Dark Matter and Dark Sectors: Lecture 1

NELSON MANDELA UNIVERSITY

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Who am I?

My name is Dr. Gopolang Mohlabeng

2009: Undergrad, Physics - University of Pretoria

2010: Honours, NASSP - University of Cape Town

2017: PhD Physics - University of Kansas

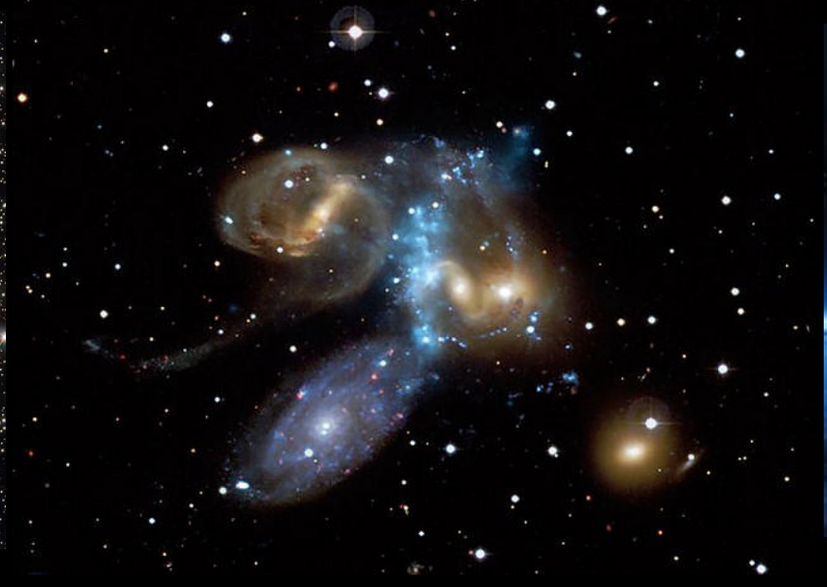
What I do: Postdoctoral Researcher at University of California, Irvine

September 2023: Assistant Professor at Simon Fraser University

Area of expertise: Dark matter phenomenology

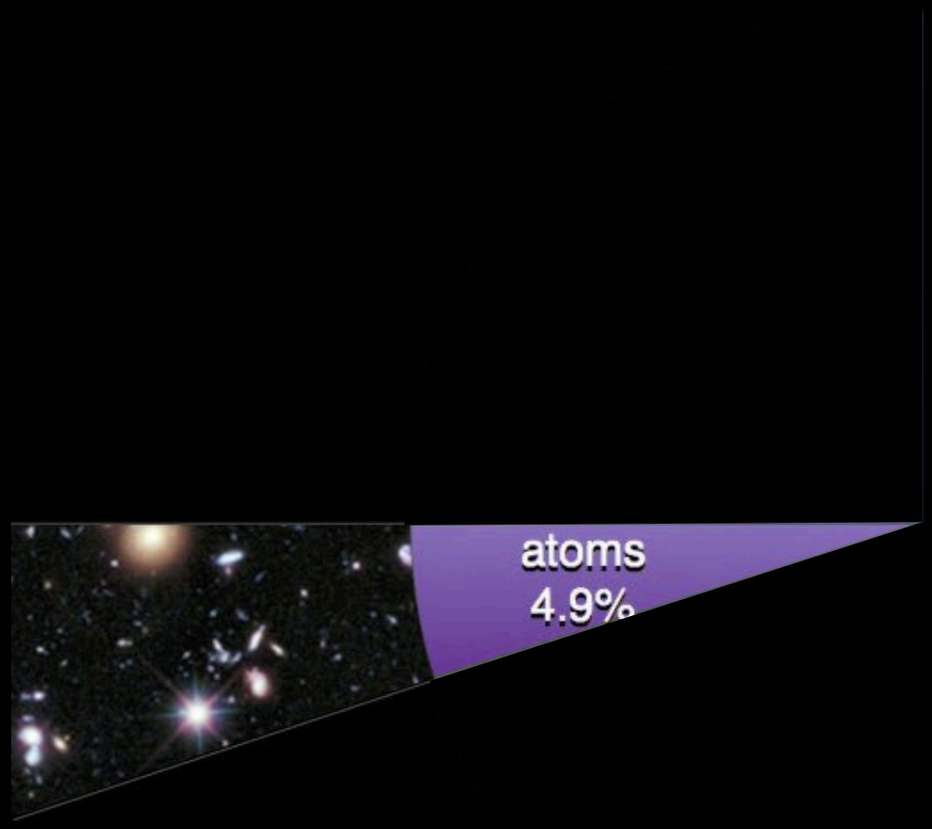
Build DM theories and compare them to data

Billions of Galaxies and Stars



Surely this is all the Universe is made of

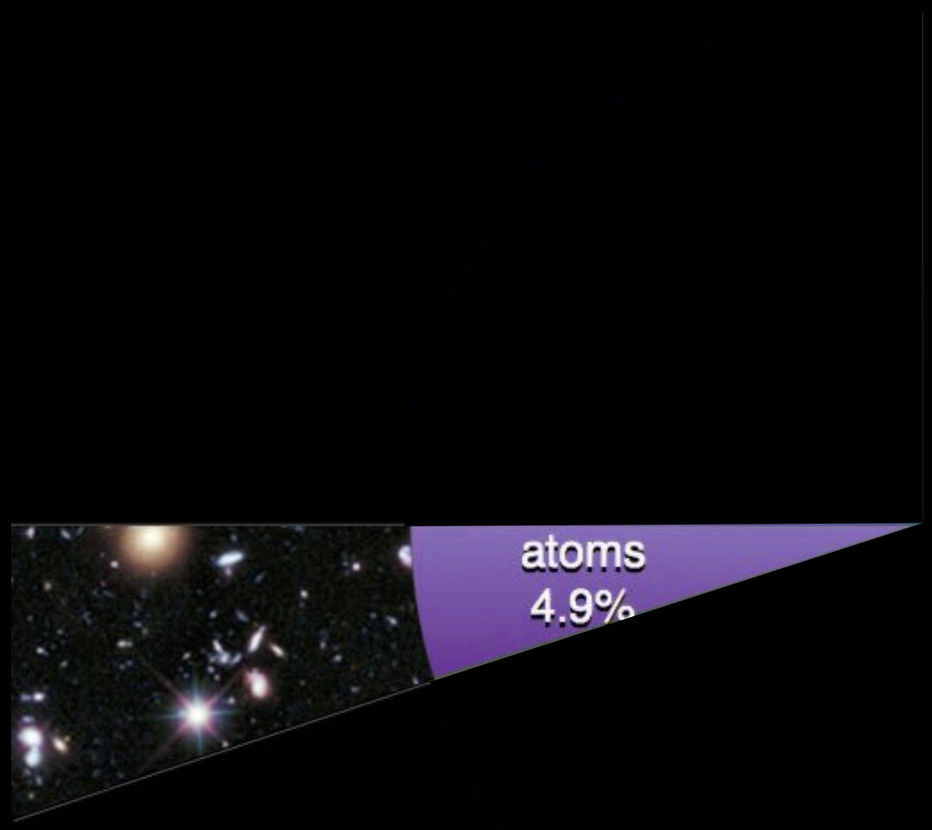
All of the visible stuff makes up only a very small component



We don’t know what all this other stuff is

It seems ~ 95% of our Universe is ‘Dark’

