Dark Matter: a debate
Cold/Warm Dark Matter is ruled out

Pavel Kroupa
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Bethe Colloquium, 18th November 2010
A historical perspective:

500 years ago

learning from experience
Step I: A convincing beautiful model (the standard model)
The geocentric world view by Aristoteles (about 4th century BC).

Step II: Making the theory fit
Add epicycles to achieve high precision (Claudius Ptolemaeus in the 2nd century AD)

\[ \Rightarrow \text{excellent description of the data.} \]

Step III: An alternative model (the exotic model)
The heliocentric model by Aristarchus (3rd century BC) (and later Copernicus 1543).

Not accepted: more complex and unsatisfying.
It needs two centers and does not fit the data well.
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    It needs *two centers* and does *not fit* the data well.

Step IV: Decision by technological advance
    Galileo's *solar system telescope data disprove the standard model*,
    but are consistent with the Heliocentric model.
A world beyond the standard model is seen for the first time!

But without an idea of the deeper physics.
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Step V: Conclusions
    It is irrelevant to debate whether the geocentric model fits any data.
    Beauty or even "high-precision" of a model can misguide.
Our current world view
Our understanding of the cosmological world relies on two fundamental assumptions:

1) **General Relativity** is valid in the weak field limit (i.e. we live in a Newtonian universe)
   - tested by studying the dynamics and structure of galaxies of the *Local Group* and *Local Volume*
   - (the best observed systems!)

2) **Conservation of matter** is valid
   - tested by studying the matter cycle

   a cosmological picture, in which structure is generated by *dark matter* into which *baryons* fall fueling the *star formation activity* of galaxies.
Step I

A convincing, beautiful theory
The Standard / Concordance Cosmological Model

LCDM = CCM
Step II

Making the theory fit
Assuming Einsteinian/Newtonian gravity (1915) to be valid

The Standard/Concordance Cosmological Model

can only be made consistent with the data by adding

inflation (1965 and 1980)

cold dark matter (around 1980)

dark energy (1999)

dark force (2010)
The Standard / Concordance Cosmological Model

Problems

dark energy: 70 %
the implied dark energy density is so small that it is unstable to quantum correction (Dvali et al. 2002); not seen by WMAP (Shanks); energy creation; may not be there at all (Wiltshire)

dark matter: 25 %
despite much search hitherto unknown stuff

baryons: 5 %
only 40% of these found - the missing baryon problem

dark force:
totally unknown (Peebles & Nusser 2010; Kroupa et al. 2010)
That is, we are trying to describe / model the universe with essentially unknown physics.

This is like trying to construct stellar models based to 95% on completely unknown ingredients.
Step III

An alternative
"Their simulations yield comparable results between MOND and the standard model for the large-scale structure, with even more clustering than with the parallel approximation. "

Combes & Tiret 2009, arXiv:0908.3289 :
MOND and structure formation and galaxies

Skordis et al. 2006, PhRvL

"We show that it may be possible to reproduce observations of the cosmic microwave background and galaxy distributions with Bekenstein’s theory of MOND."

Angus 2010 on SciLogs: "State-of-the-art cosmology: the current status"

Perfect fit to all CMB peaks with 11ev sterile neutrino.
That is:
LCDM is not a unique solution to the CMB data!!
One of the *primary arguments* for cold or warm dark matter comes from flat rotation curves . . .
"Perhaps a substantial fraction of the mass is not distributed in the disk at all."

In the Conclusions:

But

This would mean there exists a, to this day, unexplained disk-halo conspiracy.

Dark Matter is in a spheroidal halo.

