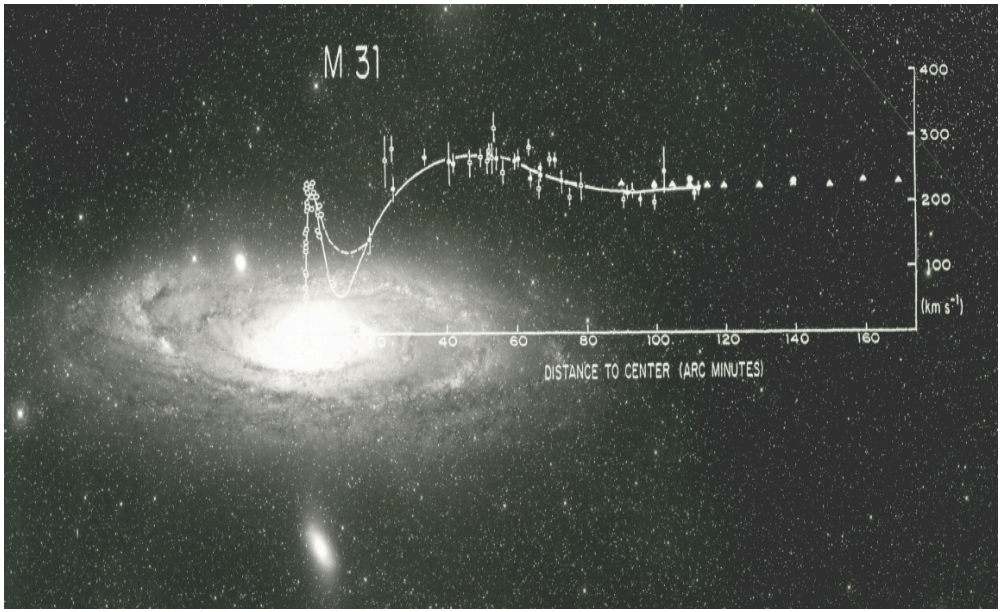
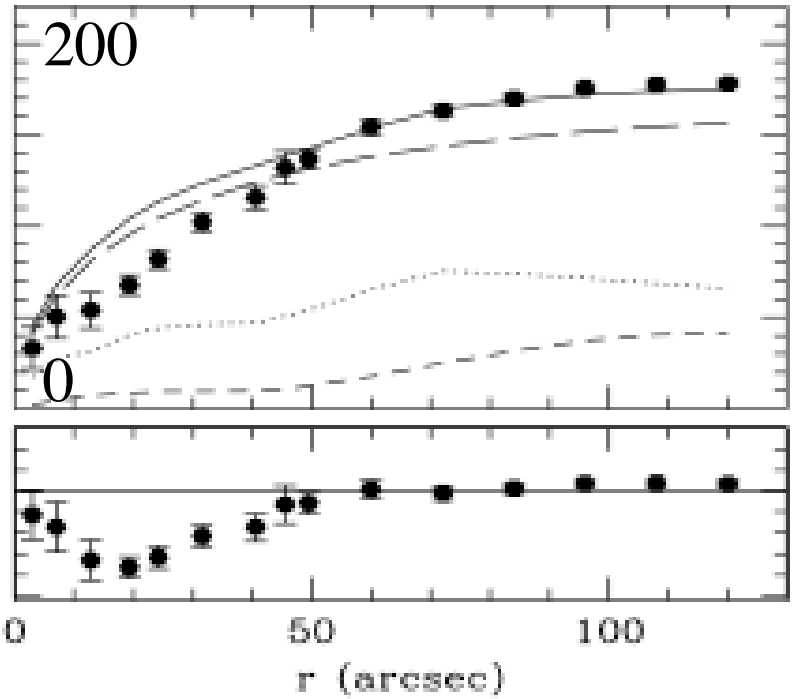
MOND: where (and why??) does it work? Where does it not?