All of the visible stuff makes up only a very small component



~ 5% of our Universe is explained by **standard model of particle physics**

Standard Model of Particle Physics

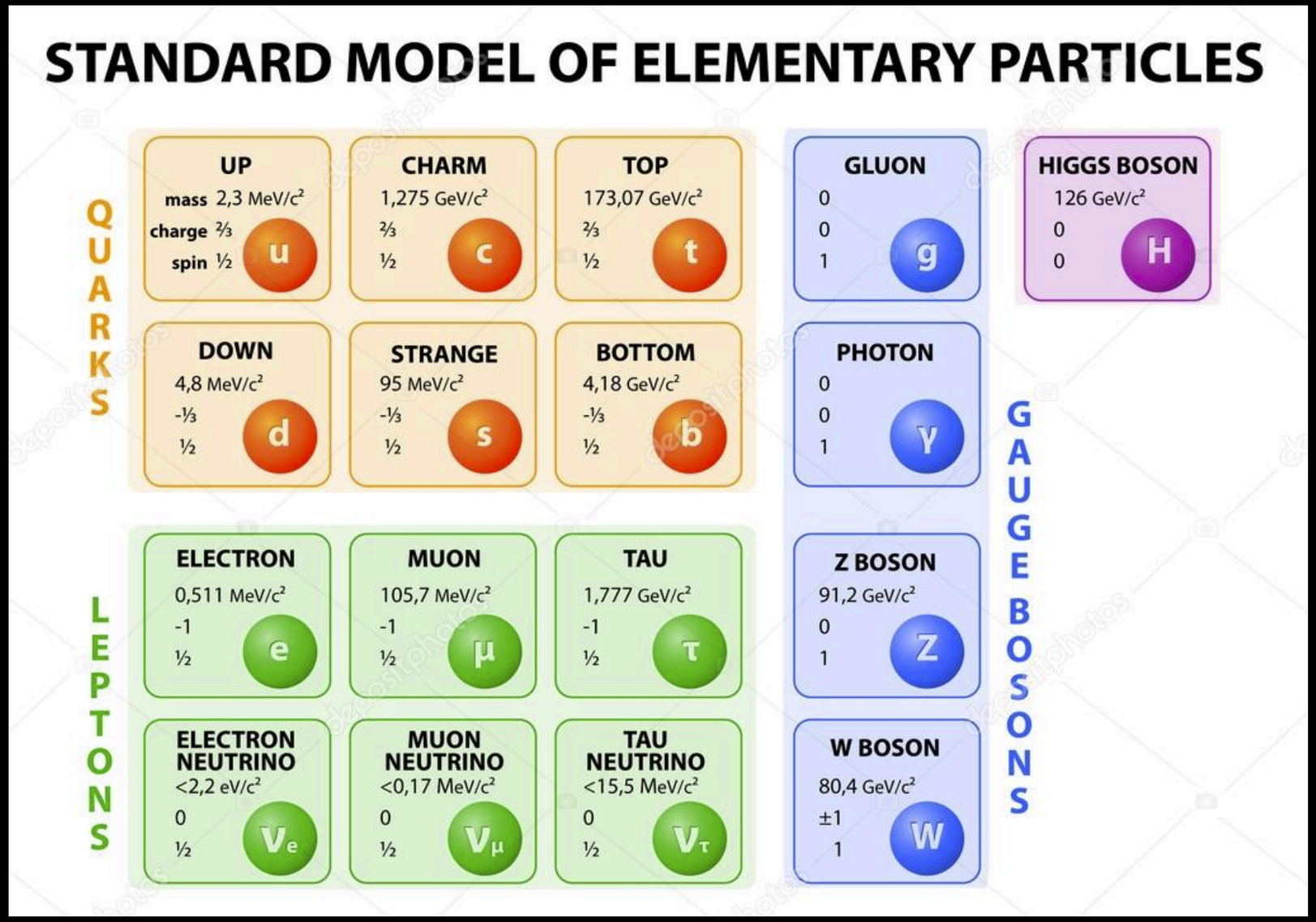


Image: 123rf.com

Standard Model of Particle Physics

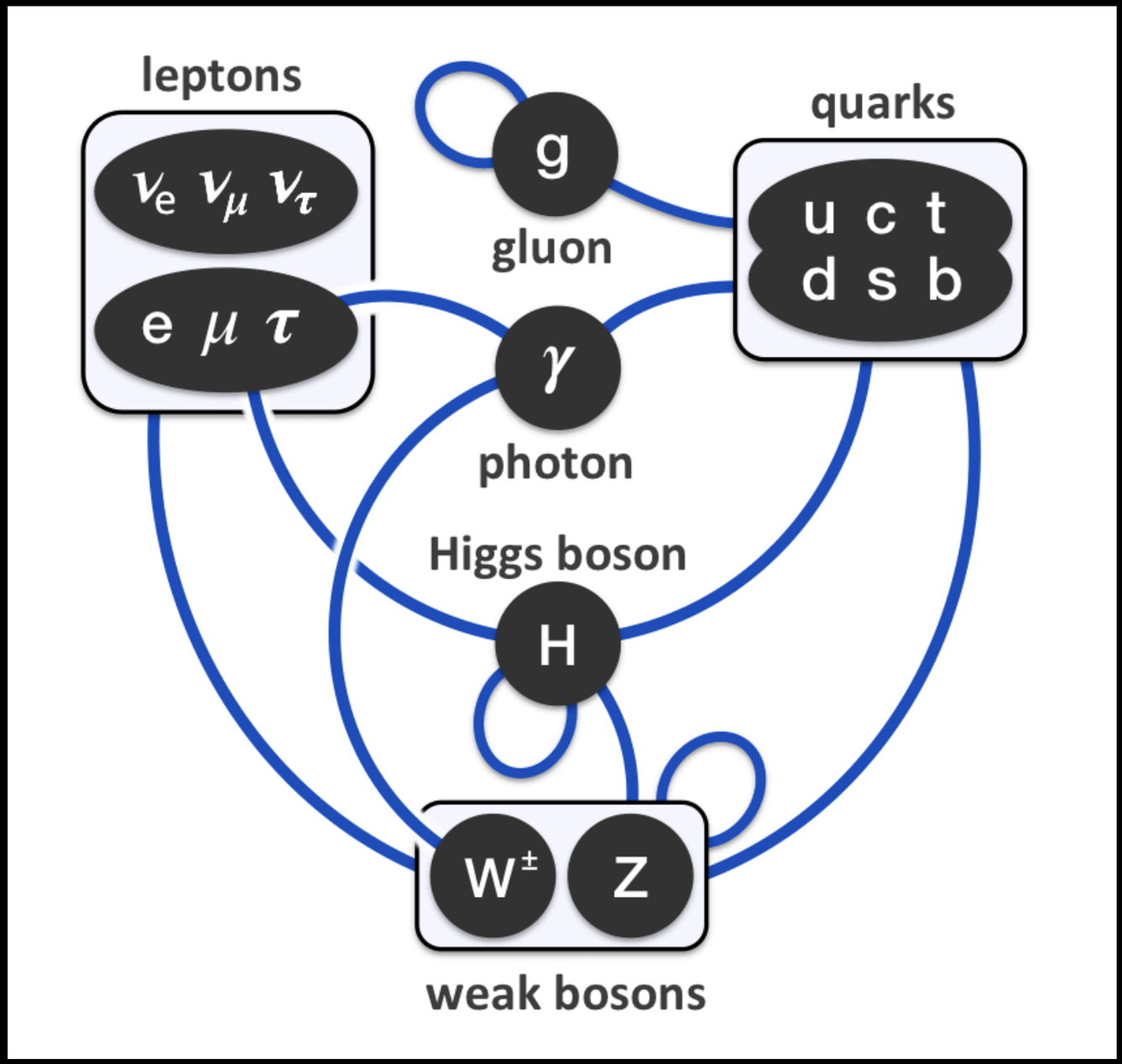
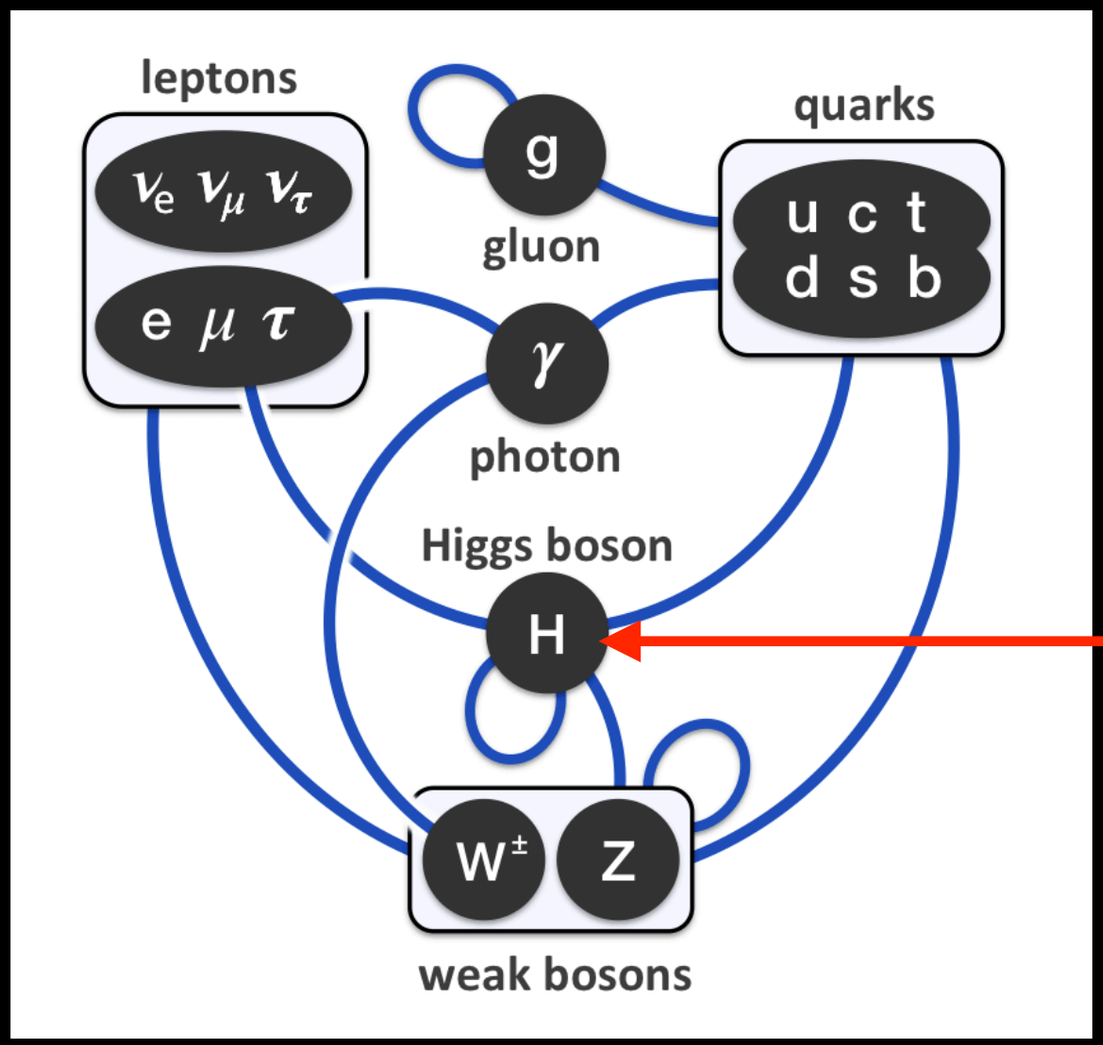
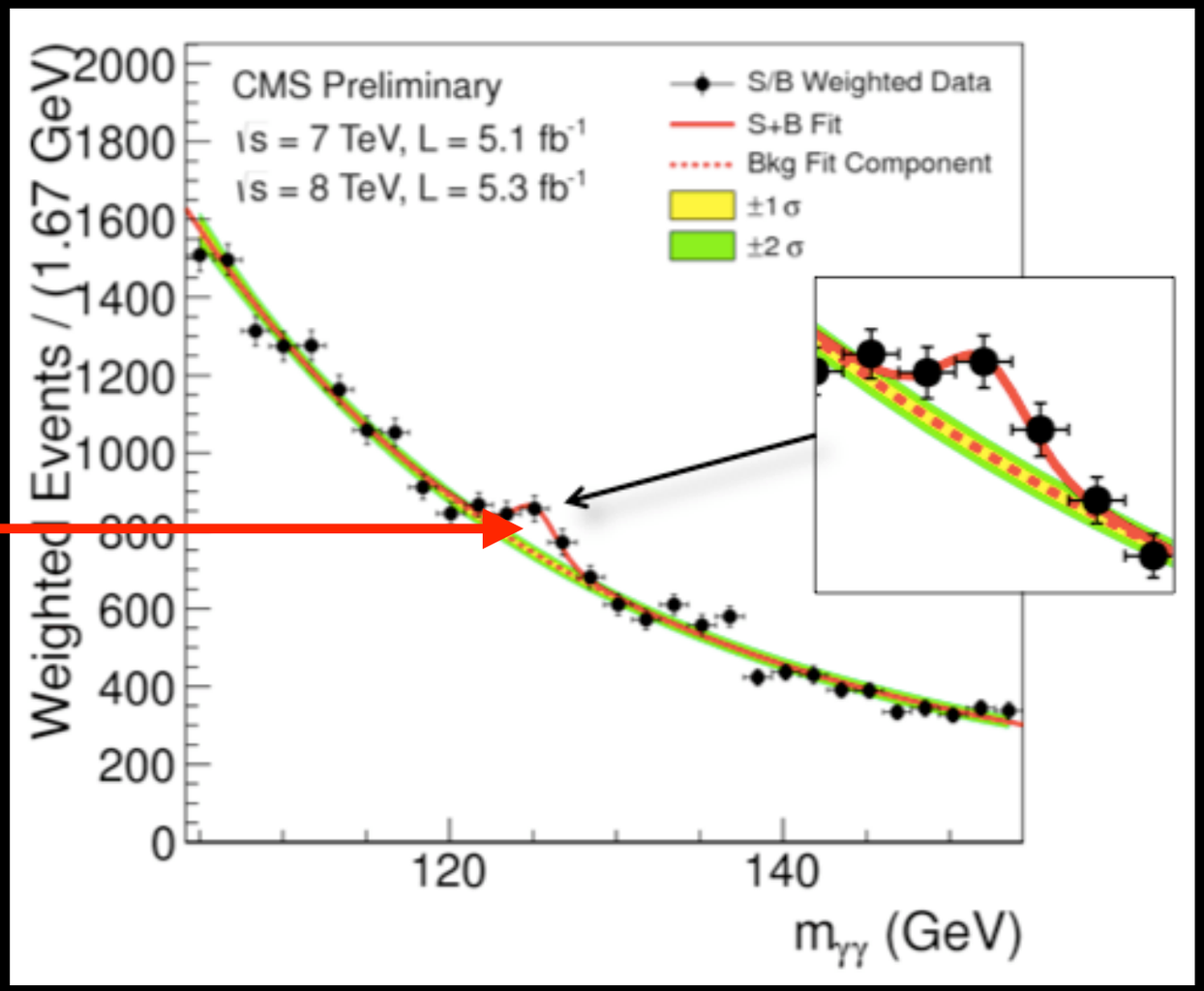


Image: blogs.scientificamerican.com

See lectures by Prof. Keaveney

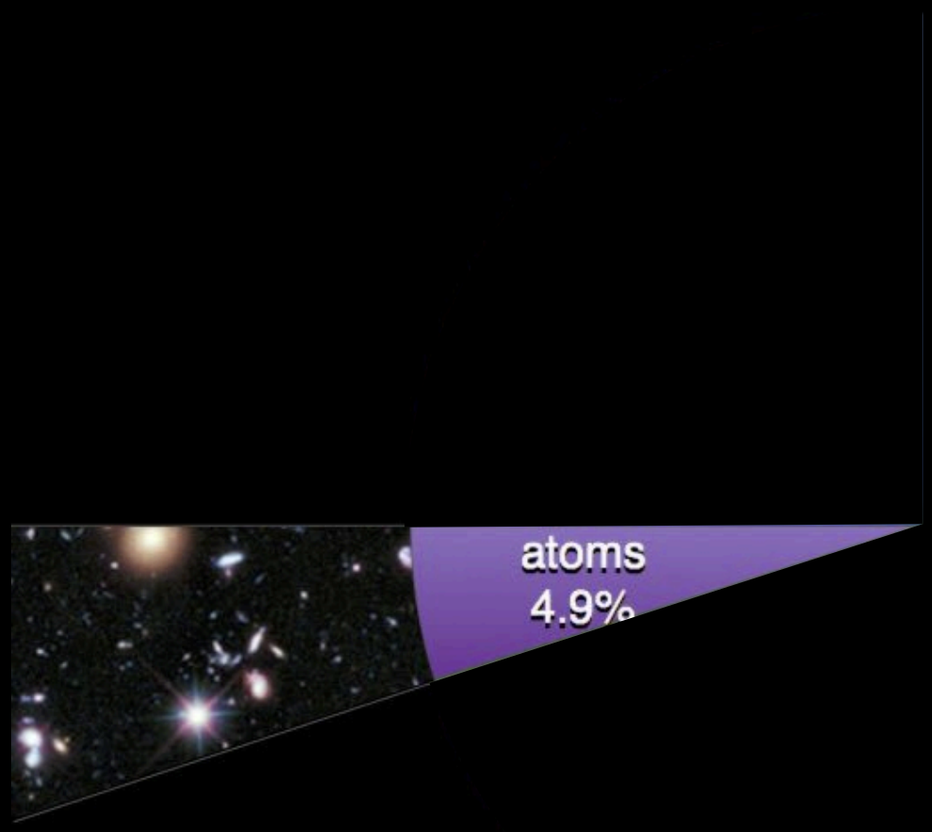
2012 Discovery of the Higgs boson means all particles predicted by SM were experimentally verified

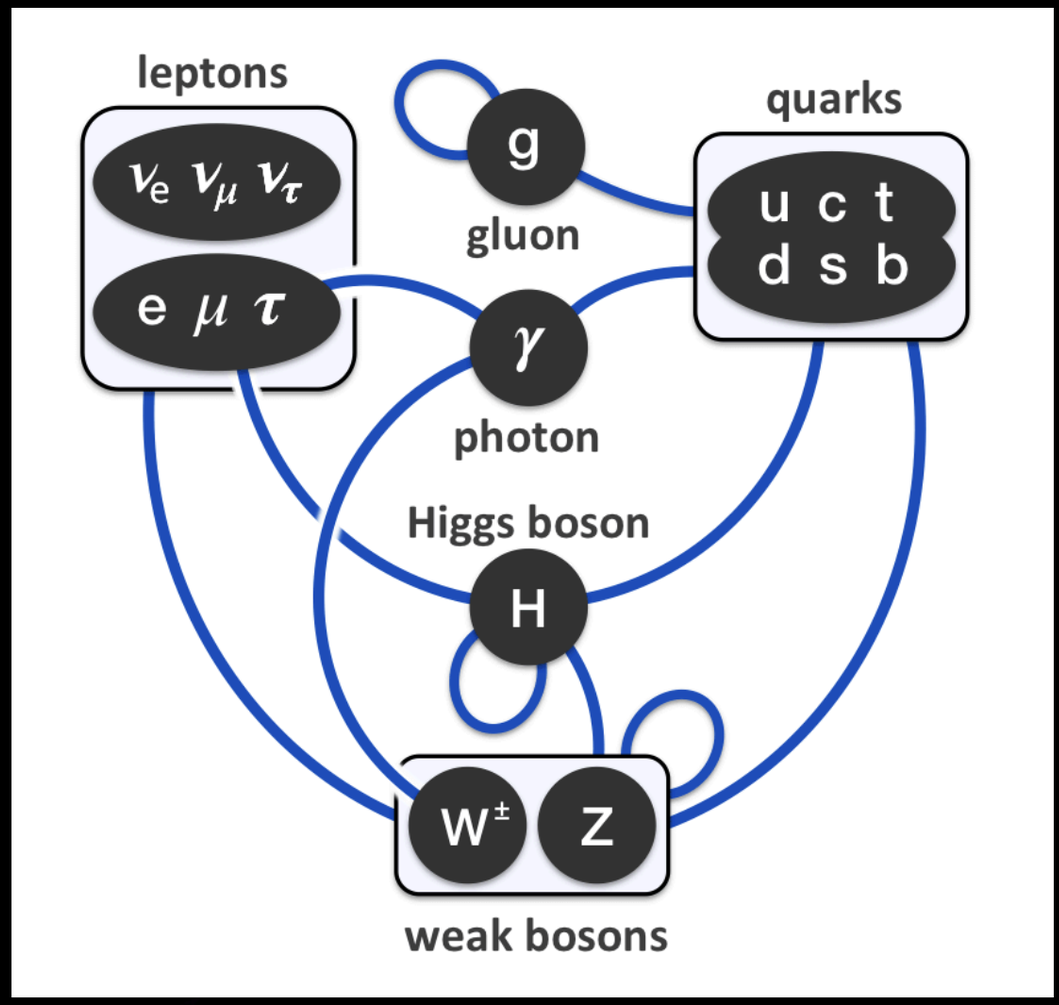




The complete standard model?

