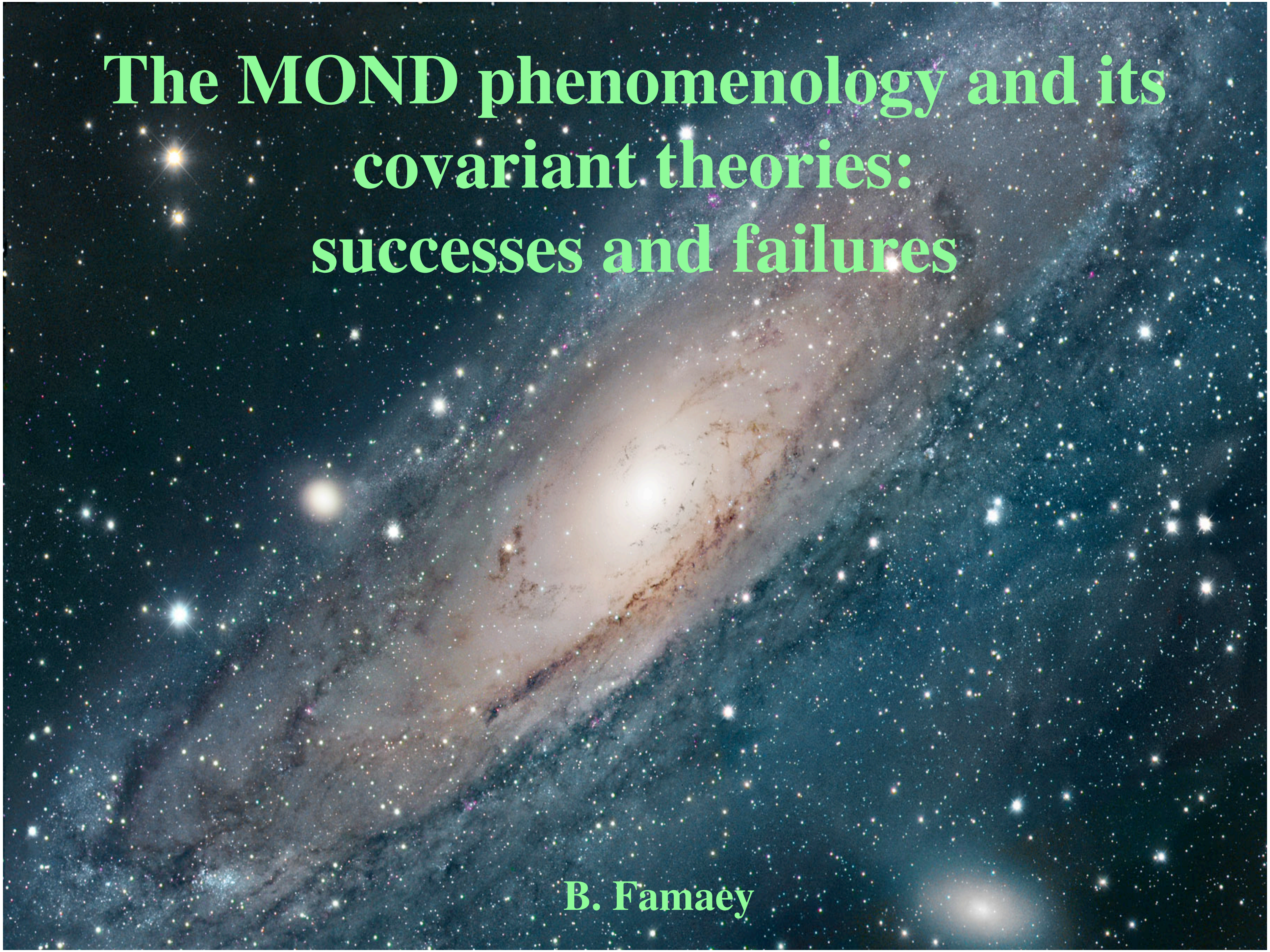
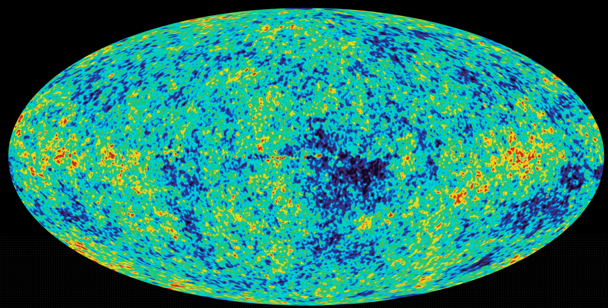
The MOND phenomenology and its covariant theories: successes and failures

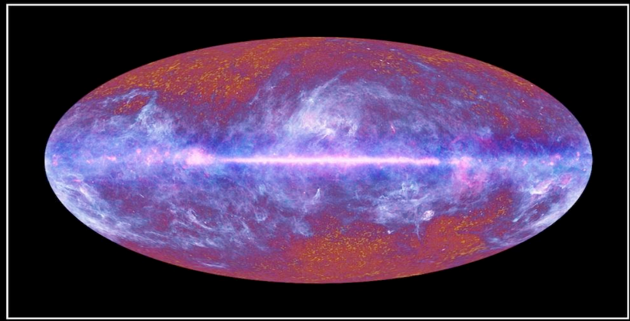


B. Famaey

The ΛCDM model of the Universe

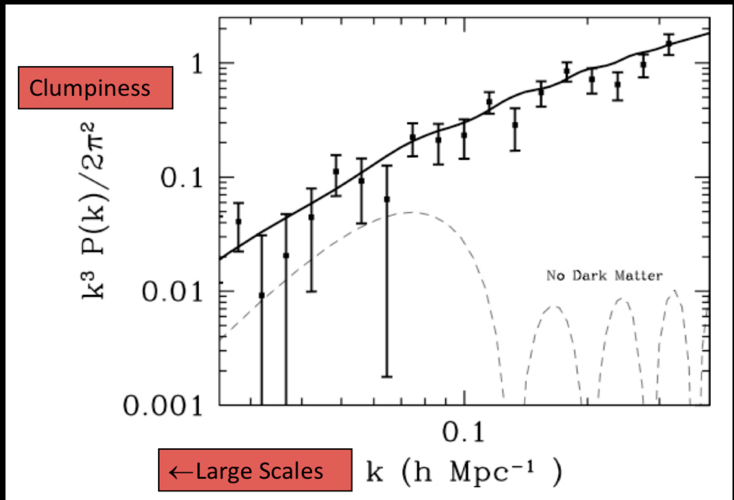
(i) Cosmic Microwave Background (WMAP, Planck soon)