Benoit Famaey (Brussels-ULB)



The cusp problem

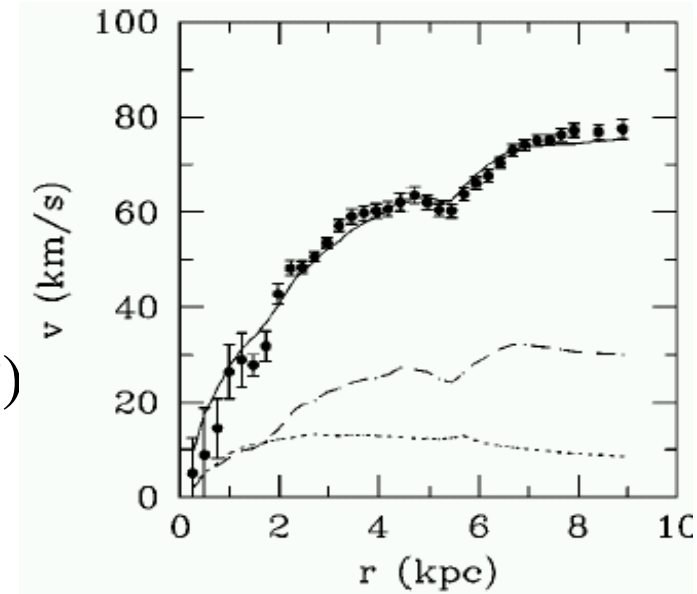
- Simulations of clustering CDM halos (e.g.Diemand et al.) predict a central cusp $\rho \propto r^{-\gamma}$, with $\gamma > 1$
- Feedback from the baryons makes the problem worse
- Angular momentum transfer from the bar?
- WDM?
- Other solutions?
- Hiding cusps by triaxiality of the halo? No

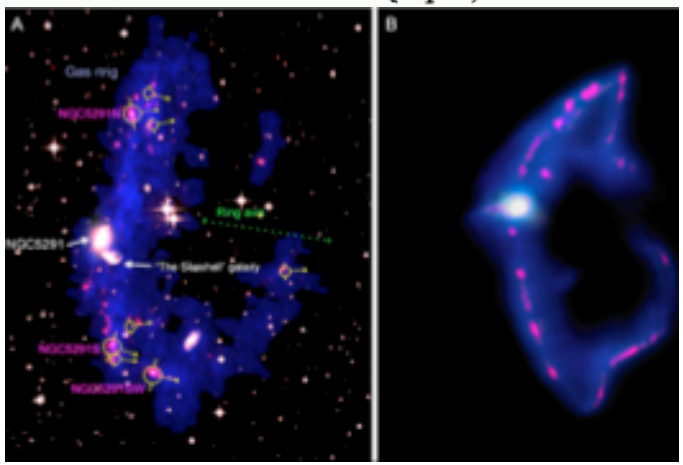


ESO79-G14 (Gentile et al. 2004)

The « conspiracy » problem

- Each time one sees a feature in the light, there is a feature in the rotation curve (Sancisi's rule)
- **Baryonic Tully-Fisher** relation $V_\infty^4 \propto M_{bar}$ (tight->triaxiality of halo?)
- Tidal Dwarf Galaxies with DM? (Bournaud et al. 2007 Science)
- Amount of DM determined by the distribution of baryons at all radii and wiggles of rotation curves even follow wiggles of baryons (**TF at all radii**)





The conspiracy can be summarized

Correlation summarized by this formula in galaxies (Milgrom 1983):