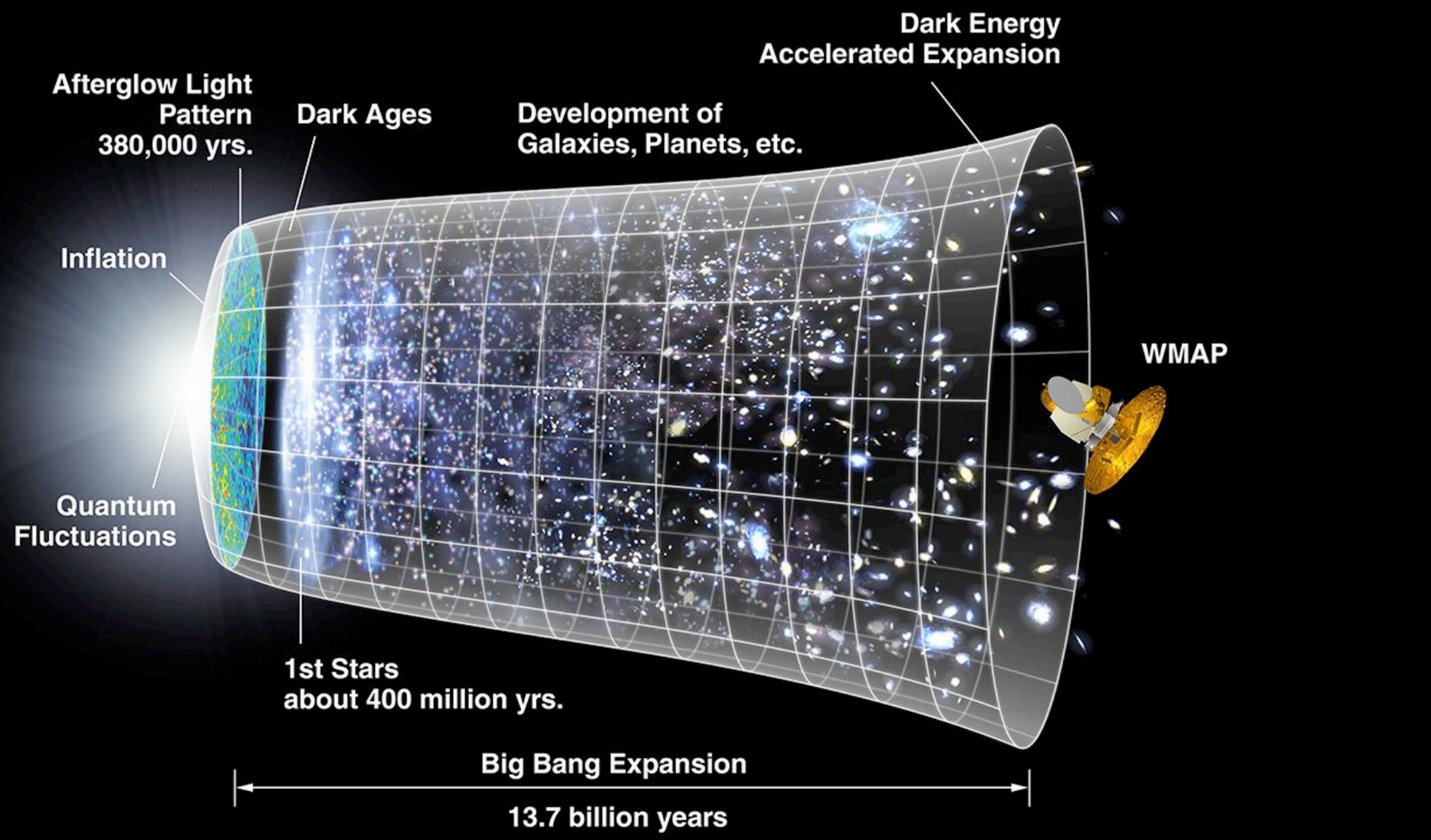
We understand our universe very well





The Standard Model is complete

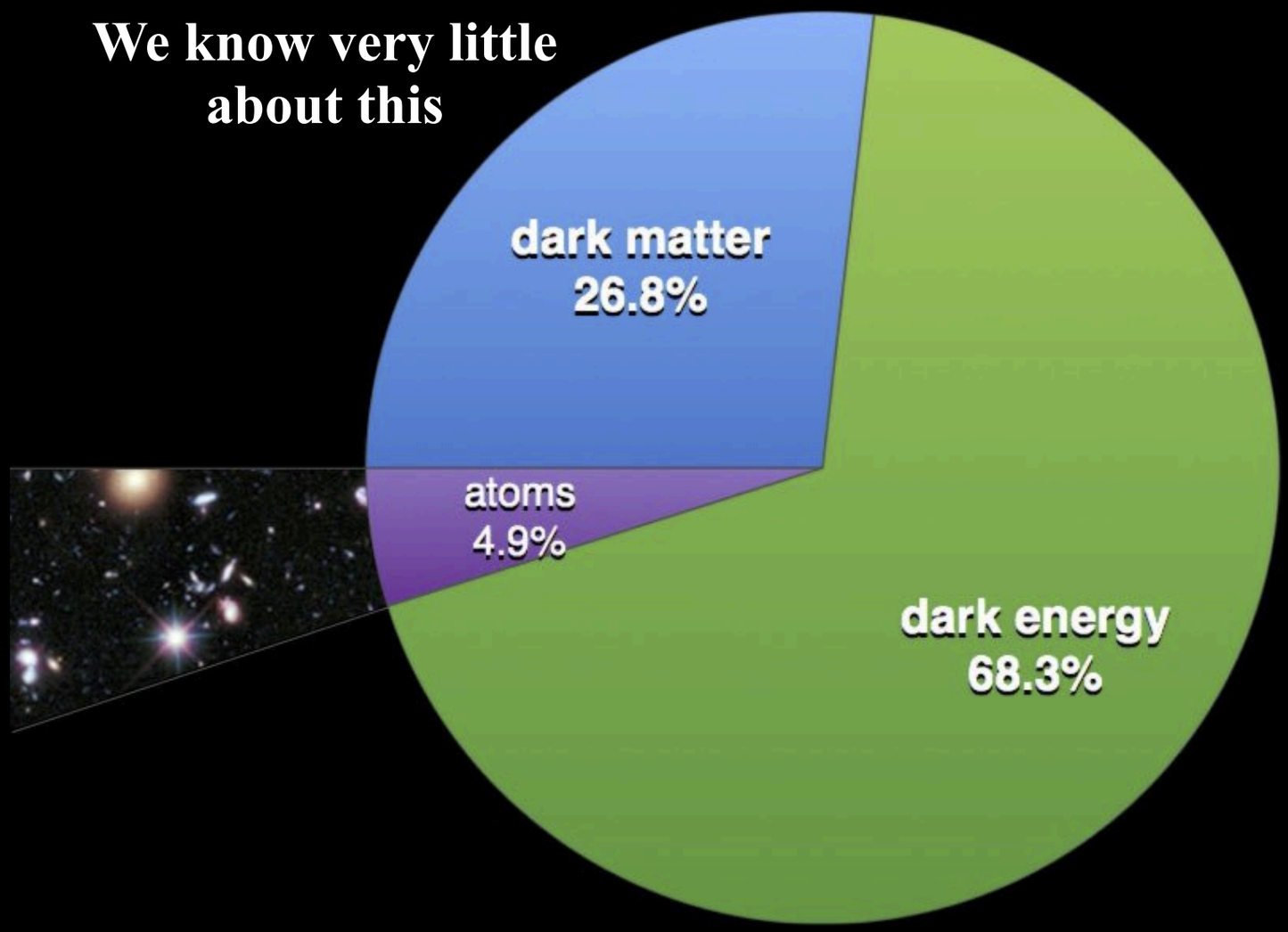
Until we add Cosmology and Gravity



Have to include General Relativity

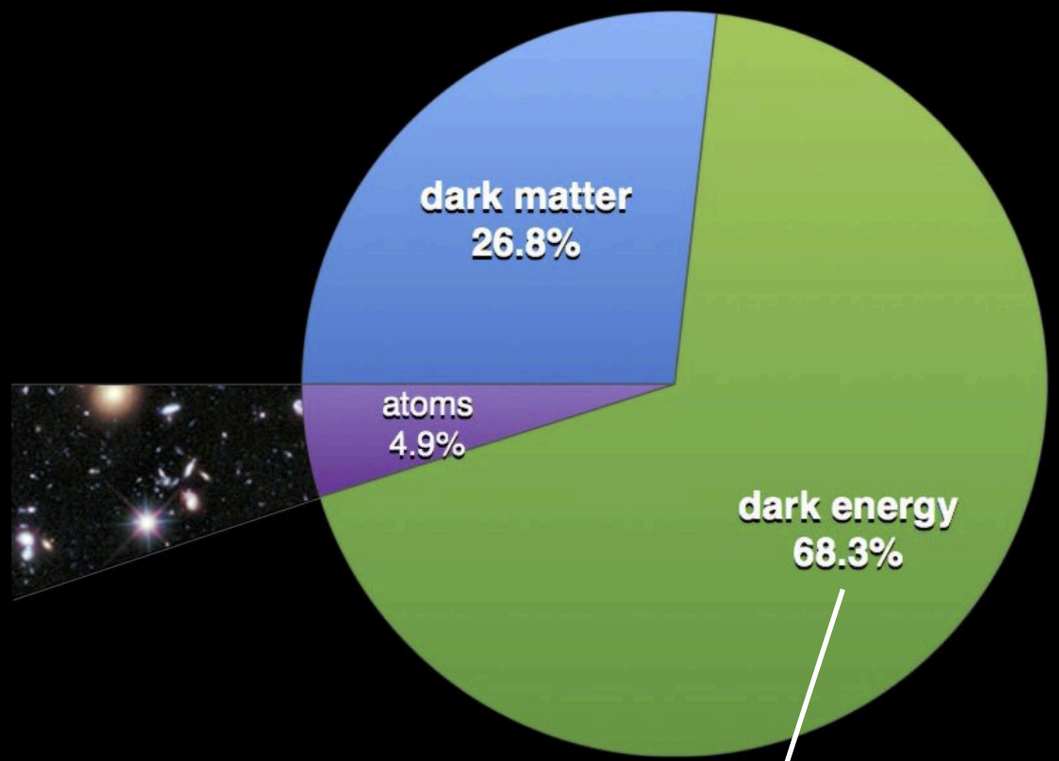
Including GR tells us Universe is made of larger component we don't understand

We know very little about this



We know almost nothing about this

Accelerated cosmic expansion (dark energy)



$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

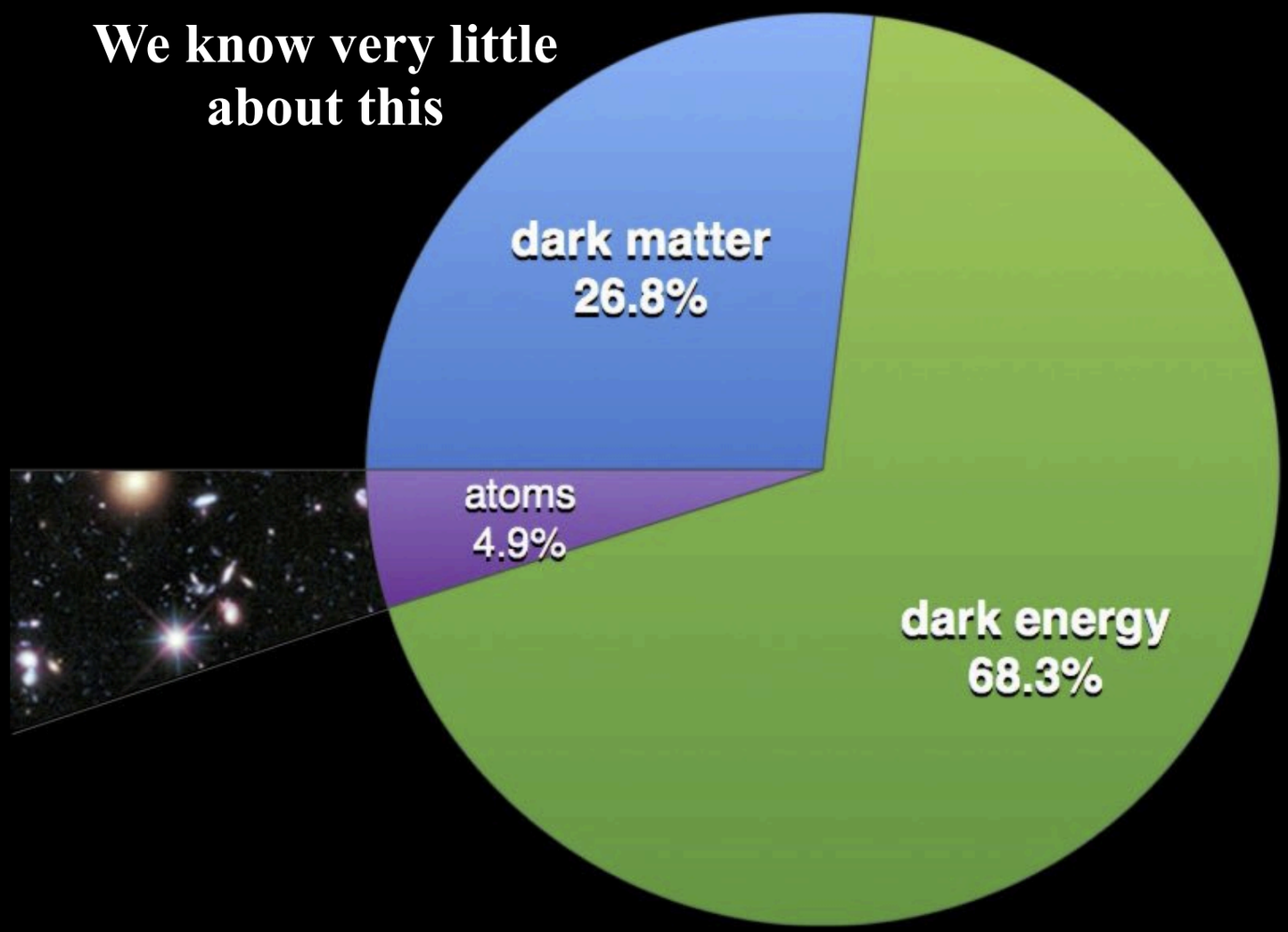
GR permits **cosmological constant** responsible for cosmic expansion

But observed value is very tiny i.e. $\sim 10^{-3}\mathrm{eV} \ll \mathrm{M_{pl}}$

SM cannot explain what dark energy is or why Λ is so small

GR also tells us there is more matter in the Universe than SM can account for, called - **Dark Matter**

We know very little about this



We know almost nothing about this

@AstroKatie/Planck13

So SM of particle physics is incomplete

What we will cover in this lecture

1. Brief History of Dark Matter (early evidence)

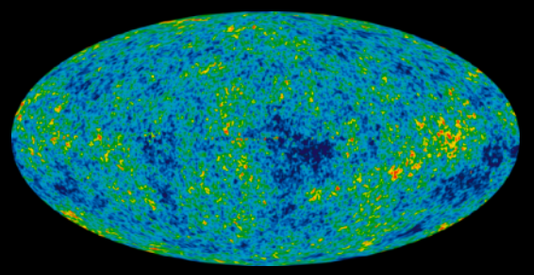
   Pioneers of dark matter studies

2. More (modern) evidence of dark matter existence

   What galaxies tell us

   What clusters of galaxies tell us

   What cosmological observations tells us



What we will cover in this lecture

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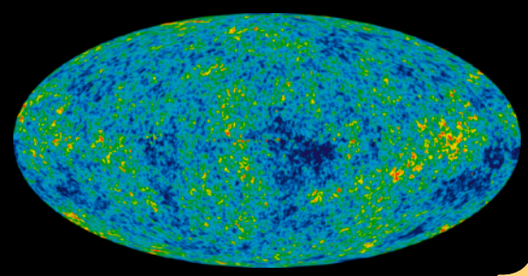


governed by gravity

2. What do we (don’t) know about DM?

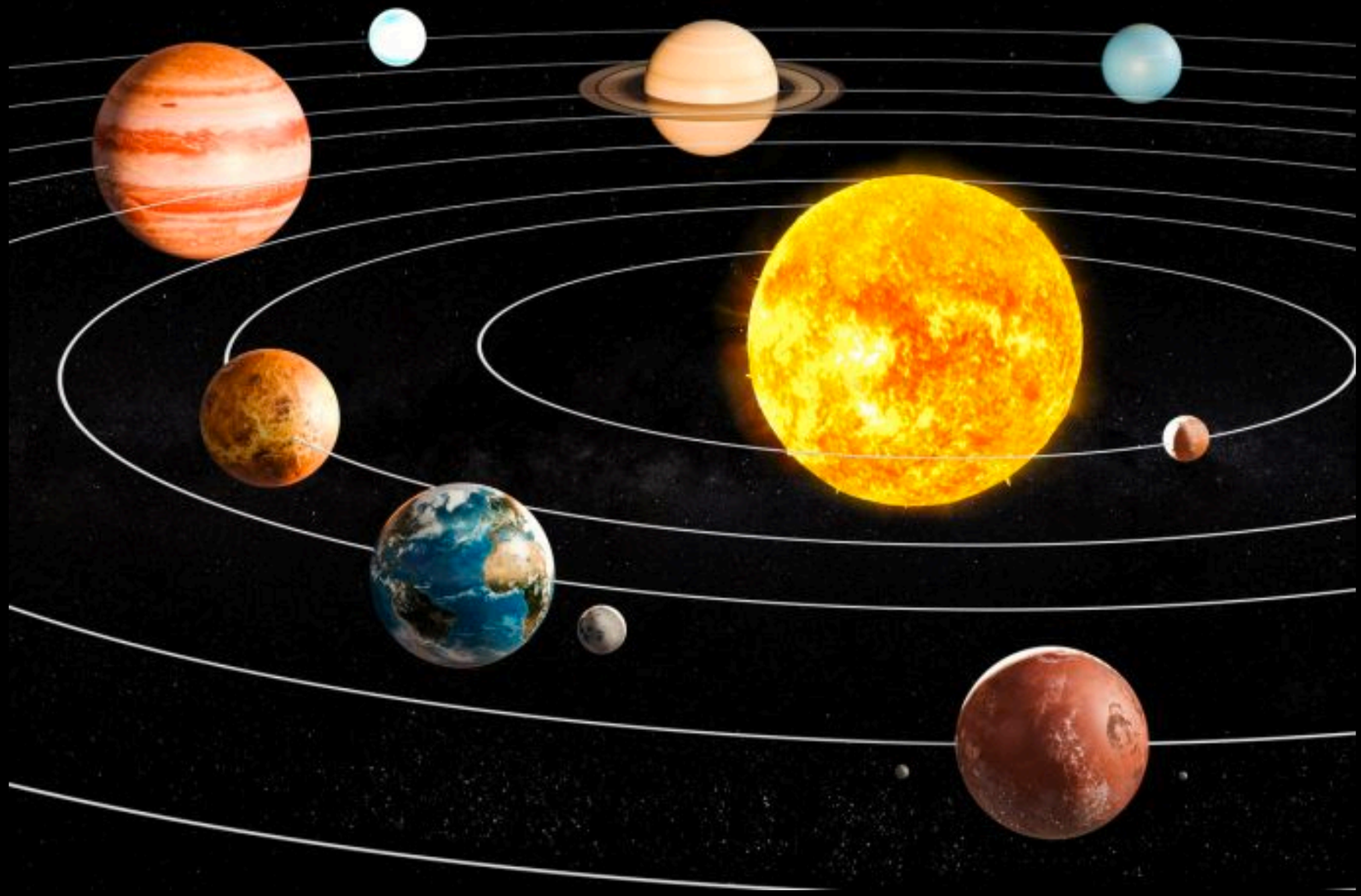
Properties of dark matter

3. Possible theories of dark matter

Examples from particle physics

Solar System

What does gravity tell us about the Solar system?



