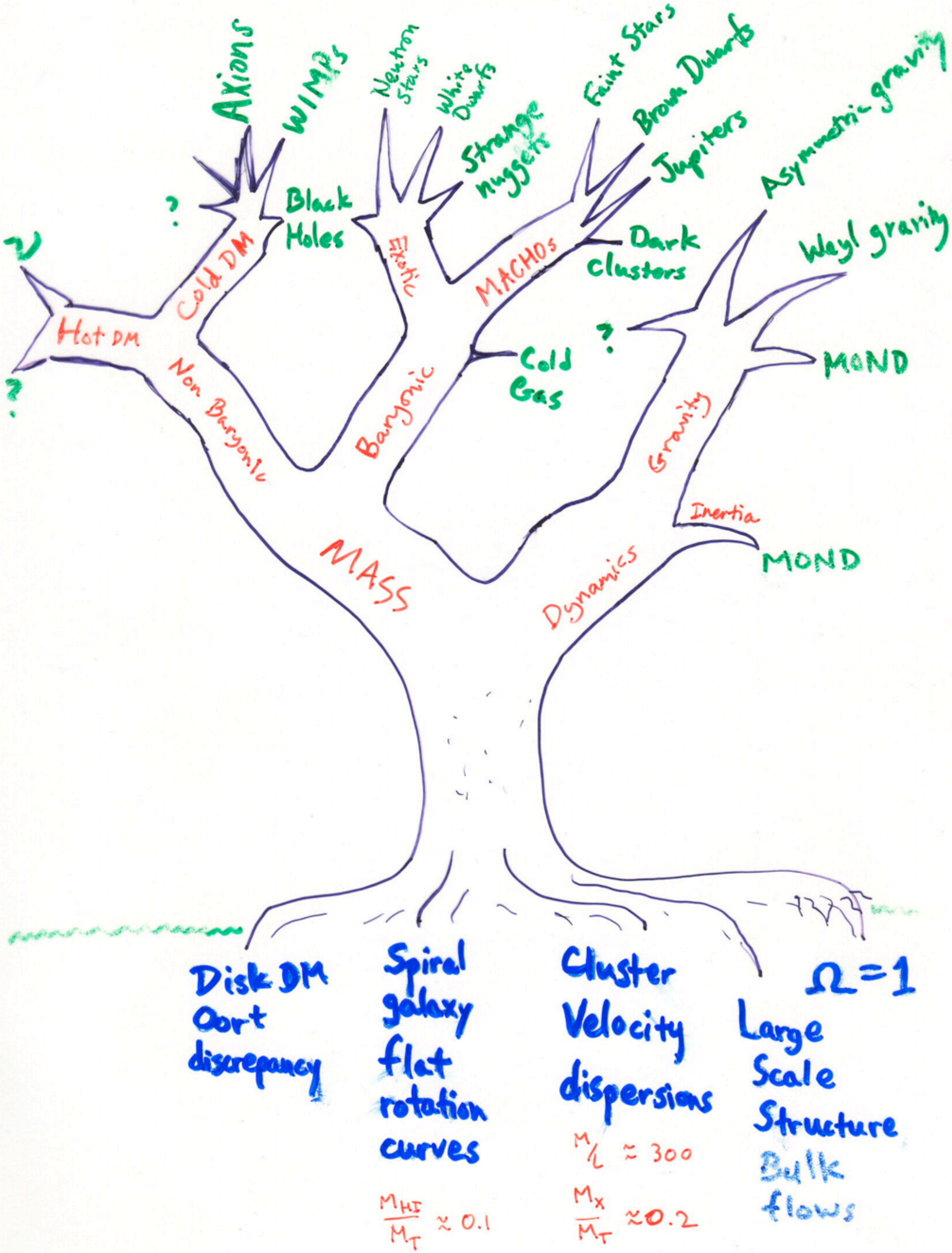
DARK MATTER

ASTR 333/433

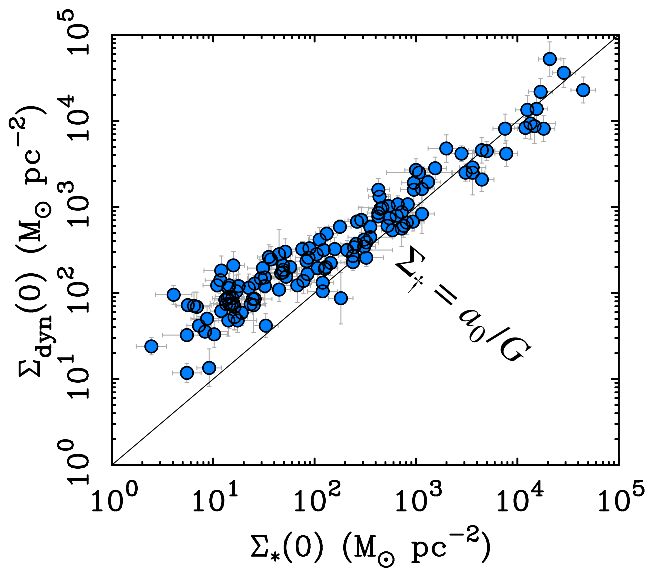
TODAY

MOND



Disk Stability

- MOND stabilizes disk in the low acceleration regime
    - High acceleration objects suffer usual Newtonian instabilities
- Predicts upper limit to disk surface brightness
    - Freeman's surface brightness marks transition between stable and unstable regimes $\Sigma \lesssim \Sigma_\dagger = a_0/G$



- Stability properties differ from DM case
    - similar at high surface brightness $t = \dfrac{T}{|W|} \approx 0.14$
    - less added stability at low surface brightness (low acceleration)

$$t = \frac{T}{|W|} \ll 0.14$$

Disk Stability in MOND

Brada (1998)
Brada & Milgrom (1999, 2000)

MOND adds stability roughly comparable to that added by a dark matter halo of ~3 times the disk mass, enclosed by the disk radius.

- Stability properties
  - similar to DM at high surface brightness
  - less added stability at low surface brightness (low acceleration)

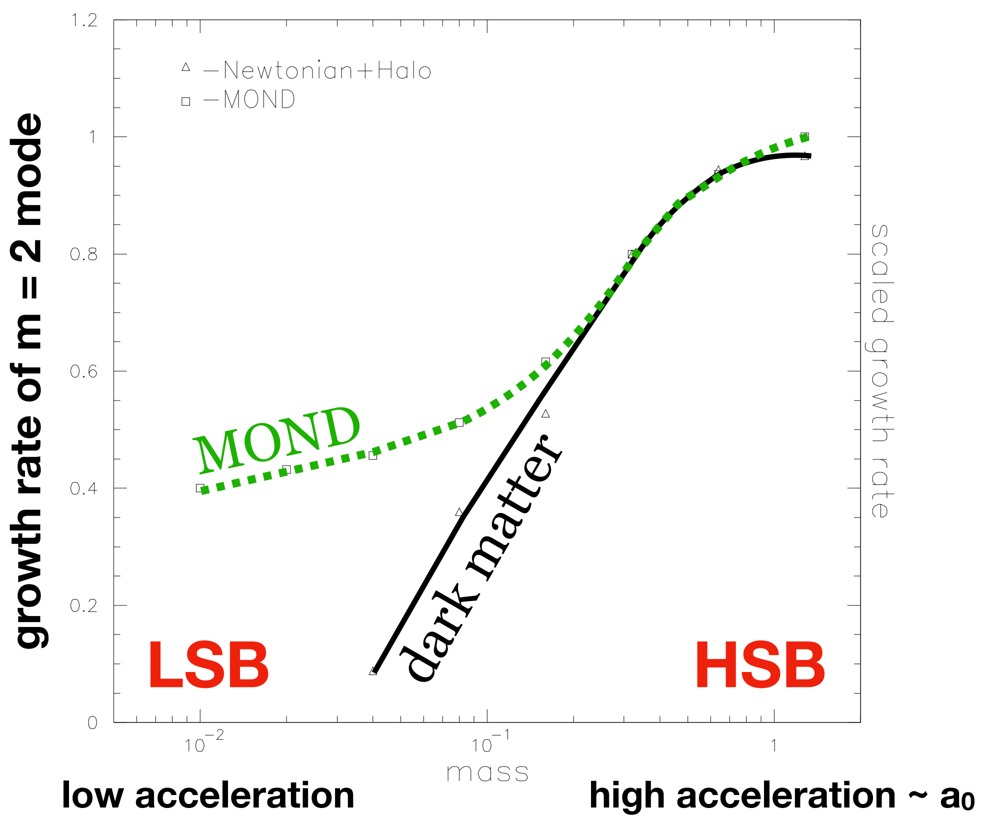
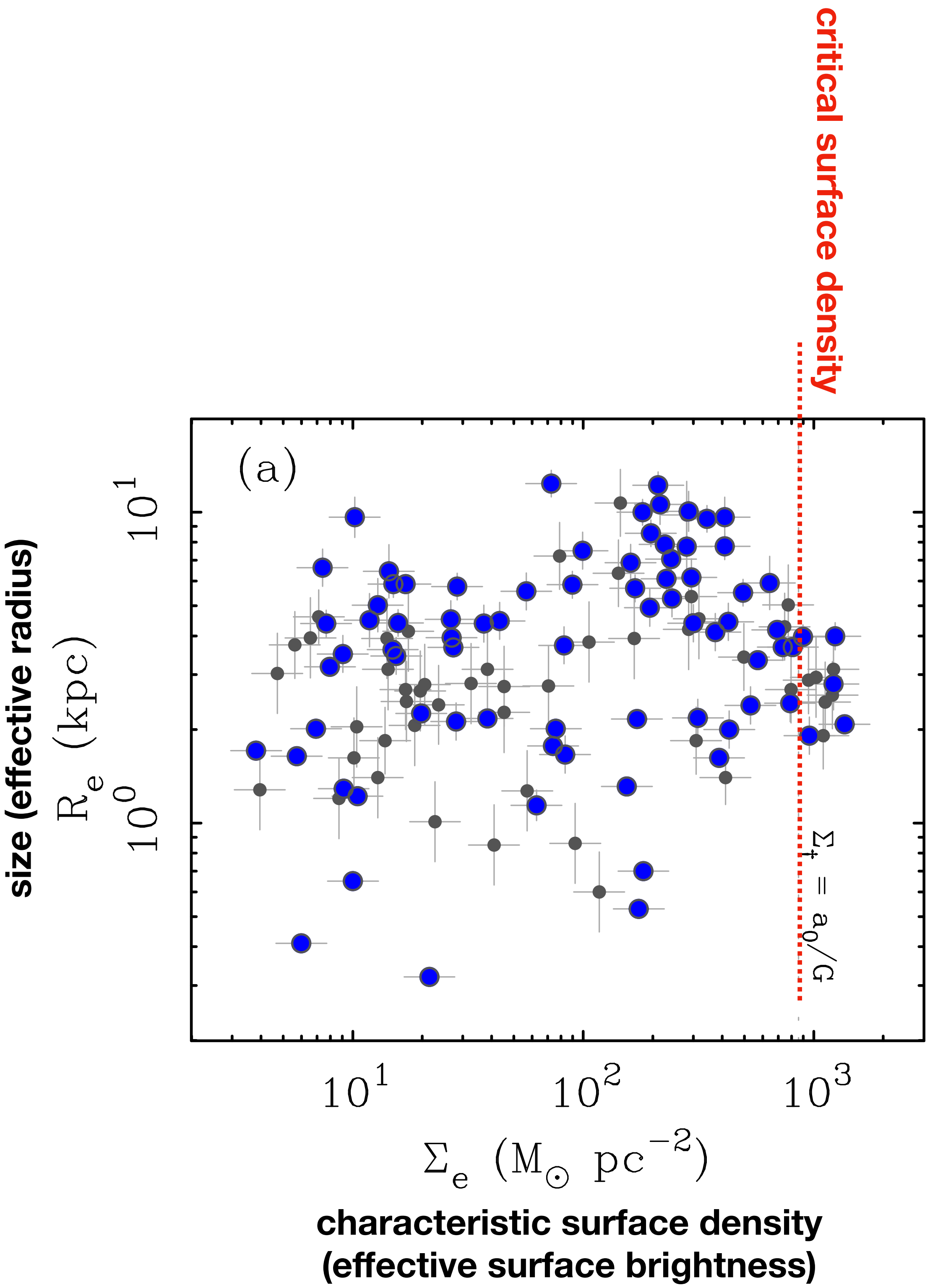
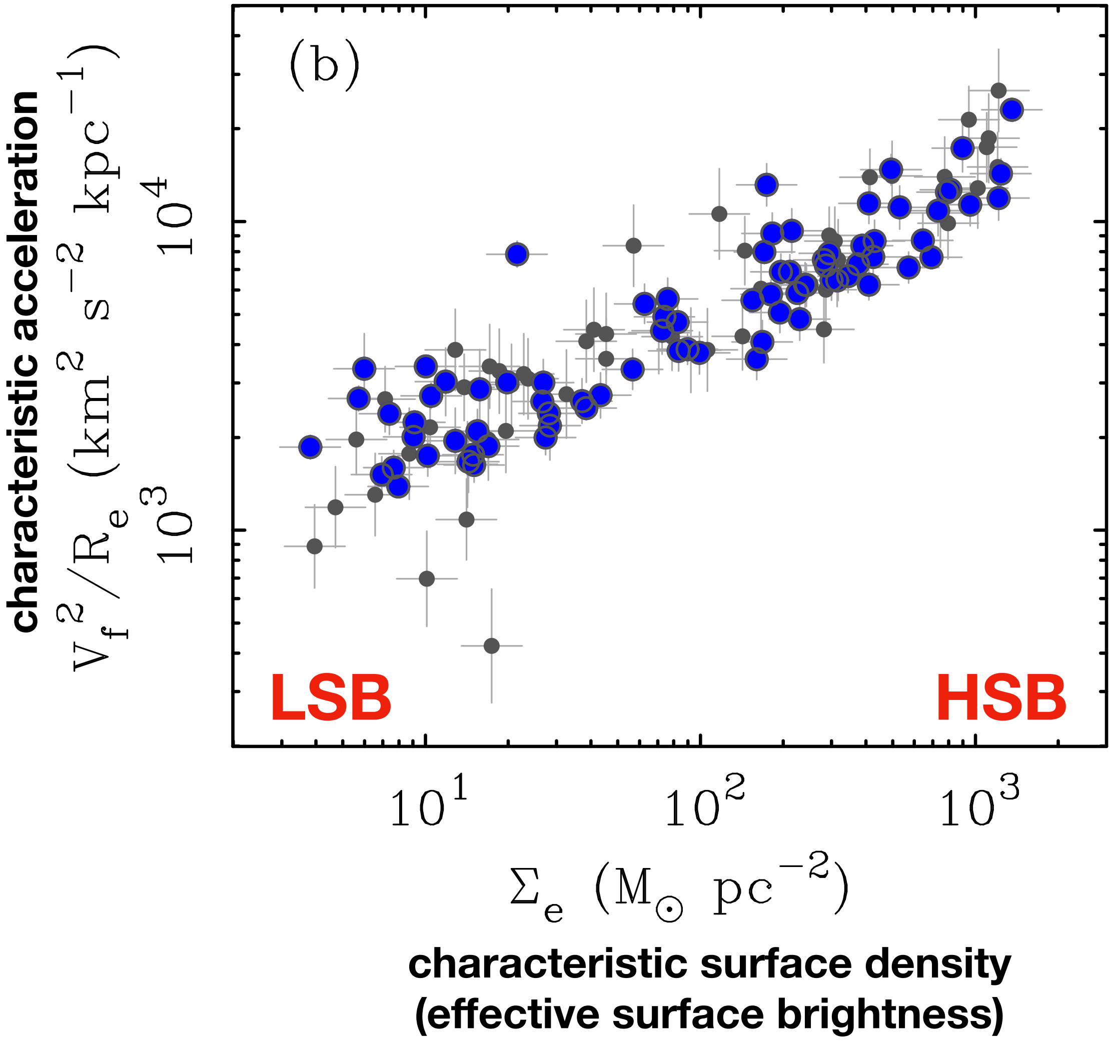


Figure 11: The growth rate, in units of the dynamical time, for the m=2 mode as a function of the total mass of the disk. □ MOND, △ Newtonian + Halo.

m	Q	time step scaling	Growth rate MOND	Growth rate Newt+DM	halo mass at R=1
0.005	2.55	1			
0.01	2.5	0.84	0.4		
0.02	2.4	0.7	0.43		
0.04	2.25	0.58	0.46	0.09	0.18
0.08	2.0	0.48	0.51	0.36	0.23
0.16	1.79	0.39	0.62	0.53	0.28
0.32	1.62	0.3	0.8	0.8	0.31
0.64	1.53	0.22	0.94	0.94	0.31
1.28	1.5	0.16	1.0	0.97	0.27

Table 1: The growth rate, in units of dynamical time, for the $m = 2$ mode, and model parameters for the different mass models.


critical surface density
(a)
size (effective radius)
R_e (kpc)
10^1
10^0
Σ_* = a_0/G
10^1
10^2
10^3
Σ_e (M_⊙ pc^−2)
characteristic surface density
(effective surface brightness)


(b)
characteristic acceleration
V_f^2/R_e (km^2 s^−2 kpc^−1)
10^4
10^3
LSB
HSB
10^1
10^2
10^3
Σ_e (M_⊙ pc^−2)
characteristic surface density
(effective surface brightness)