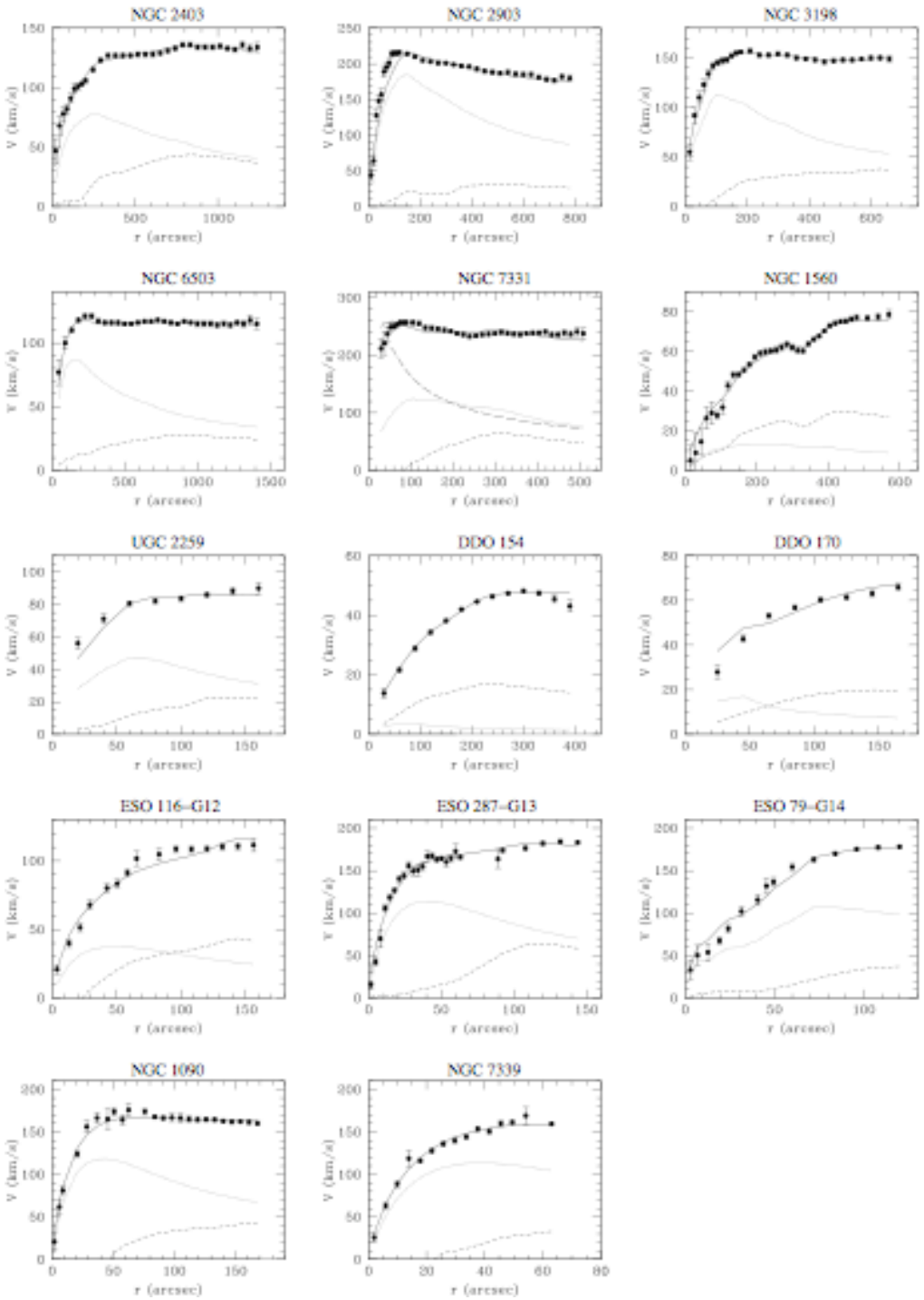
$\mu\,(V^2/ra_0)\,V^2/r = g_{\mathrm{N\ bar}}$ where $a_0 \sim cH_0 \sim c\Lambda^{1/2}$

with $\mu(x) = x$ for $x \ll 1$

$\mu(x) = 1$ for $x \gg 1$

The formula fits >2000 galaxy rotation curves data points!