Planets rotate around the Sun because of Sun's gravitational field

Newton's law of Gravity: Planets closest to Sun move faster

Planets further away from the Sun move slower

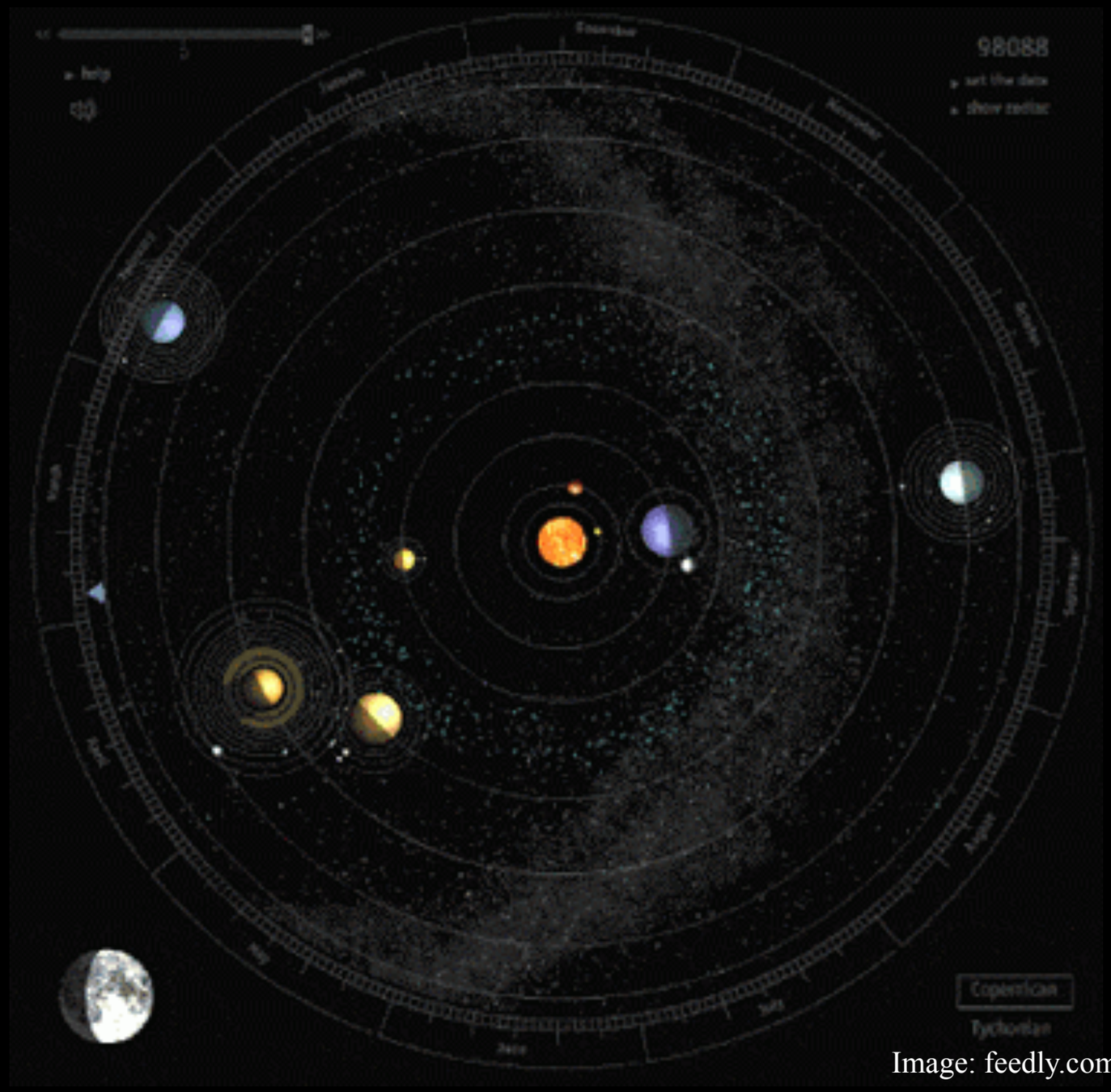


Image: feedly.com

Using this we measure mass of Sun: 1.9×10^{30} kg

Mass of entire solar system: 2×10^{30} kg

Imagine the Sun is invisible

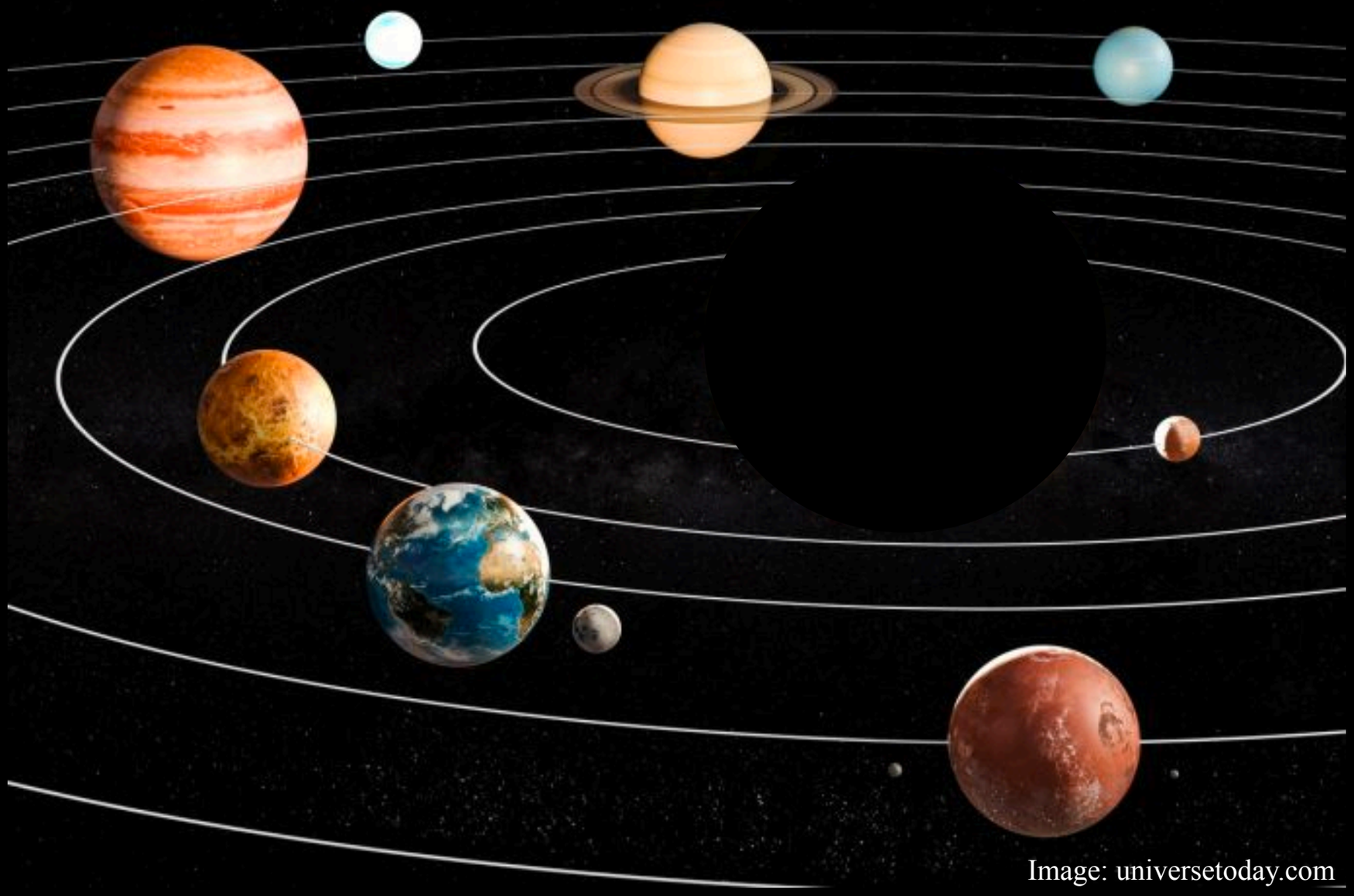


Image: universetoday.com

We would still be able to tell that entire solar system has a mass of

2×10^{30} kg

Early evidence

1884 - Lord Kelvin

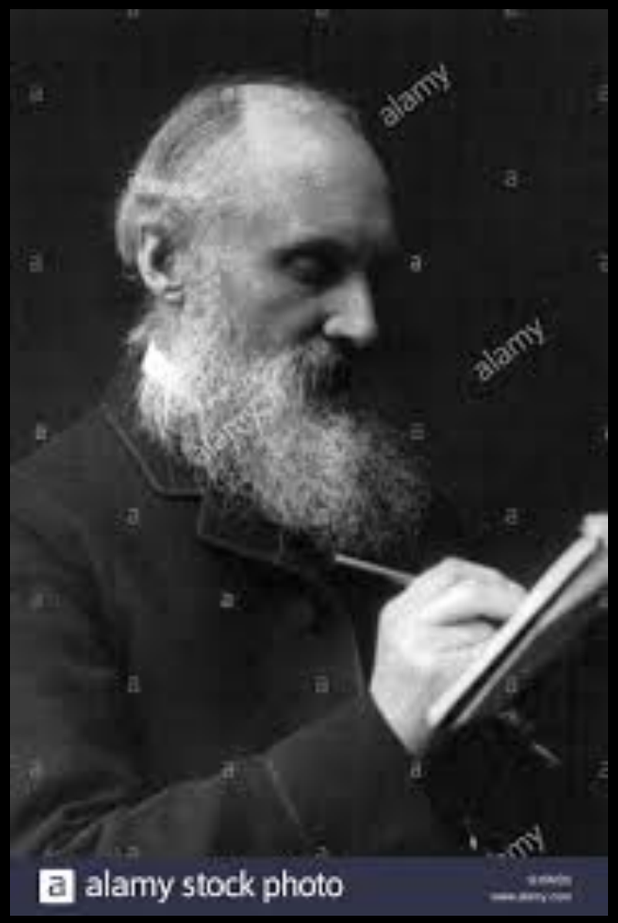


Image: alamy.com

Estimated amount of dark matter by calculating how fast stars were moving around the center of the Milky way

First to call this unobserved matter ‘Dark Matter’

1906 - Henry Poincare

Image: alamy.com

Early evidence

1933 - Fritz Zwicky

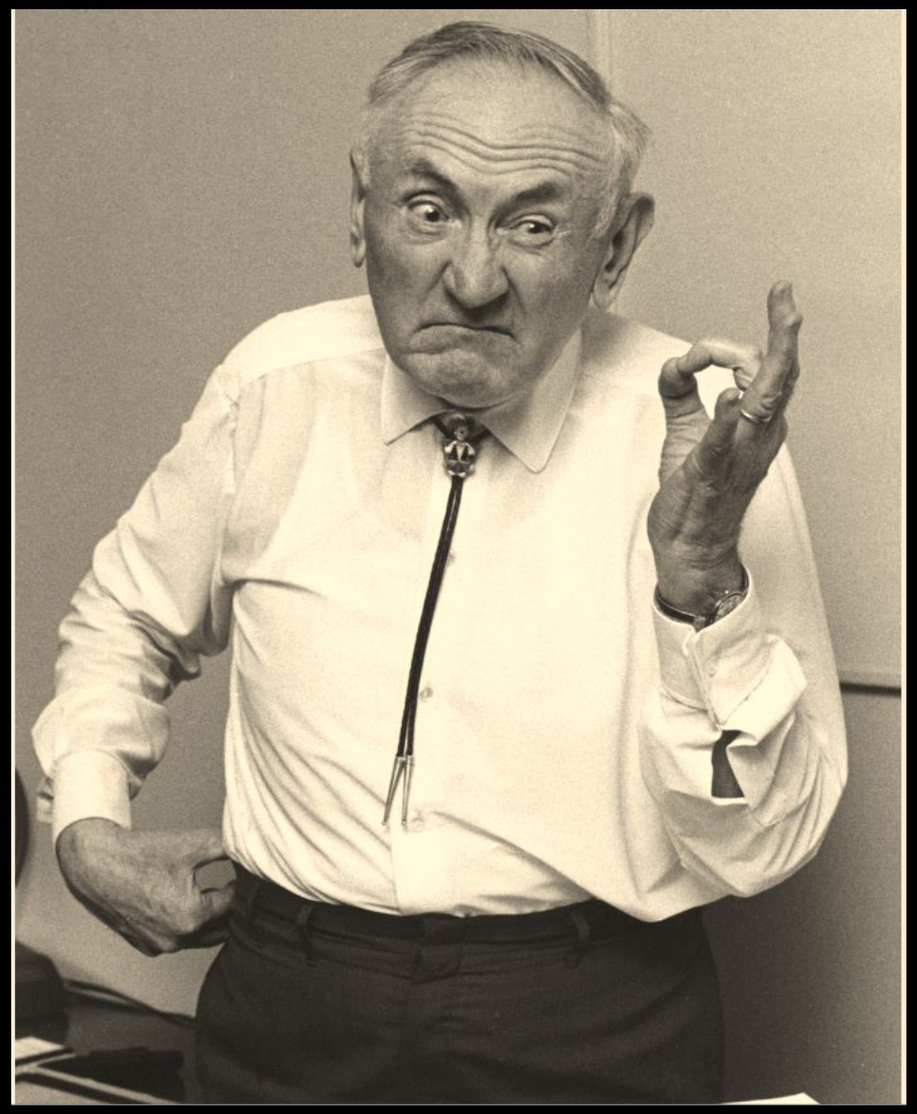


Image: Caltech Archives

Virial Theorem: $\frac{GMm}{R} = \frac{mv^2}{2}$

Calculated that there was ~400x more mass than he observed when looking at Coma cluster of Galaxies

