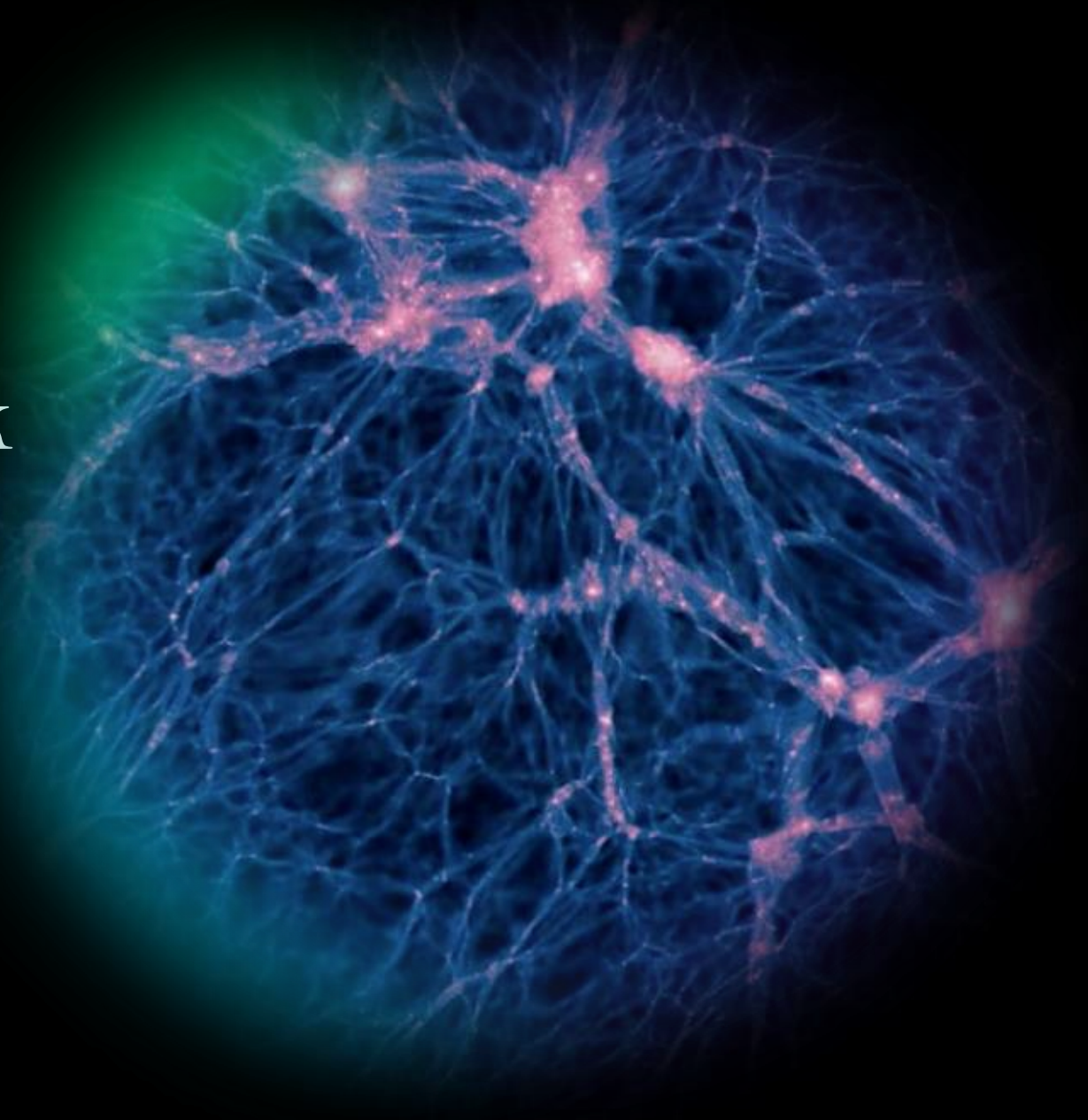
The Dark Side of The Force:

The Mysteries of Dark Matter



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The Missing Mass Problem

Throughout the 1900's several astronomers made observations which suggested there was **"missing mass"** in some astronomical systems.

Vera Rubin doing science-y stuff

In the 1970's, **Dr. Vera Rubin's** pioneering work demonstrated that this "missing mass" problem was at play in most observed galaxies.

This **missing mass** would later be recognized as **dark matter**.

She got a telescope named after her.

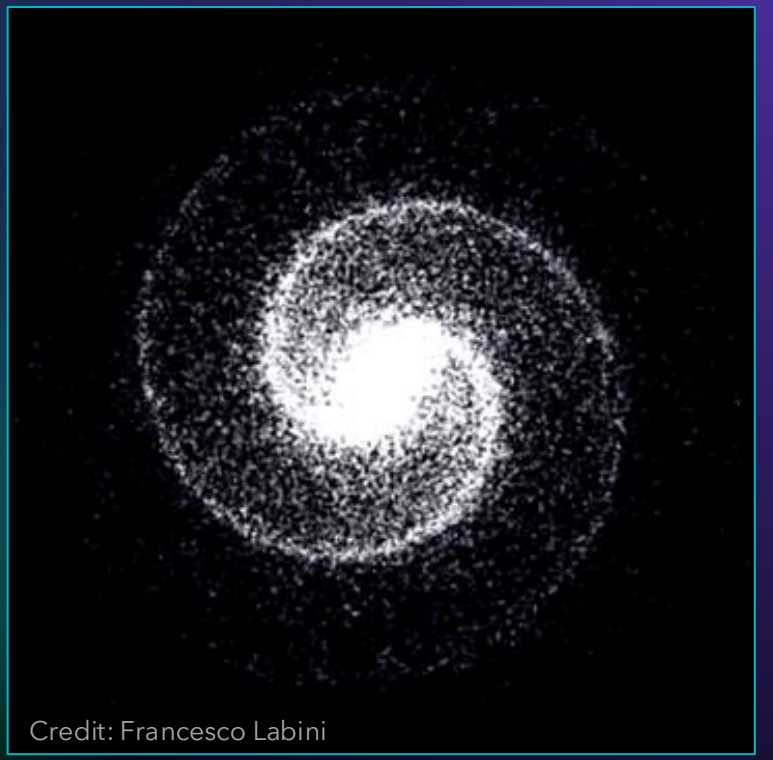
The Vera C. Rubin observatory (NSF, DOE)

A really really cool telescope!

Discovering Dark Matter

Vera Rubin looked at the **rotation of spiral galaxies**.

These galaxies are **spinning**, and they **spin at different speeds** depending on distance from the center!



