

Galaxies as simple dynamical systems: Observational data disfavor dark matter and stochastic star formation†

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† This manuscript is part of a special issue whose topic is MOND:

<http://www.nrcresearchpress.com/toc/cjp/93/2>

Summary

- Standard Model of Cosmology (SMoC)
- Dual Dwarf Galaxy Theorem
TEST I: BTFR and $R(M)R$
- Phase-space correlated satellite distribution
- TEST II: Dynamical friction
- Merger-driven evolution of galaxy populations
- Scale-Invariant Dynamics (SID)
- Overview about MOND literature and sources

SMoC hypothesis

- *Hypothesis Oi:*

Einstein's general relativistic field equation is valid in spatial scales $\tilde{O}(>6)$ and acceleration scales $\tilde{O}(>5)$ and accounts for the space-time-matter coupling.

- *Hypothesis Oii:*

All present-day matter is created as a relativistic fluid during the hot Big Bang.

Hot Big Bang nucleosynthesis broadly explains the observed abundance patterns (SmoPP).

SMoC hypothesis

- *Augmentary Hypothesis 1*: cosmic inflation to produce a Universe as flat and homogenous at large scales as the observed Universe.
Universe volume inflated by a factor of about 10^{78} in $\sim 10^{-33}$ sec.
- *Augmentary Hypothesis 2*: unseen (dark) matter must exist to boost the matter density, to aid in structure formation and in an attempt to explain the constant-rotation-velocity curves of galaxies (see review by Jaan Einasto 2013 in Brazilian Journal of Physics).
- *Hypothesis 3*: a accelerated expanding Universe driven by dark energy is needed to explain the DM vs. z diagram of the High- z SN Program (Riess et al. 1998)

Dual Dwarf Galaxy (DDG) Theorem

In any realistic cosmological model, there exist **only** two types of dwarf galaxies:

- type A dwarf galaxies are **Primordial Dwarf Galaxies (PDGs)**; and
- type B dwarf galaxies are **Tidal Dwarf Galaxies (TDGs)**.

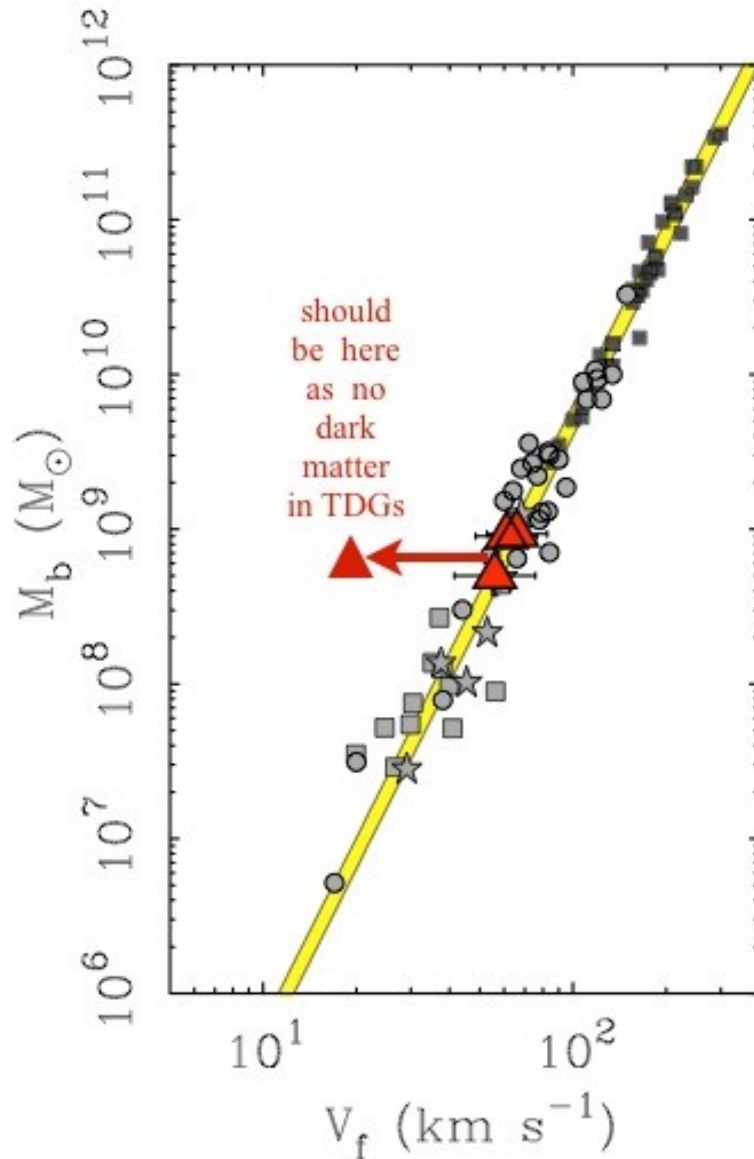
PDGs

- In the SMOc major galaxies such as the MW and Andromeda ought to have a large number of satellite PDGs each with their own dark matter sub-halo and each being brighter than a typical open cluster, but with a **very large dynamical mass-to-light ratio $M/L > 10 (M/L)_{\text{sun}}$** .
- *Indeed, the dwarf spheroidal (dSph) and ultrafaint dwarf (UFD) galaxies found around the MW and Andromeda do have $M/L \approx 10-10^3 (M/L)_{\odot}$ by observation when interpreting the data in terms of Newtonian dynamics (Simon & Geha 2007)*
- These satellite galaxies are typically **distributed spheroidally** about their host galaxy reflecting the three-dimensional structure of the hosting dark matter halo.
- *Libeskind et al 2009 find a low probability of alignment in the angular momenta of galaxy satellites (see fig. 9).*

