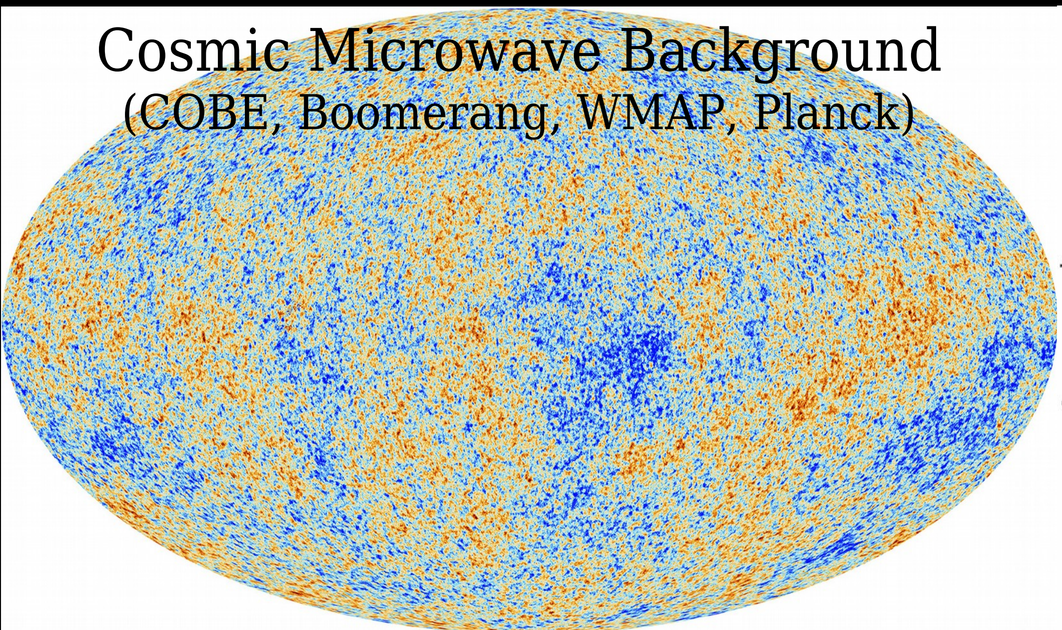
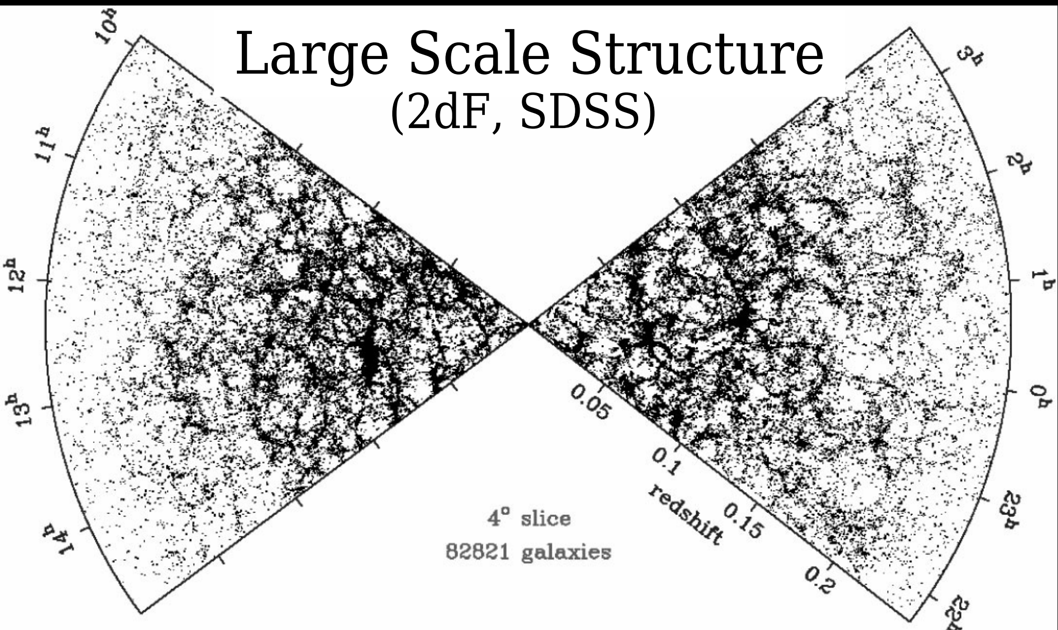
ESO Cosmic Duologue: The MOND perspective

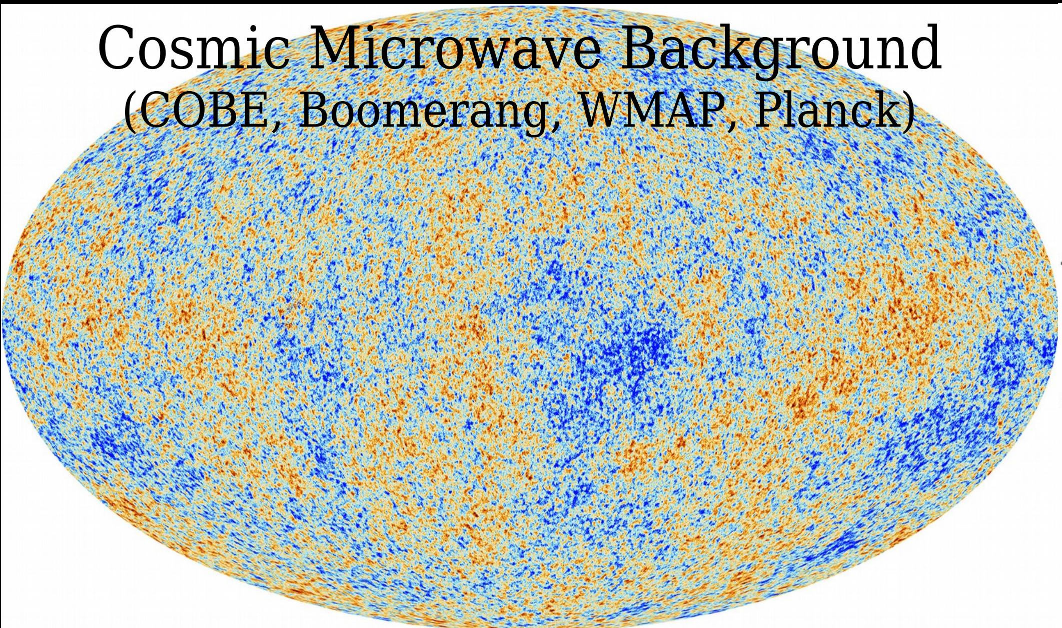
Federico Lelli
Cardiff University

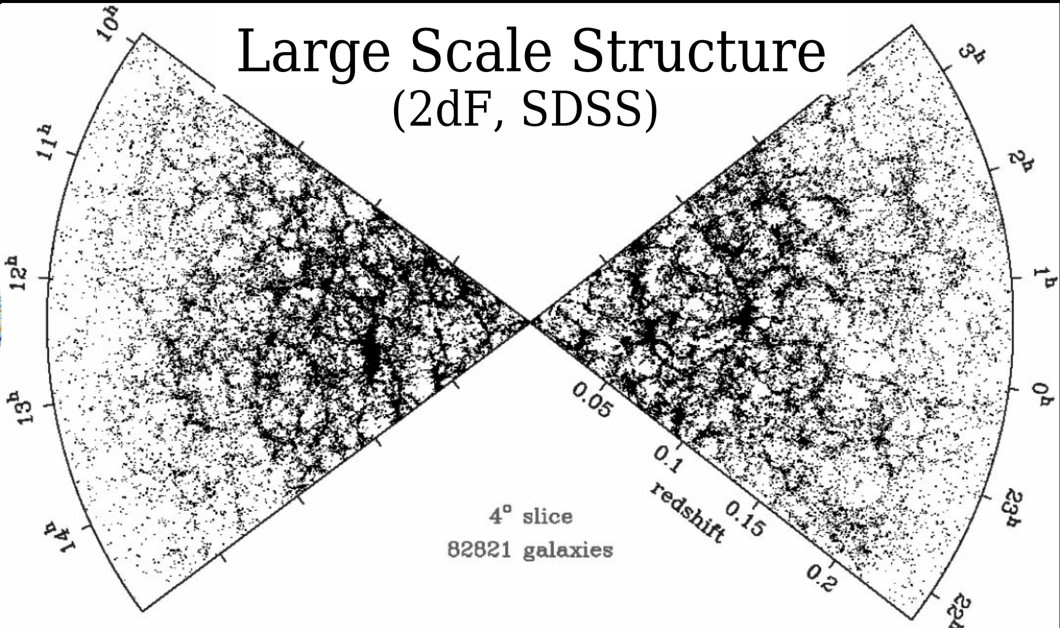
What do we *really* mean with Dark Matter?





Standard Gravity + SMoPP = Don’t Work





MOND = Modified Newtonian Dynamics or Milgromian Dynamics

Proposed by Mordehai Milgrom (1983a, 1983b, 1983c).

MOND is a general paradigm that includes several different non-relativistic theories as well as relativistic extensions.

MOND postulates (at the non-relativistic level)

1) New constant of Physics: a_0 ($\sim 10^{-10}$ m/s^2)

similar role as *c* in Relativity and *h* in Quantum Mechanics

MOND postulates (at the non-relativistic level)

1) New constant of Physics: a_0 ($\sim 10^{-10}$ m/s^2)

similar role as *c* in Relativity and *h* in Quantum Mechanics

2) For $a \gg a_0$; $a = g_N$ (correspondence principle as in QM)

$a = \frac{d^2 x}{dt^2}$ kinetic (observed) acceleration of a particle

$g_N = -\nabla \phi_N$ Newtonian gravitational field (Poisson's eq.)

MOND postulates (at the non-relativistic level)

1) New constant of Physics: a_0 ($\sim 10^{-10}$ m/s^2)

similar role as *c* in Relativity and *h* in Quantum Mechanics

2) For a » a_0; a = g_N (correspondence principle as in QM)

$a = \frac{d^2 x}{dt^2}$ kinetic (observed) acceleration of a particle

$g_N = -\nabla \phi_N$ Newtonian gravitational field (Poisson's eq.)

3) For a « a_0; scale invariance (Milgrom 2009): $(x', t') \rightarrow (\lambda x, \lambda t)$

MOND postulates (at the non-relativistic level)

1) New constant of Physics: a_0 ($\sim 10^{-10}$ m/s^2)

similar role as *c* in Relativity and *h* in Quantum Mechanics

2) For a » a_0; a = g_N (correspondence principle as in QM)

$a = \frac{d^2 x}{dt^2}$ kinetic (observed) acceleration of a particle

$g_N = -\nabla \phi_N$ Newtonian gravitational field (Poisson's eq.)

3) For a « a_0; scale invariance (Milgrom 2009): $(x', t') \rightarrow (\lambda x, \lambda t)$

$$a = \sqrt{g_N a_0}$$

MOND postulates (at the non-relativistic level)

1) New constant of Physics: a_0 (~10^{-10} m/s^2)

similar role as *c* in Relativity and *h* in Quantum Mechanics

2) For a » a_0; a = g_N (correspondence principle as in QM)

$a = \frac{d^2 x}{dt^2}$ kinetic (observed) acceleration of a particle

$g_N = -\nabla \phi_N$ Newtonian gravitational field (Poisson's eq.)

3) For a « a_0; scale invariance (Milgrom 2009): $(x', t') \rightarrow (\lambda x, \lambda t)$

$$a = \sqrt{g_N a_0} \quad \Rightarrow \quad \frac{V^2}{R} = \sqrt{\frac{a_0 G M_b}{R^2}}$$

Circular orbit
at large radii

MOND postulates (at the non-relativistic level)

1) New constant of Physics: a_0 ($\sim 10^{-10}$ m/s^2)

similar role as *c* in Relativity and *h* in Quantum Mechanics

2) For a » a_0; a = g_N (correspondence principle as in QM)

$a = \frac{d^2 x}{dt^2}$ kinetic (observed) acceleration of a particle

$g_N = -\nabla \phi_N$ Newtonian gravitational field (Poisson's eq.)

3) For a « a_0; scale invariance (Milgrom 2009): $(x', t') \rightarrow (\lambda x, \lambda t)$

$$a = \sqrt{g_N a_0} \Rightarrow \frac{V^2}{R} = \sqrt{\frac{a_0 G M_b}{R^2}} \Rightarrow V^2 = \sqrt{a_0 G M_b}$$

Circular orbit at large radii

Flat rotation curve at large radii

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXIES[1]

M. MILGROM
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study

Received 1982 February 4; accepted 1982 December 28

Milgrom 1983, ApJ, 270, 371

ABSTRACT

I use a modified form of the Newtonian dynamics (inertia and/or gravity) to describe the motion of bodies in the gravitational fields of galaxies, *assuming that galaxies contain no hidden mass*, with the following main results.

1. The Keplerian, circular velocity around a finite galaxy becomes independent of r at large radii, thus resulting in asymptotically flat velocity curves.
2. The asymptotic circular velocity (V_∞) is determined only by the total mass of the galaxy (M): $V_\infty^4 = a_0 GM$, where a_0 is an acceleration constant appearing in the modified dynamics. This relation is consistent with the observed Tully-Fisher relation if one uses a luminosity parameter which is proportional to the observable mass.
3. The discrepancy between the dynamically determined Oort density in the solar neighborhood and the density of observed matter disappears.
4. The rotation curve of a galaxy can remain flat down to very small radii, as observed, only if the galaxy's average surface density Σ falls in some narrow range of values which agrees with the Fish and Freeman laws. For smaller values of Σ, the velocity rises more slowly to the asymptotic value.
5. The value of the acceleration constant, a_0, determined in a few independent ways is approximately $2\times10^{-8}(H_0/50\ \mathrm{km\ s^{-1}\ Mpc^{-1}})^2\ \mathrm{cm\ s^{-2}}$, which is of the order of $CH_0 = 5\times10^{-8}(H_0/50\ \mathrm{km\ s^{-1}\ Mpc^{-1}})\ \mathrm{cm\ s^{-2}}$.

The main predictions are:

1. Rotation curves calculated on the basis of the *observed* mass distribution and the modified dynamics should agree with the observed velocity curves.
2. The $V_\infty^4 = a_0 GM$ relation should hold exactly.
3. An analog of the Oort discrepancy should exist in all galaxies and become more severe with increasing r in a predictable way.

Milgrom 1983, ApJ, 270, 371

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXIES[1]

M. MILGROM
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study

Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I use a modified form of the Newtonian dynamics (inertia and/or gravity) to describe the motion of bodies in the gravitational fields of galaxies, *assuming that galaxies contain no hidden mass*, with the following main results.

1. The Keplerian, circular velocity around a finite galaxy becomes independent of r at large radii, thus resulting in asymptotically flat velocity curves.(→ known before 1983)

2. The asymptotic circular velocity (V_∞) is determined only by the total mass of the galaxy (M): $V_\infty^4 = a_0 GM$, where a_0 is an acceleration constant appearing in the modified dynamics. This relation is consistent with the observed Tully-Fisher relation if one uses a luminosity parameter which is proportional to the observable mass.

3. The discrepancy between the dynamically determined Oort density in the solar neighborhood and the density of observed matter disappears.

4. The rotation curve of a galaxy can remain flat down to very small radii, as observed, only if the galaxy's average surface density Σ falls in some narrow range of values which agrees with the Fish and Freeman laws. For smaller values of Σ, the velocity rises more slowly to the asymptotic value.

5. The value of the acceleration constant, a_0, determined in a few independent ways is approximately $2 \times 10^{-8} (H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})^2 \text{ cm s}^{-2}$, which is of the order of $CH_0 = 5 \times 10^{-8} (H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1}) \text{ cm s}^{-2}$.

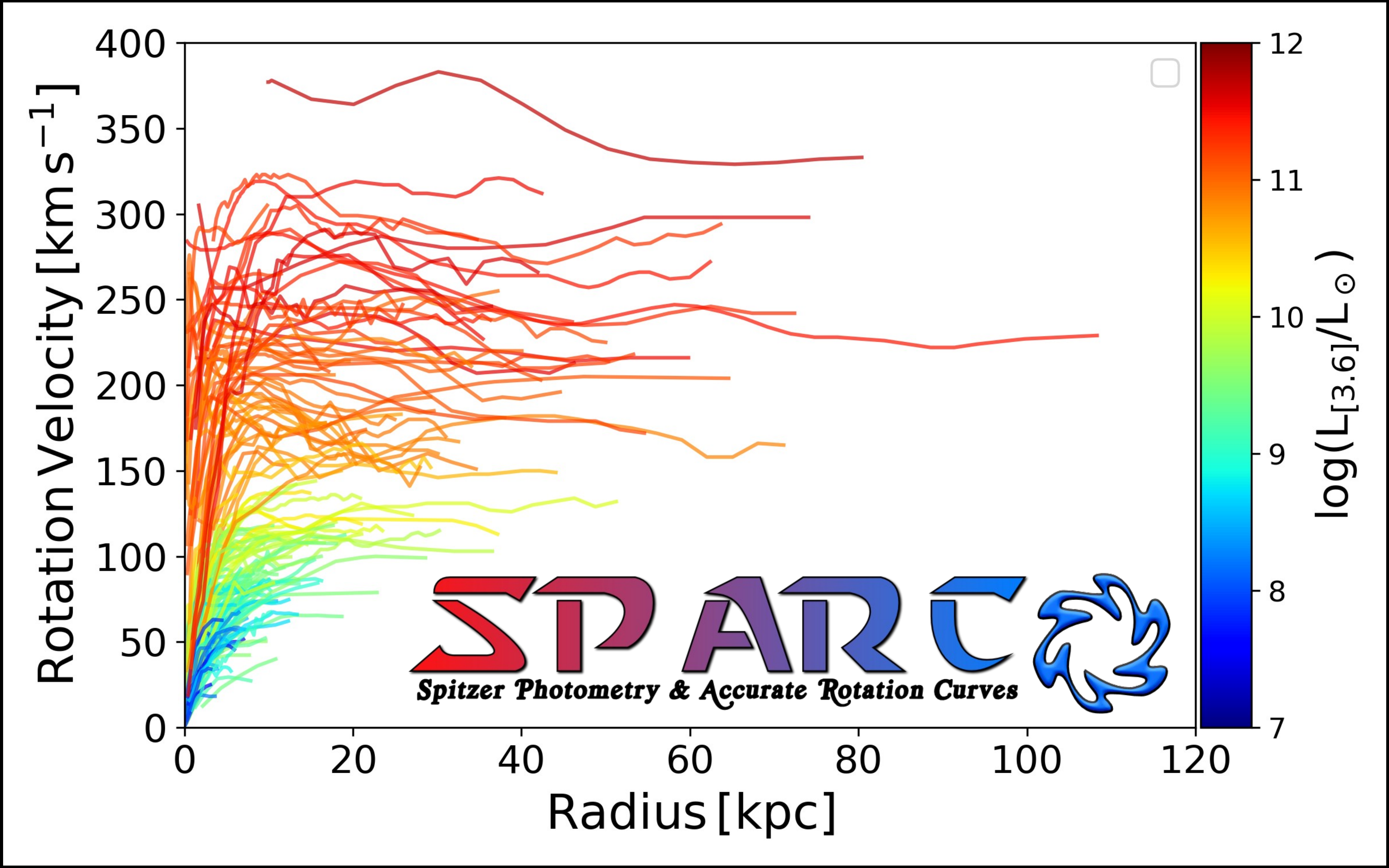
The main predictions are:

1. Rotation curves calculated on the basis of the *observed* mass distribution and the modified dynamics should agree with the observed velocity curves.

2. The $V_\infty^4 = a_0 GM$ relation should hold exactly.

3. An analog of the Oort discrepancy should exist in all galaxies and become more severe with increasing r in a predictable way.

Rotation curves stay flat out to large radii



Lelli, McGaugh & Schombert (2016). All data: http://astroweb.cwru.edu/SPARC/

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXIES[1]

M. MILGROM
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study

Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I use a modified form of the Newtonian dynamics (inertia and/or gravity) to describe the motion of bodies in the gravitational fields of galaxies, *assuming that galaxies contain no hidden mass*, with the following main results.

1. The Keplerian, circular velocity around a finite galaxy becomes independent of r at large radii, thus resulting in asymptotically flat velocity curves.

2. The asymptotic circular velocity (V_∞) is determined only by the total mass of the galaxy (M): $V_\infty^4 = a_0 GM$, where a_0 is an acceleration constant appearing in the modified dynamics. This relation is consistent with the observed Tully-Fisher relation if one uses a luminosity parameter which is proportional to the observable mass.

3. The discrepancy between the dynamically determined Oort density in the solar neighborhood and the density of observed matter disappears.

4. The rotation curve of a galaxy can remain flat down to very small radii, as observed, only if the galaxy's average surface density Σ falls in some narrow range of values which agrees with the Fish and Freeman laws. For smaller values of Σ, the velocity rises more slowly to the asymptotic value.

5. The value of the acceleration constant, a_0, determined in a few independent ways is approximately $2 \times 10^{-8}(H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})^2$ cm s^{-2}, which is of the order of $CH_0 = 5 \times 10^{-8}(H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})$ cm s^{-2}.

The main predictions are:

1. Rotation curves calculated on the basis of the *observed* mass distribution and the modified dynamics should agree with the observed velocity curves.

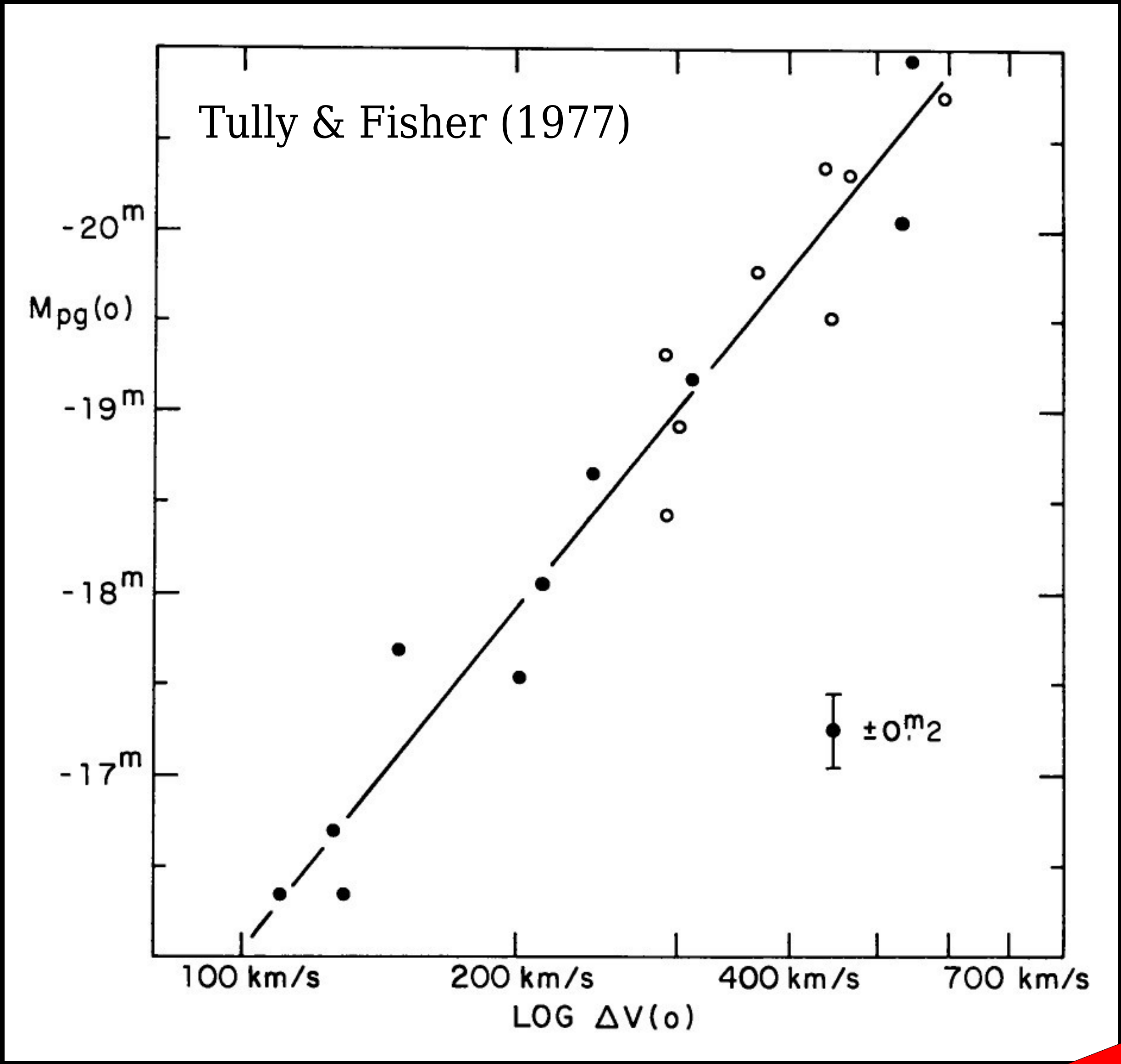
2. The $V_\infty^4 = a_0 GM$ relation should hold exactly.

