Dark Matter

ASTR 333/433
Spring 2024
TR 11:30am-12:45pm
Sears 552

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

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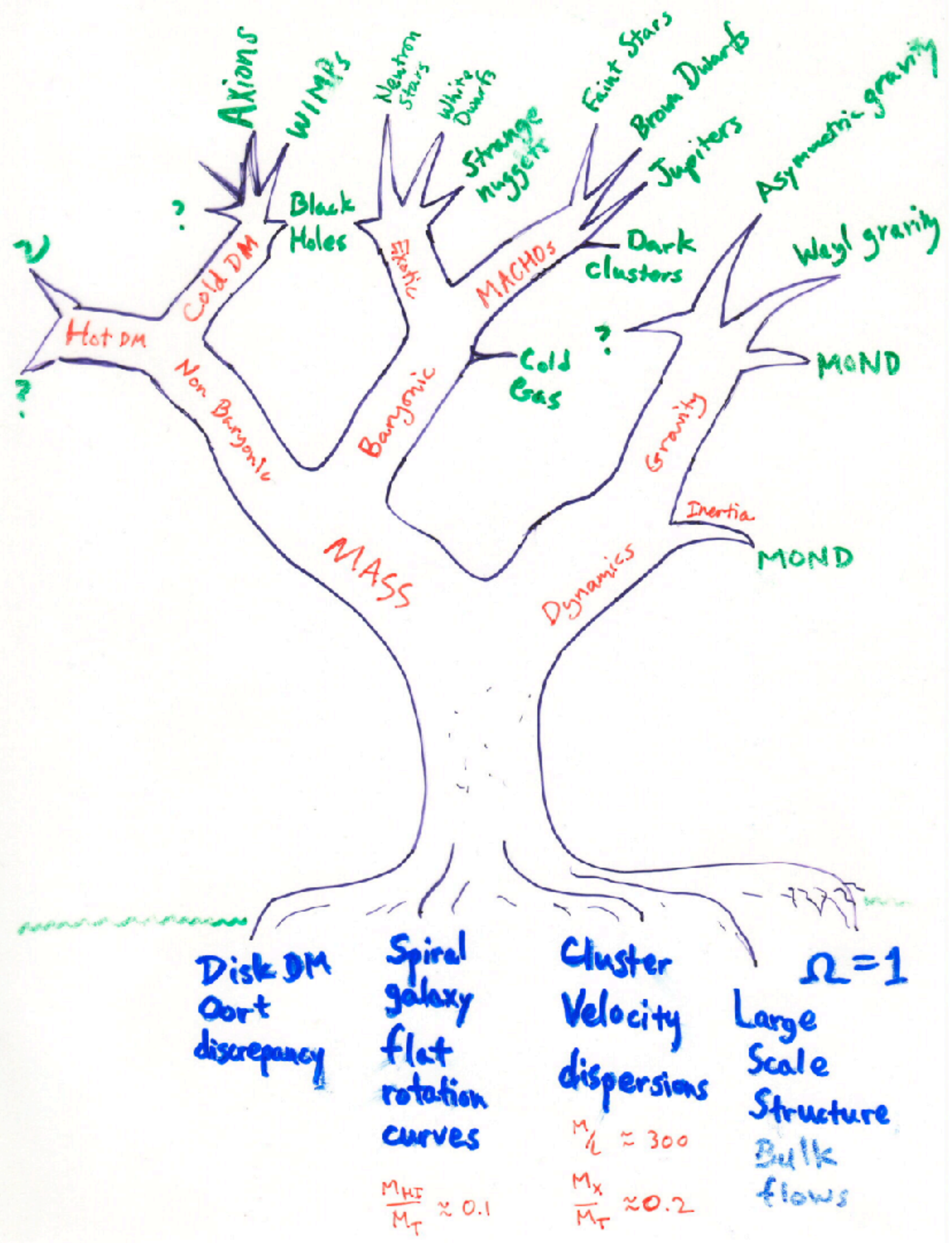


Equivalence Principle

Foundation of General Relativity

Gravitational Charge = Inertial Mass

$$m_g = m_i$$

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

$$F = m_i a$$

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

- 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

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

e.g., surface of the Earth

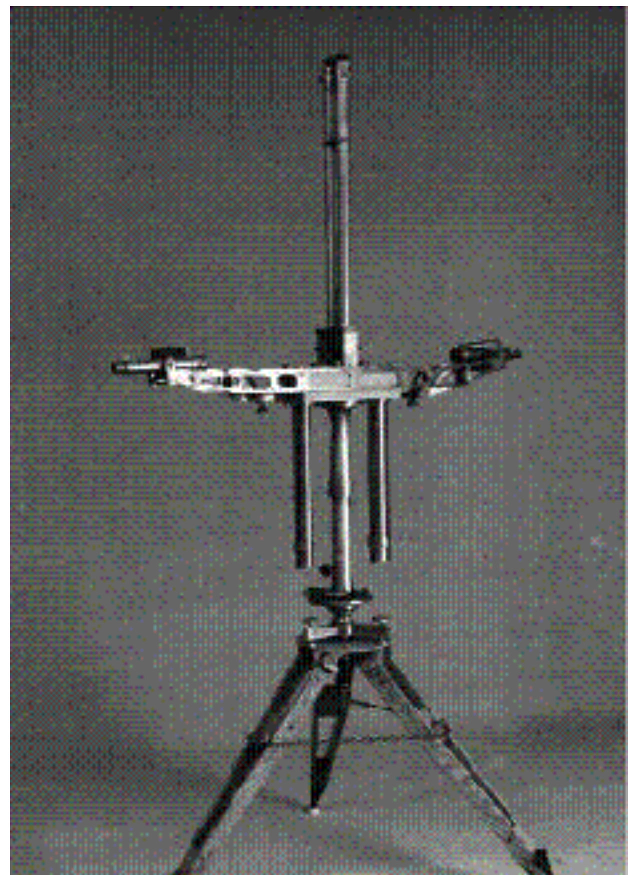
MOND regime

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

e.g., remote dwarf Leo I

External Field dominant Newtonian regime

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



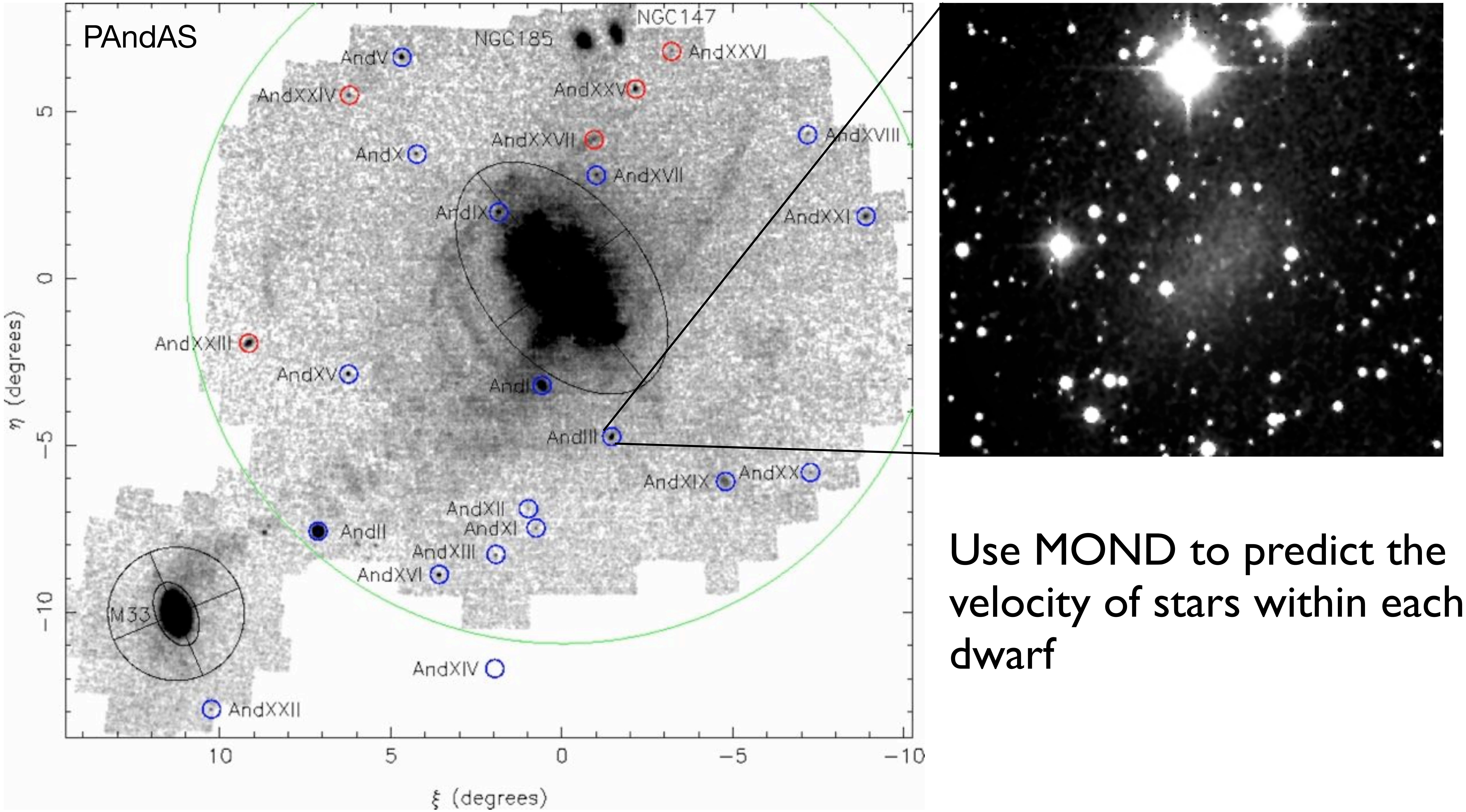
e.g., Eotvos-type experiment on the surface of the Earth