The Planck one-year all-sky survey esa (c) ESA, HFI and LFI consortia, July 2010

(ii) Matter power spectrum (SDSS)



(iii) Type Ia supernovae

(iv) Weak lensing; (v) strong lensing; (vi) temperature profiles of intracluster gas; (vii) velocity dispersion profiles of pressure-supported galaxies; (viii) rotation curves of spiral galaxies (?)

Challenges

(i) Fine-tuned value of Λ

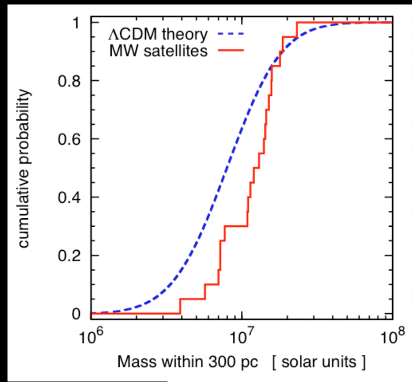
(ii) Missing satellite problem

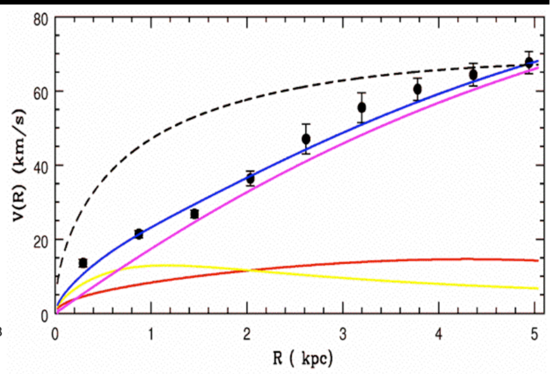
(iii) Cusp problem

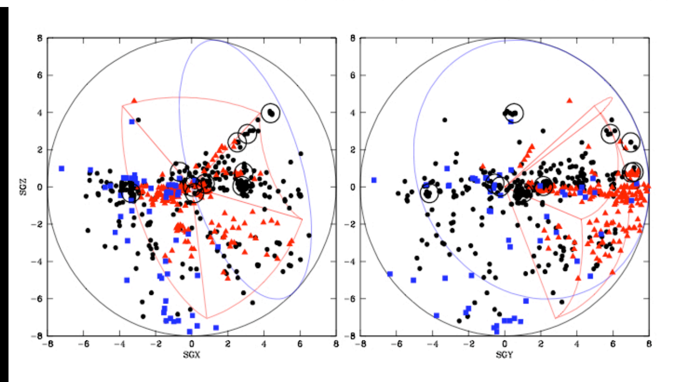
(iv) Angular momentum problem

(v) Phase-space correlation problem

(vi) Local Void problem

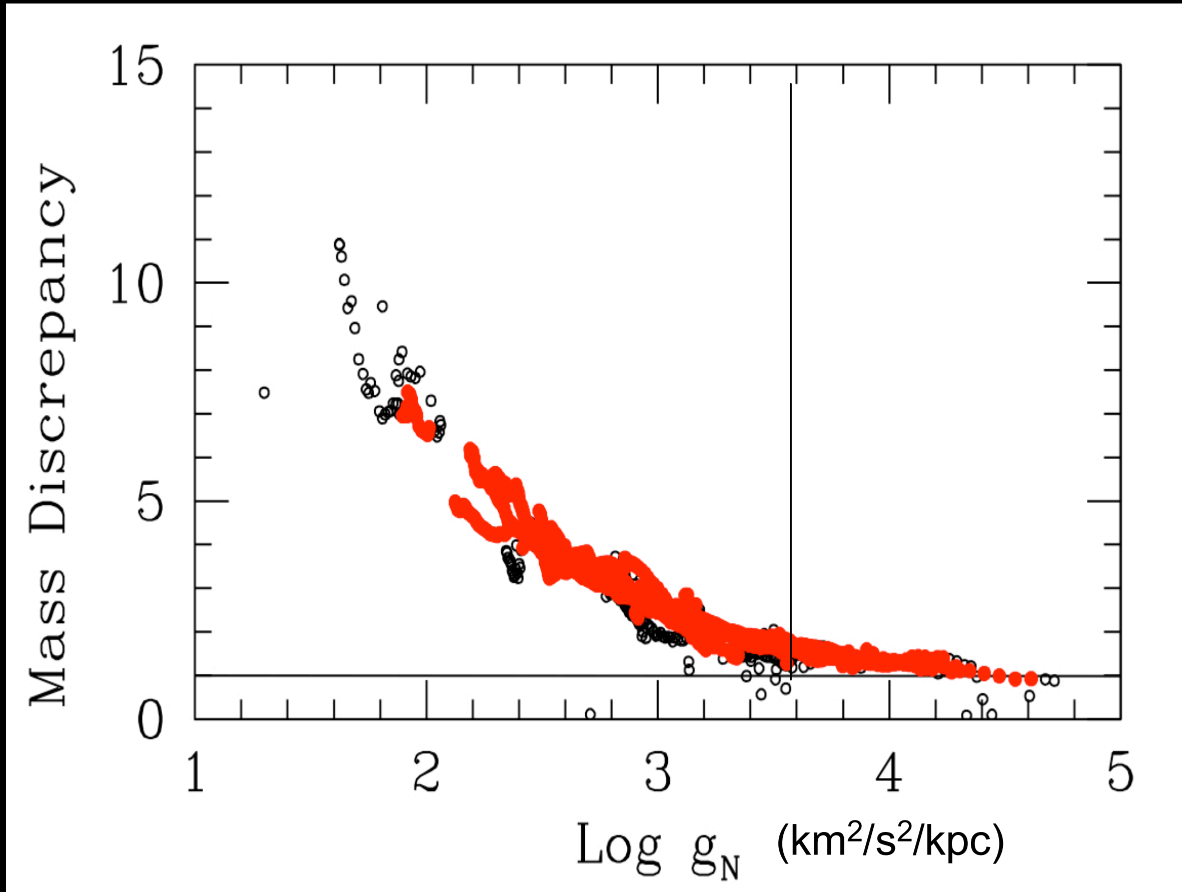






(vii) Scaling relations :