3. An analog of the Oort discrepancy should exist in all galaxies and become more severe with increasing r in a predictable way.

Milgrom 1983, ApJ, 270, 371

The classic Tully-Fisher relation in 1983

Galaxy Luminosity (~Stellar Mass)



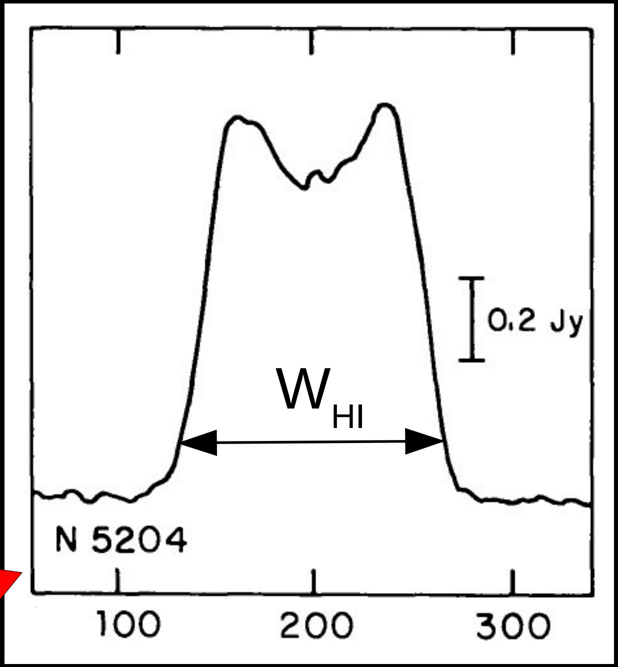
HI Linewidth (~2 Rotation Velocity)

TF slope constrained between ~2 and ~5

(Aaronson+1979; Bottinelli+1980; Rubin+1980; Visvanathan 1981; de Vaucouleurs 1982)

Global HI line profile

HI Flux (Jy)



Line-of-sight Velocity (km/s)

"The $V_\infty^4 = a_0 G M_b$ relation should hold exactly"

(Milgrom 1983)

This contains four independent predictions:

1) Luminosity in TFR → baryonic mass (stars+gas)

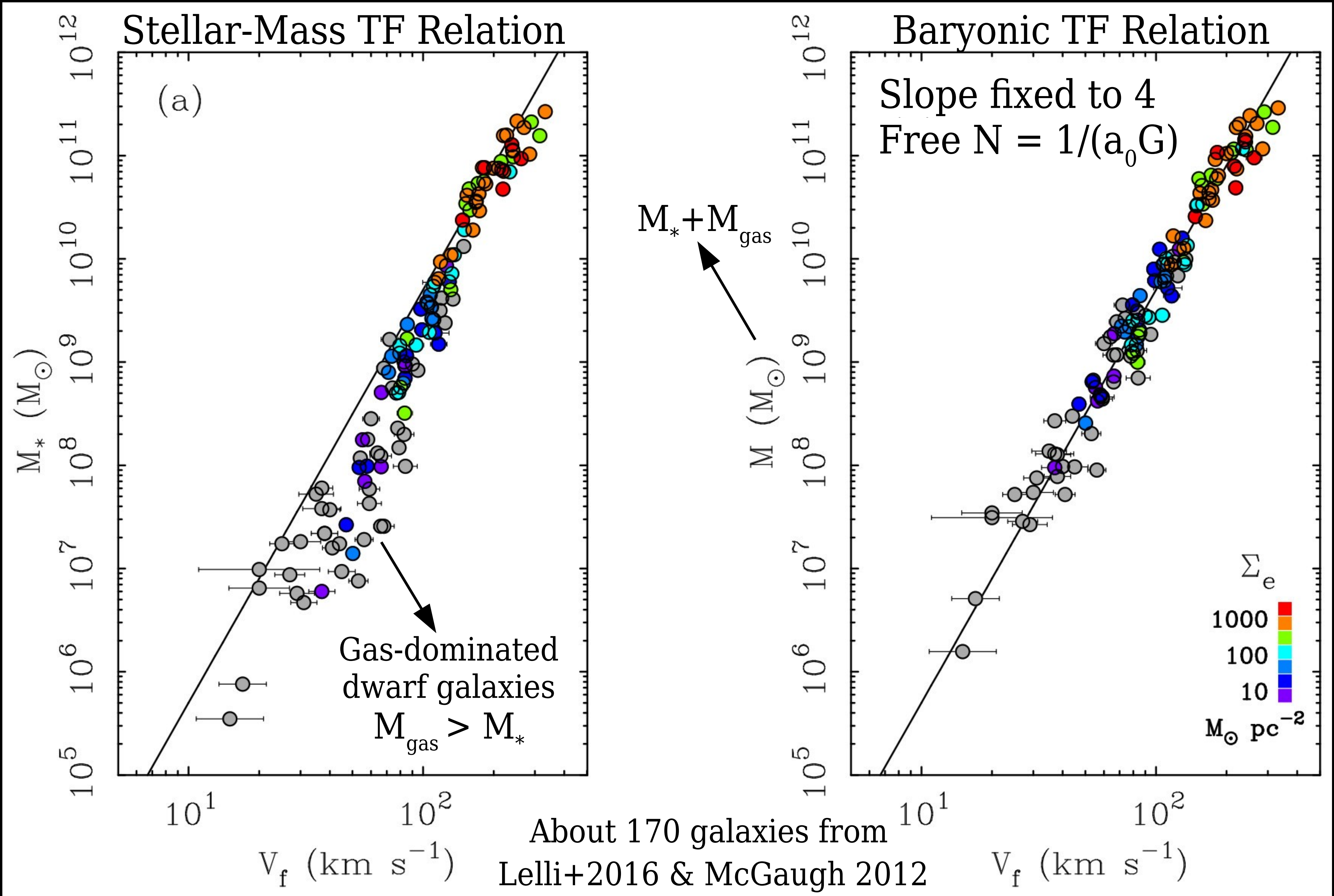
2) HI linewidth in TFR → $V_\infty \simeq V_f$ (mean V along the flat part)

3) Slope must be equal to 4

4) No dependence on galaxy size or surface density Σ_b

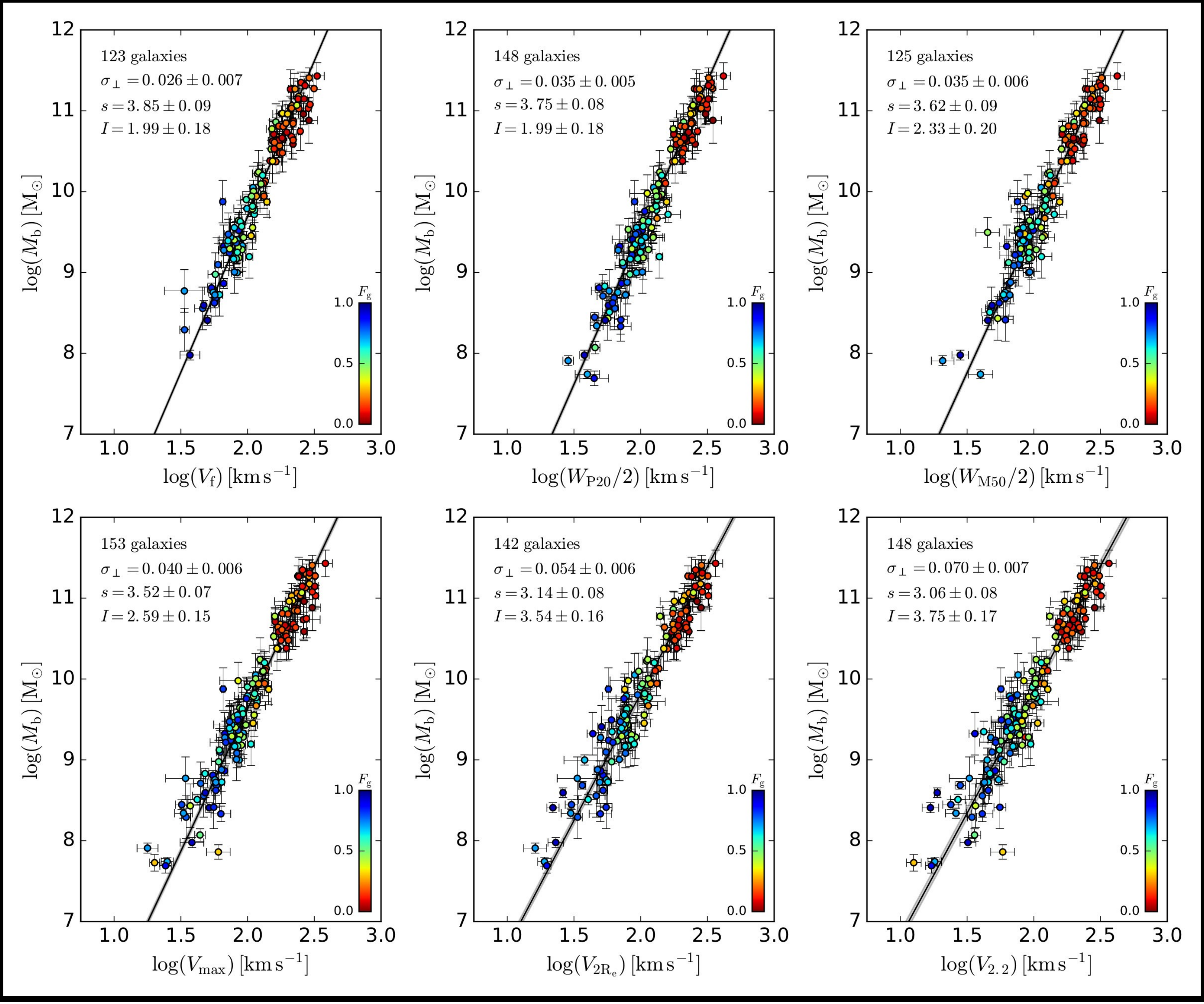
Newton says $V^2/R = GM_b/R^2 \rightarrow V^4 = G^2 \Sigma_b M_b$

37 years after the MOND prediction



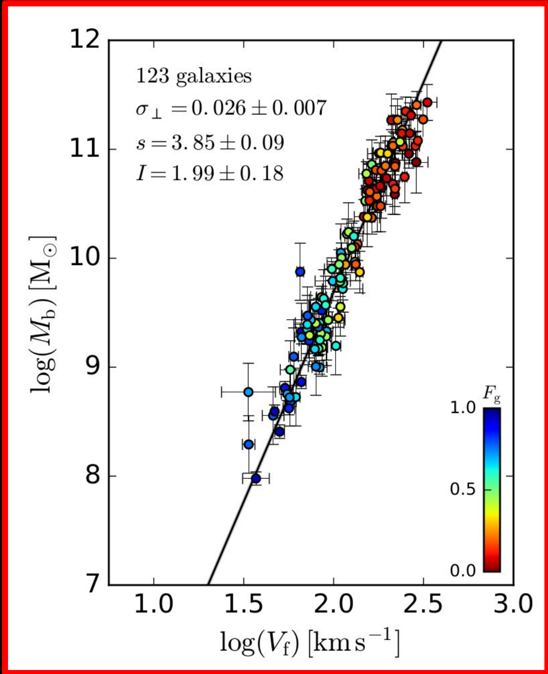
About 170 galaxies from
Lelli+2016 & McGaugh 2012

Which velocity best correlates with M_b?



Lelli+2019

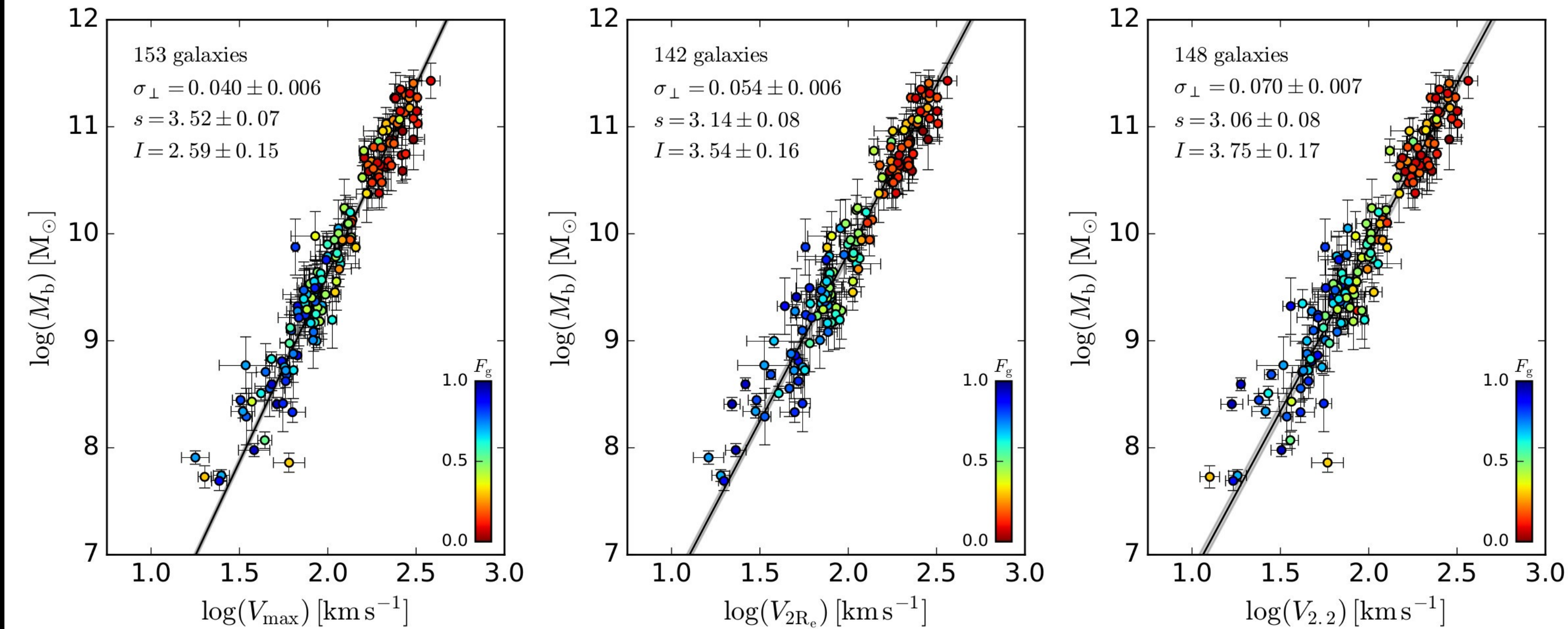
Which velocity best correlates with M_b?



V_f gives the tightest BTFR (Verheijen 2001; McGaugh 2005; Noordermeer & Verheijen 2007)

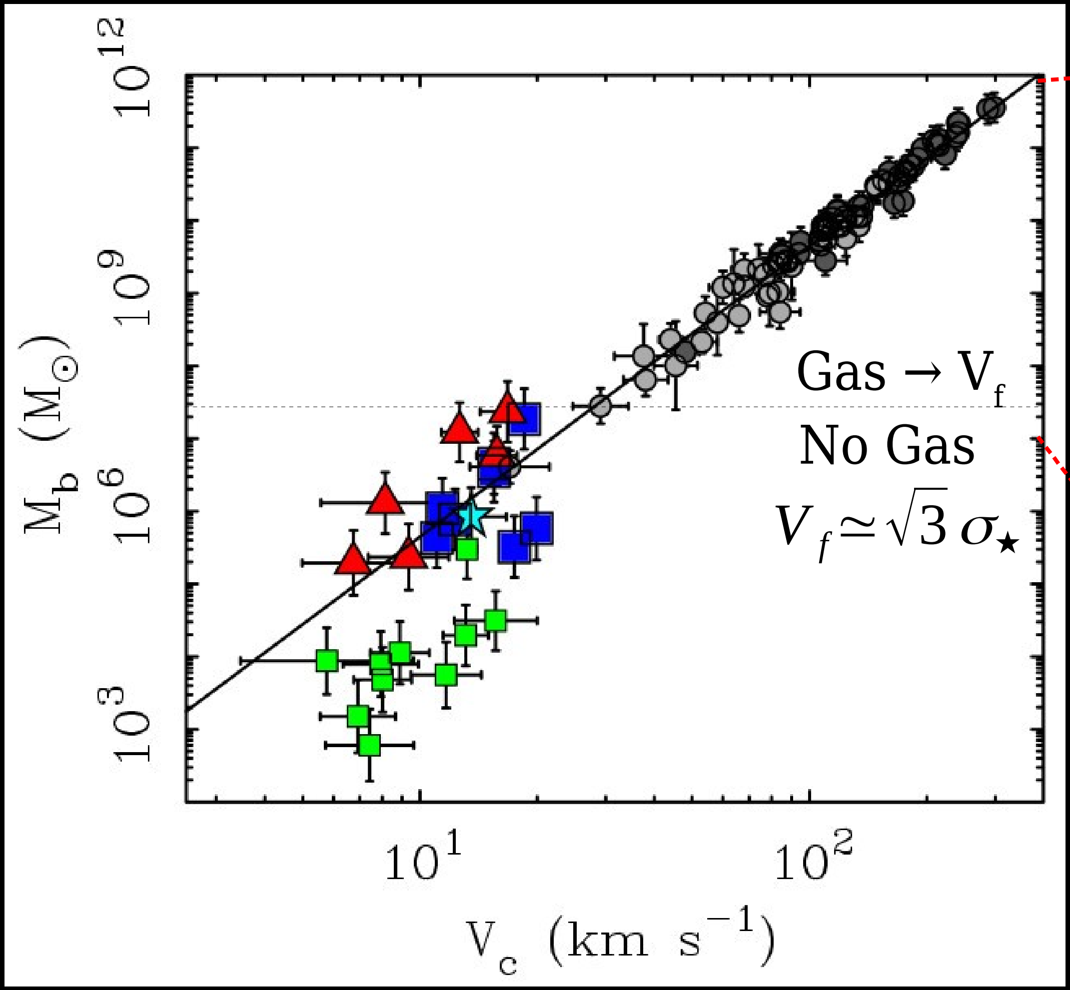
Counter-intuitive result!

Baryons are important near the center, but M_b best correlates with V at large radii where DM should dominate!

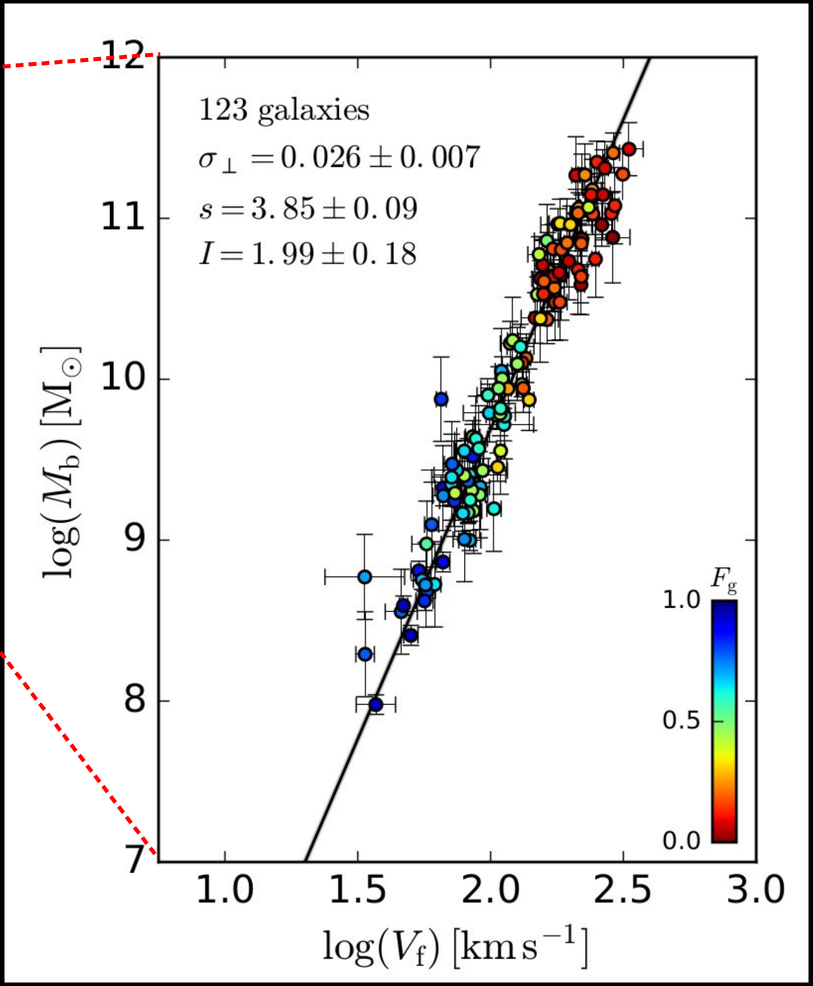


Lelli+2019

BTFR for MW and M31 Dwarf Satellites

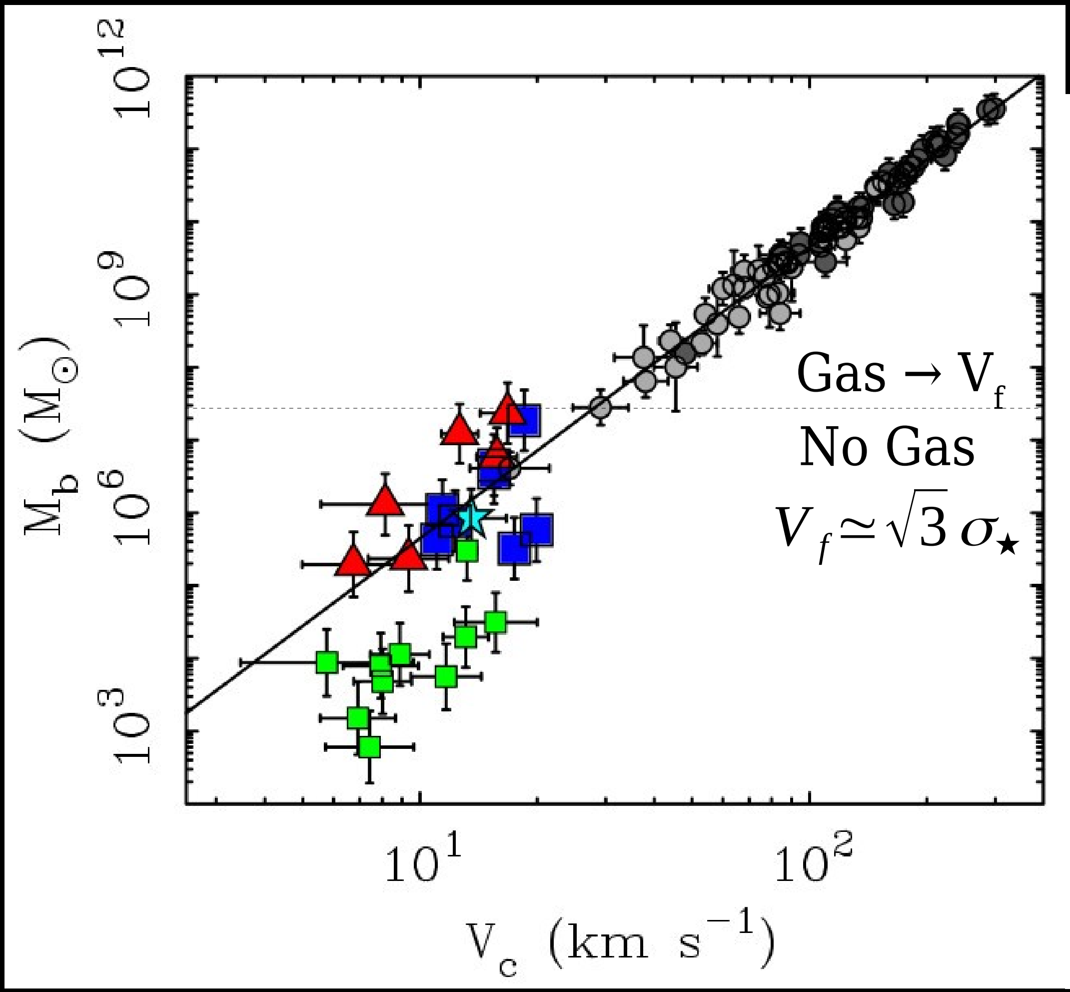


McGaugh & Wolf (2010)