External Field dominant quasi-Newtonian regime

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

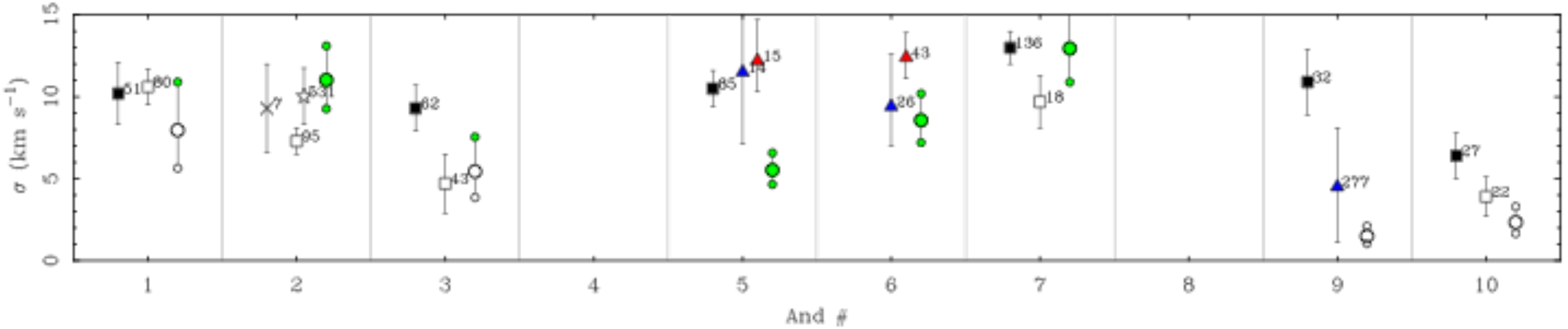
e.g., nearby Sgr dwarf

A test with the dwarf satellites of Andromeda

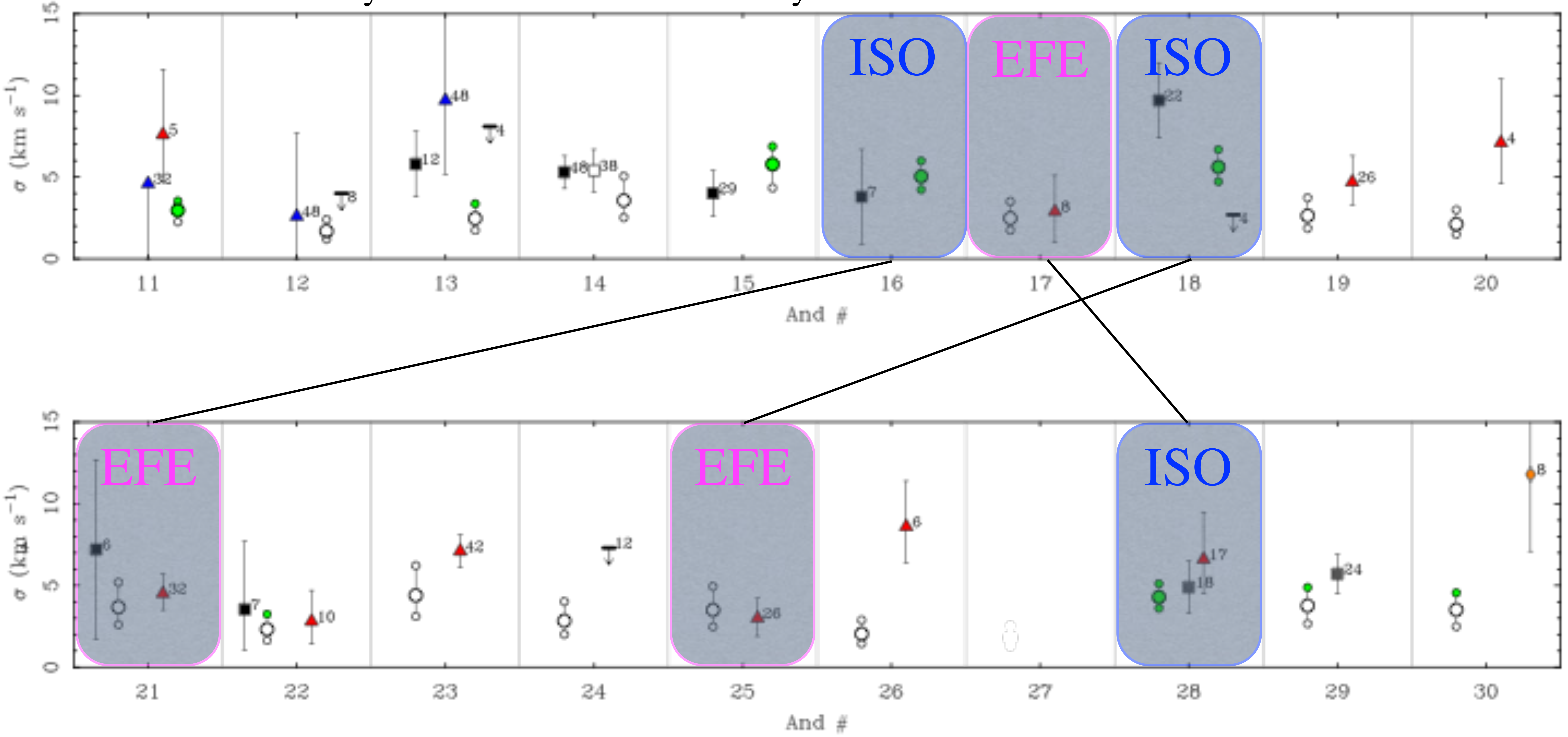


Use MOND to predict the velocity of stars within each dwarf

Velocity dispersions of the dwarf satellites of Andromeda



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)

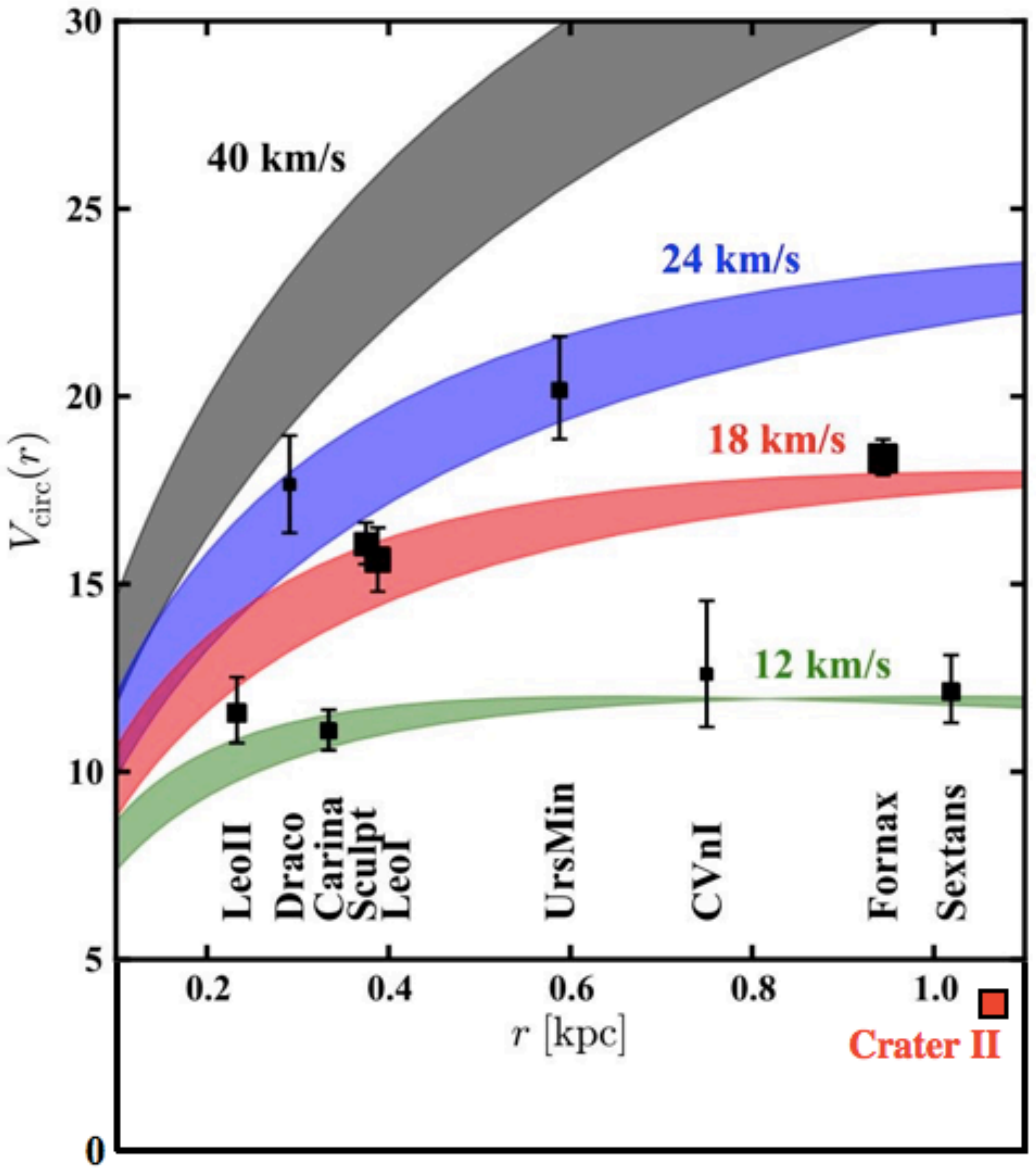
Consistent with a priori MOND prediction

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

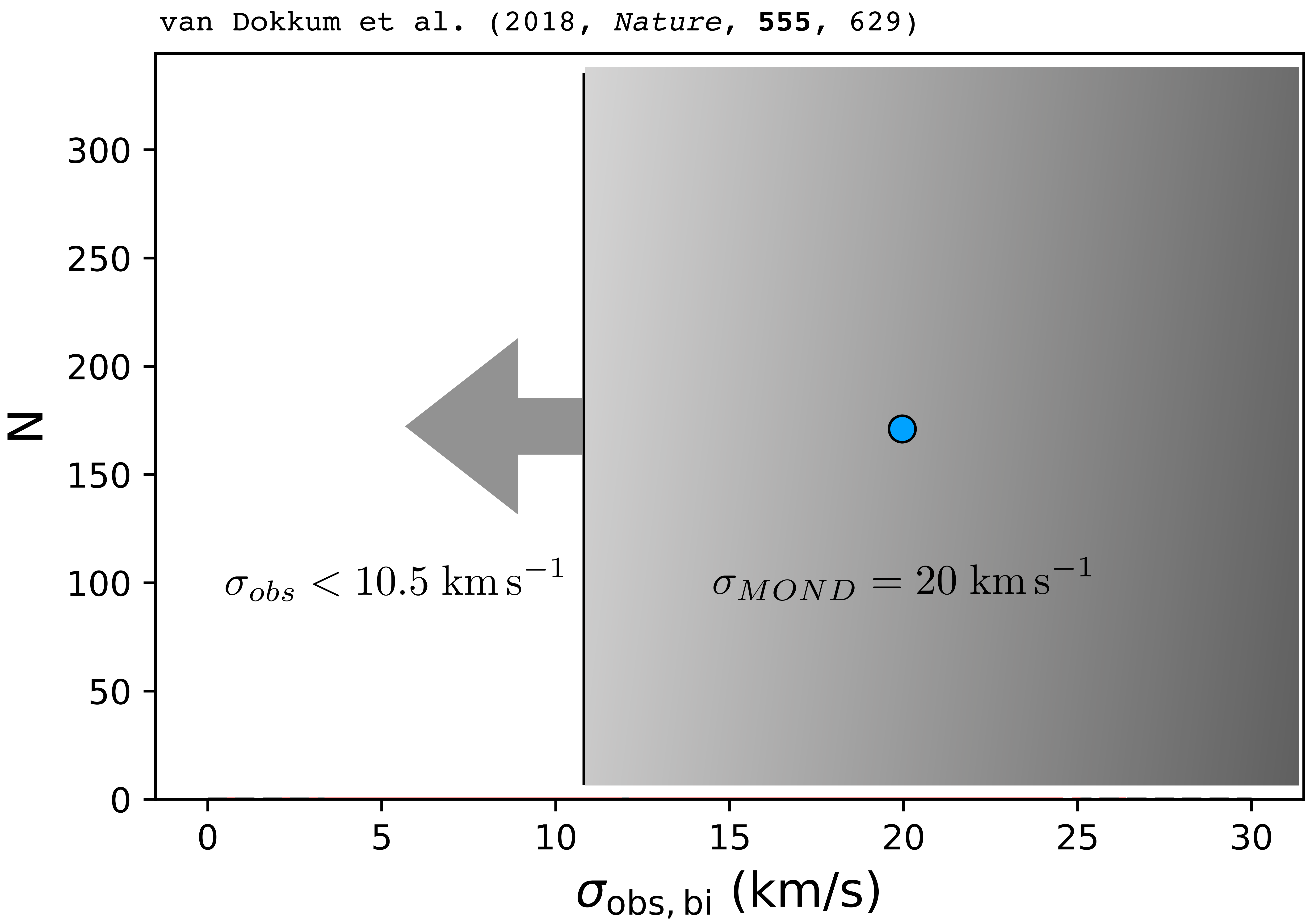
Predictions made in advance of observation are the gold standard in science.
MOND has had *many* more successful *a priori* predictions than dark matter based theories.

