Enlightening Cold Dark Matter's darkest side via a non-minimal coupling

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XXV SIGRAV Conference on General Relativity and Gravitation

5/9/23

Self-gravitating Equilibria of Non-minimally Coupled Dark Matter Halos

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The Astrophysical Journal, Volume 910, Number 1

Empirical Evidence of Nonminimally Coupled Dark Matter in the Dynamics of Local Spiral Galaxies?

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Published 2022 April 12 • © 2022. The Author(s). Published by the American Astronomical Society.

The Astrophysical Journal, Volume 929, Number 1

Looking for Traces of Nonminimally Coupled Dark Matter in the X-COP Galaxy Clusters Sample

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Published 2023 July 20 • © 2023. The Author(s). Published by the American Astronomical Society.

The Astrophysical Journal, Volume 952, Number 2

+ **Dark Matter** in **Fractional Gravity**
Benetti et al., 2023a (APJ); 2023b (MDPI Universe)

Motivation

Cold Dark Matter (**CDM**): GeV mass, non-relativistic, negligible free-streaming velocities

Interpretation of DM in the cosmological concordance model - **successes & challenges**

The Core-Cusp problem

CUSPY profiles

(e.g. **Navarro-Frenk-White**, NFW)

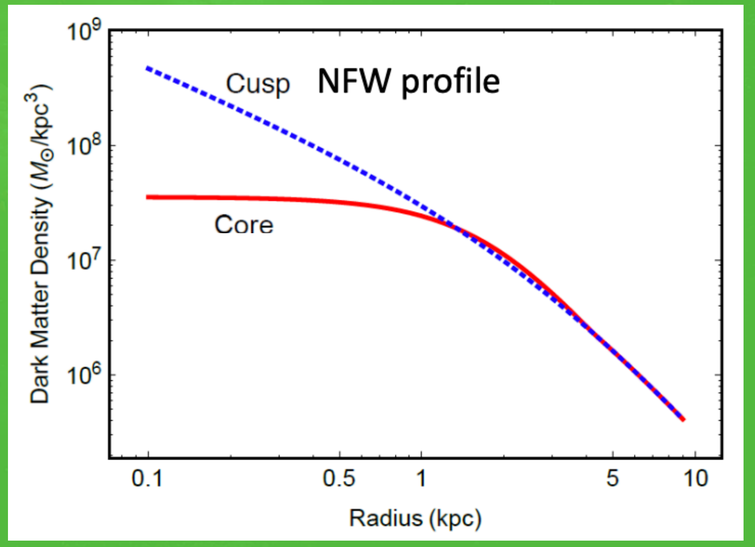
$$\rho(r) = \frac{\delta_c \rho_c r_s^3}{r\left(r + r_s\right)^2}$$

VS

CORED profiles

(e.g. the **Burkert profile**)

$$\rho(r) = \frac{\rho_0 r_0^3}{\left(r + r_0\right) \cdot \left(r^2 + r_0^2\right)}$$



δ_c : dim.less characteristic overdensity ρ_c : local critical density r_s : scale radius ρ_0 : core density r_0 : core radius

Theoretical Background

Idea: DM dynamics provides an effective metric for baryons in galaxies (modified bkg)

General Relativity (GR):
physical metric = gravitational metric

→

physical metric =
gravitational metric & extra field

Disformal transformations (Bekenstein 1993):

$$\tilde{g}_{\mu\nu} = e^{2\varphi}\left[\mathcal{A}(\mathcal{X})g_{\mu\nu} + \mathcal{B}(\mathcal{X})\nabla_\mu\varphi\nabla_\nu\varphi\right] \qquad \mathcal{X} = -\frac{1}{2}g_{\mu\nu}\nabla^\mu\varphi\nabla^\nu\varphi$$

$\tilde{g}_{\mu\nu}$: gravitational metric; $g_{\mu\nu}$: physical metric

Action of the model

(e.g. Bettoni+14; Ivanov&Liberati20)

EINSTEIN FRAME

$$S = S_{\rm EH}\left[g_{\mu\nu}\right] + S_{\rm bar}\left[\widetilde{g}_{\mu\nu}, \psi\right] + S_{\rm DM}\left[g_{\mu\nu}, \varphi\right]$$

