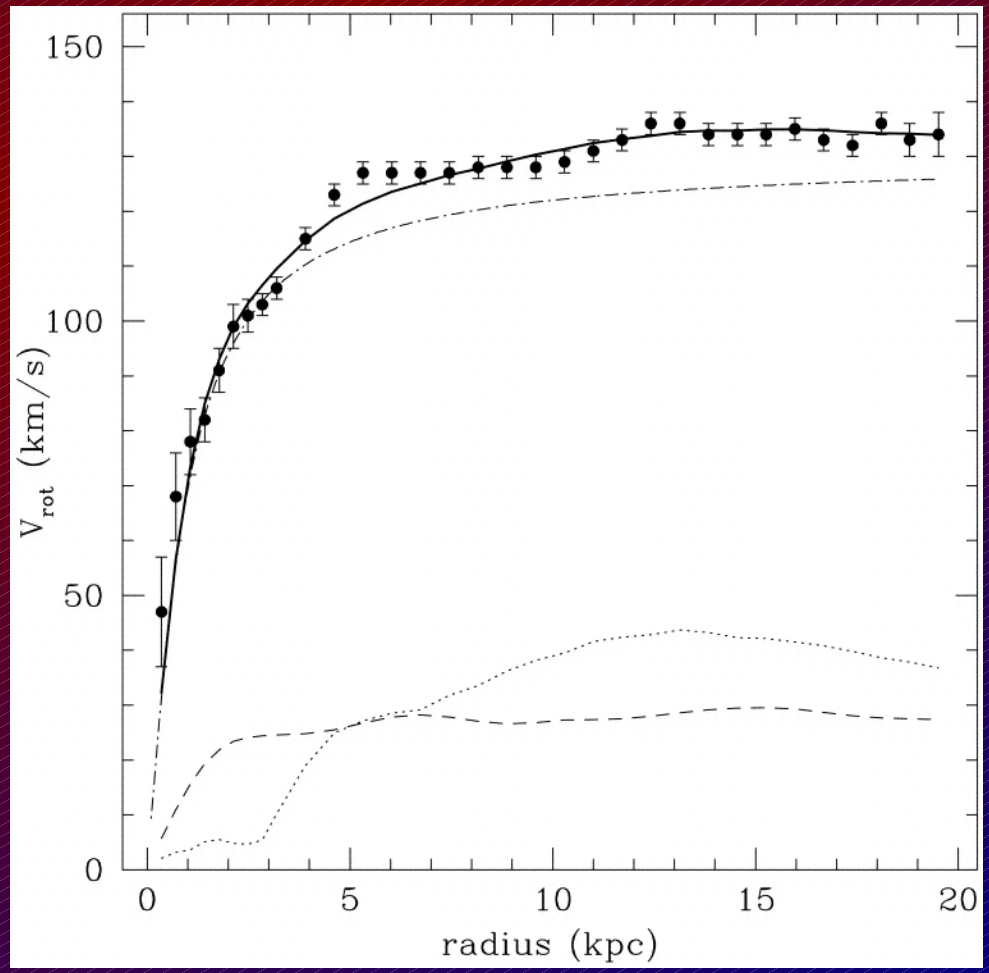
- MOND: galaxies good, cosmology... not so good
- TeVeS is complicated
- TeVeS --> MOND --> TeVeS is good with galaxies too
- TeVeS can fit solar system constraints
- TeVeS is bad with cosmology too
- TeVeS has same GR Schwarzschild solution
  - ...if you don't care about causality (maybe not a prob.)

