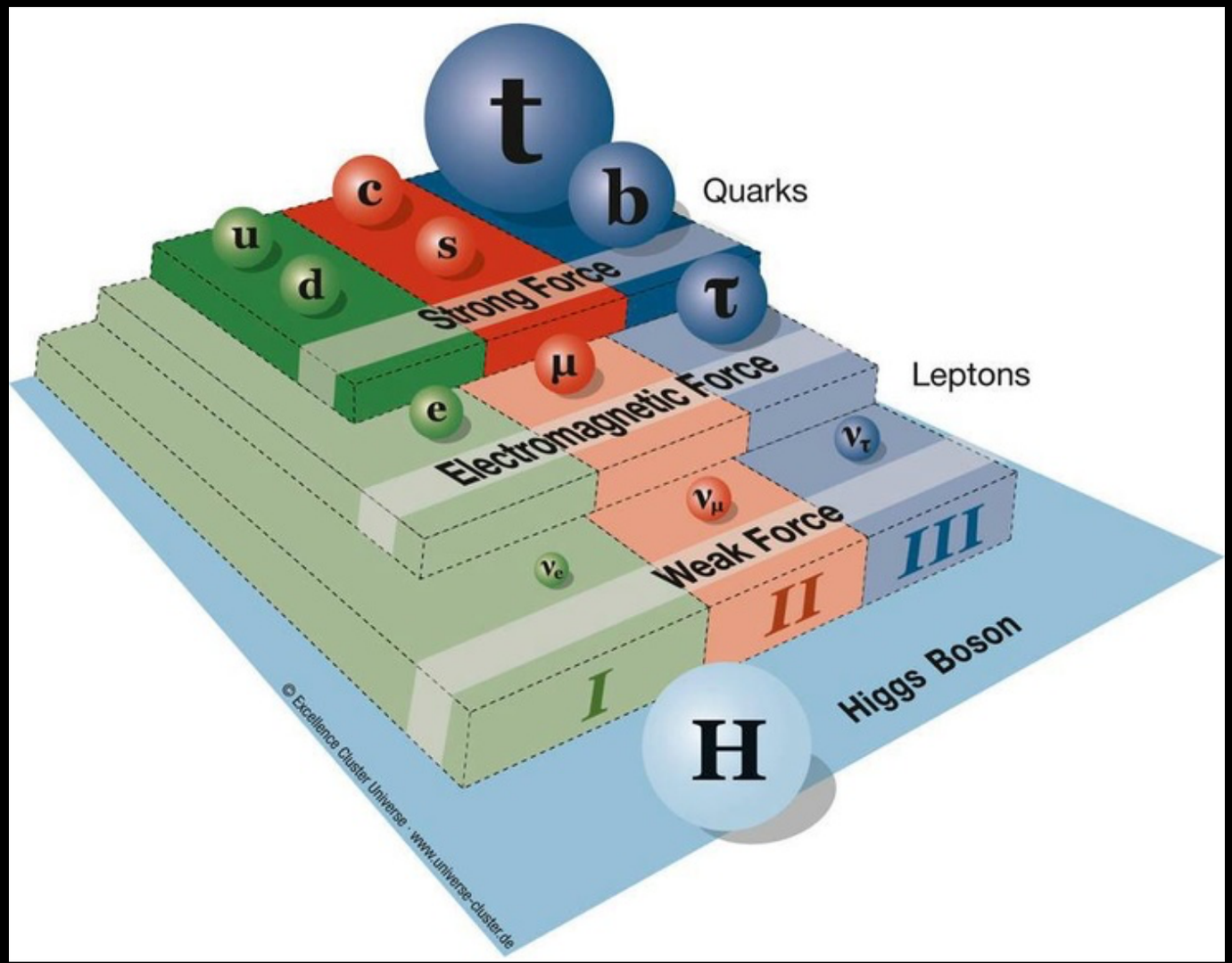
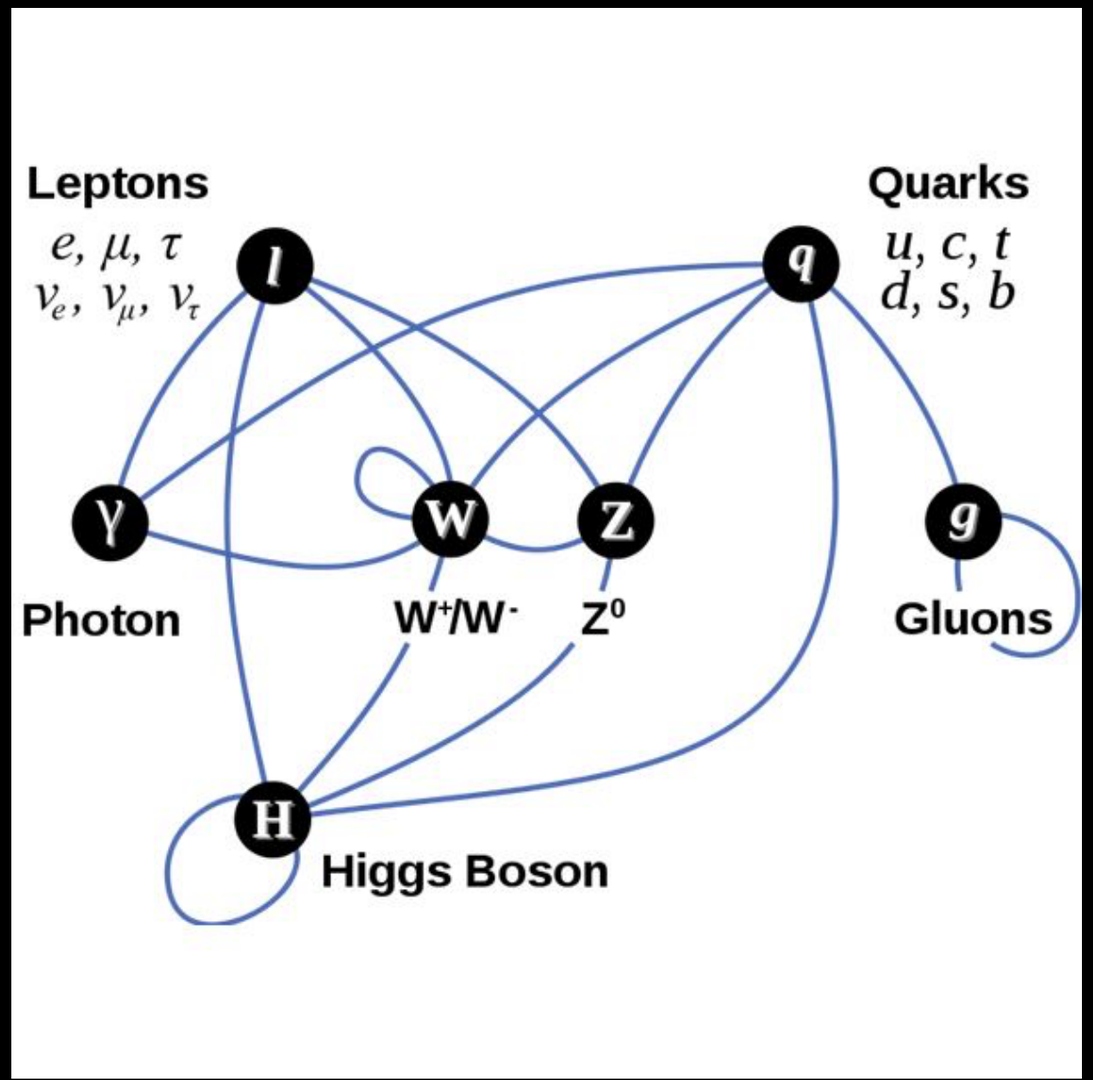
Open Questions in Particle Physics

Quarknet High School Teacher's Workshop

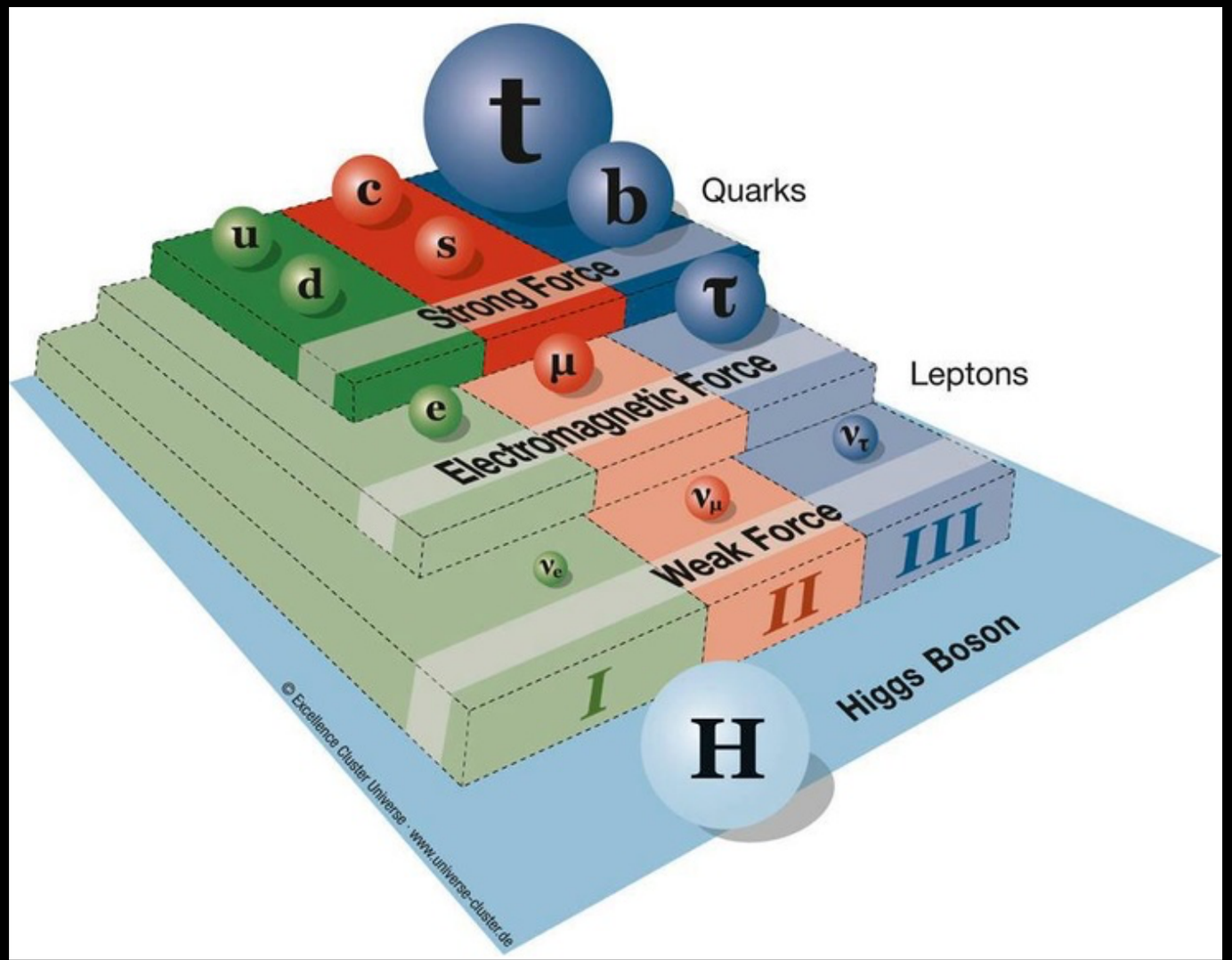
1 July 2019

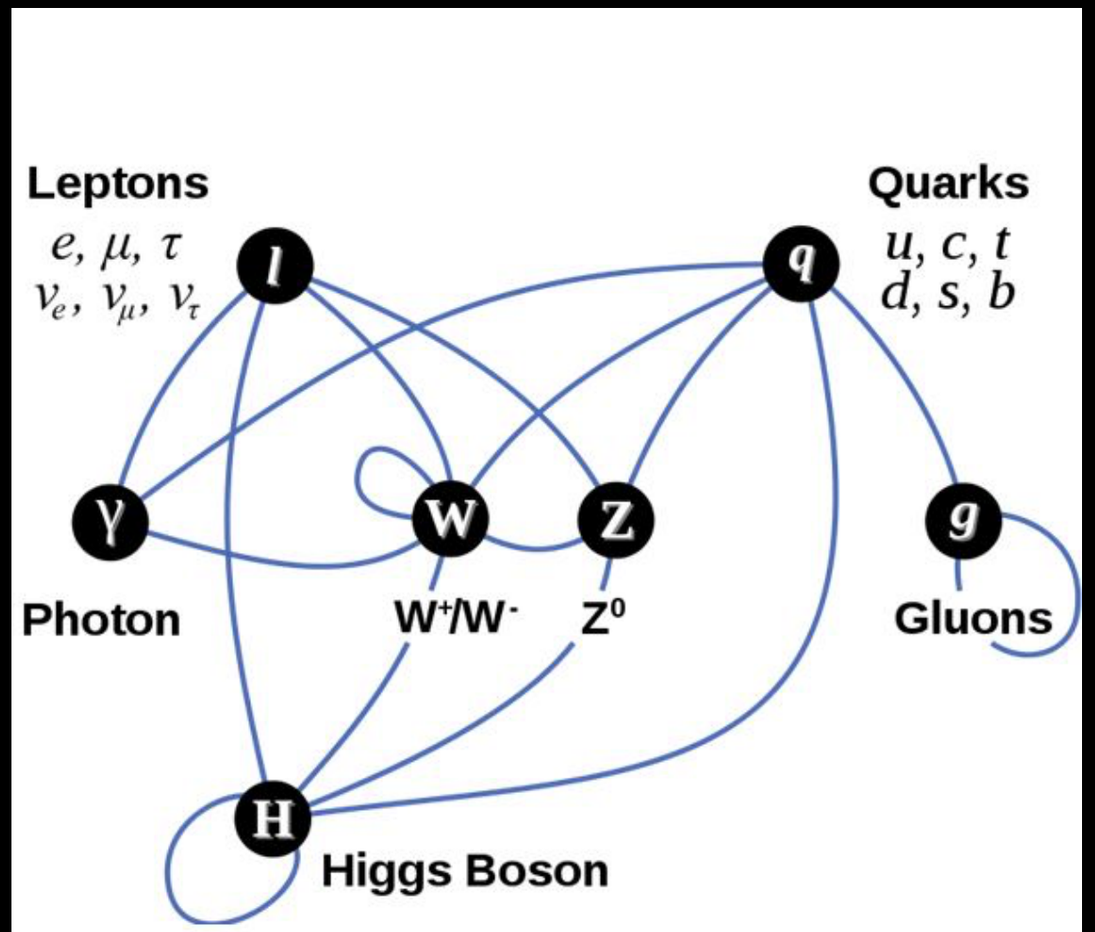
Standard Model of Particle Physics





Standard Model of Particle Physics





Elementary particle theory been successful at explaining current PP data

However….

There are many aspects of nature SM cannot explain

1. Matter - Antimatter asymmetry

Why is there more matter than Antimatter in the Universe?

If the two were the same amount, we wouldn't exist.

2. Origin of Electroweak Symmetry Breaking

The process through which the Higgs gives mass to SM particles.

Why does this process occur at the scale that it occurs.

Is there some underlying symmetry which the SM symmetry falls under?

3. Origin of Neutrino Masses

We remember from the previous talk that fermion masses arise from interaction of right and left handed chiral fermions.

$$\mathcal{L} \supset \frac{yv}{\sqrt{2}}\bar{\psi}_L\psi_R + \frac{y}{\sqrt{2}}h\bar{\psi}_L\psi_R$$

Neutrinos are fermions and thus must also get masses this way.

However…. Right handed neutrinos have never been observed and are thought not to exist in the SM.

Therefore neutrino masses cannot arise from SM processes since their mass term in the SM doesn't exist

Yet… Neutrinos were recently found to have mass so where does this mass come from?

3. Dark Energy

Dark Energy is responsible for the accelerated expansion of the Universe

Is it a form of energy as we normally define it?

Is there some particle responsible for this phenomenon?

4. Dark Matter

Unseen type of matter responsible for formation of structure as we see it in our Universe.

Is DM a particle?

What do we know about it?

All these point to new physics beyond the SM

Creates a new subfield of PP called BSM Physics

Both experimentalists and Theorists are currently hard at work trying to explain these outstanding questions.

We are trying to do this by confronting experimental data from all frontiers.

1. Searching for new particles at the LHC and other colliders

2. Searching for new physics signatures at lower energy experiments

3. Looking for imprints of new physics in astrophysical and cosmological data.

4. Proposing new models and experiments that search for "smoking gun" signatures of new physics.

My Field of Research

- Astro-Particle Physics

  Dark Matter Physics:

  Direct Detection

  various dark matter searches

- Theoretical Particle Physics

  High Energy Collider physics

  Low Energy precision physics

Lets talk about one of these outstanding
Problems, Dark Matter.