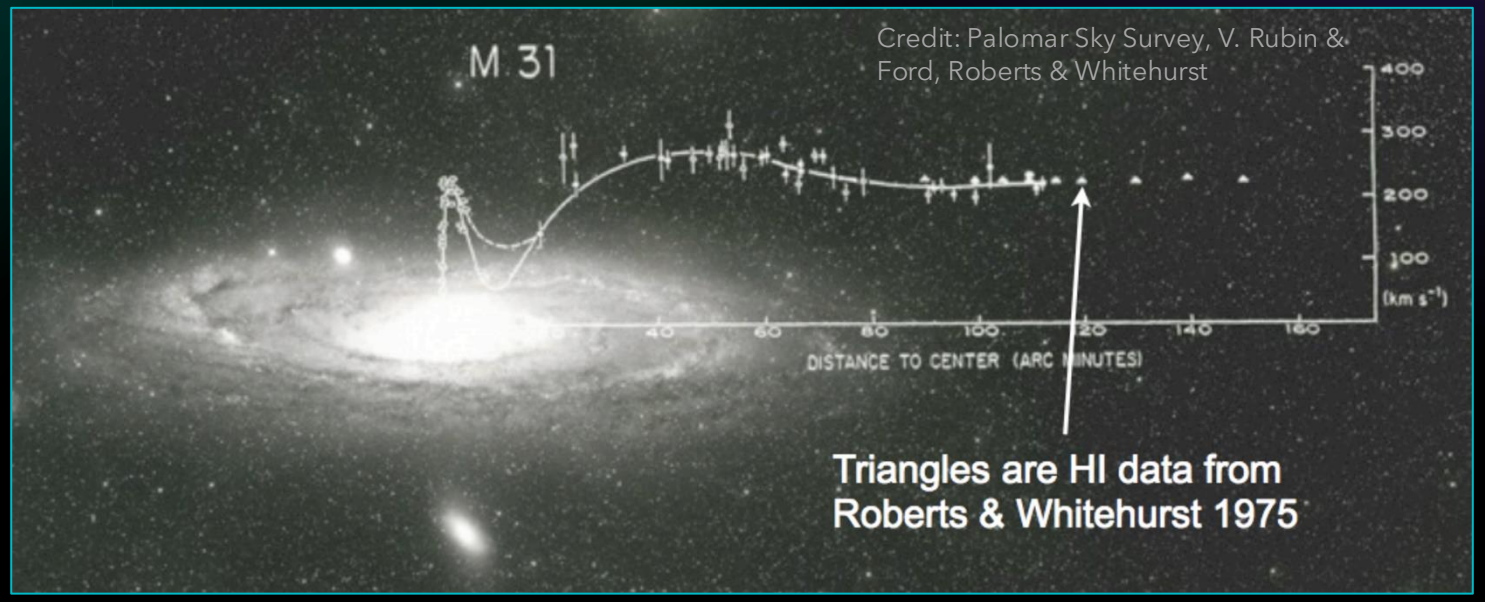
Credit: Francesco Labini

Photo by ESA/Hubble & NASA, acknowledgement: Josh Barrington

Using new techniques at the time, she measured the **rotational speed** of the spiral galaxies at **different radii**.

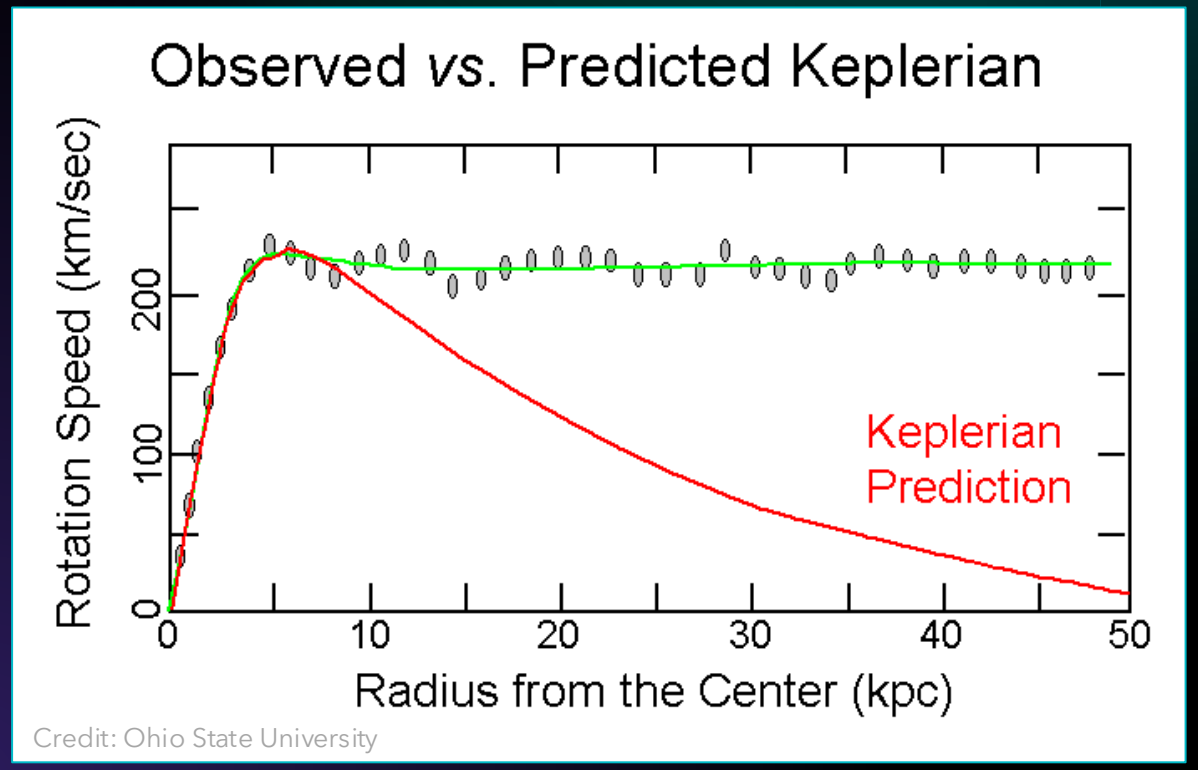
NGC 4565, Credit: ESO

Credit: NASA and the Hubble Heritage Team (STScI/AURA)



Discovering Dark Matter

Vera Rubin found that galaxy rotation curves were **flat**, contradicting theoretical predictions.



Credit: Ohio State University

Credit: European Southern Observatory. Illicitly screen captured from Youtube!

The stars in the **outer part** of the galaxy move much faster than expected!

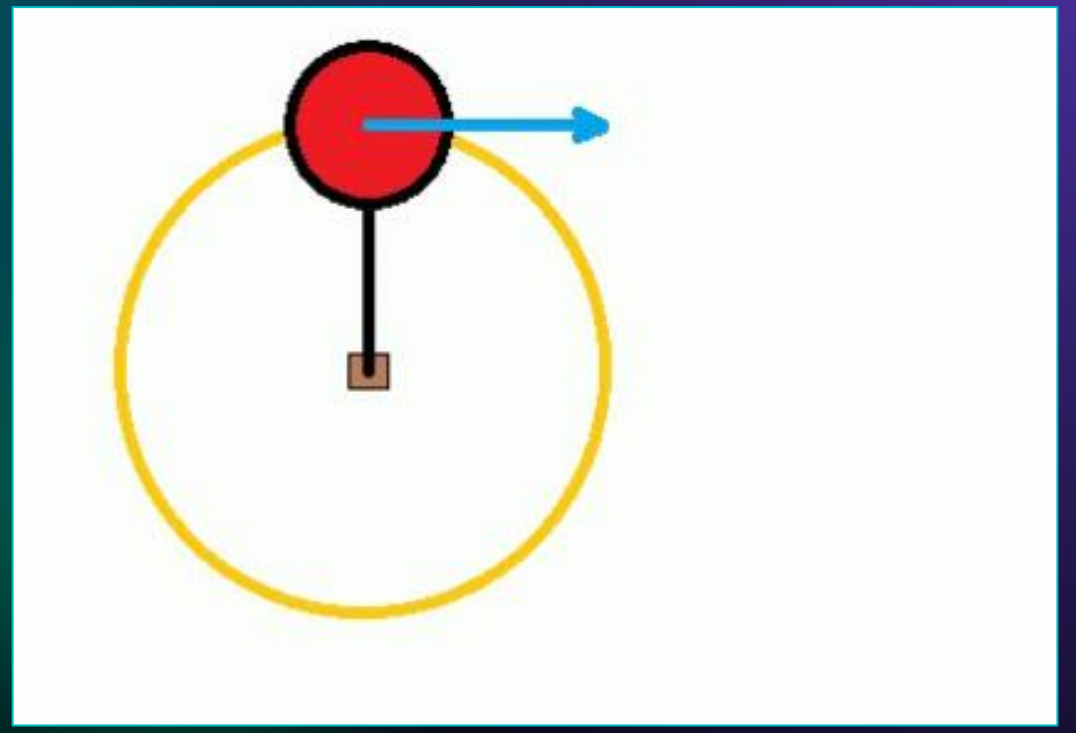
Discovering Dark Matter

Okay, cool, but what does that have to do with dark matter?

