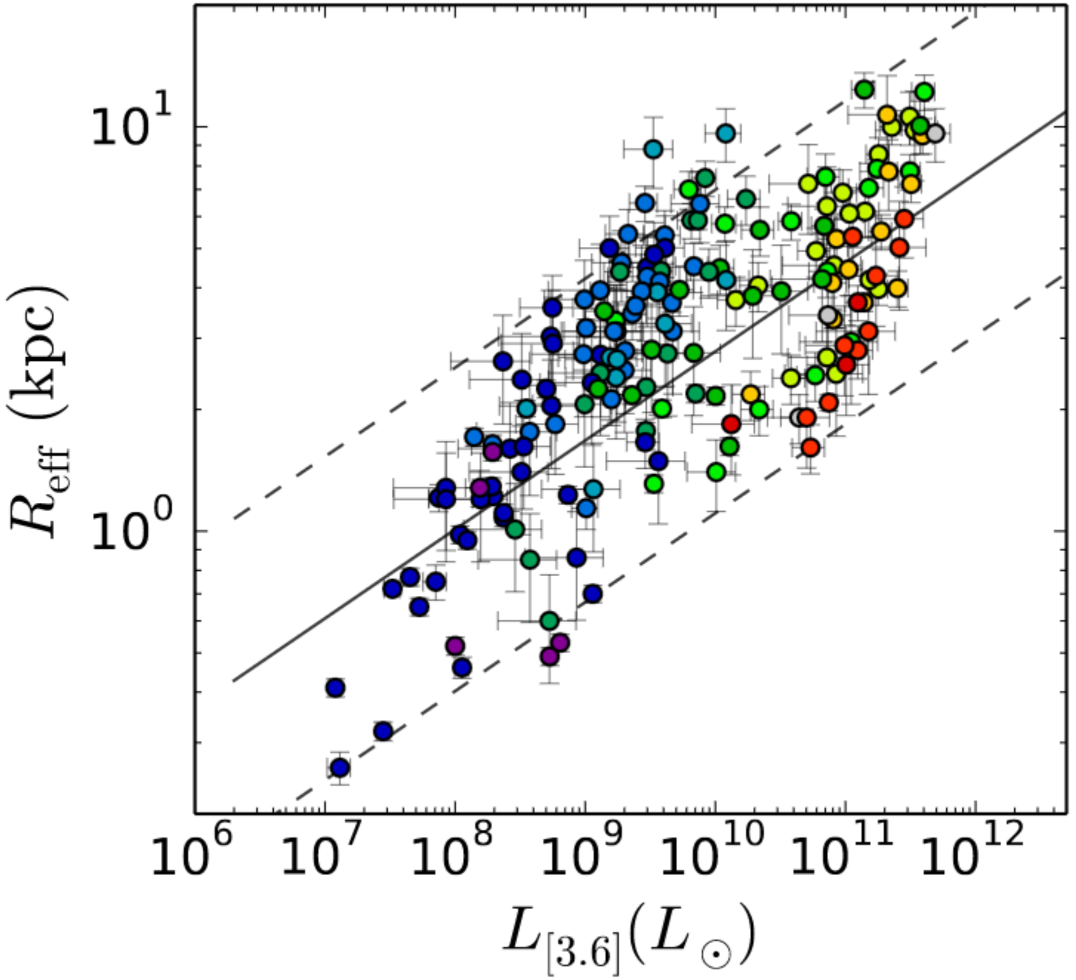
The MDAR as a guide for DM model building?

