Observatoire astronomique de Strasbourg | ObAS

Coma cluster ultra-diffuse galaxies as a testing ground for MOND

Jonathan Freundlich

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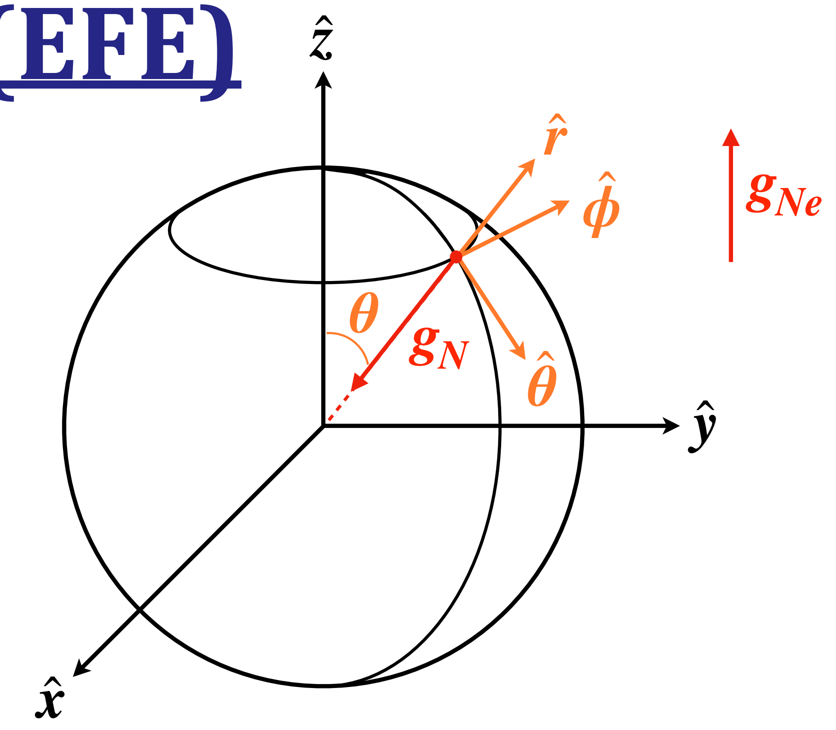
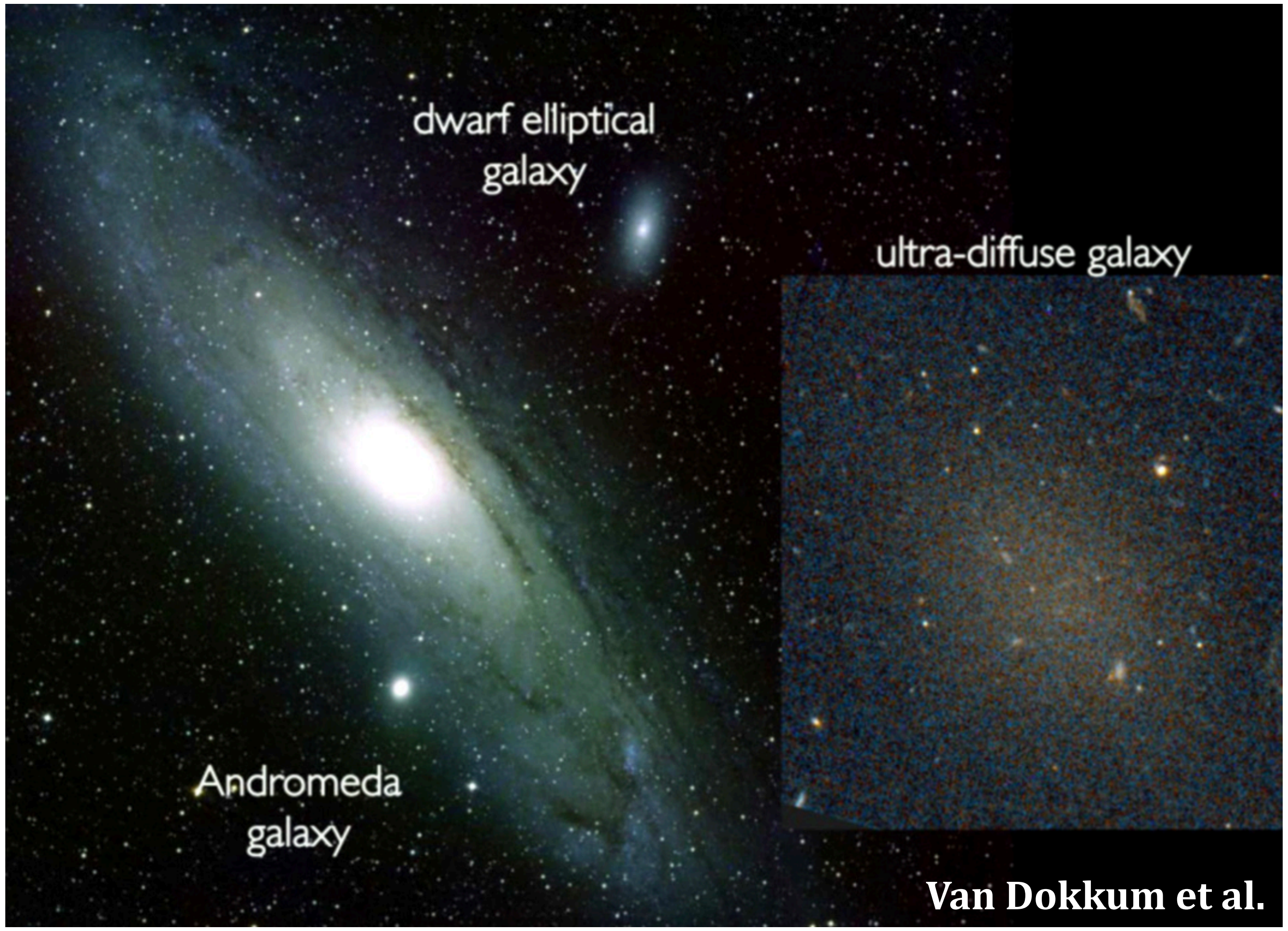
& Srikanth Nagesh (cf. next talk)

The external field effect (EFE)



- ***violation of the strong equivalence principle*** of general relativity
- internal dynamics of a self-gravitating system embedded in a constant external field may ***depend on the external field***
- ***lower velocity dispersion*** than in isolation
  + ***away from the RAR*** around a massive host

Cluster UDGs as a testing ground for MOND & the EFE



Ultra-diffuse galaxies (UDGs):