JORDAN FRAME

$$S = S_{\rm EH}\left[\widetilde{g}_{\mu\nu}\right] + S_{\rm bar}\left[\widetilde{g}_{\mu\nu}, \psi\right] + S_{\rm DM}\left[\widetilde{g}_{\mu\nu}, \varphi\right] + \epsilon L^2 \int \mathrm{d}^4x \sqrt{-\tilde{g}}\, \widetilde{G}^{\mu\nu} \nabla_\mu\varphi \nabla_\nu\varphi$$

$$\nabla^2\Phi = 4\pi G\left[\left(\rho_{\rm DM} + \rho_{\rm bar}\right) - \epsilon L^2 \nabla^2\rho_{\rm DM}\right]$$

$\epsilon = \pm 1$: NMC polarity L : NMC characteristic length-scale

Crafting the non-minimal coupling

Ingredients:

1 A **dynamical process** generating a coherence length for DM

Condensation,
EoS of DM,
Fluid description of DM...

2 This coherence length is comparable to the **local curvature scale**

... this is not really a **modified gravity theory ...**

As a consequence, L **will not have a universal value**!

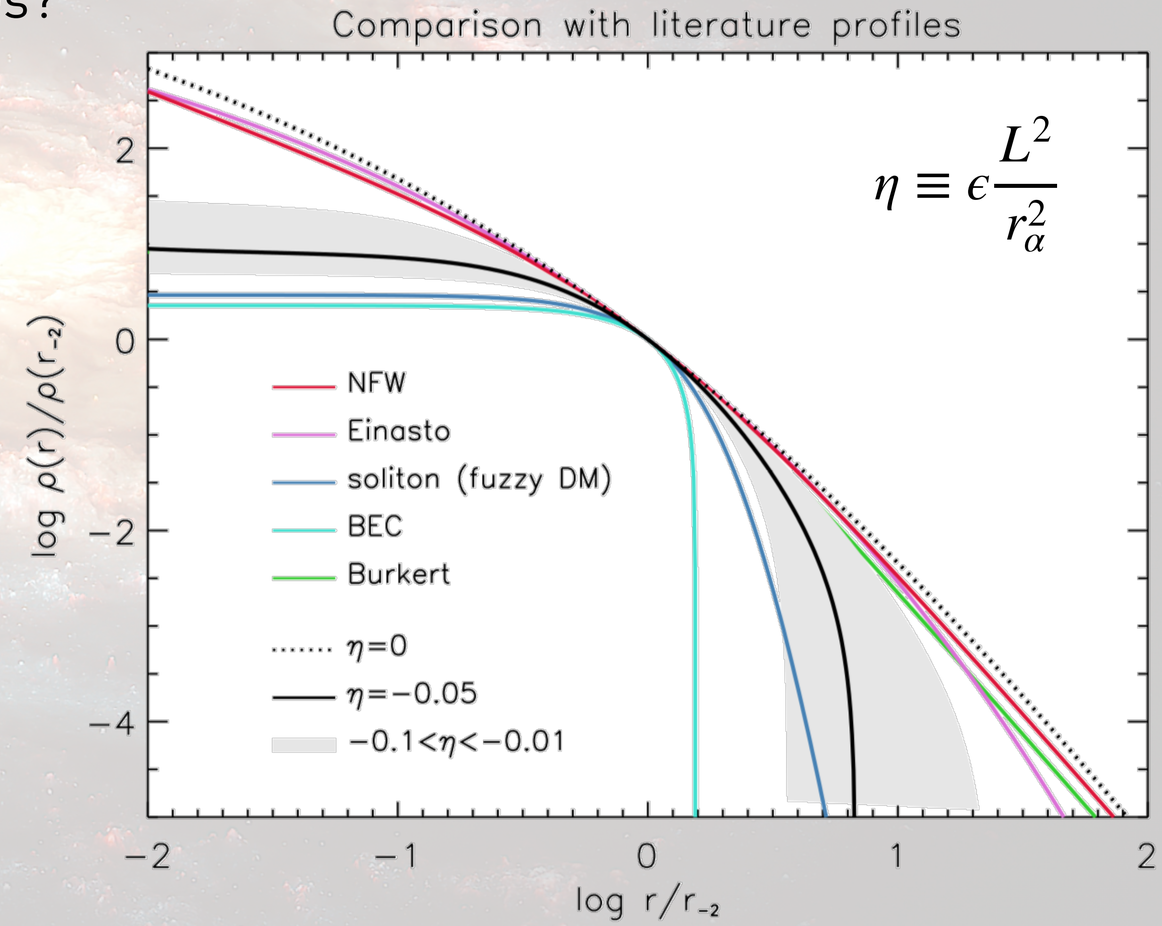
Cored profiles with NMC DM

QUESTION: Can our model produce **cored** profiles?

