Challenges for the dark-matter and dark-energy models that point towards a new model

in

Dark Energy :

from fundamental theories to observations (and back)

[Sept 11-15, 2023]

12th Sept 2023
Frascati

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University of Bonn

Outline :

I) The inflation + cold/warm dark-matter + dark-energy Newtonian/Einsteinian standard model of cosmology (LCDM)

II) The inflation + ~~cold/warm dark-matter~~ + dark-energy Milgromian nuHDM model of cosmology (the nuHDM model)

III) The ~~inflation~~ + ~~cold/warm dark-matter~~ + ~~dark-energy~~ Bohemian model of cosmology (the BMoC)

model = a model that has equations of motion such that galaxy formation and evolution with star formation can be computed .

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SIMPLER

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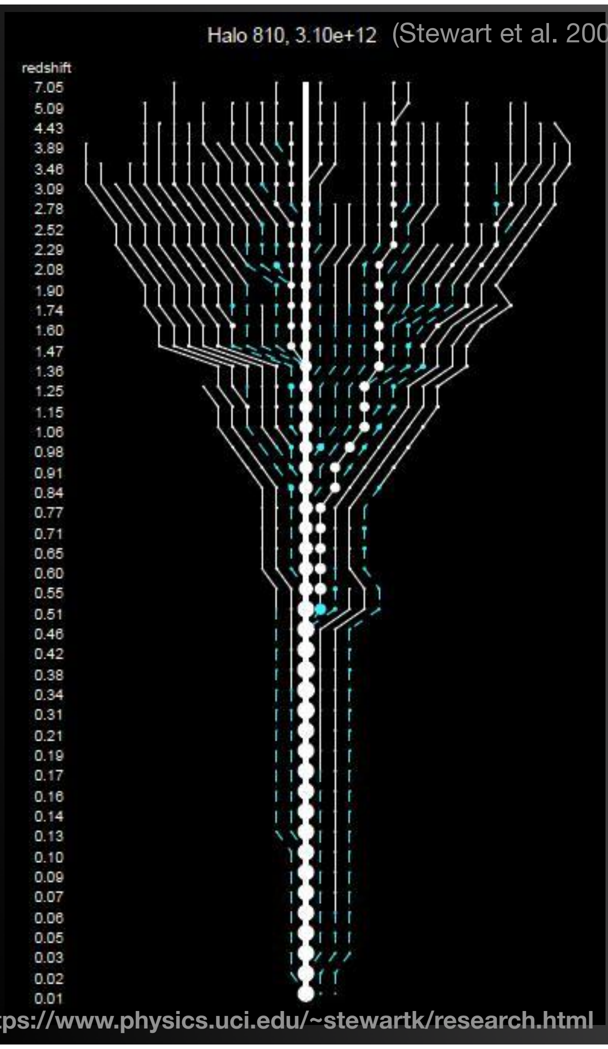
Bohemian model of cosmology (the BMoC)

model = a model that has equations of motion and which can be put into the computer with star formation to compute the formation of galaxies.

I) The LCDM model (Standard Model of Cosmology)

Newtonian / Einsteinian gravitation
with inflation
with dark matter
with dark energy



In the LCDM model galaxies grow mostly through mergers

. . . why ?

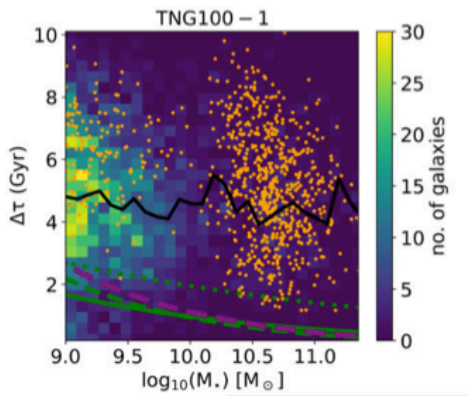
. . . due to Chandrasekhar dynamical friction on the dark matter halos (see below)

Do the observed (real) E galaxies contain stellar populations with the predicted large spread of ages ?

No !

Eappen et al. 2022 :

(orange points are central galaxies in the LCDM simulations)



Thomas et al. 2005 Recchi & Kroupa 2009 Thomas et al. 2005 McDermid et al. 2015

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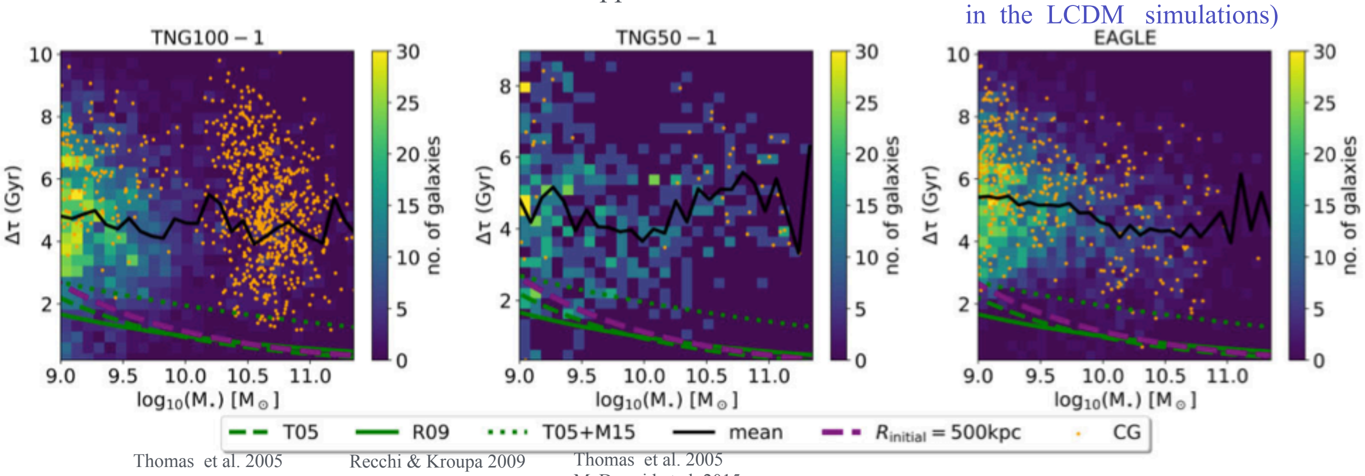
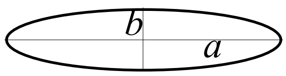


Thomas et al. 2005 Recchi & Kroupa 2009 Thomas et al. 2005 McDermid et al. 2015

This is in $>5\,\sigma$ tension with E galaxies that form in a LCDM model universe (Eappen et al. 2022) .

Does the LCDM produce mostly disk galaxies ?

No !

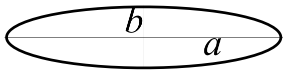


$$q_{\mathrm{sky}} = \frac{b}{a}$$

Does the LCDM produce mostly disk galaxies ?

No !

LCDM falsified with >13 sigma.



$$q_{\rm sky} = \frac{b}{a}$$

(Haslbauer et al. 2022)

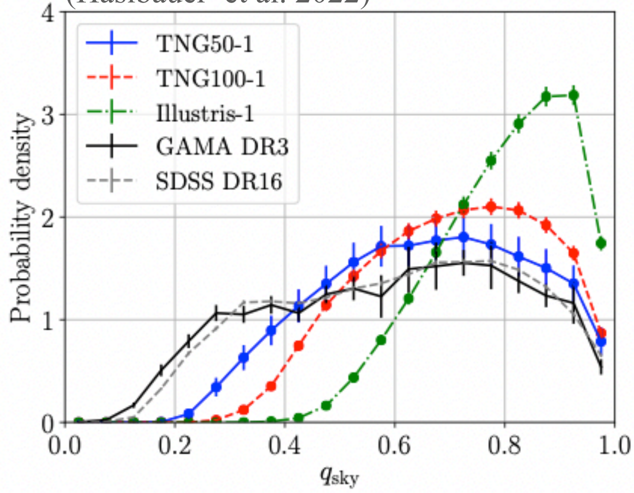


Figure 4. Comparison between the observed distribution of $q_{\rm sky}$ and that produced by different cosmological ΛCDM simulations for galaxies with $10.0 < \log_{10}(M_*/M_\odot) \leq 11.65$. The observed $q_{\rm sky}$ distributions (black and gray points with error bars) have been weighted based on the stellar mass distribution of the TNG50-1 run (shown in Figure 2). Invisible error bars (Equation 8) are smaller than the data point symbol. The total χ^2 values between the observed and simulated distributions (Equation 7) and the corresponding levels of tension are reported in Table 3. The TNG50-1, TNG100-1, Illustris-1, EAGLE50, and EAGLE100 computations shown here use 882, 6424, 6842, 480, and 3613 subhalos, respectively.

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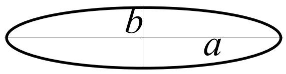

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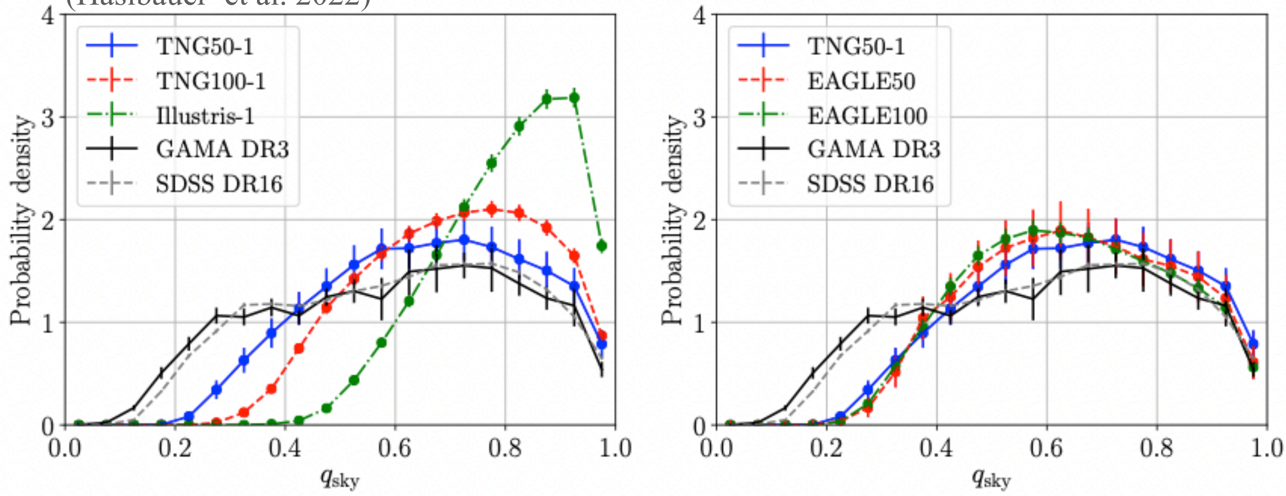

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Thus, the galaxy population

In LCDM, stars in model elliptical galaxies have ages ranging from <1Gyr to 13Gyr

and most model galaxies are spheroidal (elliptical-like), *due to the buildup through many mergers.*

total disagreement

In the real Universe, elliptical galaxies make $< 5\%$ in number which is nearly constant over half the lifetime of the Universe.

In the real Universe, most (>90 %) of all galaxies are extended thin disk galaxies.

LCDM thus
predicts a completely wrong fraction
of elliptical galaxies
and the stellar ages in real elliptical galaxies are
completely different (>12Gyr).

Both failures of LCDM are individually at $> 5\sigma$ confidence

Delgado-Serrano et al. 2010
Eappen et al. 2022
Haslbauer et al. 2022

elliptical galaxy

disk galaxy

disk galaxy

The merger-driven buildup of galaxies in LCDM is in $\gg 5\sigma$ disagreement with the observed population of galaxies.

elliptical galaxy

disk galaxy

disk galaxy

The galaxy population

In the LCDM, stars in model elliptical galaxies have ages ranging from <1Gyr to 13Gyr

and most model galaxies are spheroidal (elliptical-like), due to the buildup through many mergers.

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Immediate violation of LCDM ???

elliptical galaxy

disk galaxy

disk galaxy

If LCDM is falsified,
then what about
dark matter ?

Does it even exist ?

How can
we test for
dark matter ?

CMB peaks kaputt

No structure formation

If dark matter is falsified, then Einstein-based cosmology breaks down completely.

Galaxies would fly apart
Galaxy groups would fly apart
Galaxy clusters would fly apart

How can one test for the existence of dark matter ?

By construction of the standard cold- or warm-dark matter models,
the dark matter particle interacts only gravitationally with ordinary matter.

Any finite interaction cross section
with dark-matter particles
and particles from the Standard Model of Particle Physics
must be negligible :

Otherwise :
- galaxies would look different (e.g. E galaxies in galaxy clusters), e.g. Gnedin & Ostriker 2001
- pre-CMB structure formation would be incompatible with the CMB, and
- no trace of a dark matter particle has been found in any experiment despite a very large world-wide effort under, on, and above the ground.

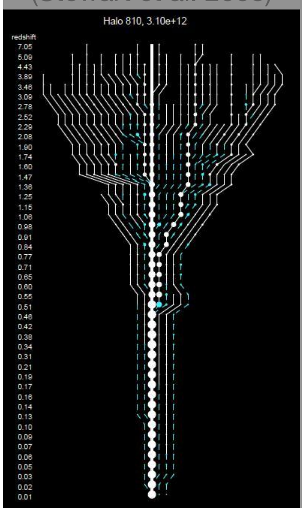
How can one test for the existence of such a dark matter particle ?

The LCDM model predicts
each galaxy to be in a massive very extended
dark matter halo.