✦ **Stellar masses of dwarf galaxies**

$7 < \log(M_{\rm star}/M_\odot) < 9$

✦ **Effective radii of MW-sized objects**

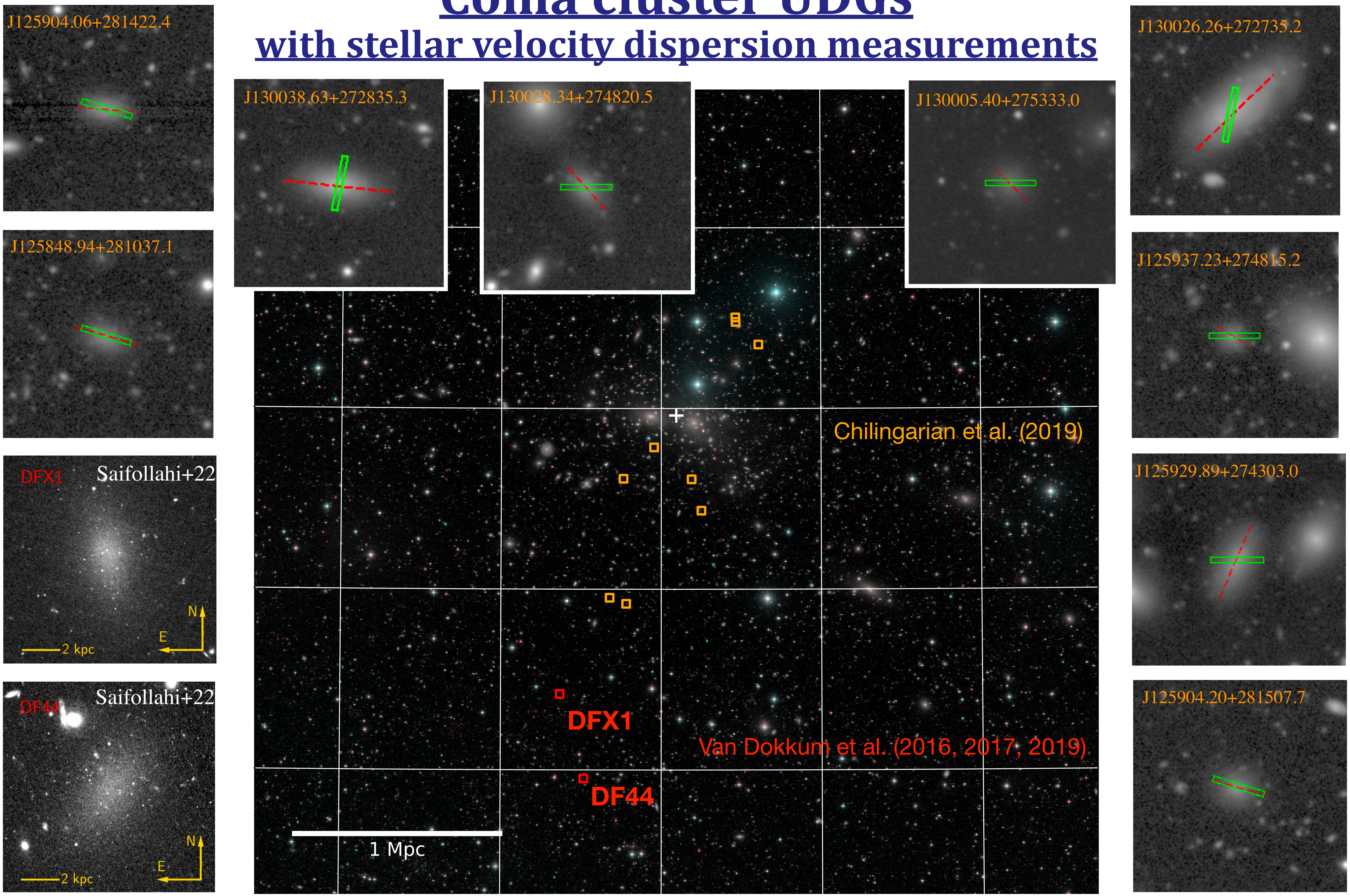
$1 < r_{\rm eff}/{\rm kpc} < 5$

Cluster UDGs:

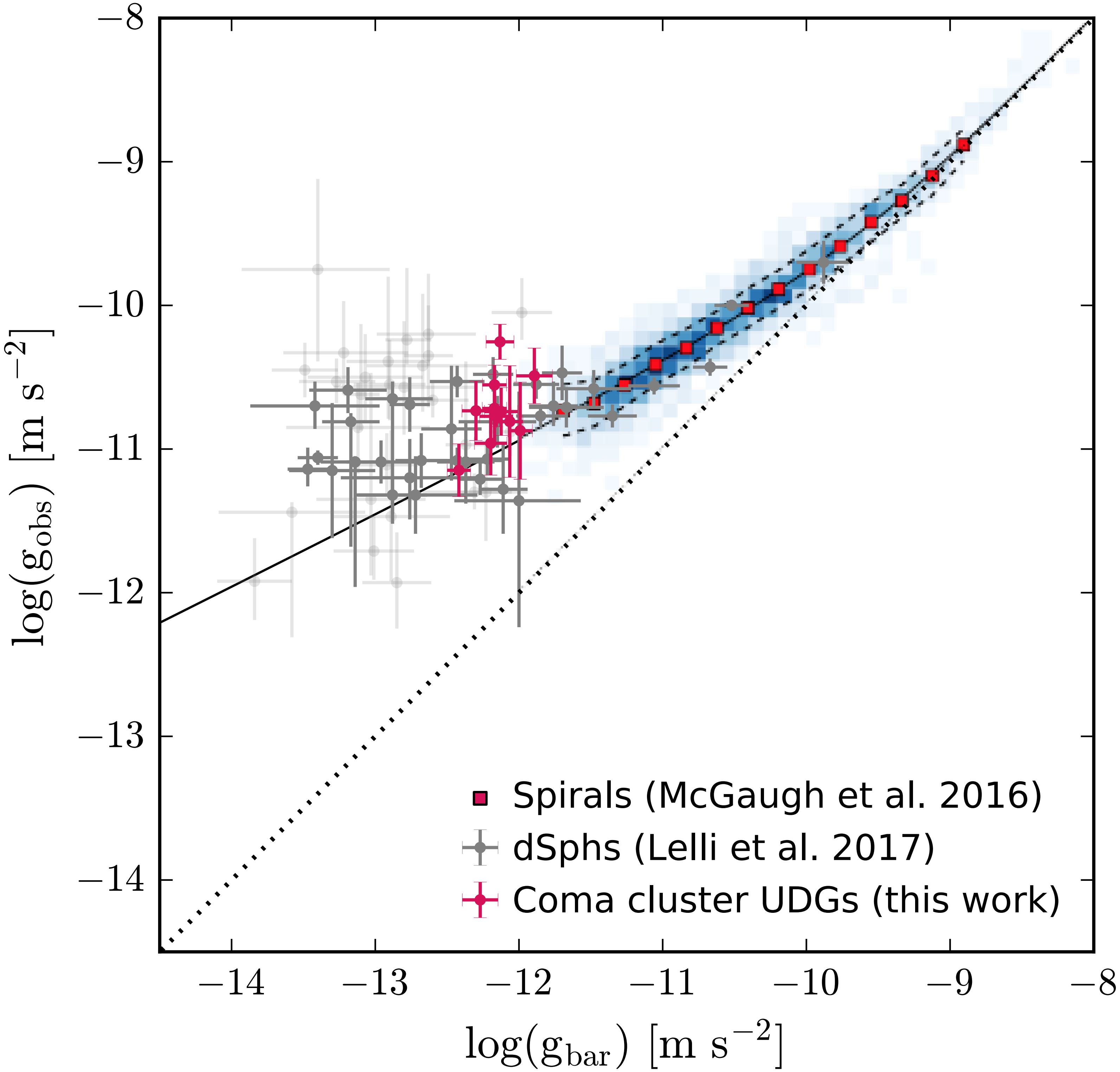
- **singularly low internal acceleration** ($g_N<0.02\ a_0$)
- **strong external field**

Coma cluster UDGs

with stellar velocity dispersion measurements



Radial acceleration relation



$$g_{\rm obs} = \frac{9}{4}\frac{\sigma_{\rm eff}^2}{R_e}$$

(cf. Wolf et al. 2010)

$$g_{\rm bar} = \frac{GM(r_{1/2})}{r_{1/2}^2}$$

$r_{1/2} \approx (4/3)R_e$
$M(r)$ deprojected Sersic
(Lima Neto et al. 1999)