"Perturbative approach": NMC acts as a perturbation on a galaxy system characterized by the cuspy NFW profile

$$\nabla^2\Phi_{\rm DM} = 4\pi G\left(\rho_{\rm NFW} - \epsilon L^2\nabla^2\rho_{\rm NFW}\right)$$
$$\rho_{\rm NMC} = \rho_{\rm NFW} - \epsilon L^2\nabla^2\rho_{\rm NFW}$$

- If the NMC is repulsive profiles are **cored!**
- **Th**eir shape closely following out to several core scale radii the **phenomenological Burkert profile**
- NMC DM mass distribution yields comparable RC fits to the Burkert profile



Core surface-density relation

Dwarf galaxies with halo mass $\mathscr{M} \lesssim 10^{11} M_\odot$ seem to obey the following relation:

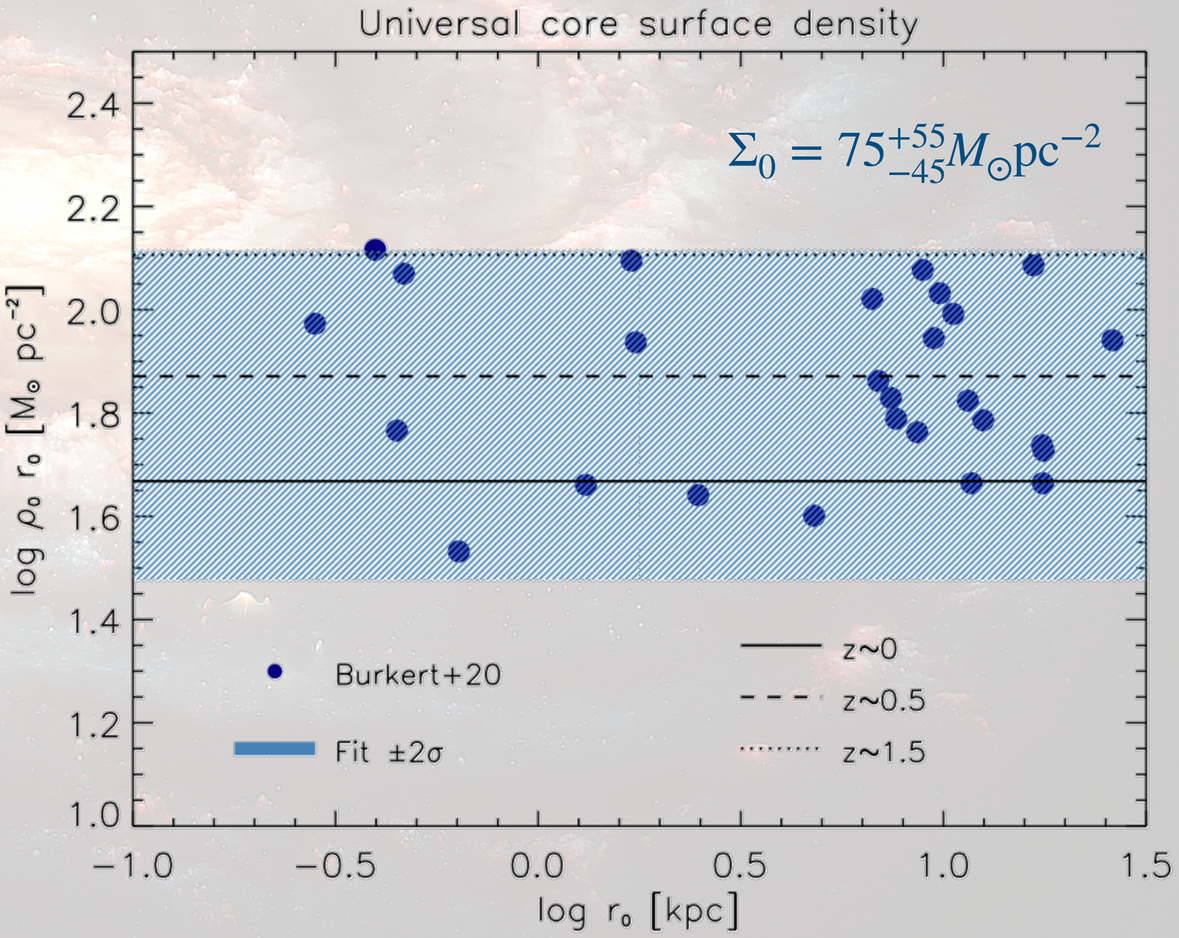
$$\rho_0 r_0 \approx 75^{+55}_{-45} M_\odot \mathrm{pc}^{-2}$$

