Mass Discrepancy in Rotating Galaxies: Visible-Invisible Conspiracy, MOND, and all that

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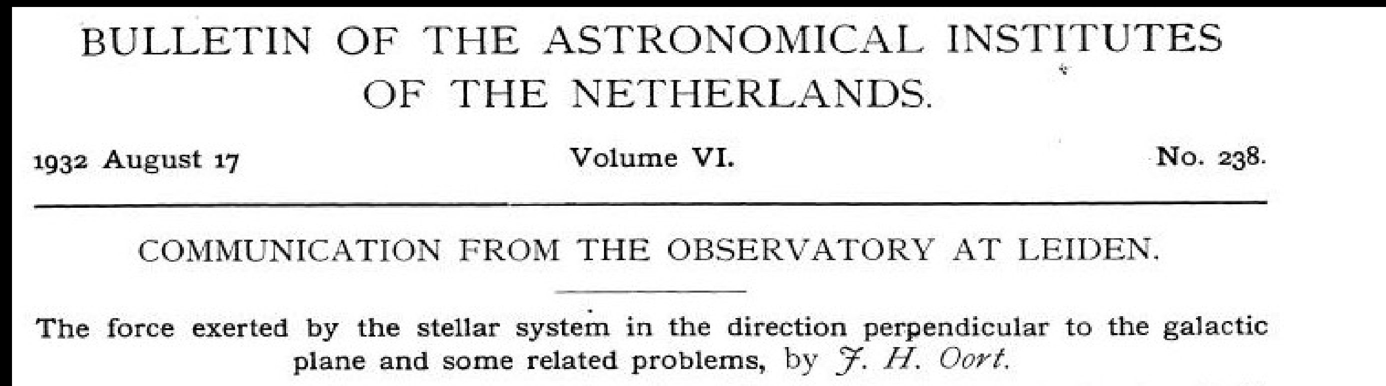
Oort (1932) …



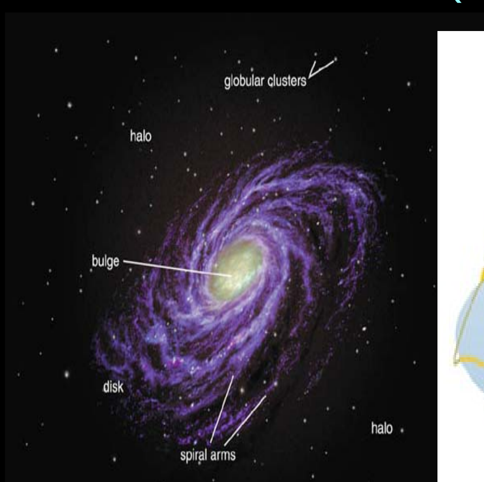
BULLETIN OF THE ASTRONOMICAL INSTITUTES
OF THE NETHERLANDS.

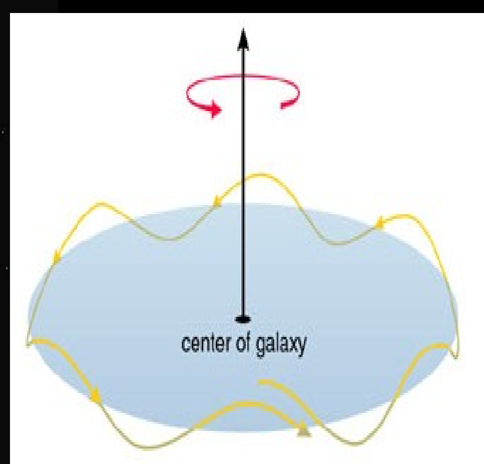
1932 August 17 Volume VI. No. 238.

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN.

The force exerted by the stellar system in the direction perpendicular to the galactic plane and some related problems, by *J. H. Oort.*

Jan Hendrik Oort (1900-1992)





To explain the kinematics of vertical motion of the disk stars, Oort needed "invisible mass" of density ~ 2 GeV / cc at the solar neighborhood.

Modern value ~ 0.3 Gev / cc

But Oort was probably referring to objects too faint to "see".

“Discovery” of Dark Matter

Fritz Zwicky (1933)

Fritz Zwicky (1898 - 1974)

F. Zwicky, "Die Rotverschiebung von extragalaktischen Nebeln", Helvetica Physica Acta 6: 110–127 (1933)

F. Zwicky, "On the Masses of Nebulae and of Clusters of Nebulae", Astrophysical Journal 86: 217 (1937)

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 86 OCTOBER 1937 NUMBER 3

ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal rotations alone no determination of the masses of nebulae is possible (sec. ii). The observed internal motions of nebulae can be understood on the basis of a simple mechanical model, some properties of which are discussed. The essential feature is a central core whose internal *viscosity* due to the gravitational interactions of its component masses is so high as to cause it to rotate like a solid body.

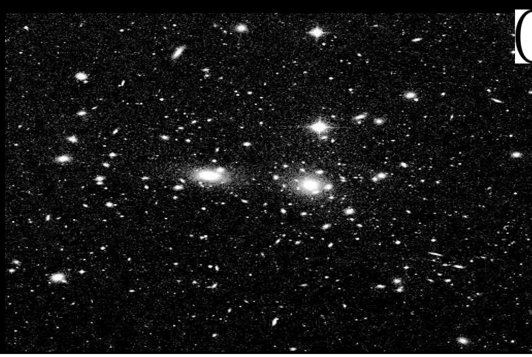
In sections iii, iv, and v three new methods for the determination of nebular masses are discussed, each of which makes use of a different fundamental principle of physics.

Method iii is based on the *virial theorem* of classical mechanics. The application of this theorem to the Coma cluster leads to a minimum value $\overline{M} = 4.5 \times 10^{10} M_\odot$ for the average mass of its member nebulae.

Method iv calls for the observation among nebulae of certain *gravitational lens* effects.

Section v gives a generalization of the principles of ordinary *statistical mechanics* to the whole system of nebulae, which suggests a new and powerful method which ultimately should enable us to determine the masses of all types of nebulae. This method is very flexible and is capable of many modes of application. It is proposed, in particular, to investigate the distribution of nebulae in individual great clusters.

As a first step toward the realization of the proposed program, the Coma cluster of nebulae was photographed with the new 18-inch Schmidt telescope on Mount Palomar.



$\text{Coma Cluster}: \sim 1000\ \text{Galaxies}$

$\mathrm{D} \sim 100\ \mathrm{Mpc}$

$\mathrm{M} \sim 10^{14} M_\odot$

Virial Theorem $\Rightarrow \langle v^2 \rangle \sim \frac{1}{2} \frac{GM}{\langle r \rangle}$

Measured $\langle v^2 \rangle^{\frac{1}{2}} \sim 1000\ \mathrm{km\,s^{-1}} \Rightarrow M \sim 400 M_{\text{visible}}$!!

— Radial velocities of galaxies in the Coma cluster are too large for the galaxies to be bound in the cluster with the known "visible" mass of the cluster.

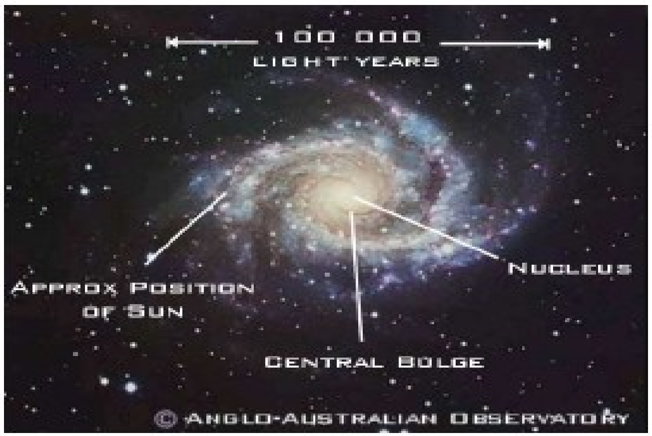
Note: Zwicky used (wrong!) $H_0 = 558\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ (as measured by Hubble!). Correct result

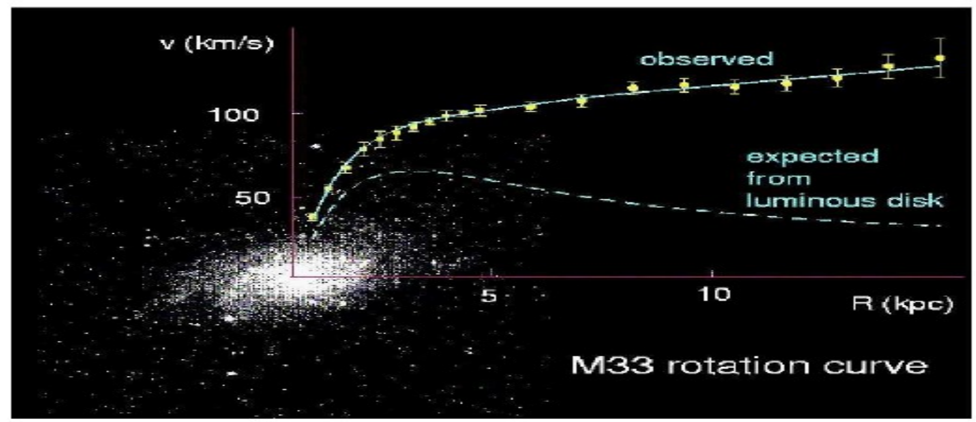
$M_{\text{Coma cluster}} \sim 50 M_{\text{visible}}$

Rotation Curve of Spiral Galaxies and Dark Matter

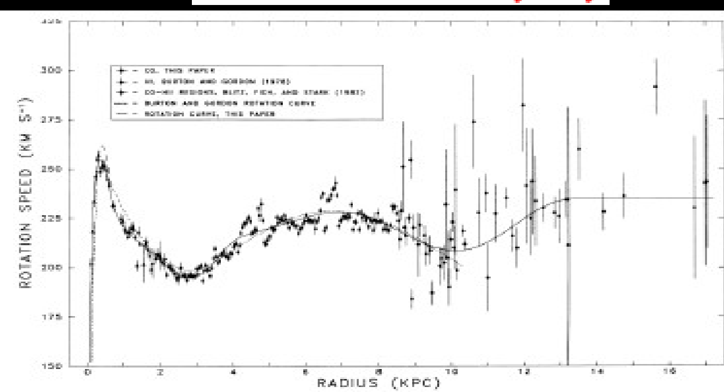
Galactic scale Dark Matter seriously studied only begining early 1970s: Vera Rubin: Rotation Curve of Spiral galaxies.

Circular Rotation Speed: $v_c^2(R) = R\frac{\partial\phi}{\partial R} = G\frac{M(R)}{R}$

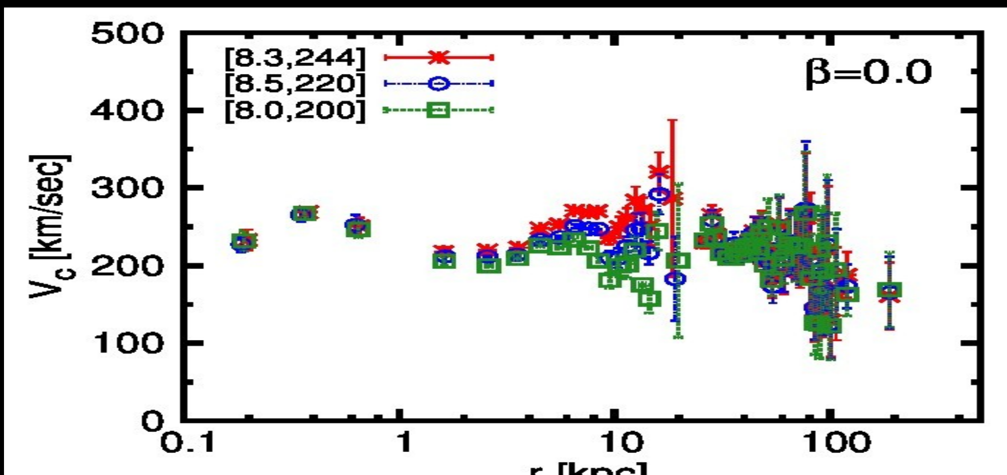




Rotation Curve of Milky Way



Clemens (1985)



