# Galaxies and the nature of dark matter & gravity

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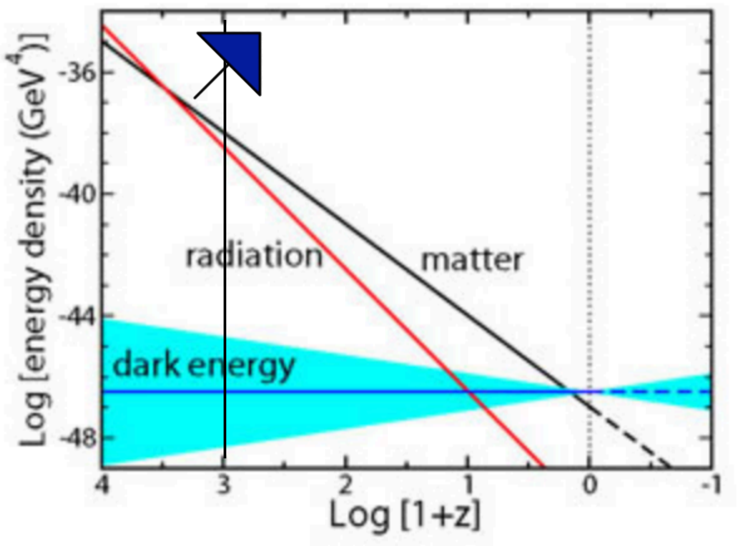
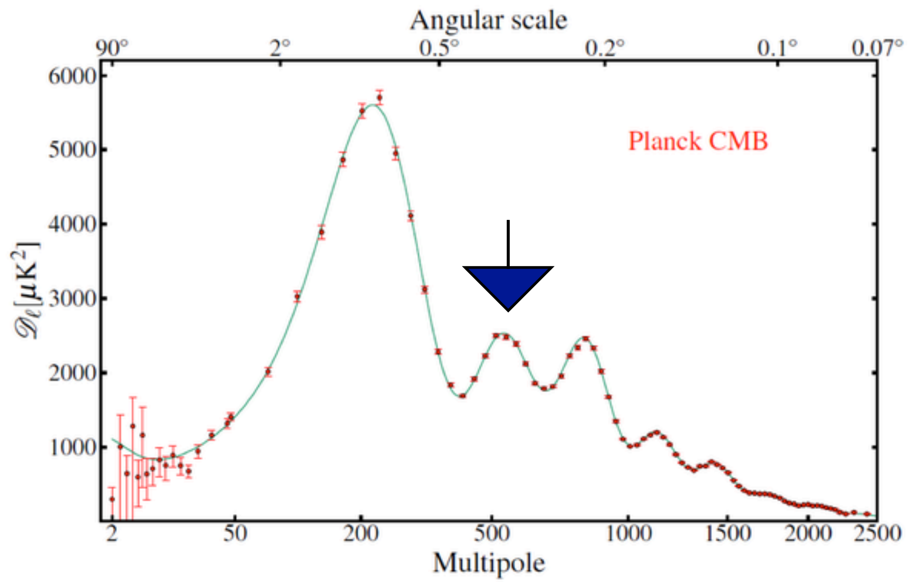
# The need for cosmic Dark Matter



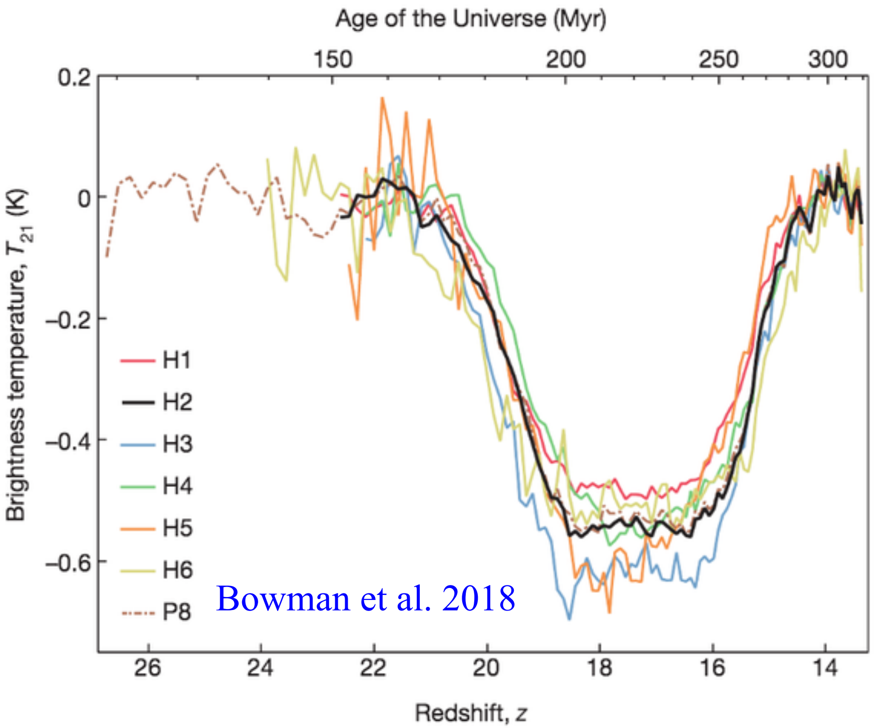

- CMB + other large scale probes => concordance ΛCDM model

- DM = **collisionless** and dissipationless fluid of stable elementary particles which interact with each other and with baryons (almost) entirely through gravity, & non-relativistic (**cold**) at matter-radiation equality to form structures down to small scales

# Cosmological tensions and the nature of DM

- The **Hubble tension**? No one is really sure what is going on (e.g., Di Valentino et al. 2021)

- The **EDGES anomaly**: no one knows either, potentially a fluke? If not, might have consequences on the nature of DM




- Cosmic dawn absorption feature at z ~ 17
- Factor of 2 too large

  => fluke?

  or background temp. higher at these wavelengths ?

  or gas cooler ?

# « Small-scale » tensions and the nature of DM

- Galaxies in non-linear ($|\delta| >> 1$) regime of structure formation

- It is **hard** because of the importance of baryonic physics (feedback!)

- Simulations have made **huge improvements** at forming more realistic galaxies, but some tensions persist…

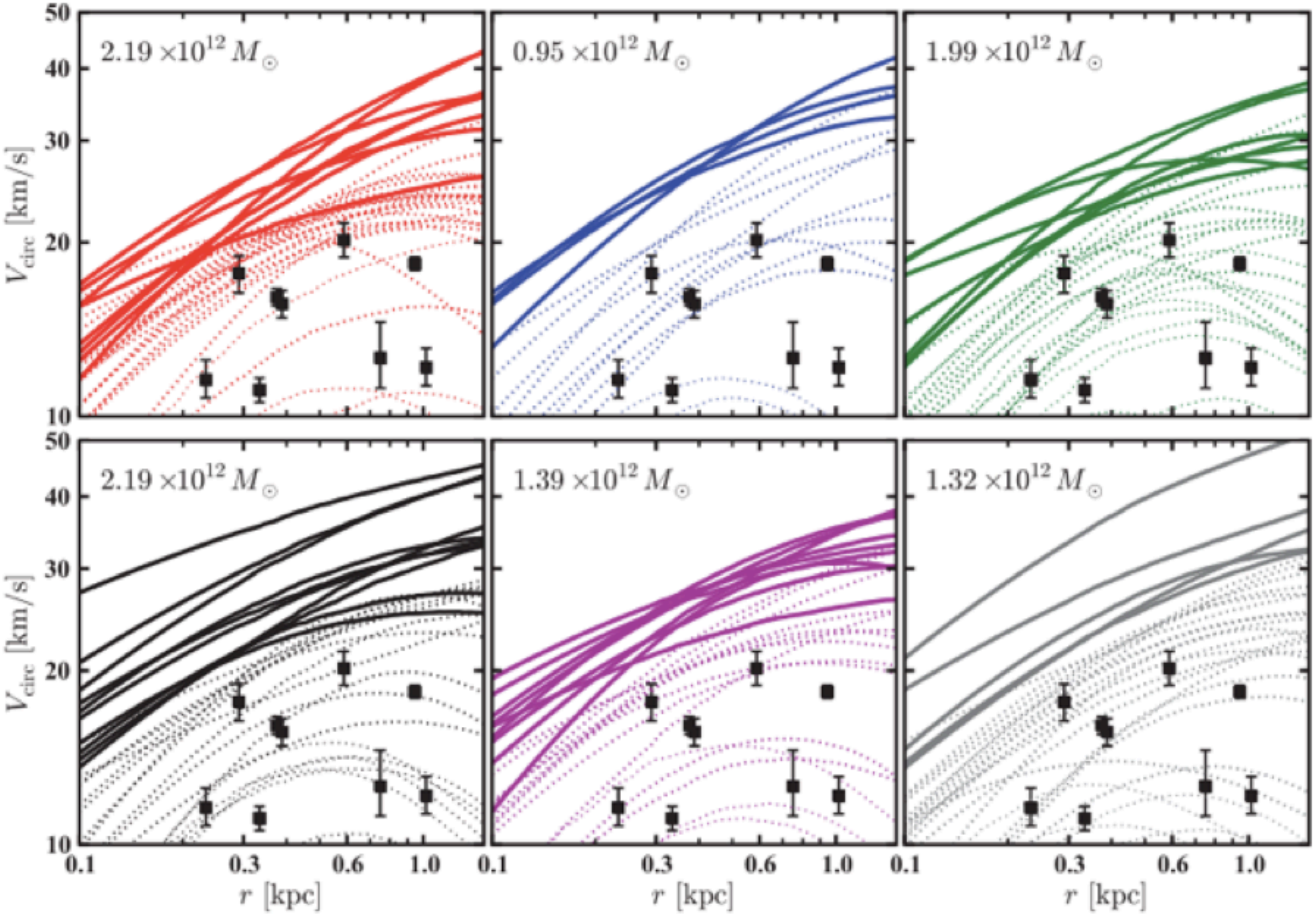
- Could the problem be **fundamental**, i.e. mostly the nature of DM in the model?