TDG

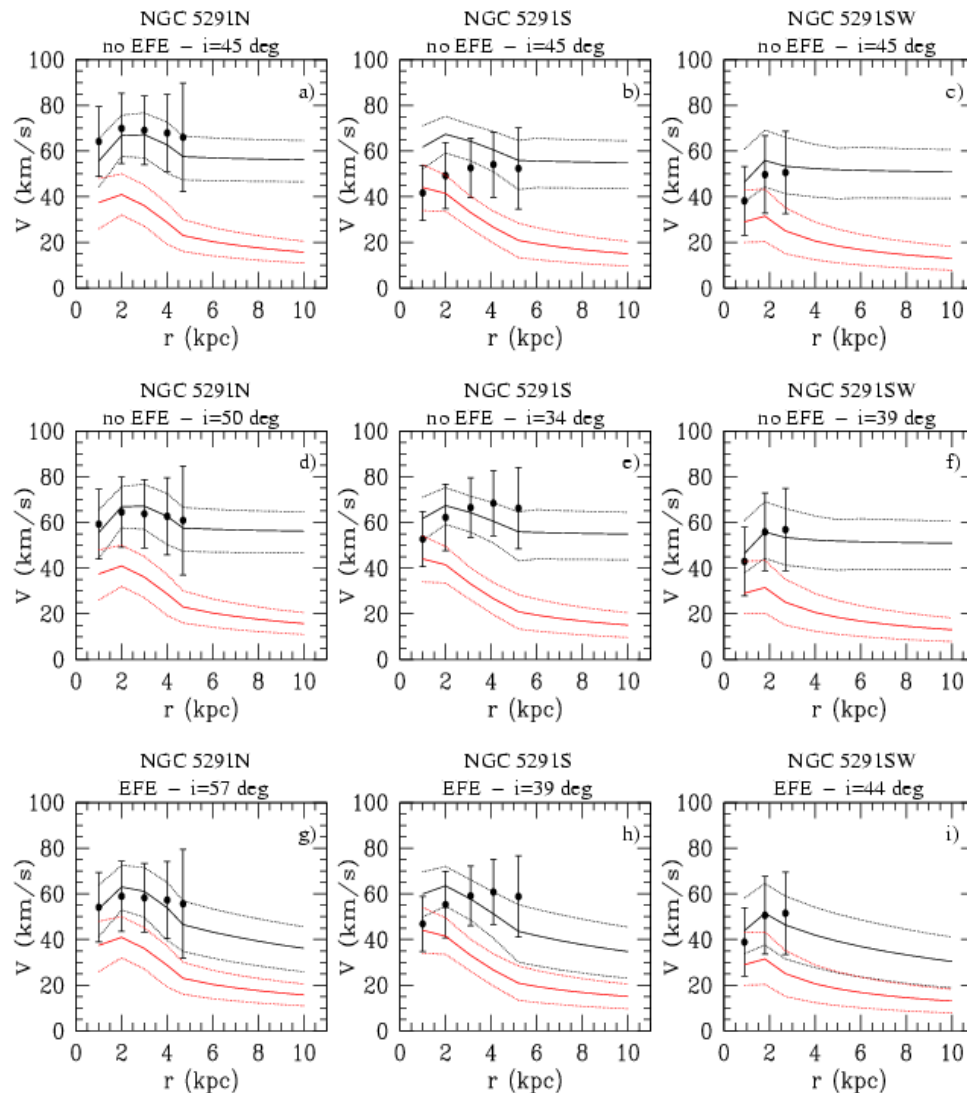
- TDG formation has been common over cosmological times. **They cannot contain significant amounts of dark matter** and they form in phase-space-correlated structures (i.e. in tidal tails). Available work suggests TDGs survive for many Gyr. It is not known yet which fraction of satellite galaxies are ancient TDGs.
- TDG potential wells correspond to maximum $v_c < 30 \text{ km s}^{-1}$ that the DM particles virialised within the massive DM halos ($v_c > 100 \text{ kms}^{-1}$) can overcome without being captured.
References on simulations: M. Wetzstein et al. 2007, Barnes & Hernquist (1992), Elmegreen, M. Kaufman, and M. Thomasson 1997, Bournaud et al. 2010.
- TDGs and star clusters that formed in one tidal tail form **highly anisotropic and correlated structures in phase-space**.
- The gas in the tidal tail is fragmented into star clusters, star-cluster complexes and dwarf-galaxy-scale star-forming clumps.
References on simulations: Hunter et al 2000, Borunaud et al. 2008

Barionic Tully-Fisher Relation - BTFR



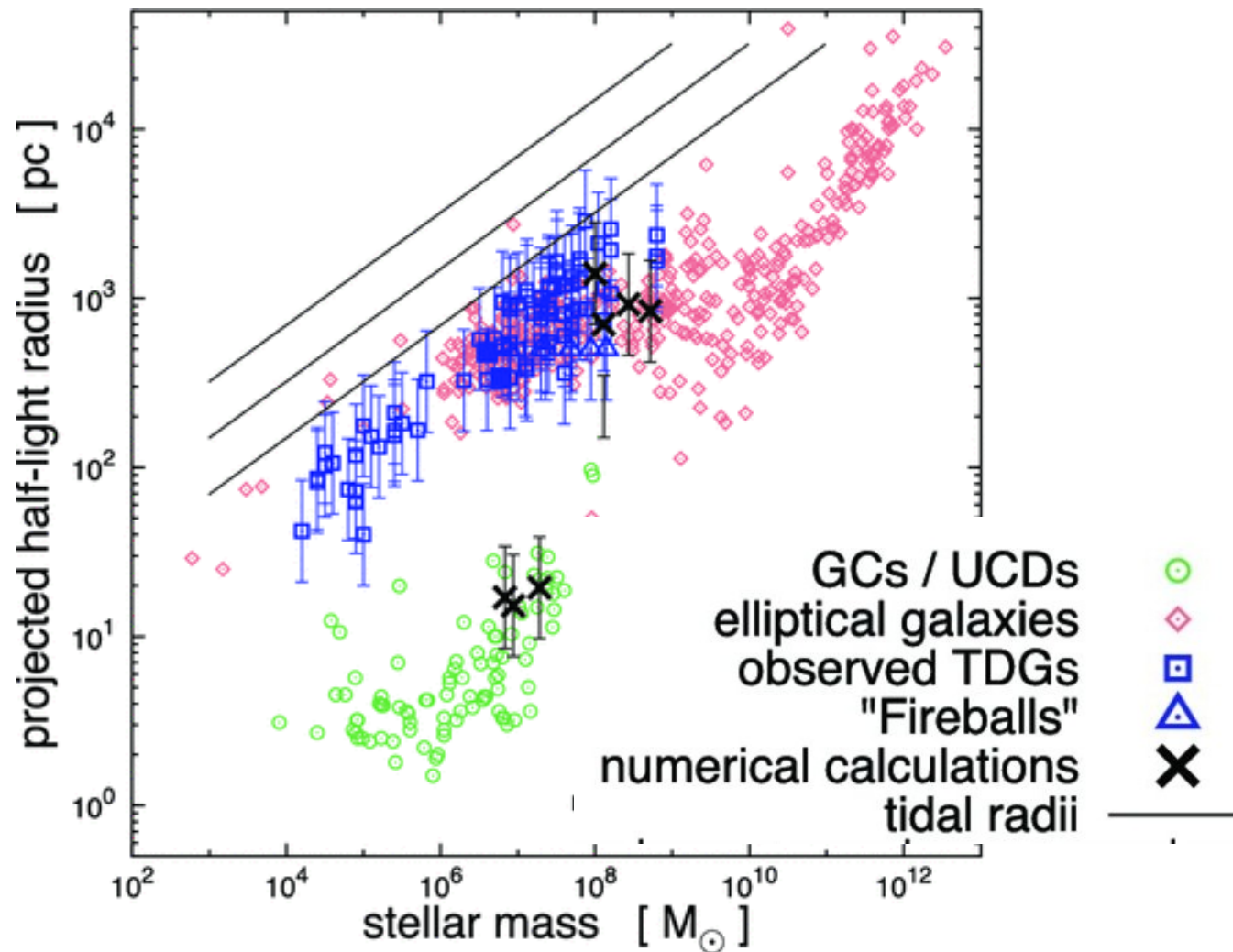
The baryonic Tully-Fisher relation (BTFR) of late-type galaxies. The grey symbols are the total observed baryonic mass (stars plus gas) and observed rotation velocity ($v_c \equiv V_f$) as collated and explained by McGaugh (2012). The three TDGs are plotted as red triangles. The red arrow points to the circular velocity at the outer radius of about 5 kpc they ought to have in this diagramme if they were virialised rotationally supported dwarfs of type B without dark matter and in Newtonian gravity (see Bournaud et al. 2007 for the rotation curves). The linear (yellow) regime is the BTFR (eq. 7). The width of the band represents the one-sigma uncertainty in the parameter $a_0 \sim 1.21 \cdot 10^{-10} \text{ms}^{-2}$ obtained from detailed fits to the rotation curves of disk galaxies by Begeman et al. (1991).