The stars in a galaxy are held in their orbits **by gravity**.

- If gravity pulls **too hard**, they'll fall inward.
- If it pulls **to little**, they'll fly away

It's like a **billiard ball on a string!**



In the galaxies, **gravity is the string** and the stars are the **billiard balls**.

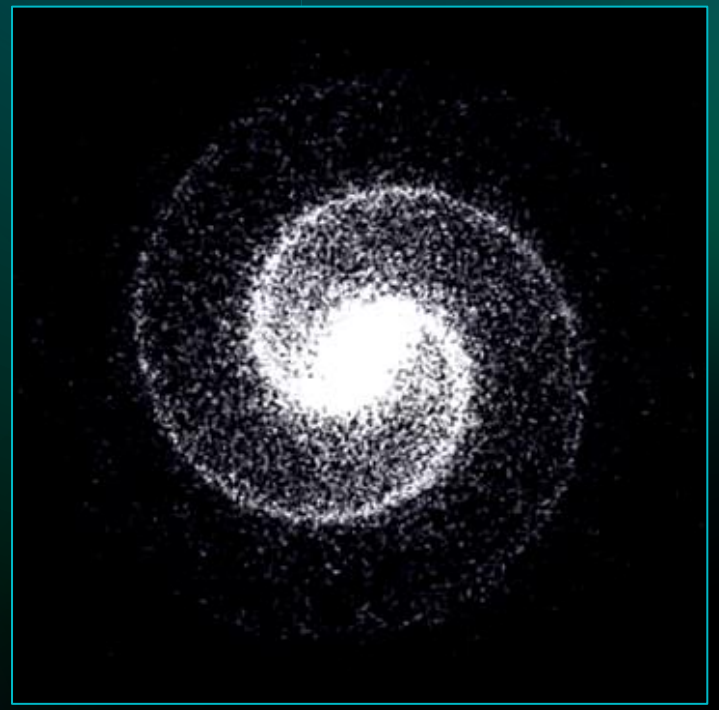
Here's the problem: the galaxies are **rotating way way too fast!**

AHHHH! It's EVERYWHERE!

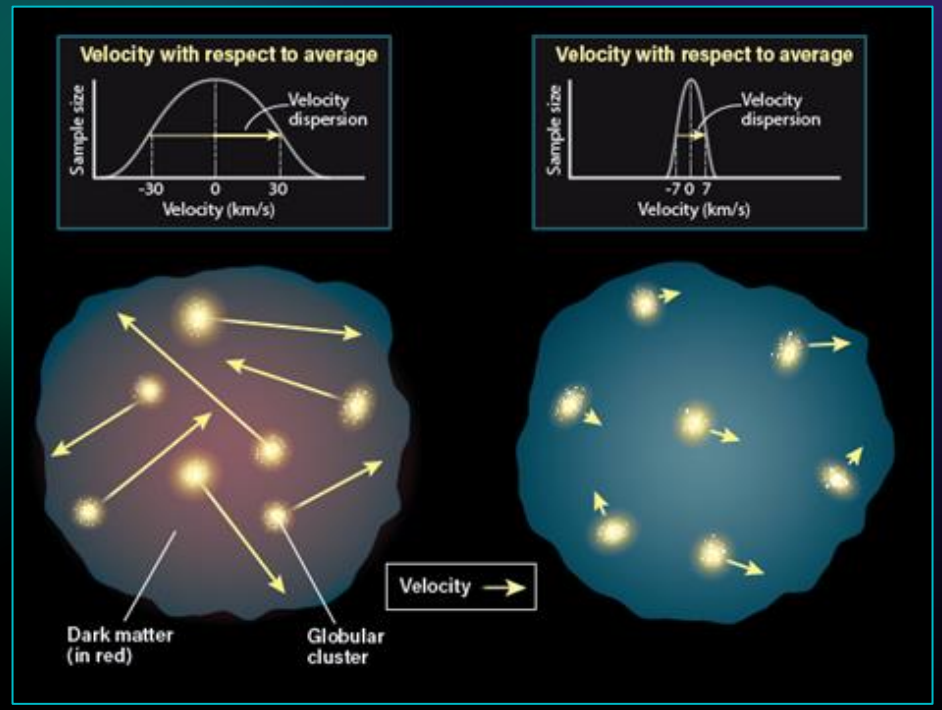
(I'm scared)

The more we look, the more we see this problem popping up **everywhere**!

Galaxies bend light more than expected!



Galaxies spin too quick



Galaxy clusters have too many fast galaxies

What's Going On!?

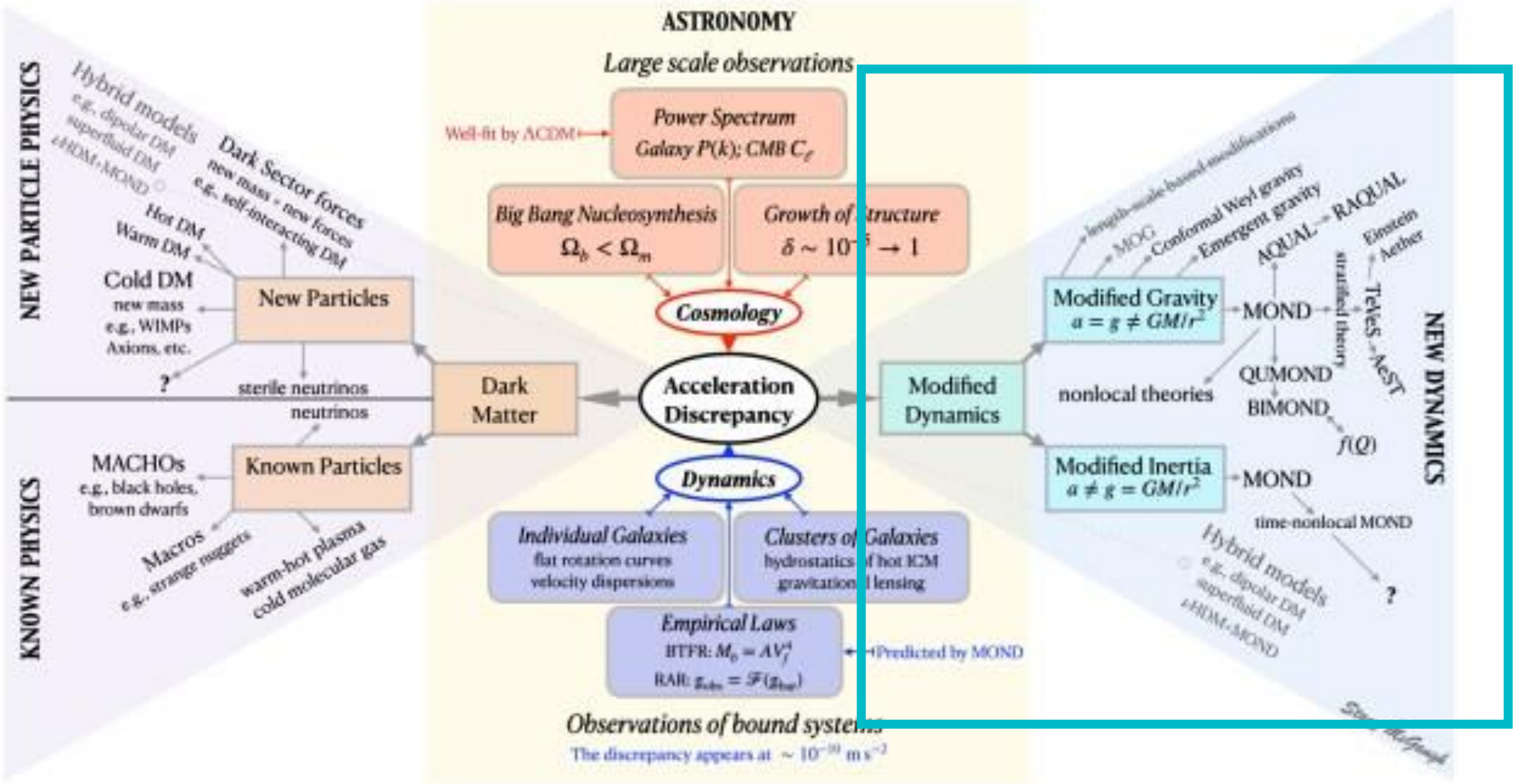
There are **two options** to explain what's going on:

There's **more stuff** in my galaxy than there should be!