What do we know about our Universe?

What do we know about our Universe?

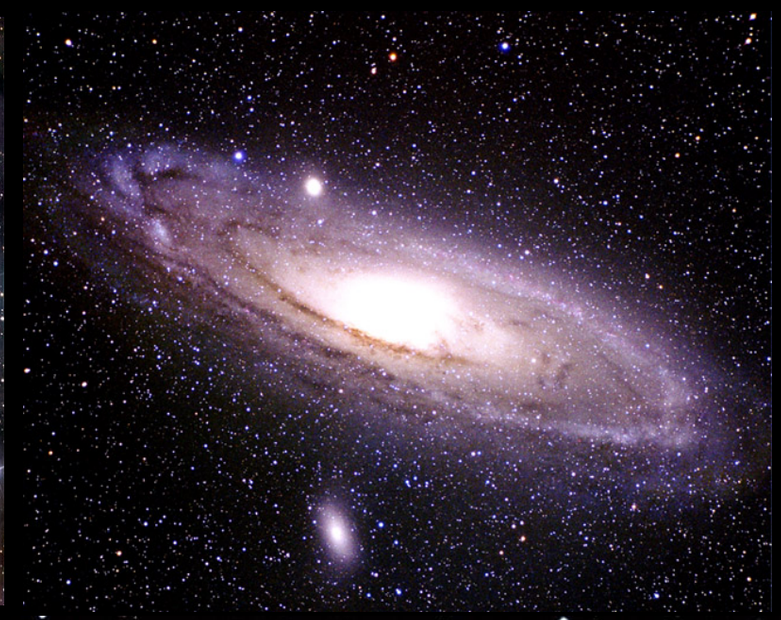
What is our Universe made of ?

What is our Universe made of ?

When we look up at the night sky….

What is our Universe made of ?

When we look up at the night sky….



more stars in universe than grains of sand on every beach on earth

Would expect stars, gas, galaxies to be
100% of Universe

On the contrary….

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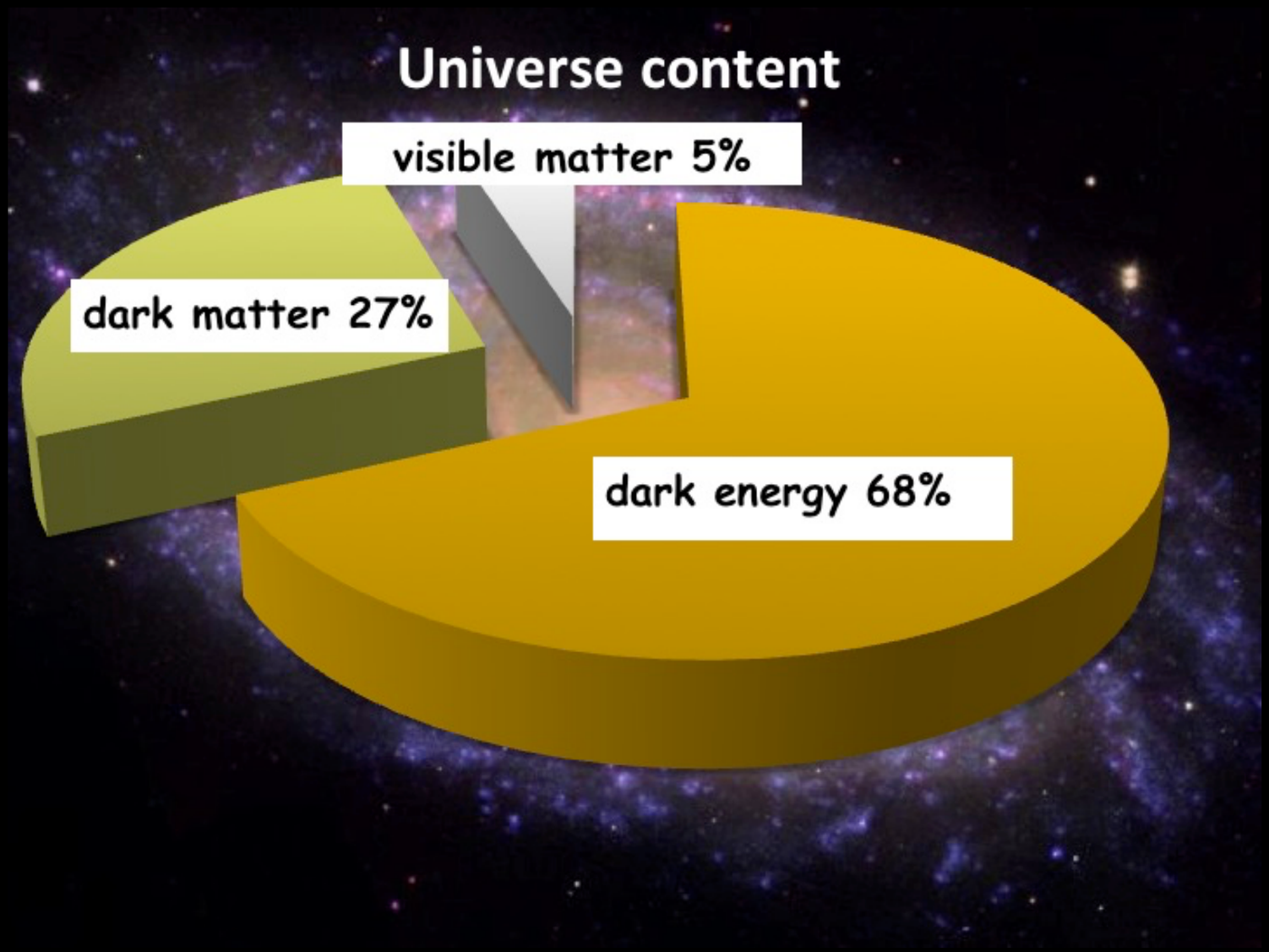
100% of Universe

On the contrary….



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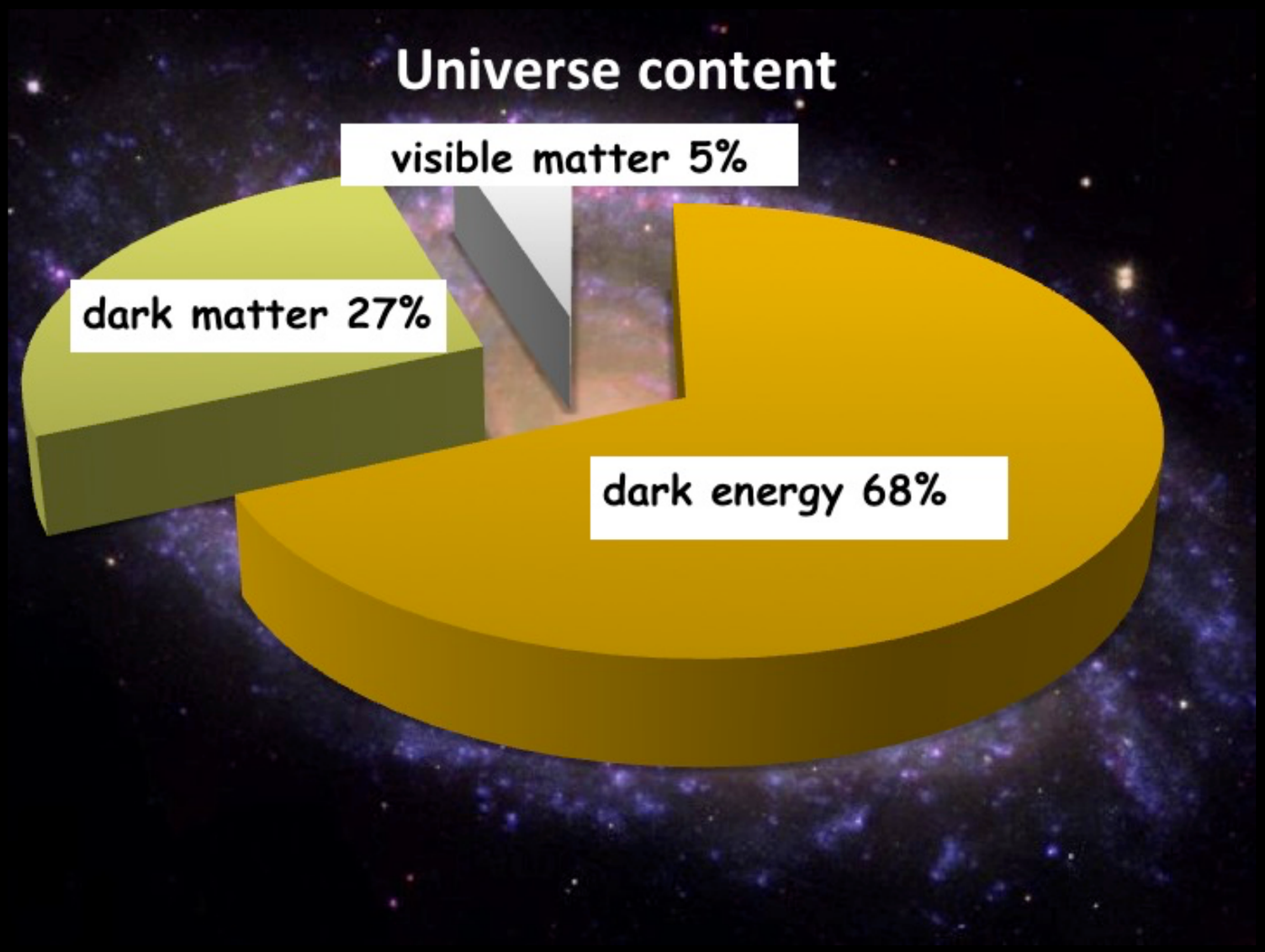

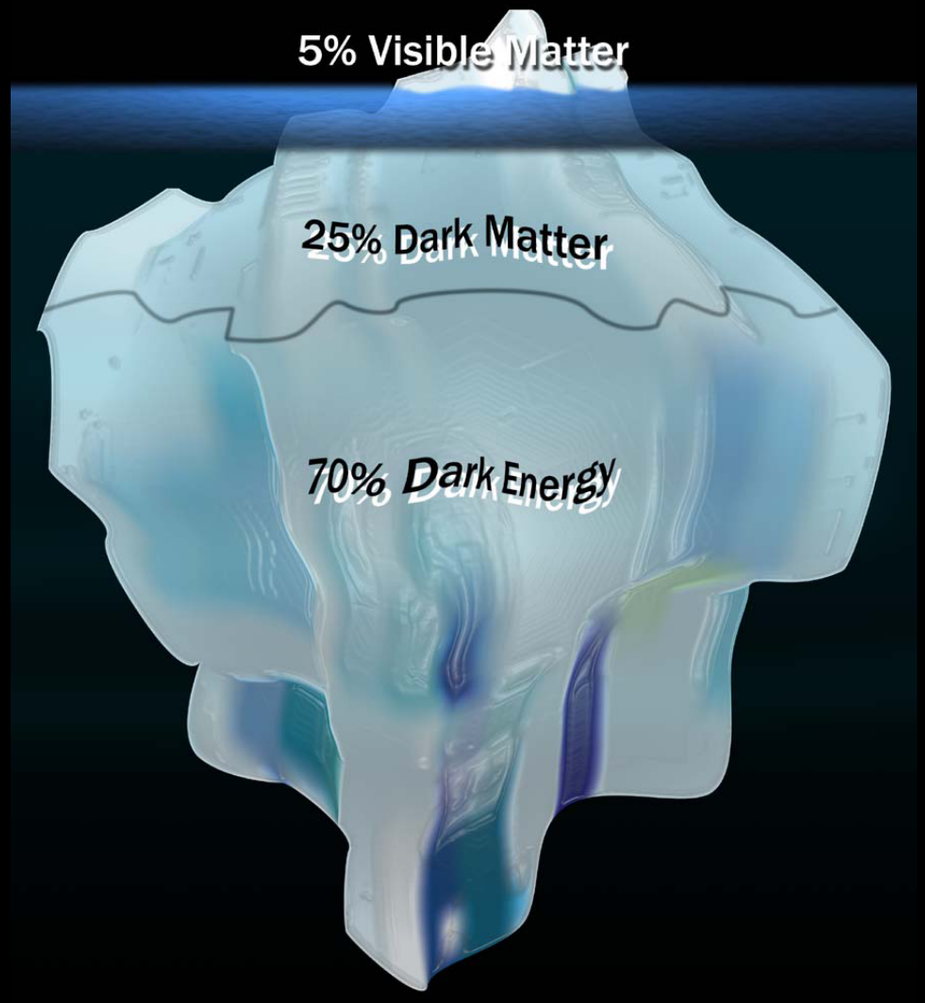

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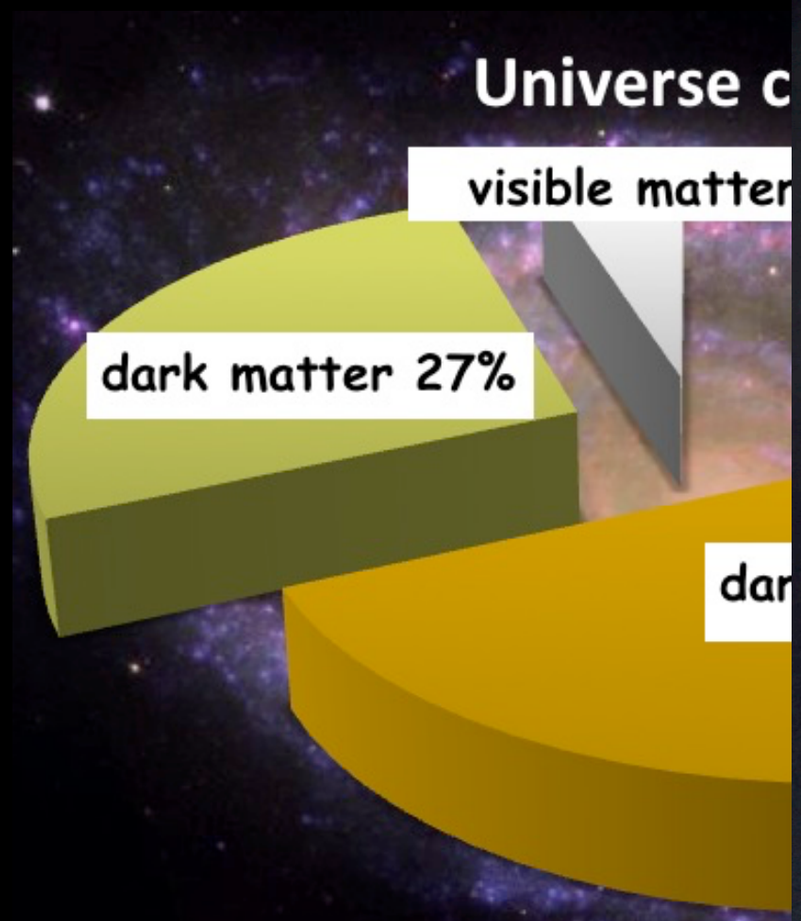
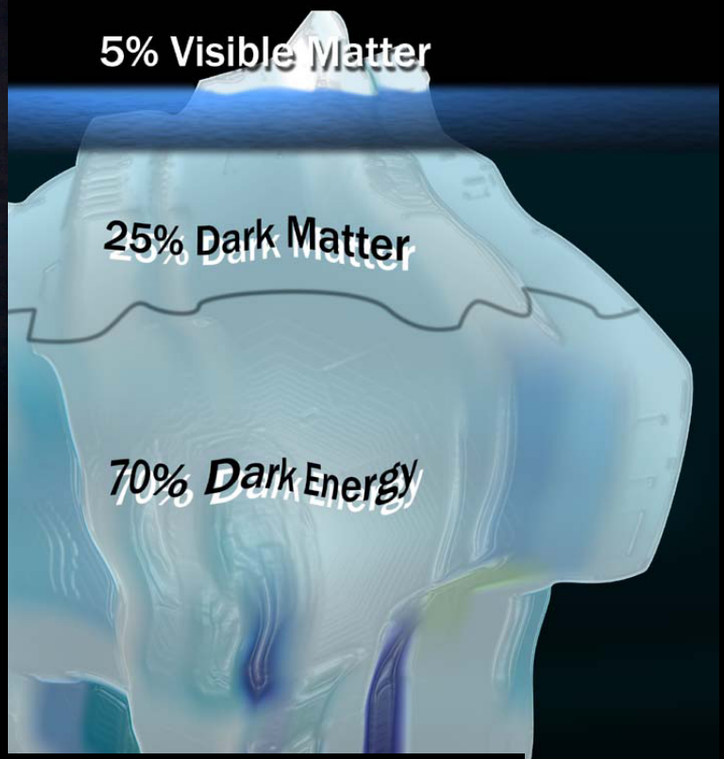
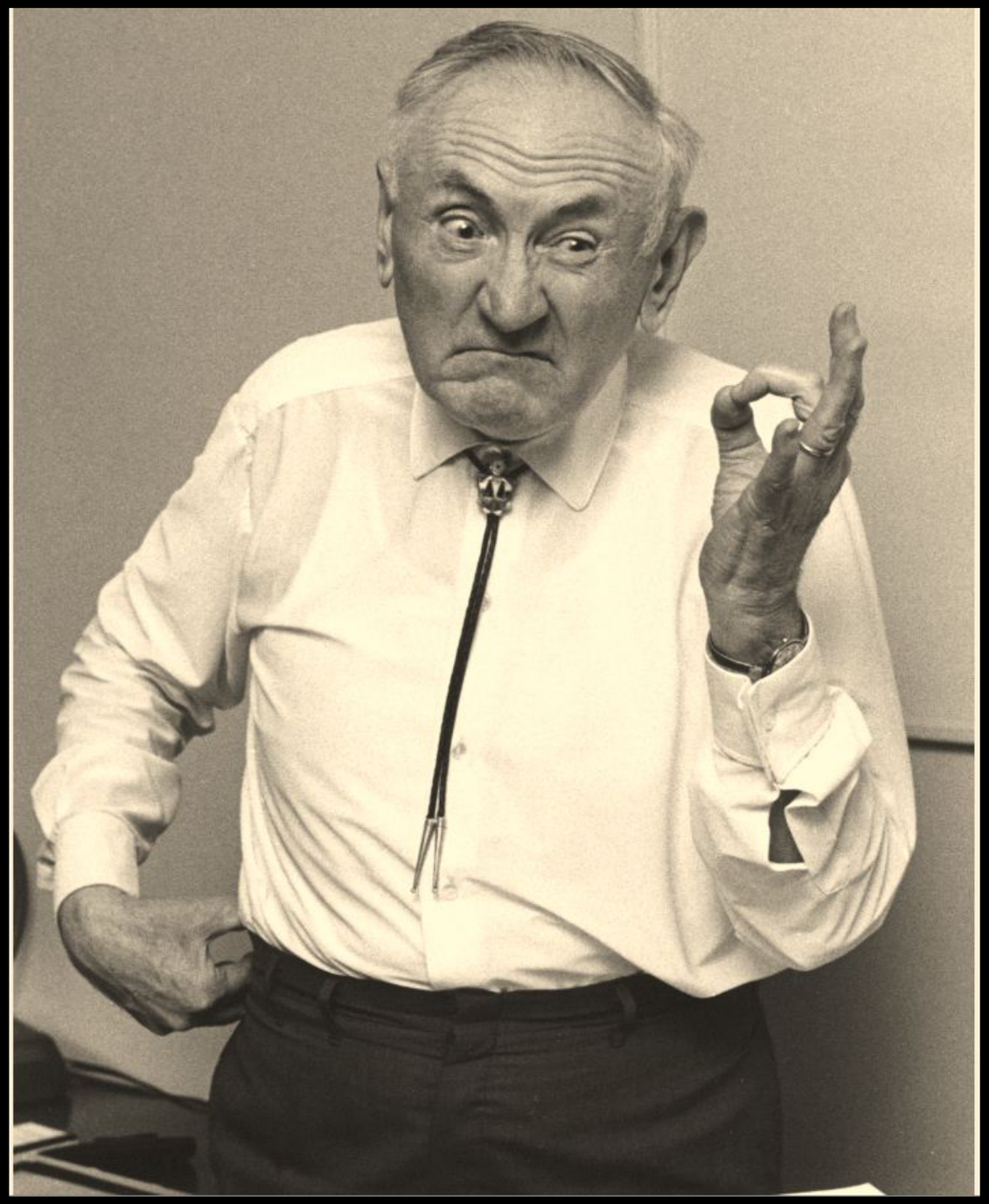




