From belief to realism and beauty:
Given the non-existence of dark matter,
how do I navigate
amongst the stars and between galaxies?
I. The words "opinion" and "belief" must not be part of the vocabulary in the natural sciences.

II. A physical theory is mathematically well defined.
   The axioms of the theory are not its predictions.

III. A physical theory can never be proven right, because for every confirmation by data, there can be many other theories which account for the same data.

IV. A physical theory is formally disproven if it fails to account for some data with at least 5 sigma confidence.
   (i.e. the chance of it happening is less than 1 in 1.74 million)
   E.g.1: The hypothesis that the Higgs boson does not exist has been falsified with at least 5 sigma confidence.

V. A physical theory must be able to make predictions prior to the measurements,
   OR to account for new observations without parameter adjustment.

As a citizen of The Commonwealth and as Subject of the Queen

I passed through the gate to professional astronomy by countining stars
My attempts to become an observational astronomer failed miserably.

Moving from The Island to The Continent
I turned to computational astrophysics

my job being to compute how satellite galaxies thicken the Milky Way disk.

and I quickly discovered entirely *new stellar-dynamical solutions* to the dwarf-spheroidal satellite galaxies

**Dwarf spheroidal satellite galaxies without dark matter**

Pavel Kroupa

*Institut für Theoretische Astrophysik, Universität Heidelberg, Tiergartenstrasse 15, D-69121 Heidelberg, Germany*

Received 5 December 1996; accepted 24 March 1997

Communicated by Gerard F. Gilmore
\[ M_V = -9 \text{ mag} \]
\[ r_{0.5} = 180 \text{ pc} \]
\[ \left( \frac{M}{L} \right)_{\text{dyn}} = 200 \]

very similar to Hercules!

but no dark matter in there

Hercules
\( D=130 \text{kpc} \)

(Coleman et al. 2007)

**TABLE 1**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R.A. (J2000)</td>
<td>16:31:02.0</td>
</tr>
<tr>
<td>Decl. (J2000)</td>
<td>12:47:29.6</td>
</tr>
<tr>
<td>( E(B-V) ) (mag)</td>
<td>0.055 ± 0.005</td>
</tr>
<tr>
<td>( m-M ) (mag)</td>
<td>20.6 ± 0.2</td>
</tr>
<tr>
<td>Distance (kpc)</td>
<td>132 ± 12</td>
</tr>
<tr>
<td>([Fe/H])</td>
<td>-2.1 ± 0.2</td>
</tr>
<tr>
<td>Age (Gyr)</td>
<td>13 ± 3</td>
</tr>
<tr>
<td>King ( r_e )</td>
<td>4.37' ± 0.29' (168 ± 11 pc)</td>
</tr>
<tr>
<td>King ( r_c )</td>
<td>4.74' ± 0.57' (182 ± 22 pc)</td>
</tr>
<tr>
<td>King ( r_s )</td>
<td>25.9' ± 11.1' (994 ± 426 pc)</td>
</tr>
<tr>
<td>( c = \log (r_s / r_e) )</td>
<td>0.74 ± 0.25</td>
</tr>
</tbody>
</table>
Hercules
D=130kpc
(Coleman et al. 2007)

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<th>Parameter</th>
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</thead>
<tbody>
<tr>
<td>RA (J2000)</td>
<td>16:31:02.8</td>
</tr>
<tr>
<td>Decl. (J2000)</td>
<td>12:47:29.6</td>
</tr>
<tr>
<td>E(B - V) (mag)</td>
<td>0.055 ± 0.005a</td>
</tr>
<tr>
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</tr>
<tr>
<td>King r_t</td>
<td>25.9' ± 11.1' (994 ± 426 pc)</td>
</tr>
<tr>
<td>c = log (r_t/r_e)</td>
<td>0.74 ± 0.25</td>
</tr>
</tbody>
</table>

This is a *real prediction* (1997)
10 years before the discovery (2007) of this type of celestial object!

Community Reactions:
"You are un-hireable"

My (counter)Reaction:
1) "There is something not quite right with the community".
2) "Once one leaves the dark matter framework, real and correct predictions become possible".
A fictitious story

The core: dark-matter approaches
other approaches
conclusions

Epilogue

Disclaimer: Partially based on real events but the characters, names and events depicted in this story are fictional.
The Standard Modell of Cosmology (SMoC)

2 fundamental assumptions / axioms:

1. The Einstein/Newton formulation of gravitation is valid everywhere.
2. All matter is created at the Big Bang.
The Standard Modell of Cosmology (SMoC)

2 fundamental assumptions / axioms:

1. The Einstein/Newton formulation of gravitation is valid everywhere.
2. All matter is created at the Big Bang.

auxiliary assumptions:
- inflation
- dark matter
- dark energy

for e.g.

observations:

rotation curves
2 fundamental assumptions / axioms:

1. The Einstein/Newton formulation of gravitation is valid everywhere.
2. All matter is created at the Big Bang.

Note: "dark matter" = cold, warm, fuzzy, axion
(results for structure formation and properties of galaxies similar)
(eg. May & Springel 2021 arXiv)
The Standard Modell of Cosmology (SMoC)

Uncomfortable properties:

- The dark matter particles, needed in the above theory, are not part of the standard model of particle physics, and no experimentally verified extension of the standard model of particle physics exists.

