Galaxy rotation curves in modified gravity models

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based on Álefe O.F. de Almeida, Luca Amendola, VN, arXiv:1805.11067 [astro-ph.GA]

Outline

Evidences for Dark Matter

- 1933: studying the Coma cluster, F. Zwicky found a discrepancy of two orders of magnitude between the mass inferred by dispersion velocity measurements of the galaxies in the cluster and the one expected by the analysis of the luminous components *F. Zwicky, Helvetica Physica Acta 6 (1933) 110-127*
- 1936: S. Smith arrived to a similar conclusion with an analysis of the Virgo cluster *S. Smith, Astrophys. J. 83 (1936) 23-30*
- 1970: V. Rubin and K. Ford measured the velocity rotation curve of the Andromeda Nebula and found a flat behaviour at large radii

  V. C. Rubin, W. K. J. Ford, Astrophys. J. 159 (1970) 379-404

  1973: M. Roberts and A. Rots extended the analysis to different galaxy types

  M. S. Roberts, A. H. Rots, Astronomy and Astrophysics 26 (1973) 483-485
- 1980: a systematic study of the velocity dispersions in spiral galaxies presented by V. Rubin, K. Ford and N. Thonnard

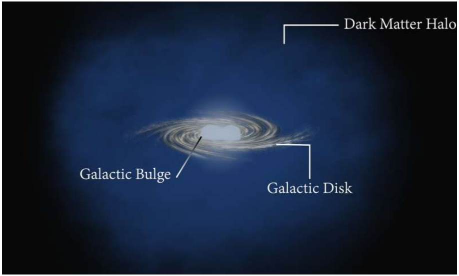
  V. C. Rubin, W. K. J. Ford, N. Thonnard, Astrophys. J. 238 (1980) 471-487

  $\Rightarrow$ presence of DM would be necessary to explain the rotation curves, if Newtonian dynamics was valid at the scale of galaxies and galaxy clusters.

Evidences for Dark Matter

$$v_{\rm rot}(r) = \sqrt{\frac{G\,M(r)}{r}}\,,$$

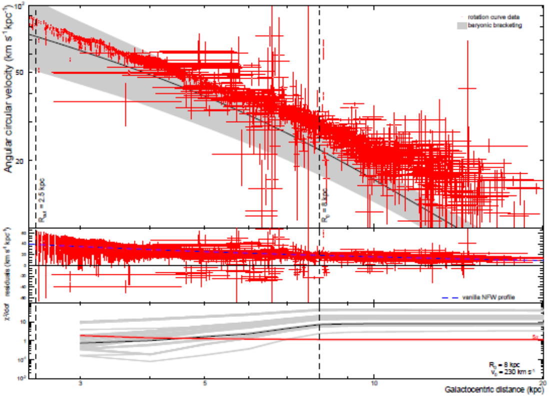
G: Newton's gravitational constant, $M(r)$: the mass contained within a distance r from the center.
Observation of flat rotation curves $\rightarrow$ the mass increases linearly with the distance from the center, in contrast to the distribution of luminous matter
Galaxies and clusters as surrounded by a DM halo that is spherically distributed.



Credit: Australian National University

https://phys.org/news/2018-03-galactic-bulge-emissions-due-dark.html

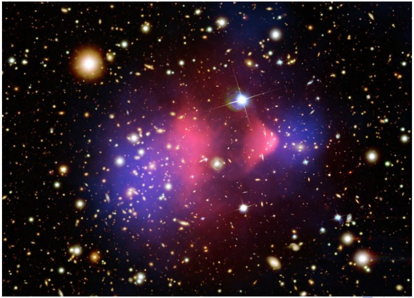
Evidences for Dark Matter in the Milky Way



