Constraining Modified Gravity Using Galaxy Cluster Dynamics

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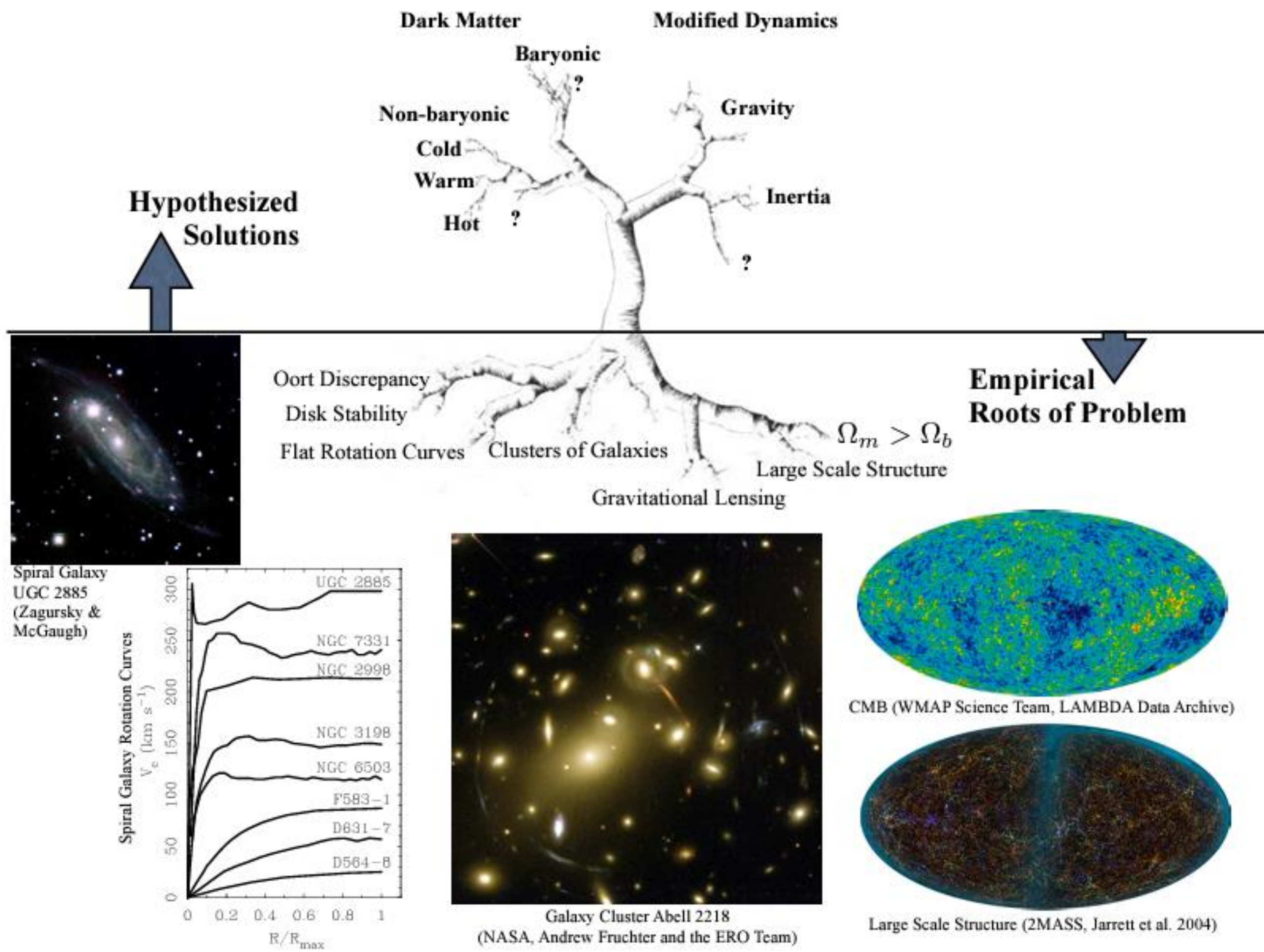
Dark Matter vs. Modified Gravity

- Rotation curves in spiral galaxies to not match theory.
  - Modified Gravity?
  - Dark matter?
- Dark matter has been more successful and is more widely accepted.
- Modified dynamics has well established points of failure.
  - **Succeeds in places where dark matter struggles**.



