EDSU-2022 Conference
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Enlightening Cold Dark Matter's darkest sides (via non-minimal coupling)

Presented by **Giovanni Gandolfi** (SISSA, Trieste, Italy)

Outline

International School for Advanced Studies (**SISSA**)

General interest: **dark matter!**
(galaxy formation & evolution)

Theoretical, data analysis & observation (JWST)

Today's Menu: Testing and developing a model in which Cold Dark Matter is dynamically non-minimally coupled with gravity.

Supervisors: Prof. Andrea Lapi and Prof. Stefano Liberati

… but why?

Motivation

Cold Dark Matter (**CDM**): great successes... and some issues.

ISSUE 1: the Core-Cusp problem

CUSPY profiles

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

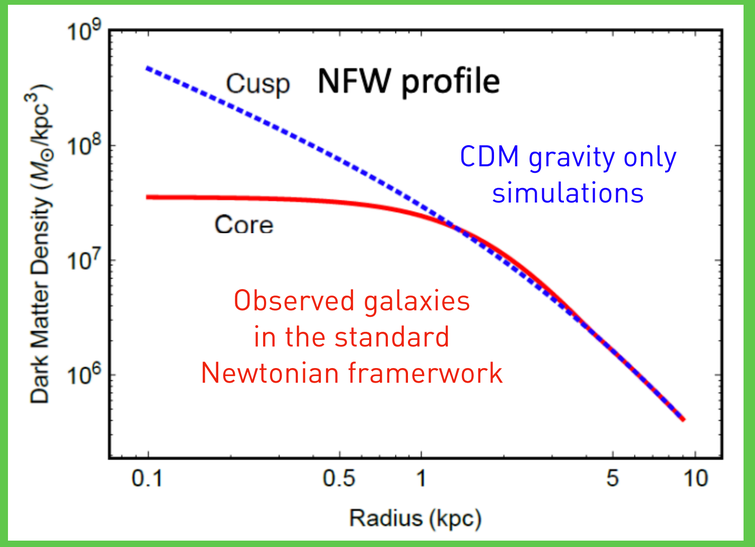
$$\rho_{\mathrm{NFW}}(r) = \frac{\delta_c \rho_c r_s^3}{r\left(r + r_s\right)^2}$$

VS

CORED profiles

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

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



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

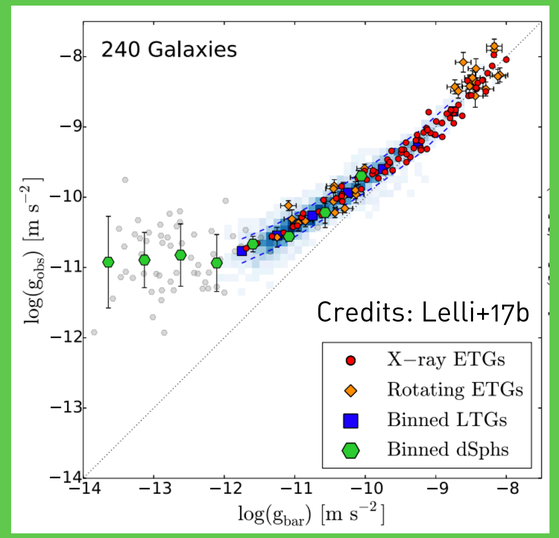
Motivation

ISSUE 2: the interplay between DM and baryons in galaxies

e.g. the **Radial Acceleration Relation** (RAR, see Lelli+17b)
(most general one?)

g_{tot} VS g_{bar}

g_{tot} : total radial acceleration
g_{bar} : **baryonic** radial acceleration



Possible solutions: baryonic/AGN feedback (e.g. Di Cintio+14 from hydro simulations), dynamical friction, non-standard particle candidates...

or... **CDM** dynamically **non-minimally coupled** with **gravity!**

Theoretical Background

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

Physical metric: metric experienced by standard matter (**Jordan Frame**)
Gravitational metric: metric describing dynamics of the gravitational field (**Einstein Frame**)

General Relativity (GR):
physical metric = gravitational metric

→

physical metric =
gravitational metric & extra field

Disformal transformations (Bekenstein 1993 - preserves causality + WEP):

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

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

Action of the model

EINSTEIN FRAME

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

How do we obtain such effective disformally-shaped metric $\widetilde{g}_{\mu\nu}$? We need to go in the Jordan frame...

JORDAN FRAME

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

Standard ΛCDM terms
minimally coupled to gravity

Non-Minimal Coupling (NMC)
(Bettoni+14; Ivanov&Liberati20: A=1, B=1)

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

Newtonian limit

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

the source of gravity is not only density but also **inhomogeneities** in the DM density distribution!