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

"Too Big To Fail"



NGC 1052-DF2 a galaxy without dark matter?



UltraDiffuse Galaxies largely consistent with MOND, albeit with large uncertainties

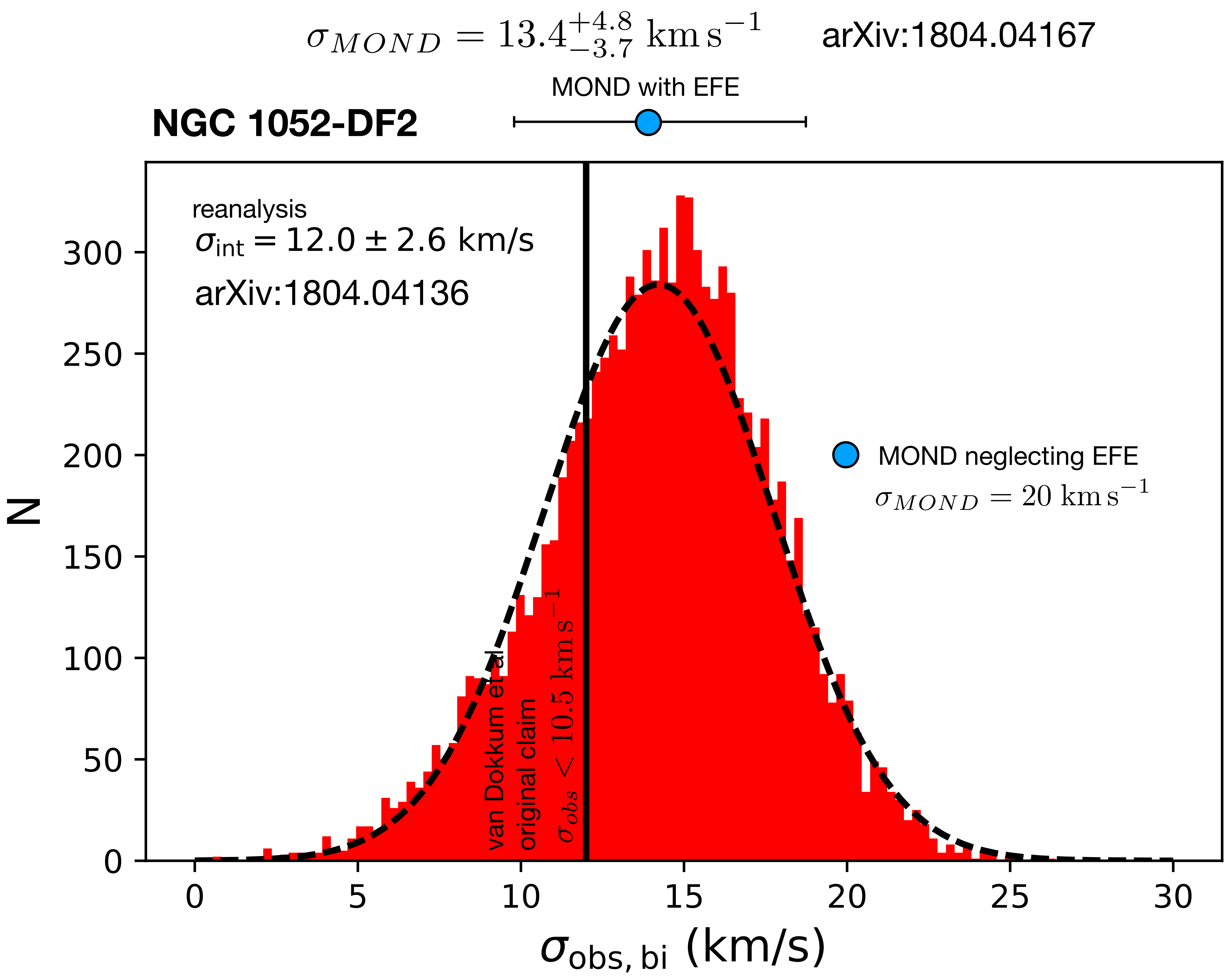


Figure 4. Results for measuring the observed biweight-midvairance dispersion from 10,000 resamples of the vD18b dataset. Here, the original velocities are perturbed within their 1 uncertainties as described in the text. The mean observed biweight for the sample comes out as $\sigma_{obs,bi} = 14.3 \pm 3.5$ km s^{-1}, giving $\sigma_{int,bi} = 12.0 \pm 2.5$ km s^{-1}, higher than the 90% upper limit from vD18b, and consistent with our MCMC analysis.

Review of relativistic theories containing MOND in the appropriate limit

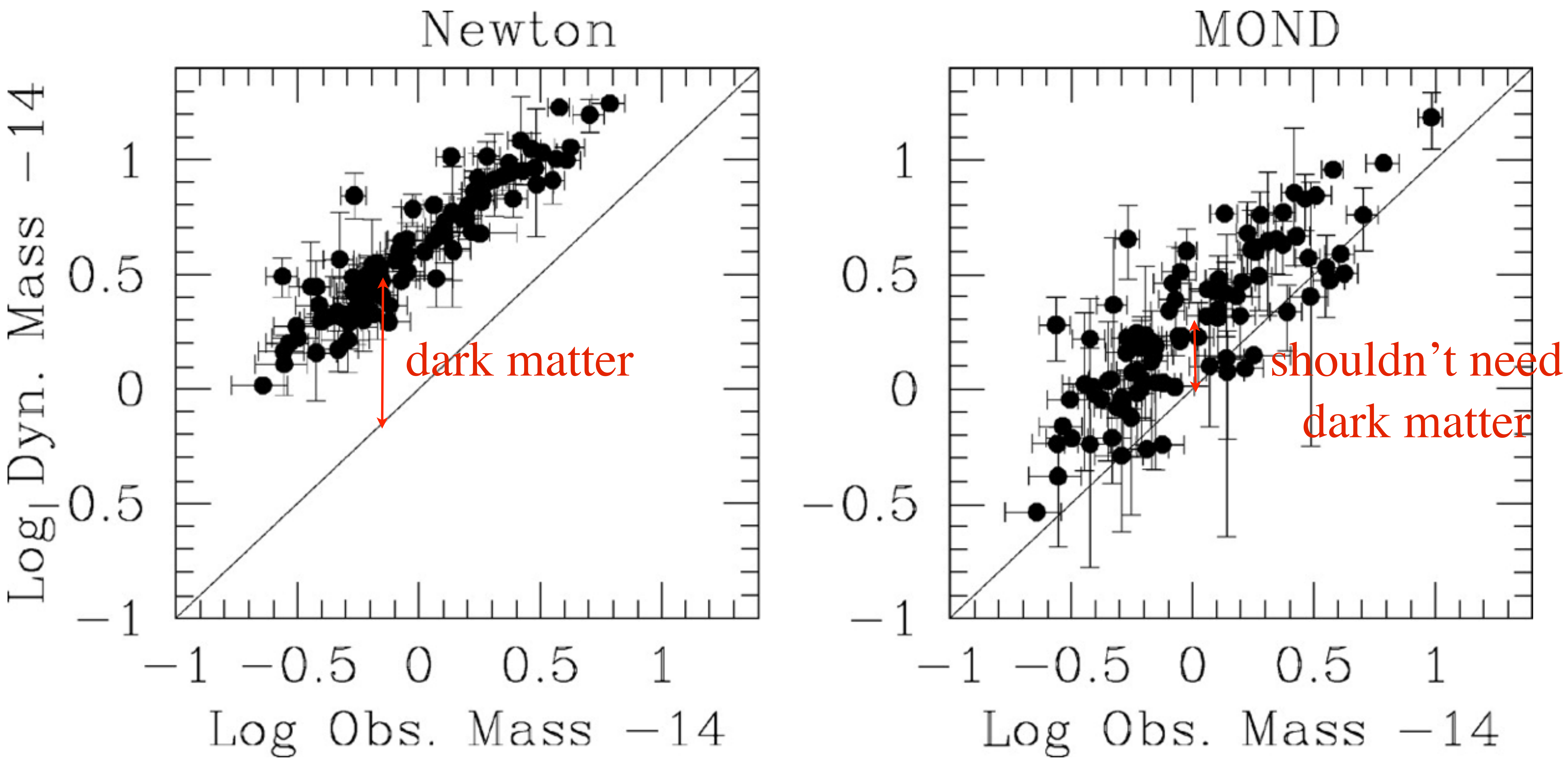
- You don't know the Power of the Dark Side
- Can MOND explain large scale structure?
- Can it provide a satisfactory cosmology?
- Can it be reconciled with General Relativity?