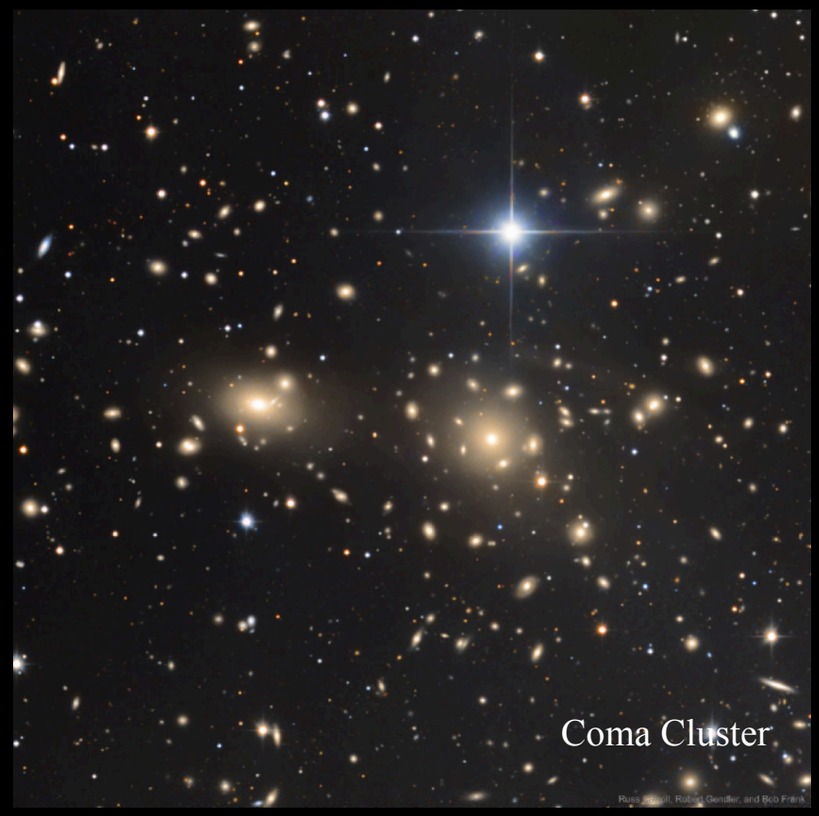


Image: NASA APoD

Called unseen matter - “Dunkle Materie”
(Black Material)

Late 1970s - Vera Rubin

Image: Carnegie Institute for Science

First scientist to measure star speeds with very high accuracy

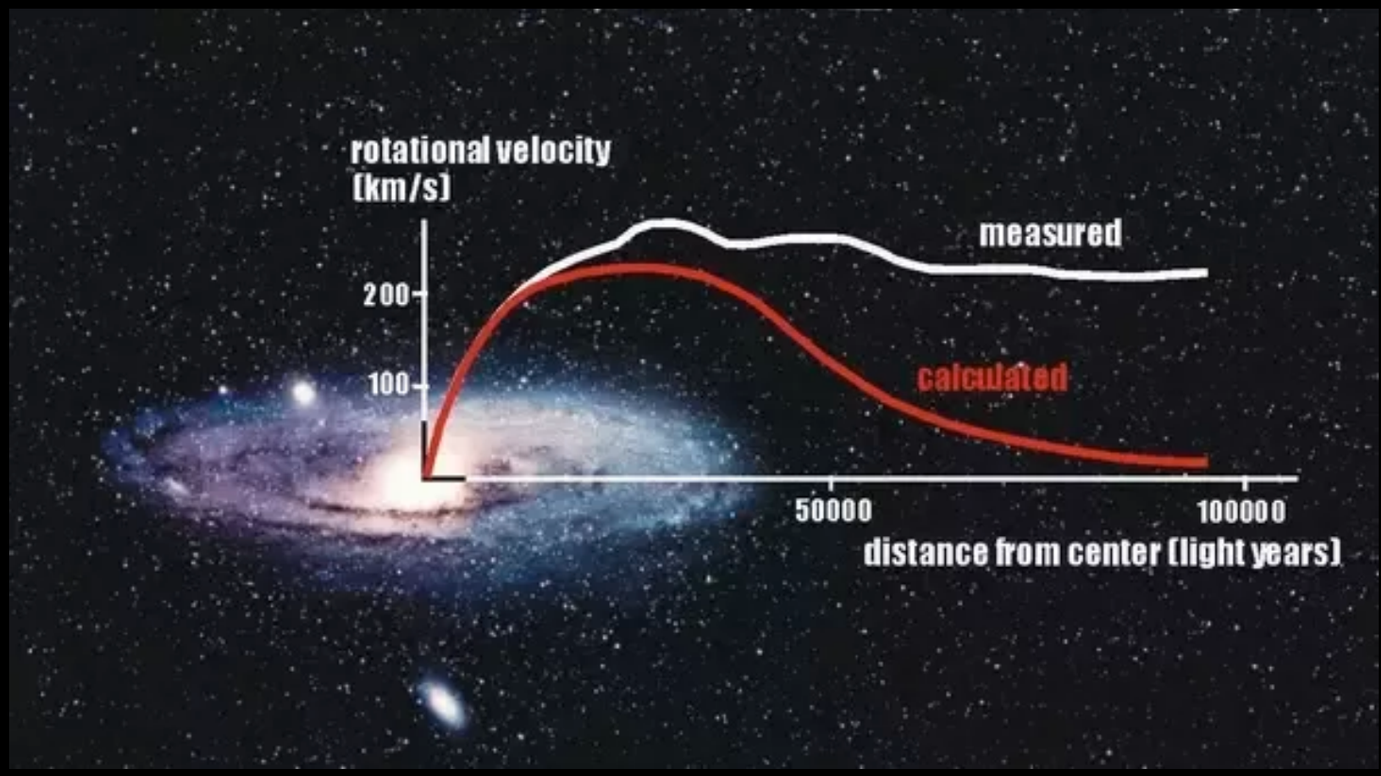
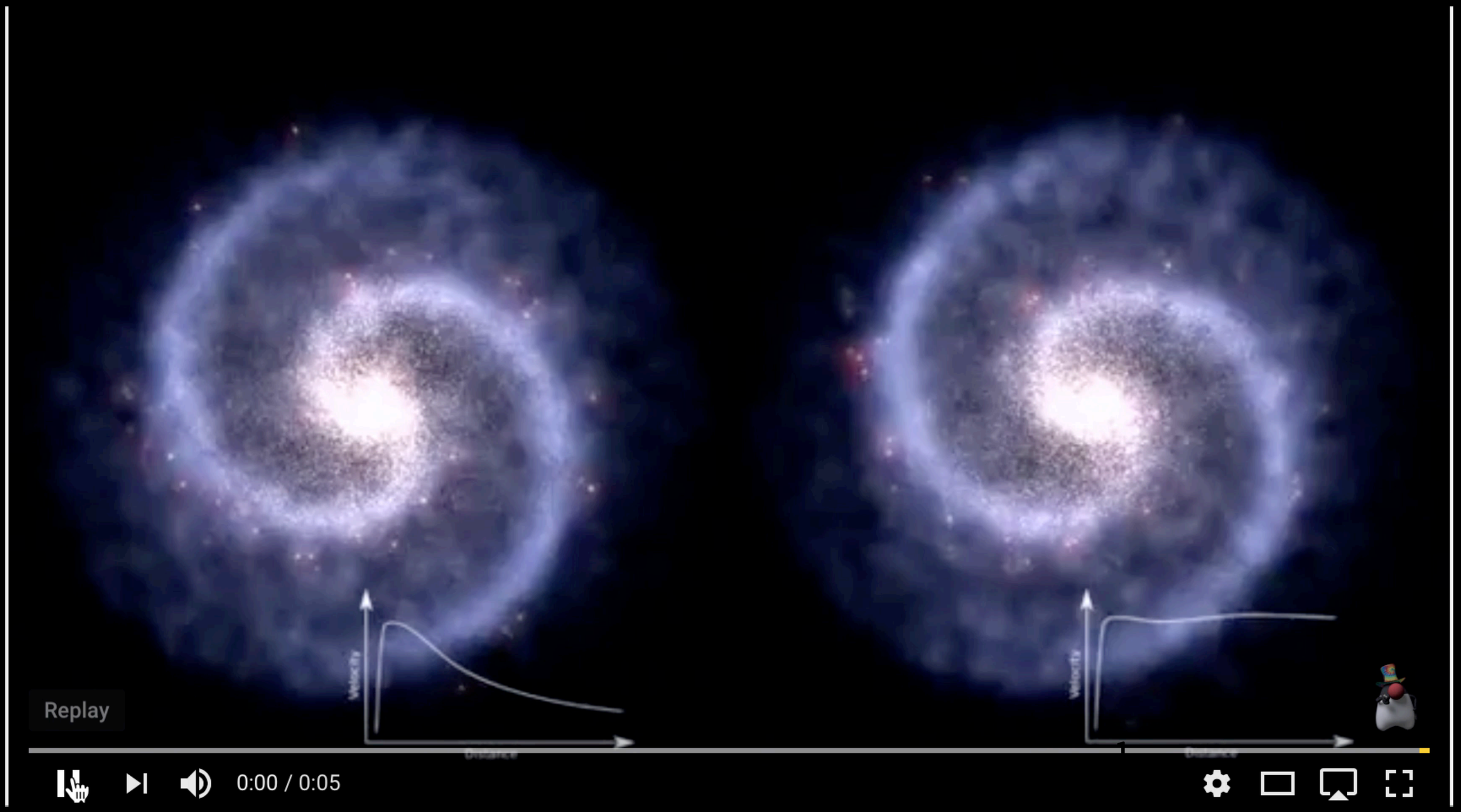


Image: quora.com

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

$$v = \sqrt{\frac{GM}{r}}$$

What do galaxies tell us about DM?



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Dark matter pioneer Vera Rubin gets a new observatory named after her

The researcher found evidence of dark matter and broke barriers for women in science

Image: Carnegie Institute for Science

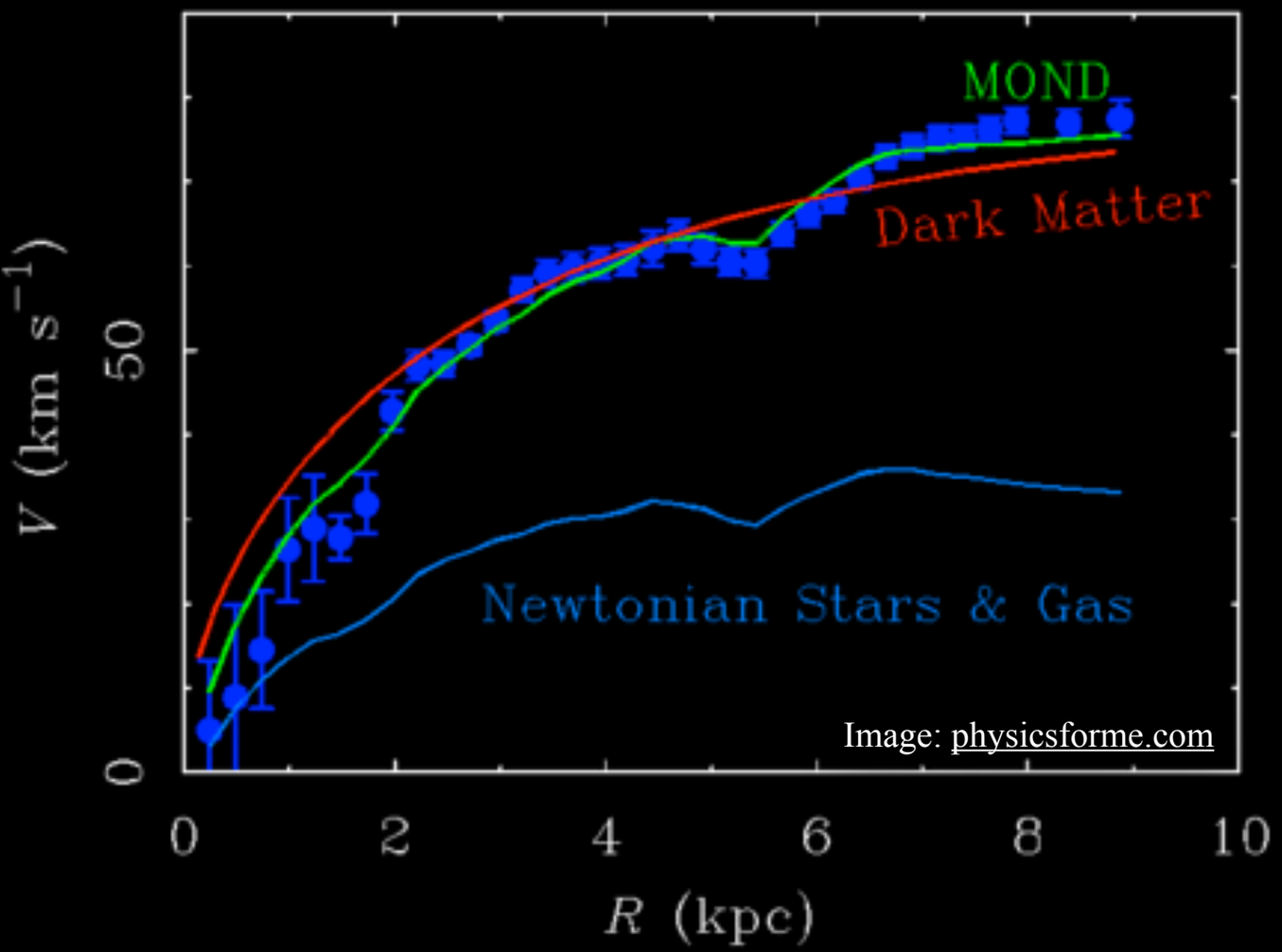
Formerly Large Synoptic Survey Telescope

Now Vera Rubin Observatory

What if Newton's gravity is wrong?