- Typically two types of cosmological galaxy formation sims:
  - **Large box**: EAGLE, IllustrisTNG, HorizonAGN, …
  - **Zoom-in**: APOSTLE, NIHAO, FIRE-2, Auriga,...
    (can also make constrained simulations like HESTIA for LG)

# « Small-scale » tensions and the nature of DM

- Too-big-to-fail (TBTF)
- Tightness of baryonic Tully-Fisher relation (BTFR)
- Failed feedback problem (FFP)
- Diversity of rotation curves problem (modern core-cusp)
- Hot orbits problem
- Fast bar problem
- Satellites phase-space correlation problem (planes of satellites)

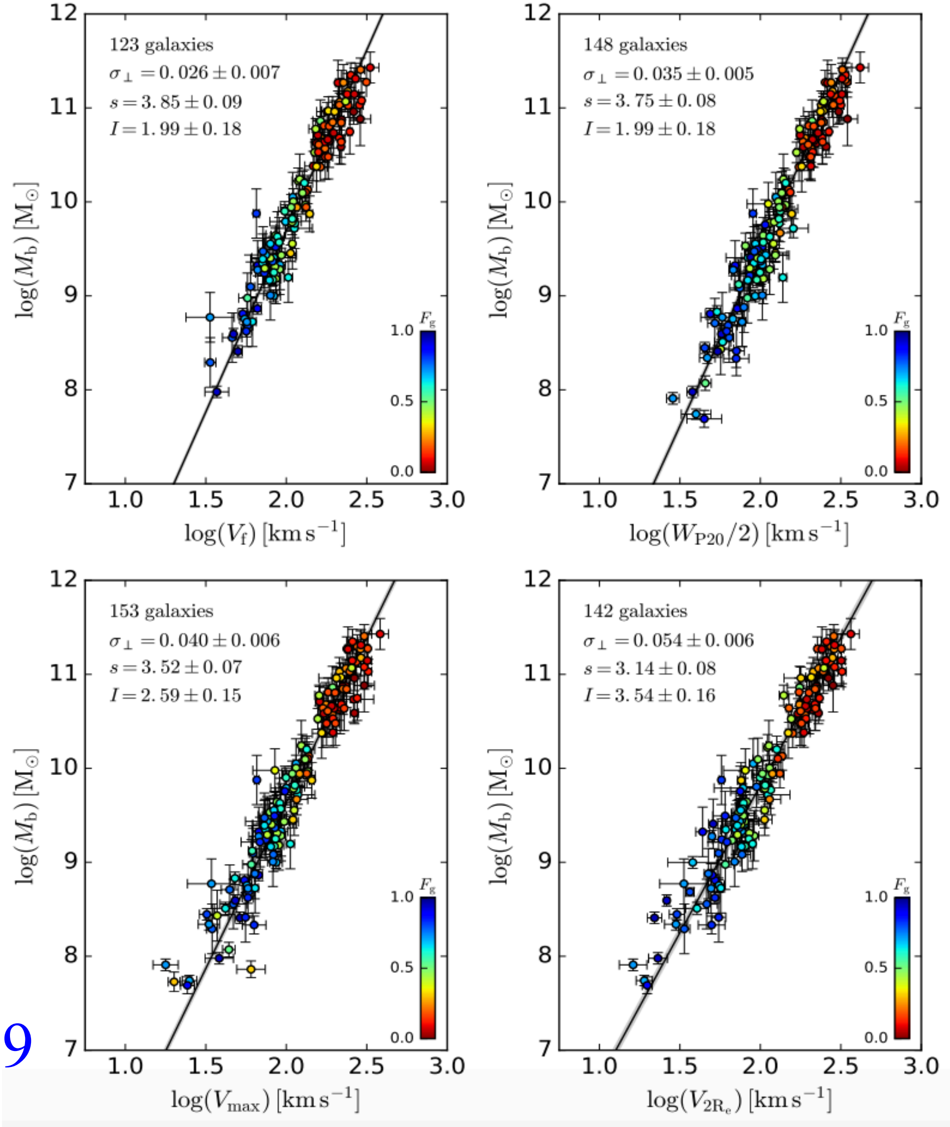
# Dwarf spheroidals: Too-big-to-fail




Boylan-Kolchin et al. 2012

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

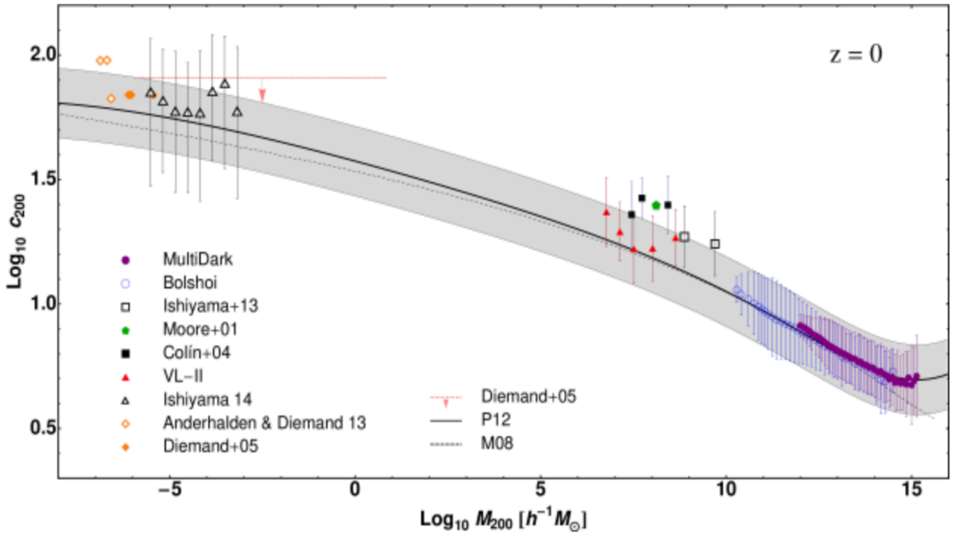
- $\text{Log } M_b = \alpha \log V_f - \log \beta$
- $\alpha \approx 3.9 - 4$



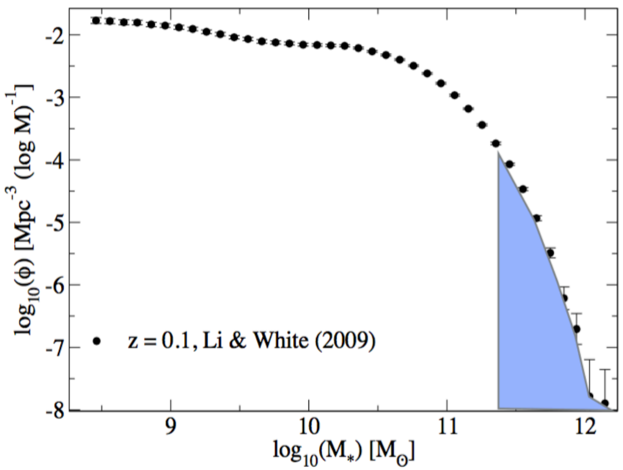

- **Intrinsic scatter**
  **~ 0.025 dex**

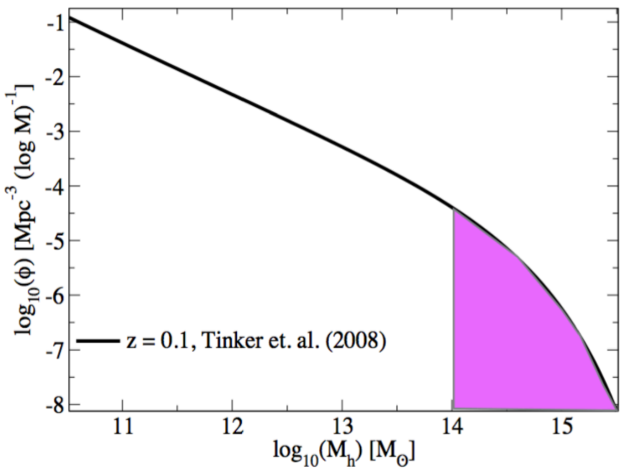
Lelli et al. 2019

# Halo scaling relations and abundance matching




Halo mass-concentration relation (with some scatter of ~0.1 dex)

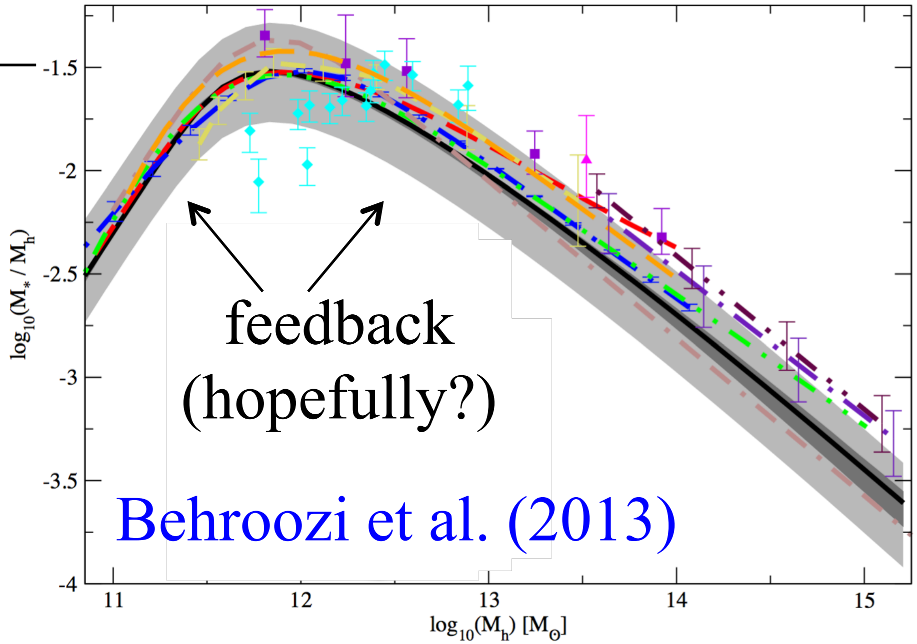



Match stellar mass function to halo mass function by assigning n(>M*) to n(>Mh)

# Stellar-to-halo mass relation (SHMR)

~20% of cosmic fraction




Typical scatter ~ 0.15 dex

⇒ Adding the gas, the intrinsic BTFR scatter **cannot go below 0.05 dex**

Twice too high!