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

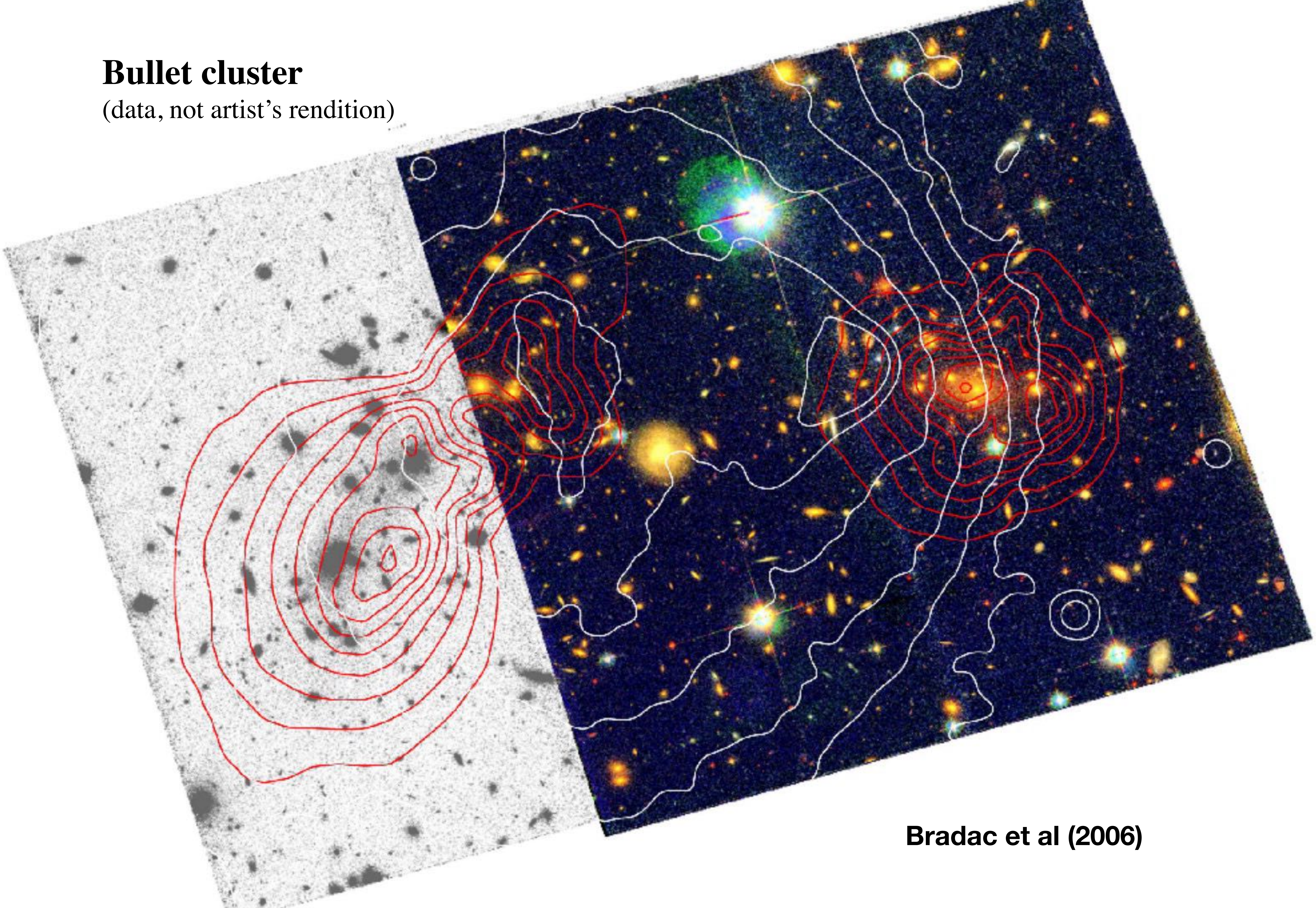


(Sanders & McGaugh 2002)

clusters ruin everything

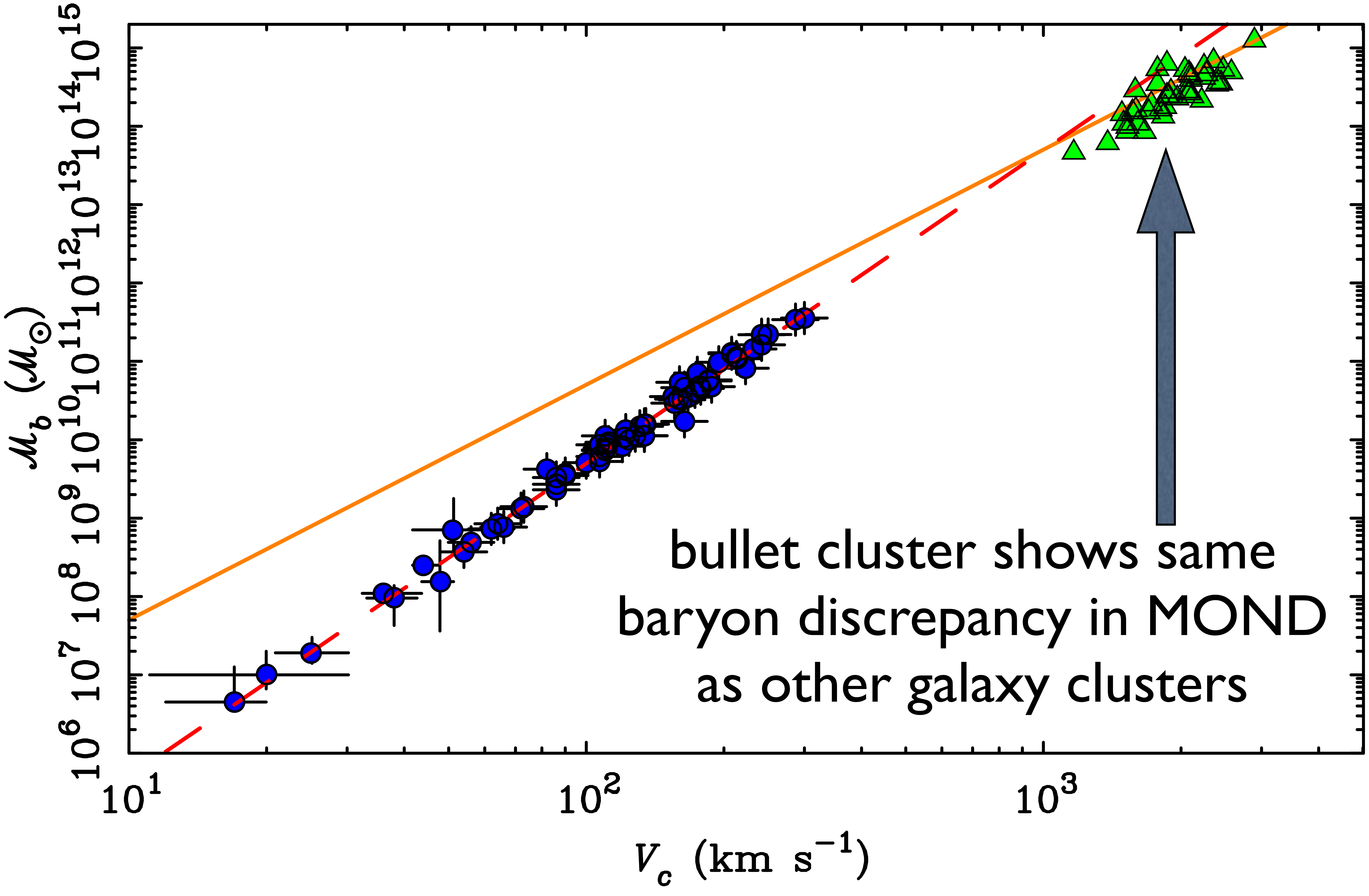
Bullet cluster

(data, not artist's rendition)

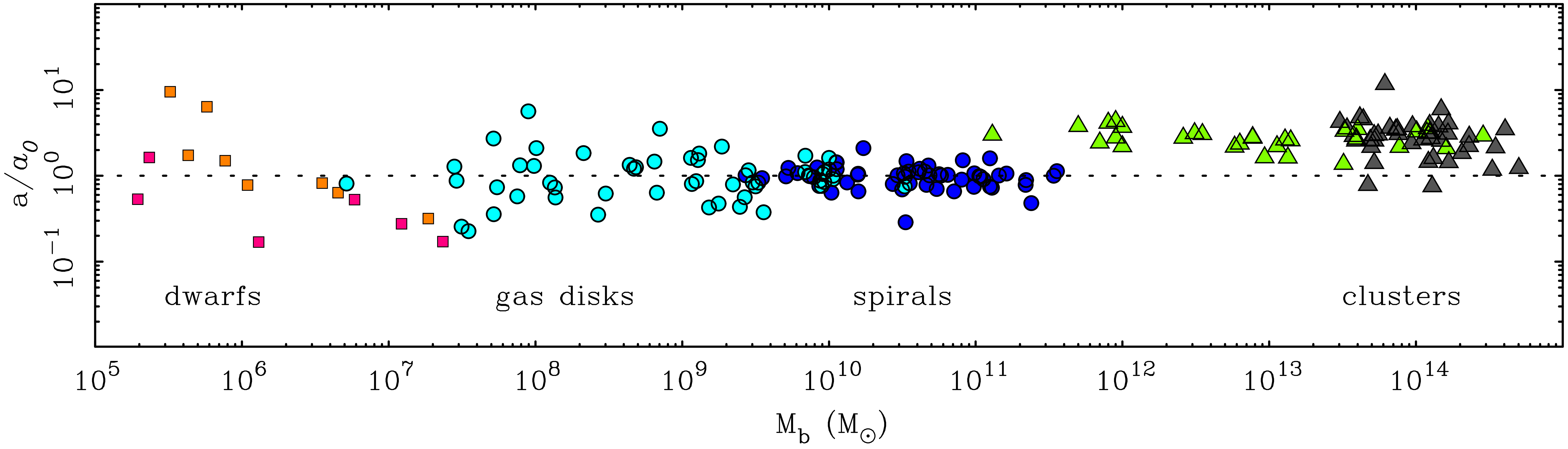


Bradac et al (2006)

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



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

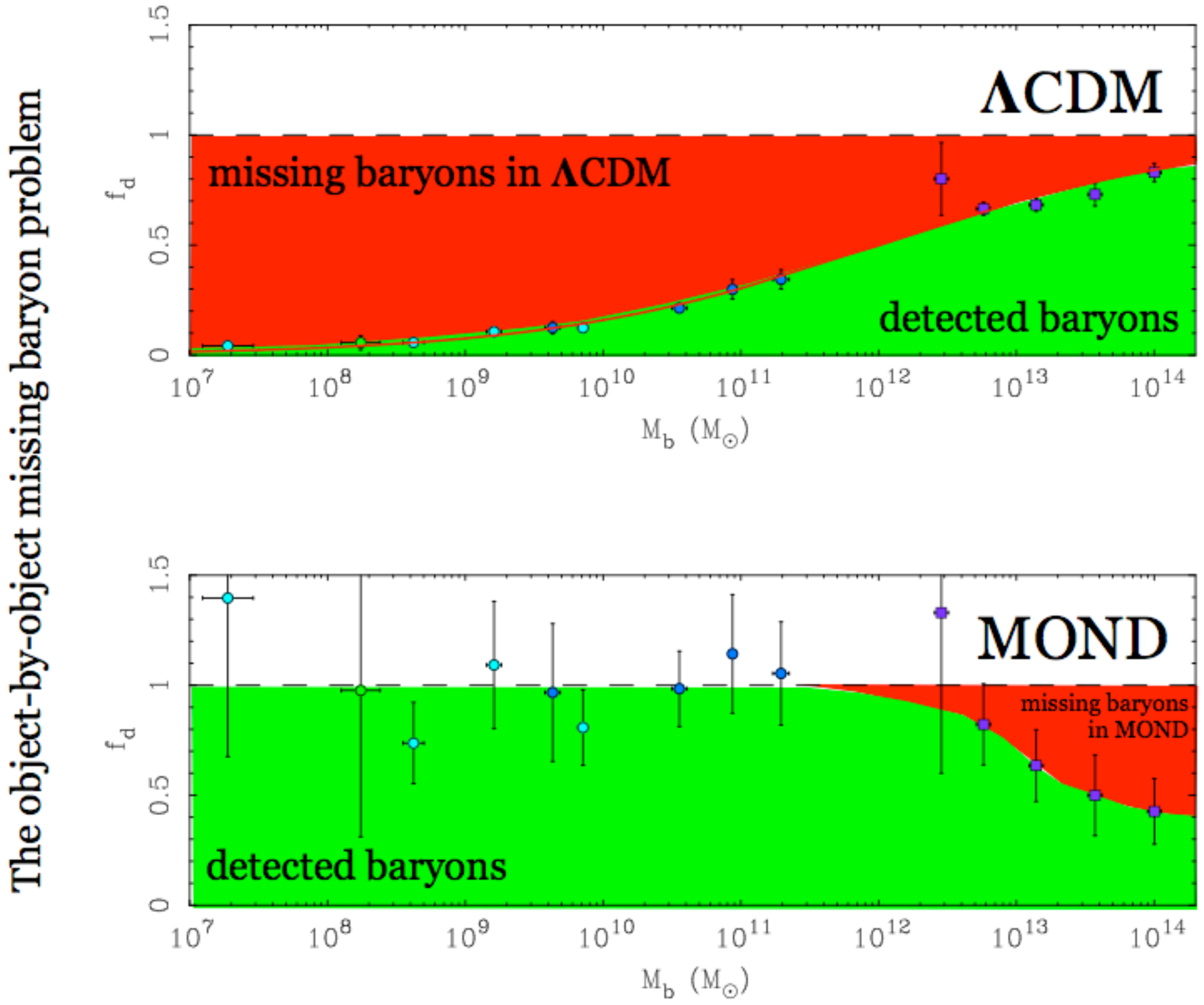


$$a_0 = 1.2 \times 10^{-10}\ \mathrm{m\,s^{-2}} \approx \frac{cH_0}{2\pi} \approx c\Lambda^{1/2}$$