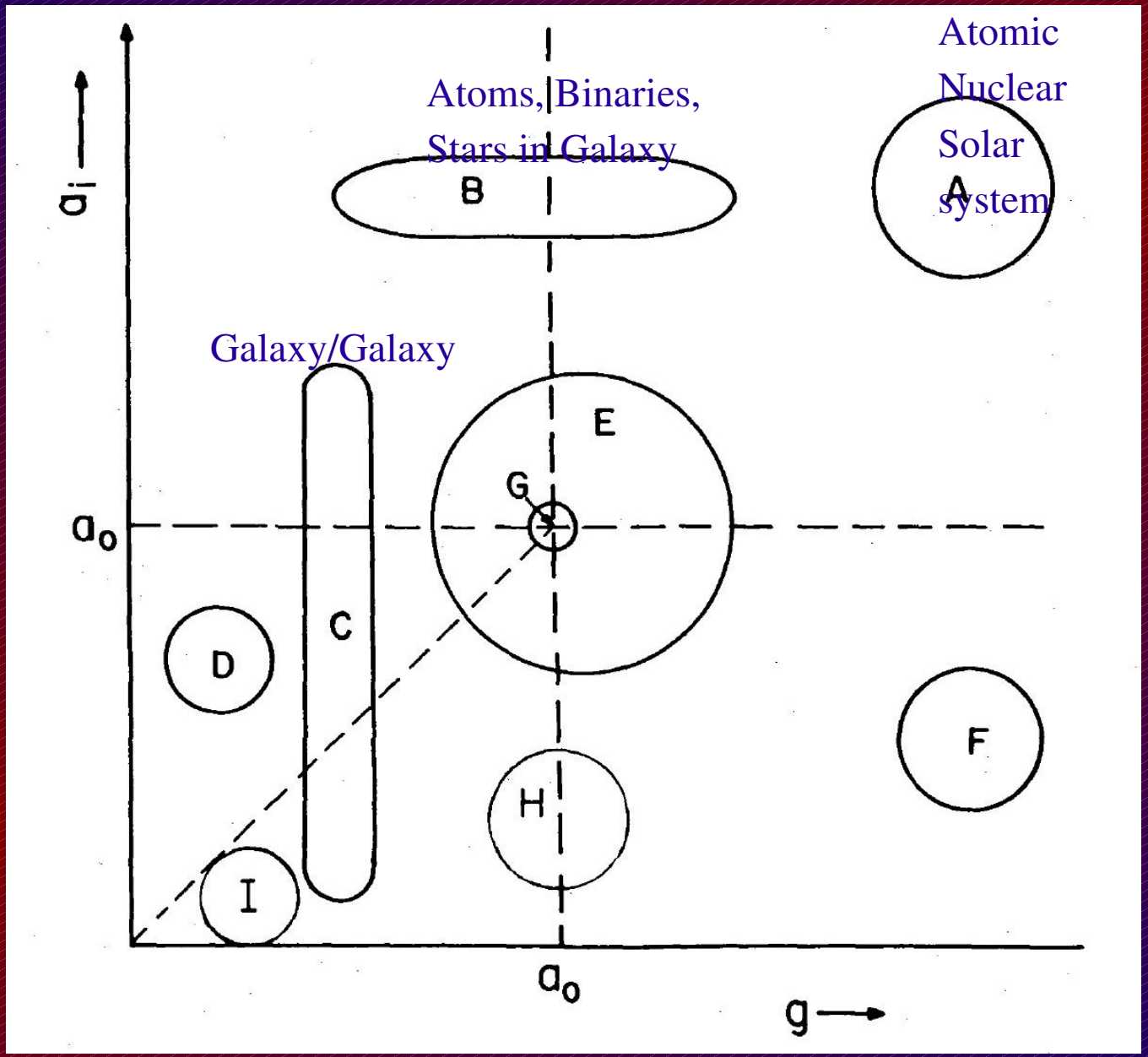
Consistency Test:

MOND



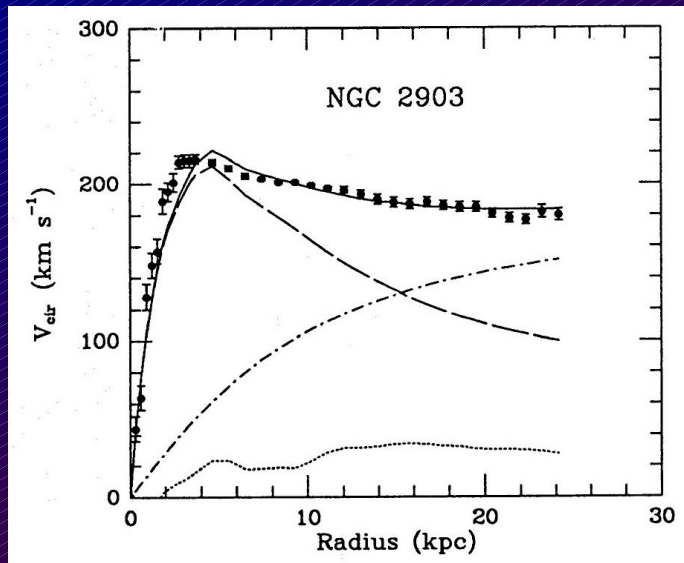
DM

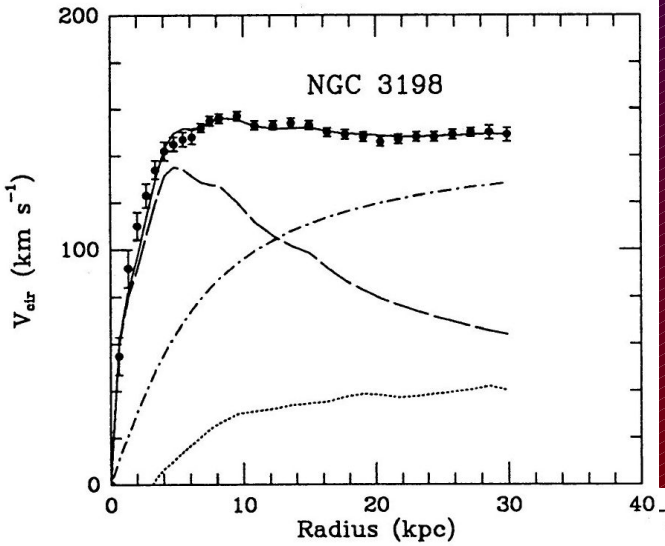


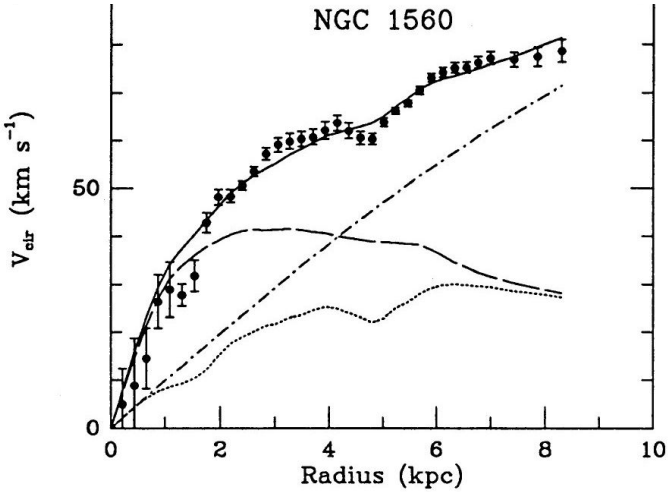


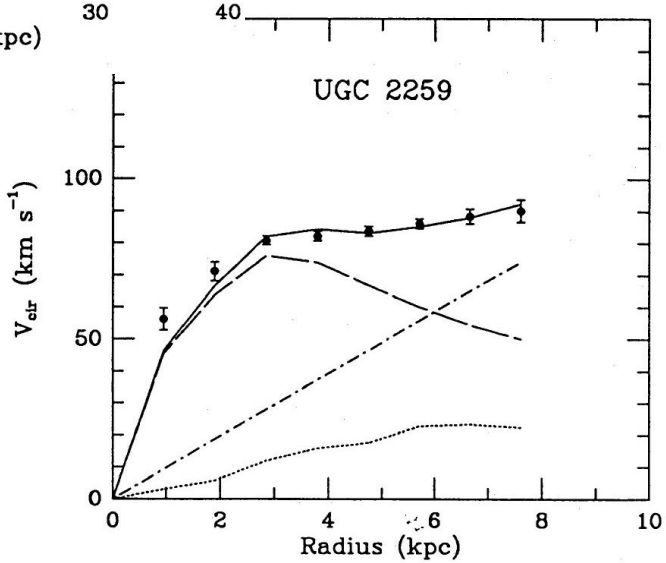
Milgrom (1983)

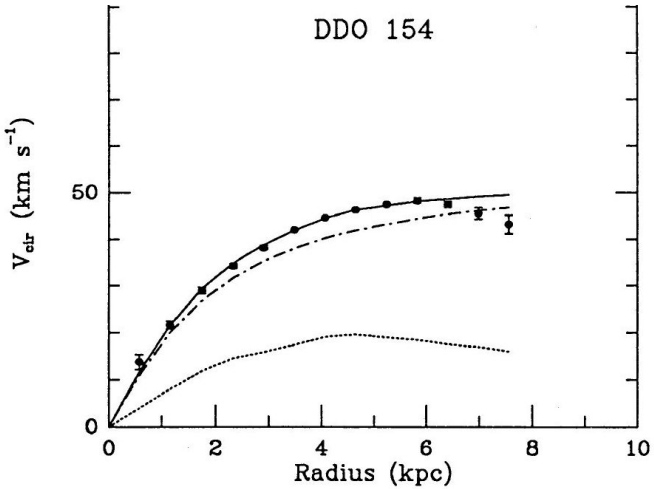
More DM velocity fits

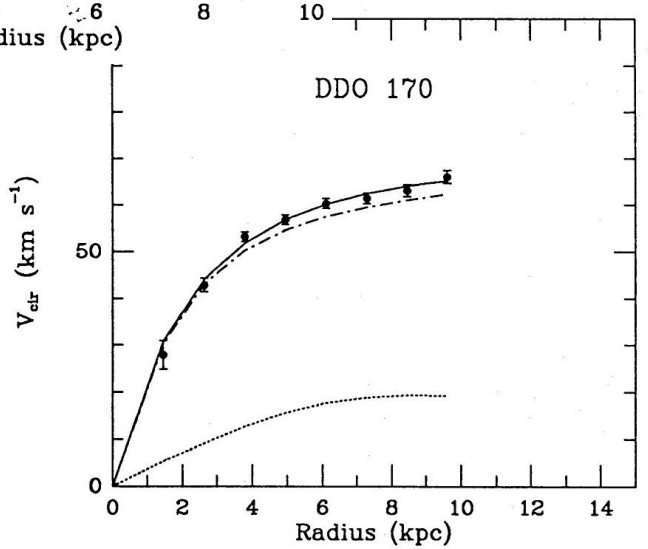












Z = 0

Z = 5

ΛCDM

MOND