(i) Tully-Fisher $V_\infty^4 \propto M_{bar}$: slope, zero point and small scatter; (ii) Mean surface density within r_0; (iii) one-to-one correlation between total and baryonic gravitational fields (MDA or the « conspiracy » problem)

Mass Discrepancy vs Acceleration



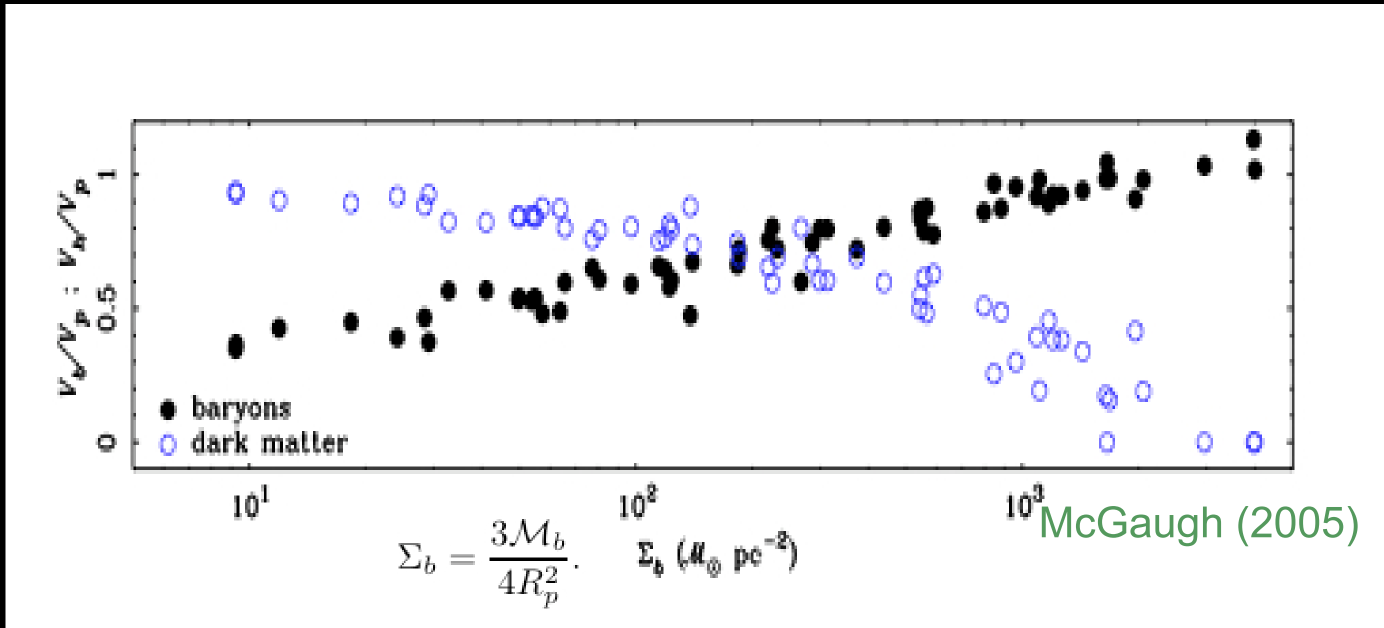
At small *a*:

$M_{tot}/M_{bar} = a^{-1}$

in units of the transition acceleration a_0 such that $\Lambda = (a_0/c)^2$ in s^{-2}

McGaugh 2004; Gentile, Famaey & de Blok 2010

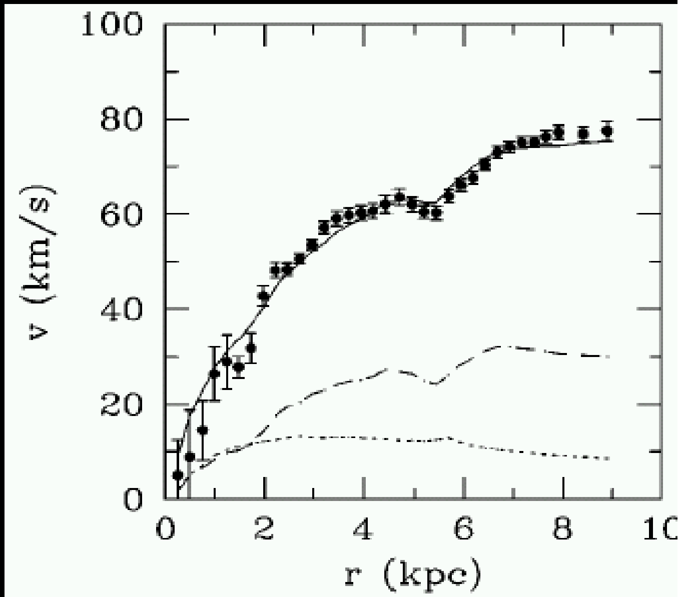
A fine balance of DM and baryons



- R_p= radius of max contribution of both gas and stars to the RC
- Comparing the contribution of baryons to the RC as a function of surface density (proxy for characteristic acceleration)
- This could point at some **repulsion** between surface densities of baryons and DM
- MDA (and this MDsurfden) is ***history-independent*** !