Barionic Tully-Fisher Relation - BTFR



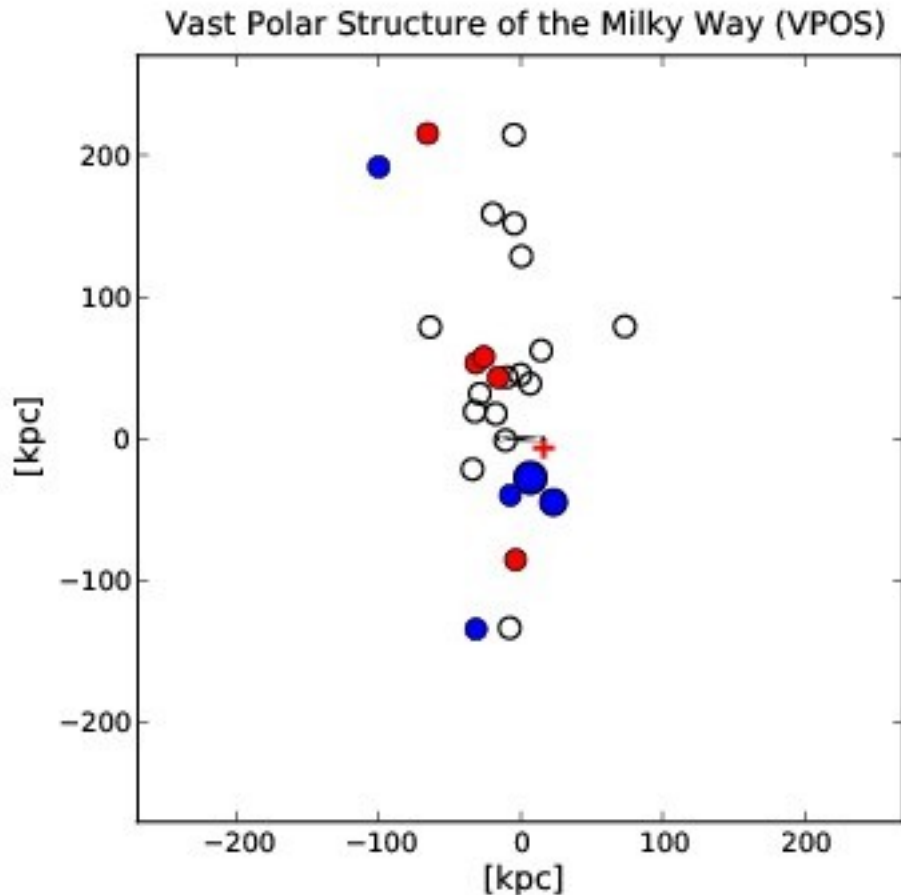
Gentile et al. (2007). Rotation curve data (full circles) of the 3 tidal dwarf galaxies (Bournaud et al. 2007). The lower (red) curves are the Newtonian contribution V_b of the baryons (and its uncertainty, indicated as dotted lines). The upper (black) curves are the MOND prediction and its uncertainty (dotted lines). The top panels have as an implicit assumption (following Bournaud et al.) an inclination angle of 45 degrees. In the middle panels the inclination is a free parameter, and the bottom panels show the fits made with the first estimate for the external field effect (EFE) (Sect. 3).

