Bigravity and Dark Matter in Galaxies

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Cargese, Aprile 2009

Summary

Z. Berezhiani, F. Nesti, L. Pilo and N.R. [arXiv:0902.0144]
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- Mirror Matter: A possible dark matter candidate (dissipative and collisional)
- Rotational curves of galaxies and mirror dark matter: Modified Newtonian potential
- How to obtain a modified potential between visible and dark matter

The Dark Sector

- Observations (CMB,LSS, astrophysical dynamics,...) $\Rightarrow$ Visible(b) is just a little component of the Universe
- The biggest part of the Universe is composed by Dark Energy (Λ) and by Dark Matter (dm) (Radiation (R) is negligible) ($\Omega_i = \rho_i/\rho_c$):

Total Amount

$$\Omega_{\rm tot} = \Omega_\Lambda + \Omega_M + \Omega_R \simeq 1 \qquad \Omega_M = \Omega_b + \Omega_{dm}$$
$$\Omega_R \sim 10^{-5} \qquad \Omega_\Lambda = 0.76$$
$$\Omega_{dm} = 0.20 \qquad \Omega_b = 0.04$$

- Candidatates: axions ($m \sim 10^{-5}$ eV), neutralinos ($m \sim$ TeV), wimpzillas (10^{14} GeV),...
- Visible and Dark Matter have not the same origin: $\Rightarrow$ Why $\Omega_b \sim \Omega_{dm}$? $\Omega_\Lambda \sim \Omega_M$?

Mirror Matter as DM candidate

- It exists a hidden duplicate of our sector of particles and interactions (M), similar to the visible ordinary matter (O)
- Sector O: weak interaction $V - A$ (chirality L, parity non-conservation).
  Sector M $V + A$ (chirality R) $\Rightarrow$ L-R symmetry of the nature is restored.

Symmetry of the $G \times G'$, $(G = SM, GUT, \ldots)$

$$\begin{aligned} \mathcal{L}_O &\leftrightarrow G \\ \mathcal{L}_M &\leftrightarrow G' \\ \mathcal{L}_{\text{tot}} &= \mathcal{L}_O + \mathcal{L}_M + \mathcal{L}_{Int} \leftrightarrow G \times G' \end{aligned}$$

E.g.: Standard Models: $G_{SM} = SU(3) \times SU(2)_L \times U(1)$

$G_{SM} \rightarrow$ 3 families of quarks and leptons and 1 Higgs
$G'_{SM} \rightarrow$ 3 families of mirror quarks and leptons and 1 mirror Higgs
Particles O are singlets of G'_{SM} and vice versa.

Symmetries and Possible Interactions

Chirality Symmetry

- direct (D): $L \to L'$, $R \to R'$, $V \to V'$, $\phi \to \phi'$
- Parity symmetry (MP) (exact symmetry): $L \to R'$, $R \to L'$, $V \to V'^{\dagger}$, $\phi \to \tilde{\phi}'$

Symmetries of VEV (Higgs) $v = \langle \phi \rangle$

- Symmetric Mirror (S): $v = v'$
- Asymmetric Mirror (A): $v \neq v'$

- $T' < T$ (post-inflation) $\Rightarrow n'_b \geq n_b$, in particular $n'_b \simeq 5 n_b \Rightarrow$ mirror matter $=$ dark matter.
- Possible interactions: gravitation ($G \times G'$), photon mixing, neutrinos, Higgs, common gauge bosons.
- In particular: $G \times G' \times H \Rightarrow$ Neutral meson oscillations ($\pi \to \pi'$, $\eta \to \eta'$, $\rho \to \rho'$, ...).