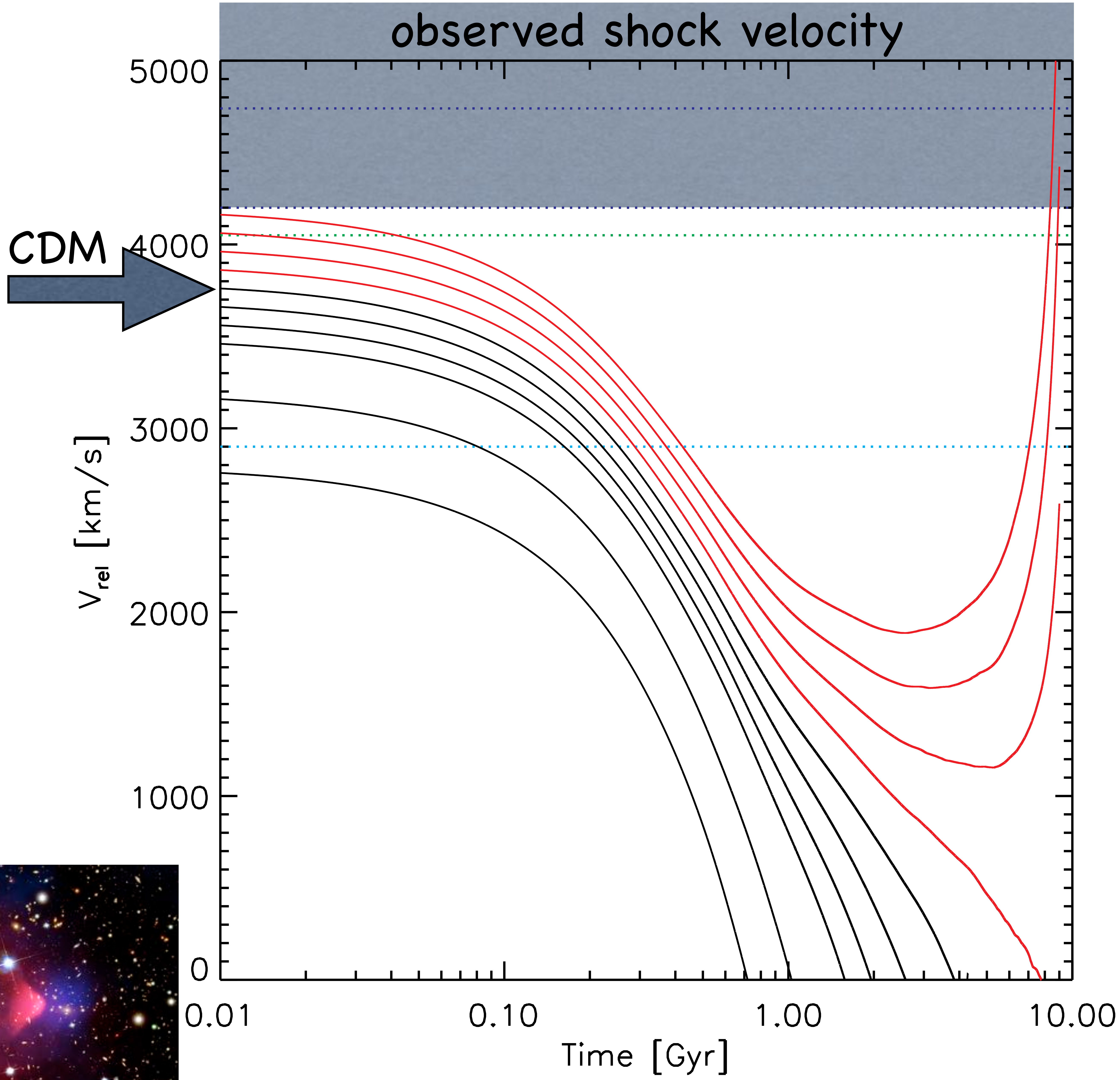
$$\Sigma_\dagger = 860\ \mathrm{M_\odot\,pc^{-2}}$$

The MOND scale is in the data.

Both paradigms suffer a missing baryon problem, albeit in different systems



The bullet cluster collision velocity provides another test



Angus & McGaugh (2008) MNRAS, 383, 417

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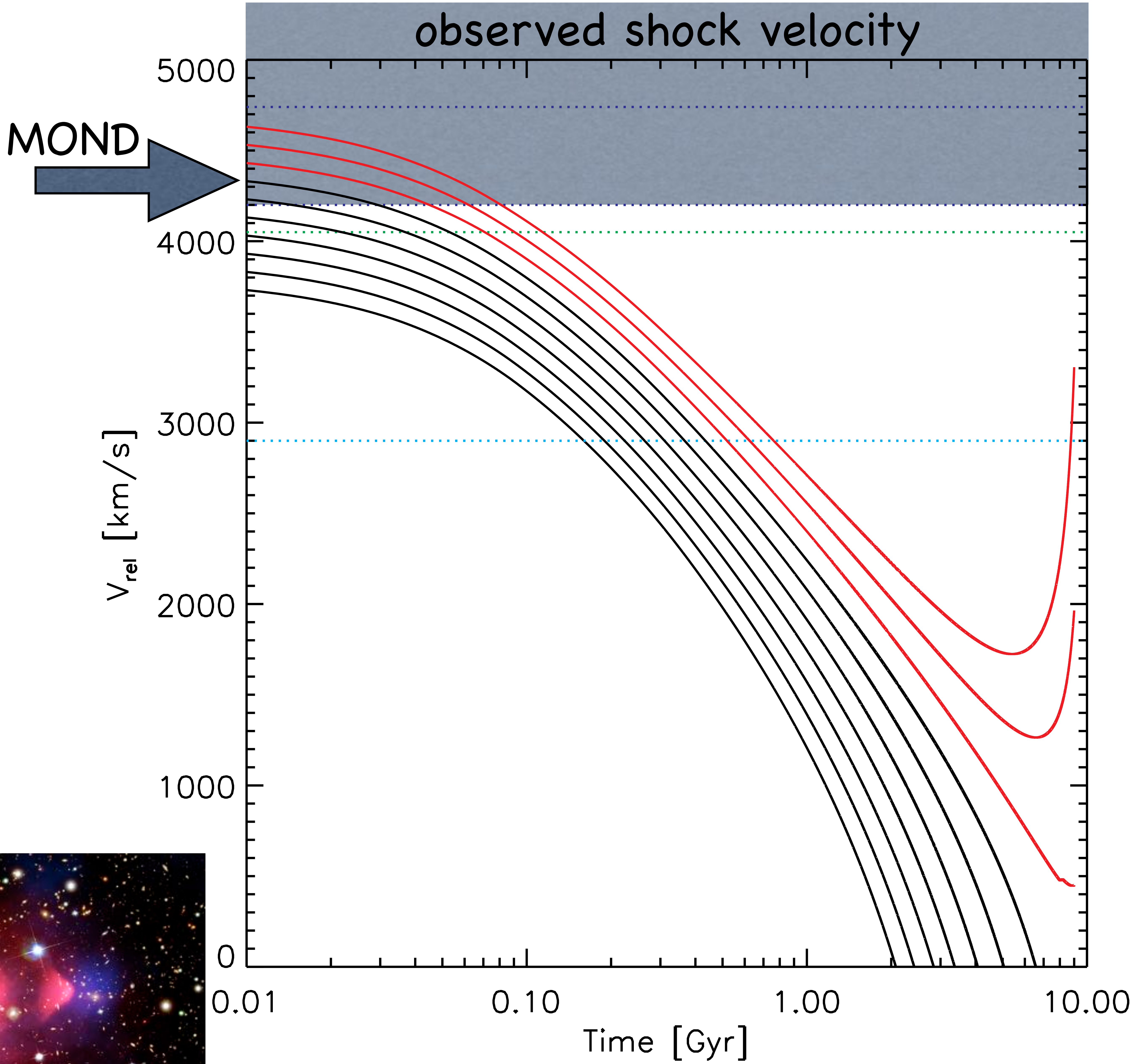


Angus & McGaugh (2008) MNRAS, 383, 417

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

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

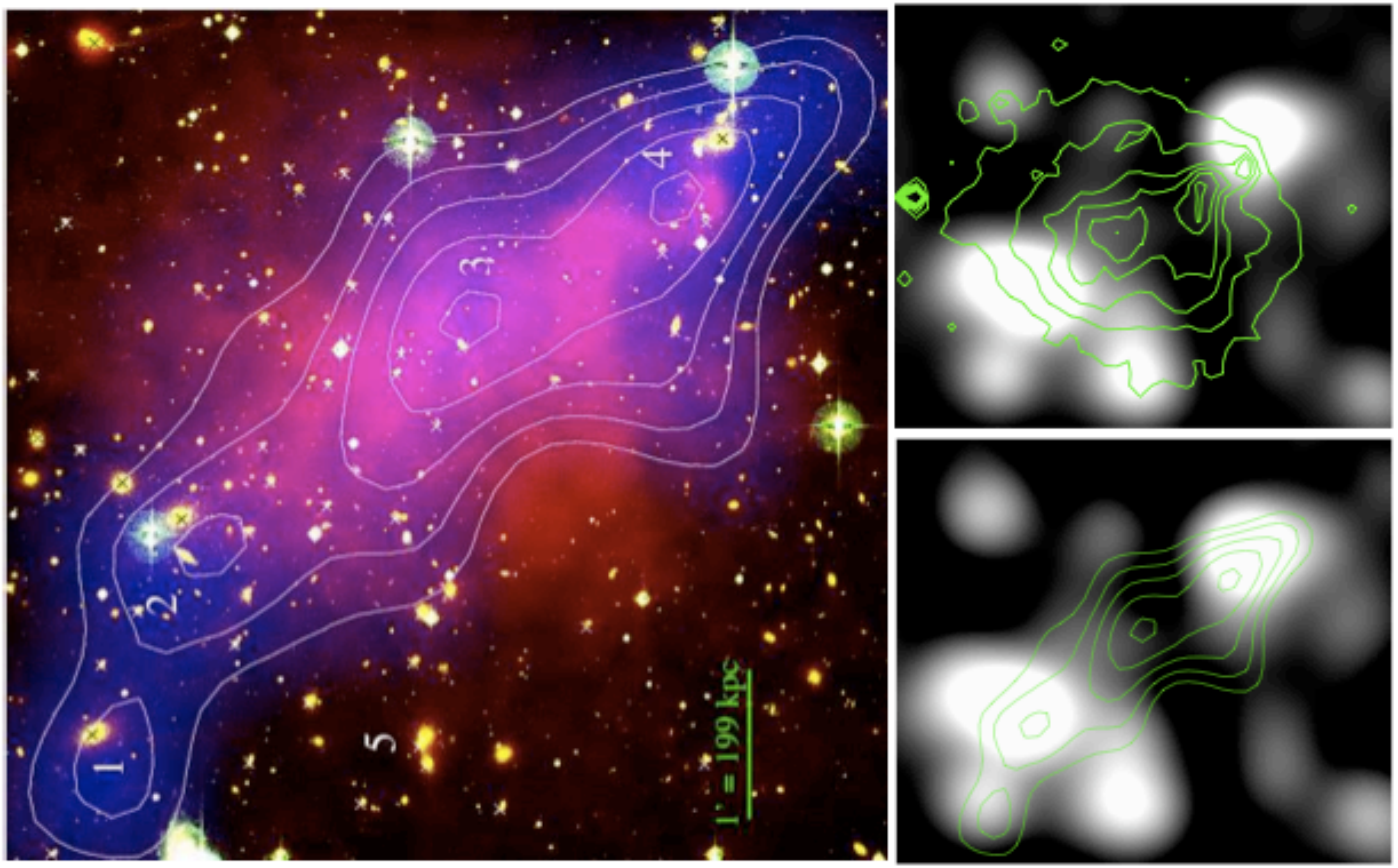


FIG. 2.— (a) Central 6.4′ × 6.4′ of Abell 520, showing the CFHT image, the diffuse Chandra X-ray emission (red), and the lensing surface mass density (blue + 3, 3.5, 4, 4.5, and 5σ contours determined from a bootstrap analysis). Spectroscopically confirmed member galaxies are marked with an X; red-sequence 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.