Dark Matter
Dark Energy

So how do we know DM exists?

In 1933, Swiss Astrophysicist, Fritz Zwicky



Found evidence for unseen matter when studying Coma galaxy cluster

Calculated 400x more mass than seen

Coined it Black Matter

For years no one believed him

Roughly 40 years later…

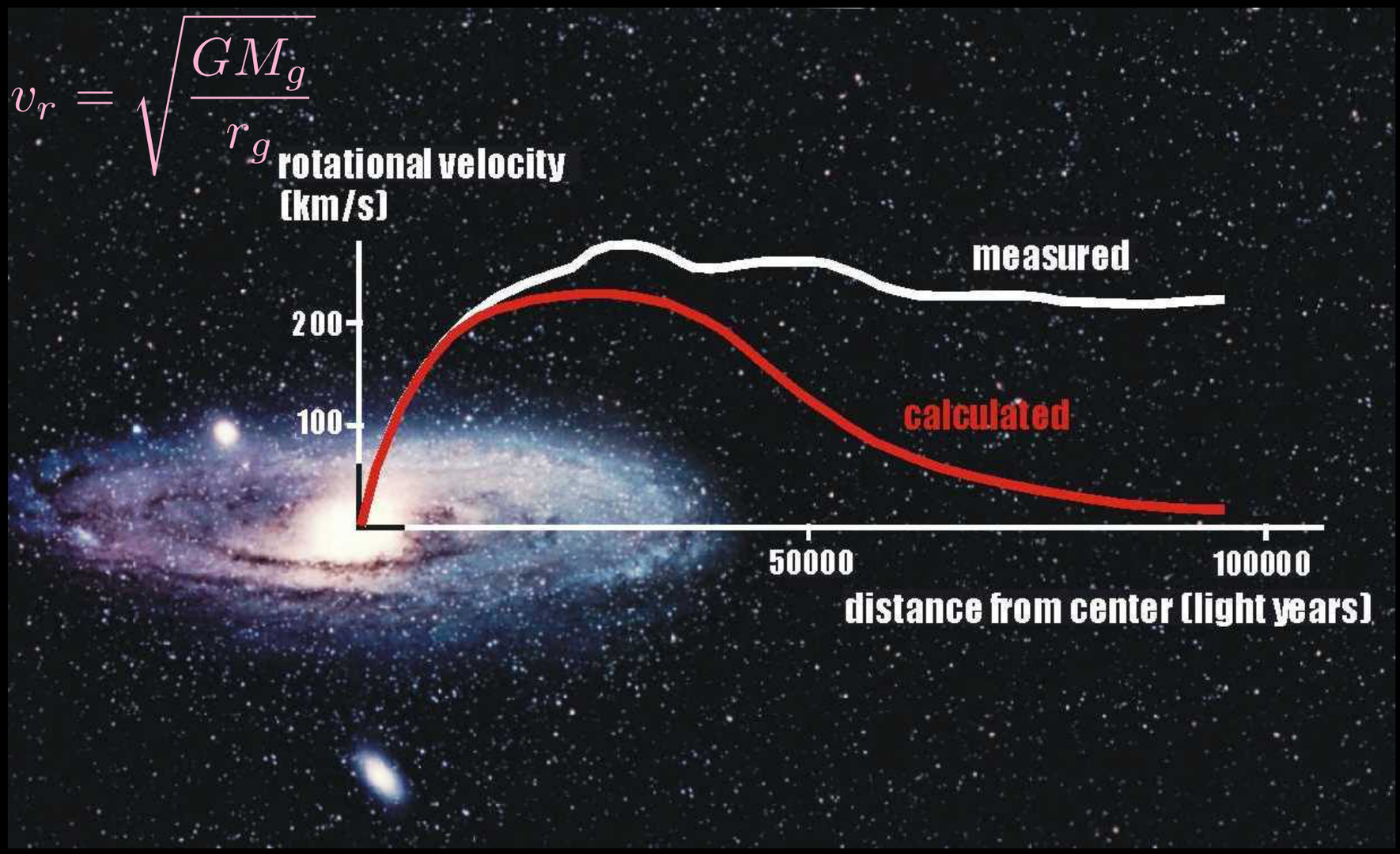
American astronomer Vera Rubin

Studied velocity curves of spiral galaxies

Found evidence of unobservable matter

Velocity curves should follow Newtonian dynamics

Measurements did not match calculations



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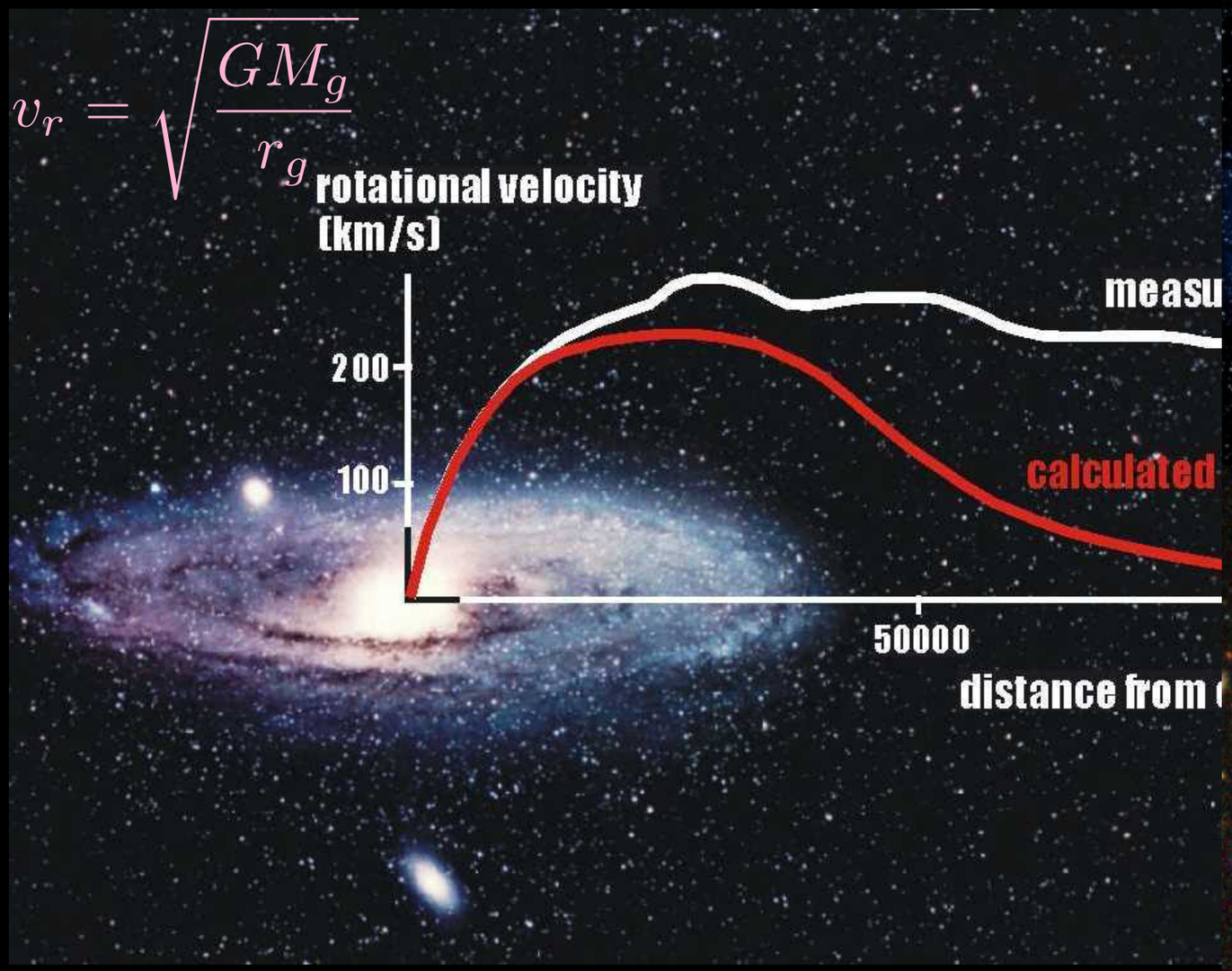
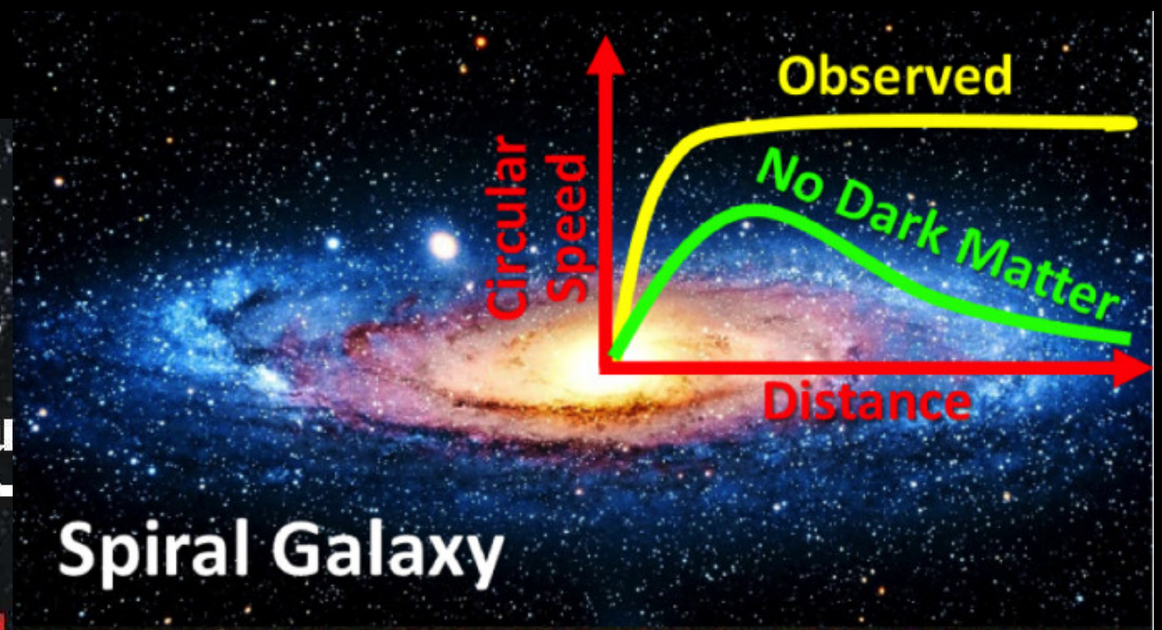
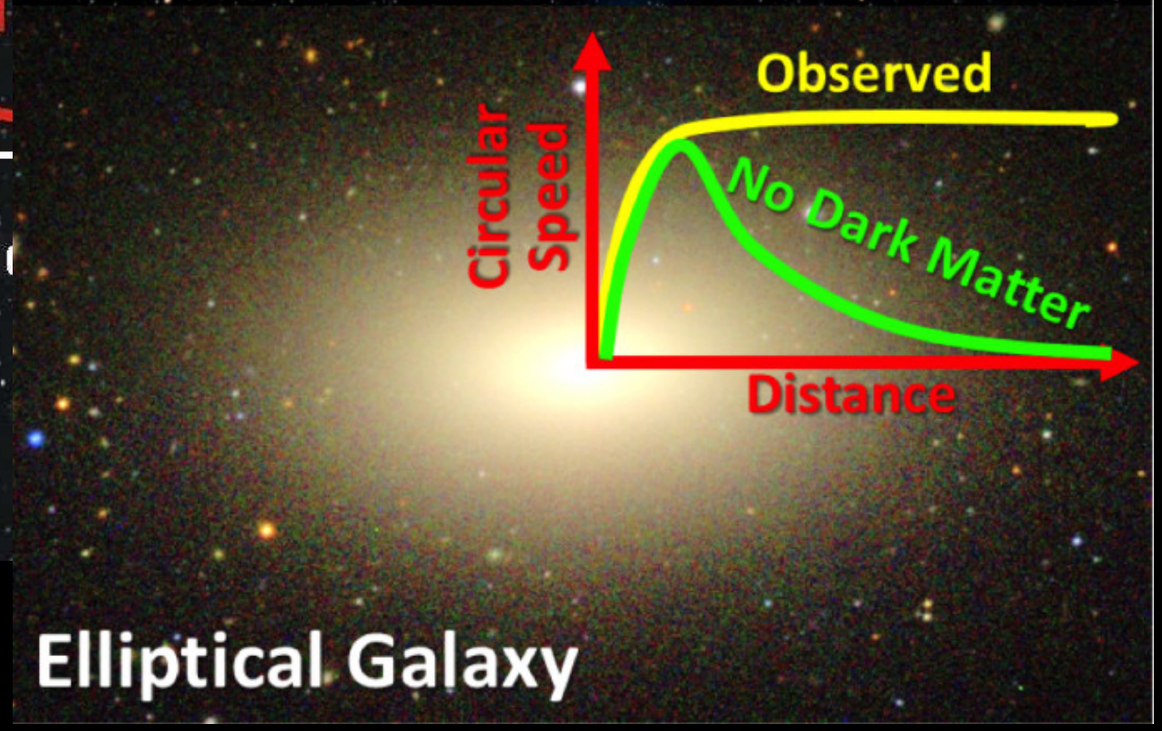
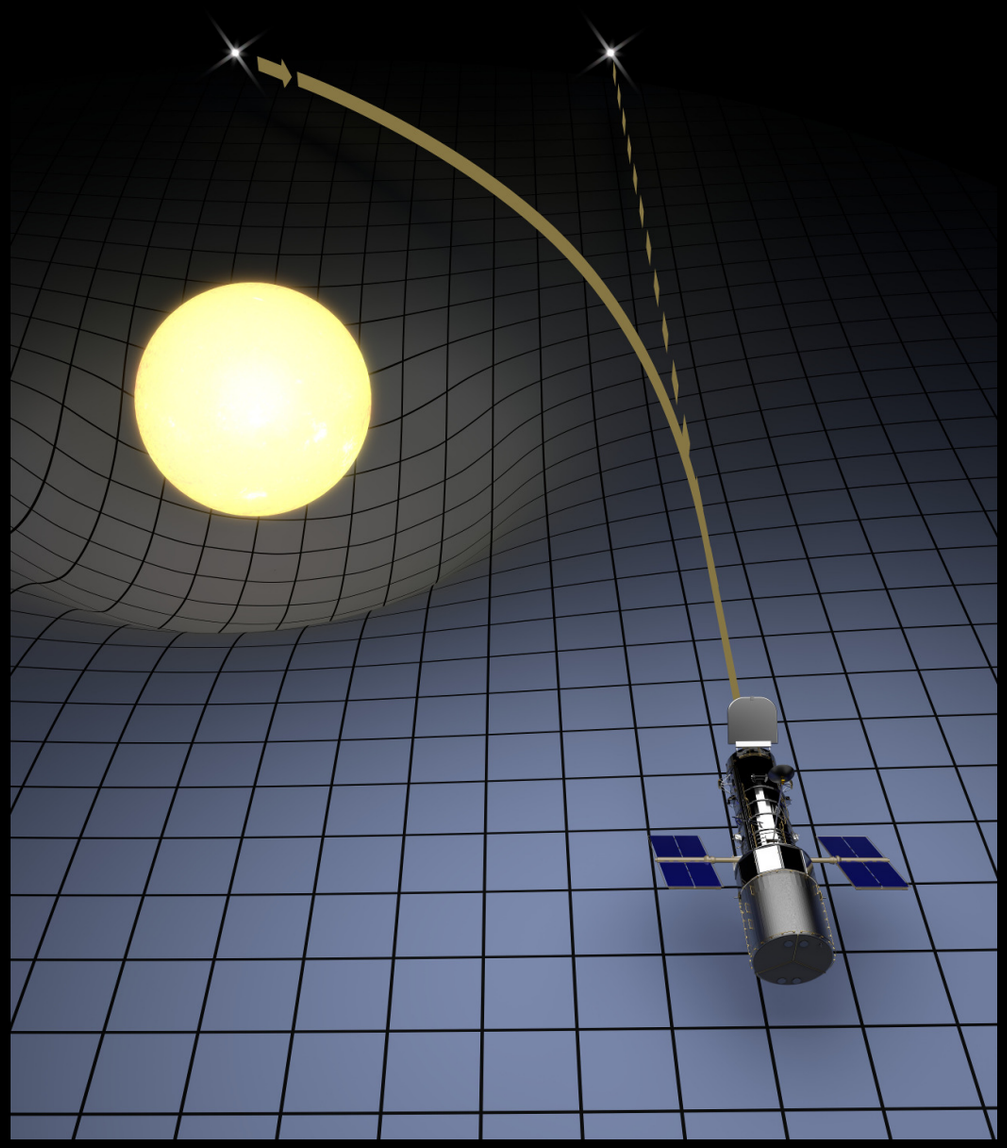