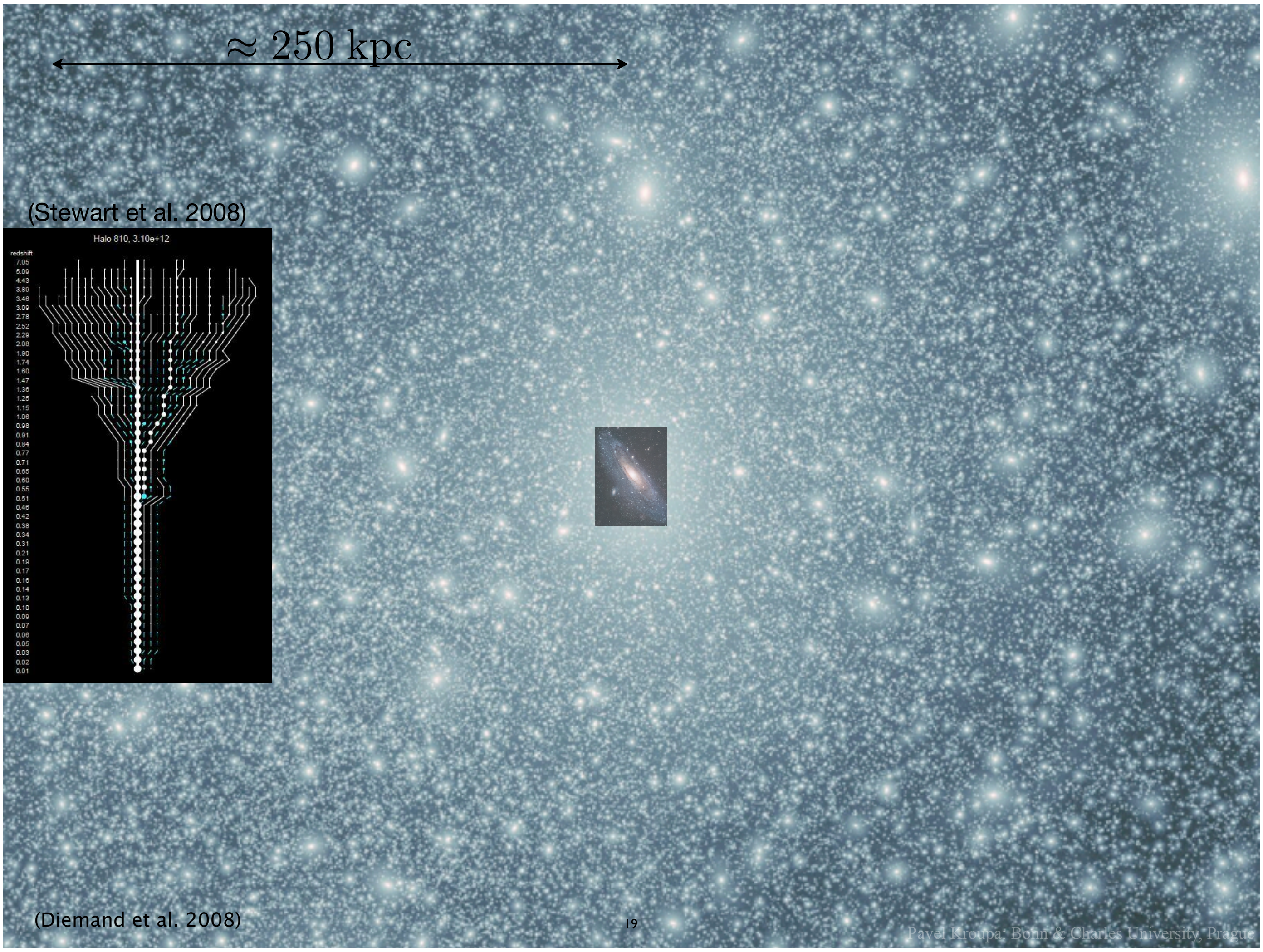
This is due to each galaxy growing
through many mergers.

$\approx$ 250 kpc

(Stewart et al. 2008)



(Diemand et al. 2008)



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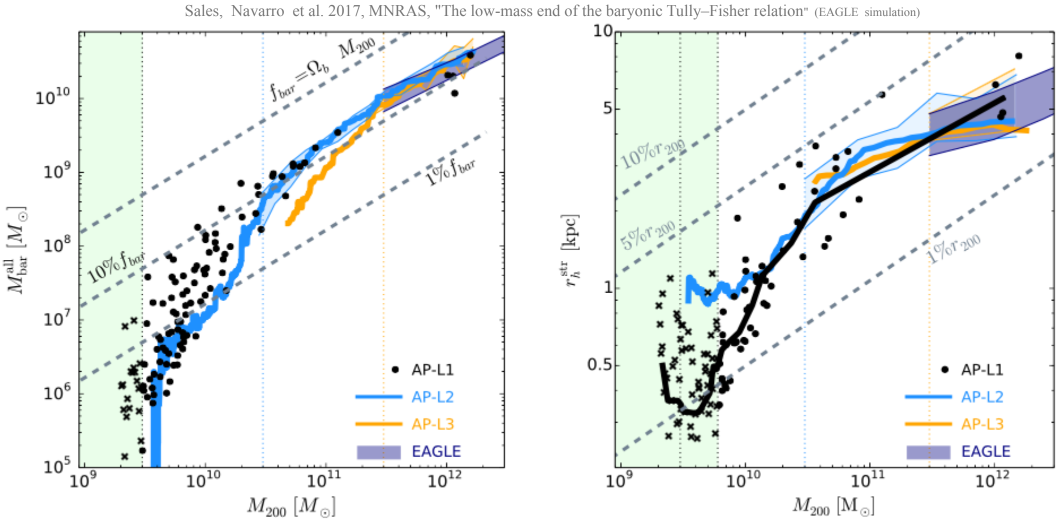
Sales, Navarro et al. 2017, MNRAS, "The low-mass end of the baryonic Tully–Fisher relation" (EAGLE simulation)

For a galaxy with a mass M_{bar} in stars + gas, LCDM predicts the properties of its dark matter halo.



For a given galaxy,
its dark-matter halo is thus known
(within a well specified range of properties)

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(within a well specified range of properties)

Given these properties,
we can test if the observed
satellite galaxies
(e.g. around our Milky Way)
comply with these
in terms of their
ages, *stellar masses*, *position and velocity vectors*.

As the satellite galaxy orbits,
it induces a wake of dark matter particles behind itself,
and this leads to
Chandrasekhar dynamical friction,
the strength of which depends on the
total mass of the satellite galaxy.

They must have fallen-in -- so, are there infall solutions **?**

Testing for the existence
of
Dark Matter
via
Chandrasekhar
dynamical friction

The problem :

In the LCDM model,
the observed satellite galaxies *must have* fallen-in.

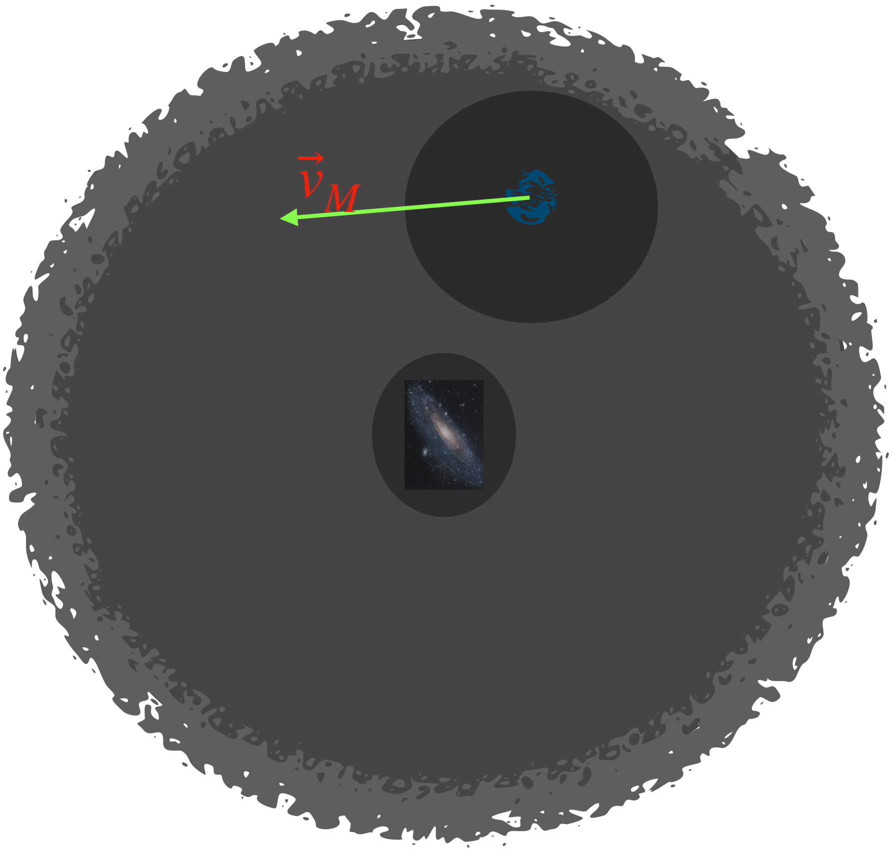
That is, they must have come in from a large distance
and get "stuck" (through dynamical friction)
in the dark matter halo of the Milky Way

So, are there infall solutions
for the observed satellite galaxies
of the Milky Way **?**

LCDM predicts a new phenomenon :

If there is dark matter, then there must be *Chandrasekhar dynamical friction*.

The situation :



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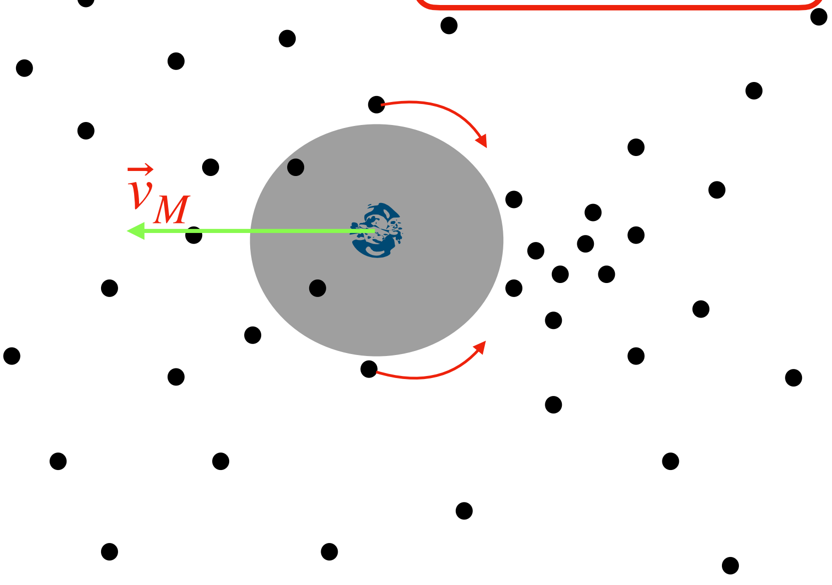
Visualisation

(integrate over all satellite--DM-particle encounters)



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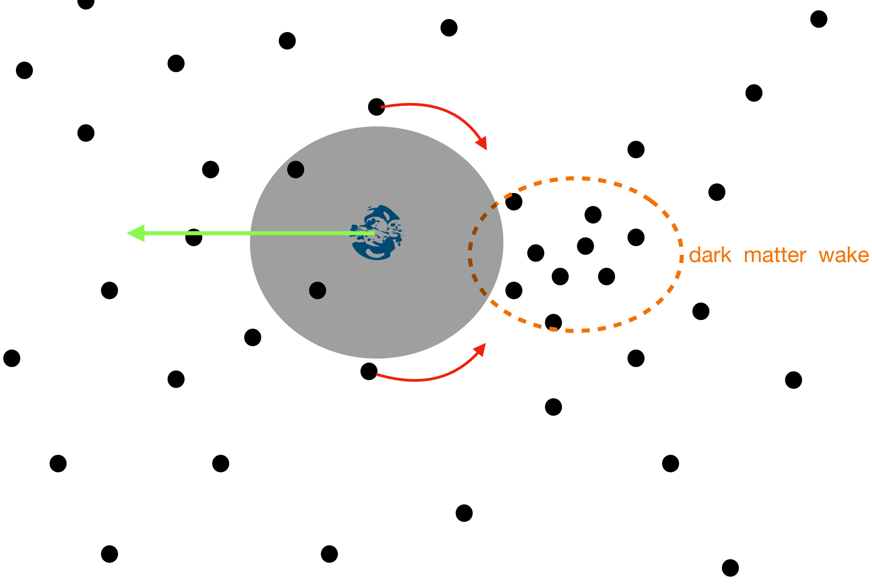

$$\frac{d\vec{v}_M}{dt} = -\frac{4\,\pi \ln\Lambda\, G^2\,(M+m)\,\rho_0\, m}{v_M^3}\left[\mathrm{erf}(X) - \frac{2\,X}{\sqrt{\pi}}\,e^{-X^2}\right]\;\vec{v}_M$$

eg. Binney & Tremaine (1987): "Galactic Dynamics"

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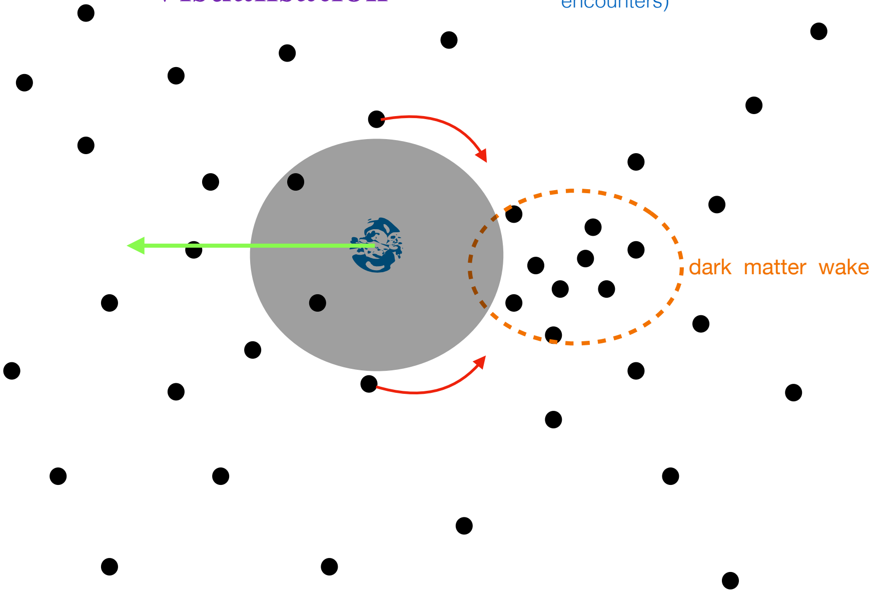