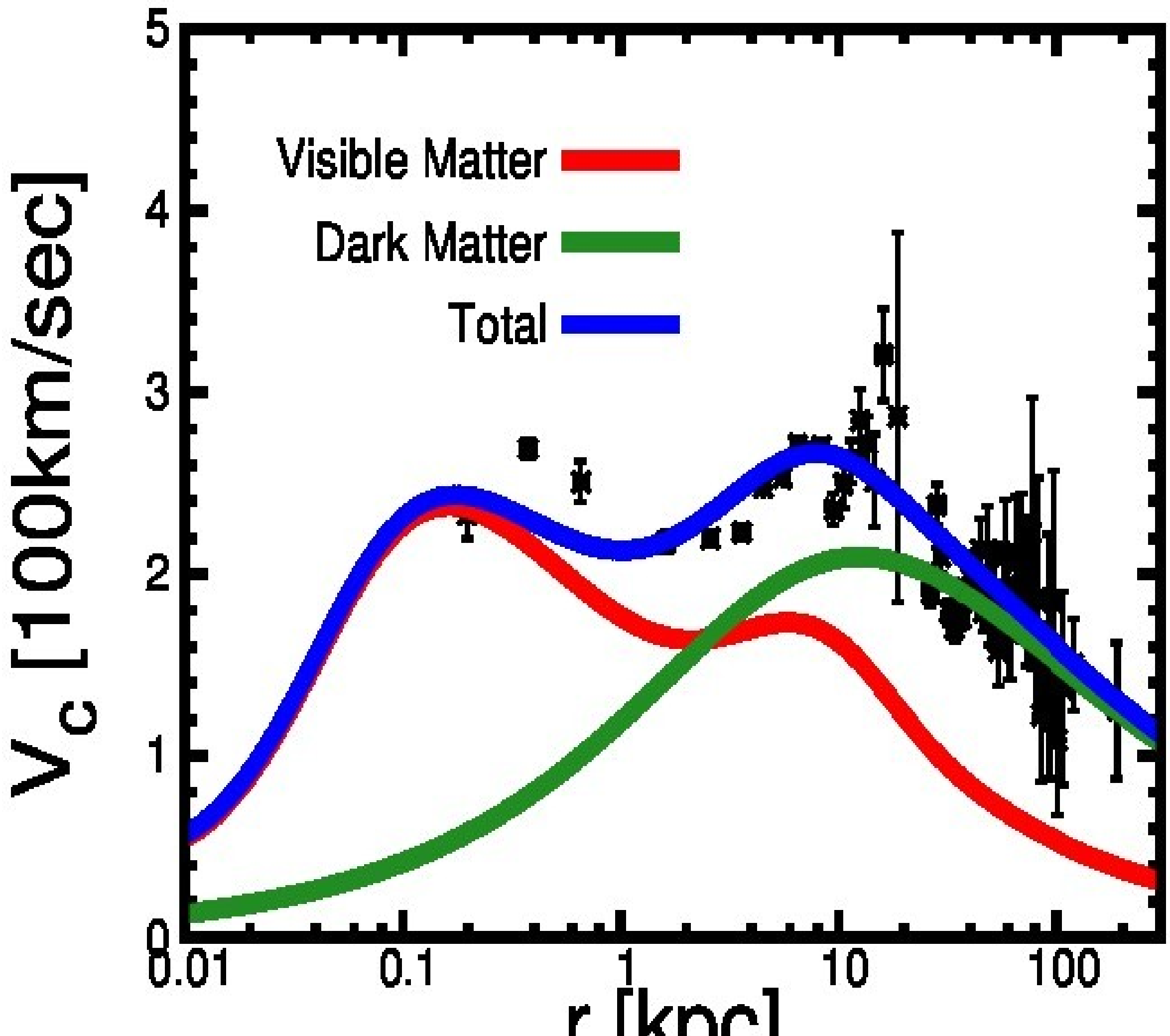
PB, S.Chaudhury, S. Kundu, ApJ (2014)

Dark Matter in the Galaxy

Mass Models : Dark Matter Halo

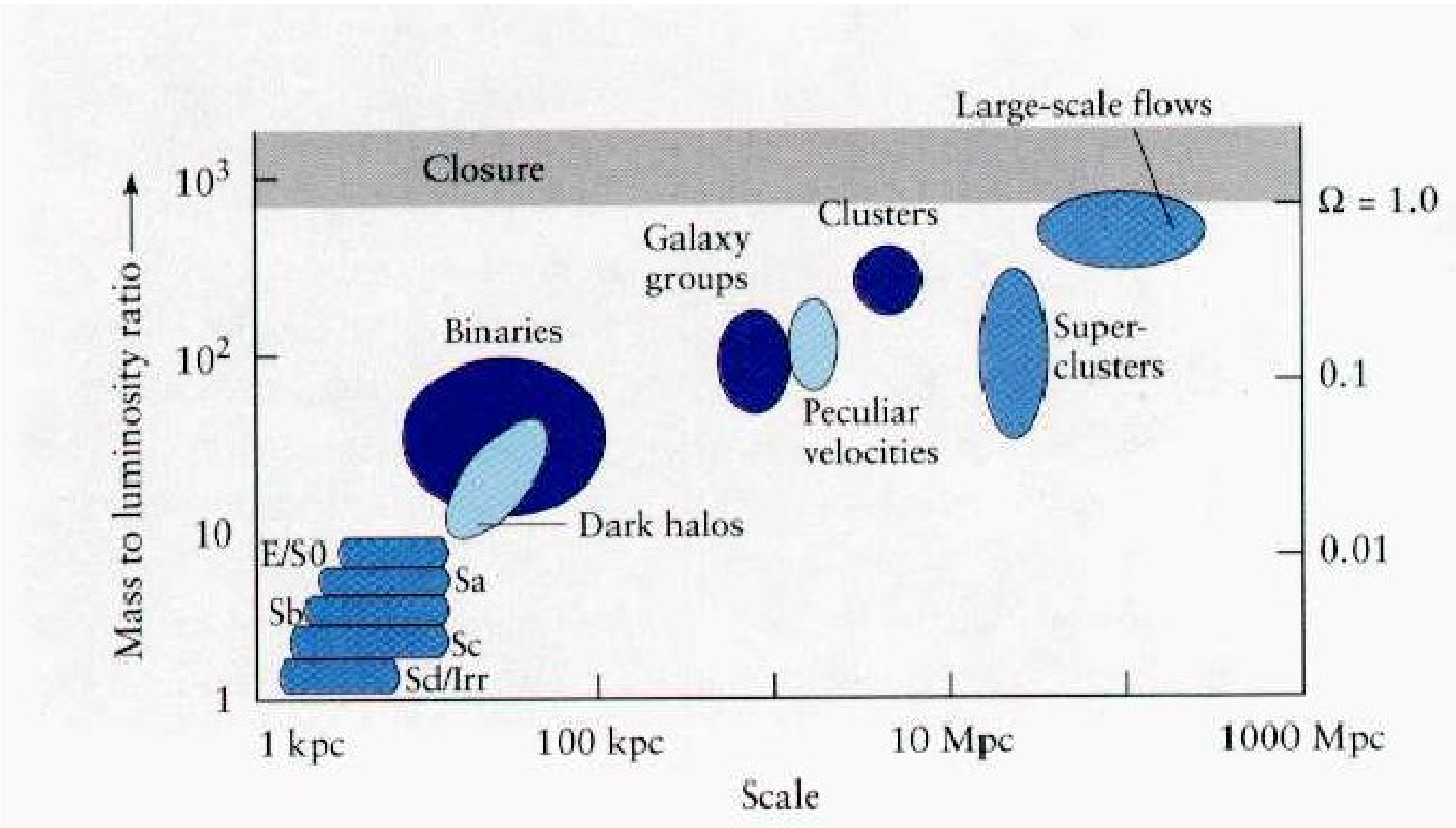
$\Phi_{\rm total} = \Phi_{\rm visible} + \Phi_{\rm DarkMatter}$

$v_c^2 = (v_c^2)_{\rm vis} + (v_c^2)_{\rm DM}$



PB, S.Chaudhury, S. Kundu (2017)

Dark Matter in the large scale Universe



Mass Discrepancy (Radial) Acceleration Relation (MDAR) for Rotationally Supported Galaxies

Selected for a Viewpoint in *Physics*

PRL **117,** 201101 (2016) PHYSICAL REVIEW LETTERS week ending 11 NOVEMBER 2016

Radial Acceleration Relation in Rotationally Supported Galaxies

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(Received 18 May 2016; revised manuscript received 7 July 2016; published 9 November 2016)

We report a correlation between the radial acceleration traced by rotation curves and that predicted by the observed distribution of baryons. The same relation is followed by 2693 points in 153 galaxies with very different morphologies, masses, sizes, and gas fractions. The correlation persists even when dark matter dominates. Consequently, the dark matter contribution is fully specified by that of the baryons. The observed scatter is small and largely dominated by observational uncertainties. This radial acceleration relation is tantamount to a natural law for rotating galaxies.

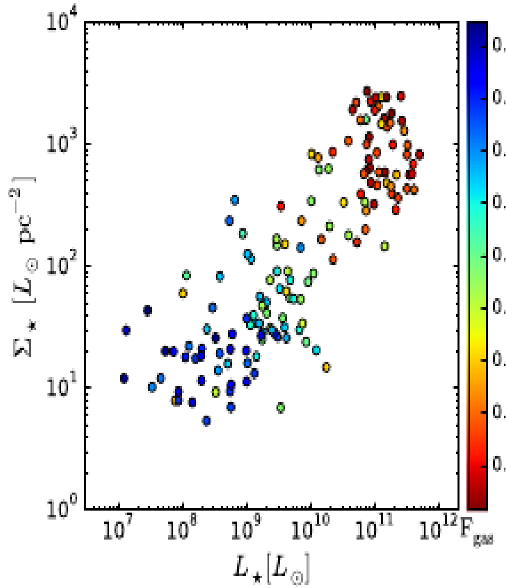


FIG. 1. The distribution of SPARC galaxies in luminosity and effective surface brightness. Points are coded by gas fraction (side bar). SPARC samples all known properties of rotationally supported galaxies, from low to high mass, low to high surface brightness, and negligible to dominant gas content.

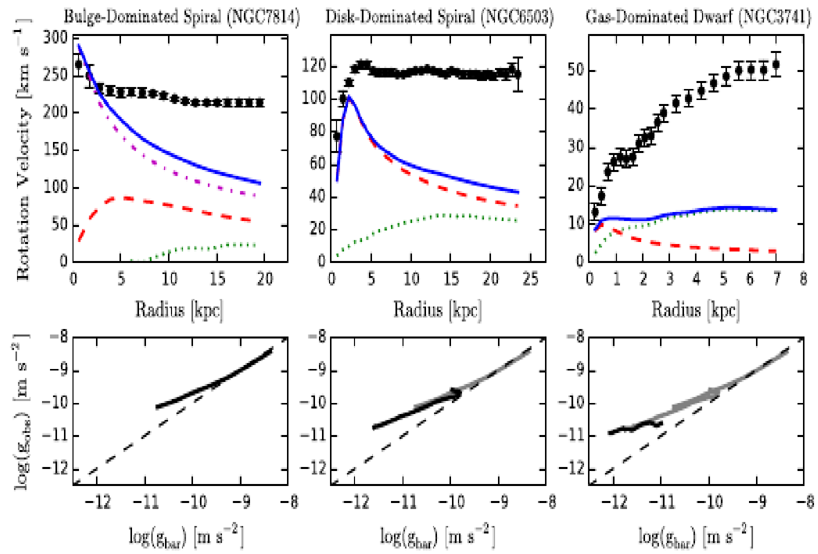
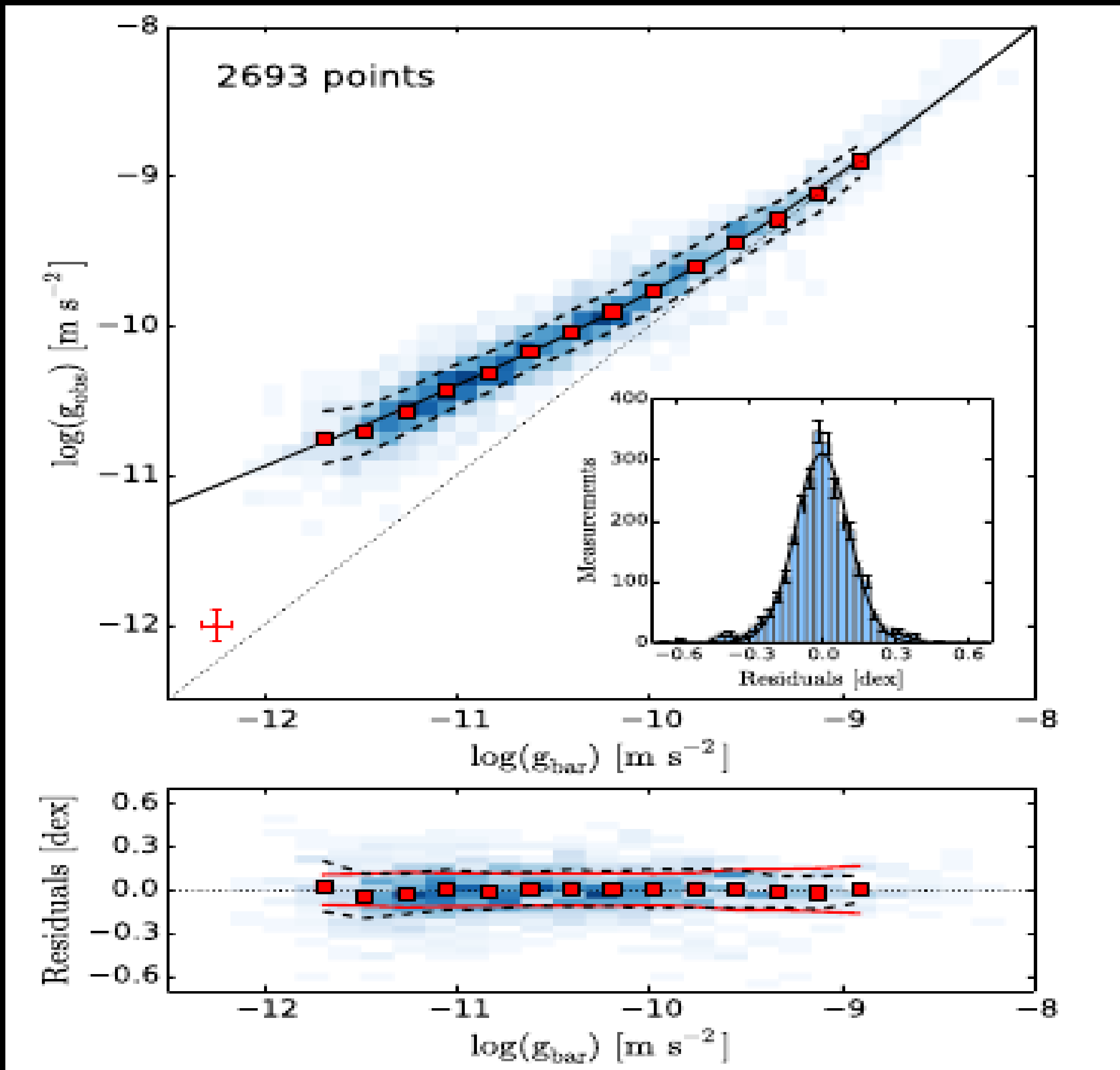


FIG. 2. Examples of mass models and rotation curves for individual galaxies. The points with error bars in the upper panels are the observed rotation curves $V(R)$. The errors represent both random errors and systematic uncertainty in the circular velocity due to asymmetry in the velocity field. In all galaxies, the data exceed the lines $v_{bar} = \sqrt{R g_{bar}}$ representing the baryonic mass models [Eq. (3)], indicating the need for dark matter. Each baryonic component is represented: dotted lines for the gas, dashed lines for the stellar disk, and dash-dotted lines for the bulge, when present. The sum of these components is the baryonic mass model (solid line). The lower panels illustrate the run of g_{bar} and g_{obs} for each galaxy, with the dashed line being the line of unity. Note that higher accelerations occur at smaller radii. From left to right each line is replotted in gray to illustrate how progressively fainter galaxies probe progressively lower regimes of acceleration.