I don't know **how the hell gravity works!**

There must be **extra stuff**, let's call it **"Dark Matter"** so no one thinks we're just ignorant.

How about we make up something that fixes the problem and call it **modified gravity**?



Credit: Stacy McGaugh

Gravity

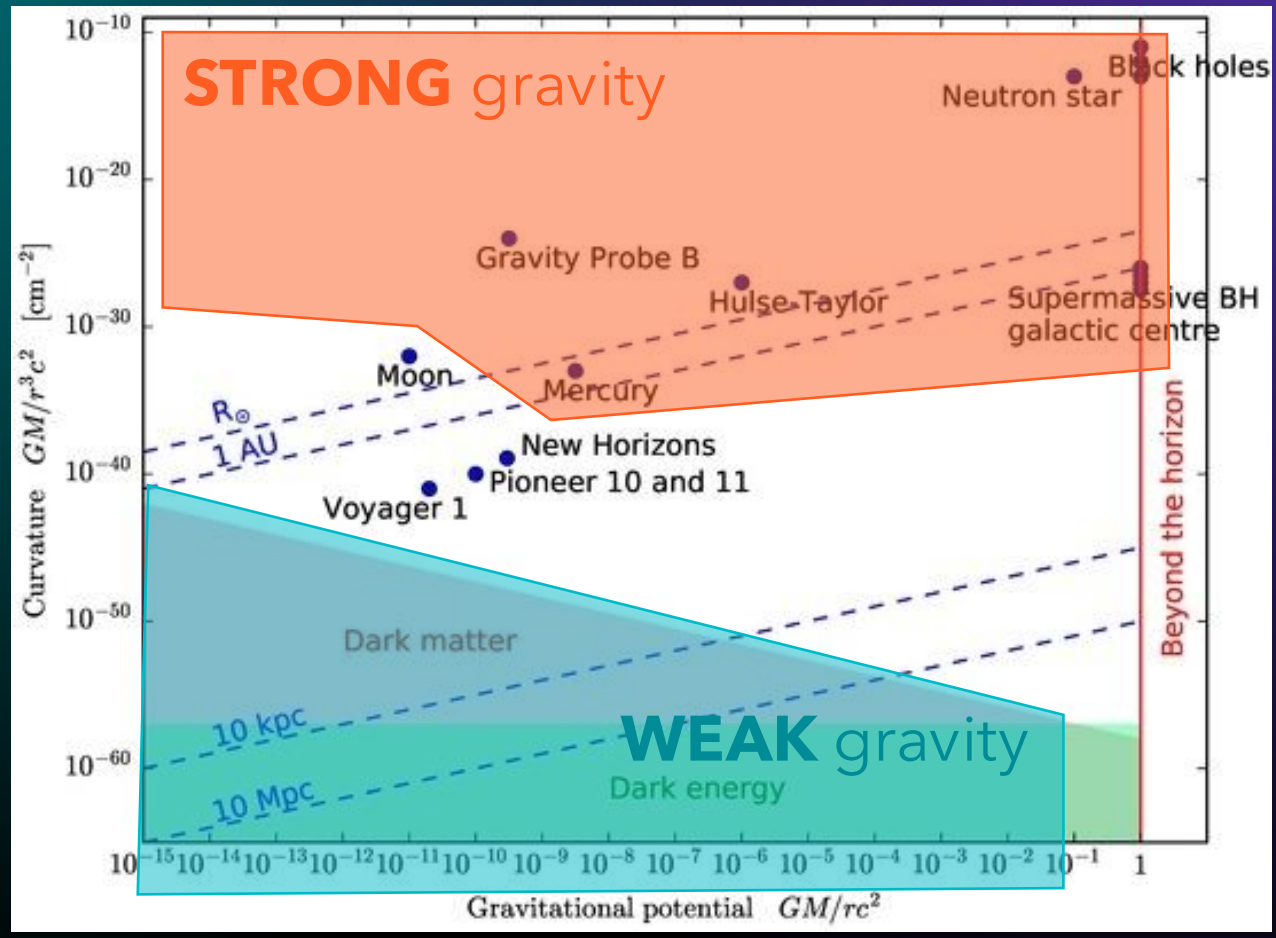
If we're going to **modify gravity**, we need to not break our current theory: **general relativity**.

Experiments to test gravity fall on 2 axes:

- How much **curvature** (mass) is involved?
- How much **gravity** (potential) is involved?

We know **a lot** about **strong gravity**

We know **relatively little** about **weak gravity**



Credit: Debono and Smoot (2016)

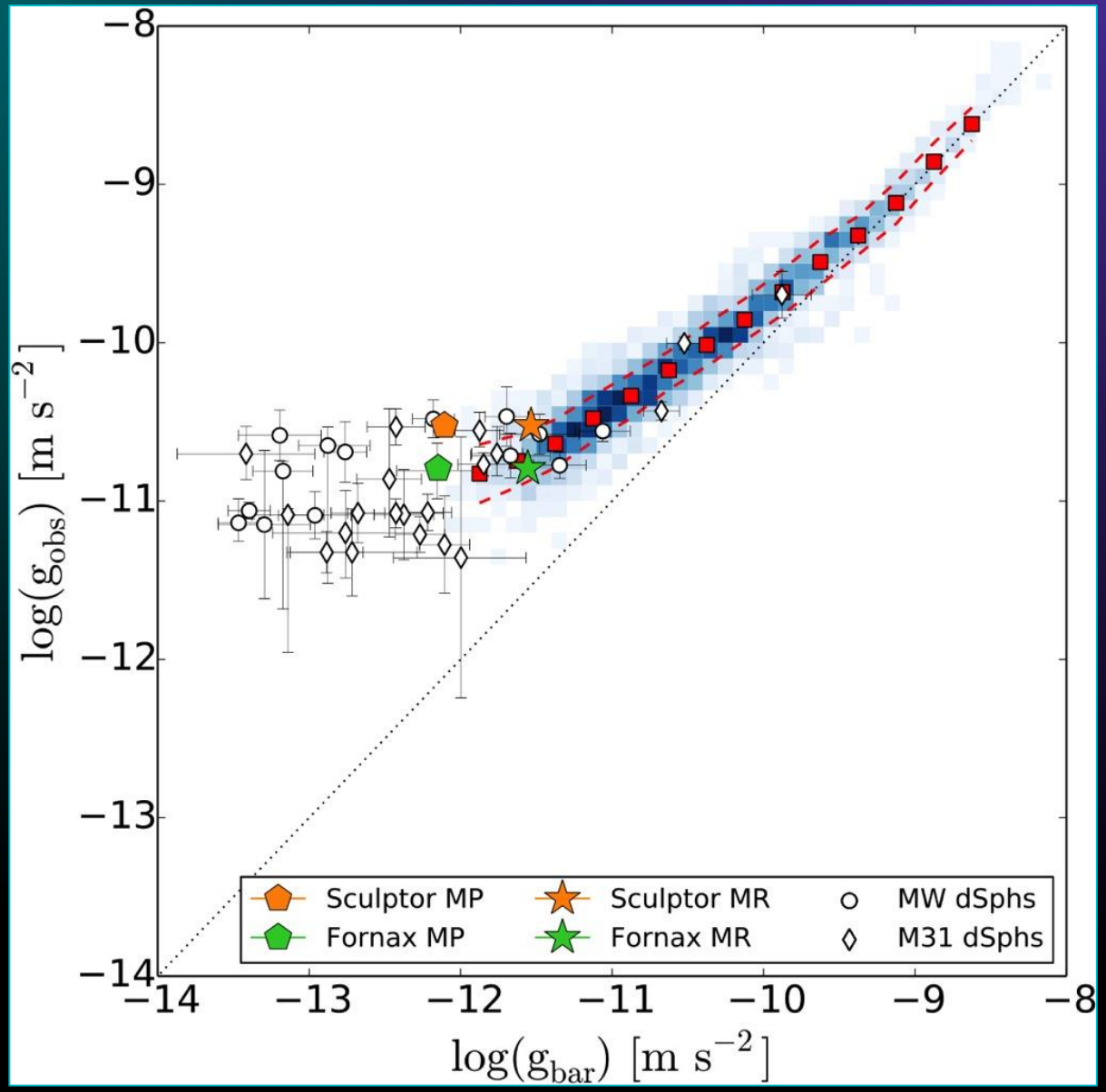
Dark Matter and **Dark Energy** are both parts of the **weak gravity realm**. Maybe we need a better theory?