- The dark matter particles have not been found despite an incredibly huge effort by many research teams.
The Standard Modell of Cosmology (SMoC)

Uncomfortable properties:

- The dark matter particles, needed in the above theory, are not part of the standard model of particle physics, and no experimentally verified extension of the standard model of particle physics exists.

- The dark matter particles have not been found despite an incredibly huge effort by many research teams.

- Dark energy is totally not understood (infinite energy creation?; total misfit to QFT vacuum energy density).

- Inflation: many issues (see "inflation debate": Ijja, Steinhardt & Loeb, Feb.2017, SciAm.).
According to the SMoC, galaxies look as follows:
And this leads us to a fundamental dysfunctionality:

Dysfunctional properties 0:

\[ \approx 90\% \text{ of all real galaxies are thin disk galaxies, but we cannot predict their rotation curves.} \]
Dysfunctional properties 0:

$\approx 90\%$ of all galaxies are disk galaxies, but cannot predict rotation curves.

That is, given an observed mass distribution, it is impossible to calculate the circular velocities of stars within it.

Why Not??
Dysfunctional properties 0:

$\approx 90\%$ of all galaxies are disk galaxies, but cannot predict rotation curves

That is, given an observed mass distribution, it is impossible to calculate the circular velocities of stars within it.

Why Not??

Dysfunctional properties 0:

That is, given an observed mass distribution, also the dark matter concentration varies from galaxy to galaxy

Figure 1. Relation between stellar mass $m_*$ and peak halo mass $M_h$ for individual central galaxies at $z = 0.01$. The colour of each point corresponds to the specific SFR (yr$^{-1}$) of the galaxy as indicated by the colour bar. The solid black line shows the median stellar mass at fixed halo mass, while the median stellar mass for active and passive central galaxies are given by the blue and red line, respectively. At fixed halo mass, passive galaxies are more massive than active galaxies.

BELTZ-MOHRMANN ET AL. 2021
https://arxiv.org/abs/2103.05076

Figure 6. Concentration as a function of $M_{\text{vir}}$ halo mass (in units of $h^{-1} M_\odot$) for Illustris (left), TNG100 (center), and EAGLE (right) halos at $z = 0$. DMO halos are plotted in gray for each simulation, while hydrodynamic halos are plotted in blue (Illustris), green (TNG100), and orange (EAGLE). The larger points in each panel are the mean concentrations in bins of halo mass for each DMO (black) and hydrodynamic (blue/green/orange) simulation, along with their standard deviations. Additionally, we fit a line to these binned points for each simulation, with the corresponding slope and y-intercept shown in the legend of each panel.
Dysfunctional properties 0:

Essentially:

\[ V \text{ (km s}^{-1}) \]

\[ R \text{ (kpc)} \]
Essentially:

**Dysfunctional properties 0:**

*Cannot predict* rotation curves

[Graph showing rotation curves]

\[ \text{v} \text{ (km s}^{-1}) \]

\[ \text{R (kpc)} \]
Prediction of **new phenomenon**:
If there is dark matter, then there must be *Chandrasekhar dynamical friction*.

**Prediction of new phenomenon:**

The situation:
Prediction of new phenomenon:
If there is dark matter, then there must be Chandrasekhar dynamical friction.

Visualisation:
(integrate over all satellite–DM-particle encounters)

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

dark matter wake

Prediction of new phenomenon:

Essentially:

And this is why galaxies merge, but only in the dark matter theory.
Bars slow down due to dynamical friction on DM halo

Dysfunctional properties 1:
Bars slow down due to dynamical friction on DM halo
**Dysfunctional properties 1:**
Bars slow down due to dynamical friction on DM halo

Research group of Mahmood Roshan, Neda Ghafourian, Tahere Kashfi:

find observed bar rotation to be in 8 sigma tension with the latest highest-resolution Illustris & Eagle models
Dysfunctional properties 1:
Bars slow down due to dynamical friction on DM halo

\[ R = \frac{R_{\text{corotation}}}{R_{\text{bar length}}} \]

\( R > 1.4 \Rightarrow \text{slow bar} \)
\( R < 1.4 \Rightarrow \text{fast bar} \)

Real galaxies have fast bars.
Dark-matter-galaxies have slow bars.

8 sigma tension

no significant dark matter halo in nature

Figure 19. The posterior inference on \( R \) and the intrinsic dispersion of \( \log_{10} R \), found by applying Equation 28 to our compilation of observational results (Table 2) and to the EAGLE simulation at \( z = 0 \) based on figure 9 of Algorky et al. (2017). Although the calculations are done in the space of \( \log_{10} R \), we change the x-axis to a linear scale when plotting so the results are more intuitive (i.e. we plot \( 10^R \)). The black (blue) contours correspond to 1\( \sigma \), 3\( \sigma \), and 5\( \sigma \) outliers from the observed (EAGLE) posterior. Due to the significant mismatch, the 6\( \sigma \) contour is also shown for the EAGLE simulation.

Dysfunctional properties 2:
Compact groups of galaxies should merge within a Gyr

Credit: Chynoweth et al., NRAO/AUI/NSF, Digital Sky Survey
Dysfunctional properties 2:
Compact groups of galaxies should merge within a Gyr

<table>
<thead>
<tr>
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<td>=&gt; no solutions with dark matter: system merges</td>
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</thead>
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<tr>
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</tr>
</tbody>
</table>

Oehm et al. (2017)
Oehm & Kroupa (2018)

... basically, all members of the M81 group would have to have fallen-in synchronously from large distances and have a peri-galactic encounter with M81 at nearly the same time without having merged yet.