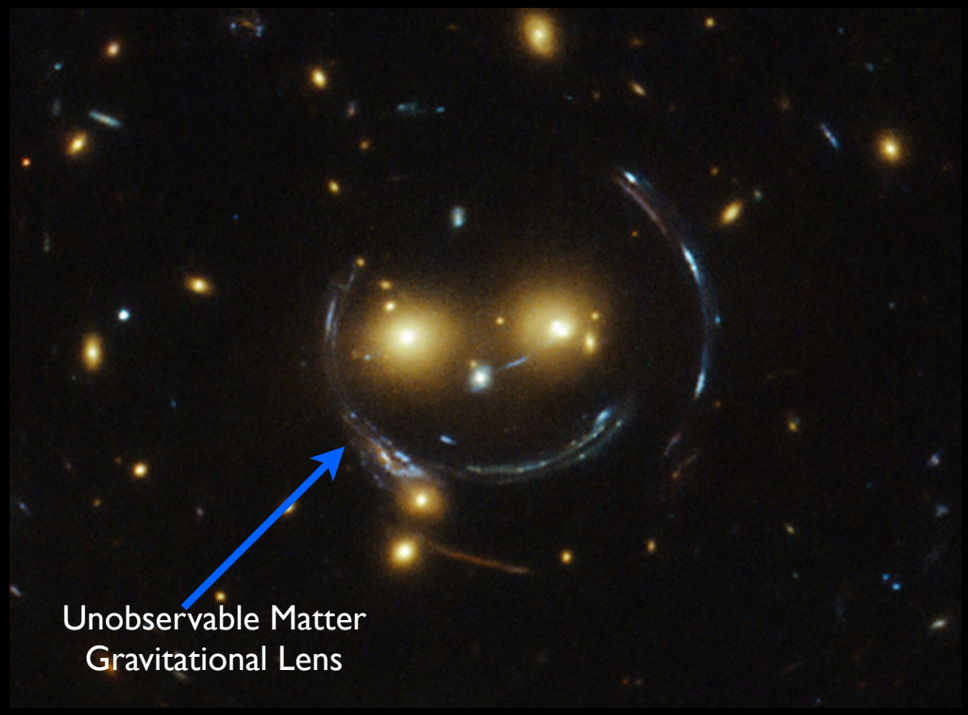




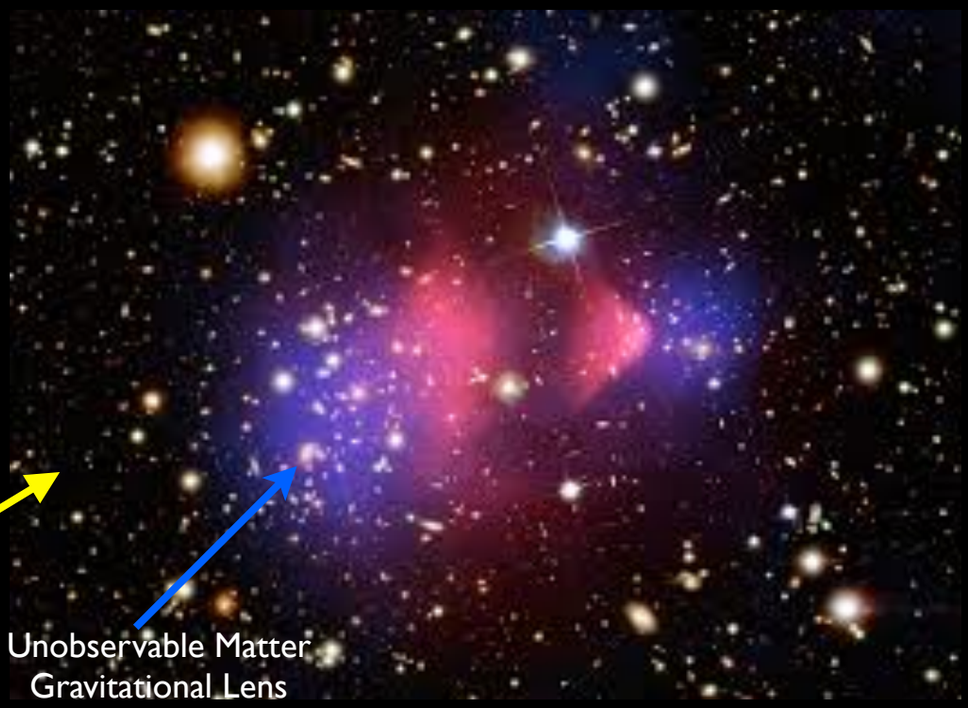
Much more evidence

Gravitational lensing - light from distant objects bent by unobserved matter





Bullet Cluster

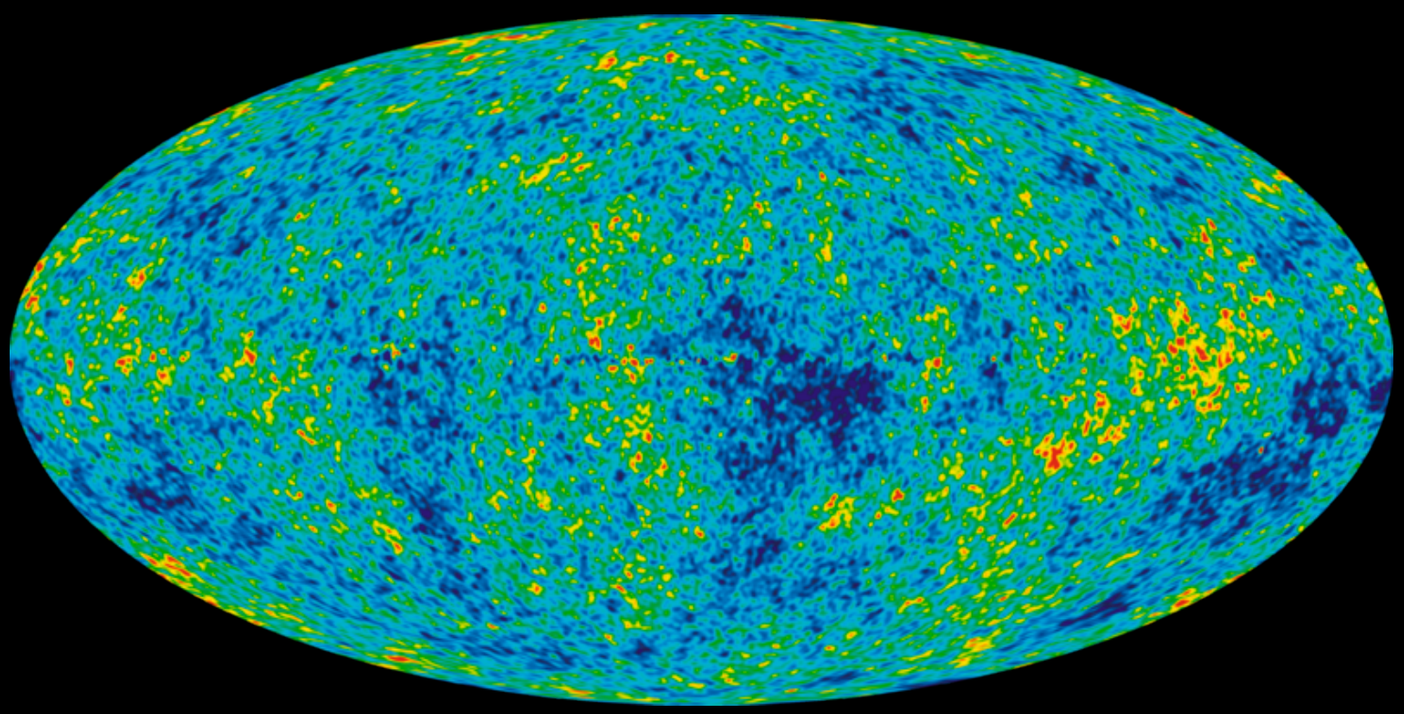


Studies of X-ray gas in galaxy clusters

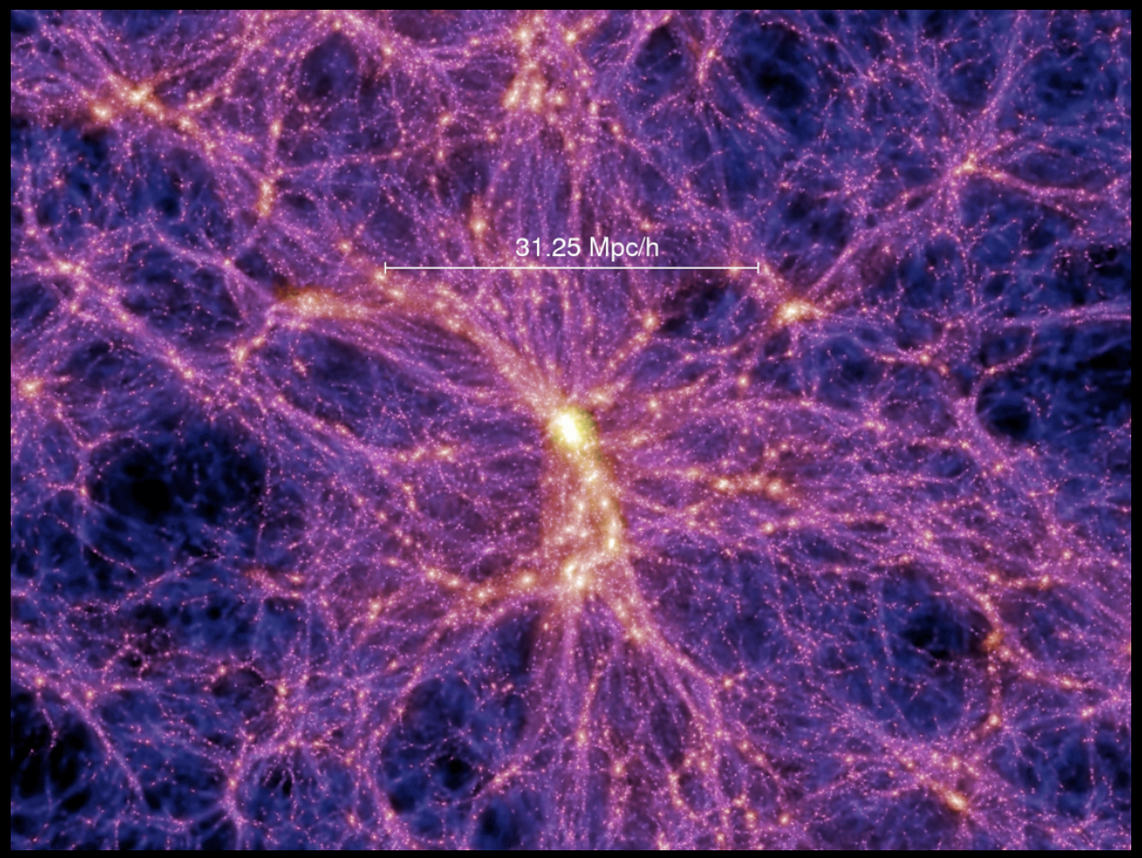
Studies of Dwarf galaxies

N-body computer simulations

Cosmic microwave background maps



CMB map from Planck
showing over-dense and under-dense regions



N-body simulations showing clumps of DM

Well What is DM?

Well What is DM?

Simple Answer?

We don't know!!!!

Well What is DM?

Simple Answer?

We don't know!!!!

But we think we do

We have some ideas

Simple definition….

Type of unobservable matter that interacts very weakly with ordinary matter

Does not emit nor does it absorb light

Only interacts through gravity

Is responsible for structure formation

Cosmic Glue

So how is DM responsible for structure formation?