S. McGaugh et al, PRL 117 (2016) 201101

Mass Discrepancy Acceleration Relation (MDAR) for Spiral Galaxies



S. McGaugh et al, PRL 117 (2016) 201101

$$g_{obs} = \mathcal{F}(g_{bar}) = \frac{g_{bar}}{1 - e^{-\sqrt{g_{bar}/g_\dagger}}}$$

$$g_{DM} = g_{obs} - g_{bar} = \frac{g_{bar}}{e^{\sqrt{g_{bar}/g_\dagger}} - 1}$$

$g_\dagger = 1.20 \pm 0.02\,(\mathrm{random}) \pm 0.24\,(\mathrm{syst}) \times 10^{-10}\ \mathrm{ms}^{-2}$

Characteristic acceleration scale

The Mass-Discrepancy (MD), and hence Dark Matter (DM), are strongly (anti)correlated with Visible Matter (VM).

The MD/DM is determined by VM ! VM-DM conspiracy!

DMAR Relation in CDM simulation

- Simulations used to be DM-only ones. Recently, more and more simulations are including baryons (hydrodynamic simulations)
- Still, they cannot capture all the important aspects of complex, dissipative baryonic physics in the galaxies.

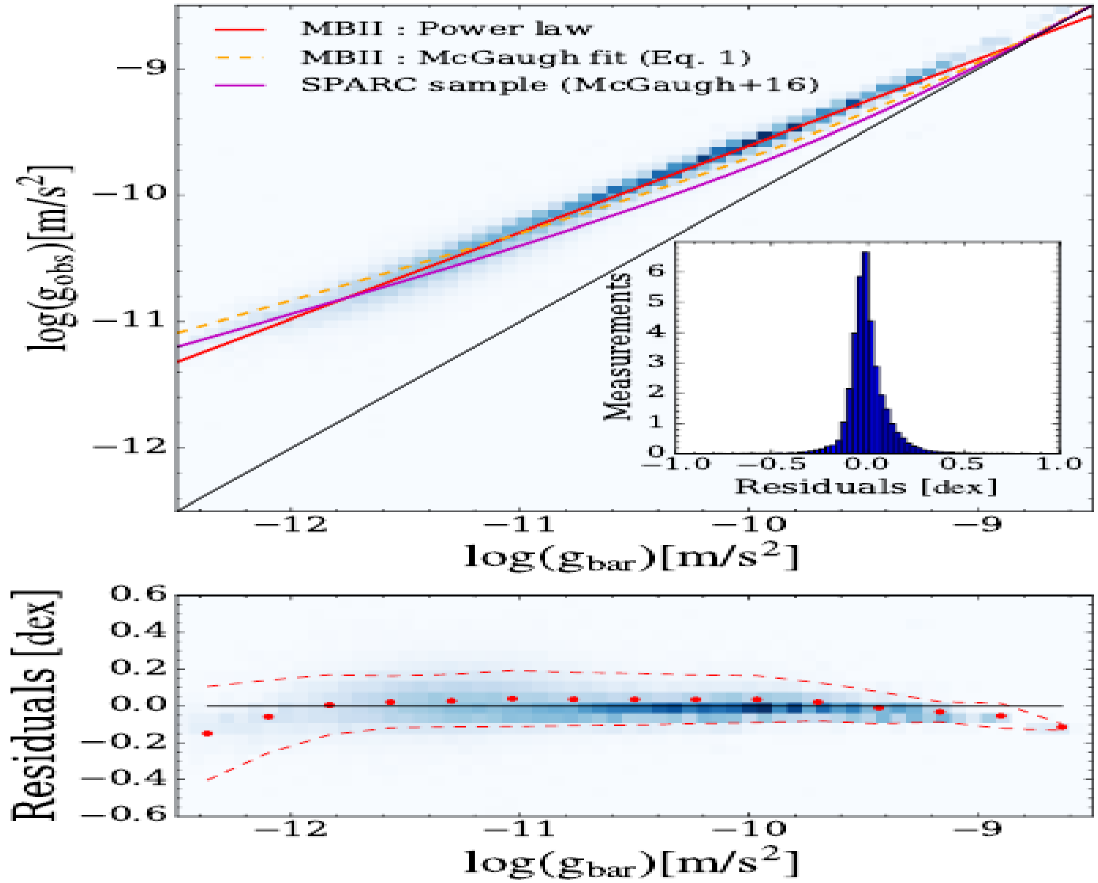


Figure 2. RAR of the baryonic component ($g_{\rm bar}$) compared with that of total matter ($g_{\rm obs}$) . *Top:* 2D weighted histogram of ($g_{\rm obs}$, $g_{\rm bar}$) for all disk galaxies in MB-II. The red solid line shows a power law fitted to the data, and the dashed orange curve shows Equation (1) with best-fit g_{+}. The observational result from SPARC sample is shown by the magenta solid line (McGaugh et al. 2016). The inset shows the total weighted distribution of residual values with respect to the best-fit power law ($g_{\rm obs}^{\rm (fit)} - g_{\rm obs}$). *Bottom:* The residual values with respect to the best-fit power law as a function of $g_{\rm bar}$. The red points and dashed lines show the mean and 1σ of the residual distribution in each of the $g_{\rm bar}$ bins.

The MDAR correlation is reproduced, but the form of the relationship is different.

Is the form of the correlation Universal?

Tenneti et al, arXiv:1703.05287

Mass Discrepancy – Acceleration Relation for the Milky Way

(Re)constructing the RC of Milky Way

For a particle in a circular orbit

$$v_c^2(r) = \frac{GM(r)}{r} = rg(r)$$

* Measure v_c(r), get total M(r). Not so simple!

* Stars on the disk have approximately circular orbits.
But stars beyond the disk (> 30 kpc) have non-circular Orbits. Also, there are not many tracer stars beyond the disk. Use 21cm line emission from atomic H as tracer.

*Also, you only measure the line-of-sight component of the velocity.

*Thus the RC, $v_c(R)$, is not directly measured.

It has to be (re)constructed from l.o.s. velocity data

Rotation Curve of the Milky Way out to ~200 kpc

The Astrophysical Journal, 785:63 (13pp), 2014 April 10 doi:10.1088/0004-637X/785/1/63

ROTATION CURVE OF THE MILKY WAY OUT TO ~200 kpc

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ABSTRACT

The rotation curve (RC) of our Galaxy, the Milky Way, is constructed starting from its very inner regions (few hundred parsecs) out to a large galactocentric distance of ~200 kpc using kinematical data on a variety of tracer objects moving in the gravitational potential of the Galaxy, without assuming any theoretical models of the visible and dark matter (DM) components of the Galaxy. We study the effect on the RC due to the uncertainties in the values of the Galactic constants (GCs) R_0 and V_0 (these being the Sun's distance from and circular rotation speed around the Galactic center, respectively) and the velocity anisotropy parameter β of the halo tracer objects used for deriving the RC at large galactocentric distances. The resulting RC in the disk region is found to depend significantly on the choice of the GCs, while the dominant uncertainty in the RC at large distances beyond the stellar disk comes from the uncertainty in the value of β. In general we find that the mean RC steadily declines at distances beyond ~60 kpc, independently of the value of β. Also, at a given radius, the circular speed is lower for larger values of β (i.e., for more radially biased velocity anisotropy). Considering that the largest possible value of β is unity, which corresponds to stellar orbits being purely radial, our results for the case of $\beta = 1$ give a lower limit to the total mass of the Galaxy within ~200 kpc, $M(200\,\text{kpc}) \gtrsim (6.8 \pm 4.1) \times 10^{11}\, M_\odot$, independently of any model of the DM halo of the Galaxy.

Key words: dark matter – Galaxy: general – Galaxy: kinematics and dynamics

Online-only material: color figures, machine-readable table

The Astrophysical Journal, 785:63 (13pp), 2014 April 10 Bhattacharjee, Chaudhury, & Kundu

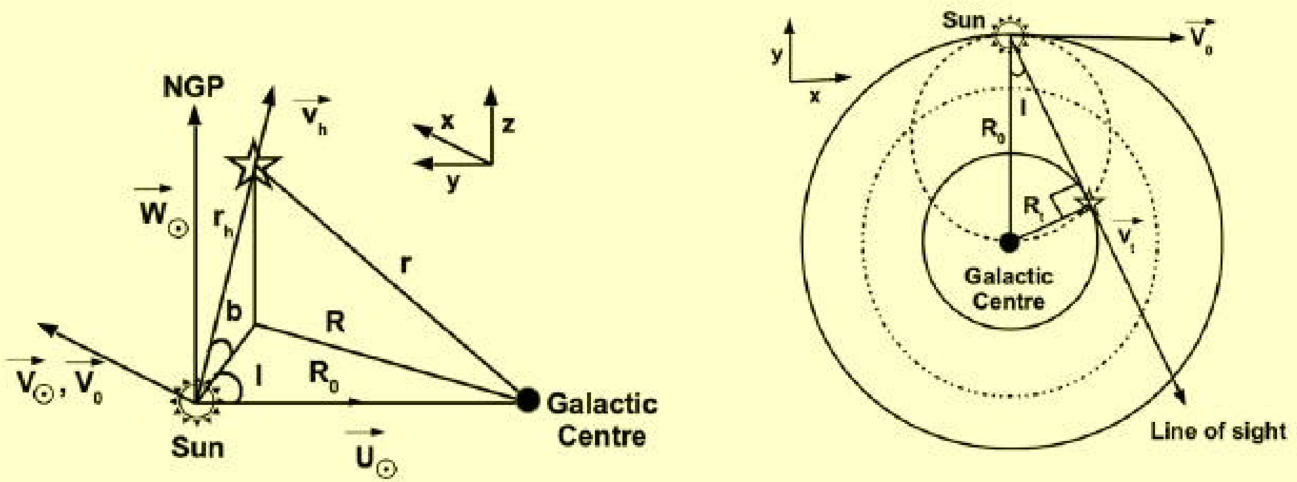

Figure 1. Left: schematic diagram showing the coordinate system, velocity and distance notations used in this work. Right: illustration of the tangent point method for deriving the circular speeds for distances $R < R_0$ on the disk.

For disk tracers:

$$V_c(R) = \frac{R}{R_0}\left[\frac{v_{\rm LSR}}{\sin l \cos b} + V_0\right],$$

$$R = \sqrt{R_0^2 + r_{\rm h}^2\cos^2 b - 2R_0 r_{\rm h}\cos b\cos l}$$

$$x = r_{\rm h}\cos b\sin l\,,\quad y = R_0 - r_{\rm h}\cos b\cos l\,,\quad z = r_{\rm h}\sin b\,,$$

$$v_{\rm LSR} = v_{\rm h} + U_\odot\cos b\cos l + V_\odot\cos b\sin l + W_\odot\sin b$$

$$(U_\odot, V_\odot, W_\odot) = (11.1, 12.24, 7.25)\ ({\rm km\,s^{-1}})$$

$$\tilde{V}_c(R) = \frac{R_0}{\tilde{R}_0}\left[V_c(R) - \frac{R}{R_0}(V_0 - \tilde{V}_0)\right]$$

The disk RC depends on the Galactic Constants $[R_0, V_0]$

For non-disk tracers: Use Jeans eqn. :

$$V_c^2(r) = \frac{GM(r)}{r} = -\sigma_r^2\left(\frac{d\ln n_{\rm tr}}{d\ln r} + \frac{d\ln\sigma_r^2}{d\ln r} + 2\beta\right)$$

$$\beta = 1 - \frac{\sigma_t^2}{2\sigma_r^2}$$

$$r = (R_0^2 + r_{\rm h}^2 - 2R_0 r_{\rm h}\cos b\cos l)^{1/2}$$

Disk Rotation Curve of the Milky Way

THE ASTROPHYSICAL JOURNAL, 785:63 (13pp), 2014 April 10 BHATTACHARJEE, CHAUDHURY, & KUNDU

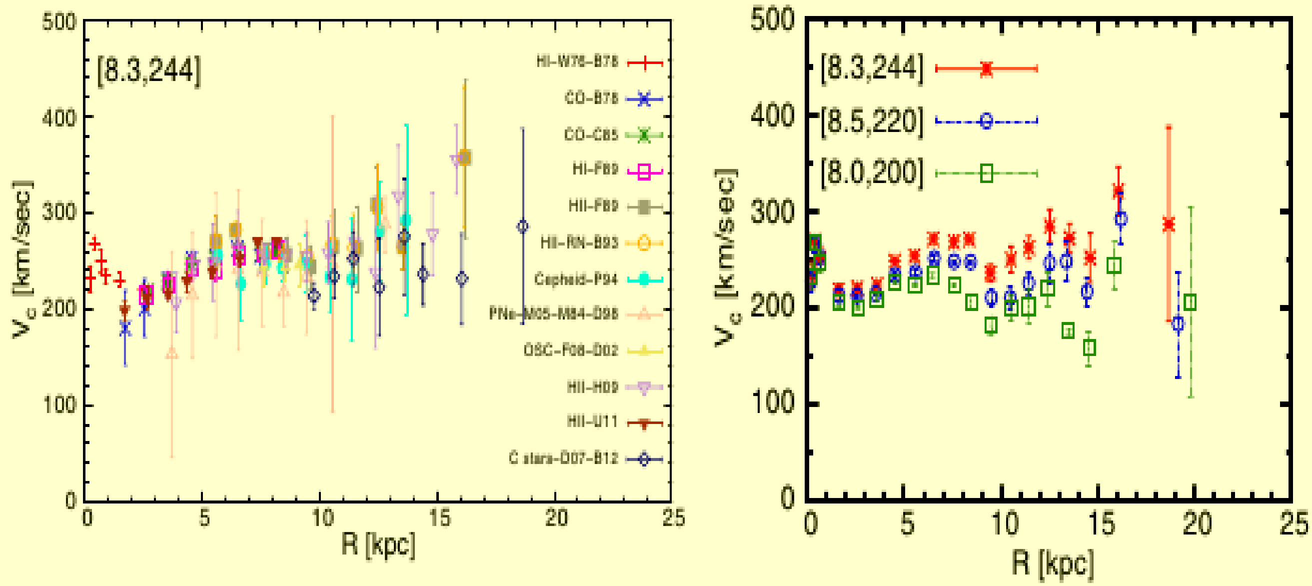

Figure 2. Left: rotation curves of the Galaxy obtained using the various different disk tracer samples listed in Table 3 in the Appendix for the Galactic constants $[(R_0/\,\text{kpc}), (V_0/\,\text{km s}^{-1})] = [8.3, 244]$. See Table 3 in the Appendix for keys to the data points. Right: averaged rotation curves obtained by weighted averaging over the combined V_c data from all the disk tracer samples listed in Table 3 and shown in the left panel, for three different sets of values of $[(R_0/\,\text{kpc}), (V_0/\,\text{km s}^{-1})]$ as indicated.