(Salucci&Burkert00; Burkert15)

$$\Sigma_0 \equiv \rho_0 \times r_0 \approx 50 \left(\frac{\Delta_{\mathrm{vir}}}{100} \right) E_z^{0.3} M_\odot \mathrm{pc}^{-2}$$

(Gandolfi+21)

A **challenge** to every model of core formation
(e.g. Deng+18; Burkert 2020)



Local Spiral Galaxies

QUESTION: Can NMC DM reproduce the dynamics of local spiral galaxies?

Baryons are not **negligible!**

Mass-modelling of **stacked RCs** of **local spiral galaxies** (> 1000) divided in 17 luminosity bins (improved S/N ratio, smoothing data fluctuations...)

SAMPLES OF STACKED RCs

Normal spirals
Persic+96 - 11 bins

+

Low Surface Brightness (LSBs)
Dehgani+20 - 5 bins

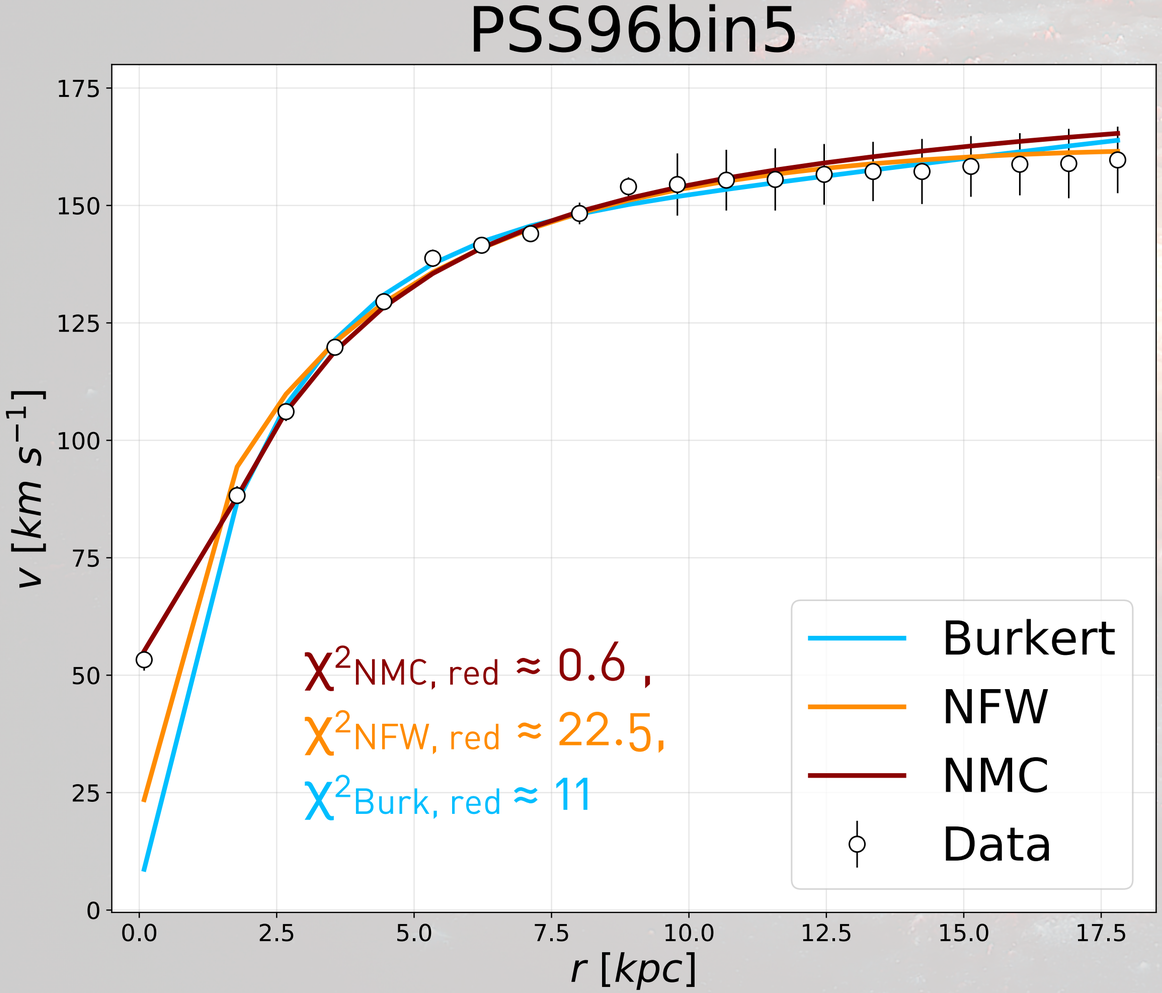
+

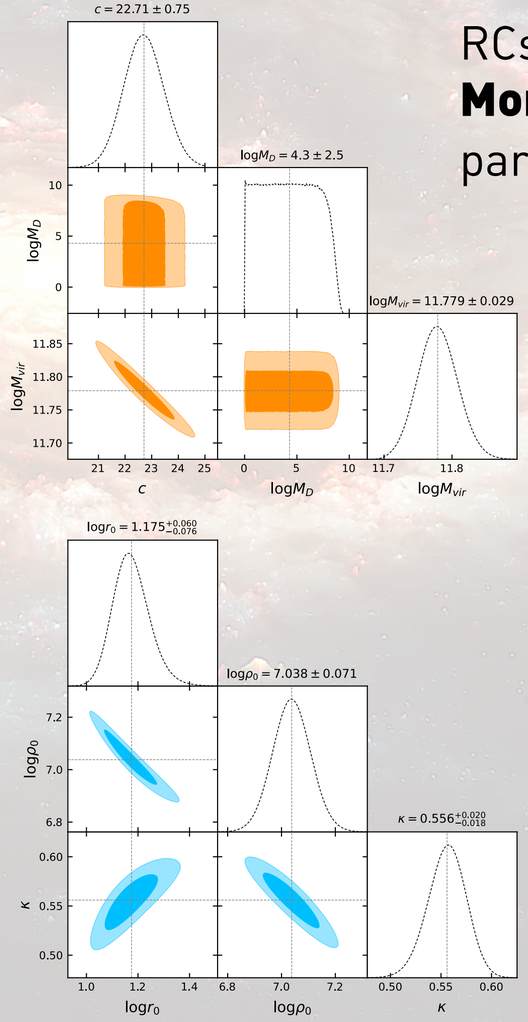
Dwarfs
Karukes & Salucci 17 - 1 bin

Baryonic distribution = exponential thin disk, Dark matter component = ...?

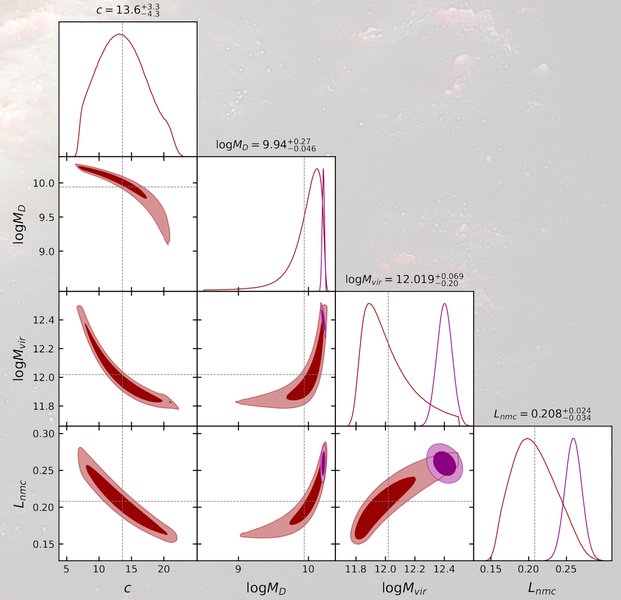
BURKERT PROFILE **vs** NFW PROFILE **vs** NMC PROFILE

Fitting stacked Rotation Curves - II





RCs fits performed with Bayesian **Monte Carlo Markov Chain** parameter estimation (emcee)



Red contours are standard NMC
Purple counters are NMC + Dutton&Macciò 2014

Fitting stacked Rotation Curves - III

Overall results for the fitting procedure (w. Bayesian MCMC parameter estimation):

The NMC model yields RC fits **always superior** to the pure NFW model (χ^2_{red})

In several instances NMC RCs fits are **comparable**/ **better** that Burkert's ones