The dynamics of galaxies will be **modified...**

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

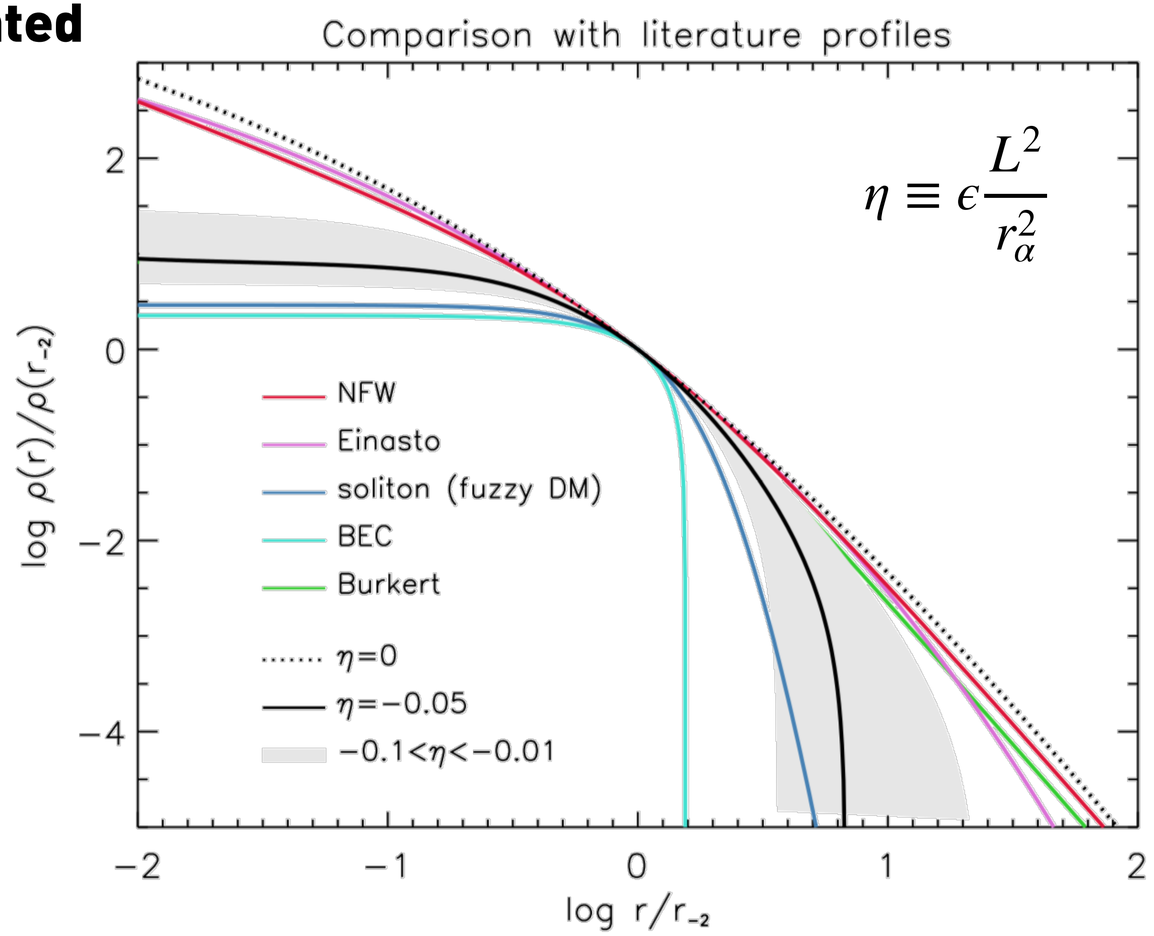
Testing the NMC DM model on dwarf, **DM-dominated** galaxies.