Radius-Mass Relation - $R(M)R$



Correlated phase-space satellite galaxy distribution

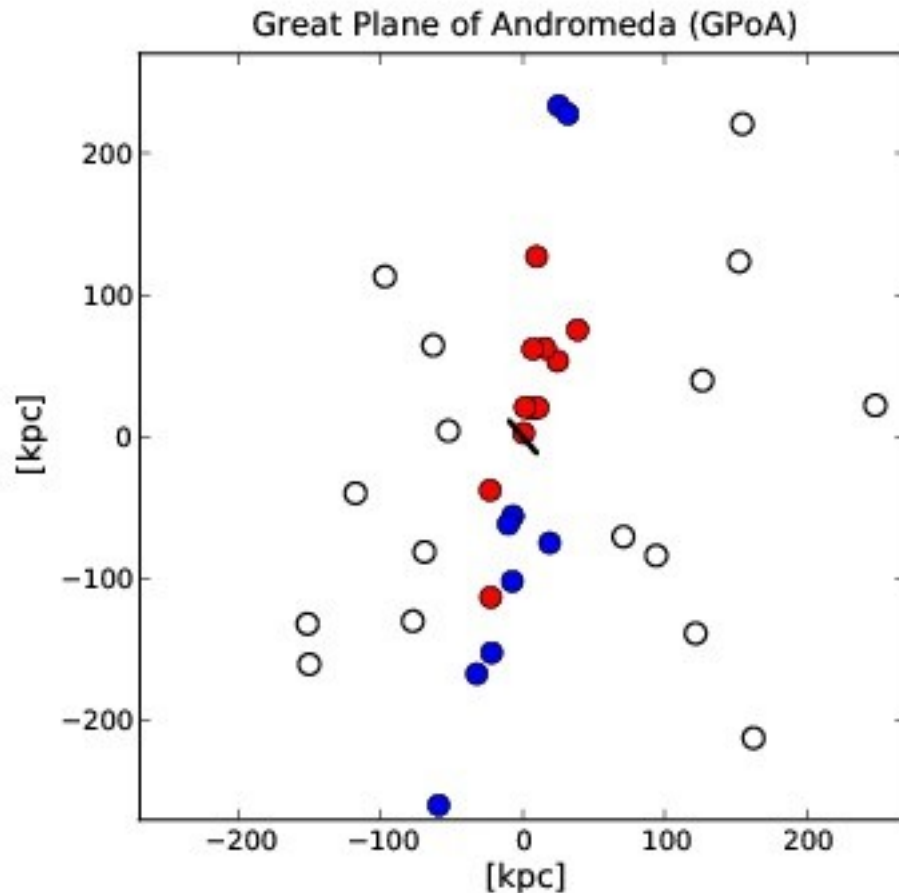
MW case



<https://www.youtube.com/watch?v=nUwxv-WGfHM>

The vast-polar structure (VPOS) or disk-of-satellites (DoS) of the MW seen edge-on (see Sec. 5.1.1.1) ("VPOS-3 orientation", see [91]) such that the north pole direction of the Local Group and of the MW is along the y-axis towards the top (see g. 6 in [91]). The face-on view is shown in g. 2 in [92]. The MW disk is seen here edge-on and is shown as a 30 kpc long thick black line at the centre of the gure. **The filled circles and the cross are the eleven classical (brightest) dSph satellite galaxies.** These have proper motion measurements such that estimates of their three-dimensional motions about the MW are available. **Satellites colored in red are moving away from the observer who is situated at infinity such that Andromeda lies behind and to the left of the MW from this viewing direction.** Open circles are ultra-faint dwarf (UFD) satellite galaxies for which proper motion measurements do not exist yet (see prediction 9.2 in Sec. 9). **The Large and Small Magellanic Clouds are shown as the largest and intermediate sized blue circles, respectively.** **The red cross depicts Sagittarius, which is close to being on a perpendicular orbit to the VPOS and around the MW and thus orbits within the here-shown plane apart from a small component away from the observer.** The counter-orbiting satellite in the north is one of the outermost satellites, Leo I, which is on a very radial orbit (and only has a small velocity component into the plane of the gure), while the one in the south may be a case which arises naturally if the satellite galaxies are TDGs : the ratio of the two counter-orbiting populations yields constraints on the MW{other-galaxy interaction which produced the tidal arms within which the TDGs formed [93]. The VPOS appears to be mass-segregated such that the most massive satellites are near its mid-plane (see Sec. 10.1.7 in [5]). The newly discovered satellite Crater or PSO J174.0675-10.8774 with absolute visual magnitude $M_V \sim -5.5$ [94,95] lies just to the lower right of the fourth open circle from the top and enhances the VPOS [96]. Andromeda also has a great plane of satellites which is discussed in Fig. 3.1. This figure was kindly provided by M. Pawlowski.

Andromeda



The great plane of Andromeda (GPoA) or vast thin disk of satellites (see Sec. 5.1.1.2) confirmed by Ibata et al. [6]. This GPoA contains 19 and thus about half the satellite population of Andromeda, has a diameter of about 400 kpc and a perpendicular scatter of about 14 kpc and constitutes therewith an even more extreme example of a phase-space-correlated population of satellite galaxies than the whole VPOS of the MW (Fig. 3.1). **The GPoA is also rotating mostly in one direction:** in this rendition the observer is situated near the MW, the y-axis points towards MW-north and **the satellites moving away in Andromeda's rest-frame are red, while the ones moving towards the MW are blue**. The other satellite galaxies not in this kinematically correlated structure are shown as open circles. Note that the GPoA and the VPOS (Fig. 3.1) are rotating in the same sense, although the two disks are inclined by about 38 deg (g. 16 in [91]), whereby the GpoA is seen edge-on from the MW. Both the GPoA and the VPOS are nearly perpendicular to the MW disk. This gure was kindly provided by M. Pawlowski.

But there are more phase-space correlated satellite systems:

- NGC1097: Galianni et al. 2010
- NGC5557: Duc et al. 2011
- NGC4631: Karachentsev et al. 2014
- NGC4216: Paudel et al. 2013
- NGC5291: Bournaud et al. 2007
- M81: Chiboucas et al. 2013
- Tadpole: Kroupa 2015

Correlated phase-space satellite galaxy distribution

But there are groups searching for disk configuration in simulations:

- **Libeskind et al. 2015** find satellite disks aligned with the fastest collapse vector \sim shear vector \mathbf{e}_1
- **Cautum et al. 2015** find that a ~ 10 per cent of Λ CDM galactic haloes have planes of satellites that are as infrequent as the MW and M31 planes.

Dynamical friction

The satellite galaxies should suffer an unavoidable orbital decay because of dynamical friction within the dark matter halo of its host galaxy.

If galaxies are embedded in massive halos of exotic DM particles then they merge whenever encounters occur with:

- galaxy-galaxy separations smaller than the sum of the virial radii of the dark halos
(**about 500 kpc** for the MW and Andromeda, for example) and with
- relative velocities comparable to the virial velocity dispersion of the dark halos (**a few hundred km/s** for the MW and Andromeda) or less.
- The merging times are comparable to the crossing times of the dominant DM halo (**a few gigayears**).

Dynamical friction

- Sagittarius (Sgr) satellite galaxy of the MW

Attempts at fitting the large number of observational constraints on the Sgr streams that are available over the past three orbits of the satellite have used models in which Sgr has a stellar mass of about 10^8 – $10^9 M_\odot$ **but no or only a minor DM halo** (references...)

Models without a DM halo may lead to better agreement with the observations.

In models in which Sgr is assumed to have a DM halo, it would fall-in to the MW DM halo about 2.5 Gyr ago with a first pericenter passage about 1.4–2 Gyr ago.

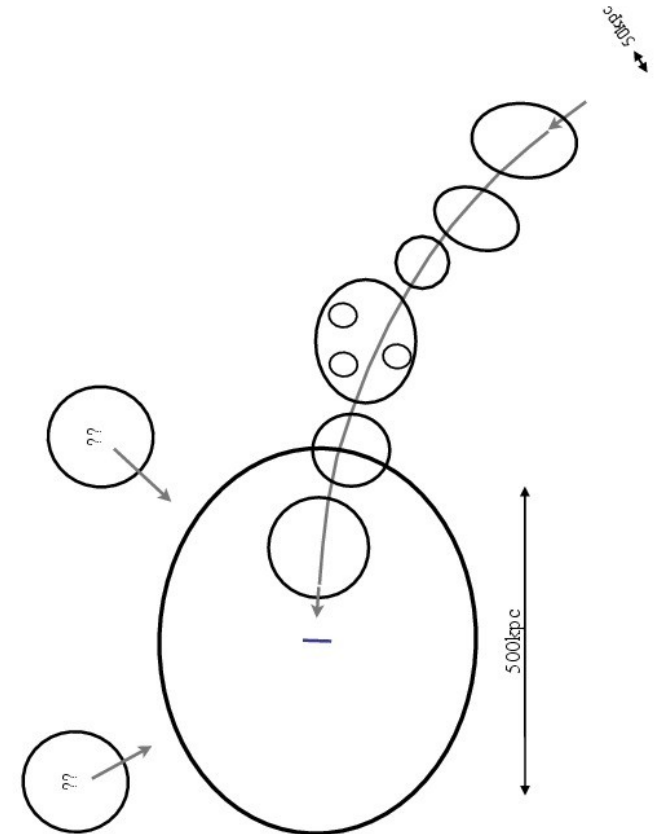
Dynamical friction

MW satellite ensemble

The unique orbits consistent with the satellite ages and distribution in the disk-of-satellites seem improbable:

MW satellites should

- walk in a very narrow channel by not merging with the MW by dynamical friction and
- not being completely dissolved by Galactic tides,
- but losing just enough DM halo mass to end up on their observed current orbits with long periods.



Dynamical friction

- M81 group

Including DM halos appear to have led to null results: solutions have not been possible because the system merges within about one crossing time.

Solutions are possible but without dynamical friction on the DM halos (Thompson et al. 1999, Yum 1999)

Merger-driven galaxy evolution

As discussed in Wu & Kroupa 2015, SMOc simulations show that:

- over the last 10 Gyr about **95%** of MW-mass-scale DM halos with a mass of $\approx 10^{12} M_{\text{sun}}$ have **undergone a minor merger** by accreting a subhalo with mass $> 5 \times 10^{10} M_{\text{sun}}$, and
- **70%** of them have accreted a subhalo with mass $> 10^{11} M$ [74].
- According to **69%** of such halos have **major mergers** since 11–12 Gyr ago and 31% have major mergers in the past 7–8 Gyr.