Galaxy Dynamics: CDM

- Visible Matter Density in the galaxy (e.g. disk galaxy): $\sigma(r) = \sigma_0 e^{-r/r_0}$ along the disk (Freeman,1970) ($r_0 \sim 3$ kpc, bulge size)
- Rotational velocity of objects (stars, gases, ...) at r form the center should be $v(r) \propto 1/\sqrt{r}$, Instead it tends to the flatness around the maximal value: Dark Matter in spherical Halo

Models: IT, NFW, M

$$\rho_{dm}(r) = \frac{\rho_0}{(r/r_s)^\gamma [1+(r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$

α	β	γ	model
2	3	0	IT
1	3	1	NFW
1.5	3	1.5	M

Gravity between two sectors is Newtonian

$$V(r) = G_N \frac{M_b + M_{dm}}{r}$$

NFW Issues

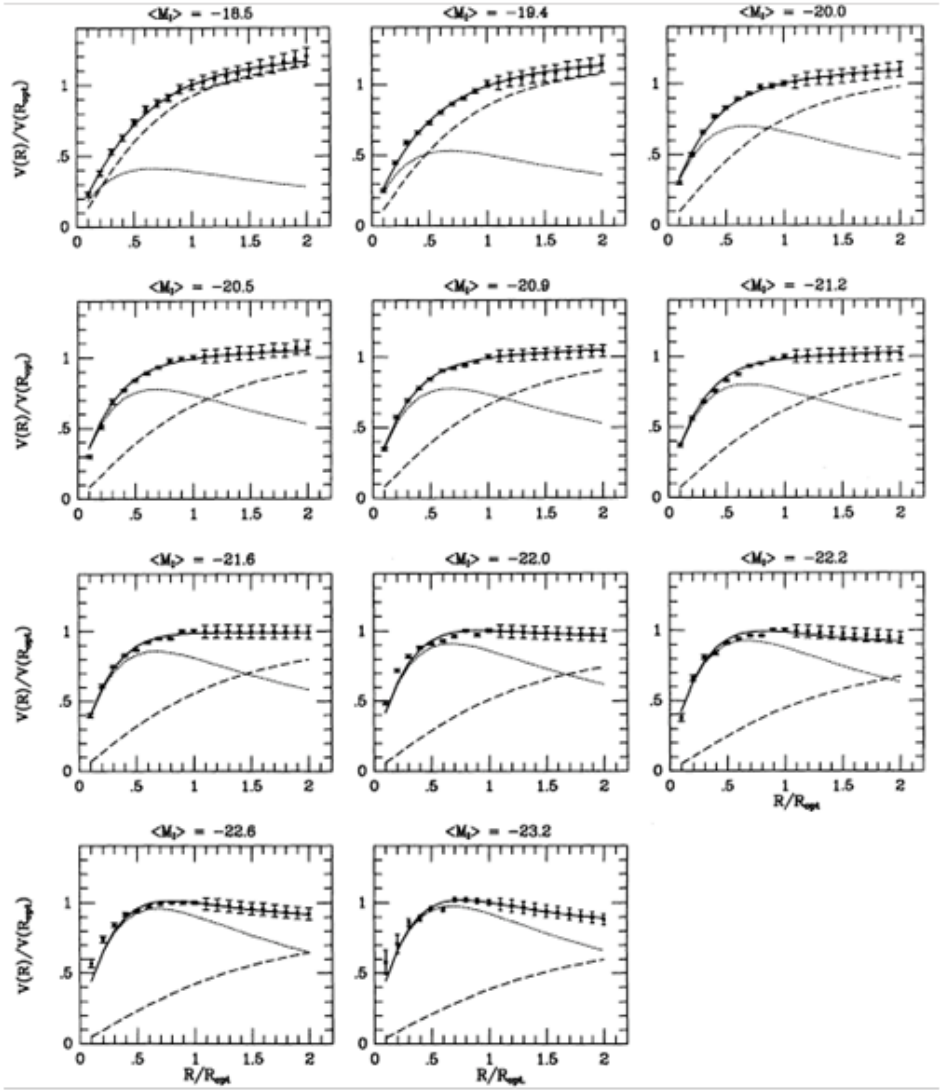
Cusp Problem

NFW, M,... have the cusp problem: divergence for $r \longrightarrow 0$
$\rho(r) \sim \frac{1}{r}, \frac{1}{r^{1.5}}$

Dwarf Galaxy Problem: e.g. DD47 (Salucci et al., 2007)

Rotational curves in dwarf galaxy grows less than those predicted by NWF mass distribution in galaxy

The Universal Rotational Curves, (Salucci, since 1988)



Galaxy Dynamics with Mirror Matter

- Mirror matter is (dissipative and collisional): visible and dark matter in the galaxy have the same distribution in galaxies
- If gravity is universal between the two sector we can not reproduce rotational curves
- Solution: gravity between two sectors is not universal,mixing mechanism between gravitons belonging to both sectors O and M.