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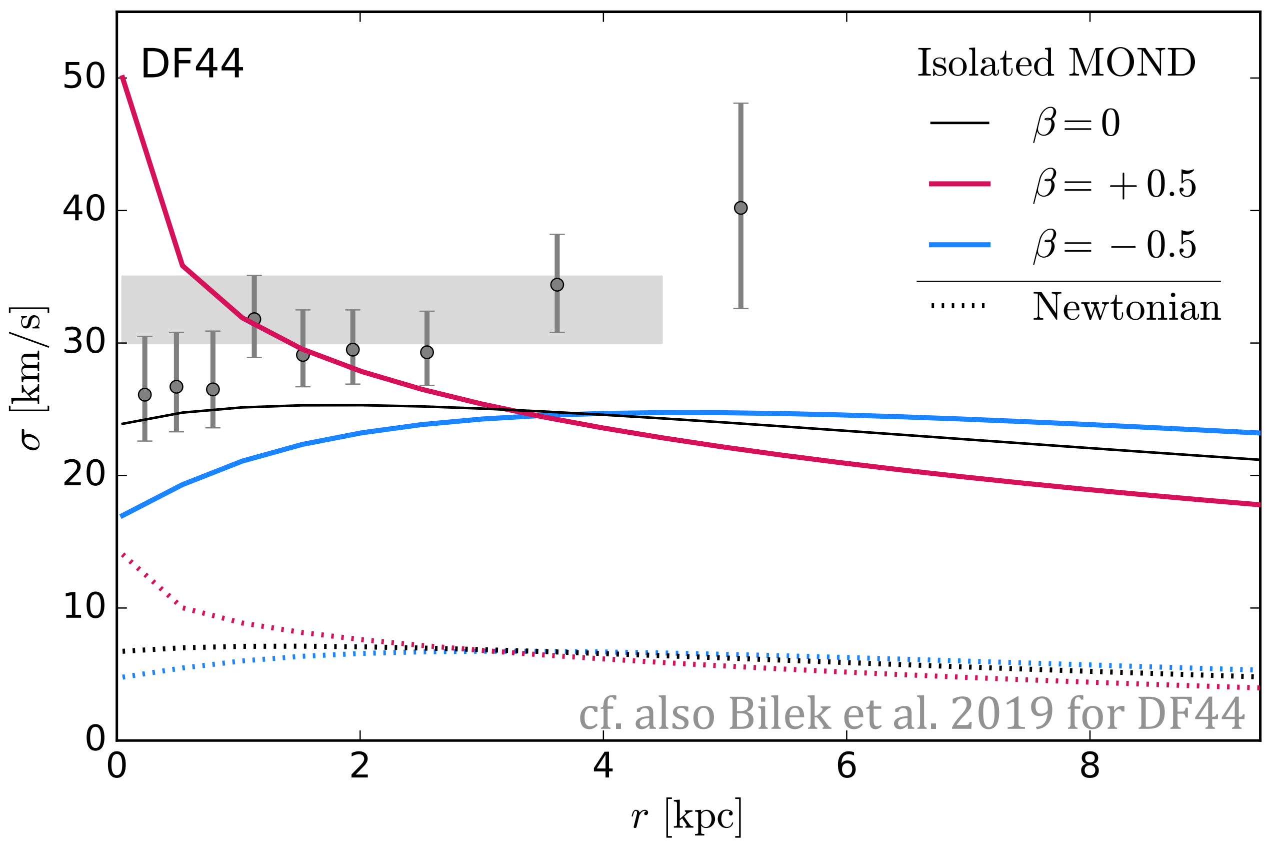
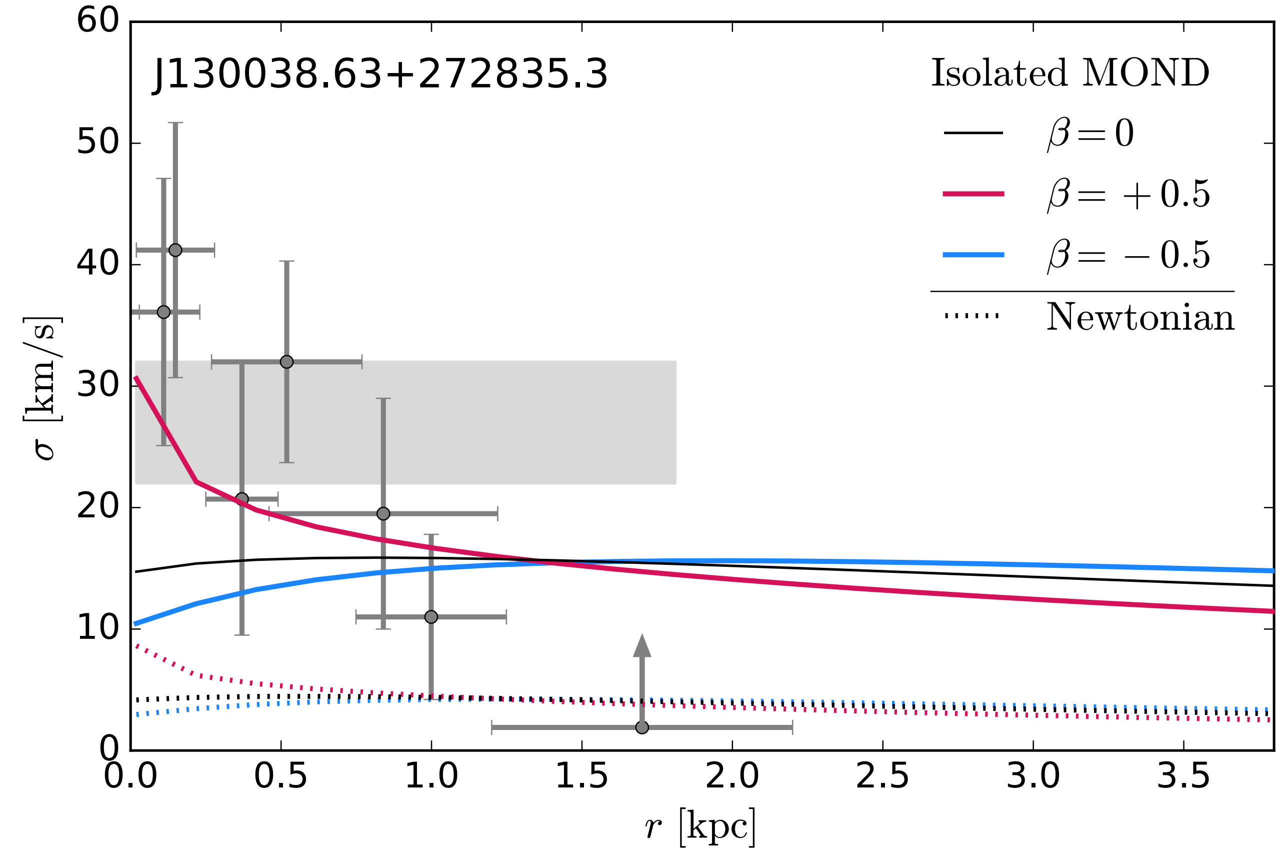
MOND models in isolation

- ✦ Deprojected spherical Sersic mass profile (Lima Neto+1999)
- ✦ Uniform M/L (~1 from Chilingarian+2019, 1.3 for DF44 and DFX1)
- ✦ Line-of-sight velocity dispersion from Jeans equilibrium (Mamon & Lokas 2005)
- ✦ No free parameter





— $\beta = 0$ (isotropic)
— $\beta = +0.5$ (radial)
— $\beta = -0.5$ (tangential)