Benoit Famaey

CNRS - Observatoire astronomique de Strasbourg

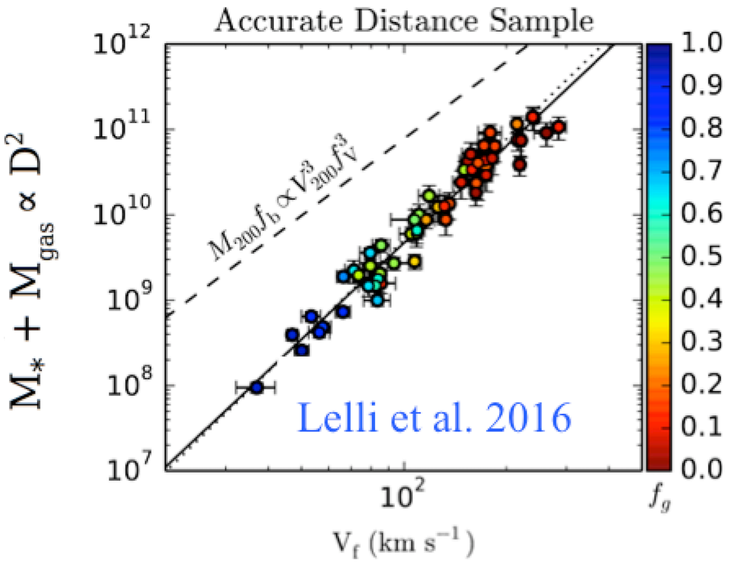
HI galaxy rotation curves

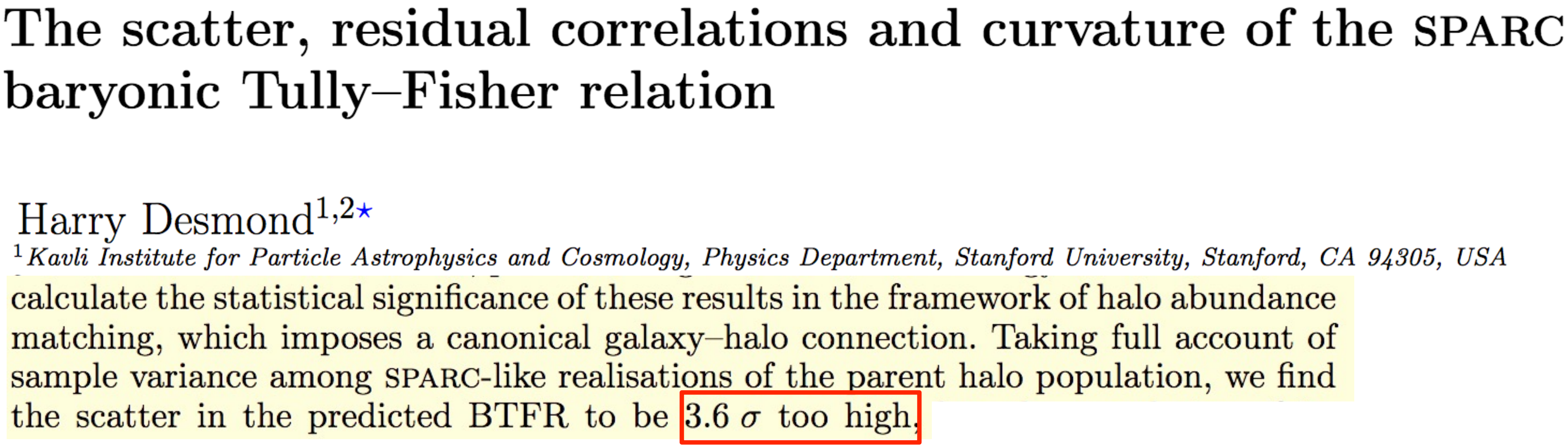
- SPARC (Lelli et al.)
- 175 galaxies with high quality HI RCs
- Homogeneous Spitzer photometry at 3.6μm
- M_*/L known to be roughly constant (0.5-0.7) in the NIR



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





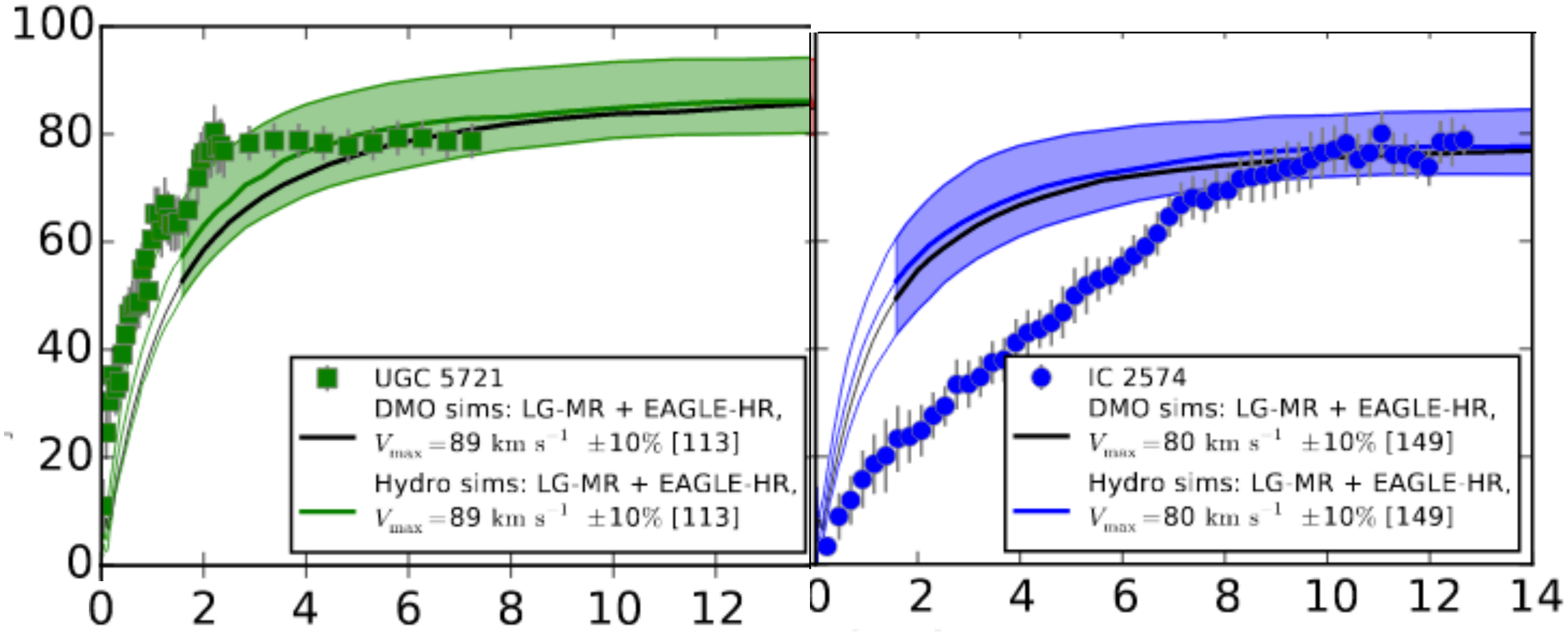
The scatter, residual correlations and curvature of the SPARC baryonic Tully–Fisher relation