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


Harry Desmond[1,2]⋆ (2017)

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

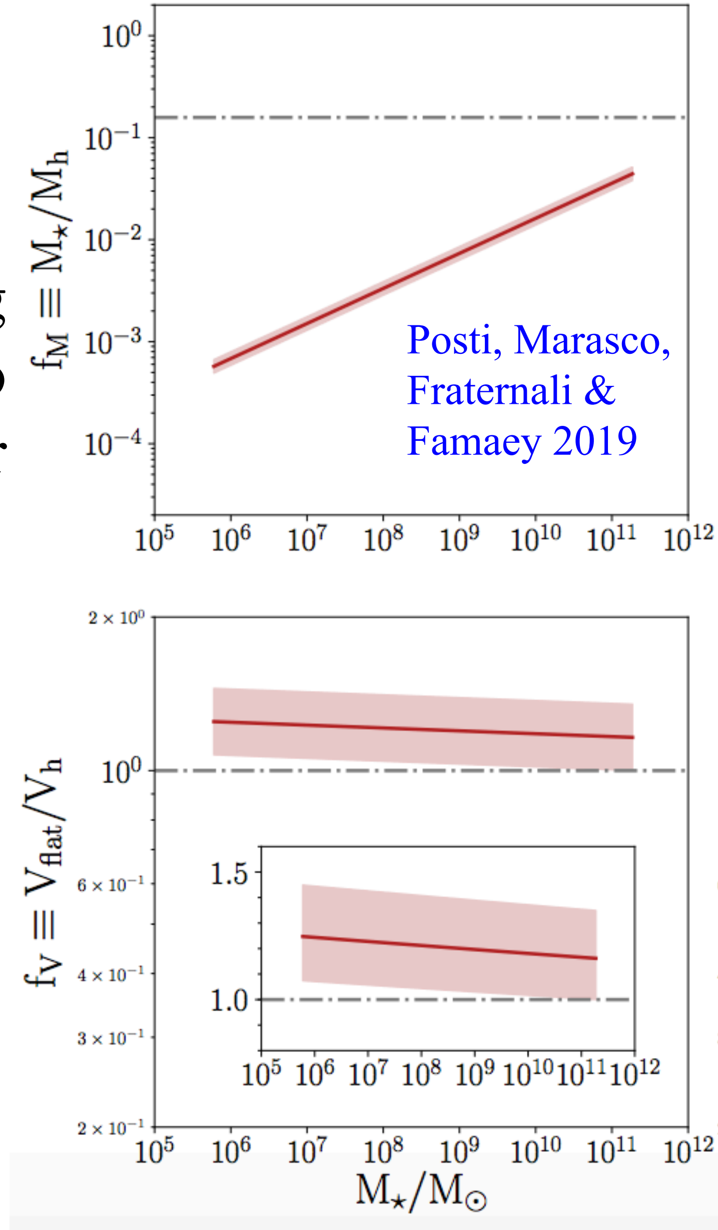

calculate the statistical significance of these results in the framework of halo abundance matching, which imposes a canonical galaxy–halo connection. Taking full account of sample variance among SPARC-like realisations of the parent halo population, we find the scatter in the predicted BTFR to be 3.6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

# The failed feedback problem

Reverting the problem: constraining simultaneously $M^*/M_{vir}$ & $V_{flat}/V_{vir}$ to fit the high-mass end of Tully-Fisher (together with M*-size and M*-j)

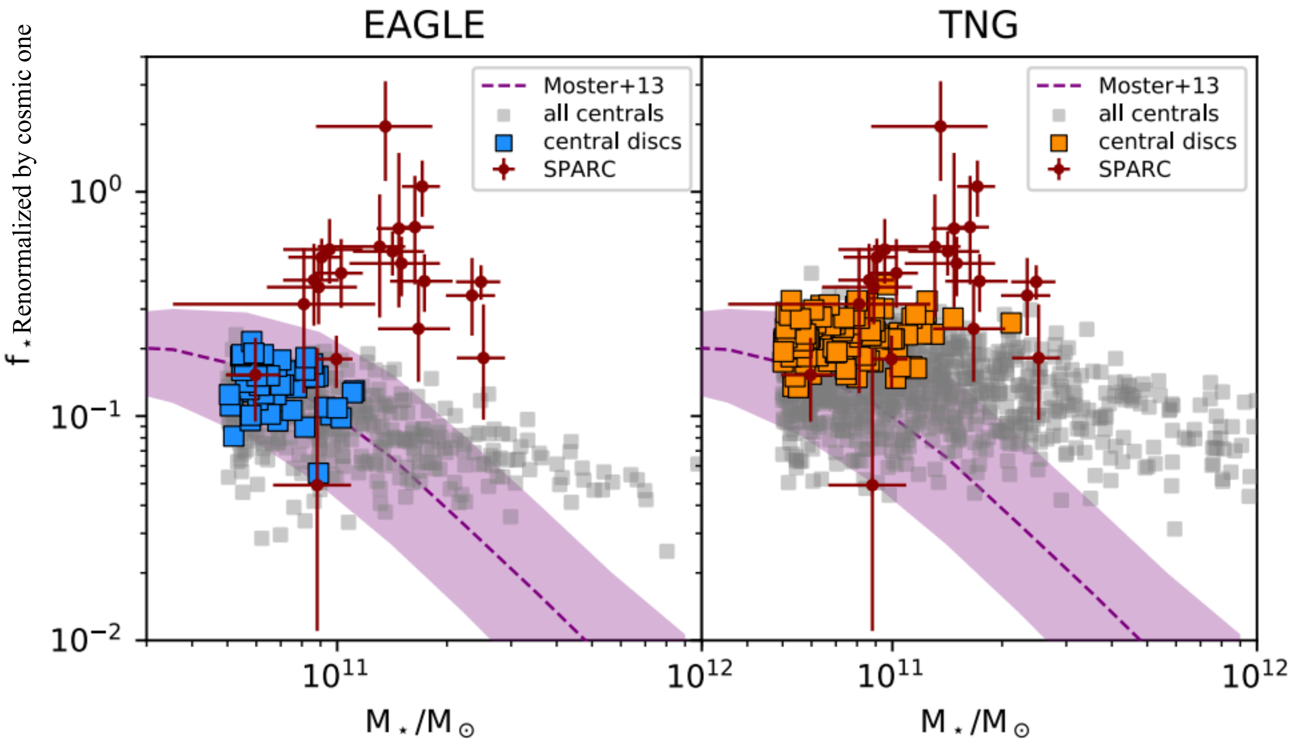
=> $M^*/M_{vir}$ **grows linearly with mass** for disk galaxies, contrary to abundance matching expectations

=> **failed feedback** in massive spirals



# The failed feedback problem

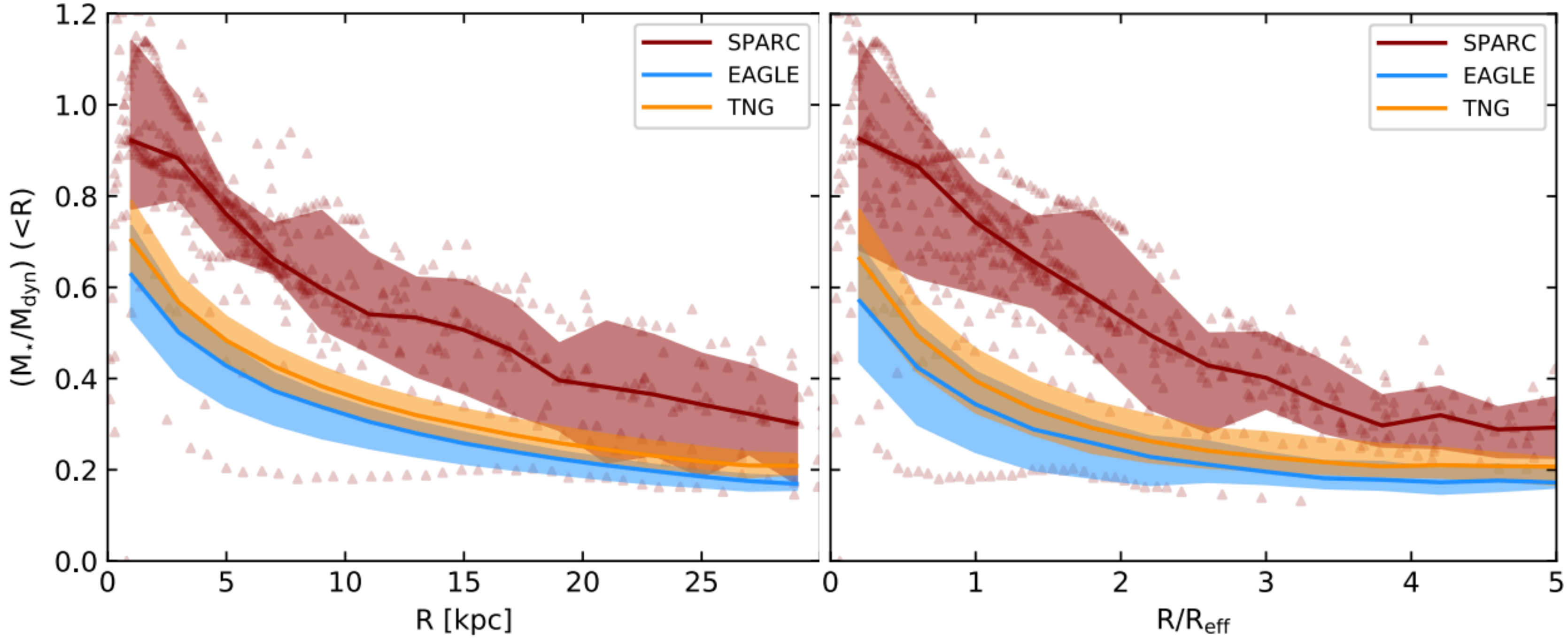
Particle DM mass resolution < $10^7$ $M_{sun}$, **EAGLE** and **Illustris TNG100** allow for a fair evaluation of the behavior of massive disks in simulations