Pavel Kroupa: AIfA, University of Bonn
But, flat rotation curves are explained much better by non-Einsteinian / Newtonian gravity:

For example:

Modified Newtonian Dynamics (MOND)  
Milgrom 1983

Modified Gravity (MOG)  
Moffat 2005
In fact, given an observed baryonic matter distribution, the rotation curve can be precisely predicted using MOND.

cannot be predicted using LCDM.
From Robert Sanders' Book on "The Dark Matter Problem", Cambridge University Press, 2010
With cold dark matter:

From Robert Sanders' Book on "The Dark Matter Problem", Cambridge University Press, 2010
In fact, given an observed baryonic matter distribution, the rotation curve

can be precisely predicted using MOND

cannot be predicted using LCDM.

plus in MOND dark matter significantly reduced in galaxy clusters

(e.g. Sanders 2009 (review):
"Modified Newtonian Dynamics:
A Falsification of Cold Dark Matter")
In fact, galaxies are MONDian objects.

i.e., MOND is the correct dynamical description for galaxies.
two hypotheses

( I )

1982
Suggestion of massive, weakly interacting dark matter particles and their role in structure formation

Cold/Warm Dark Matter

-Blumenthal, Pagels & Primack 1982, Nature
-Blumenthal, Faber, Primack, Rees, 1984, Nature

( II )

1983
Suggestion of a modification of Newton's force law

MOND
MOG

-Moffat 2005, JCAP
Progress is always linked to
cultural pre-disposition
and
Sociology

Today and in the past young researchers are

1. afraid
2. discouraged to try alternatives

Some personal examples - statements by well-known and very influential scientists:

"Pavel, in 1997 you have written that paper on dSph satellites without dark matter - you are unhirable." (about 2004)

"It is not worth reading those papers on satellite galaxies by Pavel Kroupa." (2009)

"But everyone knows that MOND is crap!" (at STScI May, 2010)

"I would be scared (mostly because I am still in search of a permanent post) of being labelled once and for all as a "hardcore-MONDian" person." (July 2010)

... as if being labeled a "hardcore-LCDM" person were acceptable ... (my own note added Nov. 2010).

"I can't do any MOND work - the director would not appreciate it" (Garching August, 2010).
The Party Line!!
This is where *resources* flow.
This is what you do, if you want a *job*:

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*Cold/Warm Dark Matter*

- Blumenthal, Pagels & Primack 1982, Nature
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---

No Go!!

( II )
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Suggestion of a modification of Newton's force law

*MOND MOG*

- Moffat 2005, JCAP
Step IV

Decision made possible through technological advance
Assume the standard cosmological model (i.e. Newtonian gravity) is valid.

Two Zwicky Conjectures of fundamental importance:


2. Zwicky (1956): Tidal-dwarf galaxies form out of the collisional debris of other galaxies.

Both have to be true!
Structures form according to the cosmological merger tree

Lacey & Cole (1993)
\[ \approx 250 \text{ kpc} \]
This has two immediate implications:

1. There exist large numbers of dark-matter dominated satellite galaxies.

2. There exist large numbers of newly formed (tidal-dwarf) satellite galaxies (they do not contain dark matter).

This is OK, but are there two different types of dwarf galaxy?
Radius vs luminosity:

Dabringhausen, Hilker, Kroupa 2008
Forbes, Lasky, Graham, Spitler 2008

Our dwarfs of interest

dSph satellite galaxies
dE galaxies

star clusters
UCDs/ Hilker objects

E galaxies
Gilmore gap

faint / low-mass
bright / massive

$10^6 M_\odot$
$10^{10} M_\odot$
$10^{12} M_\odot$
This has two immediate implications:

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2. There exist large numbers of newly formed (tidal-dwarf) satellite galaxies.

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This has two immediate implications:

1. There exist large numbers of dark-matter dominated satellite galaxies.

2. There exist large numbers of newly formed (tidal-dwarf) satellite galaxies.

No, there is only one type of dwarf galaxy!

But, which one? And why only one?
Let's consider first the *dark-matter type satellite dwarf galaxy*:

A *vast* amount of theoretical research has been done by *countless LCDM research groups* with the aim of *explaining* the observed satellite galaxy population *naturally* in LCDM.