Static modified potential, $r_m = 10 \div 20$ kpc

$$V(r) = G_N \frac{M_1 + M_2}{2r} + G_N \frac{M_1 - M_2}{2r} e^{-\frac{r}{r_m}}$$

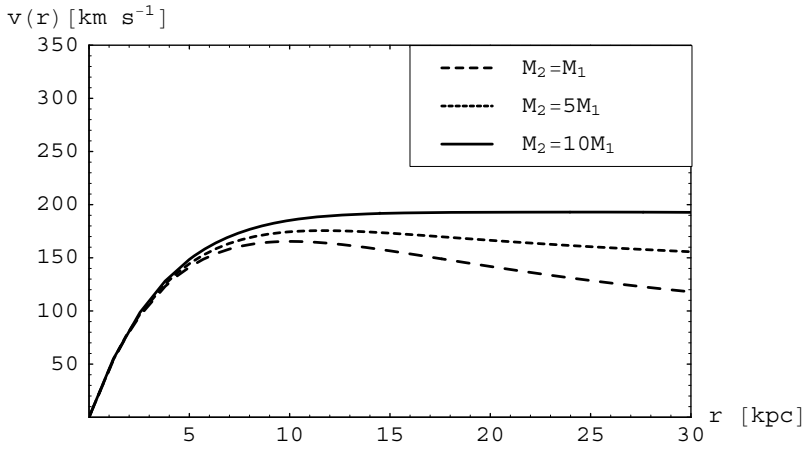
$$V(r \ll r_m) = G\frac{M_1}{r} \quad V(r \gg r_m) = G\frac{M_1+M_2}{2r}$$

Weak field limit (Bigravity)

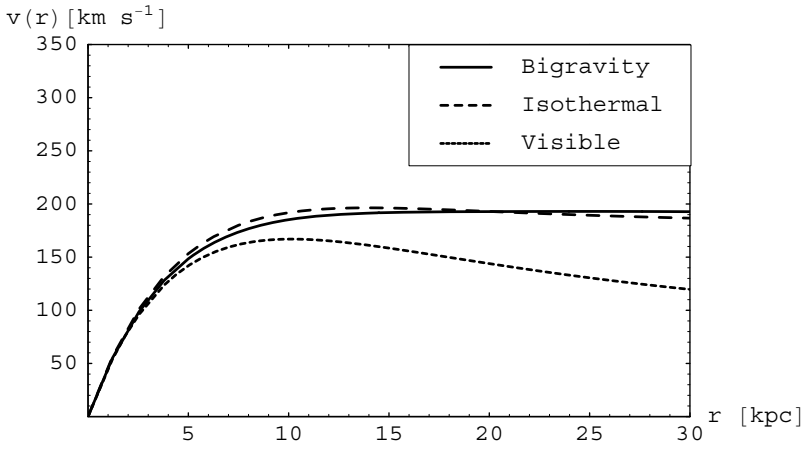
Each sector has its own gravity: $h_{1\mu\nu}$, $h_{2\mu\nu}$.

$$\mathcal{L}_{\text{Grav}} = \mathcal{L}(h_1) + \mathcal{L}(h_2) + \mathcal{L}_{\text{mass}}(h_1 - h_2)$$