Harry Desmond[1,2]⋆

[1] *Kavli Institute for Particle Astrophysics and Cosmology, Physics Department, Stanford University, Stanford, CA 94305, USA*

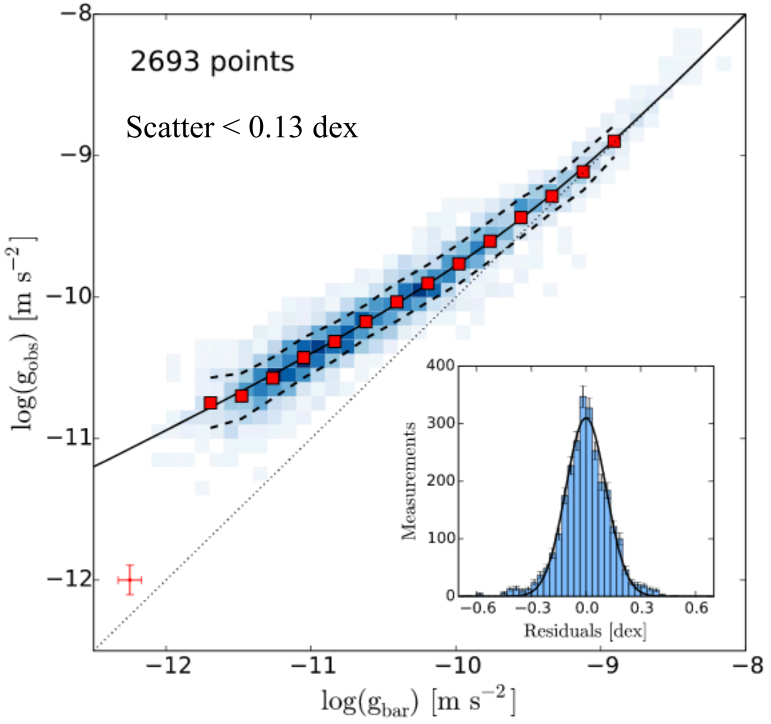
calculate the statistical significance of these results in the framework of halo abundance matching, which imposes a canonical galaxy–halo connection. Taking full account of sample variance among SPARC-like realisations of the parent halo population, we find the scatter in the predicted BTFR to be $\boxed{3.6\,\sigma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