This test *insensitive* to mass, *m*, of dark matter particle

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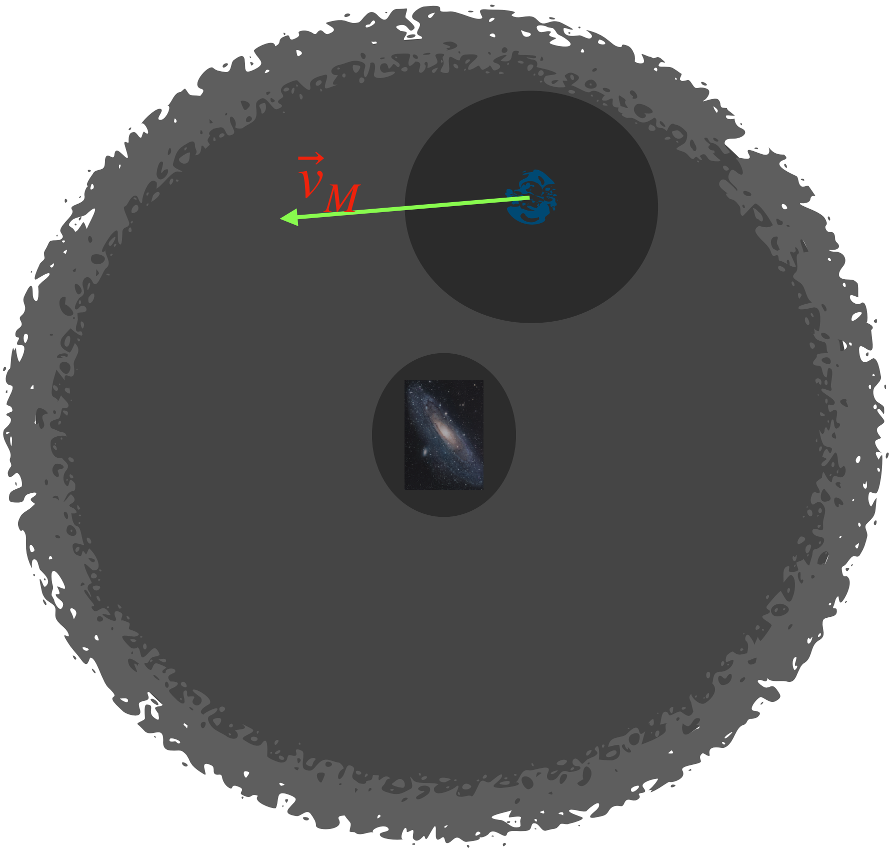
eg. Binney & Tremaine (1987): "Galactic Dynamics"

fixed by the CMB / LCDM
(cannot be adjusted)

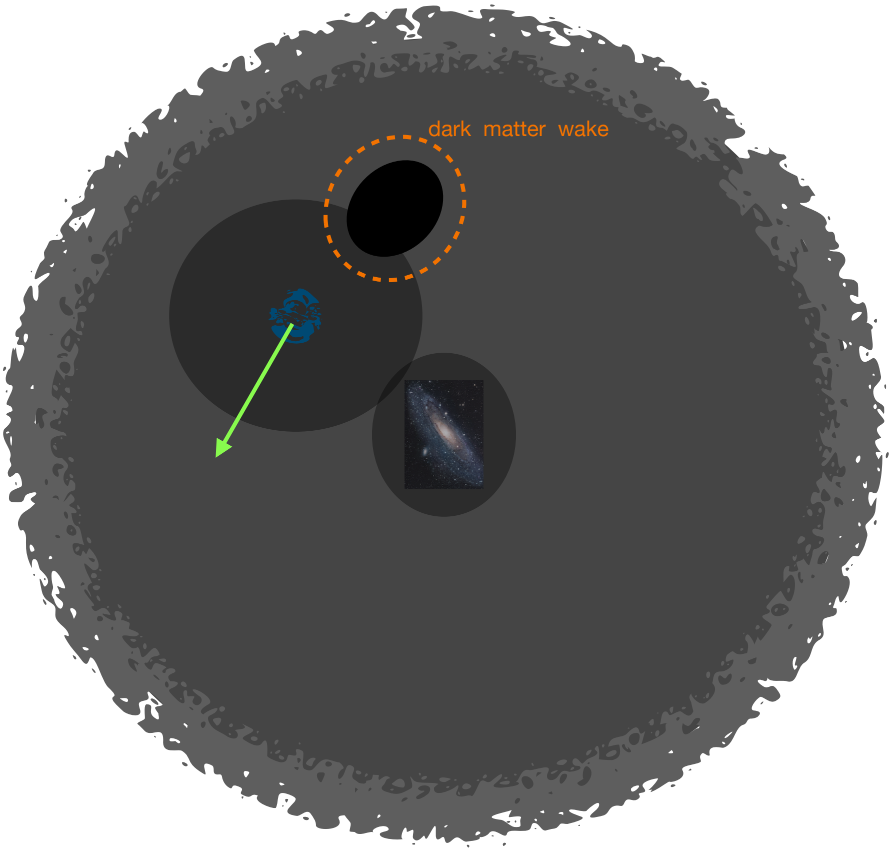
Thus, if there is dark matter, then there must be *Chandrasekhar dynamical friction*.

The situation :



Prediction of new phenomenon :

Thus, essentially :



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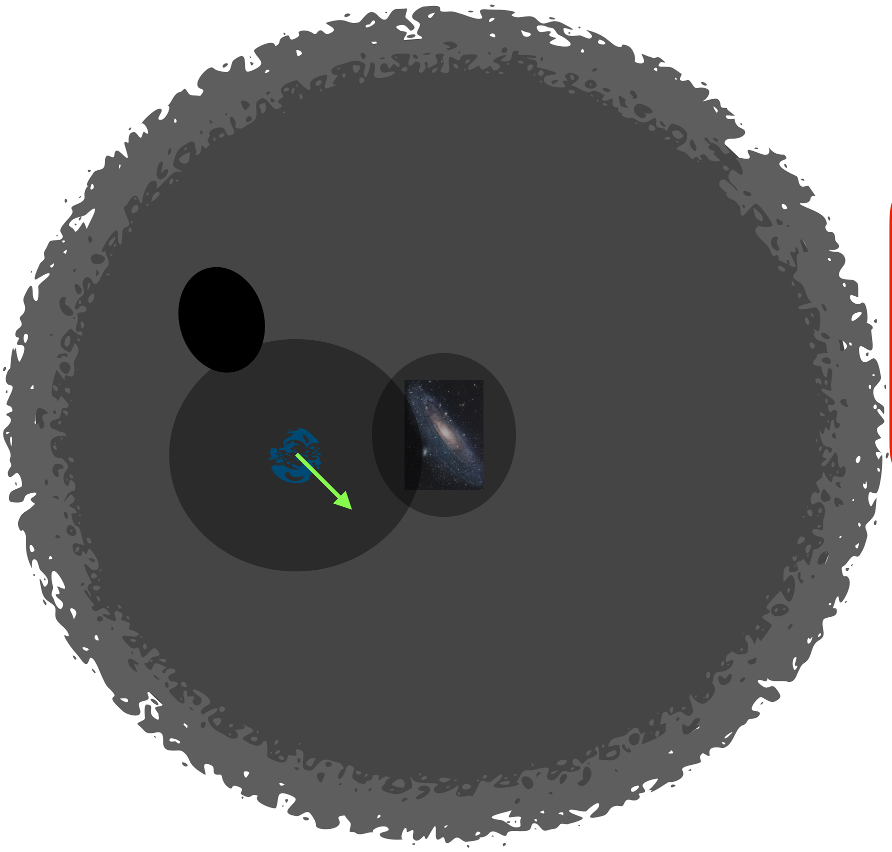
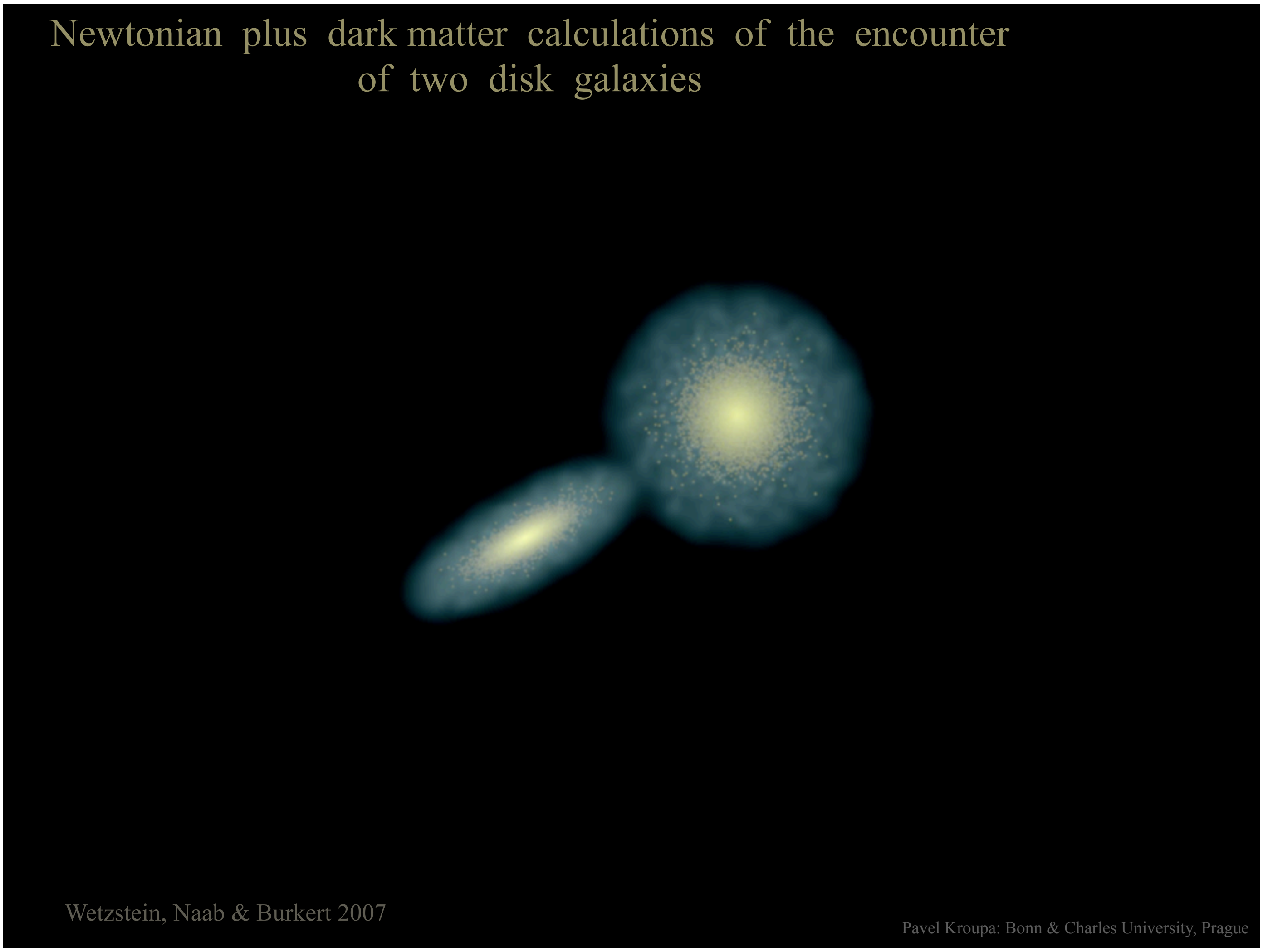


And this is why galaxies merge,

but only in the dark matter theory



Chandrasekhar dynamical friction
is very well understood.
e.g. Binney & Tremaine 1987 - textbook

Chandrasekhar dynamical friction :

Orbits of satellite galaxies

Angus et al. 2011

Table 2. Galactocentric distances and velocities of the dSphs. For Fornax, Sculptor and Ursa Minor, our V_{x_0} corresponds to Piatek et al. (2003, 2005, 2006, 2007a) V_r and our V_{y_0} to their V_t. For Carina, the proper motion comes directly from Pasetto et al. (2011). Distances come from Mateo (1998).

dSph	r_0 (kpc)	V_{x_0} (km s^{-1})	V_{y_0} (km s^{-1})	L_V ($L_\odot$)
Fornax	138 ± 8	-31.8 ± 1.7	196 ± 29	15.5×10^6
Sculptor	87 ± 4	79 ± 6	198 ± 50	2.2×10^6
Ursa Minor	76 ± 4	-75 ± 44	144 ± 50	0.29×10^6
Carina	101 ± 5	113 ± 52	46 ± 54	0.43×10^6

Note : the inner region of a satellite is affected by tides after significant tidal destruction of its outer parts (Kazantzidis et al. 2004).
I.e. the baryonic content (i.e. L_V) is a measure of the DMhalo mass according to LCDM theory.

