Possible problems for ΛCDM: status in 2018

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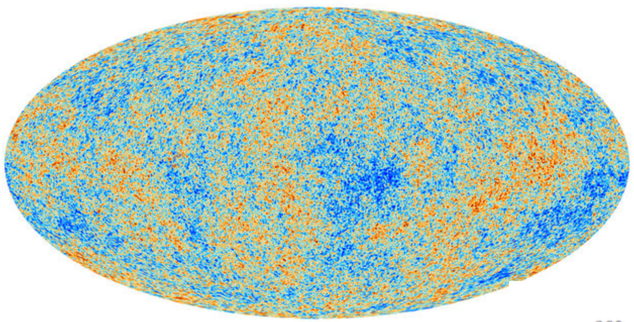
Existence of a non- dust fluid

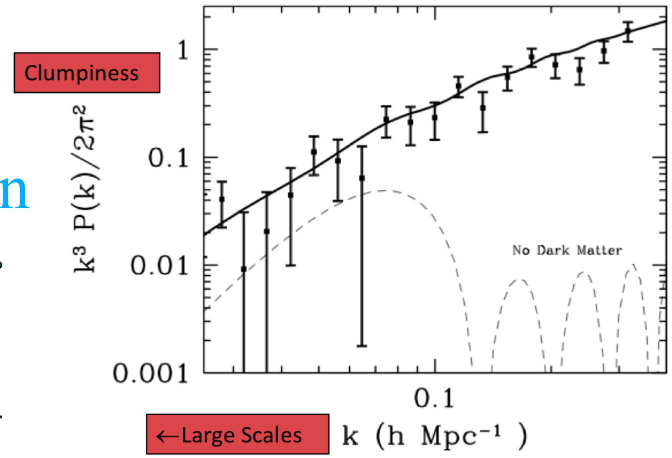
Cosmic Microwave Background => **ΛCDM cosmological model**

Baryonic matter = 16% of matter, 5% of total energy content

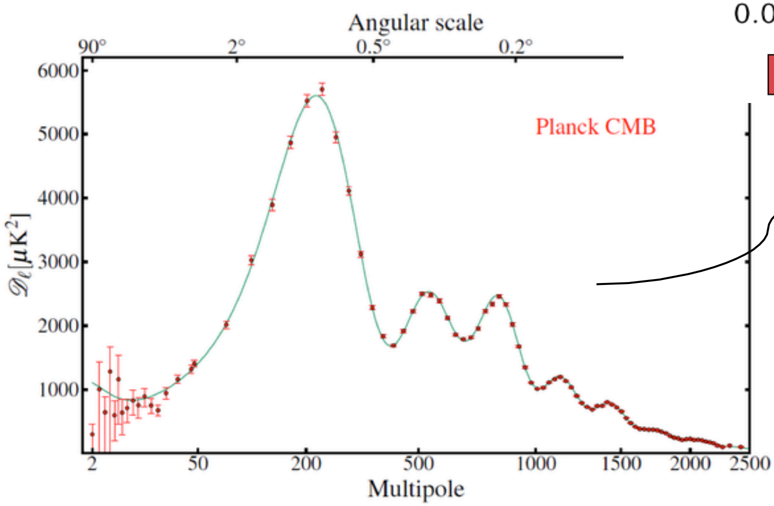
$\Lambda \approx 10^{-52}\,m^{-2}$ => 68% dark energy & 32% matter (baryons+dark) at z~0



Structure formation



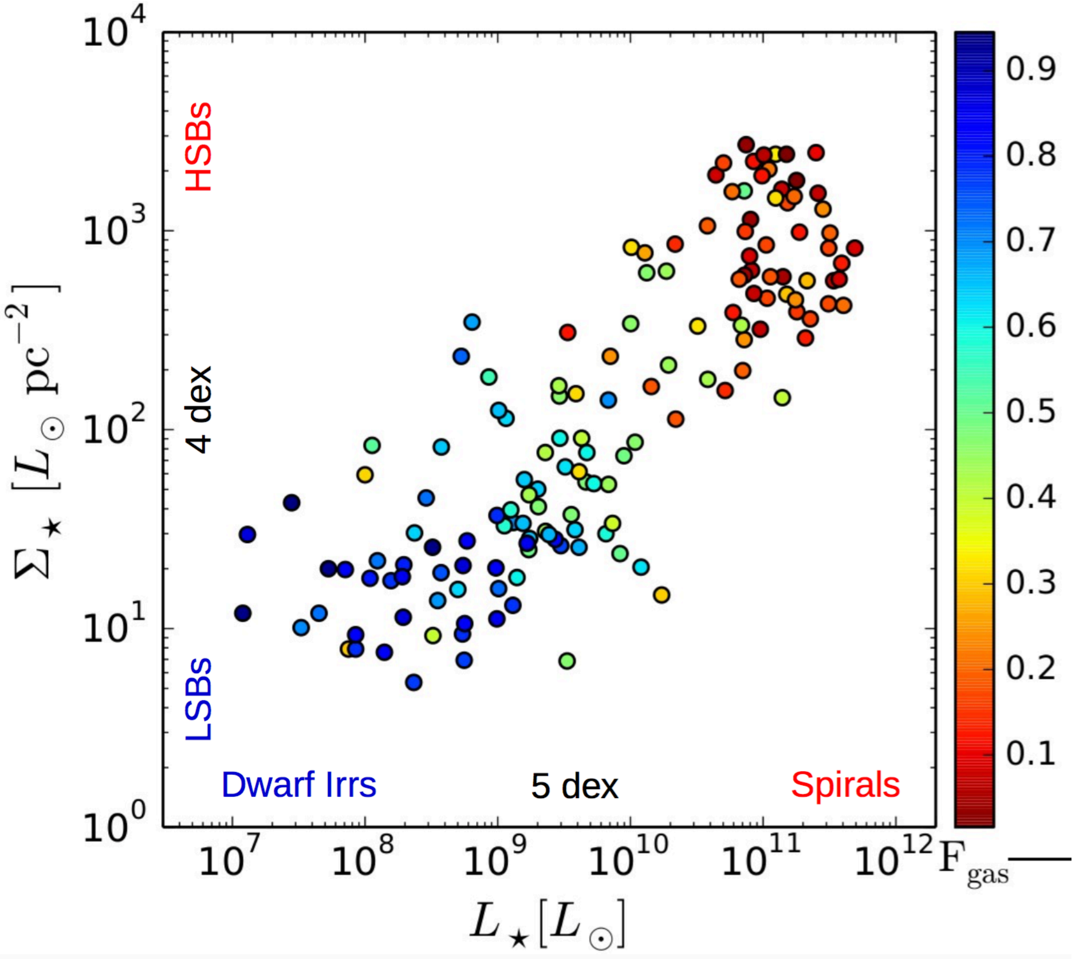
$\Delta T/T \sim 10^{-5}$



+ needs forcing term to counter Silk damping

HI galaxy rotation curves

- SPARC (Lelli et al.)
- 175 galaxies with high quality HI RCs
- Homogeneous Spitzer photometry at 3.6μm
- M_*/L known to be roughly constant (0.5-0.7) in the NIR