… or our understanding of it in Galaxies

Modification of Newtonian Dynamics - **MOND**



Modifying our understanding of newton's gravity,
we can fit galactic data

Lets look at scales larger than galaxies

Gravity can also bend light coming from distant objects

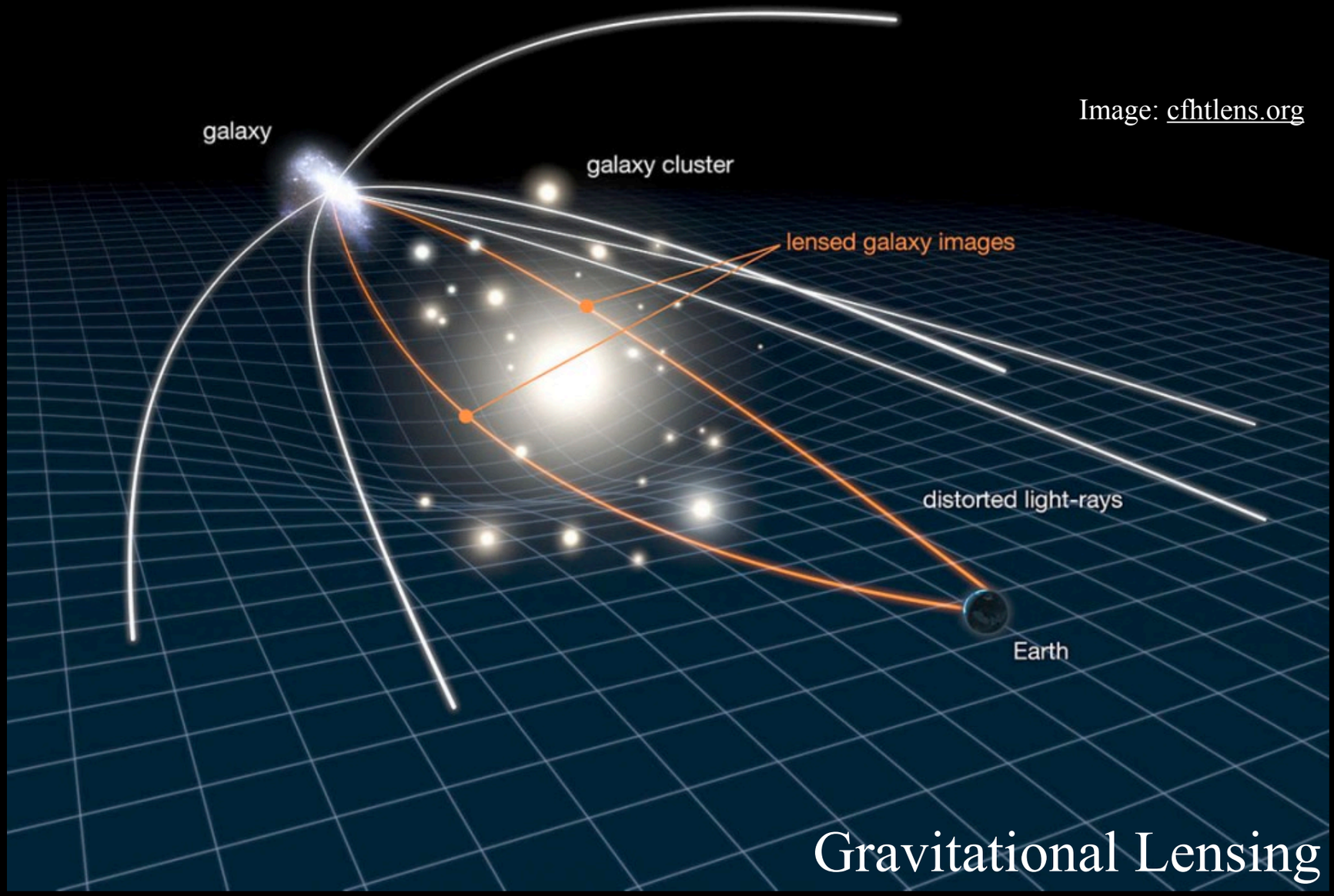


Image: cfhtlens.org

Gravitational Lensing

Light from galaxy is bent by gravitational field of galaxy cluster

Lets look at scales larger than galaxies

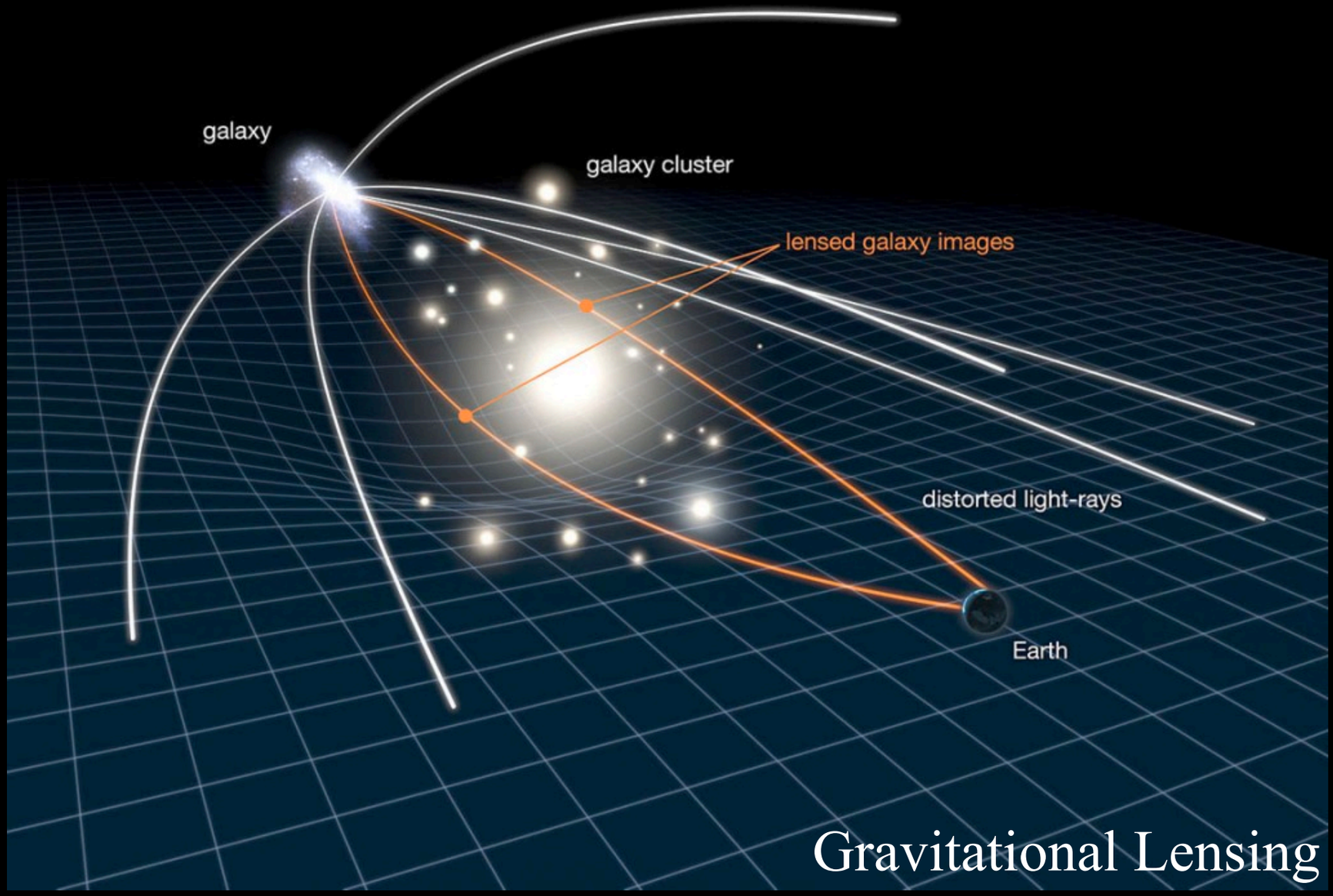
We see this Gravitational bending of light (lensing) in our telescopes

Image: slate.com

Gravitationally lensed object

Lets look at scales larger than galaxies

Again, lets imagine the galaxy cluster is invisible



We still see this bending of light

What do galaxy clusters tell us about DM?

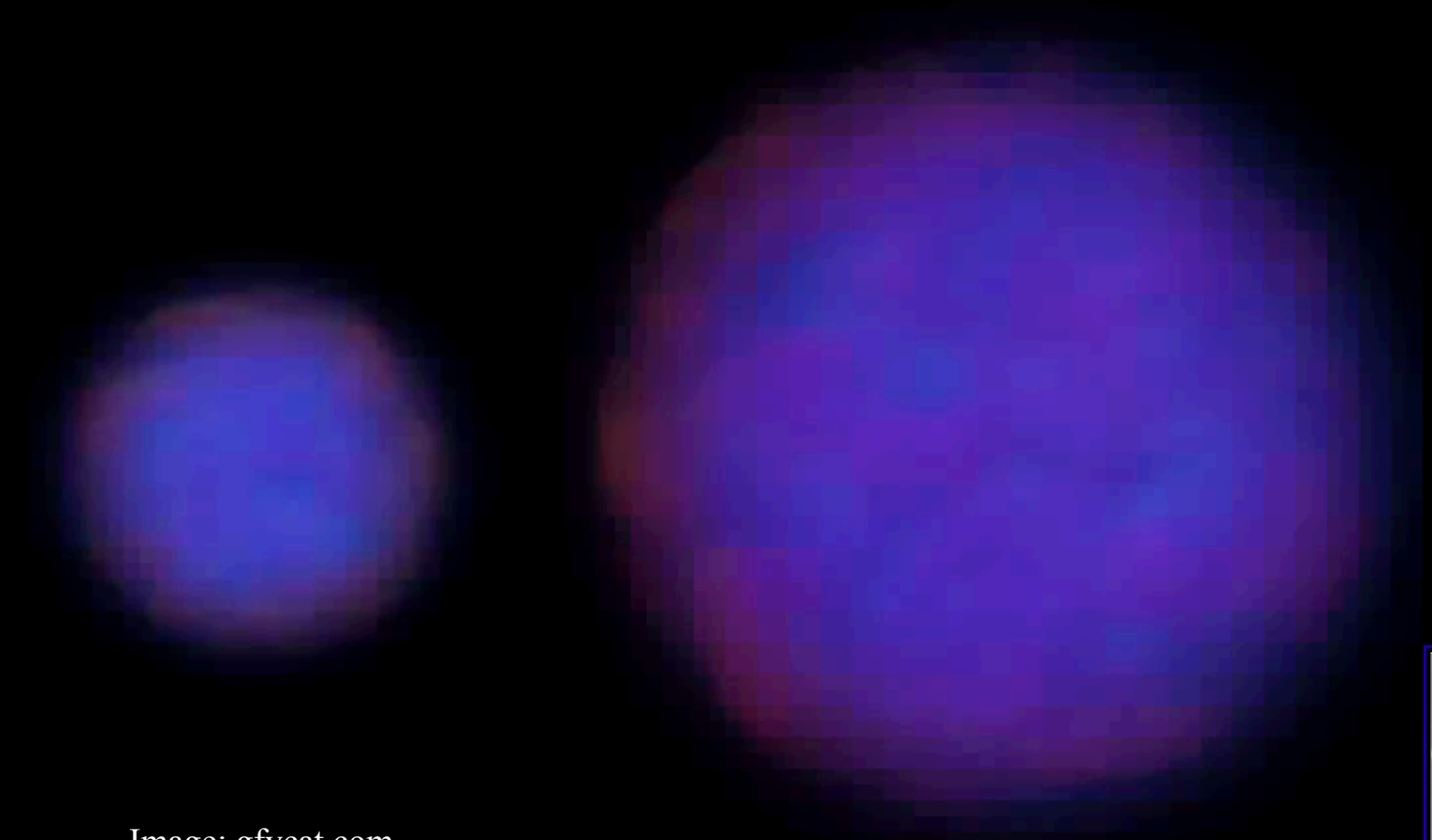


Image: gfycat.com

Visible Matter

Dark Matter

Gravitational Lens

Image: yumpu.com

At these scales we cannot modify gravity to fit data and still be consistent with modification at galaxy scales

Dark Matter ✔

MOND + more modification ✕

What do cosmological observations tell us?

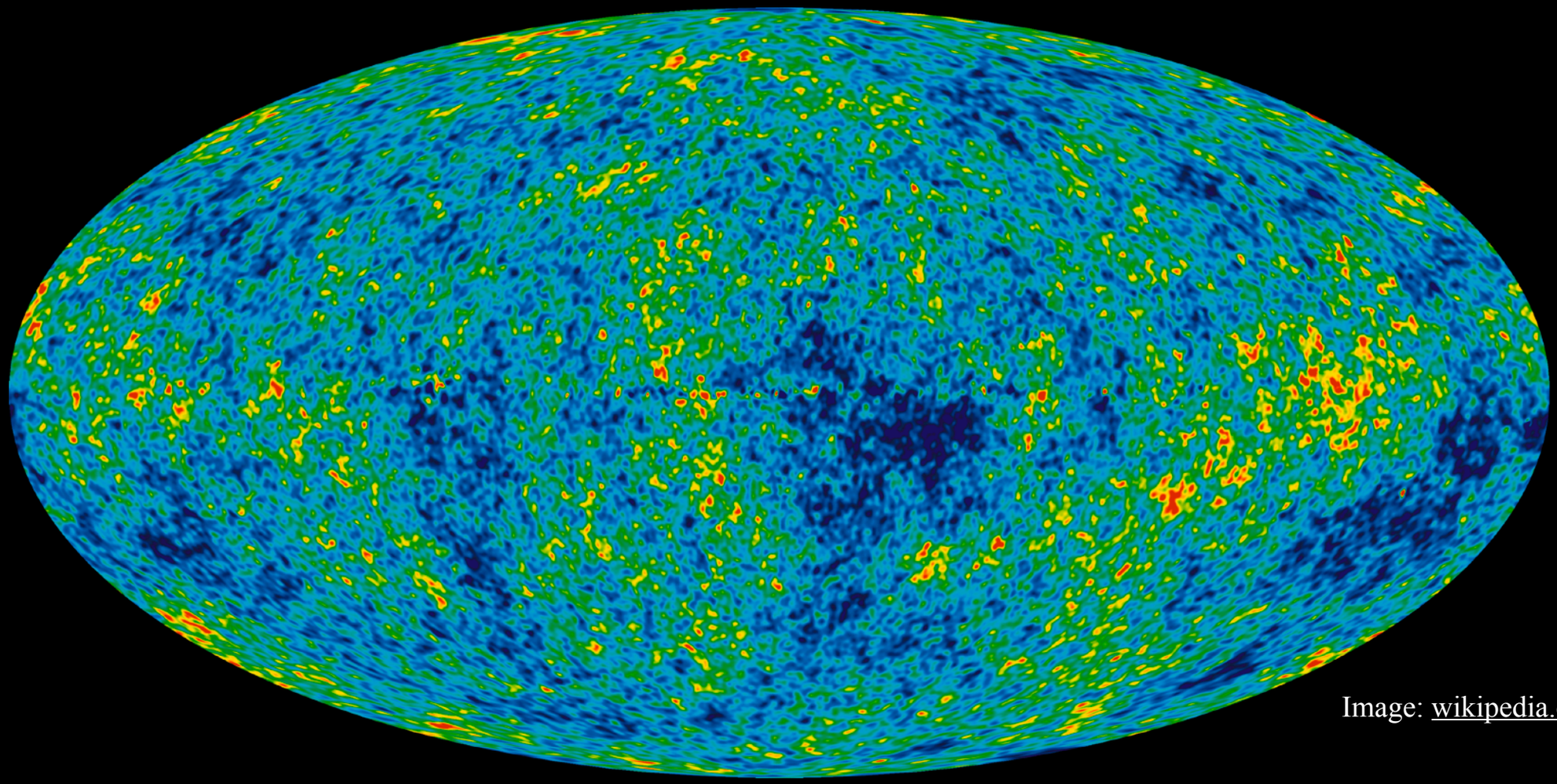


Image: wikipedia.org

- Immediately after big bang, universe was dense plasma of photons & charged particles

- After rapid initial expansion, it cooled for about 380 000 yrs

Epoch of recombination

What do cosmological observations tell us?