Sancisi's rule: locally no repulsion

Each time one sees a feature in the light, there is a feature in the rotation curve (Sancisi's rule)



⇒ Dark baryons as dark matter?

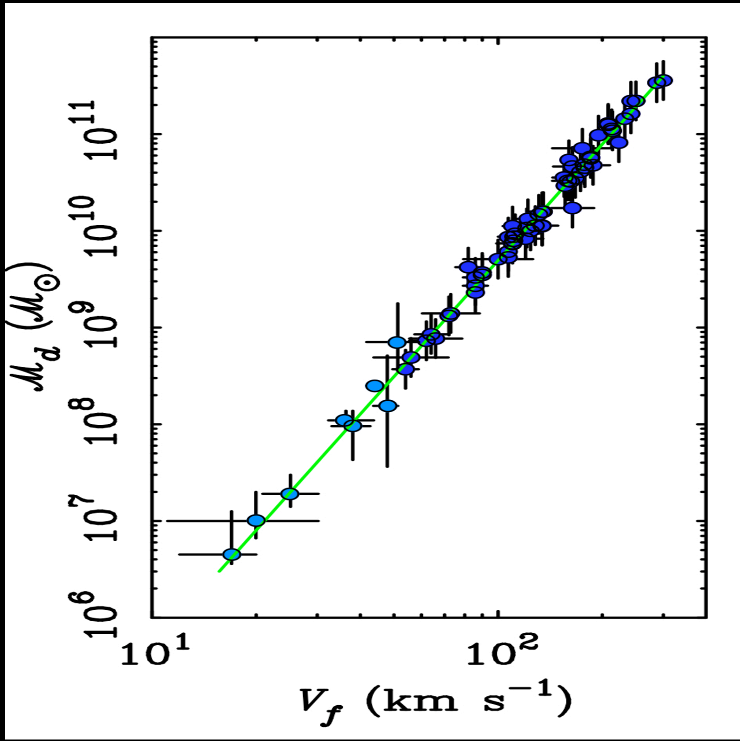
(Pfenniger & Combes 1994)

MDA asymptotes to BTF

At small accelerations, the mass discrepancy is $\boxed{M_{tot}/M_{bar} = a_0/a}$

$$\Rightarrow V^2 = GM_{tot}/r = GM_{bar}a_0/(ar) = GM_{bar}a_0/V^2$$

$$\Rightarrow V^4 \propto M_{bar}$$



Evolution of the BTF with z?

If the BTF evolves or not, and if there is something fundamental about the value of a_0, it would allow to know whether the fundamental relation is :

$a_0/c = H_0$

or

$(a_0/c)^2 = \Lambda$

or

a coincidence

The MDA can be summarized by Milgrom's formula

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

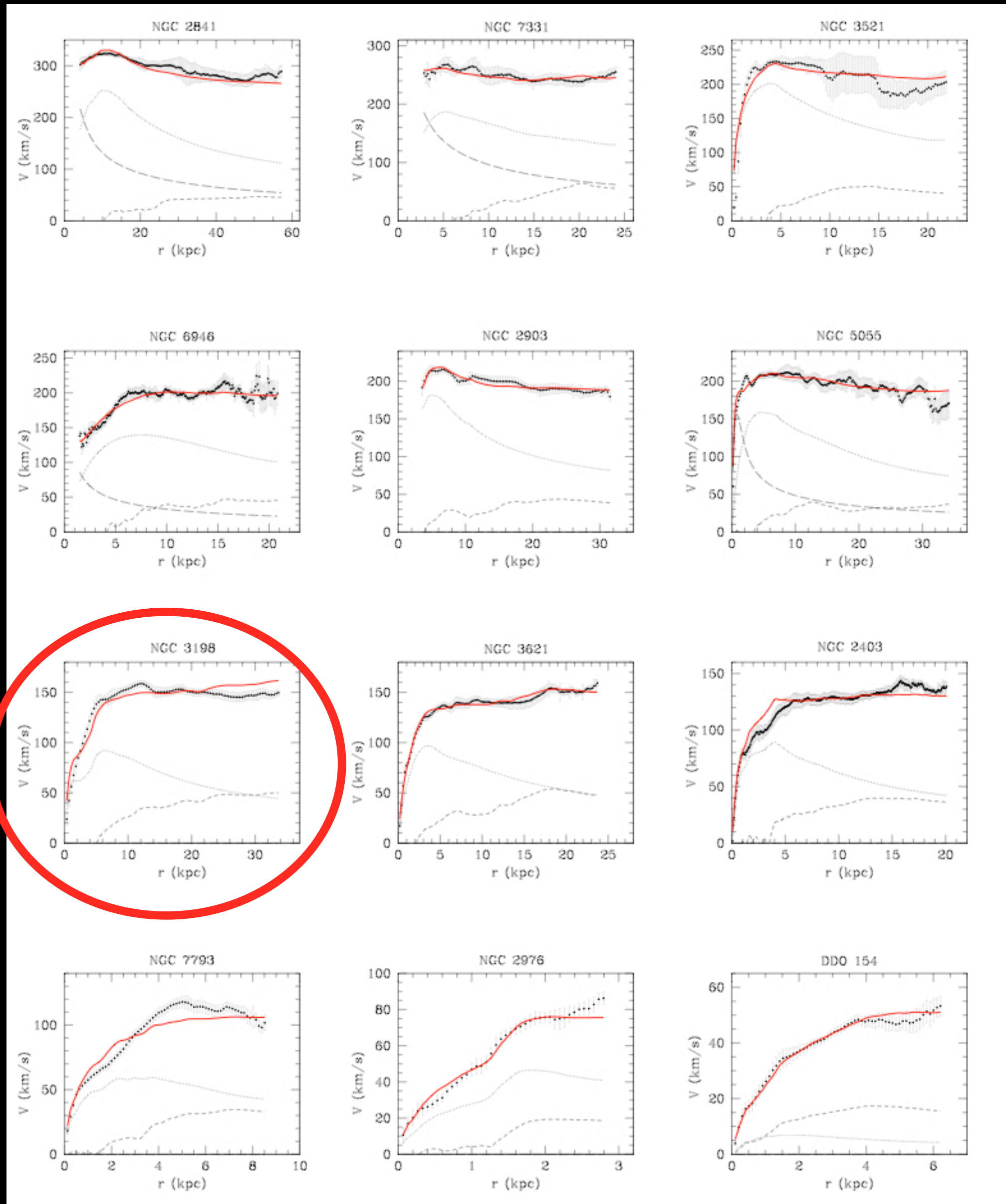
$\mu\,(g/a_0)\; g = g_{\mathrm{N\;bar}}$ or $\nu\,(g_{\mathrm{N\;bar}}/a_0)\; g_{\mathrm{N\;bar}} = g$