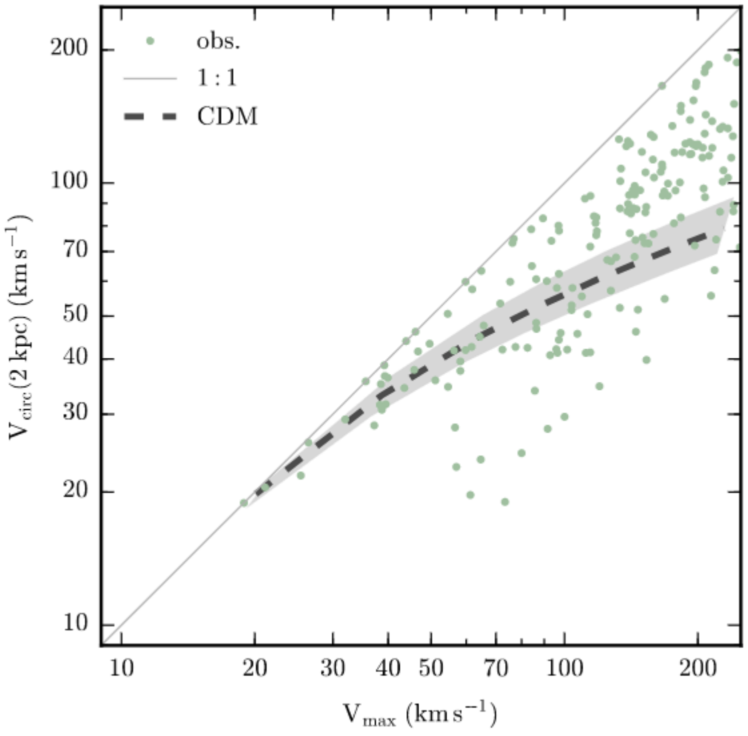
The BTFR twin paradox



EAGLE simulations

Regularity vs. diversity

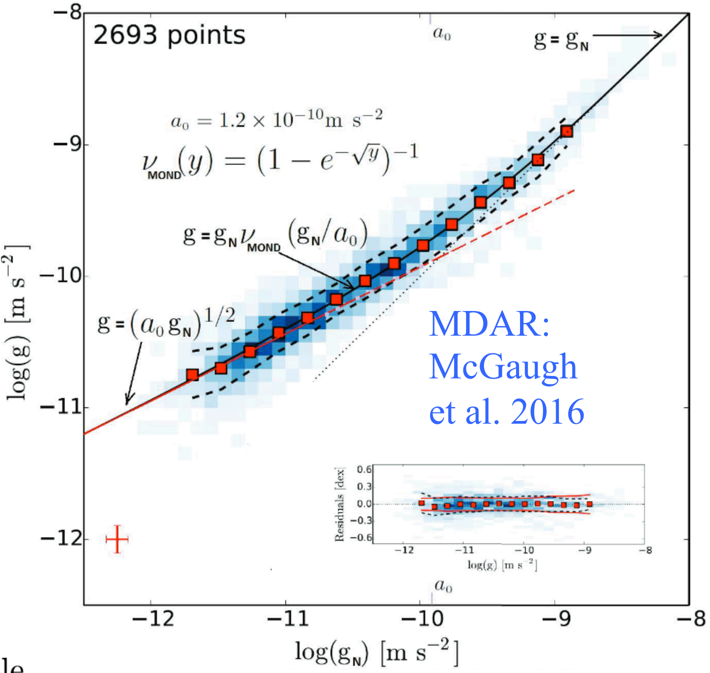




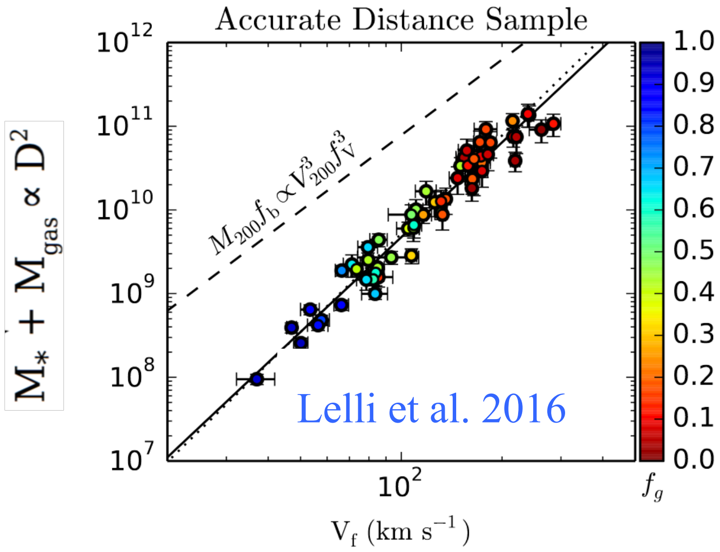
$$V_{circ}(2\ \text{kpc}) = (2\ \text{kpc x}\ g_{obs})^{1/2}$$