F. Iocco, M. Pato, G. Bertone, arXiv:1502.03821 [astro-ph.GA]

Evidences for Dark Matter

- At the scale of clusters, compelling evidences for DM arise from gravitational lensing techniques
- Bullet Cluster *D. Clowe, et al., astro-ph/0608407*
  Collision between two clusters of galaxies: the stars of the galaxies and the DM halos as collisionless components; electromagnetic interactions affect strongly the intergalactic gas distributions.
  "image" of the colliding clusters in visible light (Hubble telescope), and the one in X-rays (Chandra). The DM distribution (gravitational lensing methods) is found to follow the luminous one



Evidences for Dark Matter

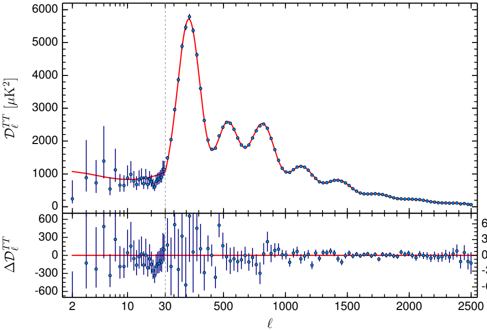
ΛCDM: Standard Model of Cosmology

Hubble parameter	H_0
Baryon density in the Universe	$\omega_b \equiv \Omega_b h^2$
Cold Dark Matter density in the Universe	$\omega_{\rm cdm} \equiv \Omega_{\rm cdm} h^2$
Optical depth at reionization	$\tau_{\rm reio}$
Amplitude of scalar power spectrum of primordial fluctuations at the pivot scale $k_* = 0.05$ Mpc^{-1}	A_s
Scalar spectral index of primordial density fluctuations	n_s
Sum of of the three active neutrino masses	$\sum m_\nu \equiv M_\nu$

$\tau_{\rm reio}$: CMB photons scattering off electrons, after reionization produced by stars, quasars

Planck results: Cosmic Microwave Background

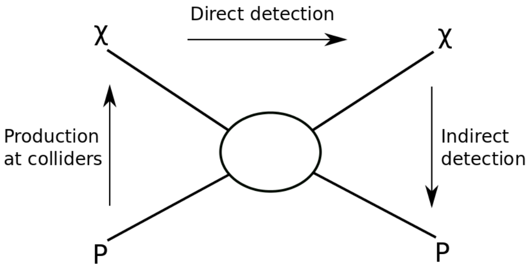
Planck 2015 data releases: measurements of temperature and polarisation anisotropies:
at $l \geq 30$: TT, TE and EE power spectra
at $l \leq 29$: low-multipole temperature (TT) and polarisation (lowP) measurements
Planck 2015 lensing: from measurements of the power spectrum of the lensing potential $C_l^{\phi\phi}$; light from the last scattering surface can be deflected by the foreground matter



Planck collaboration, arXiv:1502.01589

Detection of Dark Matter

- Direct detection: nuclear recoil
- Indirect detection: look for the products of DM self-annihilation or decay: e, γ, p, ν
- Collider experiments: missing transverse energy



T. Marrodán Undagoitia, arXiv:1509.08767 [physics.ins-det]

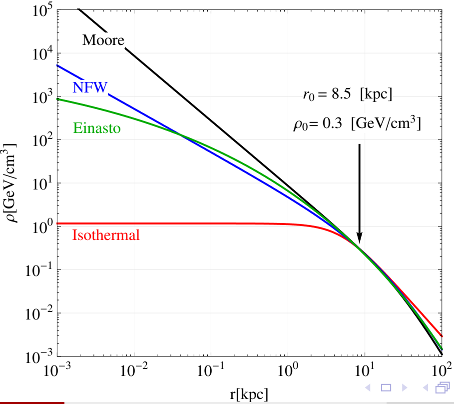
The distribution of Dark Matter

We will assume a spherical distribution for dark matter derived from N-body simulations of cold dark matter (CDM), the Navarro-Frenk-White profile

J. F. Navarro, C. S. Frenk, S. D. M. White, astro-ph/9508025

$$\rho_{\text{NFW}}(r) = \frac{\rho_s}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2} ,$$

where ρ_s is the characteristic density and r_s is the scale radius.