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

Giovanni Gandolfi,[1,2] Andrea Lapi,[1,2,3,4] and Stefano Liberati[1,2,3]

(Gandolfi+21, published in the Astrophysical Journal)

- If η < 0 NMC DM 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:

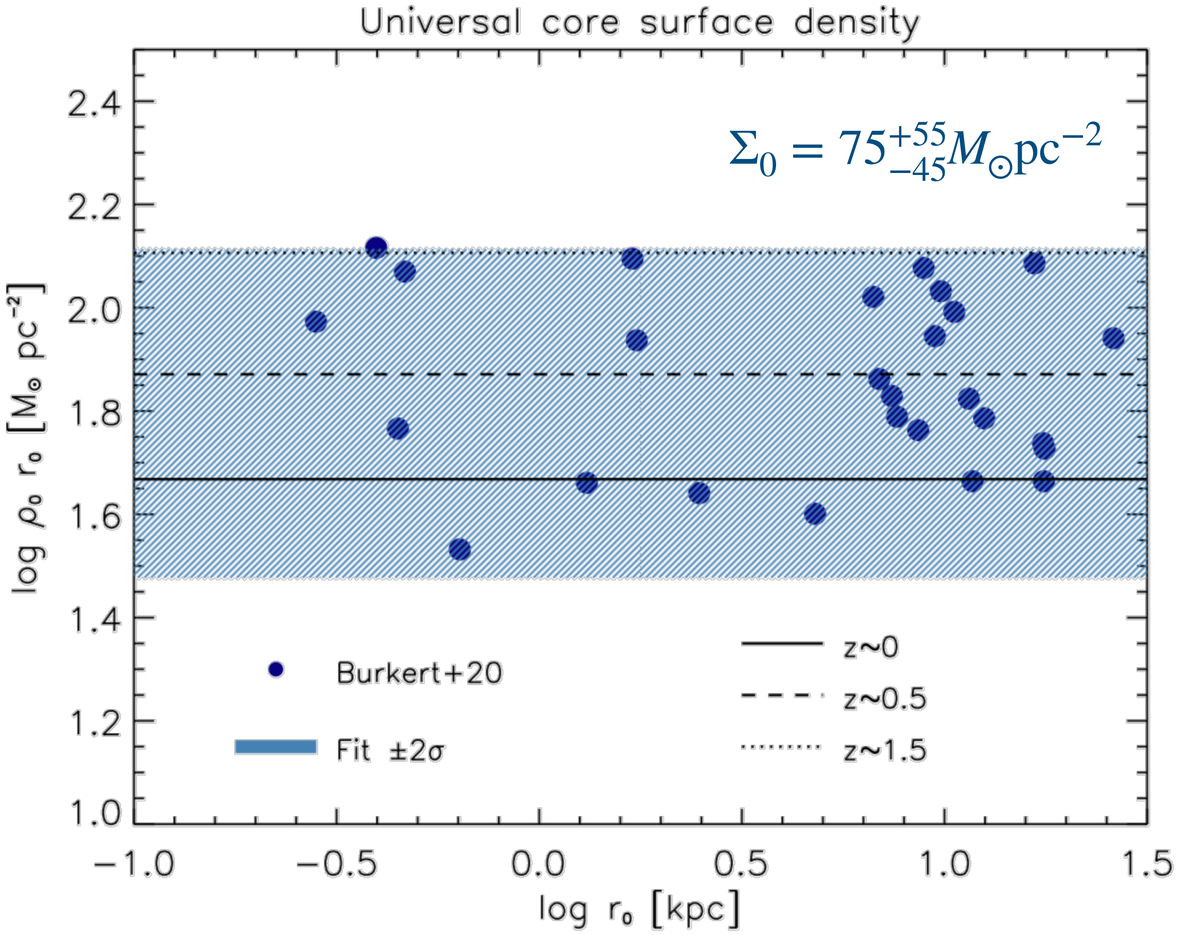
$$\rho_0 r_0 \approx 75^{+55}_{-45} M_\odot \mathrm{pc}^{-2}$$

(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. **scalar DM -** Deng+18; Burkert 2020)



NMC DM and Galactic Dynamics - I

We test the NMC DM model on local spiral galaxies (LTGs, LSBs, Dws).

Empirical Evidence of Non-Minimally Coupled Dark Matter in the Dynamics of Local Spiral Galaxies?

GIOVANNI GANDOLFI [1,2] ANDREA LAPI [1,2,3,4] AND STEFANO LIBERATI [1,2,4]

(Gandolfi+22a, , published in the Astrophysical Journal)

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

$$\rho_{\rm NMC} = \rho_{\rm NFW} - \epsilon L^2 \nabla^2 \rho_{\rm NFW} \qquad \rho_{\rm NFW}(r) = \frac{\delta_c \rho_c r_s^3}{r\left(r + r_s\right)^2}$$