DM mostly interacts gravitationally

It clumps up and forms “wells”

Ordinary matter falls in these “wells”

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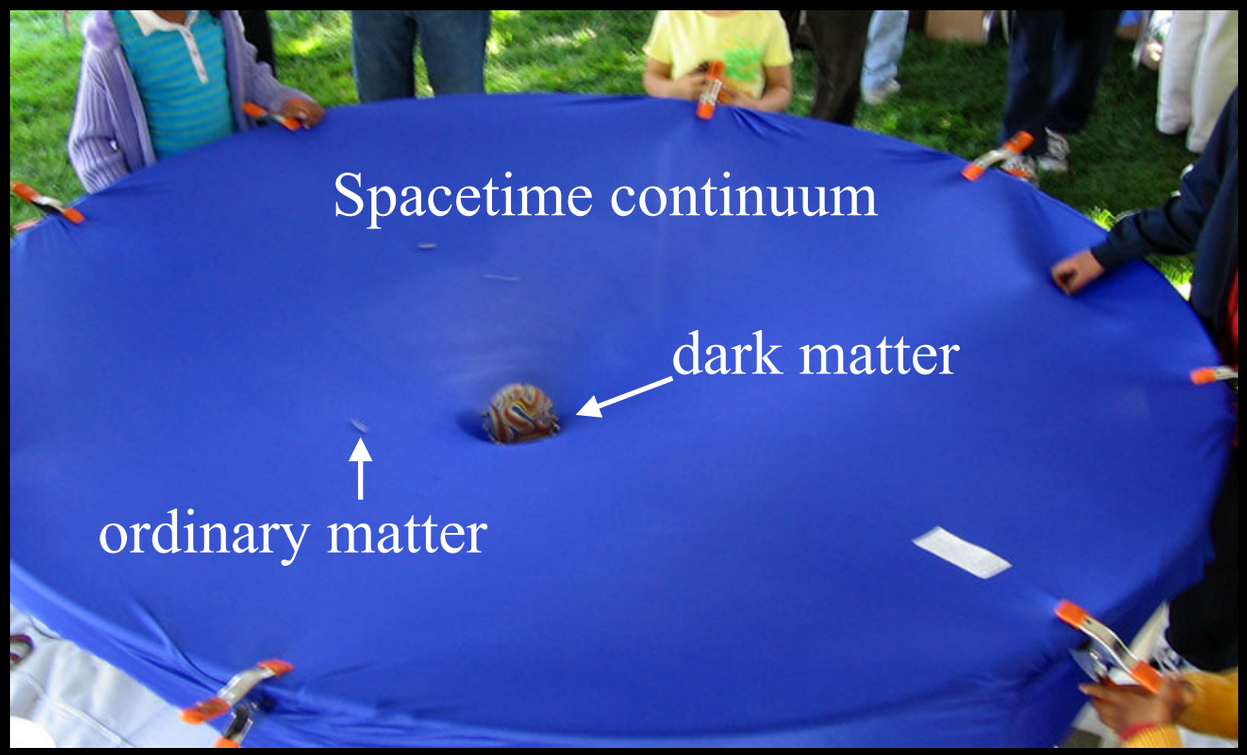

Rubber sheet with bowling ball and marbles

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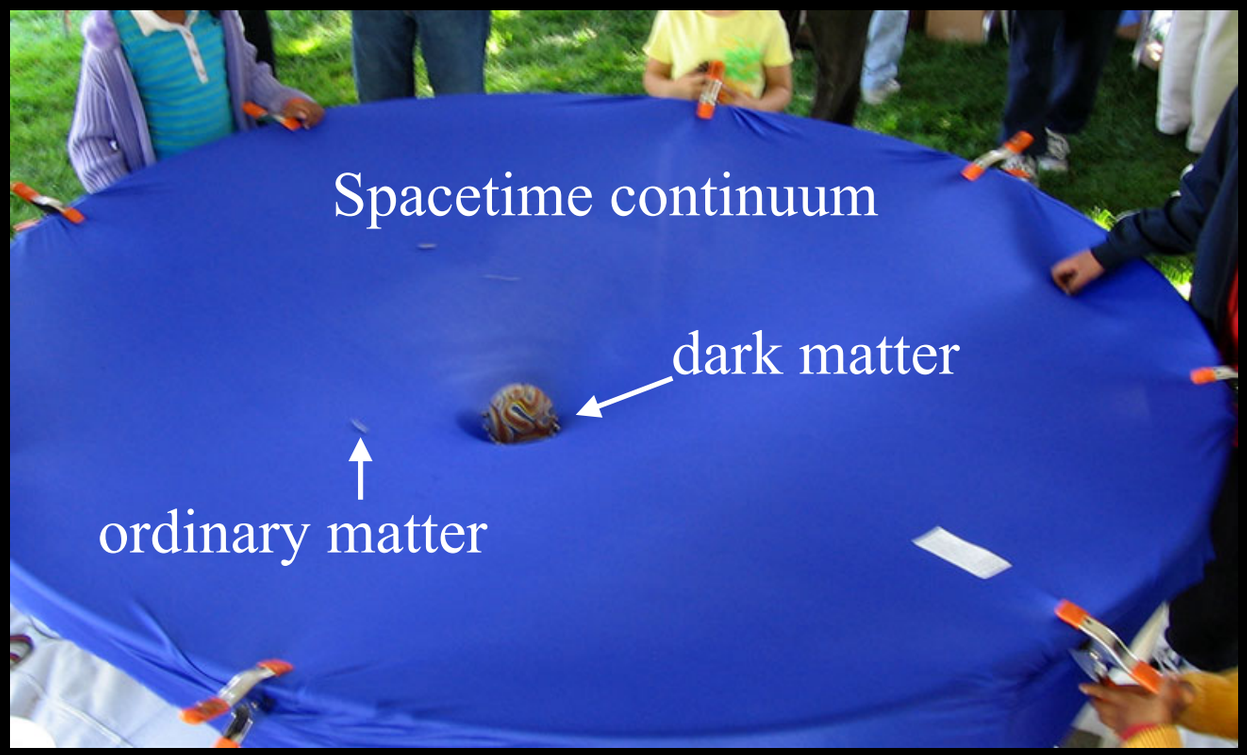

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Well known example

So how is DM responsible for structure formation?

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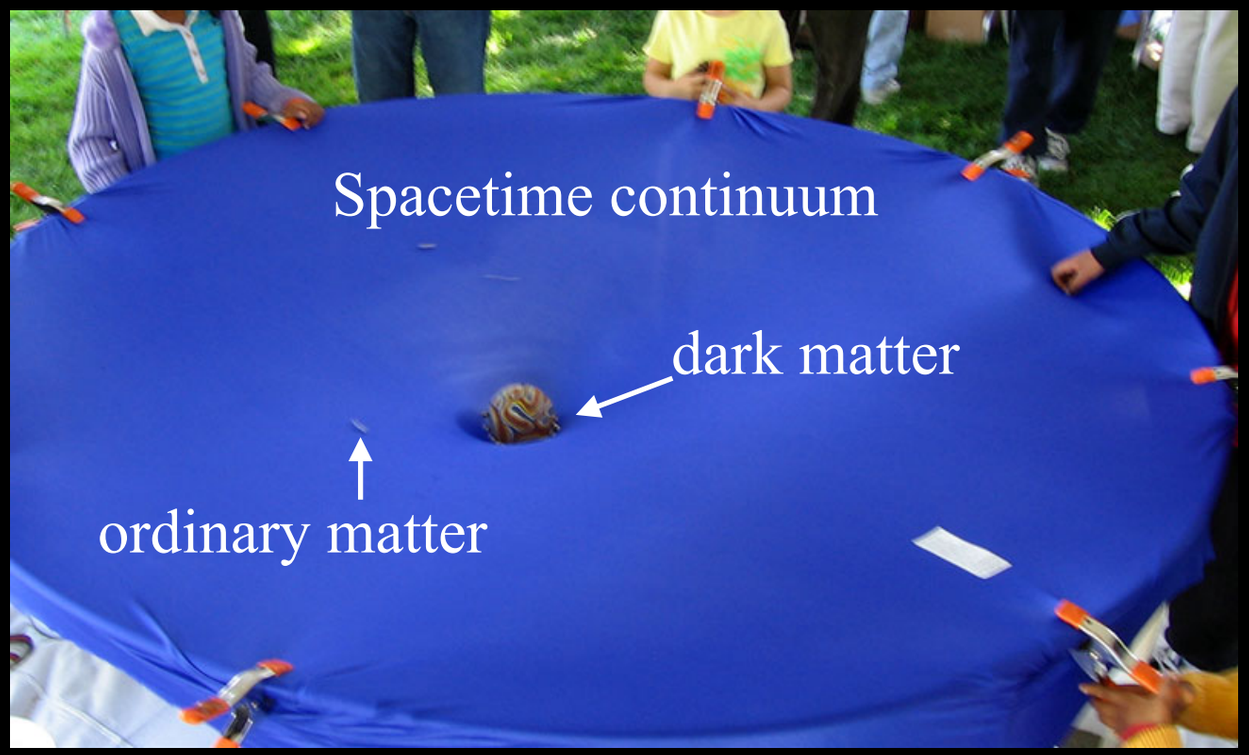

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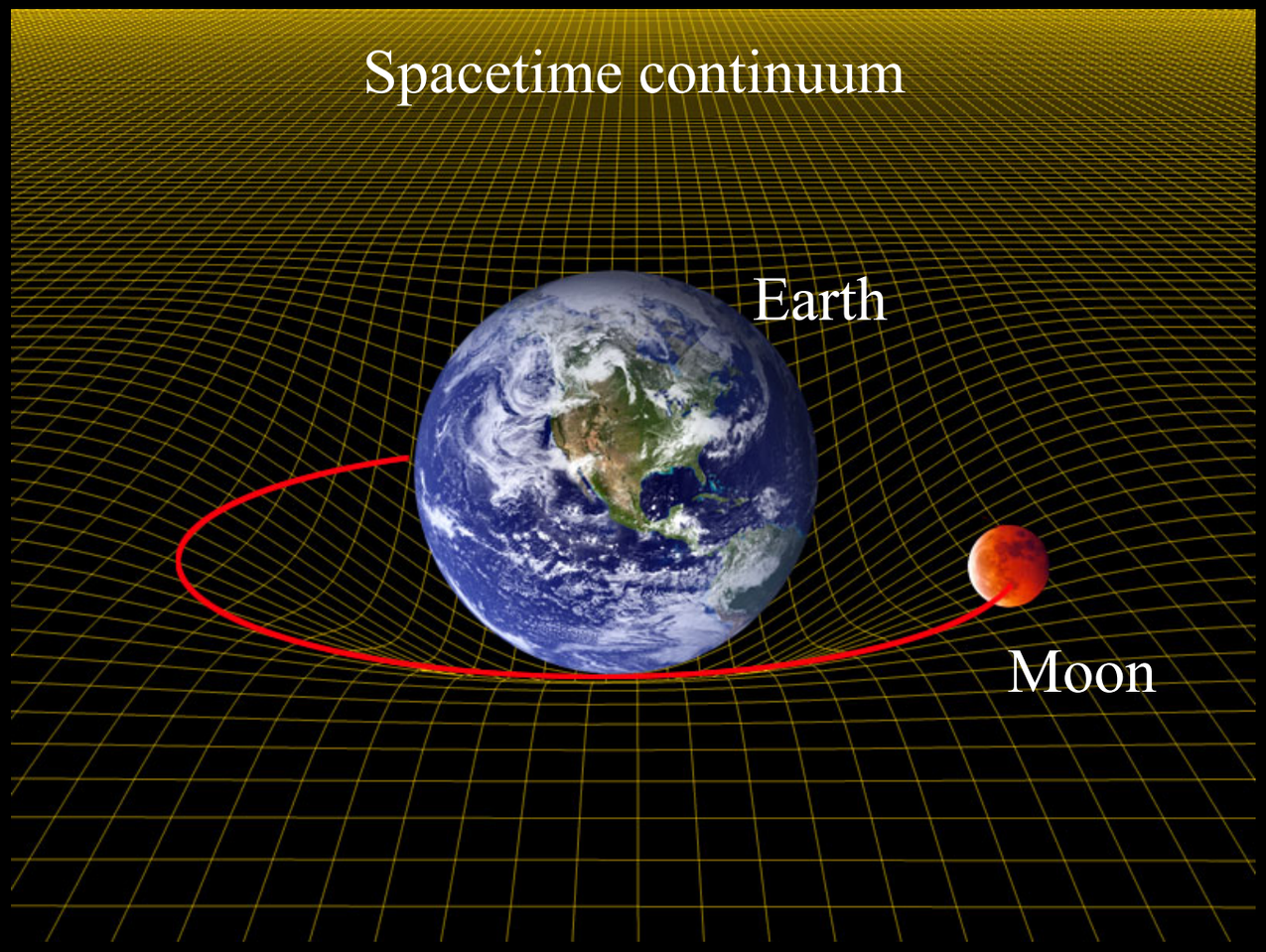

Dark Matter

Astrophysics and Cosmology

Particle Physics

Very well motivated at both scales

DM properties?

From Astrophysics and Cosmology

DM most likely elementary particle

DM properties?

From Astrophysics and Cosmology

DM most likely elementary particle

It must be cold - traveling very slow

DM properties?

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It must be cold - traveling very slow

must be stable and interact very weakly

Most favored DM candidate…

DM properties?

From Astrophysics and Cosmology

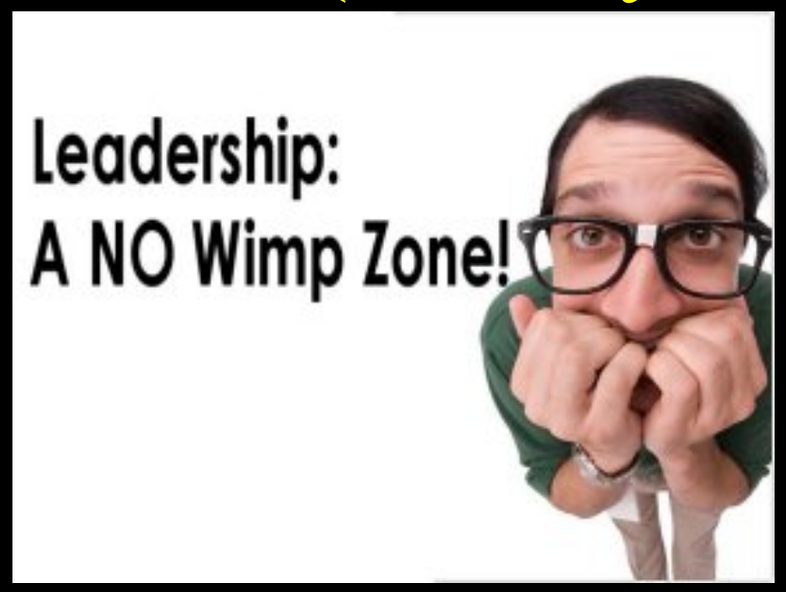
DM most likely elementary particle

It must be cold - traveling very slow

must be stable and interact very weakly

Most favored DM candidate…

WIMPs (weakly interacting massive particles)



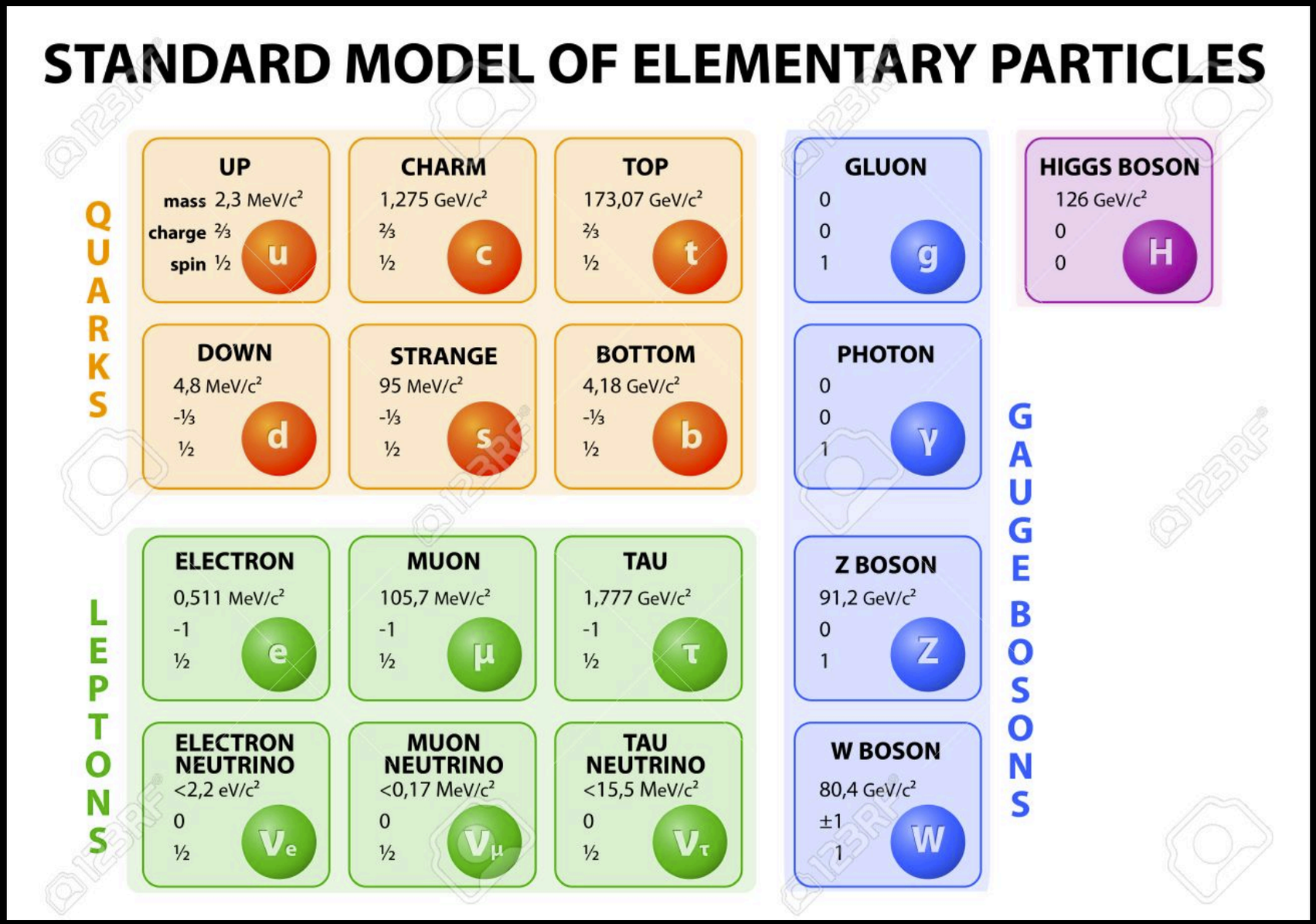
Now that we think we know what DM might be….