Bullock & Boylan-Kolchin 2017, McGaugh et al. 2016, Oman et al. 2015

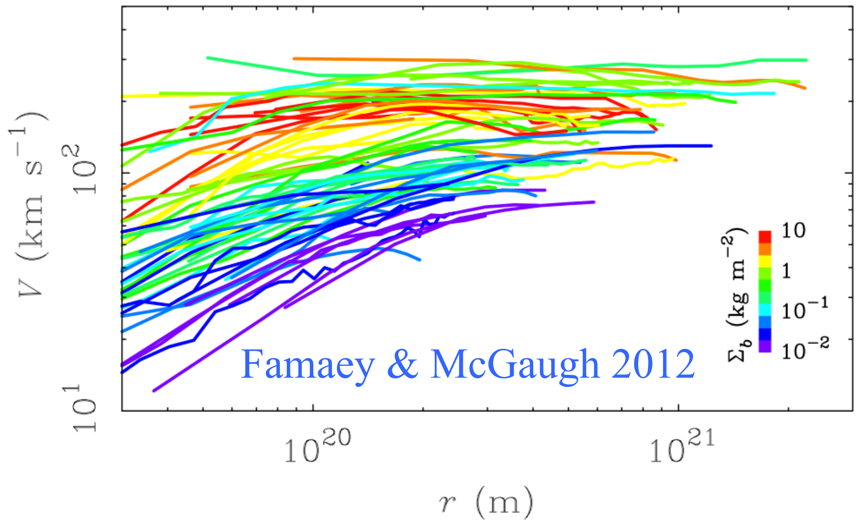
MOND paradigm



MDAR: McGaugh et al. 2016

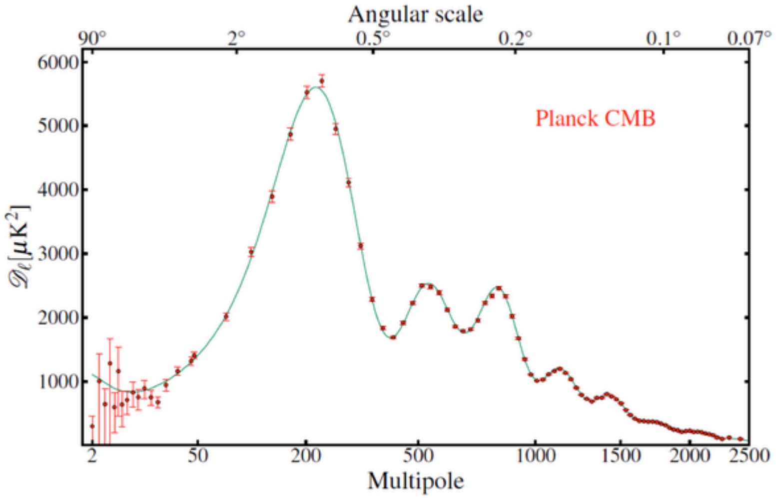

Accurate Distance Sample

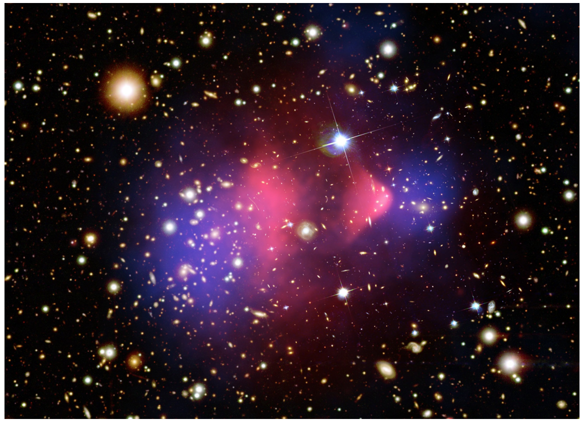
Lelli et al. 2016

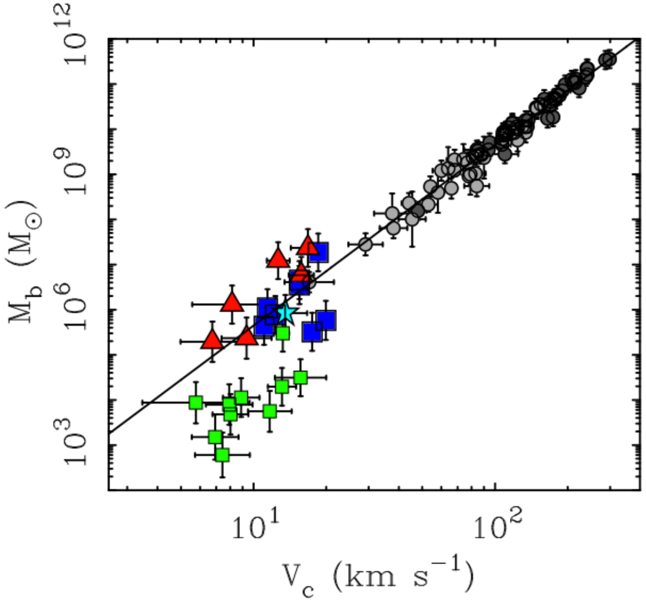


Famaey & McGaugh 2012

But...