δ_c : dim.less characteristic overdensity

ρ_c : local critical density

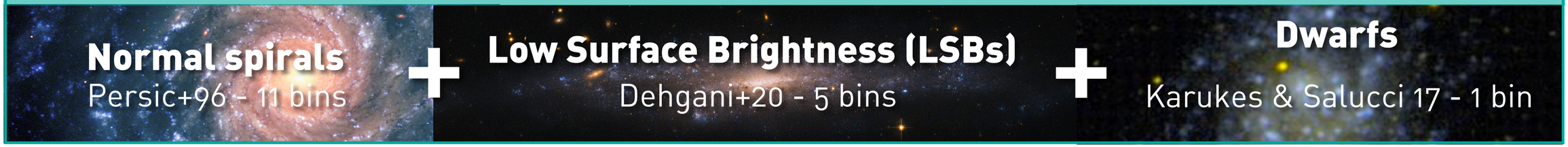
r_s : scale radius

Fitting stacked Rotation Curves - I

Mass-modelling of **stacked RCs** of **local spiral galaxies** with different velocities at the optical radius (r_{opt} = 3.2 r_d encompasses 83% of total luminosity)

One can co-add (normalized) high quality RCs to obtain some **benefits**: improved S/N ratio, smoothing data fluctuations... **Lapi+18**

SAMPLES OF STACKED RCs (17 total average velocity bins from thousands of galaxies!)

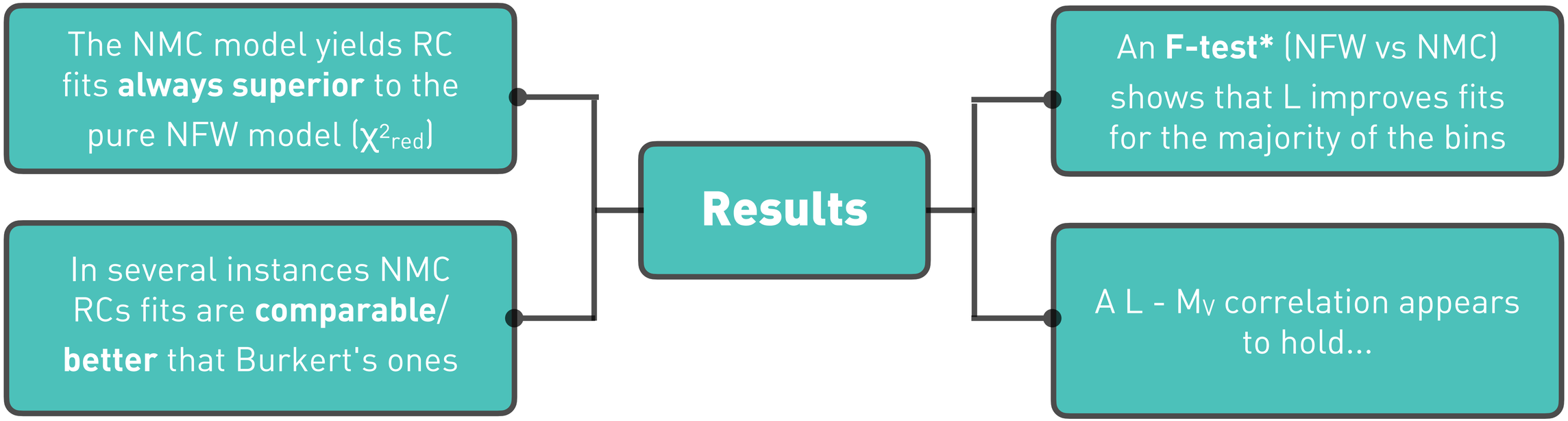


Baryonic distribution = exponential thin disk, Dark matter component = ...?