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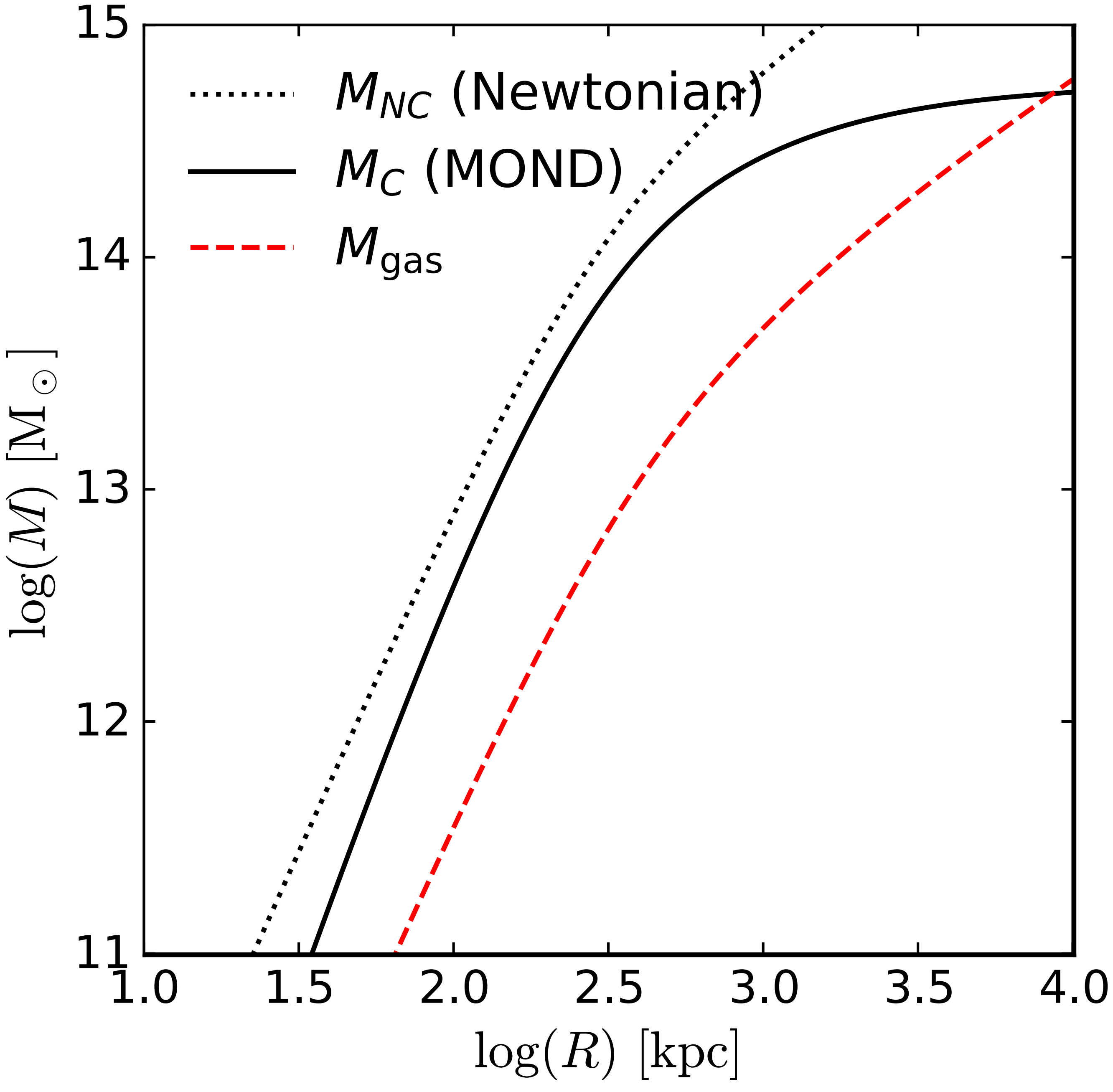
Coma cluster mass model

✦ Obtained from the hydrostatic equilibrium of the X-ray-emitting hot gas, assumed to be isothermal (cf. Reiprich 2001, Sanders 2003)



Newtonian mass model and acceleration:

$$M_{NC} = -\frac{R}{G}\frac{kT_C}{\mu m_p}\frac{d\ln\rho_C}{d\ln R}$$

$$a_{NC} = -\frac{1}{R}\frac{kT_C}{\mu m_p}\frac{d\ln\rho_C}{d\ln R}$$

MOND mass model:

$$M_C = \frac{a_{NC}}{a_{NC}+a_0}M_{NC}$$

β-model for the density:

$$\rho_C = \rho_0\left[1+\left(\frac{R}{R_C}\right)^2\right]^{-1.5\beta}$$

$$M_{gas}(r) = 4\pi\int_0^r \rho_C(r')r'^2 dr'$$

Reiprich 2001 :
$\beta = 0.71$
$kT_c = 8.6$ keV
$\mu = 0.61$
$R_C = 276$ kpc
$\rho_0 = 9.0\times10^4\ M_\odot \mathrm{kpc}^{-3}$

A new formula for the EFE in QUMOND

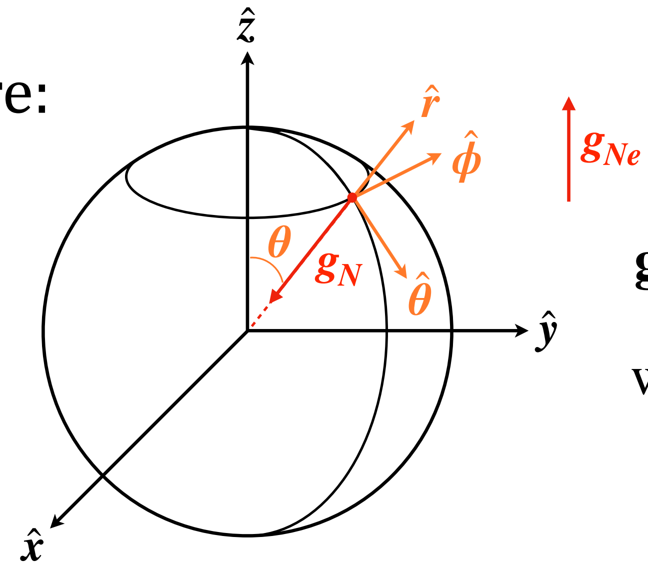
✦ When the internal acceleration field g and the external field g_e are aligned:

$$g_{\parallel} = \nu\left(\frac{g_N + g_{Ne}}{a_0}\right) g_N + \left[\nu\left(\frac{g_N + g_{Ne}}{a_0}\right) - \nu\left(\frac{g_{Ne}}{a_0}\right)\right] g_{Ne}$$

(Famaey & McGaugh 2012, Eq. 60)

✦ Taking the approximate average field over the sphere:

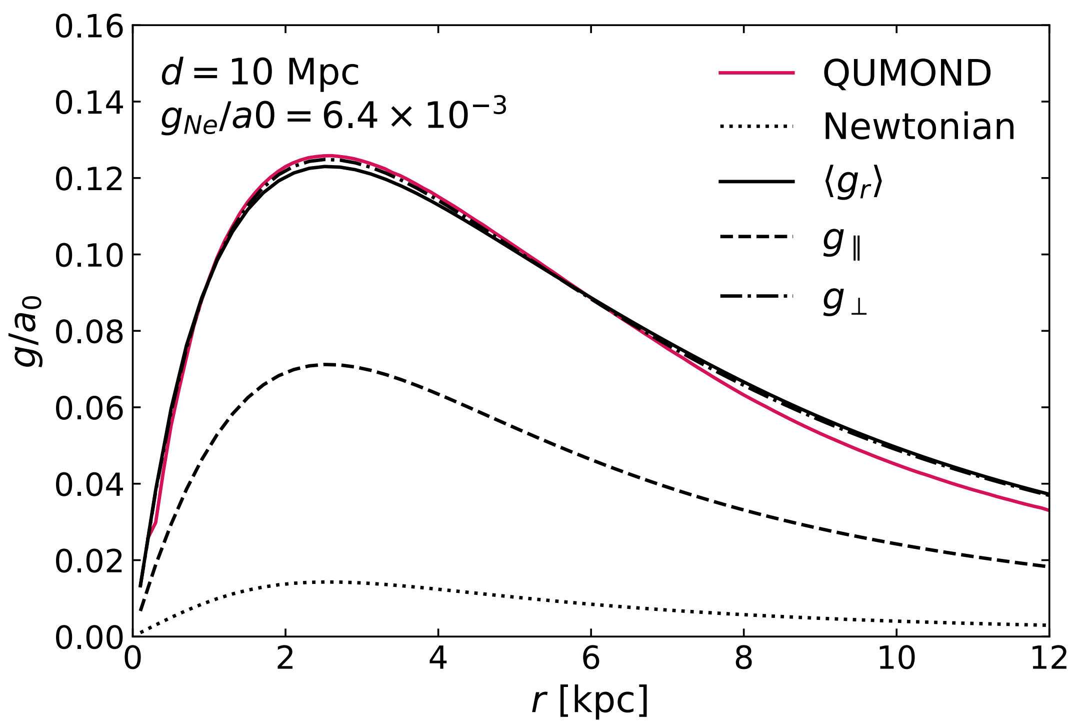
$$\langle g_r \rangle = \begin{cases} \nu\left(\frac{g_N}{a_0} + \frac{g_{Ne}^2}{3 g_N a_0}\right) g_N & \text{when } g_N \geq g_{Ne} \\ \nu\left(\frac{g_{Ne}}{a_0} + \frac{g_N^2}{3 g_{Ne} a_0}\right) g_N & \text{when } g_N \leq g_{Ne} \end{cases}$$