Mergers are common in MW-size galaxies in a DM-dominated Universe

Merger-driven galaxy evolution

Consequences

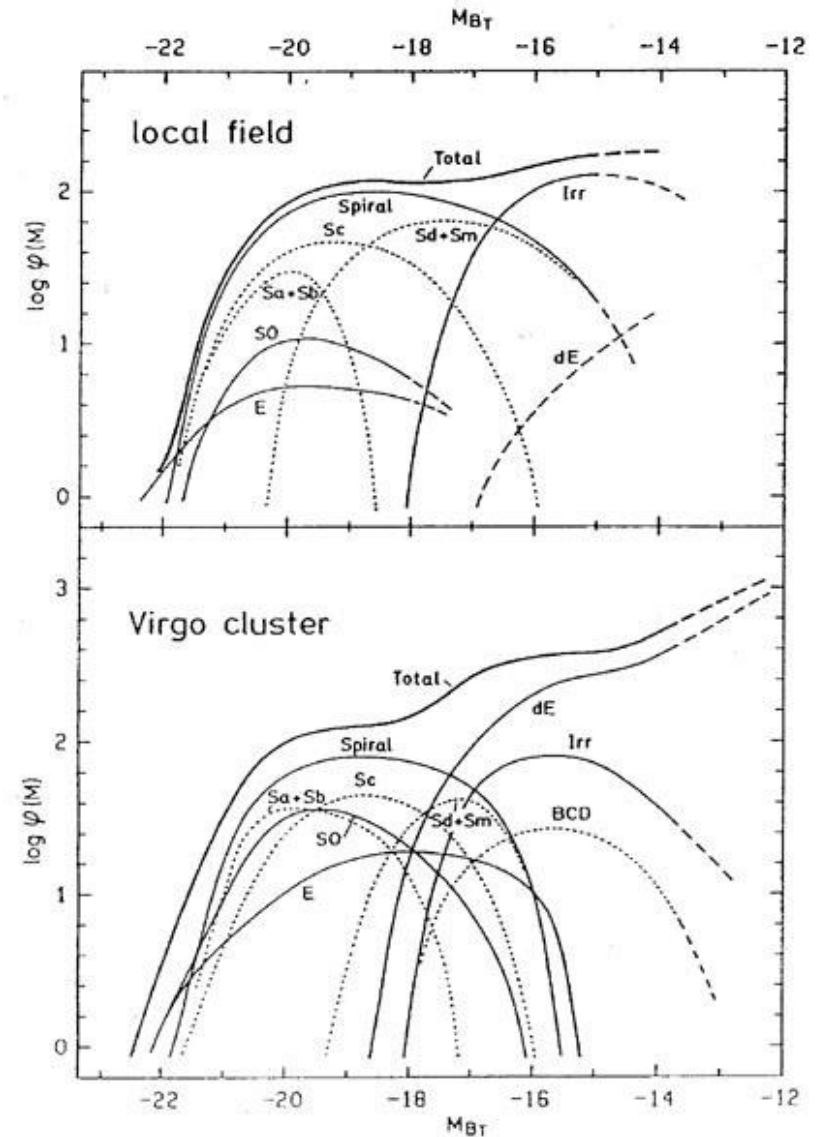
- The simulations have also shown that major mergers (with equal mass galaxy pairs) disrupt disks completely and that the remnants of such mergers become early-type galaxies (E galaxies or bulge-dominated galaxies [157]).

major mergers → early-type galaxies

- Minor mergers (with a mass ratio 10:1) also lead to growth of the bulge and thickness of the disc (see, e.g., refs. 158–160).