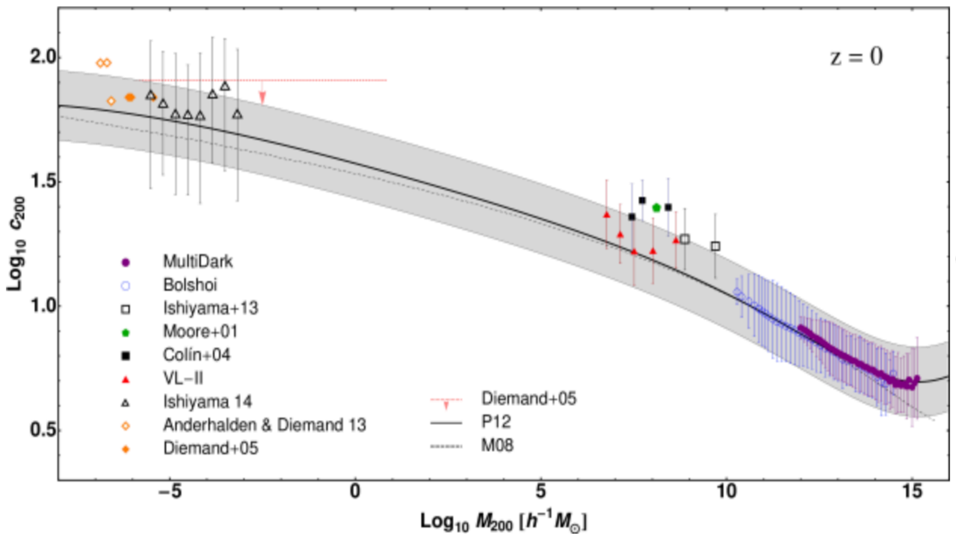

Marasco, Posti, Oman, Famaey, Cresci & Fraternali 2020

# The failed feedback problem

Simulated halos hosting massive disks are too inefficient at converting their baryons into stars, through **too efficient feedback**, AND they have undergone halo contraction because of apparently **not efficient enough feedback**...



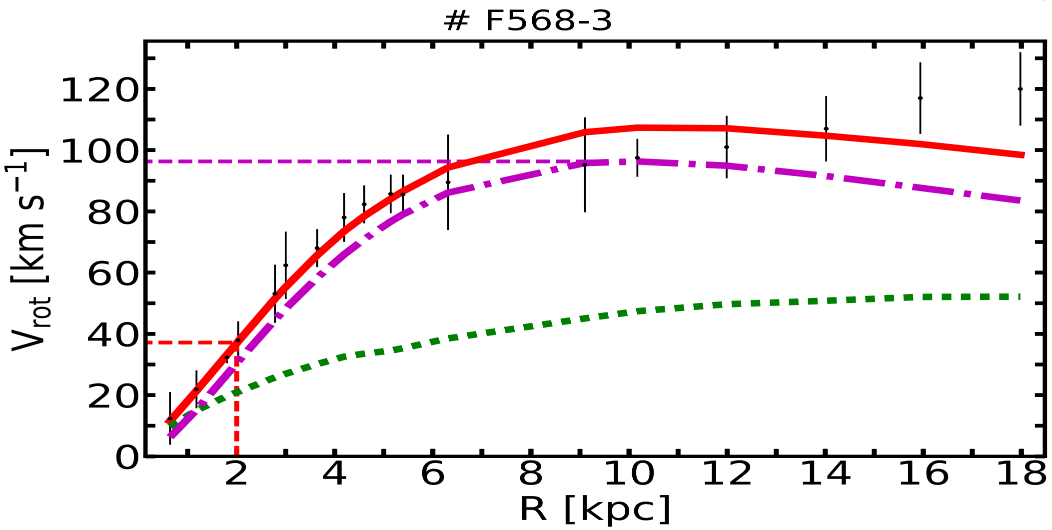
# The BTFR twin paradox

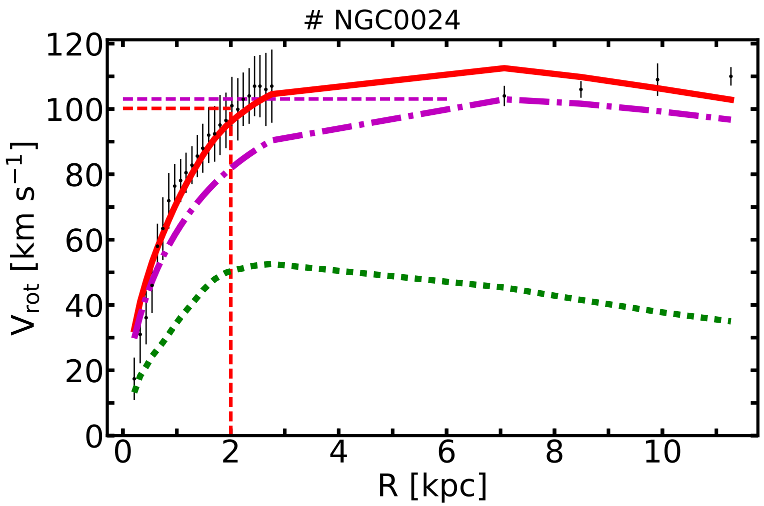



Dark matter halos are (almost) a one-parameter family (driven by mass)

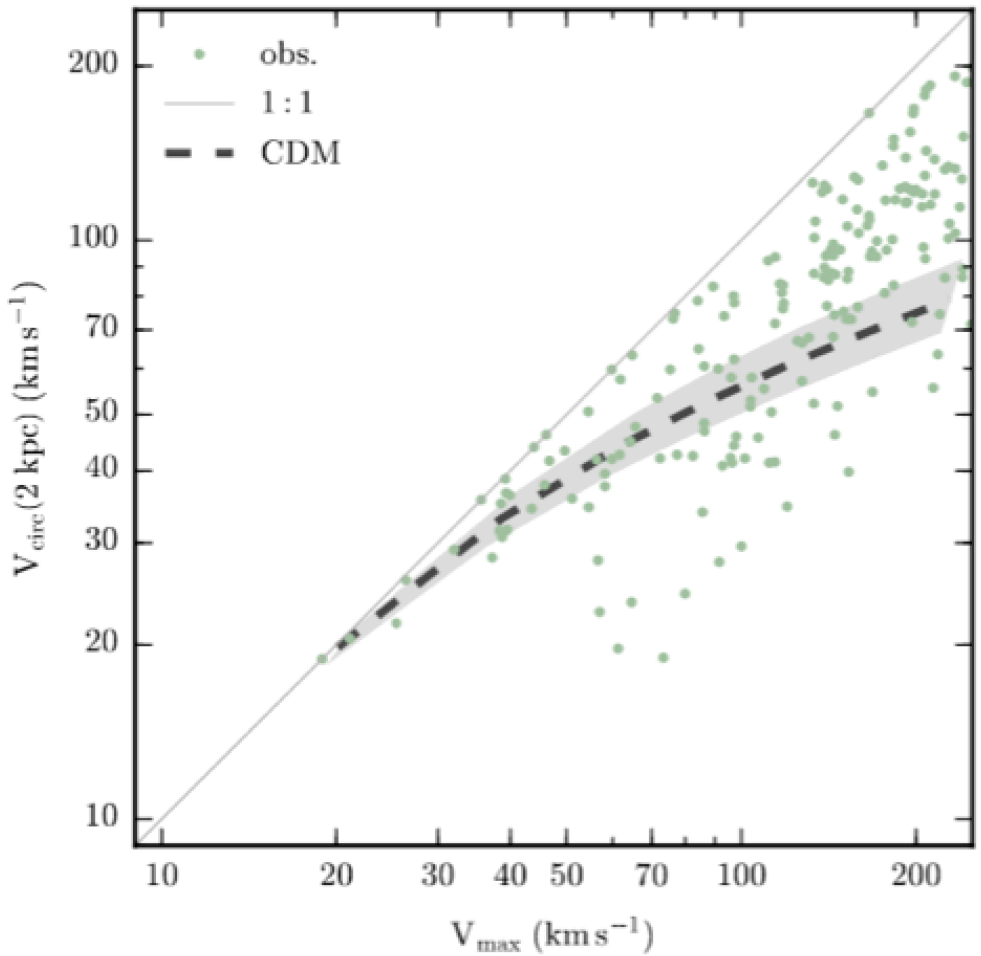
=> At the same $V_{flat}$, why so different profiles??