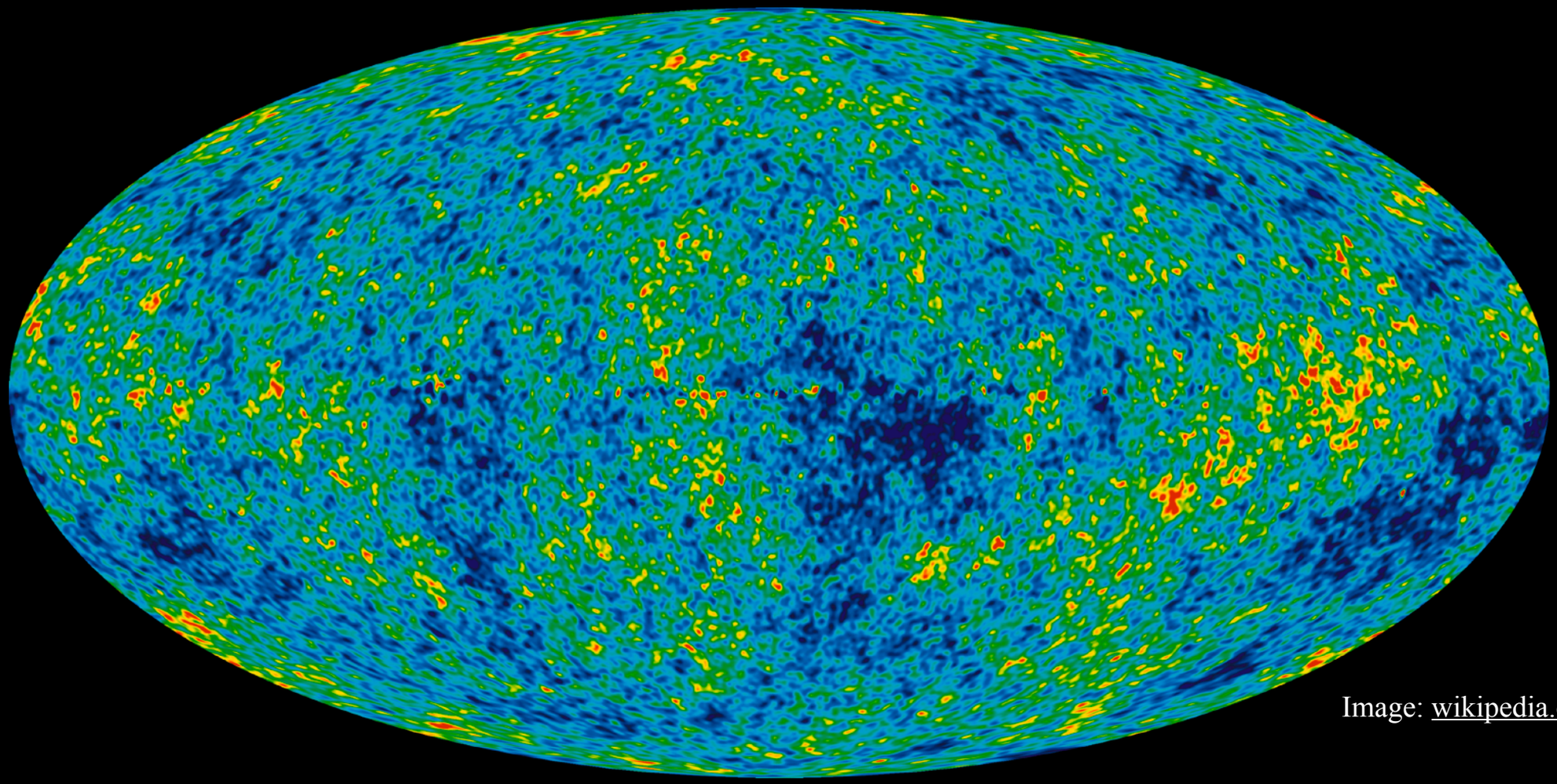


Image: wikipedia.org

Epoch of recombination

- Neutral atoms were formed, photons could move freely since they were no longer locked to charged particles

- These free moving photons reach us today

What do cosmological observations tell us?

We call these photons Cosmic Microwave Background Radiation

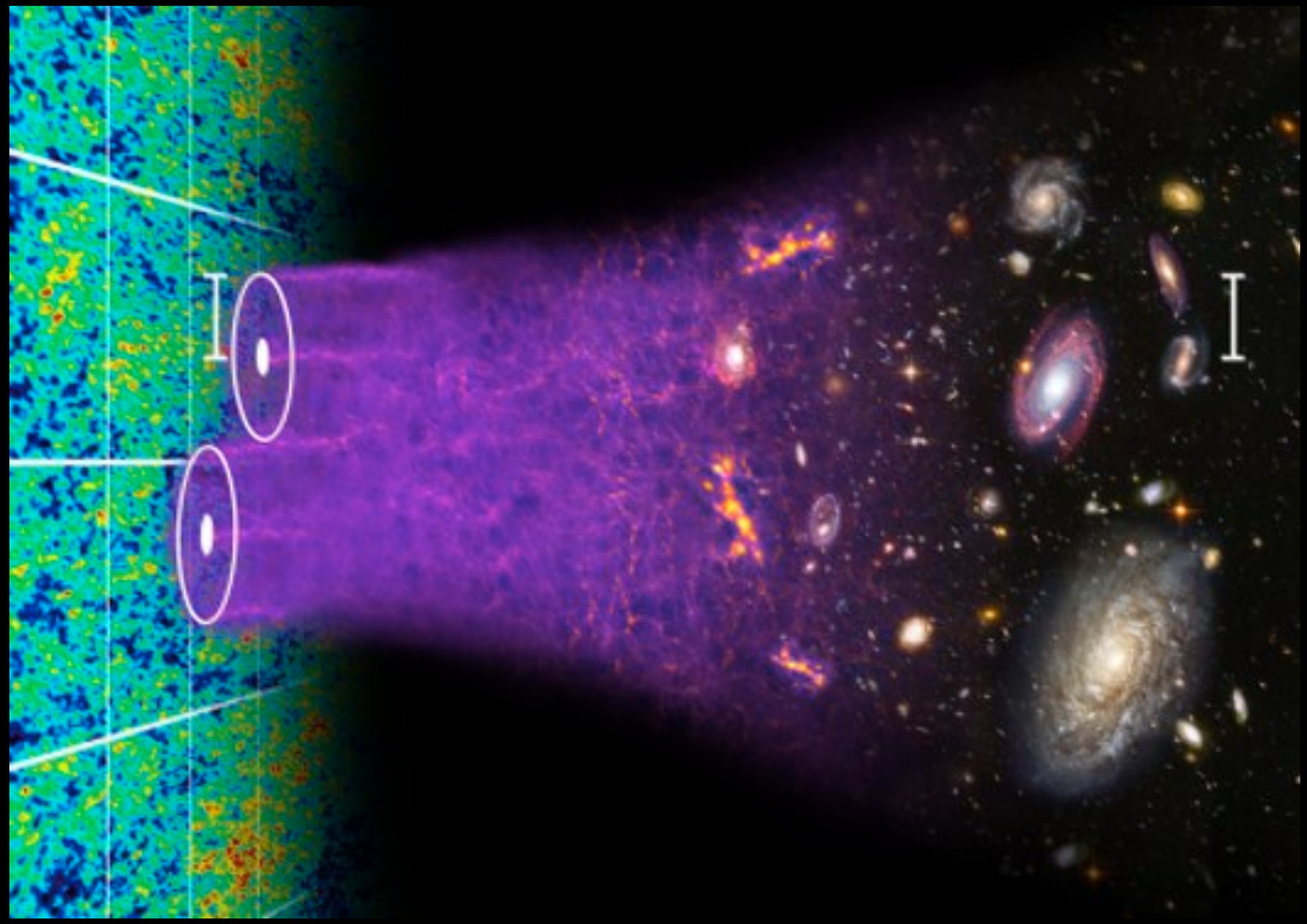


Image: medium.com

CMB gives us whole picture of our Universe

What do cosmological observations tell us?

CMB Power Spectrum -
gives cosmologists a way to mathematically understand fluctuations

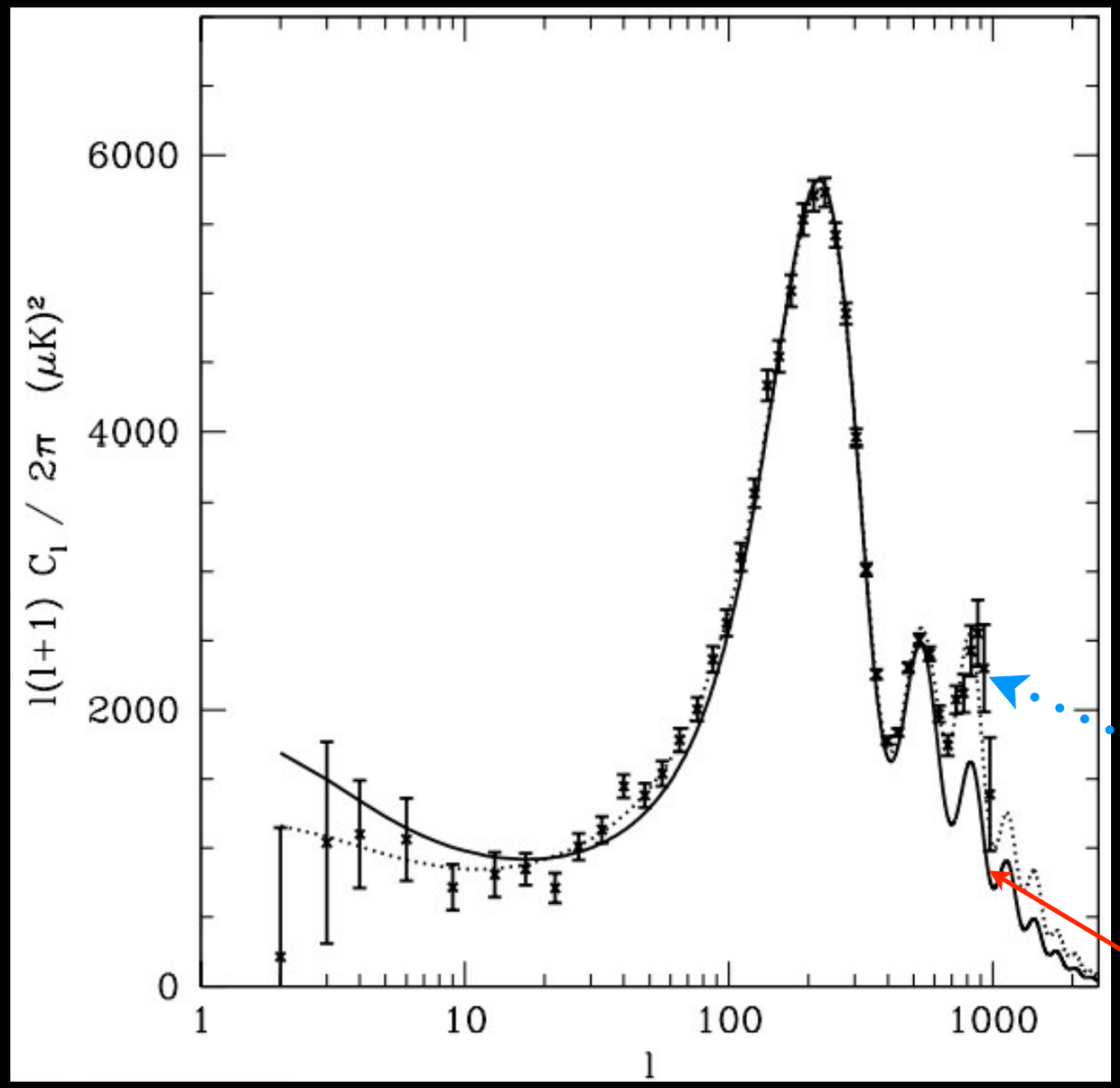
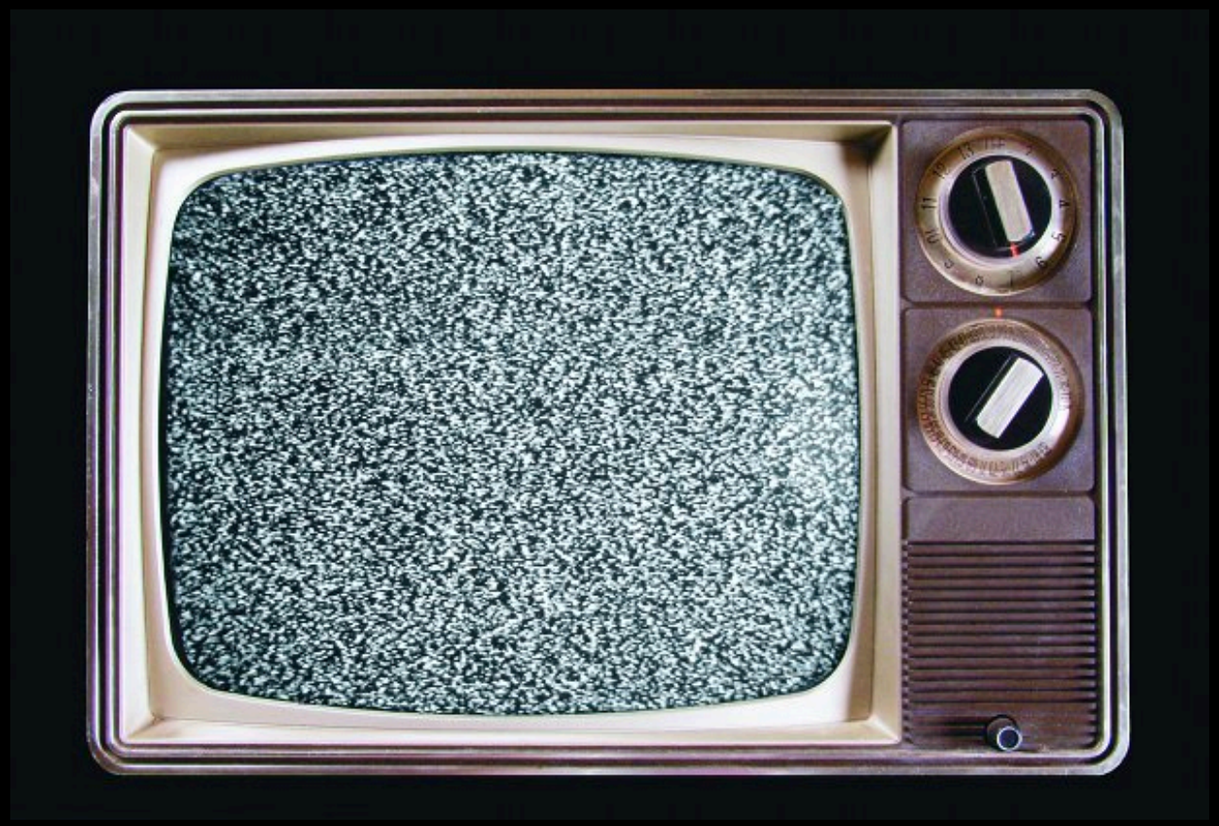