Beyond-disk Rotation Curve of the Milky Way

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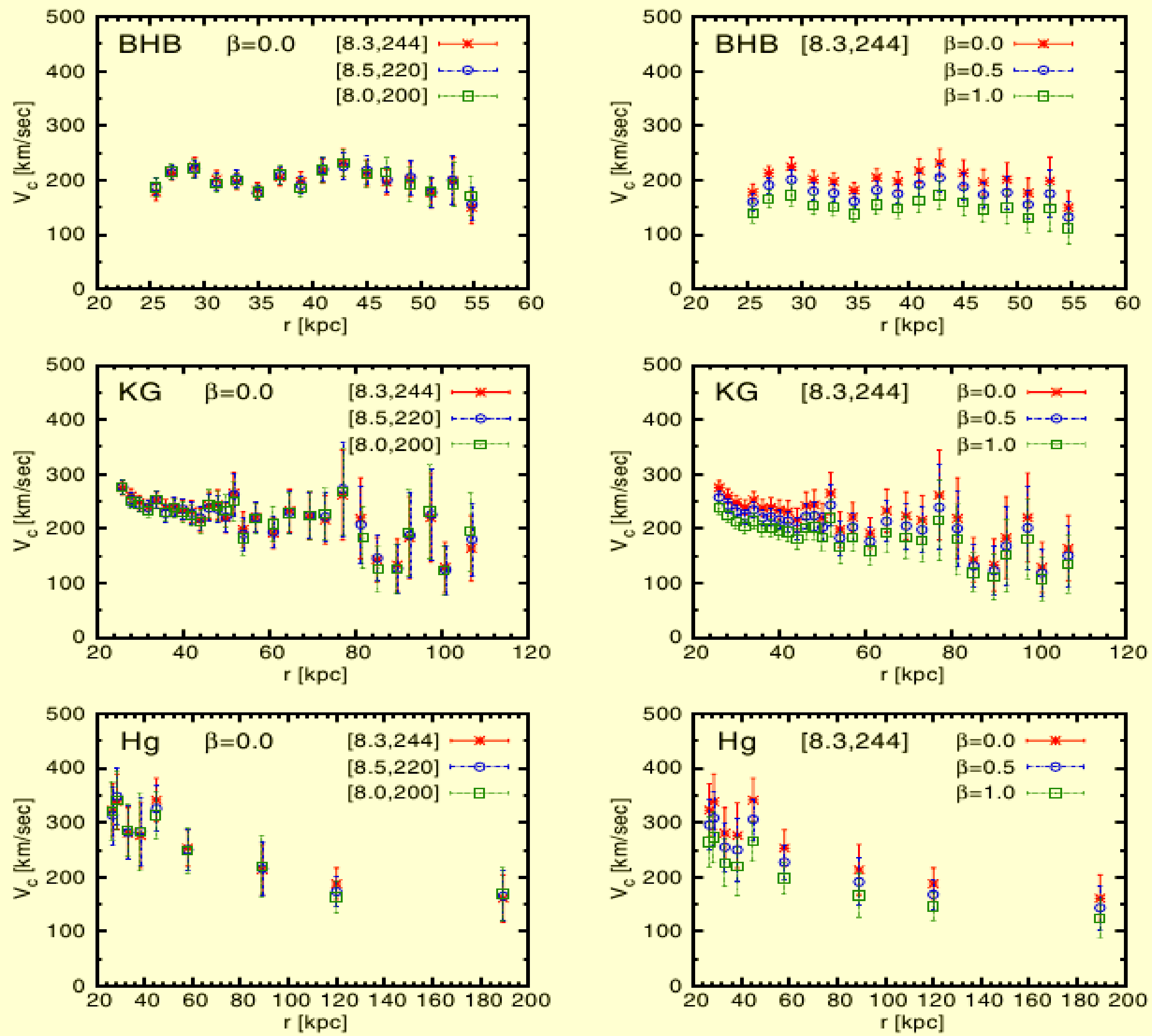
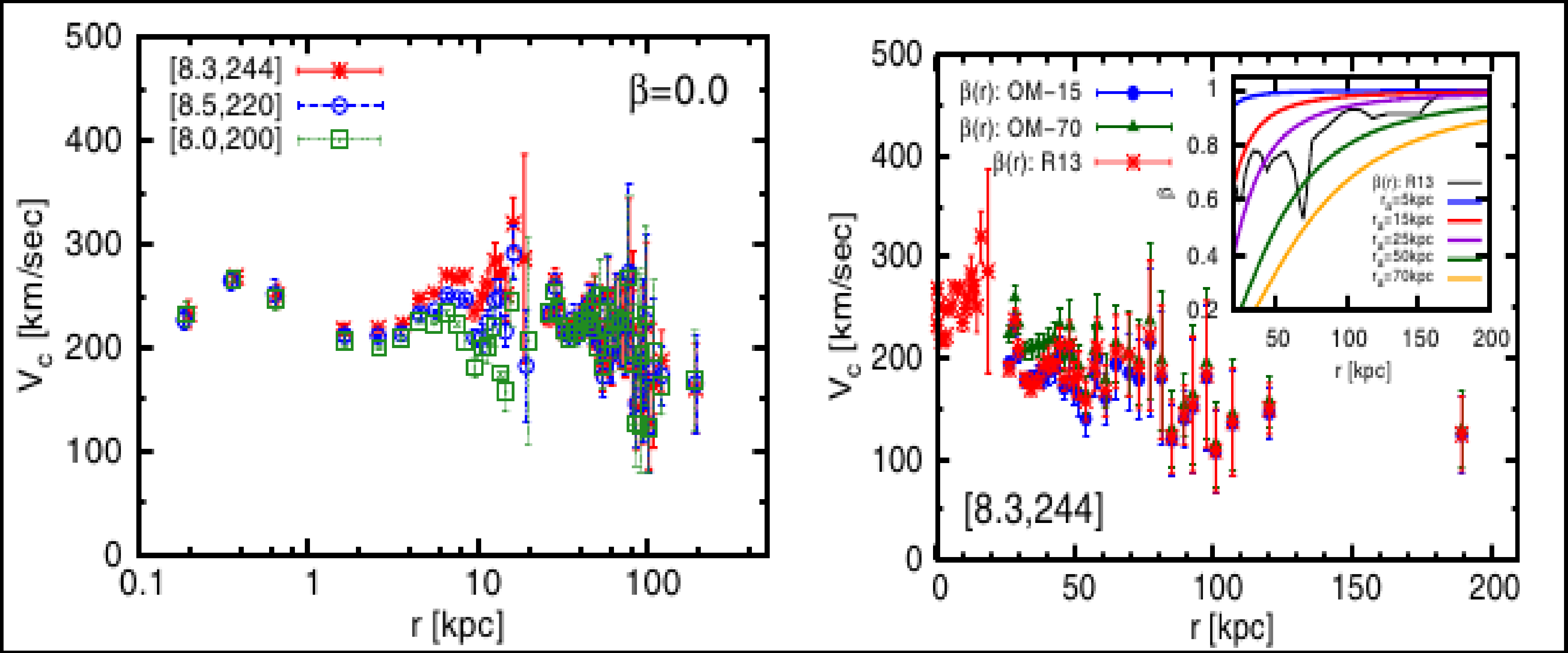


Figure 5. Circular velocities with their 1σ error bars for the three different non-disk tracer samples used in this paper (see the text and Figure 12 in the Appendix for details and source references for the samples). The left panels are for tracer velocity anisotropy $\beta = 0$ and three different sets of values of the Galactic constants, $[(R_0/\,\mathrm{kpc}),(V_0/\,\mathrm{km\,s^{-1}})]$, as indicated, whereas the right panels show the results for three different constant (r-independent) values of $\beta = 0$, 0.5 and 1, with $[(R_0/\,\mathrm{kpc}),(V_0/\,\mathrm{km\,s^{-1}})] = [8.3, 244]$.

The Grand Rotation Curve of the Milky Way



The RC is not really flat beyond the disk!

Mass of the Milky Way

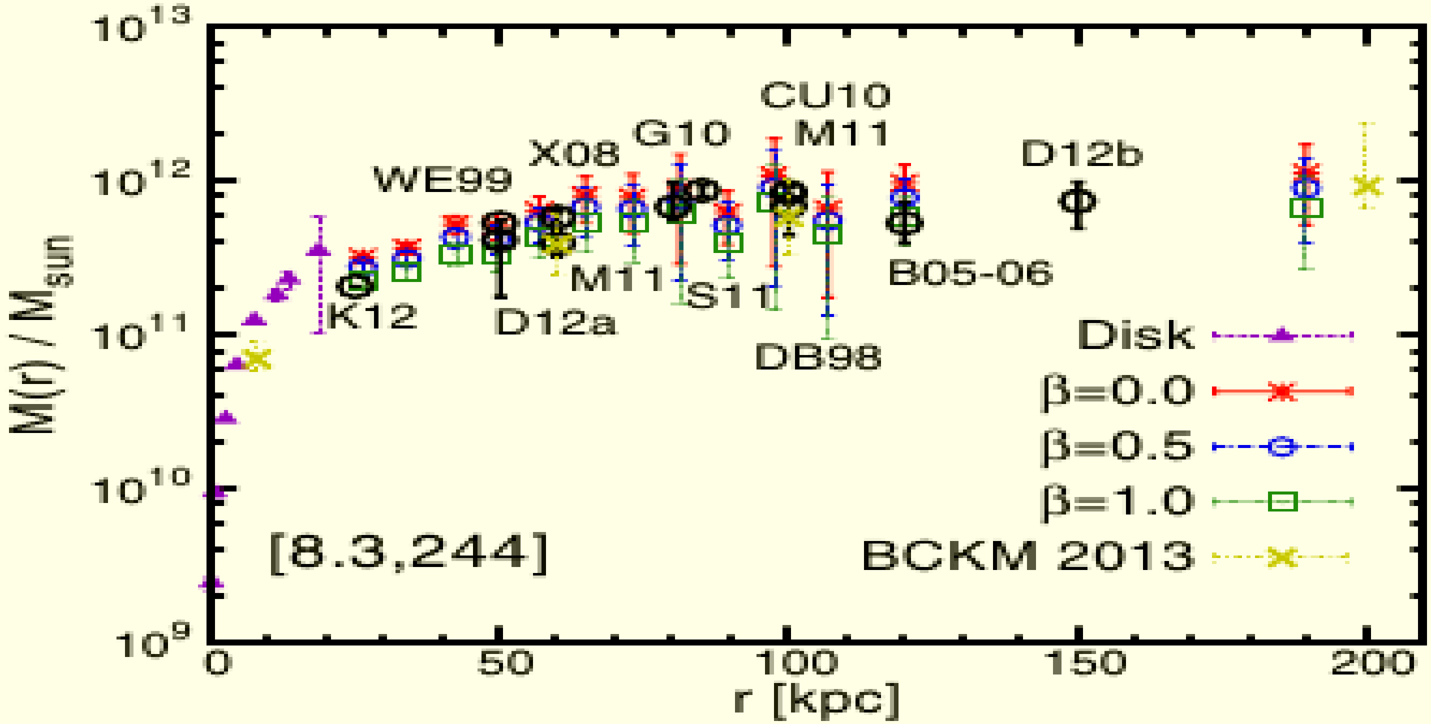
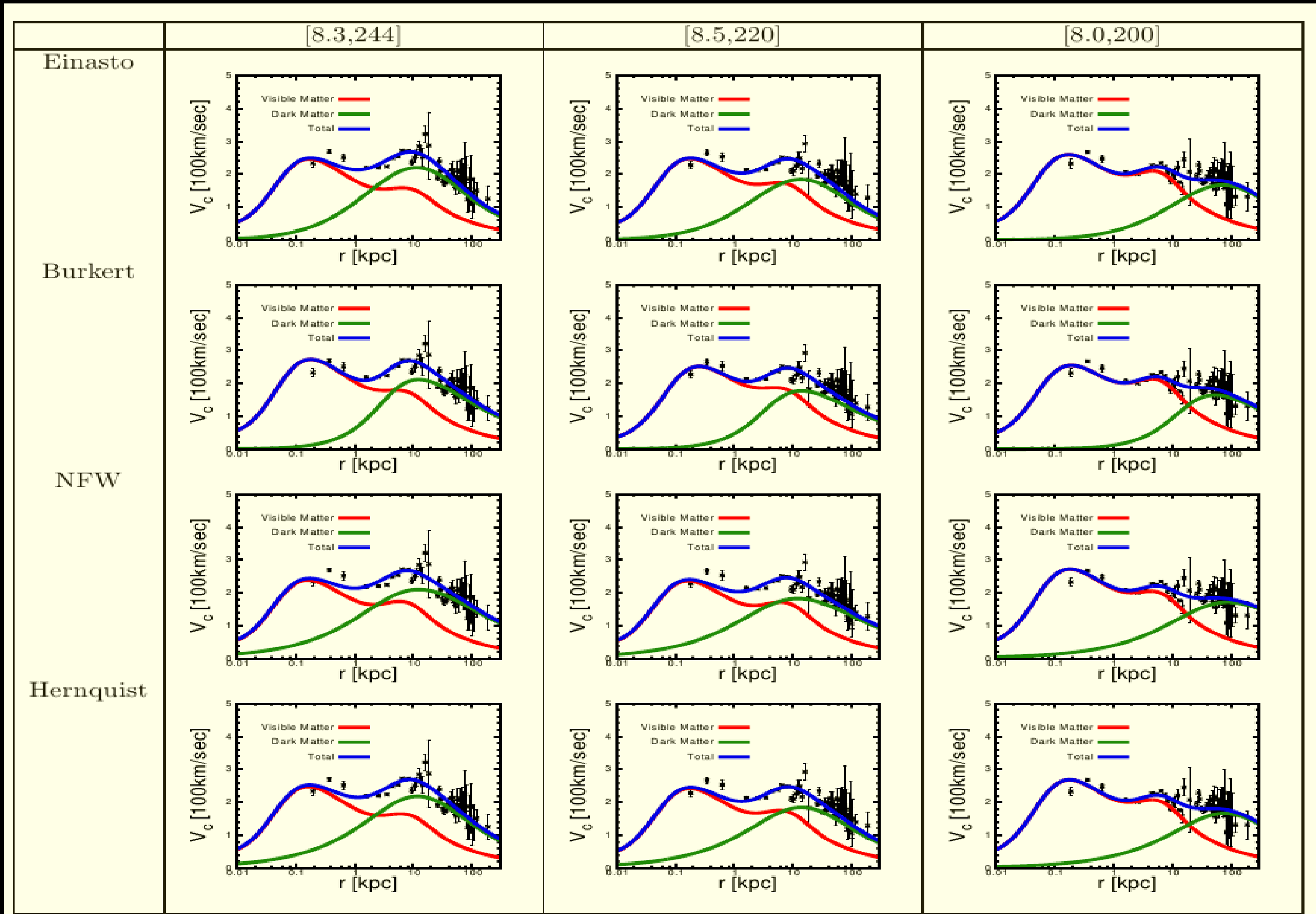