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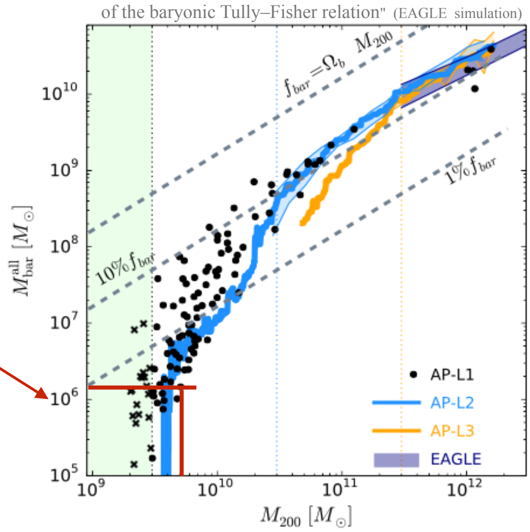

observed stellar masses

needed DMhalo masses for infall

$\Rightarrow M_{\rm DMhalo} < 5 \times 10^9\, M_\odot \longleftrightarrow$ incompatible $\quad M_{\rm DMhalo} > 10^{10}\, M_\odot$

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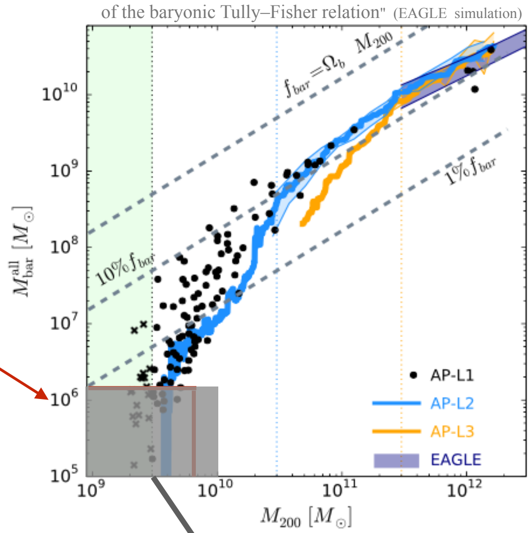


excluded by observational data.

observed stellar masses

needed DMhalo masses for infall

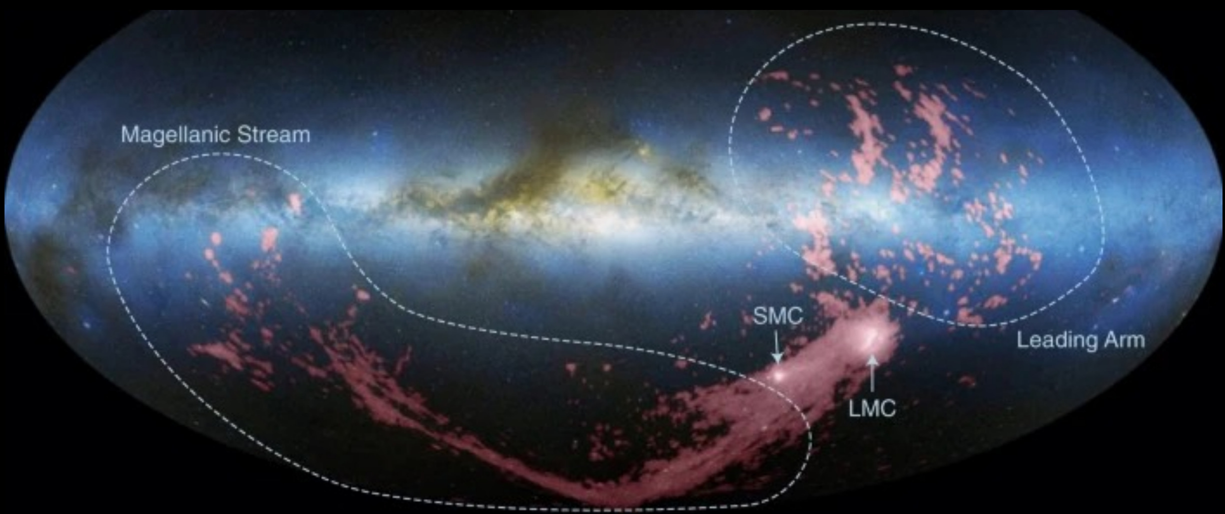
$\Rightarrow M_{\rm DMhalo} < 5 \times 10^9\, M_\odot \longleftrightarrow$ incompatible $\quad M_{\rm DMhalo} > 10^{10}\, M_\odot$

$\Rightarrow$ $\boxed{\textit{no}\ \text{LCDM infall solutions}}$ $\Rightarrow$ $\boxed{\textit{no}\ \text{dark matter halos}}$

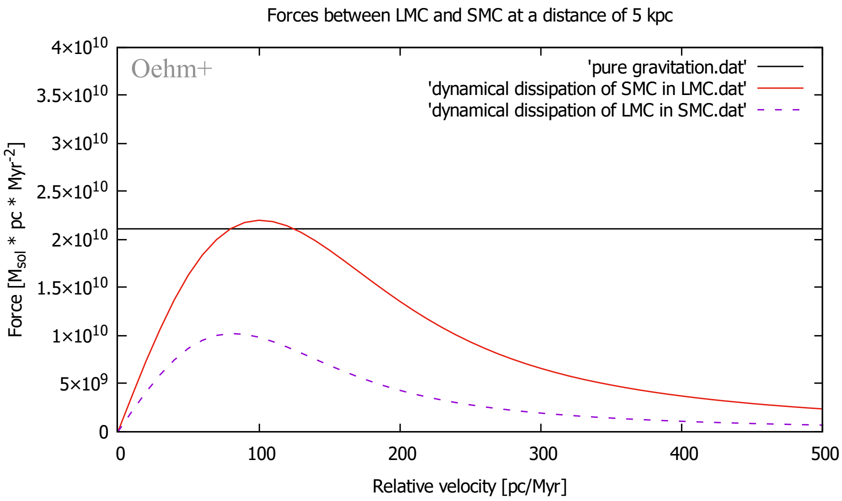
Case in point:
The orbits
of the
Large (LMC)
and
Small (SMC)
Magellanic Clouds

Magellanic clouds
Magellanic Stream began to form
about 1-2Gyr ago

e.g. Wang, Hammer...+2022



Credit: NASA/D. Nidever



Applied to the SMC and SMC

The *frictional deceleration* of the LMC / SMC orbital motion due to Chandrasekhar dynamical friction is comparable to the gravitational *attraction* between the two.

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The synchronized dance of the magellanic clouds' star formation history

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ABSTRACT

We use the SMASH survey to obtain unprecedented deep photometry reaching down to the oldest main-sequence turn-offs in the colour–magnitude diagrams (CMDs) of the Small Magellanic Cloud (SMC) and quantitatively derive its star formation history (SFH) using CMD fitting techniques. We identify five distinctive peaks of star formation in the last 3.5 Gyr, at ∼3, ∼2, ∼1.1, ∼0.45 Gyr ago, and one presently. We compare these to the SFH of the Large Magellanic Cloud (LMC), finding unequivocal synchronicity, with both galaxies displaying similar periods of enhanced star formation over the past ∼3.5 Gyr. The parallelism between their SFHs indicates that tidal interactions between the MCs have recurrently played an important role in their evolution for at least the last ∼3.5 Gyr, tidally truncating the SMC and shaping the LMC's spiral arm. We show, for the first time, an SMC–LMC correlated SFH at recent times in which enhancements of star formation are localized in the northern spiral arm of the LMC, and globally across the SMC. These novel findings should be used to constrain not only the orbital history of the MCs but also how star formation should be treated in simulations.

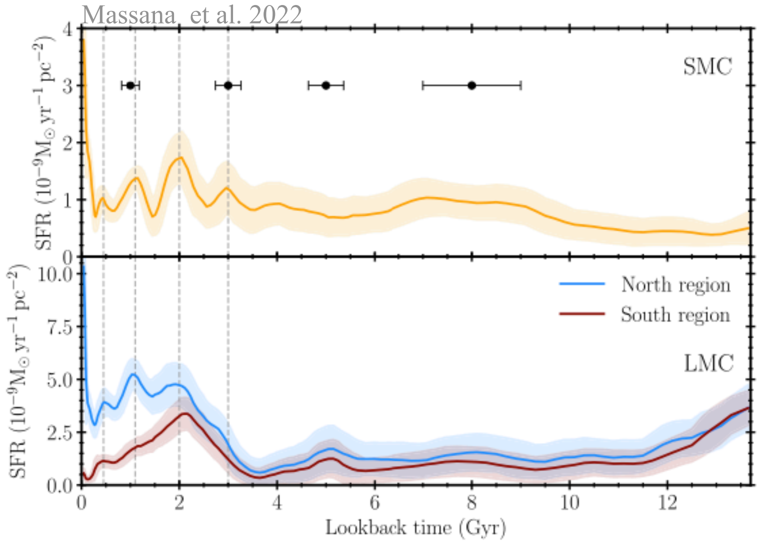
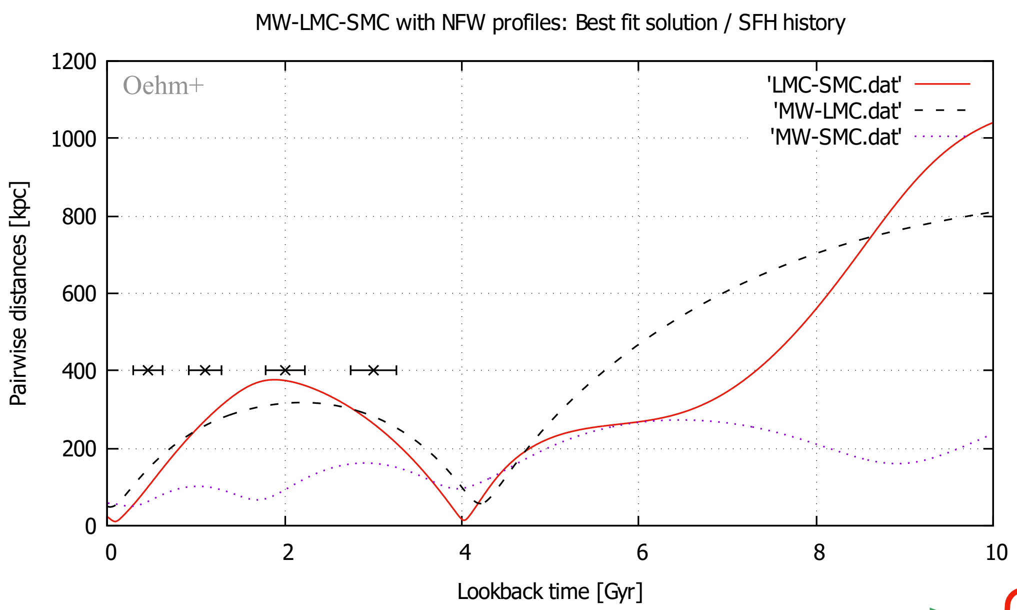


Figure 2. Comparison of the global SFRs for the SMC (this work) and the LMC (Ruiz-Lara et al. 2020b). Vertical dashed lines link the peaks at 0.45, 1.1, 2, and 3 Gyr ago in the SMC to those of the LMC. The horizontal bars in the top panel show the width of the SFH enhancement. Uncertainties in the SFHs (shaded regions) were calculated as in Hidalgo et al. (2011) and Rusakov et al. (2021).

The LMC and SMC have peaks in the SFRs at very similar times because of their orbits about each other.

This constrains the number of close encounters the SMC had with the LMC

The LMC and SMC have dark-matter halos according to the LCDM model and are integrated backwards in time (i.e. "the friction leads to an acceleration) assuming their observed position and velocity vectors (Gaia data).



No solution of SMC-LMC orbit that explains the synchronised star-formation history.

A solution of the SMC / LMC / MW system is *not* possible in the LCDM model.

no dark matter halos

Other applications of

Chandrasekhar dynamical friction :

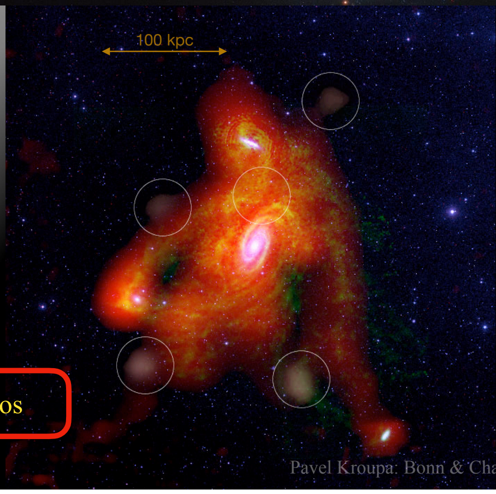
The bars of galaxies are too long

Existence of dark matter halos falsified with $> 5\sigma$ confidence

Roshan, Ghafourian et al. 2021

The observed configuration of the M81 group of galaxies *cannot exist* in LCDM

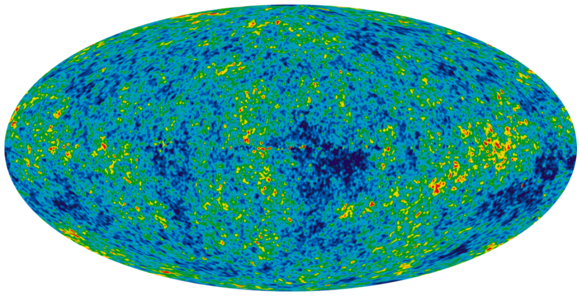
Yun 1999
Thomson, Laine & Turnbull 1999
Oehm et al. 2017; 2018



no dark matter halos

Pavel Kroupa: Bonn & Charles University, Prague

Other tests,
not based
on
Chandrasekhar dynamical
friction



The homogeneity (1 in 10^{-5}) of the cosmic microwave background radiation (CMB) ==> smoothness at z=1100

In LCDM , the galaxy dark matter halos and galaxy groups are spheroidal
and the model universe is very smooth
(isotropic and homogeneous on scales > 100Mpc)

How spheroidal are real groups and
how homogeneous and isotropic is the real Universe **?**

Observed :

A) The crystal-like Pawlowski et al. (2013) structure of the Local Group of Galaxies
($\approx$ 3 Mpc / the *PKJ structure*)

Structure of and correlations in Local group

Frighteningly symmetric structure of the Local Group

Looking along the line between Milky Way and Andromeda

Everything we know about the Local Group today :

Pawlowski, Kroupa & Jerjen (2013) :

"The discovery of symmetric structures in the Local Group"