Where do we start our investigation?

How about we take a look at the smallest scales

Lets digress for a minute…

Start at the microscopic scale



Maybe SM can help?

Neutrinos seem to fit the bill

Unfortunately they don’t

Neutrinos in the early Universe travel at the speed of light

We say they are hot and therefore cannot form structure like we see it today

If neutrinos were DM, we wouldn’t exist today

Solution?

Look for elementary particles beyond the SM

Many theories been considered

Super Symmetry

Universal Extra Dimensions

Left-Right Models

Simplified DM models

etc etc ….

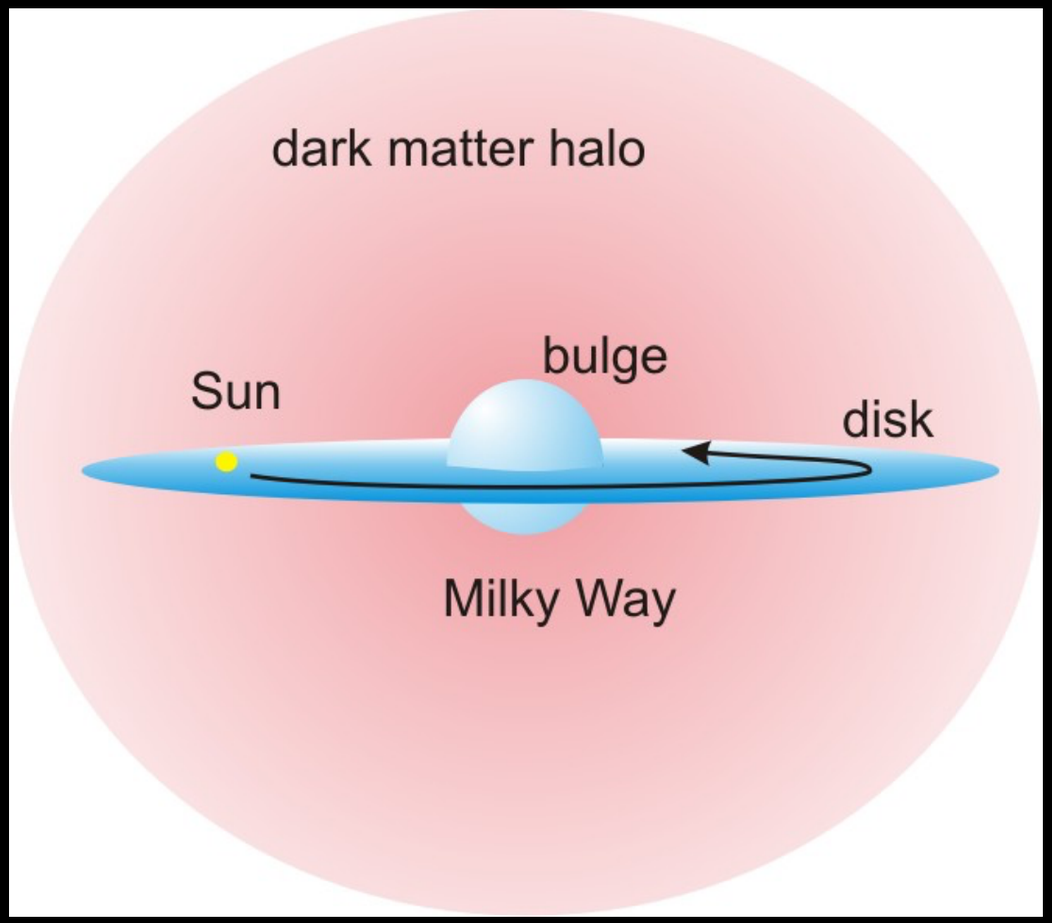
How to test these theories?

…and find these potential DM particles

Three detection strategies

1. Indirect Detection

DM halos around galaxies and galaxy clusters



Three detection strategies

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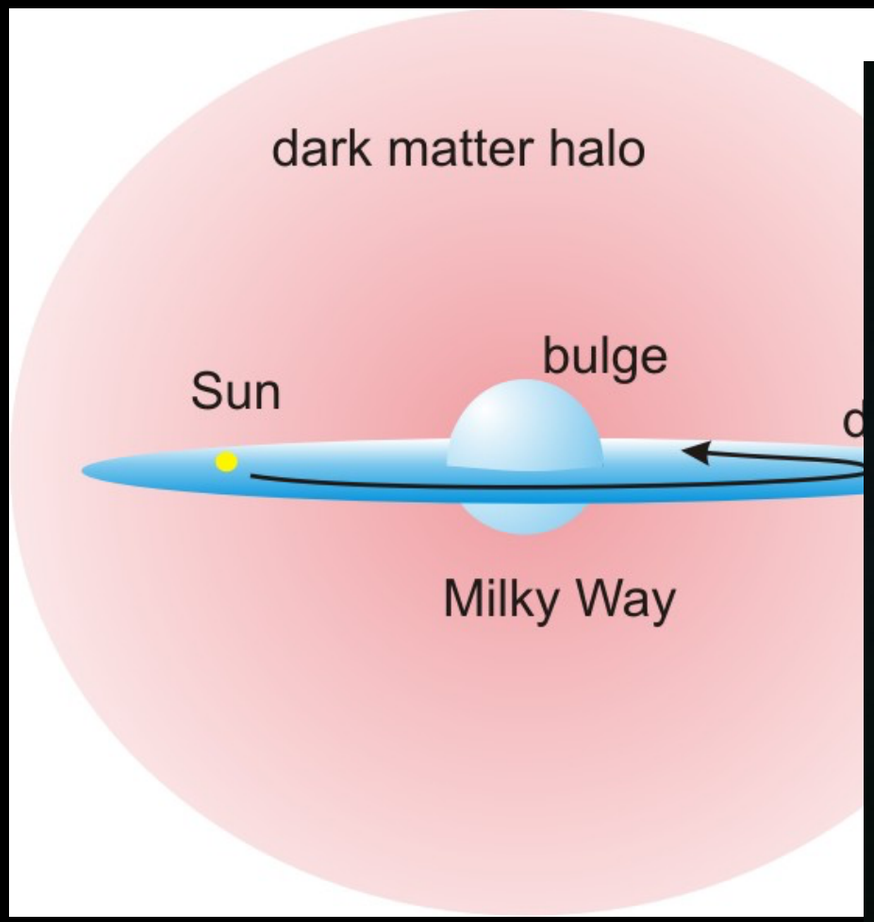

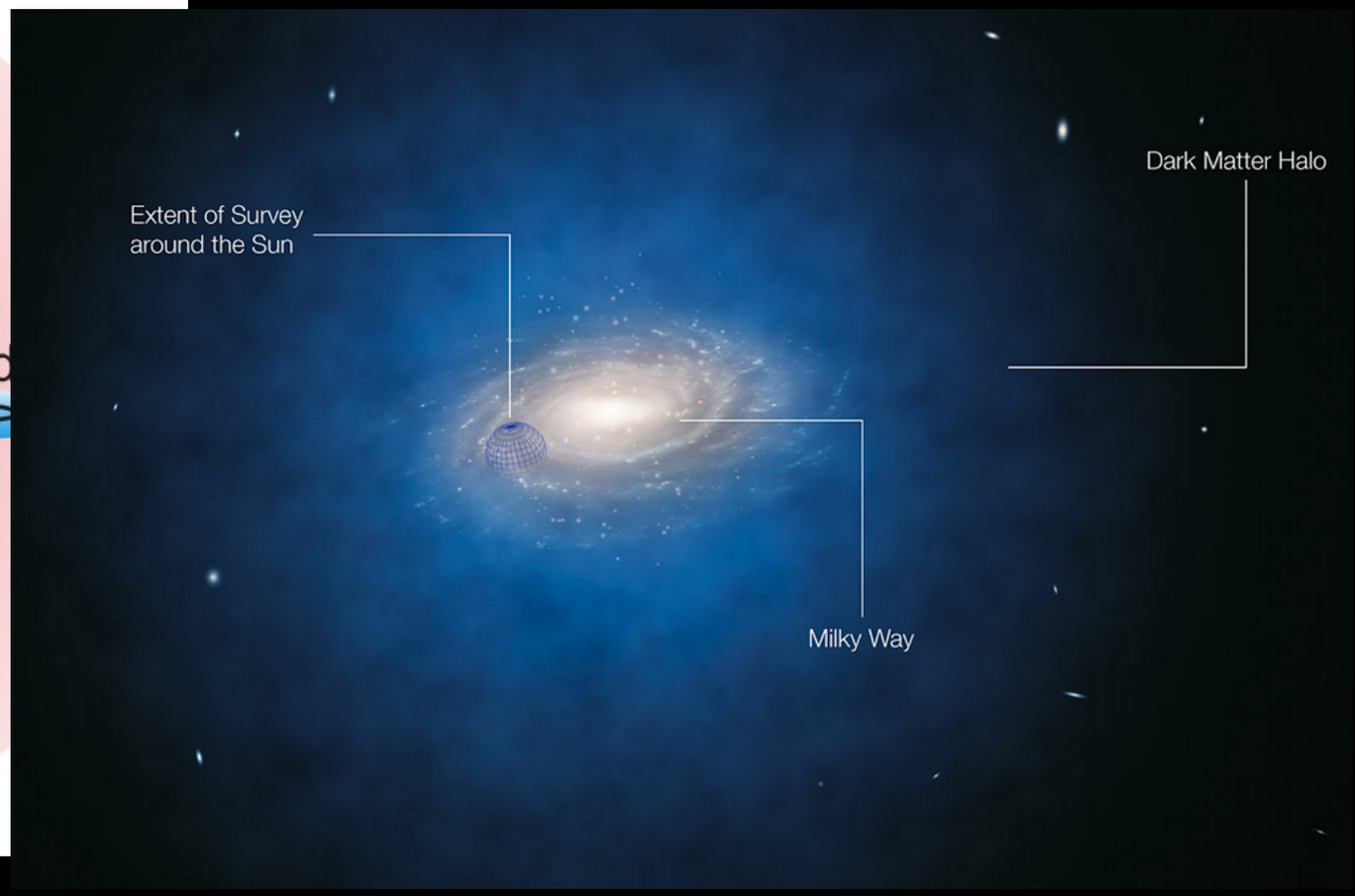

Three detection strategies

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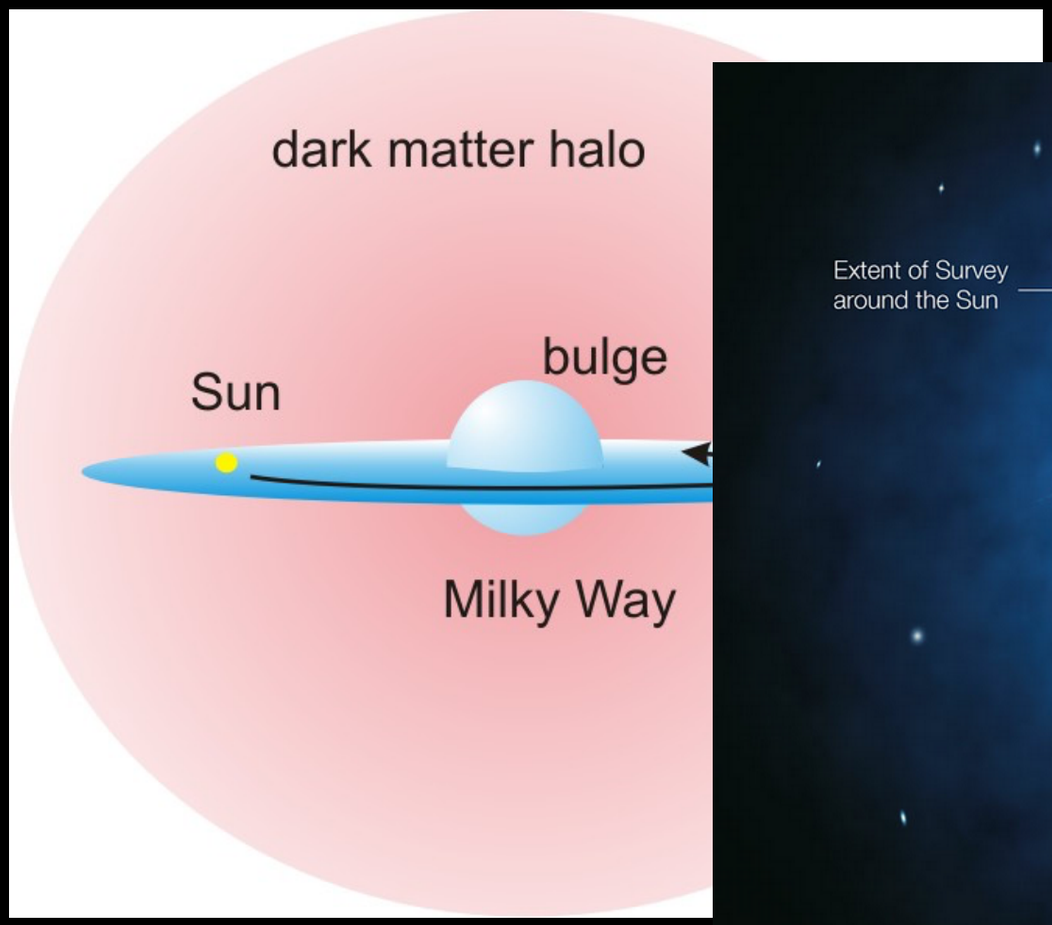
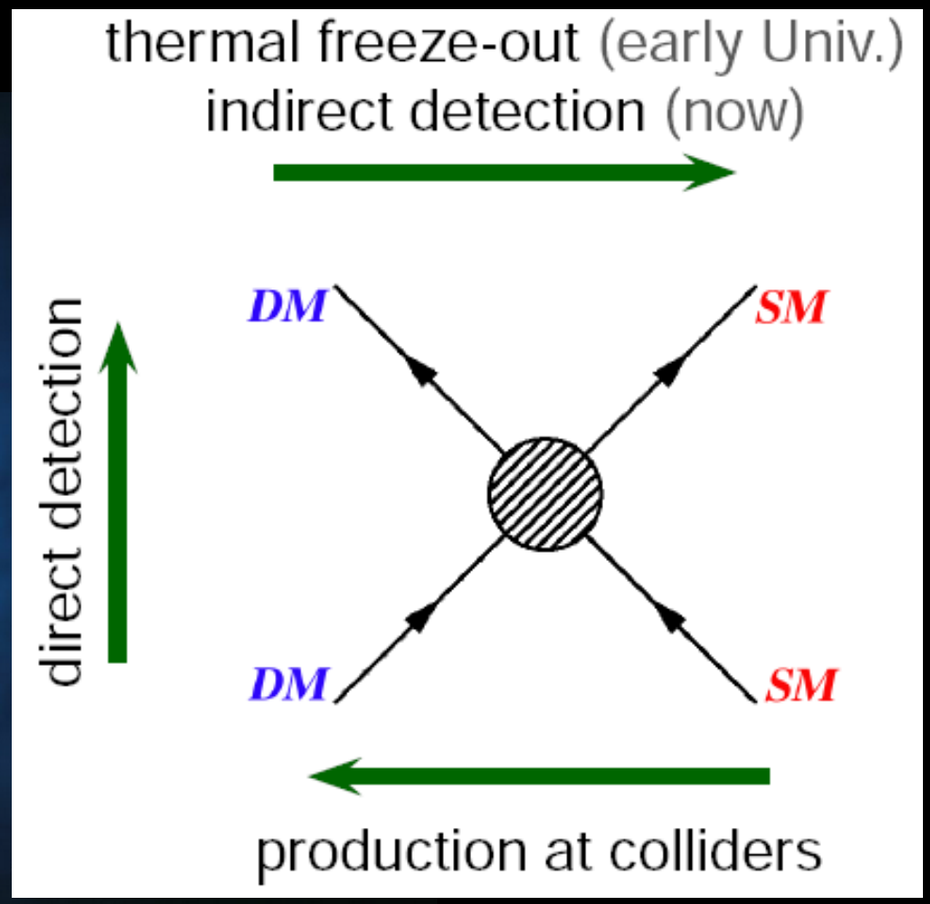
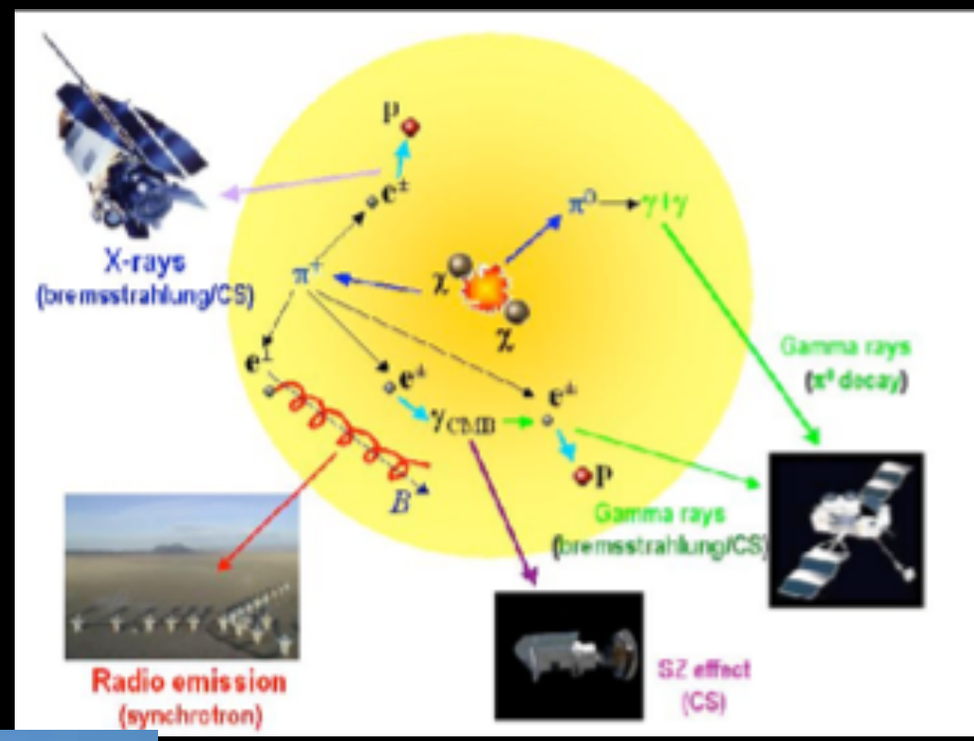