minor mergers → bulge and thick disk in in late-type galaxies

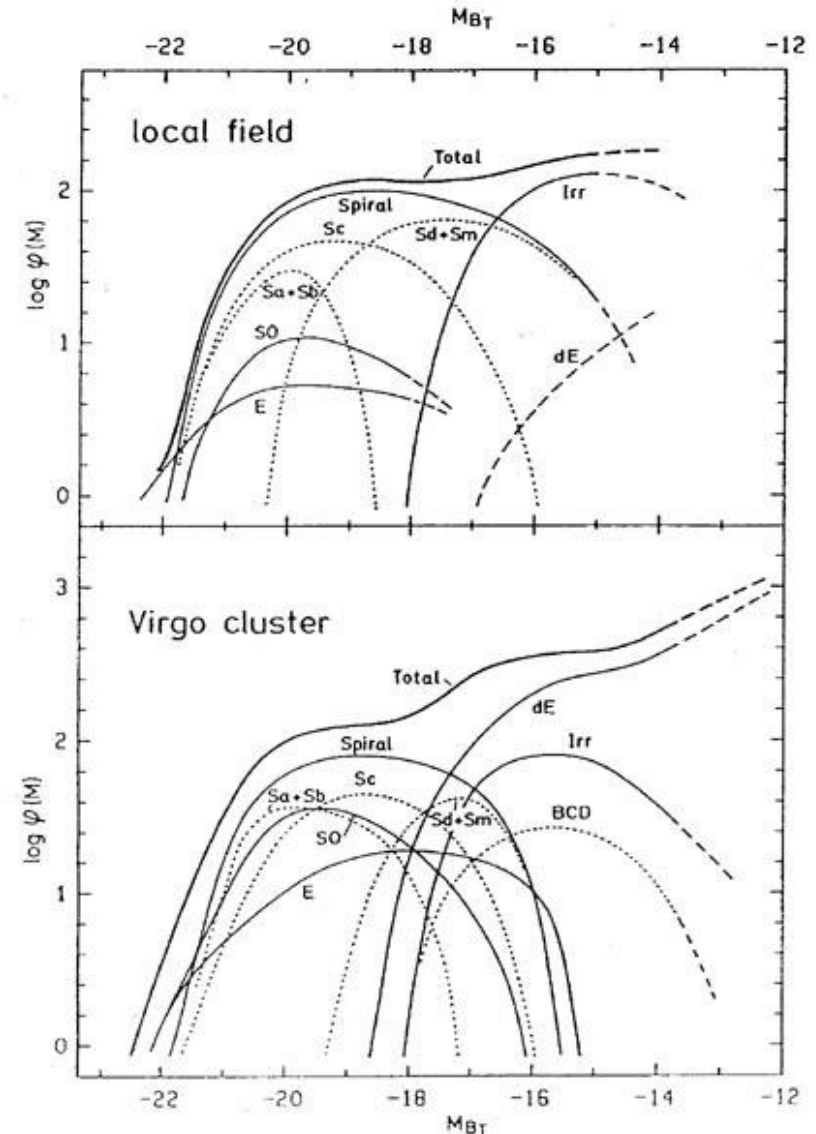
Merger-driven galaxy evolution



Binggelli, Sandage and Tamman 1988

Merger-driven galaxy evolution

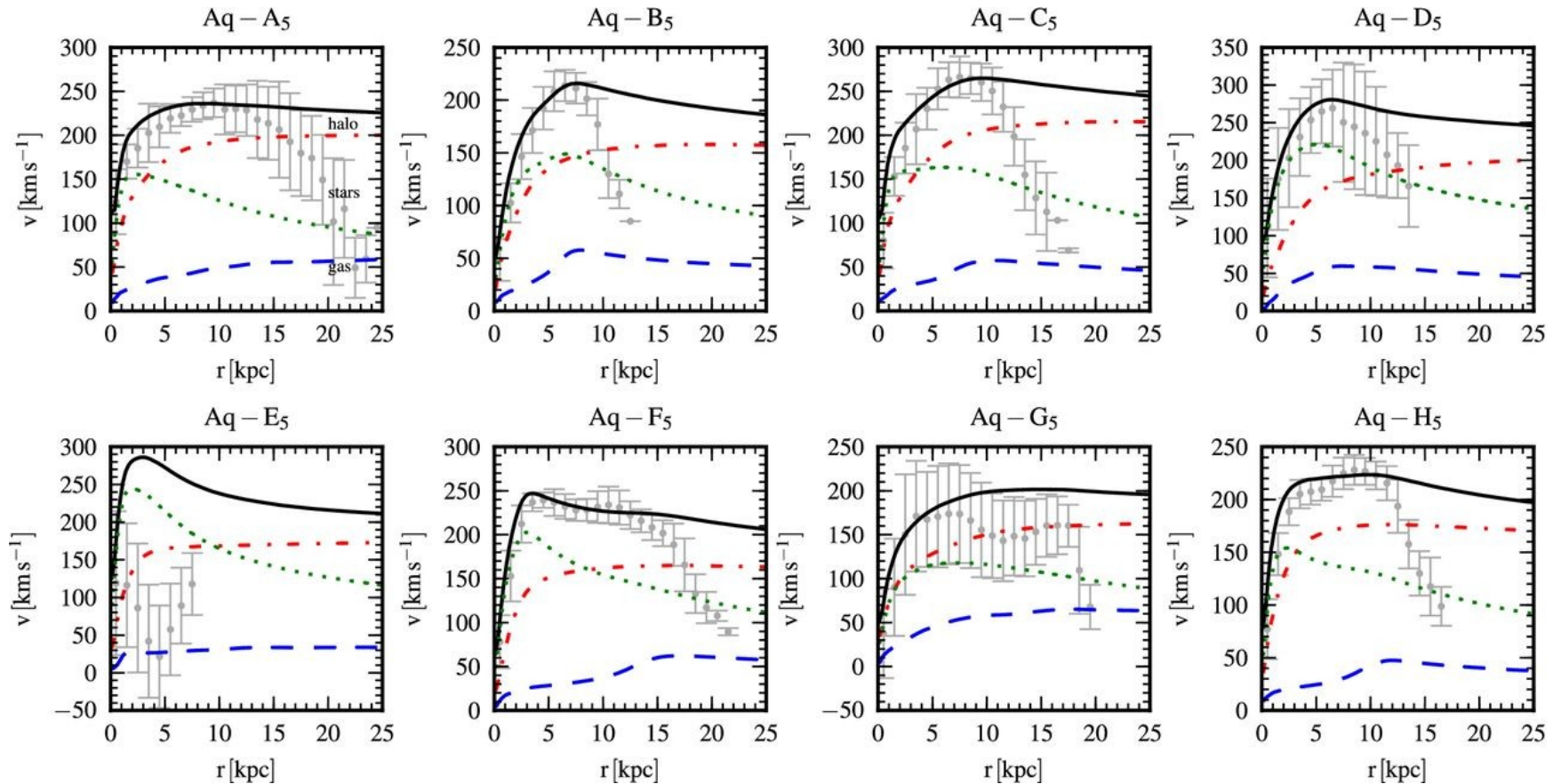
- **Bulge-less late-type galaxies:** Weinzirl et al. (2009) and Kormendy et al. (2010) that too many >50% (or 94% according to Fernández-Lorenzo et al. 2014) of all late-type galaxies (with baryonic mass $>10^{10}M_{\odot}$) **do not have a classical bulge**.
- **Massive galaxies:** The survey of galaxies more luminous than $M_J < -20.3$ (stellar mass $> 1.5 \times 10^{10}M_{\odot}$) by Delgado-Serrano et al. 2010, 90% of all galaxies are late-type star-forming galaxies, while only 3% are E galaxies.



Illustris simulation

- Their simulated galaxies with low SFRs contain about 52% of all the stellar mass, which is in galaxies more massive than $M_* = 10^9 M_{\text{sun}}$.
- The authors state that this agrees well with observations, but according to Delgado-Serrano et al. 90% of all galaxies with $M_* > 10^{10} M_{\text{sun}}$ today and 6 Gyr ago are late-type star-forming galaxies.

AREPO5 code



Federico Marinacci et al. MNRAS 2014;437:1750-1775. Rotation curves $v_c(r)=\sqrt{GM(<r)/r}$ for the eight Aquarius haloes at $z = 0$. Different line types give the contributions of various mass components to the total circular velocity: stars (dotted lines), dark matter (dot-dashed lines) and gas (dashed lines). The total rotation curves are given by solid lines, while points with error bars show the rotation velocity of the star-forming gas within $0.1 \times R_{\text{vir}}$. It is apparent that in most of the cases quite flat rotation curves are present. Some haloes (Aq-D, Aq-E and to a lesser degree Aq-F) however show that a spheroidal stellar structure (i.e. a bulge) still provides the dominant contribution to the circular velocity in the centre. The position of the sudden drop in the star-forming gas rotation velocity that can be observed in some of the haloes is set by the extension of this component.