Structure of and correlations in Local group

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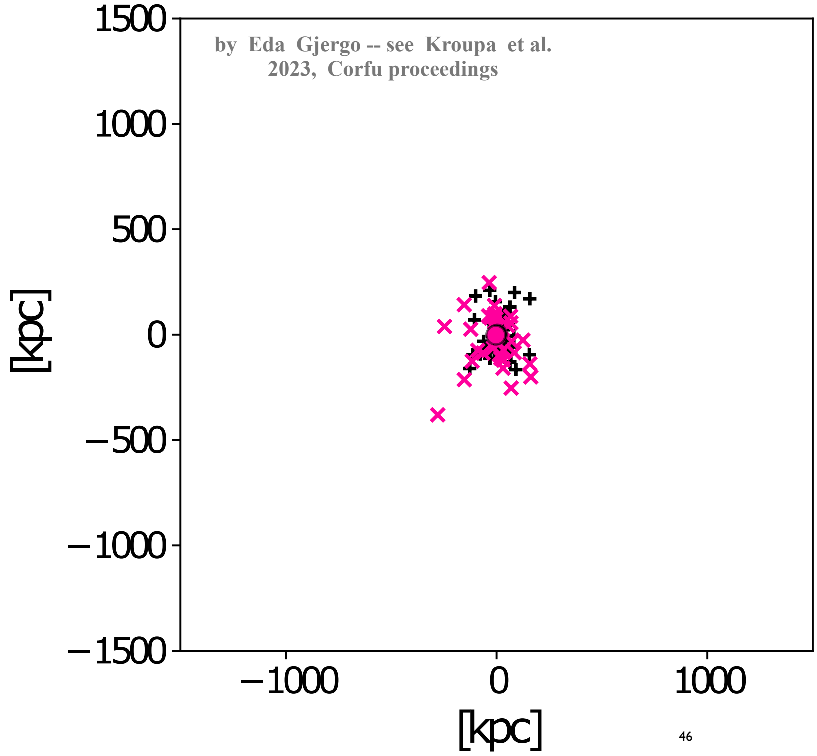

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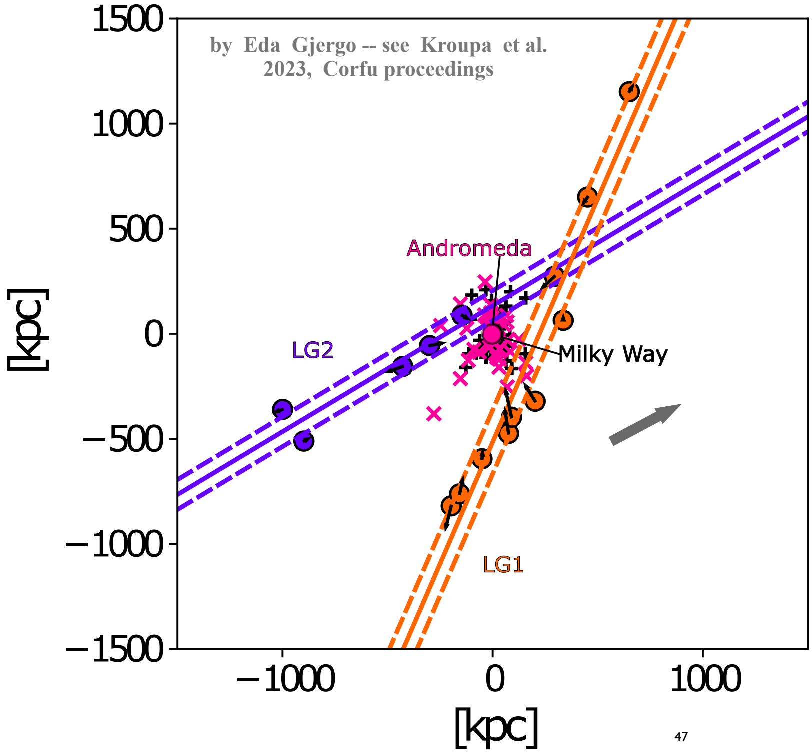
"The discovery of symmetric structures in the Local Group"

Structure of and correlations in Local group

Frighteningly symmetric structure of the Local Group

Looking along the line between Milky Way and Andromeda



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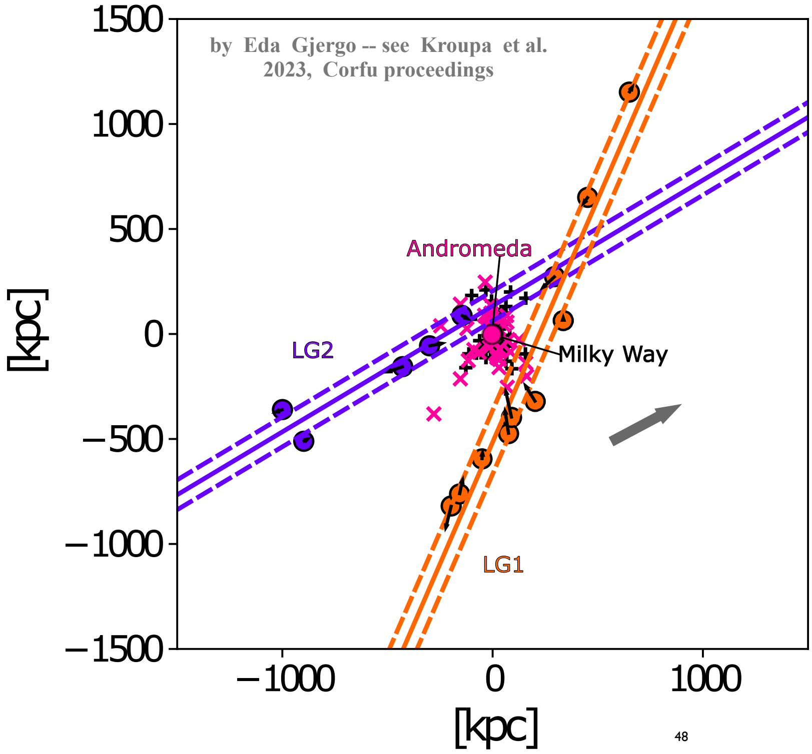


Everything we know about the Local Group today :

Pawlowski, Kroupa & Jerjen (2013) :

"The discovery of symmetric structures in the Local Group"

A frightening symmetry

NOT LCDM at ∞ sigma

Observed :

A) The crystal-like Pawlowski et al. (2013) structure of the Local Group of Galaxies ($\approx$ 3 Mpc / the *PKJ structure*)

B) The Keenan-Barger-Cowie (2013, $\approx$ 600 Mpc) void (the *KBC void*)

KBC void and Hubble Tension

The Cosmological Scale

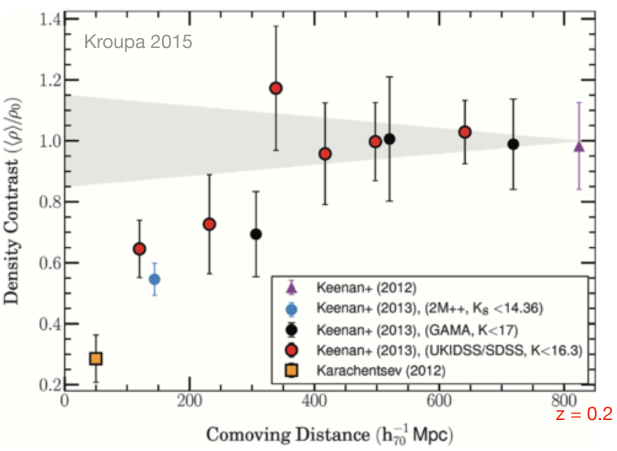


Figure 1. The KBC void: the actual density of normal matter divided by the mean cosmological density is plotted in dependence of the distance from the position of the Sun (which is in the Local Group of galaxies). The grey area indicates the density fluctuations allowed by the ΛCDM model. Taken from fig. 1 in Kroupa (2015).

Haslbauer, Banik & Kroupa 2020 :

The under-density is evident in

optical galaxy surveys
Maddox+1990; Zucca+1997

near-infrared galaxy surveys
Keenan, Barger & Cowie'13 (KBC)

X-ray cluster surveys
Böhringer+2015; Böhringer, Chan, Collins 2020; Migkas+21

CMB dipole indicating large-scale bulk flows as expected for such a void (radio observations)

Rubart & Schwarz 2013; Rubart, Bacon & Schwarz 2014; Javanmardi+ 2015; Secrest+ 2020

Additionally :
Strong evidence for highly significant over- and under-densities in galaxy-cluster data
Migkas & Reiprich (2018); Migkas et al. (2021)

4.9 sigma exclusion of cosmological principle based on distribution of 10^6 quasars Secrest+... Sarkar et al. (2021)

KBC void and Hubble Tension

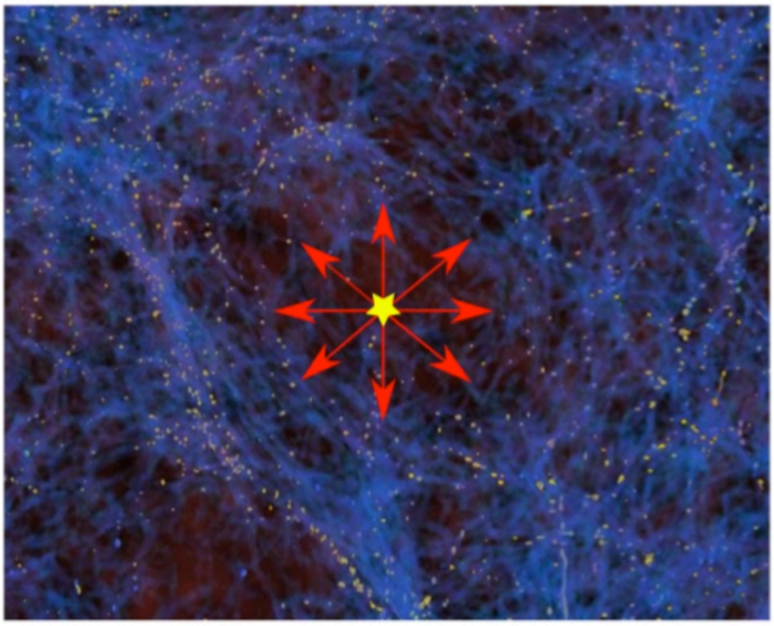
The Cosmological Scale

Haslbauer, Banik & Kroupa 2020

observed KBC void

diameter: ≈1 Gpc

density contrast: ≈50%



there is no Hubble Tension !!!

The KBC void automatically solves the **Hubble Tension**,

but KBC void not possible in LCDM

Not SMoC at $> 6\sigma$ confidence .

Observed :

A) The crystal-like Pawlowski et al. (2013) structure of the Local Group of Galaxies (≈ 3 Mpc / the *PKJ structure*)

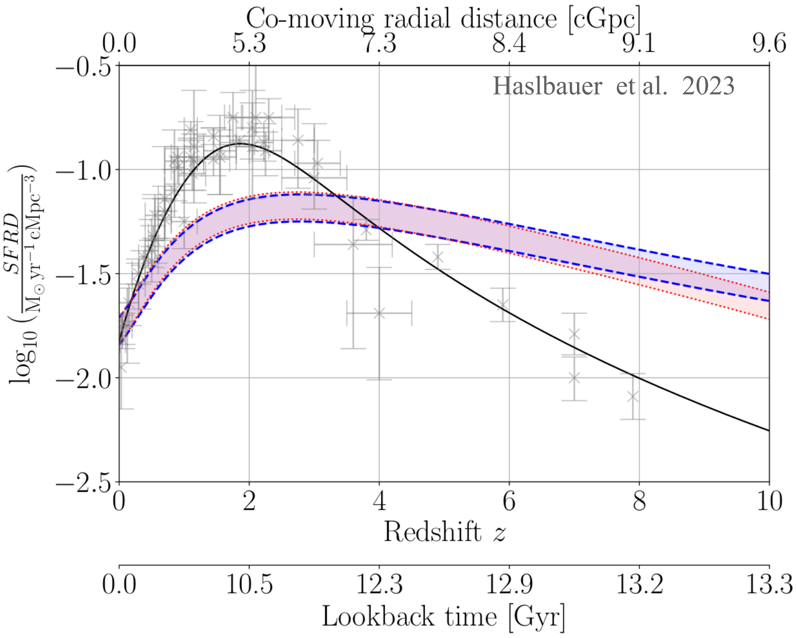
B) The Keenan-Barger-Cowie (2013; ≈ 600 Mpc) void (the *KBC void*)

C) The Haslbauer et al. (2023; ≈ 5 Gpc) void (the *HKJ giga-void*)

Assume the ≈ 500 galaxies in our 11Mpc neighbourhood
are representative of all galaxies in the Universe.
(*cf*: the stars in the Solar neighbourhood are representative of all stars in the Milky Way and in the Universe)

The 11 Mpc galaxies have nearly constant star formation histories.
(*i.e.* present-day SFR $\approx$ average SFR)

The maximum in the observed cosmic star-formation rate density near $z \approx 1.8$
thus implies a massive matter-overdensity about 5 Gpc away



A 5 Gpc-scale inhomogeneity suggests that the Universe is structured on all scales.

Not LCDM at $\infty\sigma$ confidence .

The real Universe
is thus highly orderly structured on Mpc scales
and highly inhomogeneous on all larger scales,
up the the horizon
(CMB hemispherical anisotropy)
Schwarz et al. 2016

Overview of LCDM tests

Many tests made. All independent.