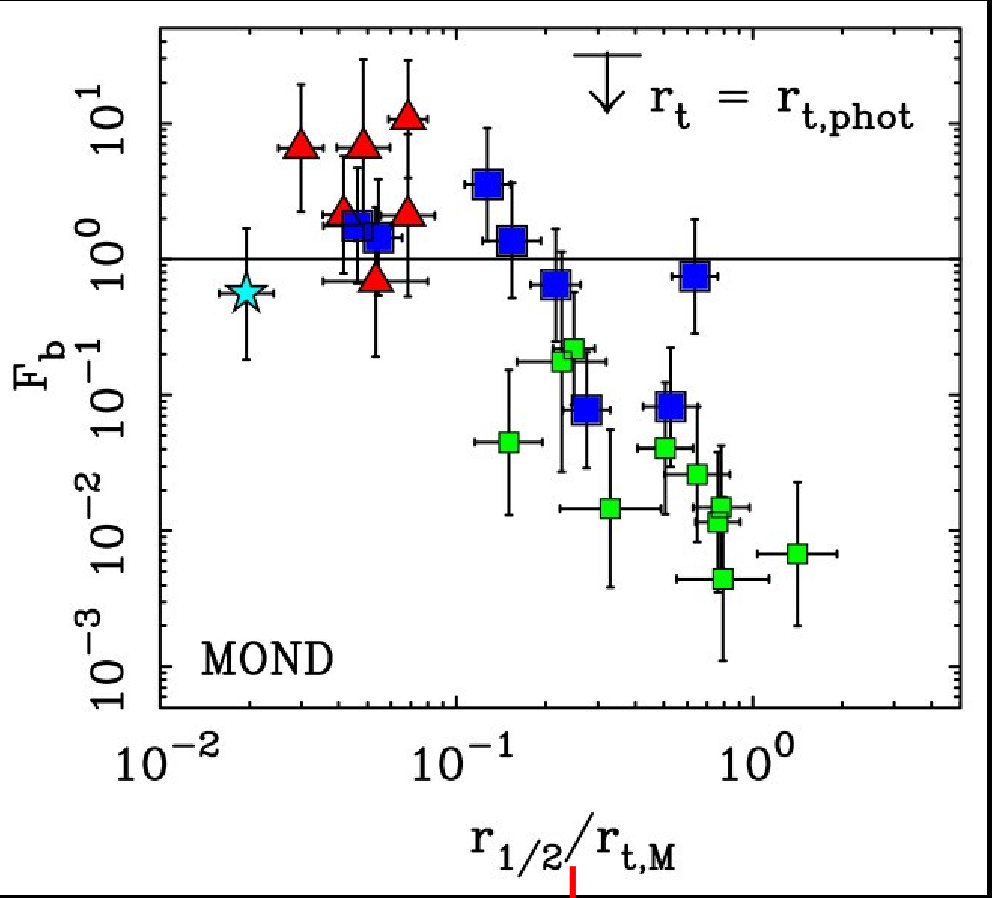
Lelli+2019

BTFR for MW and M31 Dwarf Satellites



McGaugh & Wolf (2010)

Strength of Deviations vs Tides



Half-Light Radius / Tidal Radius

BTFR holds for equilibrium systems

→ some satellites are out of dynamical equilibrium due to tidal forces

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXIES[1]

Milgrom 1983, ApJ, 270, 371

M. MILGROM
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study

Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I use a modified form of the Newtonian dynamics (inertia and/or gravity) to describe the motion of bodies in the gravitational fields of galaxies, *assuming that galaxies contain no hidden mass*, with the following main results.

1. The Keplerian, circular velocity around a finite galaxy becomes independent of r at large radii, thus resulting in asymptotically flat velocity curves.

2. The asymptotic circular velocity (V_∞) is determined only by the total mass of the galaxy (M): $V_\infty^4 = a_0 GM$, where a_0 is an acceleration constant appearing in the modified dynamics. This relation is consistent with the observed Tully-Fisher relation if one uses a luminosity parameter which is proportional to the observable mass.

3. The discrepancy between the dynamically determined Oort density in the solar neighborhood and the density of observed matter disappears.

4. The rotation curve of a galaxy can remain flat down to very small radii, as observed, only if the galaxy's average surface density Σ falls in some narrow range of values which agrees with the Fish and Freeman laws. For smaller values of Σ, the velocity rises more slowly to the asymptotic value.

5. The value of the acceleration constant, a_0, determined in a few independent ways is approximately $2 \times 10^{-8} (H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})^2$ cm s^{-2}, which is of the order of $CH_0 = 5 \times 10^{-8} (H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})$ cm s^{-2}.

The main predictions are:

1. Rotation curves calculated on the basis of the *observed* mass distribution and the modified dynamics should agree with the observed velocity curves.

2. The $V_\infty^4 = a_0 GM$ relation should hold exactly.

3. An analog of the Oort discrepancy should exist in all galaxies and become more severe with increasing r in a predictable way.

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXIES[1]

M. MILGROM
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

Milgrom 1983, ApJ, 270, 371

ABSTRACT

I use a modified form of the Newtonian dynamics (inertia and/or gravity) to describe the motion of bodies in the gravitational fields of galaxies, *assuming that galaxies contain no hidden mass*, with the following main results.

1. The Keplerian, circular velocity around a finite galaxy becomes independent of r at large radii, thus resulting in asymptotically flat velocity curves. ✓

2. The asymptotic circular velocity (V_∞) is determined only by the total mass of the galaxy (M): $V_\infty^4 = a_0 GM$, where a_0 is an acceleration constant appearing in the modified dynamics. This relation is consistent with the observed Tully-Fisher relation if one uses a luminosity parameter which is proportional to the observable mass. ✓

3. The discrepancy between the dynamically determined Oort density in the solar neighborhood and the density of observed matter disappears. ?

4. The rotation curve of a galaxy can remain flat down to very small radii, as observed, only if the galaxy's average surface density Σ falls in some narrow range of values which agrees with the Fish and Freeman laws. For smaller values of Σ, the velocity rises more slowly to the asymptotic value.

5. The value of the acceleration constant, a_0, determined in a few independent ways is approximately $2\times10^{-8}(H_0/50\ \mathrm{km\ s^{-1}\ Mpc^{-1}})^2\ \mathrm{cm\ s^{-2}}$, which is of the order of $CH_0 = 5\times10^{-8}(H_0/50\ \mathrm{km\ s^{-1}\ Mpc^{-1}})\ \mathrm{cm\ s^{-2}}$.

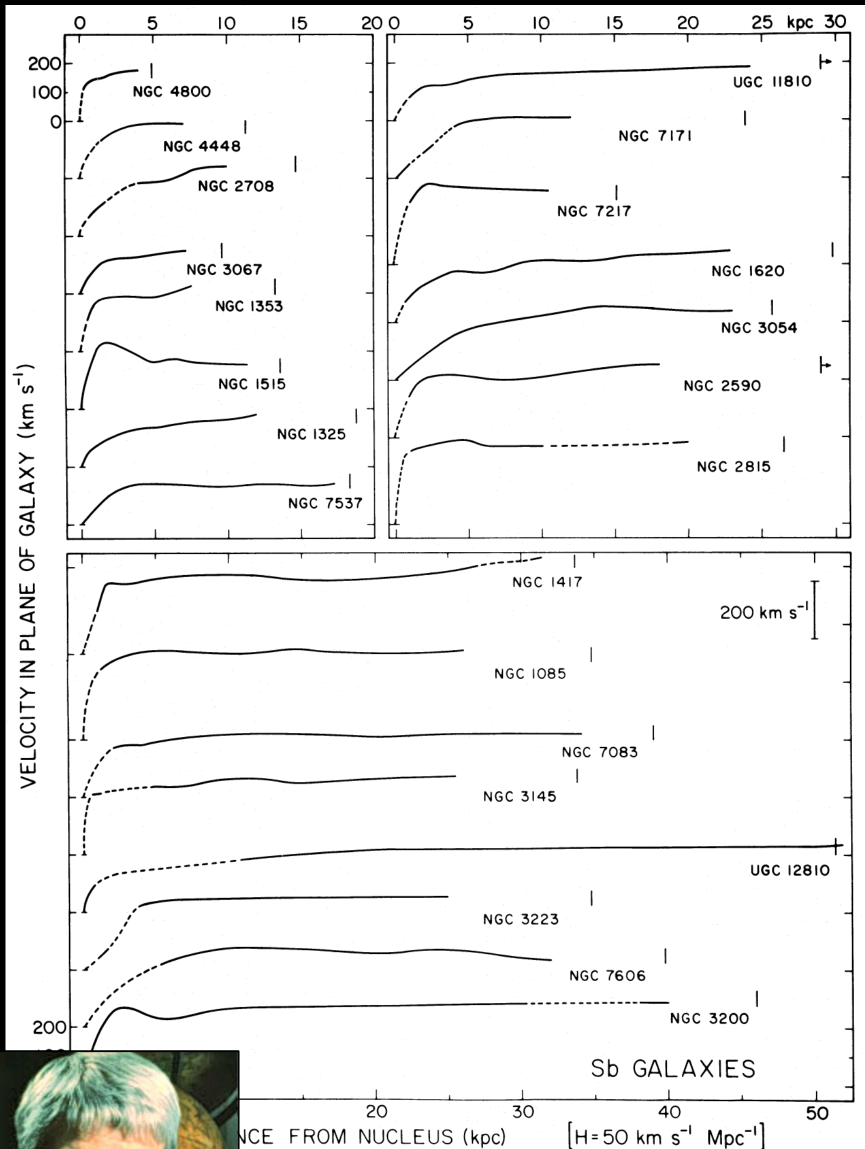
The main predictions are:

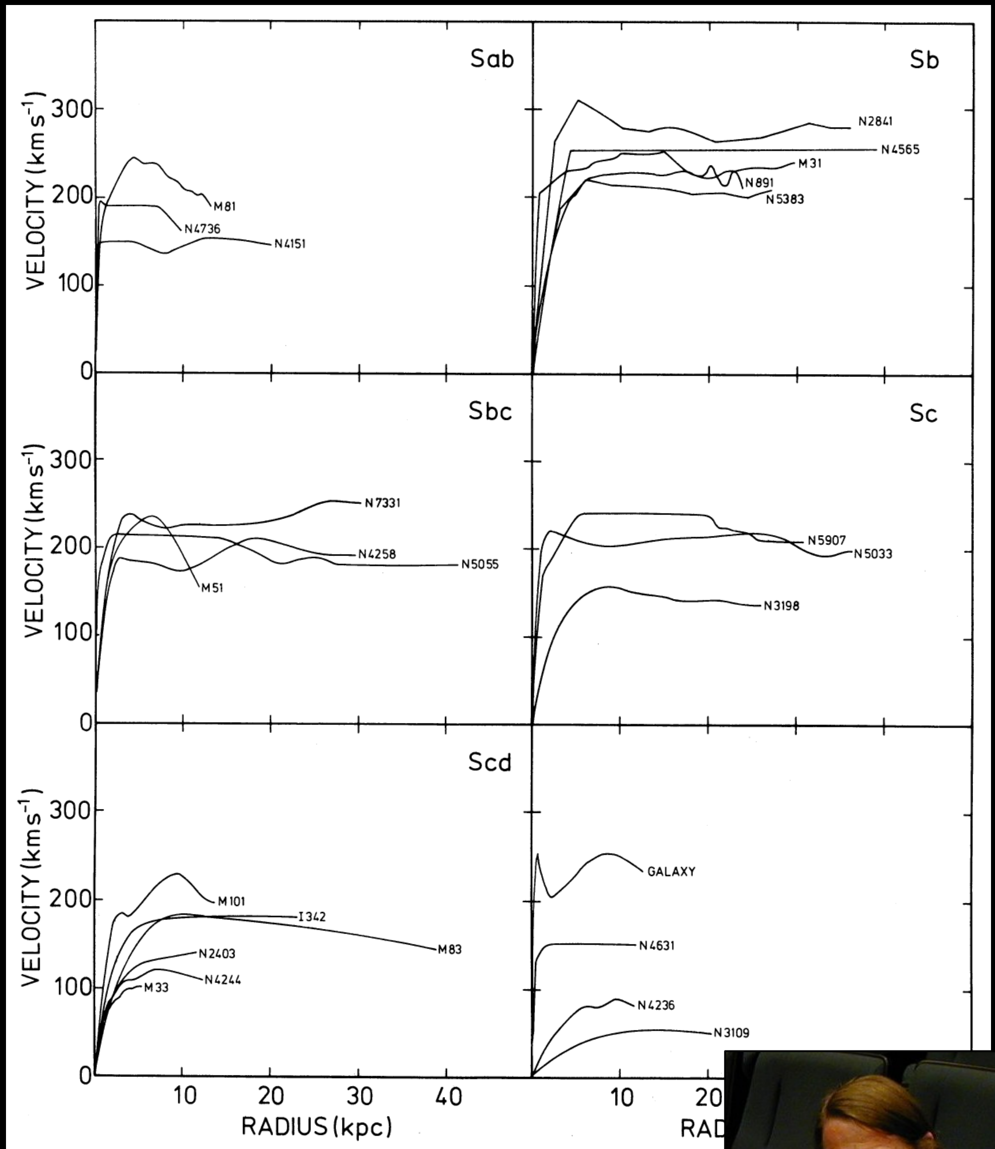
1. Rotation curves calculated on the basis of the *observed* mass distribution and the modified dynamics should agree with the observed velocity curves.

2. The $V_\infty^4 = a_0 GM$ relation should hold exactly. ✓

3. An analog of the Oort discrepancy should exist in all galaxies and become more severe with increasing r in a predictable way. ?

Rotation curves: state of the art in 1983





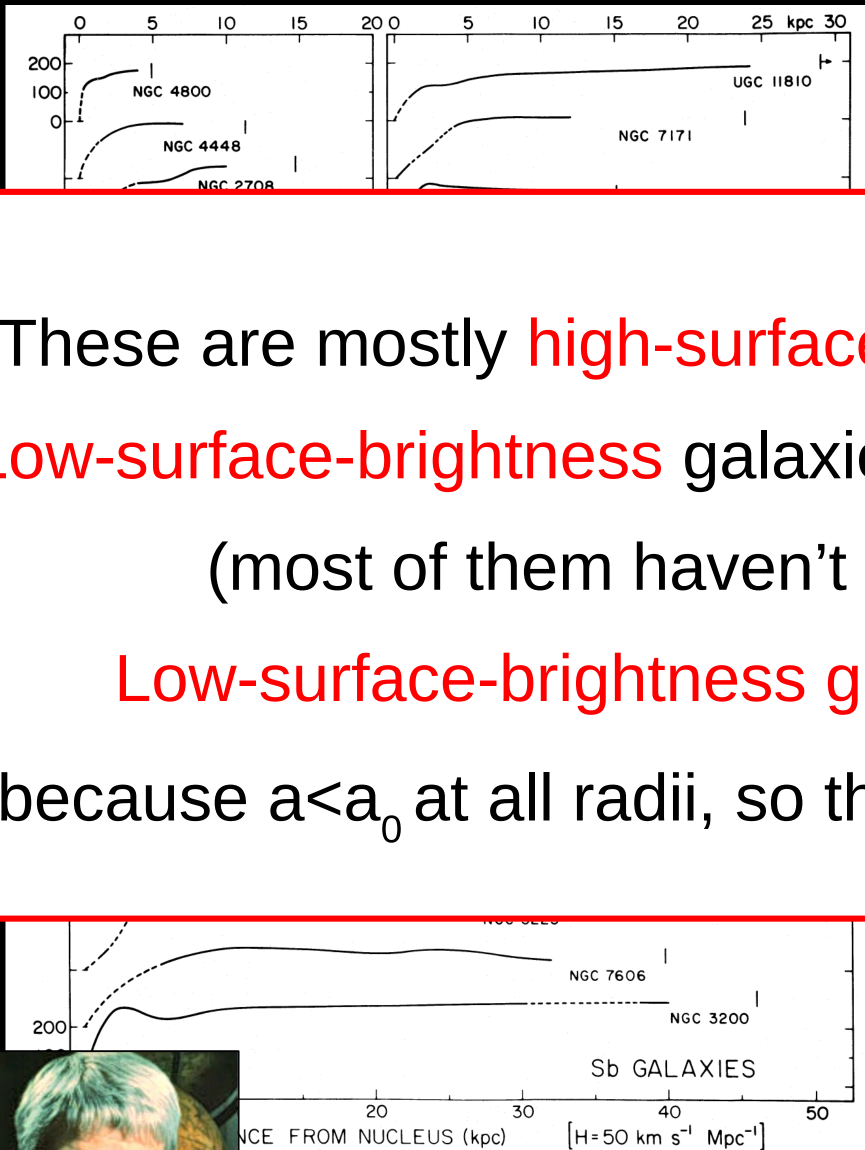
Optical - Ionized Gas (Hα)

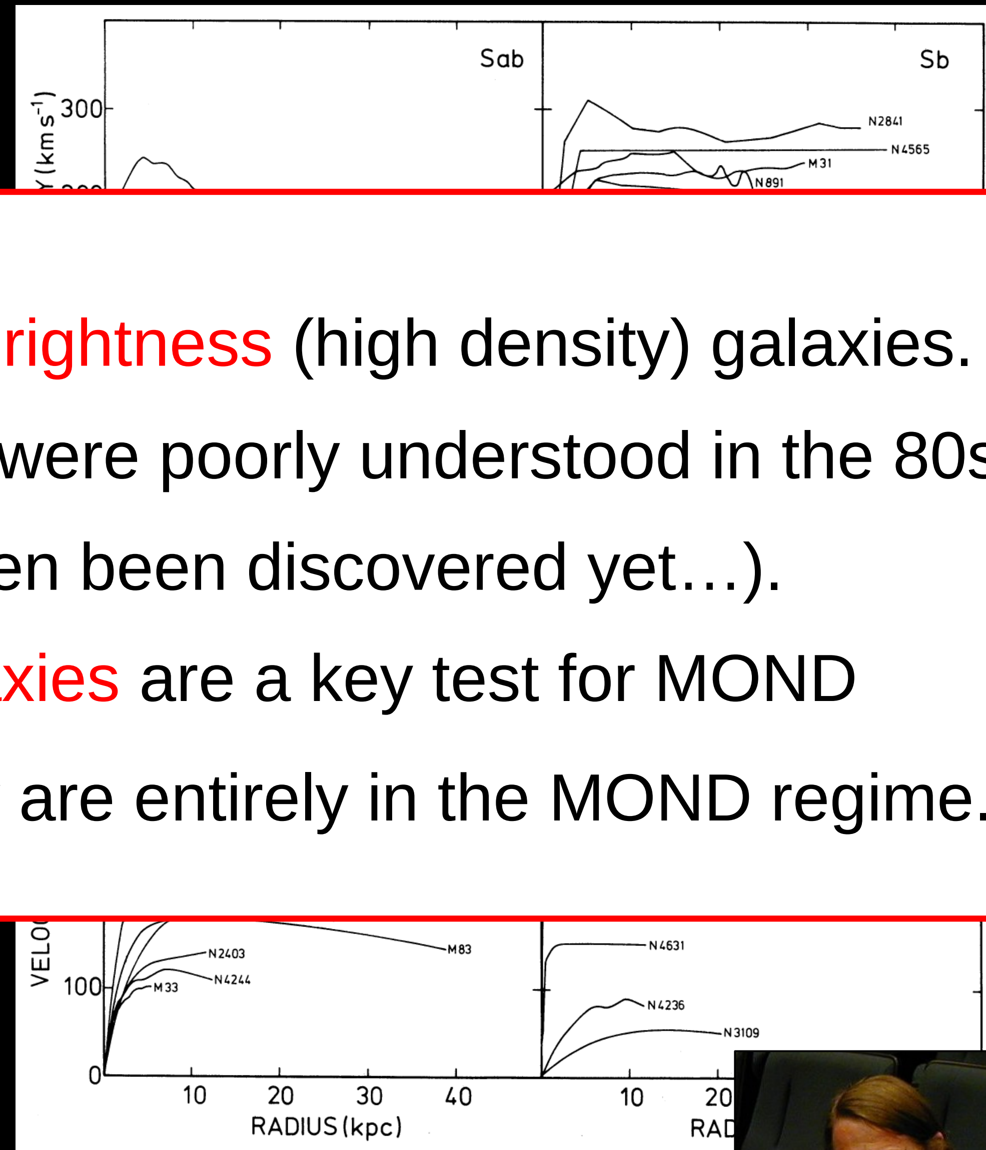
V. Rubin et al. (1981)

Radio - Atomic Gas (HI)

A. Bosma (1981)

Rotation curves: state of the art in 1983





These are mostly high-surface-brightness (high density) galaxies.

Low-surface-brightness galaxies were poorly understood in the 80s (most of them haven't even been discovered yet…).

Low-surface-brightness galaxies are a key test for MOND because $a<a_0$ at all radii, so they are entirely in the MOND regime.