Angular scale
90°
2°
0.5°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
$\mathcal{D}_\ell [\mu K^2]$
Planck CMB
2
50
200
500
1000
1500
2000
2500
Multipole




10^{12}
10^9
10^6
10^3
M_b $(M_\odot)$
10^1
10^2
V_c (km s^{-1})

MOND paradigm

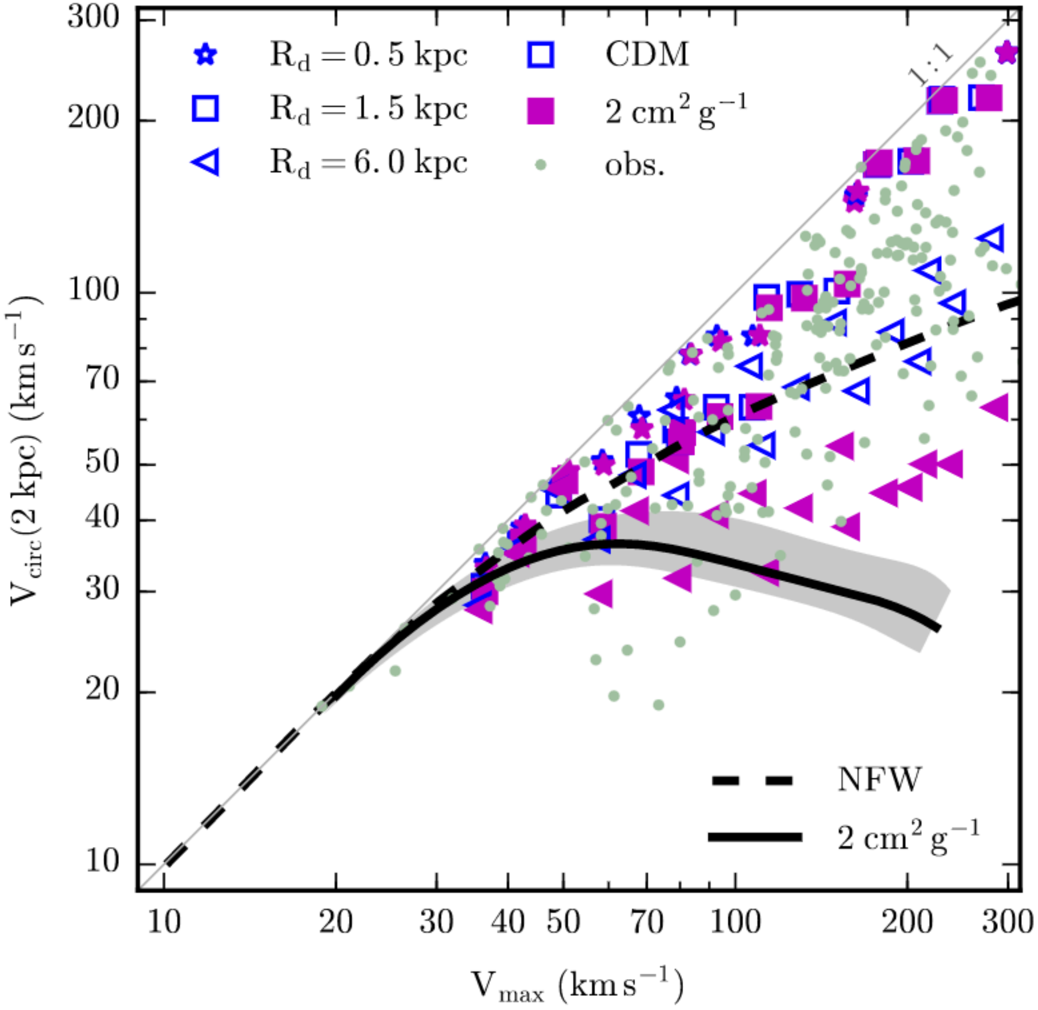
$$S_N = S_{\rm kin} + S_{\rm in} + S_{\rm grav} = \int \frac{\rho \mathbf{v}^2}{2} d^3x\, dt - \int \rho \Phi_N d^3x\, dt - \int \frac{|\nabla \Phi_N|^2}{8\pi G} d^3x\, dt$$

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

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

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

SIDM



Creasey et al. (2017)

Crazier ideas:

Use the MDAR as a fundamental relation guiding ‘bottom-up’ DM model-building

Justin Khoury

Lasha Berezhiani

Riccardo Penco

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)

$\Rightarrow$ Superfluid core (~50-100 kpc in MW) where collective excitations (phonons) are the only relevant degree of freedom (represented by a scalar field in EFT) and can couple to baryons and mediate a long-range force + NFW-like « normal » atmosphere outside of the core

Parameters of the theory (or rather, of the toy-model theory):

- DM particle mass m (~eV)
- Self-interaction cross-section σ ($\sigma/m \ll 1$ cm^2/g)
- Self-interaction « strength » Λ (~0.05 meV)
- Coupling constant of the scalar field to baryons α

} combination of Λ^2 and α^3 related to a_0

- Parameter accounting for non-zero temperature effects β (will be fixed)