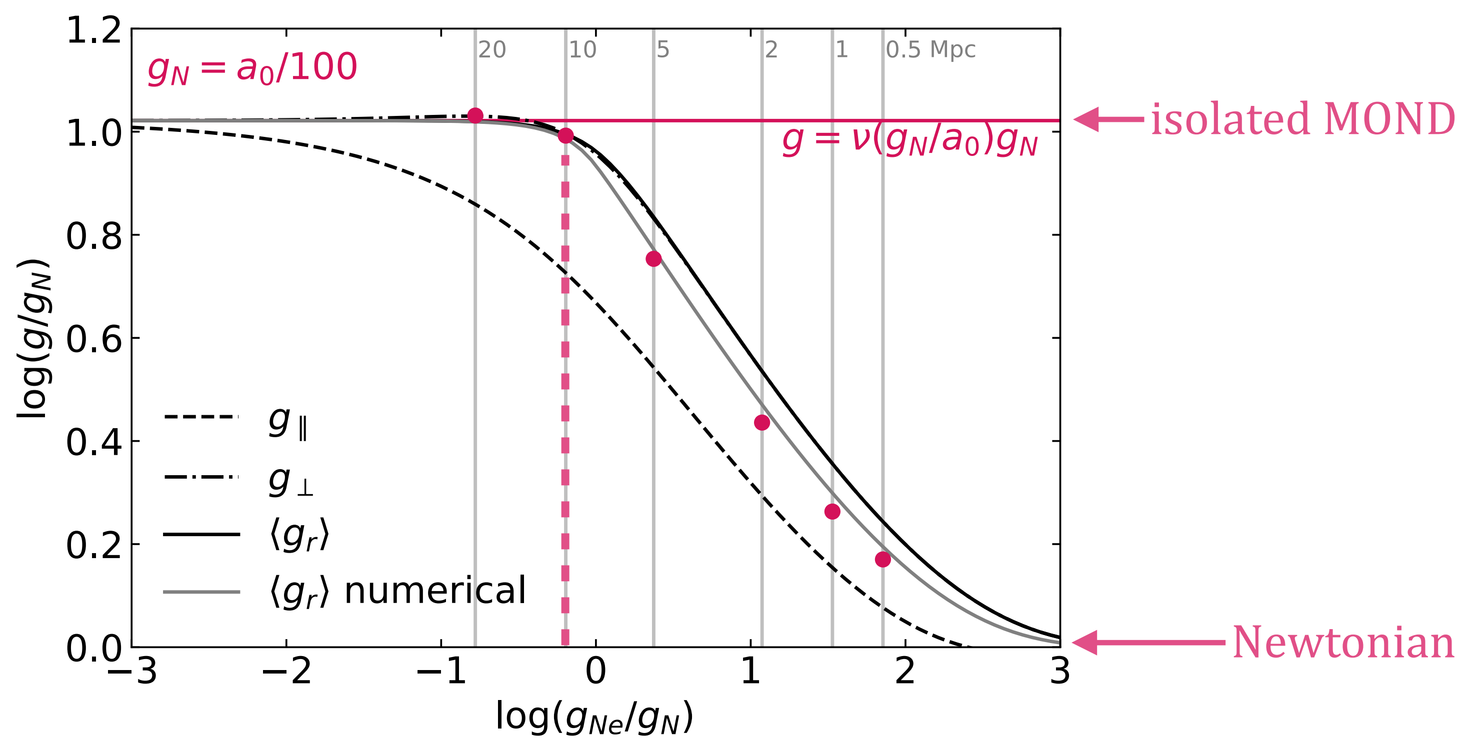
$$\mathbf{g}_{\text{tot}} = \nu\left(\frac{g_{N\text{tot}}}{a_0}\right) \mathbf{g}_{N\text{tot}}$$

with $\mathbf{g}_{\text{tot}} = \mathbf{g} + \mathbf{g}_{\mathbf{e}}$

✦ Validation with a numerical Poisson solver:



(Plummer sphere $M_0 = 3.9 \times 10^8\ M_{\odot}$, $R_P = 3.6$ kpc at 10 Mpc from a point mass equal to $5.6 \times 10^{14}\ M_{\odot}$)



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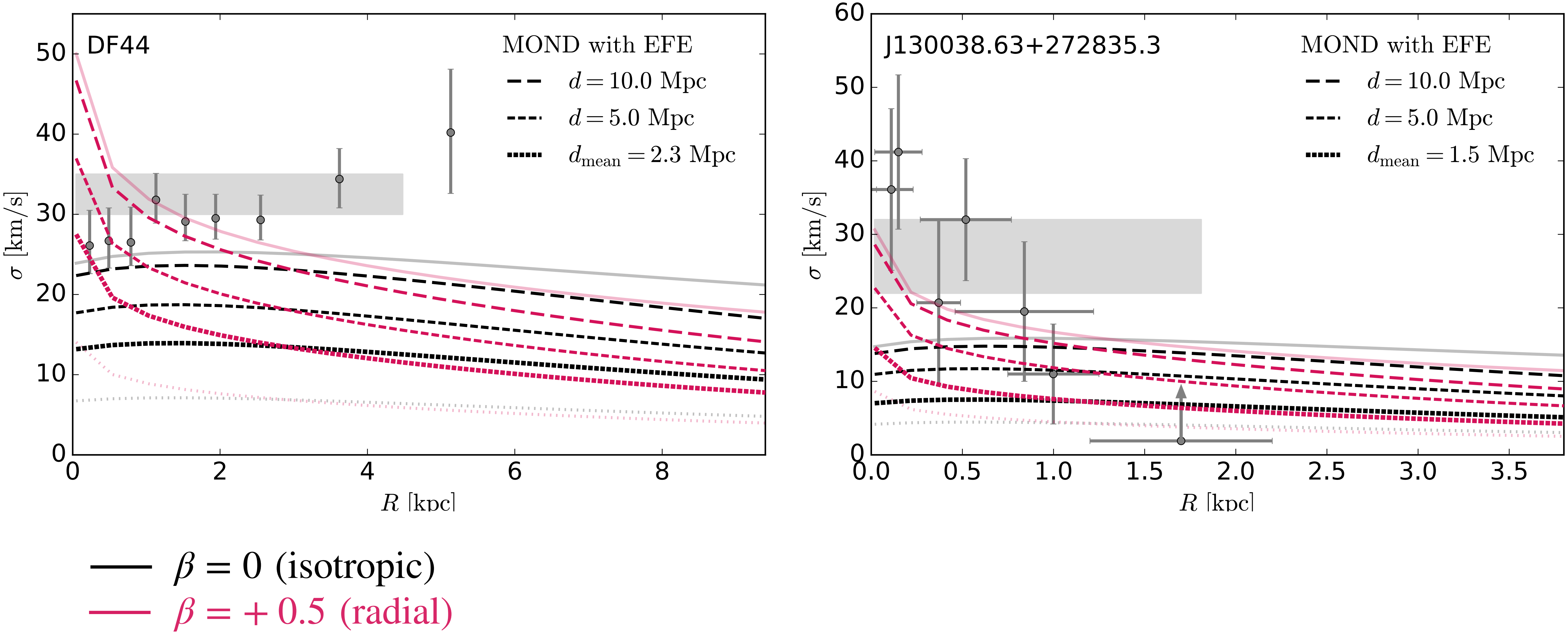
MOND models with EFE