Merging galaxies provide a test

- need enough dynamical friction to prevent flyby
  - big dark matter halos do this; how can MOND?
- formation and properties of tidal dwarf galaxies (TDGs)
  - tidal material should be stripped of dark matter
  - TDGs form naturally in MOND
  - can TDGs form at all in CDM?

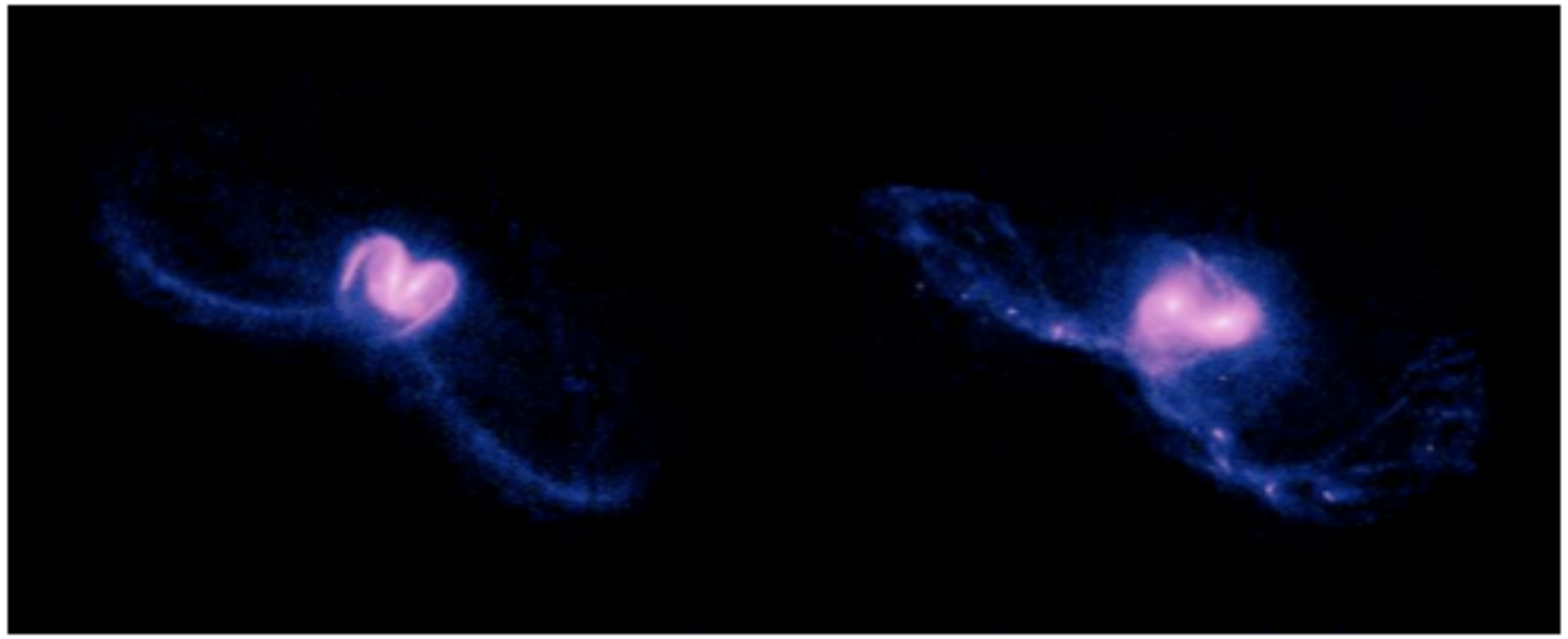
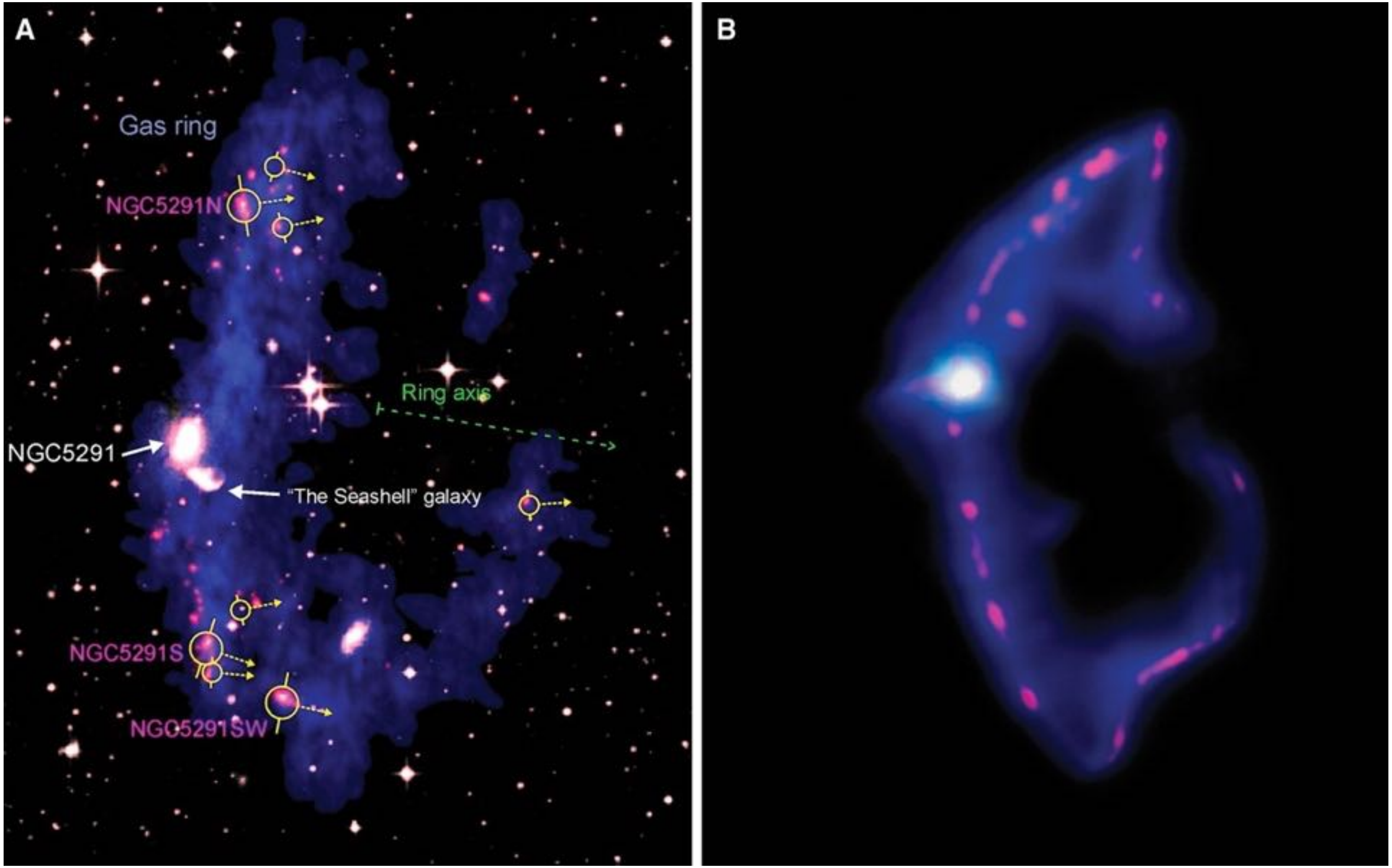


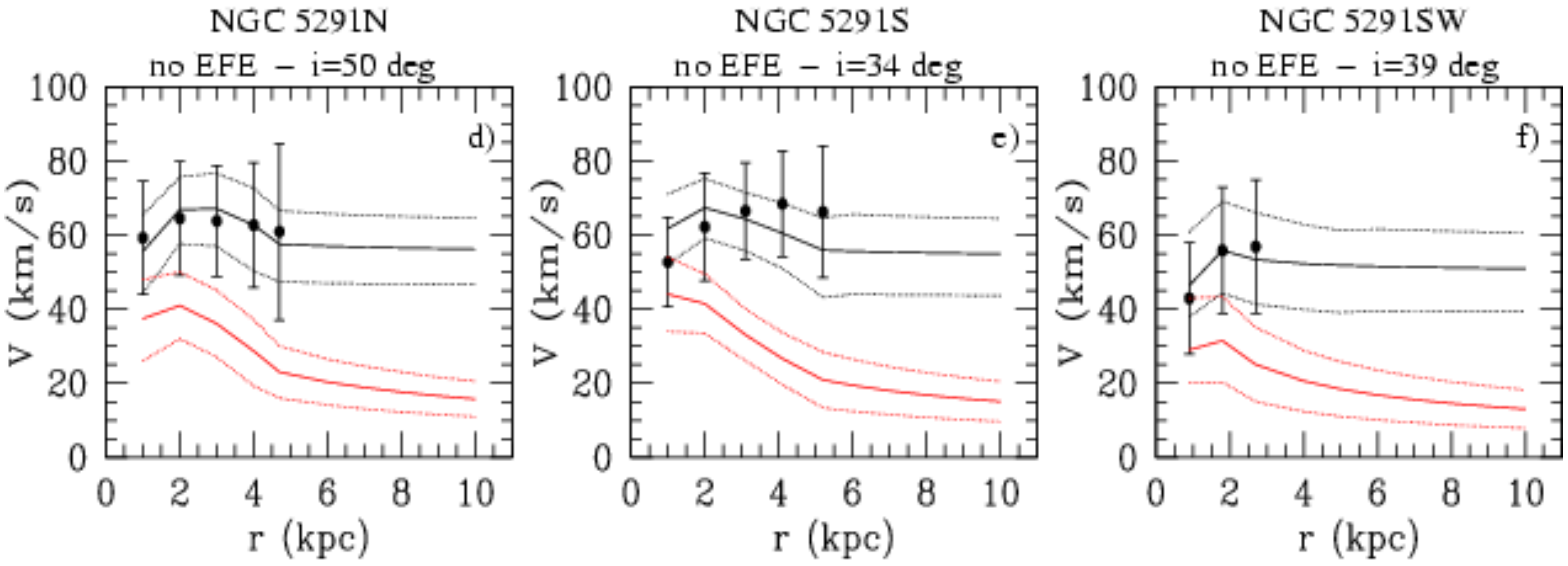
Fig. 5. Simulations of the Antennae galaxies in the DM model (left) and MOND model(right).