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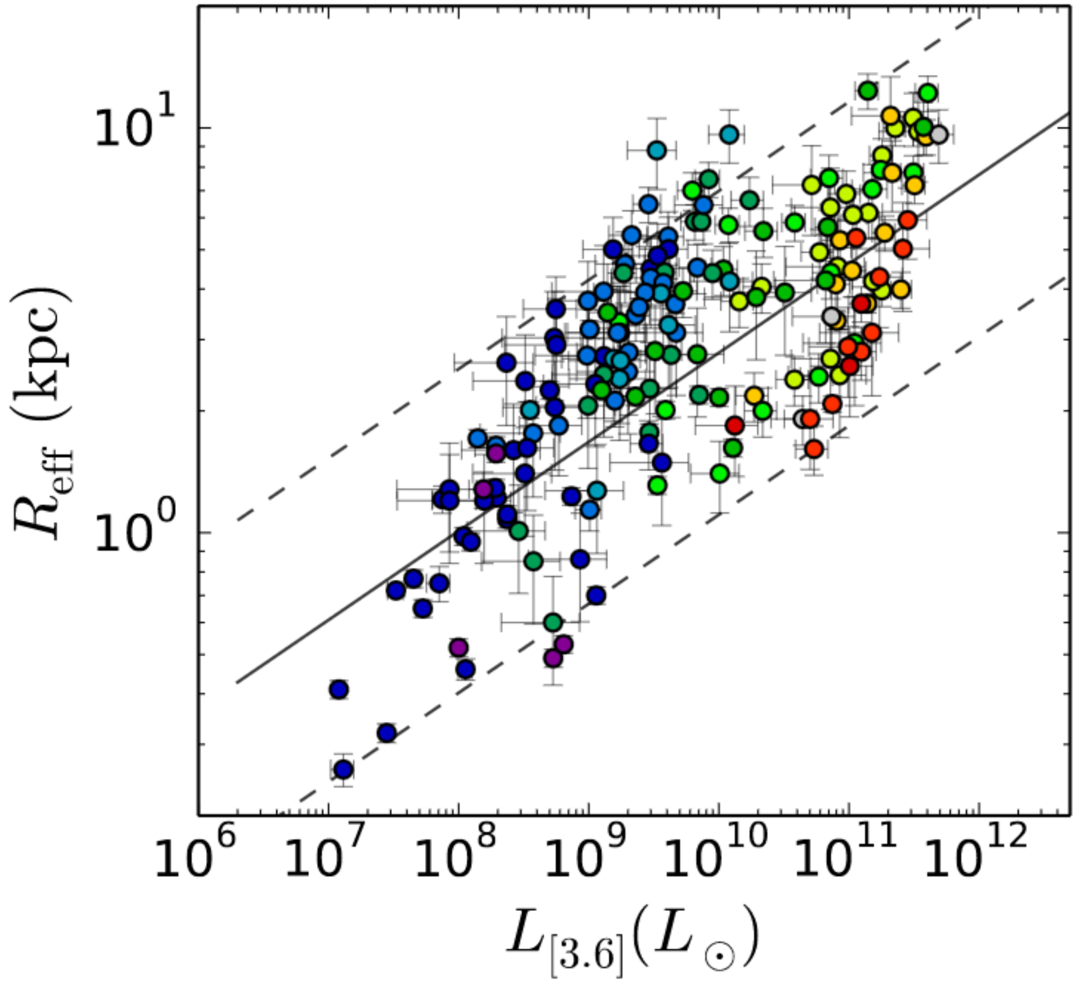
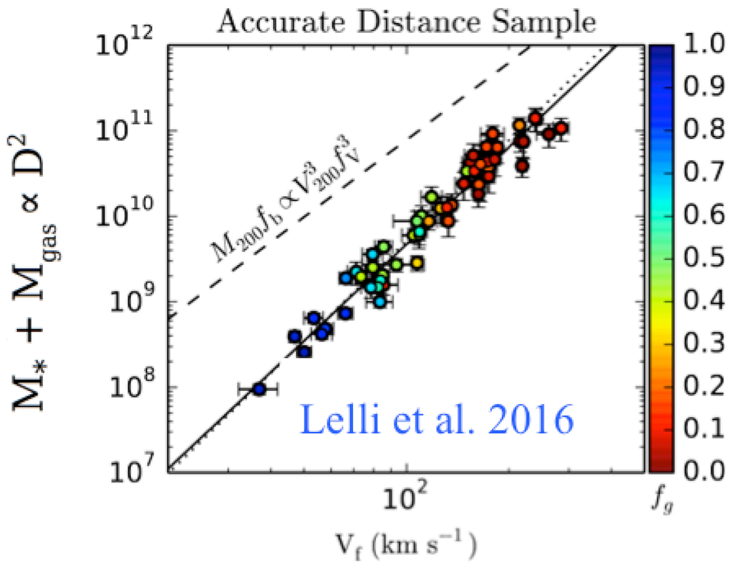


BTFR

- $\log M_b = \alpha \log V - \log \beta$
- $\alpha = 3.9 \pm 0.4$
- Zero-point defines an acceleration constant $a_0 \approx V^4/(GM_b) \approx 10^{-10}$ m/s^2 such that $\beta = Ga_0$
- Scatter ~ 0.1 dex in M_b



The scatter, residual correlations and curvature of the SPARC baryonic Tully–Fisher relation