The distribution of Dark Matter

Several N-body simulations claims that there is a relation between the NFW parameters

A. A. Dutton, A. V. Maccio', arXiv:1402.7073; A. V. Maccio', A. A. Dutton, F. C. v. d. Bosch, arXiv:0805.1926

This relation is parametrized by the concentration parameter $c \equiv r_{200}/r_s$ and $M_{200} \equiv (4\pi/3)200\rho_{\rm crit} r_{200}^3$.

Thus, we can relate $(\rho_s, r_s) \to (c, M_{200})$ via

H. Mo, F. V. d. Bosch, S. White, Galaxy formation and evolution, Cambridge University Press, 2010

$$
\rho_s = \frac{200}{3} \frac{c^3 \rho_{\rm crit}}{\ln(1+c) - \frac{c}{1+c}} \,,
$$

$$
r_s = \frac{1}{c} \left(\frac{3M_{200}}{4\pi 200 \rho_{\rm crit}} \right)^{1/3}
$$

We will then assume, for galaxy-sized halos, the following $c - M_{200}$ relation

A. A. Dutton, A. V. Maccio', arXiv:1402.7073

$$
c(M_{200}) = 10^{0.905} \left(\frac{M_{200}}{10^{12} h^{-1} \mathrm{M}_\odot} \right)^{-0.101}
$$

$$
\Rightarrow \quad r_s \approx 28.8 \left(\frac{M_{200}}{10^{12} h^{-1} \mathrm{M}_\odot} \right)^{0.43} \mathrm{kpc} \,,
$$

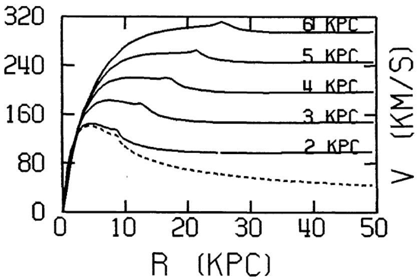
where $h = 0.671$ *Planck collaboration, arXiv:1502.01589*

The Yukawa correction

The Yukawa-like corrections to the Newtonian potential:

$$\Phi(\mathbf{x}) = -G \int \frac{\rho(\mathbf{x}')}{|\mathbf{x}-\mathbf{x}'|} \left(1 + \beta e^{-|\mathbf{x}-\mathbf{x}'|/\lambda}\right) d^3\mathbf{x}'$$

We recover Newtonian gravity when $\beta = 0$, or at scales much larger than λ
For scales much smaller than λ, gravity stronger/weaker than Newtonian (sign of β)

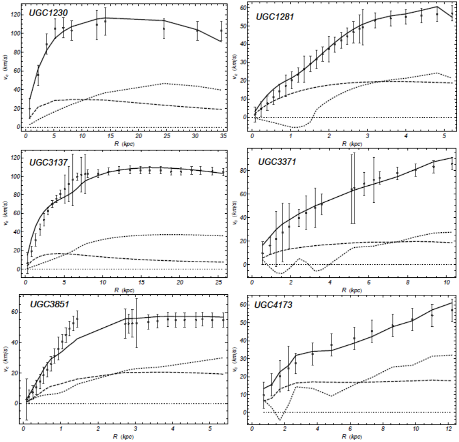


$-0.95 \leq \beta \leq -0.92$; $\lambda \simeq 25 - 50$ kpc

R. H. Sanders, Astron. Astrophys. 136 (1984) L21

The Yukawa correction

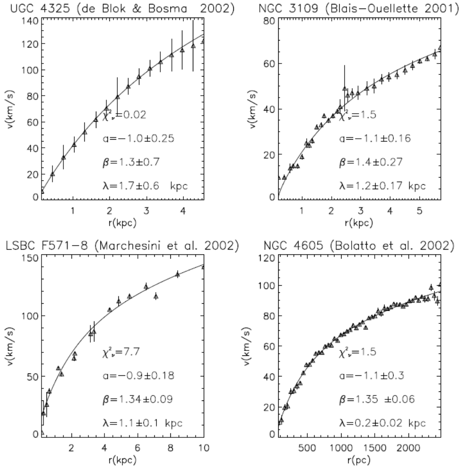
Only positive β: values from 1.83 to 11.67; λ: values from 0.349 kpc to 75.810 kpc