Adapted from Famaey & McGaugh (2012)

Modified Newtonian Dynamics

- Proposed as an alternative to dark matter.
  - Basic premise was to change the behavior of gravity on low acceleration regimes.
  - Very successful in galaxies.
  - Several *a priori* unexpected predictions which are highly corroborated / confirmed:
    - Baryonic Tully-Fischer Relation
    - External Field Effect
  - Incapable of matching observations in galaxy clusters.

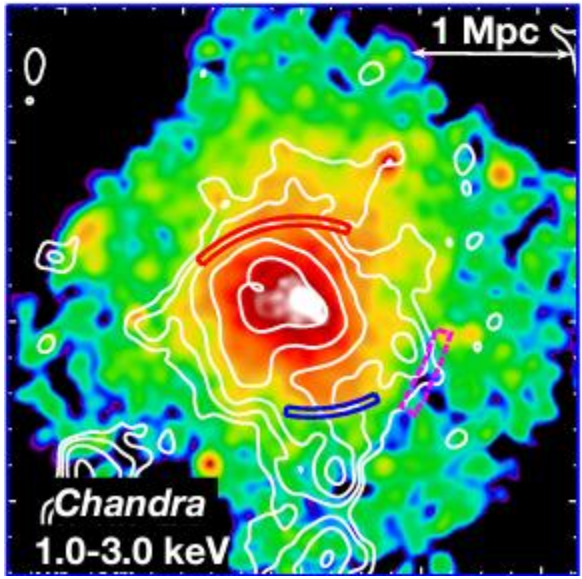
	Newtonian Dynamics	MOND (AQUAL)
Poisson Equation	$4\pi G\rho = \nabla^2\Phi$	$4\pi G\rho = \nabla \cdot \left[\mu\left(\frac{\lvert\nabla\Phi\rvert}{a_0}\right)\nabla\Phi\right]$

μ is the interpolation function.

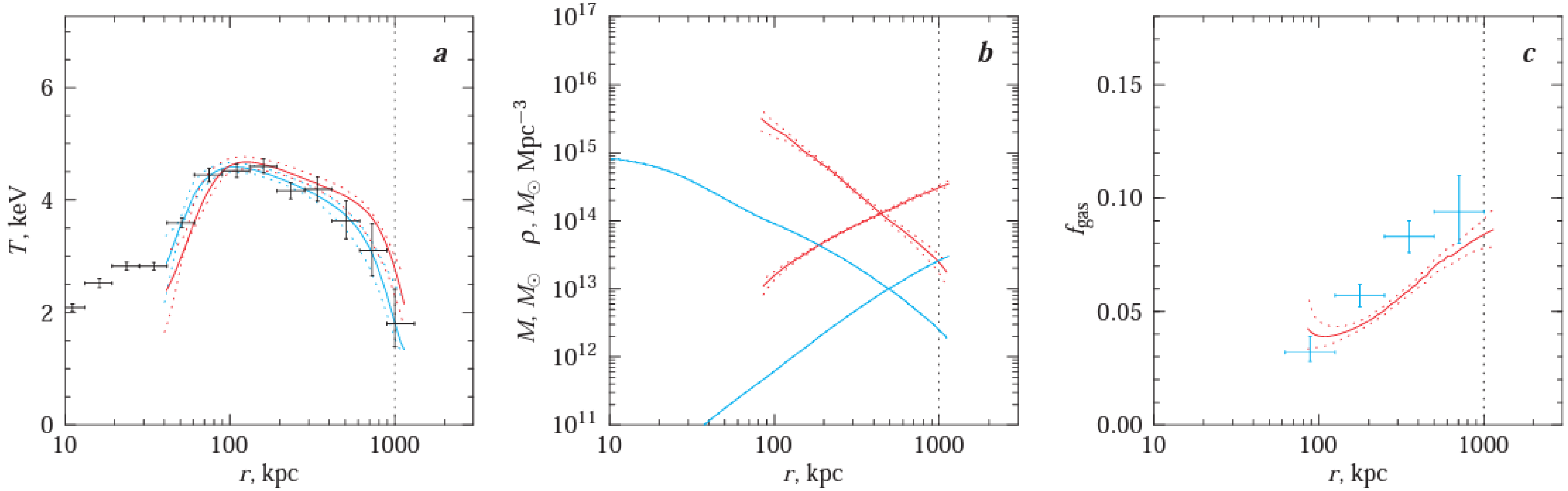
$$\underbrace{\lim_{x\to\infty}\mu(x) = 1}_{\text{Newt. Regime}} \quad \text{and} \quad \underbrace{\lim_{x\to 0}\mu(x) = x}_{\text{Deep-MOND Regime}} \quad .$$