Harry Desmond[1,2]★

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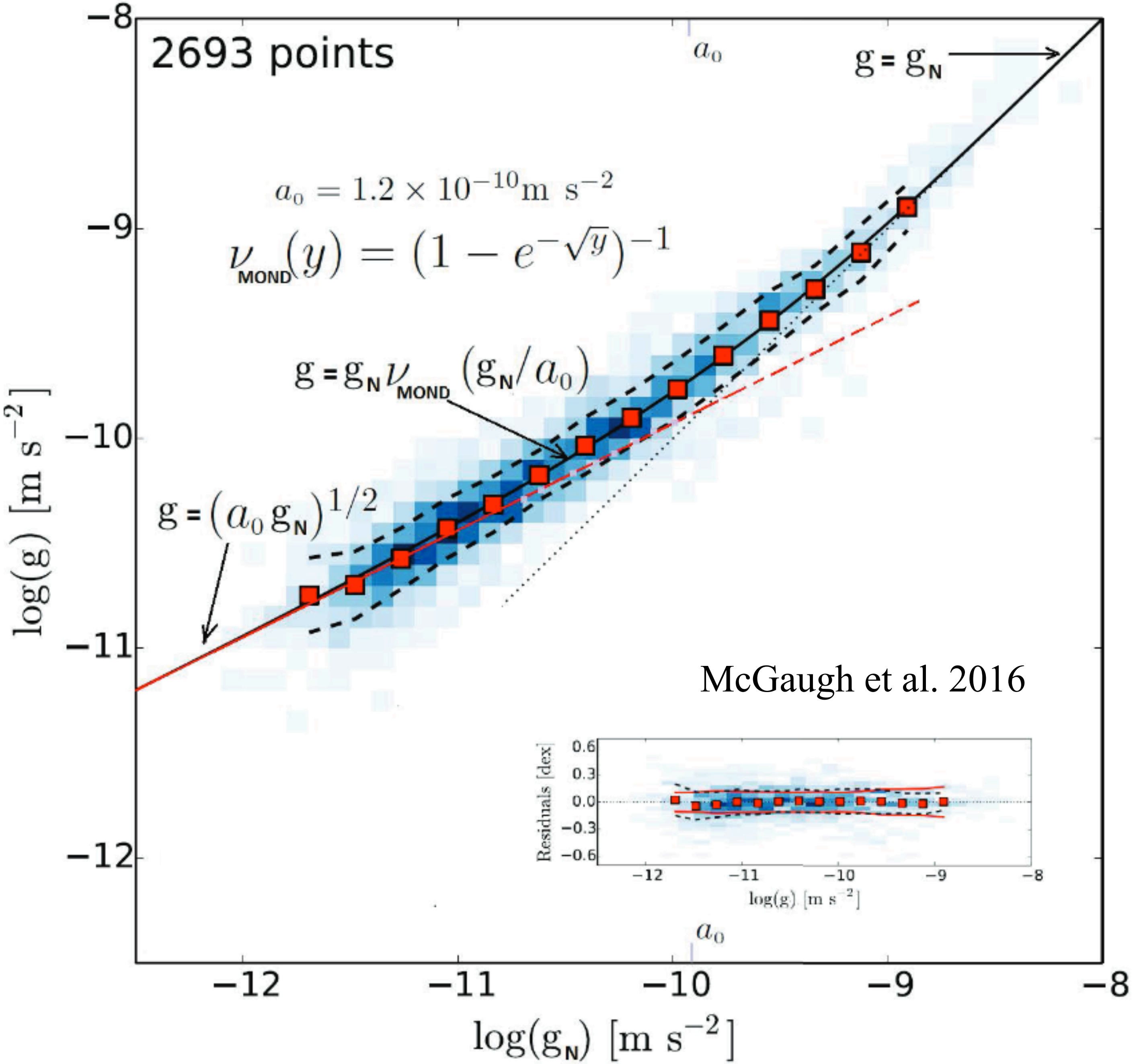
calculate the statistical significance of these results in the framework of halo abundance matching, which imposes a canonical galaxy–halo connection. Taking full account of sample variance among SPARC-like realisations of the parent halo population, we find the scatter in the predicted BTFR to be 3.6 σ too high.

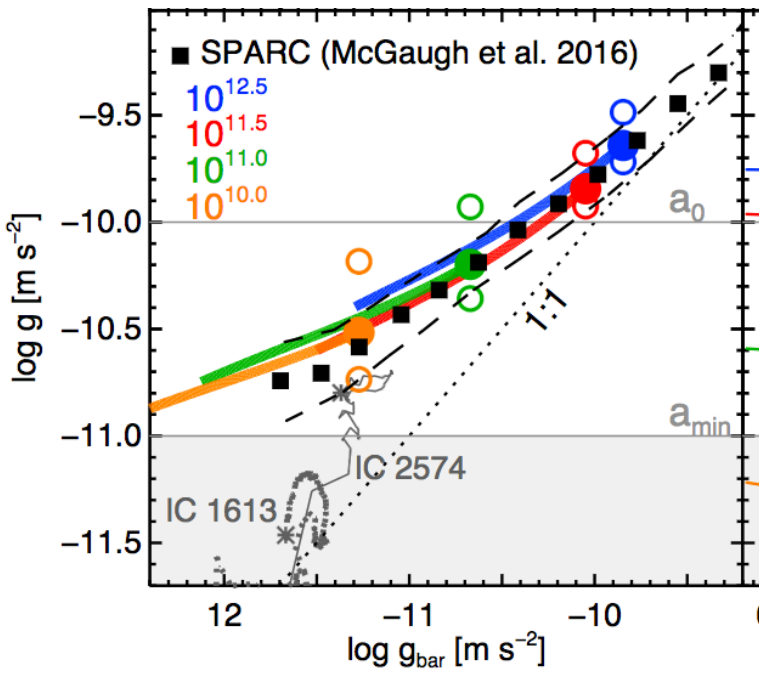


2693 points
a_0
g = g_N
$a_0 = 1.2 \times 10^{-10}$m s^{-2}
$\nu_{MOND}(y) = (1 - e^{-\sqrt{y}})^{-1}$
g = $g_N \nu_{MOND}$ (g_N/a_0)
g = $(a_0 g_N)^{1/2}$
McGaugh et al. 2016
Residuals [dex]
log(g) [m s^{-2}]
log(g_N) [m s^{-2}]

Not natural in ΛCDM

Navarro et al (2016):

1) Match stellar and halo mass function [abundance matching of n(>M*) to n(>M)] => tight M*-Mh relation
2) Add a relation between stellar mass and size:



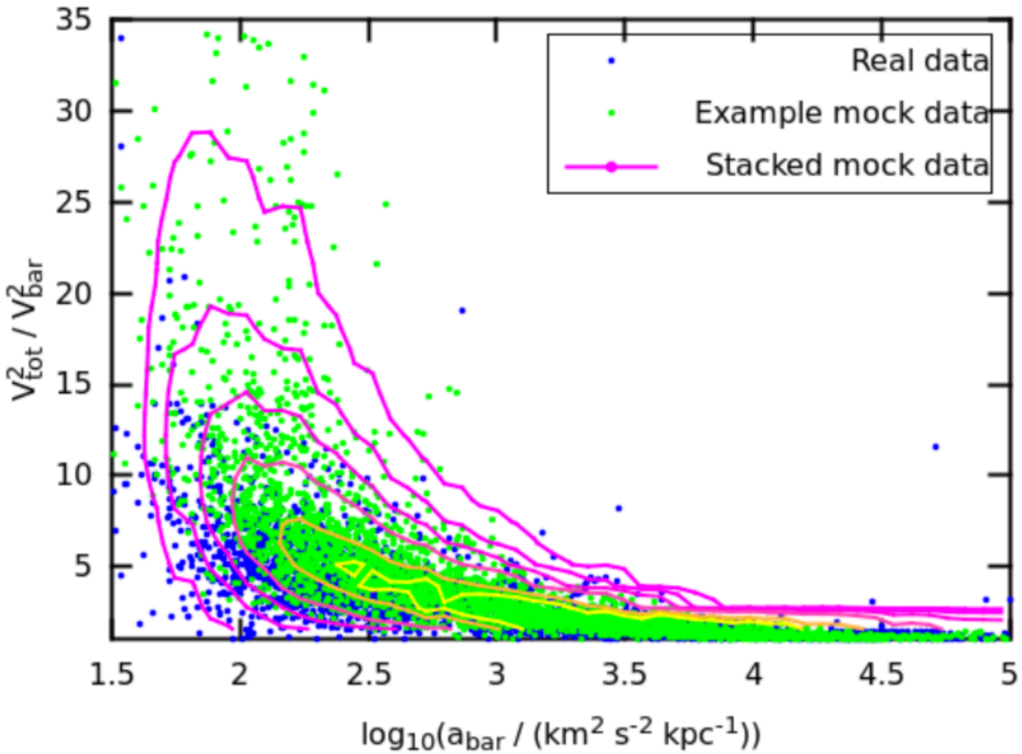
Overprediction of g means substantial core creation is needed

BUT

real problem=scatter

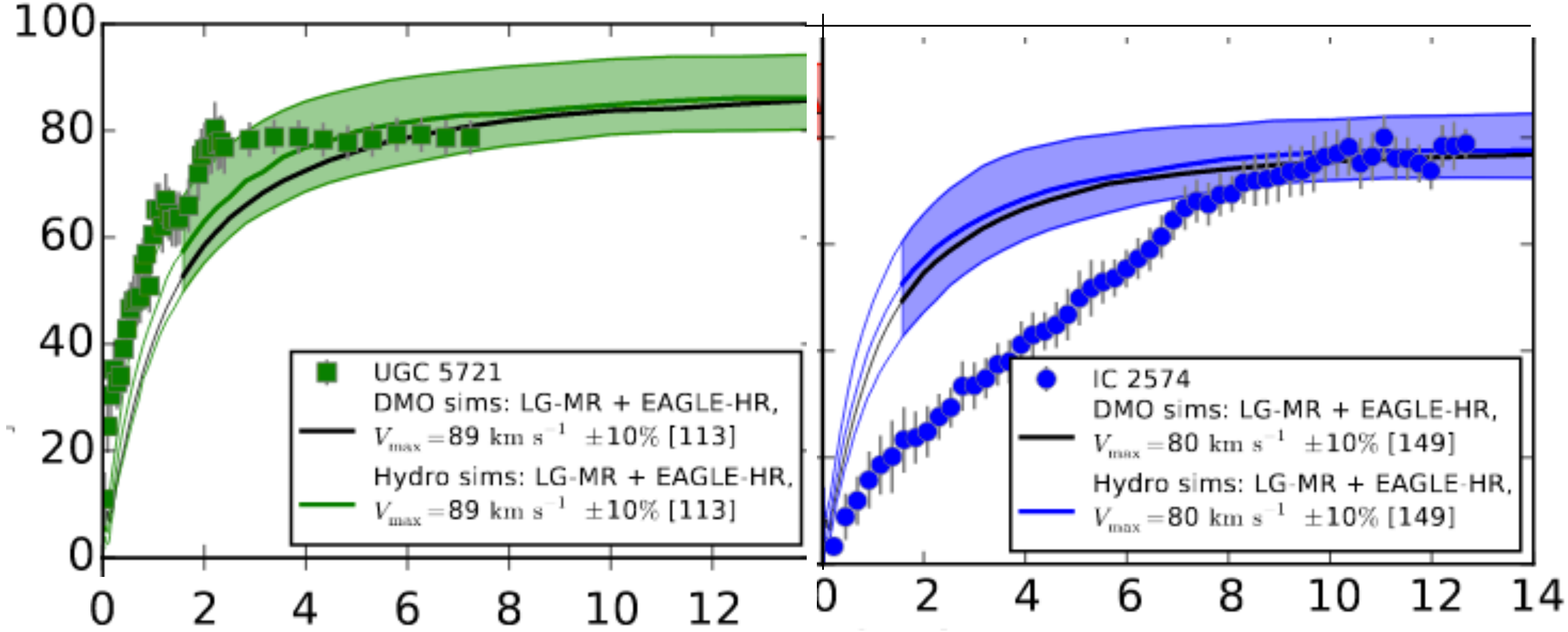
Not natural in ΛCDM

But the relation between mass & size is not that tight, and when anticorrelating R_d and c, the AM variation in M_{vir} alone at fixed M_*, scale-length and c is too high to produce the observed RAR scatter (<0.13 dex)



Desmond (2017)