Figure 8. Mass, $M(r) = rV_c^2(r)/G$, within r, as a function of r, obtained from the RCs shown in Figure 7 for $[(R_0/\mathrm{kpc}), (V_0/\mathrm{km\,s^{-1}})] = [8.3, 244]$ and various values of the tracers' velocity anisotropy parameter β. Estimates of $M(r)$ at certain specific values of r obtained from various independent considerations in some earlier works, namely, Kafle et al. (2012; K12), Wilkinson & Evans (1999; WE99), Deason et al. (2012a; D12a), Xue et al. (2008; X08), McMillan (2011; M11), Gnedin et al. (2010; G10), Samurovic et al. (2011; S11), Catena & Ullio (2010; CU10), Dehnen & Binney (1998; DB98), Battaglia et al. (2005; B05-06), Deason et al. (2012b; D12b), and Bhattacharjee et al. (2013; BCKM 2013), are shown for comparison.

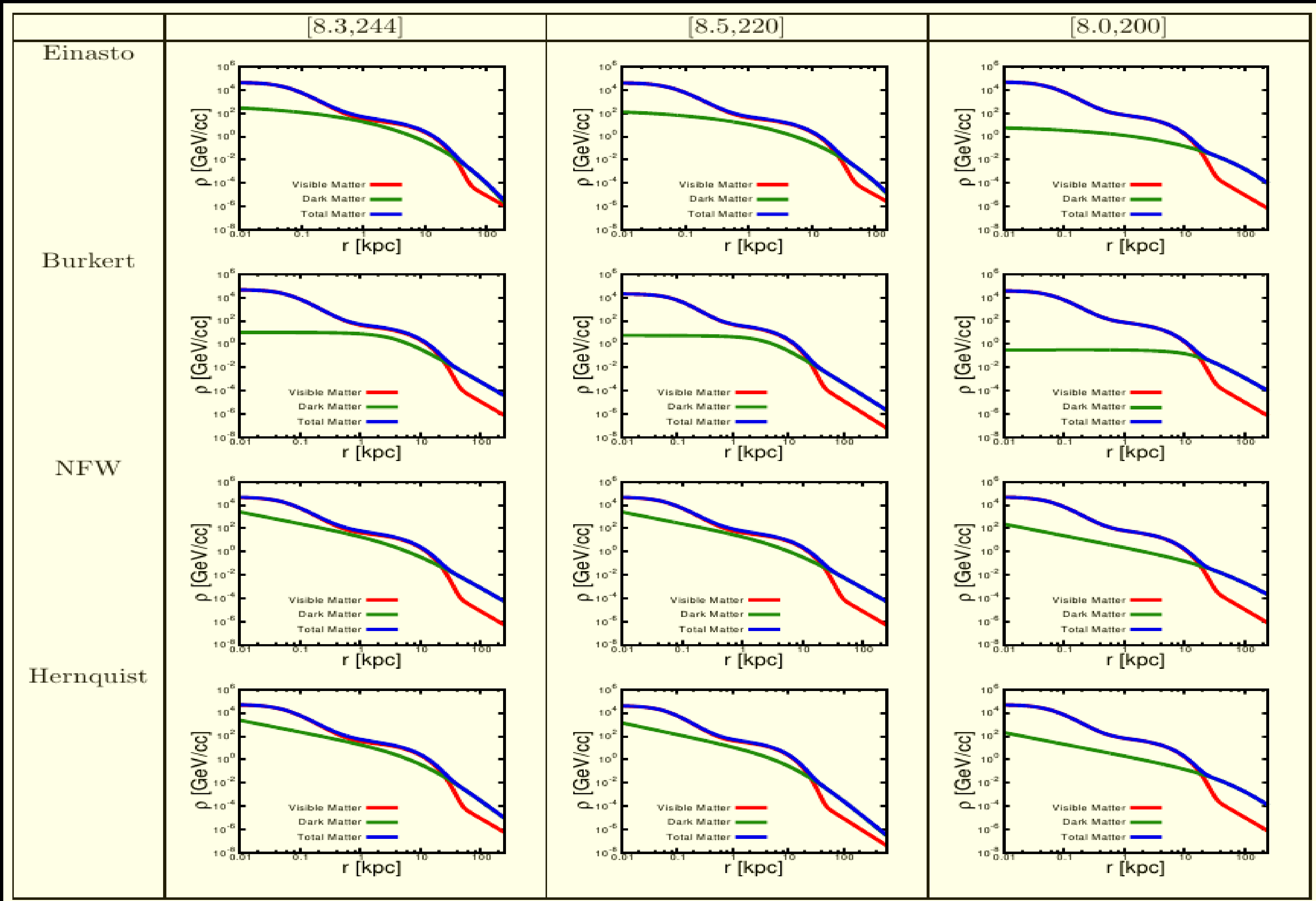
THE ASTROPHYSICAL JOURNAL, 785:63 (13pp), 2014 April 10 BHATTACHARJEE, CHAUDHURY, & KUNDU

Milky Way Mass Models from RC fit



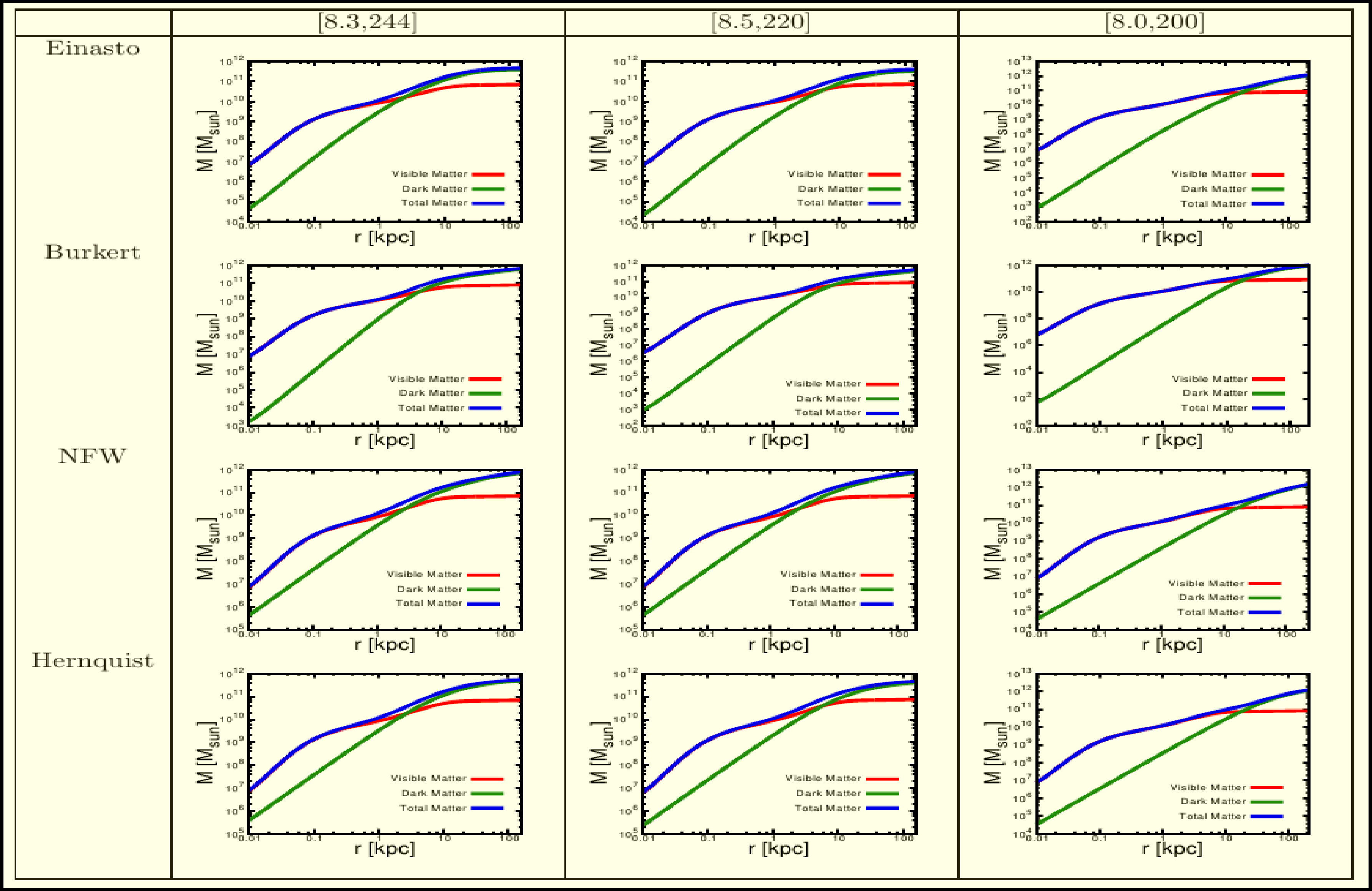
PB, S. Chaudhury, S. Kundu (2017)

Best-fit density profiles



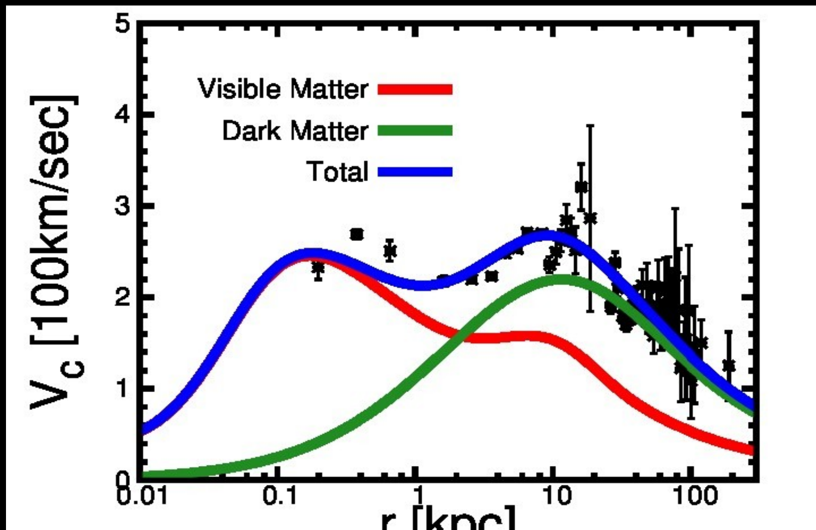
PB, S. Chaudhury, S. Kundu (2017)