Modified Gravity

For **galaxies**, modifying gravity might even be **more natural**

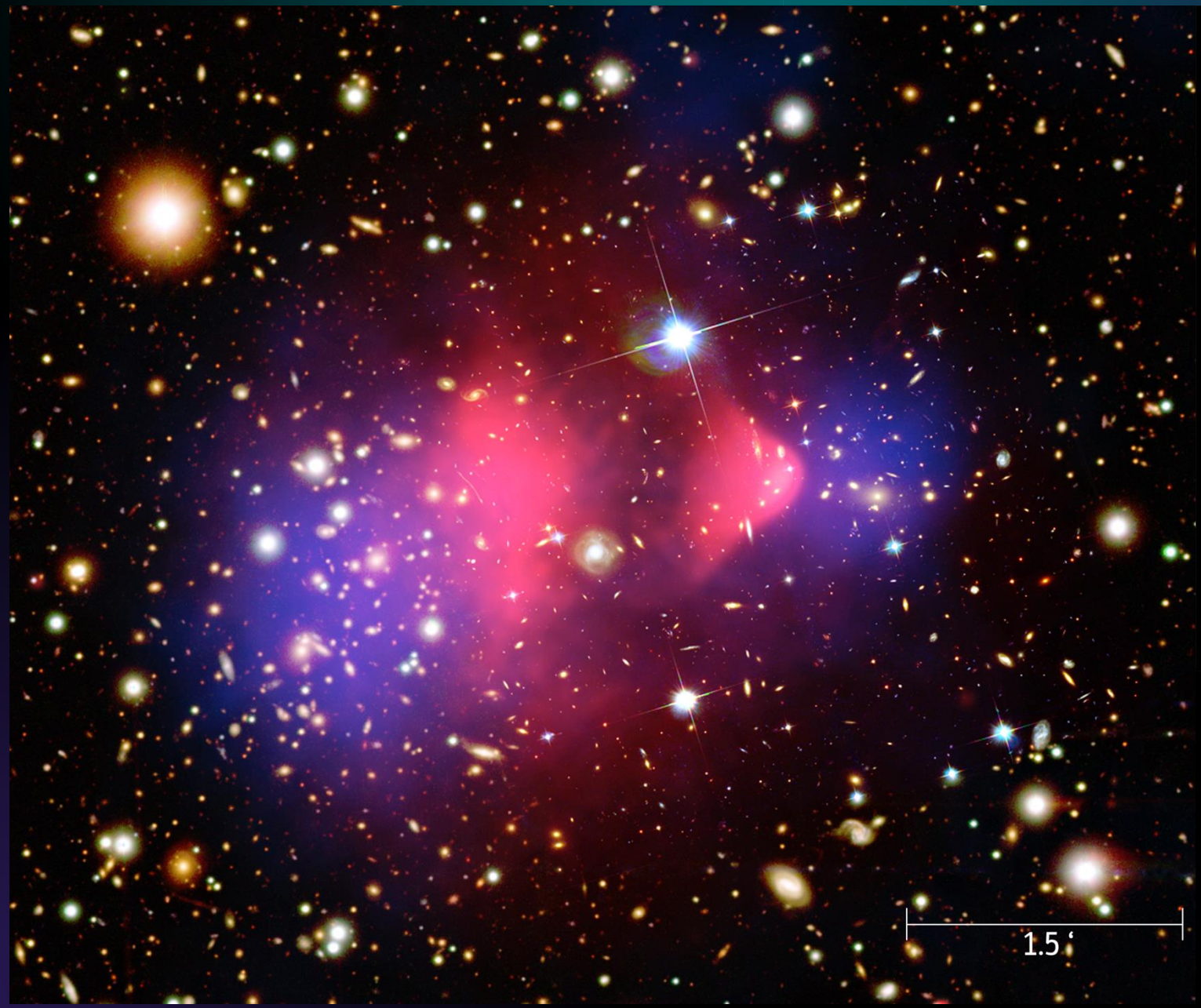
"Dark Matter" fits very nicely into a modification to gravity in **low acceleration regimes**.

This is the so-called **radial acceleration relation (RAR)**



Credit: Lelli and McGaugh (2016)

The Bullet in the Heart of Modified Gravity



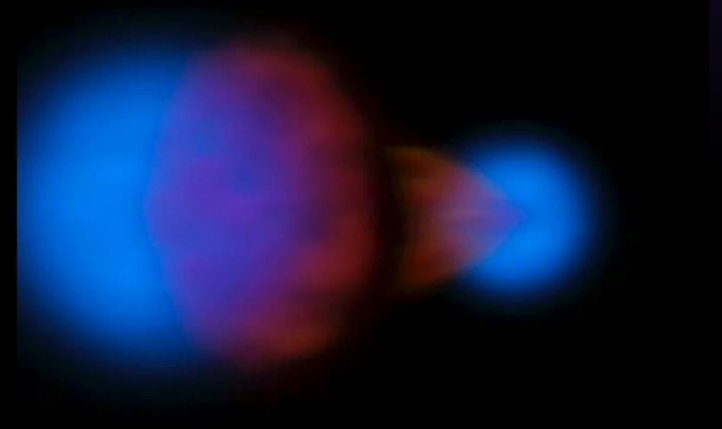
Direct Proof of Dark Matter

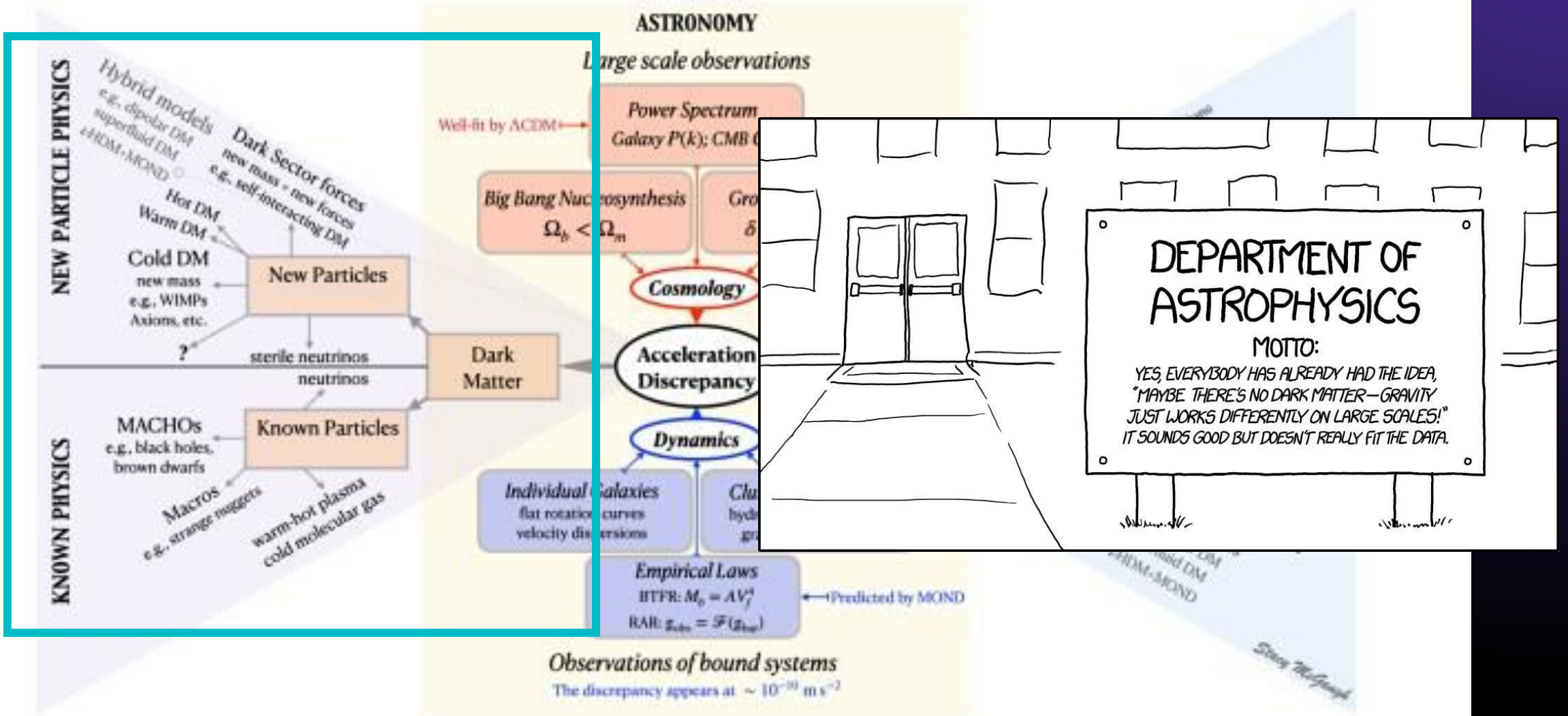
This composite image shows the galaxy cluster 1E 0657-56, also known as the "bullet cluster." This cluster was formed after the collision of two large clusters of galaxies, the most energetic event known in the universe since the Big Bang.

Hot gas detected by Chandra in X-rays is seen as two pink clumps in the image and contains most of the "normal," or baryonic, matter in the two clusters. The bullet-shaped clump on the right is the hot gas from one cluster, which passed through the hot gas from the other larger cluster during the collision. An optical image from Magellan and the Hubble Space Telescope shows the galaxies in orange and white. The blue areas in this image show where astronomers find most of the mass in the clusters. The concentration of mass is determined using the effect of so-called gravitational lensing, where light from the distant objects is distorted by intervening matter. Most of the matter in the clusters (blue) is clearly separate from the normal matter (pink), giving direct evidence that nearly all of the matter in the clusters is dark.

The animation below shows an artist's representation of the huge collision in the bullet cluster. Hot gas, containing most of the normal matter in the cluster, is shown in red and dark matter is in blue. During the collision the hot gas in each cluster is slowed and distorted by a drag force, similar to air resistance. In contrast, the dark matter is not slowed by the impact, because it does not interact directly with itself or the gas except through gravity, and separates from the normal matter.

Left: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al., Below: NASA/CXC/M.Weiss





Credit: Stacy McGaugh

Dark Matter: For real this time

Okay, so we're confident its **actually dark matter**.
We're not just confused about gravity.

But **what is dark matter?**

Since we cannot see the **dark matter**, it must not interact much via the electromagnetic force.

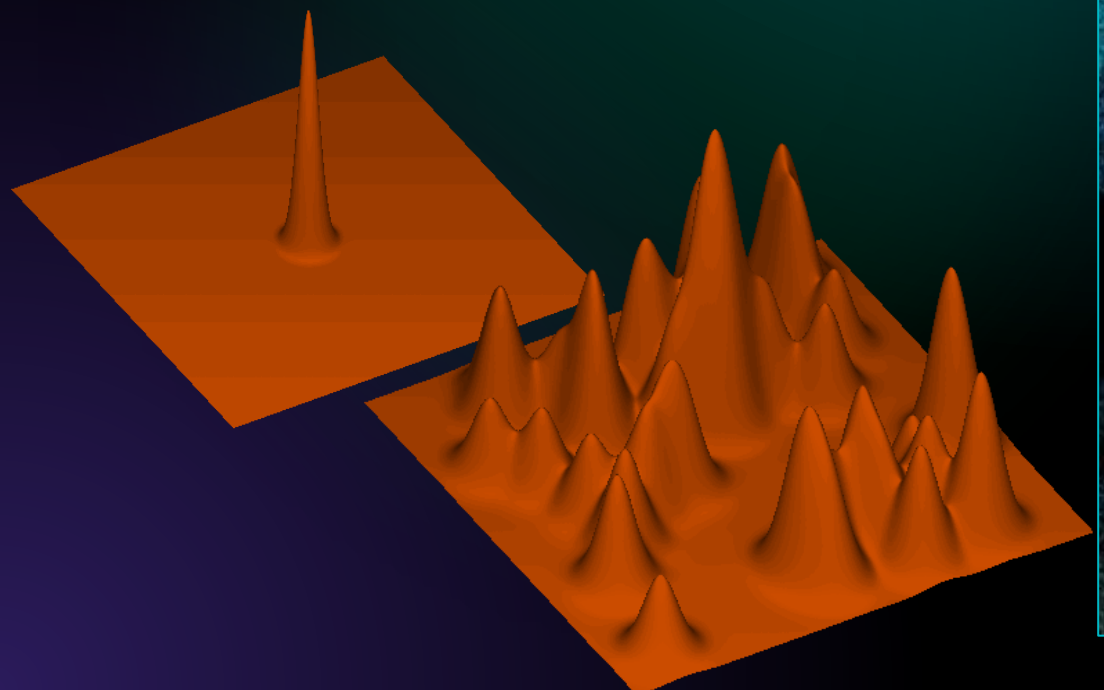
(Dark matter is **dark**)

It could be **anything** else!