This is arbitrarily unlikely.
Dysfunctional properties 2:
Compact groups of galaxies should merge within a Gyr

... too many exist ...

The HiLoSeon Compact groups observed in this CARMA study; 3-color g-r-i images are from PanSTARRS,

Dysfunctional properties 2:
Compact groups of galaxies should merge within a Gyr

no significant dark matter halo in nature
Dysfunctional properties 3:
Orbit of the Large and Small Magellanic Clouds

Credit: ESA/Gaia/DPAC, CC BY-SA 3.0 IGO

Courtesy of Nidever, et al. (Montana State University/NOAO), NRAO/AUI/NSF and Meilinger, Leiden-Argentina-Bonn Survey, Parkes Observatory, Westerbork Observatory, Arecibo Observatory.

Pavel Kroupa: Charles University in Prague / University of Bonn
Dysfunctional properties 4:
Orbit of the Large and Small Magellanic Clouds

Oehm et al. (in prep.)
Haslbauer et al. (in prep.)

5 sigma tension

no orbit solutions that are consistent with cosmology
thus no significant dark matter halo in nature

Tension significantly increased when taking into account the other satellite galaxies:

Using dwarf satellite proper motions to determine their origin
Angus, G. W.; Diaferio, Antonaldo; Kroupa, Pavel

no significant dark matter halo in nature
Marcel Pawlowski

Oliver Mueller

Dysfunctional properties 5:
Planes of Satellites / Disks of Satellites


Figure 16. Edge-on view of the satellite galaxy planes around the MW and M31, similar to Fig. 9 for the LG planes. As before, galaxies which are

The satellite galaxies are in a plane much like the planets around the Sun.
How can the MW and Andromeda satellite systems be so correlated, if they are sub-halos falling-in individually?

Dysfunctional properties 5: Planes of Satellites / Disks of Satellites

Figure 16. Edge-on view of the satellite galaxy planes around the MW and M31, similar to Fig. 9 for the LG planes. As before, galaxies which are


"A whirling plane of satellite galaxies around Centaurus A"
Dysfunctional properties 5:
Planes of Satellites / Disks of Satellites

Mueller, Pawlowski et al. (2018, Science)

MW & M31 planes of satellites are not unique!

NOT "look elsewhere effect"


Dysfunctional properties 5:
Planes of Satellites / Disks of Satellites

Combining probabilities
(tests relative to LCDM Millenium II, Illustris simulations)

5 sigma disagreement
with SMoC results

no significant dark matter halo around Milky Way
(i.e. MW did not form from many mergers of sub halos)

Pawlowski (2018, Modern Physics Letters A)
Dysfunctional properties 6:
Frighteningly symmetric structure of the Local Group

"The discovery of symmetric structures in the Local Group"

Pawlowski, Kroupa & Jerjen
(2013 MNRAS)

Figure 9. Edge-on view of both LG planes. The orientation of the MW and M31 are indicated as black ellipses in the centre. Members of the LGP1 are plotted as yellow points, those of LGP2 as green points. MW galaxies are plotted as plus signs (+), all other galaxies as crosses (x), the colours code their plane membership as in Fig. 6. The best-fitting planes are plotted as...
Dysfunctional properties 6:
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Pawlowski, Kroupa & Jerjen
(2013 MNRAS)

"The discovery of symmetric structures in the Local Group"

A frightening symmetry

Figure 9. Edge-on view of both LG planes. The orientation of the MW and M31 are indicated as black ellipses in the centre. Members of the LGP1 are plotted as yellow points, those of LGP2 as green points. MW galaxies are plotted as plus signs (+), all other galaxies as crosses (×), the colours code their plane membership as in Fig. 6. The best-fitting planes are plotted as

Dysfunctional properties 7:
The Local Cosmological Volume

Figure 1: Galaxies at radial distances 1 < D < 8 Mpc from the centre of the Local Group of galaxies.
Local void is too empty $\Rightarrow$ "We conclude that there is a good case for inconsistency between the theory and our observations of galaxies in the Local Void."

Large/massive galaxies too far from sheet:

"at well below 1% probability it is an unlikely consequence of standard ideas."

According to the SMoC massive galaxies need to be in the sheet because that is where the matter is, from which they form via mergers.
Massive colliding galaxy clusters at high $z$

**Bullet cluster**

$z = 0.296$

$M_{200} \approx 1.9 \times 10^{15} M_\odot$

mass ratio $\approx 7.3$

$V_{\text{infall}} \approx 3000 \text{ km/s}$

**El Gordo cluster**

$z = 0.87$

$M_{200} \approx 20 \times 10^{15} M_\odot$

mass ratio $\approx 3.6$

$V_{\text{infall}} \approx 2500 \text{ km/s}$. 
Massive colliding galaxy clusters at high $z$

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Credit: NASA/CXC/CfA/M.Markevitch, Optical and lensing map: NASA/STScI, Magellan/U.Arizona/D.Clowe, Lensing map: ESO WFI
Massive colliding galaxy clusters at high $z$

Use Big Jubilee SMoC/LCDM simulation (Watson+ 2014)

Dysfunctional properties 8:
The Cosmological Scale

Bullet cluster

$z = 0.296$

$M_{200} \approx 1.9 \times 10^{15} M_\odot$

mass ratio $\approx 7.3$

$V_{\text{infall}} \approx 3000 \text{ km/s}$

Dysfunctional properties 8:
The Cosmological Scale

El Gordo cluster

$z = 0.87$

$M_{200} \approx 20 \times 10^{15} M_\odot$

mass ratio $\approx 3.6$

$V_{\text{infall}} \approx 2500 \text{ km/s}$

All four clusters individually very rare!