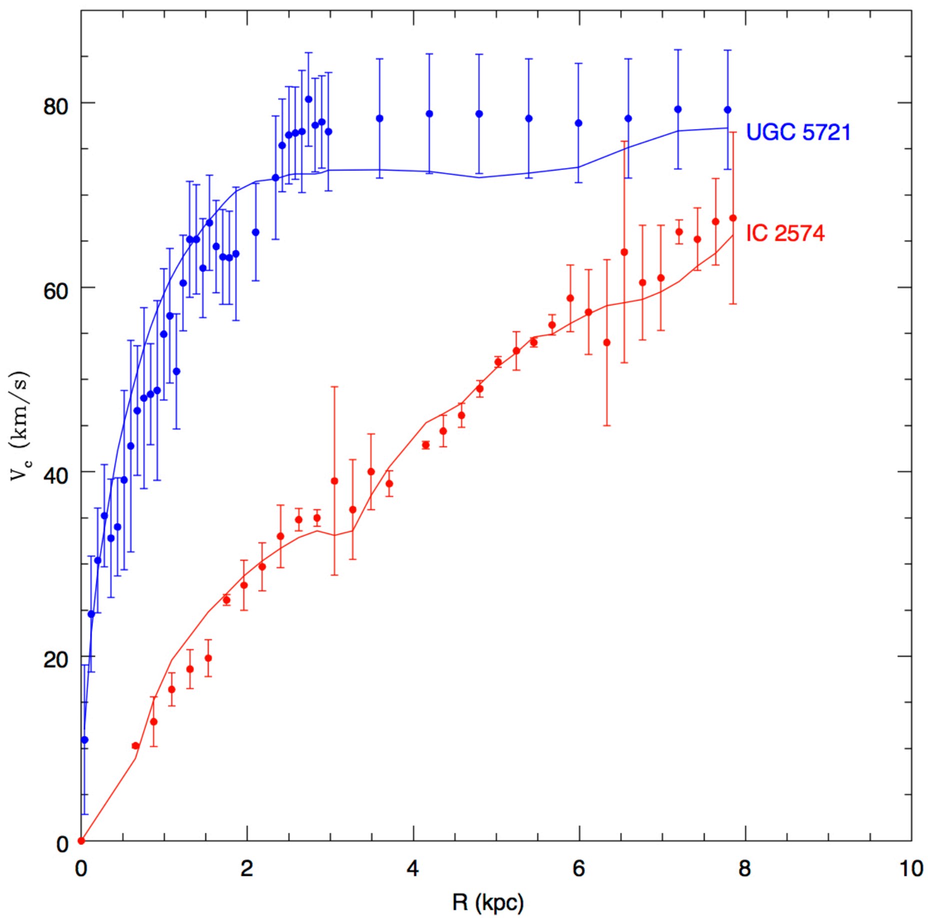
Diversity of RC profiles at given Vmax scale



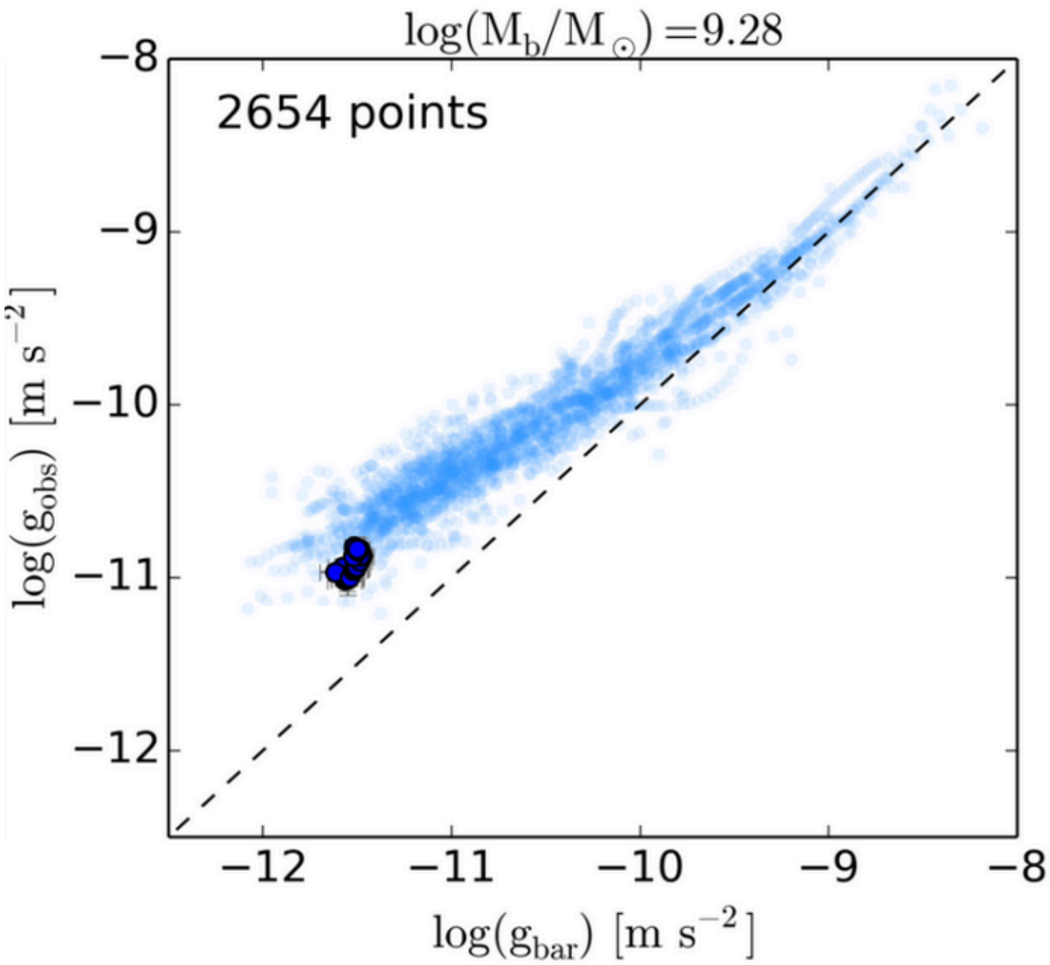
EAGLE simulations

Oman, Navarro, Fattahi, Frenk, Sawala, White, et al. (2015)