Galaxy Clusters

- Largest dynamically relaxed structures in the universe.
  - 1% stellar component, 10% ionized plasma, 89% DM.
- Systems are <u>pressure supported</u>, the intra-cluster medium produces (to reasonable approximation) hydrostatic equilibrium.
- X-ray observations of the ICM provide gas density and temperature profiles
  - Can be used to deduce pressure » gravitational mass component.



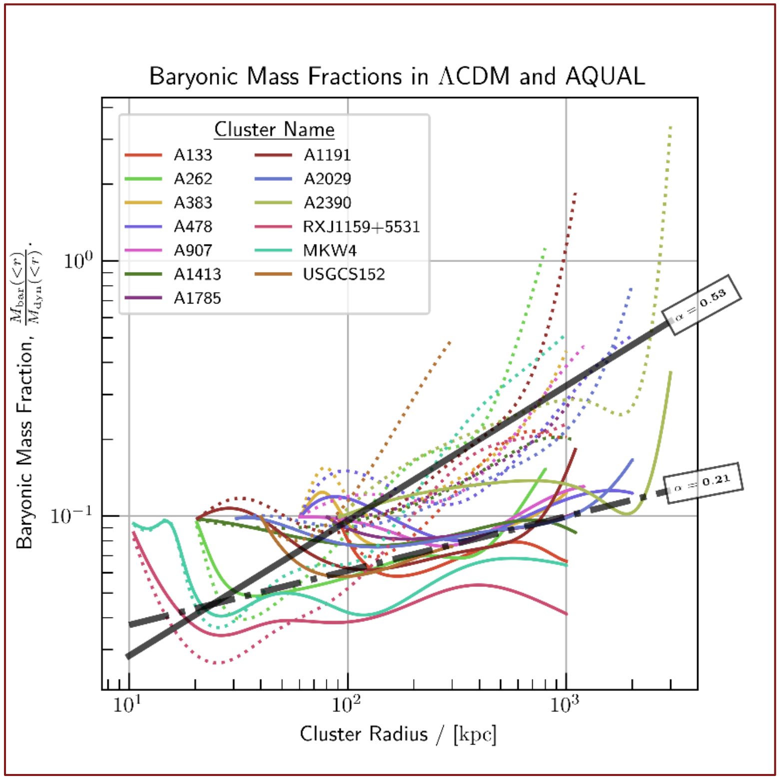
Adapted from Tumer et. al. 2022.



Adapted from Vikhlinin et. al. 2006

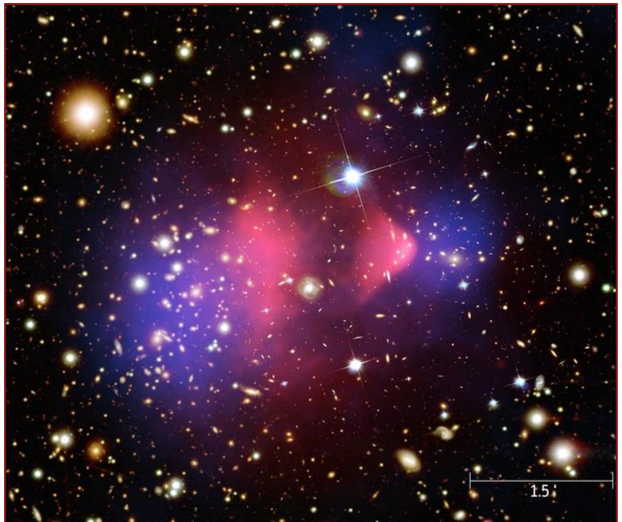
What's Going On Galaxy Clusters?

- "Classical" MOND theories fail to correctly predict the observed mass.
  - Off by factor of ~10 in Newtonian dynamics (without DM). Off by ~2 in MOND.
  - Bullet Cluster indicates decoupling of baryonic and dynamical mass components.



Baryonic mass fraction in MOND and Newtonian clusters. In principle, MOND clusters should be at 1 over the entire domain.

- New MOND Extensions
  - MOND + DM: Popular explanation. Could be sterile neutrinos?
    - Kind of defeats the purpose of the classical MOND paradigm.
  - EMOND (Extended-MOND): Lets $a_0 \rightarrow A_0(\Phi)$.



1E 0657-56 as observed by Chandra (pink) and through its weak lensing map (purple, Clowe et. al. 2004). The dissociation of the dark matter from the gaseous component is compelling evidence against MOND.

Testing MOND + DM

- Galaxy clusters are in hydrostatic equilibrium: $M_{dyn}(< r) = -\frac{k_b T r^2}{G m_p \mu}\left[\frac{d\ln\rho_g}{dr} + \frac{d\ln T}{dr}\right]$

- Implies tight constraints on asymptotic behavior for physically realistic mass distributions

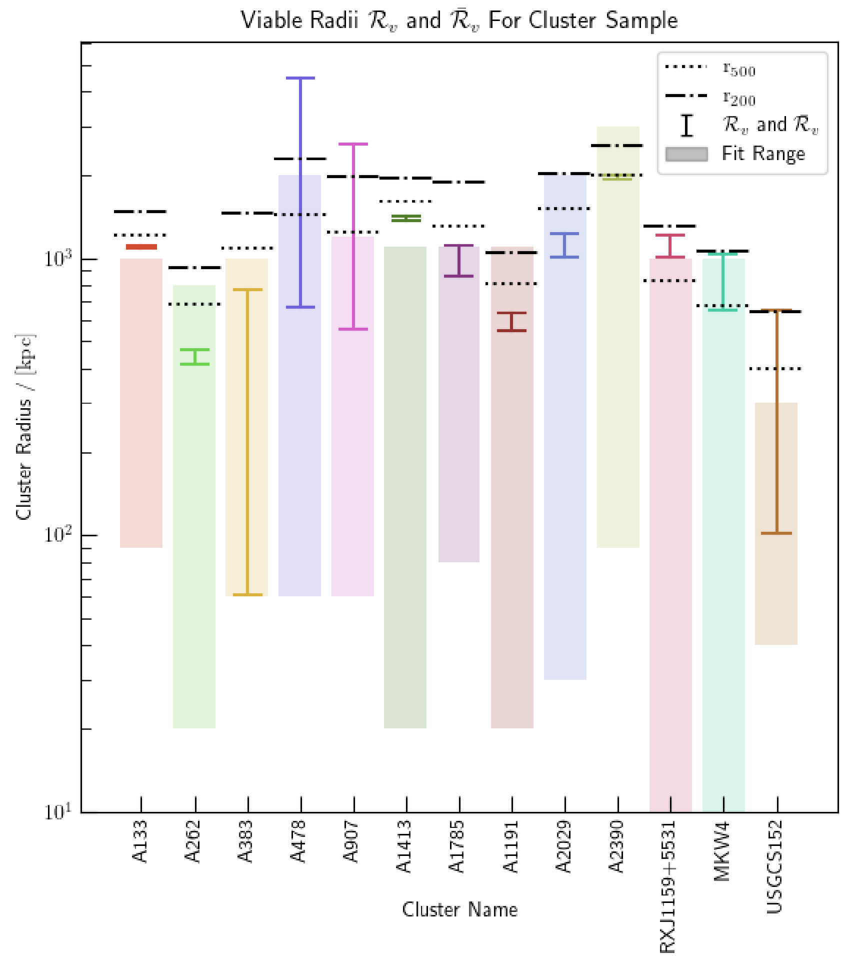
MOND-CDM Disequivalence Principle

For all self consistent sets of profiles (ρ_g, T) corresponding to an observed galaxy cluster, there cannot exist a self-consistent galaxy cluster in MOND with the same profiles.

- One can derive a maximal radius of viability of any attempt to construct such a cluster.
  - Generally falls within r_{200}.

1 Problem:

- Uncertainties prevent us from applying this principle blindly.
- You can't exactly match profiles, but what about within error limits?

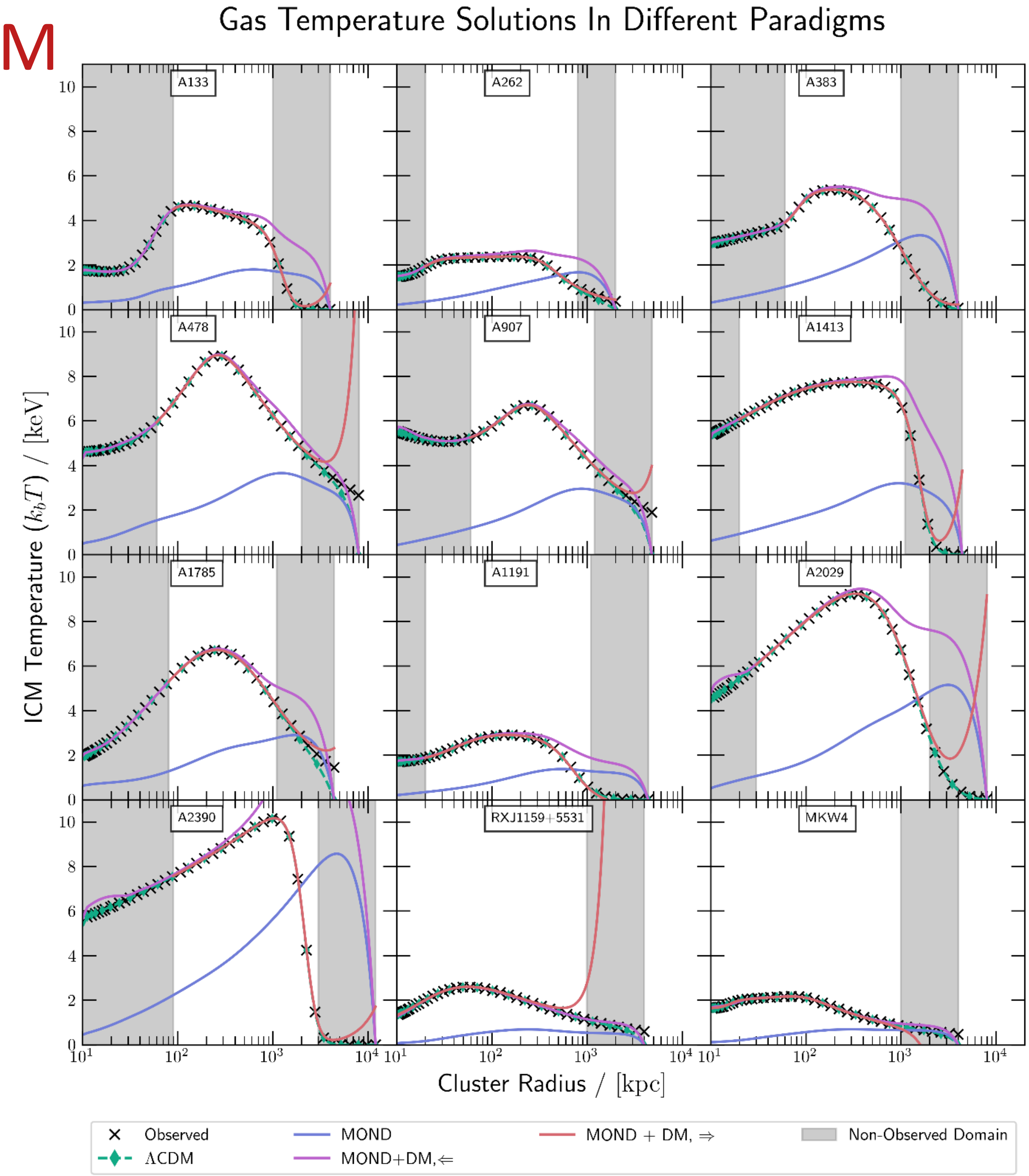


Testing MOND + DM

- Idea: Construct the best, physically consistent, match to the observed profiles.
- Ideally, there should be variation large enough to detect within the observable radius.

Is It Observable?

It's marginal. In some clusters it might be possible but generally variations are small. XRISM will allow us to get better constraints.



Conclusions

- Simple extensions of MOND phenomenology seem unlikely to resolve the issues MOND faces in galaxy clusters.
  - Places *even more importance* on probing modified gravity in these regimes.
  - WHY does MOND work so well elsewhere?
- Justifies further interest in galaxy cluster dynamics:
  - How valid is hydrostatic equilibrium?
  - Are they really all that relaxed?
  - Are MOND and associated extensions capable meeting observation in merger scenarios?
  - How do those effects play into the MOND / CDM debate?
- Cluster physics is emerging as an important regime in CDM as well for its uses in cosmology.