Tiret & Combes (2007, 2008)

MOND numerical simulations of galaxy morphology

real galaxies simulated galaxies

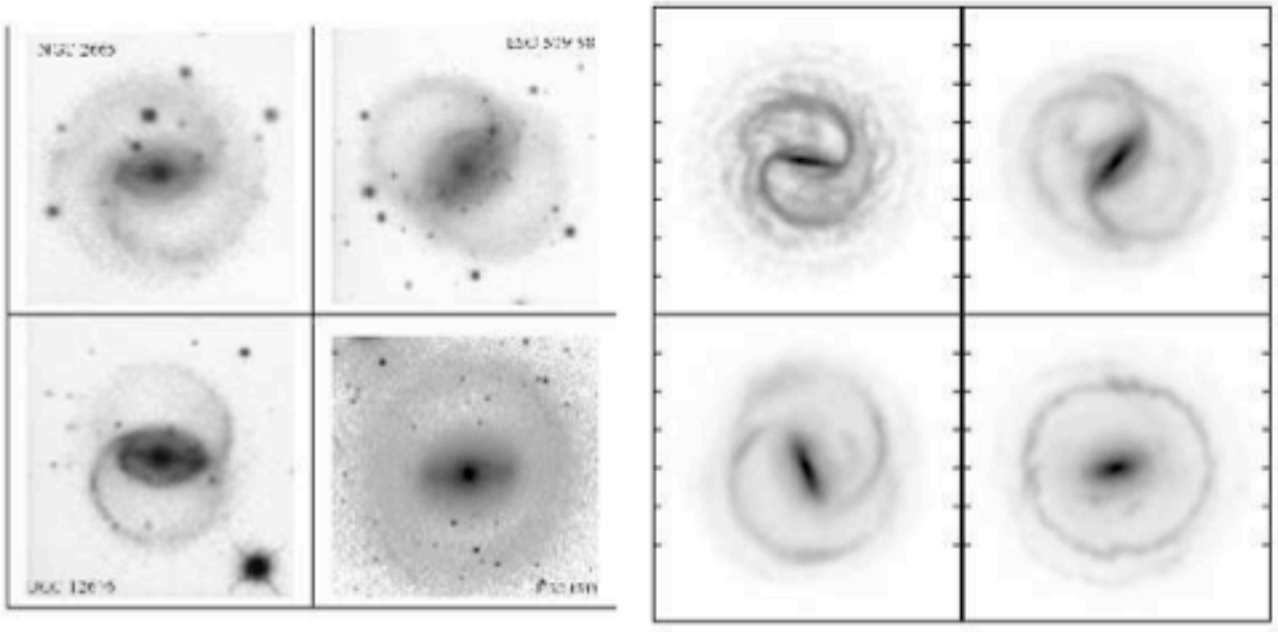
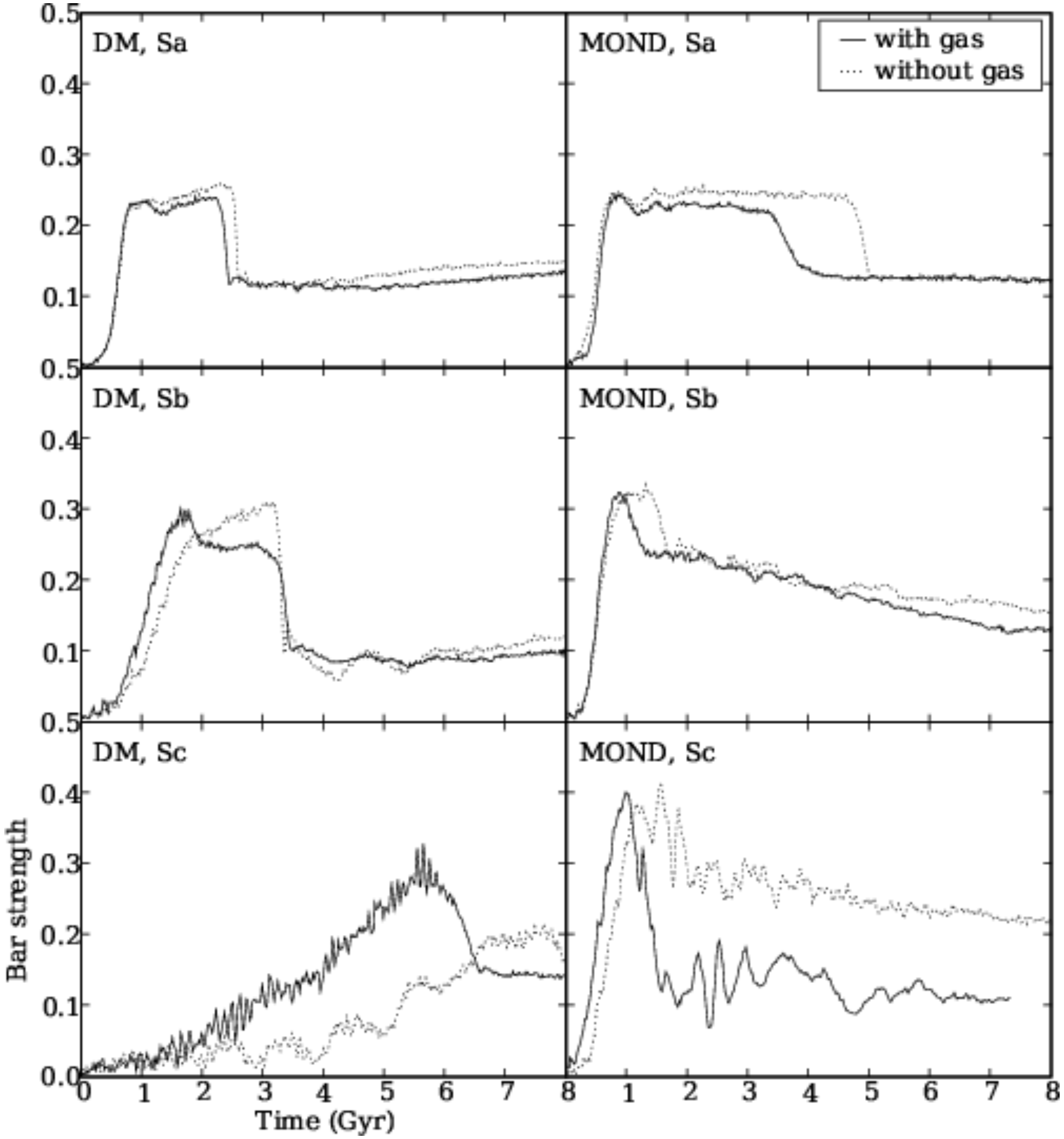


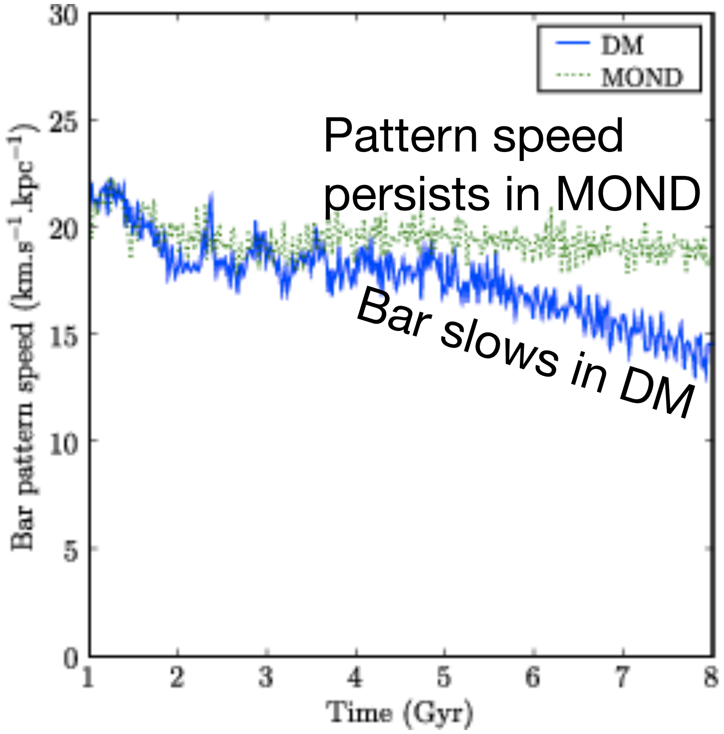
Fig. 3. Several examples showing the morphological structures of NGC 2665, ESO 509-98, UGC 12646 and NGC 1543 (top panel) compared to simulated galaxies in MOND (bottom panel). Rings and pseudo-rings structures are well reproduced with modified gravity.

Tiret & Combes (2007, 2008)

Bar strength



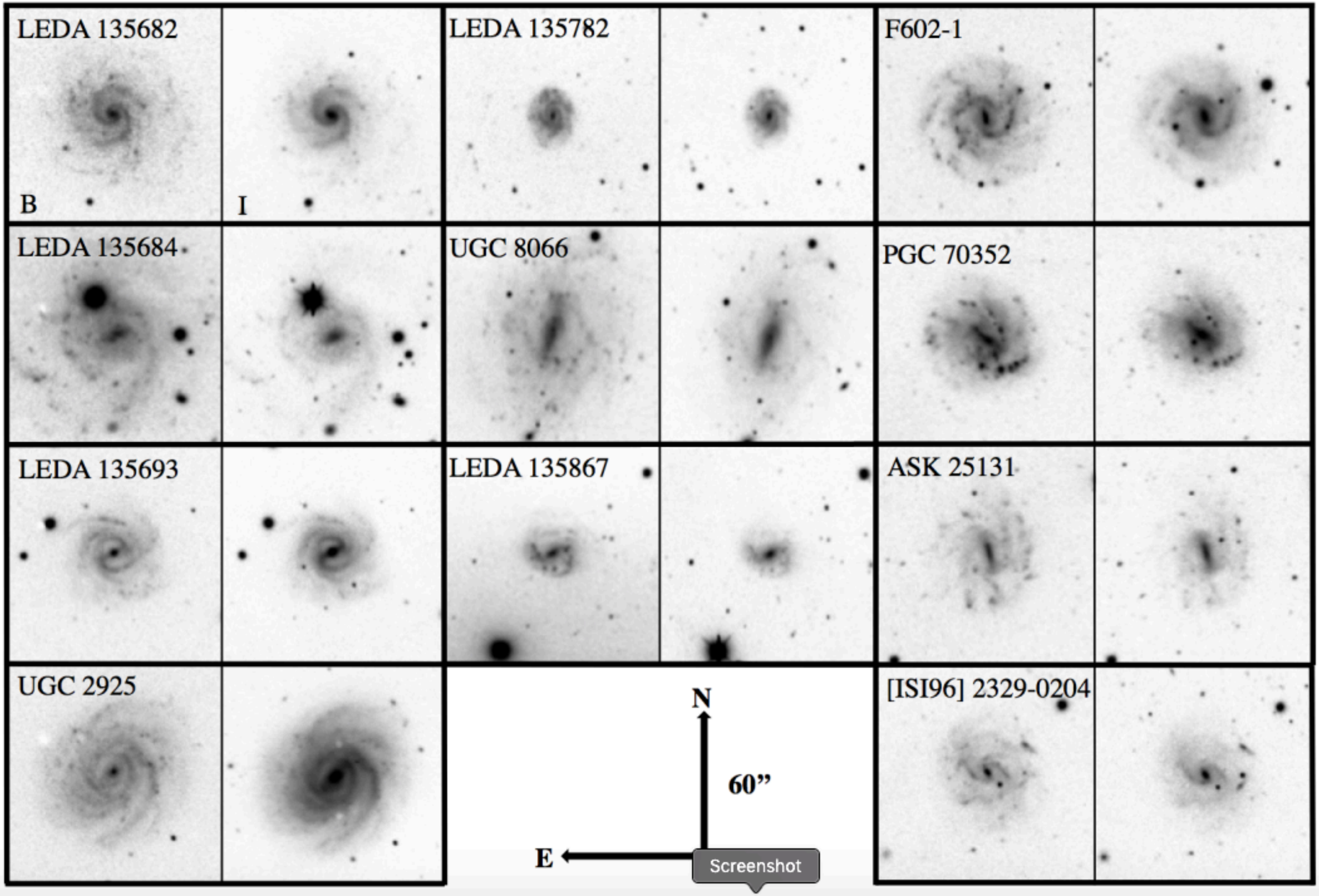
Bar pattern speed



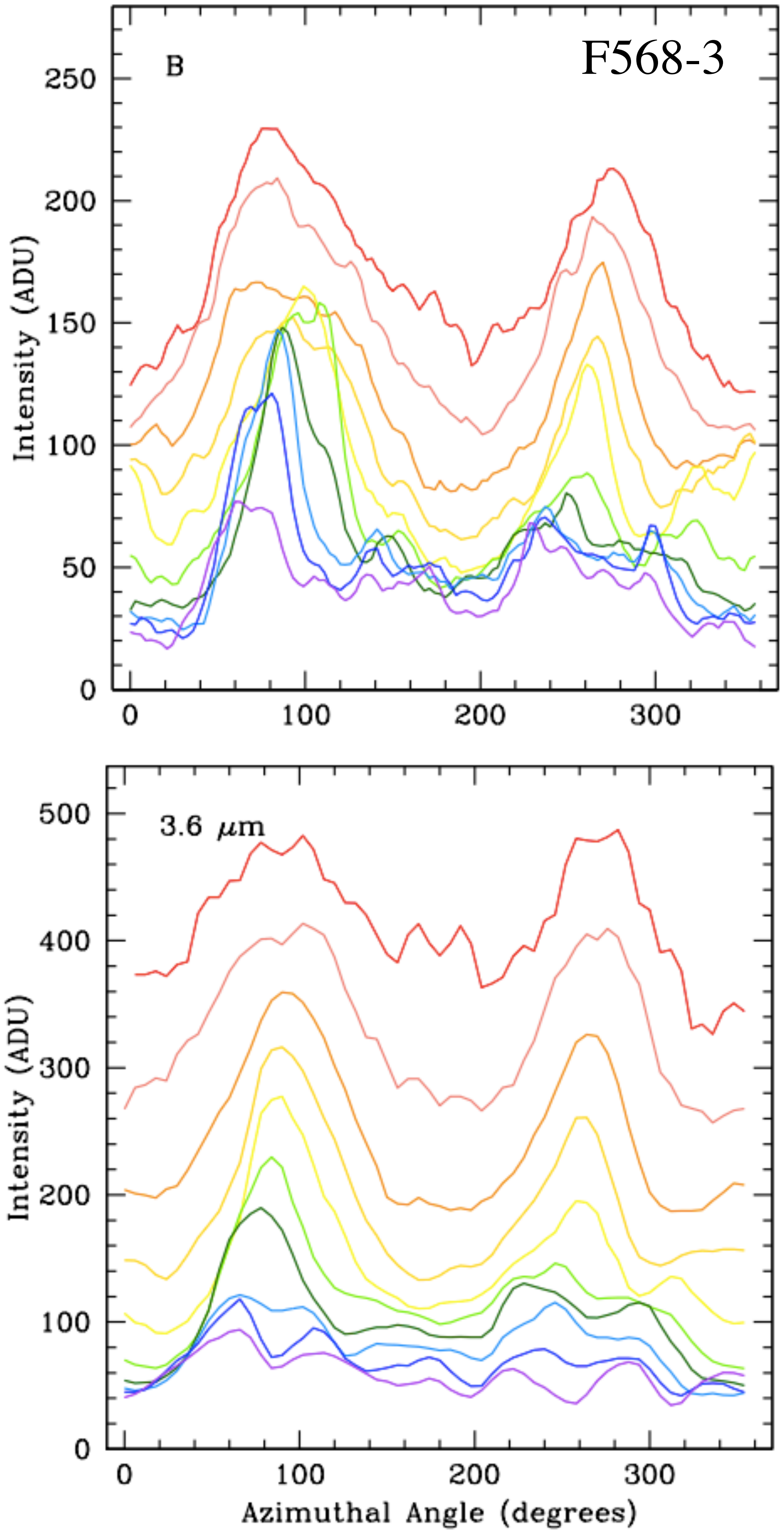
Pattern speed persists in MOND

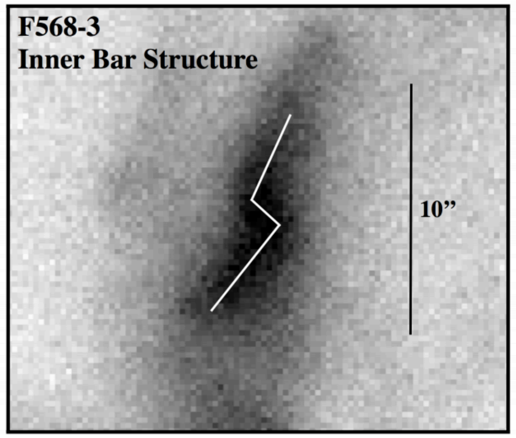
Bar slows in DM

Bars in LSB galaxies



Bars in LSB galaxies





Bar lengths/pattern speeds

Bars in LSBs fast; no sign of dynamical friction

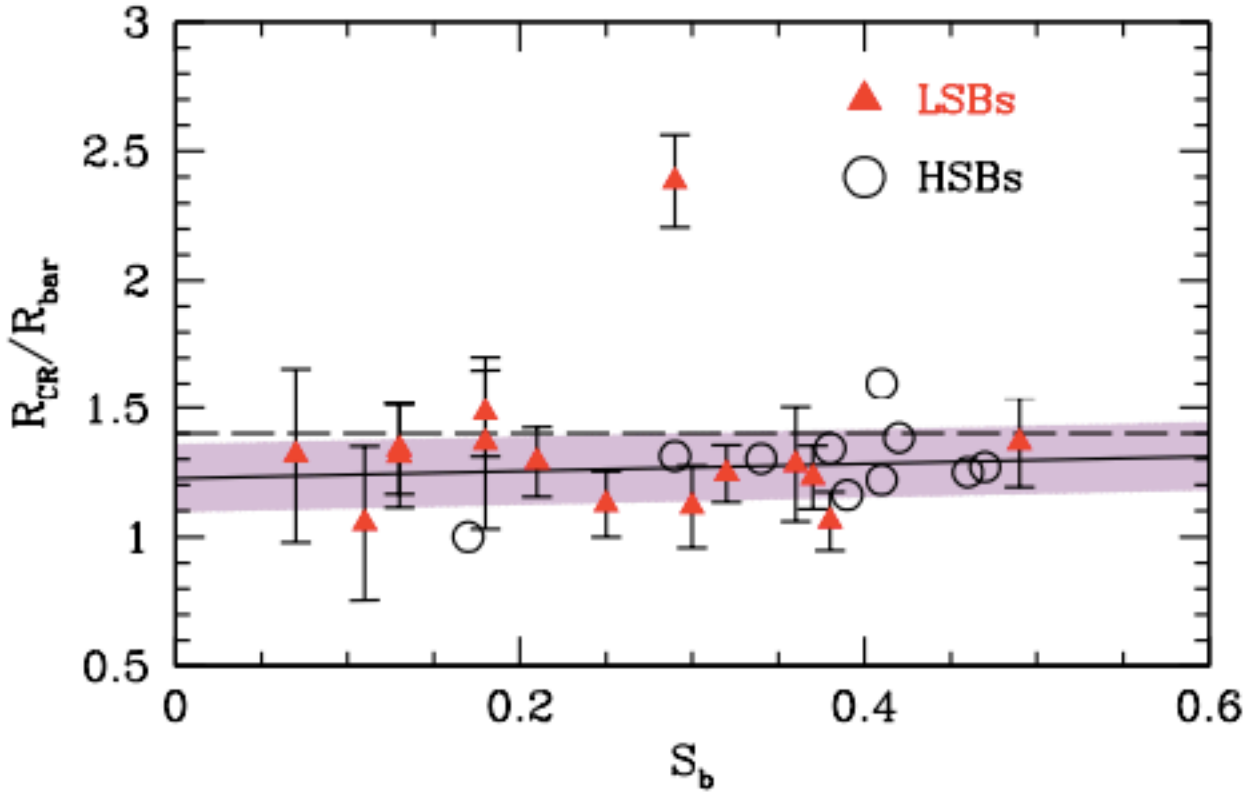
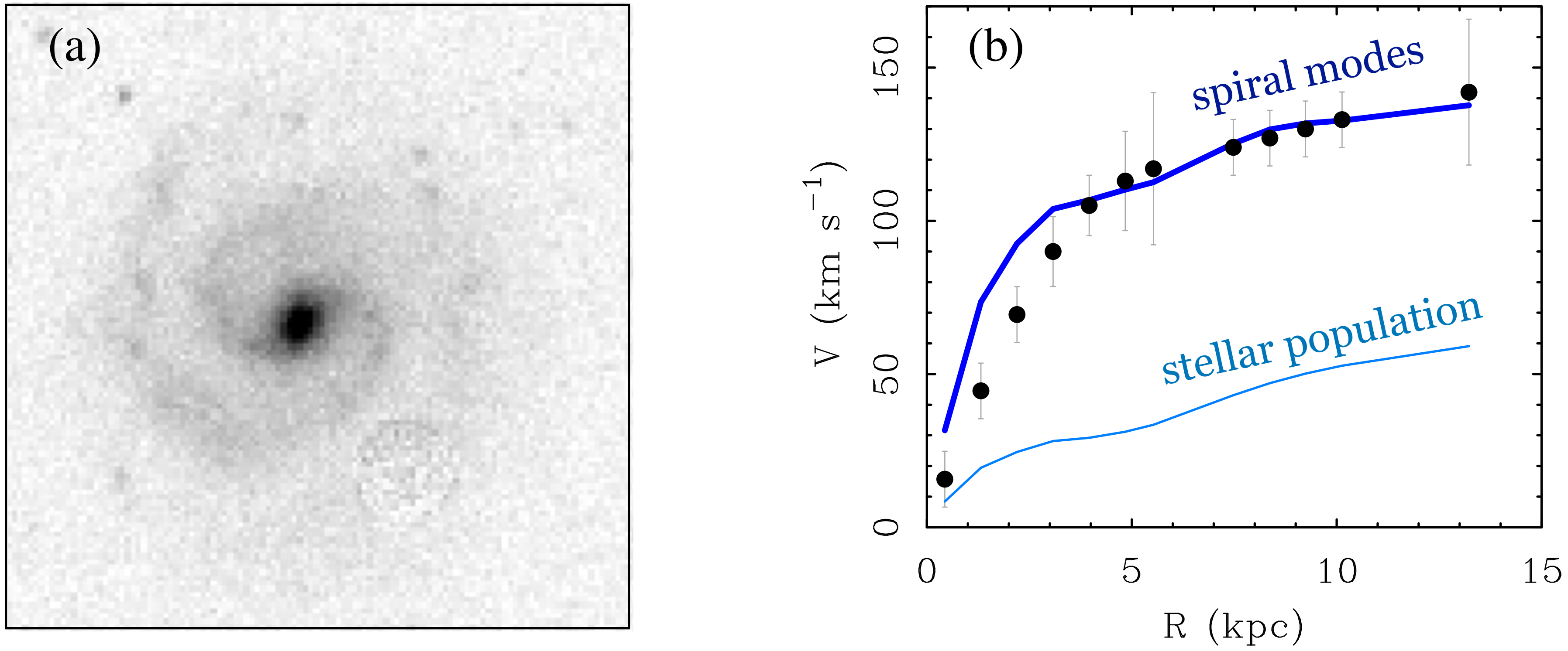


Figure 10. Relative bar pattern speed ($\mathcal{R} = R_{\rm CR}/R_{\rm bar}$) as a function of bar strength (S_b) for our sample (red triangles) and HSBs from Aguerri et al. (1998) (open circles). The solid line indicates the fit to the HSBs and LSBs, excluding the outlier discussed in the text: $\mathcal{R} = 1.23+0.14S_b$. The shaded region shows the scatter in the relation: $\sigma = 0.13$. The horizontal dashed line is the separator between fast and slow bars (i.e. $\mathcal{R} = 1.4$).

The different stability properties at high and low surface brightness predict different morphologies. In DM, bars and spiral modes should be strongly suppressed. To generate them will require increasing the disk mass over that expected for ordinary stellar populations.

“In LSB disks, it is conceivable that the minimum disk mass required to generate spiral arms might exceed the maximum disk mass allowed by the rotation curve.” (McGaugh & de Blok 1998)

F568-1

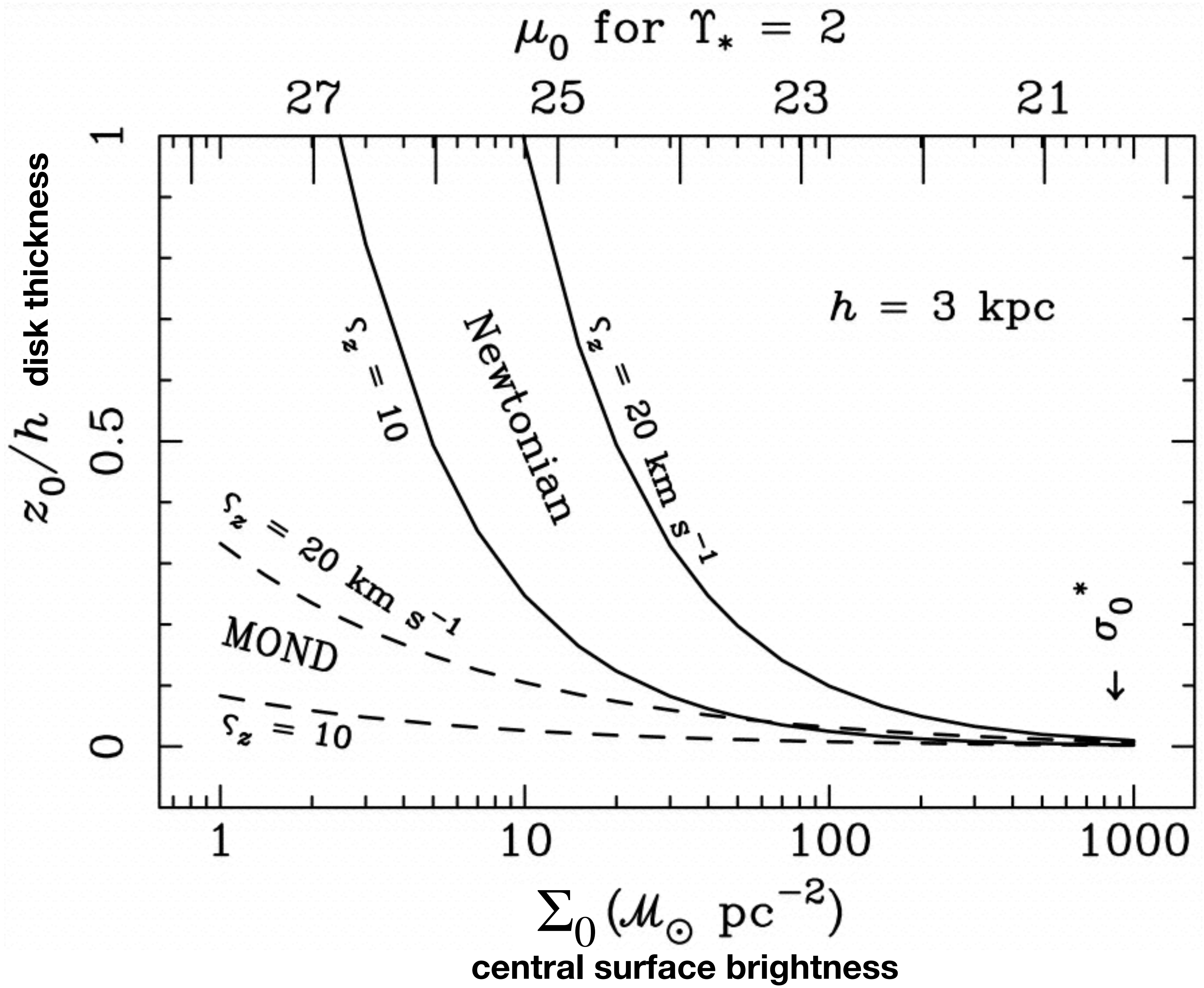


The disk mass required to drive the observed spiral arms is much larger than that expected for the stellar population.

In this case, more disk mass is required than is allowed by the rotation curve. Taken at face value, this is a contradiction to the existences of dark matter.

Galaxy disks should flare less in MOND than in Newtonian dynamics.

Equivalently, they can sustain higher velocity dispersions without become unduly thick.



The outer, LSB regions of disks should have velocity dispersions of ~2 km/s conventionally; ~7 km/s is typically observed.

Conventionally, non-gravitational forces are invoked to explain the difference. These are not necessary in MOND.

McGaugh & de Blok (1998)

The External Field Effect in MOND

Subtly different effects occur in non-isolated systems

- At high accelerations, everything is Newtonian $a_{in} \gg a_0$ or $a_{in} < a_0 < a_{ext}$
- The deep MOND regime occurs for isolated systems in the limit of low acceleration $a_{ext} < a_{in} < a_0$
- The external field effect comes into play for low acceleration systems exposed to a stronger external field $a_{in} < a_{ext} < a_0$
- Tidal effects become strong when the external field dominates

http://astroweb.case.edu/ssm/mond/EFE.html

http://astroweb.case.edu/ssm/mond/milgromonefe.html

Newtonian regime

$g_{in} > a_0$

$$M = \frac{RV^2}{G}$$

e.g.,
surface
of the
Earth

MOND regime

$g_{in} < a_0$

$$M = \frac{V^4}{a_0 G}$$

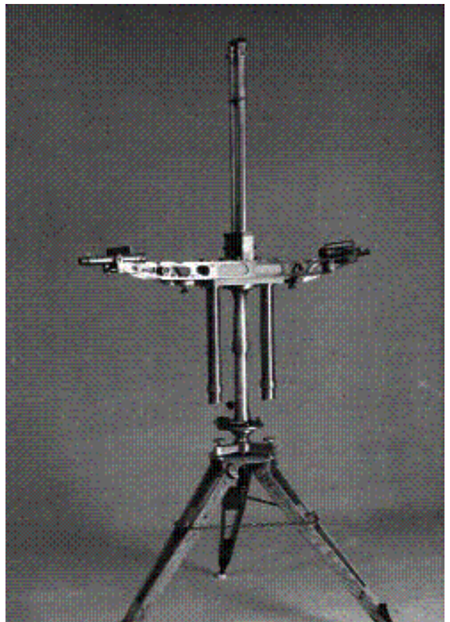
e.g.,
remote
dwarf
Leo I

© Anglo-Australian Observatory

External Field dominant Newtonian regime

$g_{in} < a_0 < g_{ex}$

$$M = \frac{RV^2}{G}$$



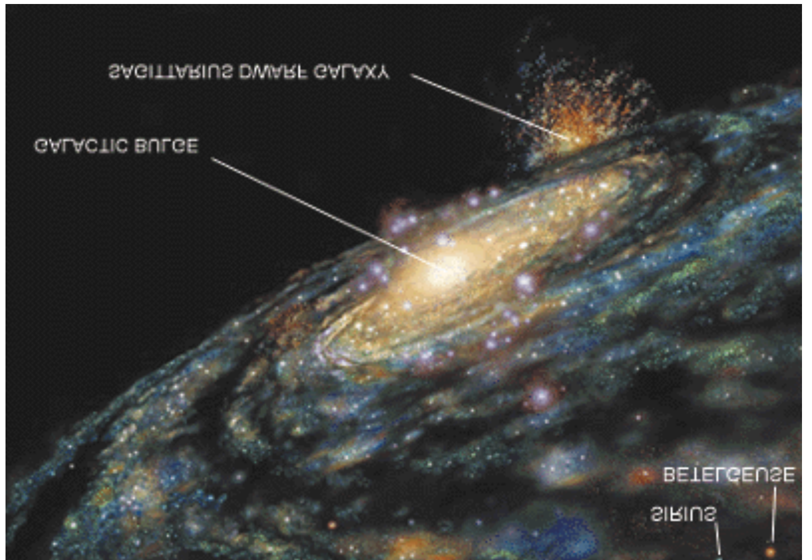
e.g.,
Eotvos-type
experiment on
the surface of
the Earth

External Field dominant quasi-Newtonian regime

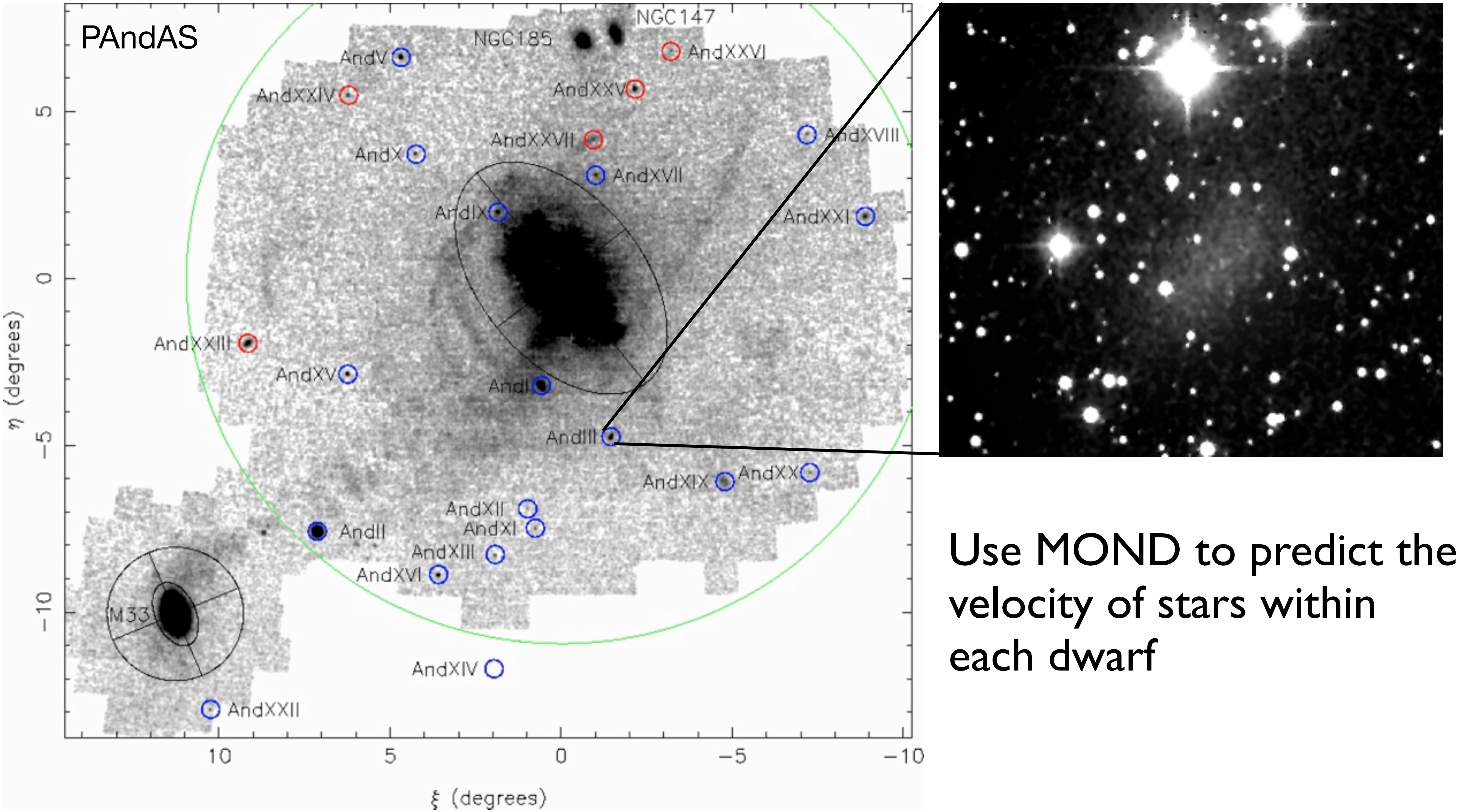
$g_{in} < g_{ex} < a_0$

$$M = \frac{a_0}{g_{ex}} \frac{RV^2}{G}$$

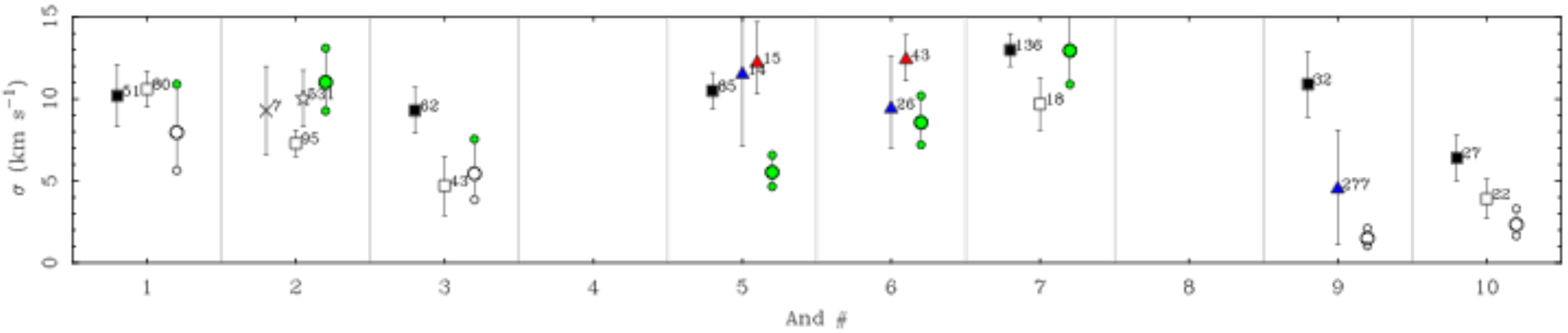
e.g.,
nearby
Sgr
dwarf



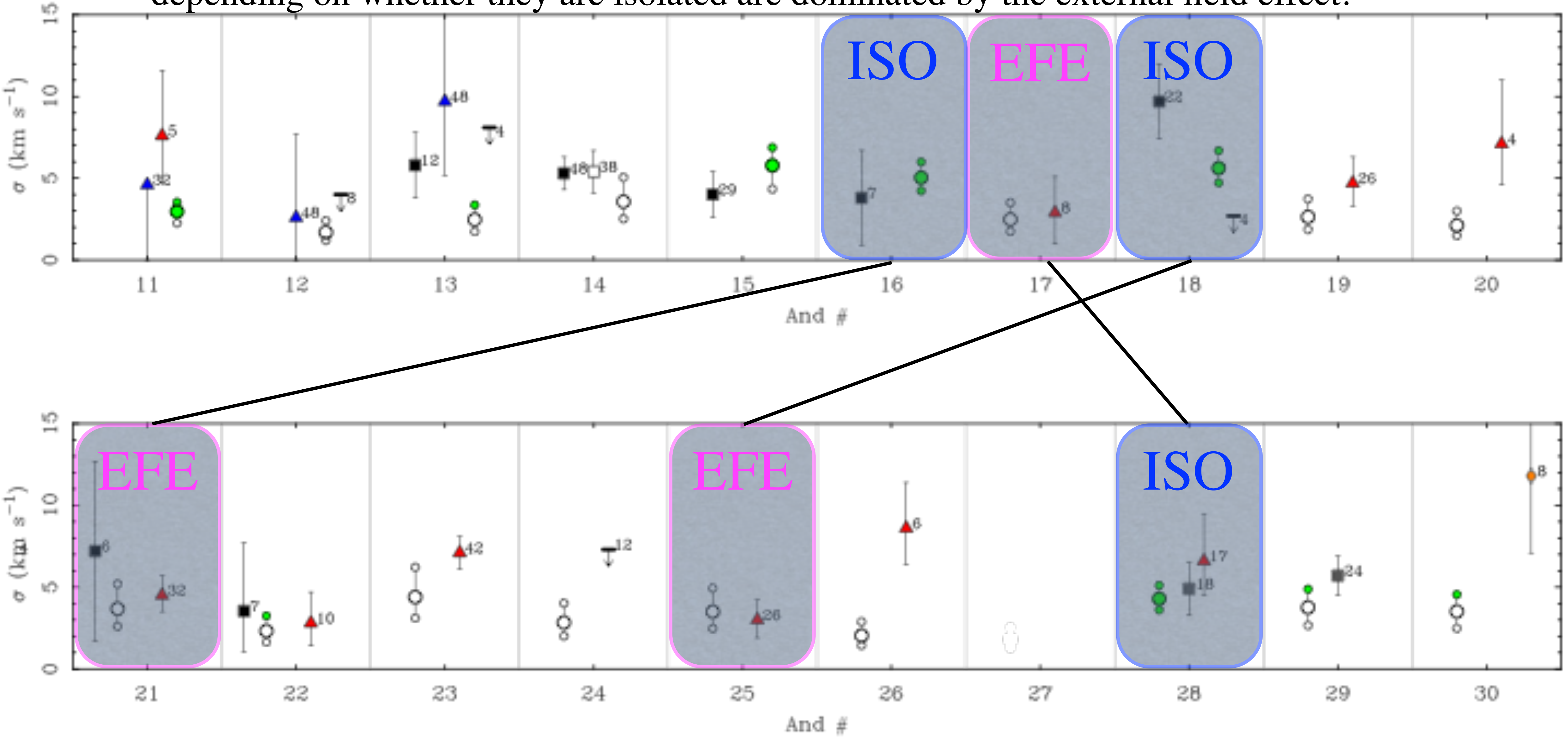
A test with the dwarf satellites of Andromeda



Use MOND to predict the velocity of stars within each dwarf



Pairs of photometrically identical dwarfs should have different velocity dispersion depending on whether they are isolated are dominated by the external field effect.



There is no EFE in dark matter - this is a unique signature of MOND.

I find your lack of faith disturbing.

- You don’t know the Power of the Dark Side
- Can MOND explain large scale structure?
- Can it provide a satisfactory cosmology?
- Can it be reconciled with General Relativity?

Review of relativistic theories containing MOND in the appropriate limit

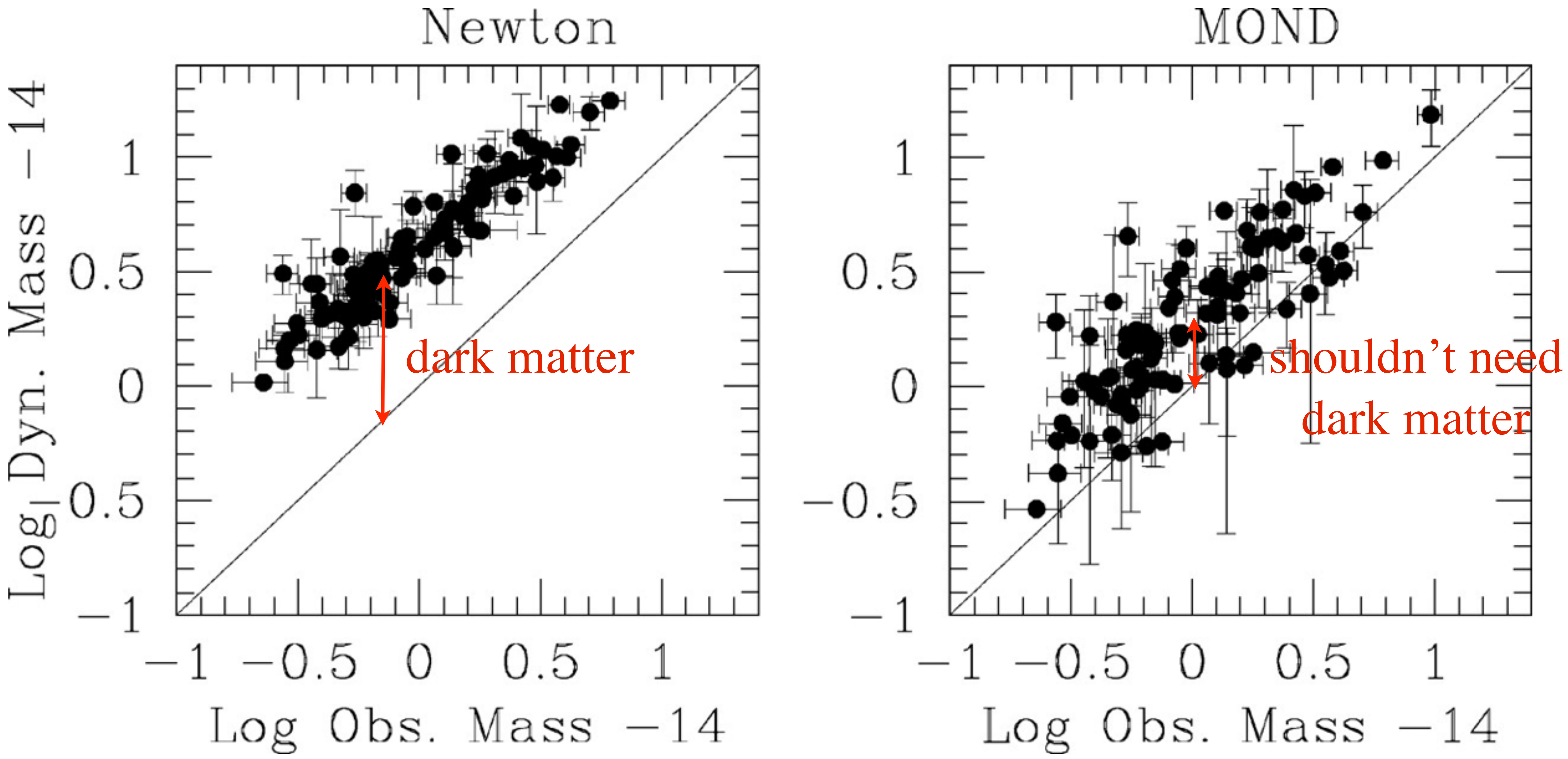
- You don't know the Power of the Dark Side
- Can MOND explain large scale structure?
- Can it provide a satisfactory cosmology?
- Can it be reconciled with General Relativity?

Famaey, B., & McGaugh, S.S. 2012,
Living Reviews in Relativity, 15, 10

7.1 Scalar-tensor k-essence
7.2 Stratified theory
7.3 Original Tensor-Vector-Scalar theory
7.4 Generalized Tensor-Vector-Scalar theory
7.5 Bi-Scalar-Tensor-Vector theory
7.6 Non-minimal scalar-tensor formalism
7.7 Generalized Einstein-Aether theories
7.8 Bimetric theories
7.9 Dipolar dark matter
7.10 Non-local theories and other ideas
e.g., dark superfluid

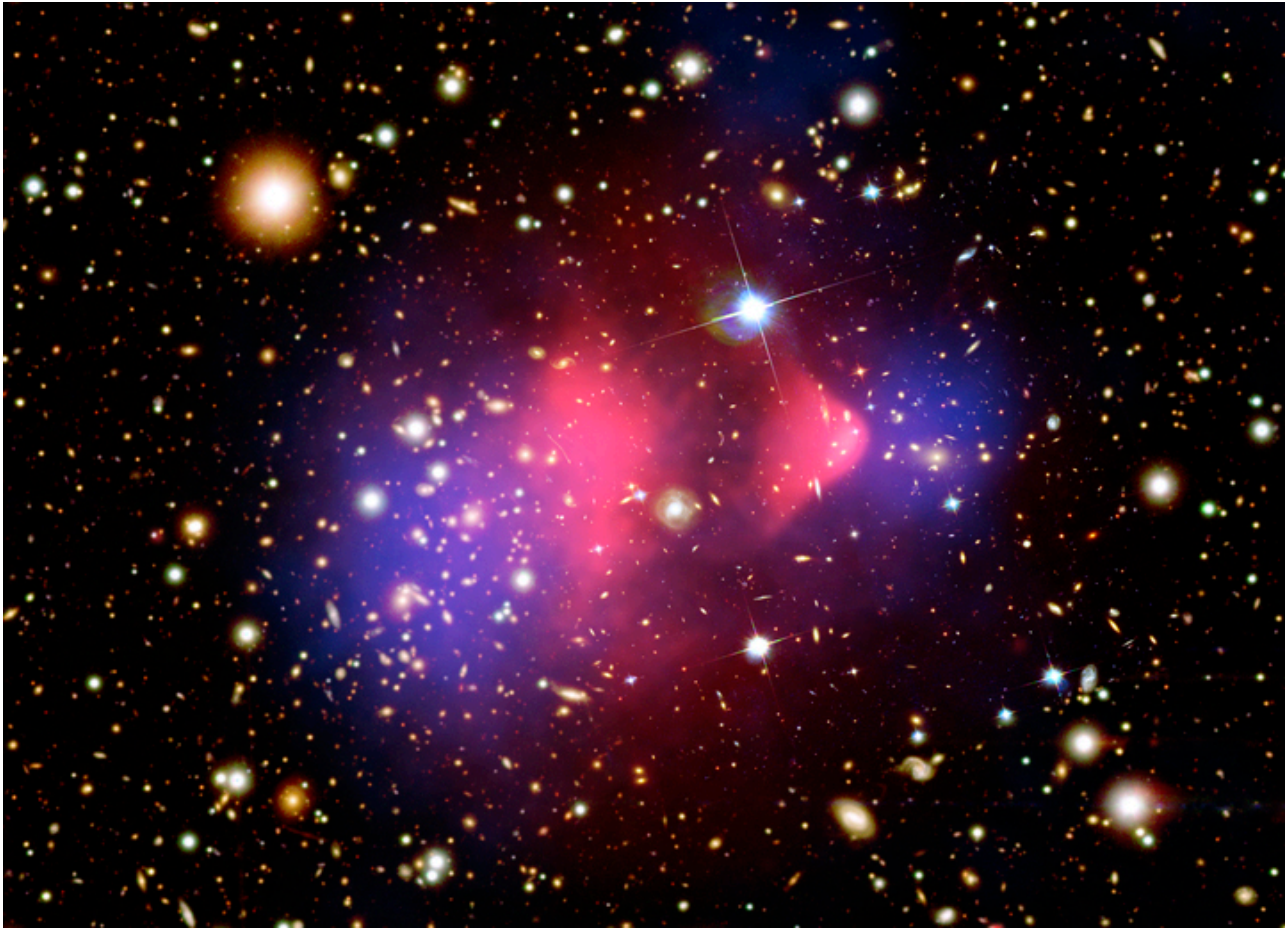
Clusters of galaxies

Clusters problematic



(Sanders & McGaugh 2002)

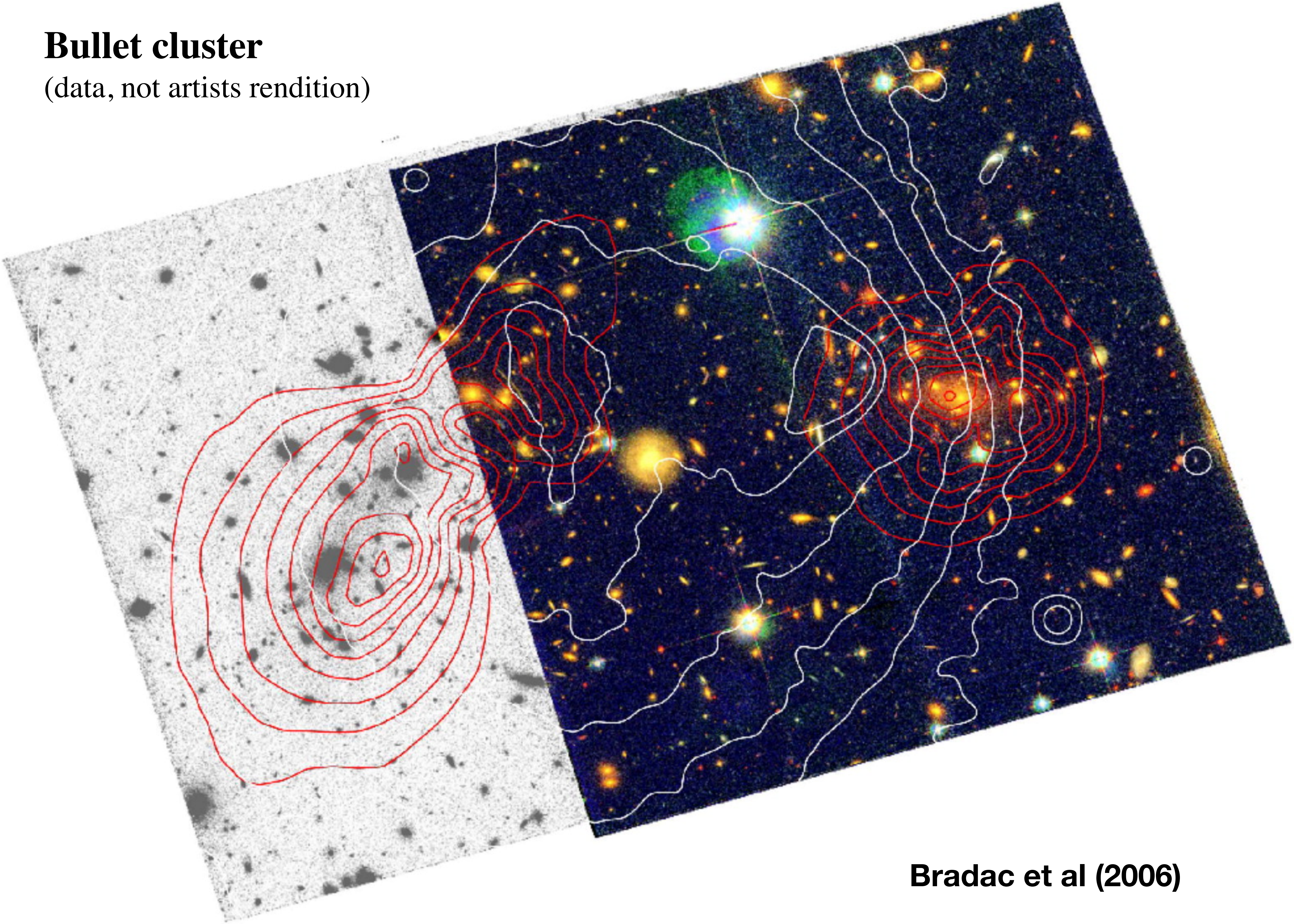
1E 0657-56 - “bullet” cluster (Clowe et al. 2006)



direct proof of dark matter?

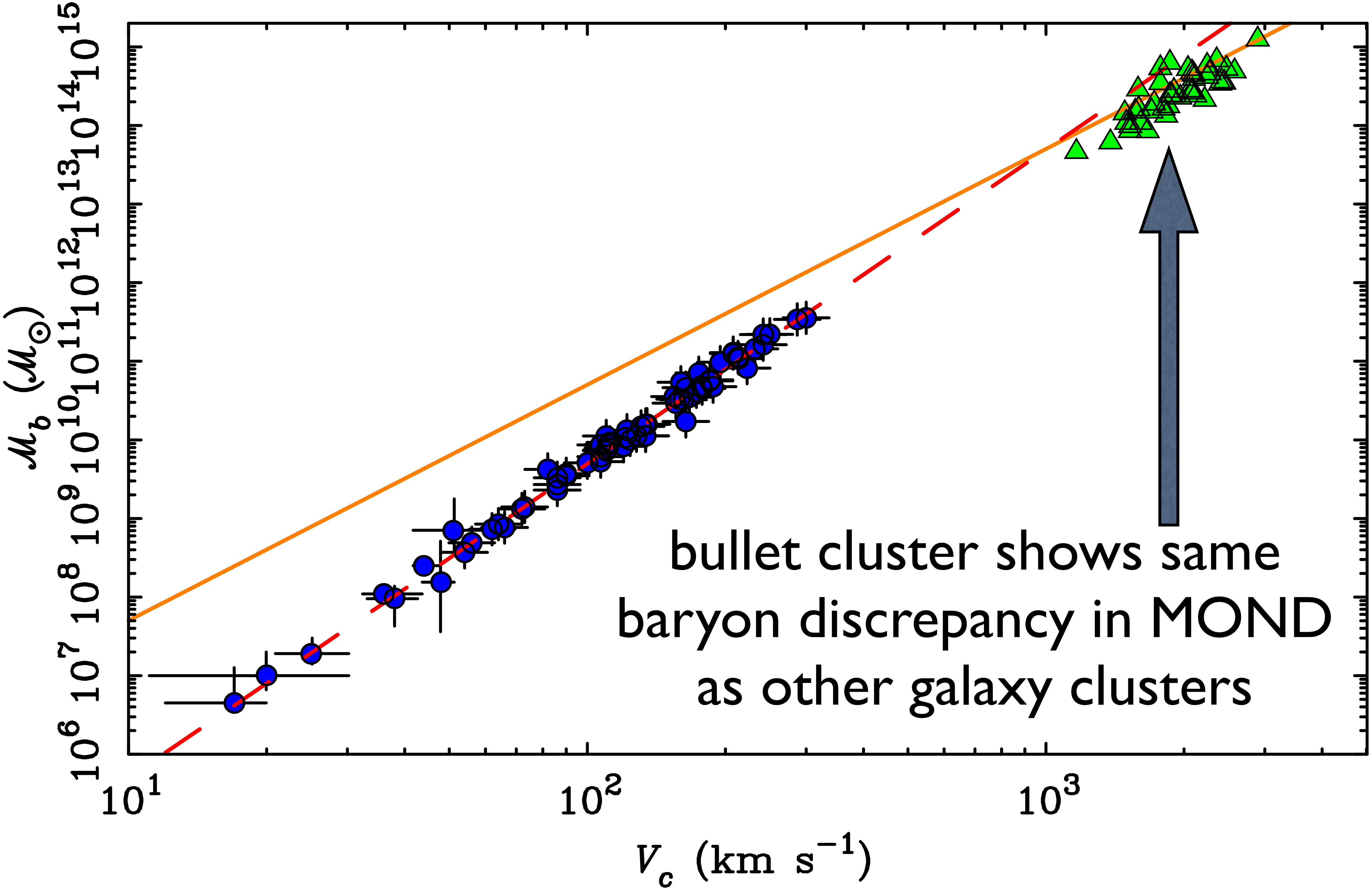
Bullet cluster

(data, not artists rendition)



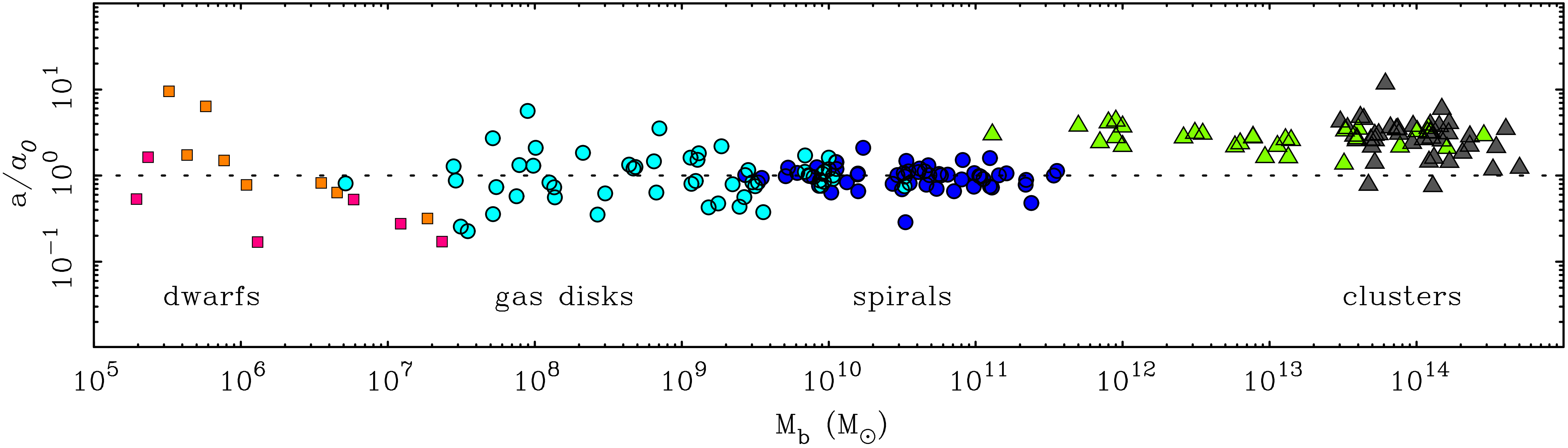
Bradac et al (2006)

It isn’t just the bullet cluster. All clusters show a discrepancy from MOND



bullet cluster shows same baryon discrepancy in MOND as other galaxy clusters

Data for groups & cluster offset from MOND prediction, but slope pretty good over many decades in baryonic mass.

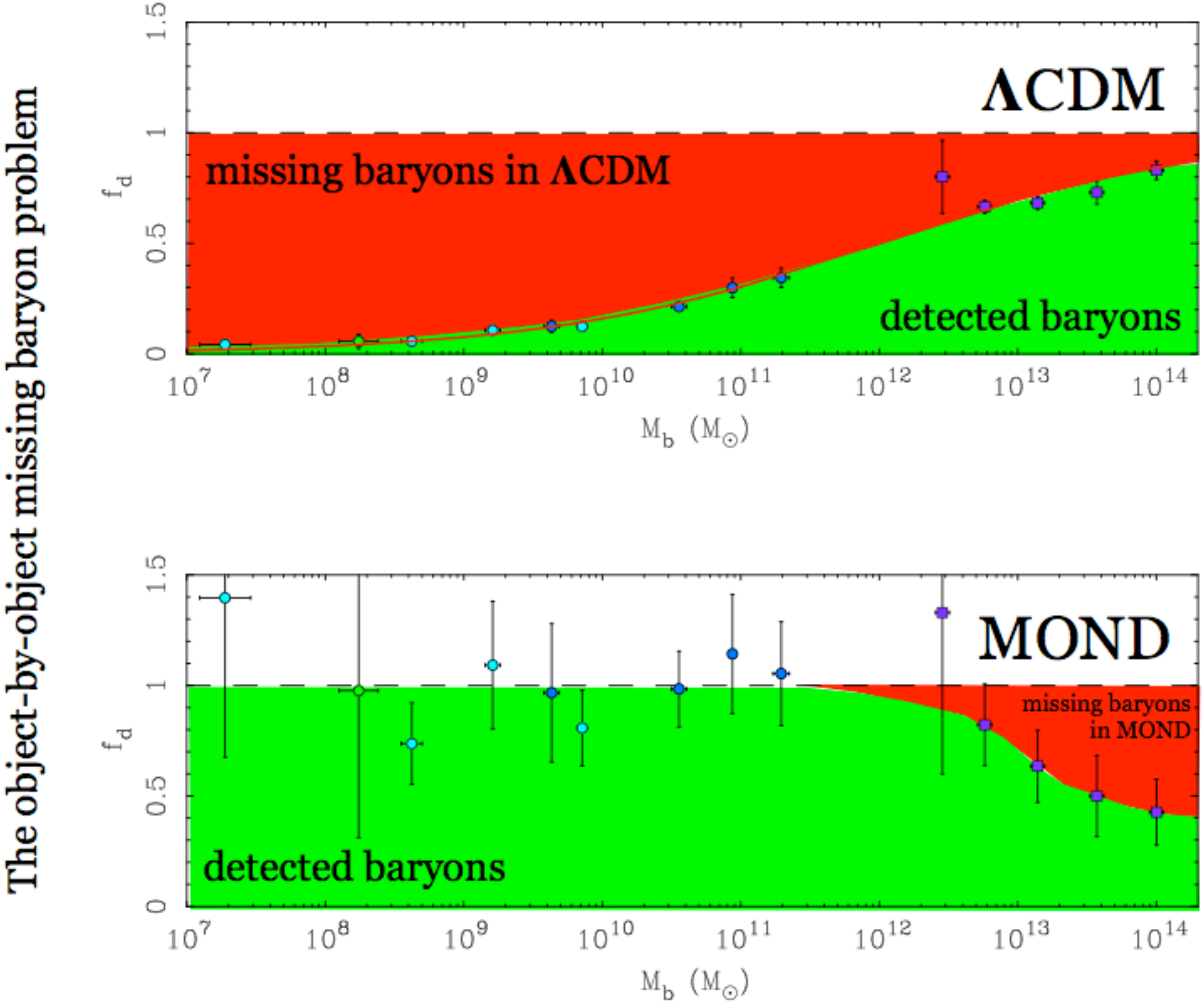


$$a_0 = 1.2 \times 10^{-10}\ \mathrm{m\,s^{-2}} \approx \frac{cH_0}{2\pi} \approx c\Lambda^{1/2}$$

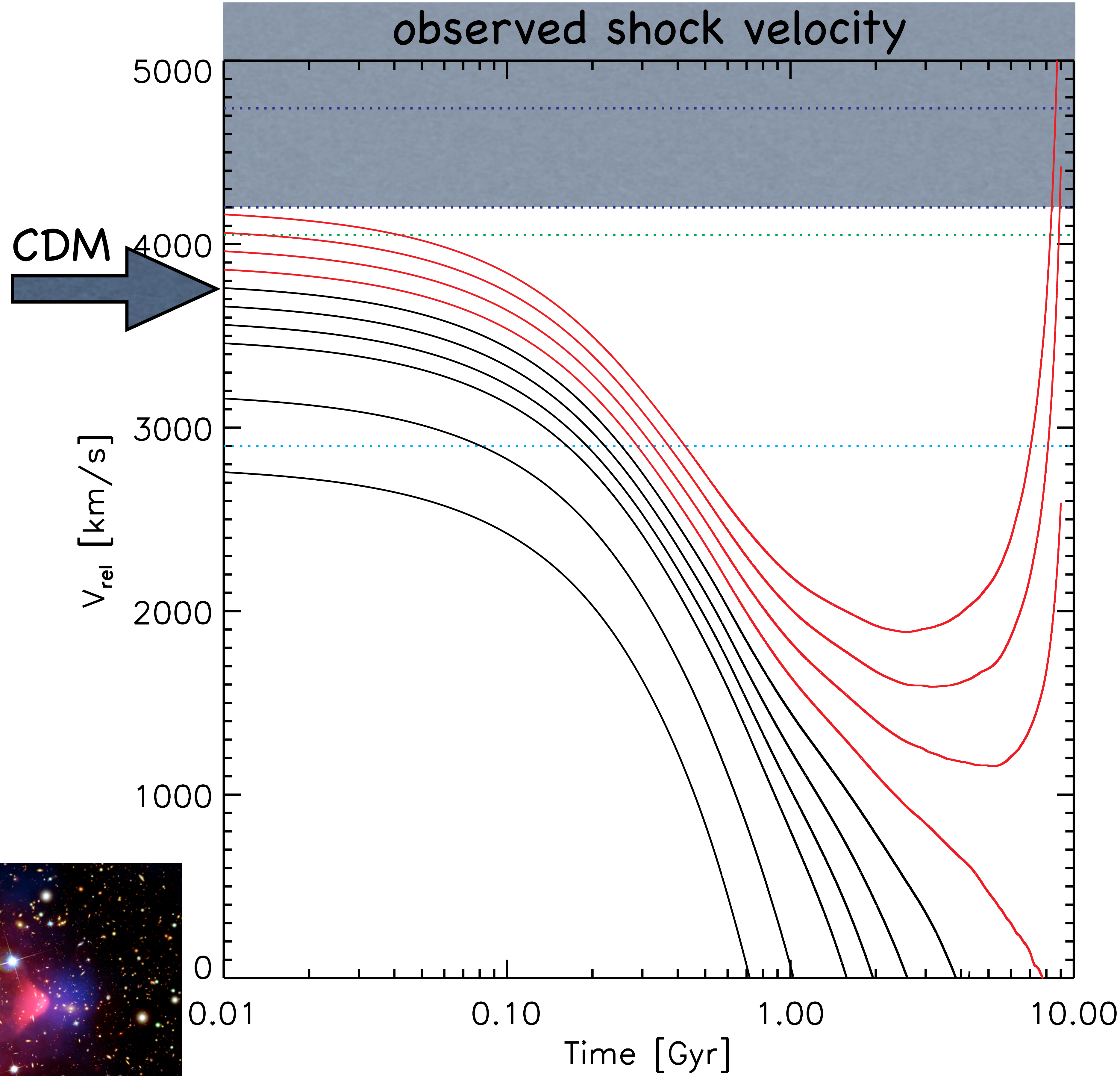
$$\Sigma_\dagger = 860\ \mathrm{M_\odot\,pc^{-2}}$$

The MOND scale is in the data.

Both paradigms suffer a missing baryon problem

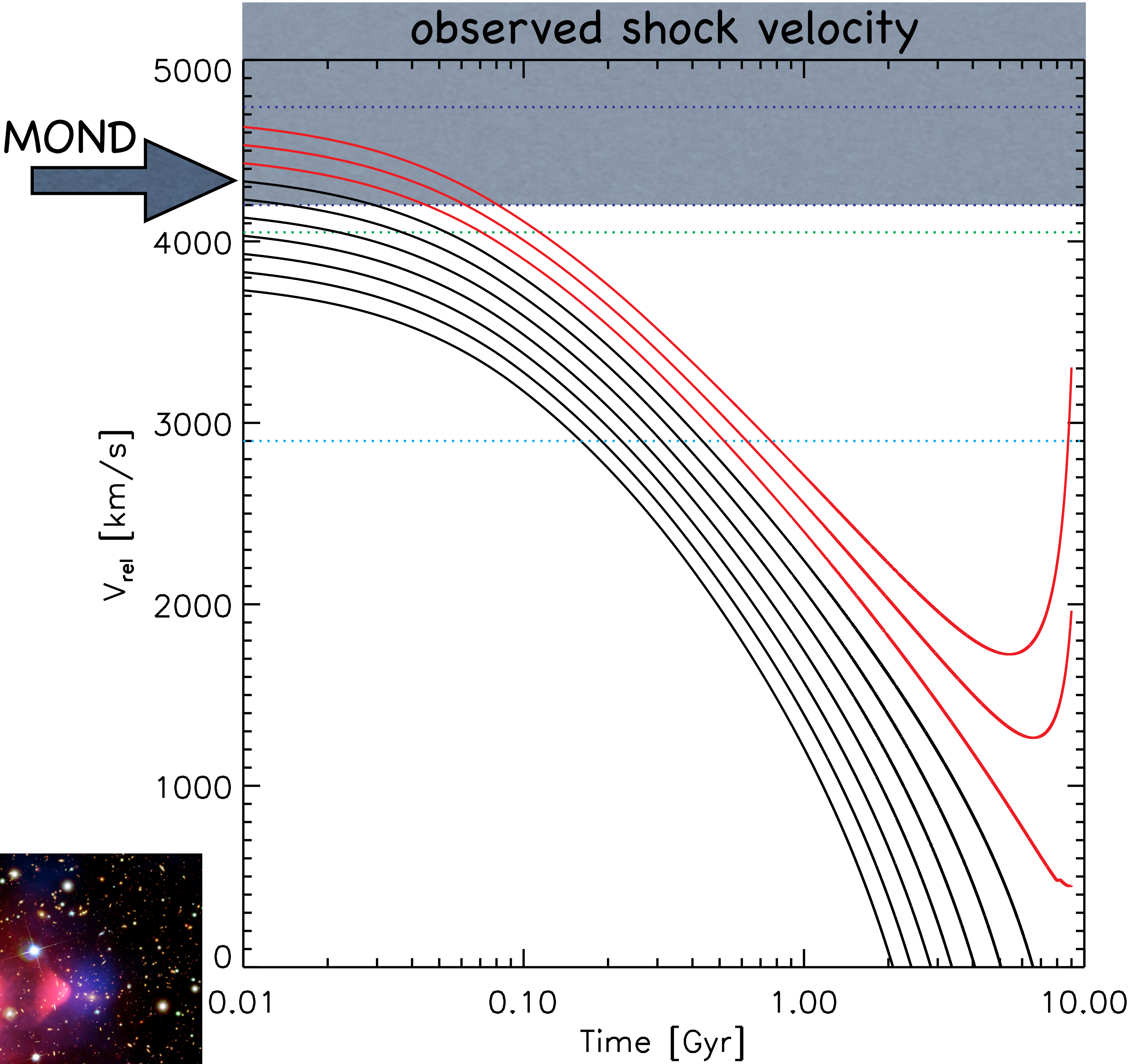


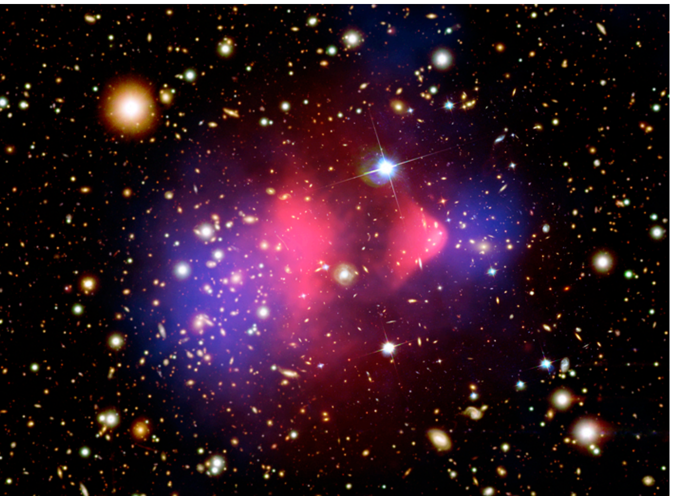
The bullet cluster collision velocity provides another test



Angus & McGaugh (2008) MNRAS, 383, 417

The bullet cluster collision velocity provides another test



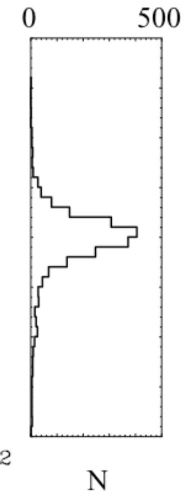


Angus & McGaugh (2008) MNRAS, 383, 417

Bullet cluster

- Mass discrepancy more naturally explained with dark matter.
- Collision velocity more naturally explained with MOND.
  - Predicts that high collisions should be more frequent than expected in LCDM

MOND predictions



- The Tully-Fisher Relation
  - ✓ Slope = 4 ★
  - ✓ Normalization = $1/(a_0G)$ ★
  - ✓ Fundamentally a relation between Disk Mass and V_{flat} ★
  - ✓ No Dependence on Surface Brightness
- ✓ Dependence of conventional M/L on radius and surface brightness ★
- ✓ Rotation Curve Shapes ★
- ✓ Surface Density ~ Surface Brightness
- ✓ Detailed Rotation Curve Fits ★
- ✓ Stellar Population Mass-to-Light Ratios

- Disk Stability
  - ✓ Freeman limit in surface brightness distribution
  - ✓ thin disks
  - ✓ velocity dispersions
  - ✓ LSB disks not over-stabilized
- ✓ Dwarf Spheroidals ★
- ✓ Giant Ellipticals

New Andromeda dwarfs and Crater 2 velocity dispersions predicted correctly in advance

- ✗ Clusters of Galaxies
- ? Structure Formation —

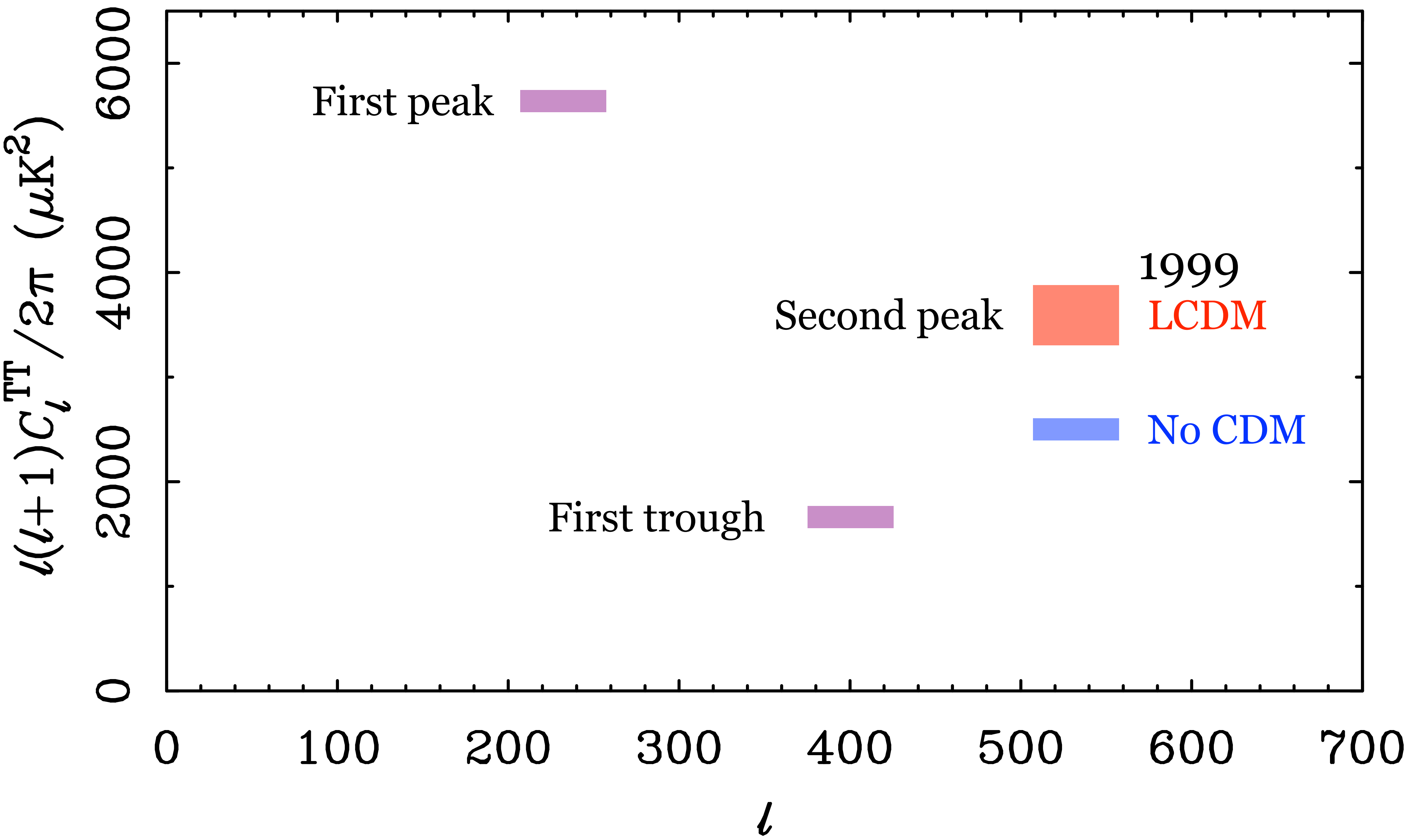
Sanders (1998)
First galaxies z > 10 ★
cosmic web at z = 5 ★
big clusters z > 2
voids swept clear by z = 0

- Microwave background
  - ✓ 1st:2nd peak amplitude; BBN
  - ✓ early reionization
  - enhanced ISW/gravitational lensing
  - ✗ 3rd peak

It's not "just" for galaxies. MOND has had many more successful a priori predictions than LCDM.

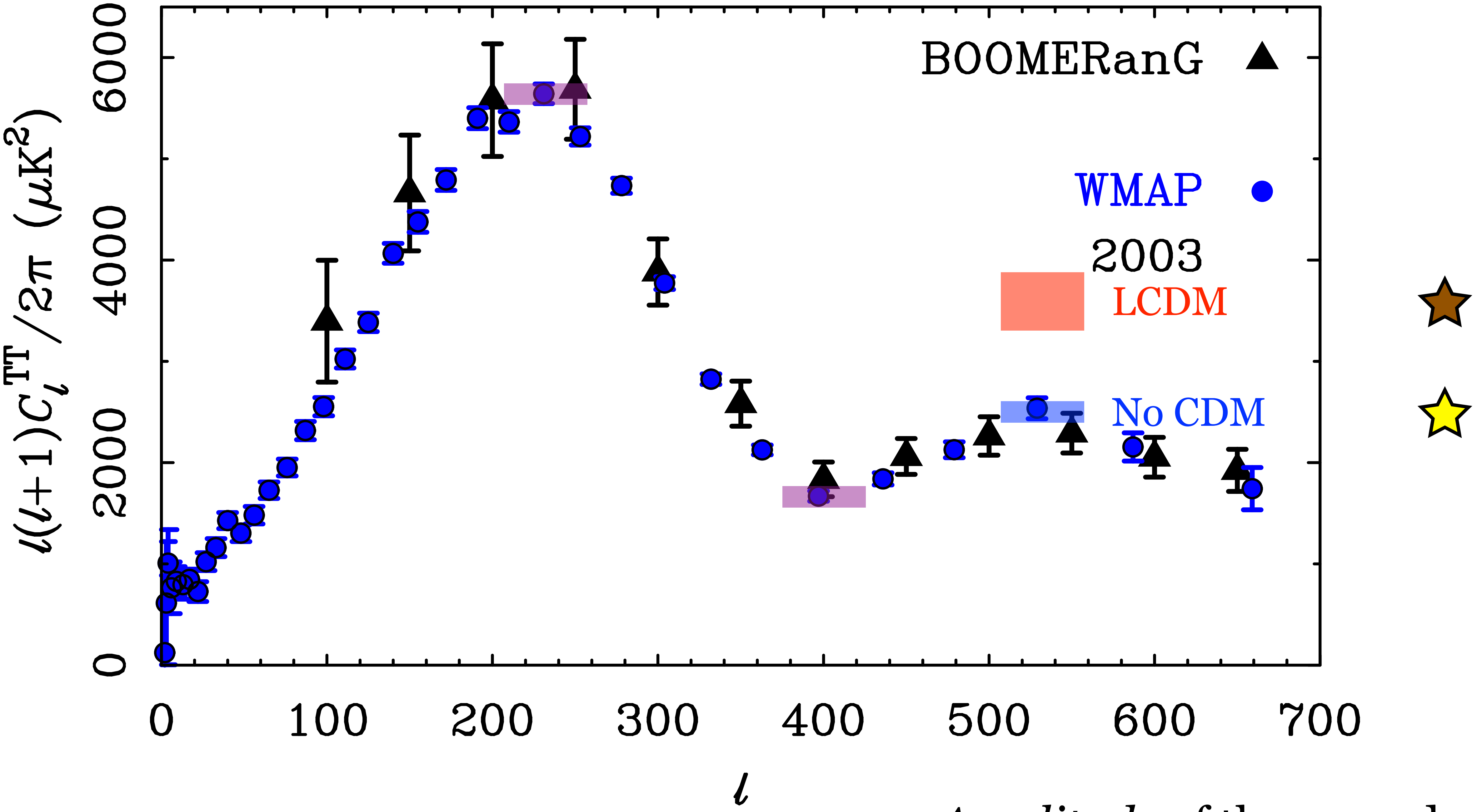
LCDM correctly predicted the *location* of the first peak

No CDM *ansatz* correctly predicted the *amplitude* of the second peak



The models differ only in the presence or absence of CDM.
Full range of then-plausible baryon densities considered. (McGaugh 1999)

Location of the first peak
consistent with flat
FLRW geometry



Amplitude of the second peak
consistent with No CDM

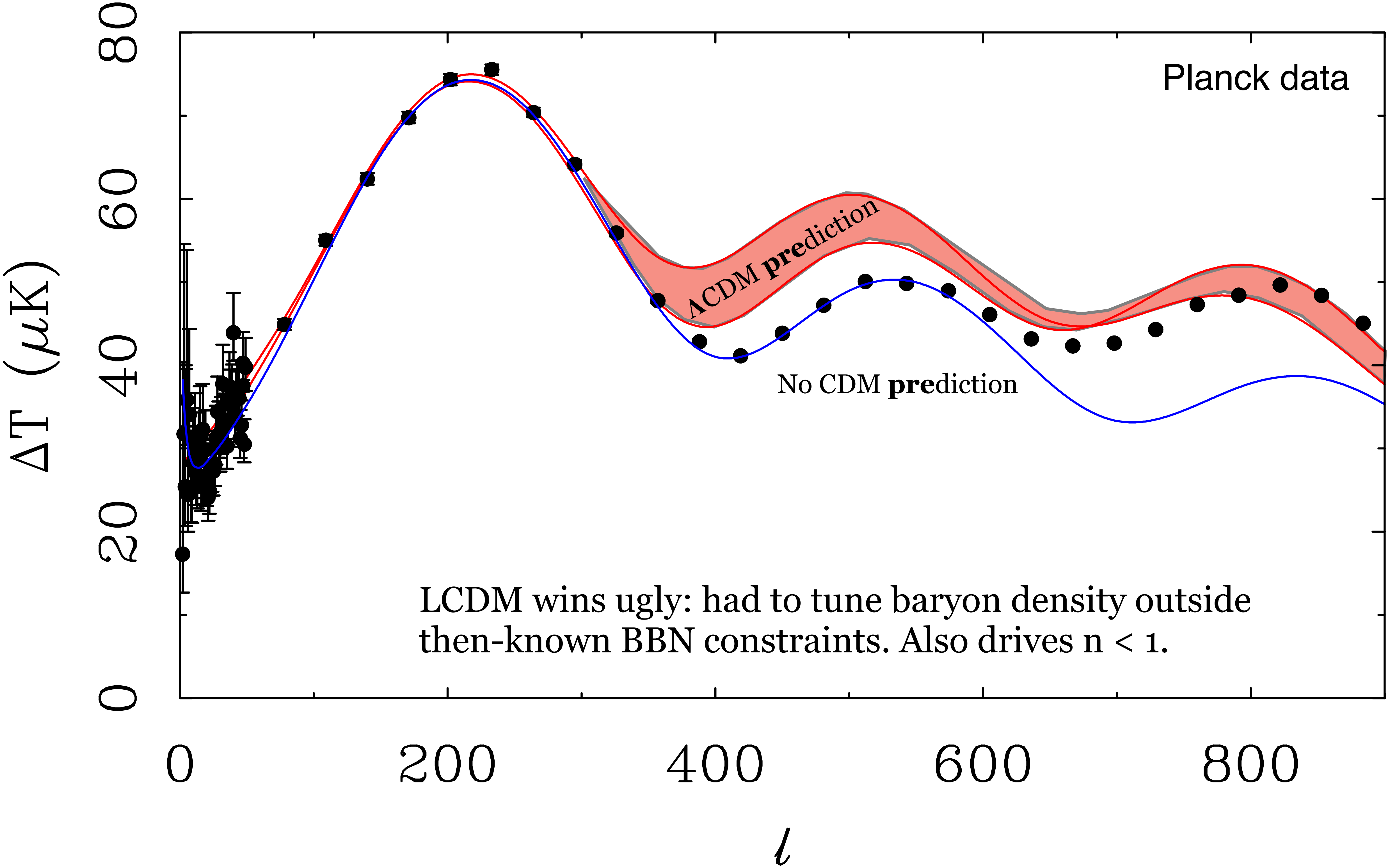
(McGaugh 2004)

The prediction for the first:second peak amplitude ratio by McGaugh (1999) remains accurate in modern data.

ΛCDM prediction misses 2nd peak but can be tuned by increasing the baryon density ★

★ X

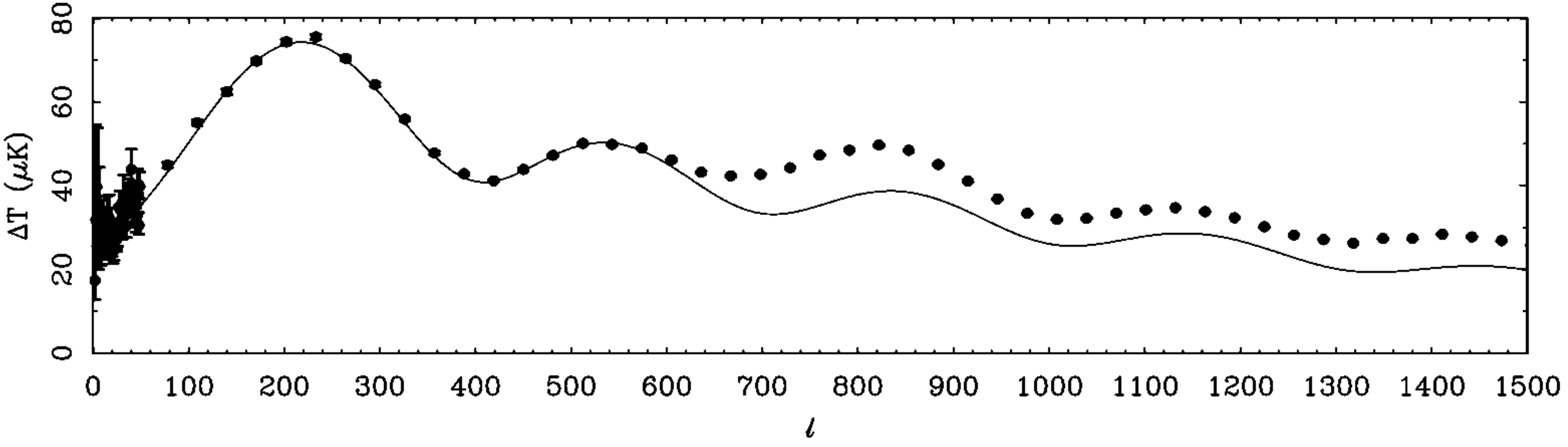
No CDM prediction nails 2nd peak but misses 3rd; cannot be tuned



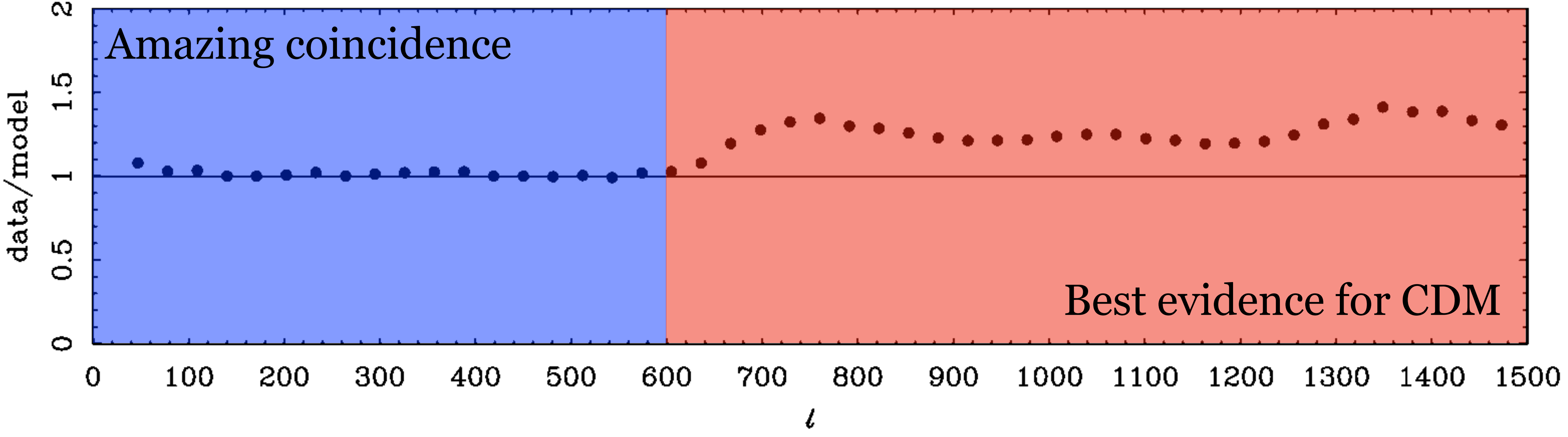
LCDM wins ugly: had to tune baryon density outside then-known BBN constraints. Also drives n < 1.

This falsifies the No CDM ansatz, which had to fail at some level. It does not test MOND itself.

No CDM model from McGaugh (2004) compared to Planck (2013) data



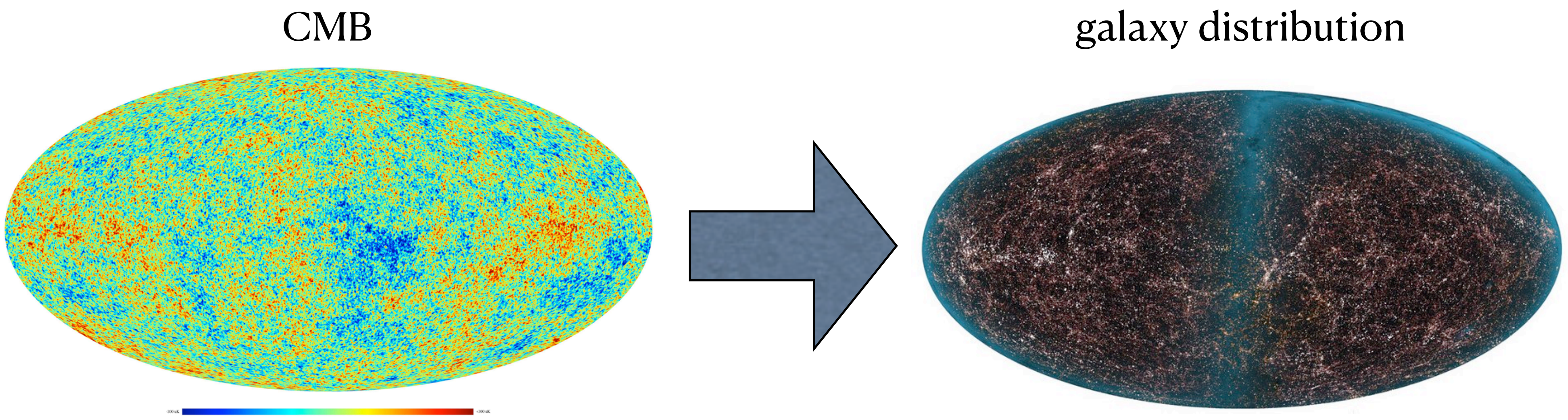
High multipole data also where tension with other constraints starts to bite


Amazing coincidence

Best evidence for CDM

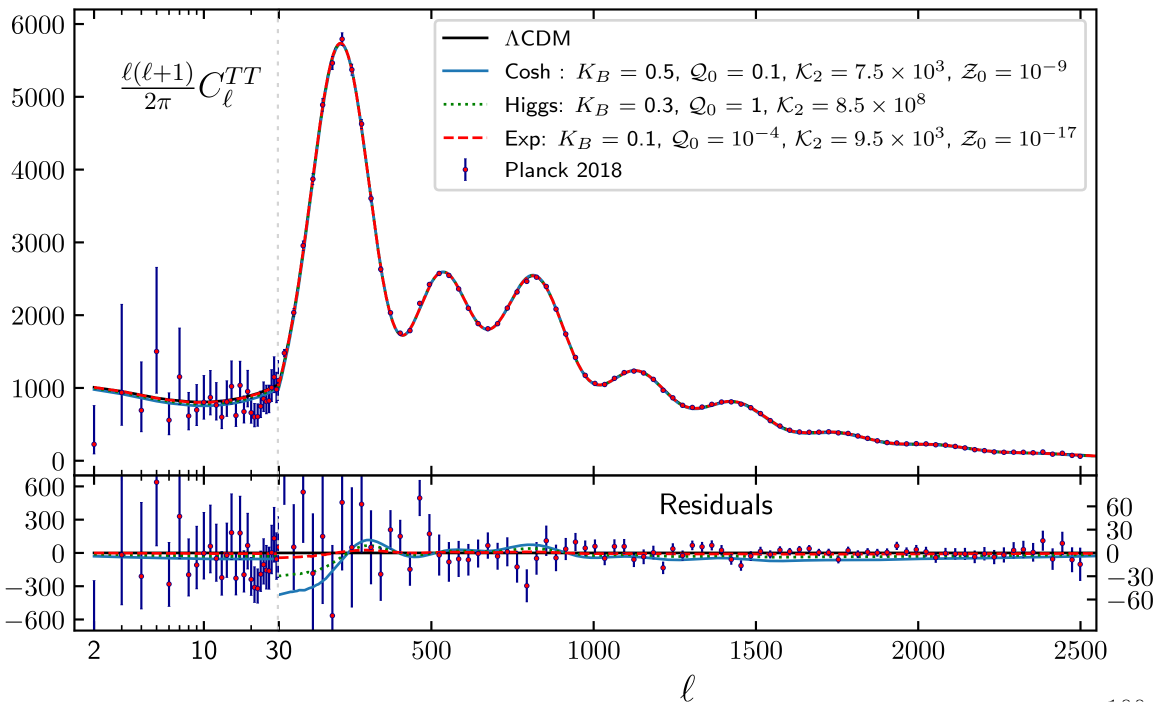
This falsifies the No CDM ansatz, which had to fail at some level. It does not test MOND itself.

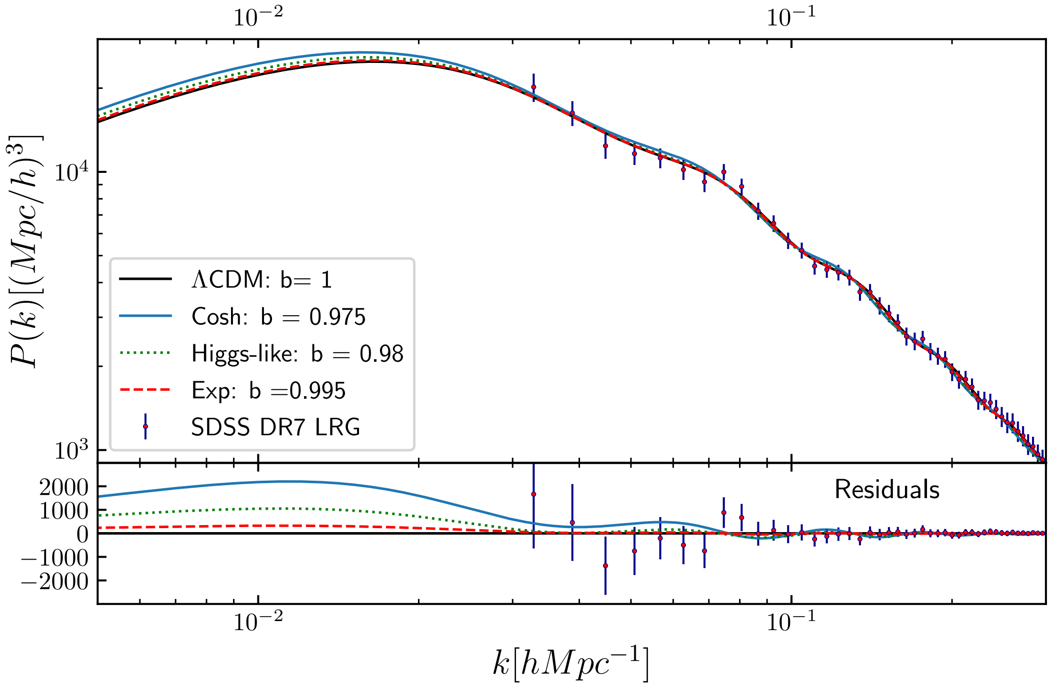
Power spectrum in Relativistic MOND (RMOND)


CMB

galaxy distribution

The third peak has remained problematic for over a decade until this recent work by Skordis & Zlosnik (2021)



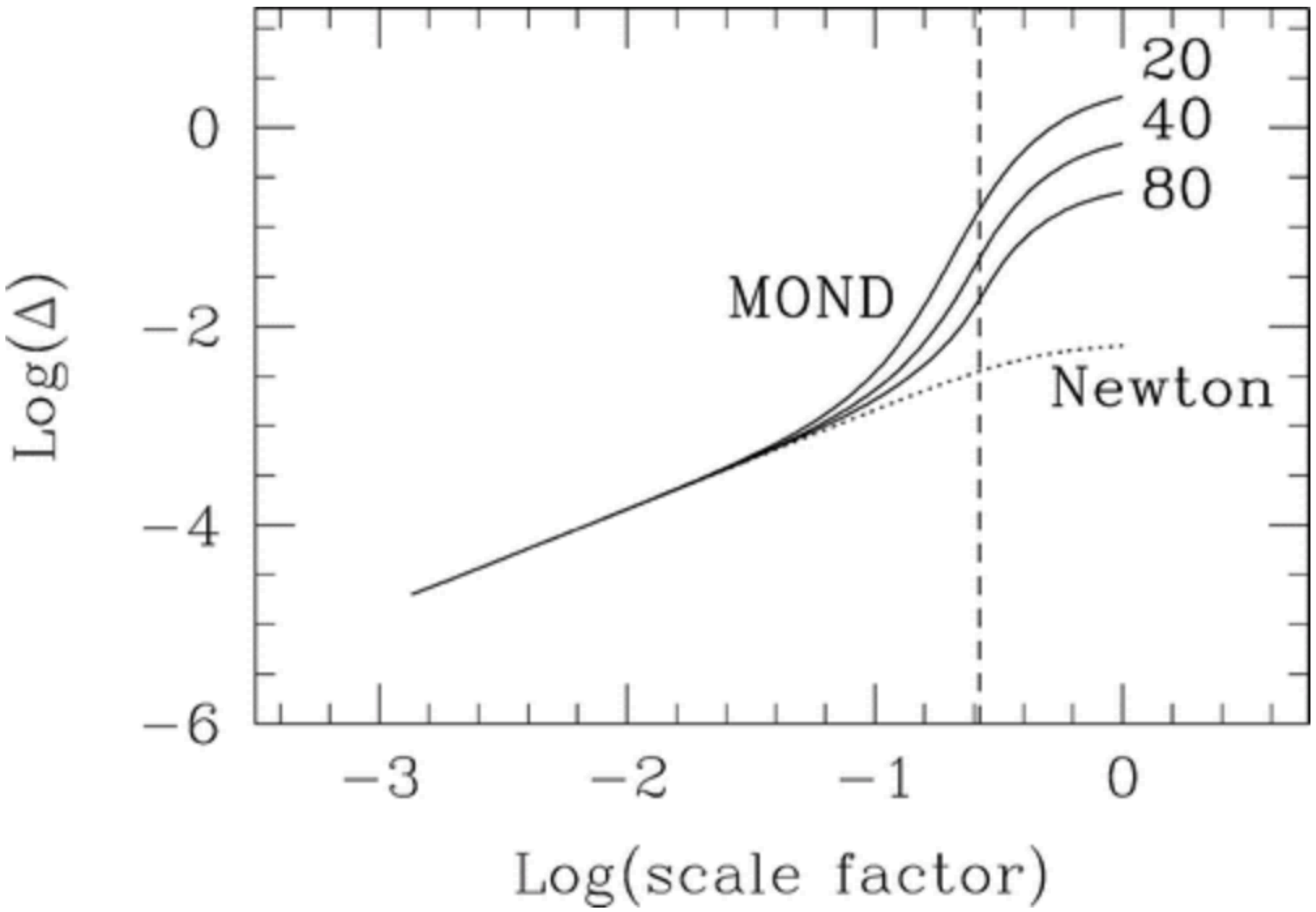


RMOND: Skordis & Zlosnik (2021) Phys. Rev. Lett. 127, 161302. doi:10.1103/PhysRevLett.127.161302

Structure formation in MOND

- Initially, at the time of recombination, the universe is very nearly homogeneous.
- Radiation domination persist until a later epoch than conventionally owing to the lower mass density. Unlike the case of CDM where density perturbations can grow in the dark sector, the initial growth of density perturbations is suppressed until matter domination (z ≈ 200).
- Once released by the photons, expanding overdensities suddenly find themselves deep in the MOND regime, and act like they have a lot of dark matter.
- Structure formation proceeds qualitatively as it would conventionally (MOND is, after all, just a boost to Newton), but structure forms harder and faster.

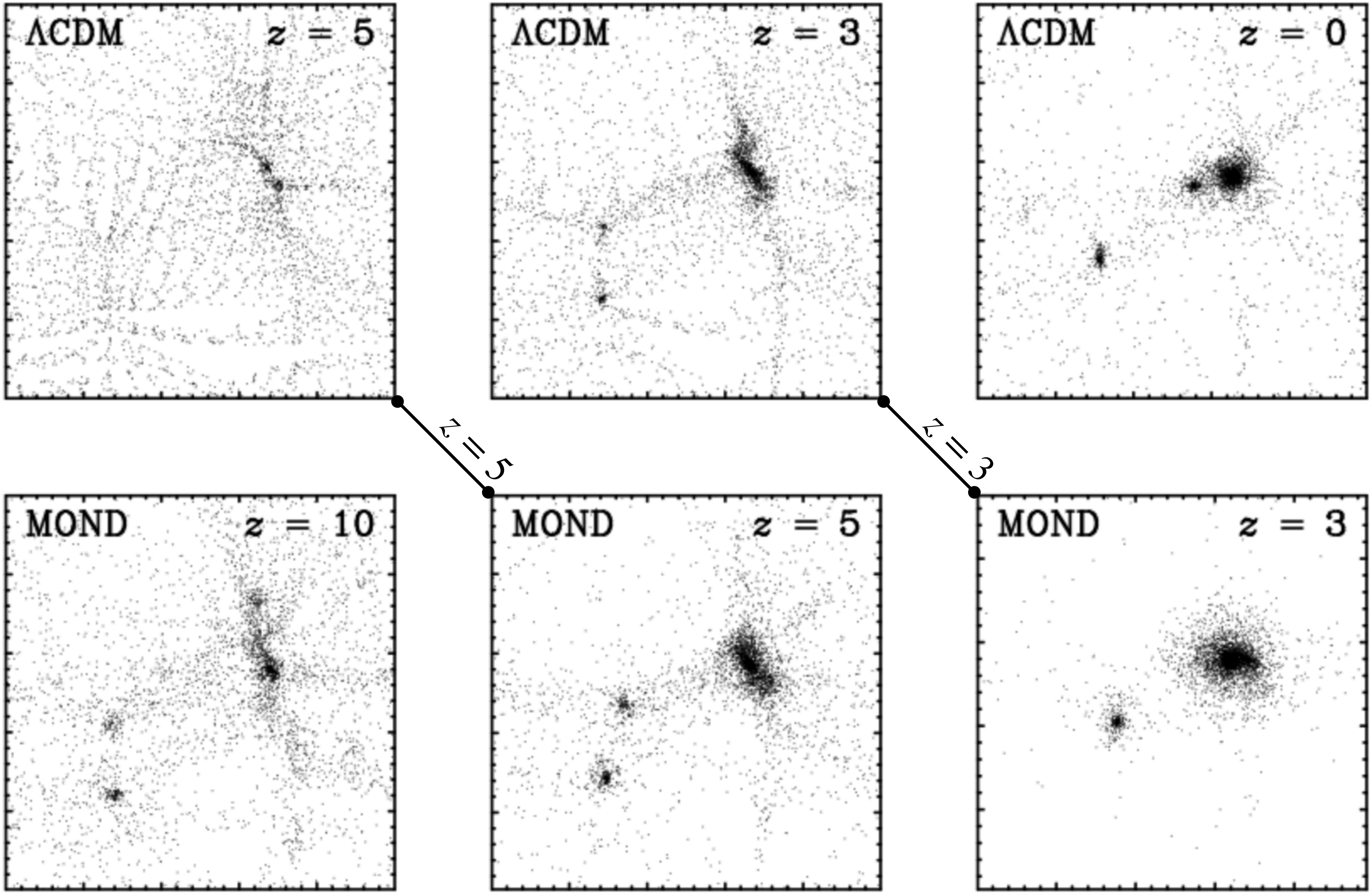
The growth of overdensities in MOND



The growth of spherically symmetric over-densities in a low-density baryonic universe as a function of scale factor in the context of a two-field Lagrangian theory of MOND. The solid curves correspond to regions with comoving radii of 20, 40, and 80 Mpc. The dotted line is the corresponding Newtonian growth. With MOND, smaller regions enter the low-acceleration regime sooner and grow to larger final amplitude. The vertical dashed line indicates the epoch at which the cosmological constant begins to dominate the Hubble expansion. [Reproduced from Sanders & McGaugh 2002.]

http://astroweb.case.edu/ssm/mond/LSSinMOND.html

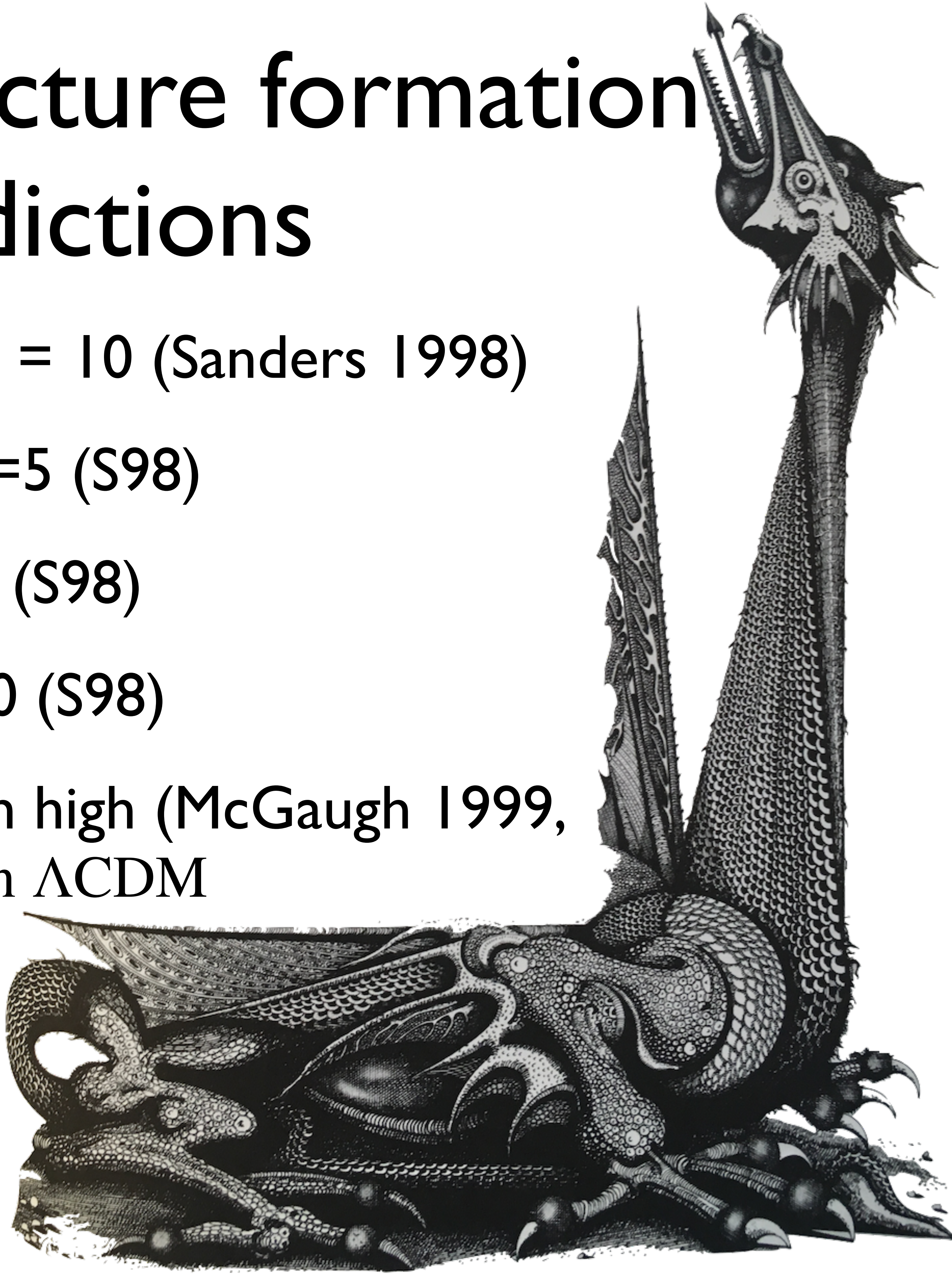
Simulated structure formation in ΛCDM and MOND



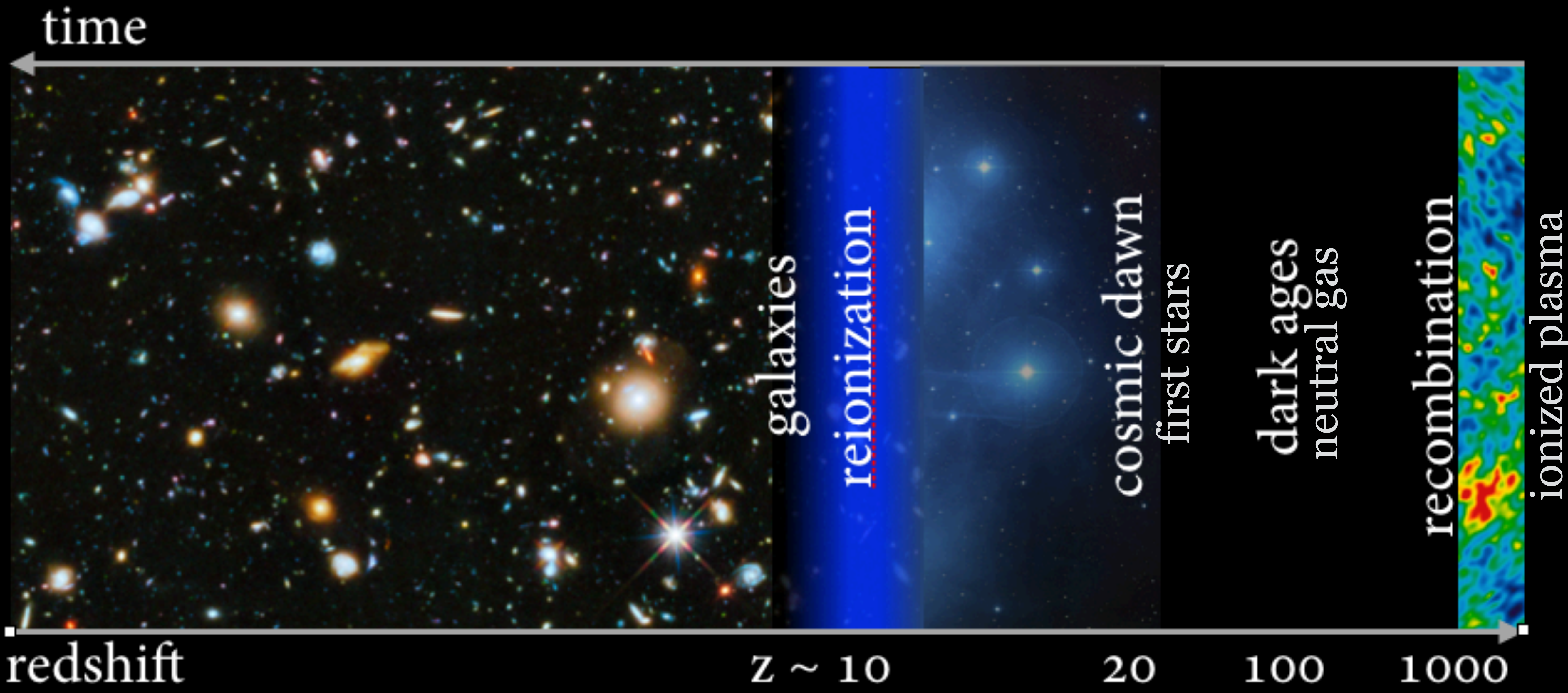
MOND Structure formation predictions

- ✓ L* galaxies from around z = 10 (Sanders 1998)
- Cosmic web in place at z=5 (S98)
- ✓ Big clusters form at z > 2 (S98)
- ✓ Voids swept clear by z = 0 (S98)
- Reionization optical depth high (McGaugh 1999, 2004) $\tau \approx 0.17$ vs . 0.06 in ΛCDM

See also
Nusser (2002)
Stachniewicz & Kutschera (2002)
Skordis et al (2005)
Llinares et al (2008)
Feix 2016



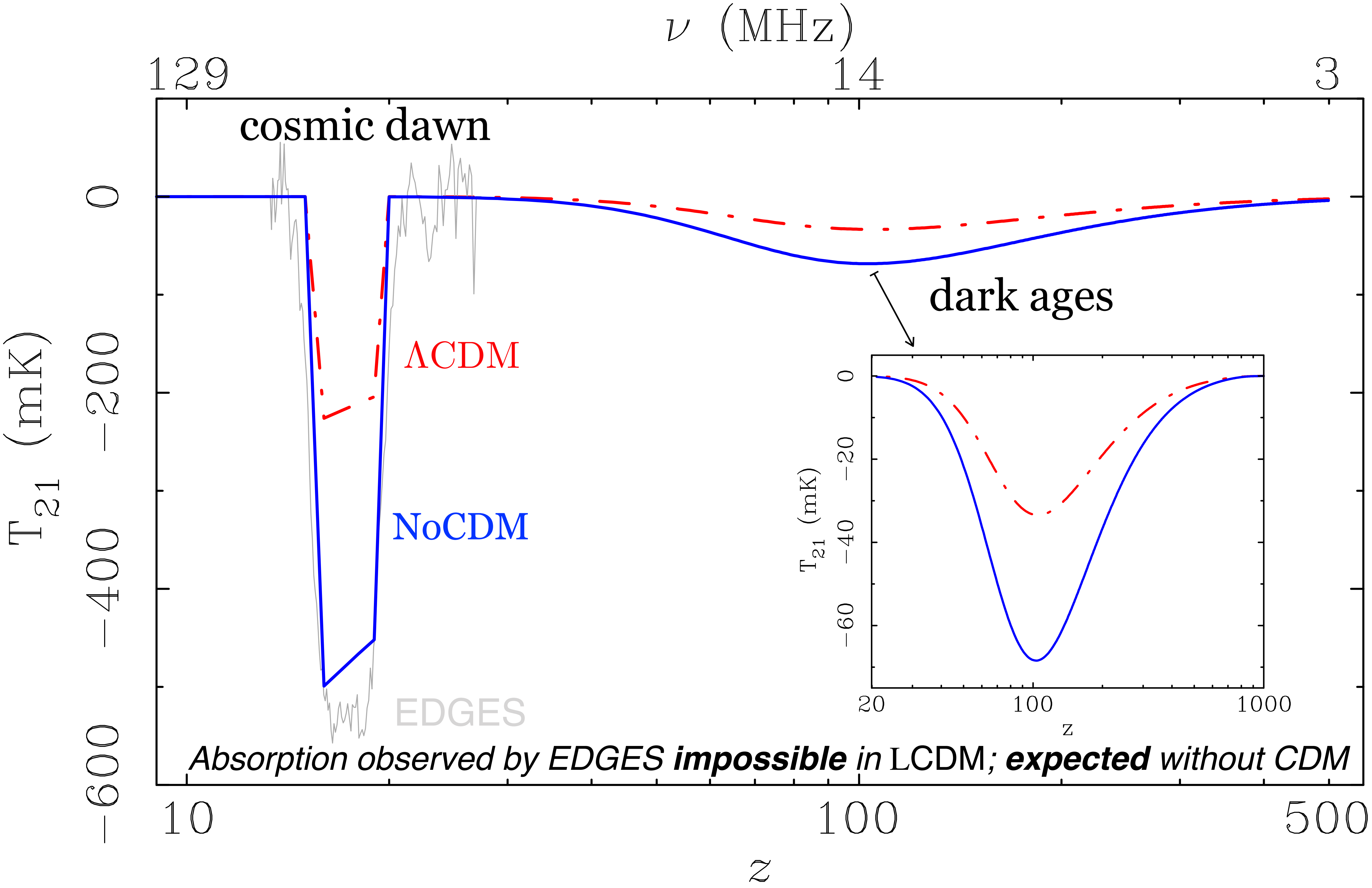
Upcoming test: 21 cm absorption at high redshift



Radio wavelength photons traveling to us from the epoch of recombination can be absorbed by neutral gas during the dark ages and at cosmic dawn

2004 model prediction for 21 cm absorption at high redshift

McGaugh, S.S. 2018, PRL, 121, 081305



Absorption observed by EDGES ***impossible*** *in* LCDM; ***expected*** *without CDM*

WAYS OUT

Falsify LCDM

Is this even possible?

- Dynamical Friction
  - Galaxies (Kroupa)
- Neutrino Mass
  - constrained to narrow range

$$0.06 < \sum m_\nu < 0.12\mathrm{eV}$$

A larger neutrino mass
would be a falsification

- Cosmic Dawn
  - strong absorption
  - less power early; more late

Falsify MOND

Has this already happened?

- Genuine mis-fit
  - (MOND RCs, dSph)
- Galaxies lacking a mass discrepancy
  - TDGs, UDGs
- Detect the DM already
  - need a convincing signal

Why does MOND get *any* prediction right?