D. F. Mota, V. Salzano, S. Capozziello, arXiv: 1103.4215

The Yukawa correction

Including Dark Matter in the fit



F. Piazza, C. Marinini, hep-ph/0304228

Our work

We wish to constrain β and λ with galaxy rotation curves data:

- we do not exclude dark matter
- we assume that the fifth-force couples differently to dark matter and to baryons, without restriction on the coupling sign
- we include baryonic gas, disk and bulge components, according to observations, separately for each galaxy, along with a NFW dark matter halo profile
- we do not fit β, λ individually to each galaxy, but rather look for a global fit
- we adopt a much larger datasets than earlier work, 40 galaxies from the Spitzer Photometry & Accurate Rotation Curves (SPARC) catalogue

  F. Lelli, S. S. McGaugh, J. M. Schombert, arXiv: 1606.09251

The data sample

SPARC catalogue: 175 disk galaxies. This catalogue includes observations at near-infrared (3.6μm), which can trace the stellar distribution, and 21-cm line, which trace the HI distribution.

The main physical quantity is the total circular velocity at the galactic plane, V_c, which is related to the total gravitational potential, Ψ, via

$$V_c^2 = r\frac{d\Psi}{dr}$$

$$\Psi = \Phi_{\rm gas} + \Phi_{\rm disk} + \Phi_{\rm bulge} + \Phi_{\rm NFW} + \Phi_{\rm mg}$$

We have therefore the following formula

$$V_c^2(r) = V_{\rm gas}^2(r) + \Upsilon_{*\rm D} V_{\rm disk}^2(r) + \Upsilon_{*\rm B} V_{\rm bulge}^2(r) + V_{\rm NFW}^2(r) + V_{\rm mg}^2(r)\ ,$$

where $\Upsilon_{*\rm D}$ ($\Upsilon_{*\rm B}$) is the stellar mass-to-light ratio for the disk (bulge) and it is equivalent to the mass $M_{\rm D}$ of the disk ($M_{\rm B}$ of the bulge) divided by the luminosity $L_{\rm D}$ of the disk ($L_{\rm B}$ of the bulge).

The data sample

Table for the galaxy UGCA442 emphasizing each baryonic component (there is no bulge in this galaxy). $\Sigma_{\rm disk}$ is the surface density for the disk.

Radius (kpc)	$V_{\rm obs}$ (km s^{-1})	$V_{\rm gas}$ (km s^{-1})	$V_{\rm disk}$ (km s^{-1})	$\Sigma_{\rm disk}$ ($L_\odot pc^{-2}$)
0.42	14.2 ± 1.9	4.9	4.8	11.0
1.26	28.6 ± 1.8	13.1	10.8	5.8
2.11	41.0 ± 1.7	19.6	13.6	2.7
2.96	49.0 ± 1.9	22.4	13.3	1.0
3.79	54.8 ± 2.0	22.8	12.6	0.7
4.65	56.4 ± 3.1	21.4	12.3	0.4
5.48	57.8 ± 2.8	18.7	12.0	0.2
6.33	56.5 ± 0.6	16.7	10.6	0.0

Fitting the rotation curves

It is assumed that the errors of the observed rotation curve data follow a Gaussian distribution:

$$\mathcal{L}_j(p_j, \beta, \lambda) = (2\pi)^{-N/2} \left\{ \prod_{i=1}^{N} \sigma_i^{-1} \right\} \exp \left\{ -\frac{1}{2} \sum_{i=1}^{N} \left(\frac{V_{\mathrm{obs},j}(r_i) - V_c(r_i, p_j, \beta, \lambda)}{\sigma_i} \right)^2 \right\}$$

where $p_j = \{\Upsilon_{*\mathrm{D},j}, \Upsilon_{*\mathrm{B},j}, M_{200,j}\}$, N is the number of observational points for each galaxy, σ_i is the data error, $V_{\mathrm{obs},j}(r_i)$ is the observed circular velocity of the j-th galaxy at the radius r_i. We use the values of $V_{\mathrm{obs},j}(r_i)$ as provided by the SPARC catalogue.