Rotational Curves and Mirror Matter



Rotational Curves varying M_2/M_1 with $r_m = 20$ kpc



Mirror rotational curve with modified potential and isothermal with ordinary CDM

Mirror Dark Matter

$$\sigma_1(r) = \sigma_1(0)e^{-r/r_1}$$

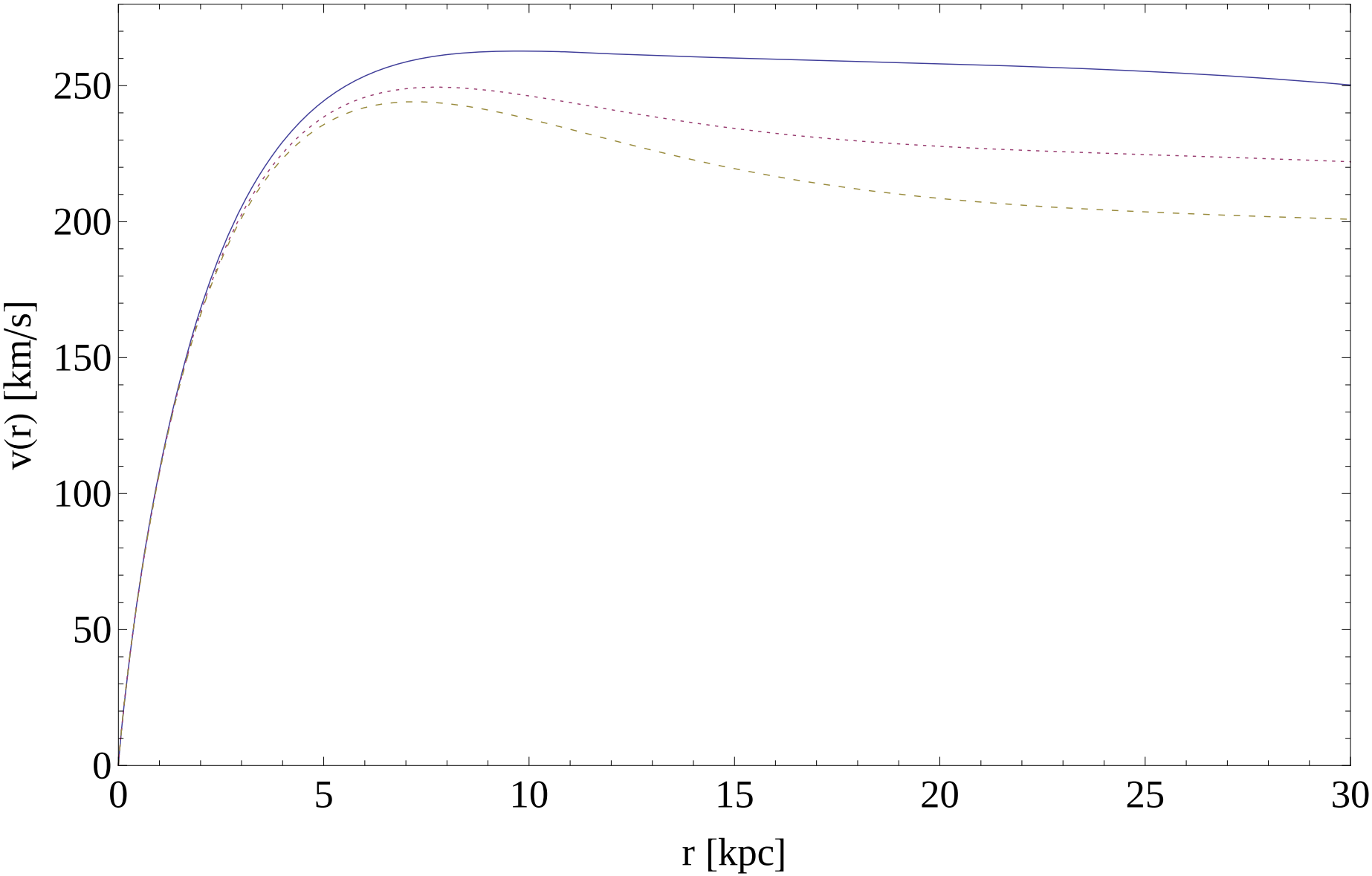
$$\sigma_2(r) = \sigma_2(0)e^{-r/r_2}$$

Newtonian Model

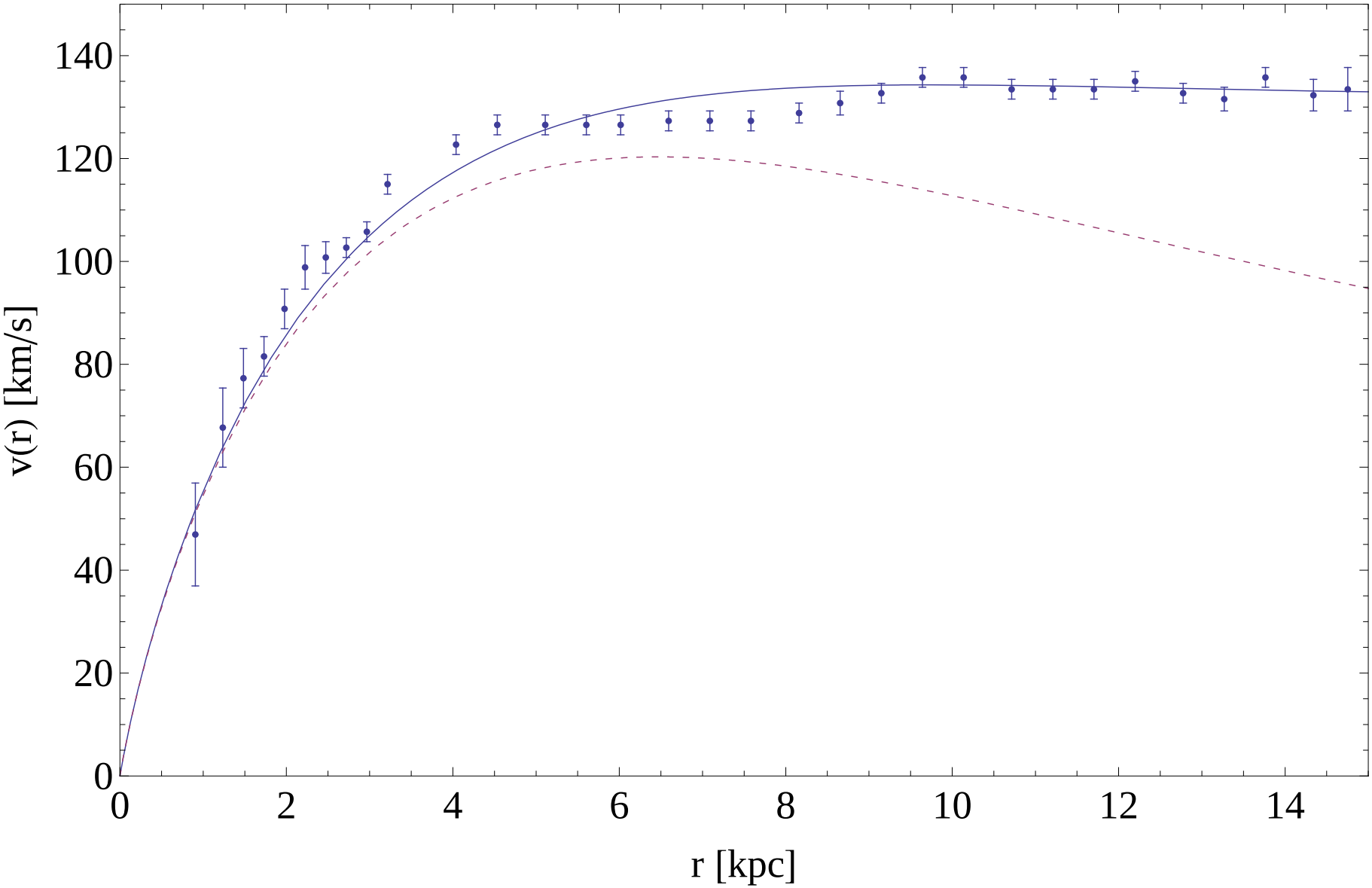
$$\rho_b(r) = \rho_b(0)e^{-r/r_v}$$

$$\rho_{dm}(r) = \rho_{dm}(0)\frac{1}{(1+(r/a)^2)}$$

Varying r_m=10,15,20 kpc



NGC 2403: $M_2/M_1 = 10$, $r_m = 10$ KPC



vDVZ Discontinuity Problem

- Weak field model in bigravity $\Rightarrow$ massive graviton $\propto h_{\mu\nu}h^{\mu\nu} - h^2$ (Pauli-Fierz, ghost-free) but with van Dam-Veltmann-Zhakarov Discontinuity (vDVZ).
- It exist a deviation of $4/3$ with respect the GR prediction for the light bending (precision tests in the Solar System 10^{-4}).