E.g. : (there are more tests)

I) Mutually independent tests for the existence of dark matter particles :

- The orbits of the Large and Small Magellanic Clouds Oehm+ 2023
- The lengths of galactic bars Roshan+ 2021
- The backsplash NGC3109 group of galaxies (at distance of a Mpc) Pawlowski&McGaugh 2018; Banik+2021
- The M81 group of galaxies (at distance of 3.6 Mpc) Oehm+ 2017
- No dark matter in dwarf galaxies in Fornax galaxy cluster Asencio+ 2022

Based mostly on Chandrasekhar dynamical friction and dynamical dissipation

II) Tests for the matter-distribution predicted by the dark matter models :

- Disks of Satellites around 6 nearby galaxies Kroupa+ 2005; Pawlowski+; Asencio+ 2022
- The 3d structure of the Local Group of galaxies (within one Mpc) Pawlowski+ 2013
- The KBC void (within one Gpc) Haslbauer+ 2020
- The Hubble Tension (within one Gpc) Haslbauer+ 2020
- The Lilly-Madau plot (5 Gpc scale) Haslbauer+ 2023
- The over-massive El Gordo galaxy cluster (8 Gyr away) Asencio+ 2021
- Bulk flows on cosmological scales Migkas+ 2021; Secrest +2022
- CMB anomalies (hemispherical power and temp. difference, lack of correlation on large angular scales, cold spot). Schwarz+ 2016

Based on the predicted stochastic merger histories and large-scale homogeneity of matter distribution

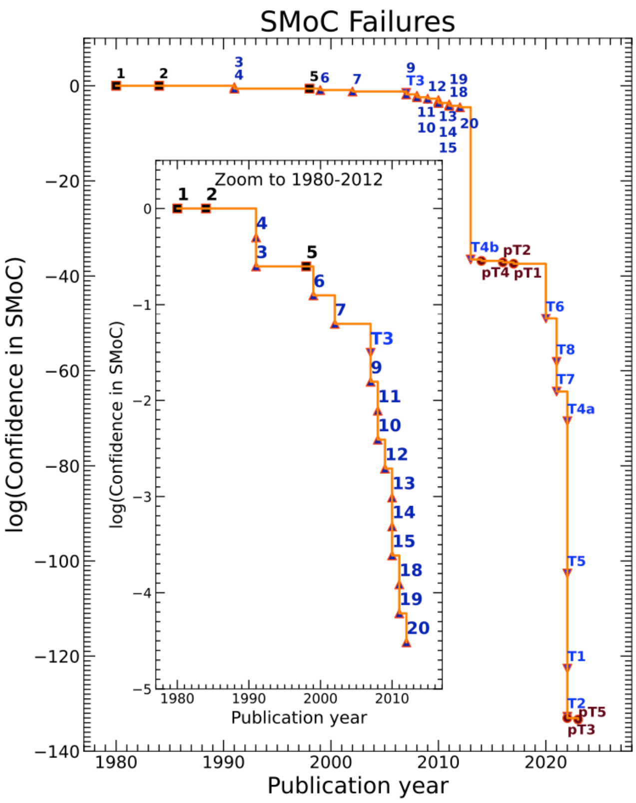


Figure 8: The SMoC-Confidence Graph: the cumulative loss in confidence that the Standard Model of Cosmology (SMoC) is a valid description of nature. The numbers 1-20 are based on a previous review (Kroupa, 2012, [6]), where an original form of the current plot appeared. Black squares (1, 2, and 5, representing inflation, dark matter, and dark energy, respectively) are treated in the SMoC as "new physics", so they are not assigned a loss of confidence. Upward blue triangles indicate failures, still current, already recognized in [6], while downward blue triangles (T1–T8) represent newly identified tensions where the loss of confidence was computed formally, as presented in Section 2.2. From the same section come the possible tensions (pT1–pT5), shown with red circles. Wherever the loss of confidence was not computed formally, we assign a drop in confidence by 50%. The inset graph zooms into the falsifications up to 2012.

The LCDM model
(standard model of cosmology)
is the
most falsified
but
believed-to-be-true
model ever
in the history of
woman / man / them
kind.

The greatest
crisis in physics
ever.

Pavel Kroupa: Bonn & Charles University, Prague

The issue of gravitation

With dark matter
off
the table,
a new law of universal gravitation
needs to be developed

Pavel Kroupa: Bonn & Charles University, Prague

Reminder :

For understanding galaxies it is of paramount importance to know which law of gravitation is valid.

Newton derived Newtonian gravitation (1648) as an *empirical law* based only on Solar system data (discovery of Uranus : 1781, Neptune : 1846).

It is the non-relativistic limit of *Einsteinian general relativity* (EGR).

But: EGR was developed prior to 1916 based on the constraint that EGR must comply to Newtonian gravitation in the non-relativistic limit.

Galaxies were not understood in 1917 :

- The Shapley-Curtis debate on the nature of spiral nebulae took place in 1920.
- The motion of matter in them -- the flat rotation curve -- was measured in the late 1930s (Andromeda).

By assuming Newtonian / Einsteinian gravitation to be valid beyond the Solar System, physicists thus *extrapolated an empirical law by many orders of magnitude* in spatial, mass and acceleration scale to a regime where independent tests are not available.

E.g. in Solar system we can test the law of gravitation with independent tests.

Nearly all existing theoretical work on the formation and evolution of galaxies is today based on this extrapolation.

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BUT A PHYSICIST IS TAUGHT IN KINDERGARTEN :
EXTRAPOLATIONS TYPICALLY DON'T WORK !!

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E.g. in Solar system we can test the law of gravitation with independent tests.

Nearly all existing theoretical work on the formation and evolution of galaxies is today based on this extrapolation.

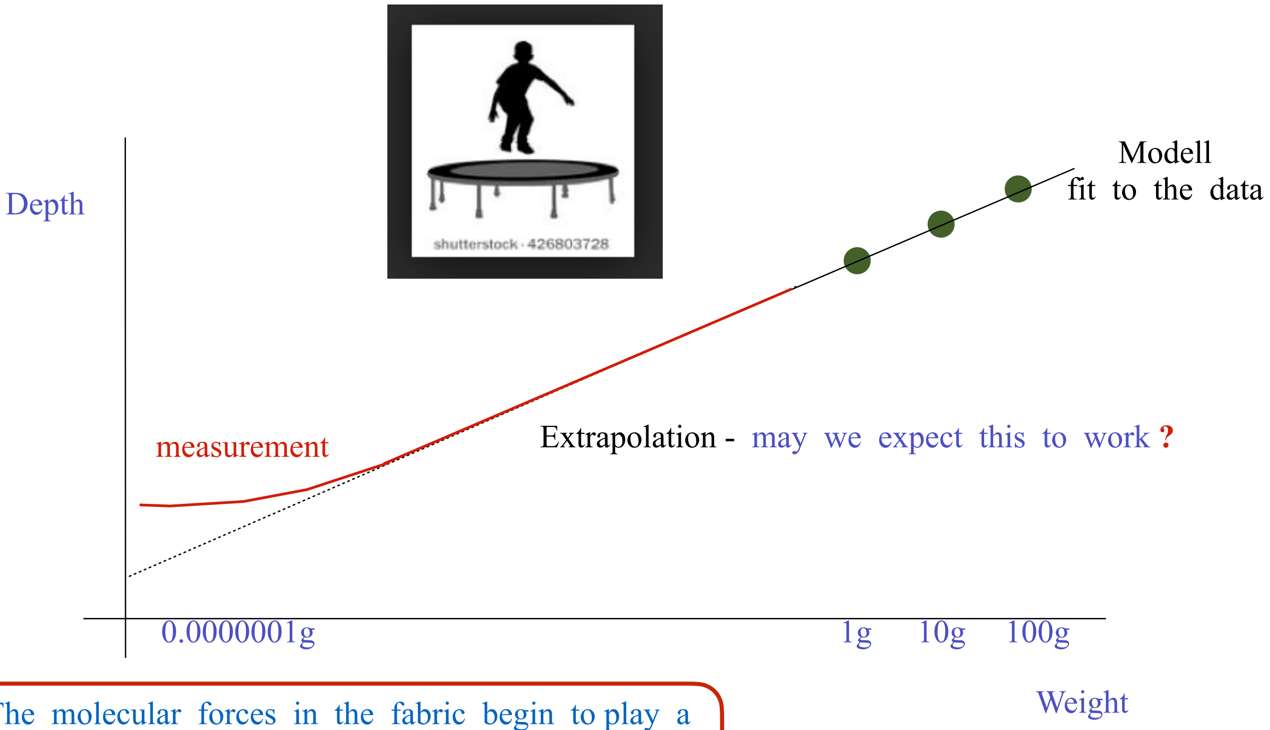
Gravitational theory,
as today implemented in all computer simulations of galaxies and cosmology
is Newtonian,
based on the belief,
that this empirical law remains valid despite an extrapolation in scale by many orders of magnitude
from the Solar system to galaxies and beyond.

Should one expect an empirical law to hold over an extrapolation of orders of magnitude ?

Gedankenexperiment

by Indranil Banik
(St. Andrews)

Depth of a trampolin with increasing weight :



The molecular forces in the fabric begin to play a role and the system shifts from bulk properties to molecular-based behaviour.

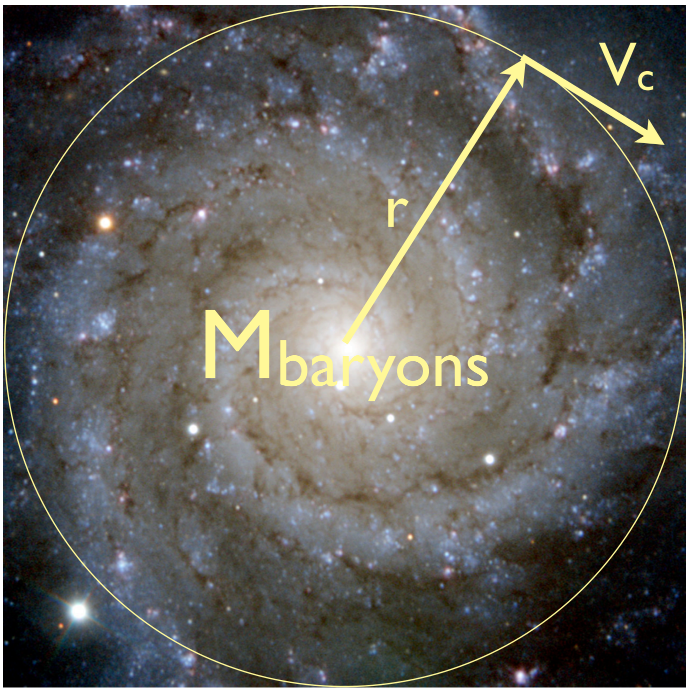
How to proceed ?

A clue is provided
by the
radial--acceleration
data
in galaxies

Disc galaxies

Balance between
gravitation
and
centrifugal force

Disc galaxies



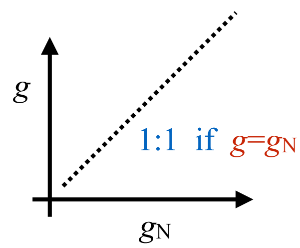
Balance between
gravitation
and
centrifugal force

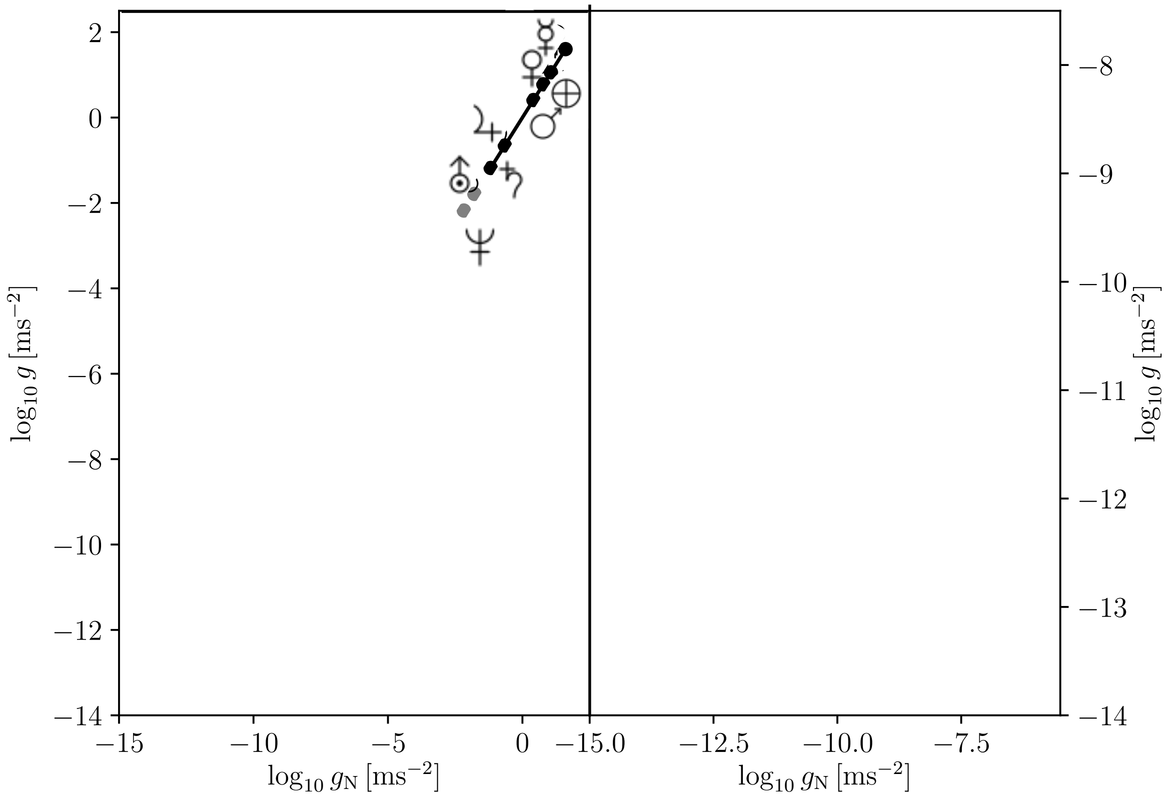
According to Newton :