Tiret & Combes

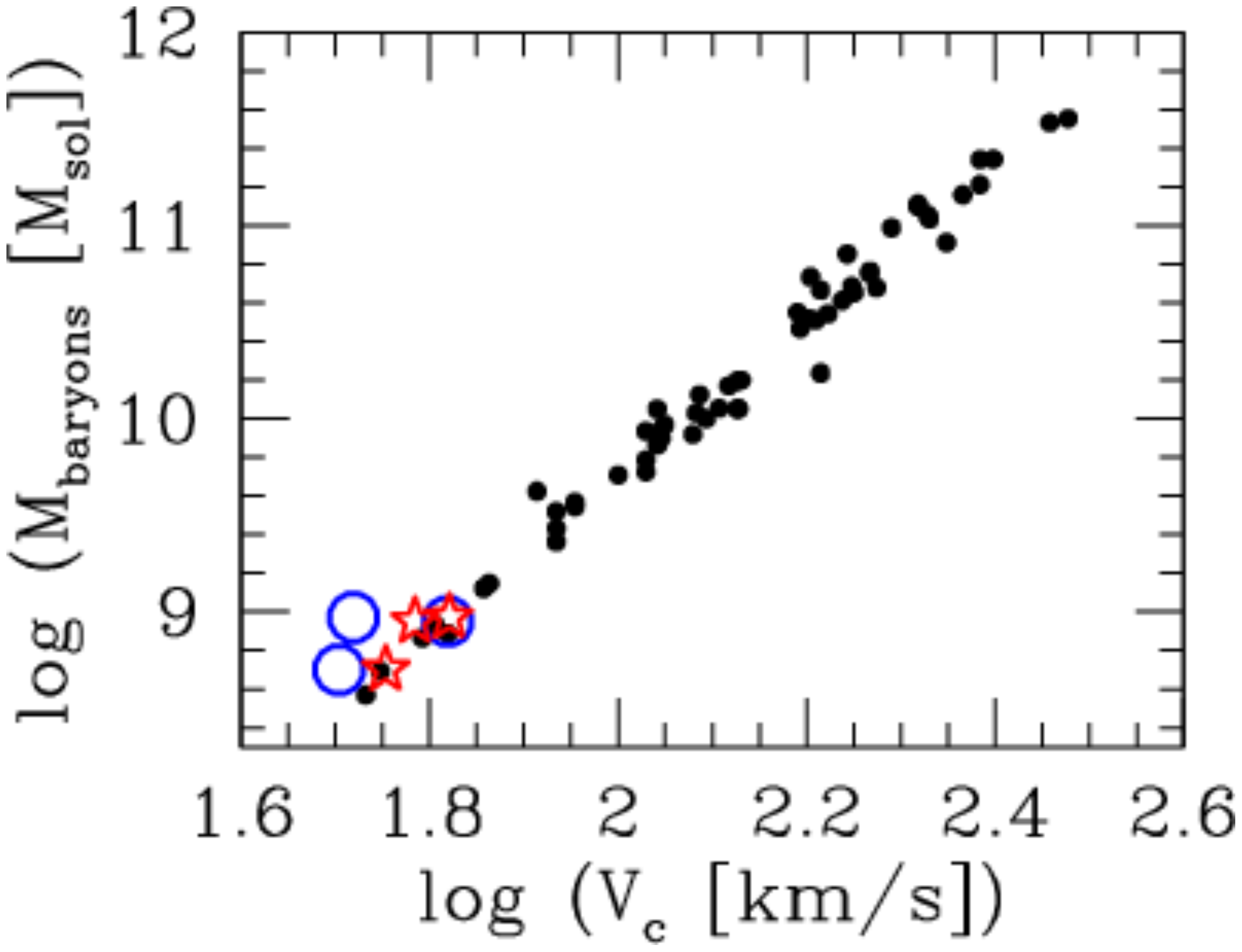
Tidal Debris Dwarfs - should be devoid of Dark Matter



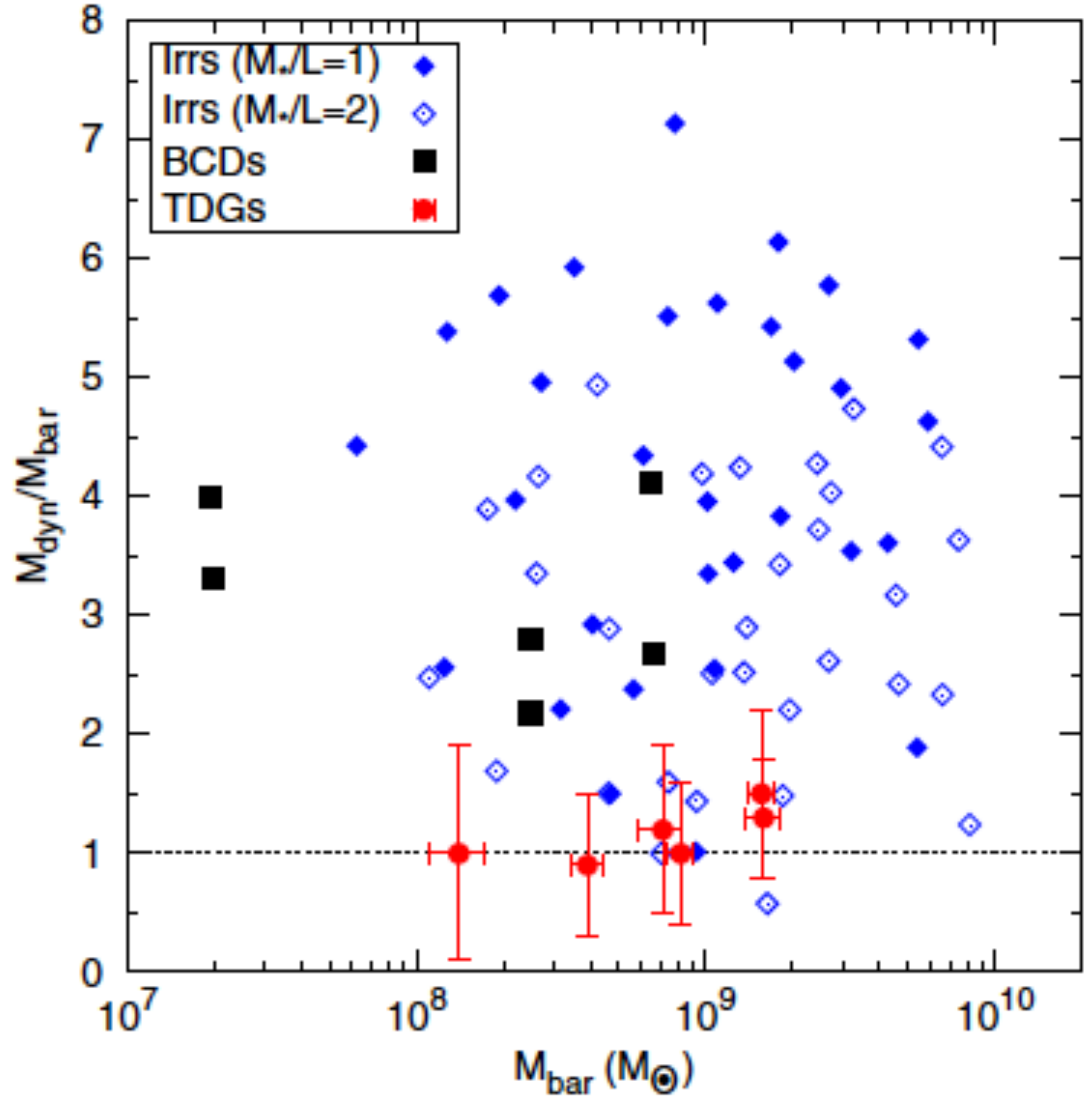
Bournaud et al. (2007) *Science*, **316**, 1166