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

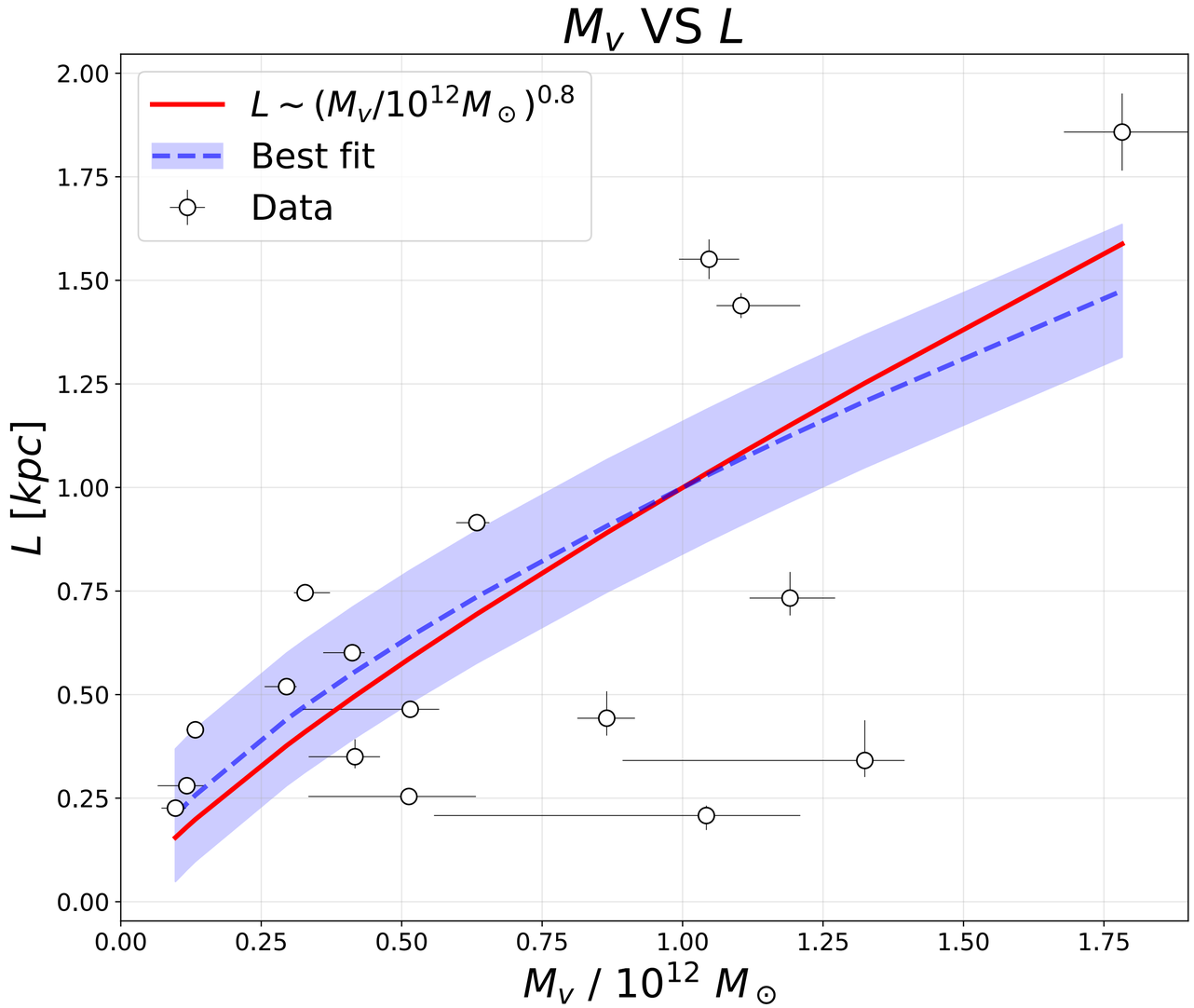
Fitting stacked Rotation Curves - III

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



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

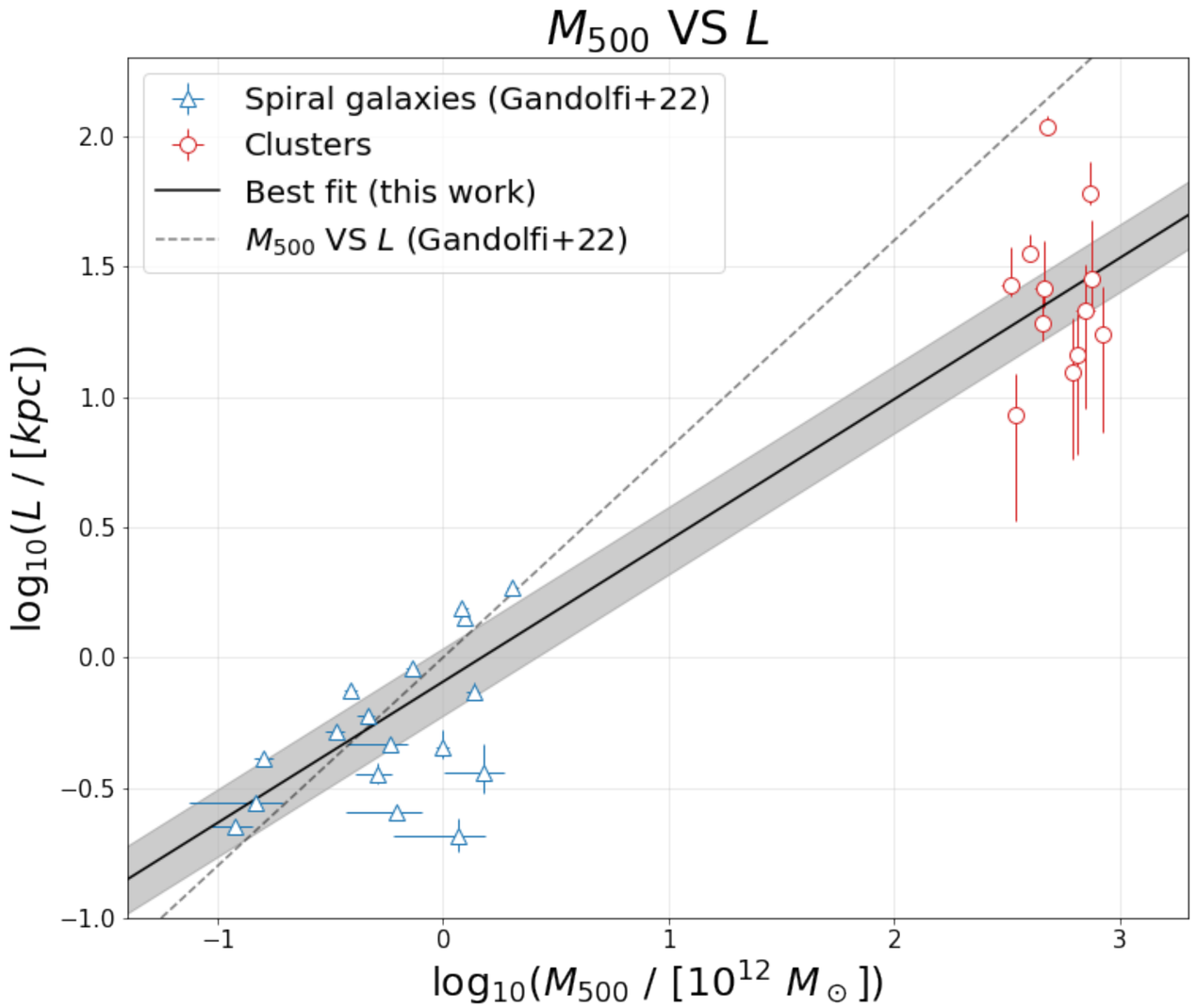
Virial mass VS NMC length-scale



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

... does it hold up to **galaxy clusters scales**? (Gandolfi+22b, in prep.)

Virial mass VS NMC length-scale



*** Preview from Gandolfi+22b! ***

Blue dots: **spiral galaxies** from our previous work