$$g_{\rm N} = G\,\frac{M_{\rm baryons}}{r^2}$$

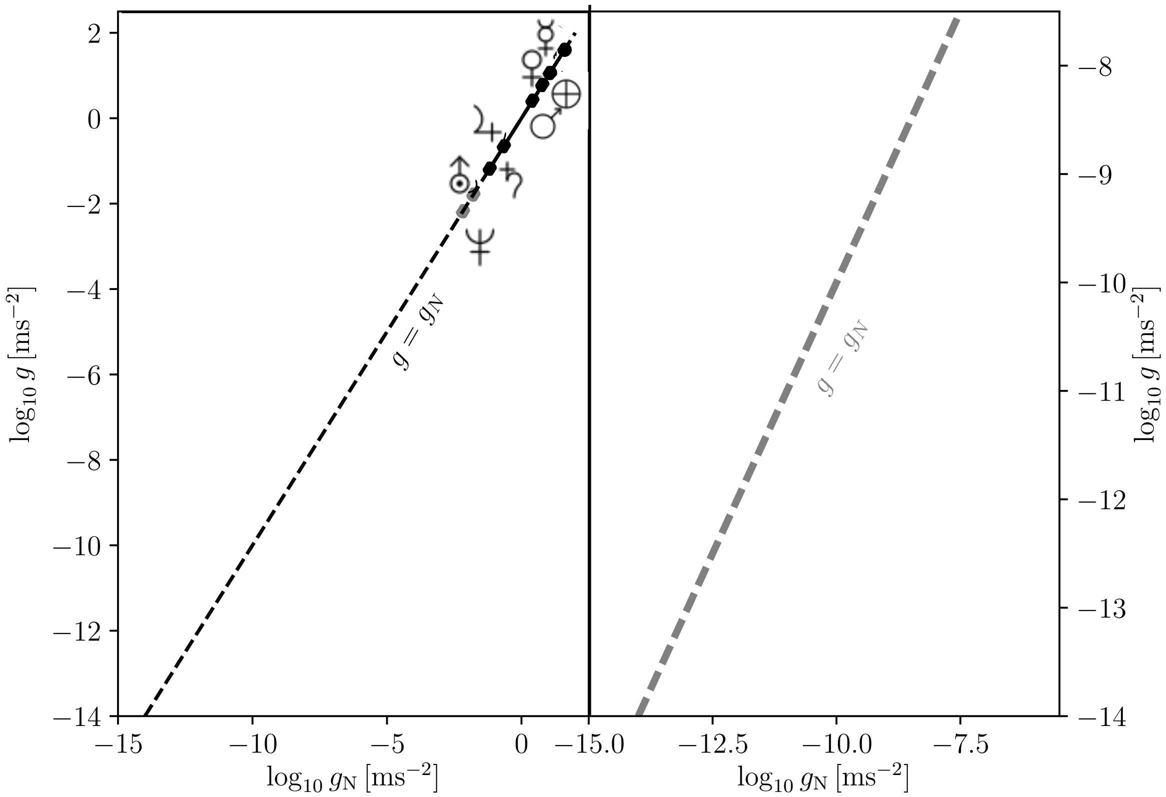
Measured :

$$g = \frac{V_{\rm c}^2}{r}$$





g = observed acceleration from rotation curve
g_N = expected acceleration from observed matter distribution



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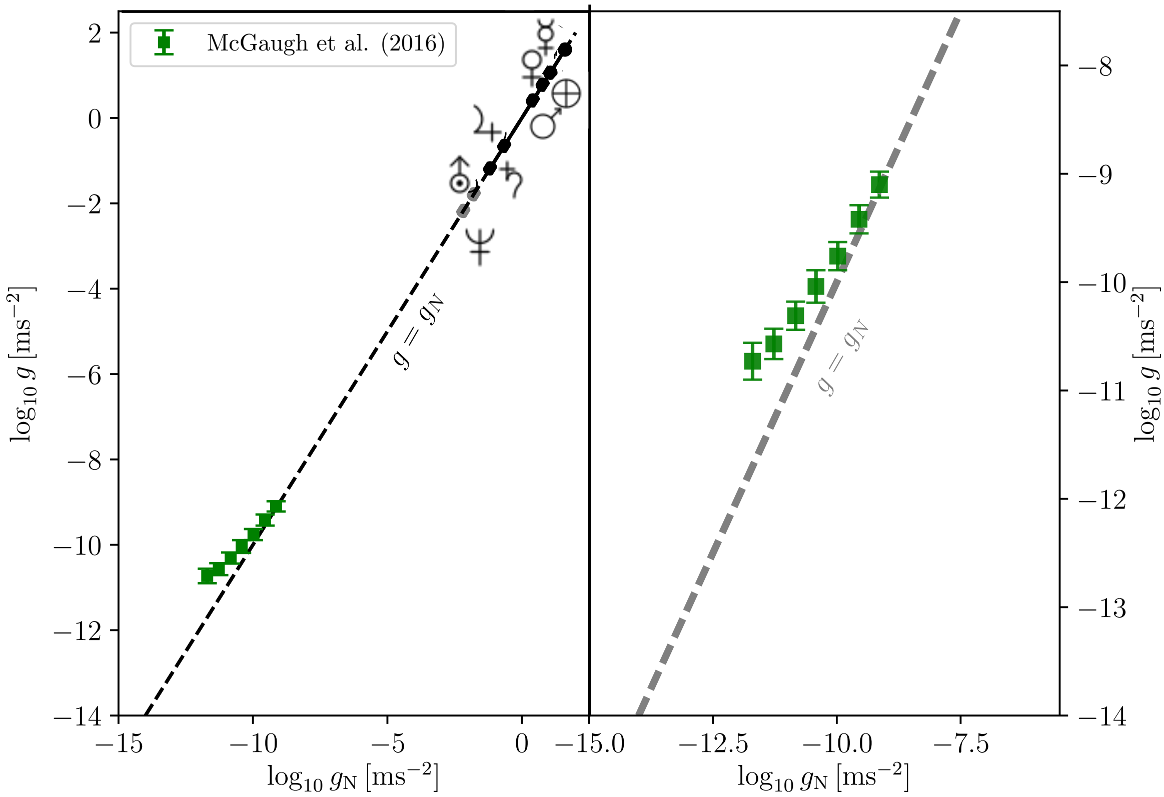

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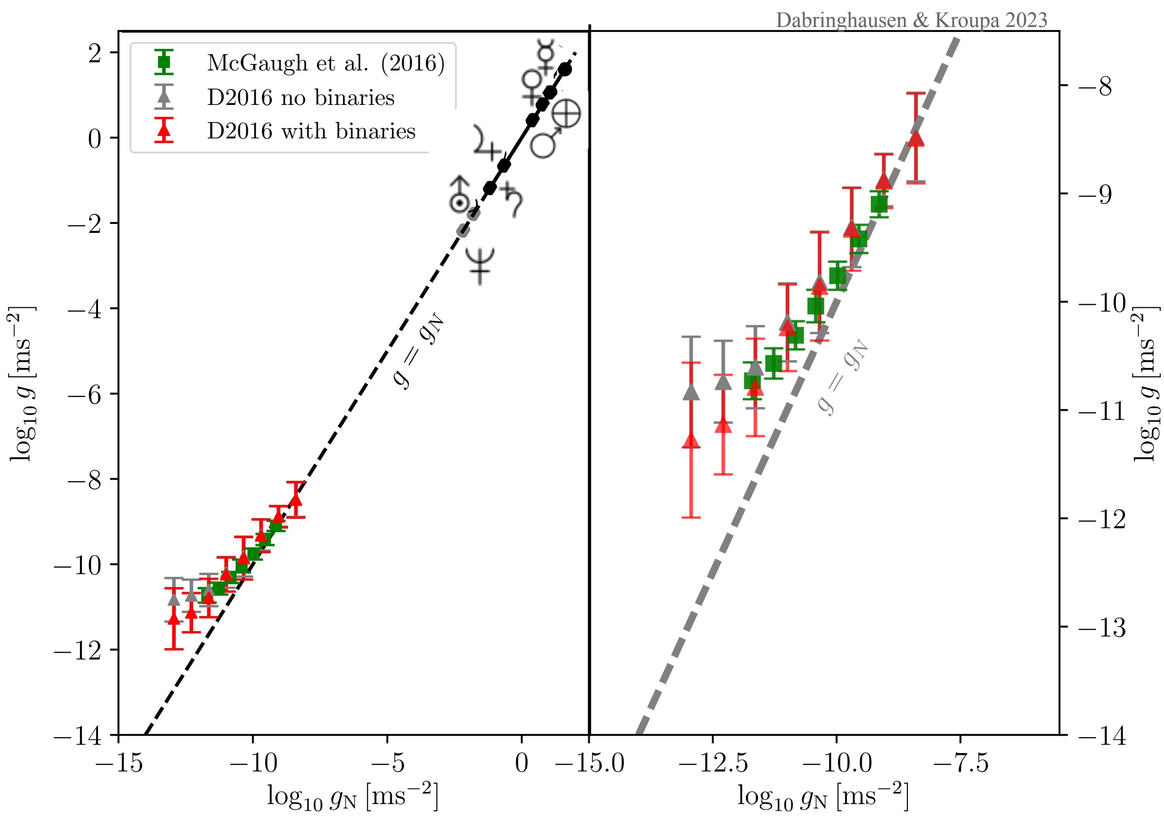

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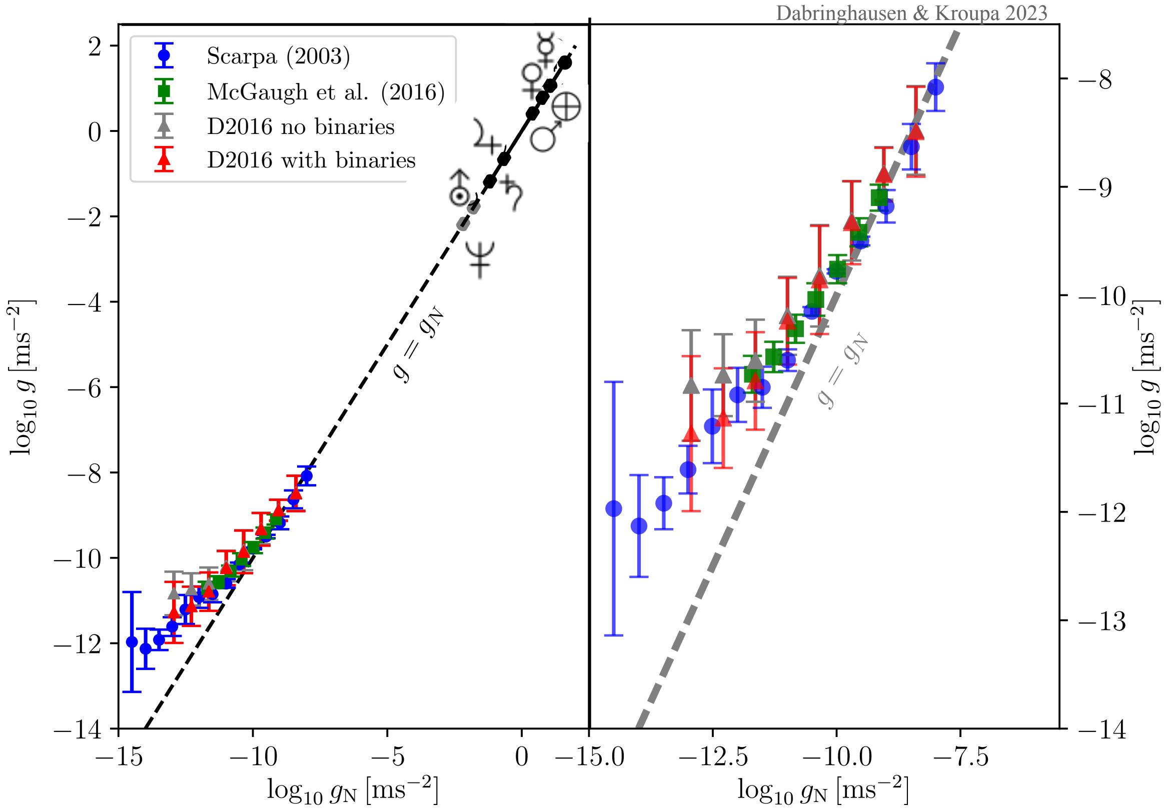


g = observed acceleration from rotation curve
g_N = expected acceleration from observed matter distribution

The standard Poisson equation : $\vec{\nabla} \cdot \vec{\nabla} \Phi = 4\pi G \rho$

This can be re-written in terms of the *p-Laplace operator*, $\Delta_p u := \nabla \cdot (|\nabla u|^{p-2} \nabla u)$, as

$$\vec{\nabla} \cdot \left[\left(\frac{|\vec{\nabla} \Phi|}{a_o} \right)^{p-2} \vec{\nabla} \Phi \right] = 4\pi G \rho$$

$p=2$ standard Poisson equation above

→ Newtonian gravitation

$p=3$ non-standard Poisson equation

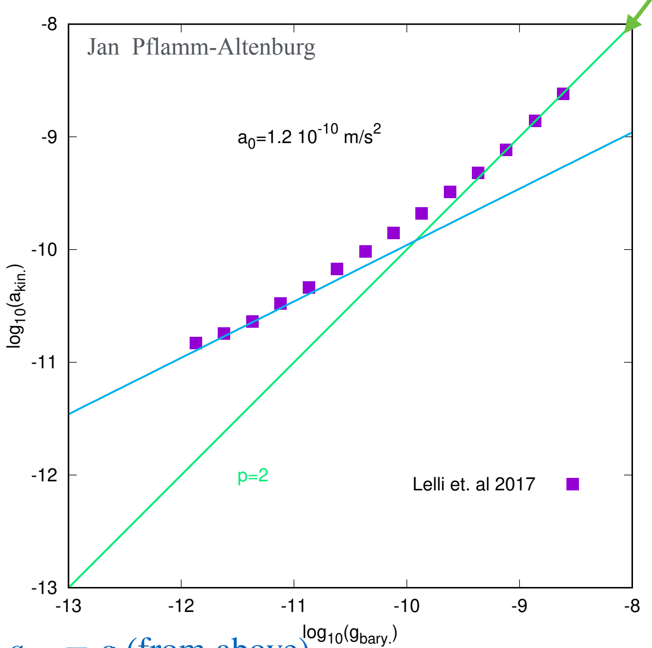
→ which gravitational dynamics ?