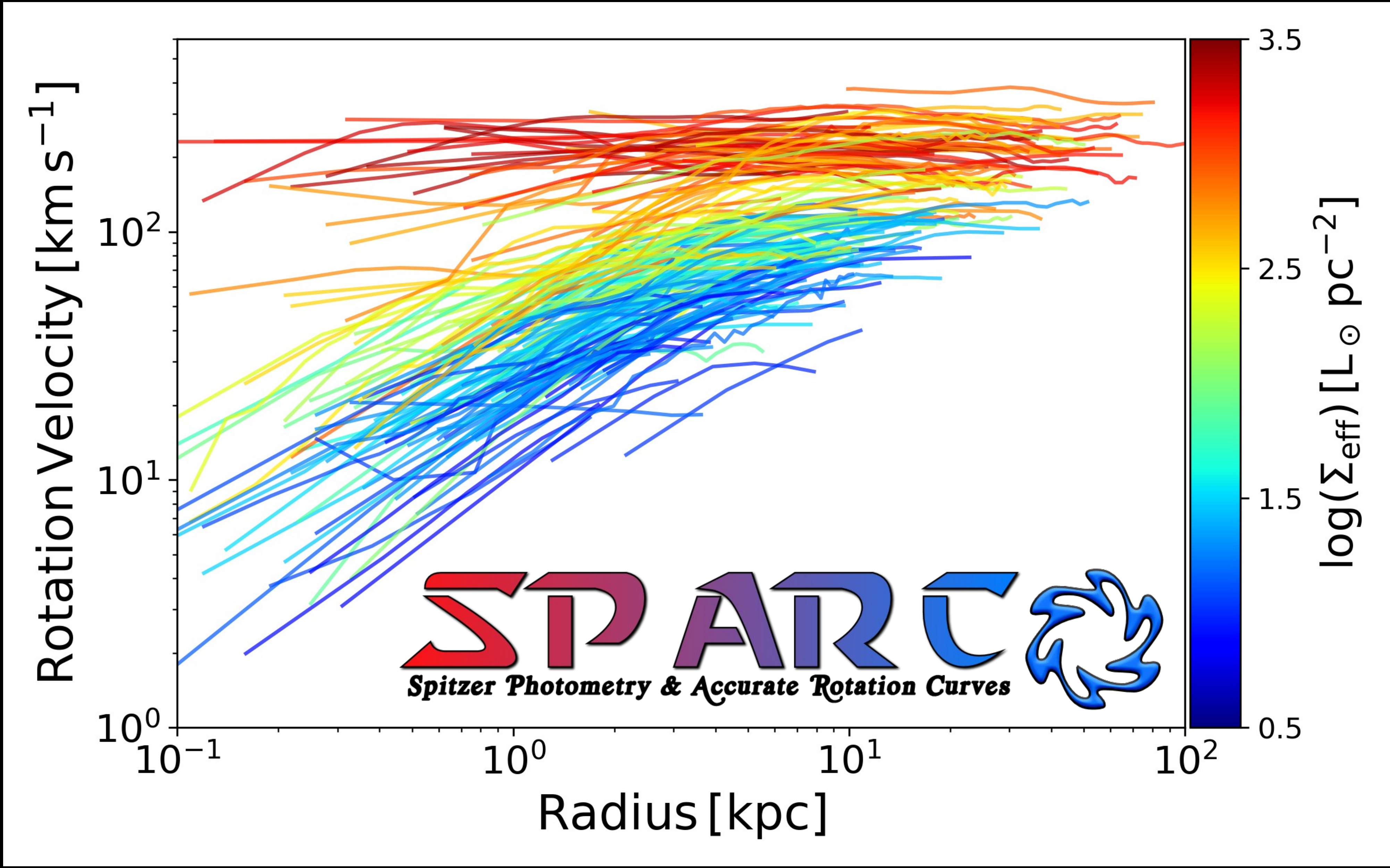
Optical - Ionized Gas (Hα)

V. Rubin et al. (1981)

Radio - Atomic Gas (HI)

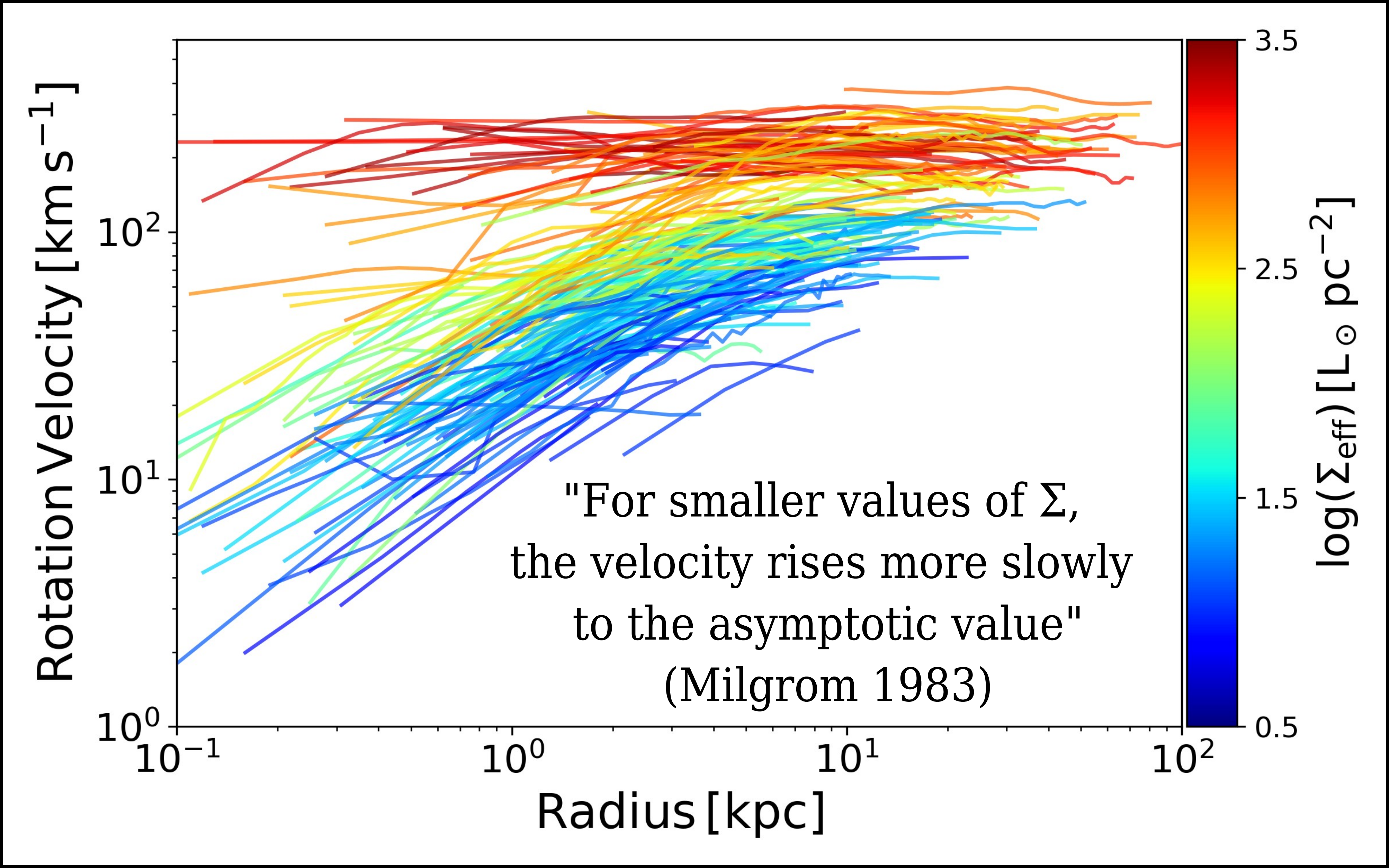
A. Bosma (1981)

37 years after Milgrom's prediction



Lelli, McGaugh & Schombert (2016). All data: http://astroweb.cwru.edu/SPARC/

37 years after Milgrom’s prediction



Lelli, McGaugh & Schombert (2016). All data: http://astroweb.cwru.edu/SPARC/

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXIES[1]

M. Milgrom
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

Milgrom 1983, ApJ, 270, 371

ABSTRACT

I use a modified form of the Newtonian dynamics (inertia and/or gravity) to describe the motion of bodies in the gravitational fields of galaxies, *assuming that galaxies contain no hidden mass*, with the following main results.

1. The Keplerian, circular velocity around a finite galaxy becomes independent of r at large radii, thus resulting in asymptotically flat velocity curves.

2. The asymptotic circular velocity (V_∞) is determined only by the total mass of the galaxy (M): $V_\infty^4 = a_0 GM$, where a_0 is an acceleration constant appearing in the modified dynamics. This relation is consistent with the observed Tully-Fisher relation if one uses a luminosity parameter which is proportional to the observable mass.

3. The discrepancy between the dynamically determined Oort density in the solar neighborhood and the density of observed matter disappears.

?

4. The rotation curve of a galaxy can remain flat down to very small radii, as observed, only if the galaxy's average surface density Σ falls in some narrow range of values which agrees with the Fish and Freeman laws. For smaller values of Σ, the velocity rises more slowly to the asymptotic value.

5. The value of the acceleration constant, a_0, determined in a few independent ways is approximately $2 \times 10^{-8} (H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})^2$ cm s^{-2}, which is of the order of $cH_0 = 5 \times 10^{-8} (H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})$ cm s^{-2}.

$a_0 = (1.2 \pm 0.2)\, 10^{-8} \text{ cm/s}^2 = (cH_0)/(2\pi)$

The main predictions are:

1. Rotation curves calculated on the basis of the *observed* mass distribution and the modified dynamics should agree with the observed velocity curves.

2. The $V_\infty^4 = a_0 GM$ relation should hold exactly.

3. An analog of the Oort discrepancy should exist in all galaxies and become more severe with increasing r in a predictable way.

?

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXIES[1]

M. MILGROM
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I use a modified form of the Newtonian dynamics (inertia and/or gravity) to describe the motion of bodies in the gravitational fields of galaxies, *assuming that galaxies contain no hidden mass*, with the following main results.

1. The Keplerian, circular velocity around a finite galaxy becomes independent of r at large radii, thus resulting in asymptotically flat velocity curves.
2. The asymptotic circular velocity (V_∞) is determined only by the total mass of the galaxy (M): $V_\infty^4 = a_0 GM$, where a_0 is an acceleration constant appearing in the modified dynamics. This relation is consistent with the observed Tully-Fisher relation if one uses a luminosity parameter which is proportional to the observable mass.
3. The discrepancy between the dynamically determined Oort density in the solar neighborhood and the density of observed matter disappears.
4. The rotation curve of a galaxy can remain flat down to very small radii, as observed, only if the galaxy's average surface density Σ falls in some narrow range of values which agrees with the Fish and Freeman laws. For smaller values of Σ, the velocity rises more slowly to the asymptotic value.
5. The value of the acceleration constant, a_0, determined in a few independent ways is approximately $2 \times 10^{-8}(H_0/50\ \text{km s}^{-1}\ \text{Mpc}^{-1})^2$ cm s^{-2}, which is of the order of $CH_0 = 5 \times 10^{-8}(H_0/50$ km s^{-1} Mpc$^{-1})$ cm s^{-2}.

The main predictions are:

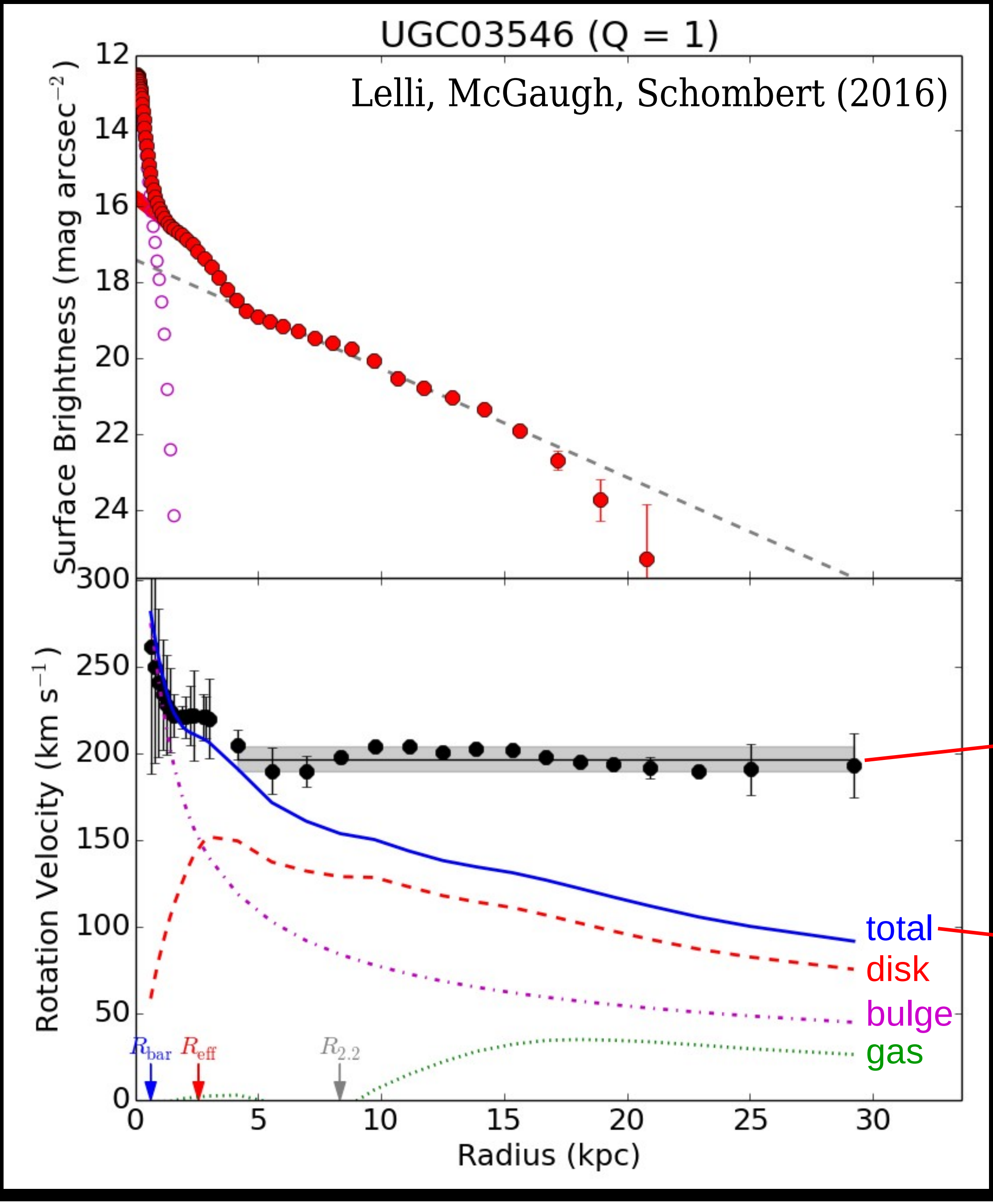
1. Rotation curves calculated on the basis of the *observed* mass distribution and the modified dynamics should agree with the observed velocity curves.
2. The $V_\infty^4 = a_0 GM$ relation should hold exactly.
3. An analog of the Oort discrepancy should exist in all galaxies and become more severe with increasing r in a predictable way.

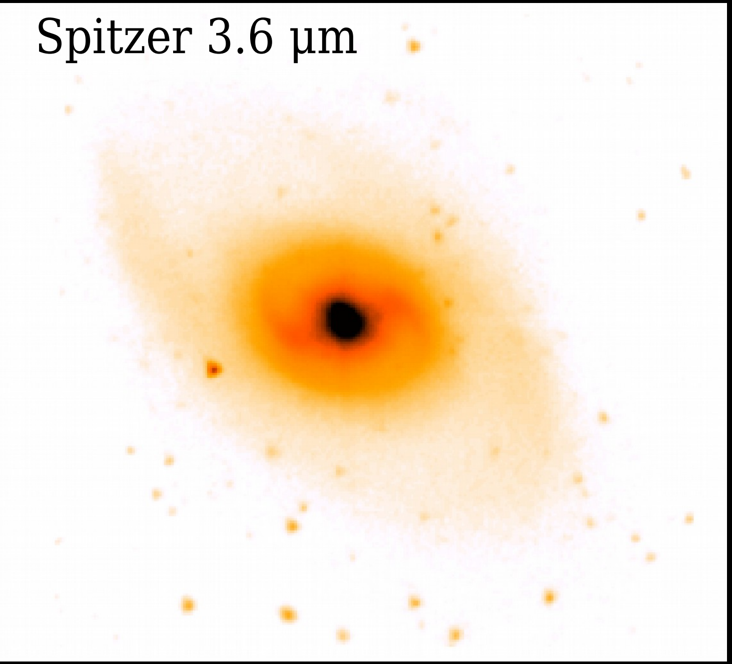
?

?

Milgrom 1983, ApJ, 270, 371

Mass Models of Disk Galaxies



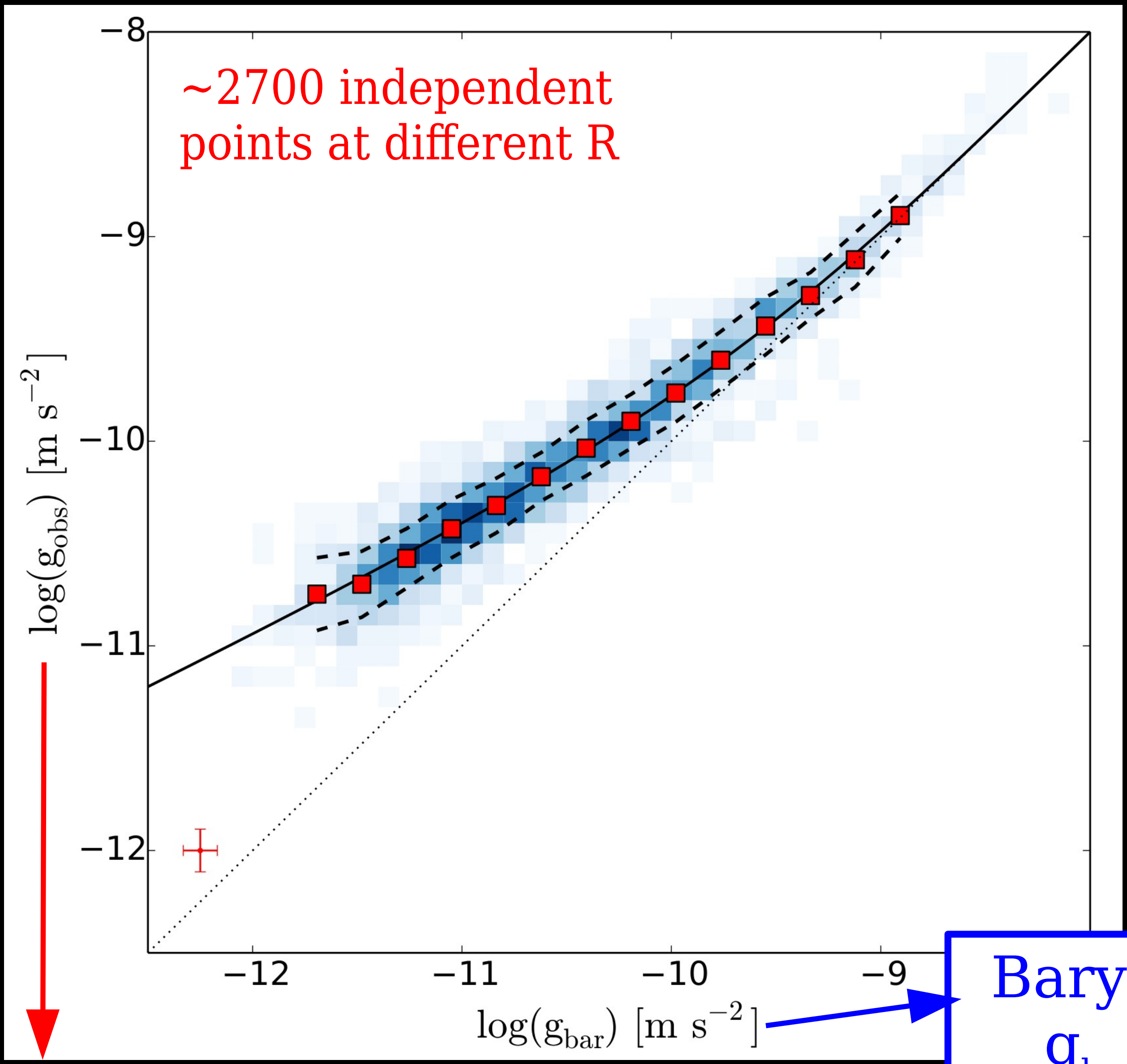


$$g_{obs} = \frac{V_{obs}^2}{R} = -\nabla \Phi_{tot}$$

$$g_{bar} = \frac{V_{bar}^2}{R} = -\nabla \Phi_{bar}$$

$$\nabla^2 \Phi_{bar} = 4\pi G \rho_{bar}$$

Radial Acceleration Relation



$g_{obs} = V^2_{obs}/R = -\nabla\Phi_{tot}$

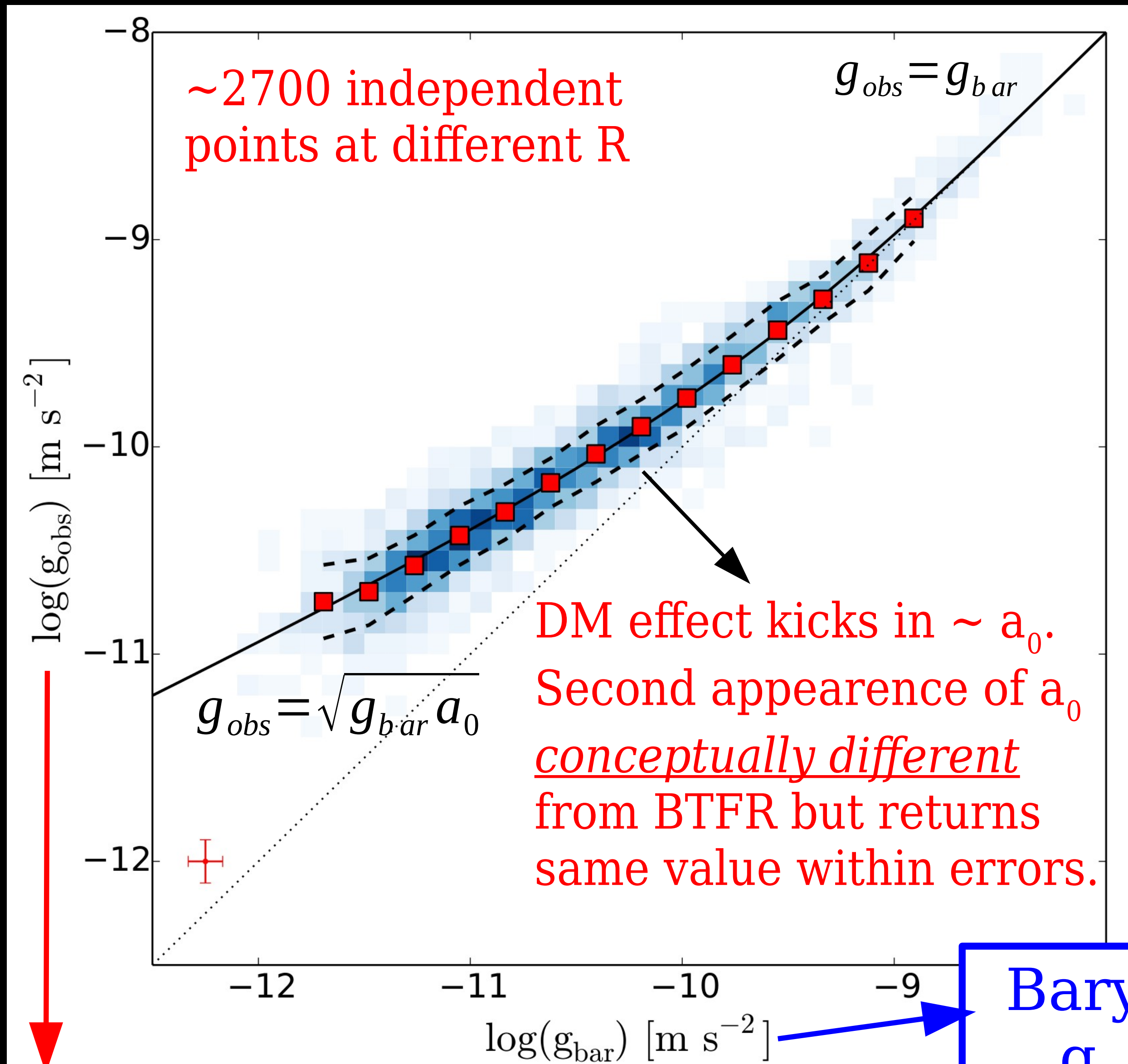
McGaugh+2016
Lelli+2017
Li, Lelli+2018

Baryon Gravity:

$g_{bar} = -\nabla\Phi_{bar}$

$\nabla^2\Phi_{bar} = 4\pi G\ \rho_{bar}$

Radial Acceleration Relation

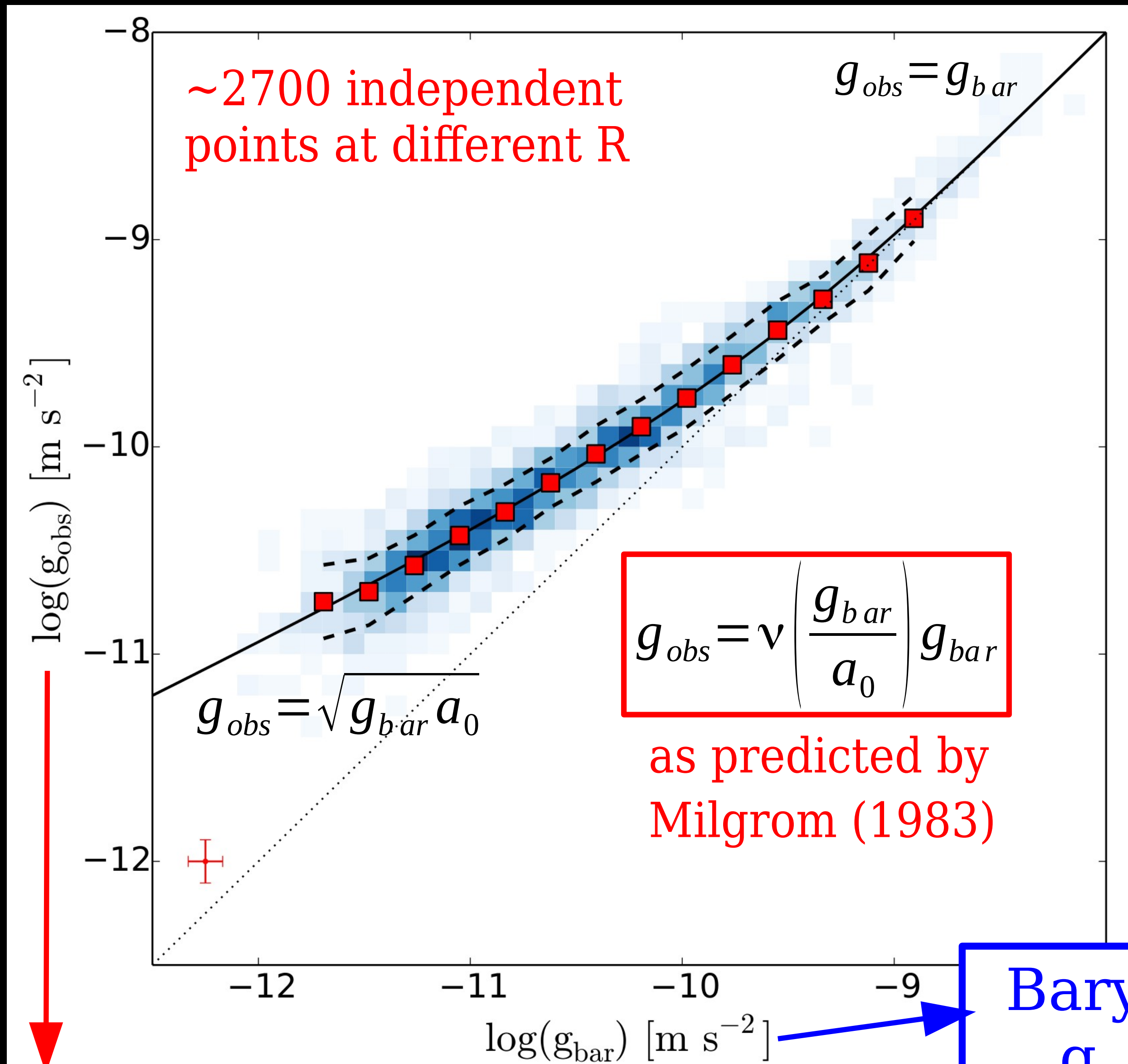


McGaugh+2016
Lelli+2017
Li, Lelli+2018

$g_{obs} = V^2_{obs}/R = -\nabla\Phi_{tot}$

Baryon Gravity:
$g_{bar} = -\nabla\Phi_{bar}$
$\nabla^2\Phi_{bar} = 4\pi G\, \rho_{bar}$

Radial Acceleration Relation



McGaugh+2016
Lelli+2017
Li, Lelli+2018

$g_{obs} = V^2_{obs}/R = -\nabla\Phi_{tot}$

Baryon Gravity:
$g_{bar} = -\nabla\Phi_{bar}$
$\nabla^2\Phi_{bar} = 4\pi G\, \rho_{bar}$

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXIES[1]

M. Milgrom
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I use a modified form of the Newtonian dynamics (inertia and/or gravity) to describe the motion of bodies in the gravitational fields of galaxies, *assuming that galaxies contain no hidden mass*, with the following main results.