Superfluid dark matter

Transition radius R_T when inverse of self-interaction rate of the order of dynamical time:

$$\Gamma = \frac{\sigma}{m}\mathcal{N} v \rho = t_{\mathrm{dyn}}^{-1}$$

EFT Lagrangian for the phonons:

$$\boxed{\mathcal{L} = \frac{2\Lambda(2m)^{3/2}}{3} X\sqrt{|X - \beta Y|} - \alpha\frac{\Lambda}{M_{\mathrm{Pl}}}\phi\rho_{\mathrm{b}}}$$

where $X = \hat{\mu}(\Phi) - (\vec{\nabla}\phi)^2/2m$

=> Varying w.r.t. to the scalar field gives the phonon equation of motion and varying w.r.t. grav. potential gives the superfluid density

Superfluid dark matter

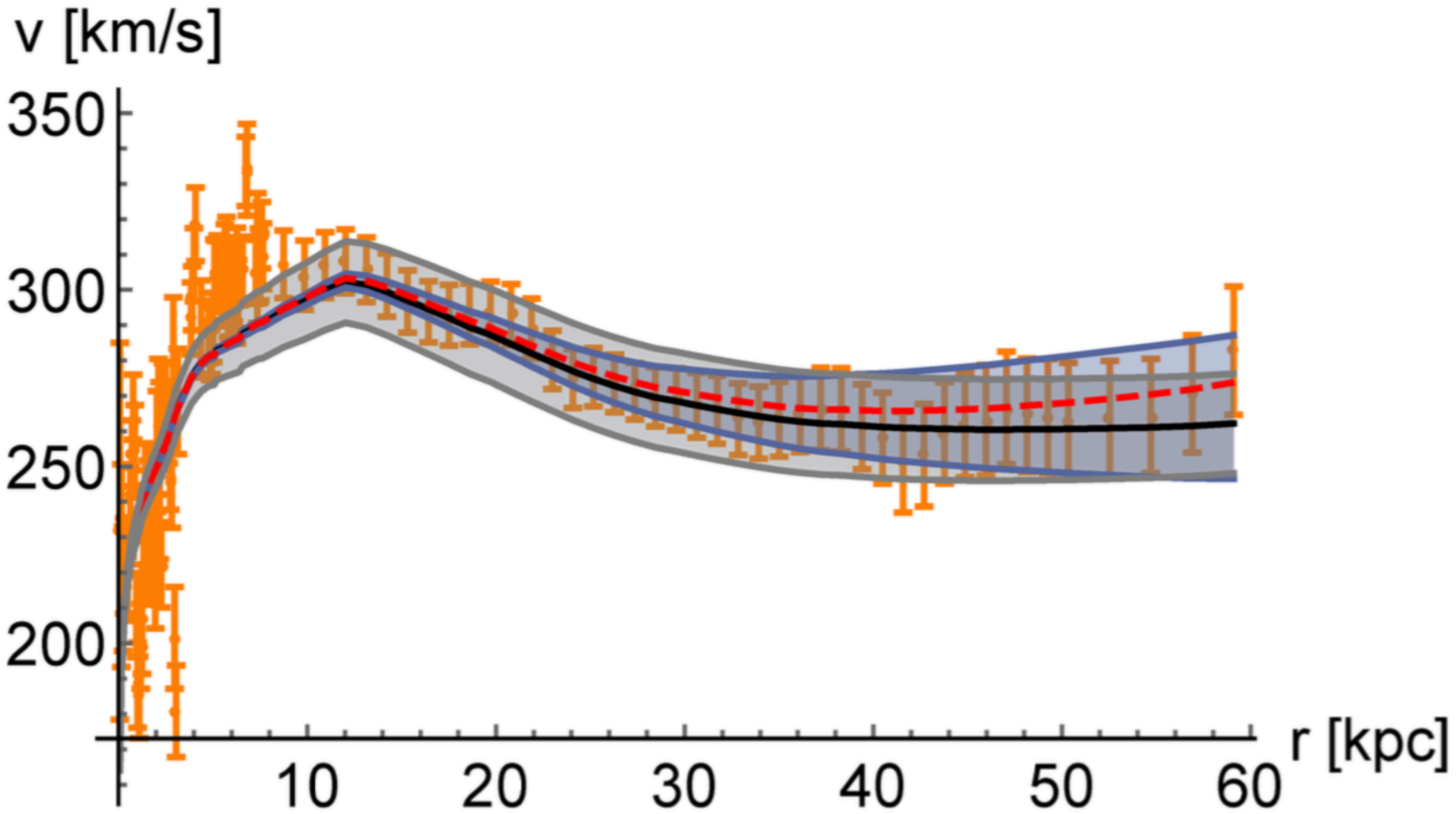
Spherical symmetry (next step: Kuzmin disks and then numerical solution for general disk configuration):