Scale-Invariant Dynamics

$$(\mathbf{r}, t) \rightarrow \lambda(\mathbf{r}, t)$$

Dynamical acceleration

$$a \equiv \frac{d^2 r}{dt^2} \rightarrow \lambda^{-1} a$$

Gravitational acceleration

$$g_N = G M / r^2$$

$$g_N \rightarrow \lambda^{-2} g_N$$

$$\Rightarrow g = (a_0 g_N)^{1/2}$$

Scale-Invariant Dynamics

Gravitational acceleration = Centripetal acceleration

$$g = \frac{\sqrt{GMa_0}}{r} = \frac{v_c^2}{r}$$

Scale-Invariant Dynamics

Gravitational acceleration = Centripetal acceleration

$$g = \frac{\sqrt{GMa_0}}{r} = \frac{v_c^2}{r}$$

$$v_c = (GMa_0)^{1/4} \quad \mathbf{BTFR!}$$

Scale-Invariant Dynamics

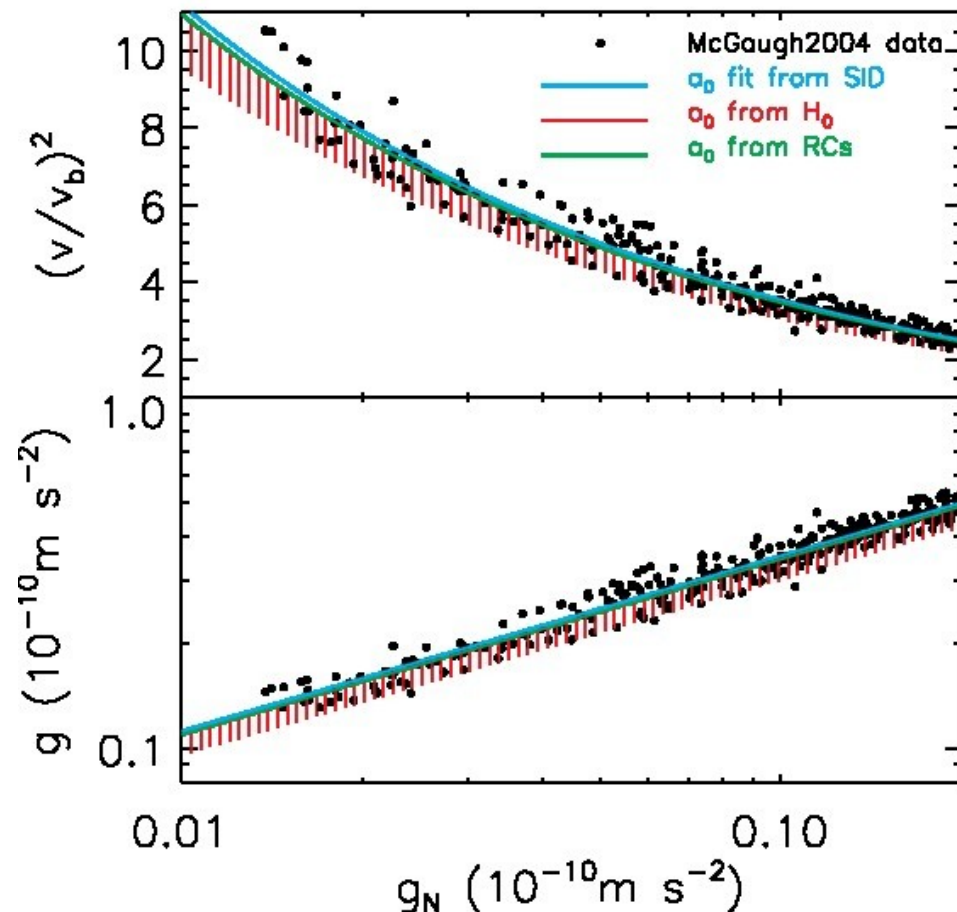
Mass-Discrepancy-Acceleration (MDA)