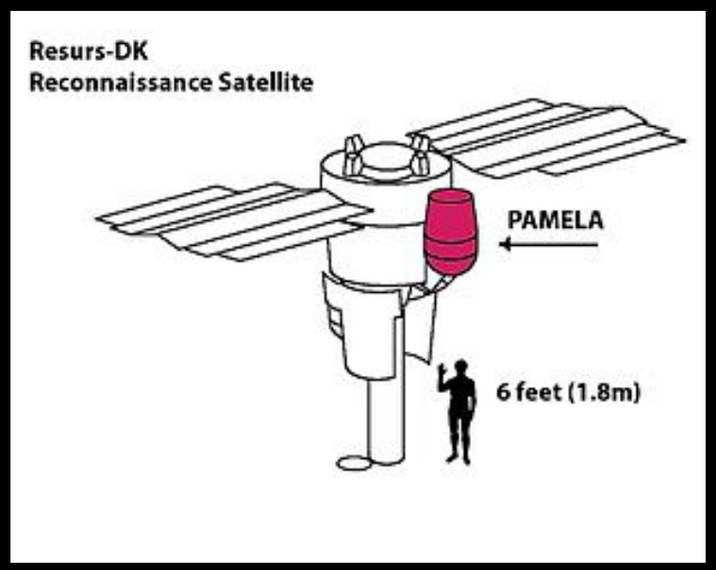


Three detection strategies

1. Indirect Detection

Some Current experiments





Pamela telescope

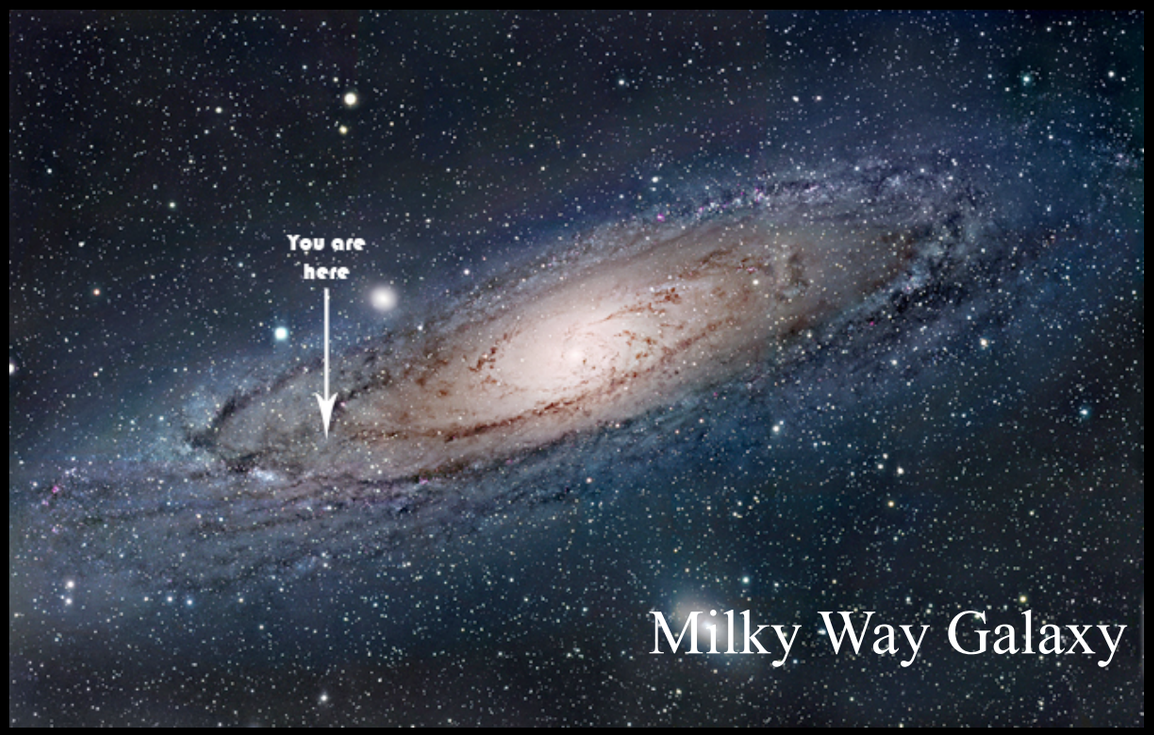
H.E.S.S

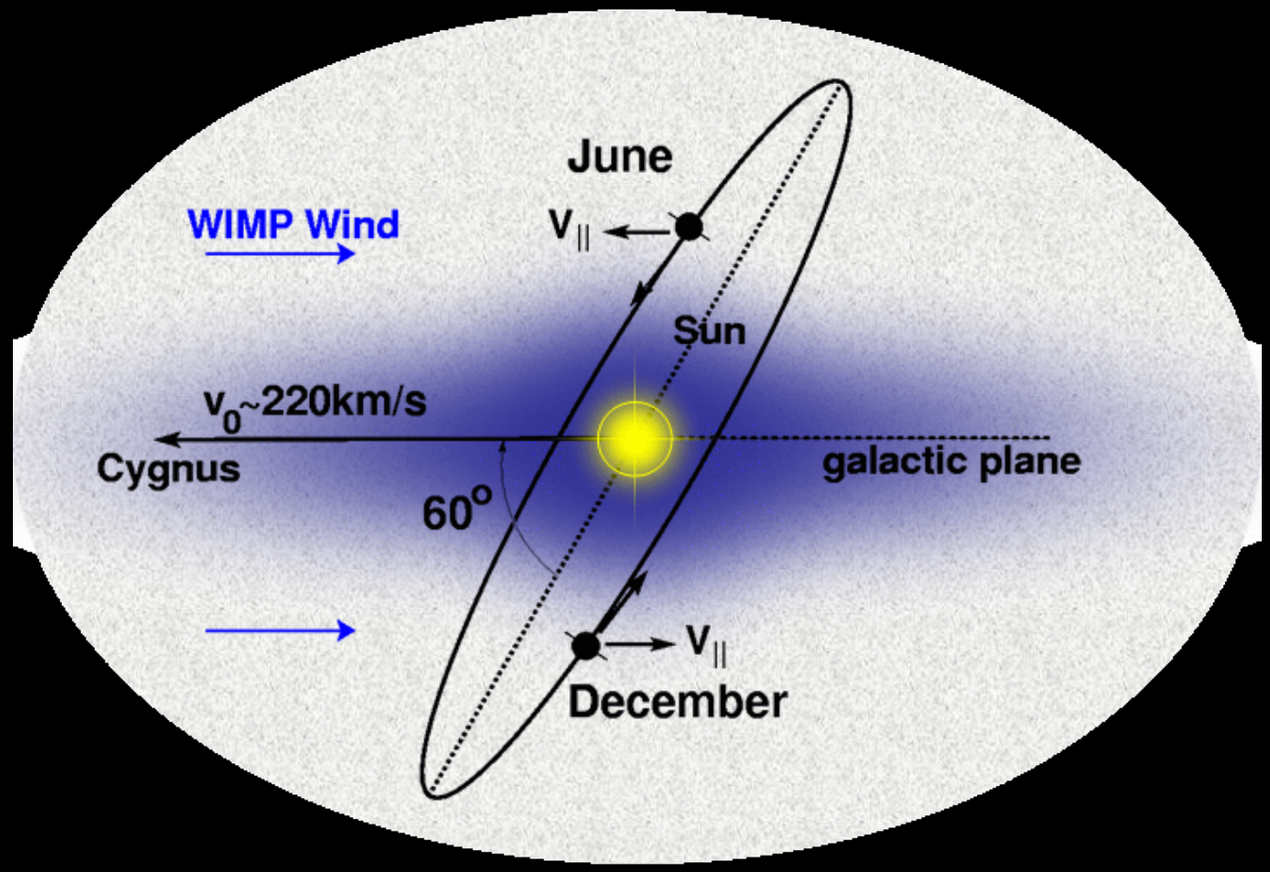
…many others

Three detection strategies

2. Direct Detection

Consider the following:





As sun moves around galactic plane

Earth gets hit by DM wind

Three detection strategies

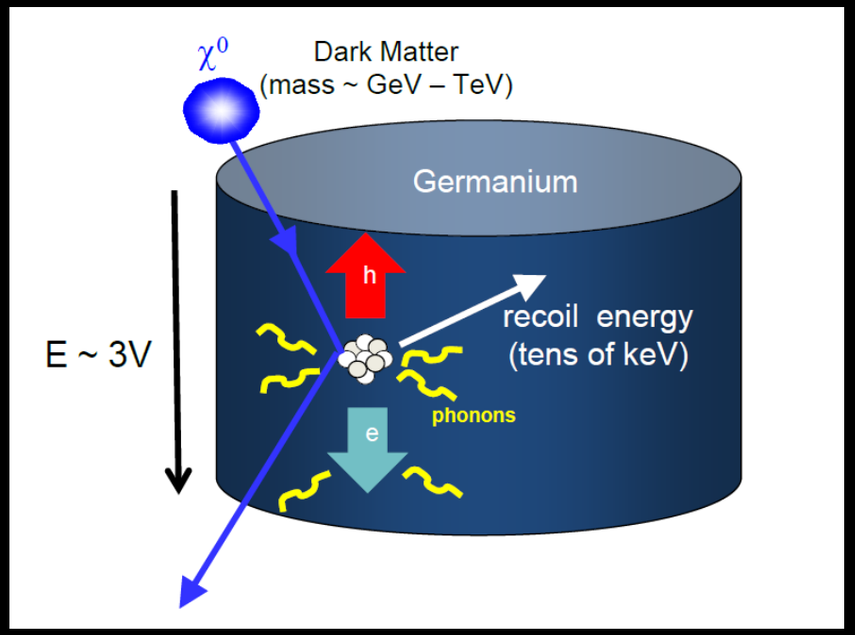
2. Direct Detection

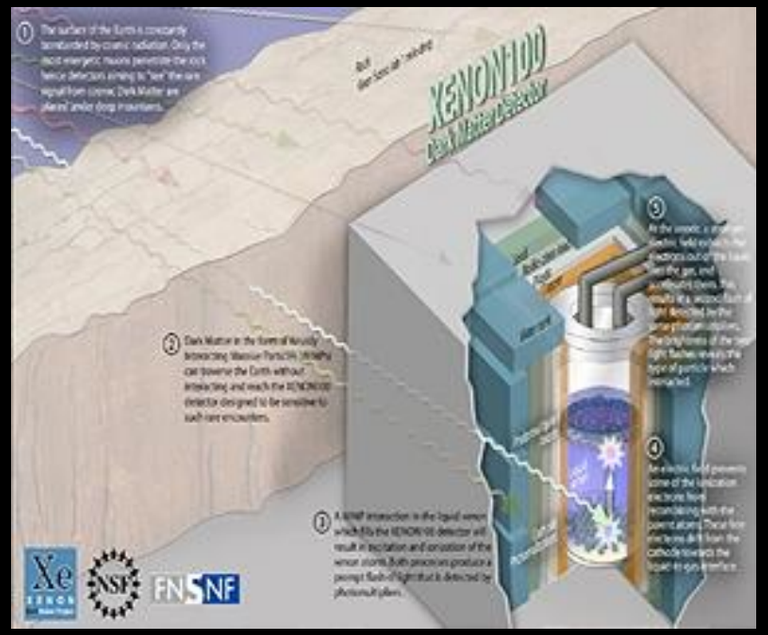
DM moves through Earth

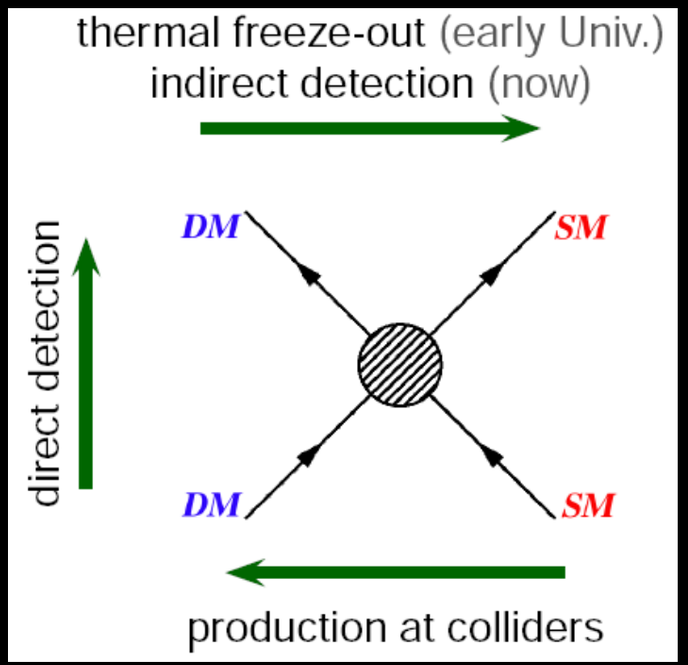
Put experiments on earth to try and detect DM