The overall likelihood can be computed multiplying the distributions for each galaxy:

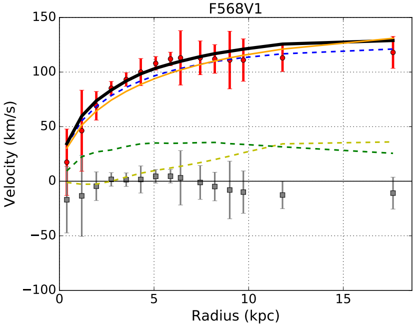
$$\mathcal{L}(\mathbf{p}, \beta, \lambda) = \prod_{j=1}^{N_g} \mathcal{L}_j(p_j, \beta, \lambda) ,$$

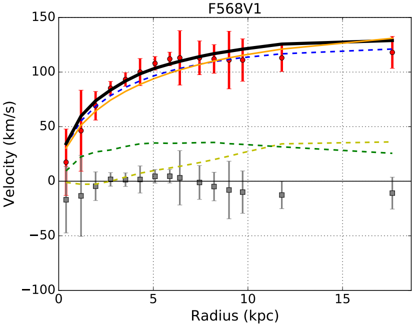
where $\mathbf{p} = \{p_1, ..., p_{N_g}\}$ and N_g is the total number of galaxies.
We assume here uniform prior for each parameter:
$0.3 < \Upsilon_{*\mathrm{D}} < 0.8$ and $0.3 < \Upsilon_{*\mathrm{B}} < 0.8$, in agreement with stellar population model analysis *S. E. Meidt, et al., arXiv: 1402.5210; J. Schombert and S. McGaugh, arXiv: 1407.6778*
$10^9 < M_{200}/\mathrm{M}_\odot < 10^{14}$, $-2 < \beta < 2$ and $\overline{\lambda}_0 < \lambda/\mathrm{kpc} < 100$

Galaxy rotation curves

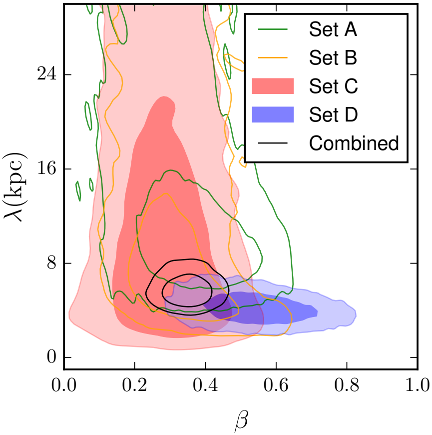
gas (dashed yellow line); disk (dashed green line);
DM with Yukawa-like corrections (dashed blue line); DM for $\beta = 0$ (orange solid line)

Red dots: observational data taken from SPARC catalogue; grey: residual of the fit