Radial Acceleration Relation

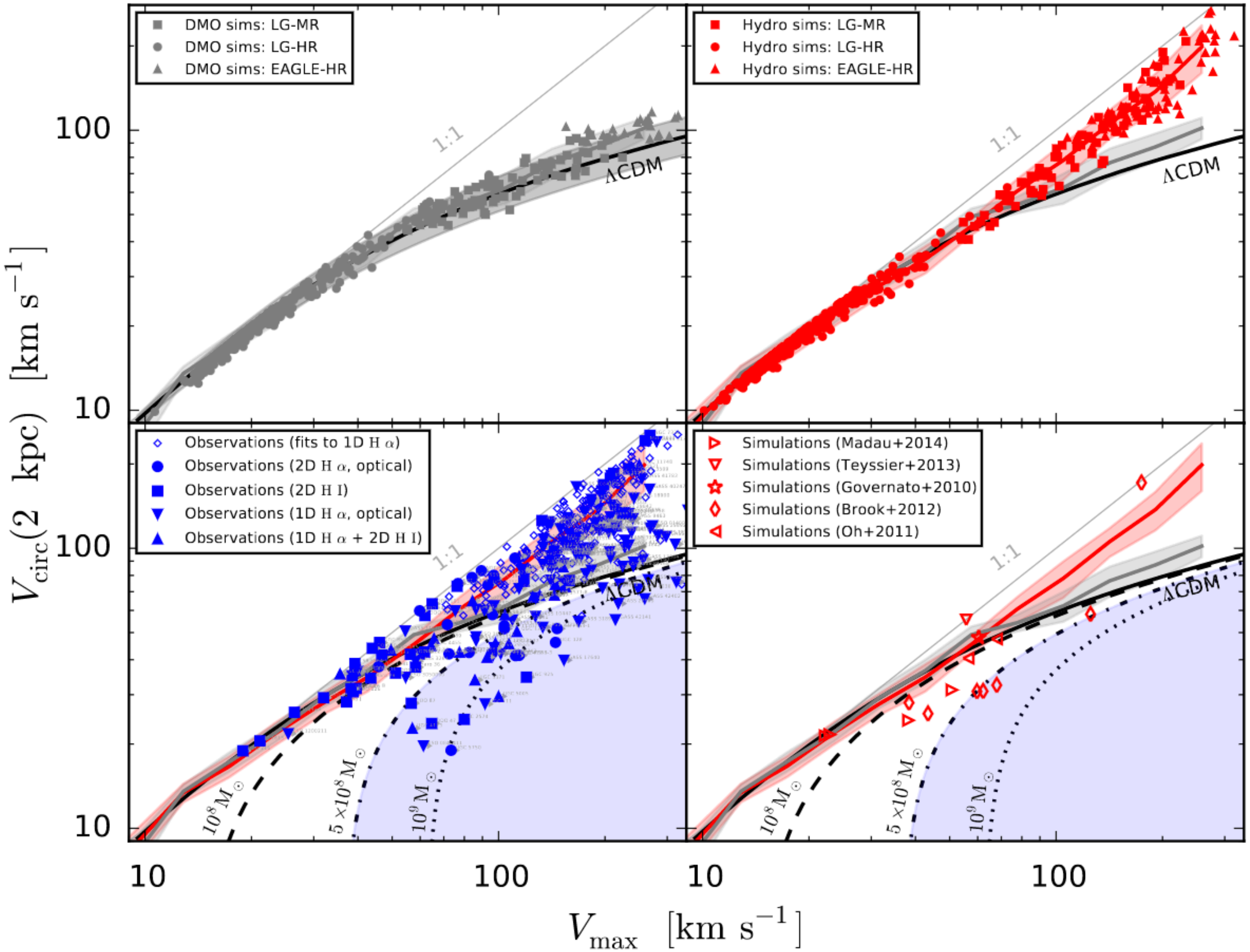


IC 2574



log(M_b/M_⊙) =9.28
2654 points
−8
−9
−10
−11
−12
log(g_obs) [m s^−2]
−12
−11
−10
−9
−8
log(g_bar) [m s^−2]

Diversity of RC profiles at given Vmax scale



The unexpected diversity of dwarf galaxy rotation curves

Kyle A. Oman[1,⋆], Julio F. Navarro[1,2], Azadeh Fattahi[1], Carlos S. Frenk[3], Till Sawala[3], Simon D. M. White[4], Richard Bower[3], Robert A. Crain[5], Michelle Furlong[3], Matthieu Schaller[3], Joop Schaye[6], Tom Theuns[3]
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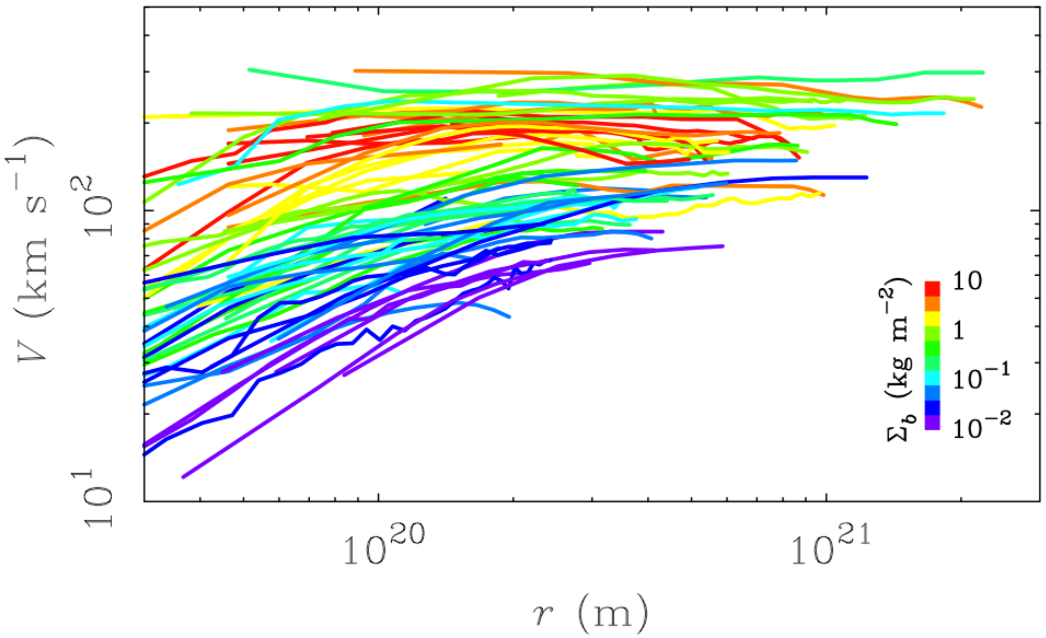
We conclude that one or more of the following statements must be true: (i) the dark matter is more complex than envisaged by any current model; (ii) current simulations fail to reproduce the diversity in the effects of baryons on the inner regions of dwarf galaxies; and/or (iii) the mass profiles of "inner mass deficit" galaxies inferred from kinematic data are incorrect.

maximum circular velocity. This is especially true for low-mass dark matter-dominated systems, reflecting the expected similarity of the underlying cold dark matter haloes. This is at odds with observed dwarf galaxies, which show a large diversity of rotation curve shapes, even at fixed maximum rotation speed. Some dwarfs have rotation curves that agree well with simulations, others do not. The latter are systems where the inferred mass enclosed in the inner regions is much lower than expected for cold dark matter haloes and include many galaxies where previous work claims the presence of a constant density "core". The "cusp vs core" issue is thus better characterized as an "inner mass deficit" problem than as a density slope mismatch. For several galaxies the magnitude of this inner mass deficit is well in excess of that reported in recent simulations where cores result from baryon-induced fluctuations in the gravitational potential.
We conclude that one or more of the following statements must be true: (i) the dark matter is more complex than envisaged by any current model; (ii) current simulations fail to reproduce the diversity in the effects of baryons on the inner regions of dwarf galaxies; and/or (iii) the mass profiles of "inner mass deficit" galaxies inferred from kinematic data are incorrect.

Key words: dark matter, galaxies: structure, galaxies: haloes

The baryonic surface density (or characteristic acceleration) actually determines **the shape of rotation curves:** huge fine-tuning

DIVERSITY of observed profiles at given V_{max}
vs.
UNIFORMITY of profiles at given Σ_b



Famaey & McGaugh (2012)

MOND paradigm

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

- Emergence from feedback? => not MOND! Not found…

- Due to a fundamental reason?