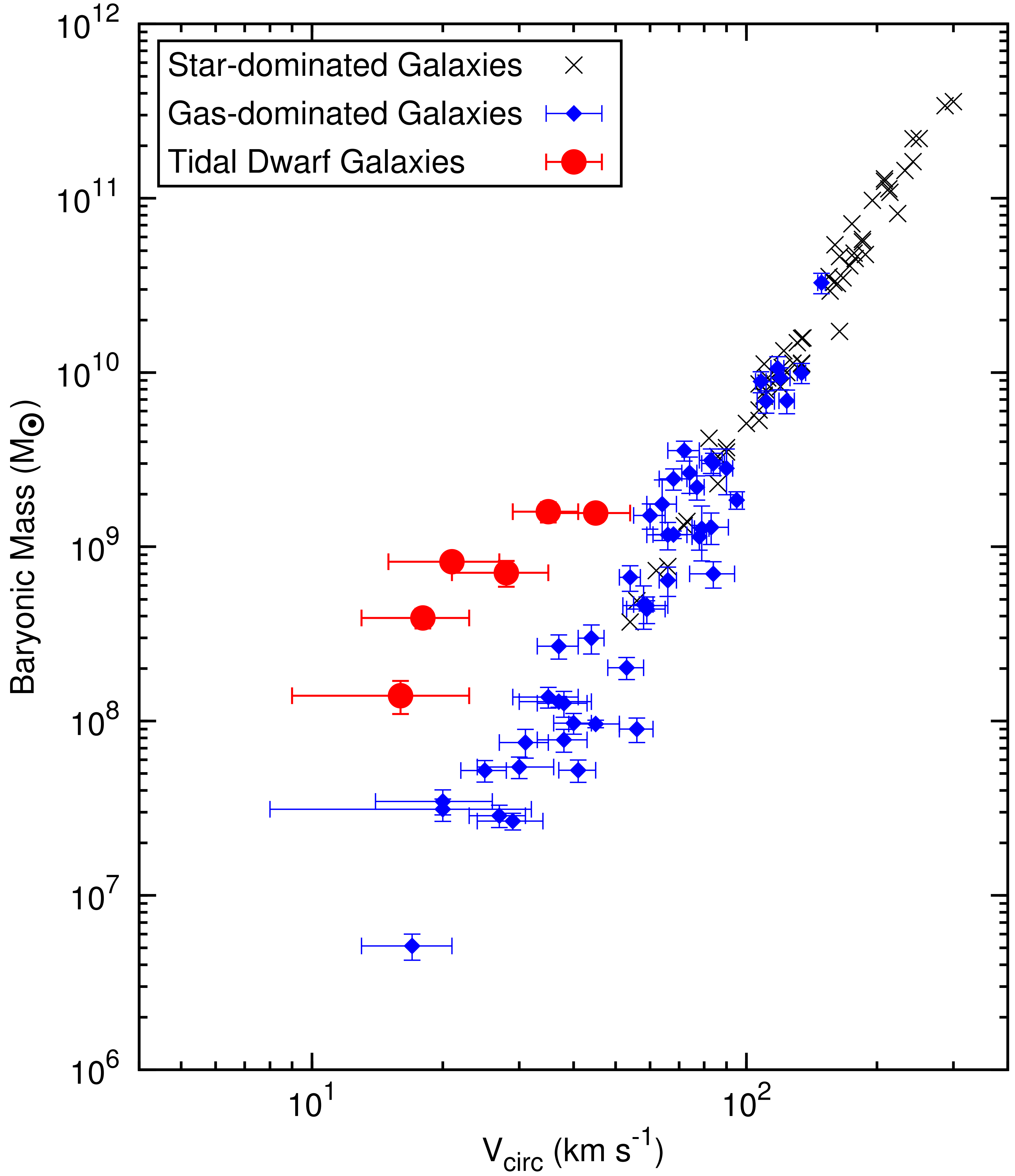
Gentile et al. (2007)
A&A, **472**, L25



Tidal dwarfs show mass discrepancies as expected in MOND



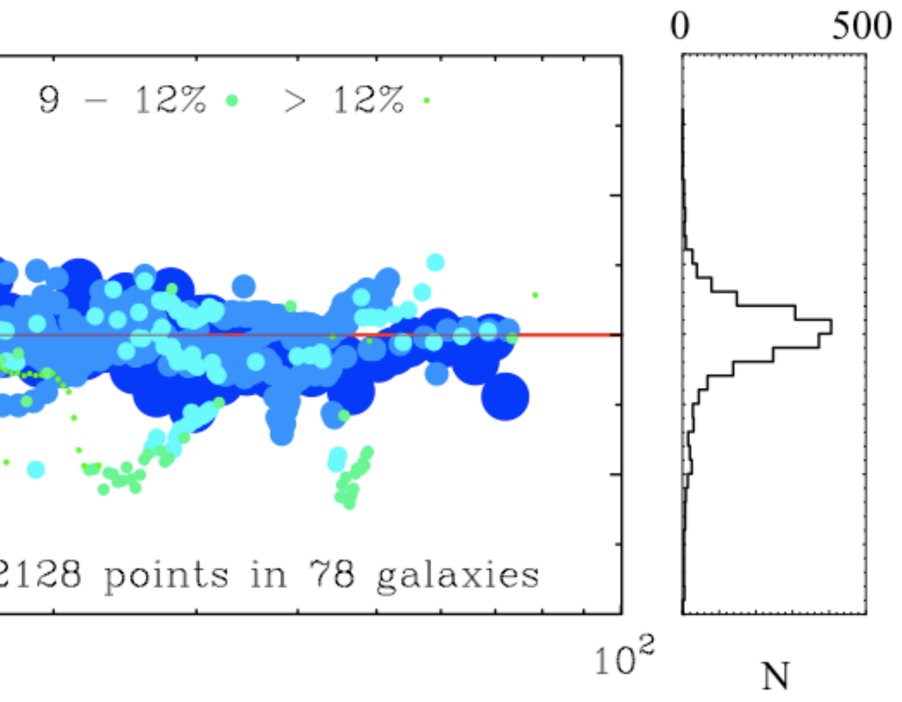
Lelli et al. (2015)
A&A, 584, A113



or is it the other way around?

Tidal dwarfs don't show mass discrepancies as expected in MOND

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

- 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
  - X 3rd peak

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

Structure formation in CDM and MOND

cold dark matter

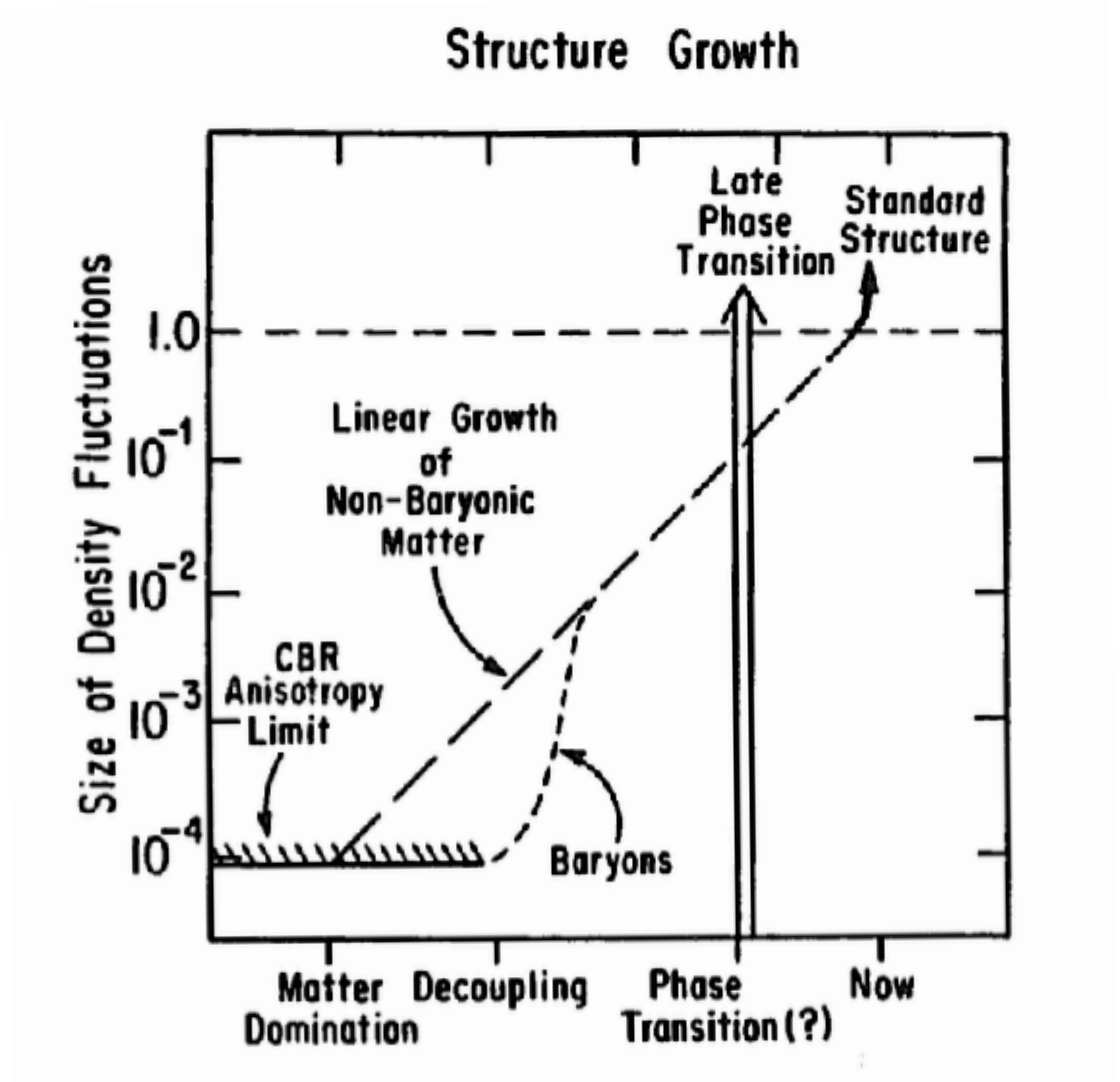
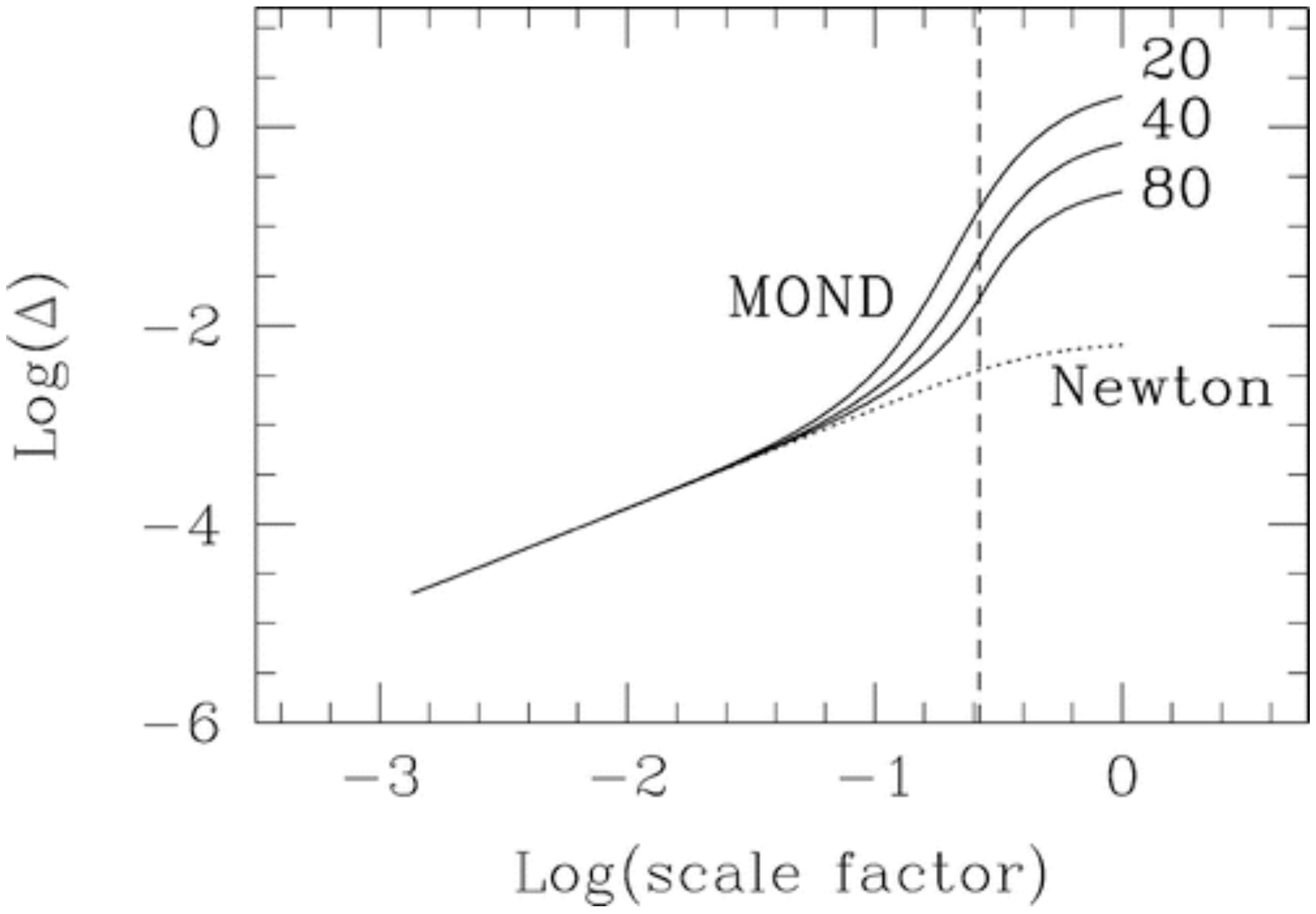


Figure 5. Linear growth of $\delta\rho/\rho$ versus inverse temperature with epochs noted.

MOND



linear growth of dark matter perturbations

$$\delta \sim a$$

nonlinear growth of baryon perturbations

$$\delta > a$$

WAYS OUT

Falsify LCDM

Is this even possible?

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

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

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?