Red dots: fits of **galaxy clusters**' pressure profiles (X-COP compilation of galaxy clusters, see Ghiradini et al. 2018; joint X-ray T and SZ pressure obs.)

Result 1: L-Mv relation holds up to the mass range probed by galaxy clusters

Result 2: NMC fits pressure profiles comparably/better than NFW

The Radial Acceleration Relation

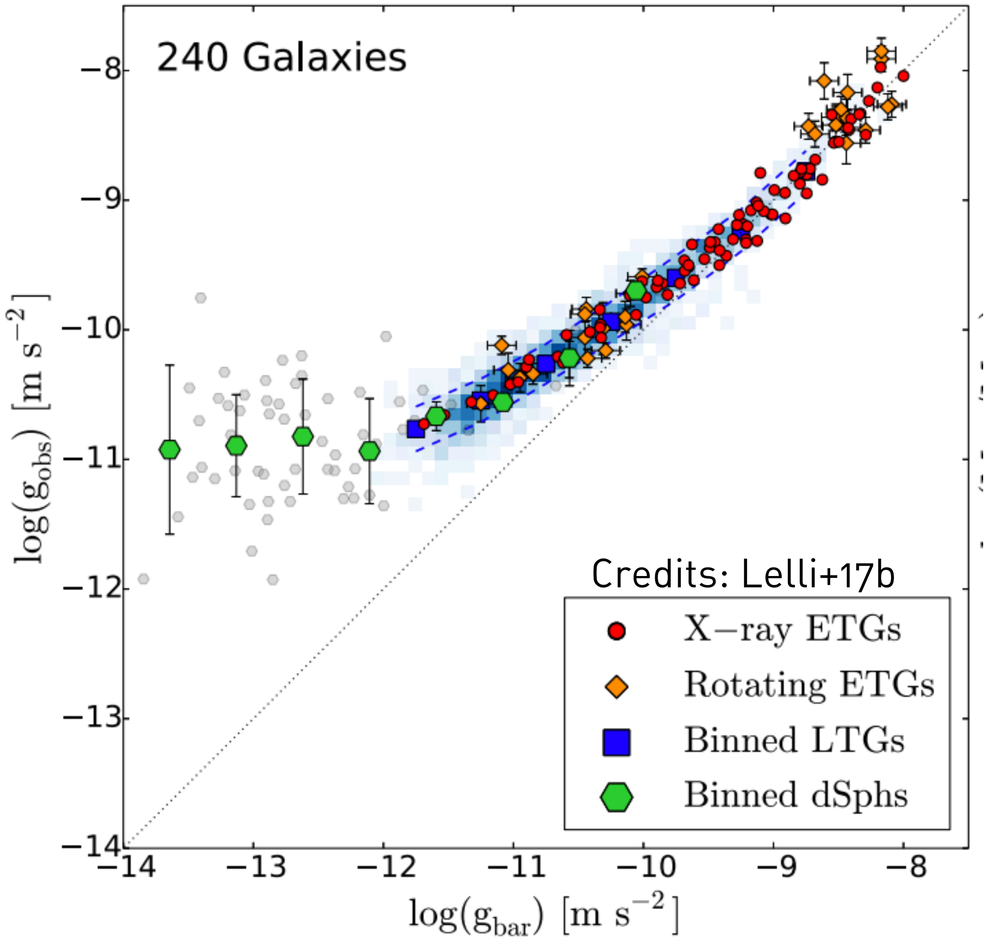
Can the NMC DM model reproduce the **most general** relation between DM and baryons, i.e. the RAR? (See Lelli+17b)

