

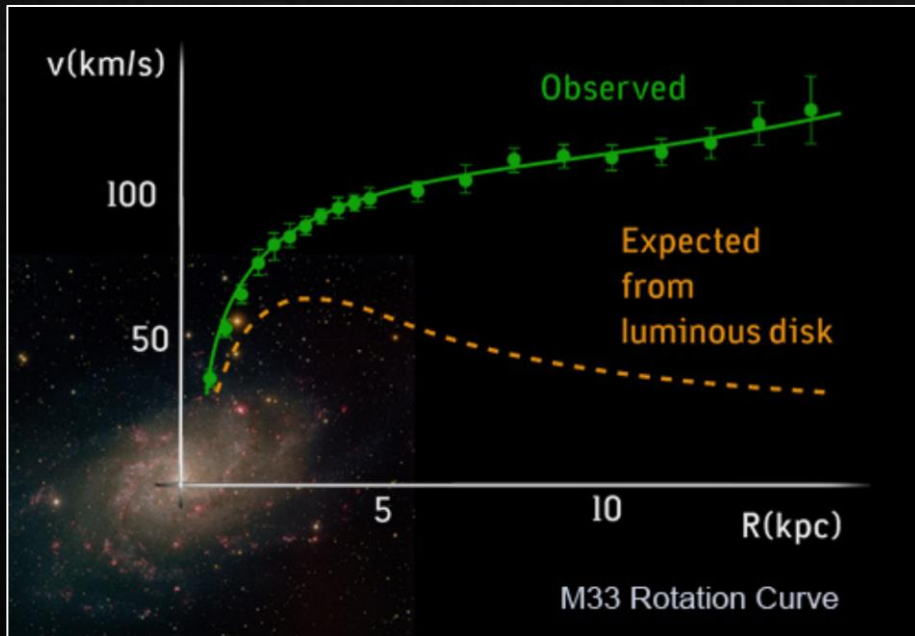
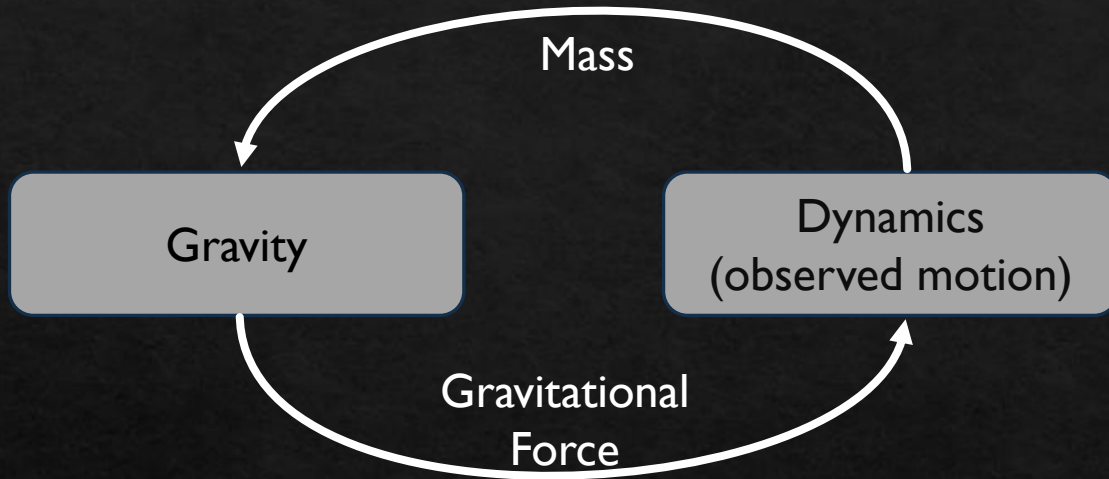


Probing Dark Matter and Modified Gravity Using Galaxy Clusters

Eliza C. Diggins

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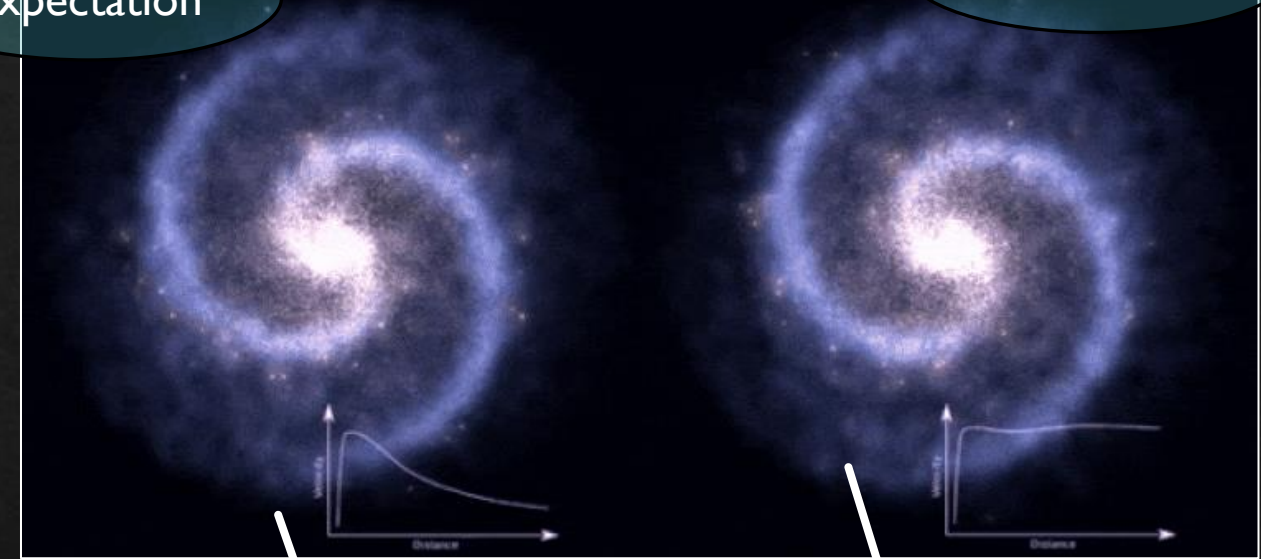
The Missing Mass Problem