... they all claim success
The DM mass-luminosity relation:

more gravitating mass,
more luminous mass?
The DM mass-luminosity relation of satellite galaxies

\[ \log_{20} \left( \frac{M_{0.3 \, \text{kpc}}}{M_\odot} \right) = \log_{10} \left( \frac{M_{0.3}}{M_\odot} \right) + \kappa \log_{10} \left( \frac{L_V}{L_{V,\odot}} \right) \]

expected \( \kappa > 0 \)
The DM mass - luminosity relation of satellite galaxies

Theory - Models of Satellites

Wadepuhl & Springel (2010) + many other groups

Dark-matter models ✓

expected $\kappa > 0$
The DM mass-luminosity relation of satellite galaxies

Observations - empirical data of Satellites

Strigari et al. (2008) confirmed by Wolf et al. (2010)

*Observed: $\kappa = 0$*

*Expected: $\kappa > 0$*
The lack of an observed mass-luminosity relation ($\kappa \approx 0$)

nature apparently does not care about the existence of the putative dark matter halo.
Thus, the *concept* of dark-matter halos appears to be *unphysical* for dSph satellites.
Individual dSph morphology:

DM gravitating potential:

smooth luminous morphology?
Significant isophote structure is present in many dSph satellites despite a large

$$\sigma \approx 700 \, \text{pc}/100 \, \text{Myr} \quad (=7 \, \text{km/s})$$

Substructure should phase-mix away if $\sigma$ is really due to a DM halo, unless it has a harmonic core.

consistent with DM halo?
\textbf{UMi}

D=65kpc

(Martinez-Delgado et al., in prep)

\textit{S shape:}

strong evidence for extra-tidal stars

Massive CDM halo?
**Fornax**

D=140kpc

(Demers et al. 1994)

\[
\left( \frac{M}{L} \right)_{0, V} = 4.8
\]

\[
\left( \frac{M}{L} \right)_{\text{tot, } V} = 4.4
\]

(Mateo 1998)

Not consistent with being embedded / shielded by an extensive dark-matter sub-halo!

Fig. 4. Isophotes of equal stellar density of field 1 reveal that the structure of Fornax, near the center, is not symmetric.

Pavel Kroupa: AIfA, University of Bonn
The distortions apparent in many of the dSph satellites do not support the notion that they are shielded by $10^9 M_{\odot}$ dark-matter halos.
The spatial distribution of the MW satellites

... further clues
Structures form according to the cosmological merger tree

Lacey & Cole (1993)
MW satellites are in a disk-like configuration:

- the 11 “classical” (brightest) satellites
- new satellites

Kroupa et al. (2010, A&A)
MW satellites are in a disk-like configuration:

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Kroupa et al. (2010, A&A)
Disk of Satellites

a rotational structure?

- the 11 “classical” (brightest) satellites
- new satellites

Kroupa et al. (2010, A&A)

Pavel Kroupa. AIfA, University of Bonn
Directions of orbital angular momenta of MW satellites

Pawlowski et al. 2011
Directions of orbital angular momenta of MW satellites

the Galactic sky
(Galactic spherical coordinates)

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Pawlowski et al. 2011
The MW satellite DoS is defined mostly by the outer satellites; but the angular momenta of the inner satellites are aligned to the pole of the DoS.

The satellites form a highly correlated phase-space population.
This correlated phase-space population is inconsistent with the satellites being dark-matter sub-haloes that fell into the MW halo in a group or individually.
**Within about 2 Mpc (Local Group):**

Combined likelihood that the $\Lambda$CDM model accounts for the observed Local Group $< 0.056 \%$.

(Kroupa et al. 2010)

Based on nearly $10^9$ particle - LCDM simulation.

(Libeskind et al. 2009)

**Within about 8 Mpc (Local Volume):**

Likelihood that the $\Lambda$CDM model accounts for the 3 massive galaxies above Local Sheet $P < 1 \%$ and far too few galaxies in the void ($P \sim 10^{-3} \%$).

(Peebles & Nusser 2010, Nature)

And, *disk galaxies far too similar.*

(Peebles & Nusser 2010 citing Disney et al. 2008, Nature)
Do we live in a Bubble of Extreme Exception?