1. The Keplerian, circular velocity around a finite galaxy becomes independent of r at large radii, thus resulting in asymptotically flat velocity curves.

2. The asymptotic circular velocity (V_∞) is determined only by the total mass of the galaxy (M): $V_\infty^4 = a_0 GM$, where a_0 is an acceleration constant appearing in the modified dynamics. This relation is consistent with the observed Tully-Fisher relation if one uses a luminosity parameter which is proportional to the observable mass.

3. The discrepancy between the dynamically determined Oort density in the solar neighborhood and the density of observed matter disappears. ?

4. The rotation curve of a galaxy can remain flat down to very small radii, as observed, only if the galaxy's average surface density Σ falls in some narrow range of values which agrees with the Fish and Freeman laws. For smaller values of Σ, the velocity rises more slowly to the asymptotic value.

5. The value of the acceleration constant, a_0, determined in a few independent ways is approximately $2 \times 10^{-8}(H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1})^2 \text{ cm s}^{-2}$, which is of the order of $CH_0 = 5 \times 10^{-8}(H_0/50 \text{ km s}^{-1} \text{ Mpc}^{-1}) \text{ cm s}^{-2}$.

The main predictions are:

1. Rotation curves calculated on the basis of the *observed* mass distribution and the modified dynamics should agree with the observed velocity curves.

2. The $V_\infty^4 = a_0 GM$ relation should hold exactly.

3. An analog of the Oort discrepancy should exist in all galaxies and become more severe with increasing r in a predictable way. ?

Milgrom 1983, ApJ, 270, 371

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXY SYSTEMS[1]

M. MILGROM
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

ABSTRACT

I consider the implications of a modification of the Newtonian dynamics to galaxy systems. Masses and mass-to-light ratios are rederived, on the basis of existing data, for binary galaxies, small groups, clusters of galaxies, and the Virgo Supercluster. For each type of galaxy system, the average M/L values come out to be a few solar units. These results eliminate the need to assume large amounts of hidden mass in galaxy systems, if the modified dynamics applies.

A MODIFICATION OF THE NEWTONIAN DYNAMICS: IMPLICATIONS FOR GALAXY SYSTEMS[1]

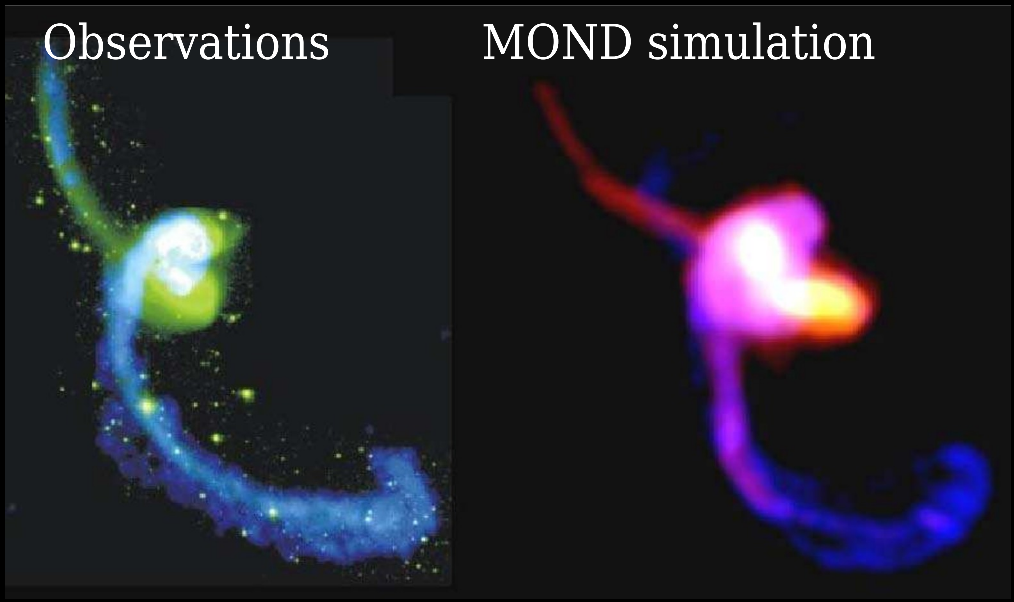
M. MILGROM
Department of Physics, Weizmann Institute, Rehovot, Israel; and The Institute for Advanced Study
Received 1982 February 4; accepted 1982 December 28

ABSTRACT

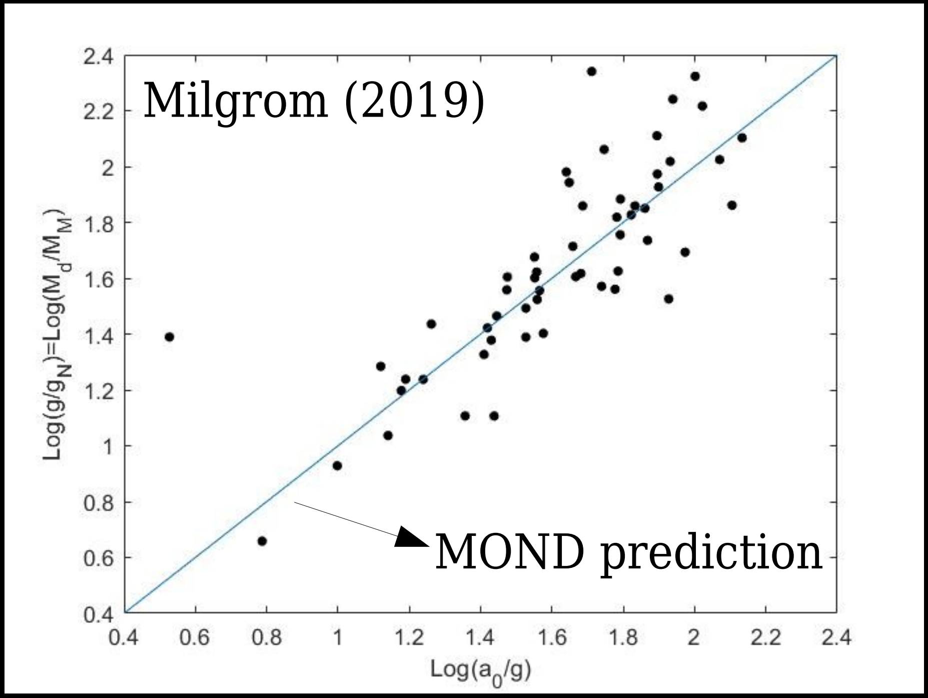
I consider the implications of a modification of the Newtonian dynamics to galaxy systems. Masses and mass-to-light ratios are rederived, on the basis of existing data, for binary galaxies, small groups, clusters of galaxies, and the Virgo Supercluster. For each type of galaxy system, the average M/L values come out to be a few solar units. These results eliminate the need to assume large amounts of hidden mass in galaxy systems, if the modified dynamics applies.

Binary Galaxies / Galaxy Interactions ✓

Galaxy Groups ✓

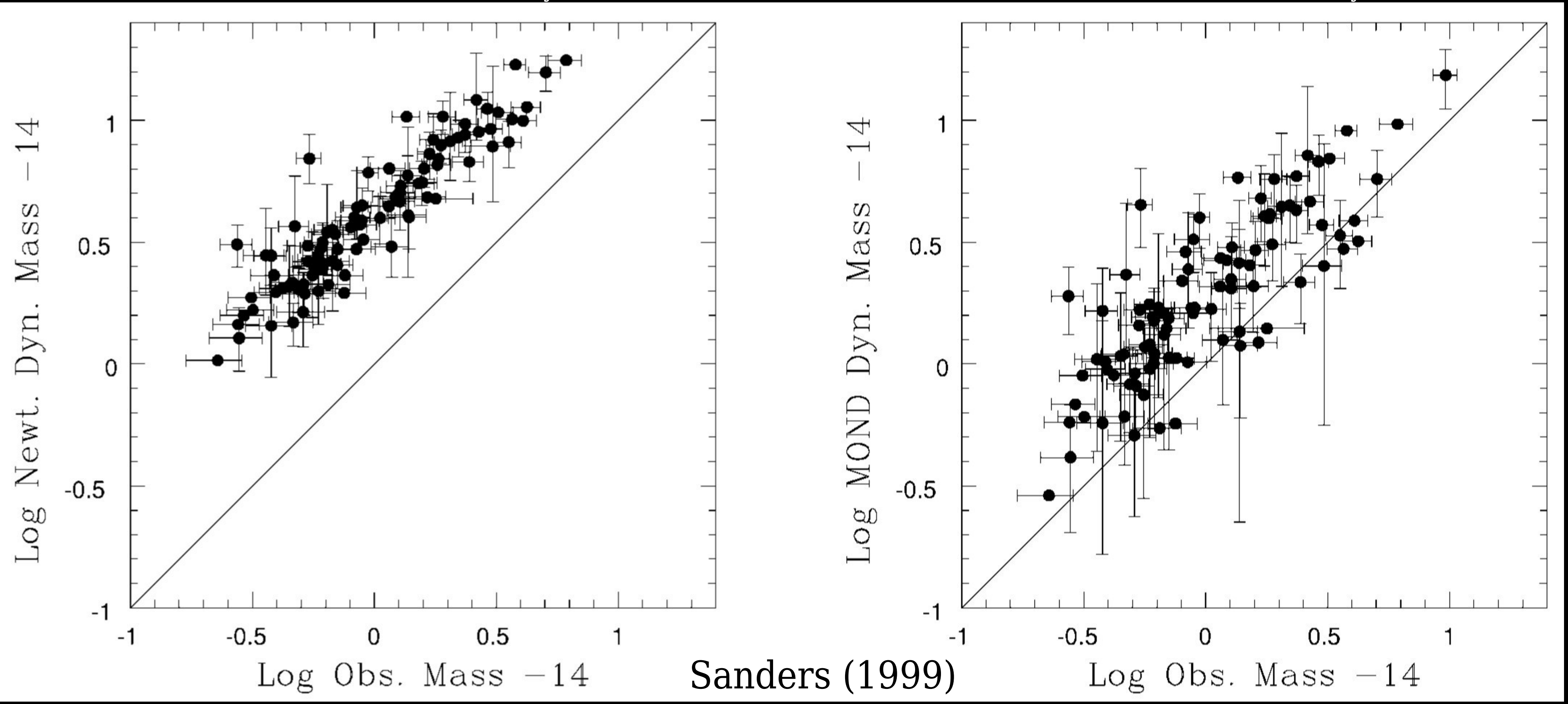


The Antennae - Tiret & Combes (2008)



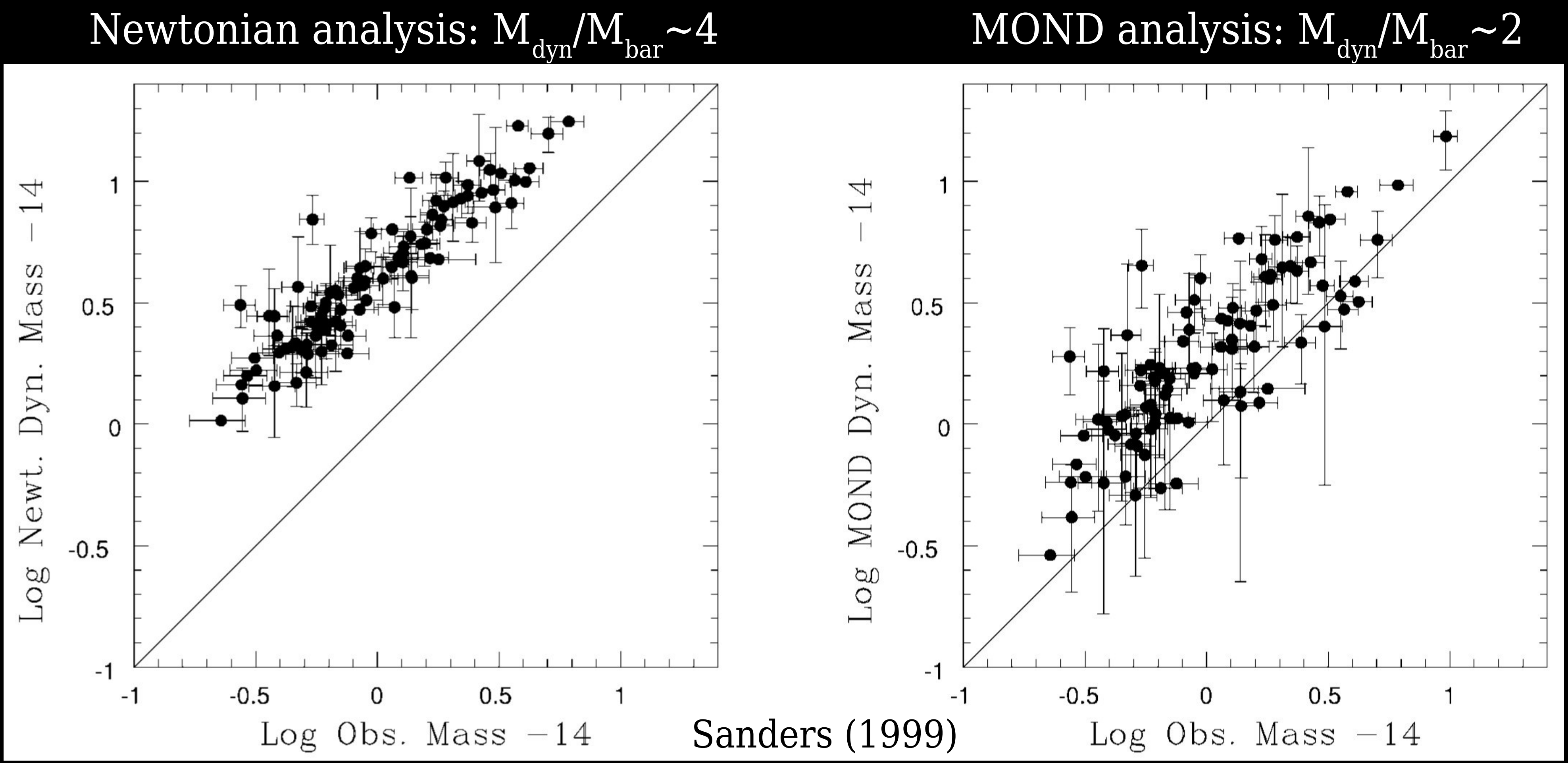
Key Problem for MOND: Galaxy Clusters

Newtonian analysis: M_{dyn}/M_{bar}~4 MOND analysis: M_{dyn}/M_{bar}~2



Sanders (1999)

Key Problem for MOND: Galaxy Clusters



Sanders (1999)

Proposed solutions:

1) Undetected baryons (Milgrom 2008) → BBN implies ~30% missing baryons

2) Sterile neutrinos with m~10 eV (Angus 2008) → υ oscillations and masses

3) Extended MOND: $a_0 \propto \Phi$ (Zhao & Famaey 2012) → deeper theory?

Why did MOND get *any* prediction right?

What is the *deeper* meaning of MOND?

MOND paradigm

Modified Gravity
(→ Poisson's eq.)

Modified Inertia
(→ F = ma)

MOND paradigm

Modified Gravity
(→ Poisson's eq.)

Modified Inertia
(→ F = ma)

Non-Relativistic theories:

Nonlinear (Bekenstein & Milgrom 84)

Quasi-linear (Milgrom 2010)

MOND paradigm

Modified Gravity
(→ Poisson's eq.)

Modified Inertia
(→ F = ma)

Non-Relativistic theories:

Nonlinear (Bekenstein & Milgrom 84)

Quasi-linear (Milgrom 2010)

Relativistic theories:

Original TeVeS (Bekenstein 2004)

Einstein-Aether (Zlosnik+2007)

Bimetric Theories (Milgrom 2009)

Non-local Metric (Deffayet+2011)

Horava Gravity (Sanders 2011)

Finsler Geometry (Namouni 2015)

New TeVeS (Skordis & Zlosnik 2019)

MOND paradigm

Modified Gravity
(→ Poisson's eq.)

Modified Inertia
(→ F = ma)

Non-Relativistic theories:
Nonlinear (Bekenstein & Milgrom 84)
Quasi-linear (Milgrom 2010)

Strongly non-local theories:
$a = \nu(g_N/a_0)g_N$ holds exactly for circular orbits (Milgrom 1994)

Relativistic theories:
Original TeVeS (Bekenstein 2004)
Einstein-Aether (Zlosnik+2007)
Bimetric Theories (Milgrom 2009)
Non-local Metric (Deffayet+2011)
Horava Gravity (Sanders 2011)
Finsler Geometry (Namouni 2015)
New TeVeS (Skordis & Zlosnik 2019)

MOND paradigm

Modified Gravity
(→ Poisson's eq.)

Non-Relativistic theories:
Nonlinear (Bekenstein & Milgrom 84)
Quasi-linear (Milgrom 2010)

Relativistic theories:
Original TeVeS (Bekenstein 2004)
Einstein-Aether (Zlosnik+2007)
Bimetric Theories (Milgrom 2009)
Non-local Metric (Deffayet+2011)
Horava Gravity (Sanders 2011)
Finsler Geometry (Namouni 2015)
New TeVeS (Skordis & Zlosnik 2019)

Modified Inertia
(→ $F = ma$)

Strongly non-local theories:
$a = \nu(g_N/a_0)g_N$ holds exactly for circular orbits (Milgrom 1994)

Heuristic ideas:
Mach's principle for inertia
Quantum Vacuum → $a_0 \sim c\,\Lambda^{1/2}$

MOND paradigm

Modified Gravity
(→ Poisson's eq.)

Non-Relativistic theories:
Nonlinear (Bekenstein & Milgrom 84)
Quasi-linear (Milgrom 2010)

Relativistic theories:
Original TeVeS (Bekenstein 2004)
Einstein-Aether (Zlosnik+2007)
Bimetric Theories (Milgrom 2009)
Non-local Metric (Deffayet+2011)
Horava Gravity (Sanders 2011)
Finsler Geometry (Namouni 2015)
New TeVeS (Skordis & Zlosnik 2019)

Modified Inertia
(→ F = ma)

Strongly non-local theories:
$a = \nu(g_N/a_0)g_N$ holds exactly for circular orbits (Milgrom 1994)

Heuristic ideas:
Mach's principle for inertia
Quantum Vacuum → $a_0 \sim c\,\Lambda^{1/2}$

Other ideas:
Entropic Gravity (Verlinde 2017)
Bipolar DM (Blanchet & LeTiec 2008)
Superfluid DM (Khoury 2015)

MOND *vs* ΛCDM

Small scales (galaxies) Large scales (cosmology)

How do we weight the different evidence? (Kroupa 2012, McGaugh 2015)

Should the CMB & LSS weight more than individual galaxies?

MOND *vs* ΛCDM

Small scales (galaxies) Large scales (cosmology)

How do we weight the different evidence? (Kroupa 2012, McGaugh 2015)

Should the CMB & LSS weight more than individual galaxies?

A-priori predictions A-posteriori reactions

ΛCDM simulations can explain nearly everything *after* the fact.

MOND *vs* ΛCDM

Small scales (galaxies) Large scales (cosmology)

How do we weight the different evidence? (Kroupa 2012, McGaugh 2015)

Should the CMB & LSS weight more than individual galaxies?

A-priori predictions A-posteriori reactions

ΛCDM simulations can explain nearly everything *after* the fact.

Is ΛCDM falsifiable? What about Karl Popper (Merritt 2017 & his book)?

MOND *vs* ΛCDM

Small scales (galaxies) Large scales (cosmology)

How do we weight the different evidence? (Kroupa 2012, McGaugh 2015)

Should the CMB & LSS weight more than individual galaxies?

A-priori predictions A-posteriori reactions

ΛCDM simulations can explain nearly everything *after* the fact.

Is ΛCDM falsifiable? What about Karl Popper (Merritt 2017 & his book)?

What would make us change our mind about the existence of DM?