M33 Image: NOAO, AURA, NSF, T.A. Rector

Expectation

Reality



Slow rotation

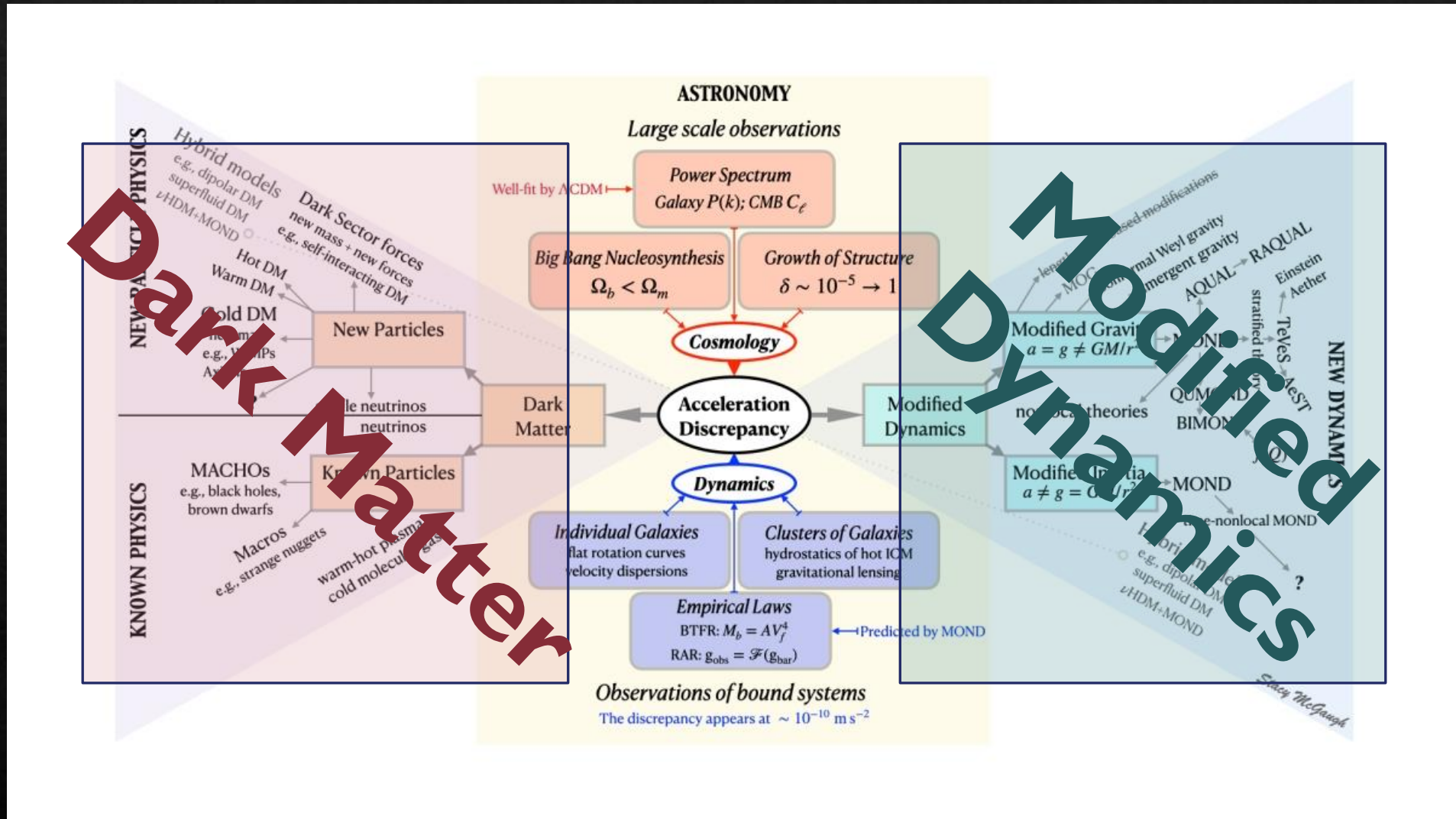
Faster Rotation



Big Idea:

The motion of gravitational systems is inconsistent with our theories – **indicative of additional (missing) mass.**

A Tale of Two Theories:



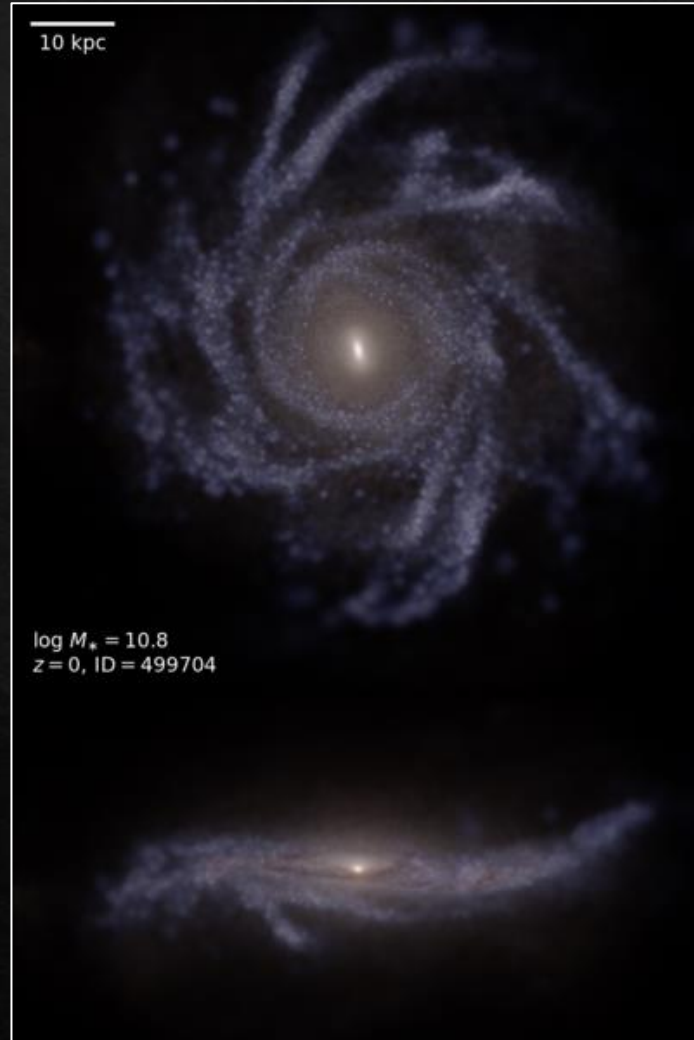
Dark Matter

Successes

- Consistent with galaxies.
- Foundation of concordance cosmology.
- Consistent with galaxy clusters.

Failures/ Issues

- We can't detect it, despite trying.
- No great candidates for what it is.
- Requires a lot of *ad hoc* modelling to be consistent with some observations.
- Current tensions of cosmology may indicate new physics.



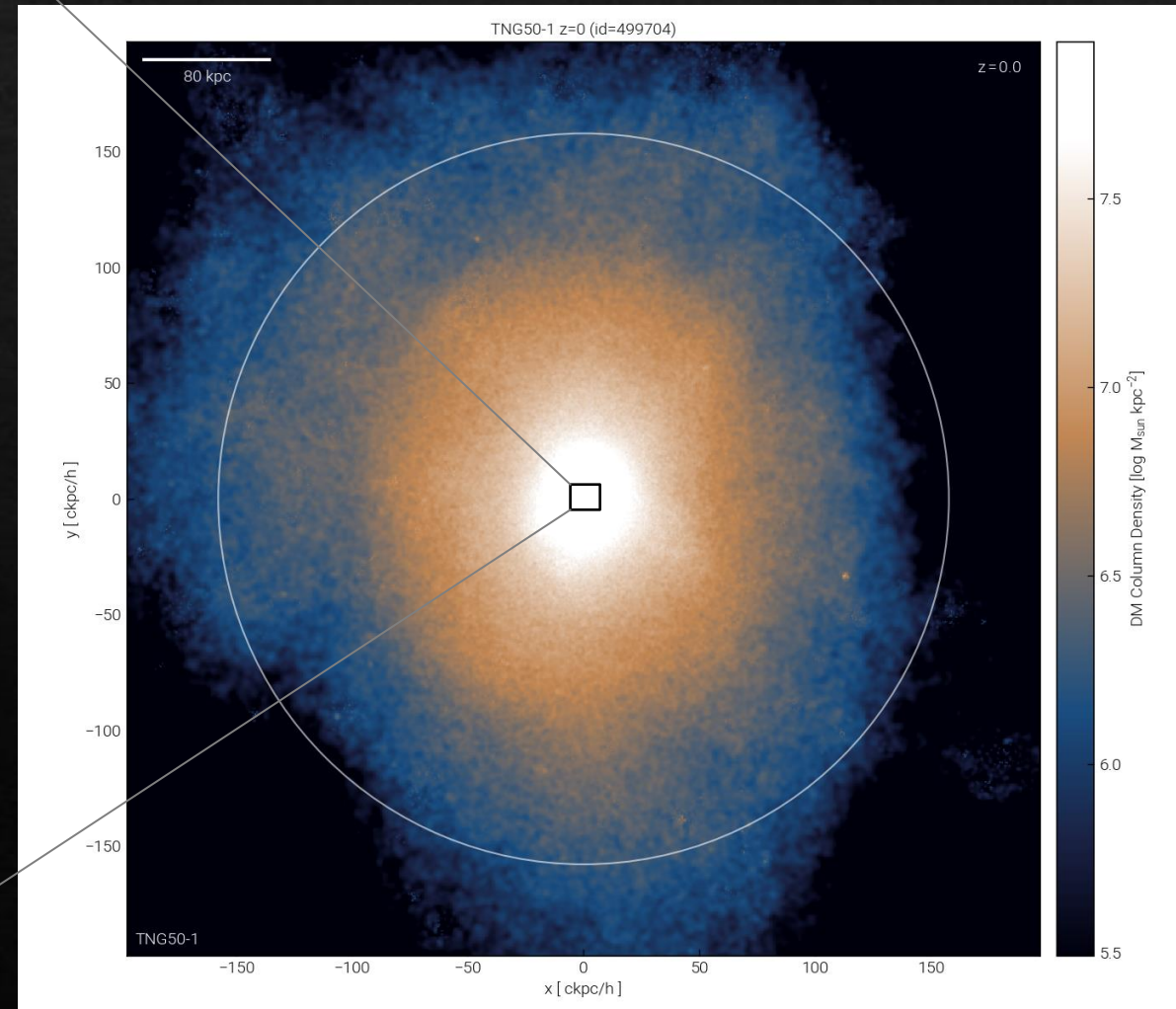
Adapted from IllustrisTNG-100

Springel+2019



Big Idea: (Dynamics is wrong)

Missing mass is real – some sort of matter we cannot easily detect. Galaxies are embedded in “halos”



Modified Gravity (MOND)

Successes

- Largely consistent with galaxies (work ongoing)
- Several novel, corroborated predictions
- Doesn't require dark matter; no detection crisis!

Failures/ Issues

- Generally, lacks consistency with cosmology.
- Falls short in clusters of galaxies.
- Phenomenological, no clear fundamental theory.