1) DM-baryons interactions?

2) More radical:

2a) Fundamental nature of DM?
(gravitational dipoles, surperfluid,…)
2b) Modified Gravity + DM?
2c) Even more exotic (modified « inertia », …)?

MOND paradigm

$\nabla . [\mu (|\nabla\Phi| / a_0) \nabla\Phi] = 4 \pi G \rho_{bar}$ AQUAL: Bekenstein & M (1984)

or

$\nabla^2 \Phi = \nabla . [\nu (|\nabla\Phi_N| / a_0) \nabla\Phi_N]$ QUMOND: Milgrom (2010)

- Differing only slightly outside of spherical symmetry

- Both have possible relativistic counterparts

- Numerical Poisson solvers exist: recently, PoR (Phantom of Ramses) for QUMOND (Lüghausen, Famaey & Kroupa)

Solar System constraints

Hees et al. (2016):

Strong constraints on modified gravity versions of MOND from Cassini

$$\nabla^2\Phi = \nabla.\left[\nu\left(\frac{|\nabla\Phi_N|}{a_0}\right)\nabla\Phi_N\right]$$

$$\nu_n(y) = \left[\frac{1+\left(1+4y^{-n}\right)^{1/2}}{2}\right]^{1/n},$$

$$\tilde{\nu}_\alpha(y) = \left(1-e^{-y}\right)^{-1/2} + \alpha e^{-y},$$

$$\bar{\nu}_\alpha(y) = \left(1-e^{-y^\alpha}\right)^{-1/2\alpha} + (1-1/2\alpha)\, e^{-y^\alpha},$$

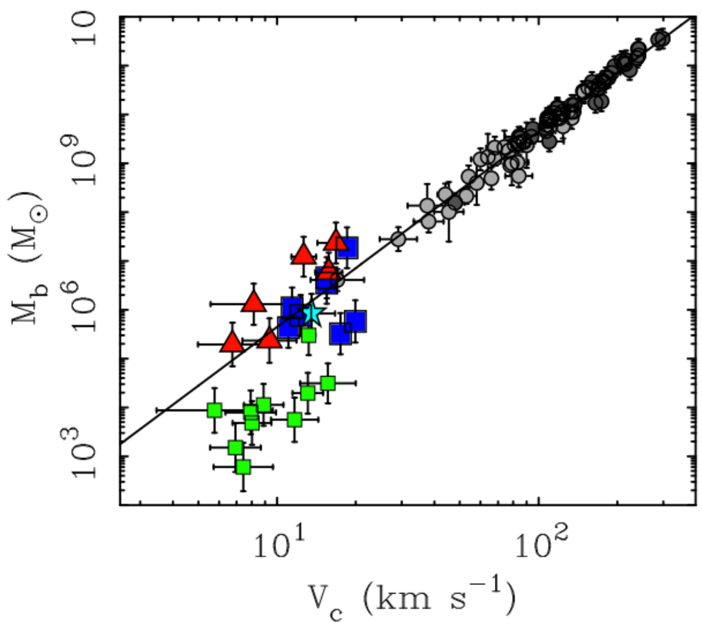
$$\hat{\nu}_\alpha(y) = \left(1-e^{-y^{\alpha/2}}\right)^{-1/\alpha}.$$

	a_0 10^{-10} [m/s^2]	χ^2_{red}	$g_e = g_{emin}$ η	$-q$ 10^{-2}	Q_2 10^{-27} [s^{-2}]	$g_e = g_{emax}$ η	$-q$ 10^{-2}	Q_2 10^{-27} [s^{-2}]
ν_2	1.60	2.02	1.20	10.	26.	1.50	11.3	30.
ν_3	1.55	1.97	1.20	8.29	21.	1.50	7.82	20.
ν_4	1.51	1.94	1.30	6.76	16.	1.60	5.34	13.
ν_5	1.49	1.93	1.30	5.51	13.	1.60	3.71	8.7
ν_6	1.46	1.92	1.30	4.55	11.	1.60	2.67	6.2
ν_7	1.45	1.92	1.30	3.82	8.7	1.70	2.01	**4.6**
ν_8	1.44	1.92	1.30	3.27	7.3	1.70	1.58	**3.5**
$\tilde{\nu}_{0.5}$	1.48	2.16	1.30	14.8	35.	1.60	18.5	44.
$\tilde{\nu}_1$	1.38	2.12	1.40	18.3	38.	1.70	25.	53.
$\tilde{\nu}_{1.5}$	1.18	2.16	1.60	24.1	40.	2.00	34.2	57.
$\tilde{\nu}_2$	0.815	2.24	2.30	44.8	43.	2.90	47.9	46.
$\tilde{\nu}_{2.5}$	0.977	2.23	1.90	33.1	42.	2.50	51.7	65.
$\tilde{\nu}_3$	0.743	1.07	2.60	56.8	47.	3.20	65.5	55.
$\tilde{\nu}_4$	0.723	2.01	2.60	54.8	44.	3.30	85.9	69.
$\tilde{\nu}_5$	0.715	1.97	2.70	48.1	38.	3.40	94.7	75.
$\bar{\nu}_1$	1.38	2.12	1.40	16.1	34.	1.70	19.5	41.
$\bar{\nu}_{1.5}$	1.18	2.16	1.60	19.3	32.	2.00	15.8	26.5
$\bar{\nu}_2$	0.815	2.24	2.30	6.2	**5.9**	2.90	2.63	**2.52**
$\bar{\nu}_3$	0.743	2.07	2.60	1.9	**1.6**	3.20	0.82	**0.68**
$\bar{\nu}_4$	0.723	2.01	2.60	1.3	**1.**	3.30	0.56	**0.45**
$\bar{\nu}_5$	0.715	1.97	2.70	1.08	**0.85**	3.40	0.	**0.**
$\bar{\nu}_6$	0.713	1.95	2.70	1.02	**0.8**	3.40	0.	**0.**
$\bar{\nu}_7$	0.729	1.95	2.60	1.07	**0.87**	3.30	0.	**0.**
$\hat{\nu}_1$	1.48	2.15	1.30	13.1	31.	1.60	17.5	41.
$\hat{\nu}_2$	1.59	2.01	1.20	10.2	27.	1.50	11.4	30.
$\hat{\nu}_3$	1.55	1.96	1.20	8.32	21.	1.60	7.49	19.
$\hat{\nu}_4$	1.51	1.94	1.30	6.66	16.	1.60	4.79	12.
$\hat{\nu}_5$	1.48	1.93	1.30	5.34	13.	1.60	3.1	7.3
$\hat{\nu}_6$	1.46	1.92	1.30	4.31	9.9	1.60	2.11	**4.9**
$\hat{\nu}_7$	1.45	1.92	1.30	3.55	8.	1.70	1.55	**3.5**