"*The only relevant evidence is the evidence anticipated by a theory*"

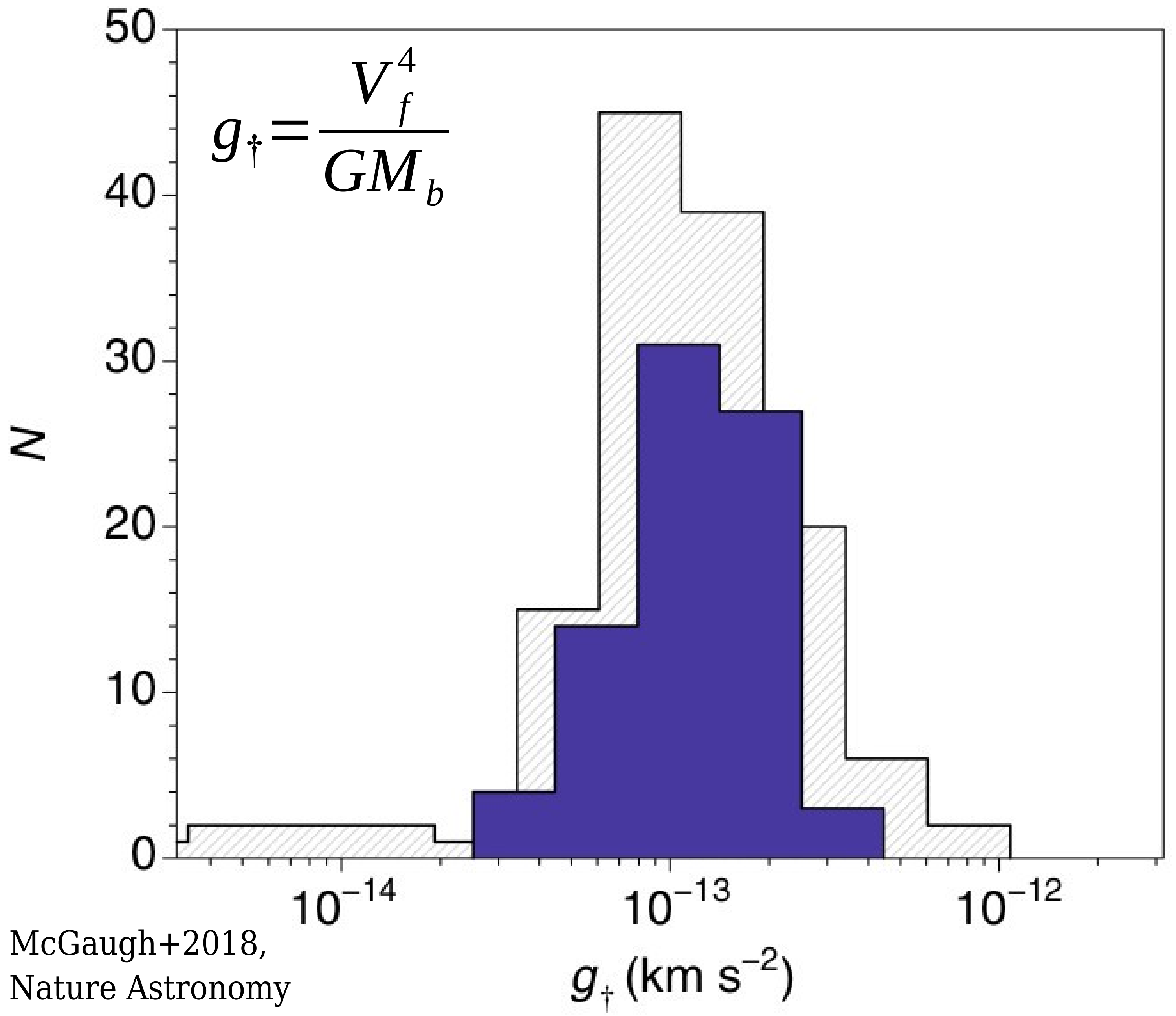
in Methodology of Scientific Research Programmes (Imre Lakatos 1971)

"*The only relevant evidence is the evidence anticipated by a theory*"

in Methodology of Scientific Research Programmes (Imre Lakatos 1971)

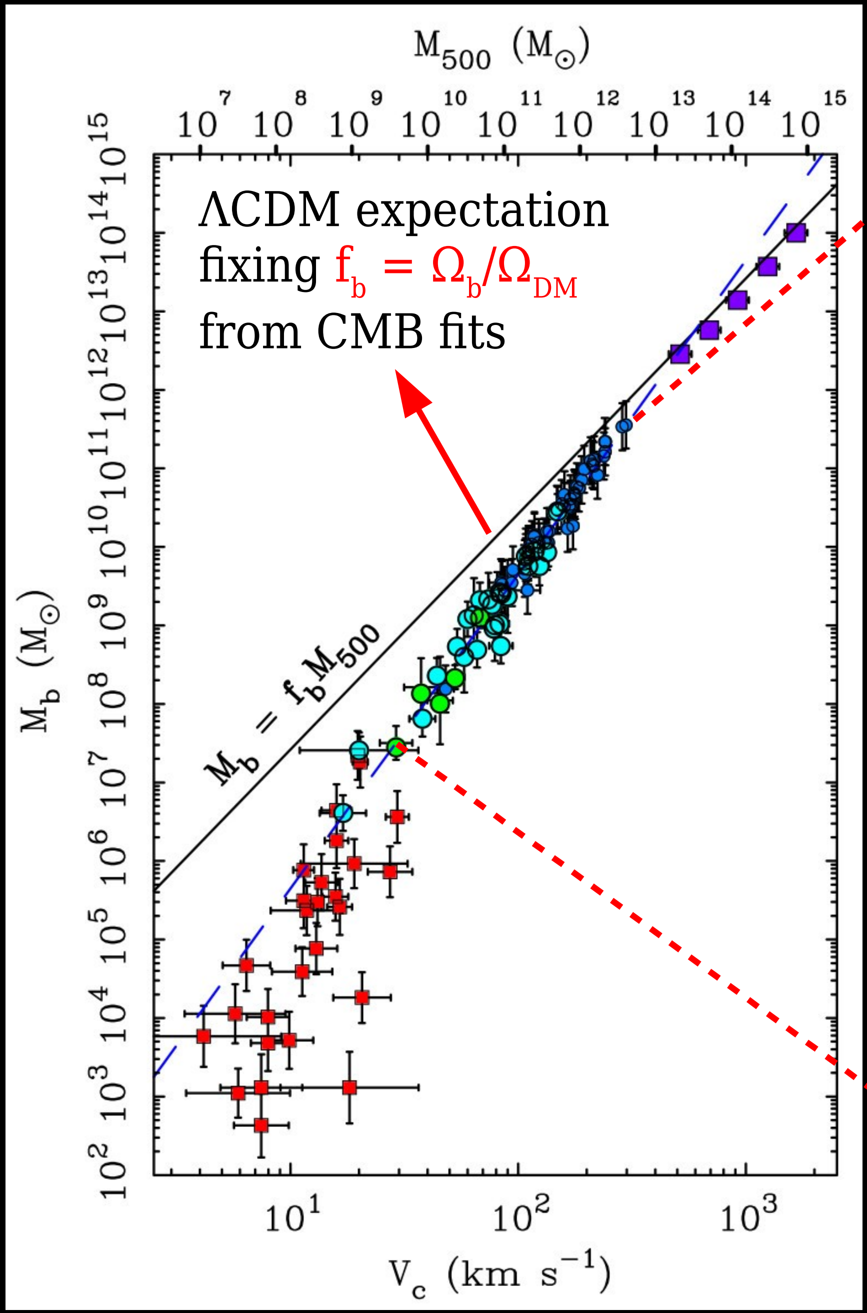
Thank you!

Independently of MOND, a_0 is in the data



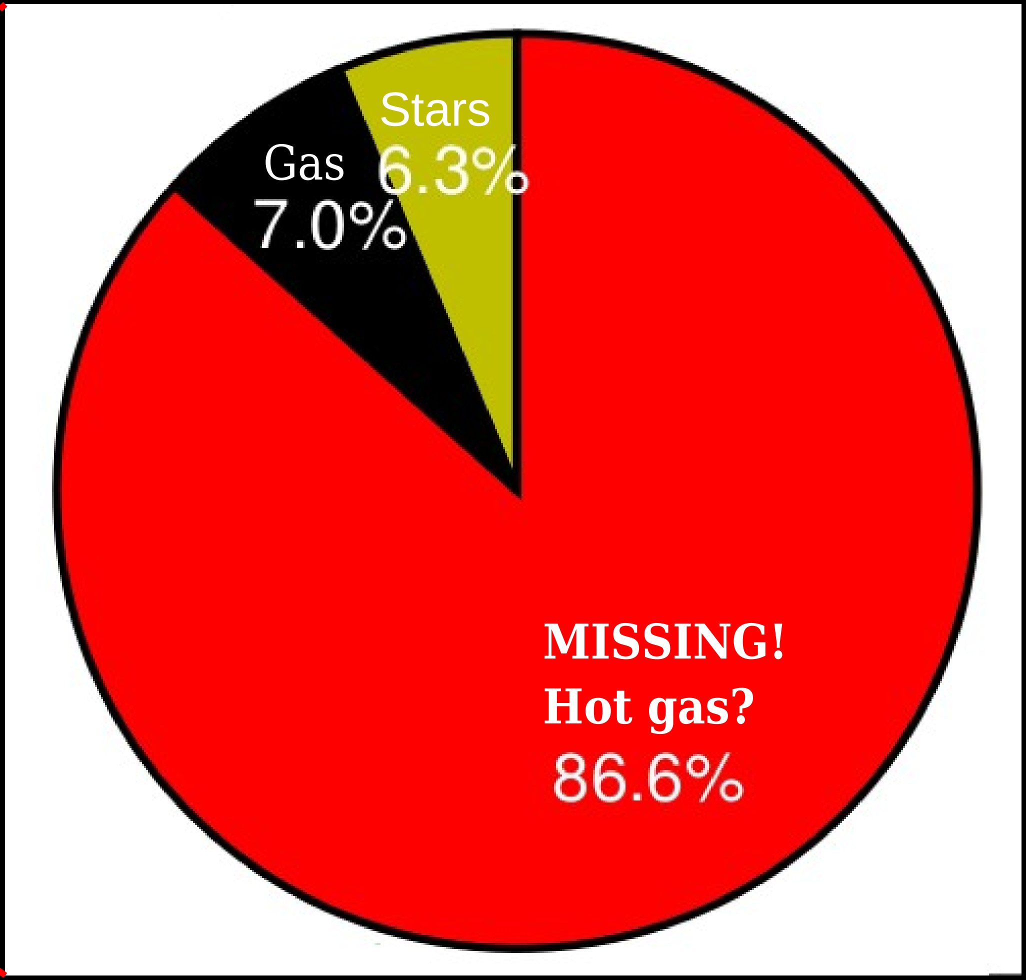
McGaugh+2018, Nature Astronomy

Baryon Content of Cosmic Structures



McGaugh+2012

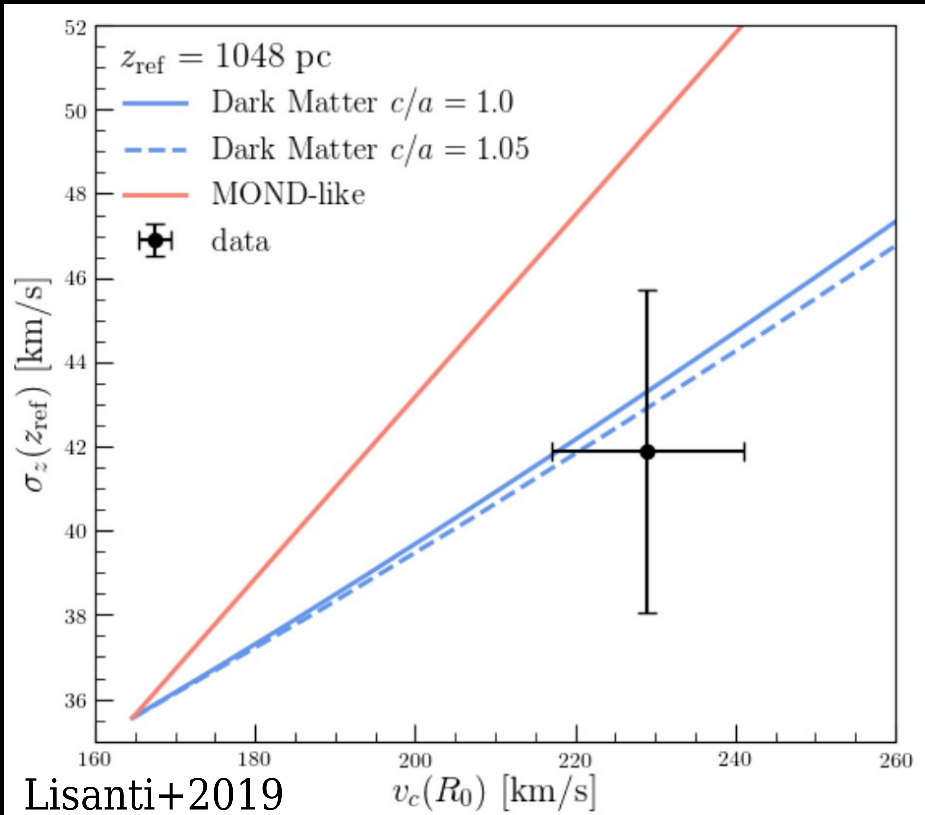
Mean Budget in Galaxies in a ΛCDM context:



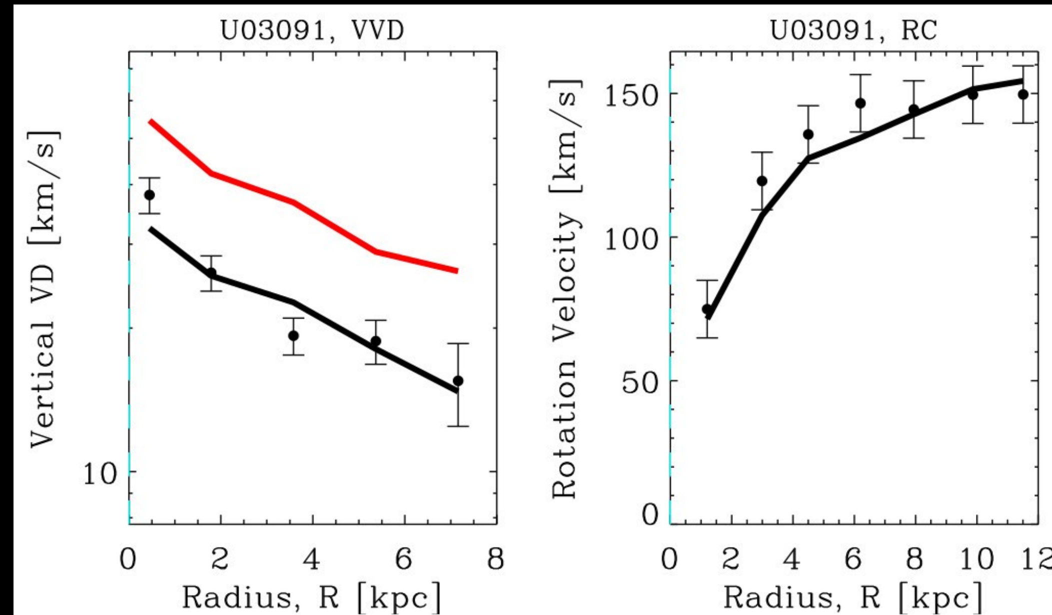
Katz, Desmond, Lelli et al. 2018

Vertical Disk Dynamics: Oort's Problem

Milky Way data near the Sun's location



30 *face-on* galaxies from the DiskMass Survey



Black: MOND best-fit with free M_*/L and h_z

Red: fixed h_z from observed scaling relations for edge-on disk galaxies (Angus et al. 2015).

Caution: Gaia DR2 shows that the MW is *not* in vertical equilibrium

→ Interaction with Sagittarius?

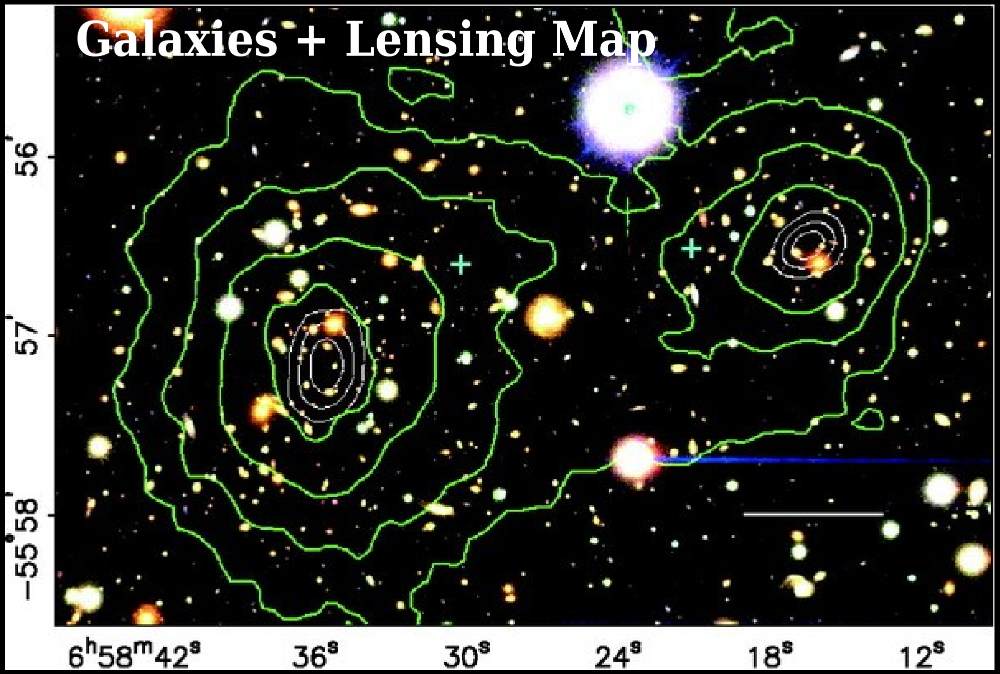
(Antoja+2018; Morgan & Bovy 2019; Carrillo+2019; Bland-Hawthorn+2019)

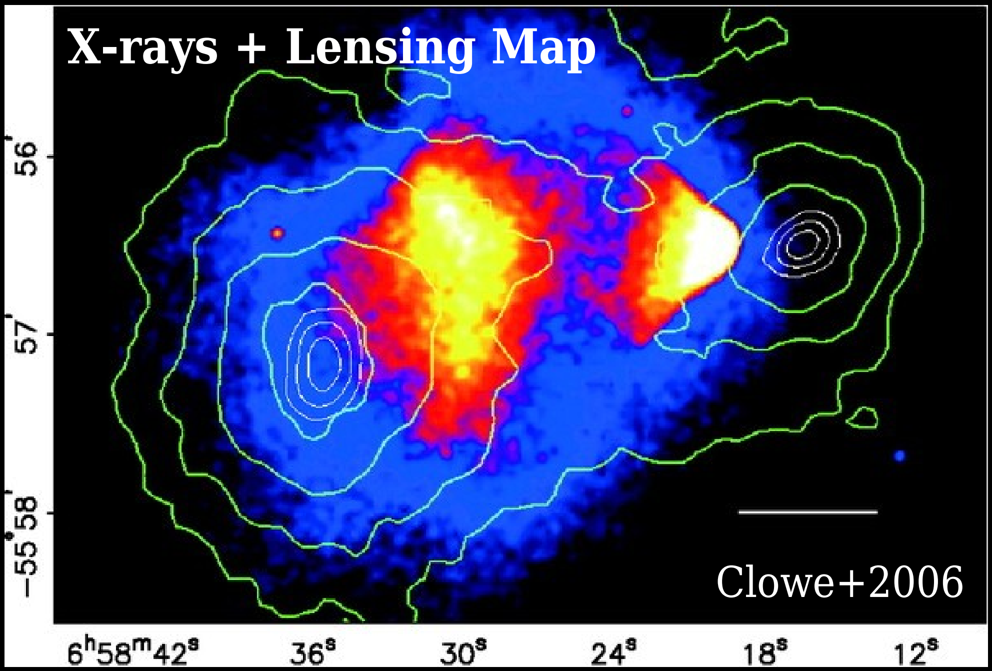
Caution: h_z → old stars (NIR images)

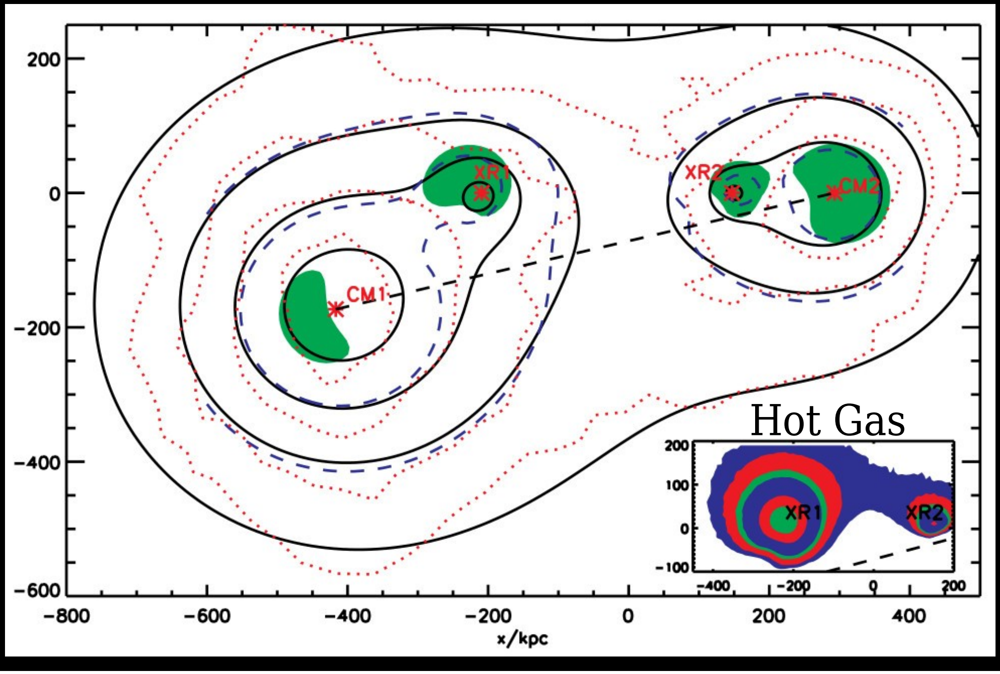
σ_z → light-weighted for a mixed pop. of stars of different ages (optical IFUs)

(Aniyan+2016,2018; Milgrom 2016, 2018)