Ghari, Famaey, Laporte & Haghi 2019



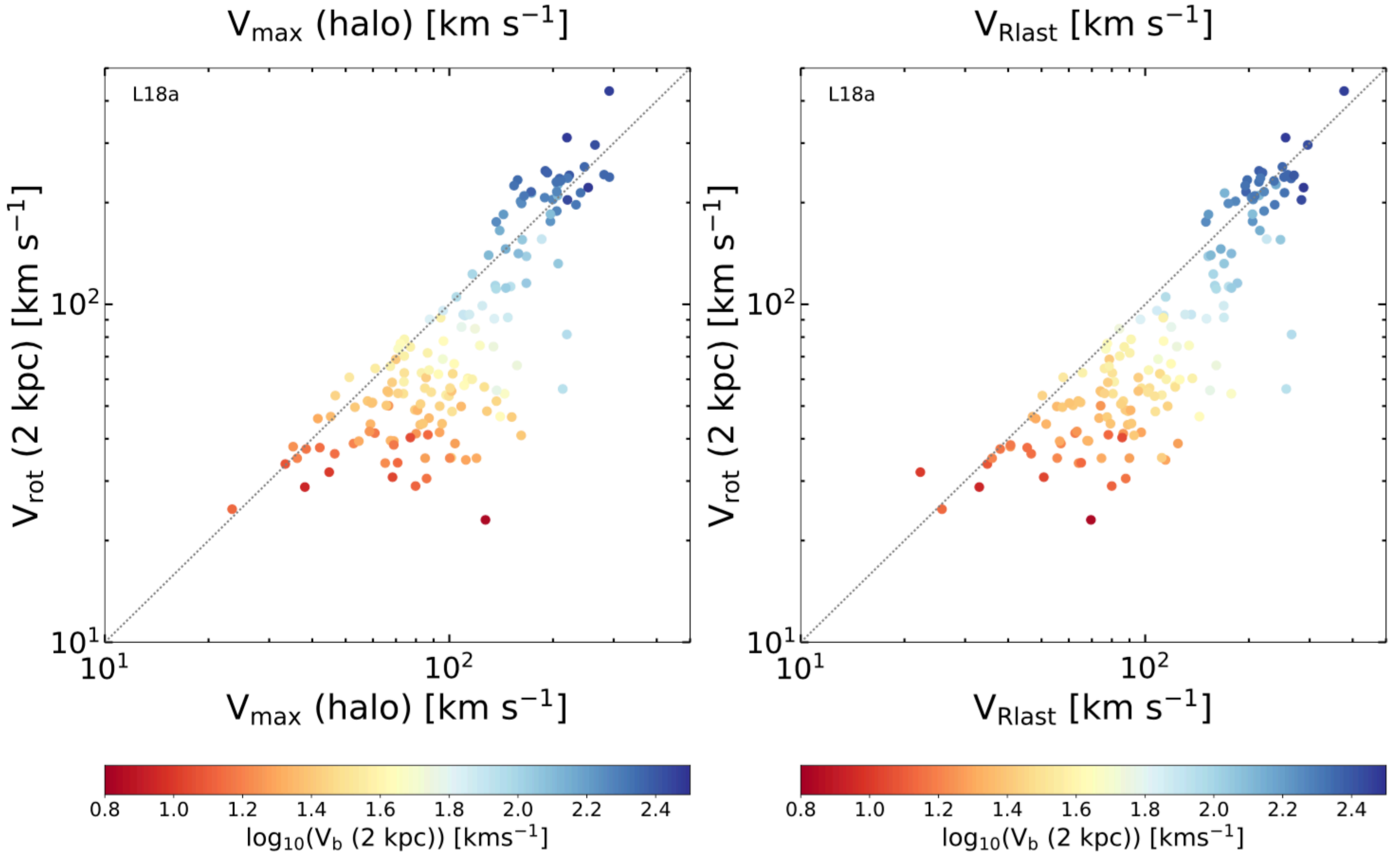
# The diversity problem




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

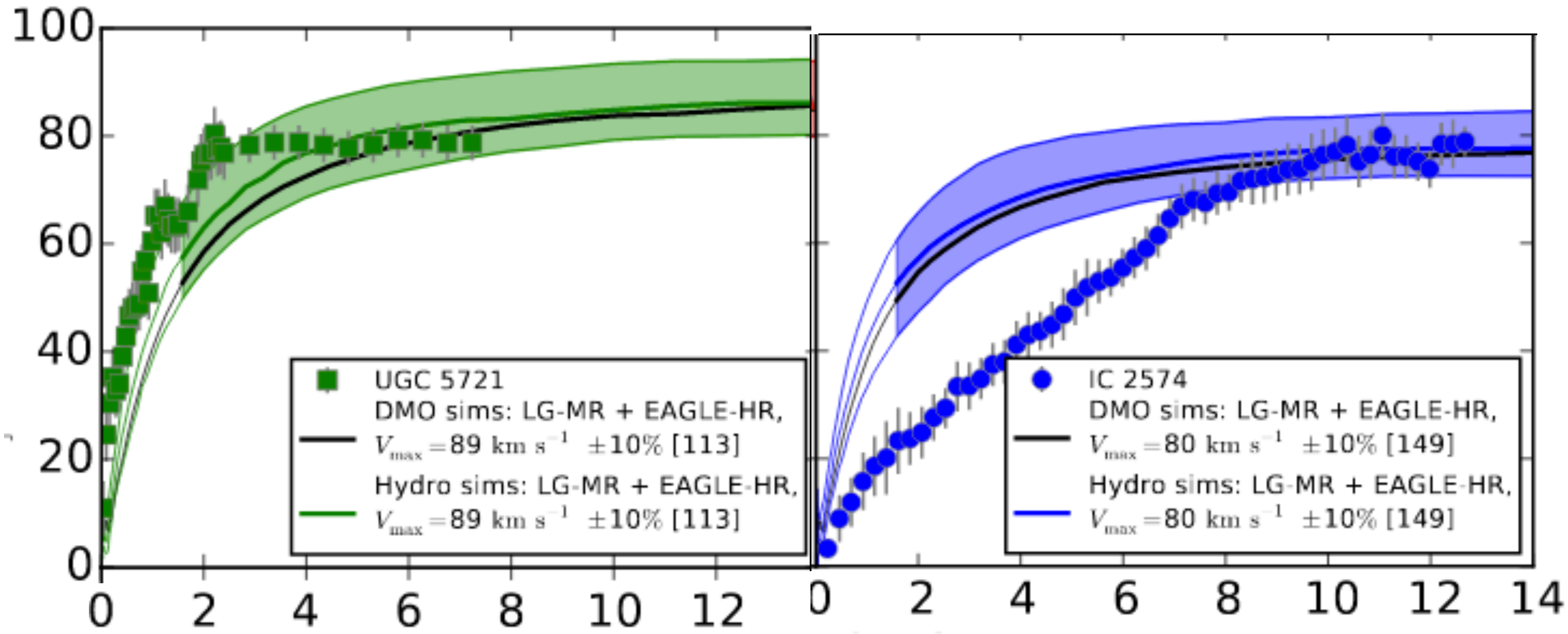
Oman et al. 2015, Bullock & Boylan-Kolchin 2017

# Diversity driven by the baryons




Ghari, Famaey, Laporte & Haghi (2019)