- ✦ Deprojected spherical Sersic mass profile (Lima Neto+1999)
- ✦ Uniform M/L (~1 from Chilingarian+2019, 1.3 for DF44 and DFX1)
- ✦ Line-of-sight velocity dispersion from Jeans equilibrium (Mamon & Lokas 2005)
- ✦ MOND mass model of the Coma cluster (Sanders 2003)
- ✦ **A new analytic formula for the EFE**, tested with QUMOND Poisson solver



‣ **There is a tension with the EFE**

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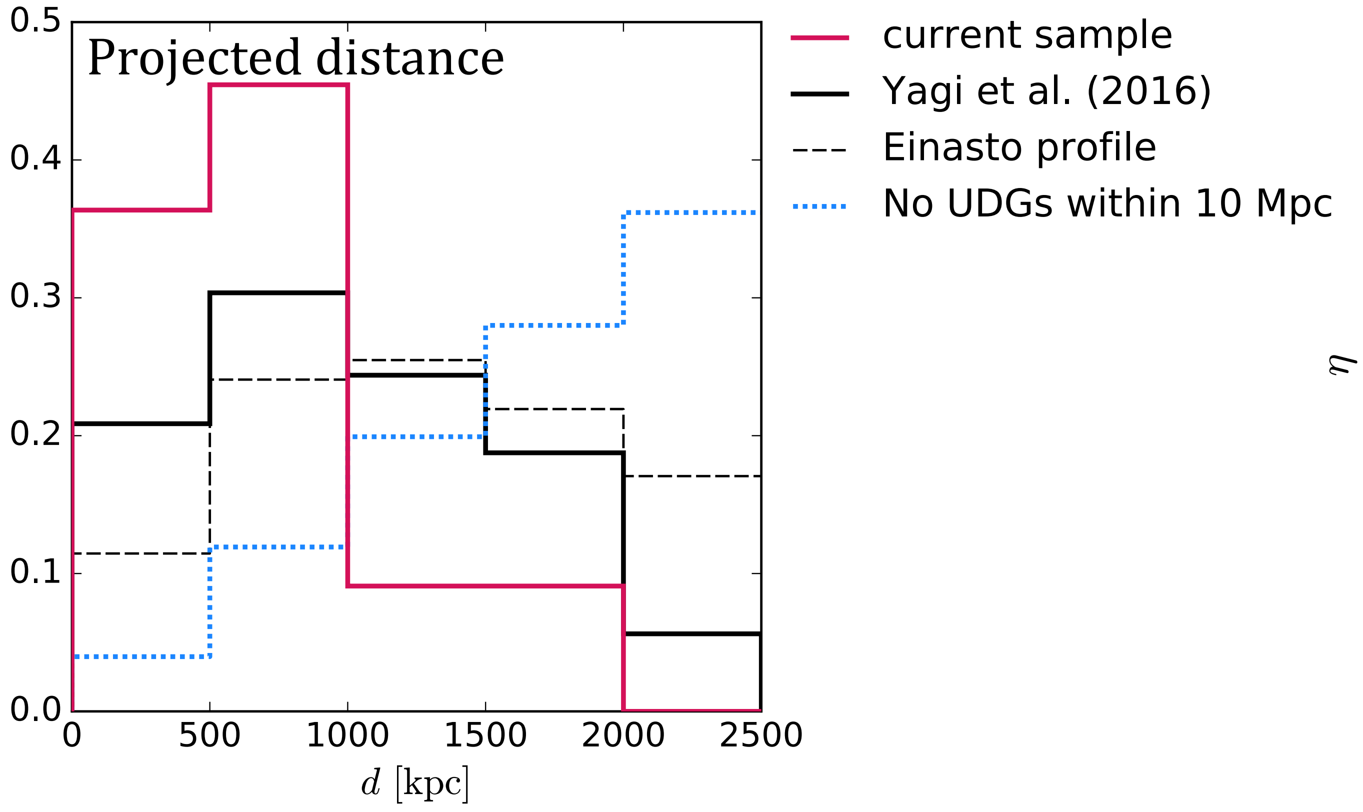
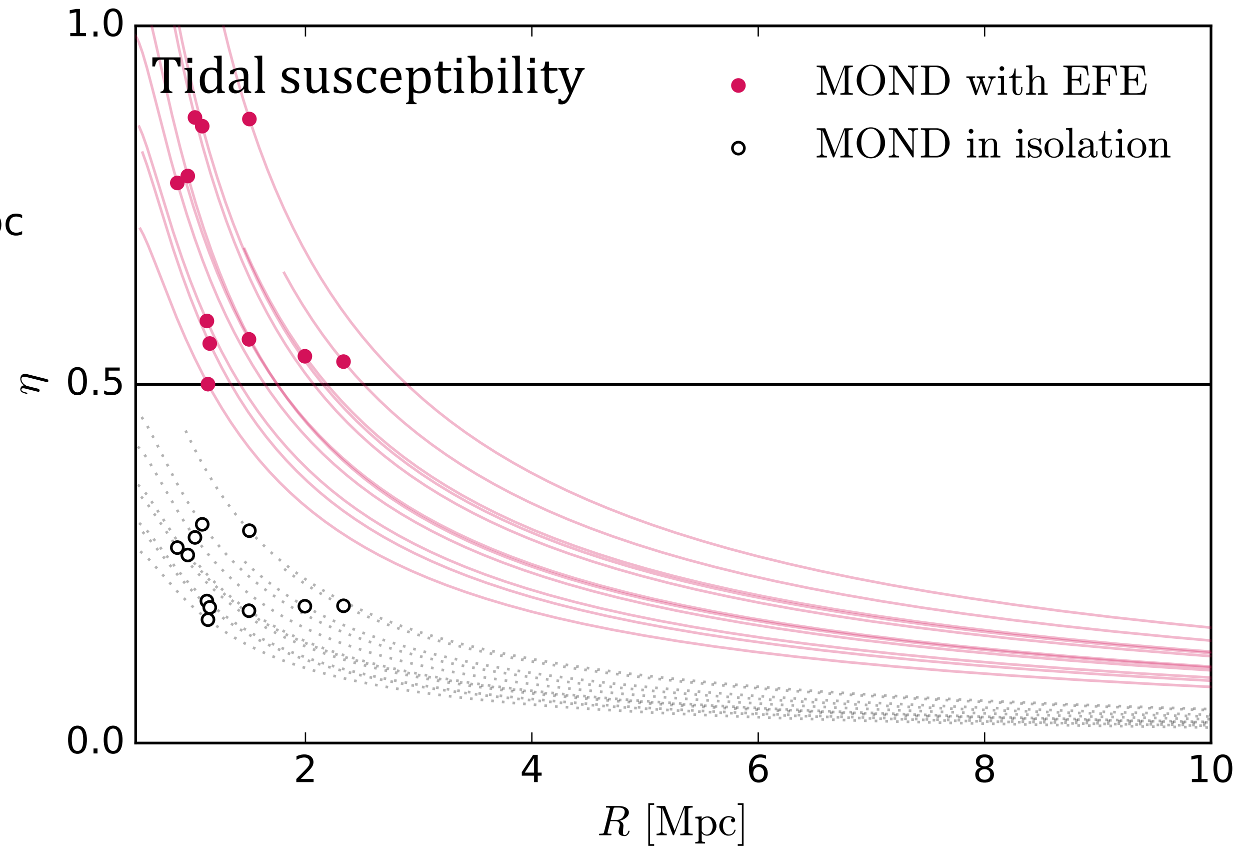
EFE tension: possible explanations

➡ **UDGs further away from the cluster centre, arrived recently (survivor bias), and/or tidally disrupted?**





- ✦ A centrally-depleted UDG distribution is unlikely (cf. projected distance)
- ✦ Recent infall onto the cluster possible but orbital times $t_{cluster} \sim 3\text{-}6\, t_{UDG}$
- ✦ Tidally disrupted **or tidally heated**: elongated morphologies, tidal susceptibility

See Srikanth's talk!