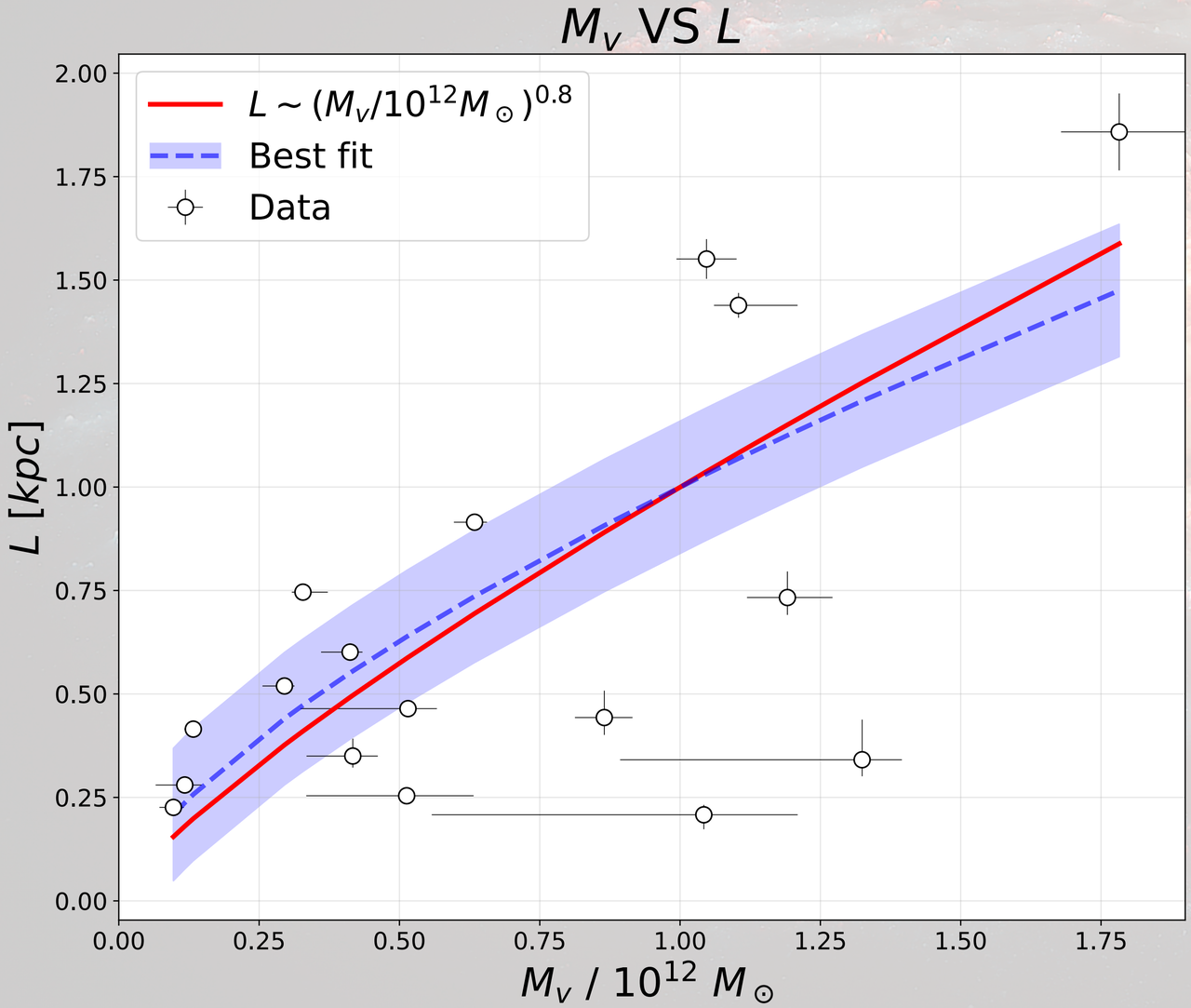
Results

An **F-test*** (NFW vs NMC) shows that L improves fits for the majority of the bins

A L - M_V correlation appears to hold...

* $F = (\chi^2_{NFW} - \chi^2_{NMC})/\chi^2_{NMC,red}$ (Bevington & Robinson 2003)
Null h.p.: L = 0

Virial mass VS NMC length-scale



L depends on the **environment** (single parameter) with a very simple scaling law!