# The diversity problem or the modern core-cusp problem

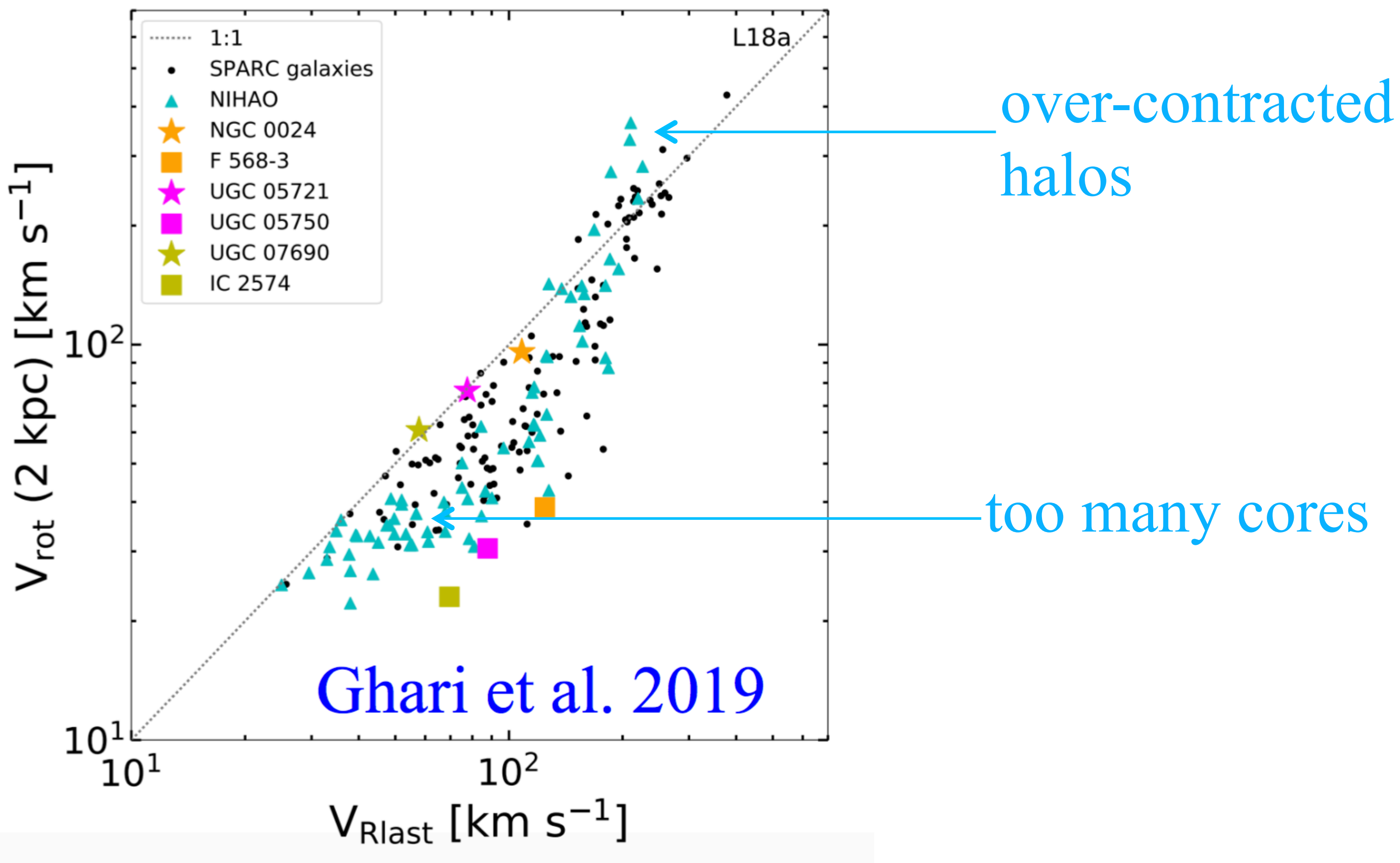



**APOSTLE/EAGLE** simulations
=> cannot form cores

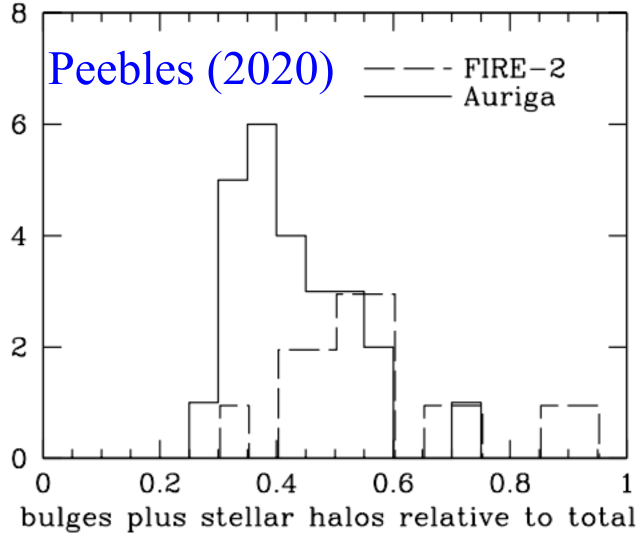
Oman et al. 2015

# The diversity problem or the modern core-cusp problem

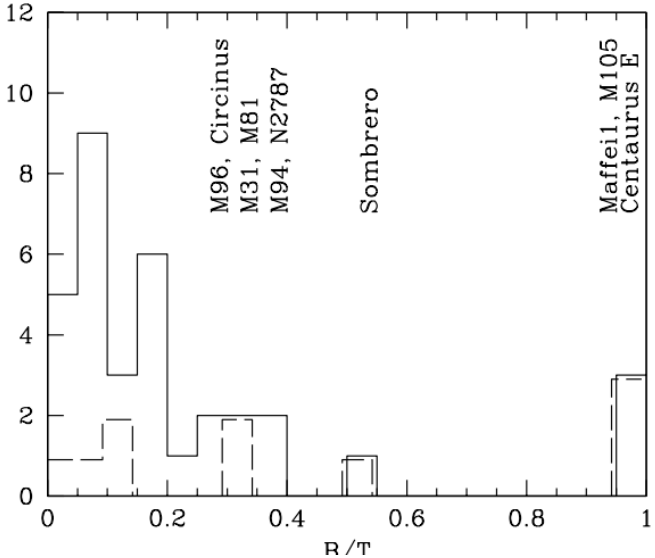
**NIHAO** has a rather extreme feedback recipe, leading to **too many cores** at low masses :

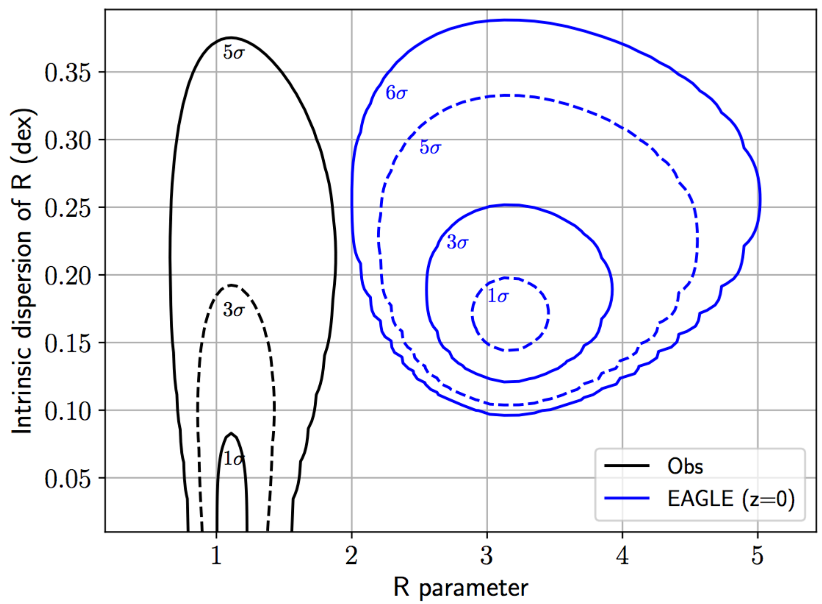


# The hot orbits problem and the fast bar problem



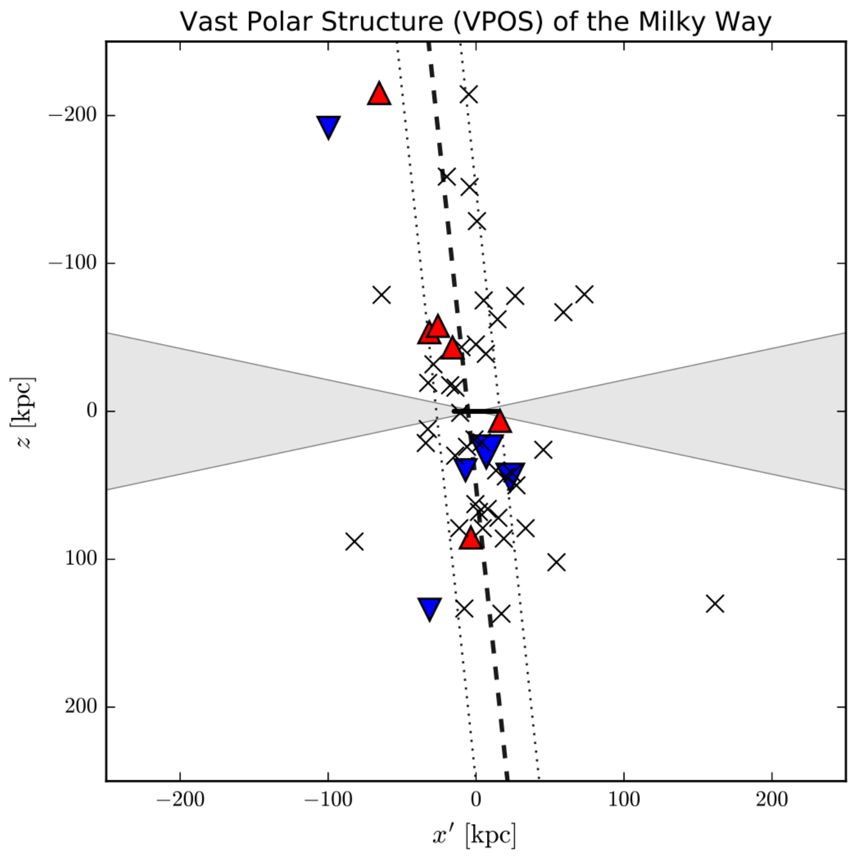

- Most local disk galaxies are nearly **bulgeless** with light stellar halos
- **70% are barred** at $M_* \sim 10^9$-$10^{10} M_{sun}$ (Erwin 2018)
- Bars are **fast** $R_{CR}/R_{bar}$ <1.4 (Aguerri et al. 2015)




Roshan et al. (2021)

# The satellites phase-space correlation problem

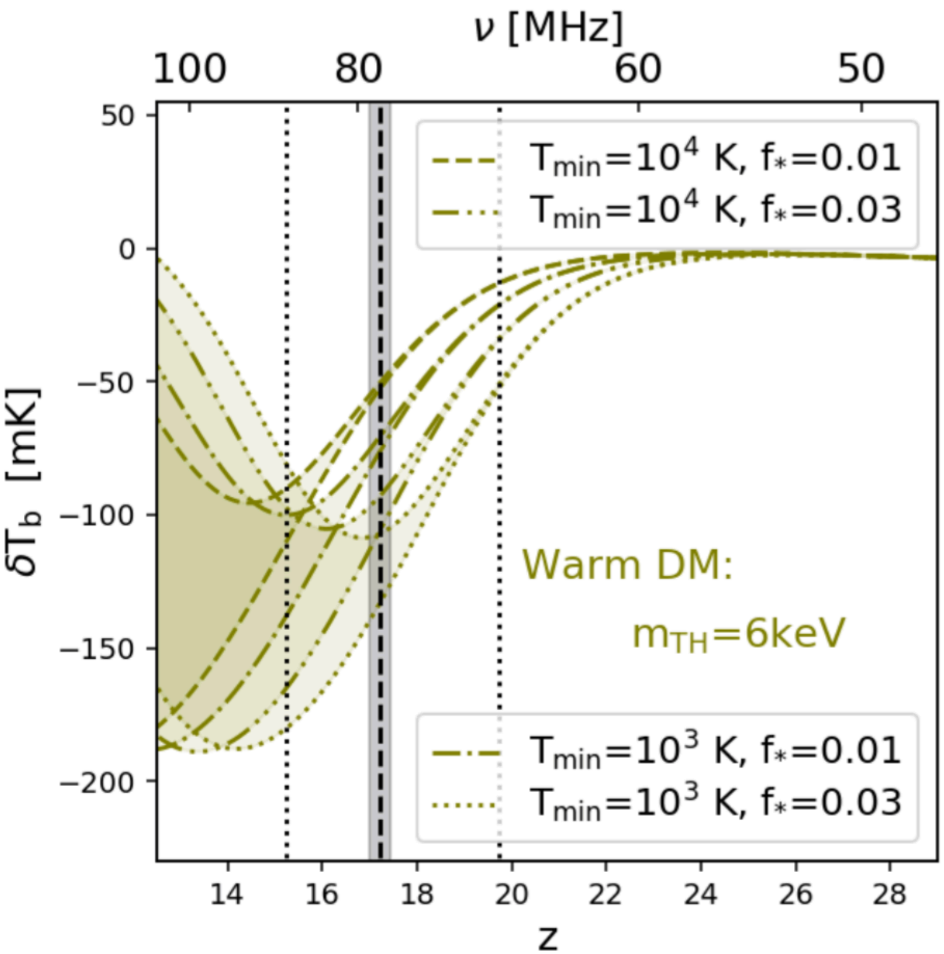



Pawlowski (2018)