- Bigravity $\tan\theta = M_{2Pl}/M_{1Pl}$

$$\begin{pmatrix} h_0 \\ h_m \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix}$$

Bigravity: vDVZ modulated by θ

$$V(r) = G\frac{M_1 + M_2}{2r} + \frac{4}{3}G\frac{M_1\tan^2\theta - M_2}{2r}e^{-r/r_m}$$

Maximal Mixing $\theta = \pi/4$

$$V(r) = G\frac{M_1 + M_2}{2r} + \frac{4}{3}G\frac{M_1 - M_2}{2r}e^{-r/r_m}$$

Gravity Without discontinuty

- Mass term, with $m_i \neq m_j$ (Rubakov, 2004)

$$\mathcal{L}_{\rm mass} = \frac{M_{Pl}^2}{2}\left(m_0^2 h_{00}^2 + 2m_1^2 h_{0i}^2 - m_2^2 h_{ij}^2 + m_3^2 h_{ii}^2 - 2m_4^2 h_{00} h_{ii}\right),$$

  breaks the Lorentz Invariance by preserving the spatial rotations $SO(3)$.
- Yukawa solution $((1/r)e^{-r/r_m})$
- The mass term emerges in the weak field limit in multigravity models.

Multigravity

$$\sum_{i=1}^{N} \frac{M_{{\rm Pl}i}^2}{2} \int d^4x\sqrt{-g_i}(R[g_i] + \mathcal{L}[\Phi_i]) + \mu^4 \int d^4x \mathcal{V}(g_1, \ldots, g_N)$$