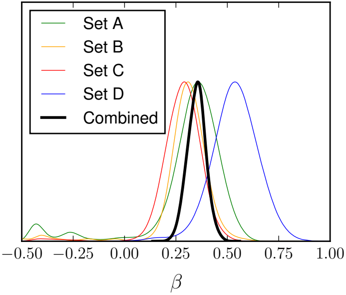
Results

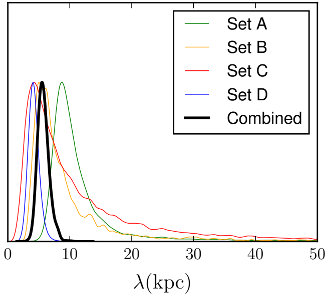


Set A
Set B
Set C
Set D
Combined
λ(kpc)
24
16
8
0
0.0
0.2
0.4
0.6
0.8
1.0
β

Results

1D posterior distributions for the parameters β and λ





Set	Best-fit values		k_Y	$\chi^2_{red,tot}$	k_{sg}	$\chi^2_{red,tot}\|_{\beta=0}$	N
	β	λ(kpc)					
A	$0.34^{+0.12}_{-0.10}$	$10.27^{+2.89}_{-3.82}$	25	0.88	23	1.11	206
B	0.30 ± 0.08	$7.42^{+2.94}_{-3.99}$	23	0.80	21	0.96	180
C	$0.28^{+0.09}_{-0.08}$	$8.18^{+5.39}_{-6.31}$	25	0.83	23	1.04	163
D	$0.54^{+0.11}_{-0.10}$	$4.15^{+0.81}_{-0.95}$	23	0.78	21	1.02	196
Combined	0.34 ± 0.04	5.61 ± 0.91	90	0.82	88	1.03	745

The maximum likelihood estimation for the $\Upsilon_{*D}, \Upsilon_{*B}$ and M_{200} parameters, and the goodness of fit χ^2_{red} for each galaxy, for the Yukawa model.

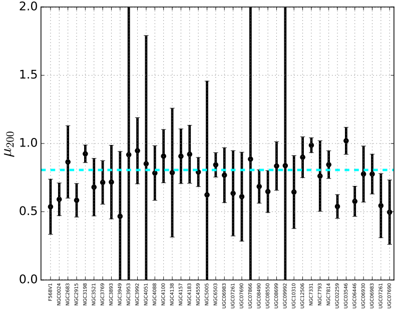
Set	Galaxy	Best-fit values			χ^2_{red}
		Υ_{*D}	Υ_{*B}	$M_{200}(10^{11} M_{\odot})$	
A	F568V1	$0.60^{+0.20}_{-0.10}$	-	$1.31^{+0.26}_{-0.38}$	0.35
A	NGC0024	$0.79^{+0.01}_{-0.01}$	-	$0.73^{+0.10}_{-0.13}$	1.68
A	NGC2683	$0.64^{+0.04}_{-0.04}$	$0.52^{+0.15}_{-0.21}$	$1.71^{+0.29}_{-0.37}$	1.37
A	NGC2915	$0.32^{+0.01}_{-0.02}$	-	$0.34^{+0.05}_{-0.06}$	0.98
A	NGC3198	$0.40^{+0.04}_{-0.05}$	-	$1.94^{+0.13}_{-0.12}$	1.31
A	NGC3521	$0.49^{+0.01}_{-0.02}$	-	$5.40^{+1.00}_{-1.26}$	0.37
A	NGC3769	$0.33^{+0.02}_{-0.03}$	-	$0.86^{+0.11}_{-0.14}$	0.75
A	NGC3893	$0.46^{+0.04}_{-0.04}$	-	$3.89^{+1.16}_{-1.00}$	1.26
A	NGC3949	$0.36^{+0.03}_{-0.05}$	-	$3.99^{+2.09}_{-2.78}$	0.45
A	NGC3953	$0.62^{+0.07}_{-0.07}$	-	$1.53^{+0.74}_{-1.27}$	0.73

The maximum likelihood estimation for the $\Upsilon_{*D}, \Upsilon_{*B}$ and M_{200} parameters, and the goodness of fit $\chi^2_{red}|_{\beta=0}$ for each galaxy in the case of $\beta = 0$.