NMC & Galaxy Clusters

THERMAL PRESSURE PROFILE

$$P^{\rm th}(R) = P^{\rm th}(0) - 1.8\mu m_{\rm p}\int_0^R n_{\rm e}(r)\left[\frac{GM_{\rm DM}(r)}{r^2} - 4\pi G\epsilon L_{\rm NMC}^2\frac{{\rm d}\rho}{{\rm d}r}\right]{\rm d}r$$

n_e: Vikhlinin profile (Vikhlinin et al., 2006)

$$\mathscr{L} = \mathscr{L}_{\rm P_X} + \mathscr{L}_{\rm P_{SZ}} + \mathscr{L}_{\rm ED}$$
$$\Theta_e = \{n_0, \alpha, \beta, \varepsilon, r_{\rm c}, r_{\rm s}\}$$
$$\Theta_{\rm M} = \{M_{500}, c\} \;\; / \;\; \Theta_{\rm M} = \{M_{500}, c, L_{\rm NMC}\}$$

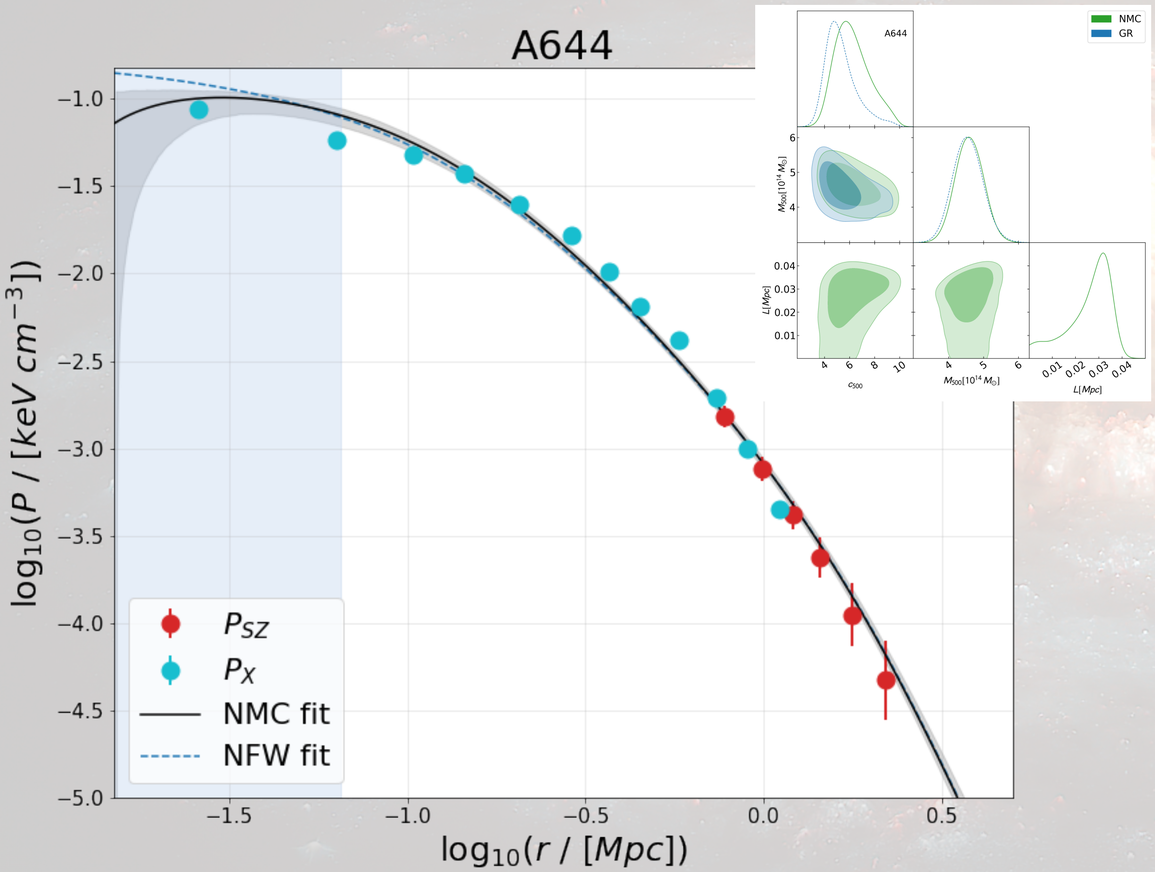
Cluster	z	$\chi^2_{\rm red,NFW}$	$\chi^2_{\rm red,NMC}$	$\Delta_{\mathcal{B}}$
A85	0.0555	2.9	2.7	-0.89
A644	0.0704	2.4	2.2	0.11
A1644	0.0473	3.9	3.4	1.01
A1759	0.0622	1.7	1.6	1.34
A2029	0.0773	1.6	1.6	-0.15
A2142	0.0909	3.3	3.3	-1.32
A2255	0.0809	6.7	1.8	2.64
A2319	0.0557	7.8	7.1	2.05
A3158	0.0597	2.3	2.1	2.81
A3266	0.0589	6.7	6.8	-1.89
RXC1825	0.0650	3.3	6.1	-3.53
ZW1215	0.0766	0.97	0.86	-0.81