NOT LCDM at $>6$ sigma
Dysfunctional properties 9:
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).

Dysfunctional properties 9:
The Cosmological Scale

The Millennium XXL (MXXL) simulation Angulo et al. 2012

Test how often does a KBC void occur? Haslbauer, Banik & Kroupa 2020

Dysfunctional properties 9:
The Cosmological Scale

Figure 1. Distribution of the apparent relative density contrast $\delta$ (equation 22) of spheres with a 300 Mpc radius less an inner 40 Mpc hole in the $\Lambda$CDM MXXL simulation, calculated at redshift $z = 0$ (Section 2.1). The red solid curve shows the observed density contrast of $\delta_{obs} = 0.46 \pm 0.06$ with Gaussian errors (see also fig. 11 and table 1 in Keenan et al. 2013). The $\delta$ values closely follow a Gaussian distribution with a dispersion of $\sigma_{\Lambda CDM} = 0.048$ (the black curve). A more detailed Gaussianity test is performed in Appendix A. Both curves are normalized to the same area.

Moritz Haslbauer, Indranil Banik

Dysfunctional properties 9:
The Cosmological Scale

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Moritz Haslbauer, Indranil Banik

Difference of >6 sigma
The KBC void automatically solves the **Hubble Tension**, but not helpful since KBC void not possible in LCDM.

**Dysfunctional properties 9**

**The Cosmological Scale**

---

**observed KBC void**

diameter: \(\approx 1 \text{ Gpc}\)

density contrast: \(\approx 50\%\)

---

Use **Millennium (MXXL) SMoC/LCDM simulation** (Angulo+ 2012)

**observed KBC void**

diameter: \(\approx 1 \text{ Gpc}\)

density contrast: \(\approx 50\%\)

**CMB at z = 1100**

density contrast \(\approx 1\text{e-5}\)
The Cosmological Scale

Dysfunctional properties 9:

On 600 Mpc diameter scales expect
density contrast of 0.032, observe 0.46 ± 0.06

NOT LCDM at >6 sigma

Note: Kenworthy et al. (2019) claim this KBC void not possible, but they made an error, see Haslbauer et al. (2020)
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

**Generally:**

Much evidence for highly significant over- and under-densities in galaxy-cluster data

4.9 sigma exclusion of cosmological principle based on distribution of $10^6$ quasars

Secrest + Sarkar et al. (2021)

---

Kroupa 2015

Dysfunctional properties 9:

The Cosmological Scale

---

No Dark Matter!

$\rightarrow$ galaxies merge rarely

What about Dark Energy?
The evidence is thus that the real Universe is far more structured than allowed in the SMoC.

As it evolves, at time $z=0.9$ (6 Gyr after BigBang) voids fill-out about 59% of the volume.

"Cosmic acceleration is an apparent effect [Ref.11,16] . . ."

Same effect as Hubble Tension
(apparent faster expansion)
except on much larger scales.

Observed from a deep void, the Universe appears Gyr older than viewed from a Galaxy cluster.

No Dark Matter!

$\Rightarrow$ galaxies merge rarely

No Dark Energy

What now?
Non-dark-matter theories:

The observed lack of dynamical friction
(galactic bars, satellite galaxies, compact groups of galaxies) +
the observed much larger density contrasts
on large cosmological scales

need effectively stronger gravitation

BUT

All hybrid and other approaches which mimic the "success" of LCDM on large scales (>50Mpc),
e.g. fluid dark matter,
are ruled out
with equal significance as the LCDM model
(KBC void, El Gordo cluster + Bullet cluster)
(>5 sigma)

This leaves few possibilities...

Non-dark-matter theories:
Modified Gravity (MOG)

A covariant modification of Einstein gravity.
The theory introduces two additional scalar fields and one vector field.
Non-dark-matter theories:
Modified Gravity (MOG)

The Star Formation History and Dynamics of the Ultra-diffuse Galaxy Dragonfly 44 in MOND and MOG

Hosein Haghi\textsuperscript{1,}*, Vahid Amiri\textsuperscript{1}, Akram Hasani Zonoozi\textsuperscript{1,2,}*, Indranil Banik\textsuperscript{2}, Pavel Kroupa\textsuperscript{2,3,}*, and Moritz Haslbauer\textsuperscript{2}

\textsuperscript{1}Department of Physics, Institute for Advanced Studies in Basic Sciences (IASBS), P.O. Box 13365-9161, Zanjan, Iran; haghi@iasbs.ac.ir
\textsuperscript{2}Helmholtz-Institut für Strahlen- und Kernphysik (KISKP), Universität Bonn, Nussallee 14-16, D-53115 Bonn, Germany
\textsuperscript{3}Charles University in Prague, Faculty of Mathematics and Physics, Astronomical Institute, V Holešovičkách 2, CZ-180 00, Praha 8, Czech Republic

Received 2019 June 6; revised 2019 September 13; accepted 2019 September 16; published 2019 October 11