Best-Fit Mass Profiles

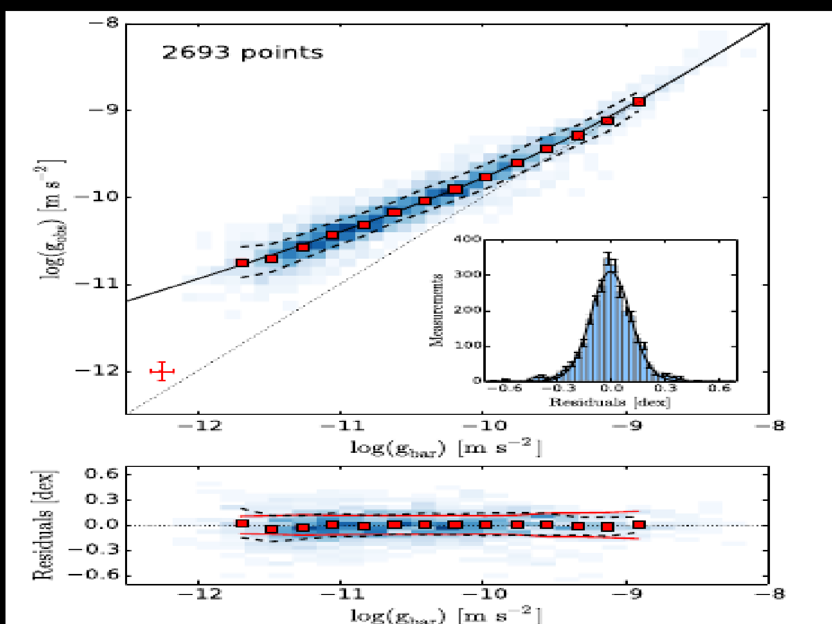


PB, S. Chaudhury, S. Kundu (2017)

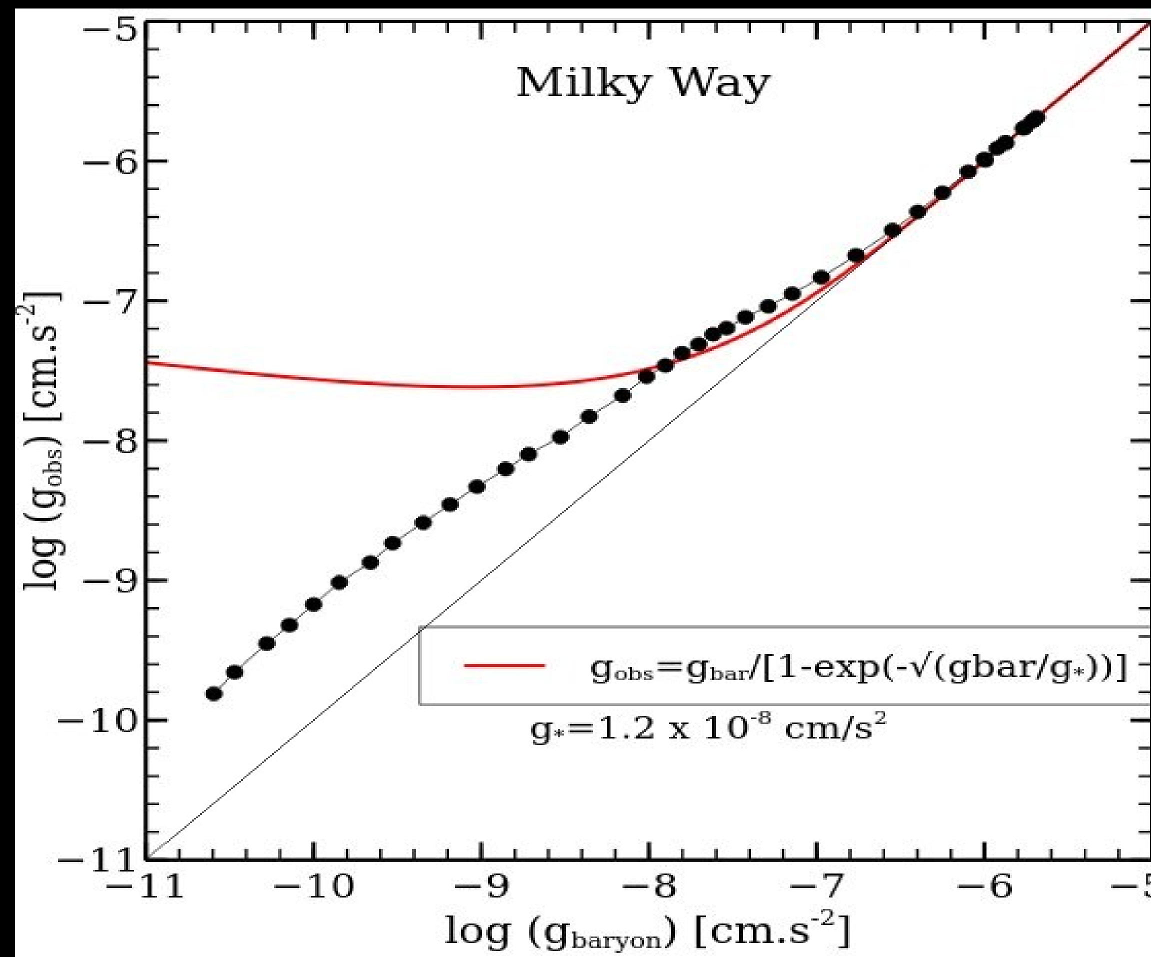
Mass Discrepancy Acceleration Relation (MDAR) for the Milky Way



$$g(r) = \frac{v_c^2(r)}{r} = \frac{GM(r)}{r^2}$$



S. McGaugh et al (2016)



P.B., S. Chaudhury, S. Kundu (2017)

Modified Newtonian Dynamics (MOND)

The Tully-Fisher Relation

Astron. Astrophys. 54, 661—673 (1977)

ASTRONOMY AND ASTROPHYSICS

A New Method of Determining Distances to Galaxies

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Received July 15, 1975, revised April 26, 1976

Summary. A good correlation between a distance-independent observable, global galaxian H I profile widths, and absolute magnitudes or diameters of galaxies offers a new extragalactic distance tool, as well as potentially being fundamental to an understanding of galactic structure. The relationships are calibrated with members of the Local Group, the M81 group, and the M101 group and have been used to derive distances to the Virgo cluster ($\mu_0 = 30^m\!.6 \pm 0^m\!.2$) and the Ursa Major cluster ($\mu_0 = 30^m\!.5 \pm 0^m\!.35$). A preliminary estimate of the Hubble constant is $H_0 = 80$ km/s/Mpc.

Key words: galaxies — distances — neutral hydrogen

I. Introduction

We propose that for spiral galaxies there is a good correlation between the global neutral hydrogen line profile width, a distance-independent observable, and the absolute magnitude (or diameter). It is well known that the intrinsic luminosity of a galaxy is correlated with the total mass, which is a derivative of the global profile width and is linearly dependent on distance (cf. Roberts, 1969), and that comparison of the total mass total mass and type). It is our contention that this correlation is primarily an accident of the fact that earlier systems that have been studied are intrinsically larger than later systems. The principal correlation should be with luminosity, with modest, if any, type dependence. This point is important with regard to the internal structure of galaxies, as well as offering a valuable tool for the measurement of extragalactic distances.

The basic difficulty with establishing the relation, and presumably the reason why it has essentially escaped notice, is that if the calibrating systems do not have extremely well known absolute or relative distances, the observational scatter thus introduced renders the relation of little use. We will attempt to demonstrate the effect in two ways: (i) based on nearby systems with well determined distances, and (ii) based on systems in clusters, hence at the same relative distance. A comparison of the two analyses will permit a preliminary determination of the Virgo and Ursa Major cluster distances.

II. Nearby Galaxies

We shall first look for the proposed relation in the nearby "calibrator" galaxies, each with:

Tully-Fisher relation

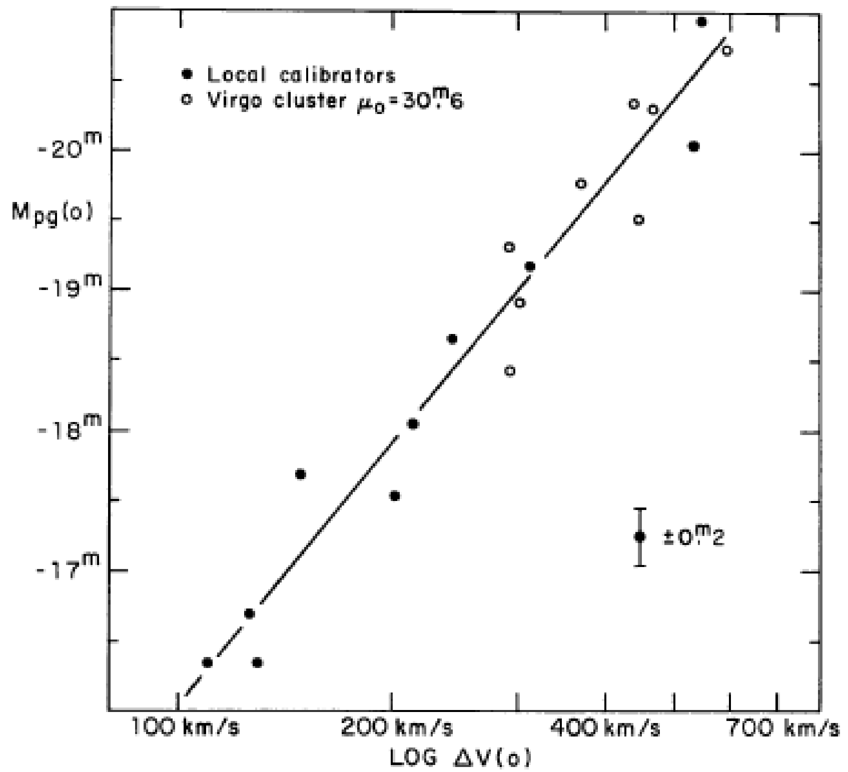
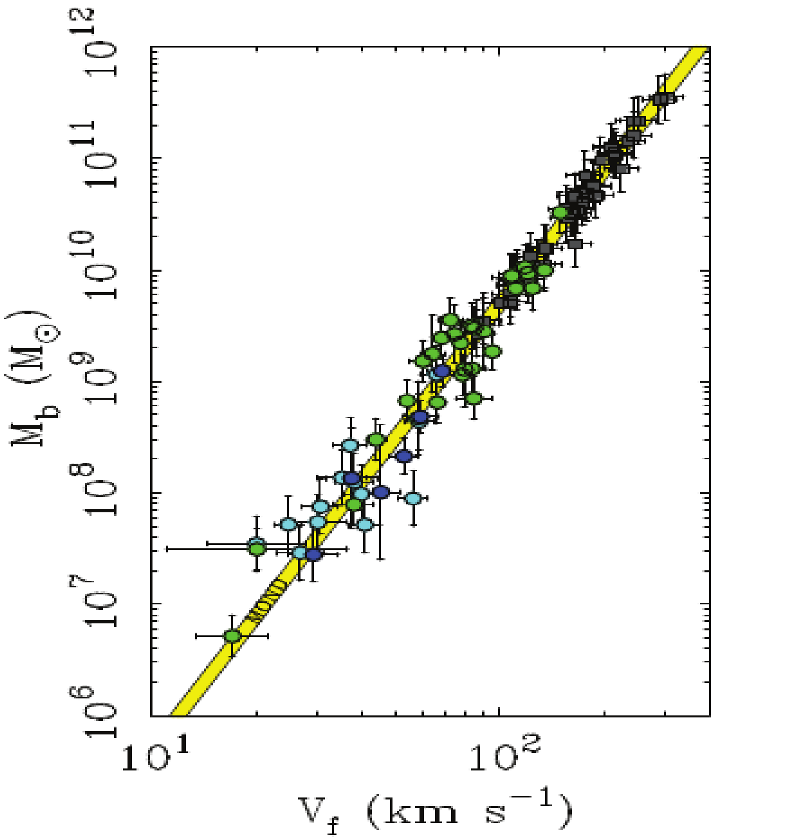


Fig. 5 (a) Absolute magnitude – global profile width relation produced by overlaying Figure 3 on Figure 1, adjusting Figure 3 vertically to arrive at a best visual fit with a distance modulus of $\mu_0 = 30^m.6 \pm 0^m.2$

Tully & Fisher, A&A (1977)

Fig. 1. Baryonic mass as a function of the asymptotic velocity, V_f, of rotation curves of galaxies. The band and its width show the expectation from MOND and detailed fits to rotation curves.



S. McGaugh (2010), D. Bugg (2015)

Tight correlation between rotation speeds (→ total mass) and luminosity (→ Baryonic mass)

$$L \propto v_{c,f}^4$$

THE ASTROPHYSICAL JOURNAL, **270**:365–370, 1983 July 15

A MODIFICATION OF THE NEWTONIAN DYNAMICS AS A POSSIBLE ALTERNATIVE TO THE HIDDEN MASS HYPOTHESIS[1]

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ABSTRACT

I consider the possibility that there is not, in fact, much hidden mass in galaxies and galaxy systems. If a certain modified version of the Newtonian dynamics is used to describe the motion of bodies in a gravitational field (of a galaxy, say), the observational results are reproduced with no need to assume hidden mass in appreciable quantities. Various characteristics of galaxies result with no further assumptions.

In the basis of the modification is the assumption that in the limit of small acceleration $a \ll a_0$, the acceleration of a particle at distance r from a mass M satisfies approximately $a^2/a_0 \approx MGr^{-2}$, where a_0 is a constant of the dimensions of an acceleration.

A success of this modified dynamics in explaining the data may be interpreted as implying a need to change the law of inertia in the limit of small accelerations or a more limited change of gravity alone.

I discuss various observational constraints on possible theories for the modified dynamics from data which exist already and suggest other systems which may provide useful constraints.

Subject headings: cosmology — galaxies: internal motions — stars: stellar dynamics

I. INTRODUCTION

The hidden mass hypothesis (HMH) explains the dynamics in galaxies and systems of galaxies by assuming that much of the mass in these systems is in, as yet, unobserved form (for recent reviews see, for example, Faber and Gallagher 1979 and Rood 1981). This hypothesis has not yet encountered any fatal objection. However, in order to explain the observations in the framework of this idea, one finds it necessary to make a large number of ad hoc assumptions concerning the nature of the hidden mass and its distribution in space.