weak field limit, quadratic order, $\Rightarrow g_{i\mu\nu} \simeq \eta_{i\mu\nu} + h_{i\mu\nu}$. Interaction $\Rightarrow$ Rubakov mass term. $h_{\mu\nu} \Rightarrow$ vectors, $m_a \Rightarrow$ matrices)

Parametrization

Fields

$$h_{00} = \psi$$
$$h_{0i} = u_i + \partial_i v$$
$$h_{ij} = \chi_{ij} + 2\partial_{(i} s_{j)} + \partial_i \partial_j \sigma + \delta_{ij} \tau$$

- Scalar Sector $\Rightarrow$ static potential.
- General Solution Static Potential

$$\Phi = \frac{T_\alpha}{2\Delta - m_\alpha^2} + \frac{T_\beta}{2\Delta - m_\beta^2},$$

- Suitable choices of parameters $\Rightarrow$ A single Yukawa. $\xi_1 = m_2/m_3$, $\xi_2 = m_2/m_4$. In particular $\xi_1^2 = (1 + \xi_2^2)/3\xi_2^2$ $\Rightarrow$:

$$\Phi = \frac{1}{M_{PL}^2} \frac{T_{00} + T_{ii}}{2\Delta - 3m_4^2}.$$

Bigravity $N = 2$

Background and fluctuations (Hypotheses $M_{Pl1} = M_{Pl2}$)