$g_{\rm tot}$ VS $g_{\rm bar}$

$g_{\rm tot}$: from galaxy RCs with different masses/velocities
$g_{\rm bar}$: from luminous matter distribution (photometry)

Proposed in McGaugh+16 exploiting the **SPARC** sample (individual high-quality RCs, Lelli+16a)

Is it **fundamental**? Could it emerge naturally from the **self-similarity** of **CDM halos** (Navarro+17) or by baryonic effects (Di Cintio+14, … , Wheeler+19)



A semi-empirical method

To obtain the RAR we used a semi-empirical method (Di Cintio & Lelli 2016). We generated e large number of virial masses $8 < \log\left(M_{\rm v}/M_{\odot}\right) < 13.3$

We used semi empirical relationships linking virial masses to quantities characterizing the **distribution of baryons**.

As for the **DM component**, we assumed different DM density profiles to perform a comparison.

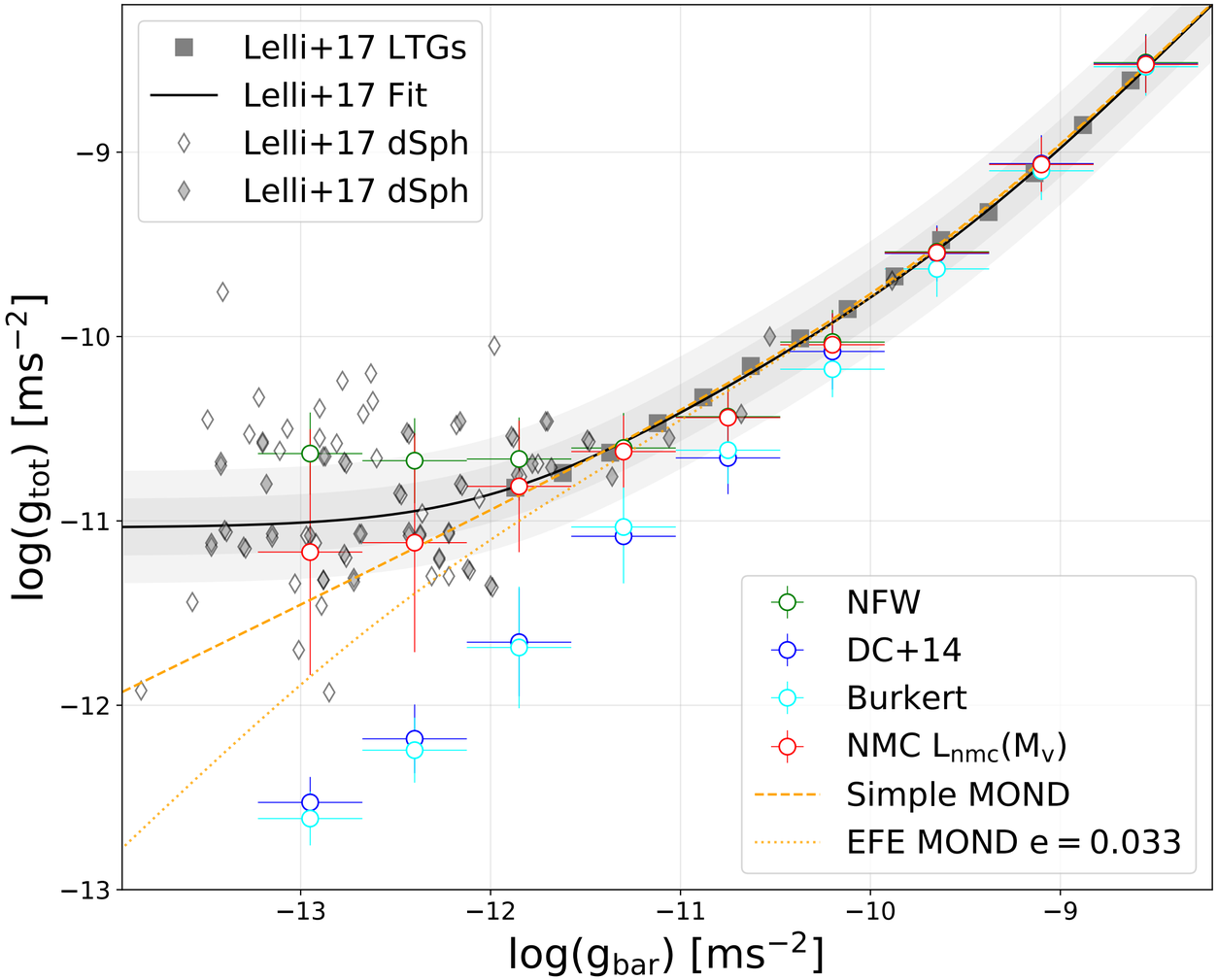