1) Solve $$\frac{(\vec{\nabla}\phi)^2 + 2m\left(\frac{2\beta}{3} - 1\right)\hat{\mu}}{\sqrt{(\vec{\nabla}\phi)^2 + 2m(\beta - 1)\hat{\mu}}}\vec{\nabla}\phi = \alpha M_{\mathrm{Pl}}\vec{a}_{\mathrm{b}}$$

2) Insert $(\vec{\nabla}\phi)^2$ in $\rho_{\mathrm{SF}} = \dfrac{2\sqrt{2}m^{5/2}\Lambda\left(3(\beta - 1)\hat{\mu} + (3 - \beta)\frac{(\vec{\nabla}\phi)2}{2m}\right)}{3\sqrt{(\beta - 1)\hat{\mu} + \frac{(\vec{\nabla}\phi)2}{2m}}}$

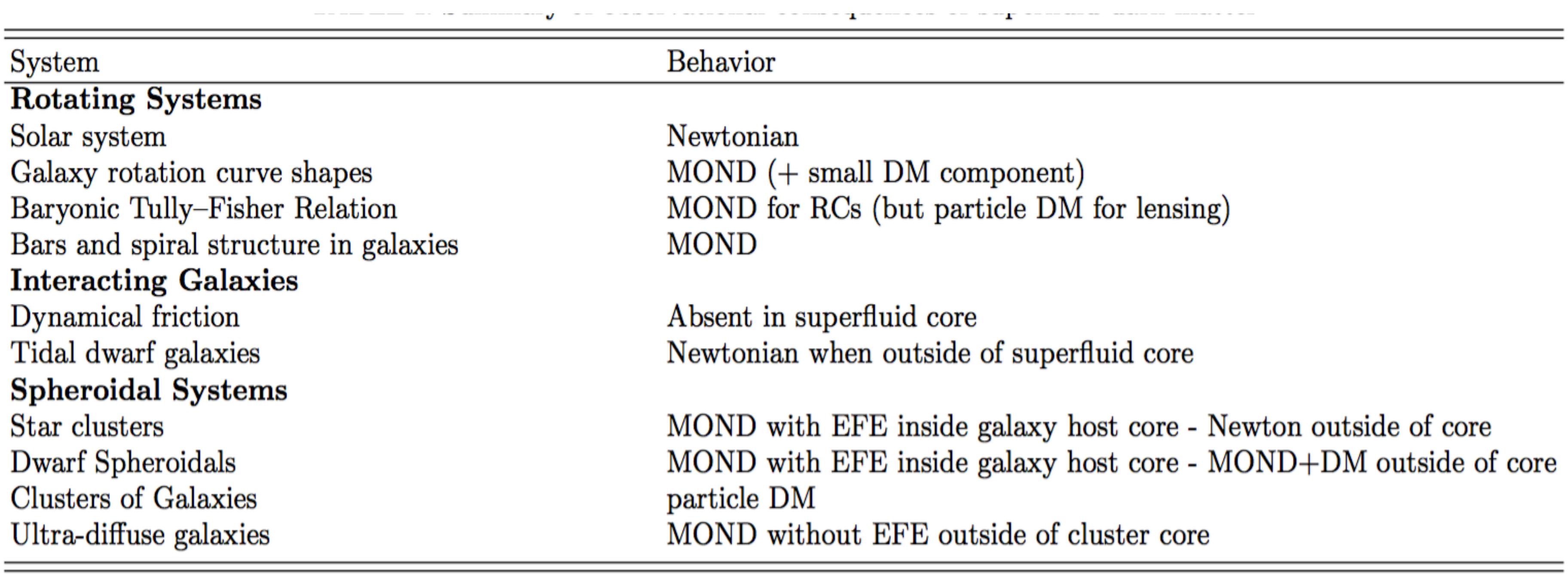
3) Solve Poisson $$\frac{1}{r^2}\frac{\mathrm{d}}{\mathrm{d}r}\left(r^2\frac{\mathrm{d}\Phi}{\mathrm{d}r}\right) = 4\pi G_{\mathrm{N}}\Big(\tilde{\rho}_{\mathrm{b}}(r) + \rho_{\mathrm{SF}}(\Phi(r), a_{\mathrm{b}})\Big)$$

4) Match density and pressure of NFW profile at R_{NFW} => get virial mass M_{200} (only free parameter, start again with different central values of potential to get different M_{200})



Berezhiani, Famaey, Khoury 2018

UGC 2953 (sphericized profile, a0 ~ 0.9 x 10^{-10} m/s^2)
Black : M_{DM}=1.6x10^{12} M_{sun} (R_T = 82 kpc, R_{NFW}=76 kpc)
Red-dashed: M_{DM}=10^{13} M_{sun} (R_T=129 kpc, R_{NFW}=95 kpc)



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

Next step: model stellar streams