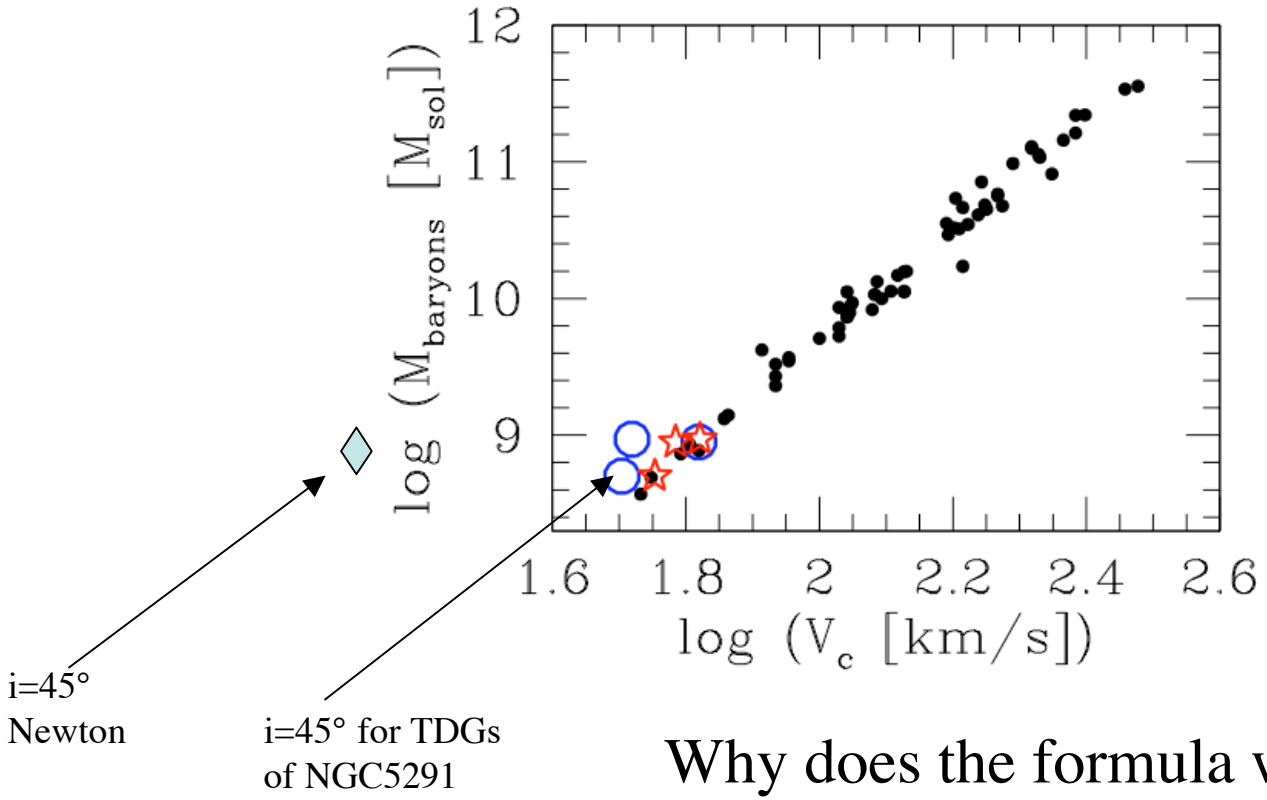
- Plateau of the Tully-Fisher relation (observed with small scatter): $V_\infty^4 = GM_{\mathrm{bar}}a_0$
- Discrepancy always appear at $V^2/r \sim a_0$ => in LSB where $\Sigma << a_0/G$
- Explains the RC wiggles following the baryons



Famaey et al. 2007

Conspiracy 10^8 -> 10^{12} baryonic M_{sun}

(Gentile et al. 2007)



Why does the formula work in CDM and CDM-free galaxies???

CDM MOND

- Rot. Curves HSB
- Rot. curves LSB
- Rot. curves TDG

Does MOND always work?

Not really:

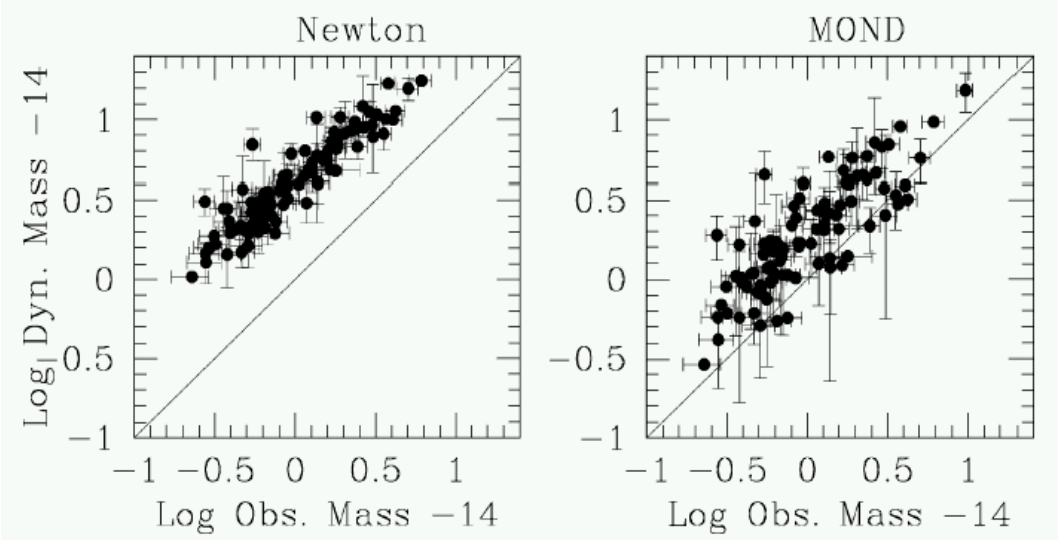
- Galactic lensing: generally **ok** but a few outliers at the center of groups and clusters (Shan et al. 2008)
- Velocity dispersion profiles of ellipticals: generally **ok** (Tiret et al. 2007) but a few outliers at the center of clusters (Richtler et al. 2008)
- Velocity dispersion profiles of dwarf spheroidals: generally **ok** but not (yet) for Sextans and Draco (Angus 2008)