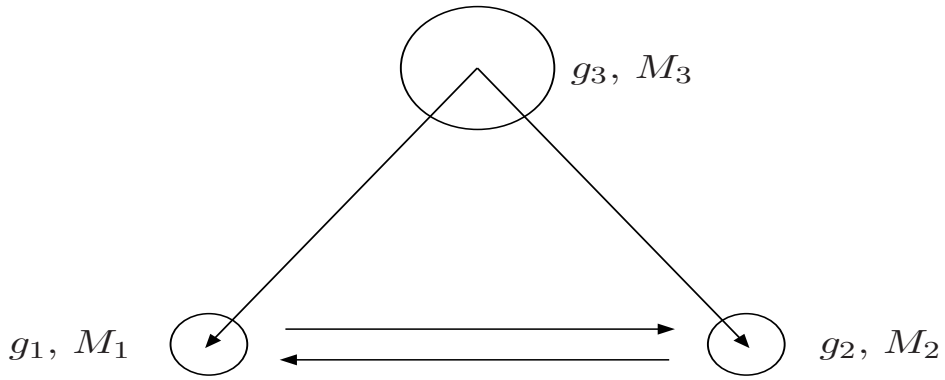
$$g_{1\mu\nu} = \eta_{\mu\nu} + h_{1\mu\nu} \quad \eta_{\mu\nu} = diag(1, -1, -1, -1)$$
$$g_{2\mu\nu} = \bar{\eta}_{\mu\nu} + h_{2\mu\nu} \quad \bar{\eta}_{\mu\nu} = \omega^2 diag(c^2, -1, -1, -1)$$

Interaction Term

$$\mu^4 \int d^4x \sqrt[4]{g_1 g_2}\mathcal{V}(g_1, g_2)$$

- $X^\mu_\nu = g_1^{\mu\rho} g_{2\rho\nu}$, Equation of Motion for $\bar{X} \Rightarrow V(\bar{X}) = V'(\bar{X} = 0)) \Rightarrow \mathcal{L}_m \sim \chi V''(\bar{X})\chi$ (where $X \sim \bar{X} + \chi$).
- Gauge invariance under the residual diffeomorphism group (massless graviton) $h_i^{\mu\nu} \rightarrow h_i'^{\mu\nu} = h_i^{\mu\nu} - \partial^\mu \xi_i^\nu - \partial^\nu \xi_i^\mu \Rightarrow m_1 = 0$ $(2 \times 2) \Rightarrow$ Static Potential is not Yukawa (BCNP,2007)

Effective Bigravity $N = 3$



Hypoteses ($M_{Pl3} \gg M_{Pl1} = M_{Pl2}$): effective bigravity

$$g_{1,2\mu\nu} = \eta_{\mu\nu} + h_{1,2\mu\nu}; \quad g_{3\mu\nu} = \bar{\eta}_{\mu\nu} + h_{3\nu\mu}; \quad \int d^4x \sqrt[6]{g_1 g_2 g_3}\mathcal{V}(g_1, g_2, g_3)$$

Defining $X^{\mu}_{12\nu} = g_1^{\mu\rho} g_{2\rho\nu}$ and $X^{\mu}_{13\nu} = g_1^{\mu\rho} g_{3\rho\nu}$ and related perturbations, we obtain $\mathcal{L}_m$ (second order); m_1 (3×3) There is a vanishing eigenvalue
$\Rightarrow$ It exist a Yukawa term in the static potential

Acceleration induced by the Mirror Matter

$$a(r) = G\left[\frac{\mathcal{M}_1 + \mathcal{M}_2}{2r^2} + \frac{\mathcal{M}_1 - \mathcal{M}_2}{2r^2}\left(1 + \frac{r}{r_m}\right)e^{-\frac{r}{r_m}}\right]$$

Conclusions

- Dark matter could be collisional and dissipative (Mirror Dark Matter)
- Dark matter is distributed in galaxy like visible matter, i.e. exponential along the disk.
- This scenario is in agreement with experimental observations if we consider a modification of gravity at galactic scale ($10 \div 20$kpc).
- The required modification of gravity can be obtained in multigravity theory with Lorentz breaking.