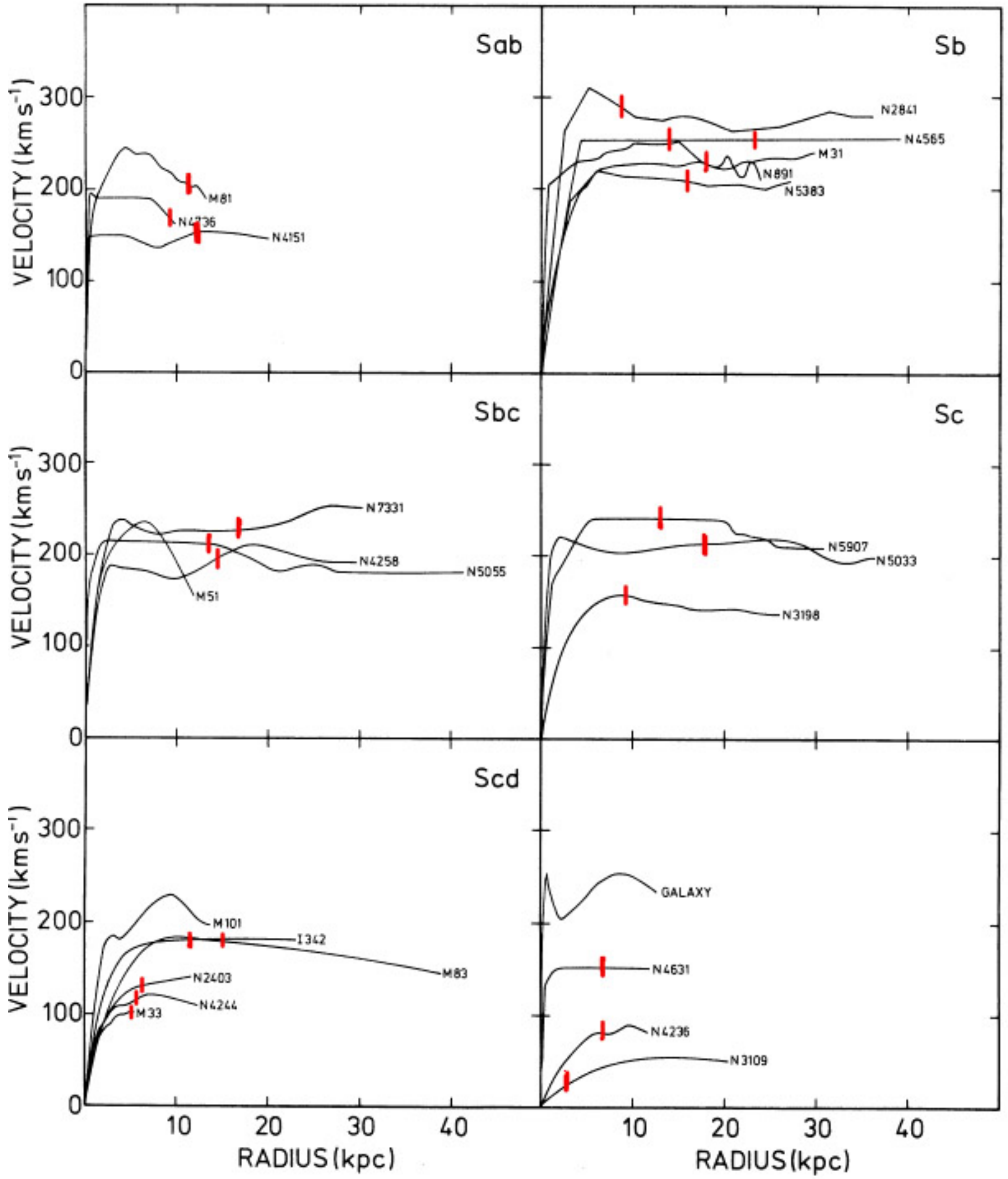
Can modified gravity (partly) emulate dark matter?

Benoit Famaey

CNRS - Observatoire astronomique de Strasbourg

France

HI galaxy rotation curves



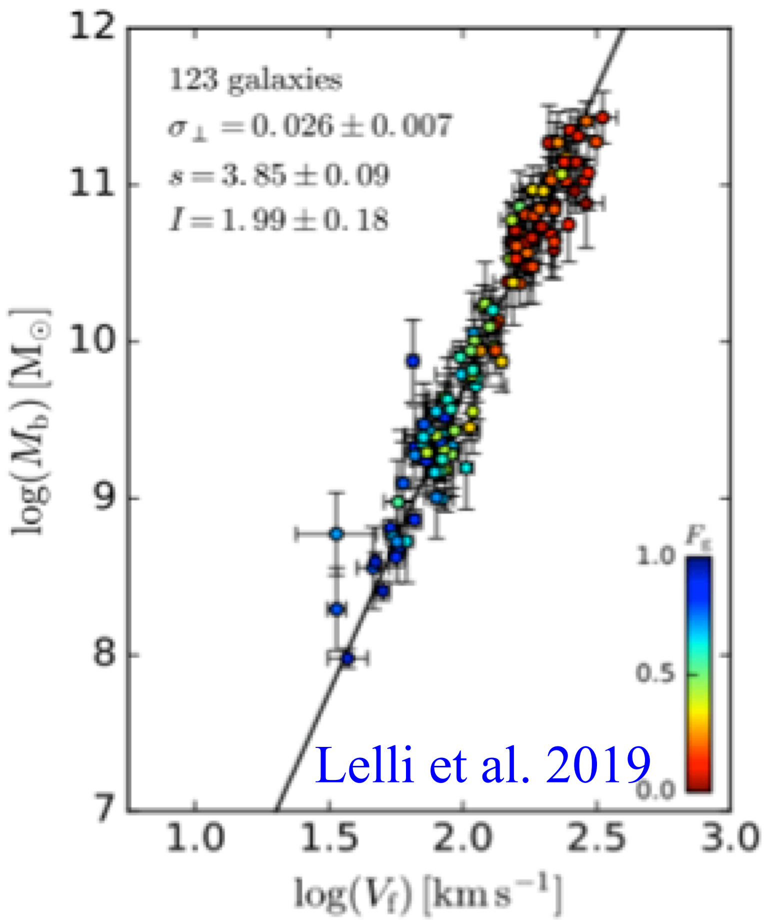
Bosma (1978)

Disk galaxies: the baryonic Tully-Fisher relation (BTFR) and its scatter

- $\log M_b = \alpha \log V_f - \log \beta$
- $\alpha \approx 3.8 - 4$
- Zero-point defines an acceleration constant :

$a_0 \approx V^4/(GM_b) \approx 10^{-10}\ m/s^2$
such that $\beta = G a_0$

- **Intrinsic scatter ~ 0.025 dex (6%)**



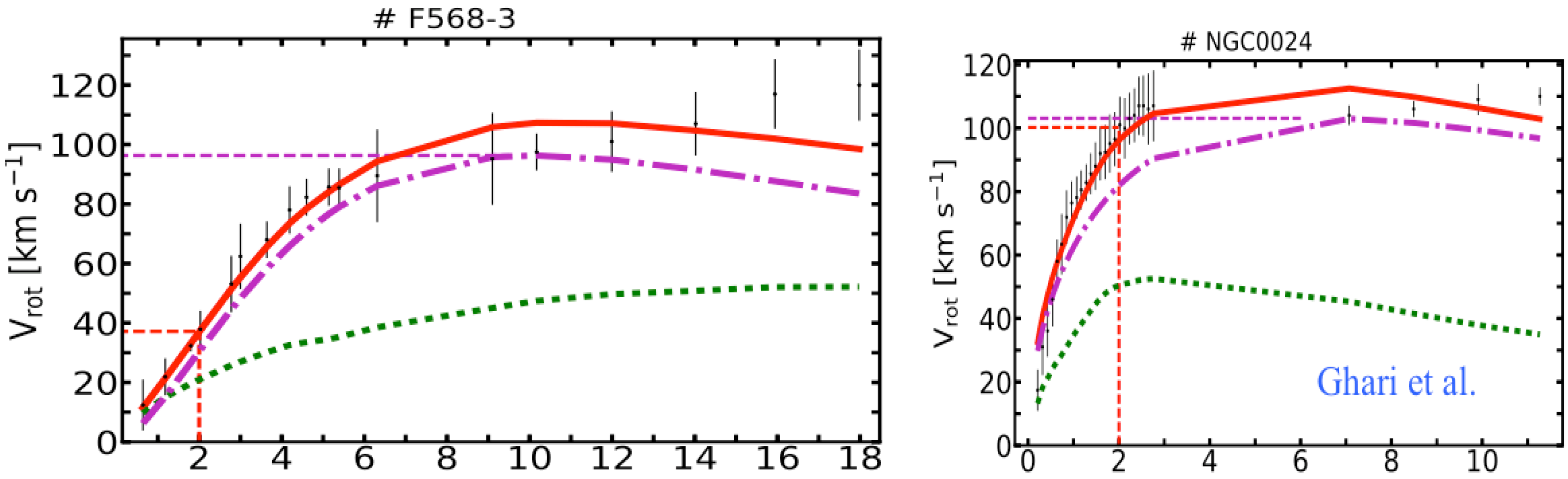
Twice too low (Desmond 2017) -> 3.6σ tension

The rotation curves shapes of late-type dwarf galaxies

R. A. Swaters[1,2,⋆], R. Sancisi[3,4], T. S. van Albada[3], and J. M. van der Hulst[3] (2009)

HI observations for a sample of 62 galaxies [...] procedure takes the rotation curve shape, the HI distribution, the inclination, and the size of the beam into account, and makes it possible to correct for the effects of beam smearing.

In spiral galaxies and even in the central regions of late-type dwarf galaxies, the shape of the central distribution of light and the inner rise of the rotation curve are related. This implies that galaxies with stronger central concentrations of light also have higher central mass densities, and it suggests that the luminous mass dominates the gravitational potential in the central regions, even in low surface brightness dwarf galaxies (NB: dominated by… dark matter?!)



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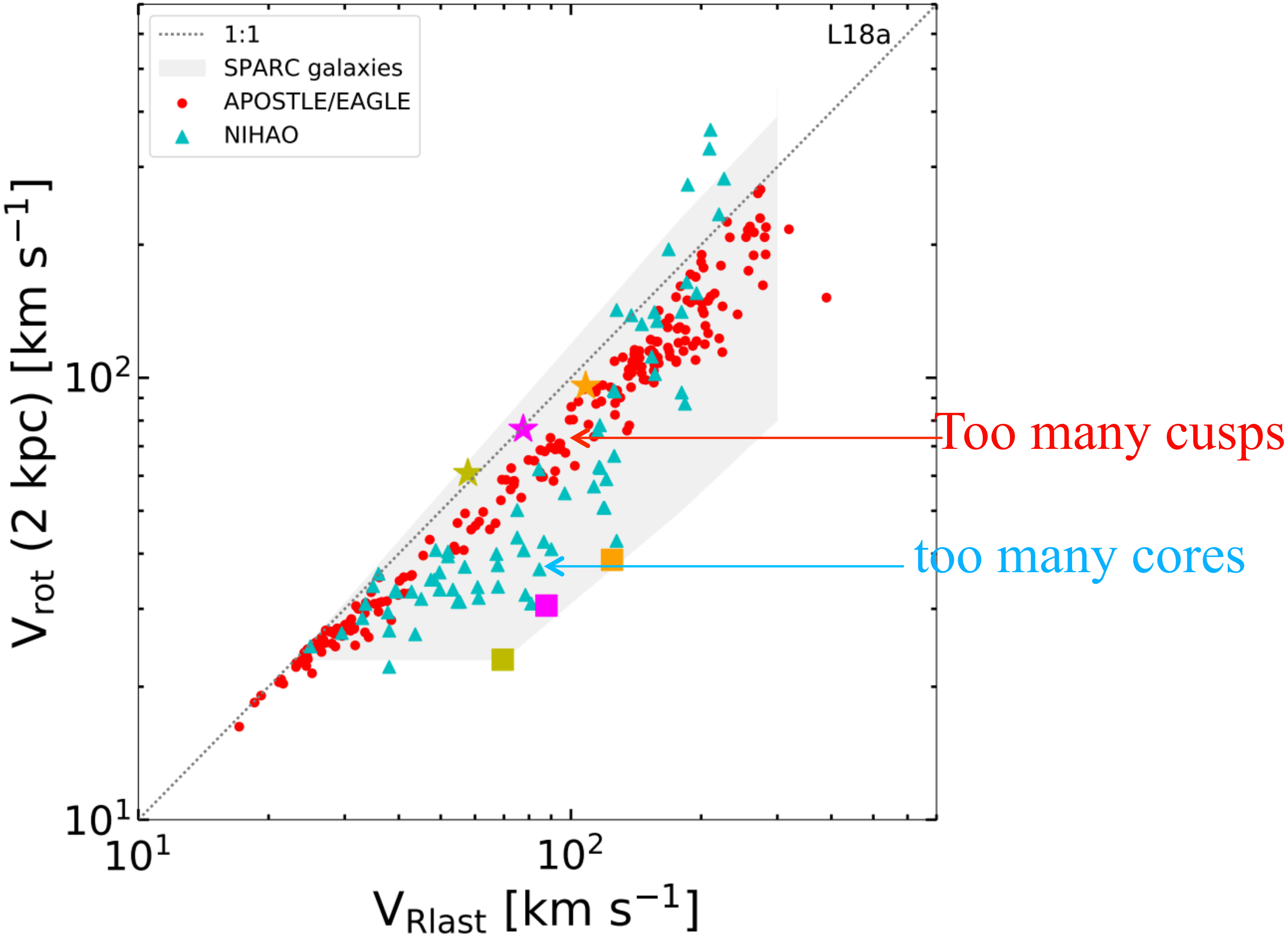
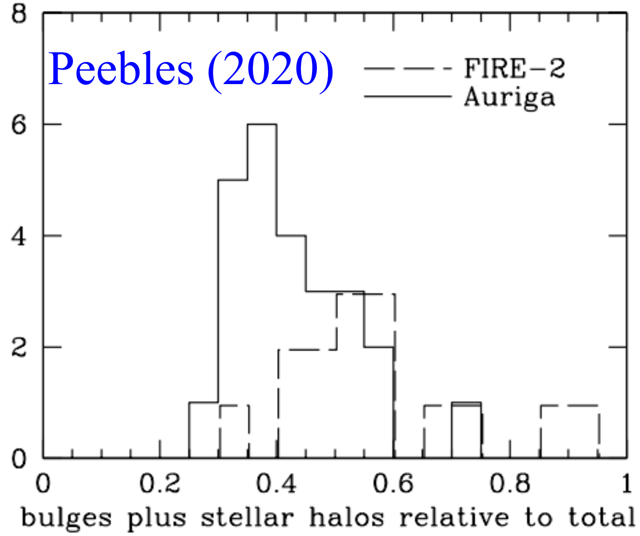
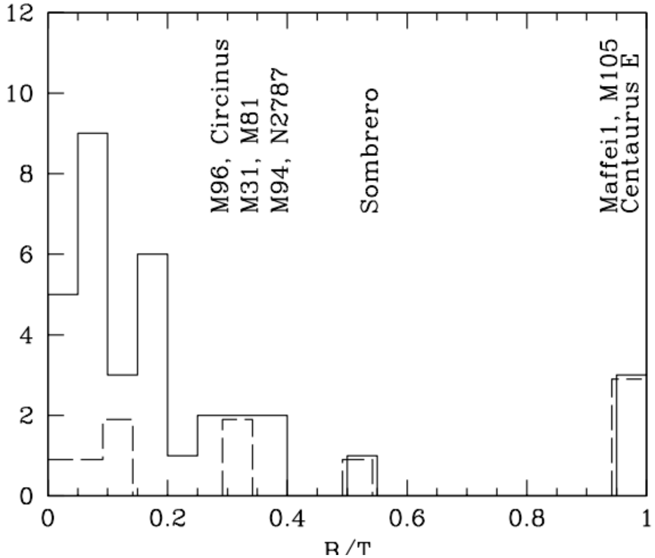
More than just the old core-cusp

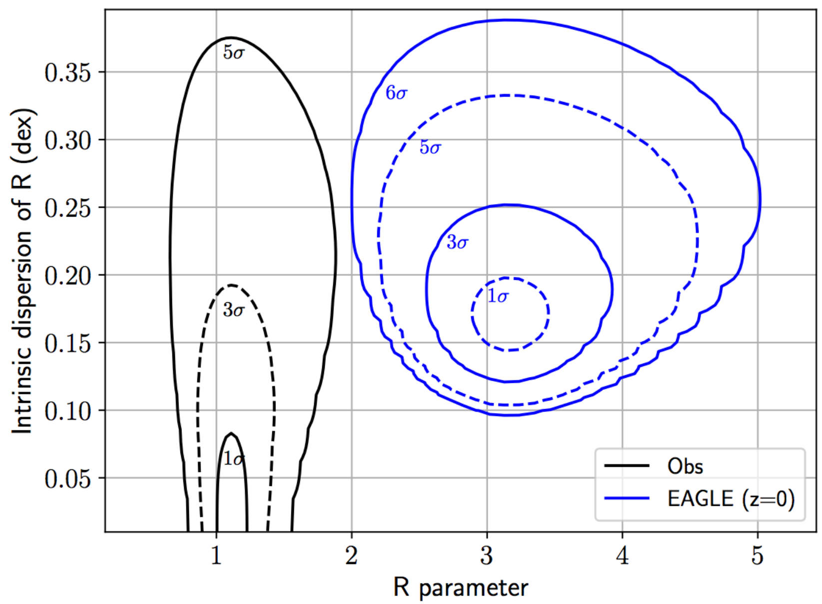


The hot orbits problem and the fast bar problem



- Most local disk galaxies are nearly **bulgeless** with light stellar halos
- **70% are barred** at $M_* \sim 10^9$-$10^{10} M_{sun}$ (Erwin 2018)
- Bars are **fast** R_{CR}/R_{bar} <1.4 (Aguerri et al. 2015)





Roshan et al. (2021)

Modifying gravity?

$g = g_N$	if $g >> a_0$
$g = (g_N\, a_0)^{1/2}$	if $g << a_0$

MOND
Milgrom 1983

A characteristic **acceleration scale** present in the BTFR and diversity

$a_0 \approx 10^{-10}\, m/s^2 \sim \sqrt{\Lambda}$ in natural (c=1) units

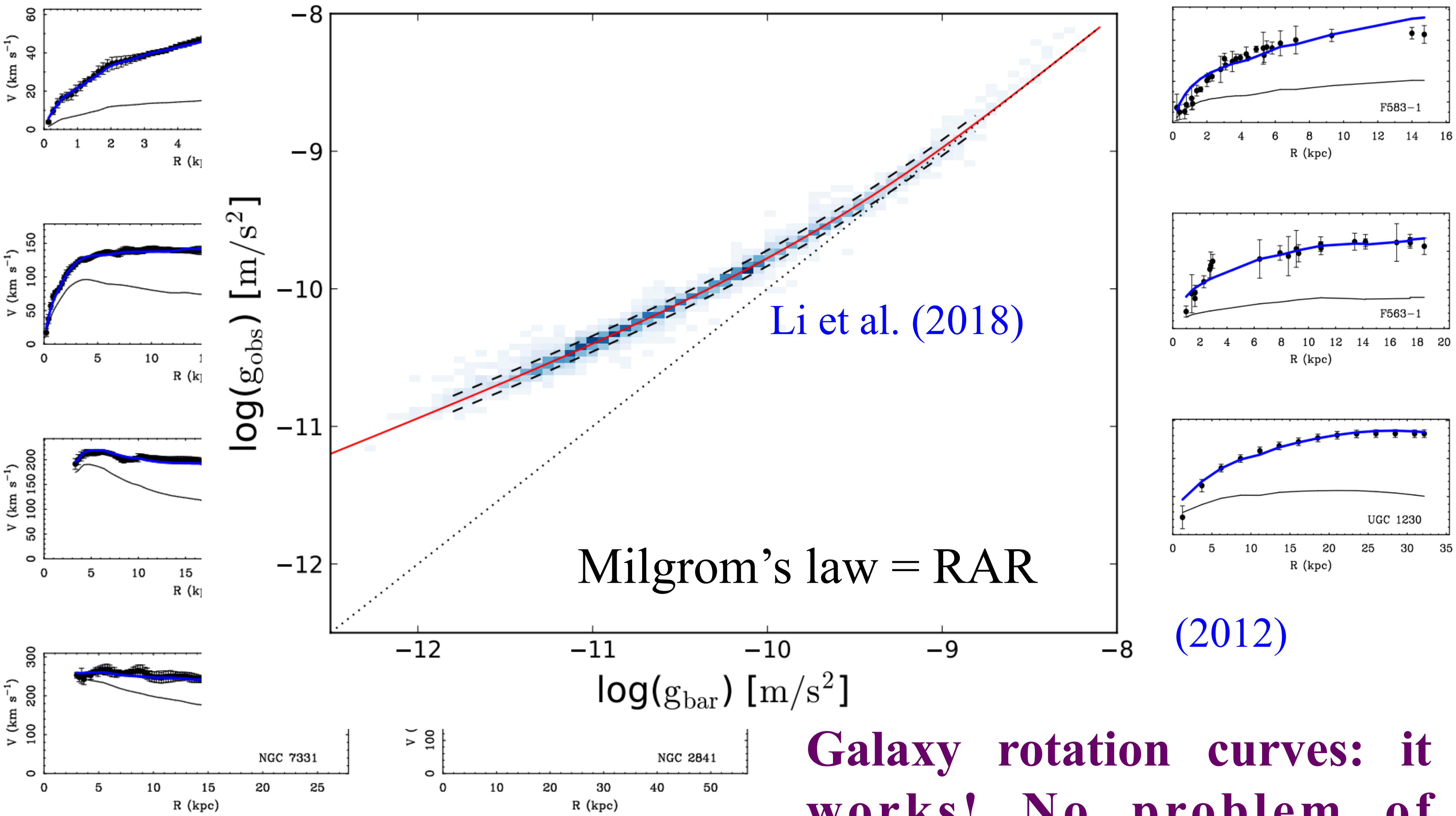
$V^2/R \approx (GMa_0)^{1/2}/R$ => **BTFR**

Take two exponential disks of **same** baryonic mass M_b in the low acceleration regime but **different** scale-length R_d (central surface density $= M_b/2\pi R_d^2$) => $M_b(\alpha\, R_d)$ identical

=> $V^2_{cb}(\alpha\, R_d) \sim 1/R_d$ **BUT** $V^2_c(\alpha\, R_d)$ identical

$\Rightarrow$ **LSB diversity solved (rotation curves 'stretched' by scalelength)**

Modifying gravity?



Galaxy rotation curves: it works! No problem of diversity or BTFR tightness

Classical action

$$S_N = S_{\rm kin} + S_{\rm in} + S_{\rm grav} = \int \frac{\rho \mathbf{v}^2}{2} d^3x\,dt - \int \rho \Phi_N d^3x\,dt - \int \frac{|\nabla \Phi_N|^2}{8\pi G} d^3x\,dt.$$

$$\Rightarrow \quad S_{\rm grav\,BM} \equiv - \int \frac{a_0^2 F(|\nabla \Phi|^2/a_0^2)}{8\pi G} d^3x\,dt,$$

$$F(z) \to z \text{ for } z \gg 1 \text{ and } F(z) \to \frac{2}{3} z^{3/2} \text{ for } z \ll 1$$

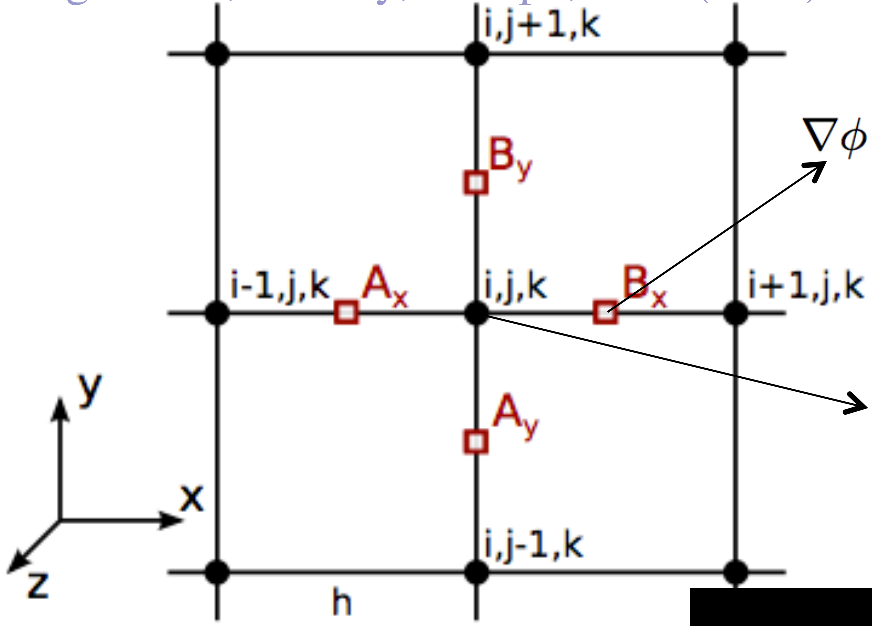
$$\Rightarrow \quad \nabla . \left[\mu \left(\frac{|\nabla \Phi|}{a_0} \right) \nabla \Phi \right] = 4\pi G \rho$$

Other version (QUMOND):

$\nabla^2 \Phi = \nabla . [\ \nu (| \nabla \Phi N | / a_0) \nabla \Phi N]$ with $\nu (x) \sim x^{-1/2}$ for $x \ll 1$

Numerical solver: Phantom of Ramses

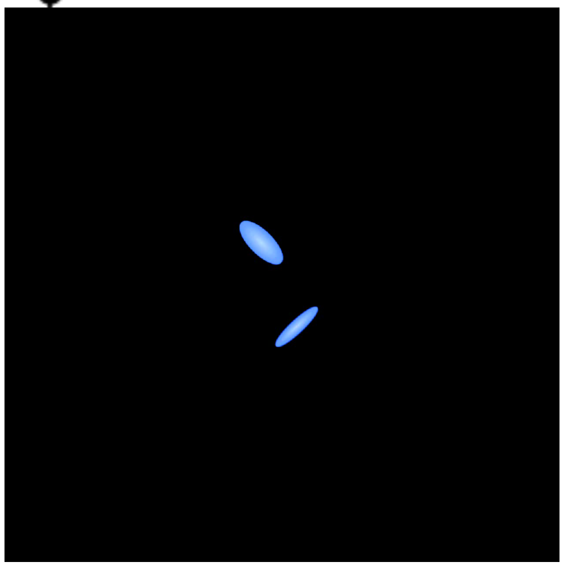
Lüghausen, Famaey, Kroupa, et al. (2013)



$$\nabla\phi = \frac{1}{4h}\begin{pmatrix} 4\left(\phi^{\mathrm{i+1,j,k}} - \phi^{\mathrm{i,j,k}}\right) \\ \phi^{\mathrm{i+1,j+1,k}} - \phi^{\mathrm{i+1,j-1,k}} + \phi^{\mathrm{i,j+1,k}} - \phi^{\mathrm{i,j-1,k}} \\ \phi^{\mathrm{i,j,k+1}} - \phi^{\mathrm{i,j,k-1}} + \phi^{\mathrm{i+1,j,k+1}} - \phi^{\mathrm{i+1,j,k-1}} \end{pmatrix}$$

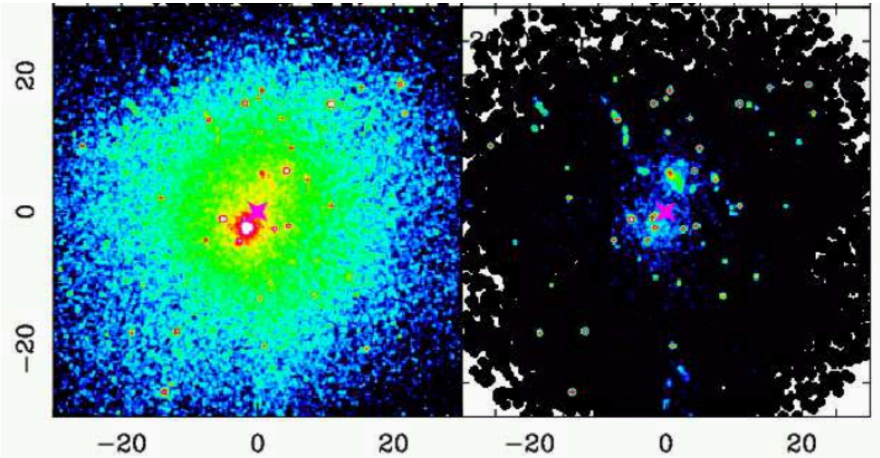
$$\begin{aligned} \rho_{\mathrm{ph}}^{\mathrm{i,j,k}} = \frac{1}{4\pi G}\frac{1}{h^2}\,\Big[& \left(\phi^{\mathrm{i+1,j,k}} - \phi^{\mathrm{i,j,k}}\right)\nu_{\mathrm{Bx}} \\ & - \left(\phi^{\mathrm{i,j,k}} - \phi^{\mathrm{i-1,j,k}}\right)\nu_{\mathrm{Ax}} \\ & + \left(\phi^{\mathrm{i,j+1,k}} - \phi^{\mathrm{i,j,k}}\right)\nu_{\mathrm{By}} \\ & - \left(\phi^{\mathrm{i,j,k}} - \phi^{\mathrm{i,j-1,k}}\right)\nu_{\mathrm{Ay}} \\ & + \left(\phi^{\mathrm{i,j,k+1}} - \phi^{\mathrm{i,j,k}}\right)\nu_{\mathrm{Bz}} \\ & - \left(\phi^{\mathrm{i,j,k}} - \phi^{\mathrm{i,j,k-1}}\right)\nu_{\mathrm{Az}}\,\Big] \end{aligned}$$

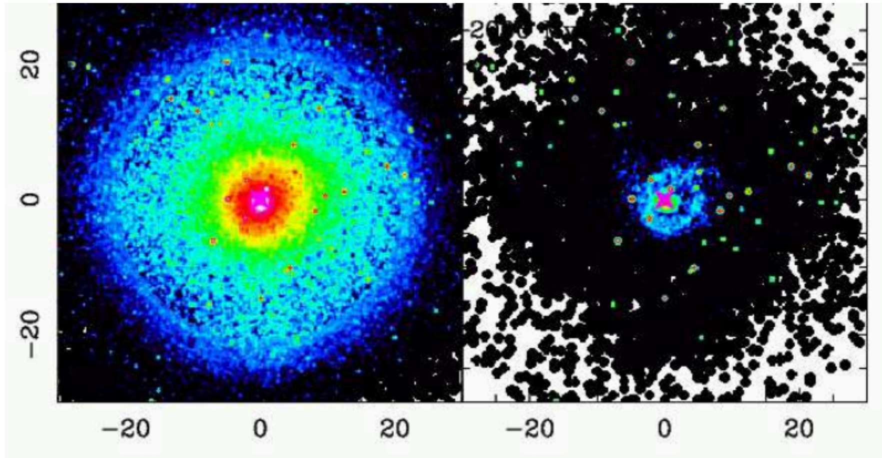
Renaud, Famaey, Kroupa (2016)



Solving the hot orbits and fast bar problems?

Too many mergers & clumps at high-z spiral-in to form **bulges**: might be solved in MOND by less mergers and **decreased dynamical friction for massive clumps** in high-z clumpy disks





MOND

Newton+DM

Same clumpy disk ICs: 2 Gyr of evolution (Combes 2014)

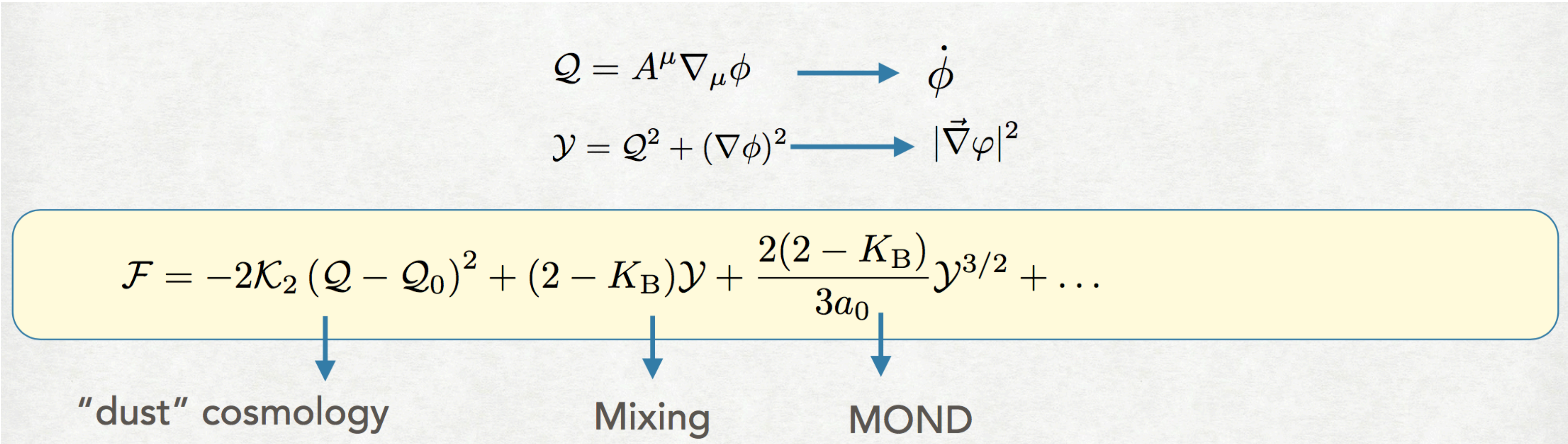
Less dynamical friction imply **faster bars**: Tiret & Combes (2007, 2008), Roshan et al. 2021

Modifying GR?

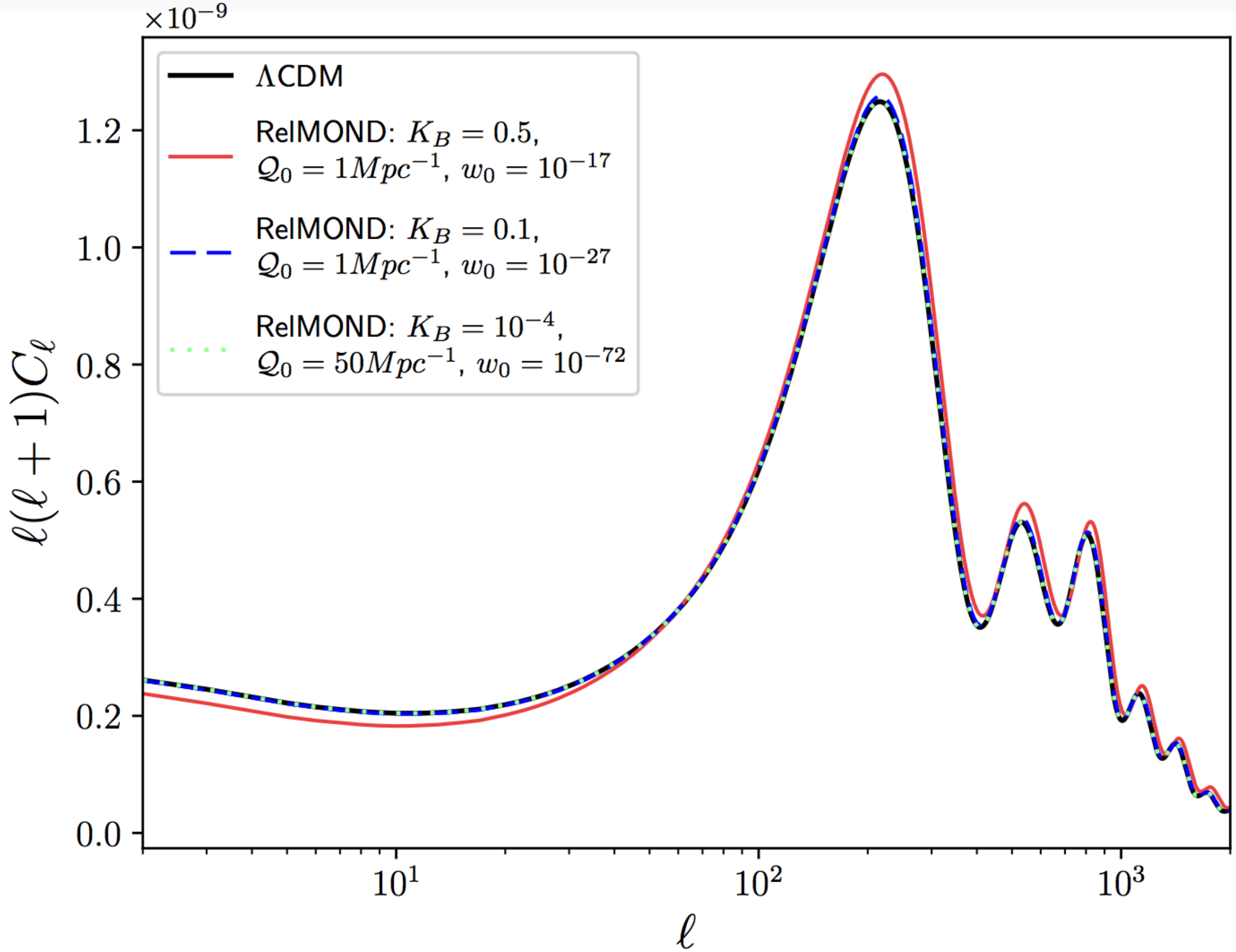
Classical action: $S_{\text{grav BM}} \equiv -\int \frac{a_0^2 F(|\nabla\Phi|^2/a_0^2)}{8\pi G} d^3x\, dt$

$\Rightarrow$ Add some k-essence like scalar + a vector field for lensing (TeVeS)

$\Rightarrow$ Latest version by Skordis & Zlosnik:



Modifying GR?

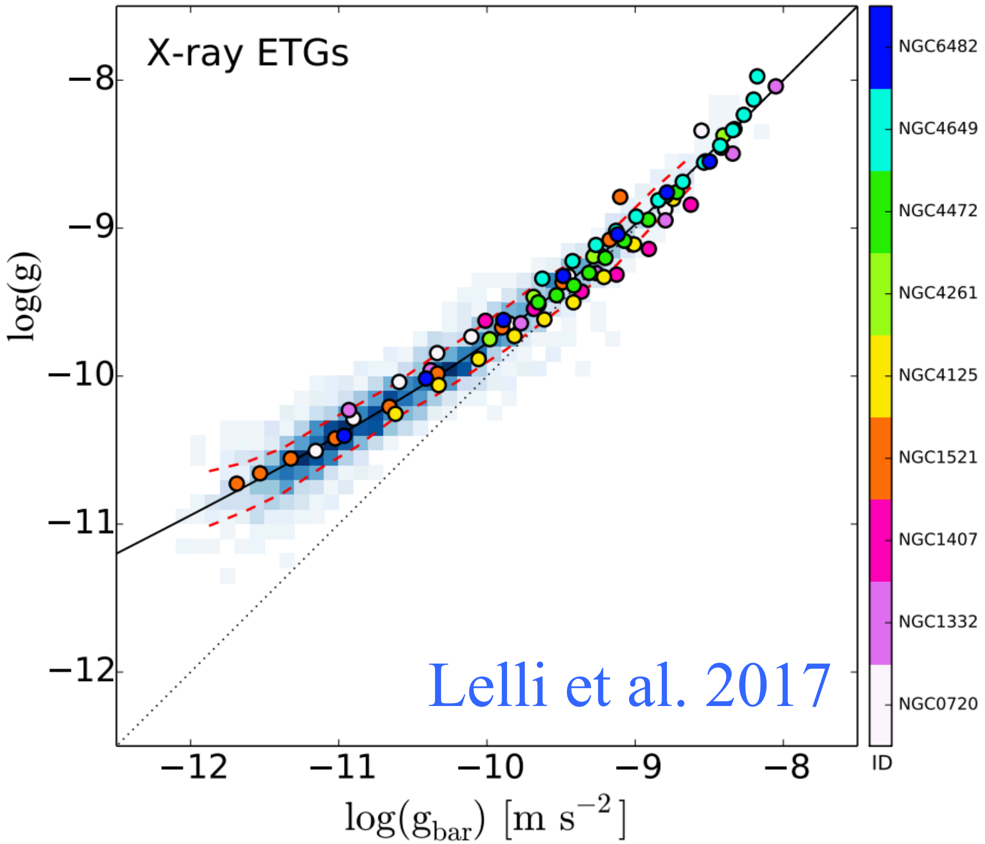


Skordis & Zlosnik

Ellipticals

Hydrostatic equilibrium for X-ray gas temperature profile:

$g = [- kT(r)/(r<m>)] \times [d\ln\rho_x/d\ln r + d\ln T/d\ln r]$



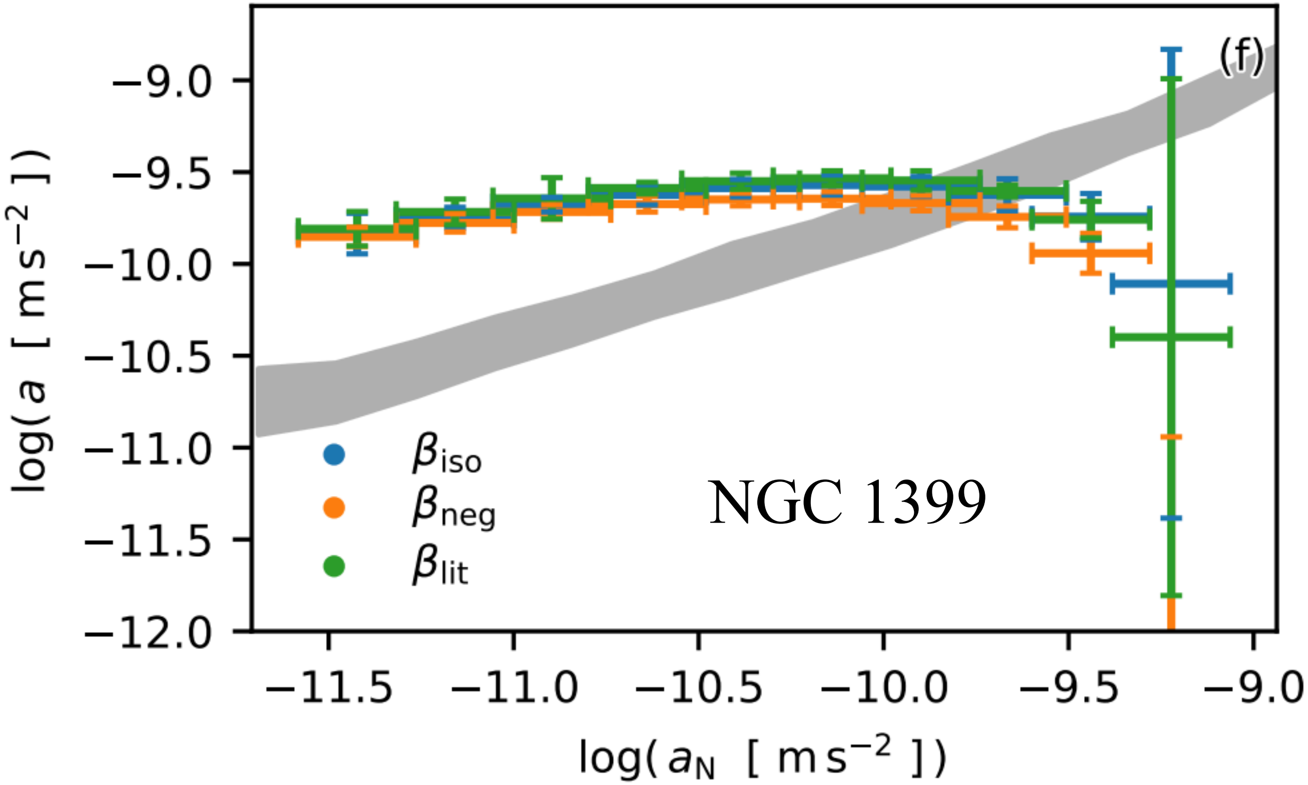
Lelli et al. 2017

Also statisically ok for galaxy-galaxy lensing for blue (spirals) and red (ellipticals) galaxies (e.g., Milgrom 2013)

Ellipticals

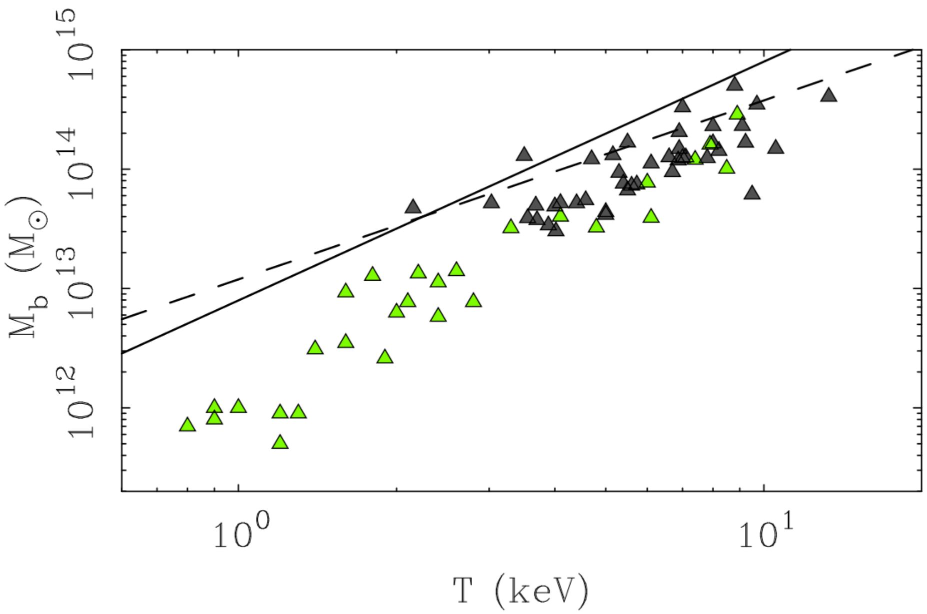
Jeans modelling of globular cluster systems:

Bilek et al. 2019: *Most galaxies can be fitted by the MOND models successfully, but for some of the galaxies,* ***especially those in centers of galaxy clusters, the observed GCs velocity dispersions are too high***

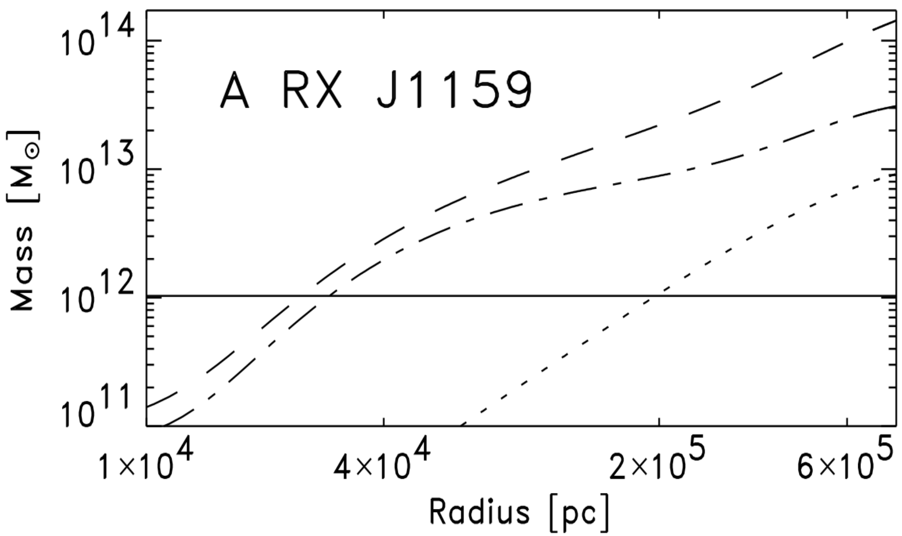


Galaxy clusters: where it all breaks down…

Temperature profiles of X-ray emitting gas in clusters:



Famaey & McGaugh (2012)



Angus, Famaey & Diaferio (2010)

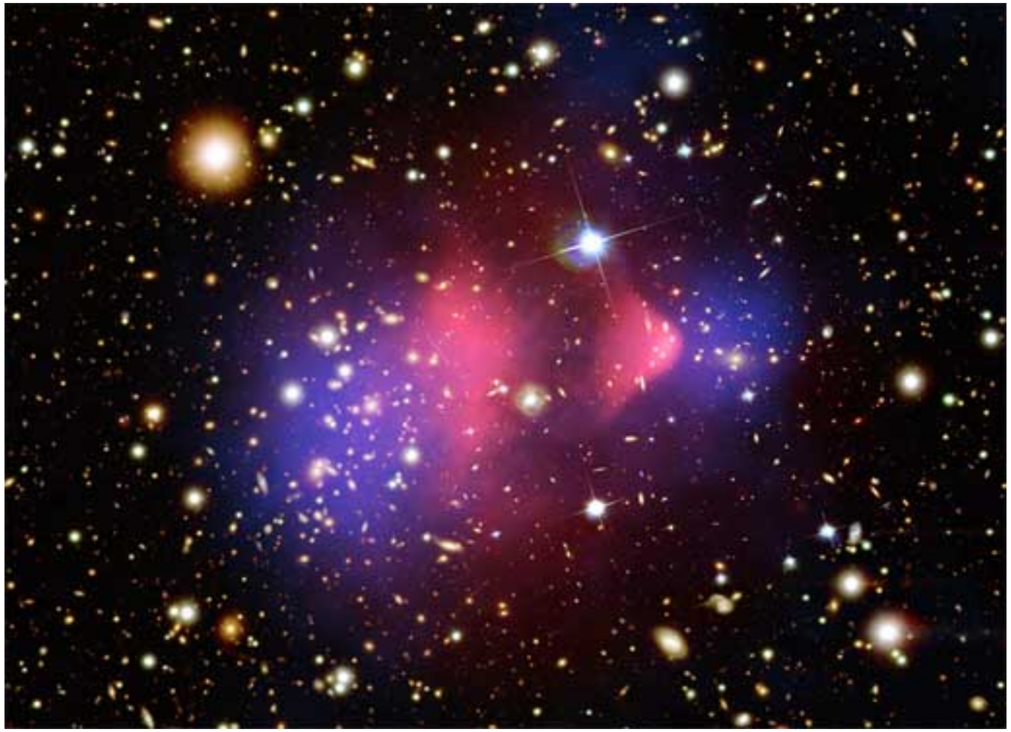
Globally, a **factor of 2** of residual missing mass

Can easily reach a **factor of 10** in central parts

Galaxy clusters: where it all breaks down…

The discrepancy seems to be related with the depth of the potential well => EMOND (Zhao & Famaey 2012) where a_0 becomes $a_0(\phi)$

BUT then hard to also make the « residual mass » collisionless !!



Galaxy clusters: where it all breaks down…

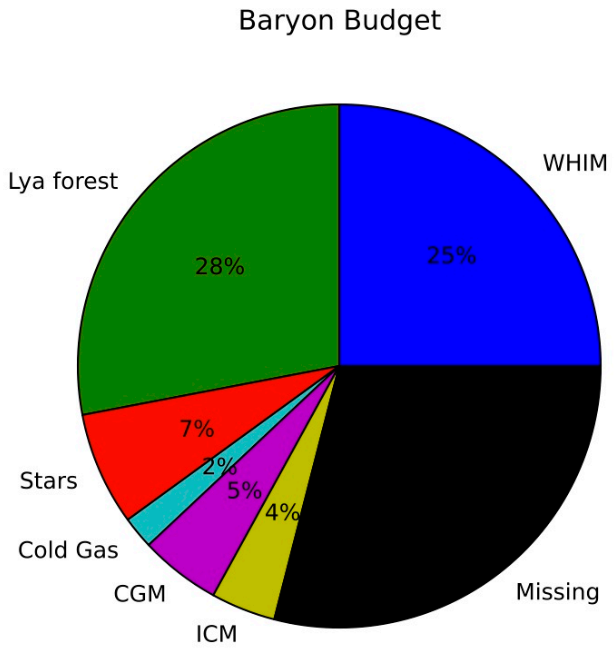
What remains:

- Hot dark matter (HDM, e.g., sterile neutrinos, Angus 2009)

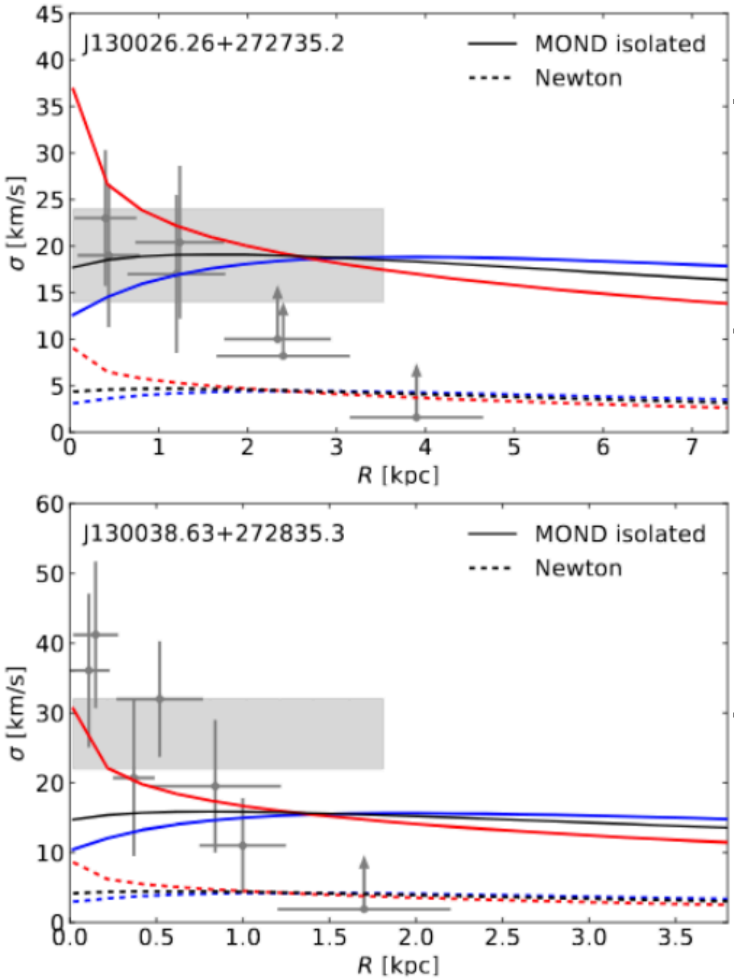
- Cluster baryonic dark matter (CBDM, Milgrom 2008), cold dense H_2 clouds

- New d.o.f. behaving like DM in clusters, see, e.g., Dai, Matsuo & Starkman (2008)

… **but not in galaxies** (like HDM)



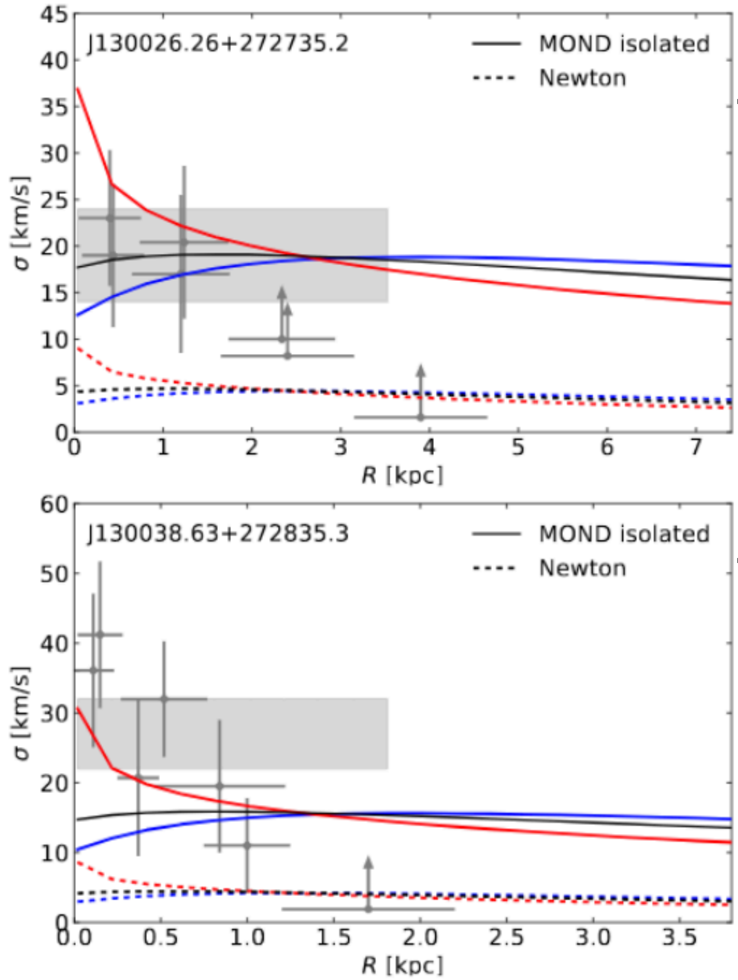
Clues from ultra-diffuse galaxies in the Coma cluster



- The agreement of the velocity dispersions with MOND are impressive !
- But the **EFE ruins the agreement** if d<5Mpc (d > 5Mpc would require a very peculiar observer-dependent bias in spatial distribution)
- Difficult to understand if HDM makes up the residual missing mass… can't cluster in the UDGs

Work in progress with J. Freundlich, P.-A. Oria, M. Bilek

Clues from ultra-diffuse galaxies in the Coma cluster



- If CBDM makes up the missing mass in the cluster, it could also make up the missing mass in the UDGs, **but why then such a good agreement with isolated MOND ?**

- **‘*Last-hope*’ hypothesis**: the new d.o.f. making up the residual missing mass (same as sourcing structure in ‘SZ-MOND’ ?) does not couple to the field generating MOND in the UDGs

=> decoupling kills the EFE in clusters (?)

Conclusion

MOND is successful at predicting the dynamics of galaxies, especially **rotationally-supported ones**: the question is **why** does it make successful predictions ?

- Emergence in ΛCDM?
- Fundamental nature of DM?
- Modified gravity?

It is possible to reproduce the CMB angular power spectrum with a (convoluted) relativistic MOND theory

The puzzling clues from galaxy clusters, where it **fails**, can perhaps give clues for further theoretical development