Set	Galaxy	Best-fit values			$\chi^2_{red}\|_{\beta=0}$
		Υ_{*D}	Υ_{*B}	$M_{200}(10^{11} M_\odot)$	
A	F568V1	$0.63^{+0.16}_{-0.10}$	-	$2.44^{+0.45}_{-0.58}$	0.63
A	NGC0024	$0.79^{+0.01}_{-0.01}$	-	$1.24^{+0.10}_{-0.13}$	2.31
A	NGC2683	$0.68^{+0.05}_{-0.04}$	$0.52^{+0.11}_{-0.21}$	$1.97^{+0.33}_{-0.43}$	1.20
A	NGC2915	$0.32^{+0.02}_{-0.02}$	-	$0.59^{+0.05}_{-0.06}$	1.17
A	NGC3198	$0.52^{+0.01}_{-0.01}$	-	$2.09^{+0.04}_{-0.05}$	1.44
A	NGC3521	$0.51^{+0.01}_{-0.01}$	-	$7.95^{+1.62}_{-1.51}$	0.29
A	NGC3769	$0.36^{+0.03}_{-0.06}$	-	$1.20^{+0.14}_{-0.17}$	0.68
A	NGC3893	$0.49^{+0.04}_{-0.03}$	-	$5.42^{+1.24}_{-1.18}$	1.27
A	NGC3949	$0.37^{+0.03}_{-0.06}$	-	$8.55^{+4.75}_{-6.35}$	0.29
A	NGC3953	$0.65^{+0.07}_{-0.07}$	-	$1.66^{+3.36}_{-1.41}$	0.54

We define the quantities $\mu_{200} \equiv \frac{M_{200}}{M_{200(\beta=0)}}$, $\gamma_{*D} \equiv \frac{\Upsilon_{*D}}{\Upsilon_{*D}(\beta=0)}$ and $\gamma_{*B} \equiv \frac{\Upsilon_{*B}}{\Upsilon_{*B}(\beta=0)}$

$\Rightarrow \langle \mu_{200} \rangle = 0.80 \pm 0.02$: 20% of reduction of dark matter due the fifth force
$\Rightarrow \langle \gamma_{*D} \rangle = 0.96 \pm 0.01$ and $\langle \gamma_{*B} \rangle = 0.96 \pm 0.04$



Bayes ratio

The evidence is given by

$$E = \int \mathcal{L}(\mathbf{p}, \beta, \lambda) \mathcal{P}(\mathbf{p}, \beta, \lambda) d\beta d\lambda d\mathbf{p} \ ,$$

where $\mathcal{P}$ is the prior distribution.
The Bayes ratio between the model 1 ($\beta \neq 0$) and model 2 ($\beta = 0$):

$$B_{12} = \frac{\int \mathcal{L}_1(\mathbf{p}, \beta, \lambda) \mathcal{P}_1(\mathbf{p}, \beta, \lambda) d\beta d\lambda d\mathbf{p}}{\int \mathcal{L}_2(\mathbf{p}) \mathcal{P}_2(\mathbf{p}) d\mathbf{p}}$$

Approximating the likelihood and the priors as Gaussian, and considering that in the ratio $\det \mathbf{P}_1 / \det \mathbf{P}_2$ all terms except the β, λ simplify

$$\Rightarrow \quad B_{12} = e^{-\frac{1}{2}(\chi^2_{\mathrm{min},1} - \chi^2_{\mathrm{min},2})} \frac{1}{p_\beta p_\lambda} \sqrt{\frac{\det \mathbf{F}_2}{\det \mathbf{F}_1}} \ ,$$

p_β, p_λ are the square root of the variance of the uniform distribution assumed for β, λ

Once we have B_{12}, then the probability $\mathcal{P}_{12}$ that the right model is 1 rather than 2 is

$$\mathcal{P}_{12} = \frac{B_{12}}{1 + B_{12}}$$

Bayesian Information Criterion

We also computed the BIC, which gives a very simple approximation to the evidence:
G. Schwarz, The annals of statistics 6 (1978) 461

$$\text{BIC} = -2 \ln \mathcal{L}_{\text{max}} + 2k \ln N \ ,$$

k is the number of free parameters and N is the number of data points. In our case, the likelihoods are Gaussian and hence we have again $-2 \ln \mathcal{L}_{\text{max}} = \chi^2_{\text{min}}$.