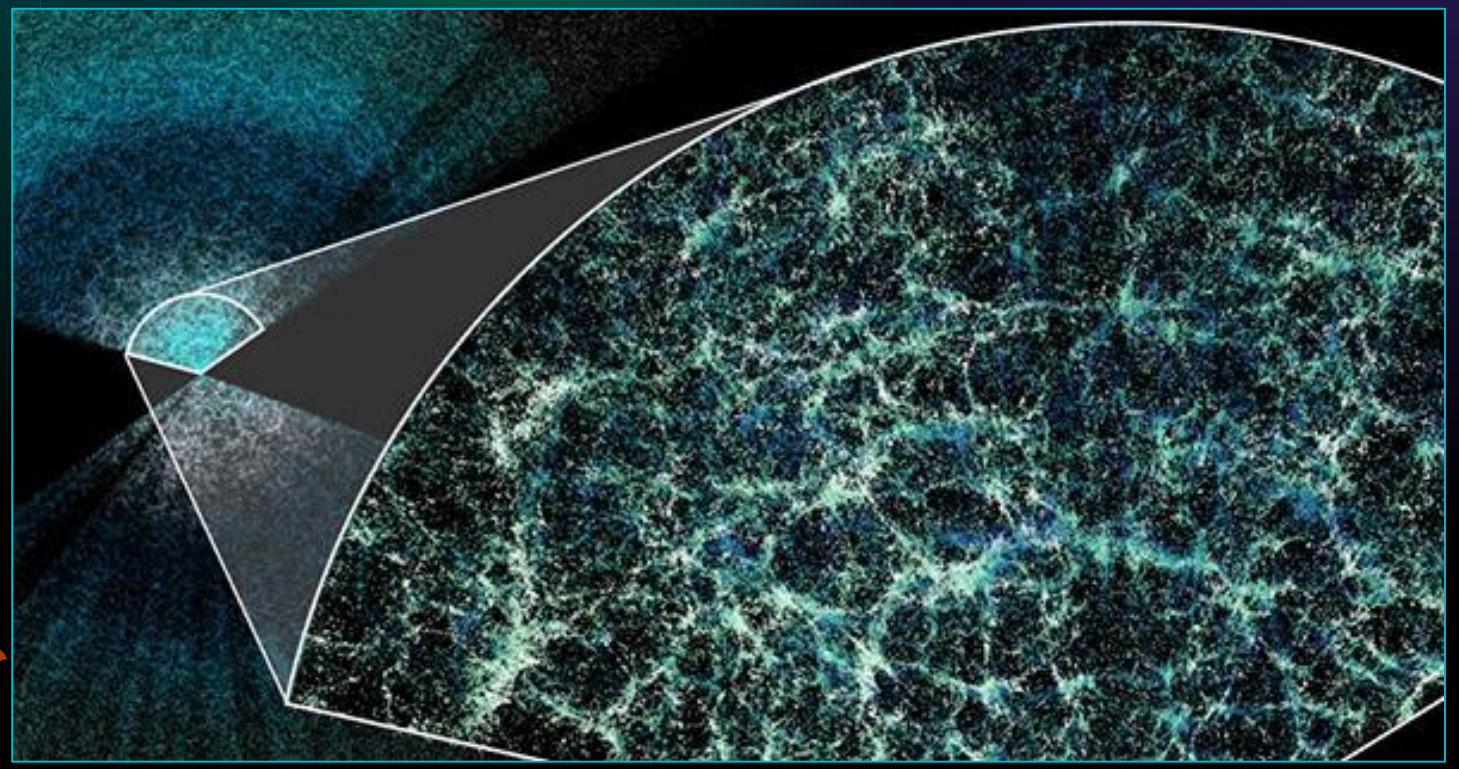
Baryon Acoustic Oscillations (BAO)

In the *very* early universe, regions with **slightly higher density** caused **pressure waves** in the universe's gas.

These **pressure waves** get **frozen** at a certain point in the evolution of the universe and form **rings**.



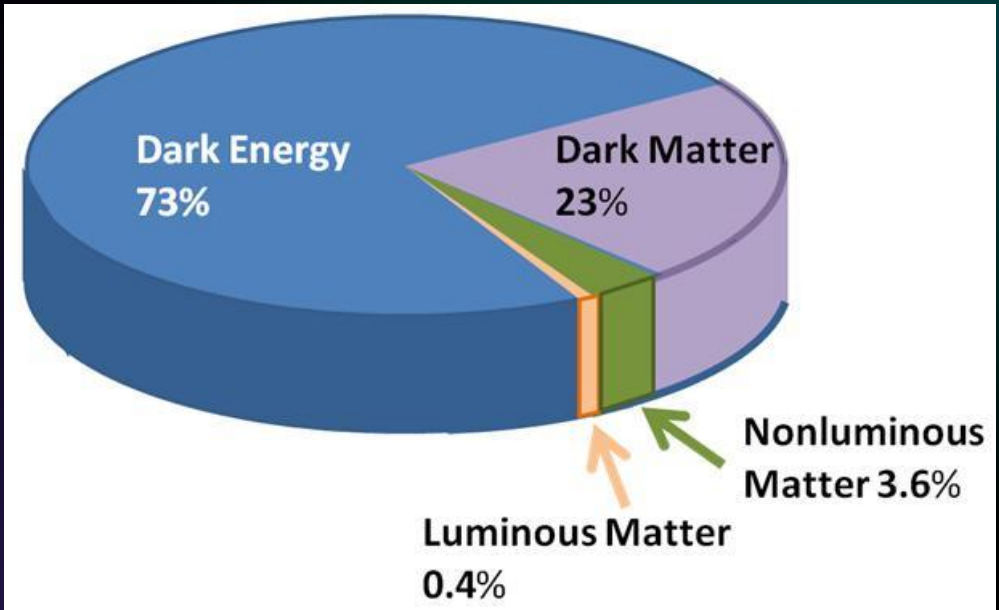
These rings are observable as **clustering** in the galaxies of the universe.



Baryon Acoustic Oscillations (BAO)

(Where the math meets the road)

Cool, sound waves from the early universe…
What does that have to do with dark matter?



The BAO can tell us **how much stuff** is in the universe*.

Turns out **there is more** matter than there are **baryons (normal stuff)**.

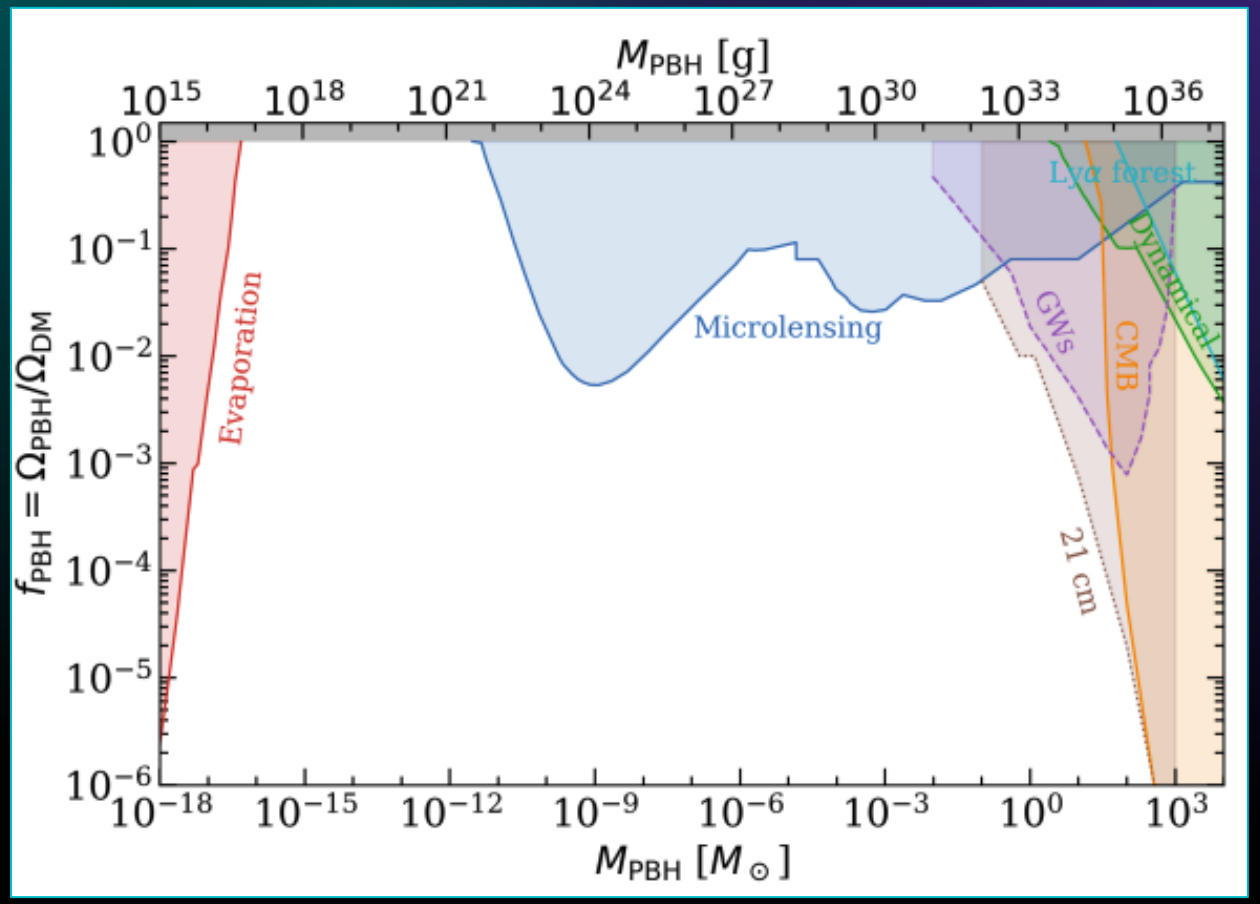
Dark matter must be abnormal stuff!