Abstract

The observed line-of-sight velocity dispersion $\sigma_{\text{los}}$ of the ultra-diffuse galaxy Dragonfly 44 (DF44) requires a Newtonian dynamical mass-to-light ratio of $M_{\text{dyn}}/L_\odot = 26^{+1}{_{-5}}$ solar units. This is well outside the acceptable limits of our stellar population synthesis (SPS) models, which we construct using the integrated galactic initial mass function (IGIMF) theory. Assuming DF44 is in isolation and using Jeans analysis, we calculate $\sigma_{\text{los}}$ profiles of DF44 in Milgromian dynamics (MOND) and modified gravity (MOG) theories without invoking dark matter. Comparing with the observed kinematics, the best-fitting MOND model has $M_{\text{dyn}}/L_\odot = 3.6^{+1.3}_{-1.2}$ and a constant orbital anisotropy of $\beta = -0.5^{+0.4}_{-1.5}$. In MOG, we first fix its two theoretical parameters $\alpha$ and $\mu$ based on previous fits to the observed rotation curve data of The HI Nearby Galaxy Survey (THINGS). The DF44 $\sigma_{\text{los}}$ profile is best fit with $M_{\text{dyn}}/L_\odot = 7.4^{+1.3}_{-1.2}$, larger than plausible SPS values. MOG produces a $\sigma_{\text{los}}$ profile for DF44 with acceptable $M_{\text{dyn}}/L_\odot$ and isotropic orbits if $\alpha$ and $\mu$ are allowed to vary. MOND with the canonical $\alpha_0$ can explain DF44 at the 2.40σ confidence level (1.66%) if considering both its observed kinematics and typical star formation histories in an IGIMF context. However, MOG is ruled out at 5.49σ ($P$-value of $4.07 \times 10^{-4}$) if its free parameters are fixed at the highest values consistent with THINGS data.

Non-dark-matter theories:
Emergent gravity

Gravity is a consequence of the "information associated with the positions of material bodies".

Combines the thermodynamic approach to gravity with Gerard 't Hooft's holographic principle.

Gravity is not a fundamental interaction, but an emergent phenomenon which arises from the statistical behaviour of microscopic degrees of freedom encoded on a holographic screen.
Non-dark-matter theories: Emergent gravity

Testing Verlinde’s emergent gravity with the radial acceleration relation

Federico Lelli,† Stacy S. McGaugh‡ and James M. Schombert§

1European Southern Observatory, Karl-Schwarzschild-Strasse 2, Garching bei München D-85748, Germany
2Department of Astronomy, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106, USA
3Department of Physics, University of Oregon, Eugene, OR 97405, USA

Accepted 2017 February 13. Received 2017 February 13; in original form 2017 January 30

ABSTRACT

It has recently been proposed that space–time and gravity may emerge from an underlying microscopic theory. In a de Sitter space–time, such emergent gravity (EG) contains an additional gravitational force due to dark energy, which may explain the mass discrepancies observed in galactic systems without the need of dark matter. For a point mass, EG is equivalent to Modified Newtonian Dynamics (MOND). We show that this equivalence does not hold for finite-size galaxies: There are significant differences between EG and MOND in the inner regions of galaxies. We confront theoretical predictions with the empirical radial acceleration relation (RAR). We find that (i) EG is consistent with the observed RAR only if we substantially decrease the fiducial stellar mass-to-light ratios; the resulting values are in tension with other astronomical estimates; (ii) EG predicts that the residuals around the RAR should correlate with radius; such residual correlation is not observed.

Non-dark-matter theories: Gravitational dipoles

If antimatter anti-gravitates, matter / antimatter pairs resulting from quantum vacuum fluctuations would be virtual gravitational dipoles.

The dynamical discrepancies in galaxies are an effect of gravitational polarization of the gravitational dipoles.
Non-dark-matter theories: 
Gravitational dipoles

Solar System limits on gravitational dipoles

Indranil Banik, Pavel Kroupa

Published: 23 May 2020

ABSTRACT

The gravitational dipole theory of Hadjikovc (2010) is based on the hypothesis that antimatter has a negative gravitational mass and thus falls upwards on the Earth. Astrophysically, the model is similar to but more fundamental than Modified Newtonian Dynamics (MOND), with the Newtonian gravity $g_n$ towards an isolated point mass boosted by the factor $\nu = 1 + (\alpha x) \tanh(\sqrt{\alpha x})$, where $x = g_n/x_0$ and $x_0 = 1.2 \times 10^{-10}$ m s$^{-2}$ is the MOND acceleration constant. We show that $\alpha$ must lie in the range $0.4 \sim 1$ to acceptably fit galaxy rotation curves. In the Solar System, this interpolating function implies an extra Sunwards acceleration of $nu_x$. This would cause Saturn to deviate from Newtonian expectations by $7000(\alpha/0.4)$ km over 15 yr, starting from known initial position and velocity on a near-circular orbit. We demonstrate that this prediction should not be significantly altered by the postulated dipole halos of other planets due to the rather small region in which each planet’s gravity dominates over that of the Sun. The orbit of Saturn should similarly be little affected by a possible ninth planet in the outer Solar System and by the Galactic gravity causing a non-spherical distribution of gravitational dipoles several kAU from the Sun. Radio tracking of the Cassini spacecraft orbiting Saturn yields a 5σ upper limit of 160 m on deviations from its conventionally calculated trajectory. These measurements imply a much more stringent upper limit on $\alpha$ than the minimum required for consistency with rotation curve data. Therefore, no value of $\alpha$ can simultaneously match all available constraints, falsifying the gravitational dipole theory in its current form at extremely high significance.

