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

Pavel Kroupa

Argelander-Institute for Astronomy

University of Bonn

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)

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

many astronomers not happy as computational model complex

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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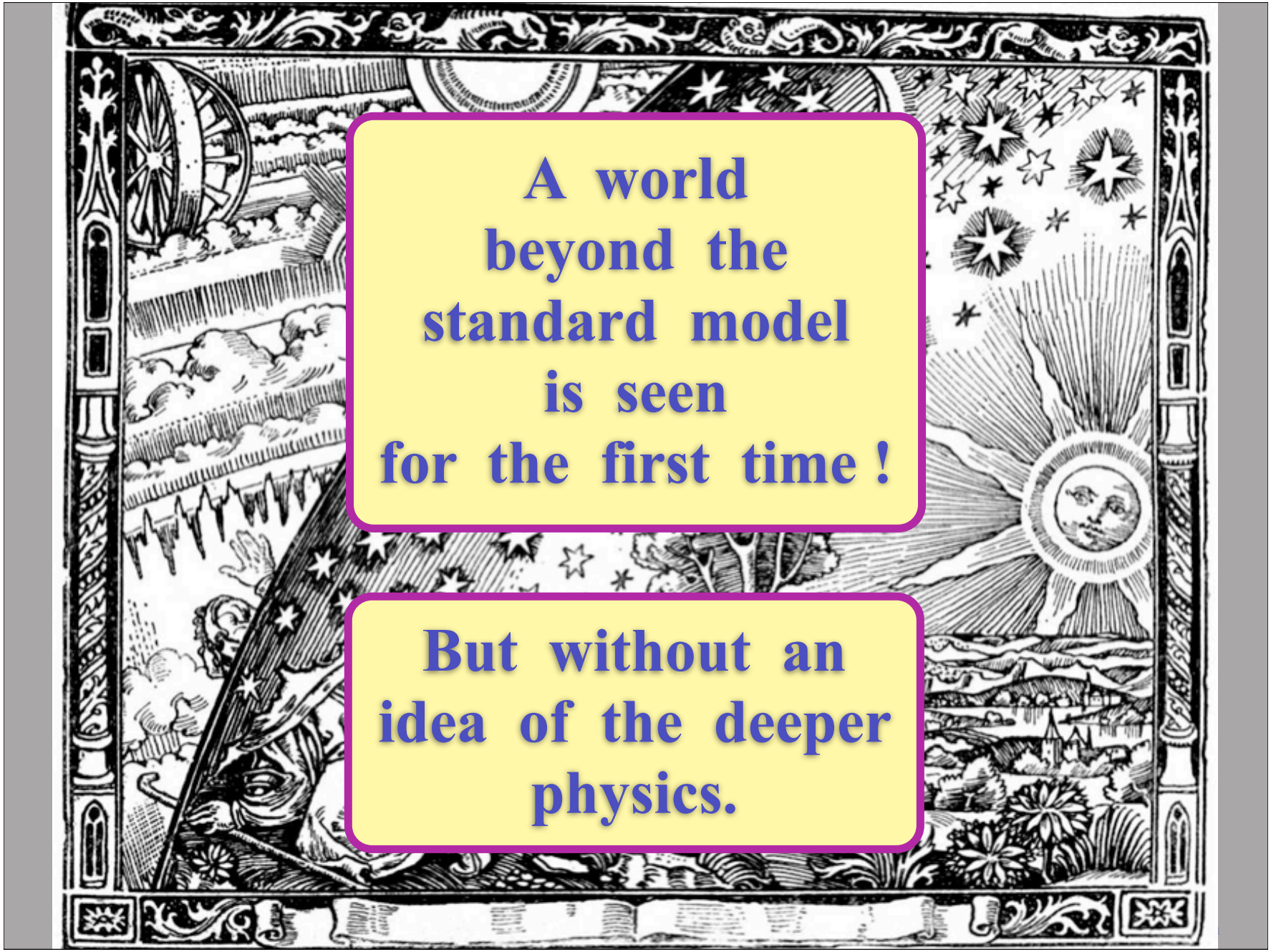
Step IV : Decision by technological advance

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!)

Must be valid here !!

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

MOND and structure formation and galaxies

Combes & Tiret 2009, arXiv:0908.3289 :

"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. "

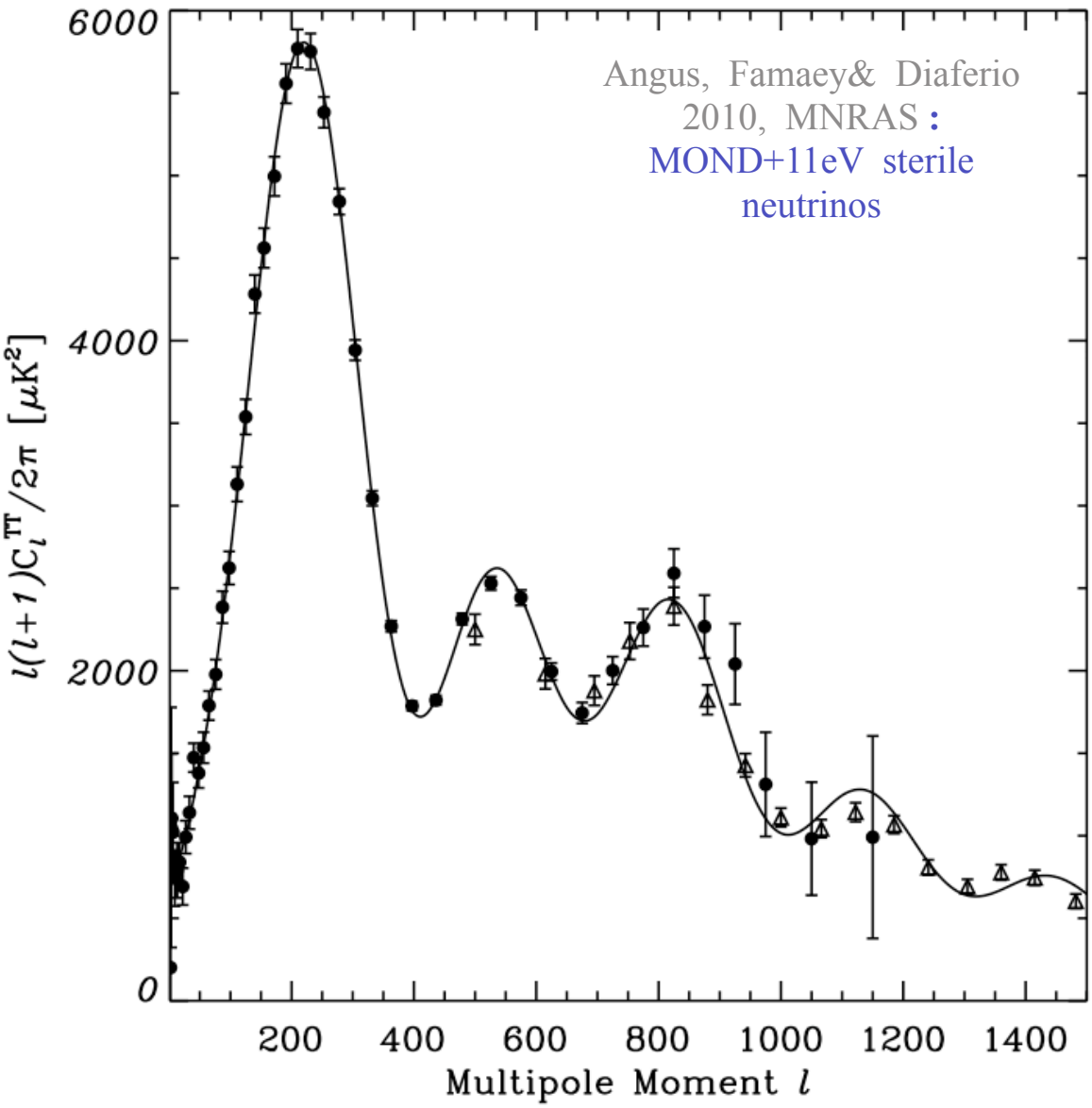
MOND and structure formation and galaxies

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 . . .

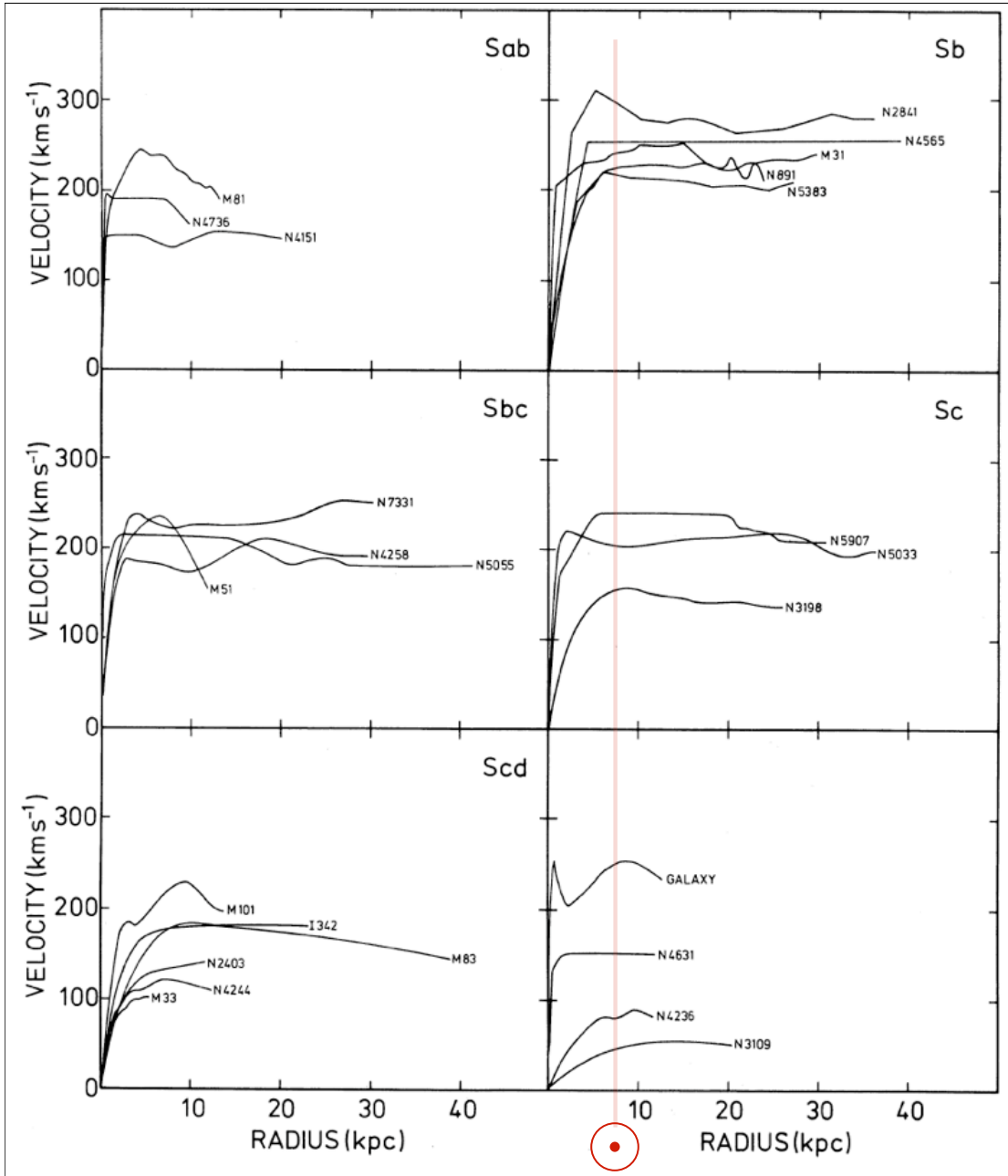


FIG. 3. Rotation curves of 25 galaxies of various Hubble types.

Bosma 1981

In the Conclusions :

"Perhaps a substantial fraction of the mass is not distributed in the disk at all."

→ Dark Matter is in a spheroidal halo

But

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

But, flat rotation curves
are explained
much better
by
non-Einsteinian / Newtonian gravity **:**

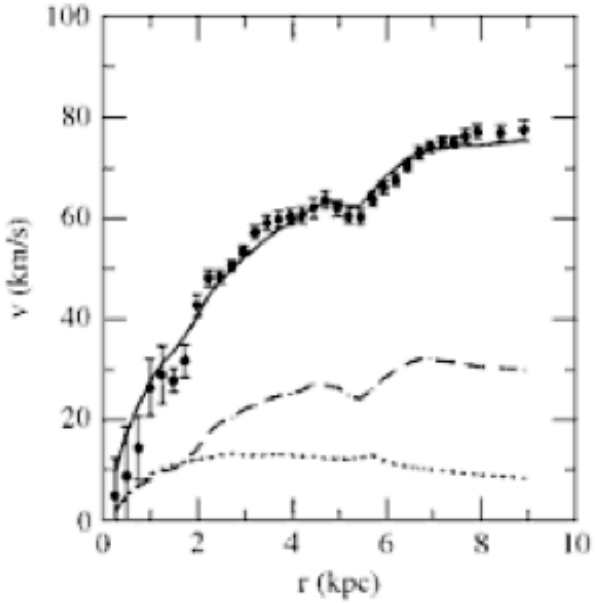
For example **:**

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

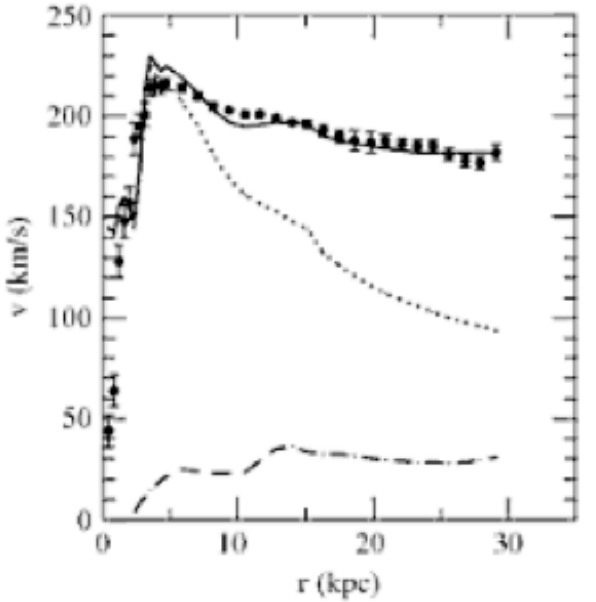
cannot be predicted using LCDM.



NGC 1560

<SB> = 12 $L_\odot$ / pc^2

$(M/L_B)_{disk}$ = 0.4



NGC 2903

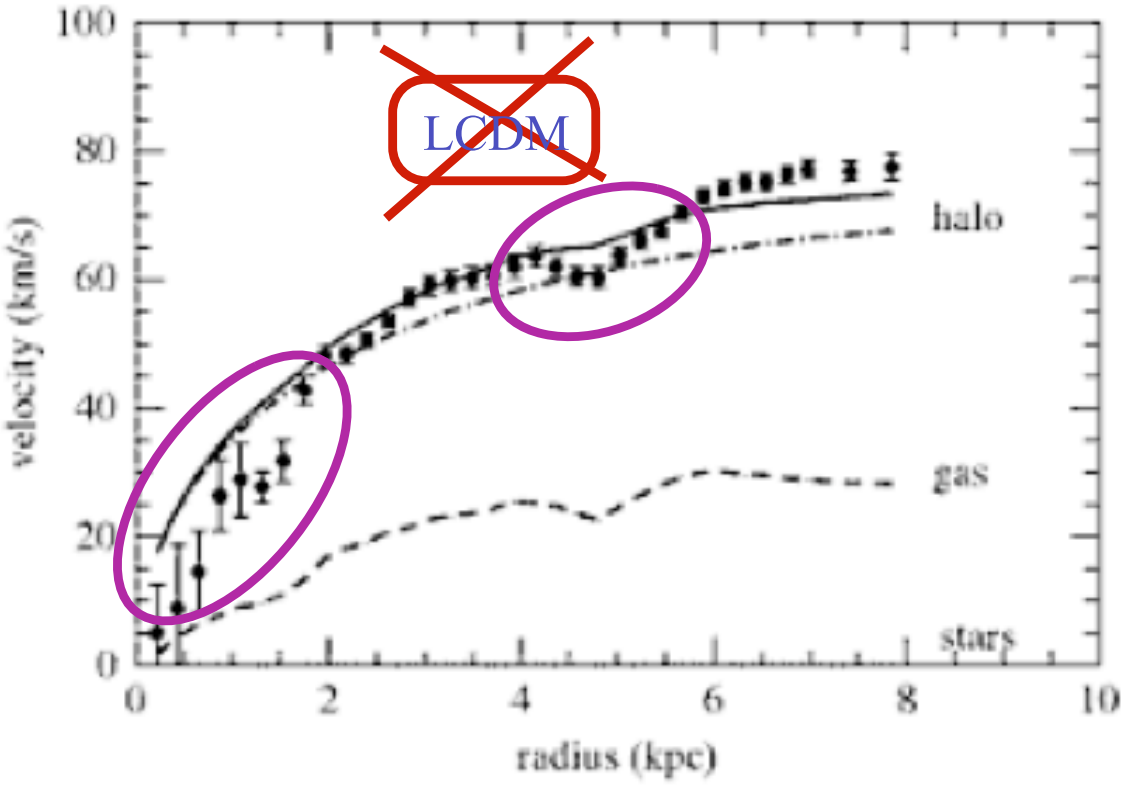
<SB> = 114 $L_\odot$ / pc^2

$(M/L_B)_{disk}$ = 1.9

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

-Bond, Szalay & Turner 1982, Phys. Rev. Lett.
-Blumenthal, Pagels & Primack 1982, Nature
-Peebles 1982, ApJL
-Blumenthal, Faber, Primack, Rees, 1984, Nature

(II)

1983
Suggestion of a modification of Newton's force law

MOND
MOG

-Milgrom 1983, ApJ
-Moffat 2005, JCAP

Progress is always linked to

cultural pre-disposition

and

Sociology

→ Fanelli D. (2010) Do Pressures to Publish Increase Scientists' Bias? An Empirical Support from US States Data. PLoS ONE 5(4): e10271. doi:10.1371/journal.pone.0010271

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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No Go !!

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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 :

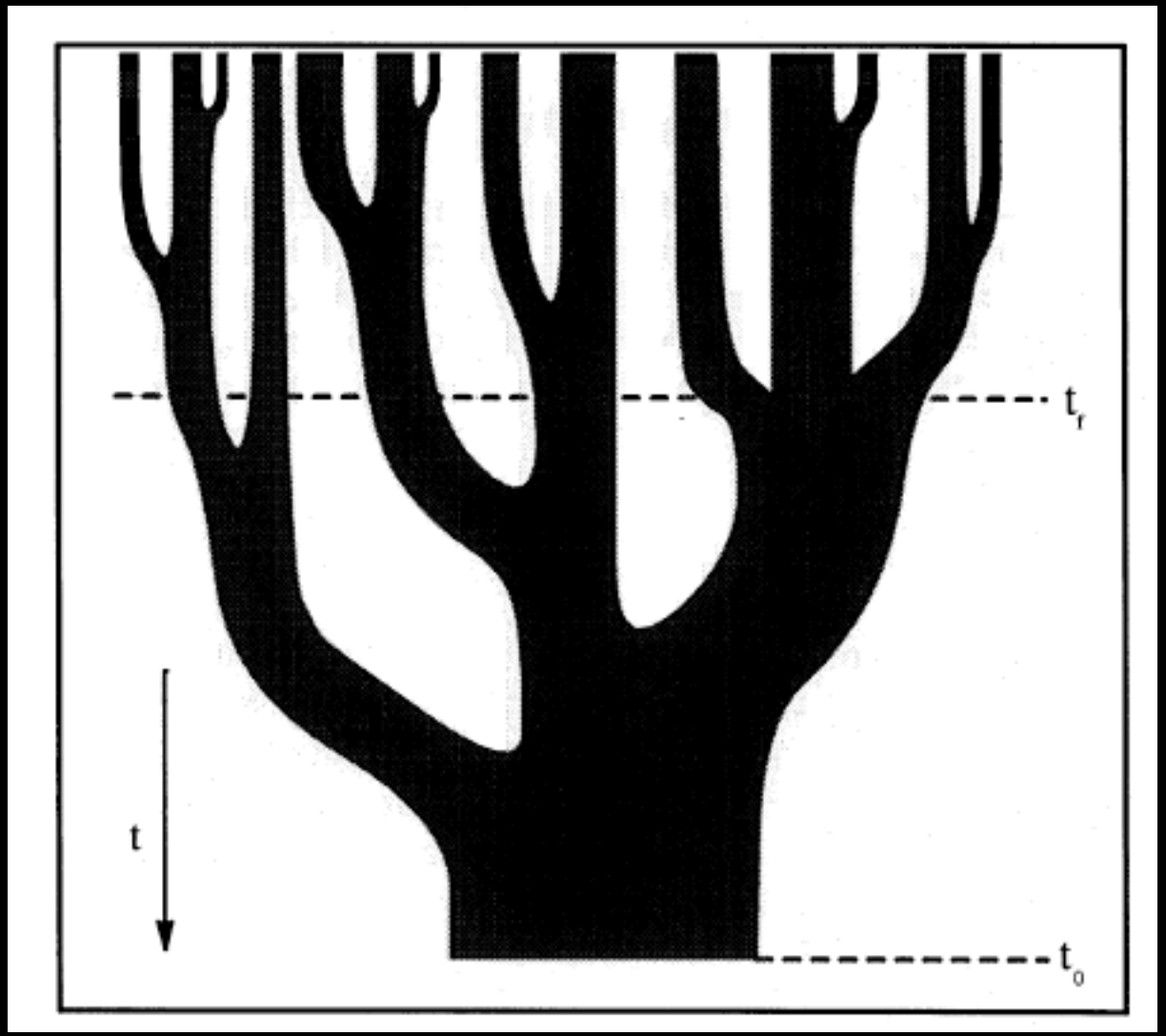
1. Zwicky (1937) **:** There must be dark matter.

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

Both have to be true **!**

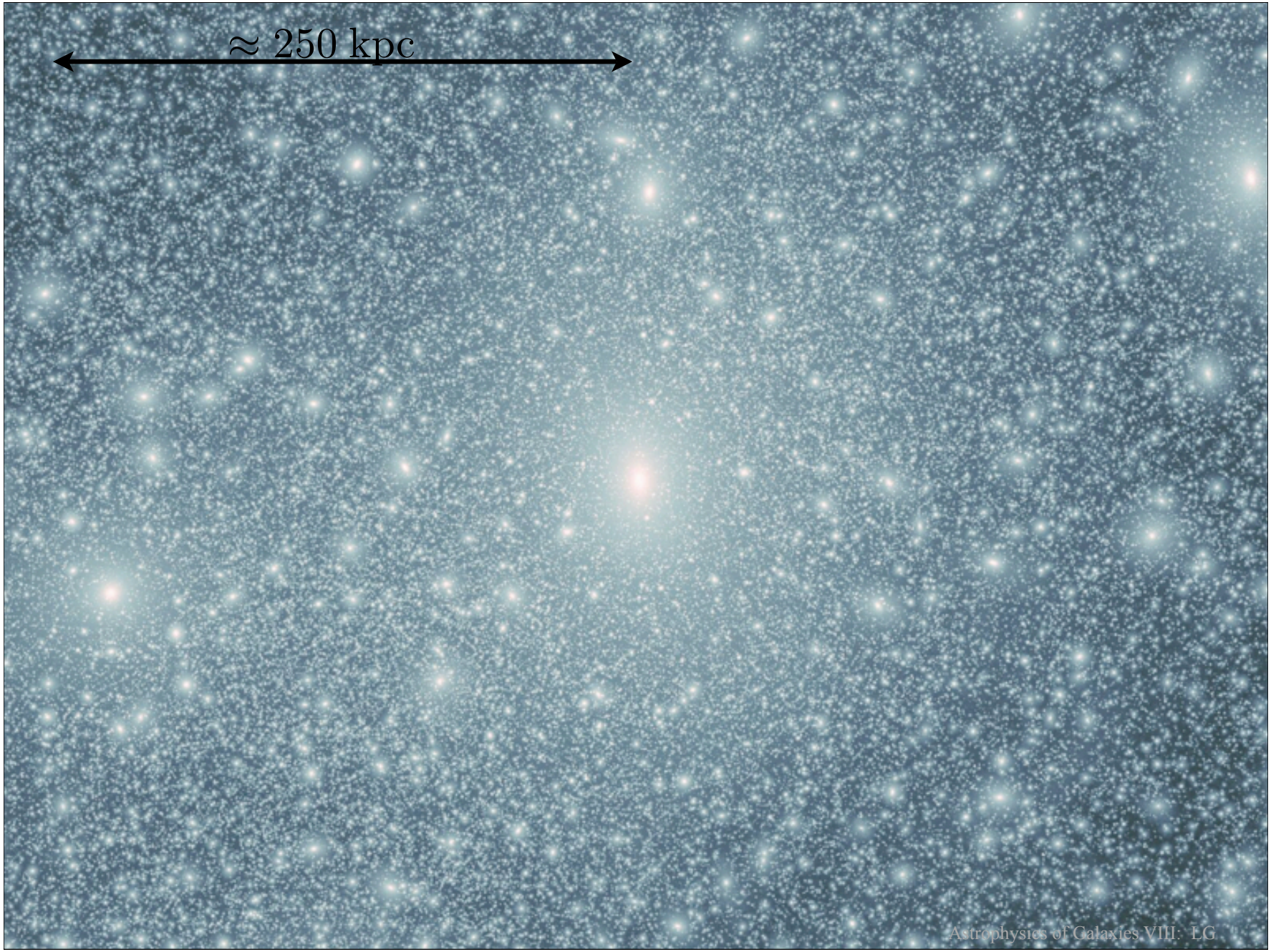
Structures form according to the cosmological merger tree

Lacey & Cole (1993)



the beginning

today


≈ 250 kpc

This has two immediate implications :

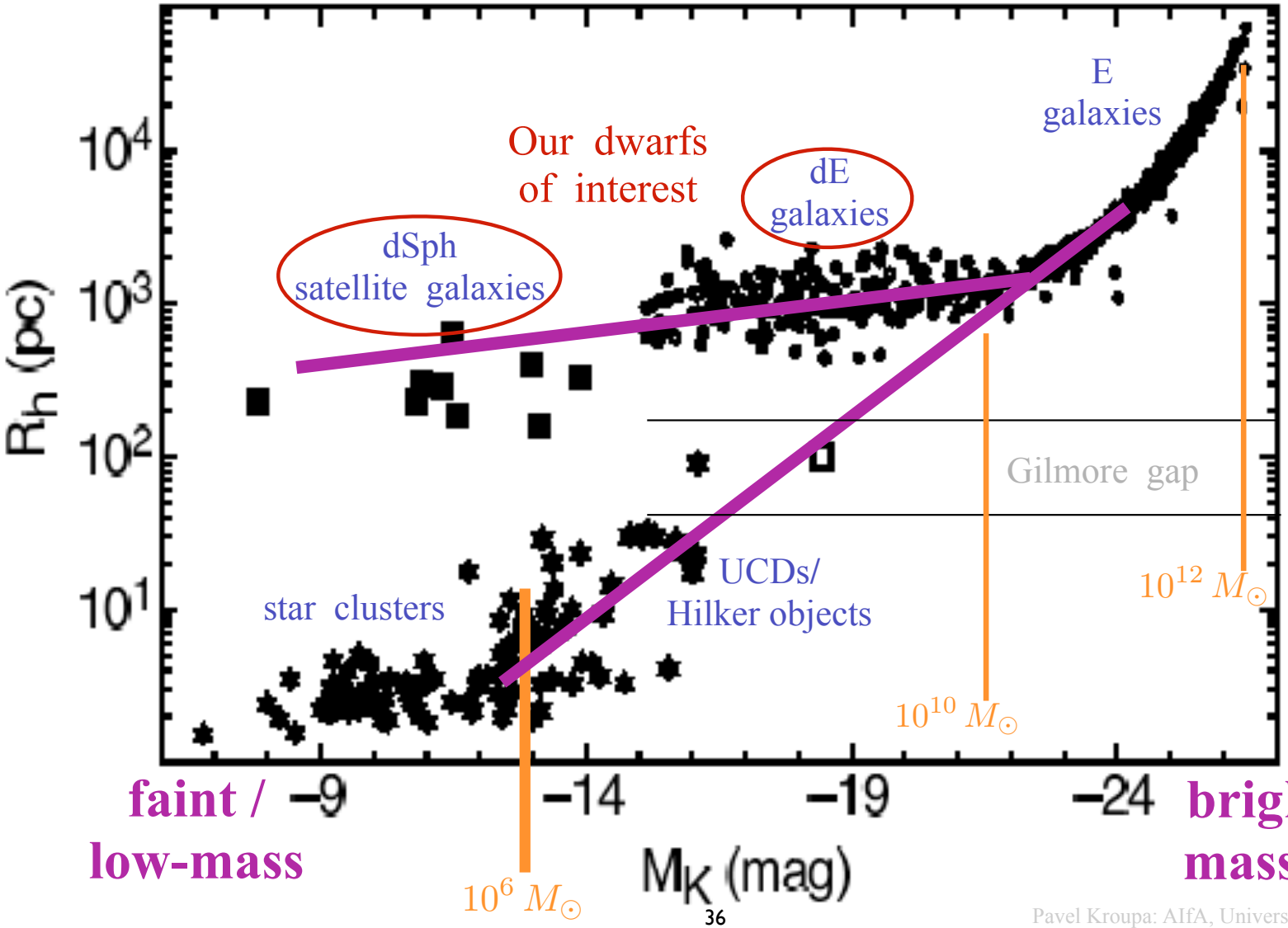
1. There exist large numbers of *dark-matter dominated satellite galaxies.*

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



Pavel Kroupa: AIfA, University of Bonn

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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 **?**

Lets consider first the *dark-matter type satellite* dwarf galaxy :

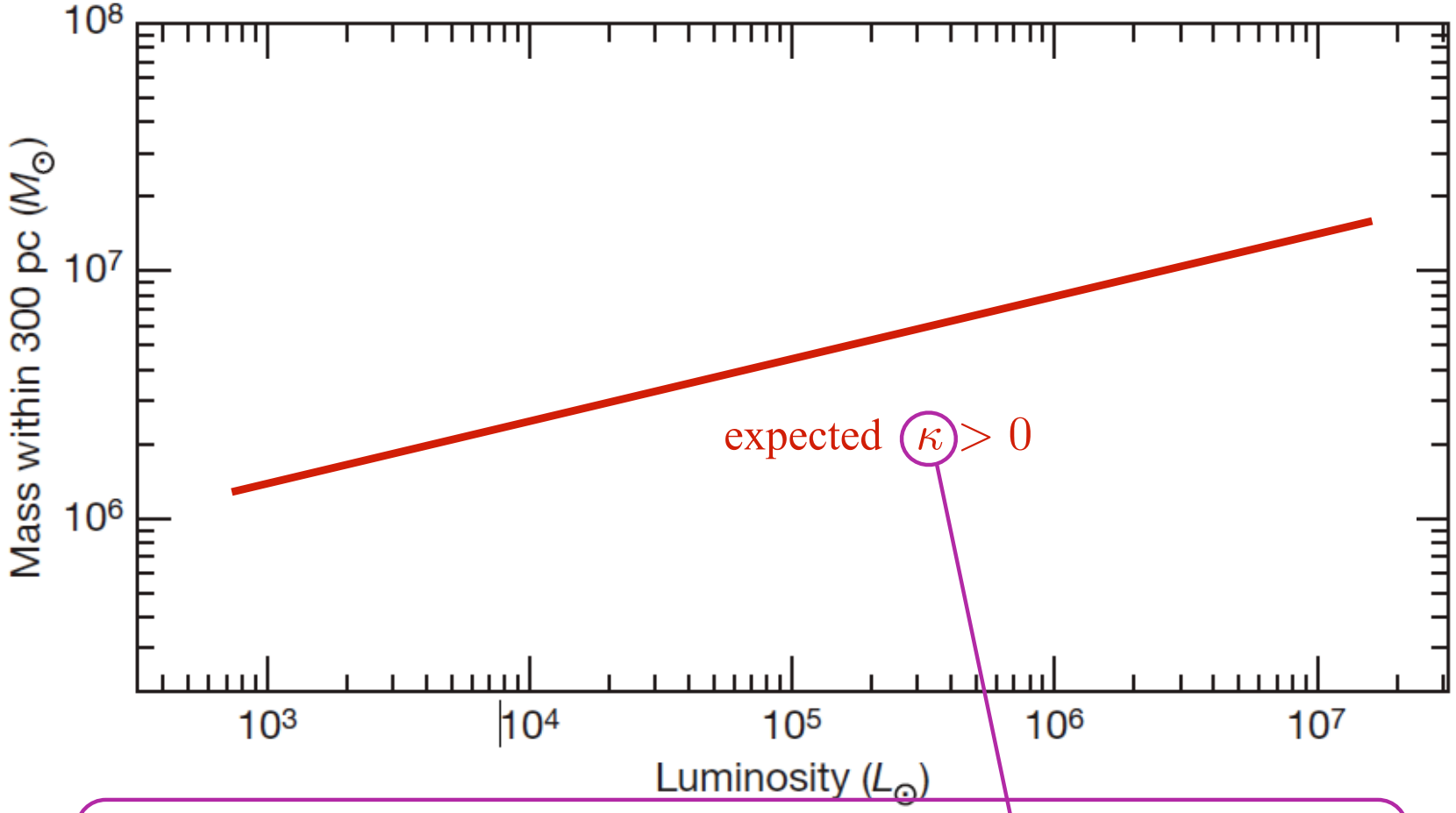
A *vast* amount of theoretical research
has been done by
countless LCDM research groups
with the aim of
explaining the observed satellite galaxy
population *naturally* in LCDM.

. . . they all claim success

The DM mass-luminosity relation :

more gravitating mass,
more luminous mass ?

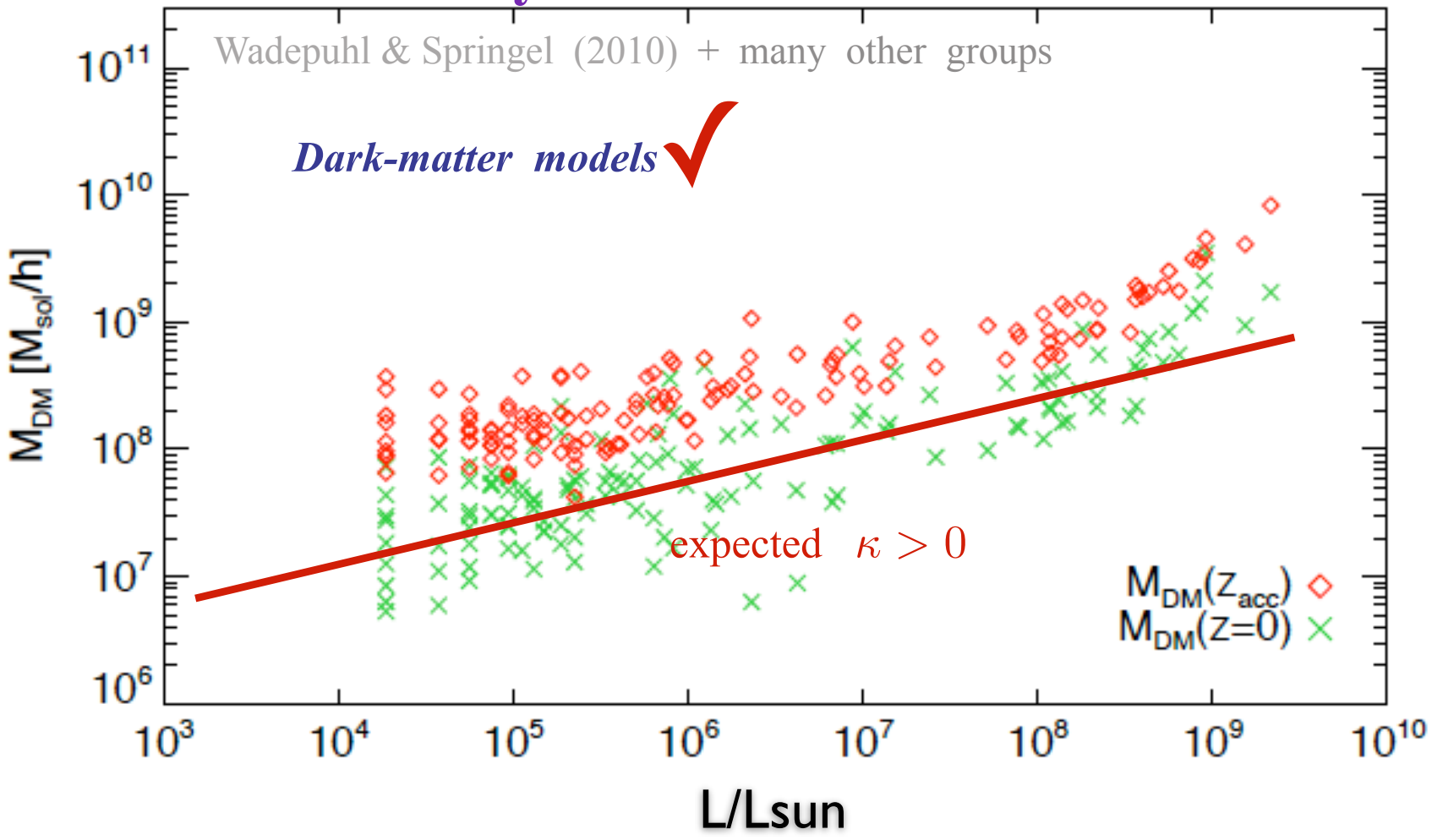
The DM mass - luminosity relation of satellite galaxies



$$\log_{20}(M_{0.3\,\mathrm{kpc}}/M_\odot) = \log_{10}(M_{03}/M_\odot) + \kappa \log_{10}(L_V/L_{V,\odot})$$

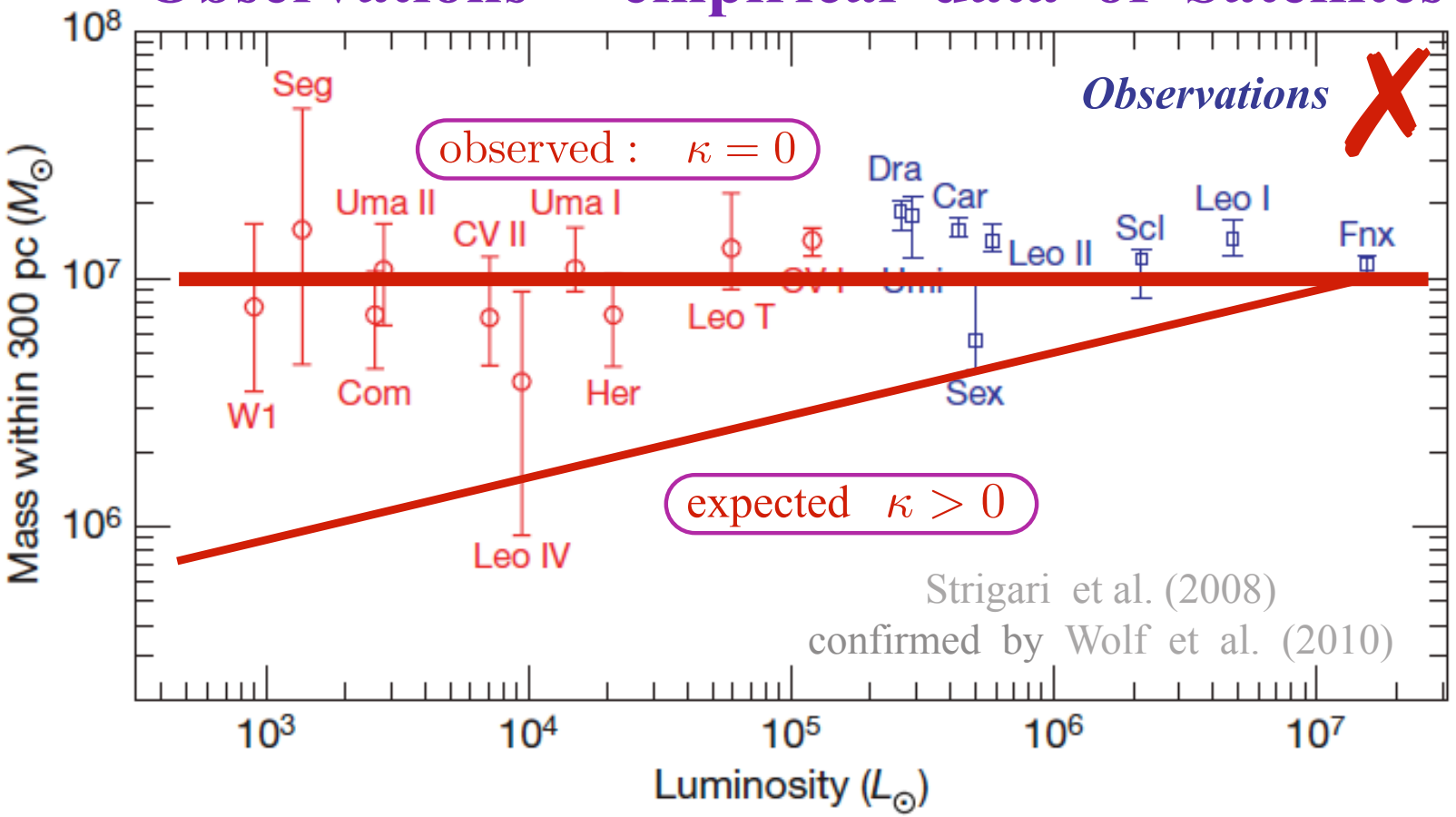
The DM mass - luminosity relation of satellite galaxies

Theory - Models of Satellites

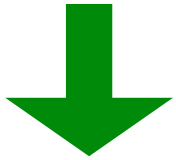


The DM mass - luminosity relation of satellite galaxies

Observations - empirical data of Satellites



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:

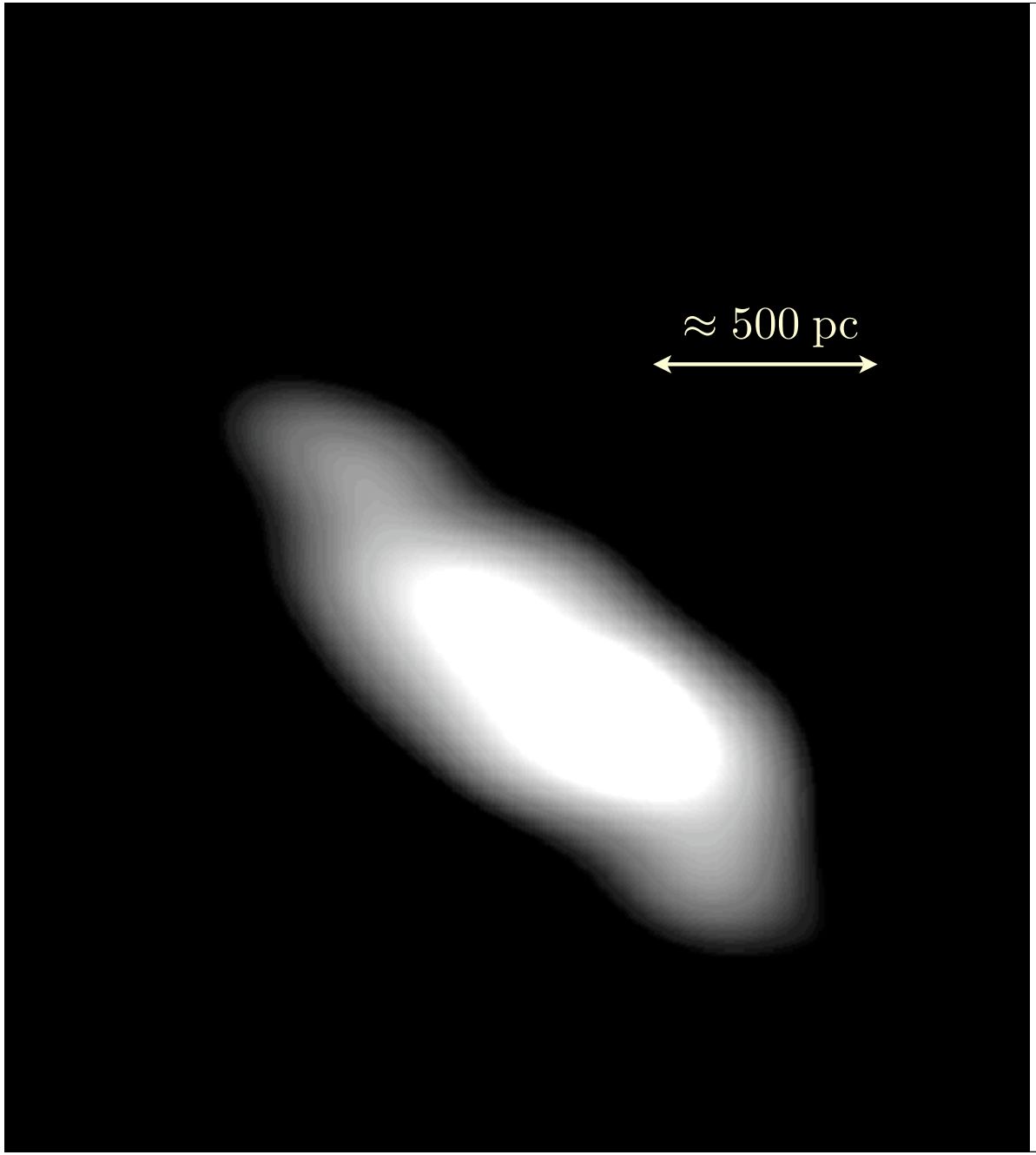
smooth luminous morphology?

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 σ is really due to a DM halo, unless it has a harmonic core.

consistent with DM halo ?



UMi

D=65kpc

(Martinez-Delgado et al., in prep)

S shape **:**
strong evidence for extra-tidal stars

Massive CDM halo ?

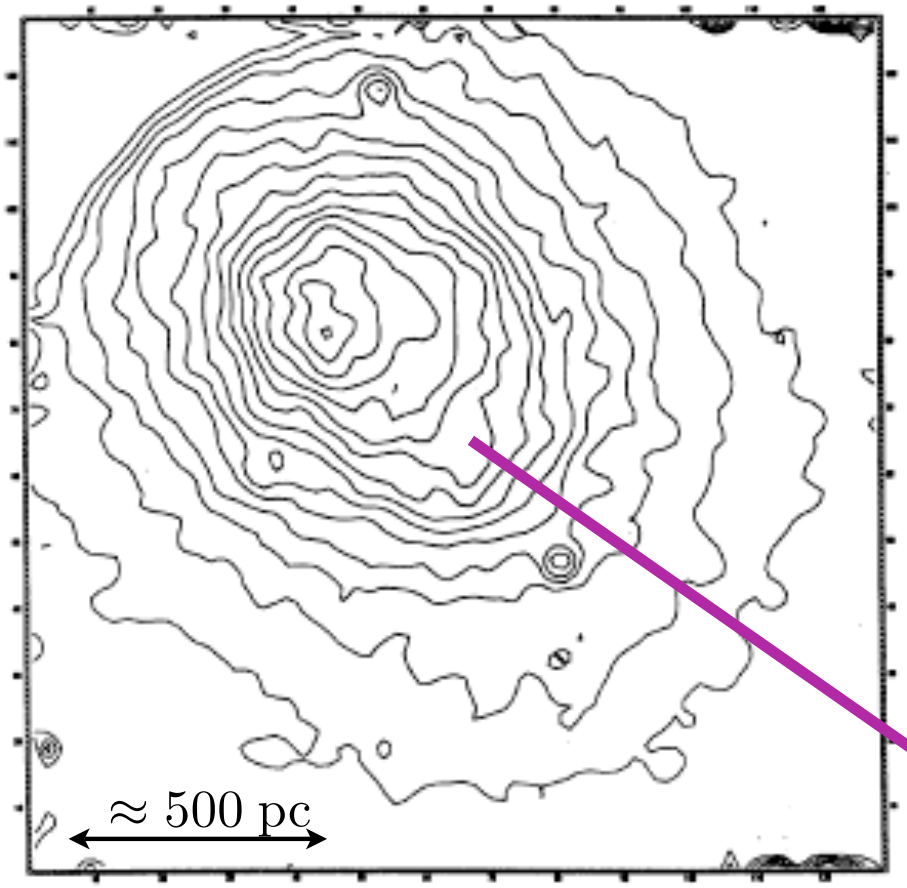


FIG. 4. Isophotes of equal stellar density of field 1 reveal that the structure of Fornax, near the center, is not symmetric.

Fornax

D=140kpc

(Demers et al. 1994)

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

$$\left(\frac{M}{L}\right)_{\mathrm{tot},\mathrm{V}} = 4.4$$

(Mateo 1998)

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

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.

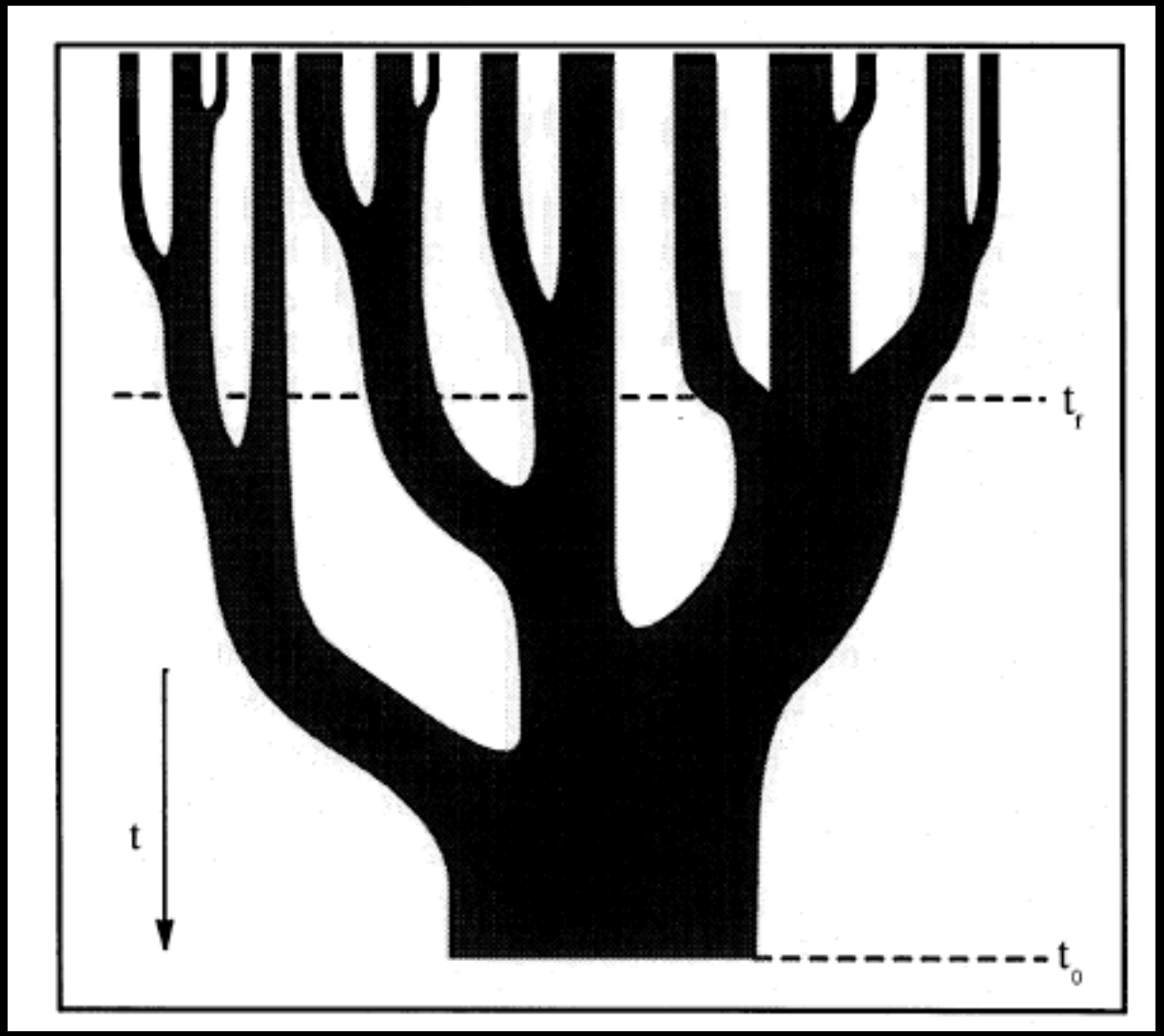
~~dark-matter halos~~

The spatial distribution of the MW satellites

. . . further clues

Structures form according to the cosmological merger tree

Lacey & Cole (1993)



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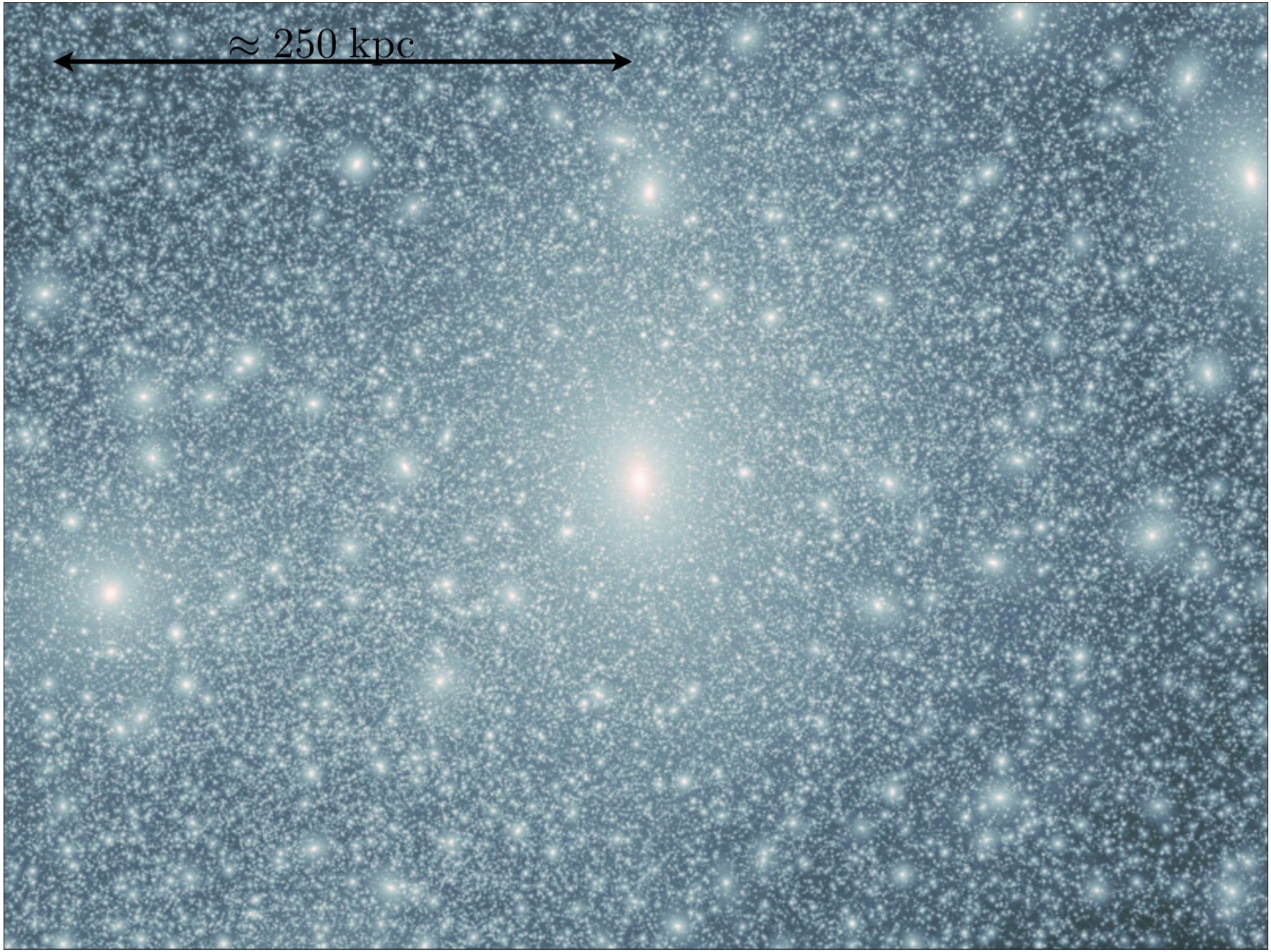
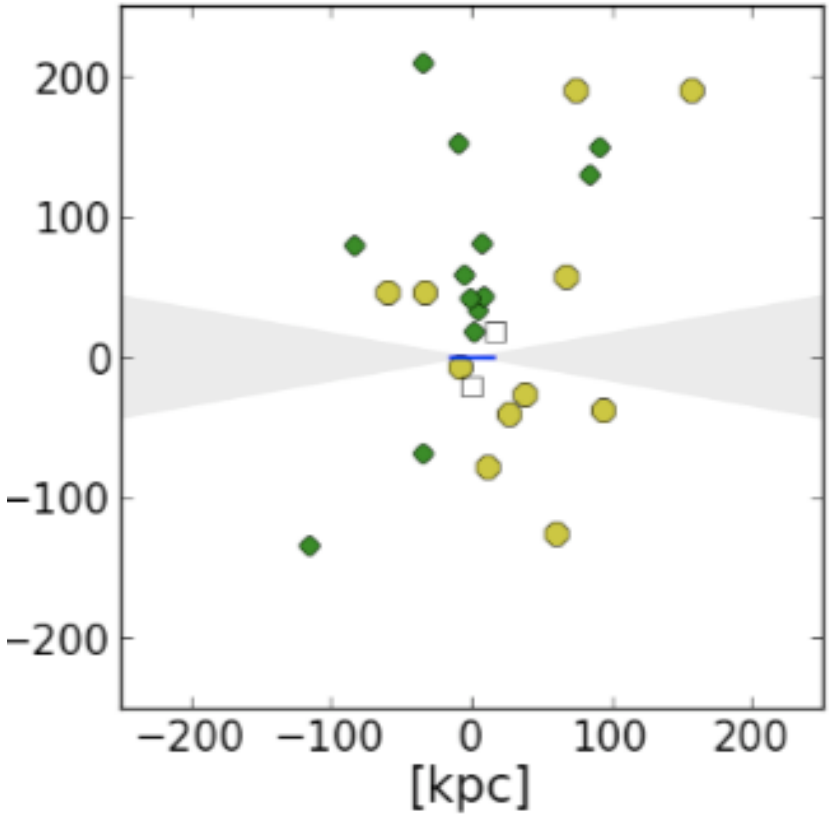

≈ 250 kpc

MW satellites are in a disk-like configuration:

- the 11 "classical" (brightest) satellites
- new satellites

Kroupa et al. (2010, A&A)



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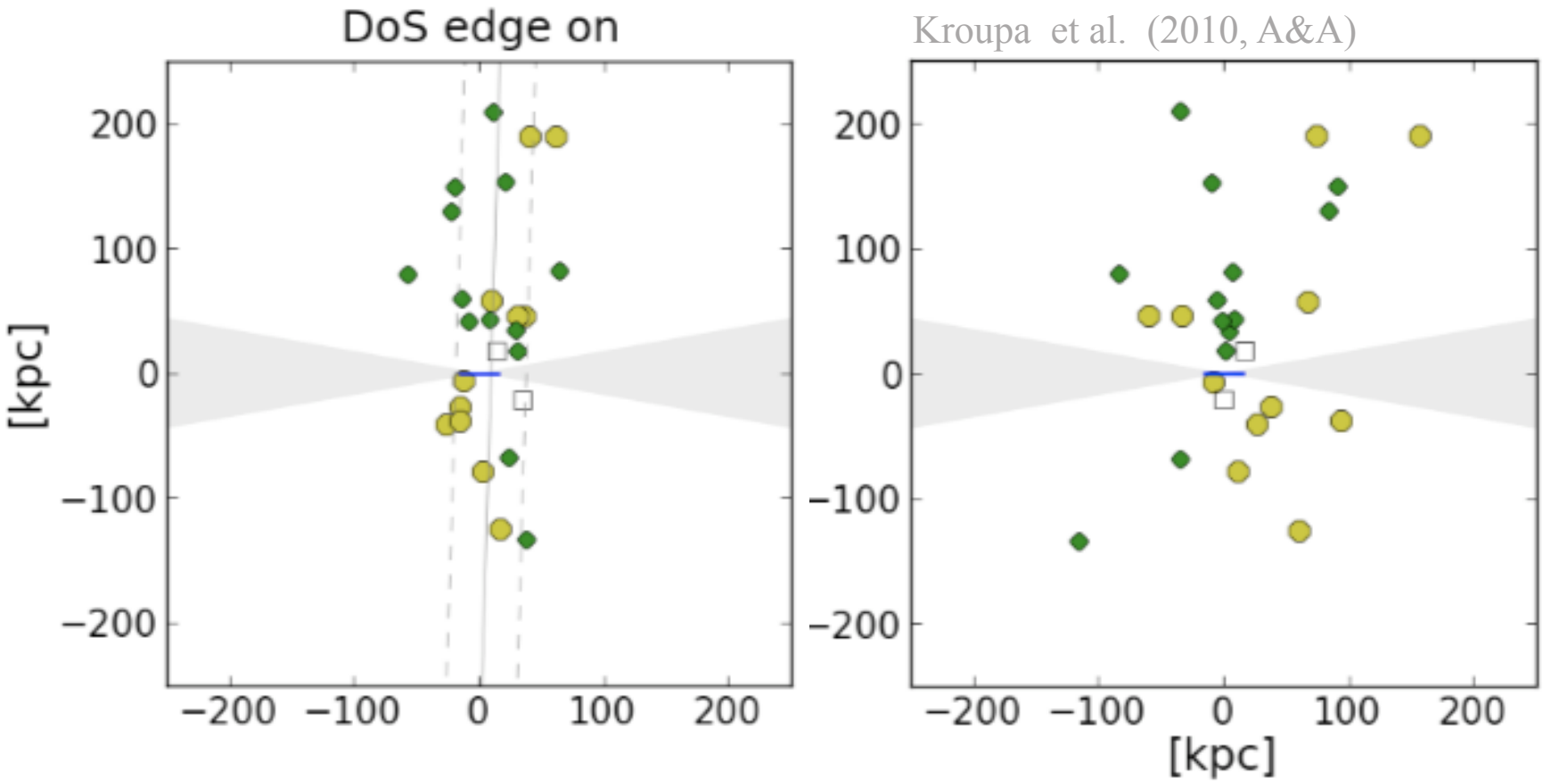
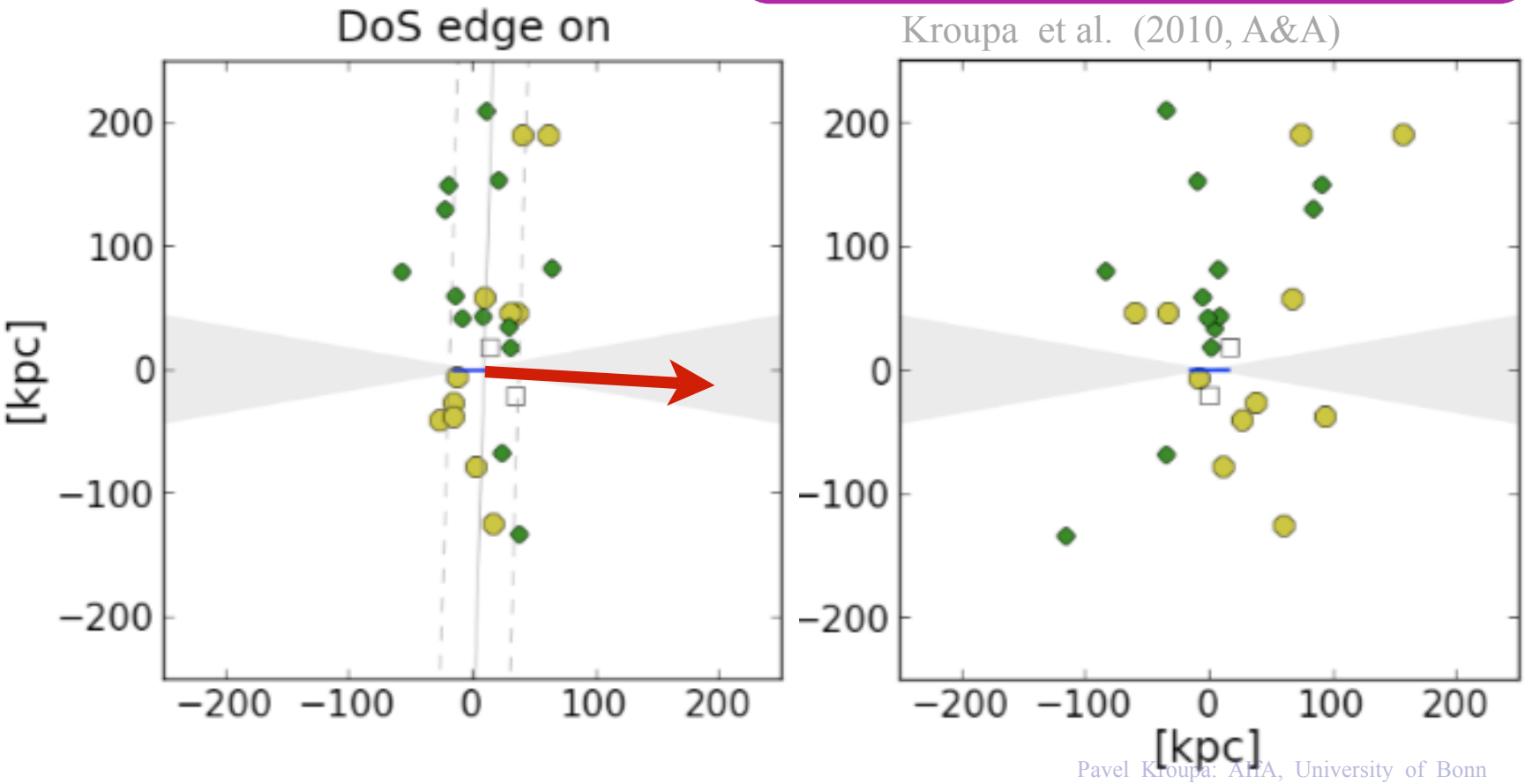


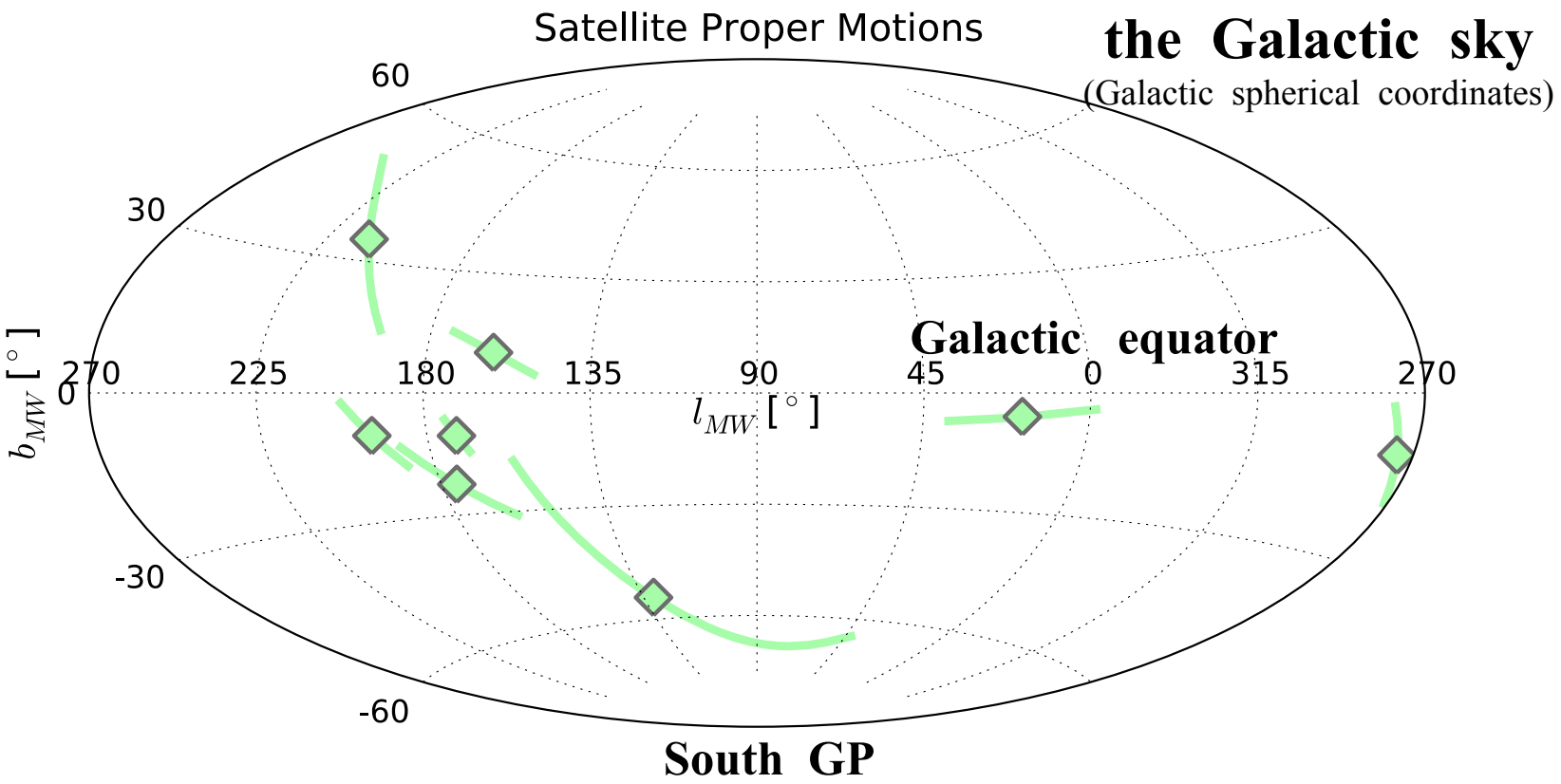
Disk of Satellites

a rotational structure ?

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



Directions of orbital angular momenta of MW satellites



Pawlowski et al. 2011

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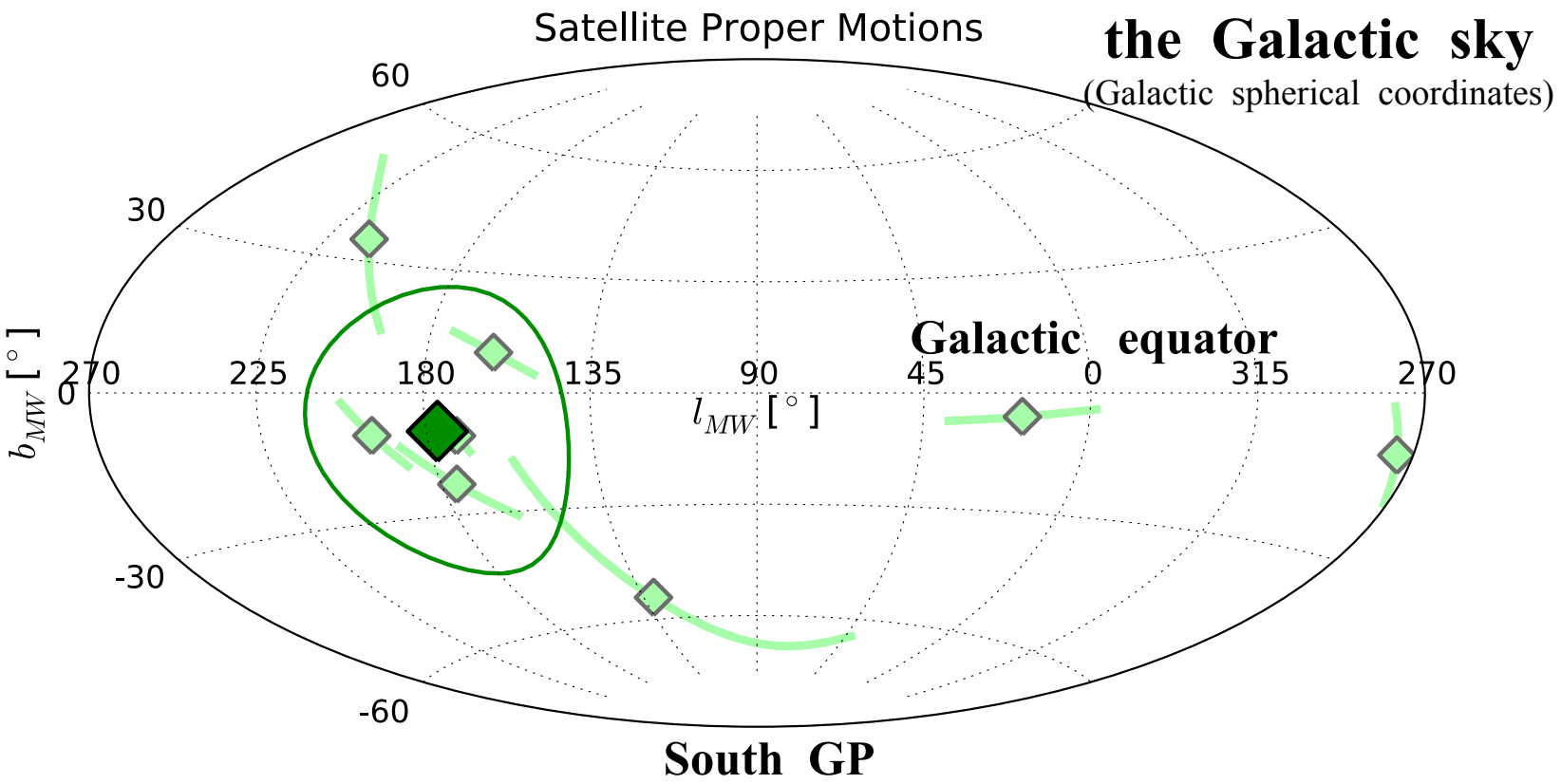

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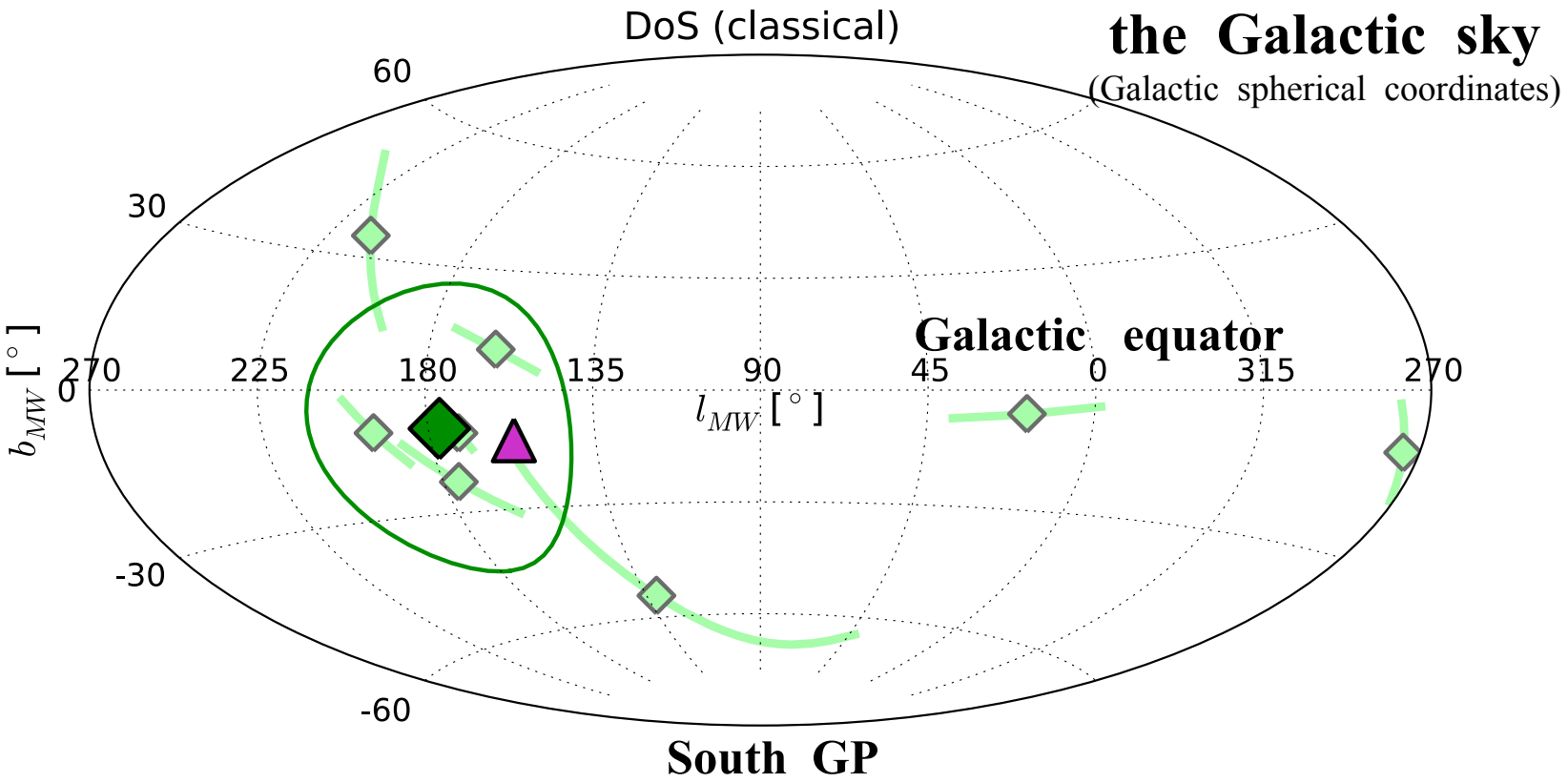

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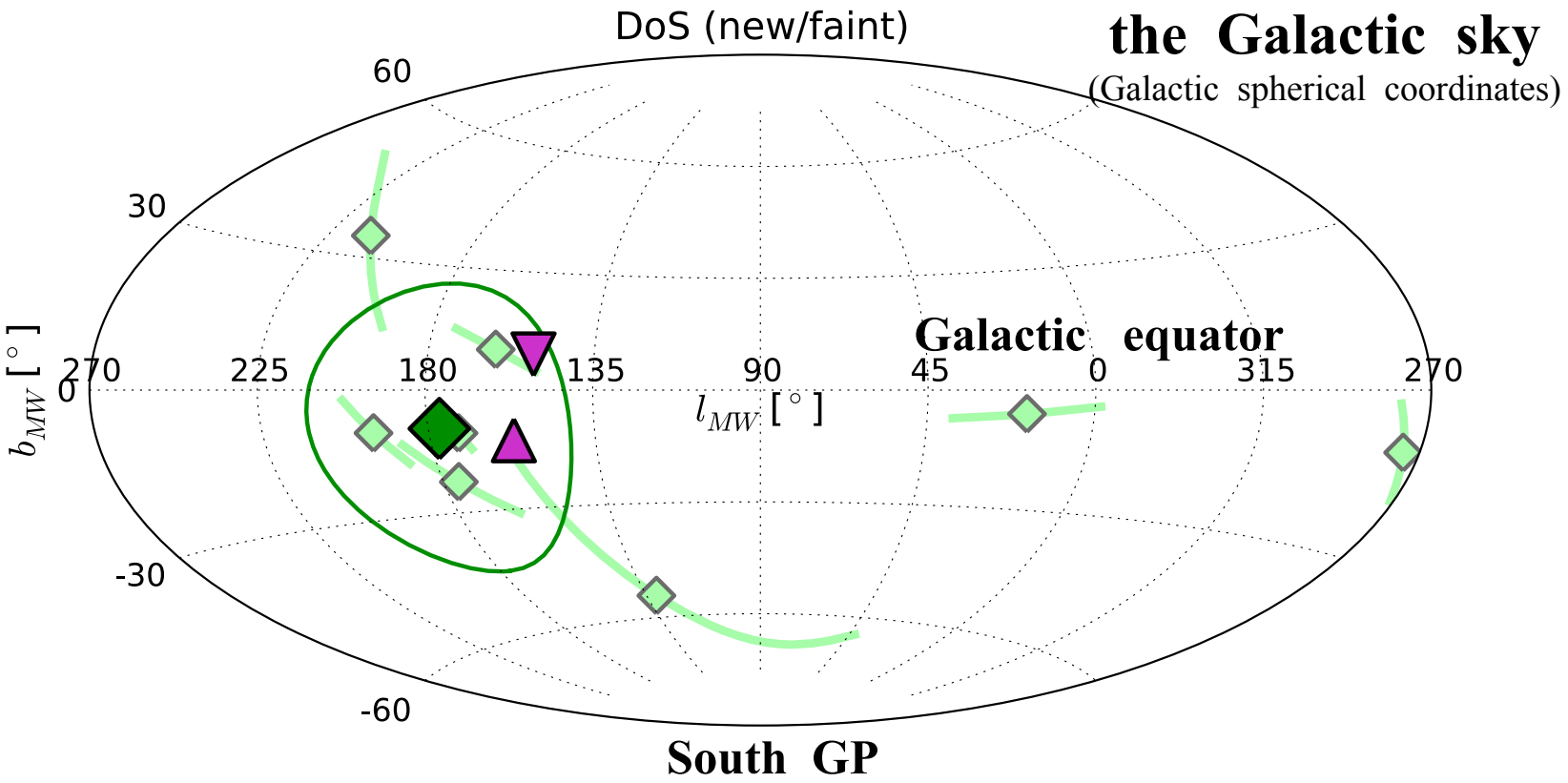

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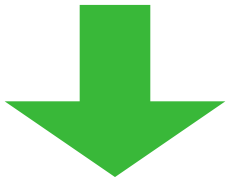


The MW satellite *DoS* is defined
mostly by the *outer satellites*;
but the *angular momenta* of the
inner satellites
are aligned to the pole of the DoS

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 ΛCDM 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 ΛCDM 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).

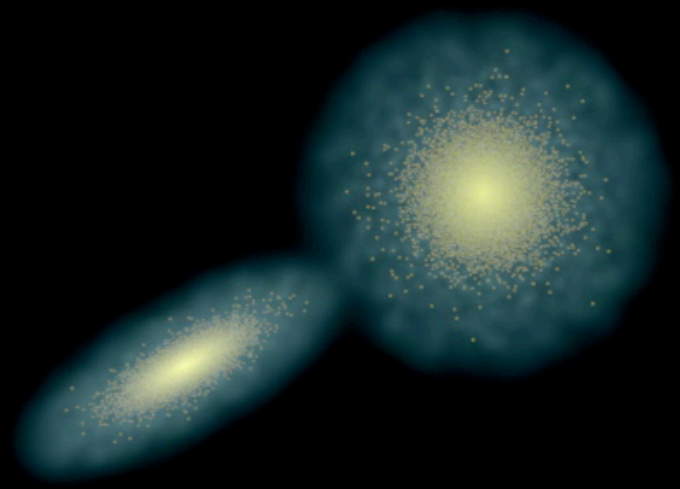
The dark-matter ansatz fails.

Lets 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

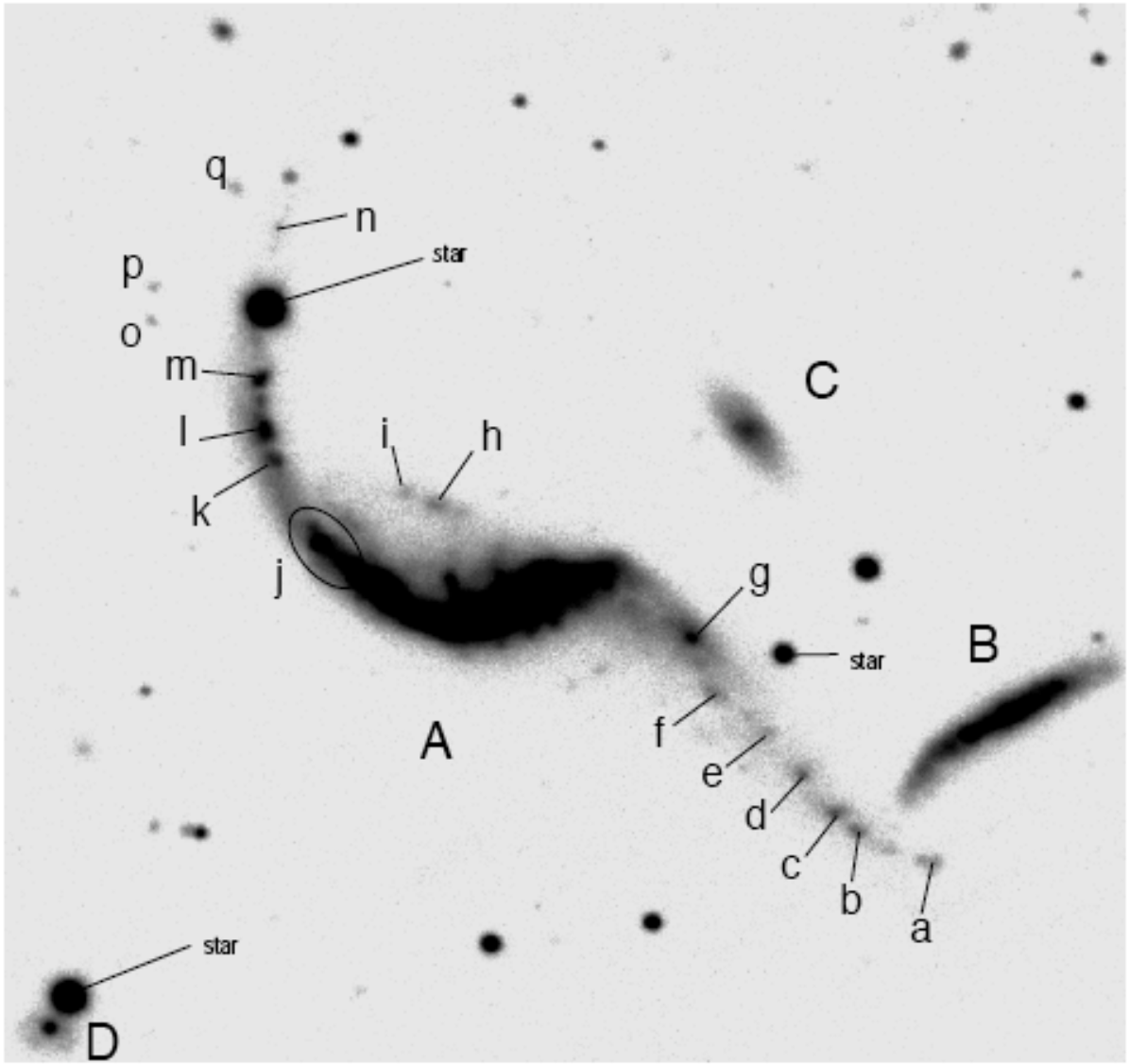


Fig. 21. Identification chart of field 10 around AM 1353-272.

(Weilbacher et al. 2000)

$$N_{\rm TDG} \approx 14$$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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


Evolve dwarf galaxies
w/o dark matter
in a computer
Pavel Kroupa: AIfA, University of Bonn

(Kroupa 1997)

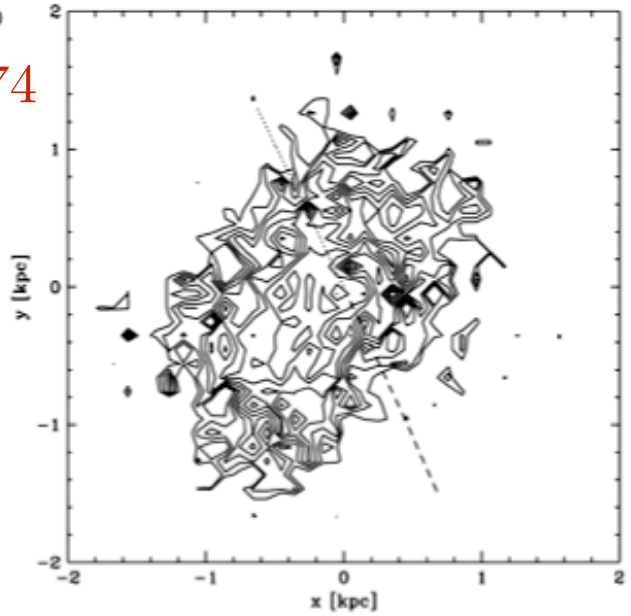
Remnants have a highly anisotropic $f(\mathbf{R}, V)$ and mass $\approx 10^5\ M_\odot$

$R \approx$ few 100 pc

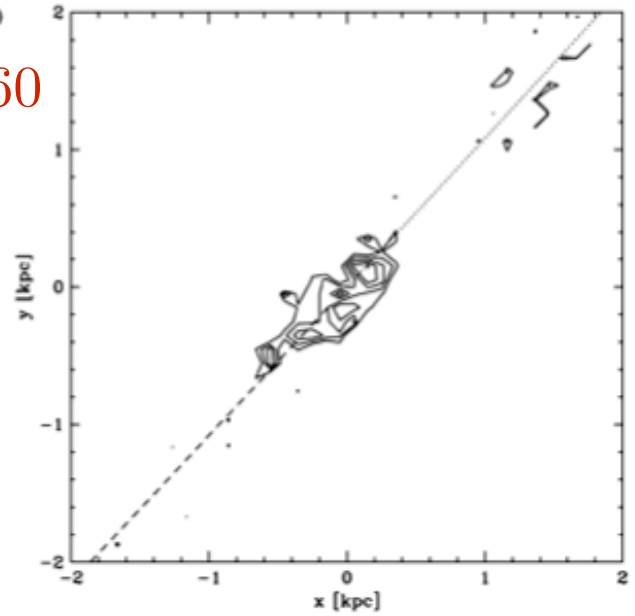
and $\frac{M}{L} \approx 10^{2-3}$!

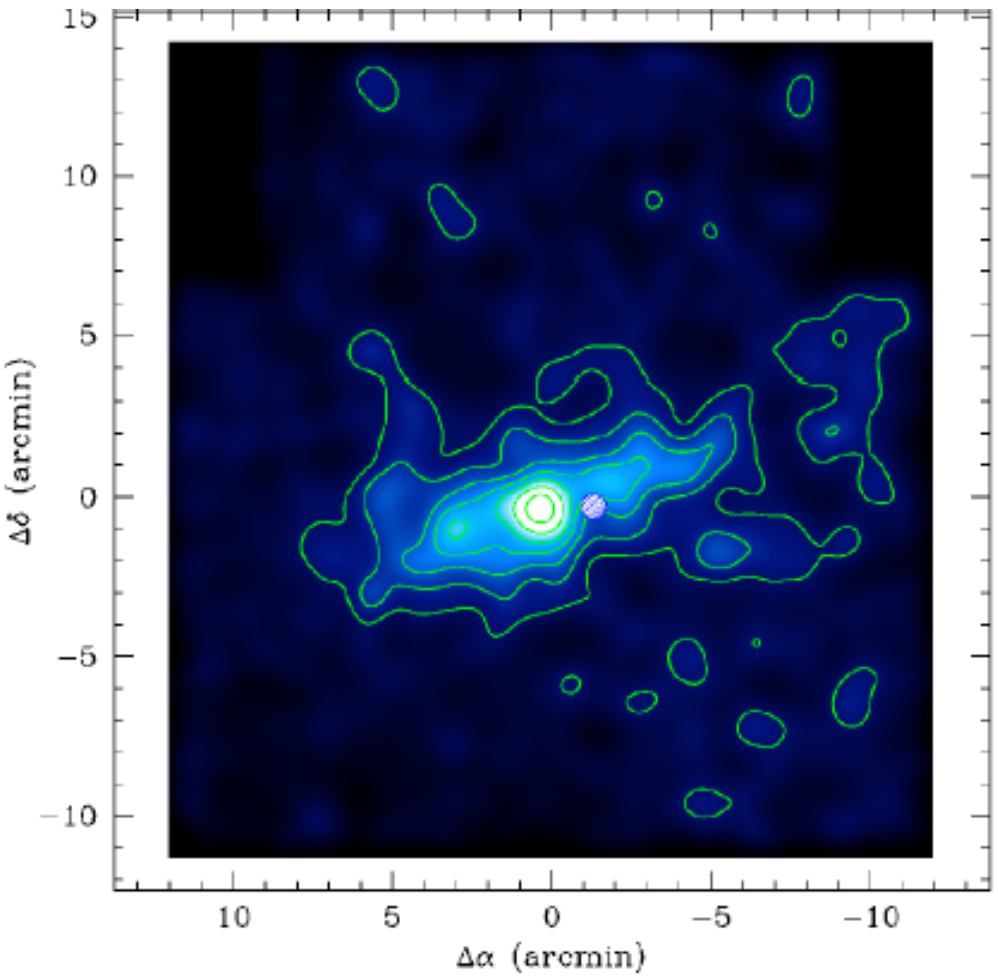
but no Dark Matter !

$e = 0.74$



$e = 0.60$





Hercules

D=130kpc

(Coleman et al. 2007)

TABLE 1
PROPERTIES OF THE HERCULES DSPH

Parameter	Value
R.A. (J2000)	16:31:02.0
Decl. (J2000)	12:47:29.6
$E(B-V)$ (mag)	0.055 ± 0.005^{a}
$(m-M)_0$ (mag)	20.6 ± 0.2
Distance (kpc)	132 ± 12
[Fe/H]	-2.1 ± 0.2
Age (Gyr)	13 ± 3
King r_h	$4.37' \pm 0.29'$ (168 ± 11 pc)
King r_c	$4.74' \pm 0.57'$ (182 ± 22 pc)
King r_t	$25.9' \pm 11.1'$ (994 ± 426 pc)
$c = \log(r_t/r_c)$	0.74 ± 0.25

Hercules

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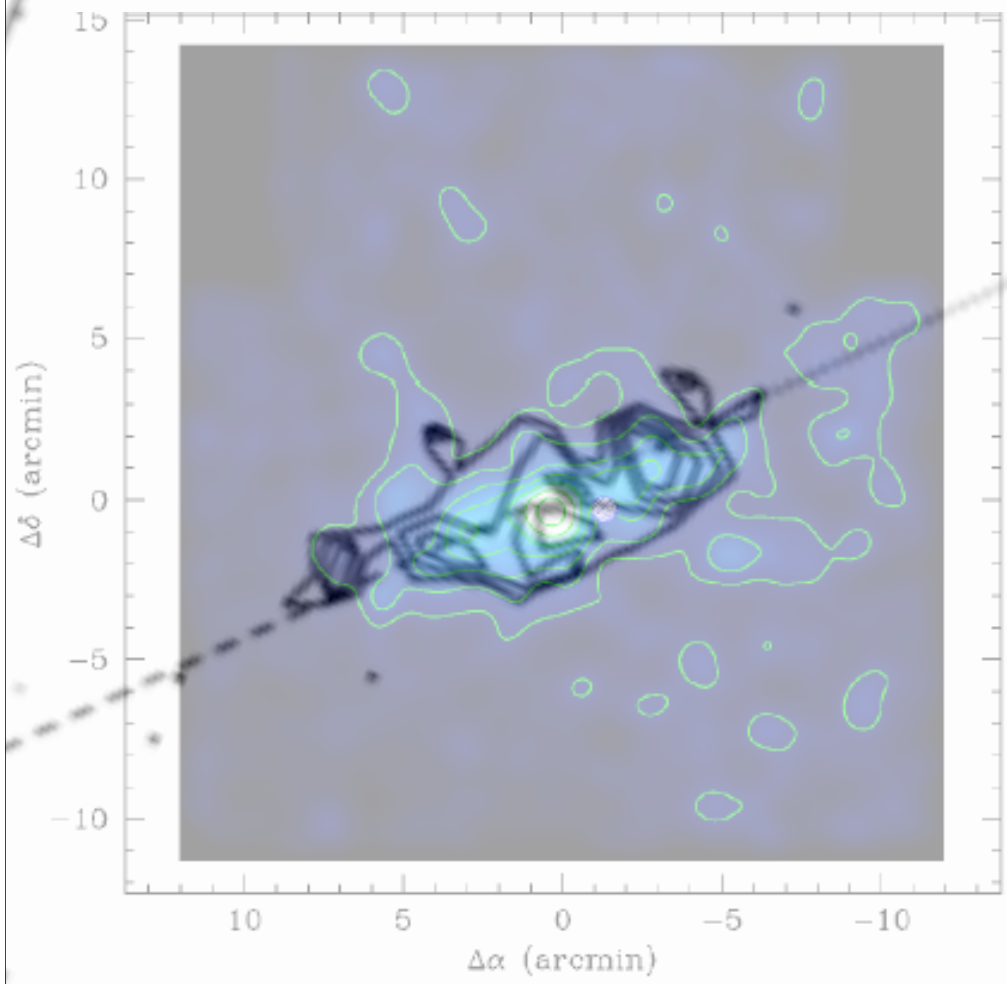
(Coleman et al. 2007)



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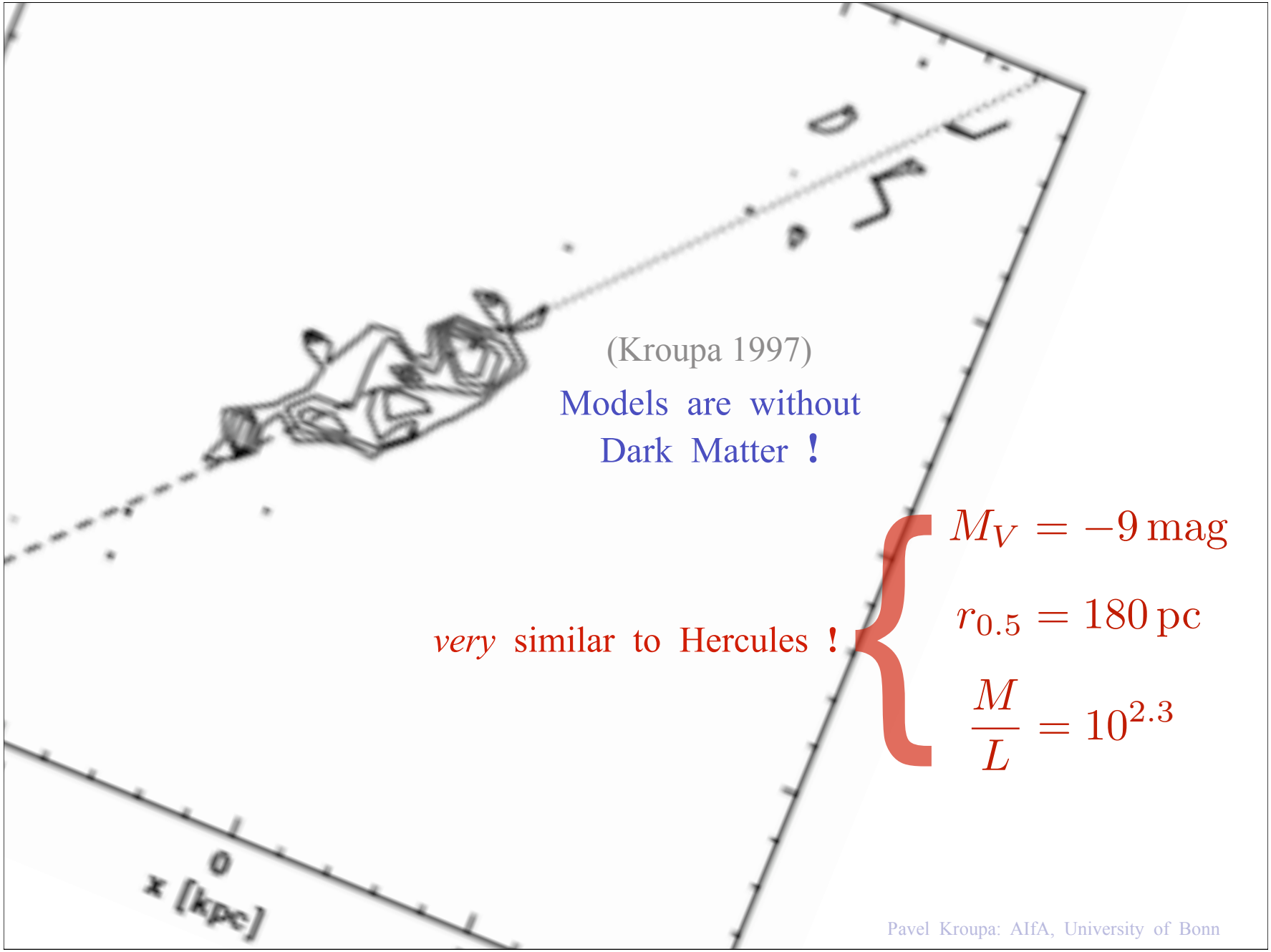
0
x [kpc]



(Kroupa 1997)

Models are without Dark Matter !

very similar to Hercules !

$$M_V = -9\,\mathrm{mag}$$

$$r_{0.5} = 180\,\mathrm{pc}$$

$$\frac{M}{L} = 10^{2.3}$$

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)

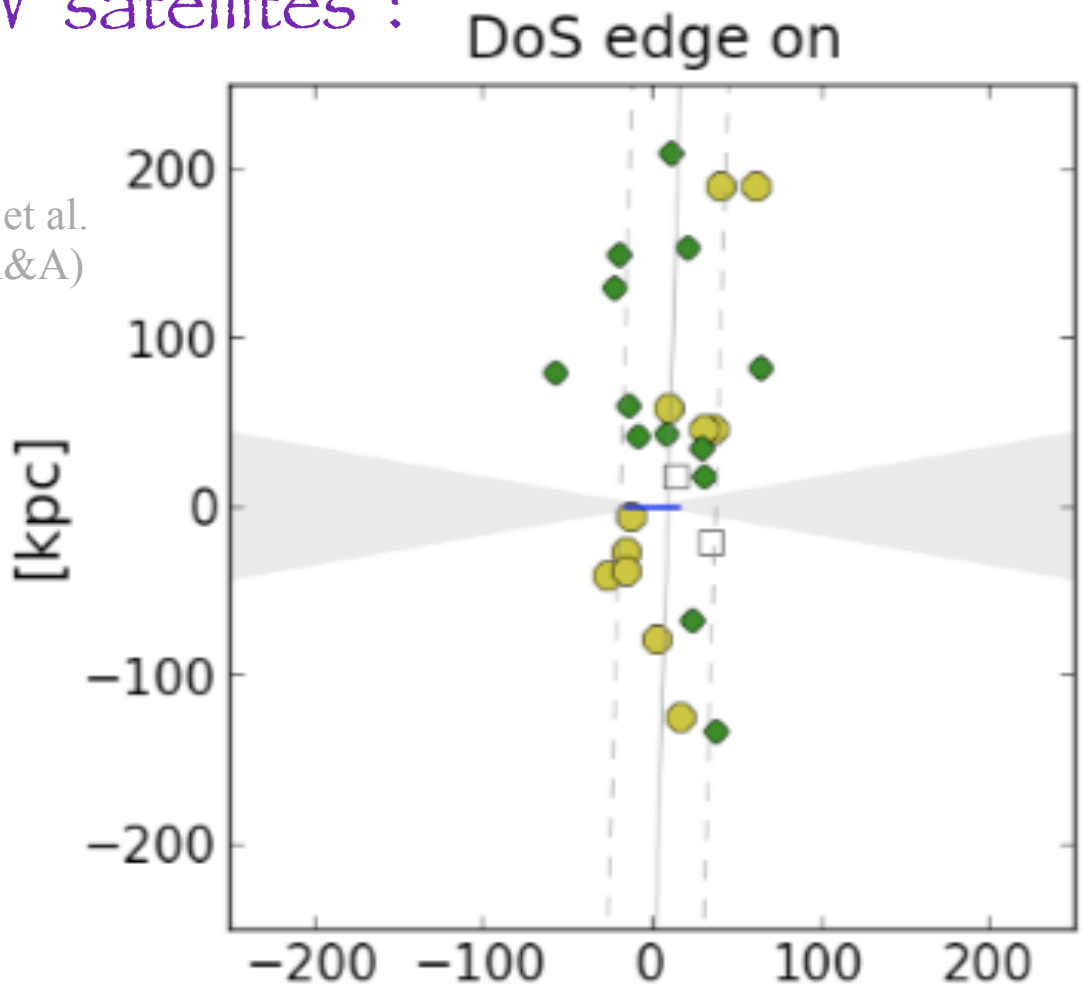
=> *breakdown of Newtonian/Einsteinian dynamics* !

This appears to be direct evidence that the LCDM model is not realistic.

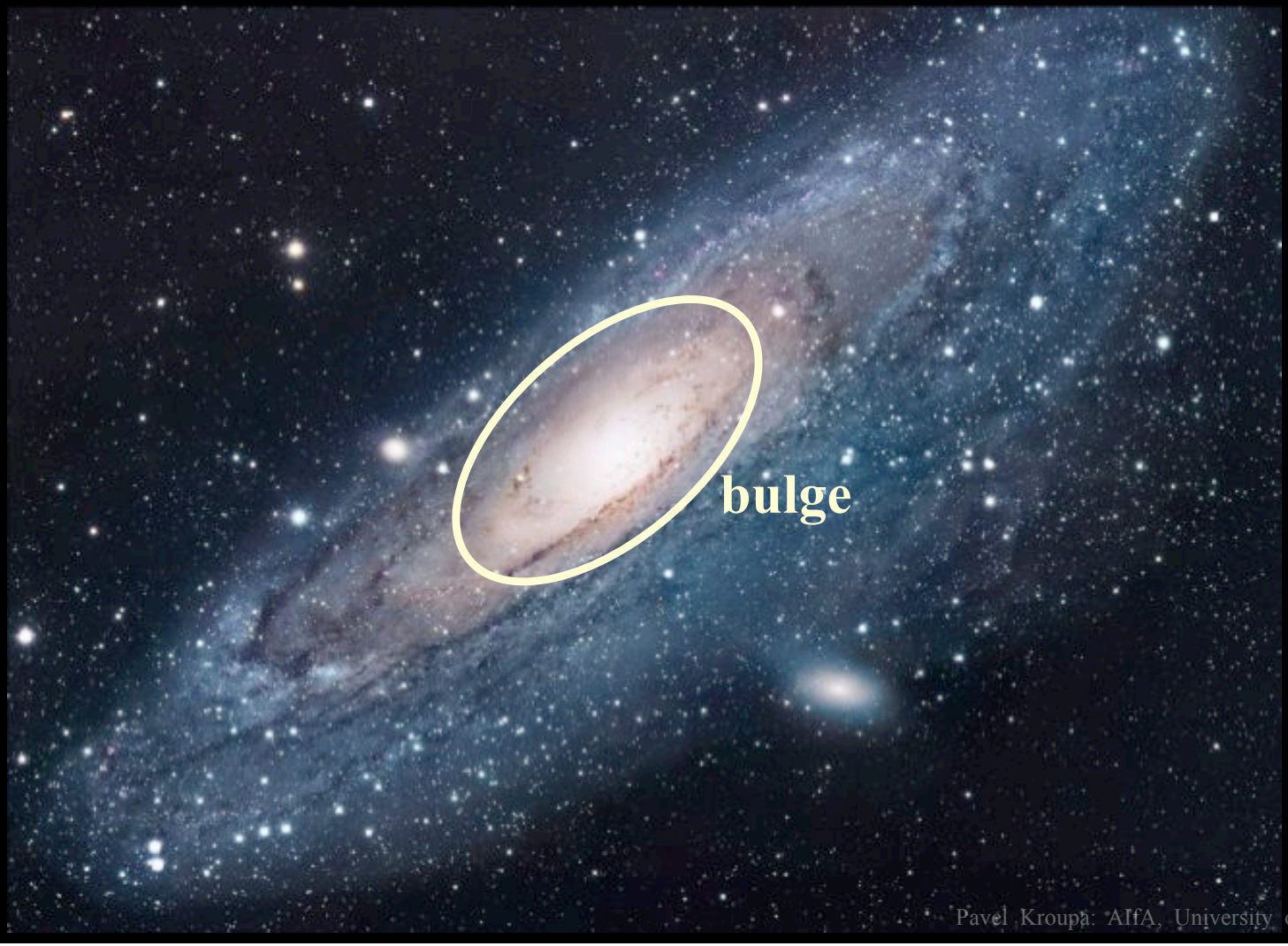
What about the disk-like configuration of MW satellites ?

- the 11 "classical" (brightest) satellites
- new satellites

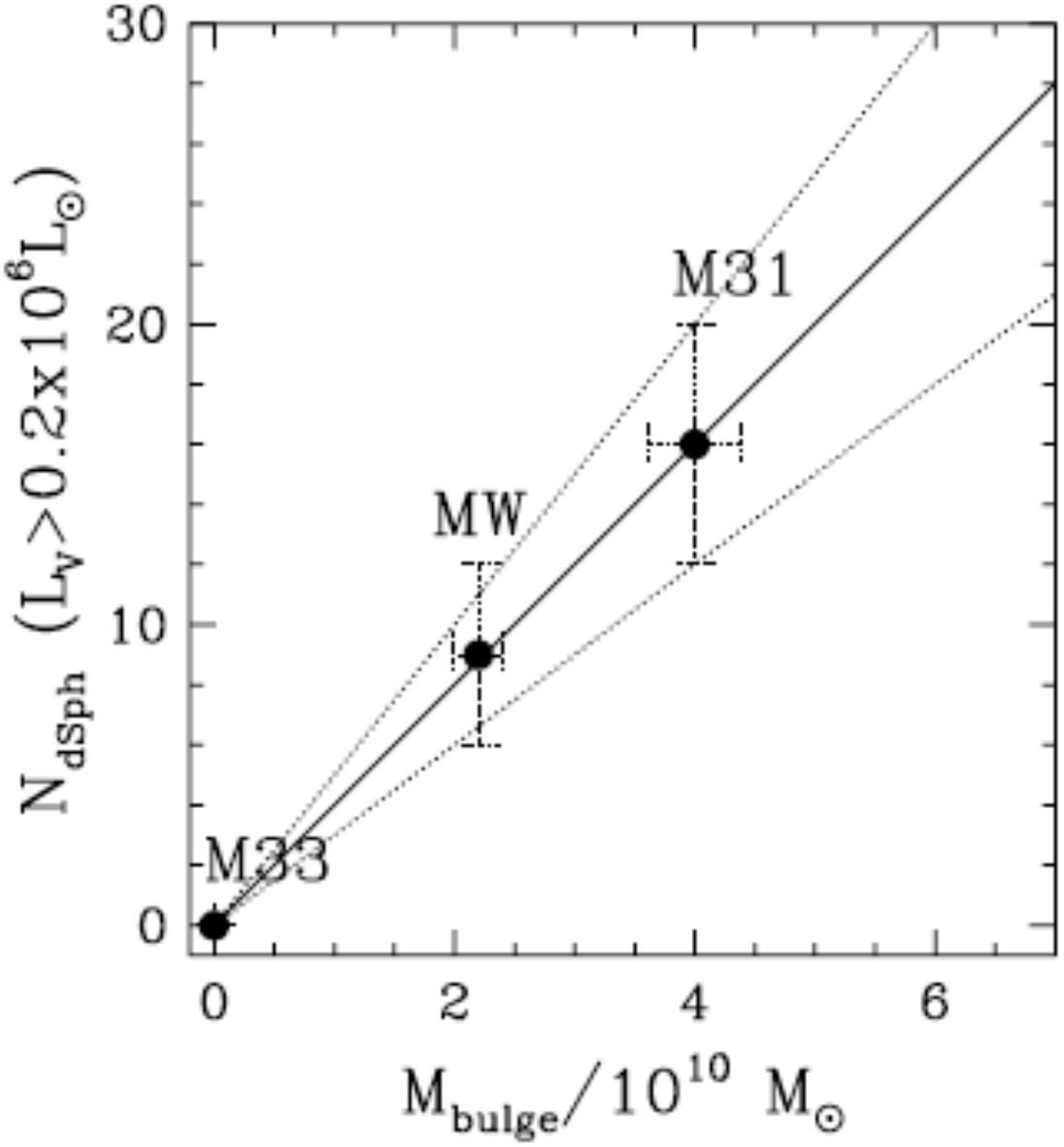
Kroupa et al. (2010, A&A)



. . . and, the bulge mass vs number of satellites correlation ?



A bulge - satellite correlation



Kroupa et al. (2010, A&A)

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

Both,
the *Disk of Satellites*
and
the *bulge--satellite correlation*
are easily understandable
if the MW satellites are *ancient TDGs.*

(Kroupa et al. 2010)

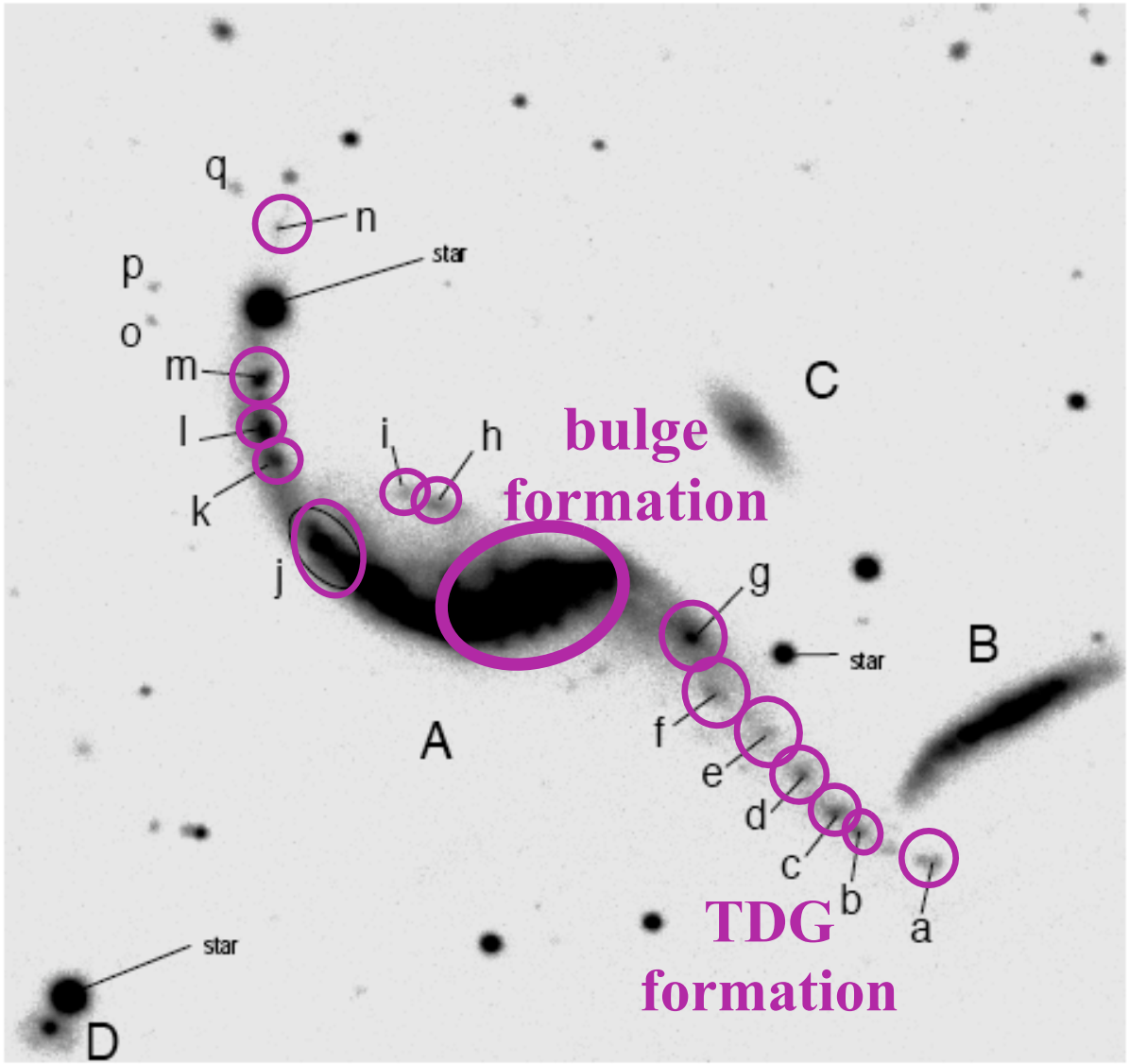


Fig. 21. Identification chart of field 10 around AM 1353-272.

(Weilbacher et al. 2000)

Phase-space correlated satellites form naturally in the same event as a *bulge* does.

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)

Problem at hand	Standard Model	MOND
irregular dSph morphology	x	✓
dSph dmass - luminosity relation (energy conservation)	x	✓
phase-space correlation (Disk of Satellites)	x	✓
bulge-mass vs satellite number correlation	x	✓
too many tidal-dwarf galaxies due to hierarchical formation	x	?
invariant baryonic galaxies	x	✓
Local Volume of galaxies	x	?
"missing mass" in young tidal dwarf galaxies	x	✓
surface density of dark matter / baryonic matter = constant	x	✓
PLUS (not covered here)		
core/cusp problem	x	✓
many bulge-less disk galaxies	x	?
missing satellite problem	x	?
downsising	x	?

Therefore,

The real
physical world is
non-Einsteinian/Newtonian
in the weak-field limit.

Remember this slide ?

Remember this slide ?

(I)

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

Cold/Warm Dark Matter

-Bond, Szalay & Turner 1982, Phys. Rev. Lett.
-Blumenthal, Pagels & Primack 1982, Nature
-Peebles 1982, ApJL
-Blumenthal, Faber, Primack, Rees, 1984, Nature

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Step V

Conclusions

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)

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

many astronomers not happy as computational model complex

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.

Step IV : Decision by technological advance

Galileo's ***solar system telescope data disprove the standard model***, but are consistent with the Heliocentric model.

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

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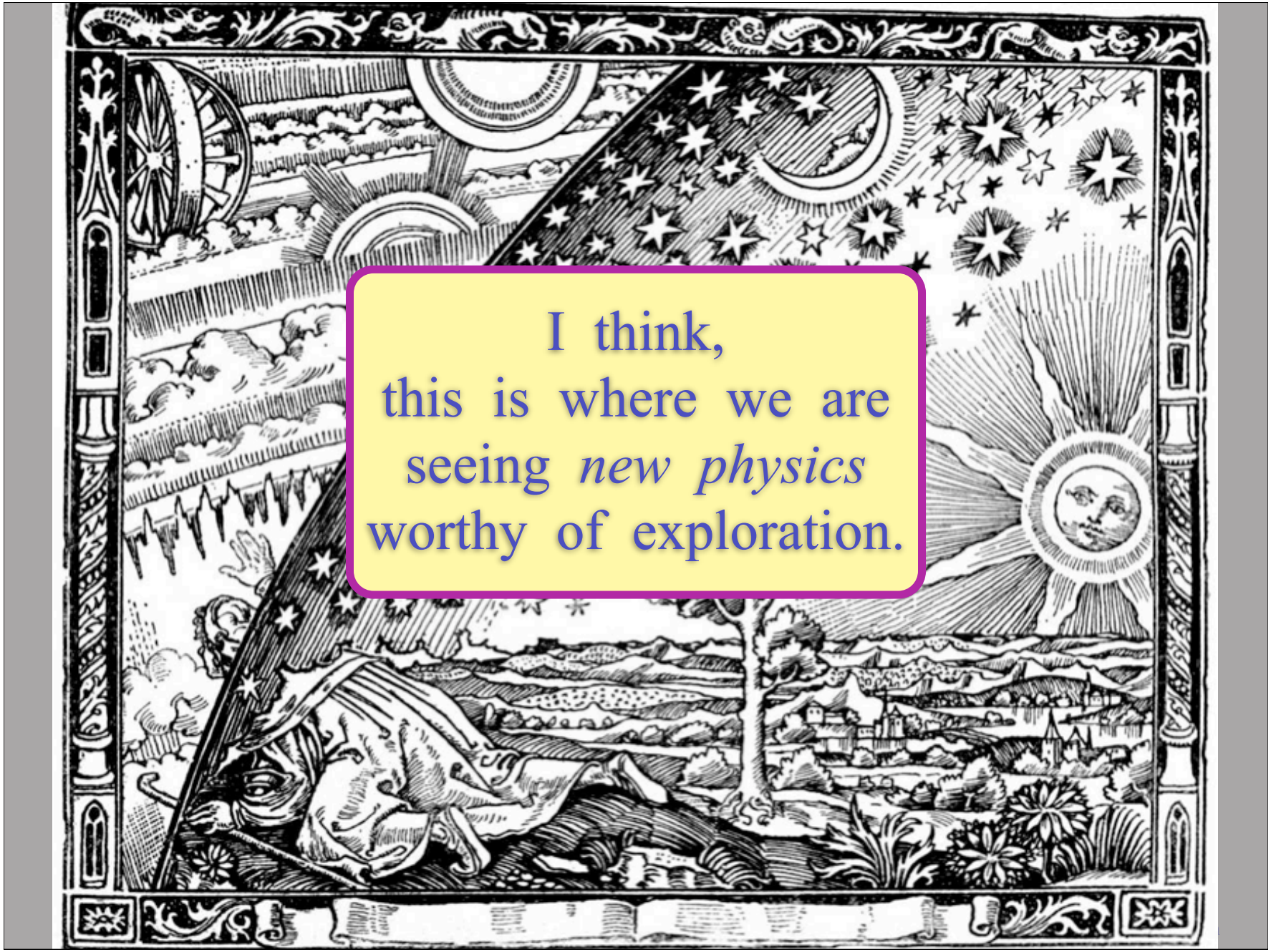
It is irrelevant to debate whether the LCMD model fits any data.
Beauty or even "high-precision" of a model can misguide.

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)

Dark Matter
and MOND

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

Prof. Gerhardt Hensler
(Vienna)

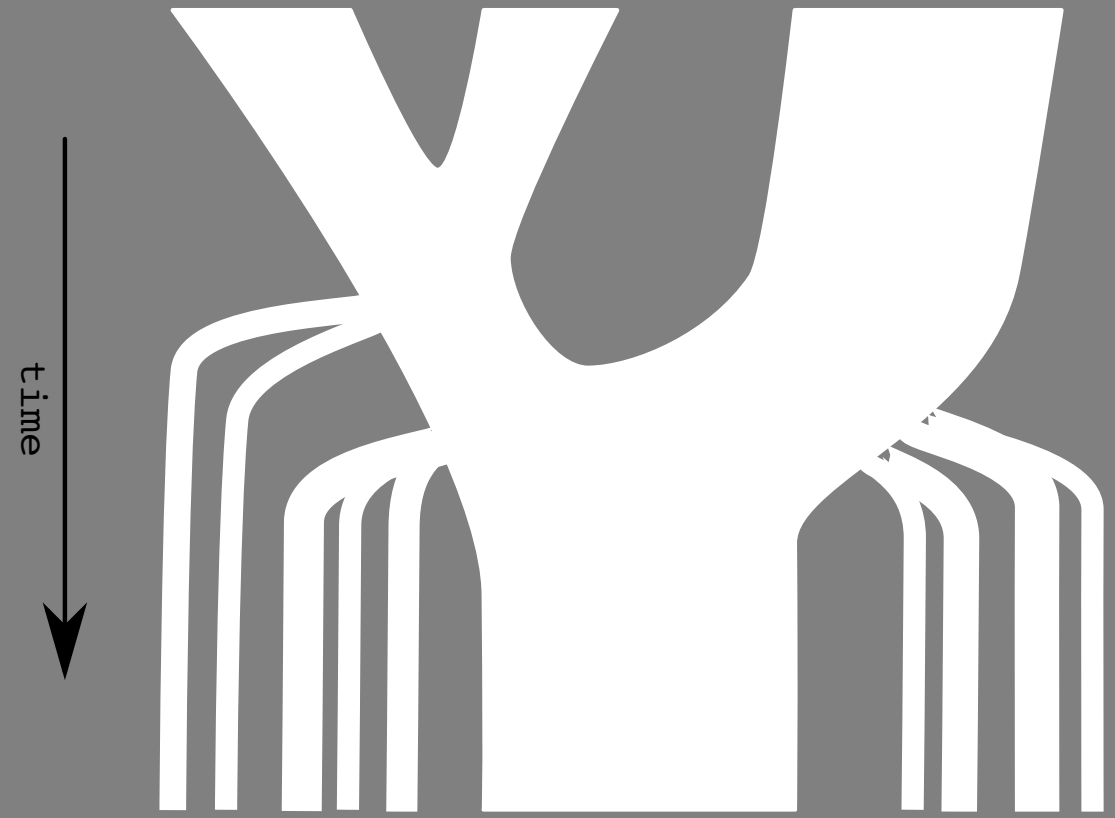
Star formation
in galaxies,
chemo-dynamical
evolution

Prof. Tom Shanks
(Durham)

CMB,
Dark Energy

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