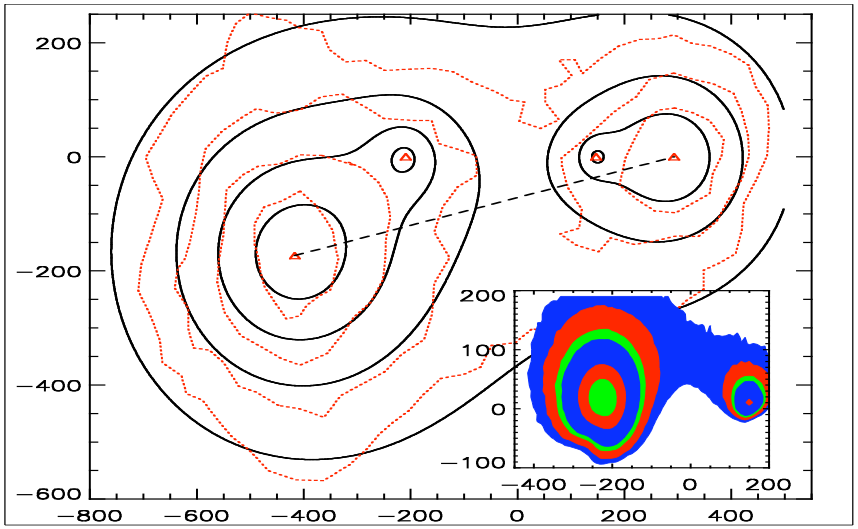
=> Not JUST modified gravity, probably needs some dark mass

Galaxy clusters

- But the purpose of the formula is to explain the conspiracies between observed baryons and the gravitational field in galaxies, **not necessarily to get rid of dark matter**
- In X-ray emitting rich galaxy clusters:

  $g(r) = -kT(r)/r\langle m\rangle\,[d\ln\rho_x/d\ln r + d\ln T/d\ln r]$
- In the bullet cluster: it really is collisionless dark matter (but not as much as in CDM, Angus et al. 2007)

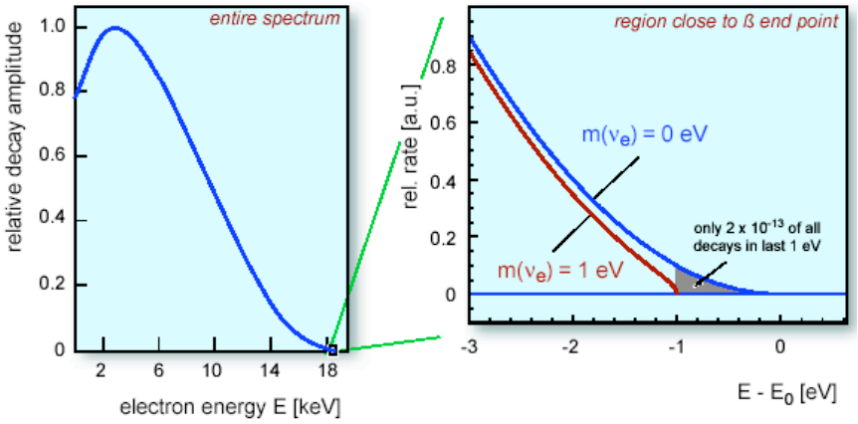




	CDM	MOND
• Rot. curves HSB		
• Rot. curves LSB		
• Rot. curves TDG		
• Ellipticals	--	--
• dSph		--
• Clusters of galaxies		

Ordinary neutrinos?