Non-dark-matter theories: 
Scale-invariant GR

Based on Weyl's Integrable Geometry, endowed with a gauge scalar field.
Non-dark-matter theories:
Scale-invariant GR

Scale-invariant dynamics in the Solar system

Indranil Banik, Pavel Kroupa

https://doi.org/10.1093/mnrasl/sia113
Published: 18 June 2020   Article history ▼

ABSTRACT
The covariant scale-invariant dynamics (SID) theory has recently been proposed as a possible explanation for the observed dynamical discrepancies in galaxies. SID implies that these discrepancies – commonly attributed to dark matter – arise instead from a non-standard velocity-dependent force that causes two-body near-Keplerian orbits to expand. We show that the predicted expansion of the Earth–Moon orbit is incompatible with lunar laser ranging data at >200σ. Moreover, SID predicts that the gravitating mass of any object was much smaller in the past. If true, a low-mass red giant star must be significantly older than in standard theory. This would make it much older than the conventional age of the Universe, which, however, is expected to be similarly old in SID. Moreover, it is not completely clear whether SID truly contains new physics beyond general relativity, with several previous works arguing that the extra degree of freedom is purely mathematical. We conclude that the SID model is falsified at high significance by observations across a range of scales, even if it is theoretically well formulated.

Summary: Non-dark-matter theories:

Emergent gravity significantly challenged by RAR data
Lelli et al. (2017)

Modified Gravity (MOG) falsified with > 5 sigma confidence
Haghi et al. (2019)

Gravitational dipoles falsified with >> 5 sigma confidence
Banik & Kroupa (2020a)

Scale-invariant GR falsified with > 200 sigma confidence
Banik & Kroupa (2020b)

MOND/Milgromian dynamics a generalisation of Solar system dynamics to the scale of galaxies
Non-dark-matter theories:  
Milgrom Dynamics (MOND)  
Milgrom (1983); Famaey & McGaugh (2012)

A formulation in the classical limit is known and is energy and momentum conserving:

A formulation in the classical limit is known and is energy and momentum conserving:


Non-dark-matter theories:
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Milgrom (1983); Famaey & McGaugh (2012)

II. THE FIELD EQUATIONS

In Newtonian gravity test bodies move with an acceleration equal to \( g_N = -\nabla \phi_N \), where \( \phi_N \) is the Newtonian gravitational potential. It is determined by the Poisson equation \( \nabla^2 \phi_N = 4\pi G \rho \), where \( \rho \) is the mass density which produces \( \phi_N \). The Poisson equation may be derived from the Lagrangian

\[
L_N = -\int d^3 x \left\{ \rho \nabla \phi_N + (8\pi G)^{-1} \nabla (\nabla \phi_N)^2 \right\}.
\]  

(2a)

In searching for a modification of this theory we will want to retain the notion of a single potential \( \phi \) from which acceleration derives. And, as in Newtonian gravity, it is desirable that \( \phi \) be arbitrary up to an additive constant. The most general modification of \( L_N \) which will yield these features is

\[
L = -\int d^3 x \left\{ \rho \nabla \phi + (8\pi G)^{-1} a_0^2 \mathcal{F} \left( \frac{(\nabla \phi)^2}{a_0^2} \right) \right\},
\]  

(2b)

where \( \mathcal{F}(x^2) \) is an arbitrary function. Note that a scale of acceleration is necessary unless we are in the Newtonian case. Variation of \( L \) with respect to \( \phi \) with variation of \( \phi \) vanishing on the boundary yields

\[
\nabla \cdot \left[ \frac{\mu}{a_0^2} \nabla \phi \right] = 4\pi G \rho ,
\]  

(3)

with \( \mu(x) = \mathcal{F}(x^2) \), as the equation determining the modified potential. A test particle is assumed to have acceleration \( g = -\nabla \phi \). We supplement equation (3) by the boundary condition \( \nabla \phi \to 0 \) as \( r \to \infty \).

MOND may be the consequence of the quantum vacuum:

\[
\mu(t) \left( \frac{\nabla \phi}{a_0} \right) = \frac{(\nabla \phi)(a_0)}{(1 + (\nabla \phi/a_0)^2)^{3/2}}
\]

Milgrom (1999, PhLA)

Pavel Kroupa: Charles University in Prague / University of Bonn
Non-dark-matter theories:
MilgrOmiaN Dynamics (MOND)
Milgrom (1983); Famaey & McGaugh (2012)

Very important:
MOND was motivated by the flatness of a few L* galaxy rotation curves known prior to 1983.

This is analogous to Newton being motivated by the falling apple and the Moon's motion ...

Non-dark-matter theories:
MilgrOmiaN Dynamics (MOND)
Milgrom (1983); Famaey & McGaugh (2012)

Very important:
MOND was motivated by the flatness of a few L* galaxy rotation curves known prior to 1983.

The predictions of rotation curves for low-surface brightness galaxies were successfully verified much later (see work by Stacy McGaugh et al.)

It is wrong to claim that MOND is phenomenological and was designed to only fit rotation curves.
Non-dark-matter theories:
Milgrom Dynamics (MOND) -- what is MOND?
Milgrom (1983); Famaey & McGaugh (2012)

New symmetry?  Space-time scale invariance  Milgrom (2009)

Non-dark-matter theories:
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New symmetry?  Space-time scale invariance  Milgrom (2009)

Deviation form Newtonian dynamics / Einstein's GR due to quantum vacuum?  Milgrom (1999)
**Analogy**

Depth of a trampoline with increasing weight:

- **Modelling fit to the data**
- **Extrapolation** - may we expect this to work?