The BEE hypothesis (to save the CCM hypothesis).

Pavel Kroupa: Alfa, University of Bonn
The dark-matter ansatz fails.
Let's consider now the tidal-dwarf galaxy (TDG):

(Zwicky's 2nd conjecture)
Tidal dwarf galaxies.
Relevance: The collision of two disks at high redshift

Wetzstein, Naab & Burkert 2007
(Weilbacher et al. 2000)

\[ N_{TDG} \approx 14 \]

**Fig. 21.** Identification chart of field 10 around AM 1353-272.
Thus, by direct observation

*new dwarf galaxies*

with masses comparable to dE/dSph galaxies form.

They are baryon dominated

(Barnes & Hernquist 1992).
Evolution of
TDGs

The Time
Evolve dwarf galaxies w/o dark matter in a computer
Remnants have a highly anisotropic and mass function $f(R, V)$ and mass $\approx 10^5 M_\odot$.

$R \approx$ few 100 pc and $\frac{M}{L} \approx 10^{2-3}$!

but no Dark Matter!

$e = 0.74$ and $e = 0.60$.
Hercules
D=130kpc
(Coleman et al. 2007)

Table 1
Properties of the Hercules dSph

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>R.A. (J2000)</td>
<td>16:31:02.0</td>
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<tr>
<td>Decl. (J2000)</td>
<td>12:47:29.6</td>
</tr>
<tr>
<td>$E(B-V)$ (mag)</td>
<td>$0.055 \pm 0.005^a$</td>
</tr>
<tr>
<td>$(m-M)_0$ (mag)</td>
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<tr>
<td>Distance (kpc)</td>
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<tr>
<td>[Fe/H]</td>
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<tr>
<td>King $r_h$</td>
<td>$4.37' \pm 0.29' (168 \pm 11$</td>
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<tr>
<td>King $r_c$</td>
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<tr>
<td>King $r_t$</td>
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<tr>
<td>$c = \log (r_t/r_c)$</td>
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Pavel Kroupa: AIfA, University of Bonn
\[ MV = -9 \text{ mag} \]
\[ r_{0.5} = 180 \text{ pc} \]
\[ \frac{M}{L} = 10^{2.3} \]

(Kroupa 1997)
Models are without Dark Matter!

very similar to Hercules!
For TDGs we know today that

The early (<100Myr) star-formation and chemical enrichment evolution is similar to the observed dSph satellites.

(Recchi et al. 2007)

Later dynamical evolution does not destroy the satellites.

(Kroupa 1997)

The number of old TDGs amounts to the dE population observed.

(Okazaki & Taniguchi 2000)

dE galaxies are observed to contain no Dark Matter, consistent with them being TDGs.

(Toloba et al. 2010, arXiv:1011.2198v1)
Young (age<100Myr) TDGs have rotation curves showing the *missing mass syndrome*. But they cannot have DM!

(Gentile et al. 2007)

=>$breakdown$ of *Newtonian/Einsteinian dynamics* !

This appears to be direct evidence that the LCDM model is not realistic.
What about the disk-like configuration of MW satellites?

Kroupa et al. (2010, A&A)

- the 11 “classical” (brightest) satellites
- new satellites

Pavel Kroupa: AI, University of Bonn
...and, the bulge mass vs number of satellites correlation?
A bulge - satellite correlation

Stressed first by Karachentsev et al. (2005) using Local Volume galaxies.

Kroupa et al. (2010, A&A)
Both, the *Disk of Satellites* and the *bulge--satellite correlation* are easily understandable if the MW satellites are *ancient TDGs*.

(Kroupa et al. 2010)
Phase-space correlated satellites form naturally in the same event as a bulge does.

Fig. 21. Identification chart of field 10 around AM 1353-272.
Both, the *Disk of Satellites* and the *bulge--satellite correlation* follow trivially if the MW satellites are *ancient TDGs*. 

And, the *DM mass--luminosity (non)correlation* 

\[ \kappa \approx 0 \]: 

there is no dark matter. 

And, *TDGs are known to form*. 

They are the result of well understood standard-physical processes. 

(Kroupa et al. 2010)
Thus,

(1) a fully self-consistent TDG scenario thus emerges which very naturally accounts for the properties of dE and satellite galaxies;

(2) no consistent, and in fact a contradictory picture emerges in the dark-matter framework;

(3) there is simply no evidence for the existence of DM satellites.
Actually,

every prediction of the standard cosmological model failed.

Some failures can be "resolved" by introducing unknown physics (Inflation, Dark Matter, Dark Energy) but on galaxy scales and beyond, failure remains the rule . . .

e.g. ● the disk-halo conspiracy remains unsolved;
    ● invariant disk galaxies;
    ● preponderance of disk galaxies without bulges;
    ● the likelihood of having a Local Group is \( < 5.6 \times 10^{-5} \).
# A comparison (galactic astrophysics)

<table>
<thead>
<tr>
<th>Problem at hand</th>
<th>Standard Model</th>
<th>MOND</th>
</tr>
</thead>
<tbody>
<tr>
<td>irregular dSph morphology</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>dSph dmass - luminosity relation (energy conservation)</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>phase-space correlation (Disk of Satellites)</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>bulge-mass vs satellite number correlation</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>too many tidal-dwarf galaxies due to hierarchical formation</td>
<td>X</td>
<td>?</td>
</tr>
<tr>
<td>invariant baryonic galaxies</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>Local Volume of galaxies</td>
<td>X</td>
<td>?</td>
</tr>
<tr>
<td>&quot;missing mass&quot; in young tidal dwarf galaxies</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>surface density of dark matter / baryonic matter = constant</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td><strong>PLUS</strong> (not covered here)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>core/cusp problem</td>
<td>X</td>
<td>✓</td>
</tr>
<tr>
<td>many bulge-less disk galaxies</td>
<td>X</td>
<td>?</td>
</tr>
<tr>
<td>missing satellite problem</td>
<td>X</td>
<td>?</td>
</tr>
<tr>
<td>downsizing</td>
<td>X</td>
<td>?</td>
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Pavel Kroupa: AIfA, University of Bonn
Therefore,
The real physical world is non-Einsteinian/Newtonian in the weak-field limit.
Remember this slide?
Remember this slide?

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Beauty or even "high-precision" of a model can misguide.
Step I: A convincing beautiful model (the standard model)
The *LCDM* model based on Einstein (1915).

Step II: Making the theory fit
Add *inflation, DM, DE* to achieve high precision

**=> excellent description of the data.**

Step III: An alternative model (the exotic model)
*MOND* by Milgrom (1983) and
*MOG* by Moffat (2005).

*Not accepted*: more complex and unsatisfying.
It needs *dark matter* and does *not fit* the data well.

Step IV: Decision by technological advance

*Local Group telescope data disprove the standard model,*
but are consistent with non-Einsteinian/Newtonian dynamics.

Step V: Conclusions

It is irrelevant to debate whether the LCMD model fits any data.
Beauty or even "high-precision" of a model can misguide.
It is therefore *irrelevant* to argue whether

*the CMB*

or

*large-scale structure*

are consistent with the

LCDM model
The relevant issue now is:

what are MOND or MOG etc. telling us about space/time and inertial mass?
I think, this is where we are seeing new physics worthy of exploration.
It is a pleasure to welcome to this debate:

Prof. R.H. (Bob) Sanders (Groningen)

Prof. Gerhardt Hensler (Vienna)

Prof. Tom Shanks (Durham)

Dark Matter and MOND

Star formation in galaxies, chemo-dynamical evolution

CMB, Dark Energy

Book on "The Dark Matter Problem",
Cambridge University Press, 2010

Pavel Kroupa: AlffA, University of Bonn
The new baryonic structure formation scenario

(Metz / Kroupa et al. 2010)

(see also Combes & Pfenniger 1997, A&A; Nieuwnhuizen, Schild & Gibson 2010, submitted)
The END