Big Idea: (Gravity is wrong)

Missing mass is an effect of our incomplete understanding of gravity.

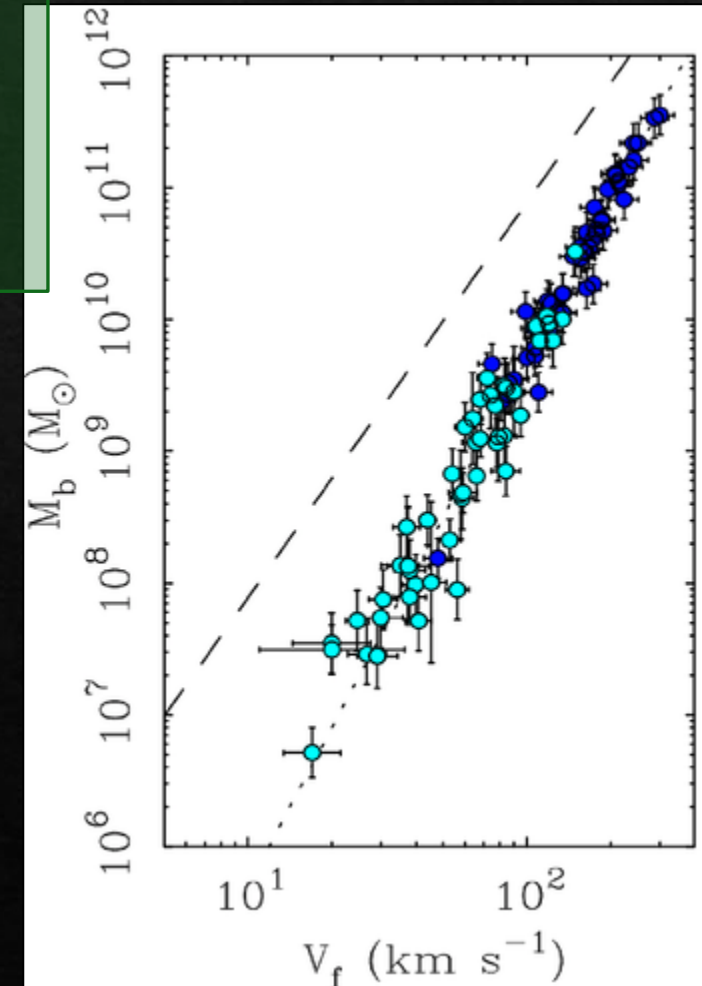
Baryonic Tully-Fisher Relation

Predicts

$$v_{\text{rot}}^4 \propto M_{\text{baryons}}$$

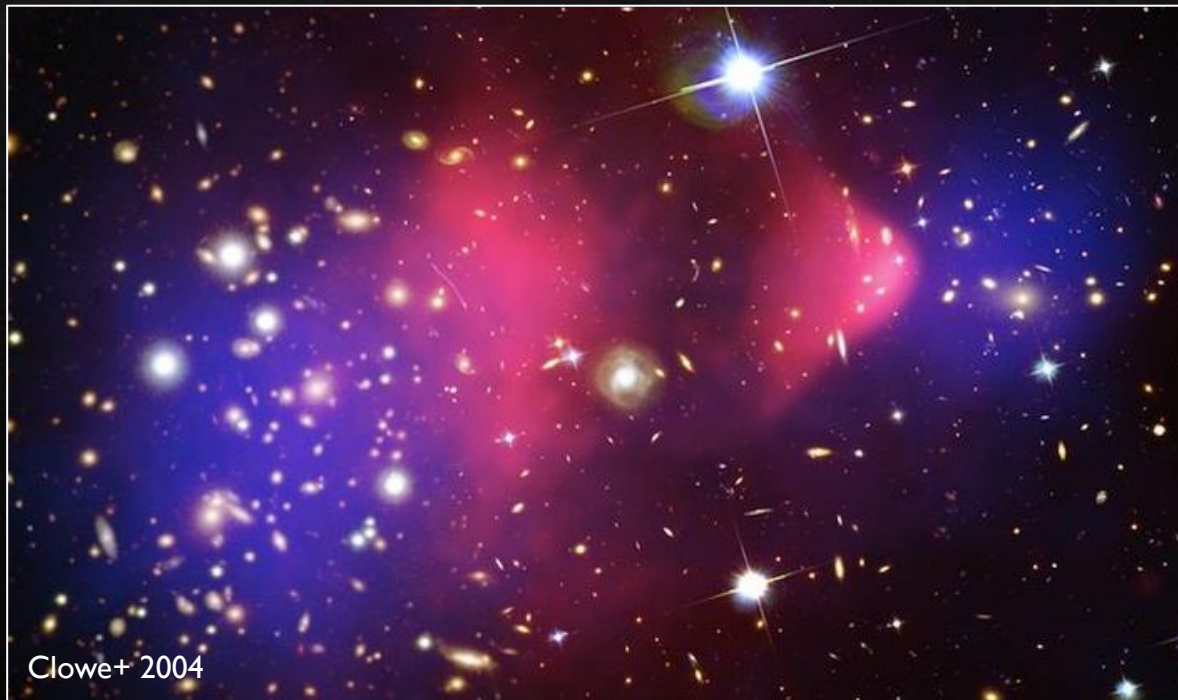
Unexpected from dark matter!

McGaugh+



The Bullet Cluster

Gravitational effects uncoupled from observed mass. Difficult to resolve with MOND.



Clowe+ 2004

Which One is Right?



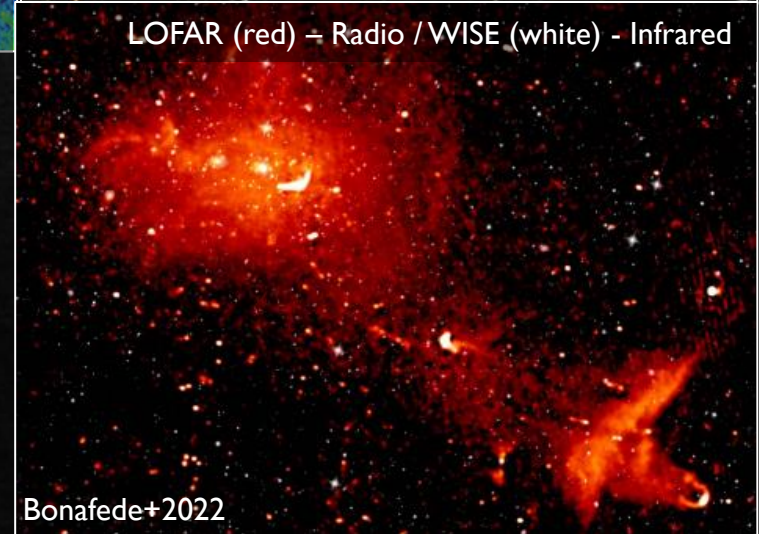
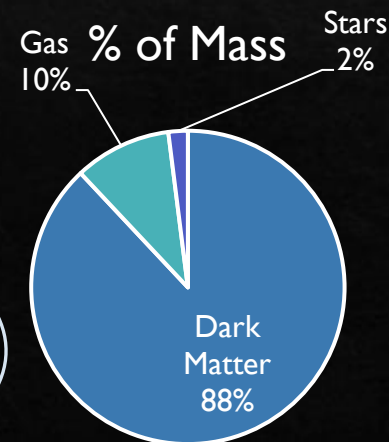
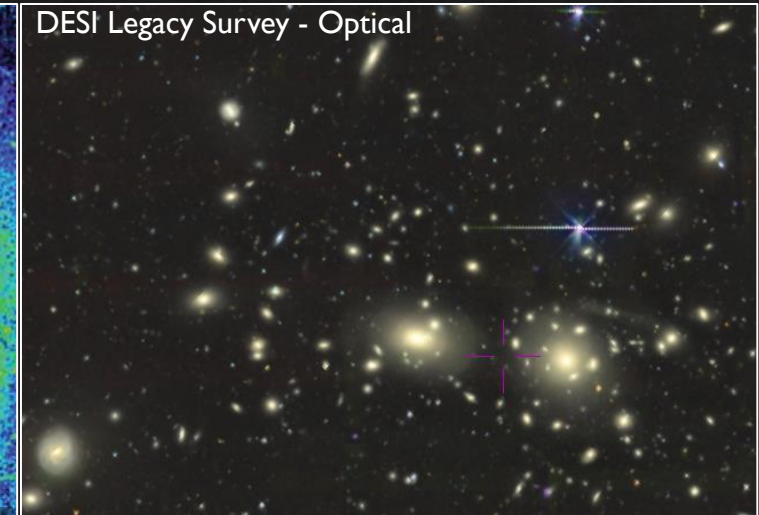
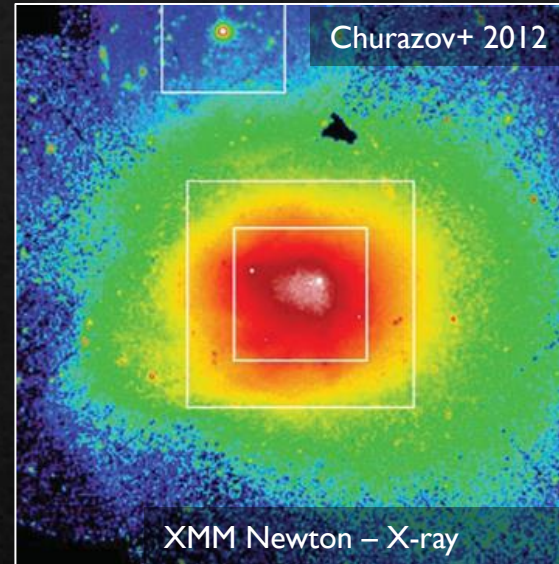
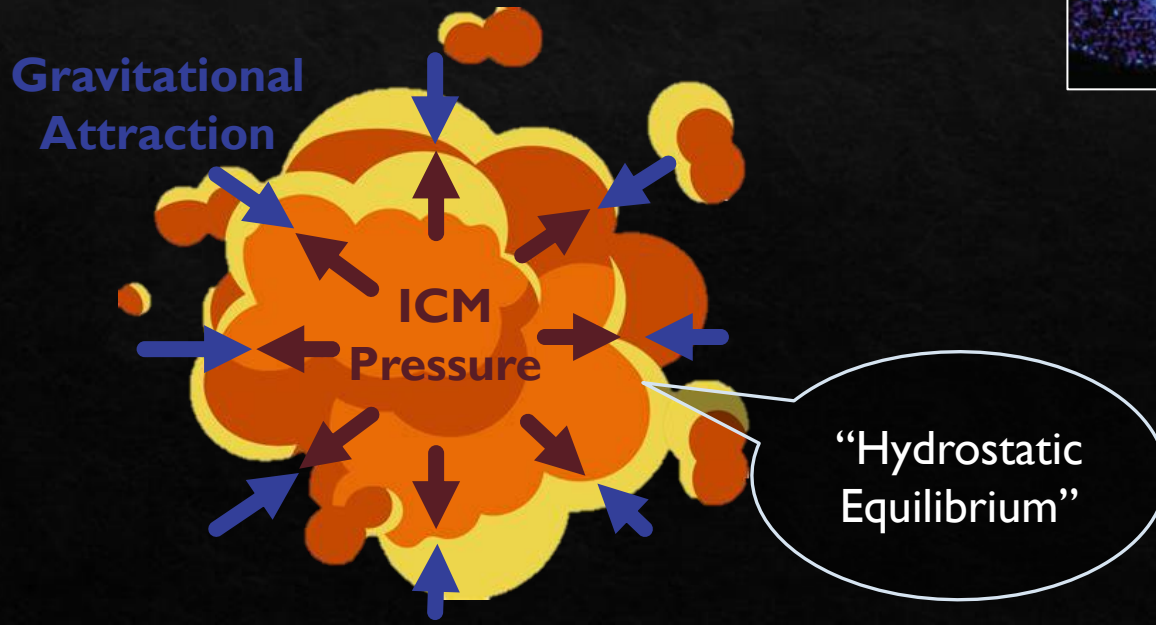
Galaxy Clusters

- Largest dynamically relaxed systems in the universe.
 - (100x size of Milky Way)
- Mostly (presumed) dark matter (85-90%)
 - Baryons are mostly X-ray emitting plasma called the intra-cluster medium (ICM).
- **The baryons can tell us about the gravity of the system, which can tell us about the mass!**
 - Use this to probe theories of gravity.



Big Idea: Gravitational Laboratories

Galaxy clusters can be challenging for both theories. Provide a good testing ground.



Constraining MOND in Clusters

- “Classical” MOND doesn’t work in galaxy clusters.
 - Reduces missing mass from 90% to 75%; but not to 0%.

Generalizing MOND to explain the missing mass in galaxy clusters

Alistair O. Hodson and Hongsheng Zhao

Improve MOND’s ability to explain galaxy clusters by adding more freedom to the theory!

Mordehai Milgrom

Center for Astrophysics, Weizmann Institute

Galaxy clusters in the context of superfluid dark matter

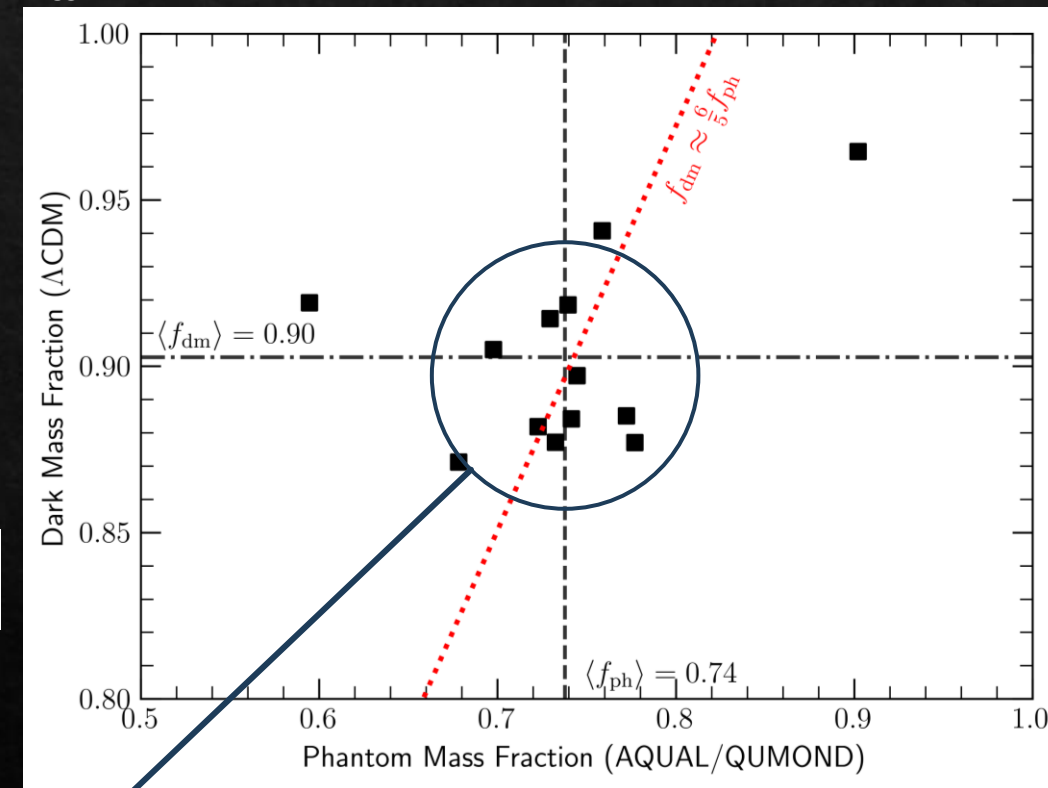
Alistair O. Hodson¹, Hongsheng Zhao¹, Justin Khoury², and Benoit Famaey³



Big Idea: Clusters break “classical” MOND.

Lots of “extensions” exist; difficult to otherwise constrain.

Diggins+2024



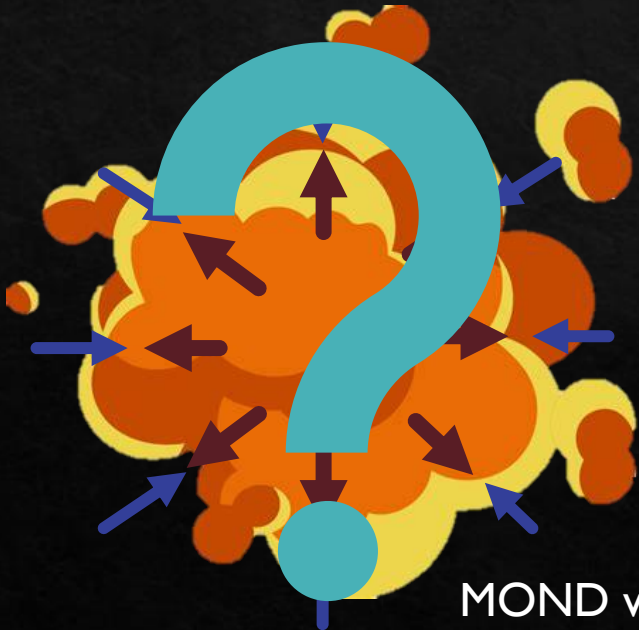
Big Idea:

MOND extensions fix the missing mass problem.

Do they do so without contradicting the X-ray observations?

MOND doesn’t solve the missing mass problem. Still needs ~60-70% “dark matter!”

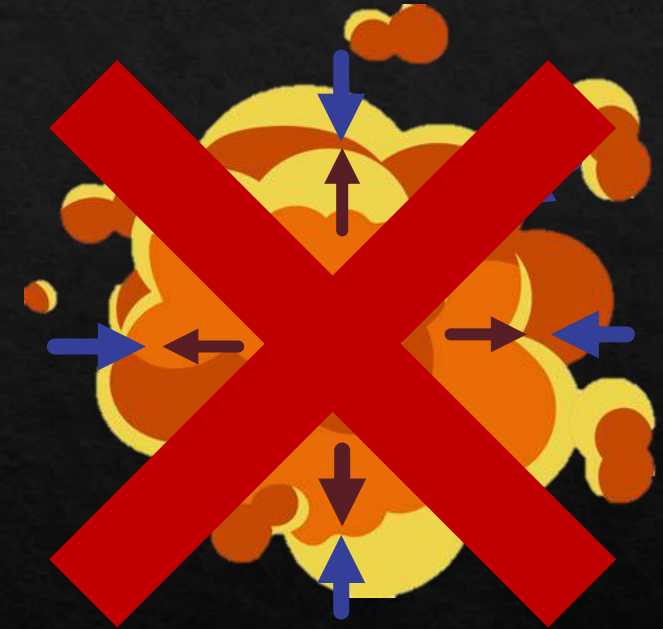
MOND without extra mass – Too Hot!



MOND with “stronger” gravity – Maybe?

Generalizing MOND to explain the missing mass in galaxy clusters

Alistair O. Hodson and Hongsheng Zhao



MOND with extra mass – Too much mass!
Collapses!

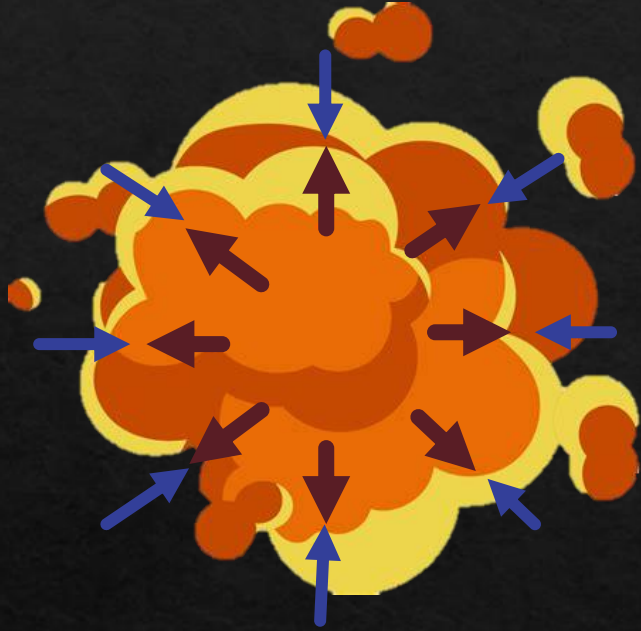
Marriage à-la-MOND: Baryonic dark matter in galaxy clusters and the cooling flow puzzle

Mordehai Milgrom
Center for Astrophysics, Weizmann Institute

Equilibrium configurations of 11 eV sterile neutrinos in MONDian galaxy clusters

G. W. Angus,^{1,2*} B. Famaey^{3,4} and A. Diaferio^{1,2}

MOND with “stronger” gravity – Maybe?



Big Idea:

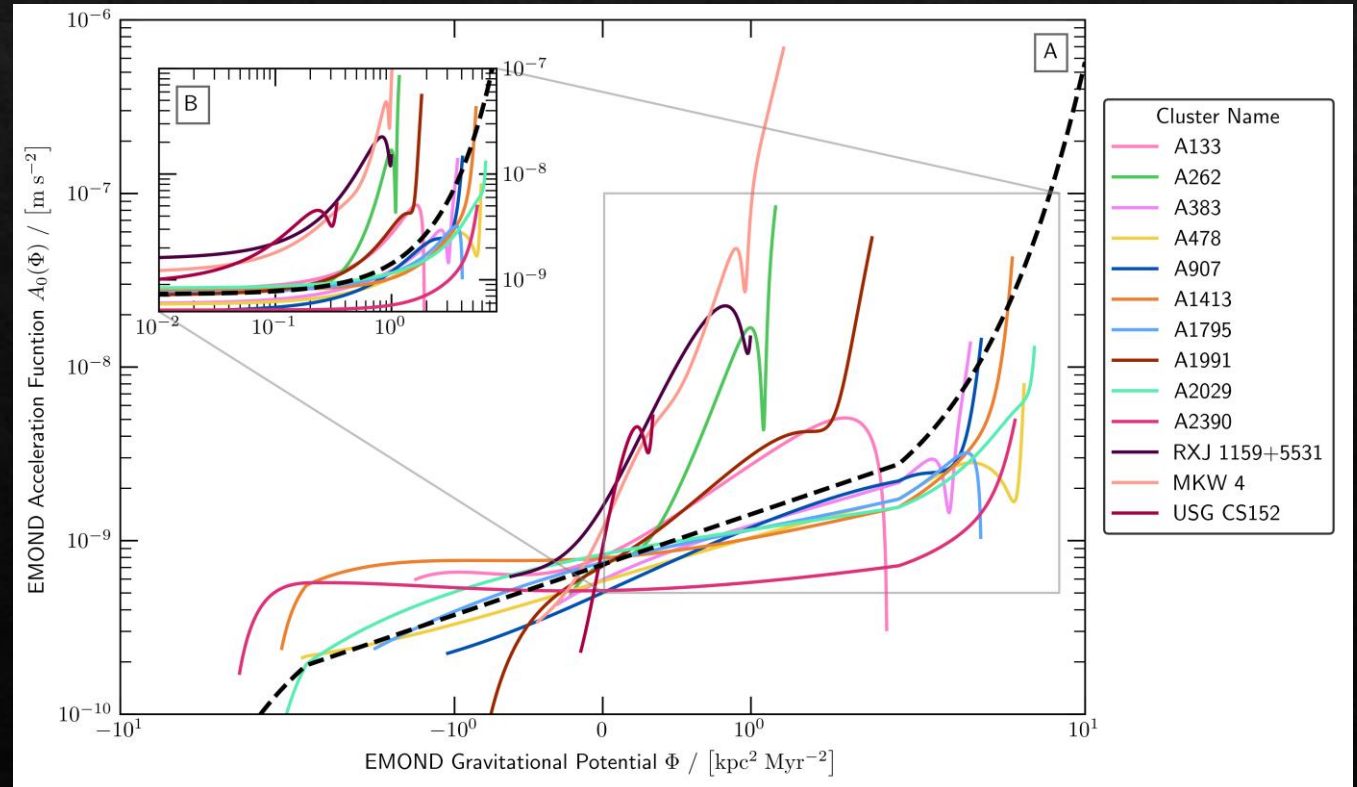
This is a very fragile balancing act.

For any “recipe” for strengthening MOND gravity, any little deviation causes big problems!



Generalizing MOND to explain the missing mass in galaxy clusters

Alistair O. Hodson and Hongsheng Zhao



Maybe the scatter is Observation Error?



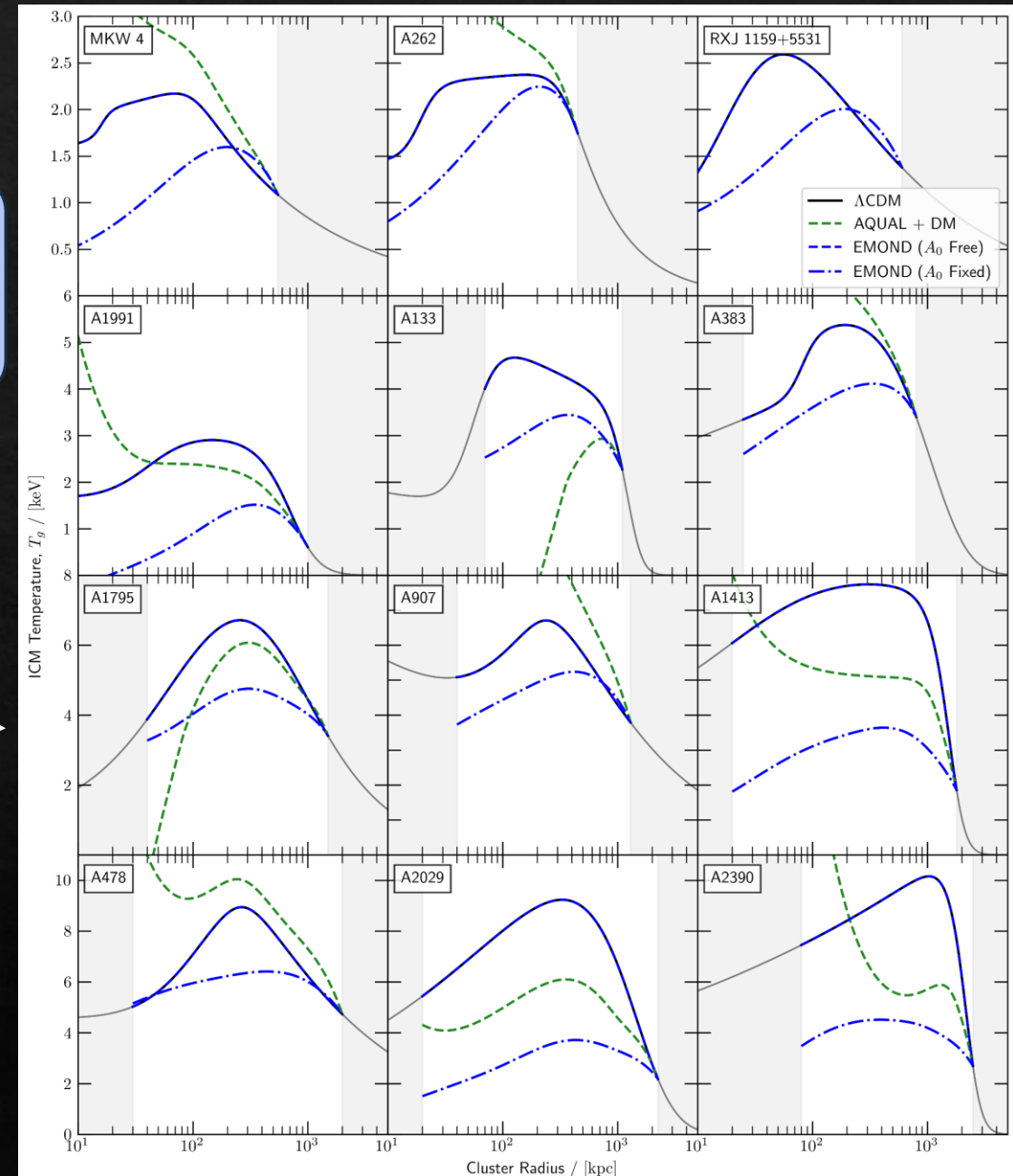
Big Idea:

Let's assume that's true; what happens to the true nature of our clusters?



The anticipated deviation is approximately a factor of 2.

Far too large to attribute to observation.



Implications