- **Weight:** 0.0000001g, 1g, 10g, 100g
- **Depth**

**Molecular forces begin to play a role**

**Measurement**
The radial acceleration relation (the RAR)

![Graph showing the radial acceleration relation](image)

The Newtonian "solar system" relation

The Milgromian (MOND) deviation

Non-dark-matter theories:

MilgrOmiaN Dynamics (MOND) -- what is MOND?

New symmetry? Space-time scale invariance

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Deviation form Newtonian dynamics / Einstein's GR due to quantum vacuum?

Milgrom (2009)

Completely predictive: even wiggles in rotation curves

many publications, e.g. by Sanders, McGaugh

\[
\nabla \cdot \left[ \mu \left( \frac{\nabla \phi}{a_0} \right) \nabla \phi(x) \right] = 4 \pi G \rho(x)
\]

(a) \( \rho \) vs \( R \) (kpc)

(b) \( \rho \) vs \( R \) (kpc)
Non-dark-matter theories:
Milgromian Dynamics (MOND)
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Planes of Satellites
--> easy as pie

many publications, e.g.
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KBC void + Hubble Tension:
  --> not even an issue
Haslbauer et al. (2020)

El Gordo + Bullet Cluster:
  --> trivial
Asencio et al. (2020)

Non-dark-matter theories:
Milgrom Dynamics (MOND)
Milgrom (1983); Famaey & McGaugh (2012)

The equations of motion in MOND account for observations
on scales from
100pc to Gpc!

Without parameter adjustments!

A most remarkable success of modern astrophysics
of great historical meaning.
**MOND predictions**

of new phenomena

A) The "external field effect"

**Remember:**

\[ \nabla \cdot \left[ \frac{\mu}{a_0} \left( \nabla \phi_M \right) \right] = 4 \pi G \rho_{\text{stars+gas}}(\vec{x}) \]

**Slightly different Lagrangian:**

\[ \nabla \cdot \nabla \phi_N = 4 \pi G \rho_{\text{stars+gas}} \]

\[ \nabla \cdot \nabla \phi_M = \nabla \cdot \left[ \mu \left( \frac{\nabla \phi_N}{a_0} \right) \right] \]

\[ \rho_{\text{phantom DM}} = \frac{1}{4 \pi G} \nabla \cdot \nabla \phi_N - \rho_{\text{stars+gas}} \]

**Figure 18:** (a) Baryonic density of a model galaxy made of a small Plummer bulge with a mass of \(2 \times 10^8 M_\odot\) and Plummer radius of 185 pc, and of a Miyamoto-Nagai disk of \(1.1 \times 10^9 M_\odot\), a scale-length of 750 pc and a scale-height of 300 pc. (b) The derived phantom dark matter density distribution: it is composed of a spheroidal component similar to a dark matter halo, and of a thin disk-like component (Figure made by Fabian Lüghausen [253]).
MOND predictions
of new phenomena

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Slightly different Lagrangian:
\[ \nabla \cdot \nabla \phi_N = 4 \pi G \rho_{\text{stars+gas}} \]
\[ \nabla \cdot \nabla \phi_M = \nabla \cdot \left( \mu \left( \frac{\nabla \phi_N}{a_0} \right) \nabla \phi_N \right) \]
\[ \rho_{\text{phantomDM}} = \frac{1}{4 \pi G} \left( \nabla \cdot \nabla \phi_M - \rho_{\text{stars+gas}} \right) \]

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Figure 18: (a) Baryonic density of a model galaxy. (b) Phantome dark matter density. Famaey & McGaugh (2012); Lueghausen et al. (2013)

MOND predictions
of new phenomena

A) The "external field effect"

phantom dark matter halo

NOT real particles, merely the extra (Milgromian) gravitational potential

Pavel Kroupa: Charles University in Prague / University of Bonn
**MOND predictions**

*of new phenomena*

A) The "external field effect"

Phantom DM halo "shrinks" ==> galaxies become more Newtonian

==> rotation curves decrease at large R when other galaxies nearby

---

8 sigma detection!!
The inertial mass remains unchanged, but the gravitating mass depends on the surrounding matter distribution.

MOND predictions of new phenomena

A) The "external field effect"

Observational verification

B) Pressure-supported stellar systems have droplet shape
**MOND predictions**

of new phenomena

A) The "external field effect"

B) Pressure-supported stellar systems have droplet shape

Non-dark-matter theories:

MilgrOmiaN Dynamics (MOND)

Milgrom (1983); Famaey & McGaugh (2012)

Simulations

At the Universidad de Valparaiso (Chile)

Graeme Candlish

is leading a cosmology group.

In Prague/Bonn/Strasbourg now:

Galaxy-formation simulations

Wittenburg et al. (2020; 2021abcd in prep)
**Non-dark-matter theories:**
MilgrOmiaN Dynamics (MOND)
Milgrom (1983); Famaey & McGaugh (2012)

At the Universidad de Valparaiso (Chile)
Graeme Candlish is leading a cosmology group.

In Prague/Bonn/Strasbourg now:
Galaxy-formation simulations and
cosmological simulations
Wittenburg et al. (2020; 2021abcd in prep)

\[ a(t) = \frac{1}{1 + z(t)} \]
In MOND, structure growth self-regulates through the EFE

A newly discovered process affecting structure formation

Haslbauer, Banik & Kroupa 2020

Non-dark-matter theories:

Milgromian Dynamics (MOND)

Milgrom (1983); Famaey & McGaugh (2012)

Very important:

The CMB can be modelled in a relativistic MOND theory in which gravitational waves travel at speed $c$

(Skordis & Zlosnik 2019)

in Prague
Conclusions

<table>
<thead>
<tr>
<th>Test</th>
<th>SMoC/LCDM</th>
<th>MOND (without parameter adjustments)</th>
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<tbody>
<tr>
<td>rotation curves (includes core/cusp)</td>
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<tr>
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</tr>
<tr>
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Conclusions

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<td>(but observed)</td>
</tr>
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And now a naive question: put on your seat belts

Is the CMB really the CMB?
The first stars formed in dense clusters.

The formation of ultra compact dwarf galaxies and massive globular clusters.
Quasar-like objects to test for a variable stellar initial mass function
Jeřábková, T.; Kroupa, P.; Dabringhausen, J.; Hilker, M.; Bekki, K. show less

Very high redshift quasars and the rapid emergence of supermassive black holes
Kroupa, Pavel; Subr, Ladislav; Jerábková, Tereza; Wang, Long show less

The possible role of stellar mergers for the formation of multiple stellar populations in globular clusters
Wang, Long; Kroupa, Pavel; Takahaishi, Koh; Jerábková, Tereza show less

the first star cluster
200 Myr after Big Bang
<0.5 pc
<1 Myr

stellar mergers blow out processed matter
dust forms
Much later some of this dust is between today's galaxies

The dust *between* galaxies has been measured

For example:

Figure 5. Extinction magnitude $A_V$ as a function of redshift using the GB07 extinction model in Figure 4. The open circle shows the result of Ménard et al. (2010a), where the dashed line shows their extrapolation from a constant comoving dust density model. The other observational constraints are extracted from Figure 9 of Ménard et al. (2010a). In the bottom panel, the model-predicted dust reddening $E(B - V)$ is plotted against $z$. 
Dust between galaxies
this dust radiates

The received radiation on Earth from intergalactic dust integrated over cosmological distances equals the observed CMB (Vavrycuk 2018)

Vaclav Vavrycuk

See YouTube video explaining this: Rachel Parziale "Universe Opacity and CMB"
https://www.youtube.com/watch?v=c5gwk-I6afo

The cosmological-dust origin of the CMB may be supported by CMB anomalies:

2016CQ Gra.33/4001S 2016/09 cited: 168
CMB anomalies after Planck
Schwarz, Dominik J.; Copi, Craig J.; Huterer, Dragan; Starkman, Glenn D. show less

report 3 anomalies:
1) the lack of > 60 degree correlation
2) mutual alignment of the lowest-multipole moments
   Also seen in SN1a data! (Javanmardi et al. 2015)
3) hemispherical asymmetry
   Also seen in galaxies! (Javanmardi et al. 2017)

Cosmological dust may solve 1) and 3).

very very very deep and fundamental implications for cosmology
Outline

Prologue

A fictitious story

The core: dark-matter approaches
other approaches
conclusions

Epilogue
We have a problem

The problem is neither the data nor the theories
but it is sociological

The standard dark-matter based cosmological model is
the most falsified model
which the very vast majority of scientists have ever believed in.

Never, in the history of humankind, have there been
so many modern ivy-league educated researchers
who have together erred so badly.

This is a completely unique
scientific crisis in history

The robust falsification of the SMoC is not new:

If each failure causes
a loss of confidence
of only 50%
The robust falsification of the SMoC is not new:

If each failure causes a loss of confidence of only 50% then, by 2012, the 19 failures lead to a remaining confidence in the dark-matter based models of

\[ 1.9 \times 10^{-6} \]
The robust falsification of the SMoC is not new:

If each failure causes a loss of confidence of only 50%, then by 2012, the 19 failures lead to a remaining confidence in the dark-matter based models of $1.9 \times 10^{-6}$

Add into this recent falsifications through the KBC void+Hubble tension plus the El Gordo+Bullet clusters, each $> 6$ sigma

Independently of this effort:

"taken at face value, the Planck data provide a significant indication against the flat LCDM scenario"

"Not fitting practically half of the current cosmological data is undoubtedly a significant blow to the LCDM model"

For a comprehensive REVIEW consult:

"the strong need for an alternative physical scenario beyond $\Lambda$CDM."
We have the most falsified physical theory ever in human history, to still be believed by the majority of physicists.

This may well be the greatest scientific crisis in all of history.

The sociological problem:

The existence of Dark ... Matter is by now well established [1,2]."

My suggestion in 2015 to the editors and authors to amend this to read

"The existence of Dark ... Matter is a leading hypothesis [1,2]."

was blatantly rejected

Respectable physicists today know Dark Matter exists!
The question to ponder is what is the role, in this stagnation, of over-invoking authority? "ivy-league" institutions? hierarchies? prestigious awards & prizes? extreme competition for research money? prestigious journals?

You can believe in Dark Matter, but it Doesn’t Matter in the real Universe.

What does matter is Milgrom’s

$$\nabla \cdot \left( \mu \left( \frac{\nabla \phi}{a_0} \right) \nabla \phi(\vec{x}) \right) = 4 \pi G \rho(\vec{x})$$

which underlies the beauty of galaxies and the real richness of the Universe.
Tycho Brahe’s tomb

Na Zdravi
to the re-start!

END