Build up **mock RCs** of spirals

We sample* them and derive $g_{\rm obs}$, $g_{\rm bar}$

(up to r = $2r_{opt}$)

The (binned) **RAR** is obtained

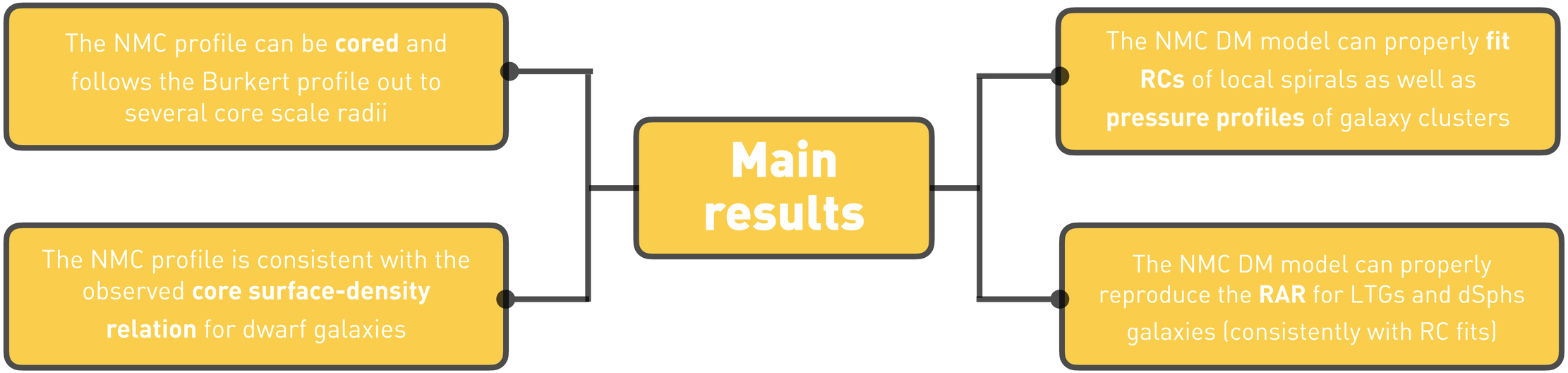
Radial Acceleration Relation - results



- Data from Lelli+17 - LTGs + dSph
- Fitting function (Lelli+17)
- **Burkert** + **DC14 struggle** in reproducing the dSph curve
- **NFW** profile traces well the dSph curve BUT yields poor RC fits
- **NMC DM** with a mass-dependent scaling for L reproduces the dSph curve + yields good RC fits!

Summary

We have hereby analyzed the phenomenology of our NMC DM model in DM-dominated systems and local spiral galaxies.



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 consistently long-standing issues of the CDM paradigm.

Thanks for your attention!

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

Find my publications here: