DARK MATTER

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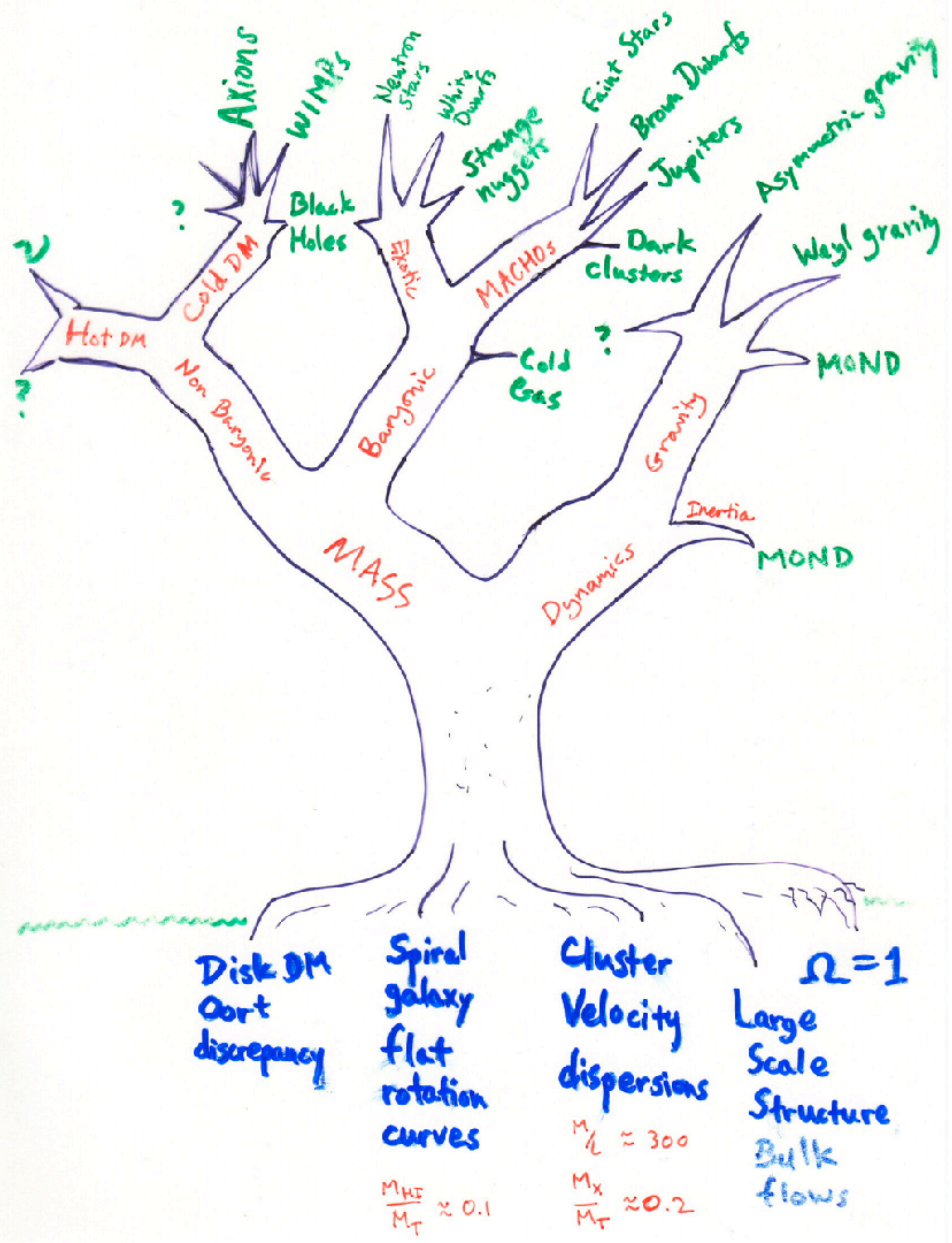
http://astroweb.case.edu/ssm/ASTR333/

PROF. STACY MCGAUGH
SEARS 558
368-1808
stacy.mcgaugh@case.edu

CASE WESTERN RESERVE UNIVERSITY EST. 1826



Lots of particle dark matter candidates:

WIMPs — Traditionally preferred candidate for CDM

Axions — Hypothesized for a perceived problem with CP symmetry; not obvious it is related to DM problem

Light dark matter — A low mass WIMP-like entity that violates the Lee-Weinberg limit ($m_X > 2$ GeV)

wimpzillas — A very high mass WIMP-like entity approaching the unitarity limit (1000s of GeV)

etc. — There are limits that exclude many possibilities, yet no limit to stuff we can make up

Can imagine other candidates as well:

Warm DM — Low mass (typically keV scale) so not dynamically cold, but not too hot either

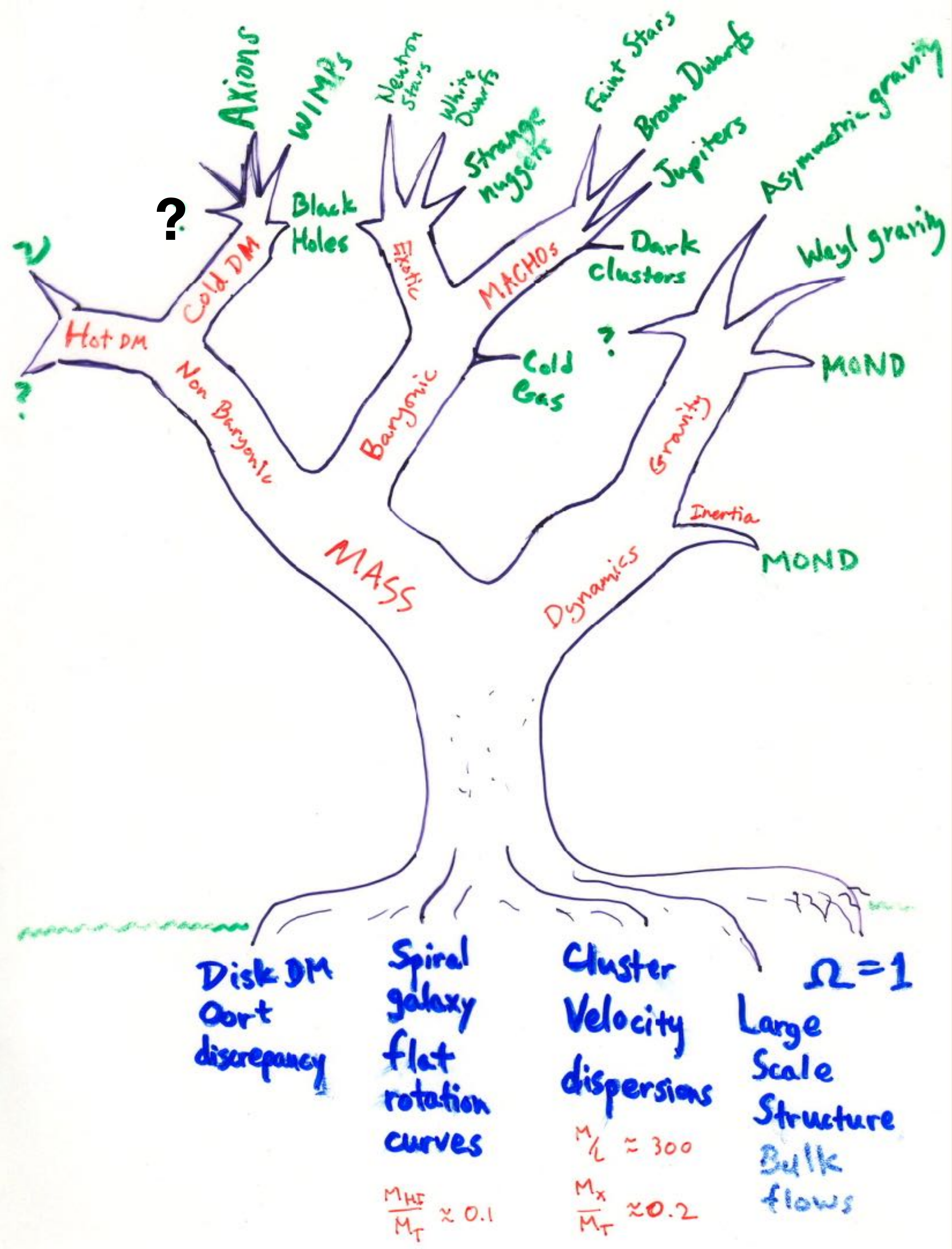
Self-interacting DM — These DM particles interact with themselves via some new force that is only active in the dark sector, mediated by dark photons

etc.

All of these ideas require a new "dark sector" beyond the known physics of the Standard Model. Some require complex dark sectors, with new forces as well as new particles (i.e., new forces of nature that only interact in the dark sector, e.g., dark E&M mediated by dark photons.)

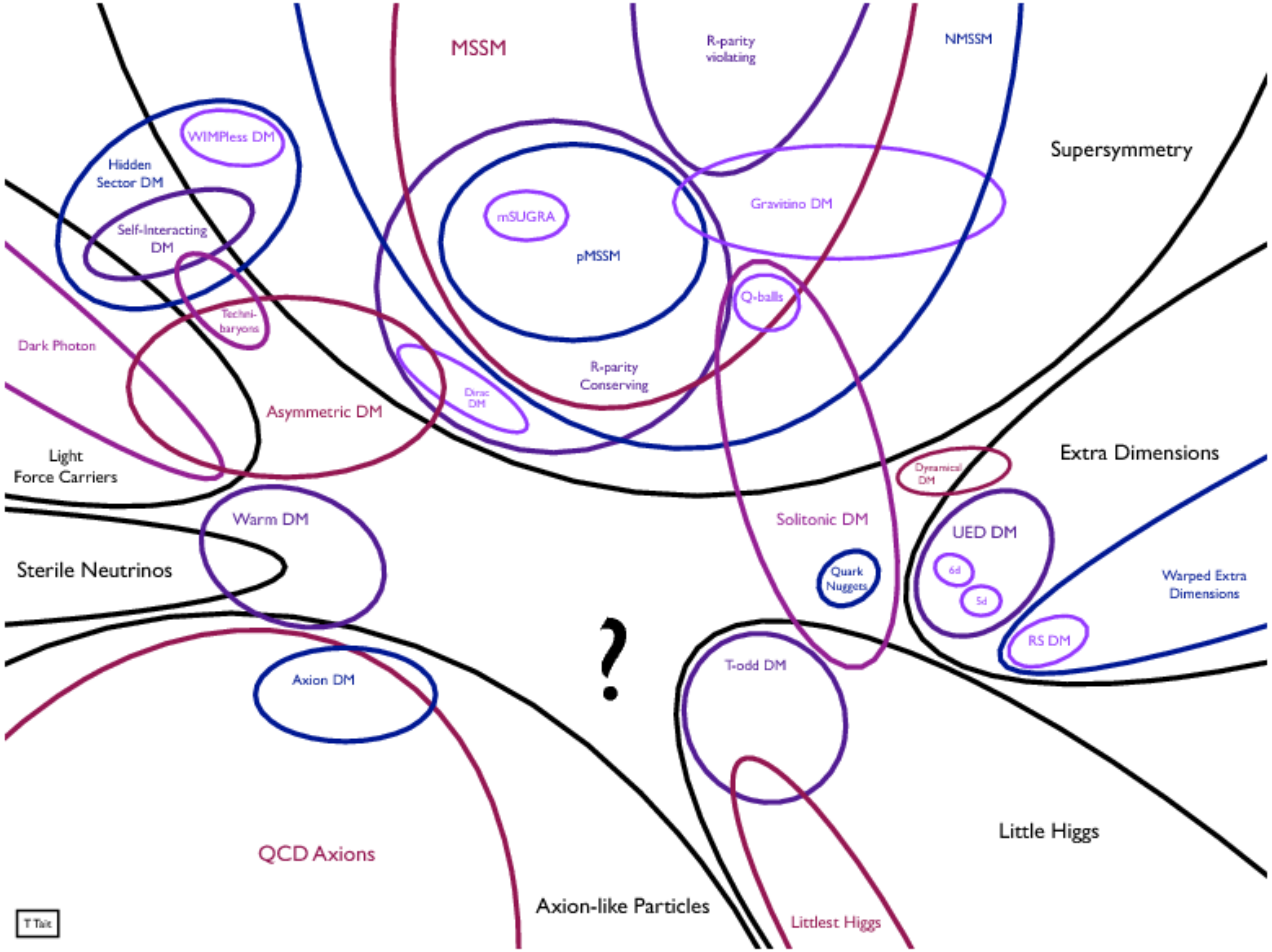
Despite efforts to prune the tree, the list of dark matter candidates continues to grow

1995



Most of these ideas fall under the ? from 1995.

2013



"Graphical representation of the (incomplete) landscape of candidates." (Tait, in arXiv:1310.8642)

Could be a modification of dynamical laws (e.g., gravity) rather than dark matter

Two big motivations for CDM:

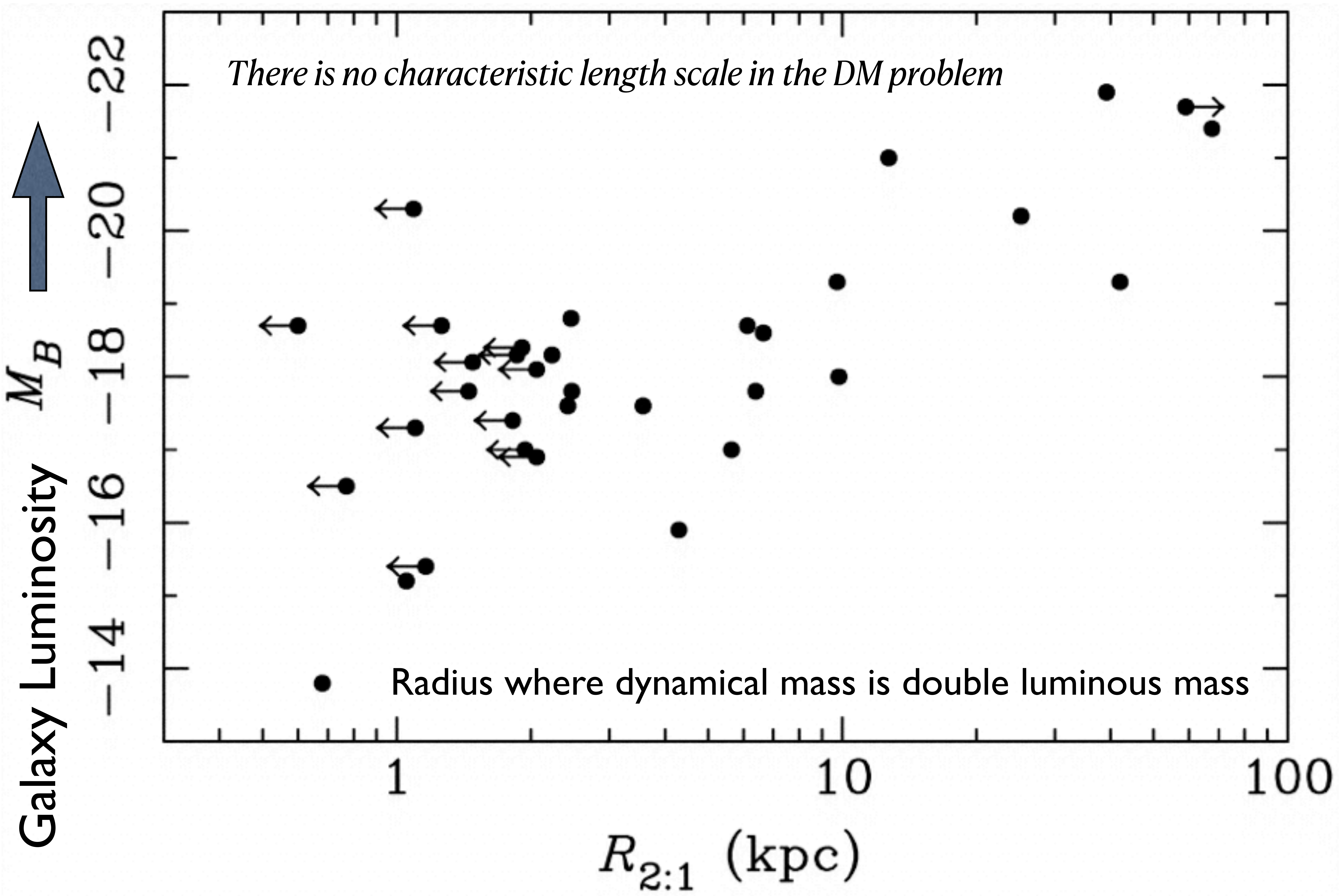
1) total mass outweighs normal mass from BBN

2) needed to grow cosmic structure

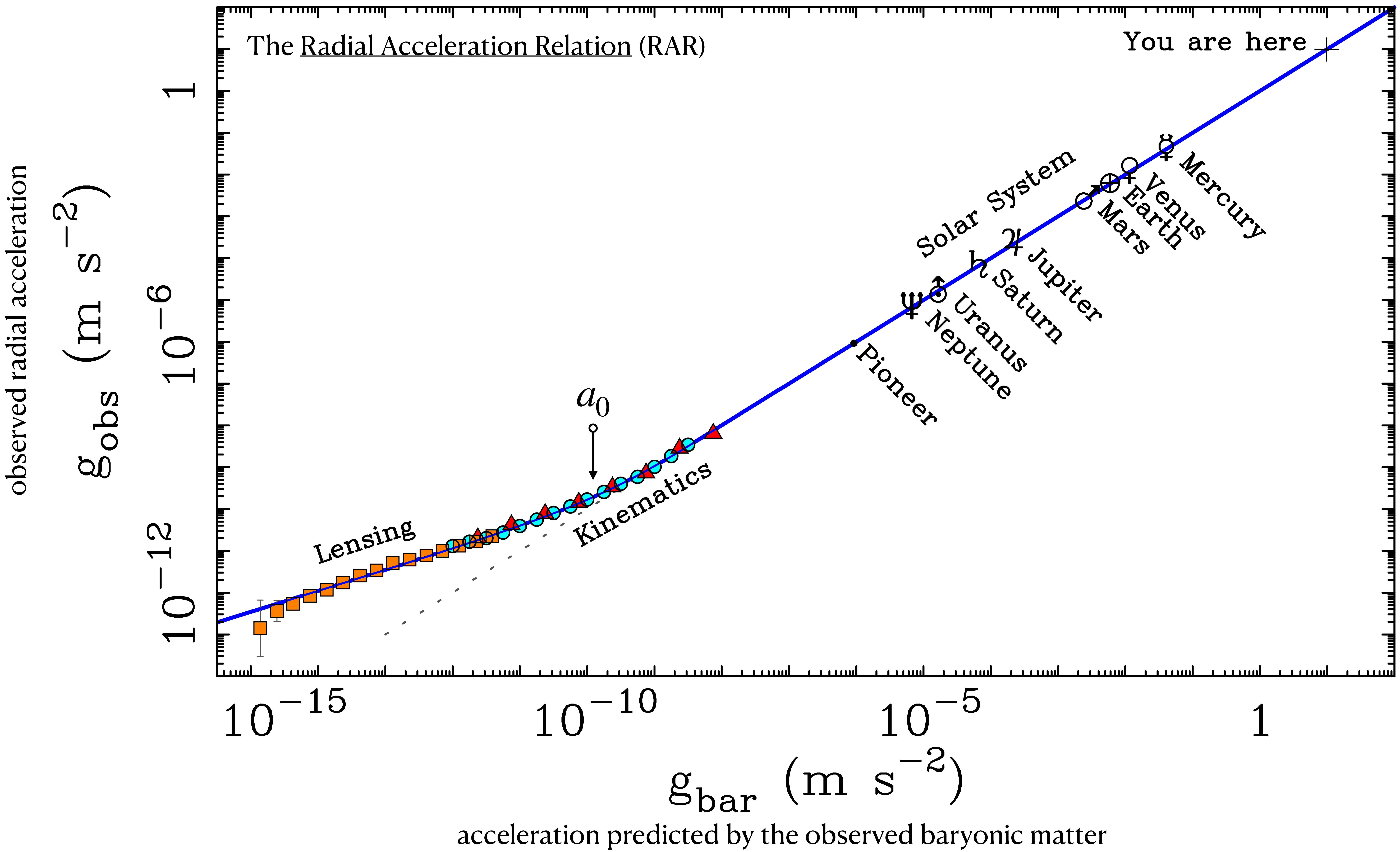
(1) and (2) only hold when gravity is normal.

Leaves room to consider modifications of dynamical laws (e.g., gravity or inertia) as alternatives to dark matter.

Can exclude length-scale based modifications



There is a characteristic acceleration scale in the DM problem



There is a characteristic acceleration scale in the DM problem

Modified dynamical theories

MOND (Modified Newtonian Dynamics) [Milgrom]

can be interpreted as either a modification of gravity or of inertia

modification at a critical acceleration scale

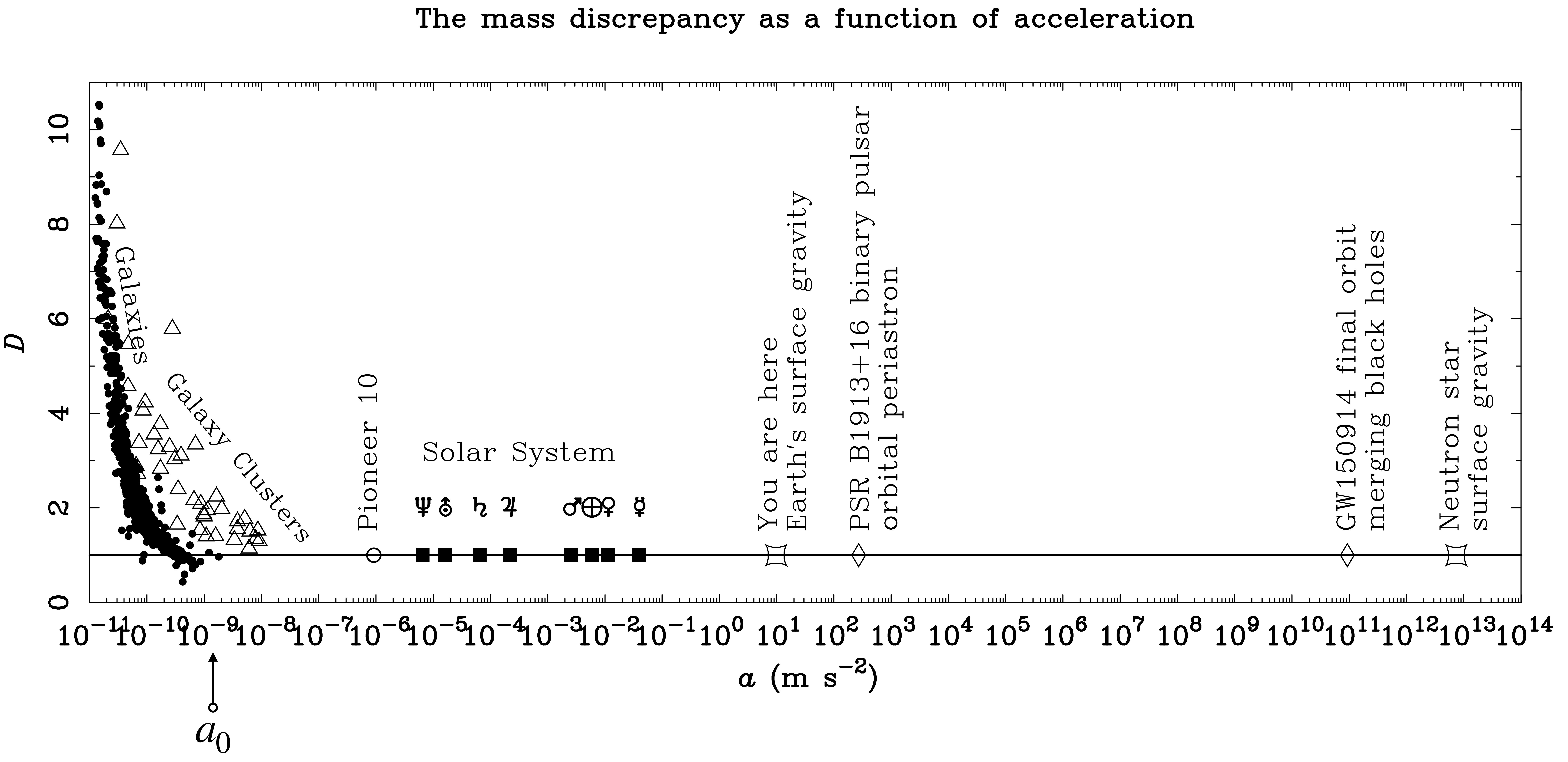
$a_0 \sim 10^{-10}$ m/s/s ~ 1 Å/s/s

MOND has had a surprising amount of predictive success, but there is no clear relativistic extension as yet

Others?

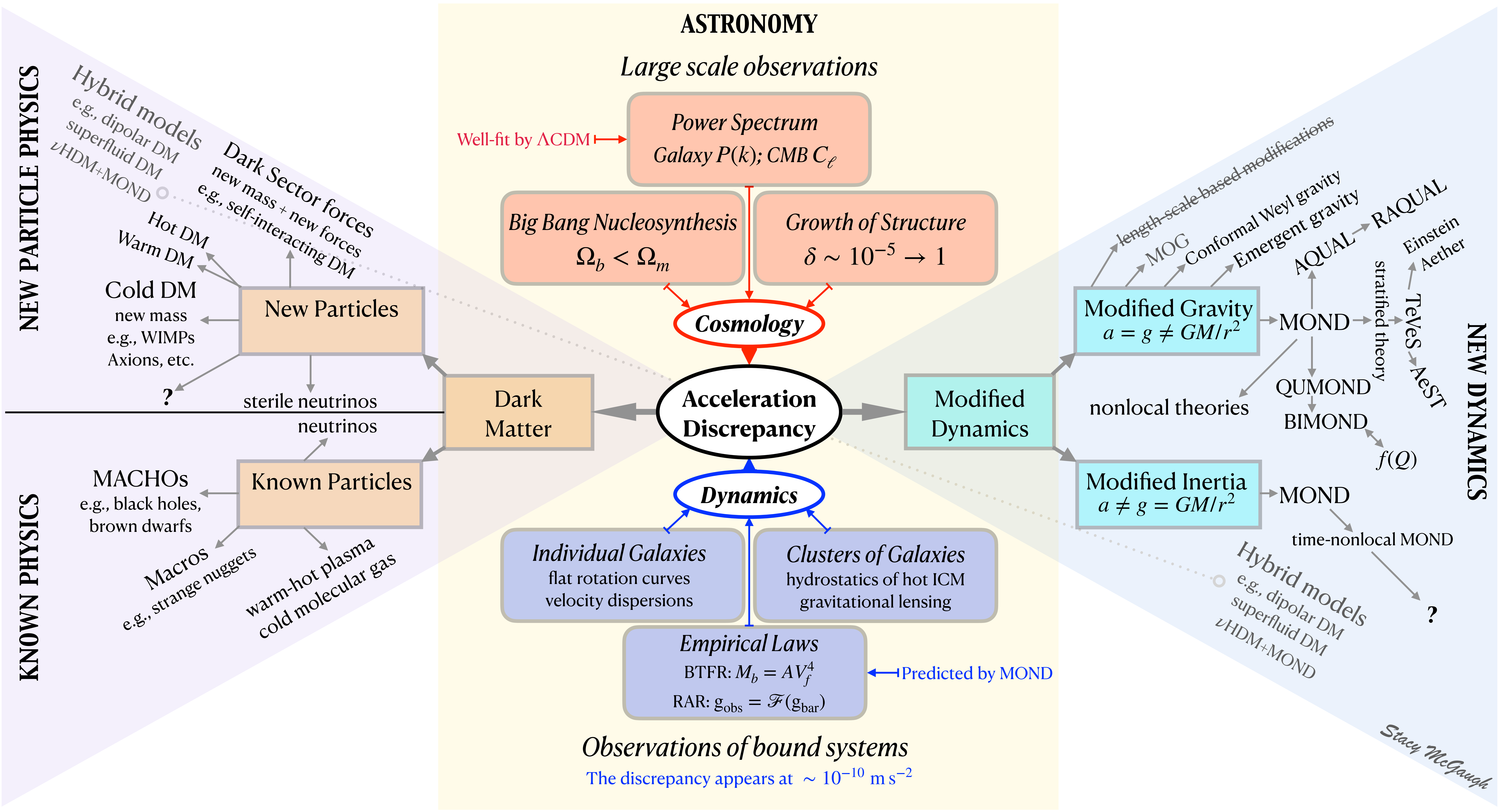
It is not easy to build a theory that is consistent with all known facts. It is also not easy to explain the predictive successes of MOND in terms of dark matter.

There is a characteristic acceleration scale in the DM problem
It is extremely low: the discrepancy only appears below $a \sim 10^{-10}\ \mathrm{m\,s^{-2}}$



This is the same plot as above, just normalized by defining the discrepancy amplitude as $D = \frac{g_{obs}}{g_{bar}}$

The ***dark matter problem*** *might more appropriately be called the* ***acceleration discrepancy*** *(Bekenstein)*



A graphical representation of the Dark Matter tree

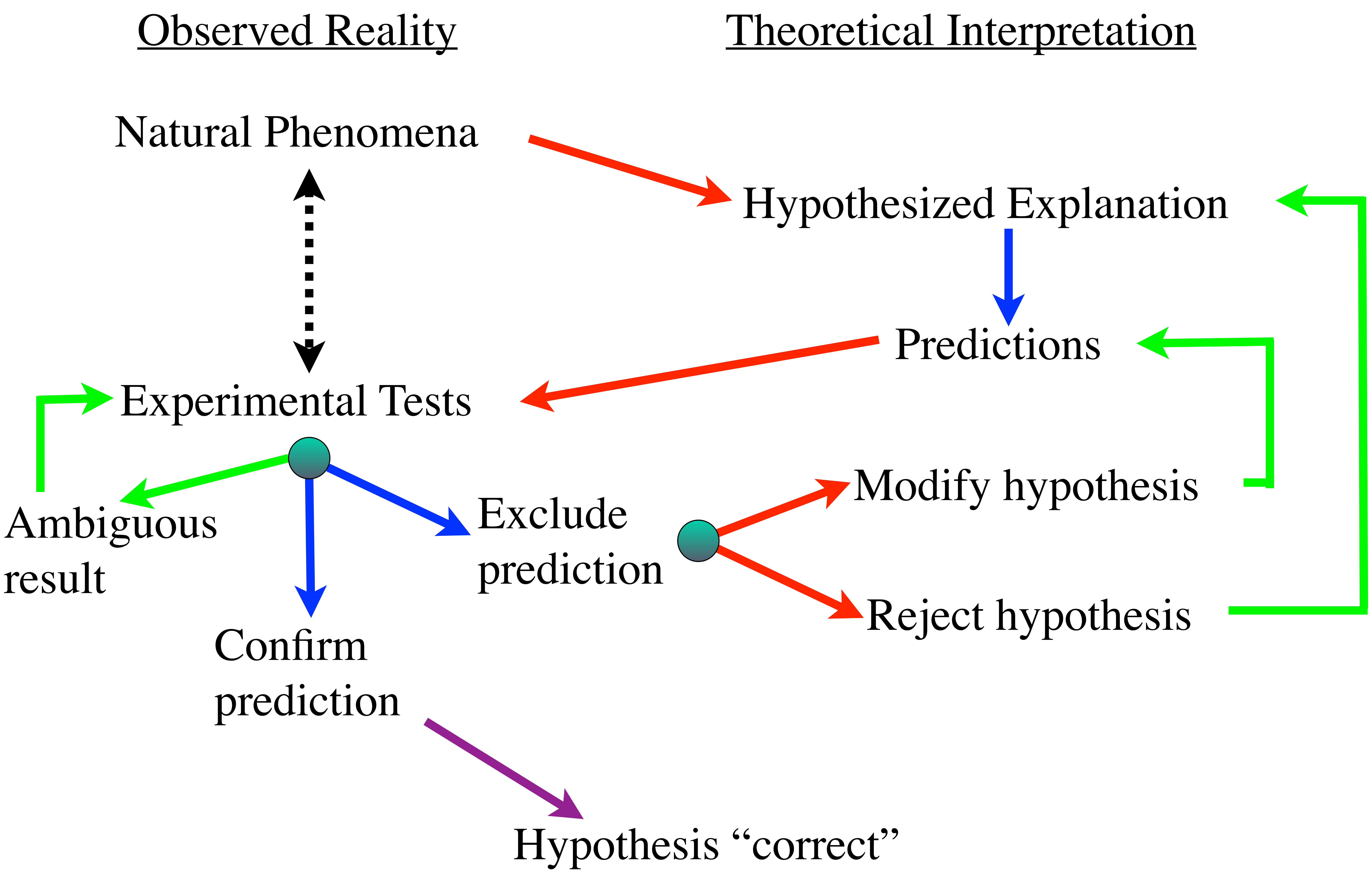
An Ancient and Intractable Problem

- The missing mass problem has been with us since at least the work of Oort and Zwicky in the 1930s
- The issue took off in the 1970s; considerable effort has been lavished on it since then
- Despite decades of experimental searches, no clear detections of dark matter have been obtained to date.

That there is a problem is extremely well-established.

What the solution is, not so much.

Hypothesis Testing



The Principle of Doubt

- Hypotheses can be *rejected* but never completely *confirmed*.
- At best, a theory can be *adequate* for describing a specific set of phenomena. What counts as adequate? When is a theory satisfactory?
- Do not trust - verify through experiment.
- Simple theories are preferable to complicated theories (Occam's Razor)
  - Any theory can be made complicated enough to explain anything. It isn't useful unless it can predict new things. (e.g., epicyclic theory)
  - If a theory has its predictions come true, we are obliged to acknowledge its efficacy, even if it means rejecting something we formerly believed.

Measurement Uncertainty

- No experiment is perfect
- Experimental uncertainty is often the difference between rejecting a hypothesis and an ambiguous result
- It is important to quantify both measurements AND their accuracy
- This is virtually impossible in astronomy
  - there are often systematic uncertainties that are not easily quantifiable: we can’t put the universe in a box and control the experiment.