$$\left(\frac{v_c}{v_{c,b}}\right)^2 = \left(\frac{a_0}{g_N}\right)^{1/2}$$

v_c depends only
on barionic mass
and

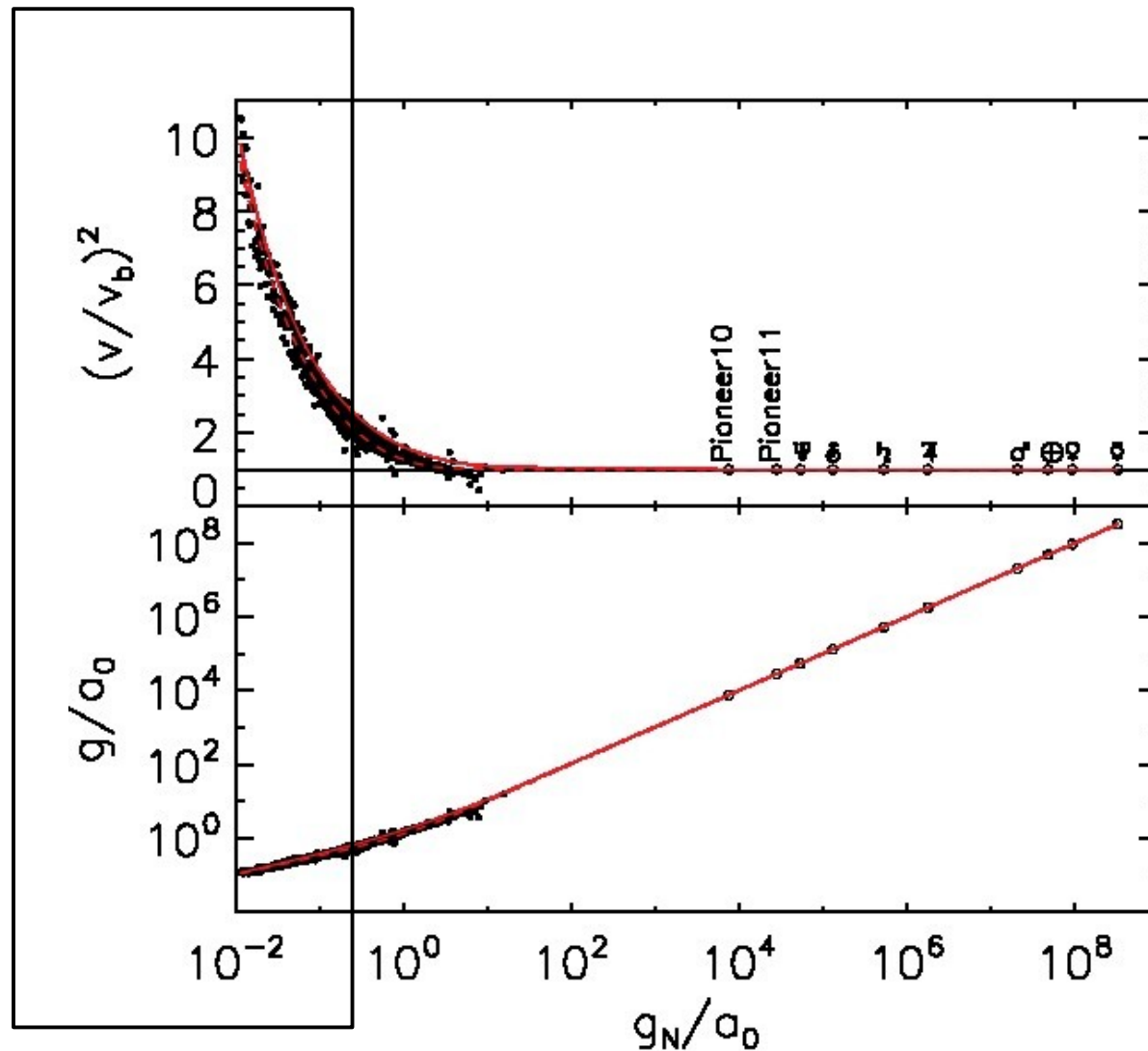
$v_{c,b}$ depends of
mass and radius

$$v_{c,b}^2 = G M / r$$



$$a_0 = \frac{cH_0}{2\pi}$$

Scale-Invariant Dynamics

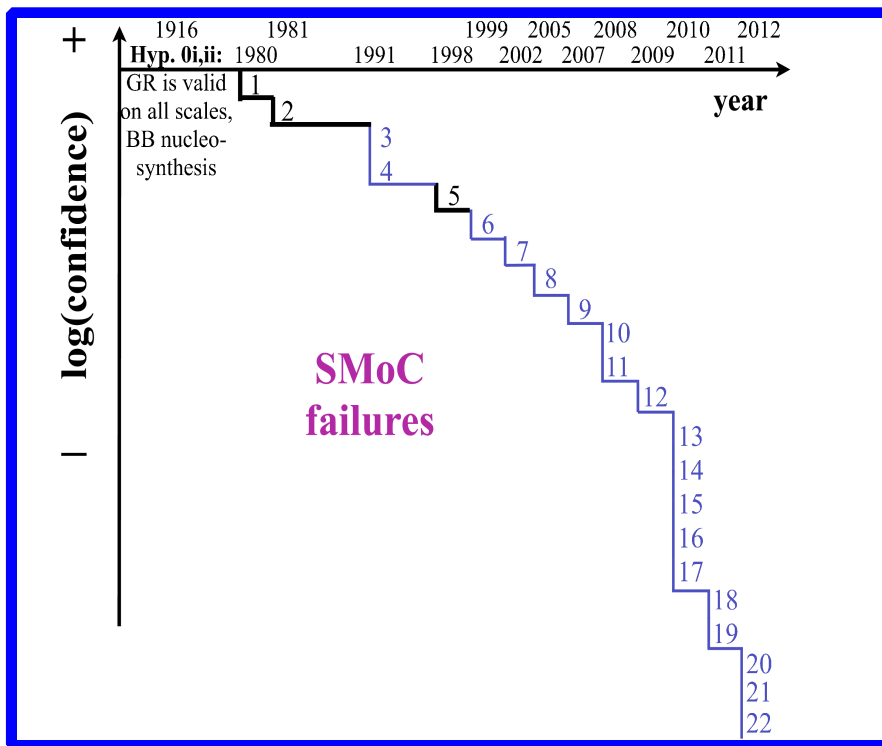


Scale-Invariant Dynamics

SID implies that galaxies:

- have flat rotation curves,
- lie on the BTFR,
- obey the MDA correlation,
- and that $g \sim \Sigma^{1/2}$
 Σ = baryonic surface mass density
(See Trippé 2014, fig. 2)

The theory confidence graph



A long list of Failures (Subsec. 17.3.2, Kroupa 2012)

- (1) 1980: Curvature and homogeneity:
- (2) 1981: The super-Keplerian galactic rotation curve
- (3) 1991: Galaxy angular momentum
- ...
- ...
- ...
- (20) 2012: The Train-Wreck Cluster
- (21) 2012: Missing Dark Matter
- (22) 2012: Massive Galaxy Clusters

Overview on MOND

Main researchers in MOND

(as far as I know...)

- Gary Angus
- Benoit Famaey
- Pavel Kroupa
- Stacy McGaugh
- Mordehai Milgrom
- Marcel Pawlowski
- ...

Interesting links

- Literature relating to the Modified Newtonian Dynamics (MOND)

<http://www.astro.umd.edu/~ssm/mond/litsub.html>

- The Dark Matter Crisis

The rise and fall of cosmological hypotheses

<http://www.scilogs.com/the-dark-matter-crisis>

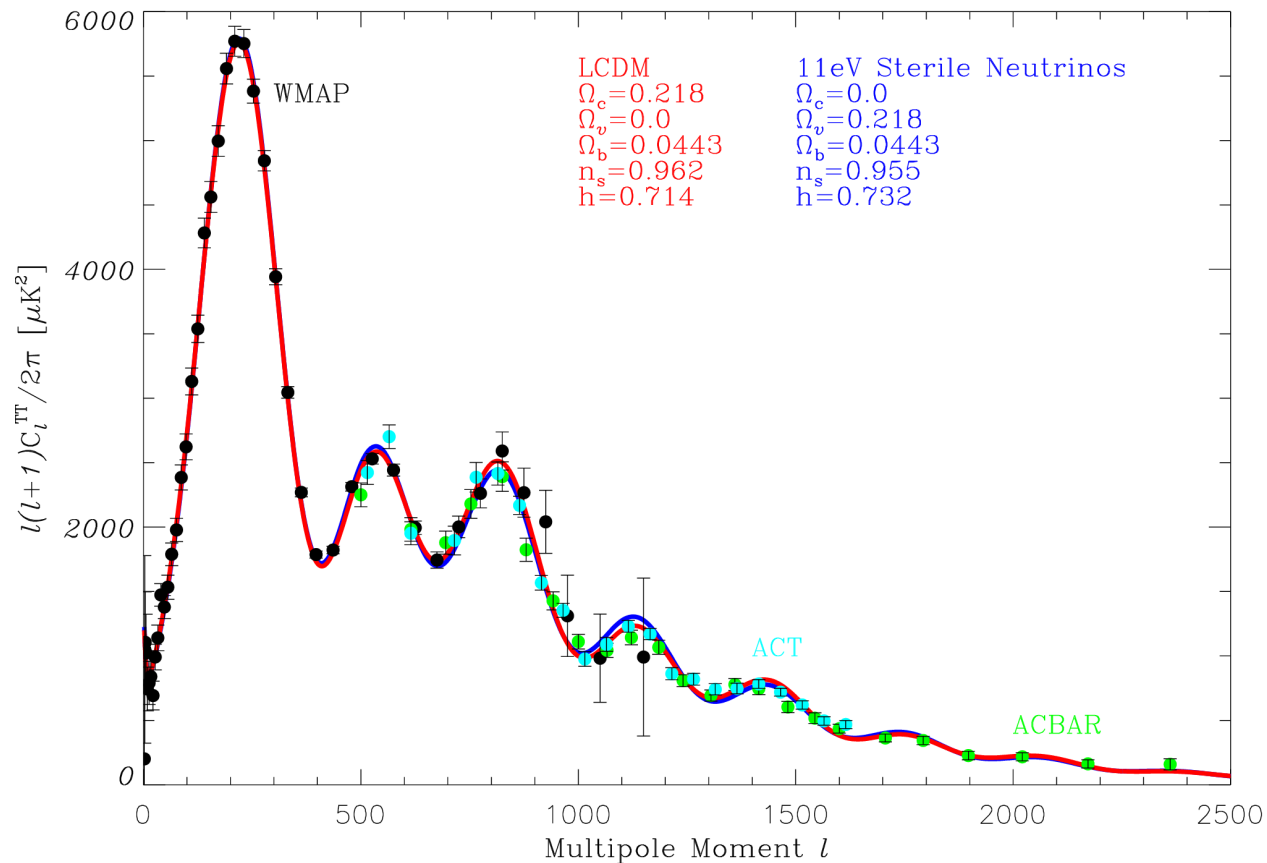
Reviews...

- Short review > Challenges for Λ CDM and MOND
Famaey, B., & McGaugh, S. (2013)
Journal of Physics Conference Series, 437, 012001
- Long review > (MOND): Observational Phenomenology and Relativistic Extensions
Famaey B., McGaugh S. S. (2012)
Living Rev. Relativ., 15:10.

Questions...

BACKUPS

CMB power spectrum: Λ CDM vs MOND



Milgromian-based cosmological theories account for the CMB power spectrum just as well as the Λ CDM. The CMB power spectrum as measured by the WMAP satellite year seven data release (filled circles), ACT (turquoise data) and the ACBAR 2008 data release (green circles). The Λ CDM and Milgromian dynamics (assuming hot DM is in the form of 11 eV sterile neutrinos) models are an identical representation of the CMB data, while the Milgromian model completely outperforms the Λ CDM on galactic scales. See Angus & Diaferio (2011) for more details. (fig. 1 from Angus & Diaferio 2011 with kind permission from Garry Angus.)