This is a very simplified picture; there are entire classes about making these measurements.

Let's Get Exotic! What about Black Holes

It's possible that **dark matter** comes from **black holes** which were formed in the very early universe. This are called **primordial black holes**.

We're getting better and finding **black holes:** fewer and fewer ways to get dark matter from black holes.

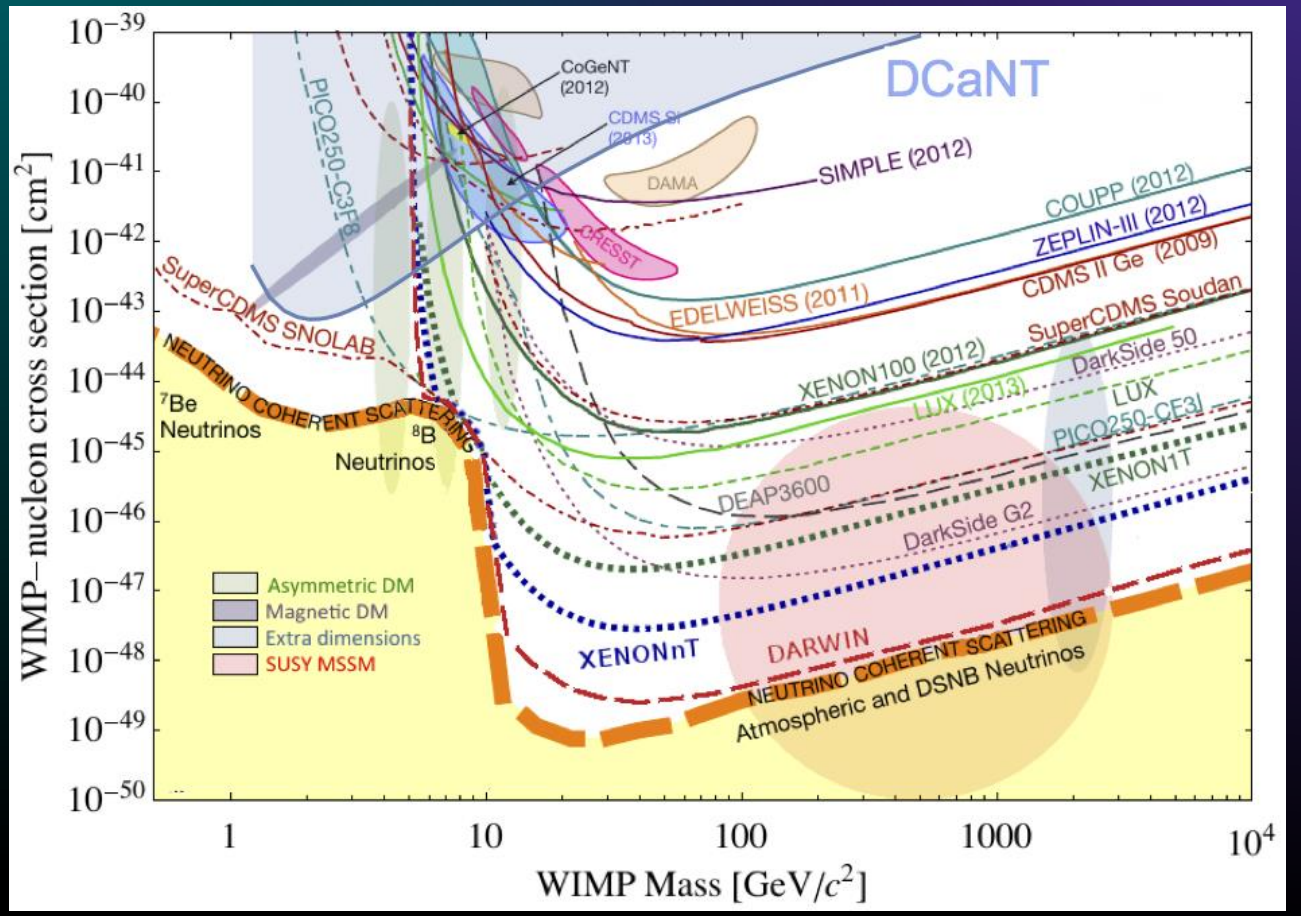


What about _____ [insert particle]?

The "**accepted picture**" of dark matter is that it is composed of some **exotic particle** which we have yet to detect on Earth.

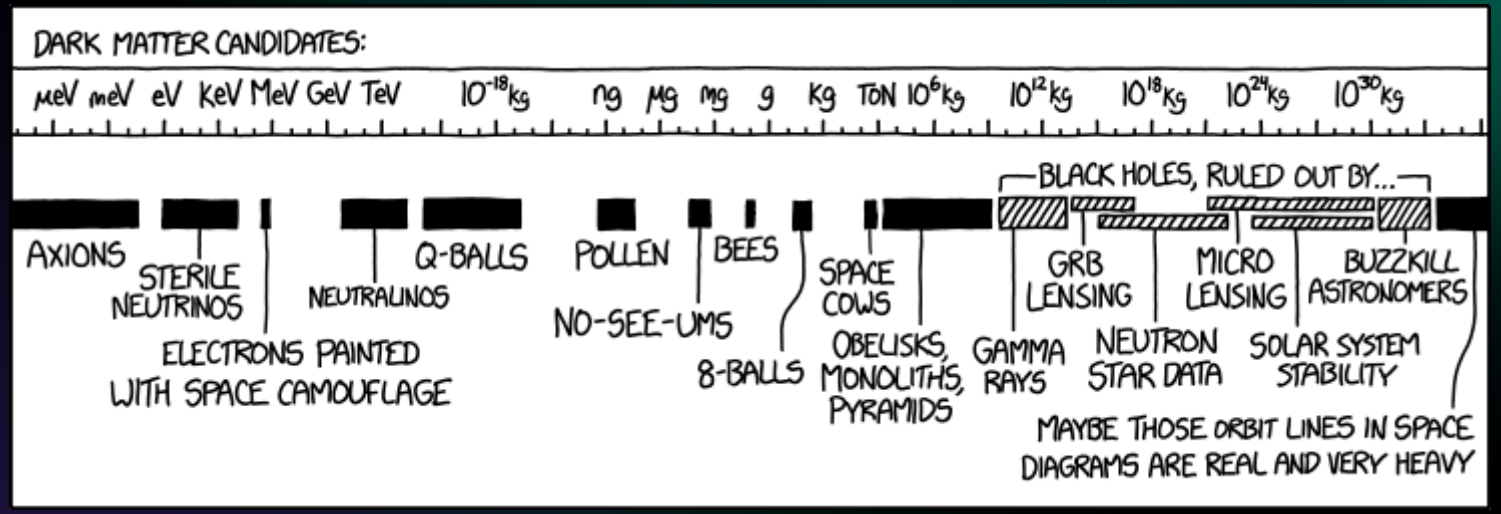
Every year, we try to detect these particles… Every year, we **fail** to detect these particles.

But hey, with just a bit more money, we'll **definitely find it!**



Conclusions

Dark matter is everywhere… and we still have **no freaking clue** what it is…



just one more collider bro. i promise bro just one more collider and we'll find all the particles bro. it's just a bigger collider bro. please just one more. one more collider and we'll figure out dark matter bro. bro cmon just give me 22 billion dollars and we'll solve physics i promise bro. bro bro please we just need to build one more collider t