The large amounts of data on galaxies and galaxy systems which have been collected to date, and in particular the various regularities which have emerged from these data (each requiring new ad hoc assumptions about the hidden mass) make, I believe, the time ripe for considering alternatives to the HMH.

The main assumptions on which the above relation is based are the following: (a) The force which governs the dynamics is gravity. (b) The gravitational force on a particle depends, in the conventional way, on the mass of the particle and on the distribution of the mass which produces this force. (c) Newton's second law holds (All along I take the second law to include the proportionality of inertial and gravitational masses). These are assumed to hold in the nonrelativistic regime (which is justified for galaxy dynamics). In addition, one assumes that particle velocities are correctly measured by line spectral shifts with the usual Doppler relation, and one also makes various "astrophysical" assumptions about the nature of the systems under study (their being isolated bound systems etc.).

It must have occurred to many that there may, in fact, not be much hidden mass in the universe and that the

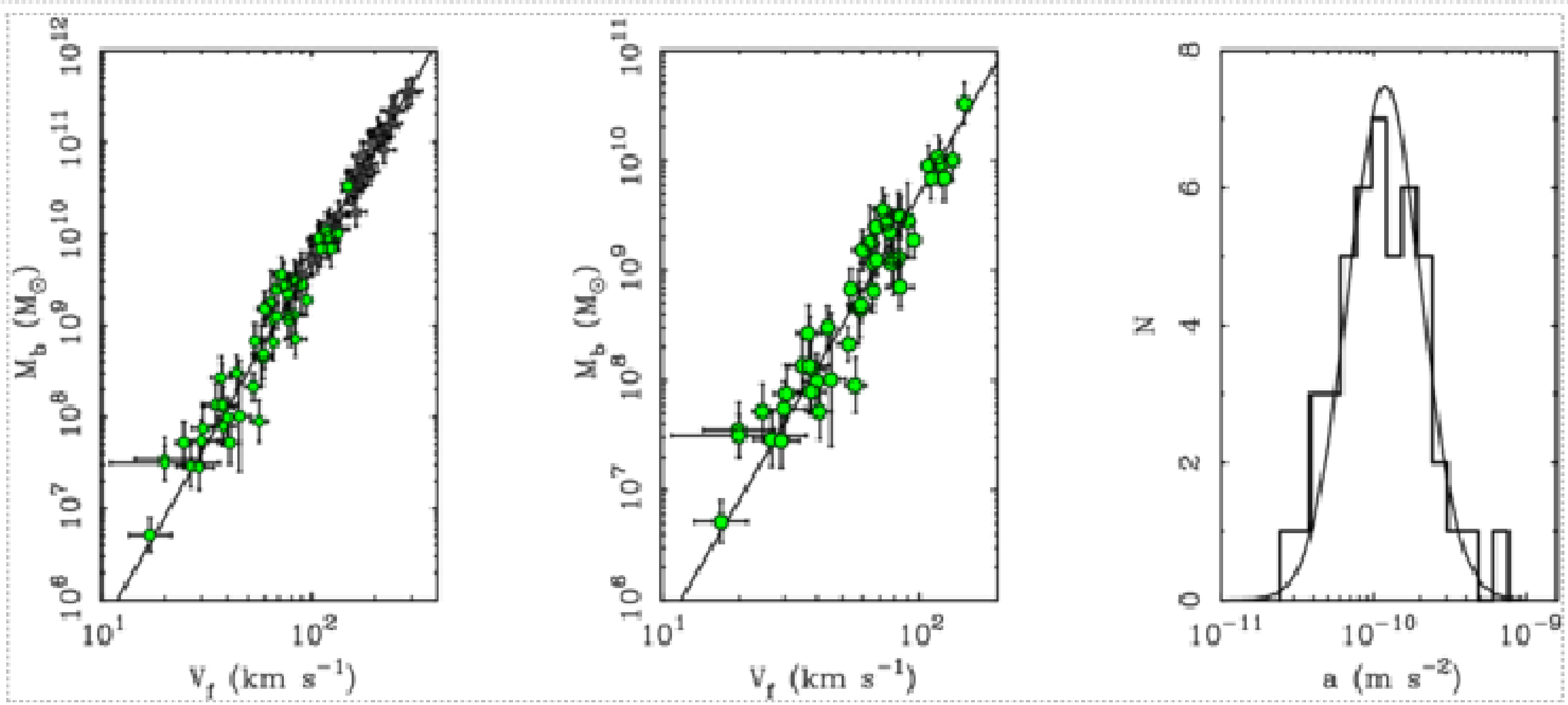

Figure 3: Data for galaxy baryonic mass plotted against the measured asymptotic rotation speed, compared with the MOND prediction (line). Left: a large sample of disc galaxies of all types (circles for gas-rich, squares for star-dominated galaxies). Middle: the same test with only gas-rich galaxies included, for which the baryonic mass is insensitive to adopted stellar mass-to-light ratios (McGaugh, 2011). In both plots, the line is the MOND prediction using the value of a_0 determined earlier from rotation-curve analysis of 11 galaxies (McGaugh, 2012). Right: distribution of V_f^4/MG for the latter sub-sample, compared with that expected from measurement errors alone; showing that the observed scatter is consistent with no intrinsic scatter in the observed relation.

Milgrom (1983)

I have considered the possibility that Newton's second law does not describe the motion of objects under the conditions which prevail in galaxies and systems of galaxies. In particular I allowed for the inertia term not to be proportional to the acceleration of the object but rather be a more general function of it. With some simplifying assumptions I was led to the form

$$m_g \mu(a/a_0)\mathbf{a} = \mathbf{F}, \qquad (1)$$

$$\mu(x \gg 1) \approx 1, \qquad \mu(x \ll 1) \approx x,$$

replacing $m_g \mathbf{a} = \mathbf{F}$. Here m_g is the gravitational mass of a body moving in an arbitrary static force field $\mathbf{F}$ with acceleration $\mathbf{a}$ $(a = |\mathbf{a}|)$. The force field $\mathbf{F}$ is assumed to depend on its sources and to couple to the body, in the conventional way. Equation (1) is assumed to h $g_N = \mu(x)\mathbf{a}$, some fundamental frame of reference. For accelerations much larger than the acceleration constant (a_0), $\mu \approx 1$, and the Newtonian dynamics is restored.

Milgrom (1983)

$$a_0 \approx 1.2 \times 10^{-8} \mathrm{cm.s}^{-2}$$

A "fundamental" acceleration scale

$$g_N = \mu(x)\mathbf{a} \qquad (1)$$

$$\mu_1(x) = \frac{x}{1+x}, \qquad \mu_2(x) = \frac{x}{\sqrt{1+x^2}}$$

(1) violates momentum conservation
→ Bekenstein & Milgrom (1984) gave a "modified" Poisson equation:

$$\nabla \cdot \left[\mu\left(\frac{|\nabla\Phi|}{a_0}\right)\nabla\Phi\right] = 4\pi G\rho.$$

$$\text{For} \quad a \ll a_0, \quad a^2 \approx g_N a_0 = \frac{GM}{r^2} a_0$$

$$\text{With} \quad a = \frac{v_c^2}{r}, \quad v_c^4 = GMa_0 = Ga_0 L \frac{M}{L} \propto L$$

If M/L is const.
T-F relation!

Criticisms of MOND

- No fully relativistic version of the “theory” is available yet
- Has difficulties in explaining the MD/DM in clusters of galaxies
- “Bullet cluster” ?
- Cosmology : CMB, structure formation, …
-
-

But the origin of MDAR in rotationally supported galaxies remains to be explained.

Visible Matter – Dark Matter Conspiracy?

Phil. Trans. R. Soc. Lond. A **320**, 447–464 (1986) **447**
Printed in Great Britain

Dark matter in spiral galaxies

By T. S. van Albada and R. Sancisi

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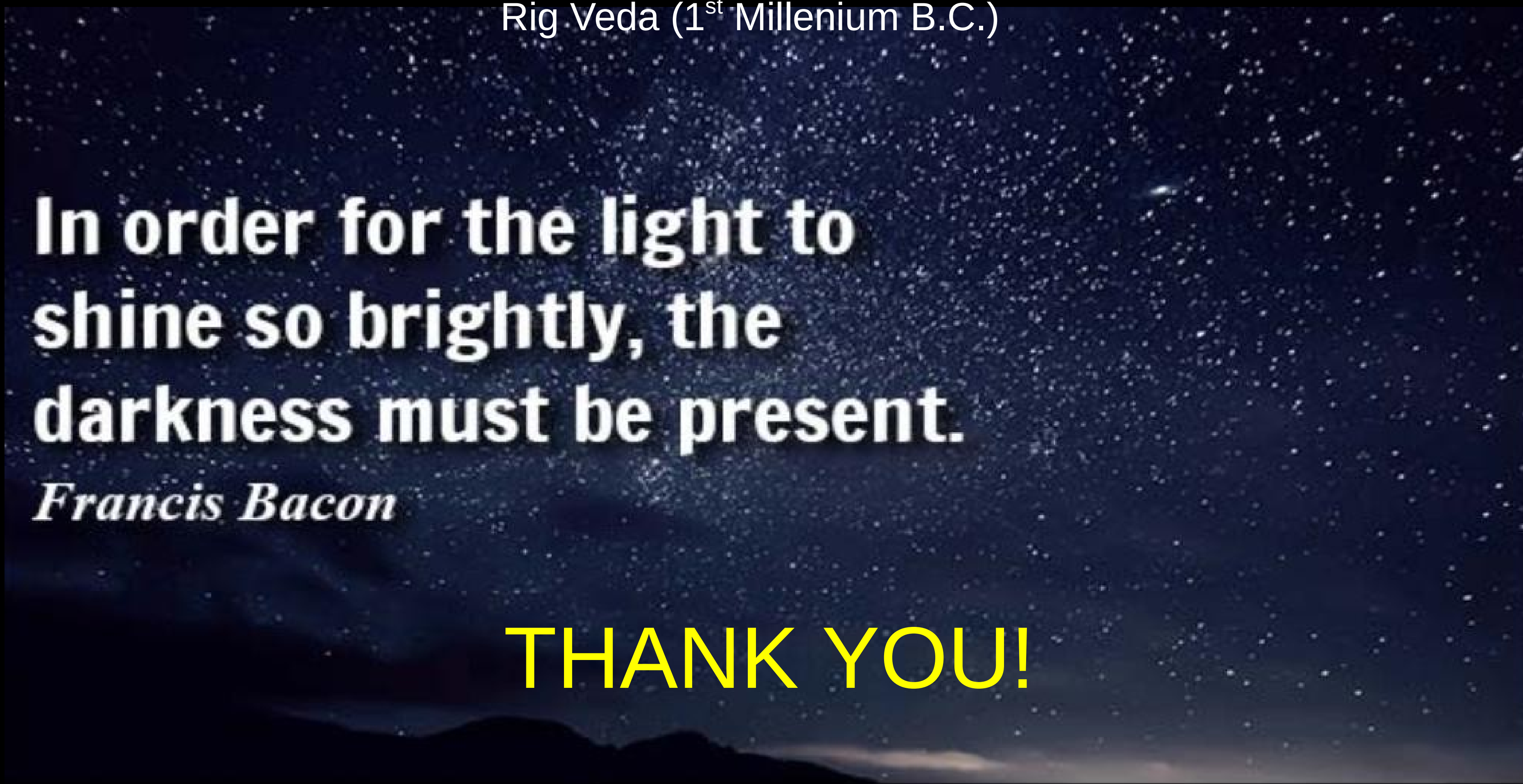
9700 *AV Groningen, The Netherlands*

Mass models of spiral galaxies based on the observed light distribution, assuming constant M/L for bulge and disc, are able to reproduce the observed rotation curves in the inner regions, but fail to do so increasingly towards and beyond the edge of the visible material. The discrepancy in the outer region can be accounted for by invoking dark matter; some galaxies require at least four times as much dark matter as luminous matter. There is no evidence for a dependence on galaxy luminosity or morphological type. Various arguments support the idea that a distribution of visible matter with constant M/L is responsible for the circular velocity in the inner region, i.e. inside approximately 2.5 disc scalelengths. Luminous matter and dark matter seem to 'conspire' to produce the flat observed rotation curves in the outer region. It seems unlikely that this coupling between disc and halo results from the large-scale gravitational interaction between the two components. Attempts to determine the shape of dark halos have not yet produced convincing results.

At first there was only darkness wrapped in darkness.
All this was only unillumined water.
That One which came to be, enclosed in nothing,
arose at last, born of the power of heat."

Rig Veda (1st Millenium B.C.)



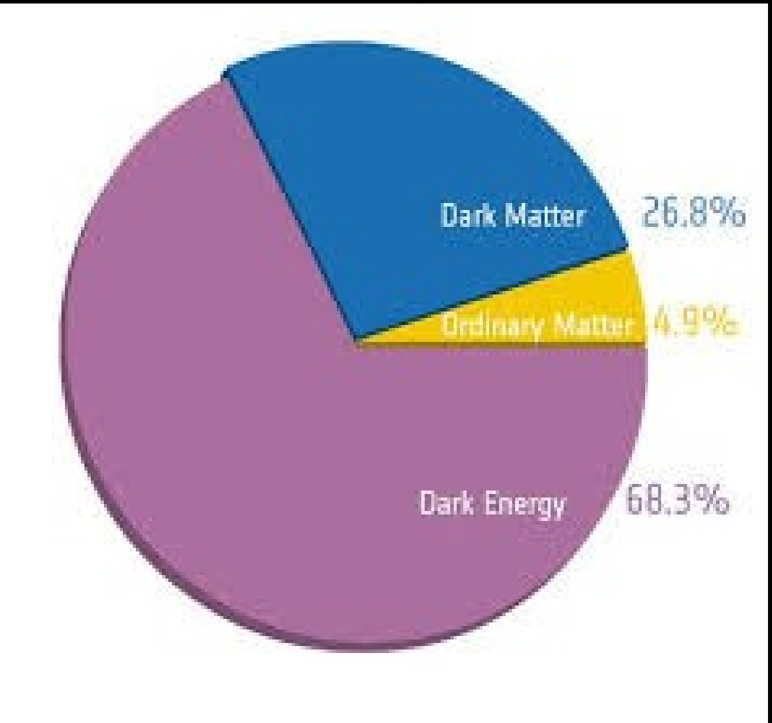
THANK YOU!