→ $$\vec{\nabla} \cdot \left(\frac{|\vec{\nabla} \Phi|}{a_o} \vec{\nabla} \Phi \right) = 4\pi G \rho$$

Sufficiently far from ρ can assume spherical symmetry - integrate using divergence theorem

→ $$\left(\frac{\partial \Phi}{\partial r} \right)^2 = \frac{a_0 \, G M(<r)}{r^2}$$

→ $$a_{p=3} = \sqrt{a_0 \, a_{p=2}}$$



$a_{kin} = g$ (from above)
$g_{bary} = g_N$ = from above

Remember the standard Poisson equation: $\vec{\nabla} \cdot \vec{\nabla} \Phi = 4\pi G \rho$

This can be re-written in terms of the *p-Laplace operator*, $\Delta_p u := \nabla \cdot (|\nabla u|^{p-2} \nabla u)$, as

$$\vec{\nabla} \cdot \left[\left(\frac{|\vec{\nabla \Phi}|}{a_o} \right)^{p-2} \vec{\nabla} \Phi \right] = 4\pi G \rho$$

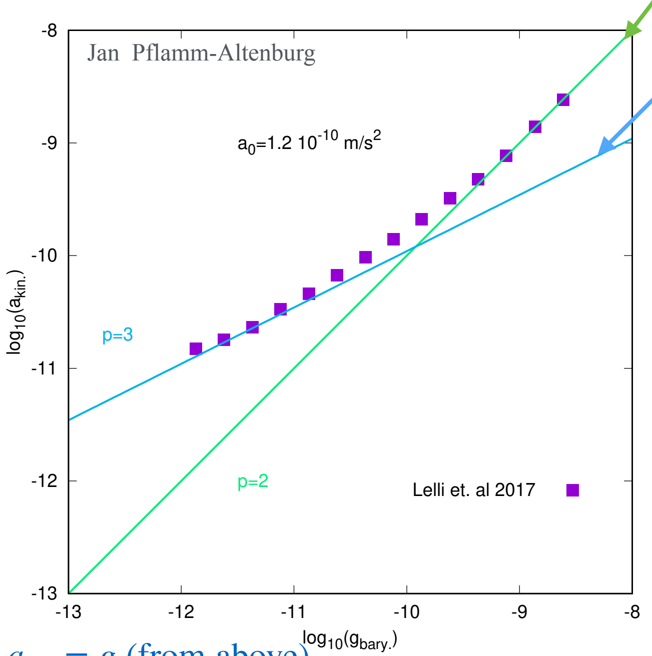
$p=2$ standard Poisson equation above

$\Rightarrow$ Newtonian gravitation

$p=3$ non-standard Poisson equation

$\Rightarrow$ which gravitational dynamics **?**

$$\Rightarrow \quad \vec{\nabla} \cdot \left(\frac{|\vec{\nabla \Phi}|}{a_o} \vec{\nabla} \Phi \right) = 4\pi G \rho$$



$a_{\rm kin} = g$ (from above)

$g_{\rm bary} = g_{\rm N}$ = from above

Sufficiently far from ρ can assume spherical symmetry - integrate using divergence theorem

$$\Rightarrow \quad \left(\frac{\partial \Phi}{\partial r} \right)^2 = \frac{a_0\, G\, M(<r)}{r^2}$$

$$\Rightarrow \quad a_{p=3} = \sqrt{a_0\, a_{p=2}}$$

i.e., the *Milgromian acceleration* in terms of the *Newtonian acceleration*: $g_{\rm M} = \sqrt{a_0\, g_{\rm N}}$

Is there a Lagrangian formulation ?

For fields :

	Newton	AQUAL-MoND (Bekenstein & Milgrom 1984)
Lagrangian	$\mathcal{L} = \rho\phi + \frac{1}{8\pi G}(\nabla\phi)^2$	$\mathcal{L} = \rho\Phi + \frac{a_0^2}{8\pi G} F\left(\nabla\Phi^2/a_0^2\right)$

from Jan Pflamm-Altenburg

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Lagrangian	$\mathcal{L} = \rho\phi + \frac{1}{8\pi G}(\nabla\phi)^2$	$\mathcal{L} = \rho\Phi + \frac{a_0^2}{8\pi G} F\left(\nabla\Phi^2/a_0^2\right)$

Newton:

$$0 = \frac{\partial \mathcal{L}}{\partial \phi_i} - \partial_\alpha \frac{\partial \mathcal{L}}{\partial(\partial_\alpha \phi_i)}$$

AQUAL-MoND:

$$\mu\left(x\right) = \left.\frac{dF(y)}{dy}\right|_{y=x^2}$$

differential equation

$$\Delta\phi = 4\pi G\rho \xleftarrow{\frac{|\nabla\Phi|}{a_0} \gg 1} \nabla\bullet\left(\mu\left(\frac{|\nabla\Phi|}{a_0}\right)\nabla\Phi\right) = 4\pi G\rho$$

$\Downarrow$

New universal law of gravitation

from Jan Pflamm-Altenburg

Skipping "II" (the nuHDM cosmological model)

II) The nuHDM model

Milgromian gravitation
with inflation
with ~~dark matter~~ sterile neutrinos
with dark energy

A conservative model,
i.e. very similar to the LCDM,
but a little simpler
because
dark matter plays little role
in structure formation

III) The Bohemian model of cosmology (the BMoC)

Milgromian gravitation
~~with inflation~~
~~with dark matter sterile neutrinos~~
~~with dark energy~~

Dark energy only needed in the context of the LCDM !

A completely new model,
independent of the 3 pillars of the LCDM.
Thus a very simple model.

Conclusions :

The many independent tests on few-pc to Gpc scales unambiguously show the dark-matter-based models to not be relevant for the Universe.

There is no dark matter.

Gravitation is compellingly Milgromian (and not Newtonian / Einsteinian).

The *nuHDM Milgromian cosmological model* that assumes inflation, sterile neutrinos as a hot-dark matter component, the CMB as the boundary condition and dark energy, appears to not describe the Universe.

A Milgromian cosmological model that avoids inflation, dark matter, dark energy appears to be very promising -- the *Bohemian Model of Cosmology* --

BMoC :
laws of physics
the same everywhere,
but
cosmological principle
does not apply.

More on the details at another opportunity.

The END

Milgromian Dynamics
from quantum mechanical processes in the vacuum

Kroupa et al. (2010), Appendix A (see Milgrom 1999) **:**

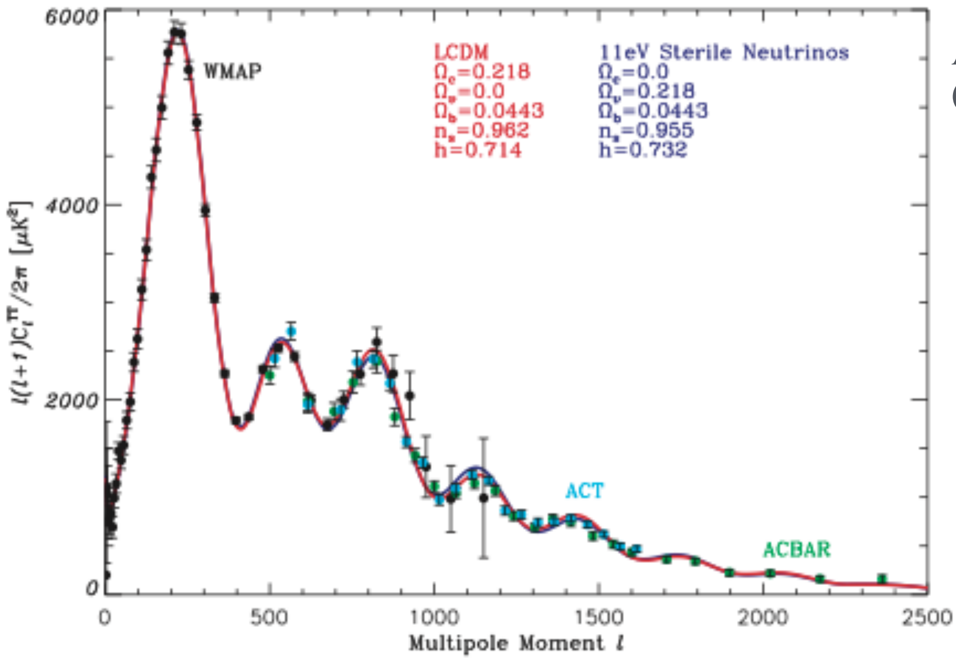
". . . an accelerated observer in a de Sitter universe (curved with a positive cosmological constant Λ) sees a non-linear combination of the Unruh (1975) vacuum radiation and of the Gibbons & Hawking (1977) radiation due to the cosmological horizon in the presence of a positive Λ. Milgrom (1999) then defines inertia as a force driving such an observer back to equilibrium as regards the vacuum radiation (i.e. experiencing only the Gibbons-Hawking radiation seen by a non-accelerated observer). Observers experiencing *a very small acceleration* would thus see an Unruh radiation with a low temperature close to the Gibbons-Hawking one, meaning that *the inertial resistance defined by the difference between the two radiation temperatures would be smaller than in Newtonian dynamics, and thus the corresponding acceleration would be larger*. This is given by the formula of Milgrom (1983) with a well-defined transition-function $\mu(x)$, and $a_0 = c\,(\Lambda/3)^{1/2}$. Unfortunately, no covariant version (if at all possible) of this approach has been developed yet."

Loosely speaking (and speculating) **:**
In curved space-time around a particle (itself composed of fluctuations in the vacuum), the side that is more curved ("distorted, squashed-up") exerts a smaller pressure on the particle, than the other, less-"squashed" side, because a less-squashed side can sustain more vibrational modes (larger spatial volume). In non-curved space, the pressure from the vacuum is symmetrically smaller.

(i.e. essentially the Cassimir effect)

Can MOND cosmology account for the CMB ?

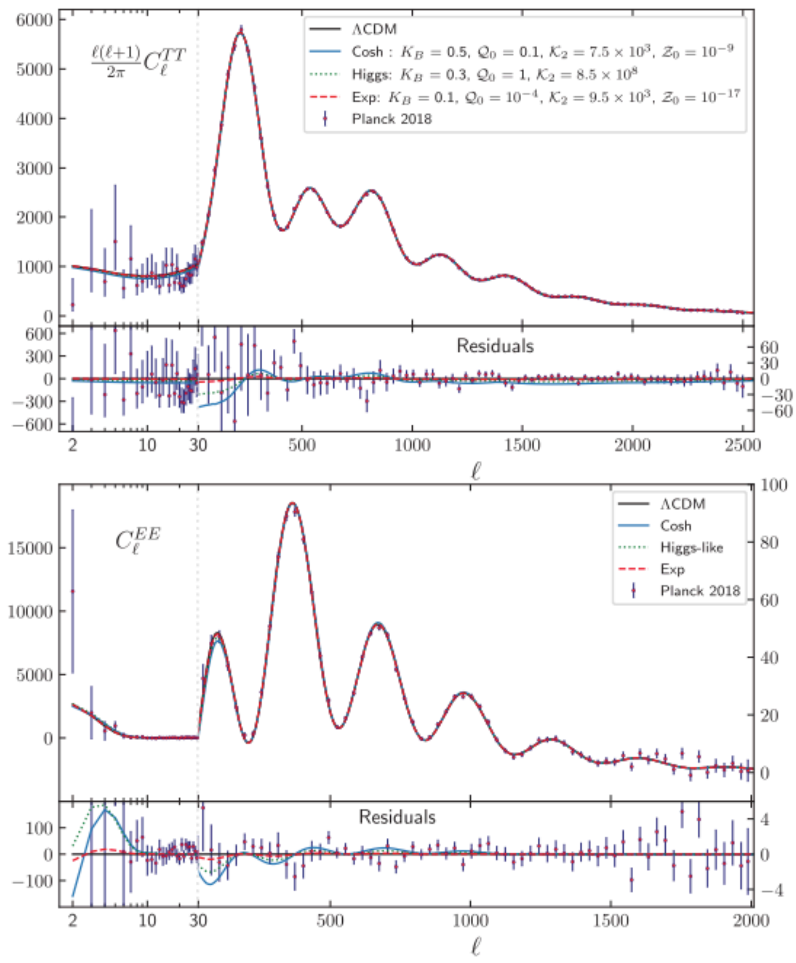
The nuHDM model of cosmology also accounts for the CMB



Angus & Diaferio (MNRAS, 2011)

Figure 1. The CMB angular power spectrum for our cosmological model (blue line), compared with the ΛCDM model (red line). The data points come from *WMAP* 7 year (black), Atacama Cosmology Telescope (ACT) (turquoise) and ACBAR (green).

The relativistic-MOND model of cosmology also accounts for the CMB



Skordis & Zlosnik (Phys. Rev. Letters, 2021)

FIG. 1. The CMB temperature (T) C_ℓ^{TT} and E-mode polarization C_ℓ^{EE} angular power spectra for ΛCDM and this theory for a collection of functions and parameter values. The ΛCDM parameters are angular acoustic scale $100\theta_s = 1.04171$, DM density $\Omega_c h^2 = 0.1202$, baryon density $\Omega_b h^2 = 0.02235$, reionization optical depth $\tau = 0.049$, helium fraction $Y_{\rm He} = 0.242$, primordial scalar amplitude $10^9 A_s = 2.078$, and spectral index $n_s = 0.963$, while the MOND curves deviate from these within $\sim\{0.07, 0.33, 3.98, 14.29, 1.57, 0.58, 2.60\}\%$. MOND models have $\lambda_s = \infty$, and their other parameters are shown in the C_ℓ^{TT} panel, with $\mathcal{Q}_0$ and $\mathcal{Z}_0$ in Mpc^{-1}. The "Higgs-like" function parameters are incompatible with a MOND limit.