- KATRIN: β-decay of tritium (^{3}H) into Helium 3 ion + electron + neutrino

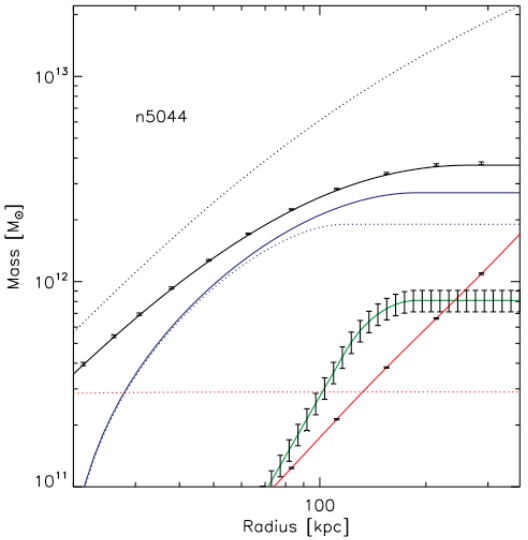


- Tremaine-Gunn limit for 2 eV neutrinos:

  ρ_ν (max) $\propto$ T $^{3/2}$

  => Problem for X-ray emitting groups with T<2 keV

  (Angus, Famaey & Buote 2008)



Other solutions

• **Note that 90% of the baryons are unseen**

How many baryons in WHIM (10^5K)? 30 - 90%?

10-20% of missing baryons is largely enough to explain the discrepancy, even without neutrinos

BUT bullet => collisionless => BDM in the form of **e.g. dense clumps of cold gas** (Pfenniger & Combes 1994) but then, X-ray emission from cloud-cloud annihilation? (Milgrom 2007)

+ Why only in clusters and groups??

• Maybe another fermionic dark **HDM** particle?

NOT clustering in galaxies

(1 light **sterile neutrino** with $m_\nu \sim$ 7-11eV ?)

+ present in elliptical galaxies at the center of clusters!!

	CDM	MOND+HDM
• Rot. curves HSB		
• Rot. curves LSB		
• Rot. curves TDG		
• Ellipticals	--	
• dSph		--
• Clusters of galaxies		
• CMB		
• Large scale structure		??

Globular clusters

- Palomar 14: fluffy and weak influence of the Milky Way gravitational field
- σ_N=0.5 km/s and σ_M=1.3 km/s (Baumgardt et al. 2005)

- Preliminary observations indicate 0.5 km/s …

- If MOND predicts too much gravity, adding negative mass would be a step too far…

	CDM	MOND+HDM
• Rot. curves HSB		
• Rot. curves LSB		
• Rot. curves TDG		
• Ellipticals	--	
• dSph		--
• Clusters of galaxies		
• CMB		
• Large scale structure		??
• Globular clusters		 ?

	CDM	MOND
• Rot. curves HSB		
• Rot. curves LSB		
• Rot. curves TDG		
• Ellipticals	--	--
• dSph		--
• Clusters of galaxies		
• CMB		
• Large scale structure		??
• Globular clusters		 ?

Baryon-DM interaction?

- Keep the CDM phenomenology EXCEPT in low acceleration AND high medium density environment

  (in galactic discs, typically 10^{-21} kg/m^3)

- Bruneton et al. 2009:

$$S = S_{EH}[g\mu\nu] + S_{SM}[\psi, g_{\mu\nu}] + S_{DM}[\chi, g_{\mu\nu}] + S_{int}[\chi, \psi, g_{\mu\nu}]$$

Only in low acc.
high gas den.

	CDM	MOND
• Rot. curves HSB	←	🙂
• Rot. curves LSB	←	🙂
• Rot. curves TDG	←	🙂🙂
• Ellipticals	--	
• dSph	🙂	
• Clusters of galaxies	🙂	
• CMB	🙂	
• Large scale structure	🙂🙂	
• Globular clusters	🙂	