with $\mu(x) = x$ or $\nu\,(x)=x^{-1/2}$ for $x \ll 1$ (deep-MOND)

$\mu(x) = \nu\,(x)= 1$ for $x \gg 1$ (Newtonian)

This formula fits >2000 galaxy rotation curves data points with *stellar M/L* as the only free parameter (*distance* can also slightly vary within observational errors)

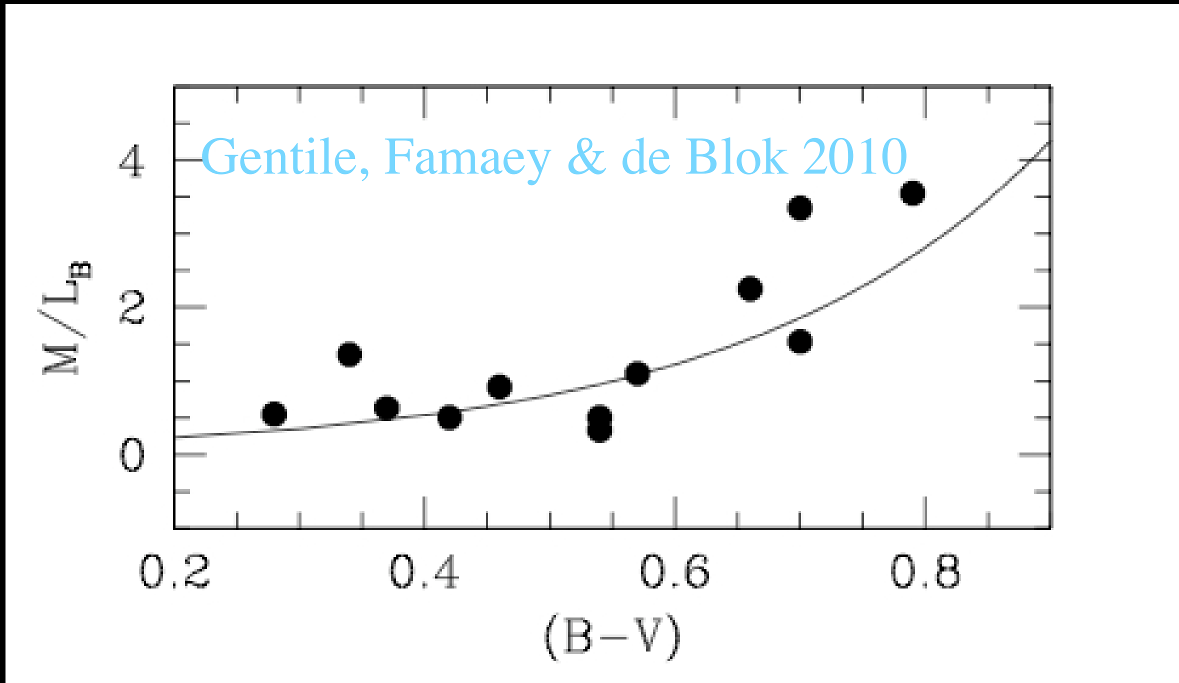
$\mu(x)=x/(1+x)$



Might indicate a smaller value of

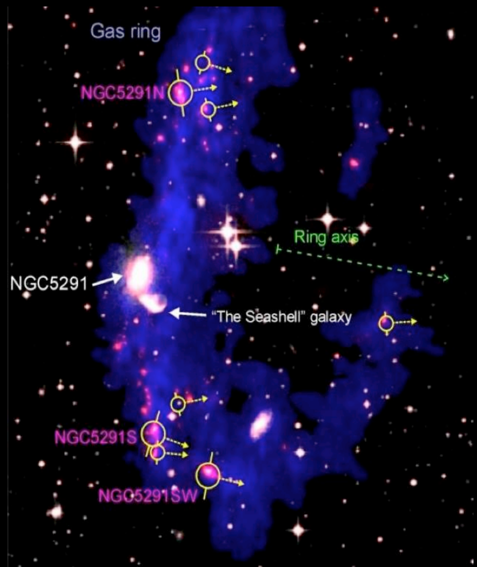
a_0=0.9 x 10-8 cm/s^2

THINGS (Gentile, Famaey & de Blok 2010)



M/L follows predictions of population synthesis models

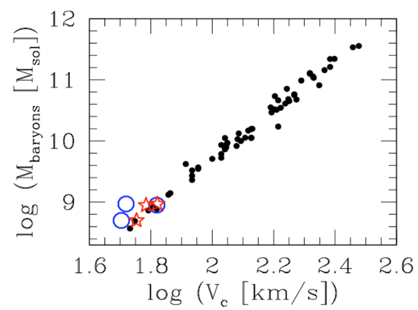
In BDM-dominated tidal dwarfs too

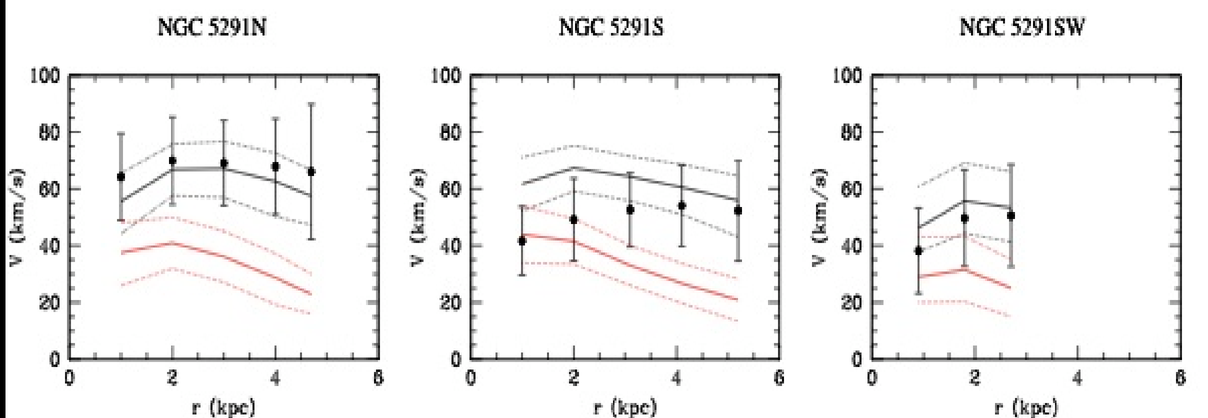


Tidal dwarf galaxies in the NGC 5291 system

Bournaud et al. (2007)

Gentile, Famaey et al. (2007)





They fall on the BTF: why?

If ΛCDM is correct

- The success of the MOND formula in rotationally supported gas-dense galaxies is a consequence of the feedback from the complex baryon physics (stellar winds and supernova explosions)

- $\Lambda = (a_0/c)^2$ would just be a coincidence since DM and DE are completely unrelated sectors

=> However, this all needs a true fine-tuning to reproduce this history-independent relation (both in CDM-dominated and BDM-dominated galaxies)

Formula cannot be exact

If we interpret it as *modified gravity*, for a point mass in the deep-MOND limit:

$g = (GMa_0)^{1/2} / r$

=> $F_m = m\,(GMa_0)^{1/2} / r$

BUT $F_M = M\,(Gma_0)^{1/2} / r$

Corresponding modification of Newtonian gravity (MOND and QUMOND):

$$\boxed{\nabla . \left[\mu \left(\left| \nabla \Phi \right| / a_0 \right) \nabla \Phi \right] = 4 \pi G \rho_{\mathrm{bar}}}$$

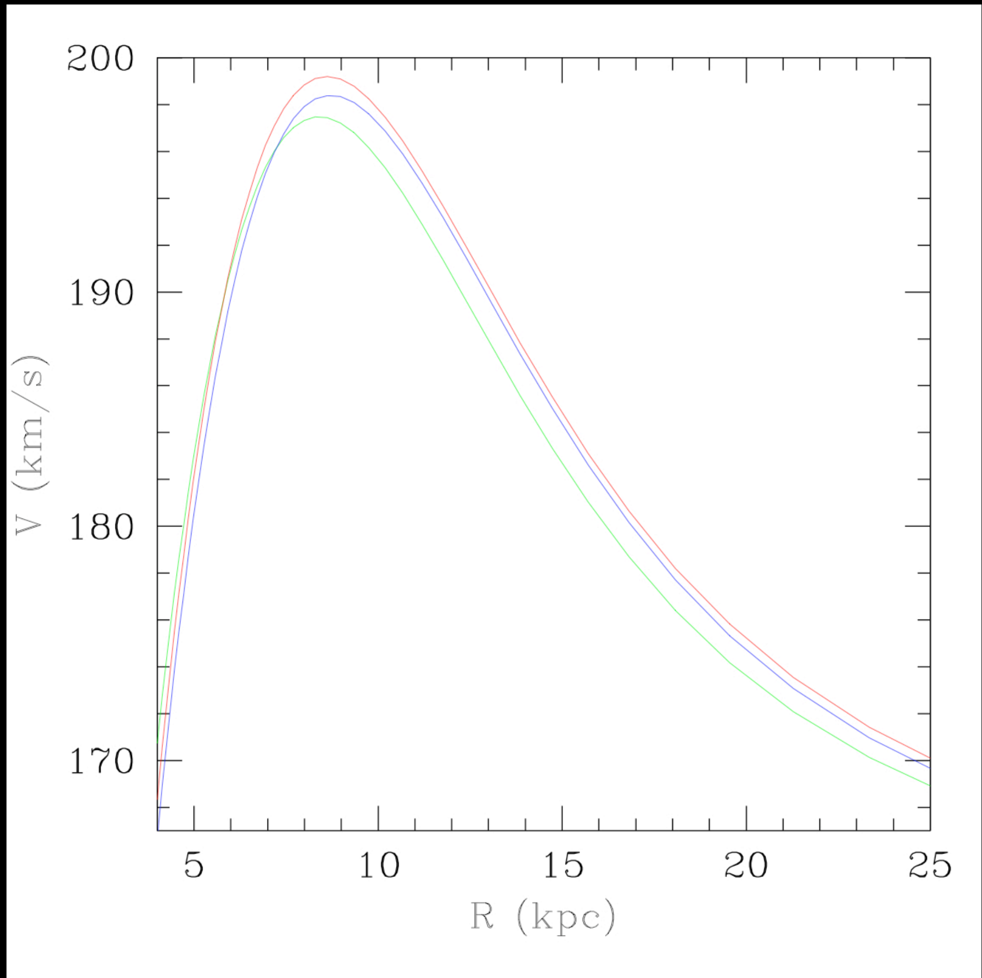
OR

$$\boxed{\nabla^2 \Phi = \nabla . \left[\nu \left(\left| \nabla \Phi N \right| / a_0 \right) \nabla \Phi N \right]}$$