Some well known experiments

Xenon 100 CDMS DAMA CoGeNT LUX DarkSide



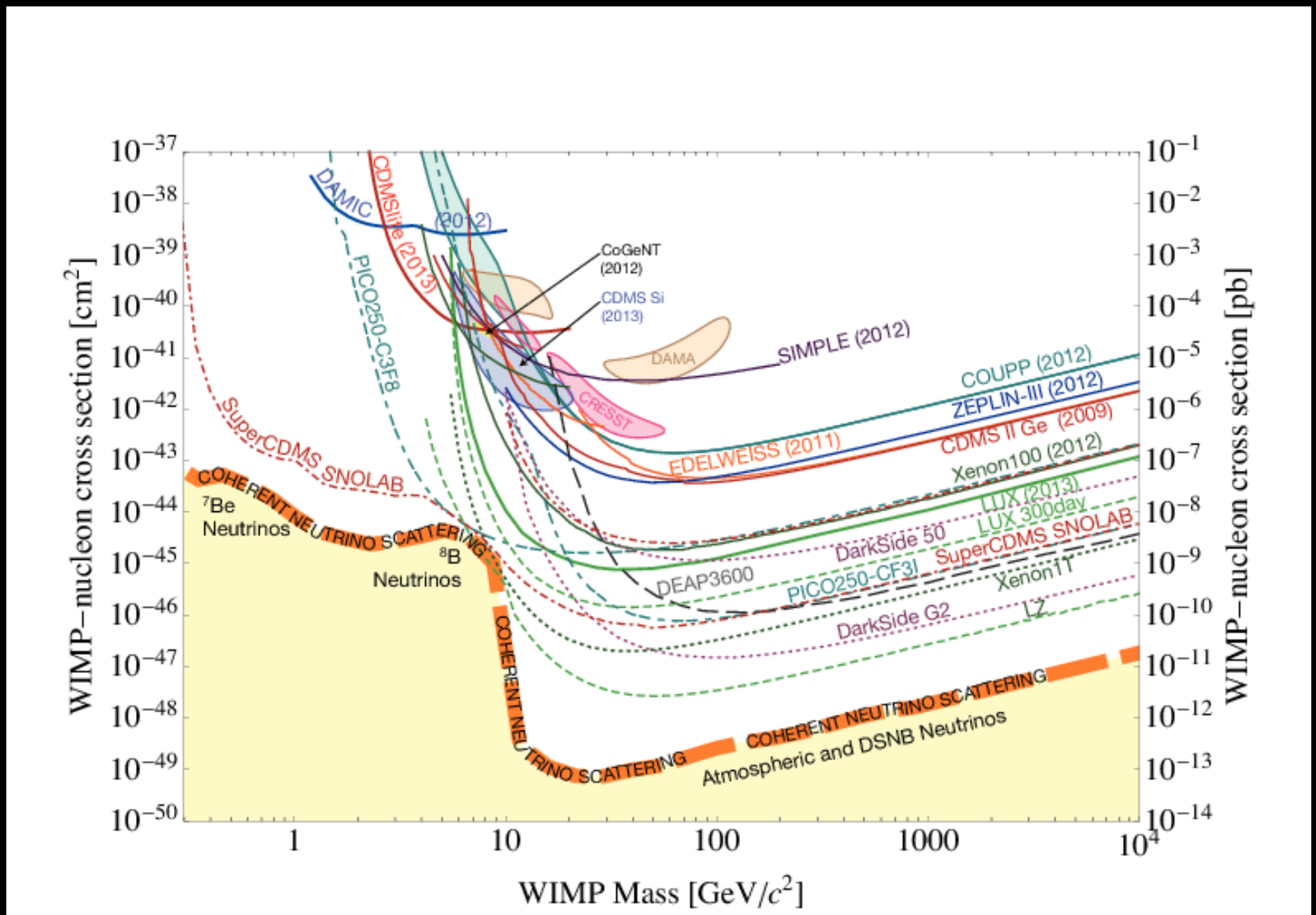




Three detection strategies

2. Direct Detection

Example of how DM experiments report results



For this talk, don't focus too much on this

Three detection strategies

3. Production at particles colliders

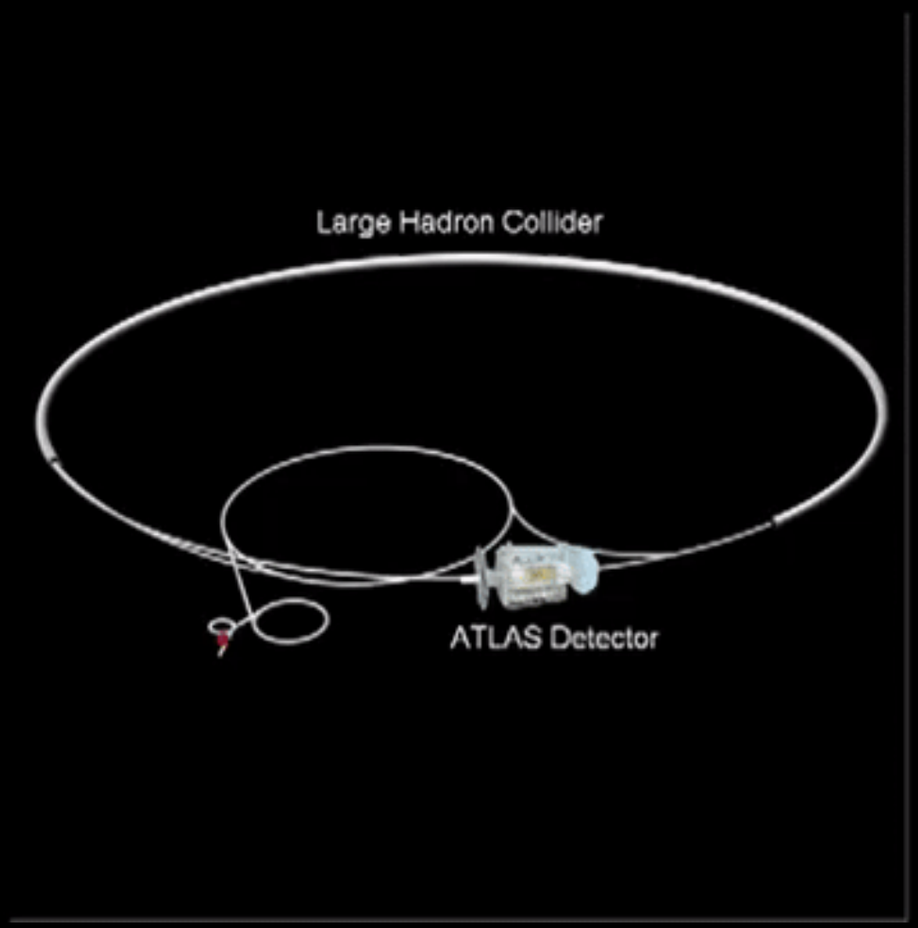
Particles colliders are controlled environment

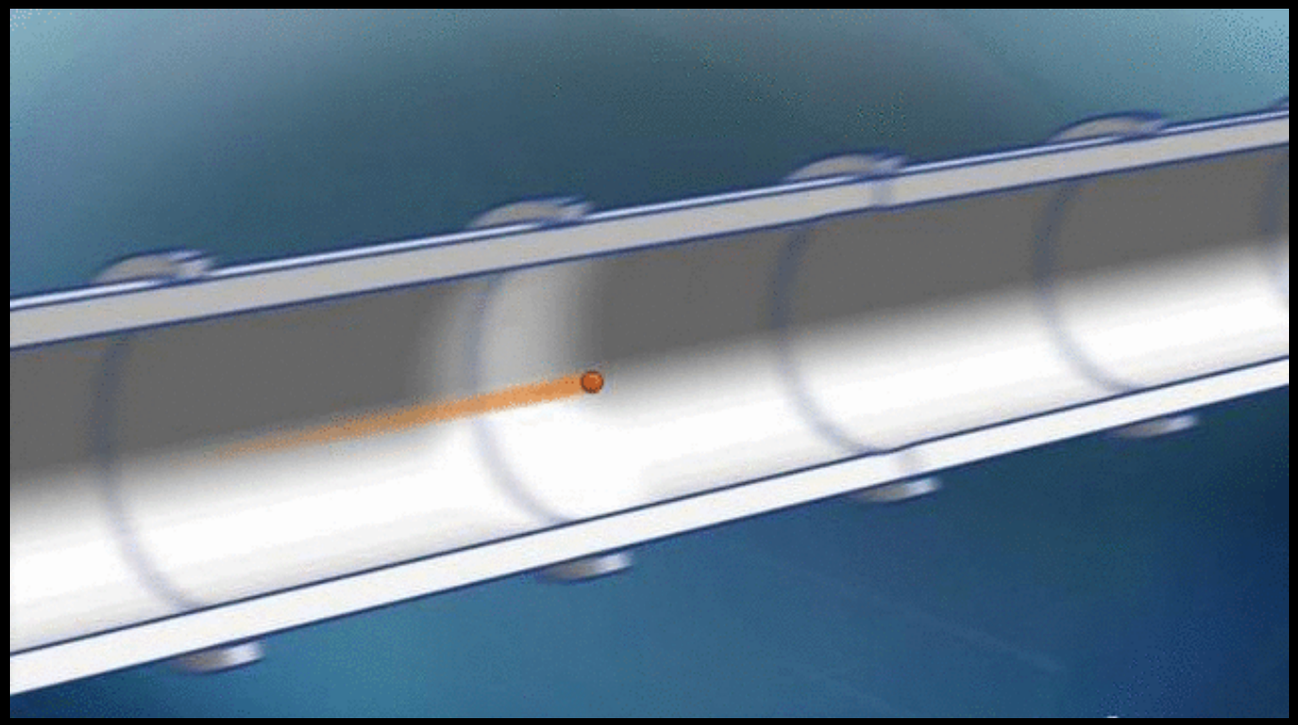
Most Well known collider…

Collides Protons at high energies

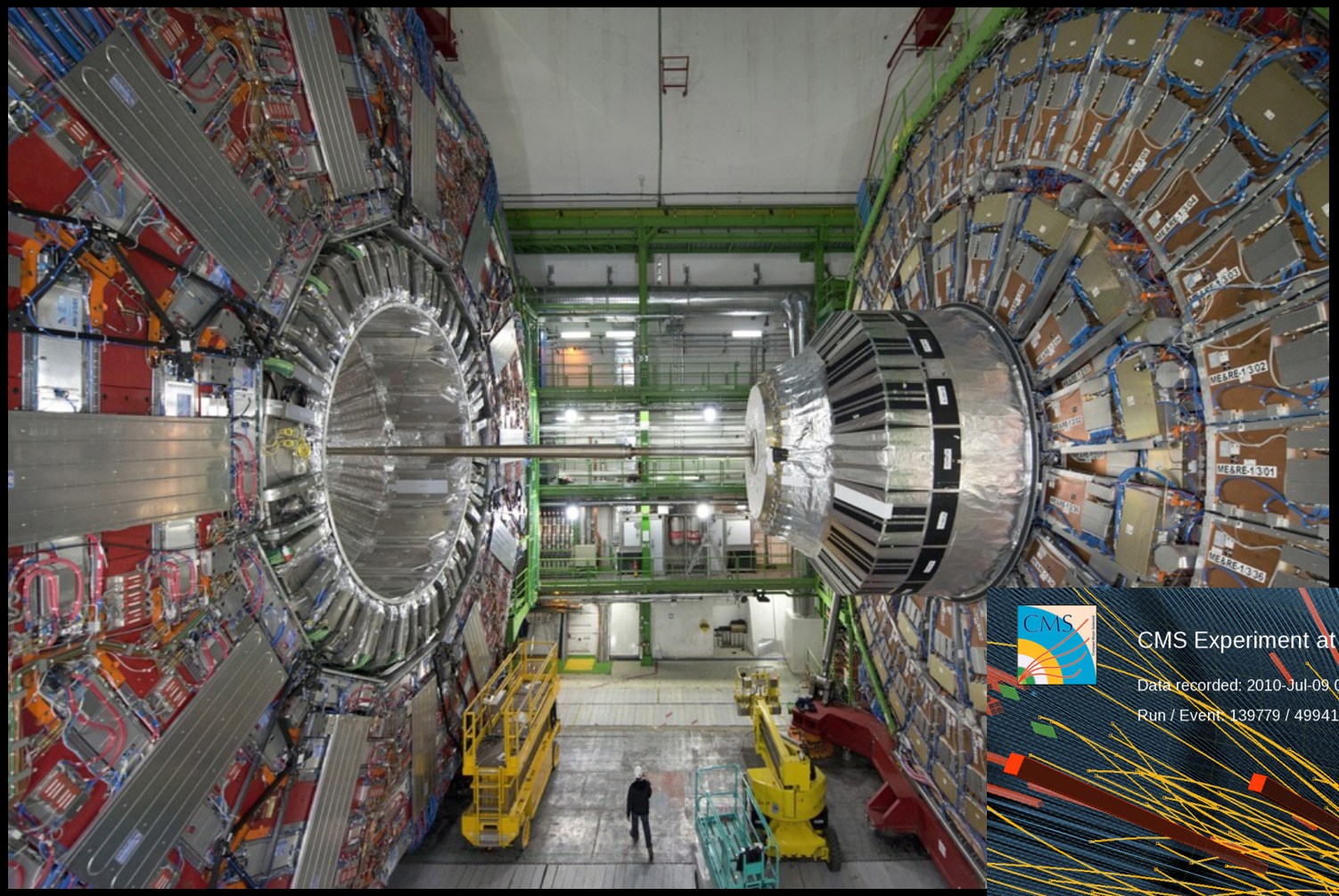
Three detection strategies

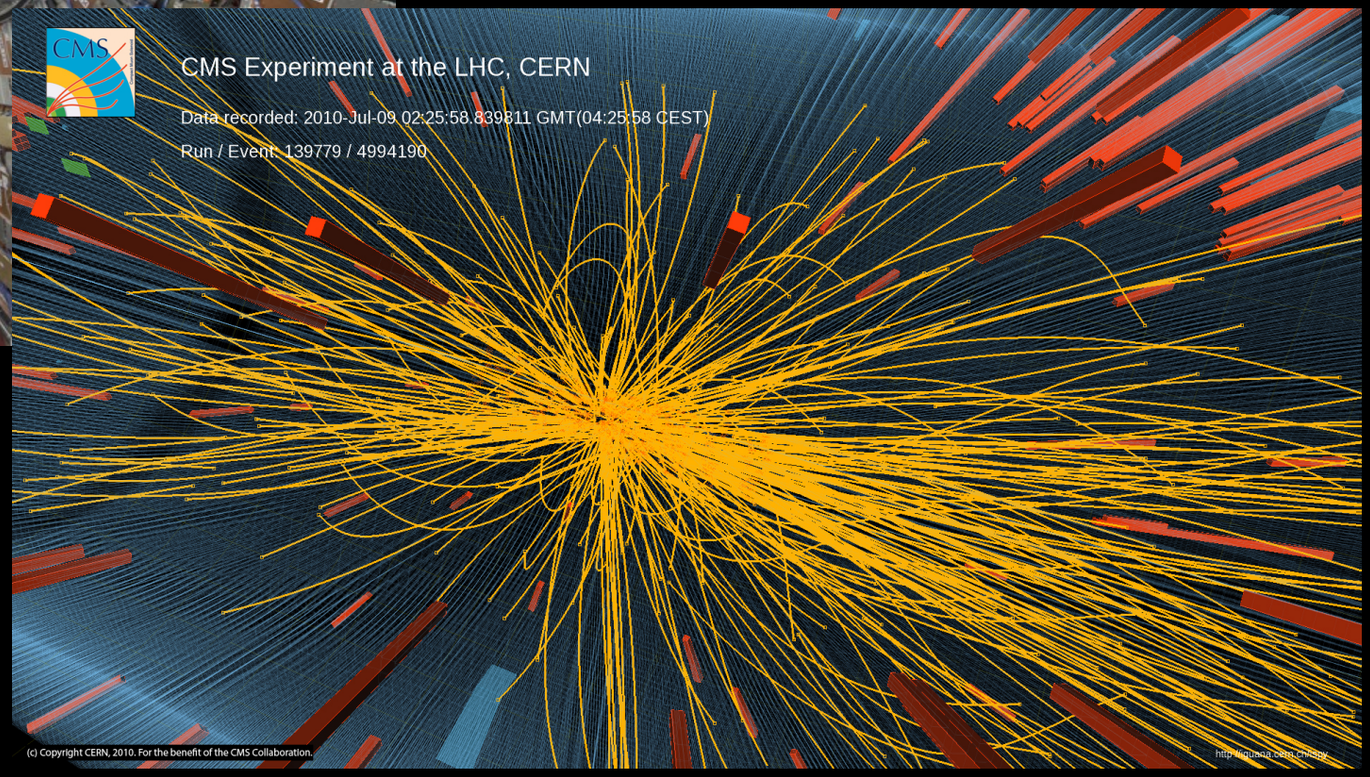
3. Production at particles colliders





3. Production at particles colliders





At high enough collision energies, we could produce DM at colliders

So far we have not seen anything yet

There are other types of DM

Non-elementary particle dark matter

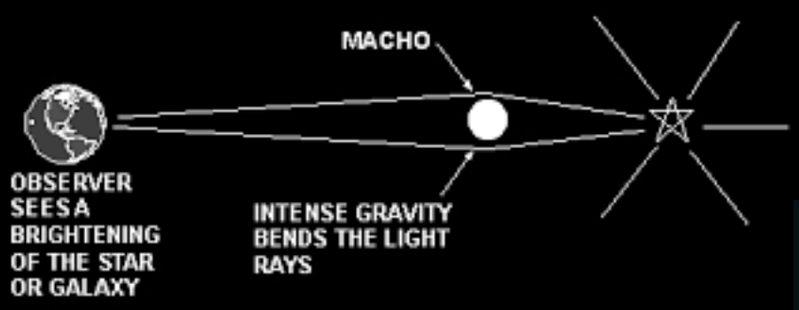
MACHOs

Macro Dark Matter

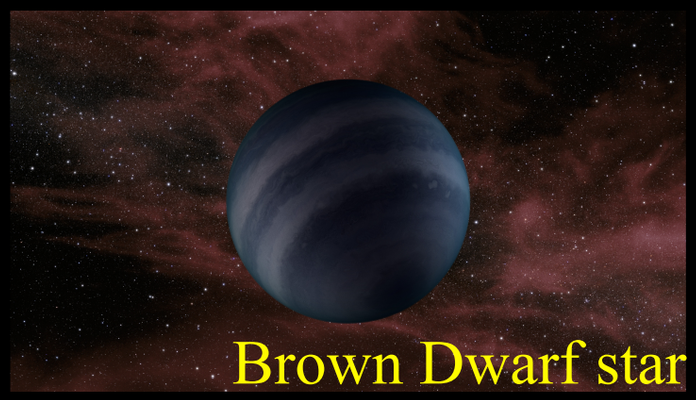
Black Holes

Brown dwarf stars

Dark Neutron Stars



Gravitational Lensing--how MACHOs focus light



Brown Dwarf star

Black Holes

Neutron stars

Ok lets wrap up

Hope you are convinced of existence of DM

Now you are Dark Matter experts

Hope you are excited about future prospects of DM

Very exciting time to be in Astroparticle Physics