MW classical dwarfs

Lüghausen et al. 2014

	$M_{0.1}/L_{V,0.1}$		$M_{0.3}/L_{V,0.3}$		$M_{r_{max}}/L_{V,tot}$	
	predicted	observed	predicted	observed	predicted	observed
Fornax	[10.9, 29.9]	$12.9^{+7.5}_{-4.3}$	[8.1, 22.8]	$6.8^{+0.5}_{-0.7}$	[14.3, 47.9]	12
Sculptor	[8.9, 40.5]	40^{+74}_{-26}	[8.9, 33.7]	23^{+2}_{-7}	[8.9, 50.1]	38
Sextans	[9.5, 50.3]	280^{+93}_{-47}	[9.5, 50.3]	143^{+113}_{-35}	[9.5, 50.3]	108
Carina	[10.7, 54.5]	293^{+43}_{-37}	[10.7, 48.0]	81^{+10}_{-5}	[10.7, 59.4]	81
Draco	[8.0, 44.7]	55^{+122}_{-12}	[8.0, 44.7]	137^{+15}_{-21}	[8.0, 44.7]	346

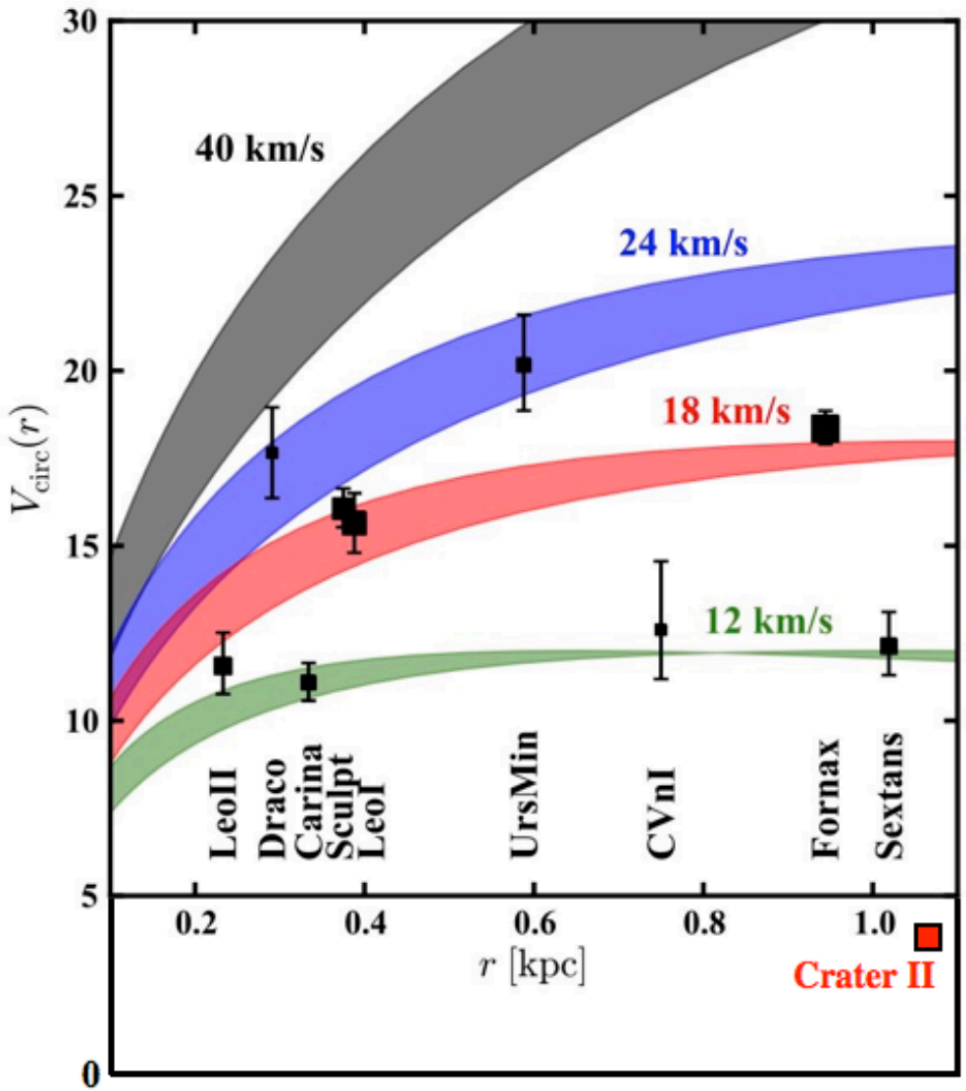


Crater II

- Half light radius =1.1 kpc
- Distance =120 kpc
- Luminosity = 1.6*10^5 M_{sun}
- σ = 2.7 +- 0.3 km/s

= MOND prediction with EFE

(McGaugh 2016)



Superfluid dark matter

Idea of Berezhiani & Khoury: DM could have strong self-interactions and enter a superfluid phase when

- cold enough (i.e; their de Broglie wavelength $\lambda \sim 1/(mv)$ is large
- dense enough (i.e. the interparticle separation is smaller than λ)

=> Superfluid core (~100 kpc) where collective excitations (phonons) can couple to baryons and mediate a long-range force + isothermal « normal » atmosphere

System	Behavior
Rotating Systems	
Solar system	Newtonian
Galaxy rotation curve shapes	MOND (+ small DM component)
Baryonic Tully–Fisher Relation	MOND for RCs (but particle DM for lensing)
Bars and spiral structure in galaxies	MOND
Interacting Galaxies	
Dynamical friction	Absent in superfluid core
Tidal dwarf galaxies	Newtonian when outside of superfluid core
Spheroidal Systems	
Star clusters	MOND with EFE inside galaxy host core - Newton outside of core
Dwarf Spheroidals	MOND with EFE inside galaxy host core - MOND+DM outside of core
Clusters of Galaxies	particle DM
Ultra-diffuse galaxies	MOND without EFE outside of cluster core

Conclusion

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

- Any galaxy formation framework should be able to ultimately reproduce the MOND formula as an **observed** relation for spiral galaxies!

- But some issues on very small scales (ultrafaint dwarf galaxies and globular clusters), and obvious presence of DM on large scales

'cherry on the cake'? common scale with DE, $a_0 \sim \Lambda^{1/2}$