# Warm dark matter?

The simplest … ave to be cold?
CDM often a … o a few TeV

What about st … DM of **a few keV?**
- Dam … streaming scale
(1 keV …
- lowe … **elps TBTF**
- To c … which prevents the
forma … esnt help diversity

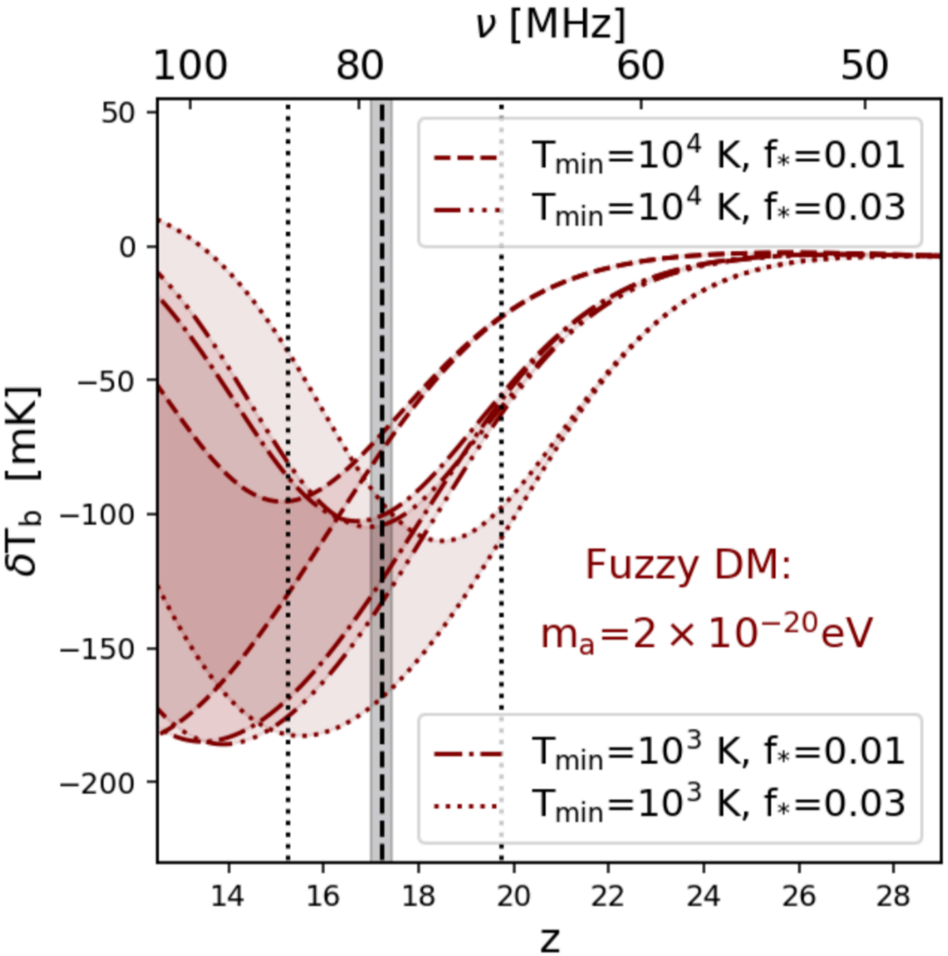



Schneider (2018): delayed formation of small-scale halos in contradiction with EDGES timing for **m<7 keV** (but at higher masses, **cannot solve any small-scale tension !** )

# Fuzzy dark matter?

An idea that ga | Vitten (2017) that
DM might be c | oglie wavelength:

$$\lambda = h/(m_b \quad 100\,\mathrm{km\,s^{-1}}/v)$$



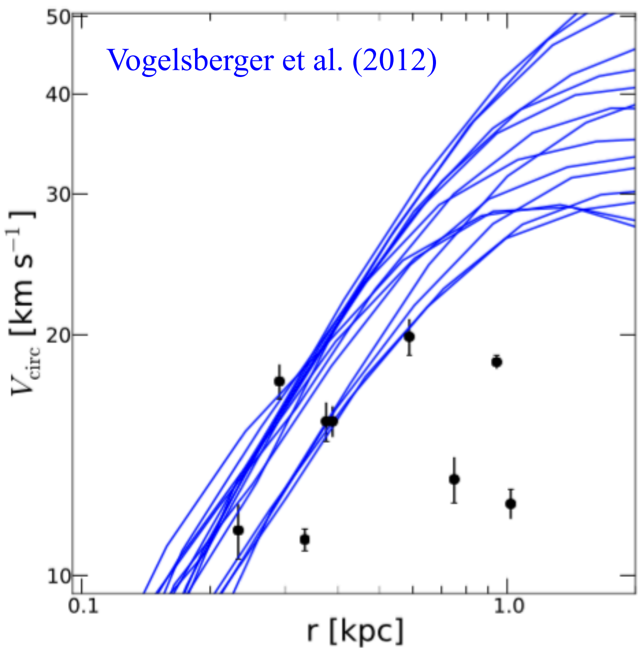

- Above | it is **different**
- **Damp** | $10^{-22}\,\mathrm{eV})^{-4/3}\,M_\odot$
- Create | **iction** by one order
of magn | ale fluctuations)
- These | roblem, maybe **hot**
**orbits** p | tness
- Not cl | sity problem

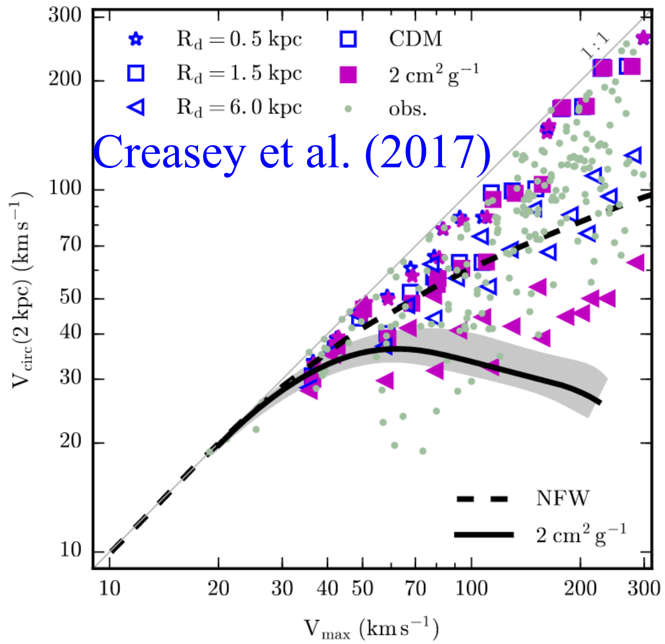
Schneider (2018): delayed formation of small-scale halos in contradiction with EDGES timing for **m < $10^{-20}$ eV** (but at higher masses, **cannot solve any small-scale tension !** )

# Self-interacting dark matter?

The 2nd simplest modif. of DM: **does it really have to be collisionless?** Self-interactions have little effect on the matter power spectrum, but can drastically change the DM profiles in relaxed clusters!

Self-interacting cross-sections **σ/m =1-10 cm²/g** can have a drastic effect on halo profiles => can solve **TBTF**, **diversity, and fast bar problem**



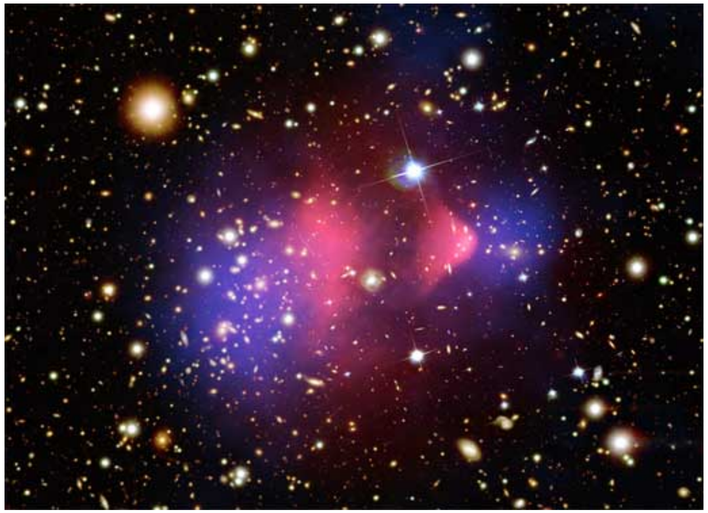

Nothing on hot orbits, and might make **FFP worse!** (Sameie et al. 2021)