Differing slightly outside of spherical symmetry

$$\Phi(r) \sim (GMa_0)^{1/2} \ln(r)$$

Comparing 3 formulations



Non-isolated systems

- In reality, ***no*** isolated systems: the external field in which an object is plunged influences the **internal** dynamics
- For instance, Milky Way in the slowly varying Great Attractor gravitational field (0.01 a_0)
- $\boxed{\nabla . [(\mathbf{g}+\mathbf{g_e}) \mu (|\mathbf{g}+\mathbf{g_e}| / a_0)] = \nabla . (\mathbf{g_n}+\mathbf{g_{ne}})}$
- In one dimension:

$$\boxed{\mathbf{g_n} = \mathbf{g} \mu (|\mathbf{g}+\mathbf{g_e}| / a_0) + \mathbf{g_e} [\mu (|\mathbf{g}+\mathbf{g_e}| / a_0) - \mu (|\mathbf{g_e}| / a_0)]}$$

When $|\mathbf{g}| \to 0$: $\mathbf{g_n} = \mathbf{g} \mu (|\mathbf{g_e}| / a_0)$, r^{-2} force, r^{-1} potential !

Escape speed

$$\frac{1}{2}v_{\rm esc}^2(r) = \Phi(\infty) - \Phi(r)$$

Apply a $0.01a_0$ external field to the Milky Way, calculate the escape speed from the solar neighbourhood

-> v_{esc}= 545 km/s as observed !

Famaey, Bruneton & Zhao 2007

Wu et al. 2007

N-body simulations

- QUMOND simulations under development
- Classical MOND (Tiret & Combes) :
  - Bar appears more quickly than in CDM and are not slowed down by dynamical friction => fast bars
  - Long merging time-scale for interacting galaxies, but each oscillation could trigger a starburst
  - There must be *less* mergers at intermediate redshift than in CDM
  - It is possible to reproduce the Antennae, but with relatively fine-tuned initial conditions
  - It is possible to create warps in apparently isolated galaxies through the external field effect

Does MOND always work?

No: pressure-supported systems can be really problematic!

- **Galaxy clusters**: lensing and dynamics require additional dark matter (about as much as baryonic matter, a factor of 10 in the central parts)
- Velocity dispersion profiles and strong lensing of **elliptical galaxies**: generally ok in the field, but a few outliers inside groups and clusters
- Velocity dispersion profiles of **dwarf spheroidals**: generally ok but not (yet) for Sextans and Draco, and stability must be checked. The new ultra-faint dwarfs cannot be in equilibrium (old TDGs?)
- The total velocity dispersion in the **globular clusters** Pal 14 and Pal 4 (but not Pal 3) might be problematic for MOND (predicts 1 km/s instead of 0.5 km/s observed). But very few stars (see Gentile et al. 2009), orbit of the GC…?

Galaxy clusters

- **Ordinary neutrinos** of 2eV are **not enough** to explain the MOND discrepancy in X-ray groups

- Maybe a fermionic dark **HDM** particle? (**hot light sterile neutrinos with $m_\nu \sim 10$eV** ?)

- BUT note that $\Omega_{bvisible}$ (=0.02) < Ω_b (=0.04) at z=0

  50% missing baryons => baryonic dark matter

  How many baryons in WHIM?

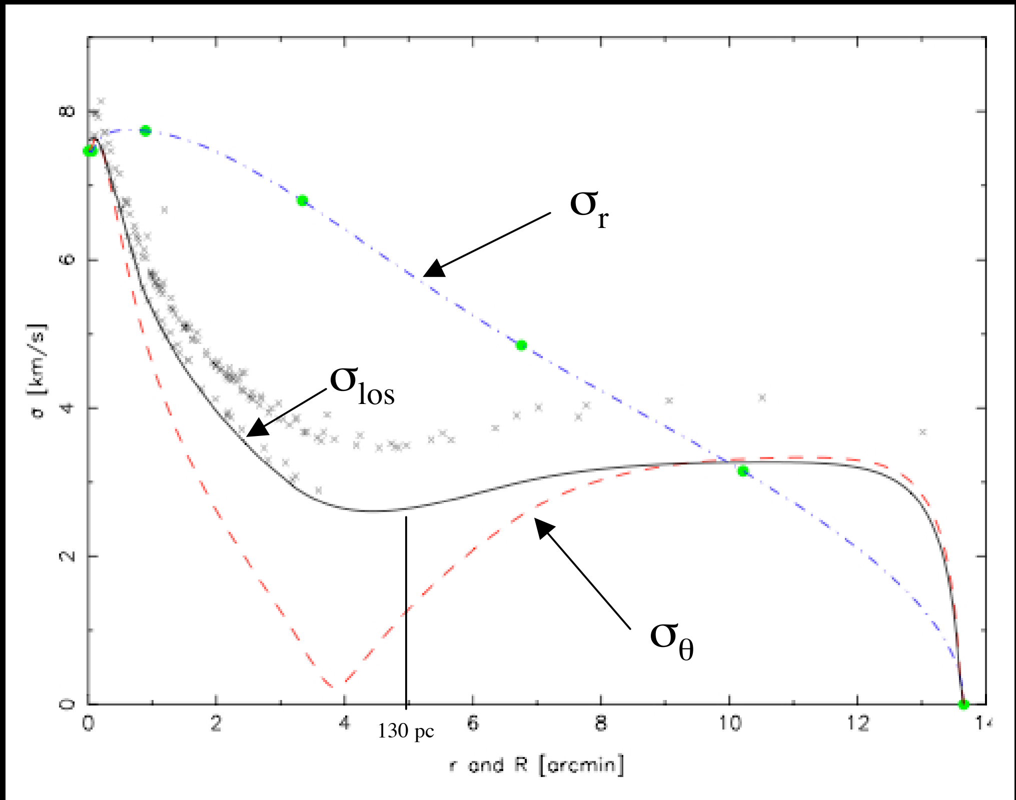
- Bullet cluster => collisionless DM (Angus, Famaey, et al) => BDM in the form of **e.g.** **dense clumps of cold gas** (Pfenniger & Combes 1994), present only in galaxy clusters?

  Microlensing? X-ray emission from cloud-cloud annihilation?

  + Why only in clusters and groups?

Globular clusters

NGC 2419 (Ibata et al.)



- Best MOND model **350 X less likely** than best Newtonian model without dark matter

- BUT NGC 2419 part of the Virgo stream… on a very eccentric orbit
=> varying external field!

- **Are remote GCs generically on quite eccentric orbits?
(cf Pal 14)**

A common solution for subgalactic and extragalactic scales?

- Modified MOND: Bekenstein 2011 (see IAP talks 2011)

- Add a suitably chosen velocity scale $\boldsymbol{s_0}$ such that s_0^2 can control the deepness of the potential and make a_0 effectively vary as :
  $\boldsymbol{a_{0eff} = a_0 \exp(-\Phi/s_0^2)}$

=> a_{0eff} is **larger** in galaxy clusters (large |Φ|) and **smaller** in globular clusters (small |Φ|). Change in the zero-point is absorbed in definition of a_0

$$\nabla . \left[\mu \left(\frac{|\nabla \Phi|}{a_{0\mathrm{eff}}} \right) \nabla \Phi \right] + \frac{|\nabla \Phi|^2}{s_0^2} \mu \left(\frac{|\nabla \Phi|}{a_{0\mathrm{eff}}} \right) - \frac{a_{0\mathrm{eff}}^2}{s_0^2} F \left(\frac{|\nabla \Phi|^2}{a_{0\mathrm{eff}}^2} \right) = 4\pi G \rho,$$

$F = \int \mu \, dx$

More predictions need cosmology, which needs a relativistic theory

- There now exists many different relativistic theories reproducing MOND

- The difficult thing is to have gravitational lensing and dynamics governed by the same potential

- In GR, the geodesic equation is:
  $d^2x^\mu / d\tau^2 = - \Gamma^\mu_{\alpha\beta} (dx^\alpha/d\tau) (dx^\beta/d\tau)$
- reducing for timelike geodesics in weak-field to
  $d^2x^k / d\tau^2 = - \Gamma^k_{00}(dx^0/d\tau)^2 = - \Gamma^k_{00}$
  thus depending only on g_{00} (but **not** for nulll geodesics)

So $\Gamma^\mu_{\alpha\beta}$ plays the role of acceleration, but doesnt transform like a tensor => needs to introduce dark fields

Modifying GR

Einstein equations relate metric to stress-energy tensor just like Poisson equation relates potential to density. In **weak-field**:

$$g_{00} = - e^{2\Phi} \quad = - (1+ 2\Phi)$$

$$g_{ij} = e^{2\Psi} \delta_{ij} = (1 + 2\Psi)\, \delta_{ij}$$

$\Phi = -\Psi = \Phi_N$ in GR (Φ => dynamics, Φ-Ψ => lensing)

- **Idea:** replace GR with a theory reducing to the SAME metric but replacing Φ_N by Φ obeying MOND

- First try: add a scalar field and couple matter to

$$g'_{\alpha\beta} = e^{2\phi} g_{\alpha\beta}$$

with action of ϕ governed by a free function depending on (grad ϕ)^2

=> works for dynamics, but *doesnt work for lensing*

TeVeS

Add a scalar field **and** a vector field and couple matter to:

$g'_{\alpha\beta} = e^{-2\phi}(g_{\alpha\beta} + U_\alpha U_\beta) - e^{2\phi} U_\alpha U_\beta$

with $g^{\alpha\beta} U_\alpha U_\beta = -1$, timelike in static situations,
and action $S = S_g + S_s + S_v + S_m$,
with action S_s of ϕ governed by a free function depending on $(\text{grad } \phi)^2$

=> ***ϕ obeys a B-M equation***, and plays the role of the dark matter potential (dynamics and lensing are governed by the **same** physical metric *g'*)

In non-static situations, the spatial part of the vector field can play the role of DM (Ferreira & Starkman 2009 => DM in disguise), can form structure but is most probably not enough to explain the missing mass in clusters nor the peaks of the CMB

Other theories have slightly different static limits

Examples:

1) BIMOND (based on a function of a combination of $\Gamma^{\mu}{}_{\alpha\beta} - \Gamma'^{\mu}{}_{\alpha\beta}$ in the action):

$$\nabla^2 \Phi = \nabla . [\, \nu (|\nabla \Phi_N| / a_0) \, \nabla \Phi_N]$$

2) Dipolar dark matter:

$$-\nabla . [\, \boldsymbol{g} - 4 \pi \boldsymbol{P}] = 4 \pi G (\rho + \rho_{dm})$$

In any case…

- All these theories have difficulties in reproducing the CMB without dark matter (=> sterile neutrinos? Dipolar DM?)

- Independently from the theoretical framework, the MOND formula is an extremely efficient way of predicting the gravitational field in rotationally supported galaxies

- Any galaxy formation theory should be able to ultimately reproduce the MOND formula as a scaling relation for spirals (and TDGs)

- What makes it difficult is that it is history-independent!

- This is the goal of the complicated MOND theories that are developed and tested. Not getting rid of dark matter…