Bullet Cluster is nothing special in MOND



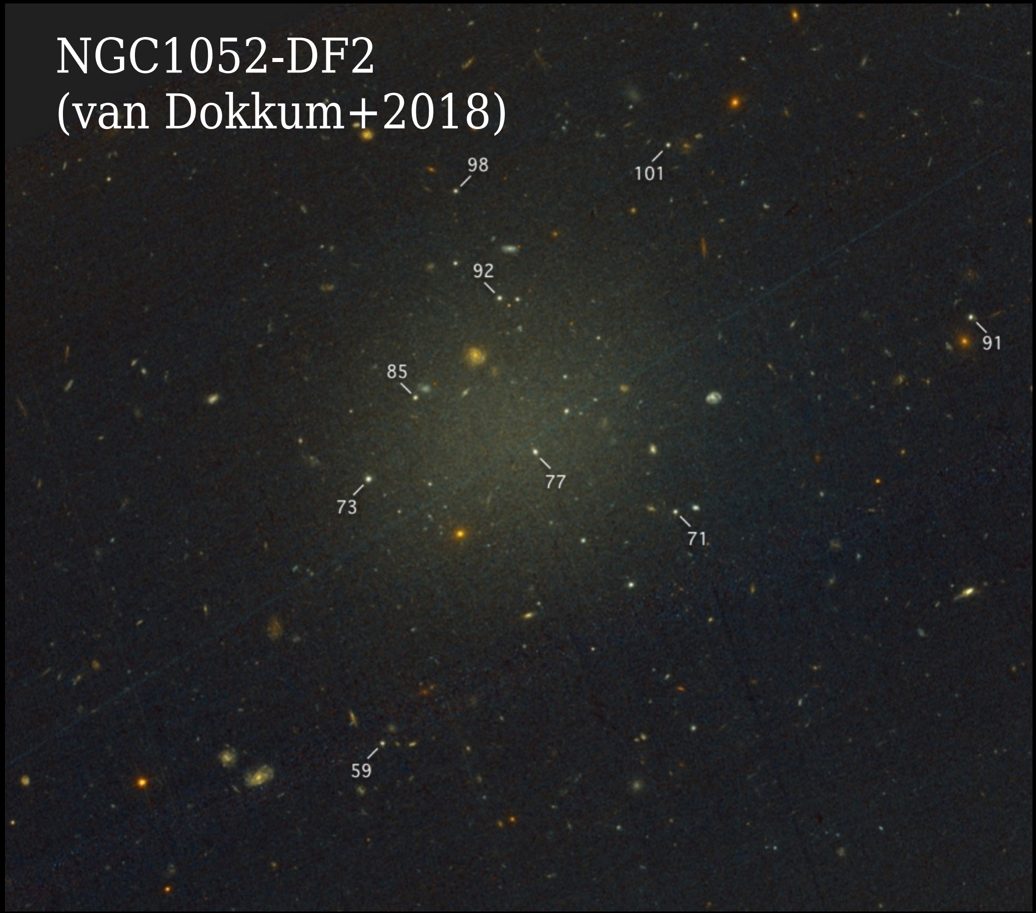


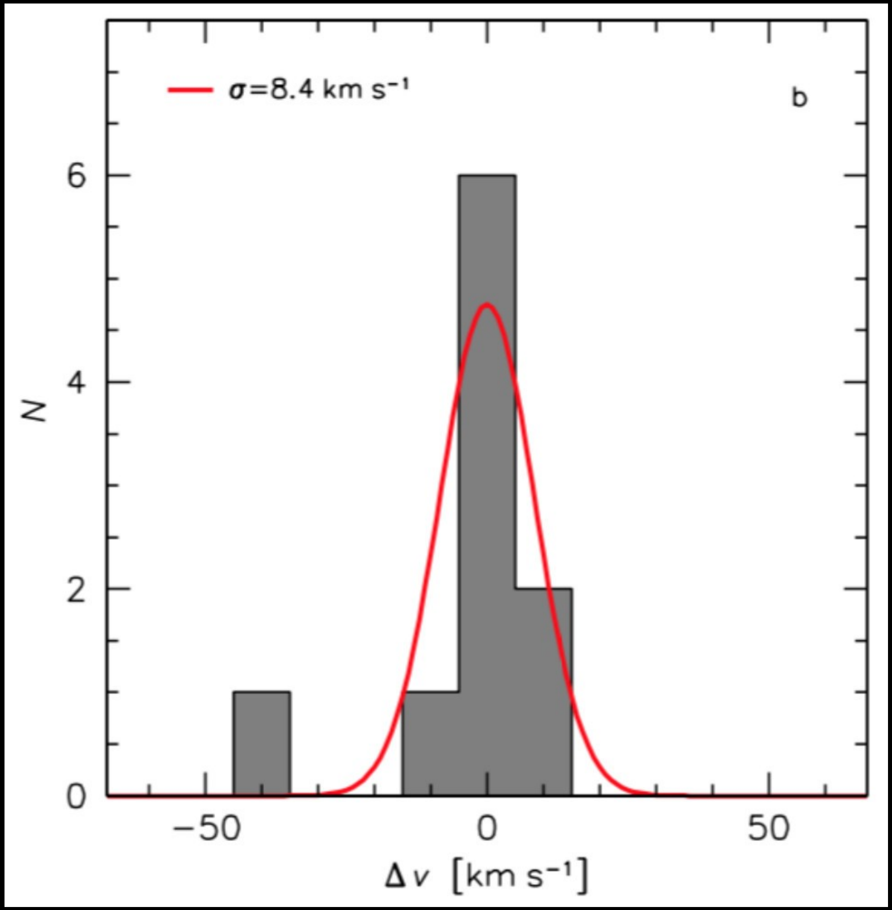


MOND model with 2eV υ (Angus+2007)**:**
Red: Observed lensing convergence map
Black: best-fit MOND+υ convergence map
Blue: total surface densities (baryons+υ)
Green: peak surface densities (neutrinos)

High collision speed (~4500 km/s) is rare in ΛCDM but natural in MOND (Hayashi & White 2006; Farrar & Rosen 2006; Angus+2007; Angus & McGaugh 2008).

DM-deficient Ultra-Diffuse Galaxies?





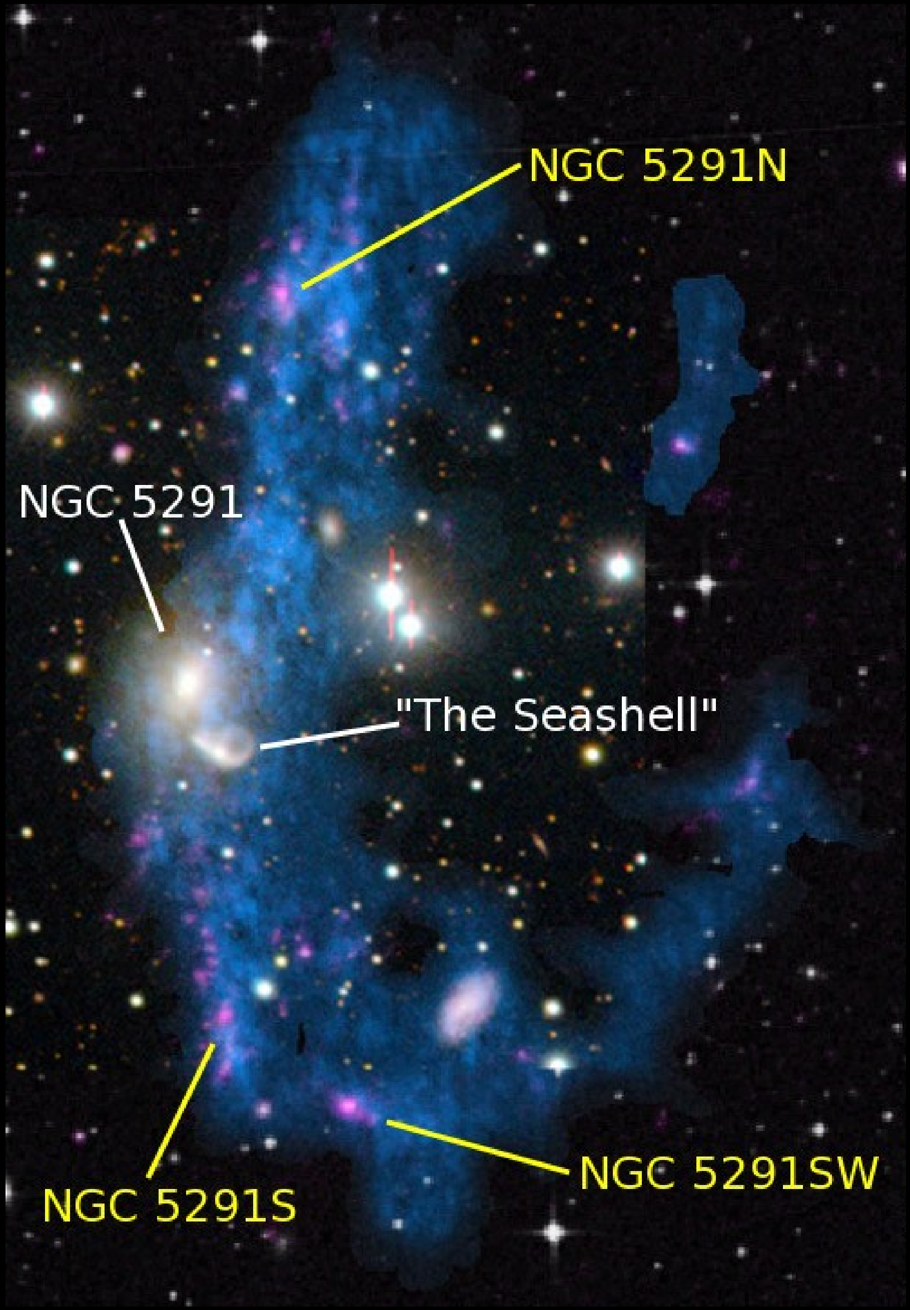
Initially, low σ_v from 10 globular clusters suggesting no mass discrepancy but:

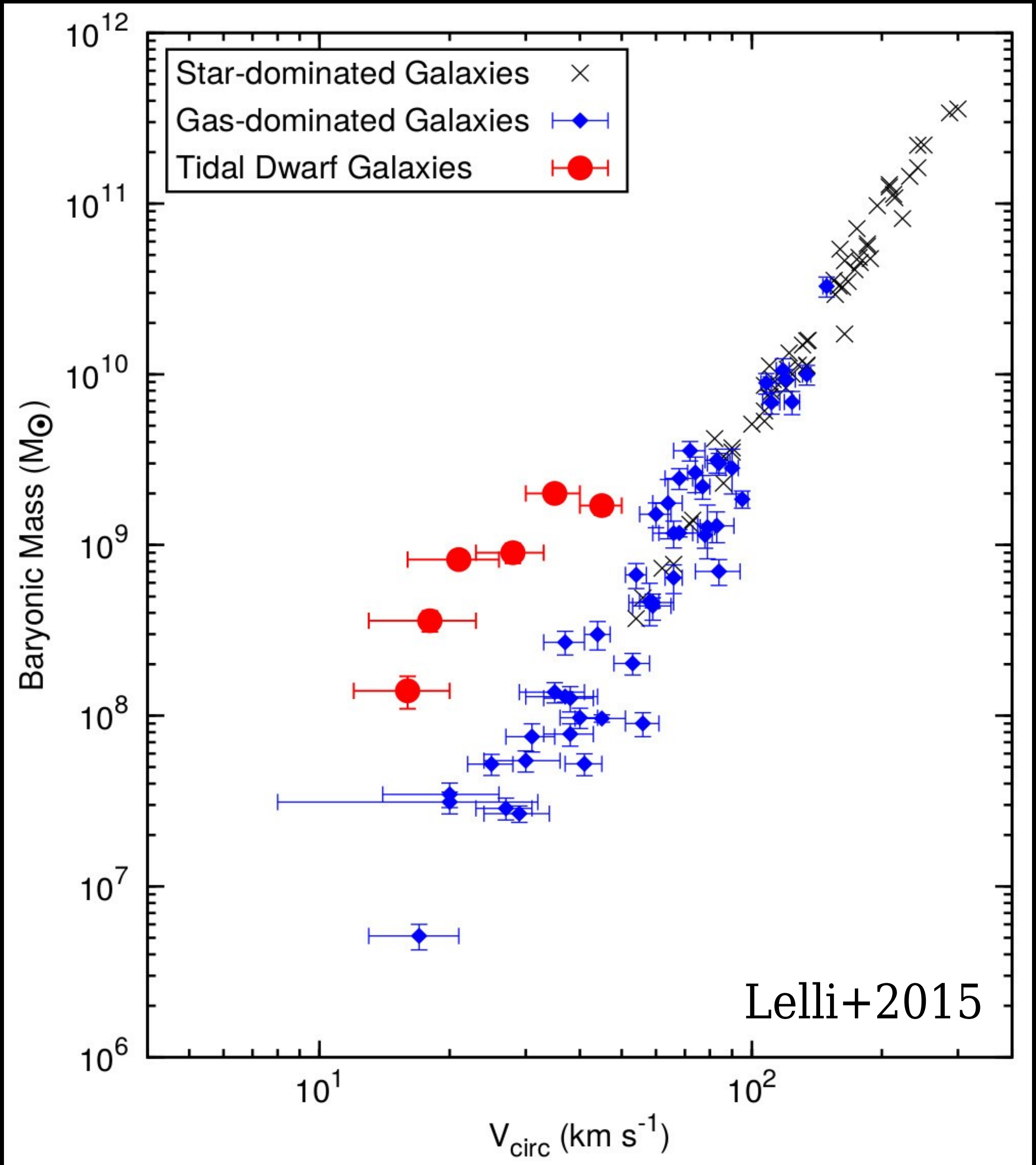
- Small number statistics (Martin+2018; Laporte+2019)
- Debated distance: D~20 Mpc (van Dokkum+2018) *vs* 13 Mpc (Trujillo+2019)

IF at 20 Mpc, MOND predicts σ_V~13±4 km/s considering the EFE (Famaey+2018).

Consistent with stellar σ_v ~11±4 (Emsellem+2019) and 8.5±3.1 km/s (Danieli+2019).

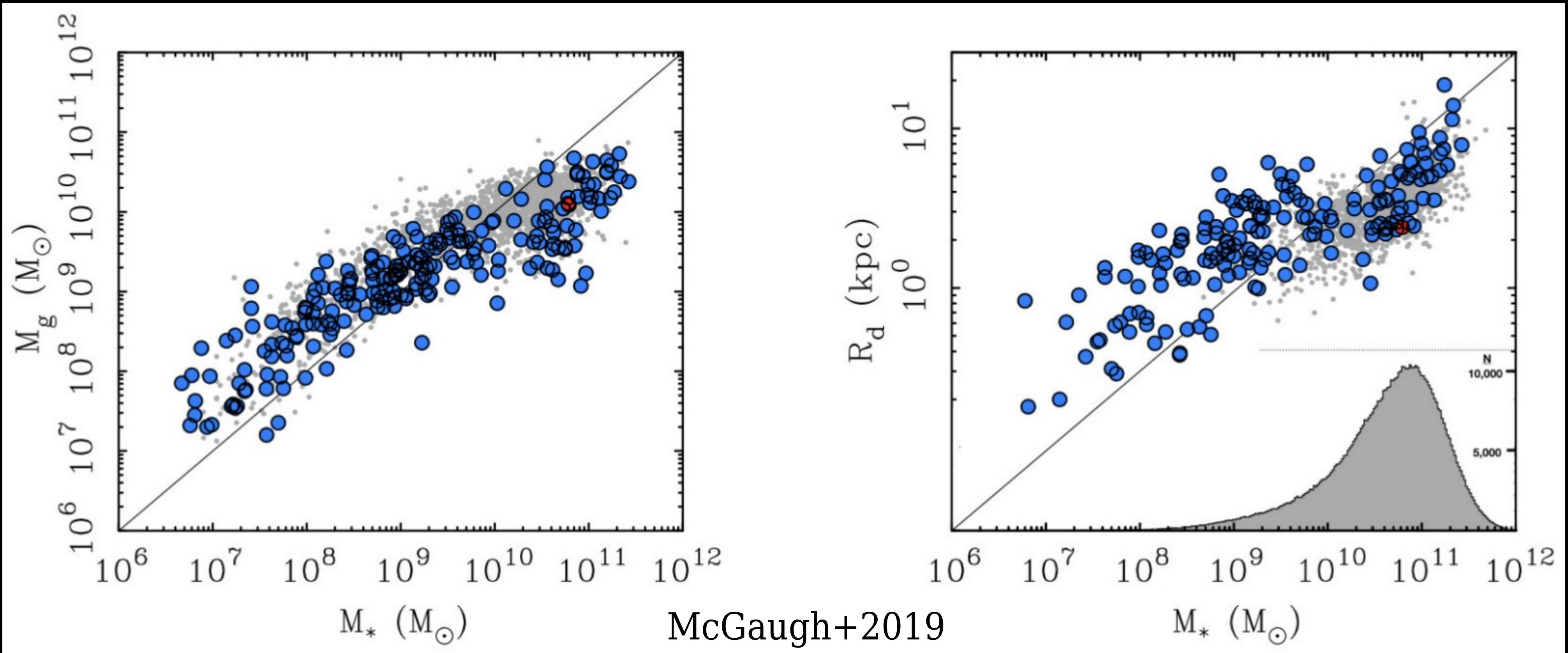
Tidal Dwarf Galaxies: Off the BTFR?





Caution: TDGs didn't have time to make a single circular orbit: out of equilibrium?

SPARC vs larger "complete" samples



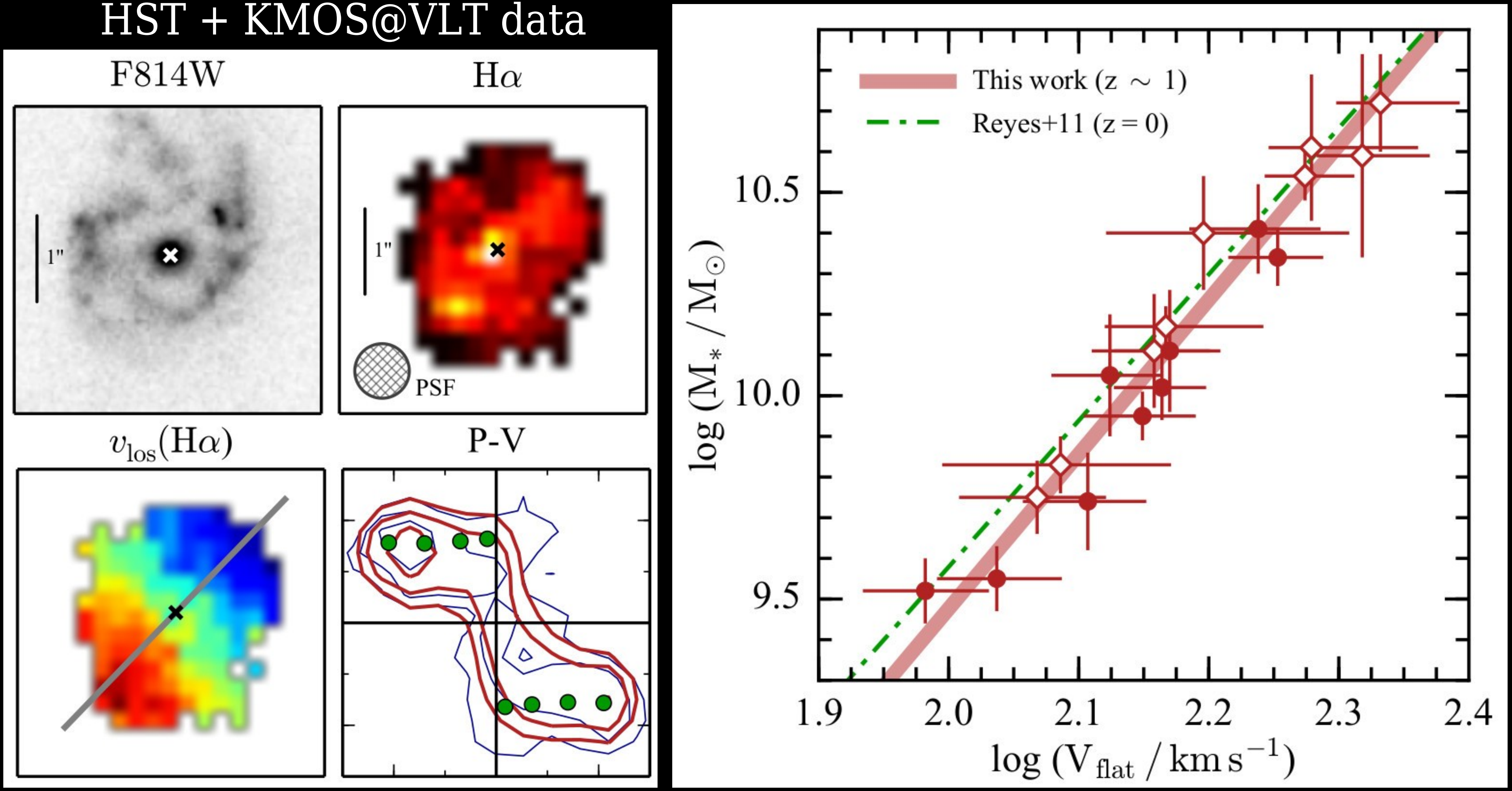
McGaugh+2019

Grey dots: HI-selected data from Bradford+2015 (single-dish survey)

Grey dots: Hα-selected galaxies from Courteau+2007 (long-slit surveys)
Histogram: all galaxies in the SDSS DR7.

Does the TF relation evolve with z?

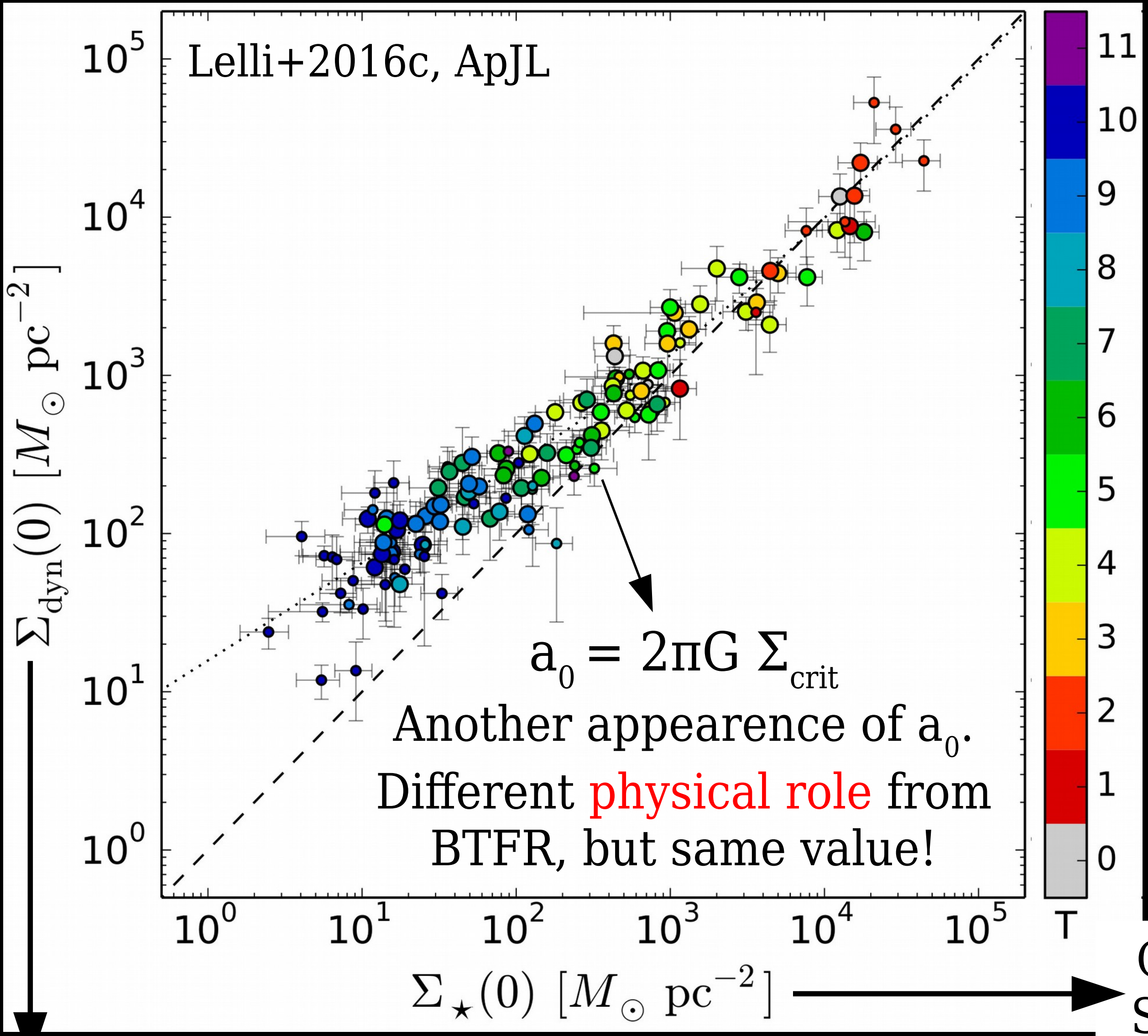
HST + KMOS@VLT data



Di Teodoro+2016

Very hard and debated measurements but consistent with no TFR evolution up to z~1