# Self-interacting dark matter?

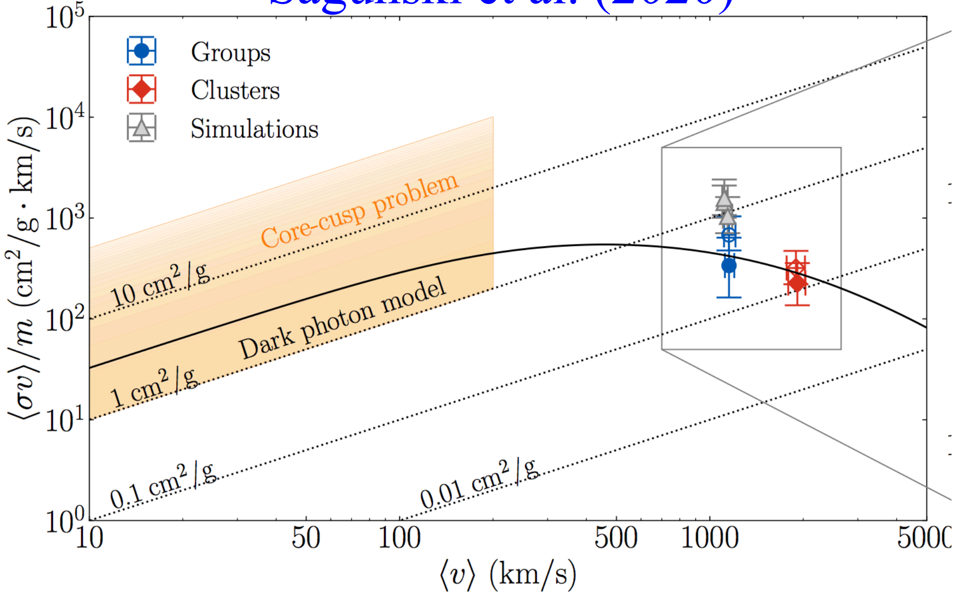
**Conflicting constraints** with galaxies coming from galaxy clusters:

Colliding clusters (bullet) => **$\sigma/m < 0.7$ cm²/g** (Randall et al. 2008)
Strong lensing of cluster centers => **$\sigma/m < 0.065$ cm²/g** (Andrade et al. 2021)

Cannot solve any tension on galaxy scales with such cross-sections
=> **velocity-dependent cross-section needed**



Sagunski et al. (2020)



# Modifying gravity?

| | | |
|---|---|---|
| $g = g_N$ | if $g \gg a_0$ | **MOND** |
| $g = (g_N\, a_0)^{1/2}$ | if $g \ll a_0$ | Milgrom 1983 |

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

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

AQUAL: Bekenstein & M (1984)

or

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

QUMOND: Milgrom (2010)

$\Rightarrow$ Getting a **tight and straight BTFR**, solving the **failed feedback** problem and the **diversity** **for free**

\+ **no dynamical friction with DM** implies for instance **faster bars as observed, and reduces formation of bulges (hot orbits problem)**

# Modifying gravity?

| | | |
|---|---|---|
| $g = g_N$ | if $g >> a_0$ | MOND |
| $g = (g_N\, a_0)^{1/2}$ | if $g << a_0$ | Milgrom 1983 |

$\Rightarrow$ Question: how to get the right CMB peaks?

Needs a new degree of freedom which decouples from the baryon-photon plasma in time-dependent configurations, and which gives MOND in equilbrium quasi-static configurations

**=> RelMOND (Skordis & Zlosnik 2020)**

# Modifying gravity?

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

MOND
Milgrom 1983

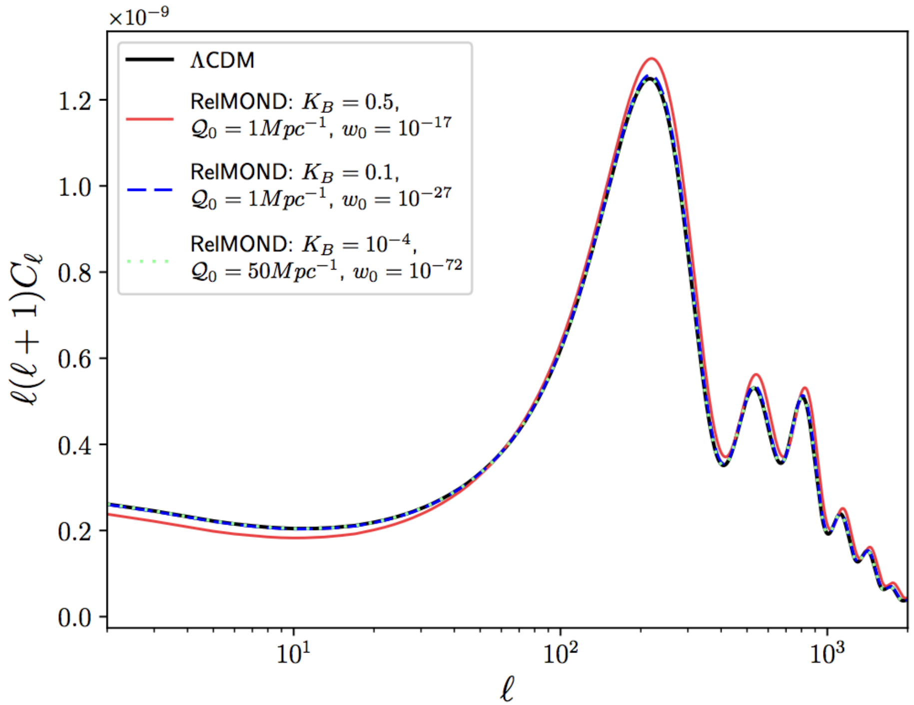


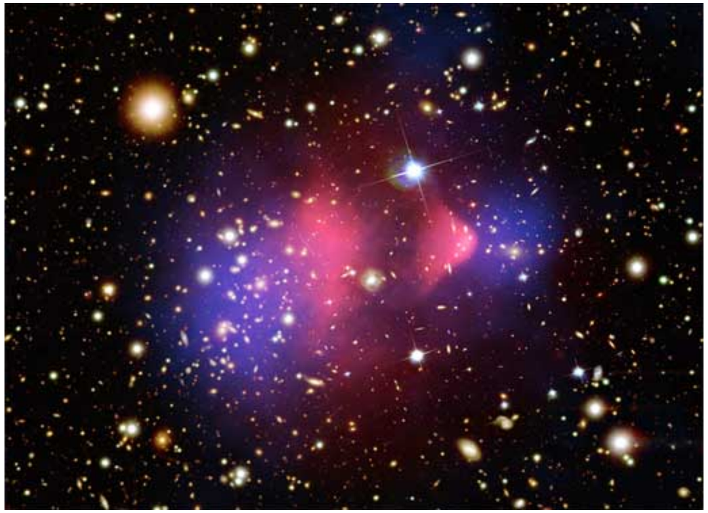

FIG. 1. The CMB temperature angular power spectrum $C_\ell$ for ΛCDM (black) and relativistic MOND for a number of parameter values (keeping all parameters common to ΛCDM the same). The green (dotted) curve is indistinguishable from ΛCDM.

# Modifying gravity?

| | | |
|---|---|---|
| $g = g_N$ | if $g >> a_0$ | MOND |
| $g = (g_N\, a_0)^{1/2}$ | if $g << a_0$ | Milgrom 1983 |

$\Rightarrow$ **Real challenge: non-linear regime and galaxy clusters!**

Intermediate regime of barely virialized systems??
Ultra-diffuse galaxies in clusters immune to the EFE?
(Freundlich, Famaey, et al. in prep.)



??

# Baryon-interacting dark matter?

Change from CBE to BTE with two fluids through some long-range interaction (Famaey et al. 2018, 2020)

$\Rightarrow$ second order moments then give a **heat equation** which can resemble the MOND equation if roughly assuming T$\propto\Phi$

$$\frac{3}{2}\left(\frac{\partial}{\partial t}+\vec{u}\cdot\vec{\nabla}\right)\frac{T}{m}+\frac{1}{\rho}P^{ij}\partial_i u_j+\frac{1}{\rho}\vec{\nabla}\cdot\vec{q}=\frac{\dot{\mathcal{E}}}{m}$$

Spherical symmetry+isotropy+no spin+equilibrium (no *t* dependence) for halo:

$$\vec{\nabla}\cdot\left(m\kappa\vec{\nabla}v^2\right)=-\rho\frac{\dot{\mathcal{E}}}{m}$$

Two things to fix: **thermal conductivity** and **heating rate**

**Thermal conductivity :**

$$\kappa = \frac{3}{2}\frac{\rho\, v^2 t_{\rm relax}}{m}$$

through some sort of DM self-interactions

Needs a relatively short relaxation time, let's take: $t_{\rm relax} = \frac{\mathcal{N}}{\sqrt{G\rho}}$

**Heating rate :**

We want $a_0$ in the denominator on the l.h.s., hence should be prop. to $a_0$, simplest is to take $a_0 v$, and dimensionless dependence on $\rho$ and $\rho_b$

$$\frac{\dot{\mathcal{E}}}{m} = C a_0 v \frac{\rho_{\rm b}}{\rho}$$

=> We showed it gives rise to right diversity

=> little interaction for CMB, just the right energy exchange for **EDGES**… (simply by putting $a_0$ scale in the heating rate)

# Conclusions on « small-scale » tensions and the nature of DM

- WDM: good for TBTF, not so much for the other challenges, **above ~10 keV, does not really solve any challenge**. Perhaps hot orbits if coupled with non-gaussianities

- FDM: good for TBTF and reducing dynamical friction, not so much other challenges such as diversity of RC**, above ~$10^{-20}$ eV, does not really solve any challenge**

- SIDM: very promising for diversity! **could make failed feedback at the high mass end worse**, velocity-dependence tightly constrained by galaxy clusters

- MOND: solves quite a few challenges at galaxy scales! But also creates new ones (convoluted relativistic theory, **missing mass in clusters, UDGs in clusters,...**)

- BIDM: not explored very much yet...