Back-up miscellaneous slides

Is all we can "see" all there is in the Universe? Evidently, no!

Planck 2015

Parameters of the Universe



$$H_0 = 70\,\mathrm{Km\,s^{-1}\,Mpc^{-1}}$$

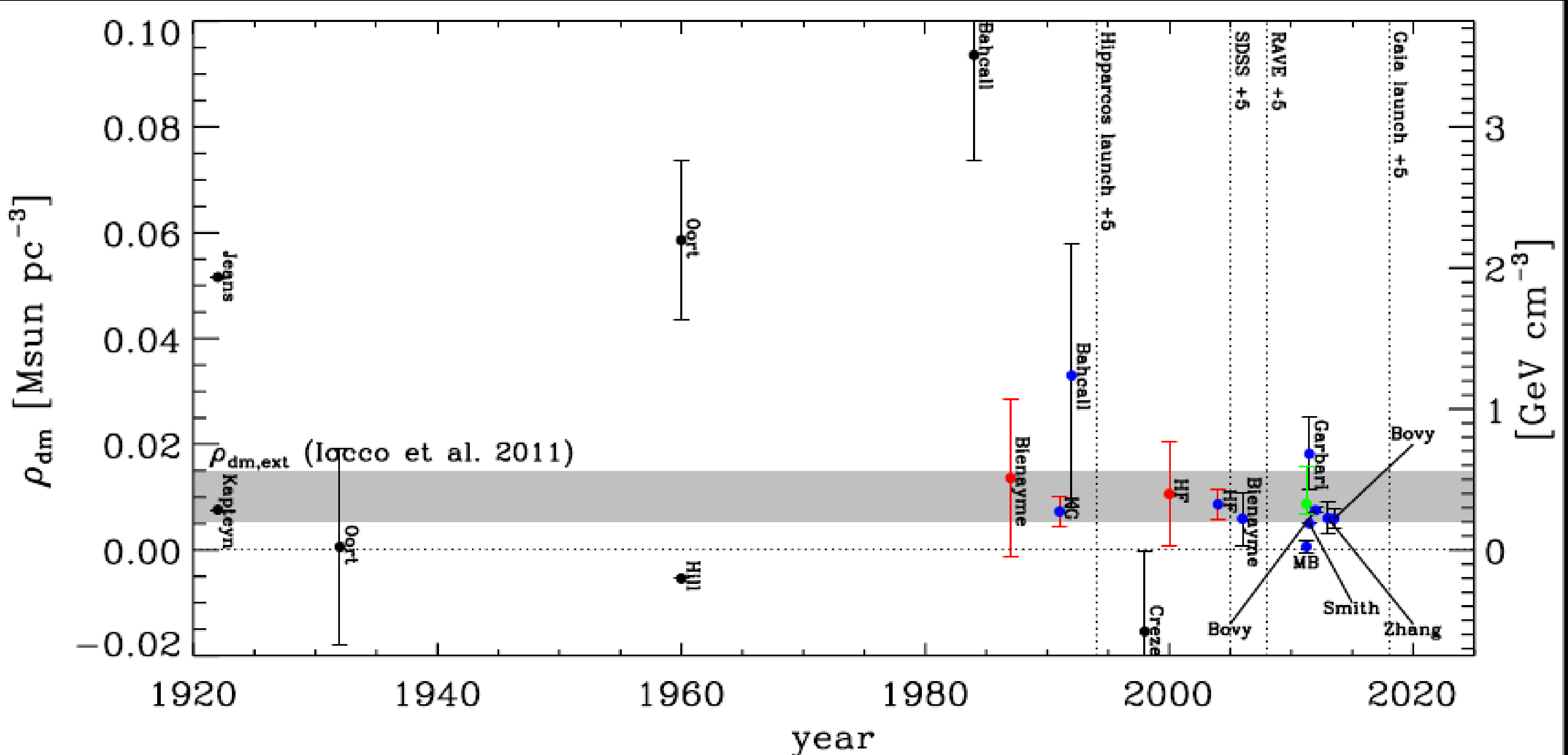
$$\rho_c = \frac{3H_0^2}{8\pi G} = 0.92 \times 10^{-29}\,\mathrm{g\,cm^{-3}} = 5.16 \times 10^{-6}\,\mathrm{GeV\,cm^{-3}}$$

$$\rho_{\mathrm{DM}} = 0.268\,\rho_c = 2.47 \times 10^{-30}\,\mathrm{g\,cm^{-3}} = 1.39 \times 10^{-6}\,\mathrm{GeV\,cm^{-3}}$$

$$\rho_{\mathrm{B}} = 0.049\,\rho_c = 0.45 \times 10^{-30}\,\mathrm{g\,cm^{-3}} = 0.25 \times 10^{-6}\,\mathrm{GeV\,cm^{-3}}$$

$$\rho_{\mathrm{DE}} = 0.683\,\rho_c = 3.52 \times 10^{-6}\,\mathrm{GeV\,cm^{-3}}$$

Dark Matter Density near the Solar System



$$\rho_{\rm dm} = 0.33^{+0.26}_{-0.075}\,{\rm GeV\,cm^{-3}}$$

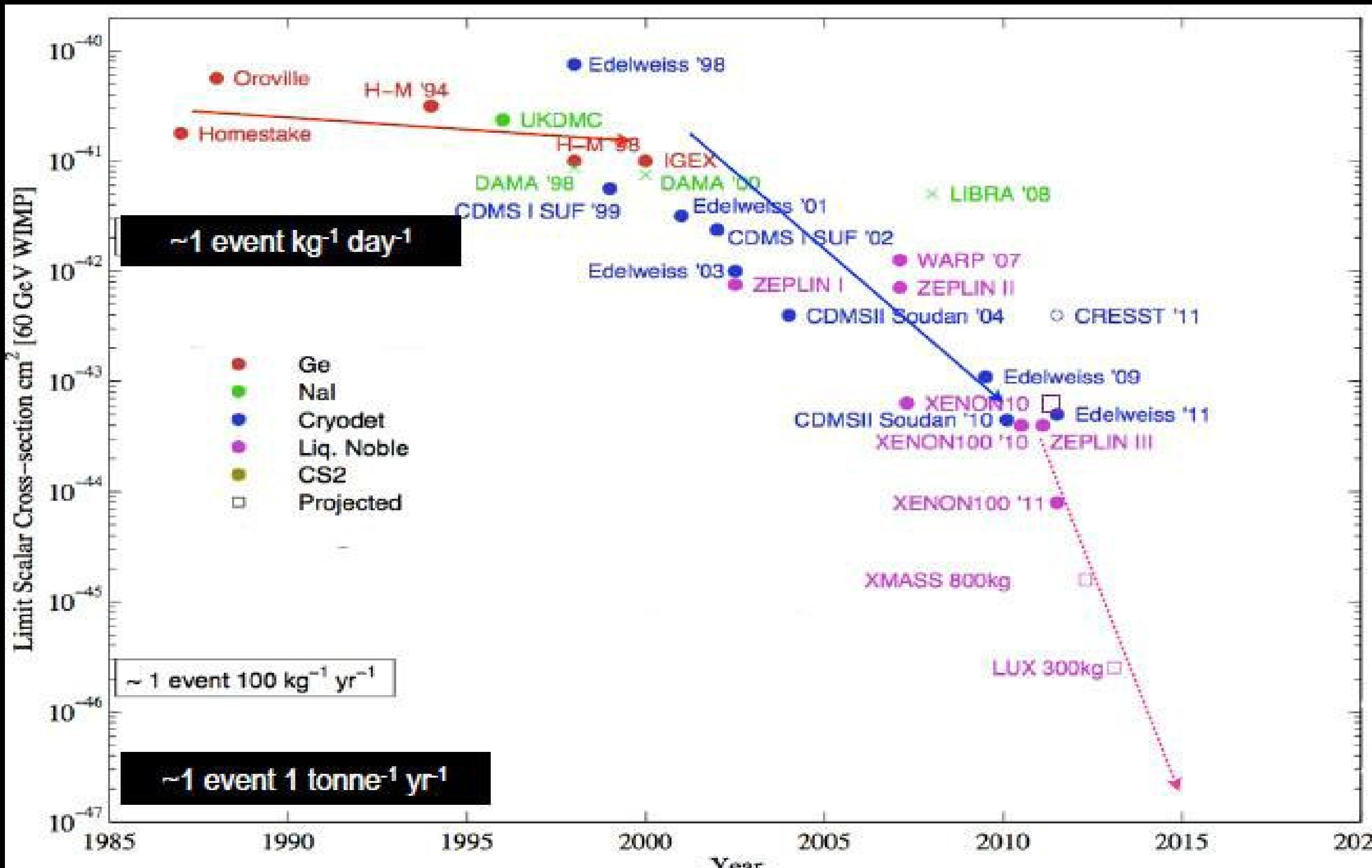
[volume complete; G12*;R14]

$$\rho_{\rm dm} = 0.25 \pm 0.09\,{\rm GeV\,cm^{-3}}$$

[SDSS; Z13]

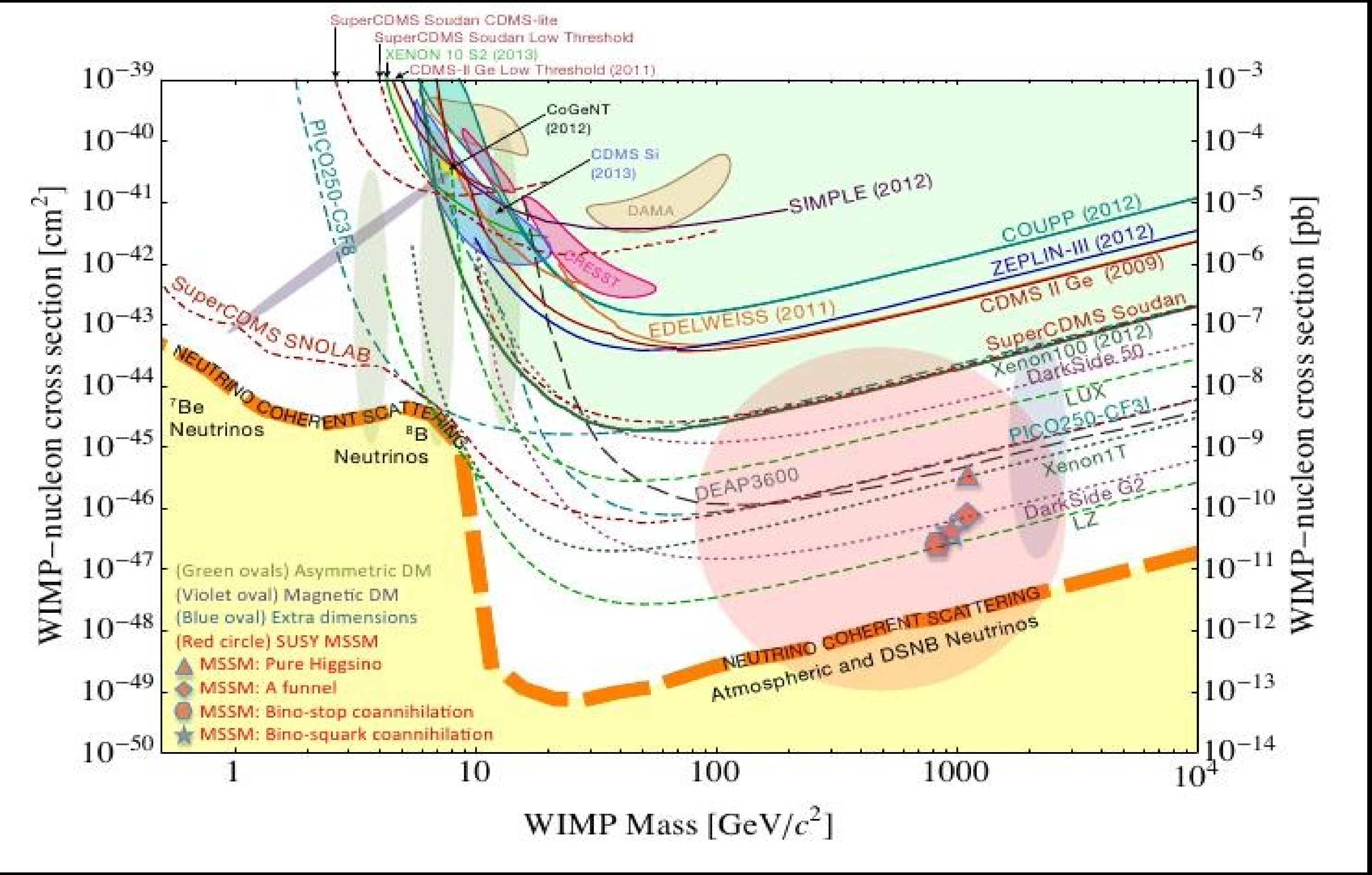
Read at IDM 2014

Wither WIMP Direct Detection?



Courtesy: Viktor Zacek (adapted from R. Gaitskell)

Ultimate Background: The Neutrino “Floor”



Cushman et al, arXiv:1310.8327

DM detectors will start detecting astrophysical neutrinos through Coherent Neutrino-Nucleus Elastic Scattering (SM process)!

Colliding Galaxy Clusters

"Bullet Cluster"