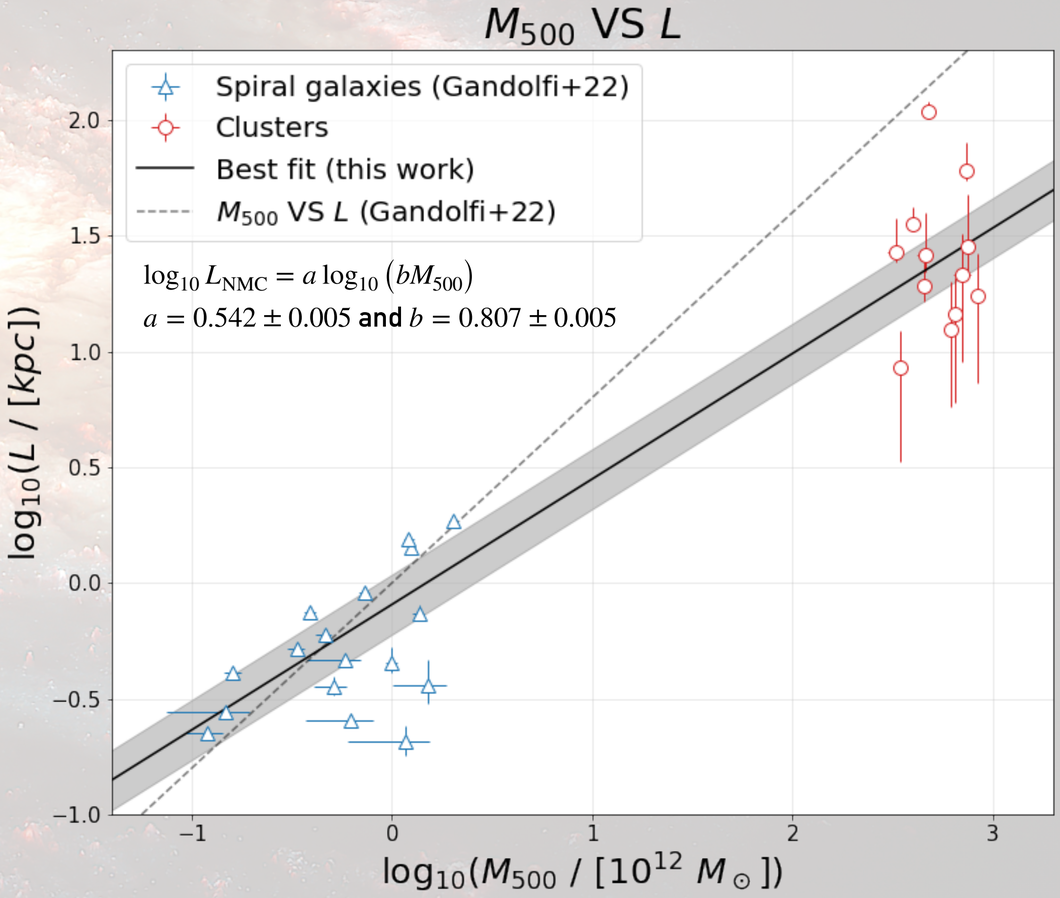
The XMM Cluster Outskirts Project (**X-COP**)
(Eckert et al., 2017)

Cluster A2744
Credits: X-COP Collaboration

Results: NMC thermal pressure profile fits are comparable or even better than the std. NFW model

NMC & Galaxy Clusters





Summary

TAKE HOME MESSAGE: this is a **simple** model depending on a **single free parameter** (L) showing a very **simple scaling** with the halo virial mass capable of solving a consistently long-standing issue of the CDM paradigm.

Thanks for your attention!

Contact me at **giovanni.gandolfi@sissa.it**

Find my publications here: