DARK MATTER

ASTR 333/433
SPRING 2026
TR 11:30AM–12:45PM
SEARS 552

http://astroweb.case.edu/ssm/ASTR333/

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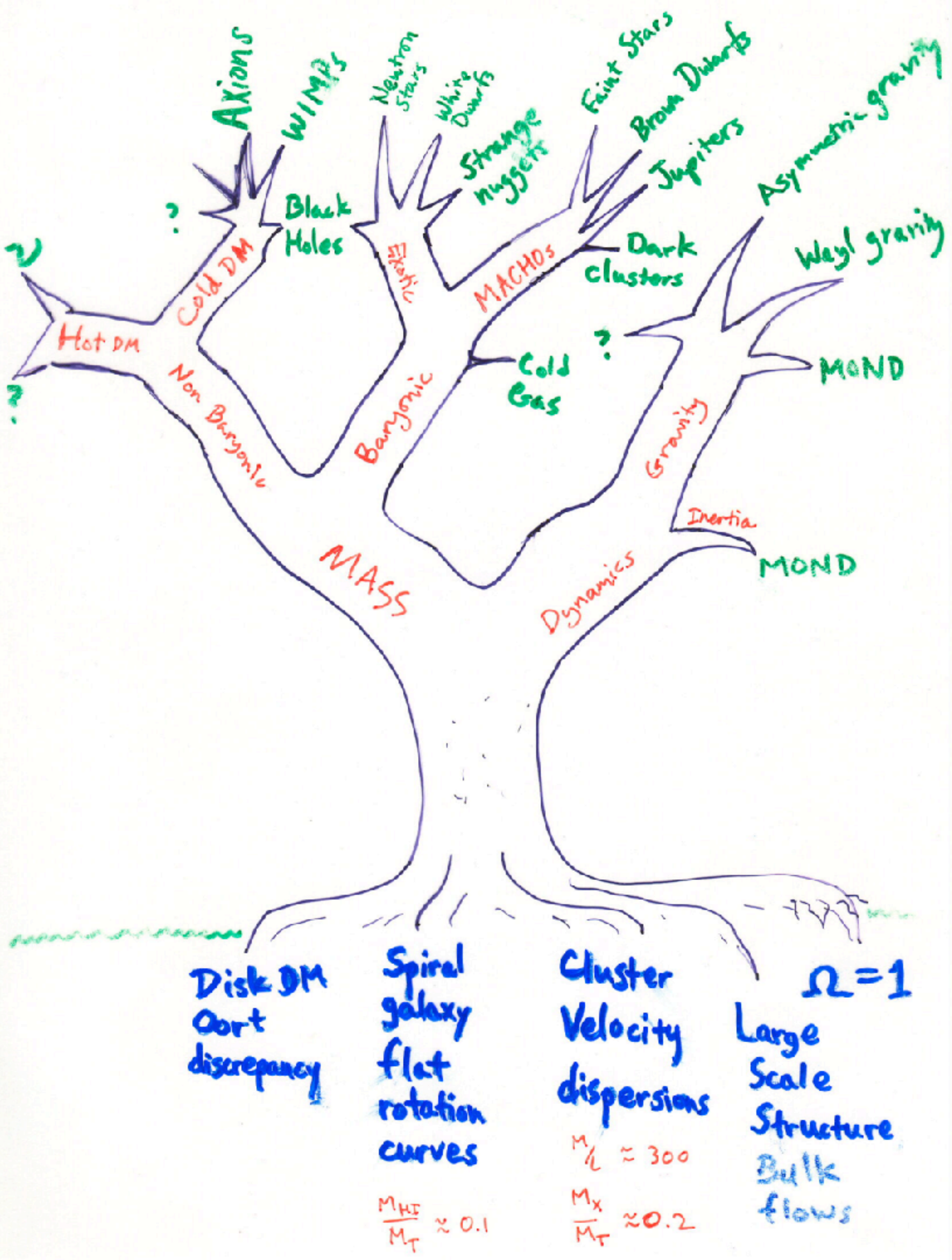


CASE WESTERN RESERVE
UNIVERSITY
EST. 1826

Equivalence Principle

Foundation of General Relativity

Gravitational Charge = Inertial Mass

$$m_g = m_i$$

Relates Newton's universal gravitation

$$F = \frac{GM}{r^2} m_g$$

with Newton's second law of motion

$$F = m_i a$$

to give universal free-fall independent of mass or composition

$$a = \frac{GM}{r^2}$$

$= 9.8\ \mathrm{m\,s^{-2}}$ on the surface of the Earth

Not included:

Mach's principle: the inertial forces experienced by a body in nonuniform motion
are determined by the quantity and distribution of matter in the universe

Equivalence Principle(s)

Foundational to General Relativity

- Weak Equivalence Principle
  - Universality of free fall (lead and feathers fall the same)
- Einstein Equivalence Principle
  - Free fall + Lorentz Invariance

The results of experiments are the same for all observers that are moving with respect to one another within an inertial frame

- Strong Equivalence Principle
  - Free fall + Lorentz Invariance + Local Position Invariance
    - No preferred frame effects - the results of experiments should not depend on when and where they are performed

The External Field Effect in MOND

Subtly different effects occur in non-isolated systems

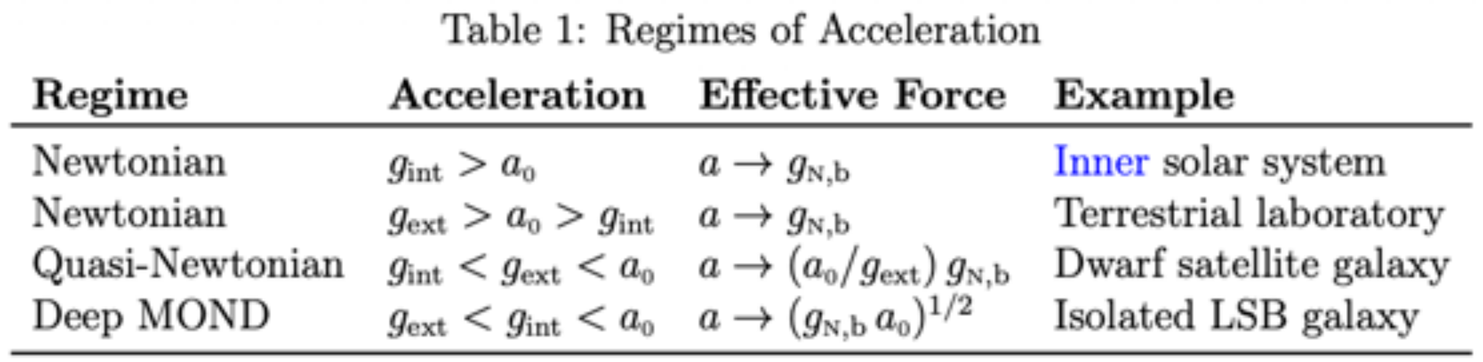


Table 1: Regimes of Acceleration

Regime	Acceleration	Effective Force	Example
Newtonian	$g_{\mathrm{int}} > a_0$	$a \to g_{\mathrm{N,b}}$	Inner solar system
Newtonian	$g_{\mathrm{ext}} > a_0 > g_{\mathrm{int}}$	$a \to g_{\mathrm{N,b}}$	Terrestrial laboratory
Quasi-Newtonian	$g_{\mathrm{int}} < g_{\mathrm{ext}} < a_0$	$a \to (a_0/g_{\mathrm{ext}})\, g_{\mathrm{N,b}}$	Dwarf satellite galaxy
Deep MOND	$g_{\mathrm{ext}} < g_{\mathrm{int}} < a_0$	$a \to (g_{\mathrm{N,b}}\, a_0)^{1/2}$	Isolated LSB galaxy

- 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

Violates Strong Equivalence Principle

specifically Local Position Invariance

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

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

Newtonian regime

$$g_{in} > a_0 \qquad M = \frac{RV^2}{G}$$

e.g., surface of the Earth

MOND regime

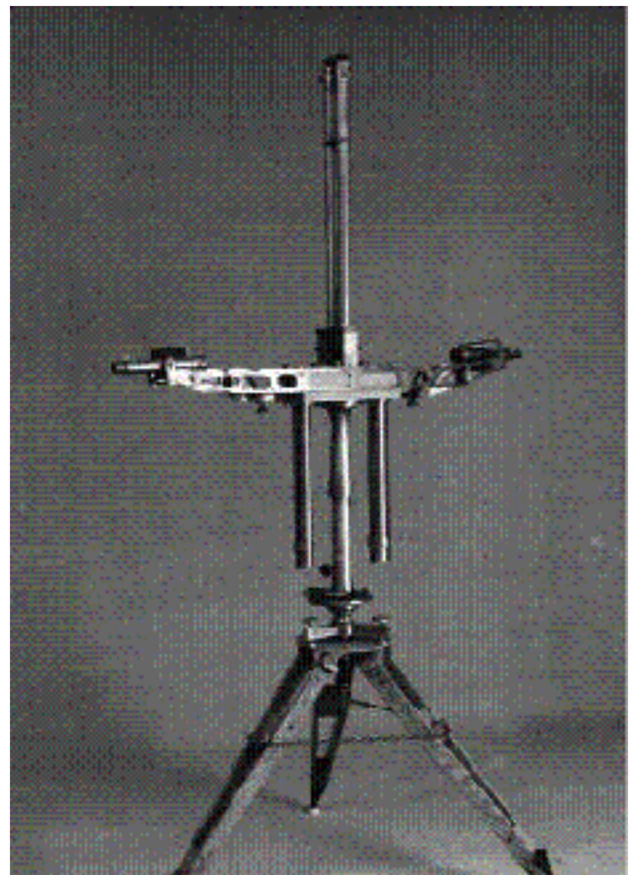
$$g_{in} < a_0 \qquad M = \frac{V^4}{a_0 G}$$

e.g., remote dwarf Leo I

© Anglo-Australian Observatory

External Field dominant Newtonian regime

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



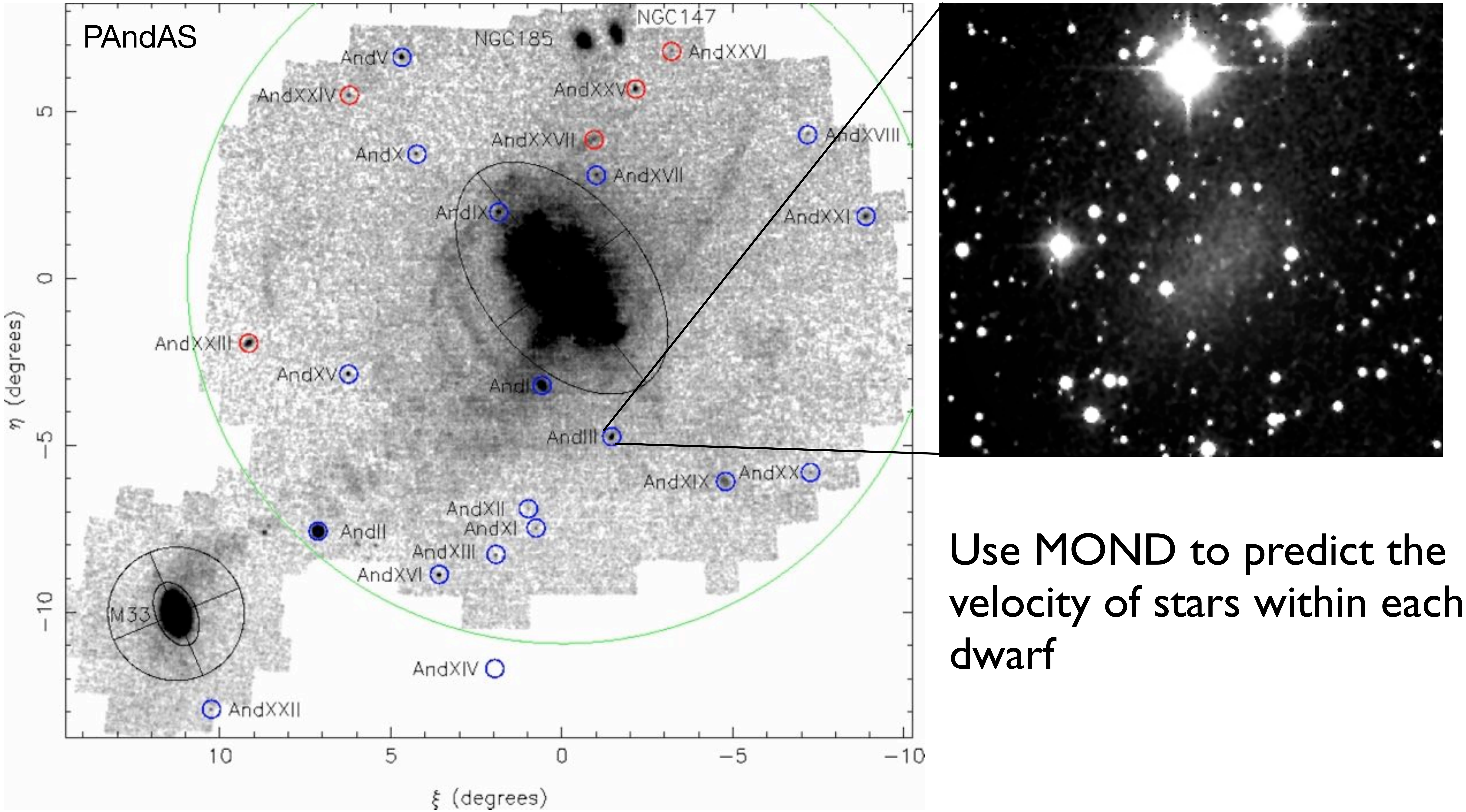
e.g., Eotvos-type experiment on the surface of the Earth

External Field dominant quasi-Newtonian regime

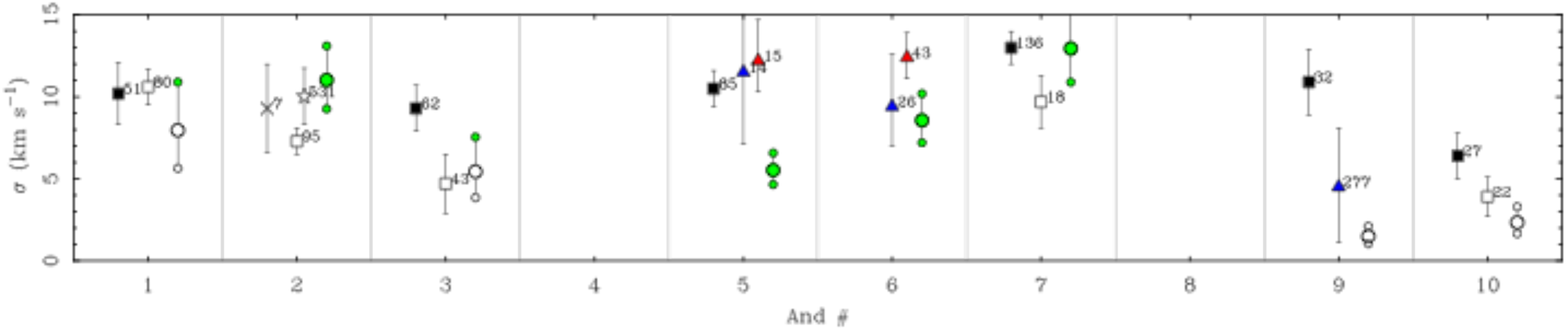
$$g_{in} < g_{ex} < a_0 \qquad M = \frac{a_0}{g_{ex}}\frac{RV^2}{G}$$

e.g., nearby Sgr dwarf

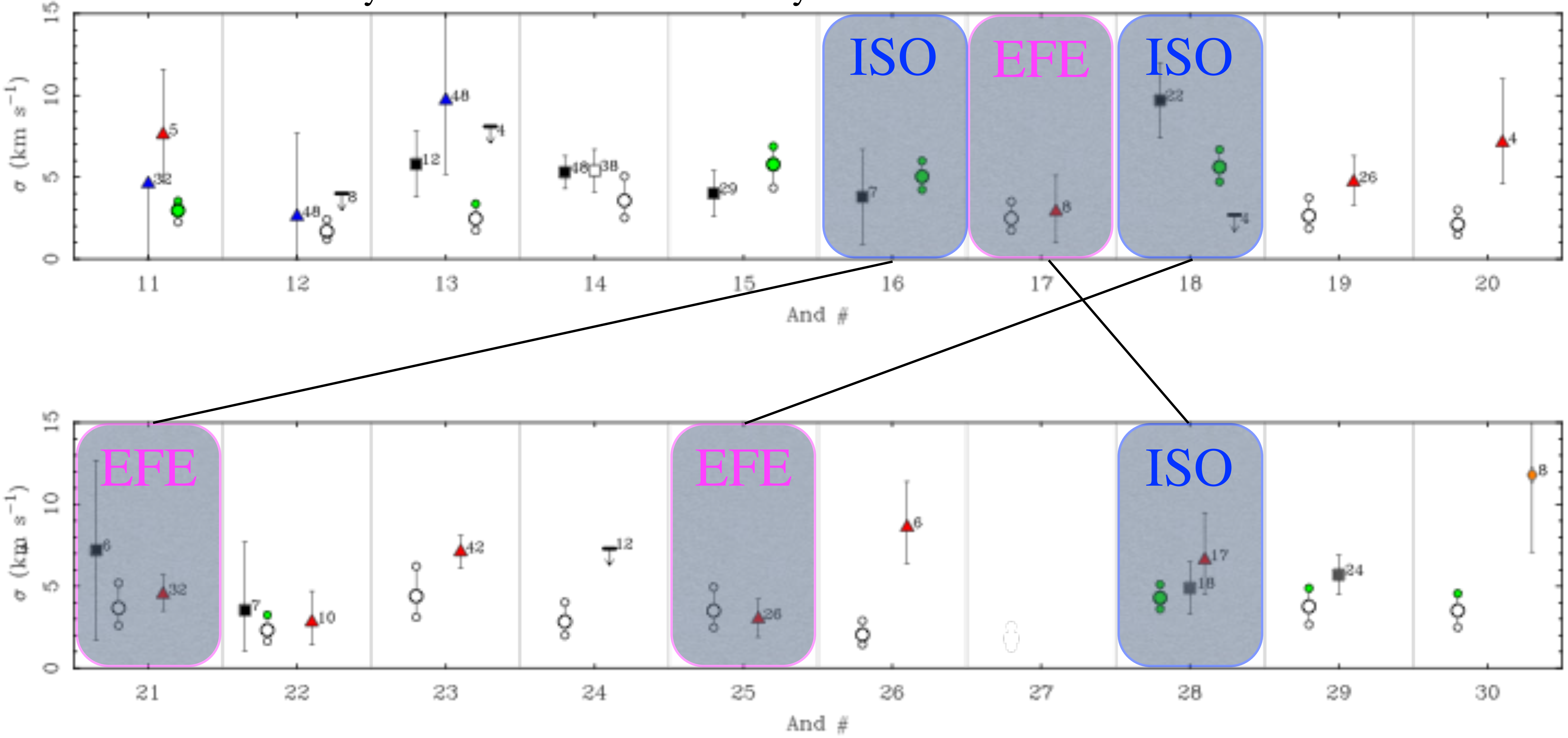
A test with the dwarf satellites of Andromeda



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.

Crater 2 - a clear example of the EFE

Crater 2

The recently discovered, ultra-diffuse Crater 2 provides another test.

$$L_V = 1.6 \times 10^5 \ \mathrm{L}_\odot$$
$$r_h = 1066 \ \mathrm{pc}$$

LCDM anticipates 10 - 17 km/s
(abundance matching; size-v. disp. rel'n)
but makes no concrete prediction

MOND predicts 2.1 +0.9/-0.6 km/s
(in EFE regime: McGaugh 2016, ApJ, 832, L8)

Subsequently observed: 2.7 ± 0.3 km/s
(Caldwell et al. 2017, ApJ, 839, 20)

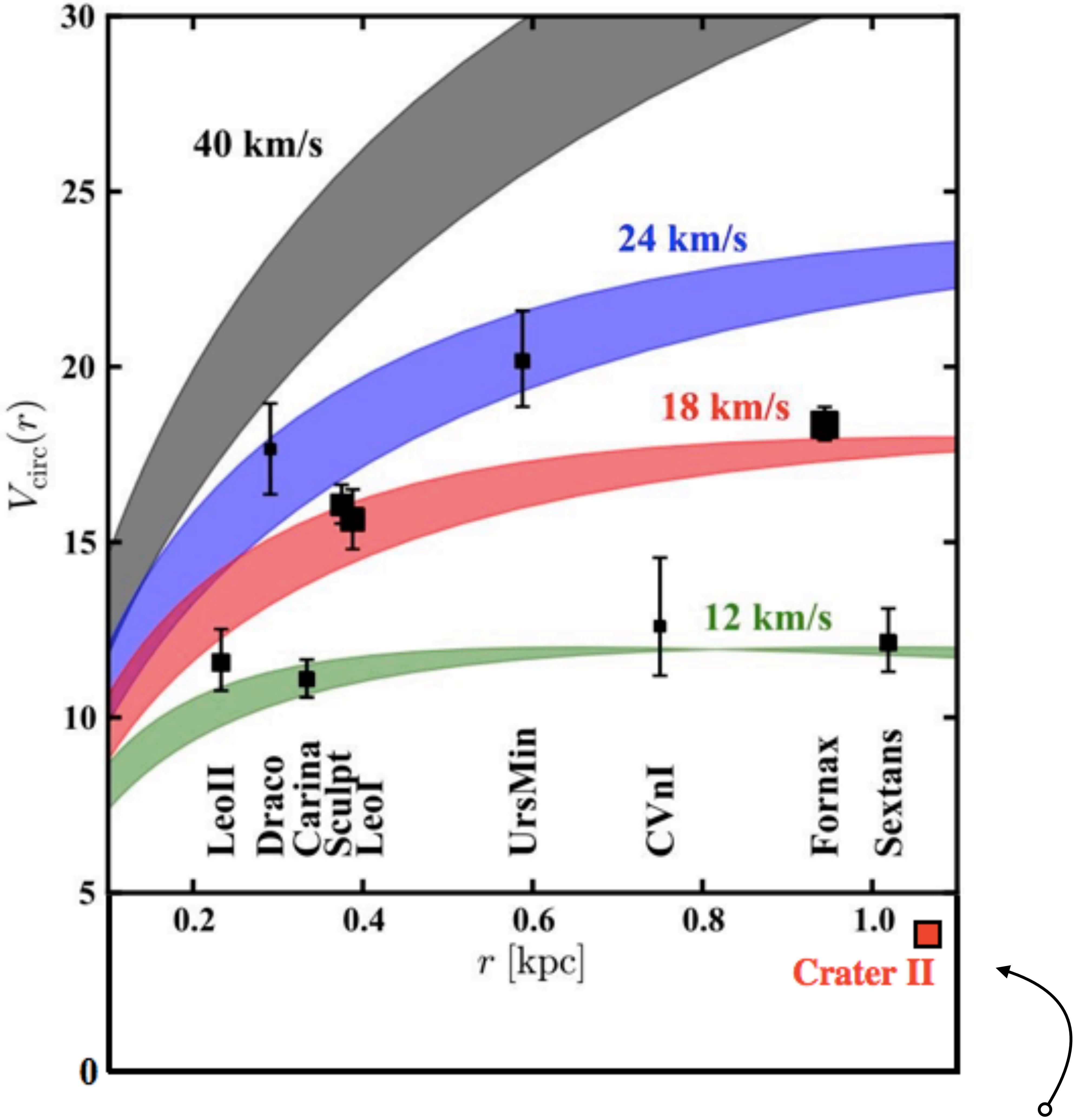
Consistent with a priori MOND prediction ★

Very hard to understand in the context of ΛCDM - incredibly low velocity at a very large radius.

Predictions made in advance of observation are the gold standard in science. ★
MOND has had *many* more successful *a priori* predictions than dark matter based theories.

Boylan-Kolchin et al. (2012) MNRAS, 422, 1203

“Too Big To Fail”



Crater 2 was so unanticipated by LCDM that I had to extend the boundary of this plot to fit it in.

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?

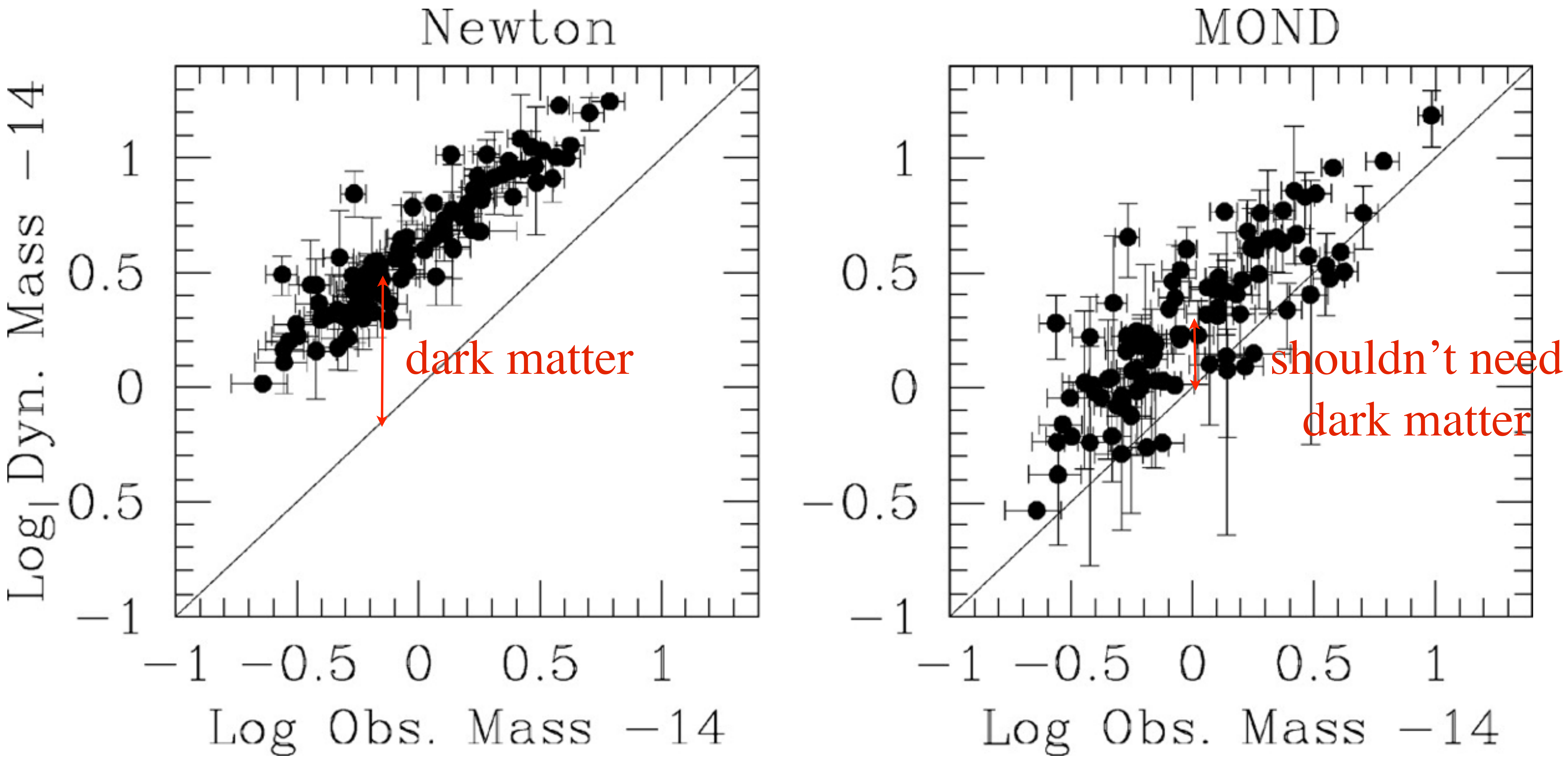
Review of relativistic theories containing MOND in the appropriate limit

- 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

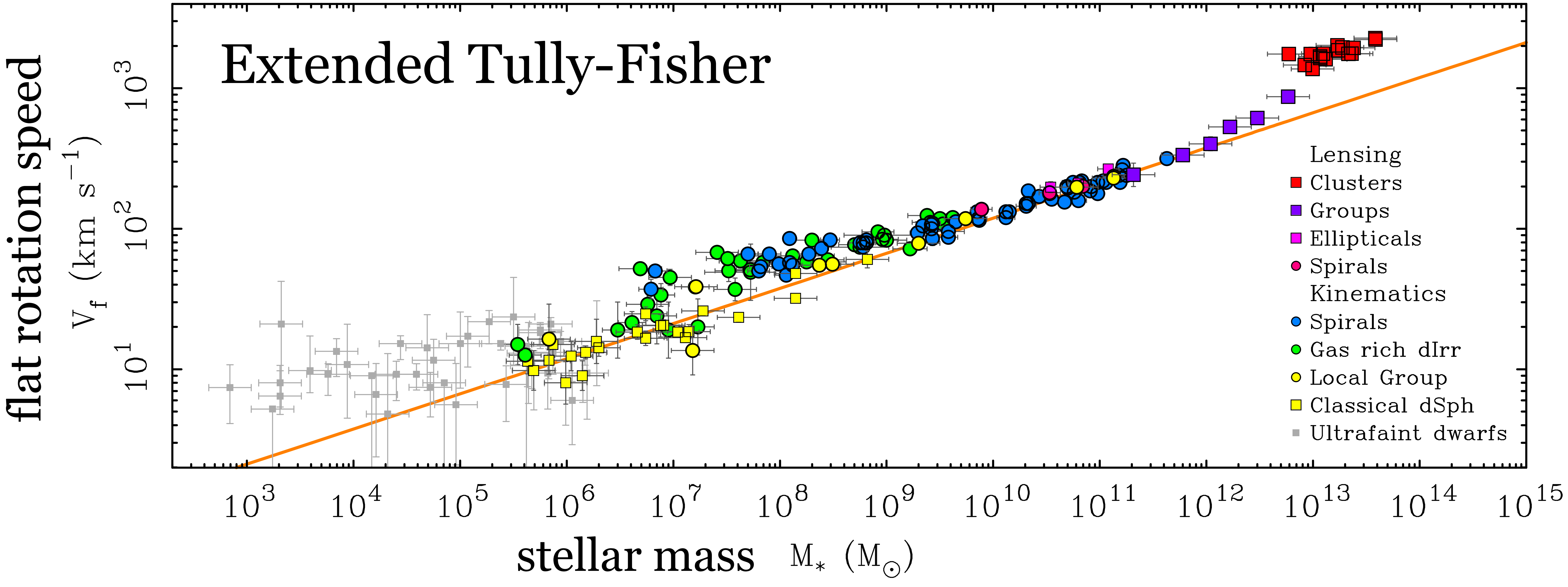


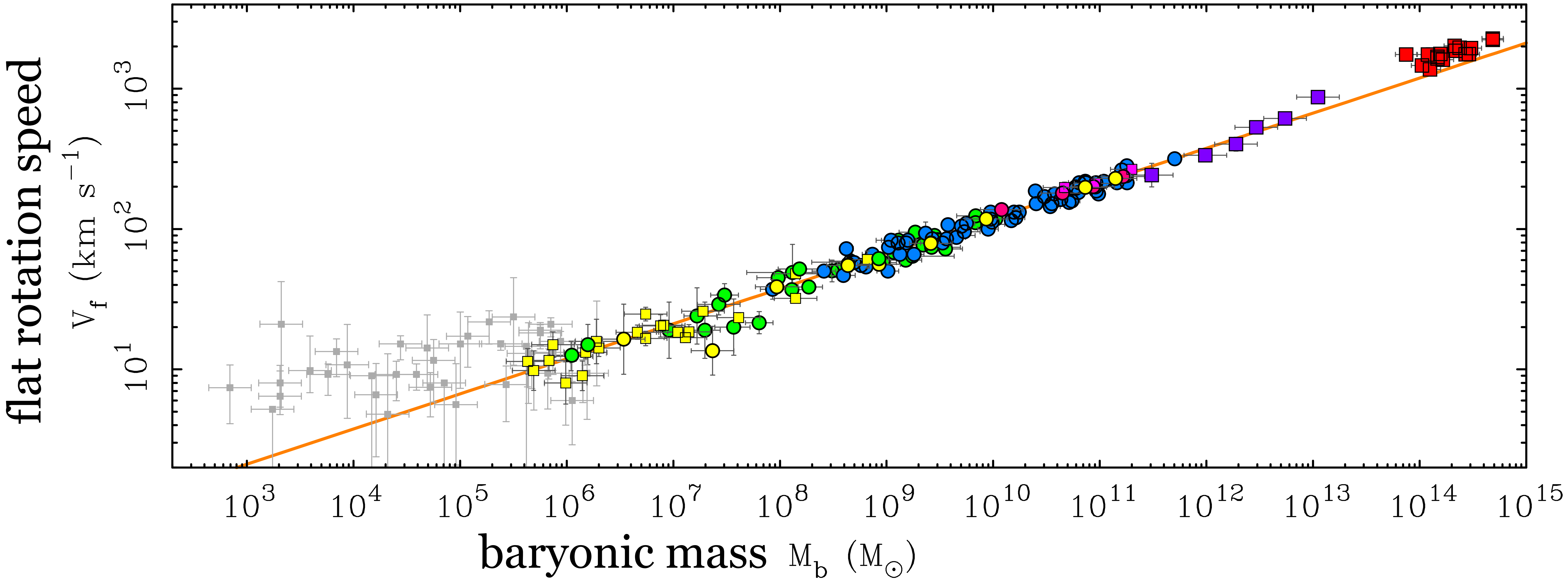
dark matter

shouldn’t need dark matter

(Sanders & McGaugh 2002)

clusters ruin everything


Extended Tully-Fisher
flat rotation speed
V_f (km s^{-1})
10^1
10^2
10^3
Lensing
🟥 Clusters
🟪 Groups
🟪 Ellipticals
● Spirals
Kinematics
● Spirals
● Gas rich dIrr
● Local Group
🟨 Classical dSph
■ Ultrafaint dwarfs
10^3
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
stellar mass M_* ($M_\odot$)


flat rotation speed
V_f (km s^{-1})
10^1
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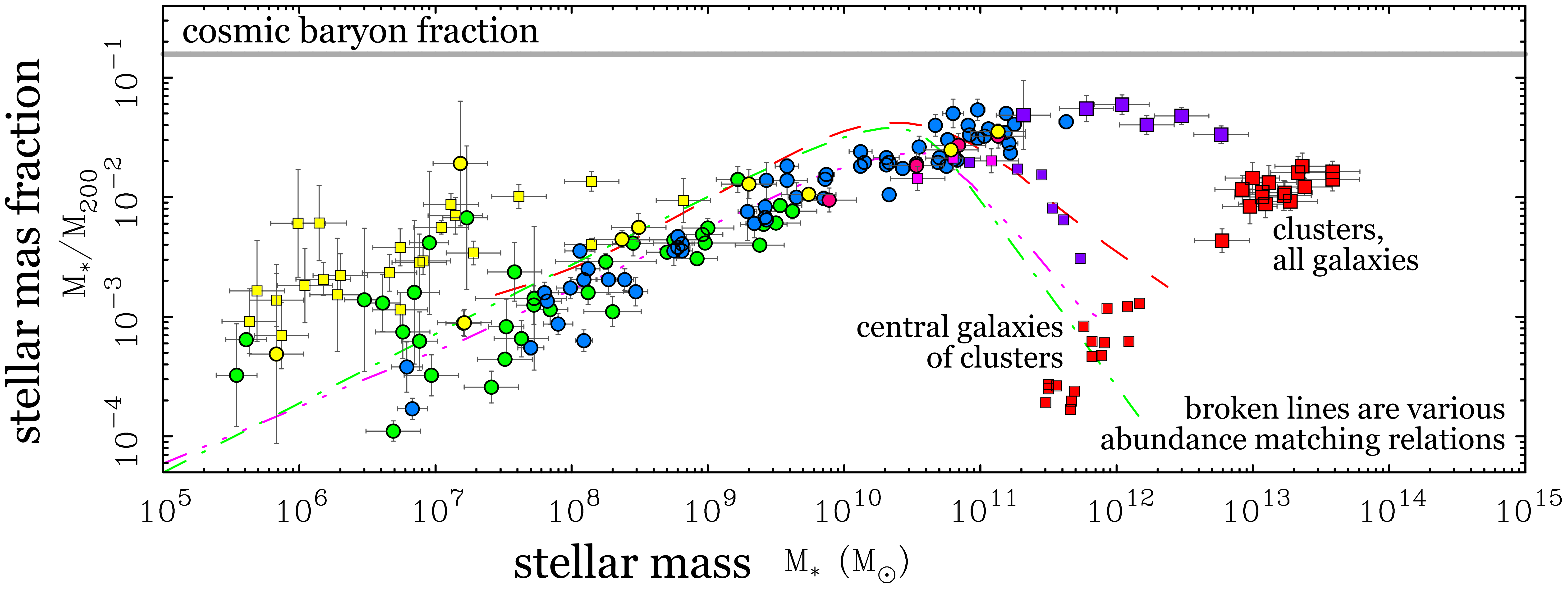
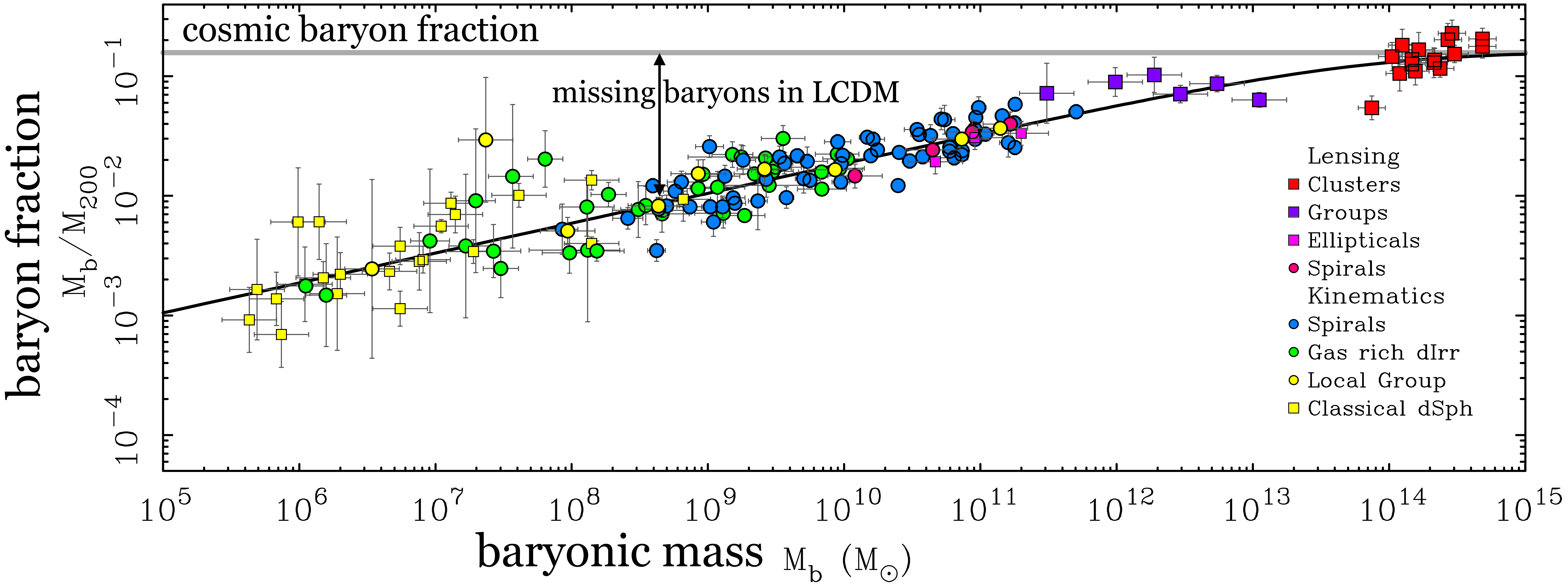
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
baryonic mass M_b ($M_\odot$)

LCDM:

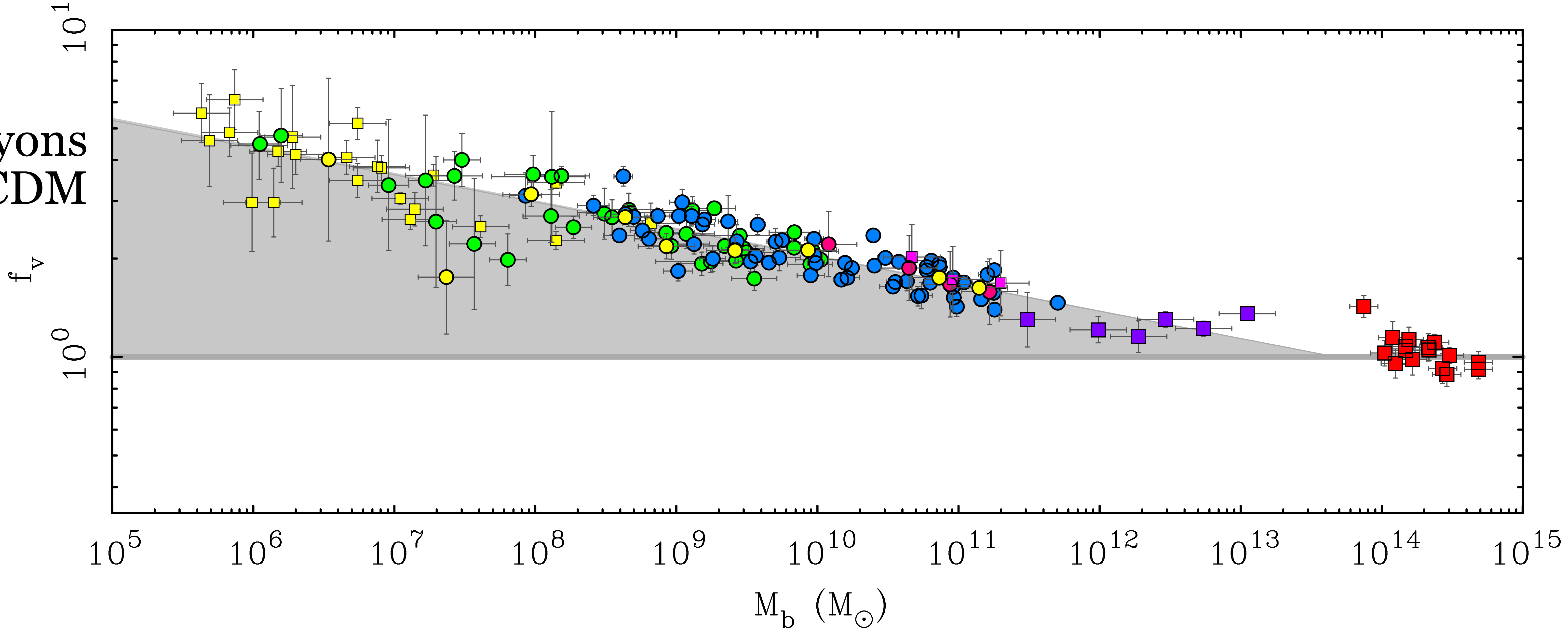

cosmic baryon fraction
stellar mas fraction
M_*/M_{200}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
clusters,
all galaxies
central galaxies
of clusters
broken lines are various
abundance matching relations
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
stellar mass
M_* $(M_\odot)$


cosmic baryon fraction
missing baryons in LCDM
baryon fraction
M_b/M_{200}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Lensing
🟥 Clusters
🟪 Groups
🟪 Ellipticals
● Spirals
Kinematics
● Spirals
● Gas rich dIrr
● Local Group
🟨 Classical dSph
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
baryonic mass
M_b $(M_\odot)$

LCDM:

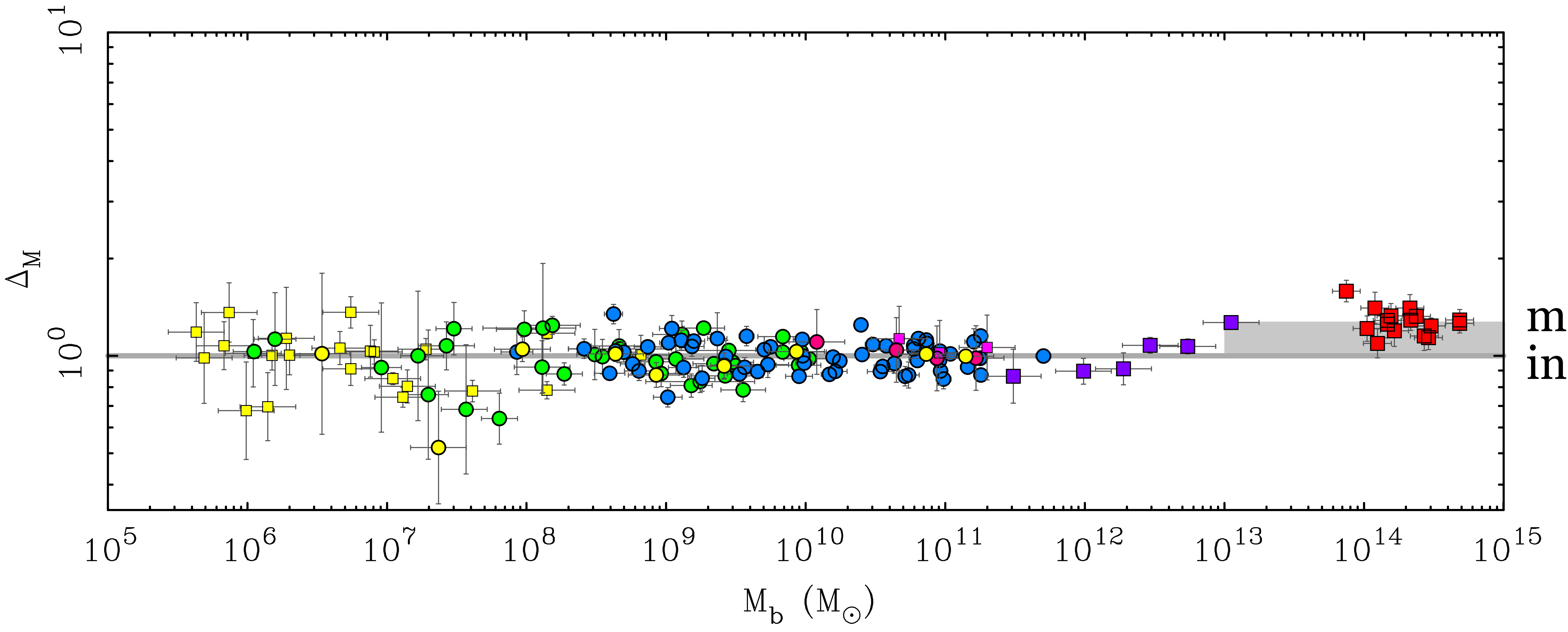
missing baryons
in LCDM

$M \sim V^3$



MOND:

$M \sim V^4$



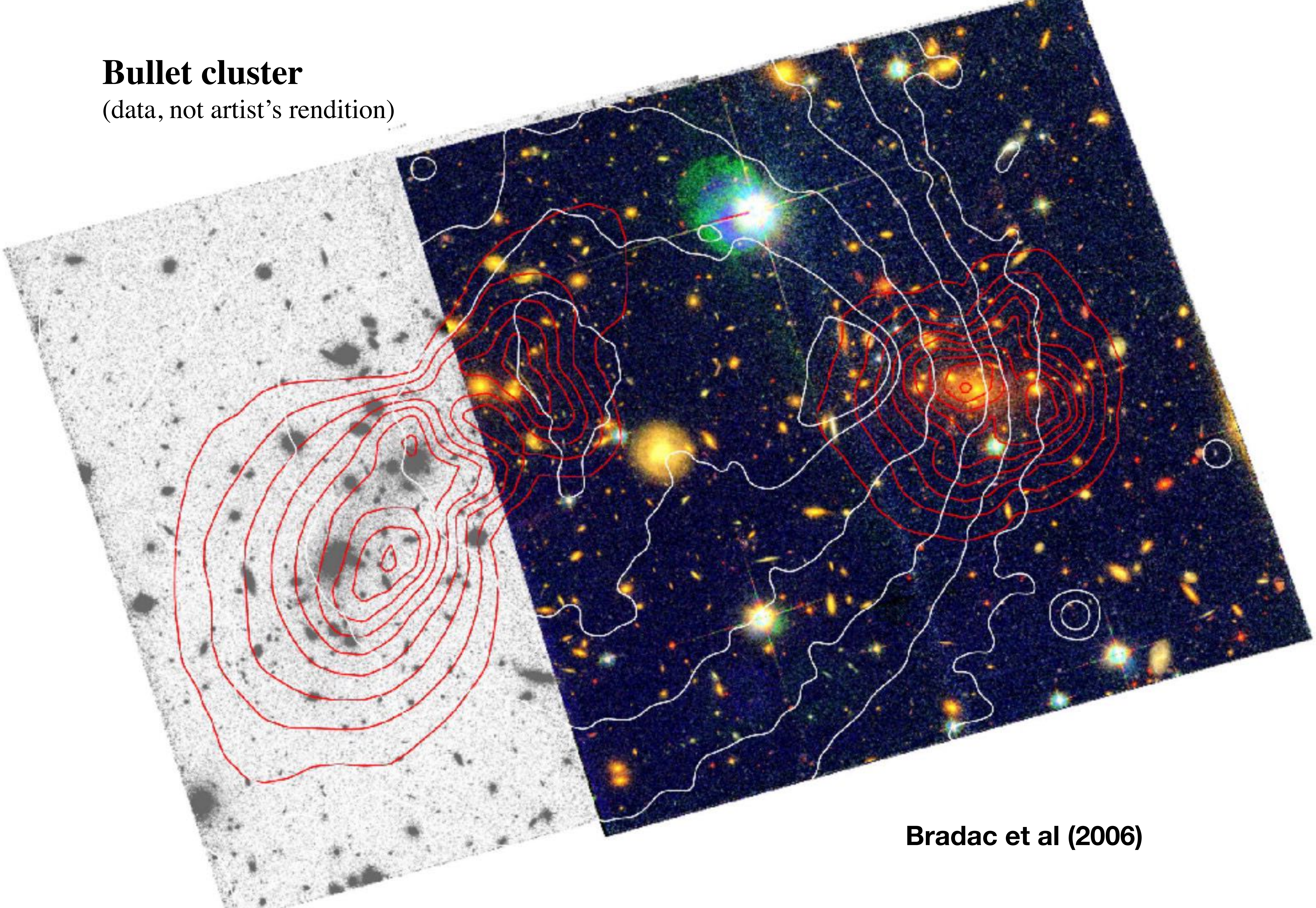
missing baryons
in MOND

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

direct proof of dark matter?

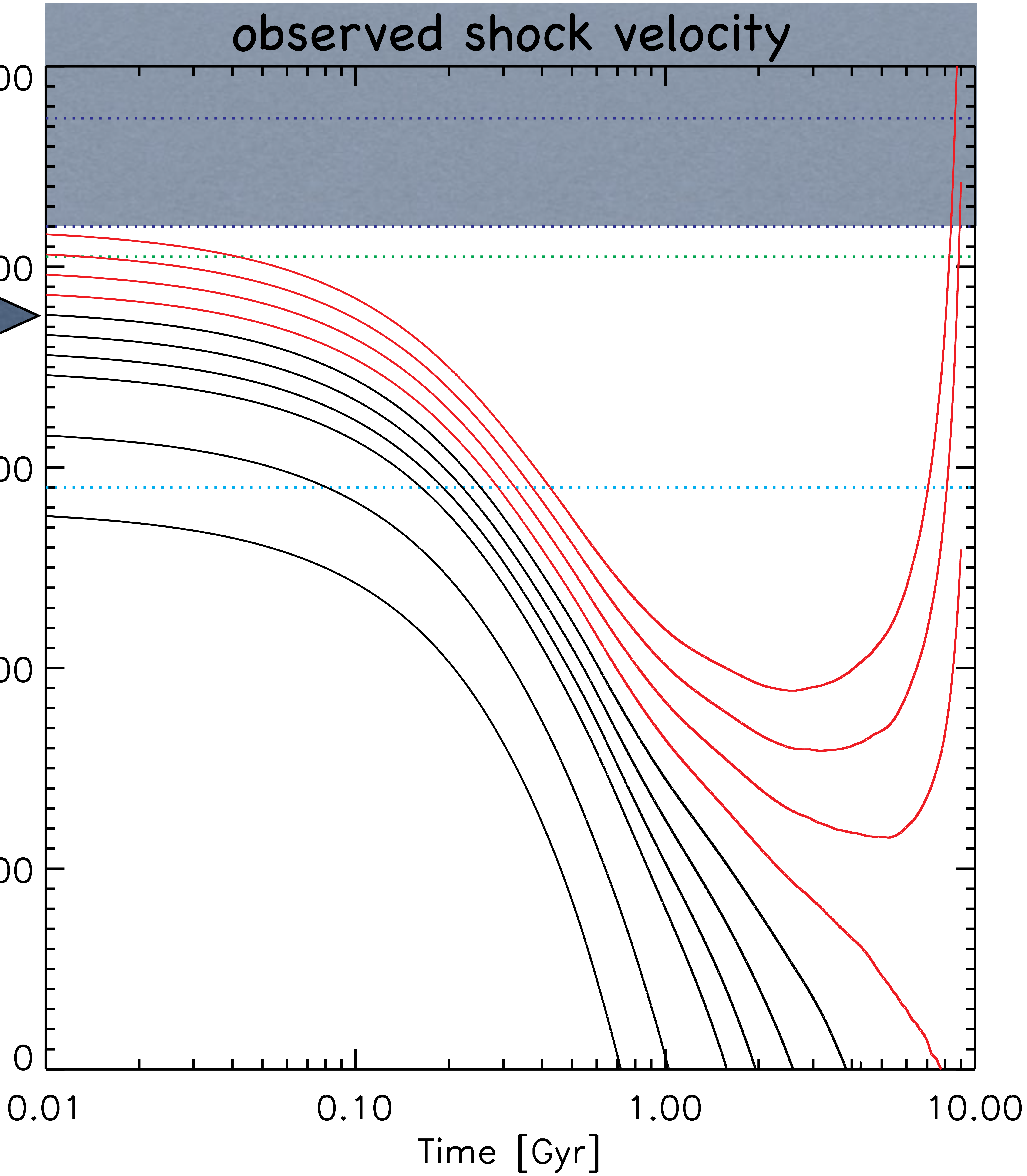
Bullet cluster

(data, not artist's rendition)



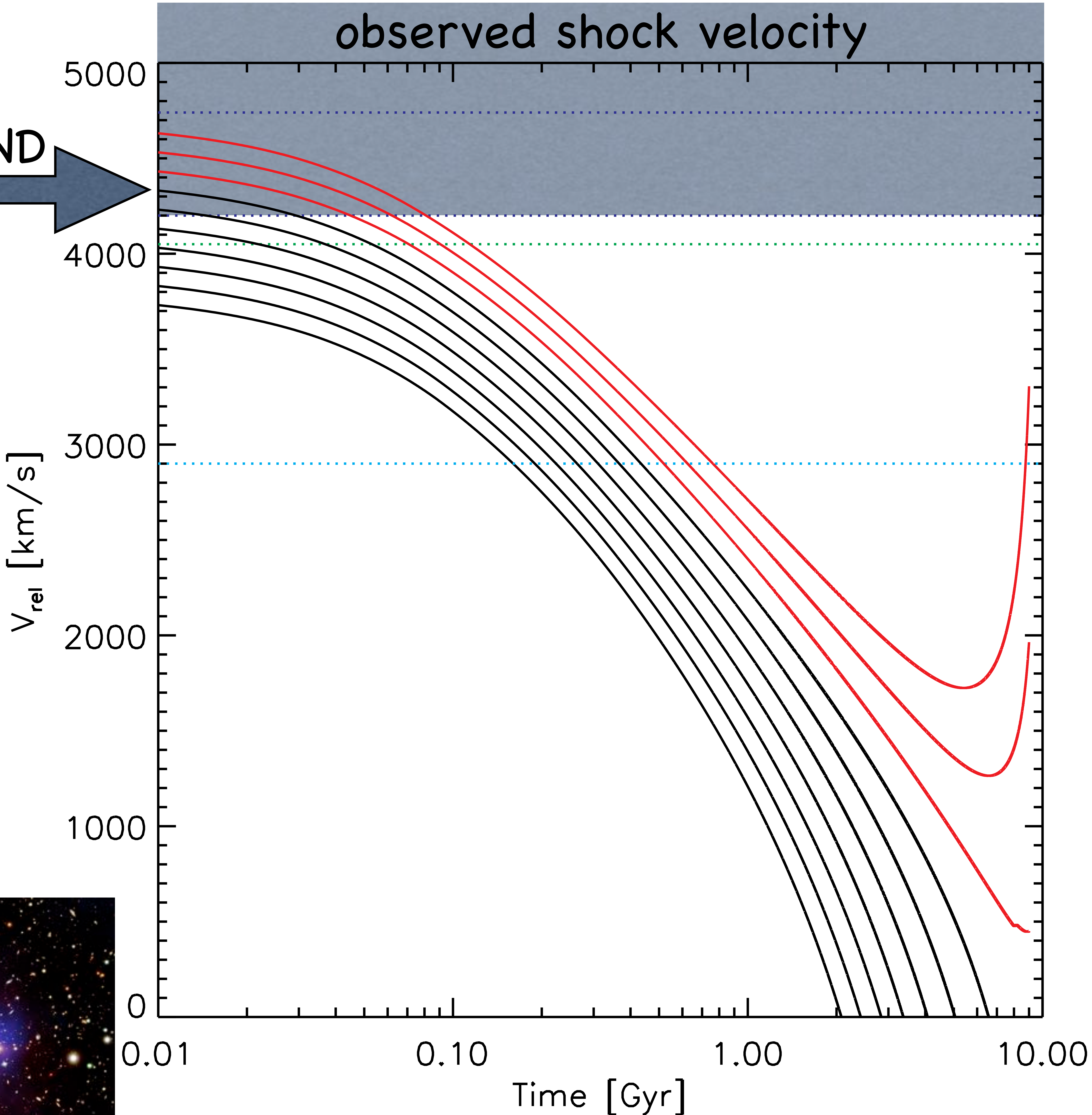
Bradac et al (2006)

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

Mahdavi et al. (2007) arXiv:0706.3048

Abell 520 - the Train Wreck cluster
Counter-example to bullet cluster
with a mass peak devoid of galaxies

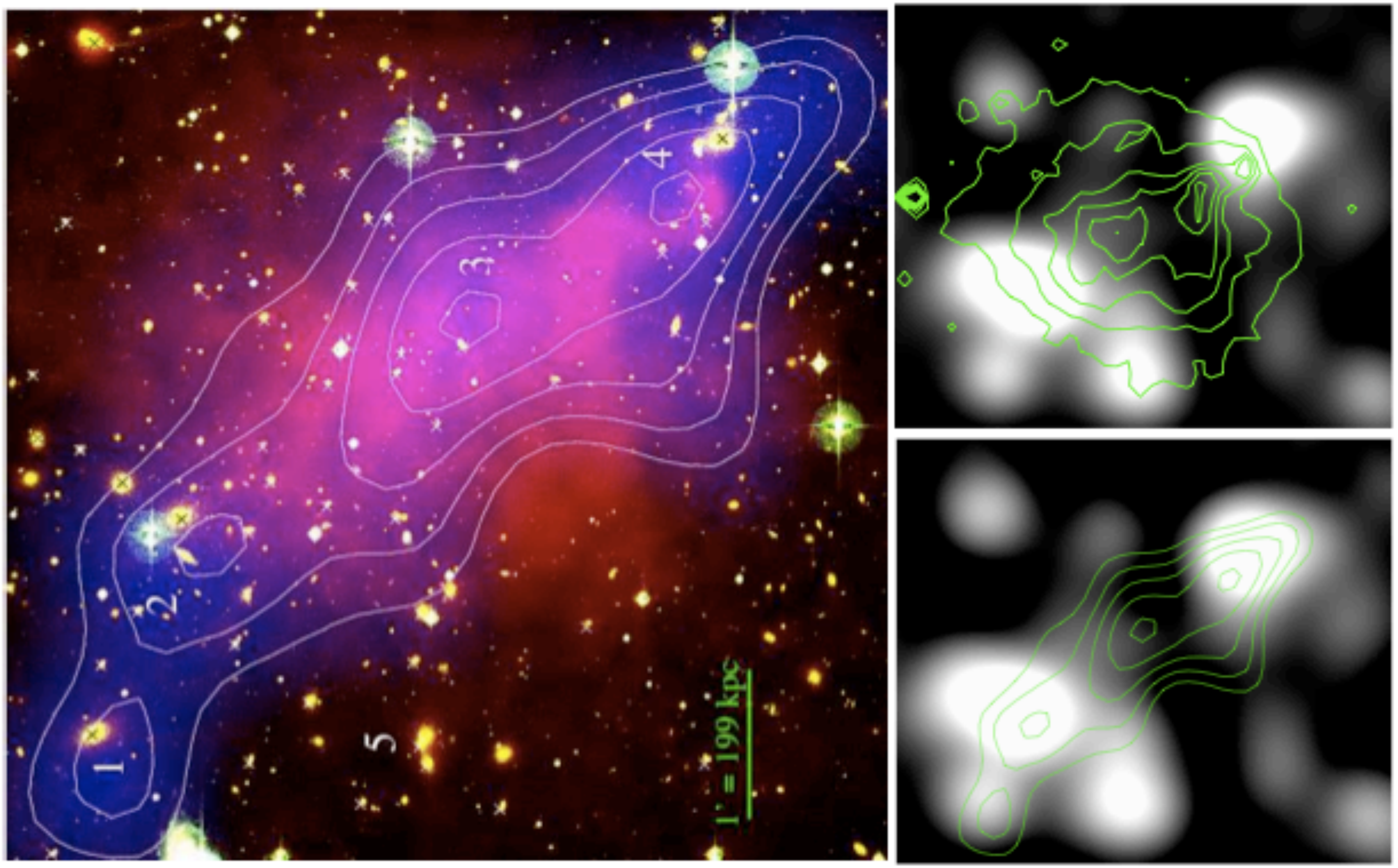
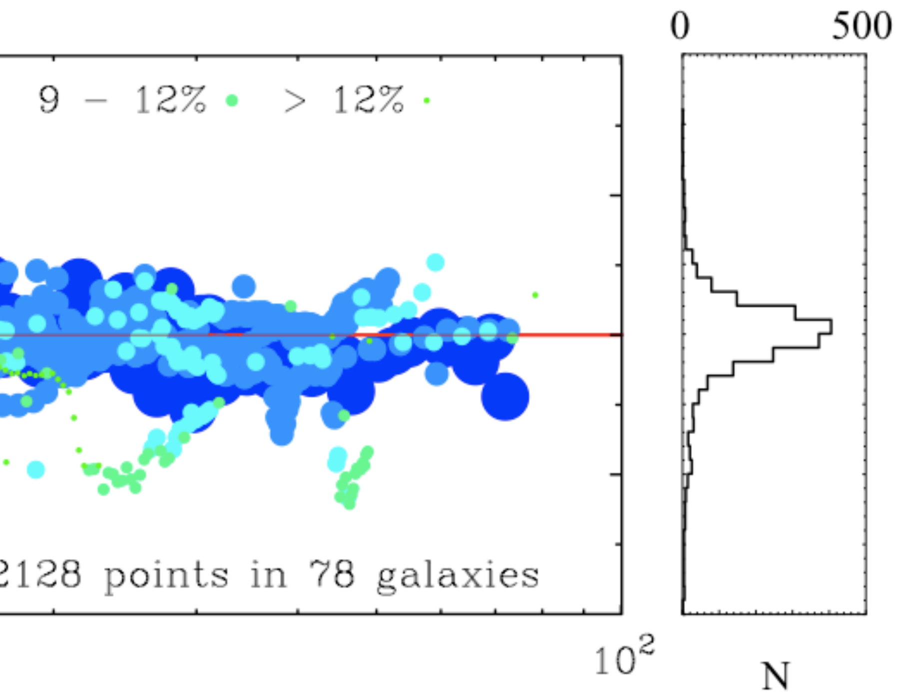


FIG. 2.— (a) Central $6.4' \times 6.4'$ of Abell 520, showing the CFHT image, the diffuse Chandra X-ray emission (red), and the lensing surface mass density (blue + 3, 3.5, 4, 4.5, and 5σ contours determined from a bootstrap analysis). Spectroscopically confirmed member galaxies are marked with an X; red-sequence galaxies appear orange. (b) Red light distribution together with lensing contours from (a). (c) Same as (b), but with X-ray contours. Note the absence of galaxies in the central lensing peak.

MOND predictions



- The Tully-Fisher Relation
  - ✓ Slope = 4 ★
  - ✓ Normalization = $1/(a_0 G)$ ☆
  - ✓ 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

- X Clusters of Galaxies
- ? Structure Formation —

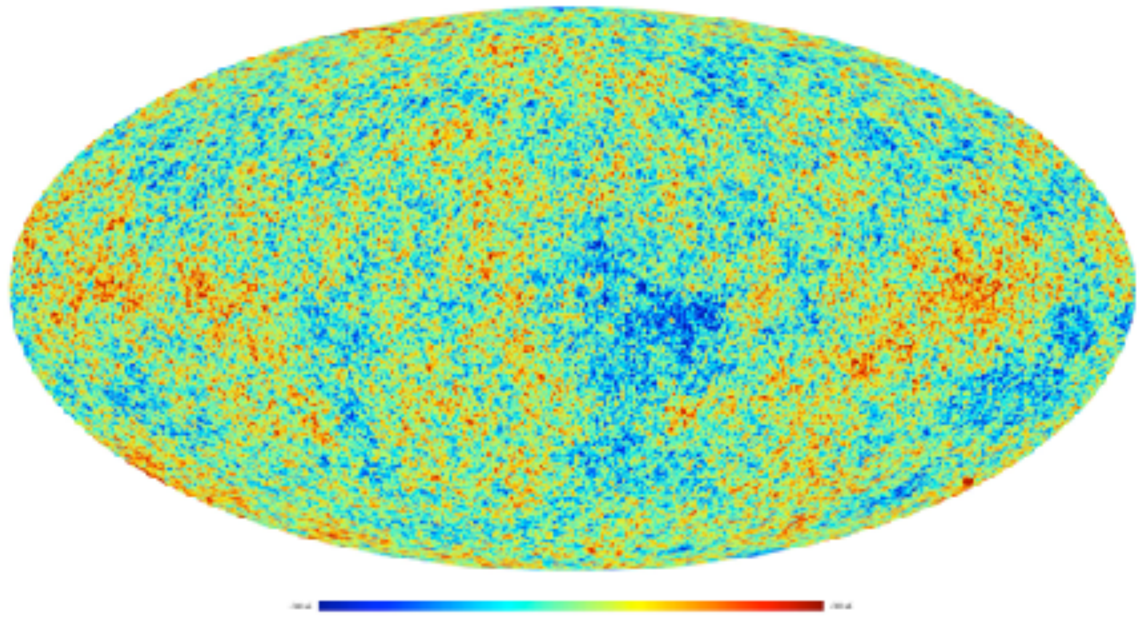
Sanders (1998)
First galaxies z > 10 ★
cosmic web at z = 5
big clusters z > 2 ★
voids swept clear by z = 0

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

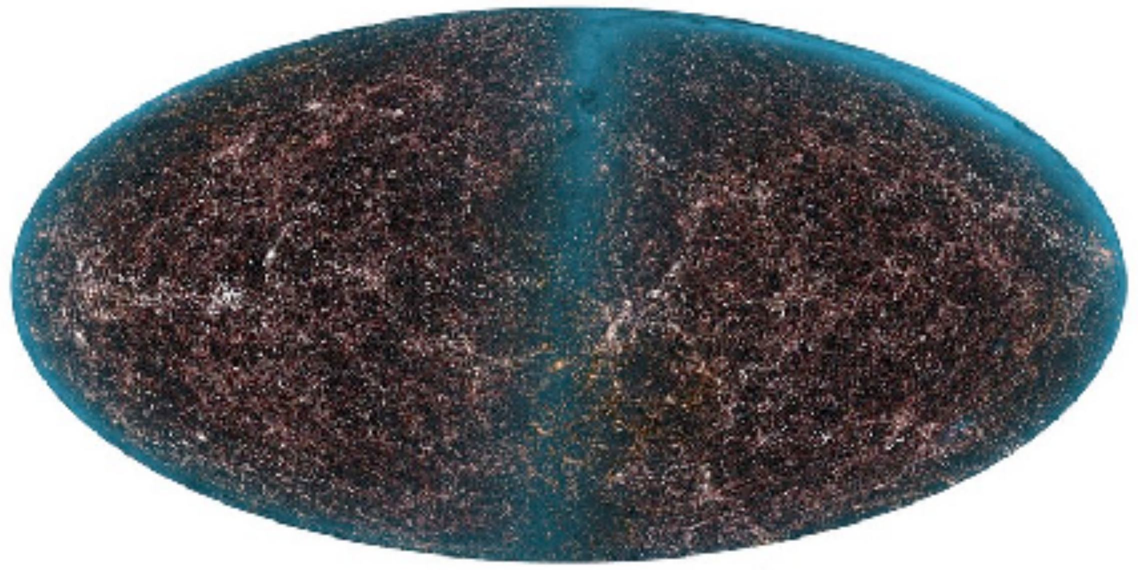
It's not "just" for galaxies. MOND has had many more successful a priori predictions than LCDM.

Power spectrum in Aether-Tensor-Scalar (AeST)

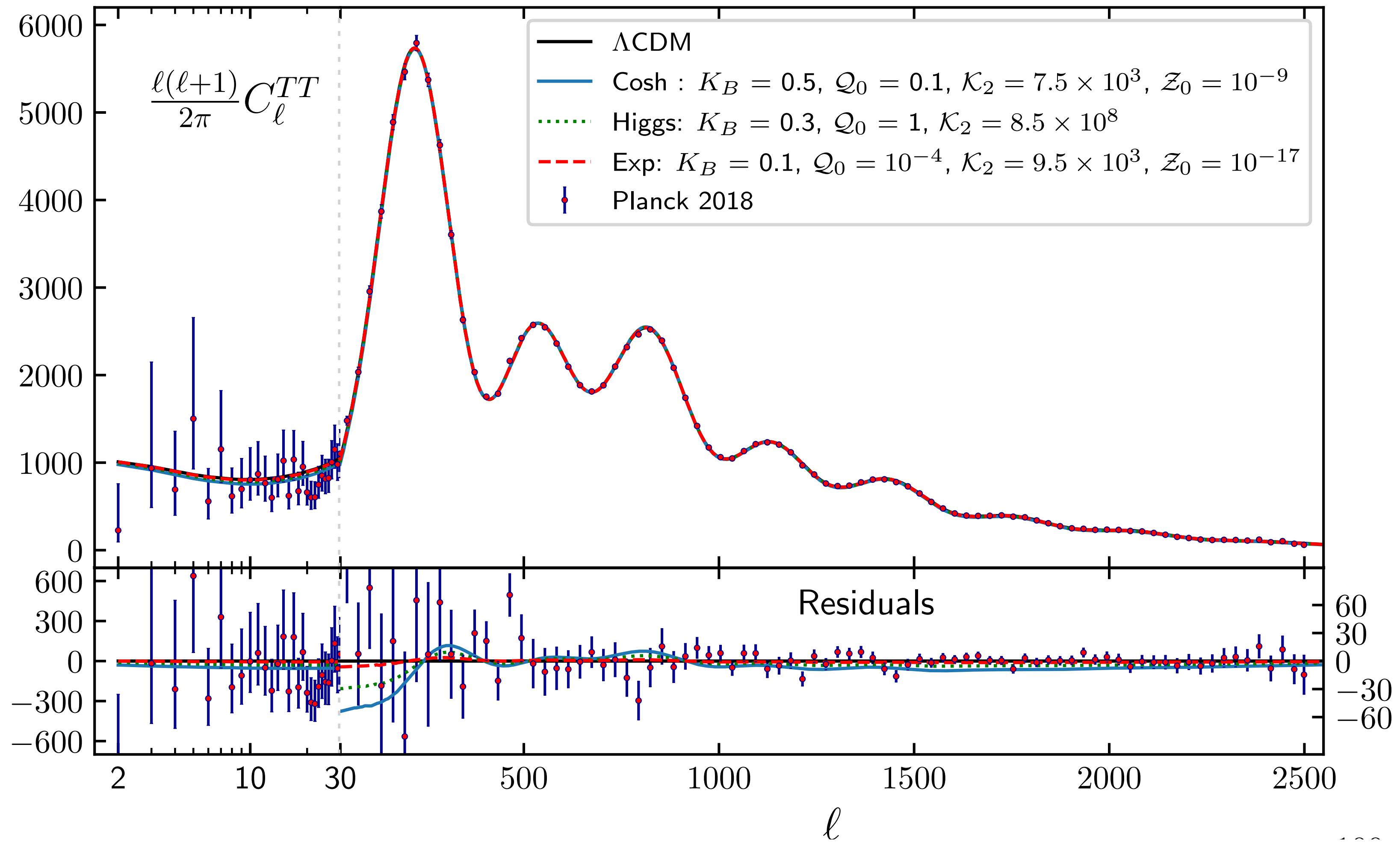
CMB

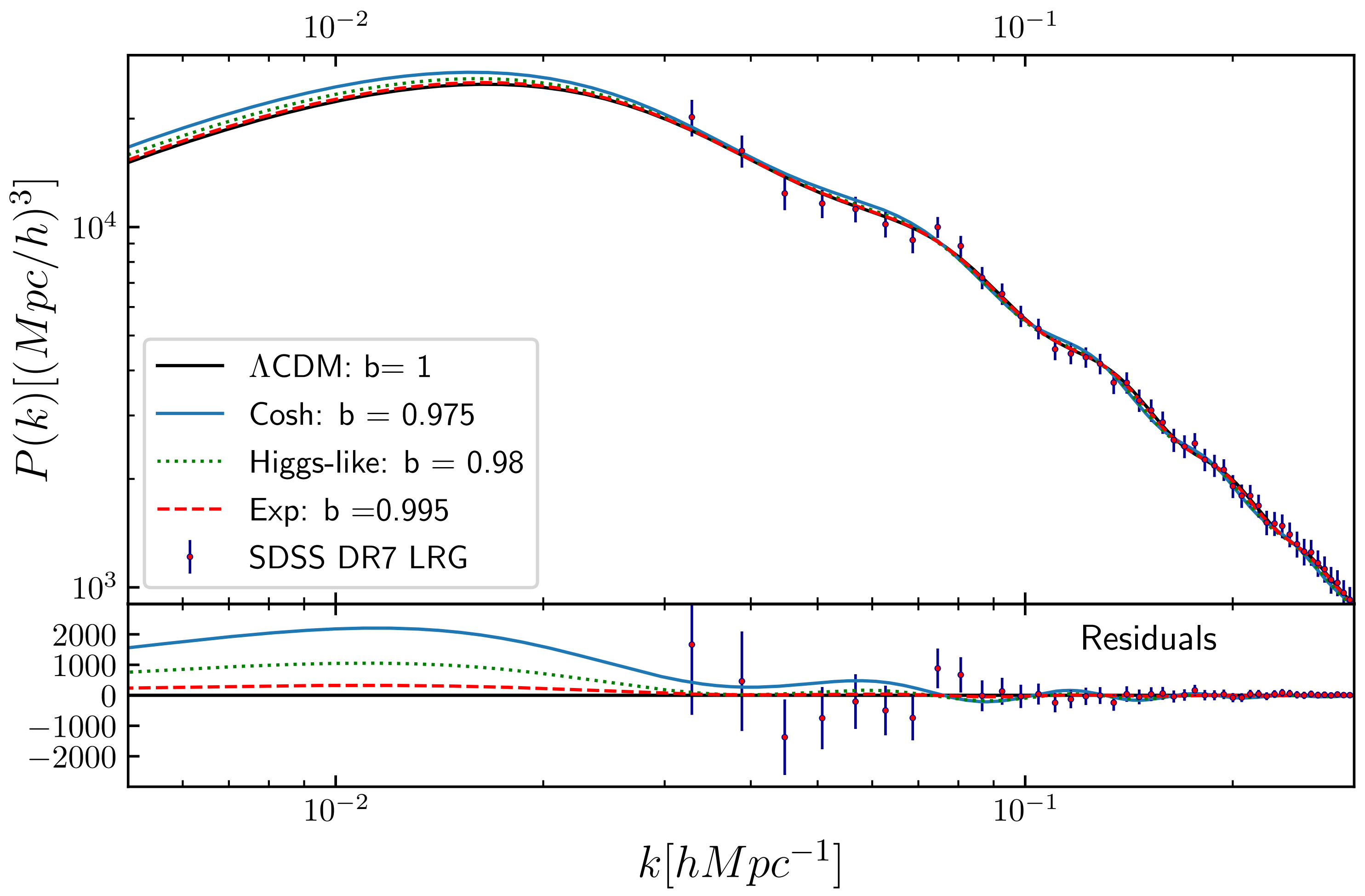


galaxy distribution



The third and subsequent peaks are well fit by Aether-Scalar-Tensor theory (Skordis & Zlosnik 2021)





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

Structure formation in CDM and MOND

cold dark matter

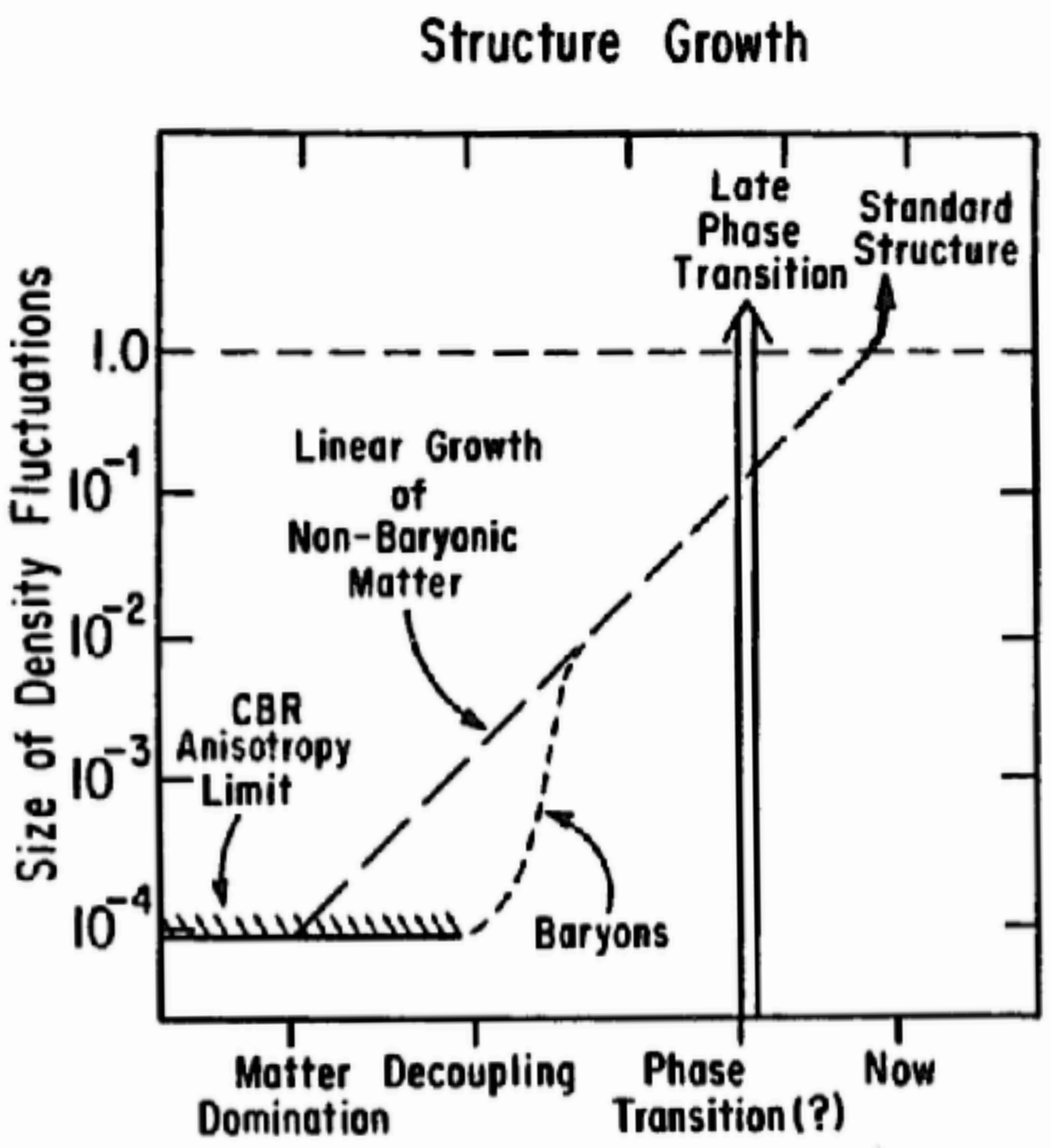
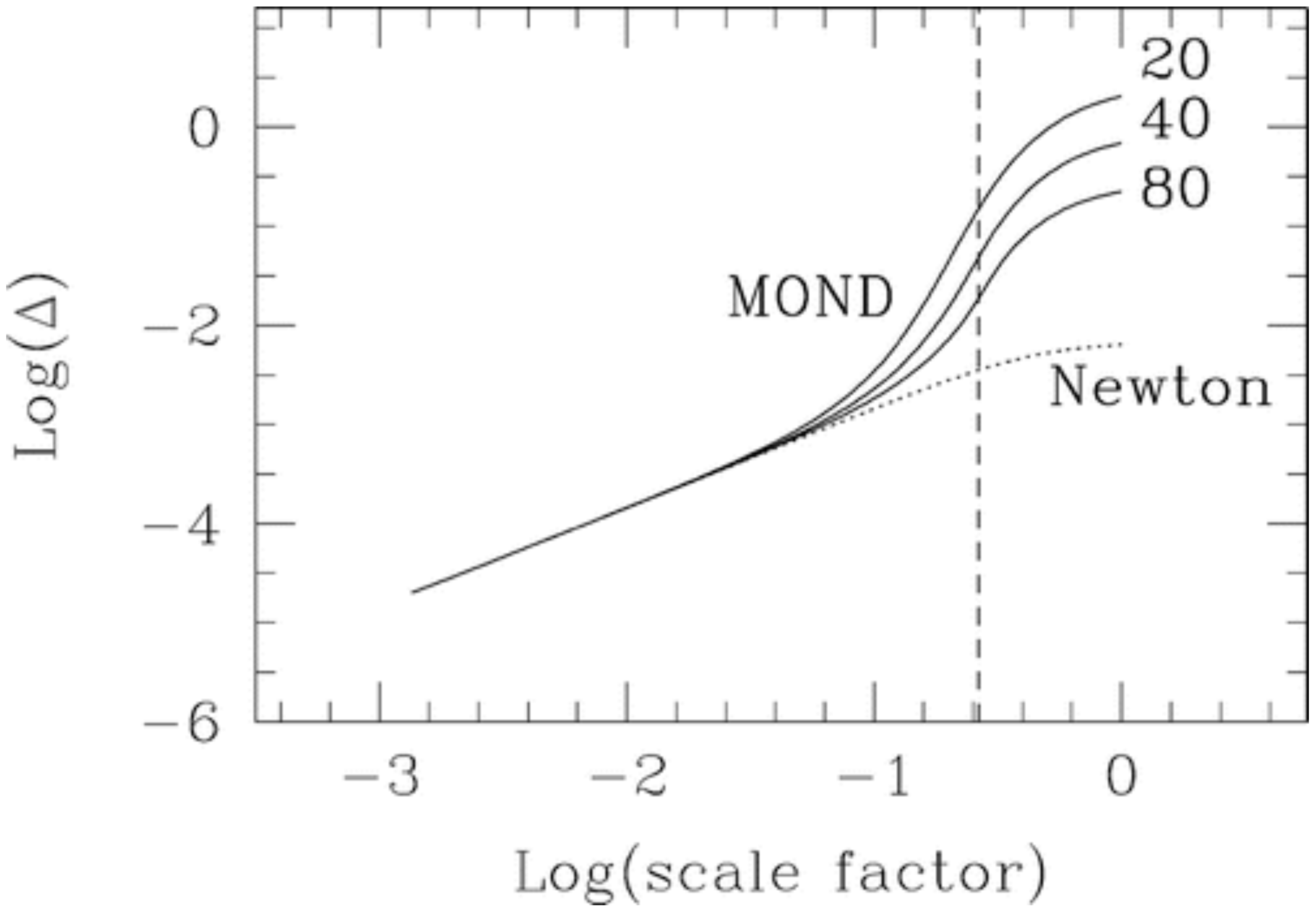


Figure 5. Linear growth of $\delta\rho/\rho$ versus inverse temperature with epochs noted.

MOND



linear growth of dark matter perturbations

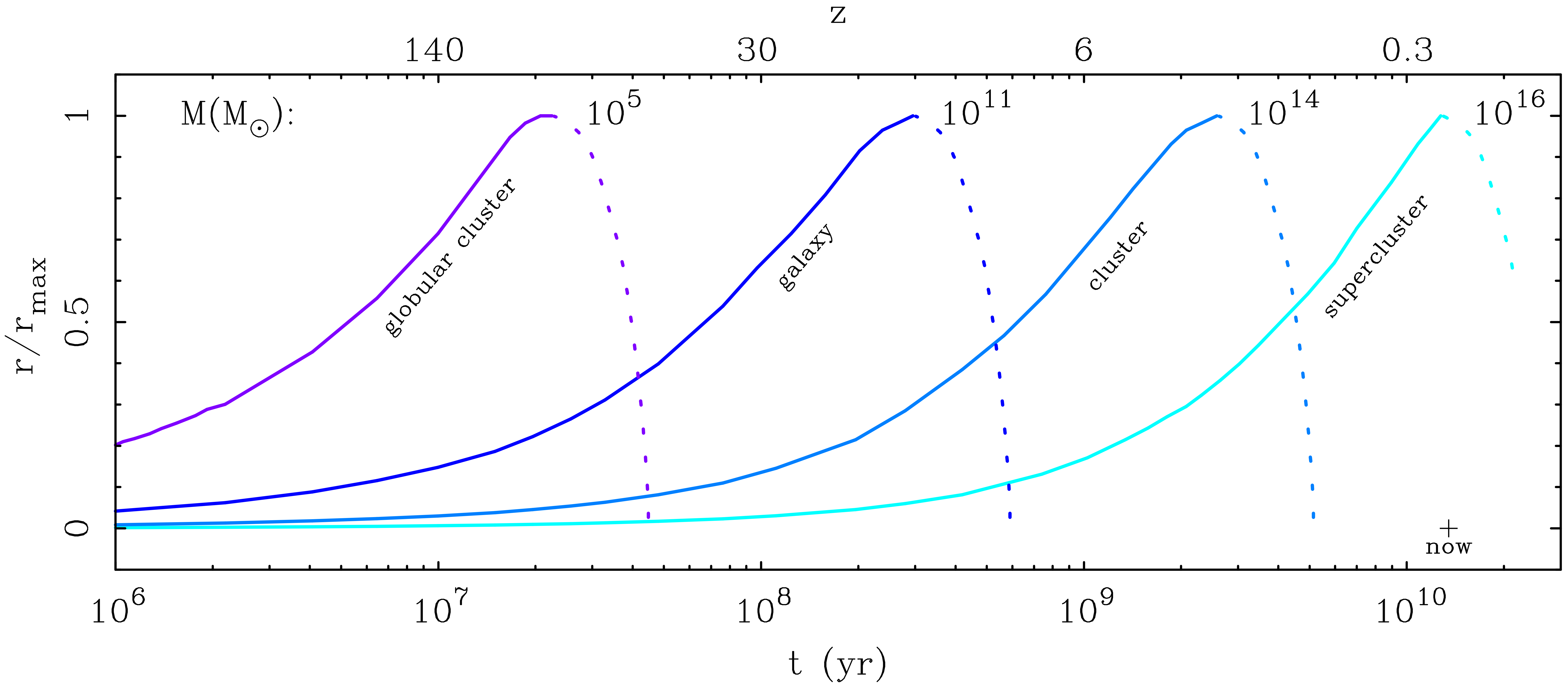
$\delta \sim a$

nonlinear growth of baryon perturbations

is it even the overdensities?

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.



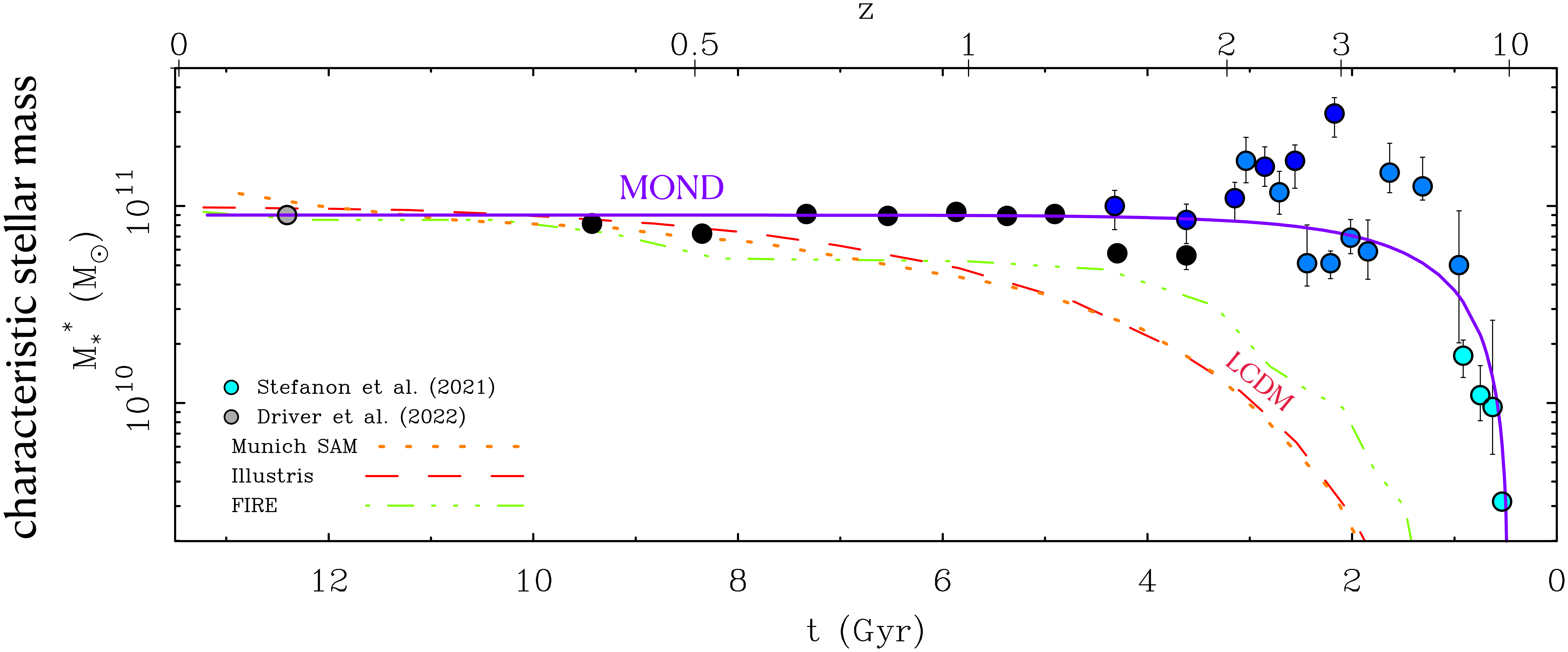
The growth of spherically symmetric over-densities in a low-density baryonic universe as a function of scale factor in the context of a two-field Lagrangian theory of MOND. The solid curves correspond to regions with comoving radii of 20, 40, and 80 Mpc. The dotted line is the corresponding Newtonian 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

Recent tests of MOND predictions: massive galaxies should form fast; appear at higher redshift than expected with dark matter

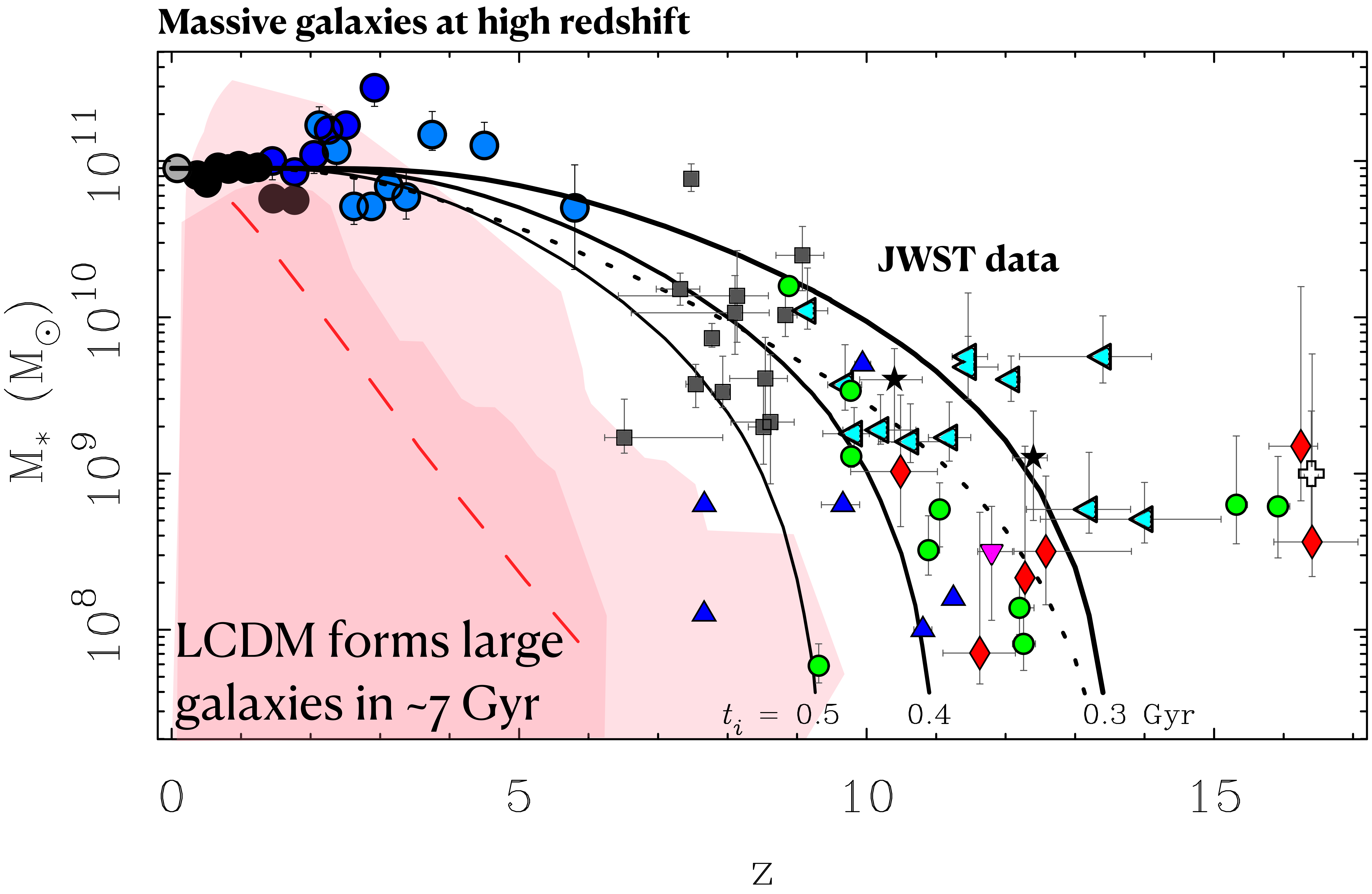
Galaxy stellar mass across cosmic time

Each point represents L* for many galaxies

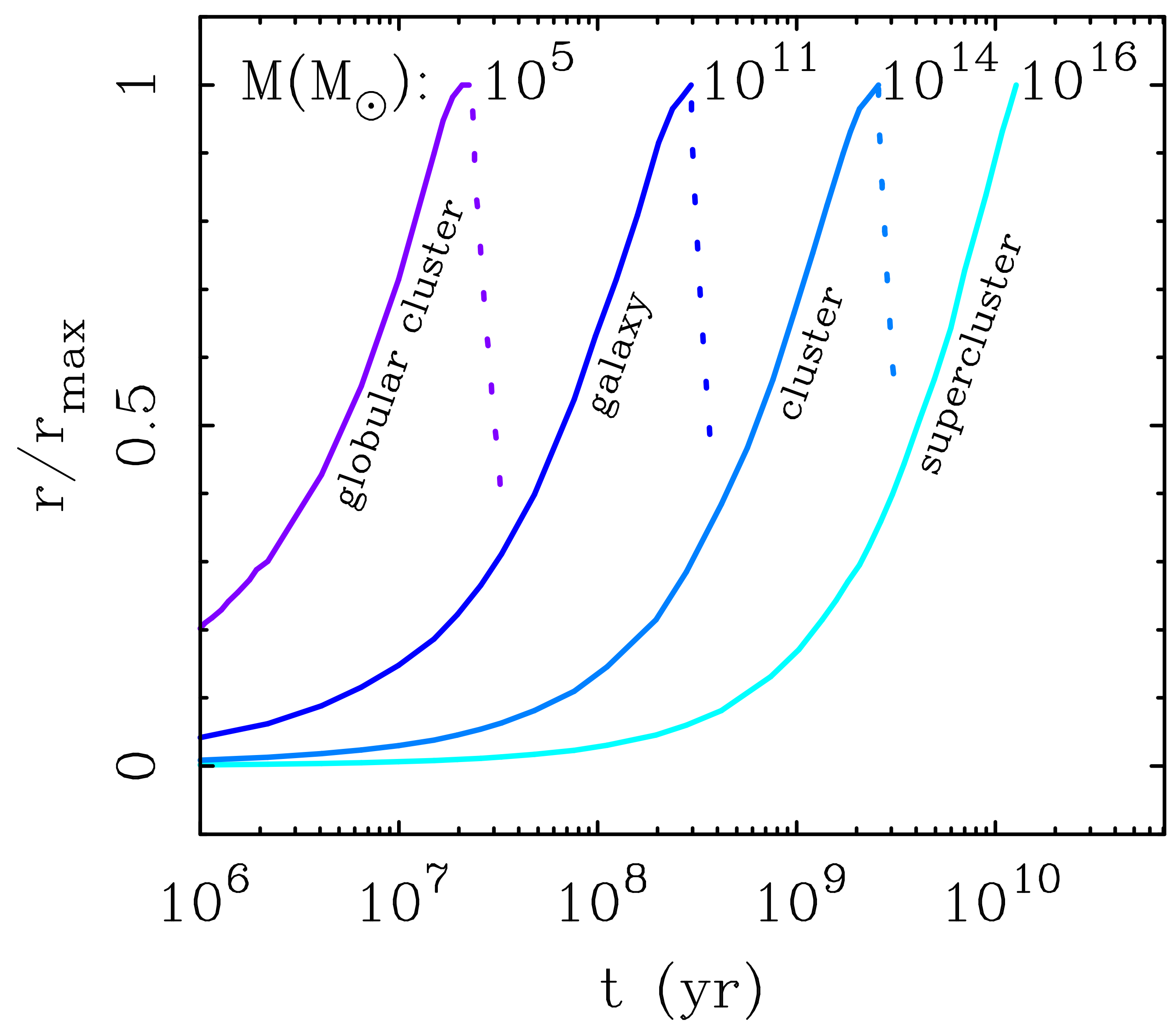


It appears that massive galaxies form too early - as predicted by MOND.

McGaugh+ (2024)



LCDM forms large galaxies in ~7 Gyr



MOND forms large galaxies in ~0.5 Gyr

That massive galaxies would form by z = 10 was explicitly predicted by Sanders (1998)

Maximum cluster mass in LCDM

(Mortonson, Hu, & Huterer 2011)

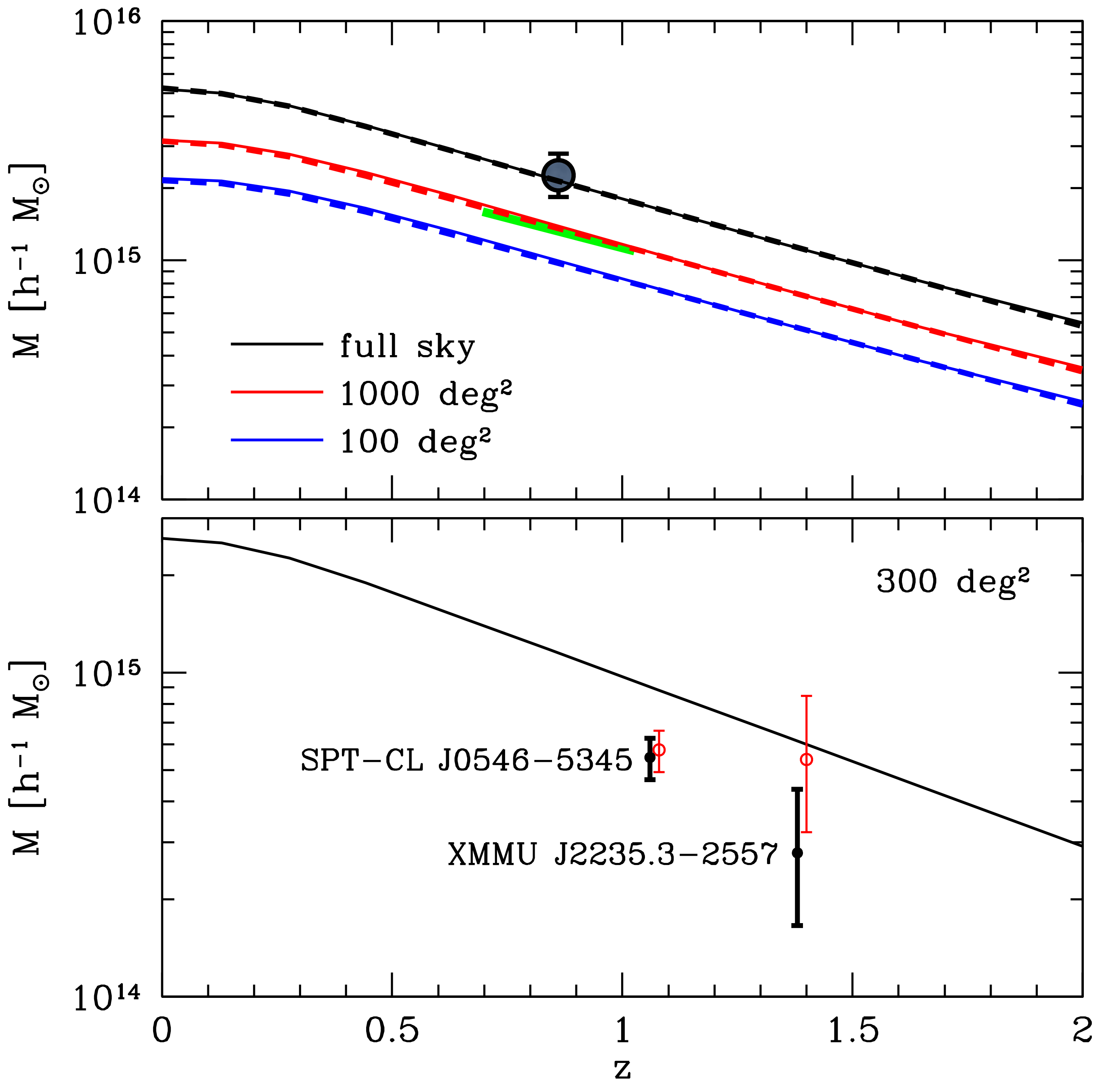


FIG. 4. $M(z)$ exclusion curves. Even a single cluster with (M, z) lying above the relevant curve would rule out both ΛCDM and quintessence. *Upper panel:* flat ΛCDM 95% joint CL for both sample variance and parameter variance for various choices of sky fraction $f_{\rm sky}$ from the MCMC analysis (thin solid curves) and using the fitting formula from Appendix A (thick dashed curves; accurate to $\lesssim 5\%$ in mass). *Lower panel:* Two of the most anomalous clusters detected to date, compared with the 95% joint CL exclusion curve for 300 deg^2 which approximates the total survey area for each cluster. We show the X-ray determined masses with and without Eddington bias correction (black solid points with thick error bars and red open points with thin error bars, respectively, offset in redshift by ±0.01 for clarity).

El Gordo:

$$M = 2.16(\pm 0.32) \times 10^{15}\ M_\odot$$

$$z = 0.87$$

755 deg^2 SZ survey

(Menanteau et al. arXiv:1109.0953)

IDCS J1426.5_3508:

$$M = 2.6^{+1.5}_{-0.5} \times 10^{14}\ M_\odot$$

$$z = 1.75$$

9 deg^2 Spitzer survey

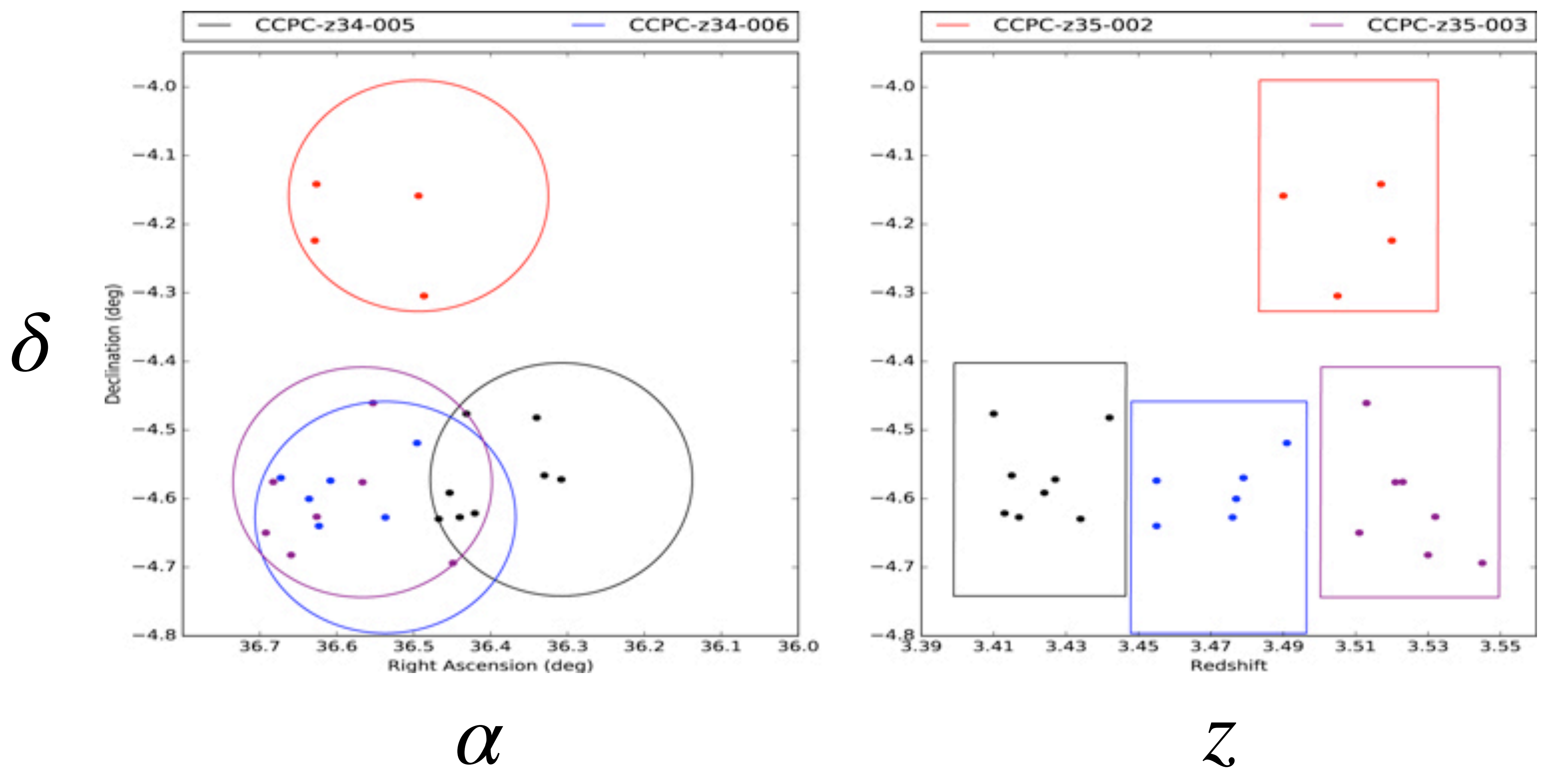
(Brodwin et al. arXiv:1504.01397)

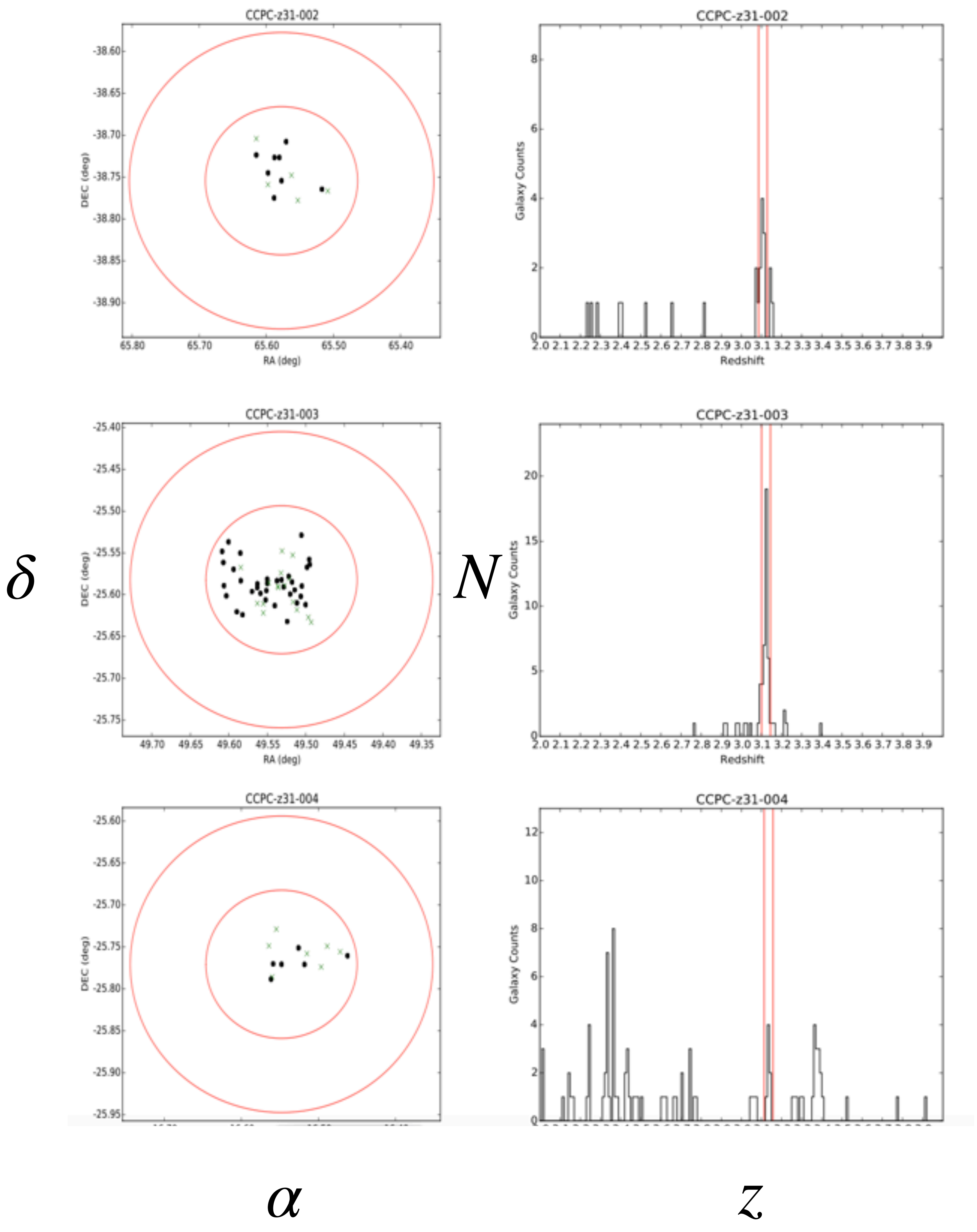
Clusters to higher redshift

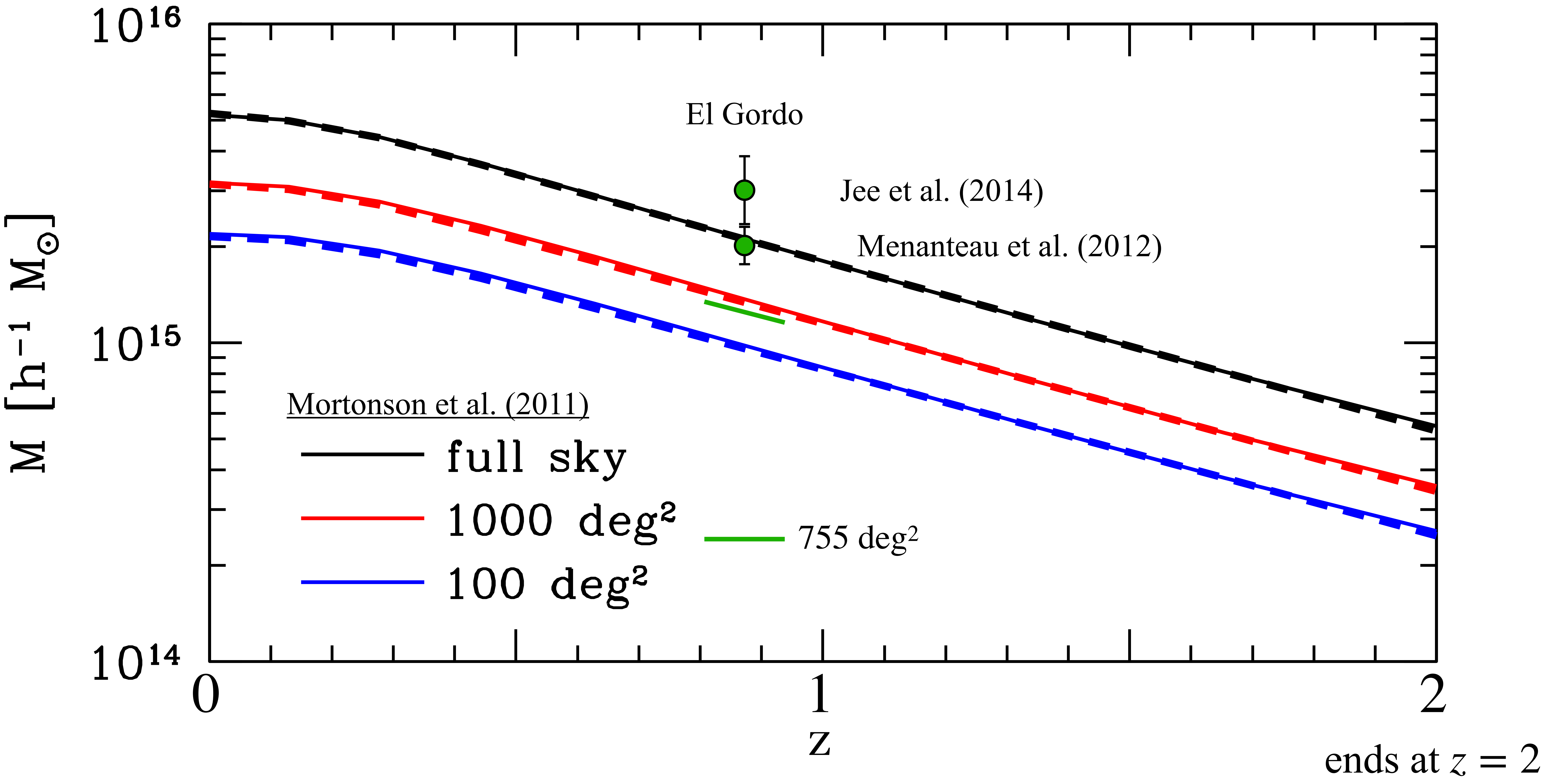
Franck & McGaugh (2016a,b)

Catalog of Clusters and Proto-Clusters (CCPC)

Comparison to LCDM simulation suggests ~1/3 of identified overdensities will become clusters by low redshift, but the measured velocity dispersions are about twice as big as found in similar structures in simulation lookback cones.



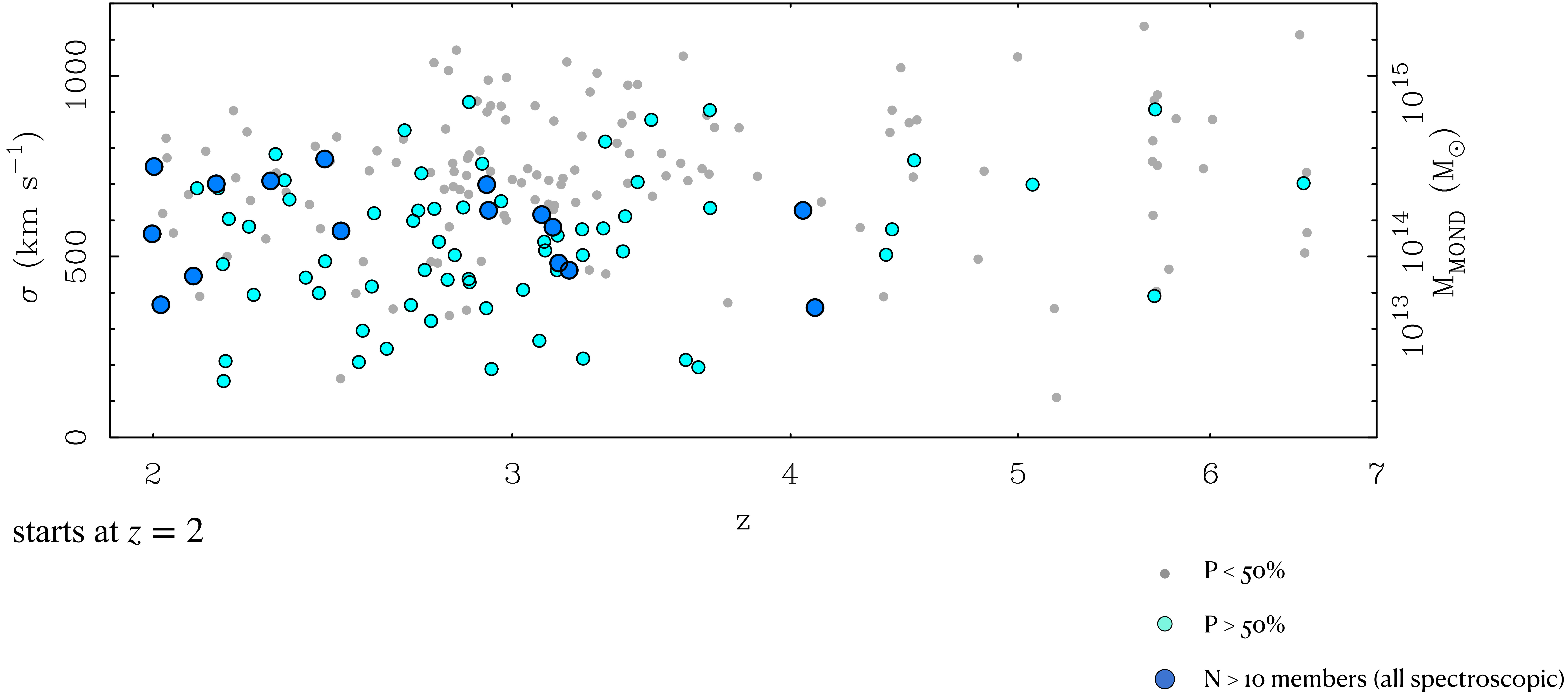



10^{16}
10^{15}
10^{14}
0
1
2
z
$M\ [h^{-1}\ M_\odot]$
El Gordo
Jee et al. (2014)
Menanteau et al. (2012)
Mortonson et al. (2011)
full sky
1000 deg²
100 deg²
755 deg²

ends at $z = 2$

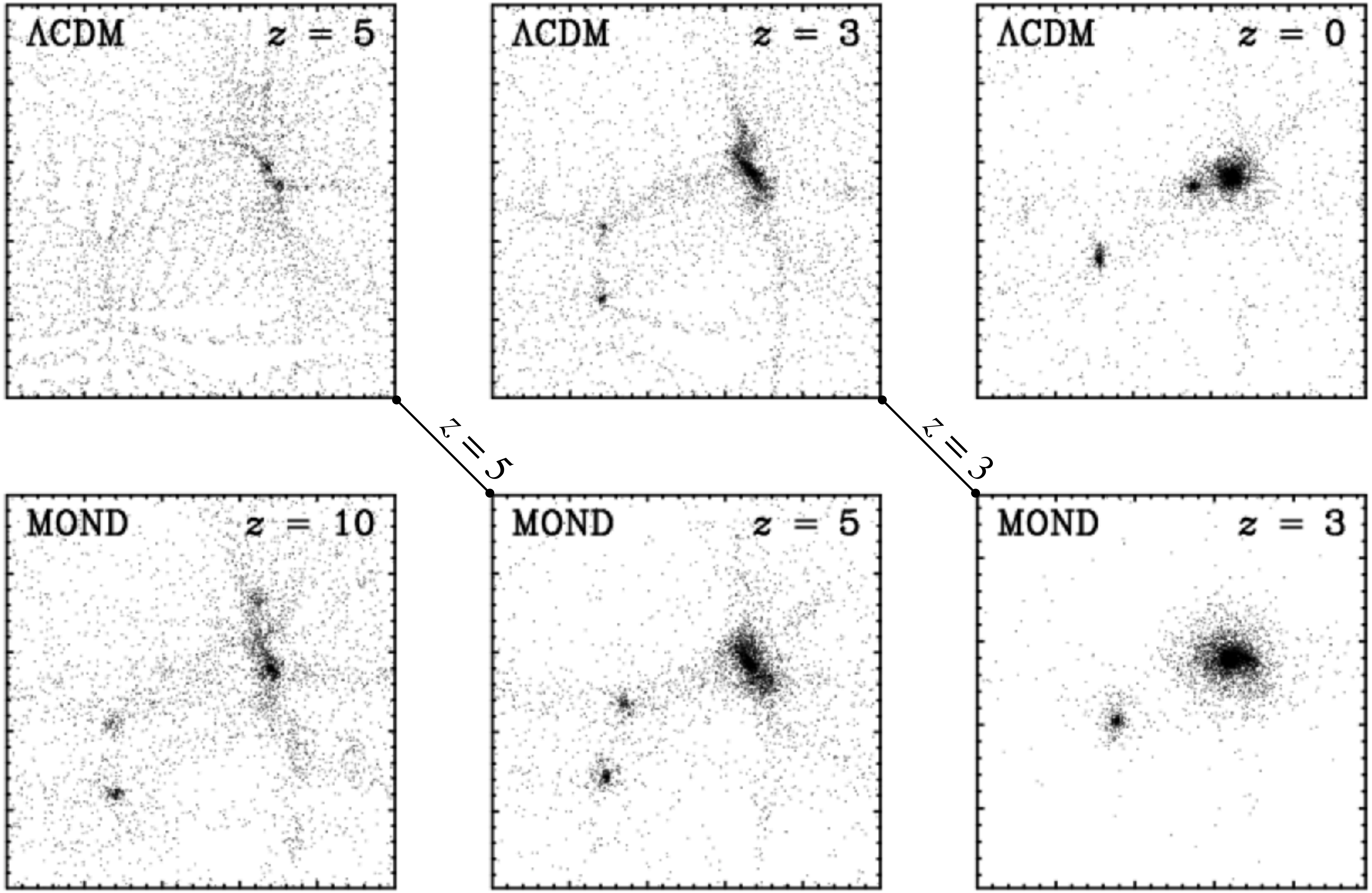
Clusters to higher redshift

Franck & McGaugh (2017)



starts at $z = 2$

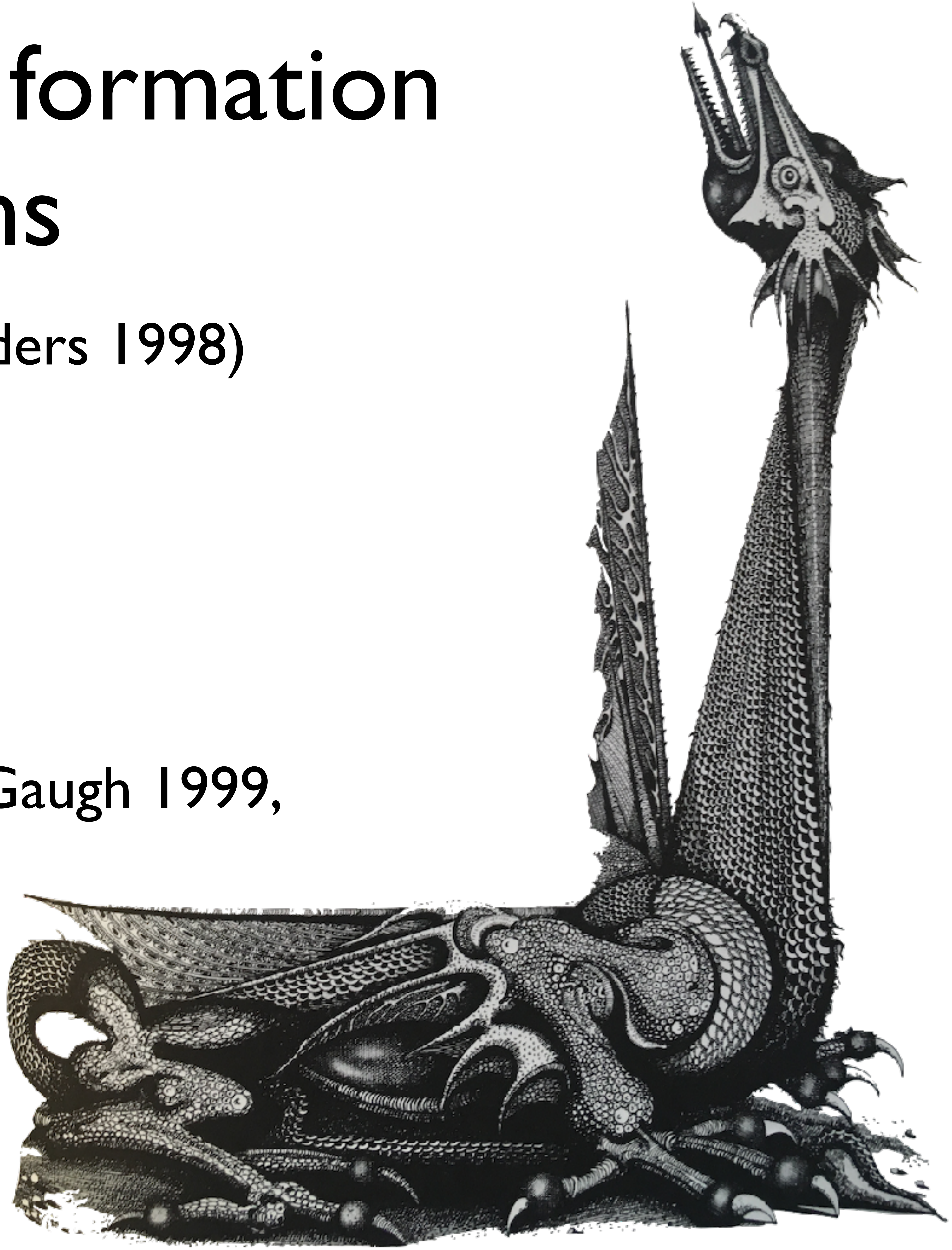
Simulated structure formation in ΛCDM and MOND



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



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), bullet cluster
- Galaxies lacking a mass discrepancy
  - TDGs, UDGs
- Detect the DM already
  - need a convincing signal

Why does MOND get *any* prediction right?