The relative BIC (ΔBIC) is defined as

$$\Delta\text{BIC} \equiv \text{BIC}|_{\beta=0} - \text{BIC}|_{\beta\neq 0}$$

The BIC gives a rough approximation to the Gaussian evidence.

Results

Set	Best-fit values		ΔBIC	$2\log B_{12}$	CL
	β	λ(kpc)			σ
A	$0.34^{+0.12}_{-0.10}$	$10.27^{+2.89}_{-3.82}$	32.18	31.84	5.29
B	0.30 ± 0.08	$7.42^{+2.94}_{-3.99}$	17.12	23.21	4.44
C	$0.28^{+0.09}_{-0.08}$	$8.18^{+5.39}_{-6.31}$	20.52	12.41	3.09
D	$0.54^{+0.11}_{-0.10}$	$4.15^{+0.81}_{-0.95}$	32.92	20.38	4.12
Combined	0.34 ± 0.04	5.61 ± 0.91	91.61	87.83	8.26

Conclusions

- In this work we have used observational data from the SPARC catalogue to constrain the properties of modified gravity models in the presence of dark matter
- We considered four different sets of 10 galaxies each and we found the region in the parameter space for λ and β that are allowed by the data
  $\Rightarrow$ the standard $\beta = 0$ model gives a much worse fit than a value different from zero, with preference for a positive value: attractive Yukawa force
- We have also calculated for each galaxies the values of the parameters Υ_{*D}, Υ_{*B} and M_{200}
  $\Rightarrow$ attractive fifth force reduces the need for dark matter by 20% in mass, on average
- We have then combined all the data sets together to find the allowed region in the parameter space
  $\Rightarrow \beta = 0.34 \pm 0.04$ and $\lambda = 5.61 \pm 0.91$ kpc

Conclusions

- Bayesian evidence ratio
  $\Rightarrow$ strongly favors the Yukawa model, to more than 8σ for the combined dataset, with respect to the $\beta = 0$ case
- We cannot conclude that standard gravity is ruled out. BUT, a model of the baryon components (gas, disk and bulge), plus a NFW profile for the dark matter, plus an attractive Yukawa term, fits much better the rotation curves of our sample
- Whether this result holds assuming different modelling for the baryon or the dark matter component, remains to be seen

Thank you!

BACKUP SLIDES

A species-dependent coupling

If the fifth force is felt differently by baryons (b) and DM (dm), one needs to introduce two coupling constants, α_b and α_{dm}. Let us assume the fifth force is carried by a scalar field with canonical kinetic term and conformal coupling.

$$T^{\mu}_{(b)\nu;\mu} = -\alpha_b T_{(b)} \phi_{;\nu}$$
$$T^{\mu}_{(dm)\nu;\mu} = -\alpha_{dm} T_{(dm)} \phi_{;\nu}$$

where $T^{\mu}_{(x)\nu}$ is the energy-momentum tensor of component x and $T_{(x)}$ its trace.
The scalar field obeys a Klein-Gordon equation

$$T^{\mu}_{(\phi)\nu;\mu} = (\alpha_b T_{(b)} + \alpha_{dm} T_{(dm)})\phi_{;\nu}$$

The total potential between two particles of species x, y acquires a Yukawa term:

$$\beta = \alpha_x \alpha_y$$

and universal range $\lambda = m^{-1}$, where m is the scalar field mass.
In a galaxy, the baryonic component follows rotation curves, determined by the sum of the potentials produced by the baryons themselves and by the DM component.
Baryons feel the sum of the baryon-baryon force ($\propto \alpha_b^2$) and the baryon-DM one ($\propto \alpha_b \alpha_{dm}$).
Local gravity experiments show that $|\alpha_b|$ has to be very small, typically less than 10^{-2}.
β is of order unity $\to \alpha_{dm}$ must be very large, $\mathcal{O}(100)$.