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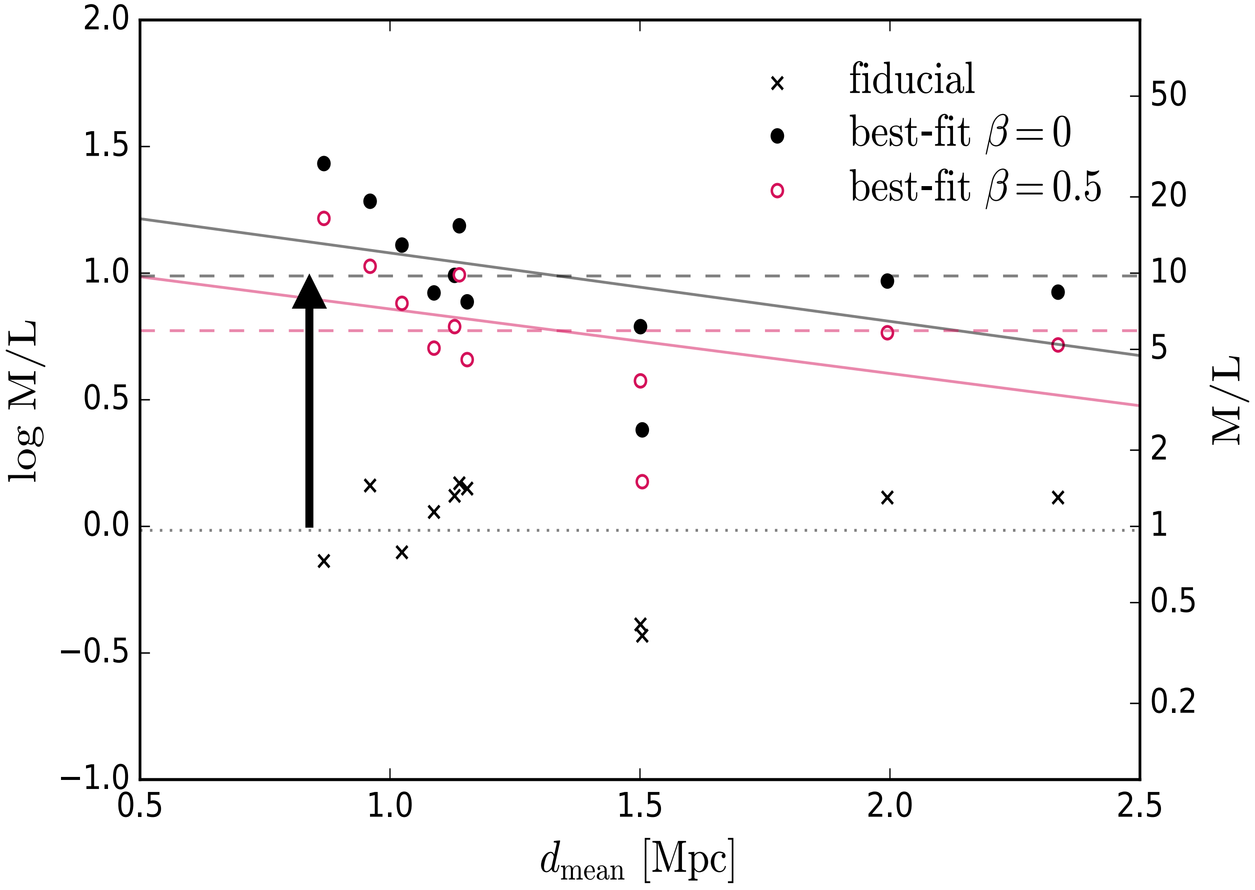
EFE tension: possible explanations

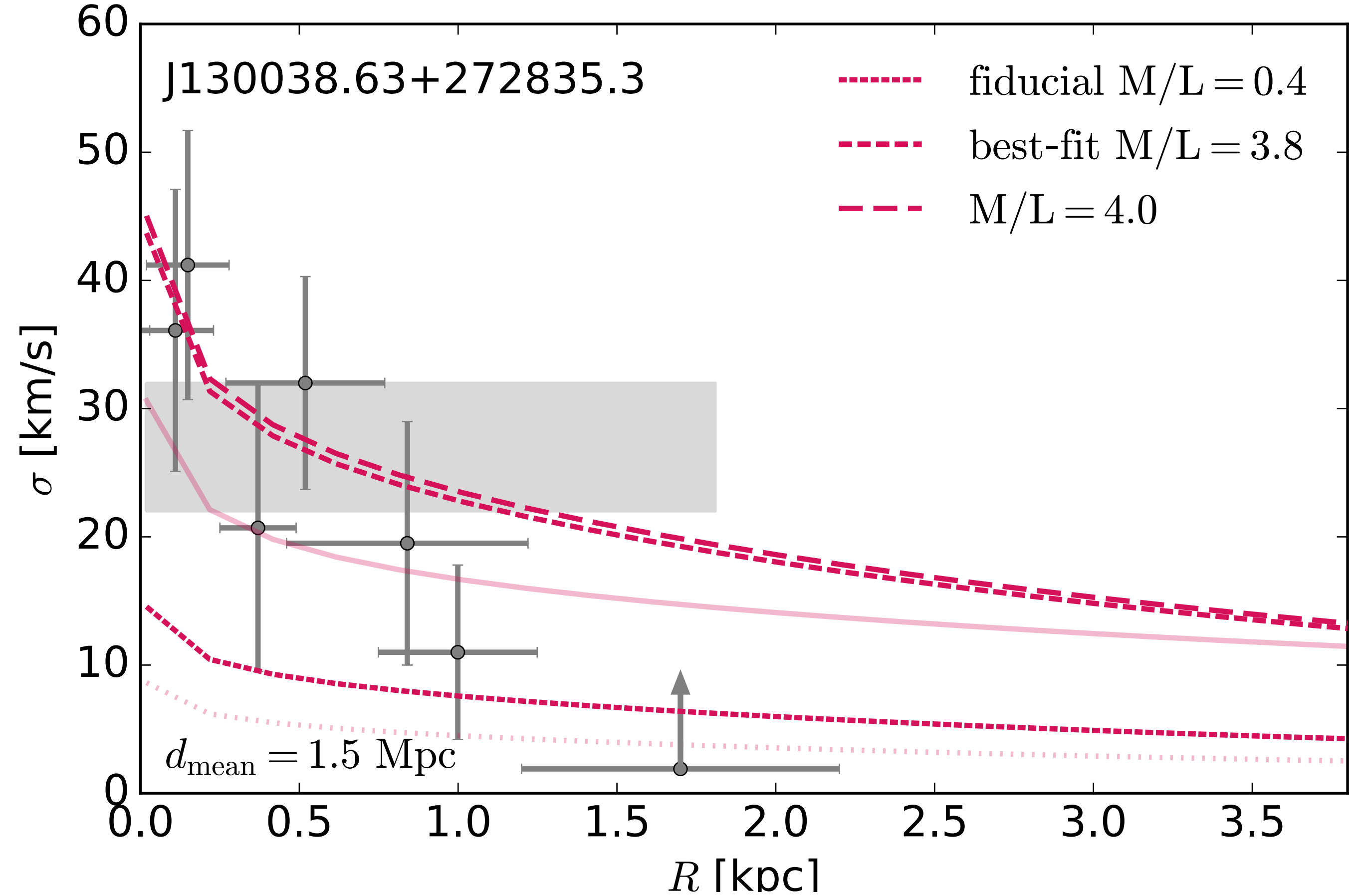
➡ **Higher stellar masses or cluster baryonic dark matter?**

Assumed M/L~1 obtained through standard procedures (e.g. Pegase.HR in Chiligarian+19)

Best-fit M/L to recover σ_{eff}:



With M/L = 4:



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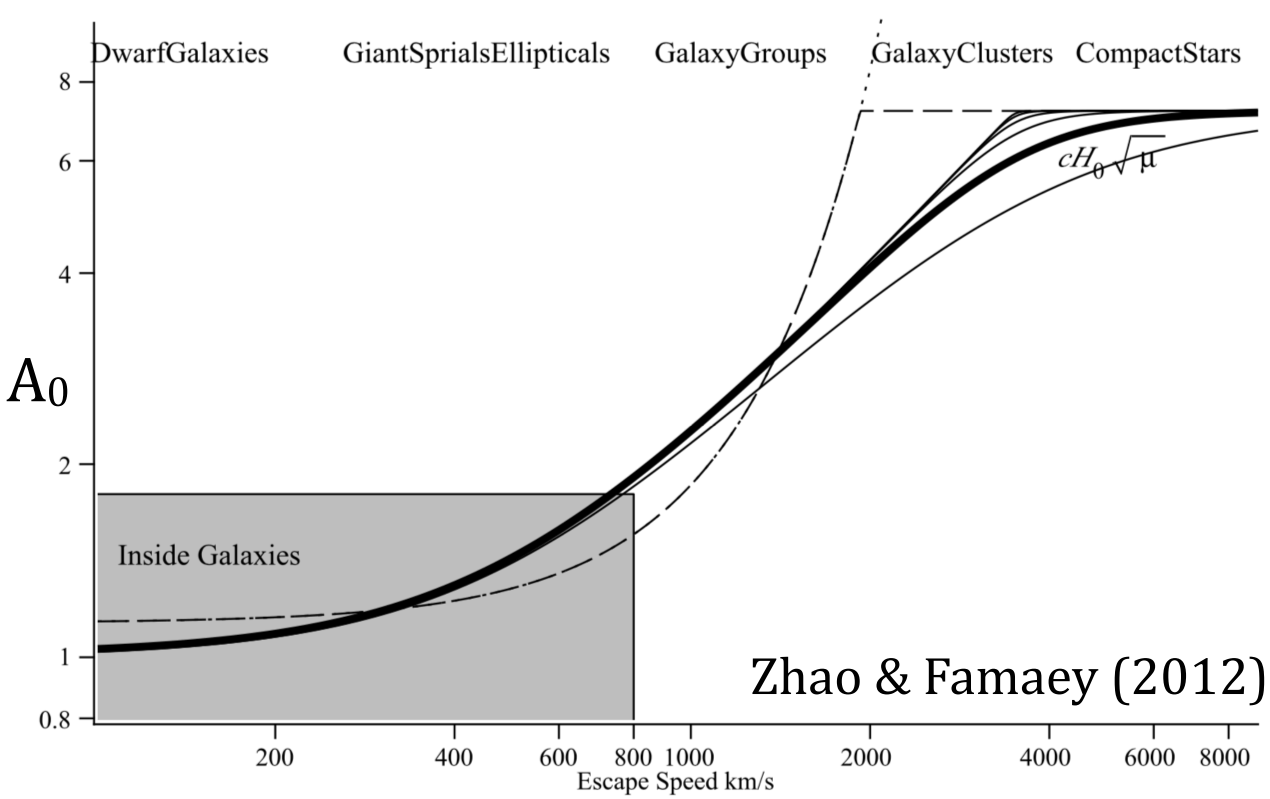
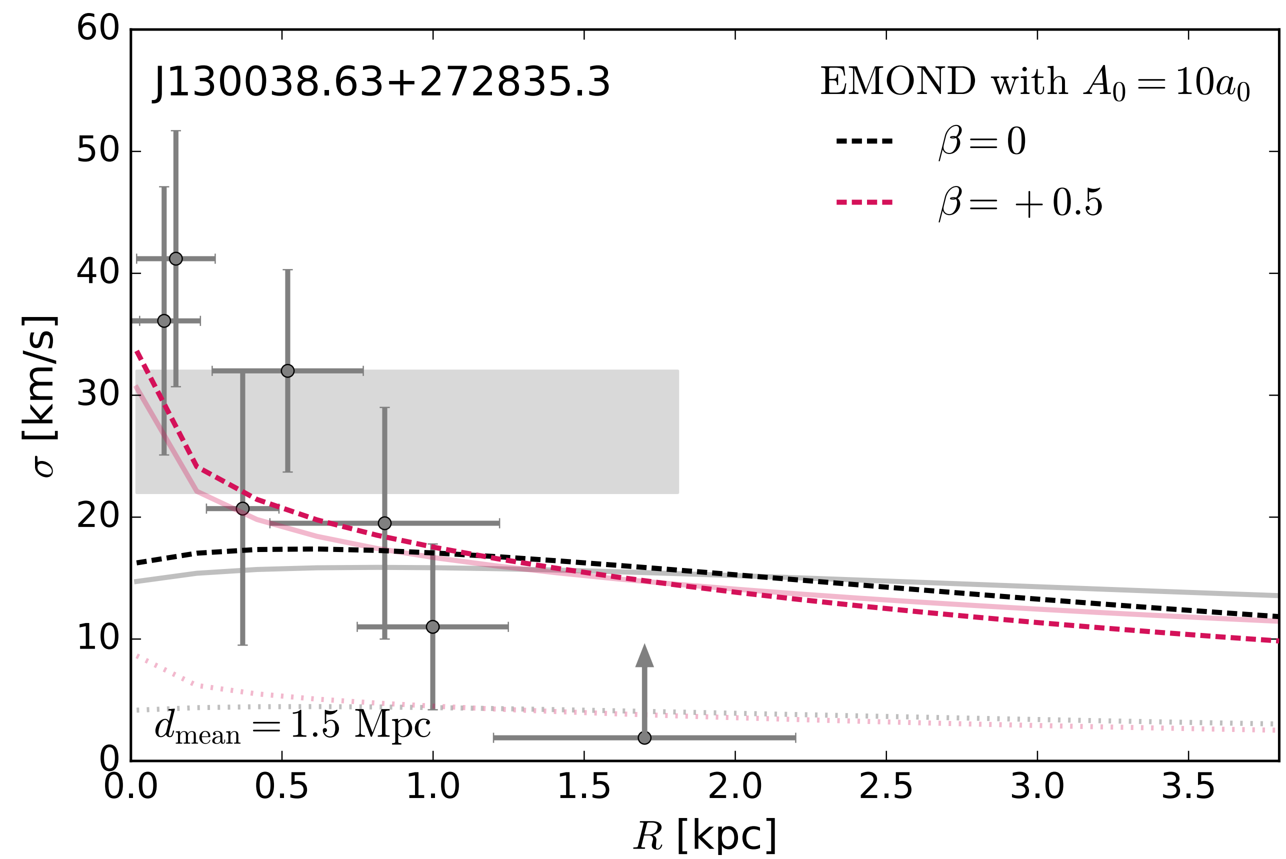
EFE tension: possible explanations

➡ **MOND without EFE or with an EFE depending on a galaxy individual history (modified inertia)** — but what about places where the EFE works and the predictive power of MOND?

➡ **EMOND** (Zhao & Famaey 2012): the acceleration A_0 would vary with the environment





➡ **Screening the EFE in galaxy clusters,** which is the case in superfluid dark matter and could be the case in theories where the additional degrees of freedom making up the residual missing mass in clusters do not couple to the field generating MOND (i.e., no EFE in clusters) — e.g. Skordis & Zlosnik (2021)?

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Conclusion

Freundlich, Famaey et al. 2022: Coma cluster ultra-diffuse galaxies as a testing ground for MOND and its external field effect (EFE)

➡ Coma cluster UDGs lie on the same radial acceleration relation as spirals in the field

➡ Velocity dispersions in agreement with isolated MOND predictions

➡ Velocity dispersions **in tension with MOND models including the EFE** *(with a new approximate analytical formula for the EFE, tested numerically)*

Caveats: sphericity, uniform M/L, Coma cluster mass model, distances, analytical formula for the EFE, Jeans equilibrium, velocity dispersion measurements

Possible explanations:

➡ Recent infall (survivor bias)
➡ Tidal interactions
➡ Higher M/L ratios
➡ Cluster baryonic dark matter
➡ Modified inertia
➡ MOND as a dark matter scaling relation

} but why does isolated MOND work so well?

➡ **EMOND $A_0(\phi)$**

➡ **Screening the EFE in clusters in theories with additional degrees of freedom?**
↳ The tension with the EFE in clusters could guide further theoretical development