Central Surface Density Relation

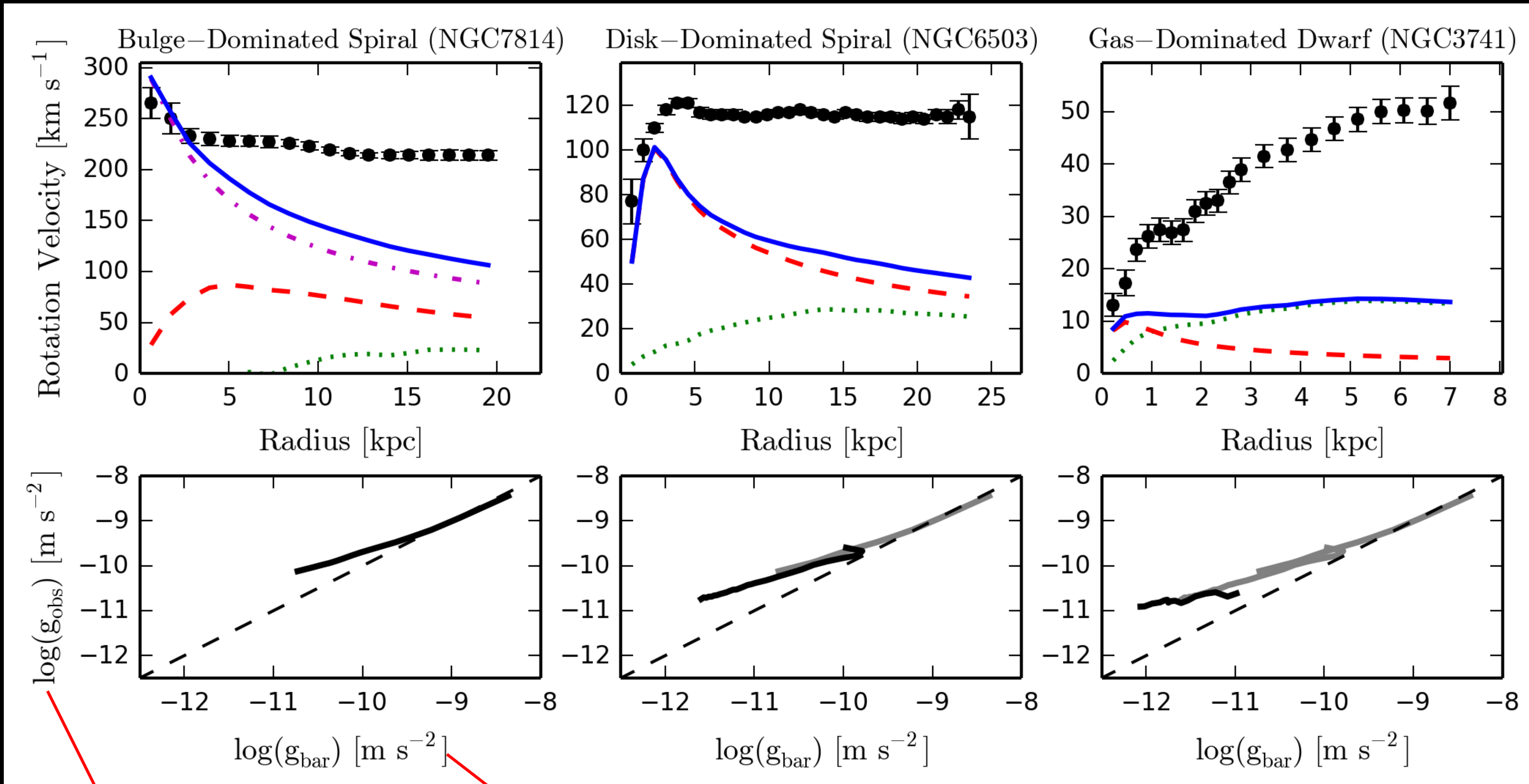


Central Stellar Surface Density

$$\Sigma_{\rm dyn}(0) = \frac{1}{2\pi G}\int_0^\infty \frac{V^2(R)}{R^2} dR,$$

Toomre (1963): central dynamical surface density
→ How fast a rotation curve reaches the flat part

Very different galaxies but same relation



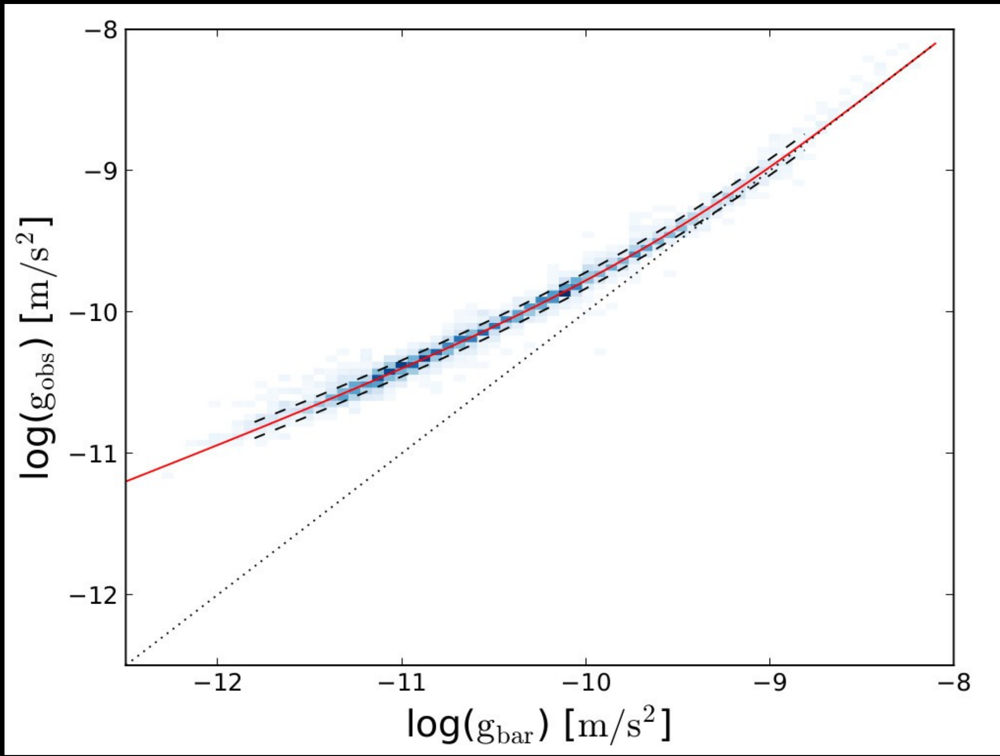
$V^2_{obs}/R = -\nabla\Phi_{tot}$

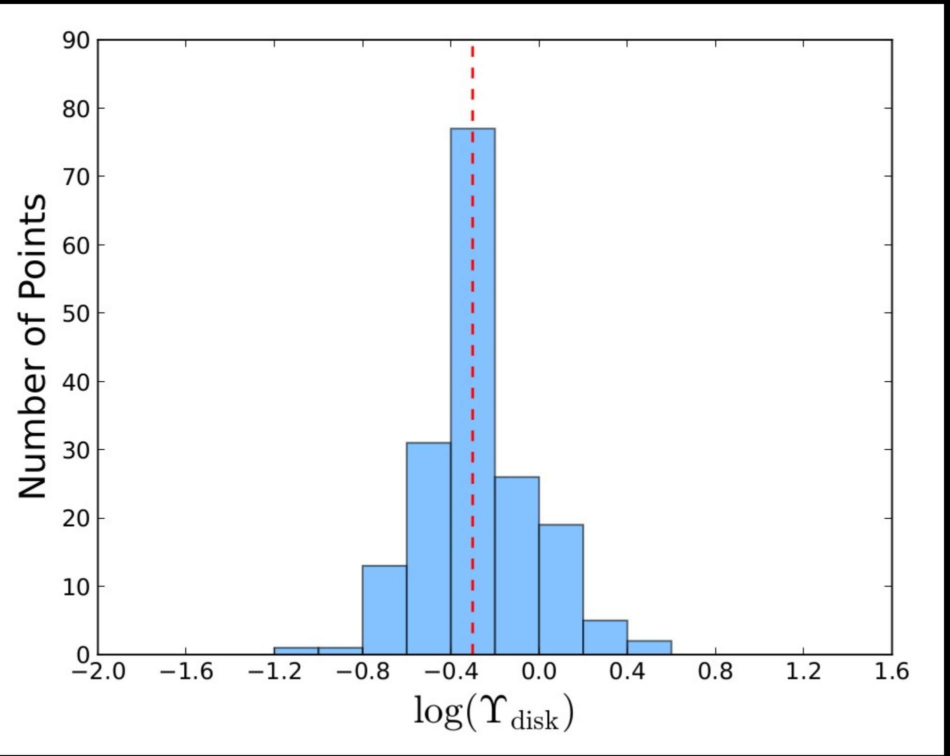
$V^2_{bar}/R = -\nabla\Phi_{bar}$

$\nabla^2\Phi_{bar} = 4\pi G\,\rho_{bar}$

McGaugh, Lelli, Schombert (2016)

What is driving the RAR scatter?



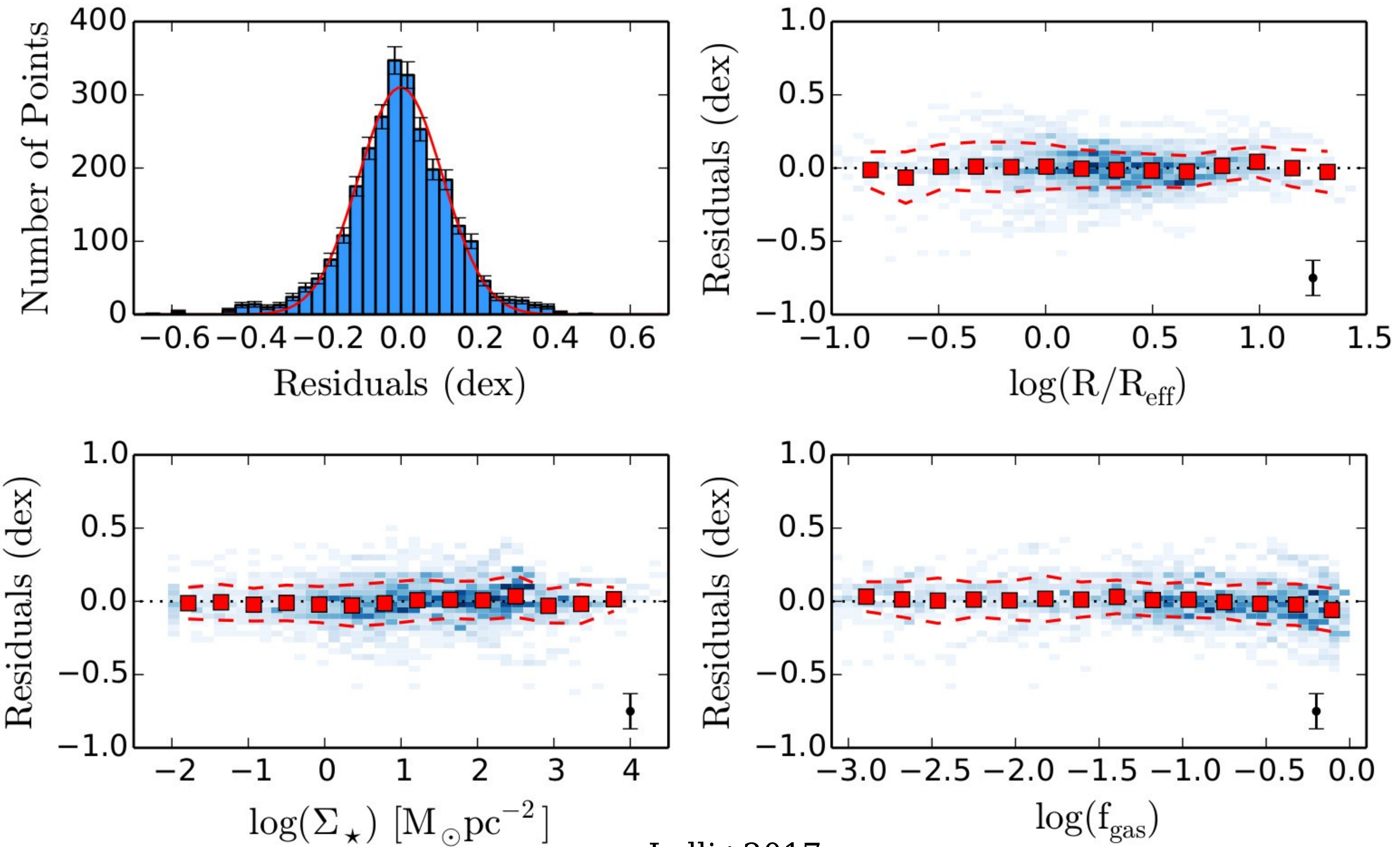


RAR fits to individual galaxies return:

- extremely tight relation (scatter ~ 13%)
- sensible distribution of stellar M_*/L
- sensible values of distance and inclination

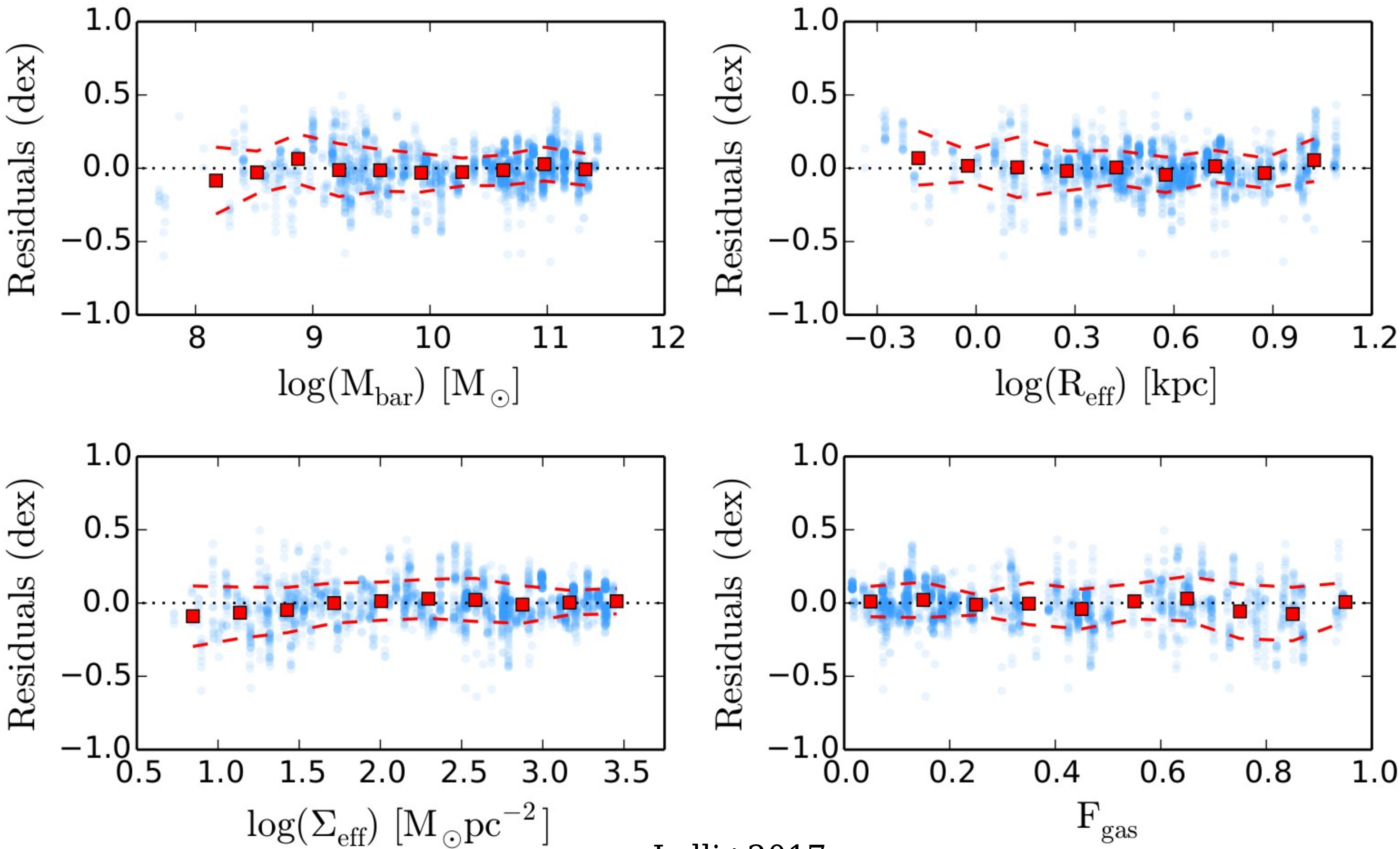
Li, Lelli, McGaugh, Schombert 2018, A&A

RAR Residuals *vs* Local Galaxy Properties



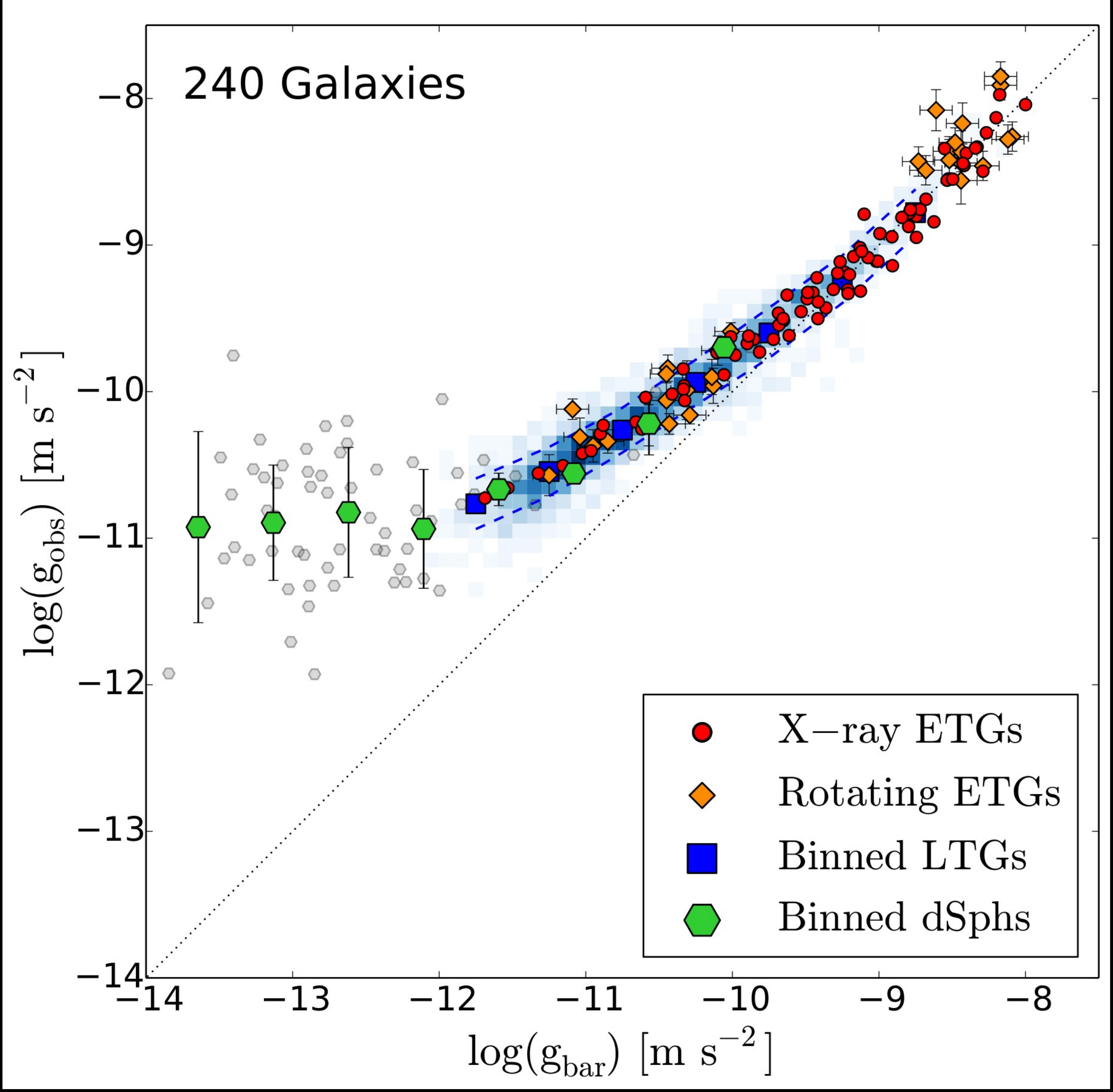
Lelli+2017

RAR Residuals *vs* Global Galaxy Properties



Lelli+2017

Works for any galaxy type with ***good*** data



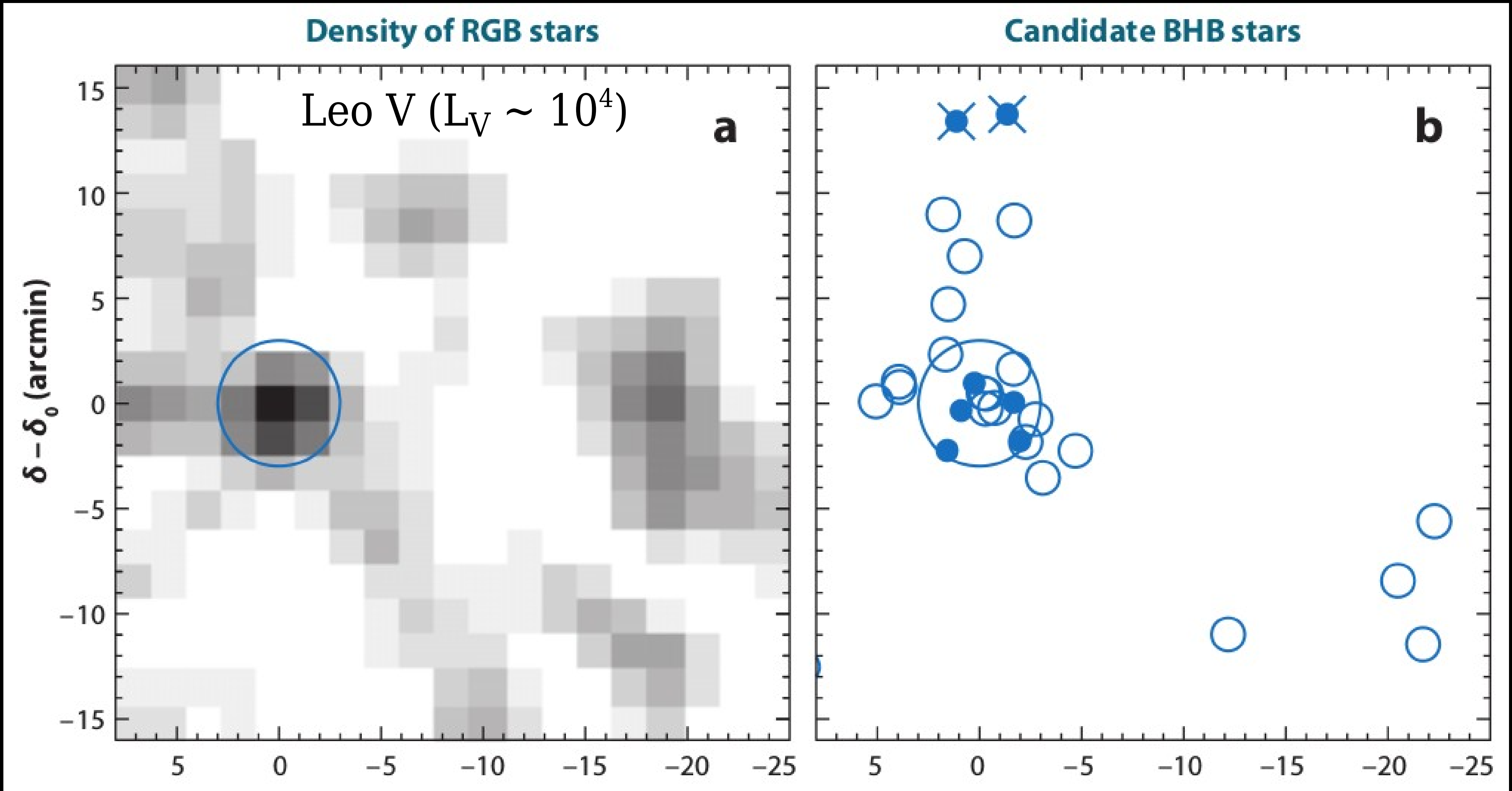
Giant Ellipticals:
with hot X-rays haloes
in hydrostatic equilibrium
(Humprey+2006,2009,2012)

Disky Es and S0s:
with stellar kinematics from
integral-field spectroscopy
(Atlas^{3D} - Cappellari+2010)

Dwarf Spheroidals:
with high-res spectroscopy
of individual bright stars
(many many references...)

Lelli+2017, ApJ

Need to be careful with ultra-faint dwarfs



Tolstoy+2009

- σ_v often based on ~5-10 stars → undetected binaries overestimate σ_V
- Tides from MW and M31 → out of dynamical equilibrium!