Image: Sean Carrol

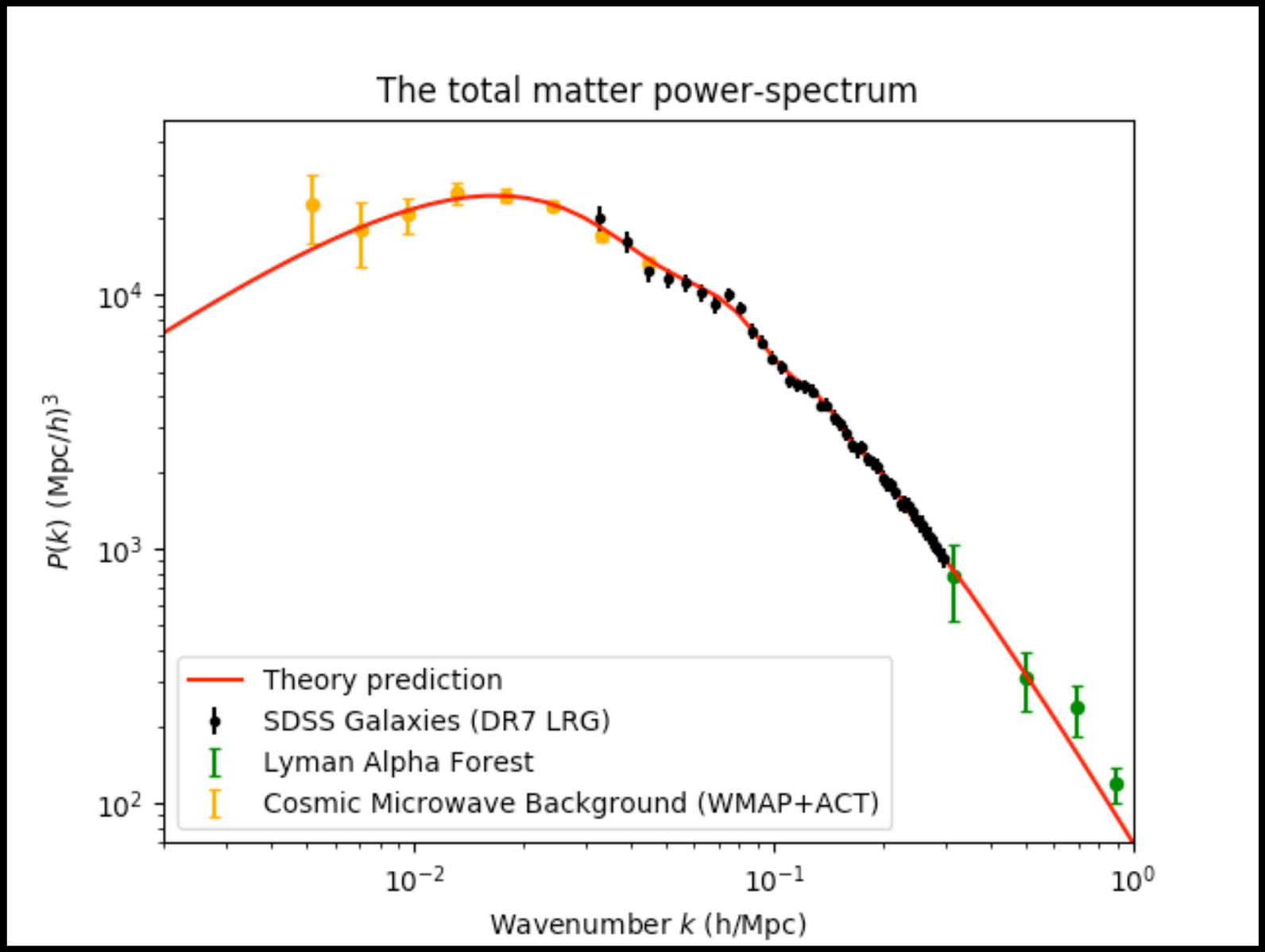
Evidence shows dark matter exists at largest scales

We can see and hear CMB photons at home



- Between stations on older TVs and FM radios

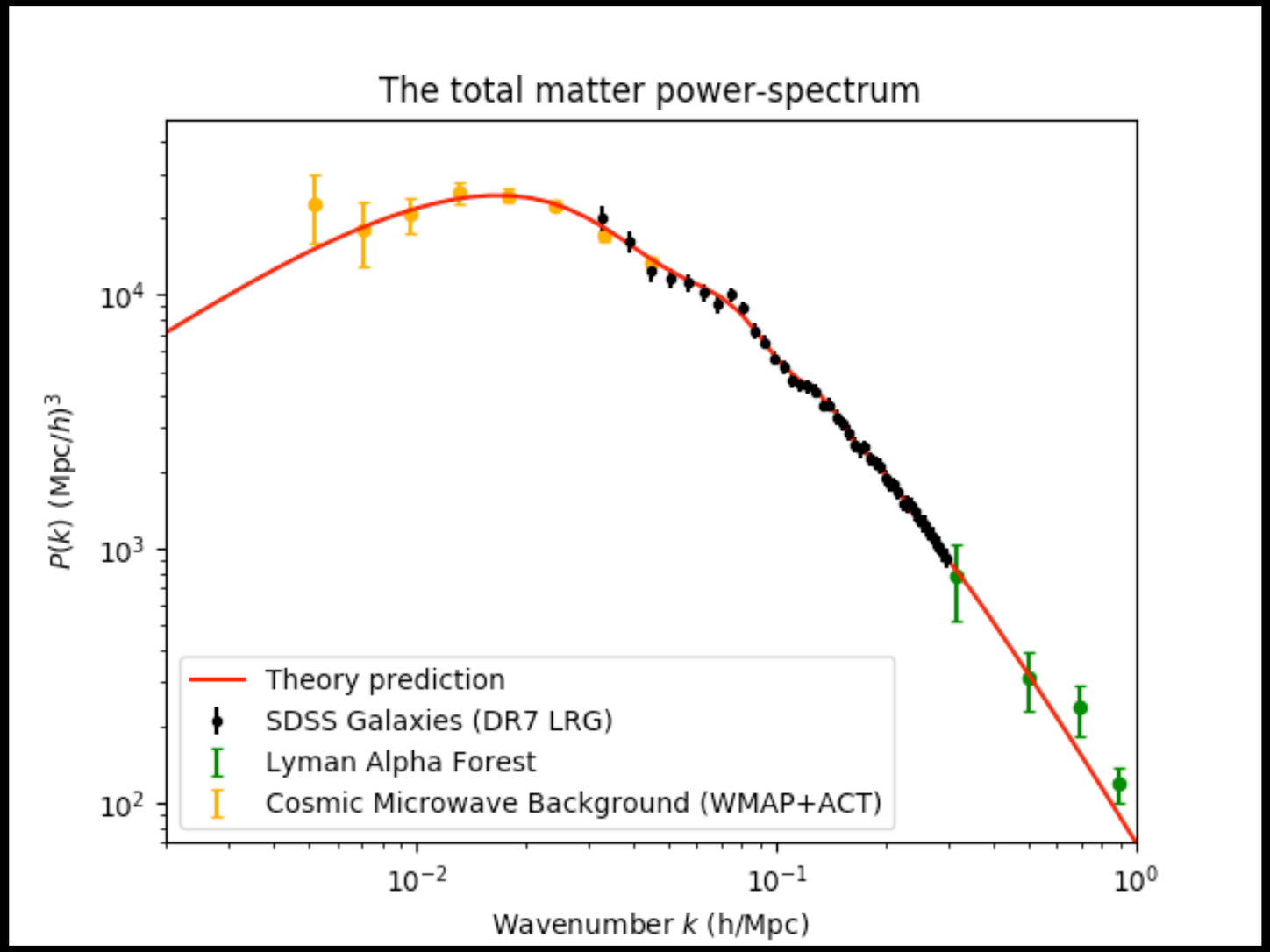
Matter Power Spectrum



- Baryon density at recombination calculated & measured to be $\Omega_b h^2 \sim 0.02$

- This density too small to account for structure formation

Matter Power Spectrum



- CMB measurements show total matter density must be $\Omega_m h^2 \sim 0.133$

- i.e. there must be some neutral matter accounting for structure formation - **dark matter**

- DM forms ~80% of total matter in Universe, SM only 20%

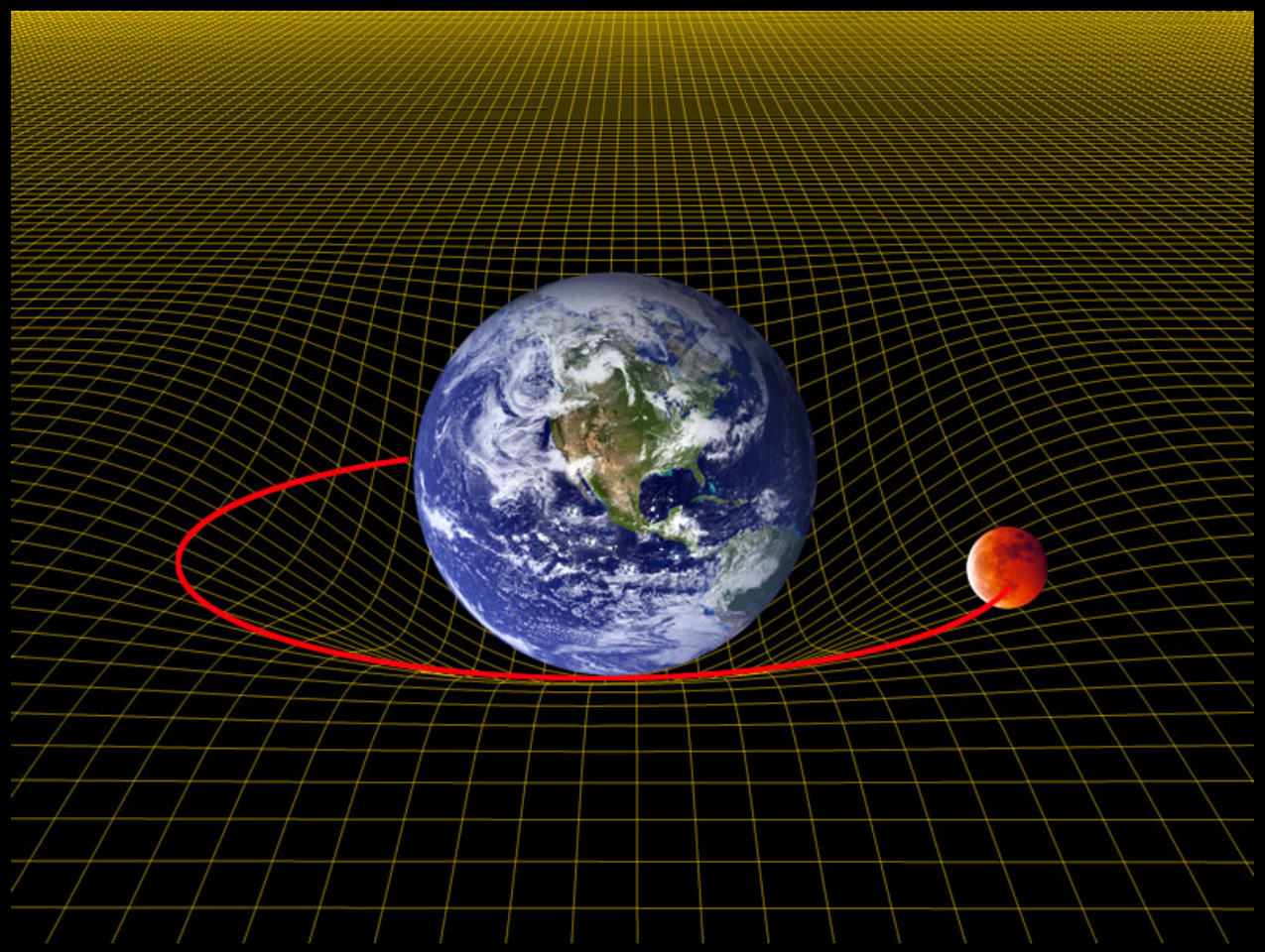
Why does dark matter Matter?

- Einstein's Gravity tells us that massive objects cause distortion in space-time continuum, bending it.

- Objects get trapped in gravitational potential wells formed as result

e.g.

Image: science photo library



Earth forms gravitational potential well for moon

Why does dark matter Matter?

Dark Matter has shaped the universe as we know it!

Visible matter particles get trapped by DM and form Galaxies, clusters, etc.

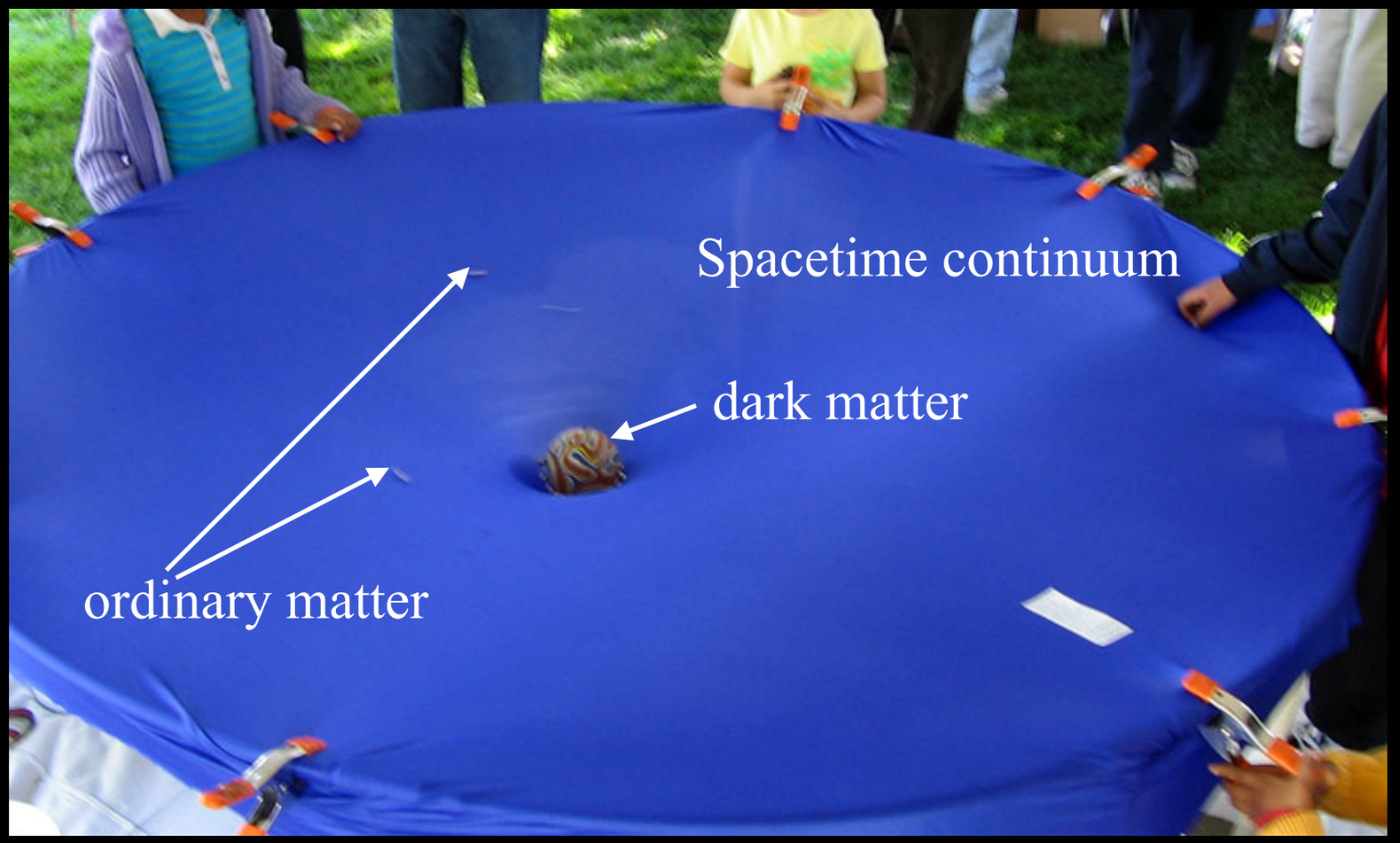
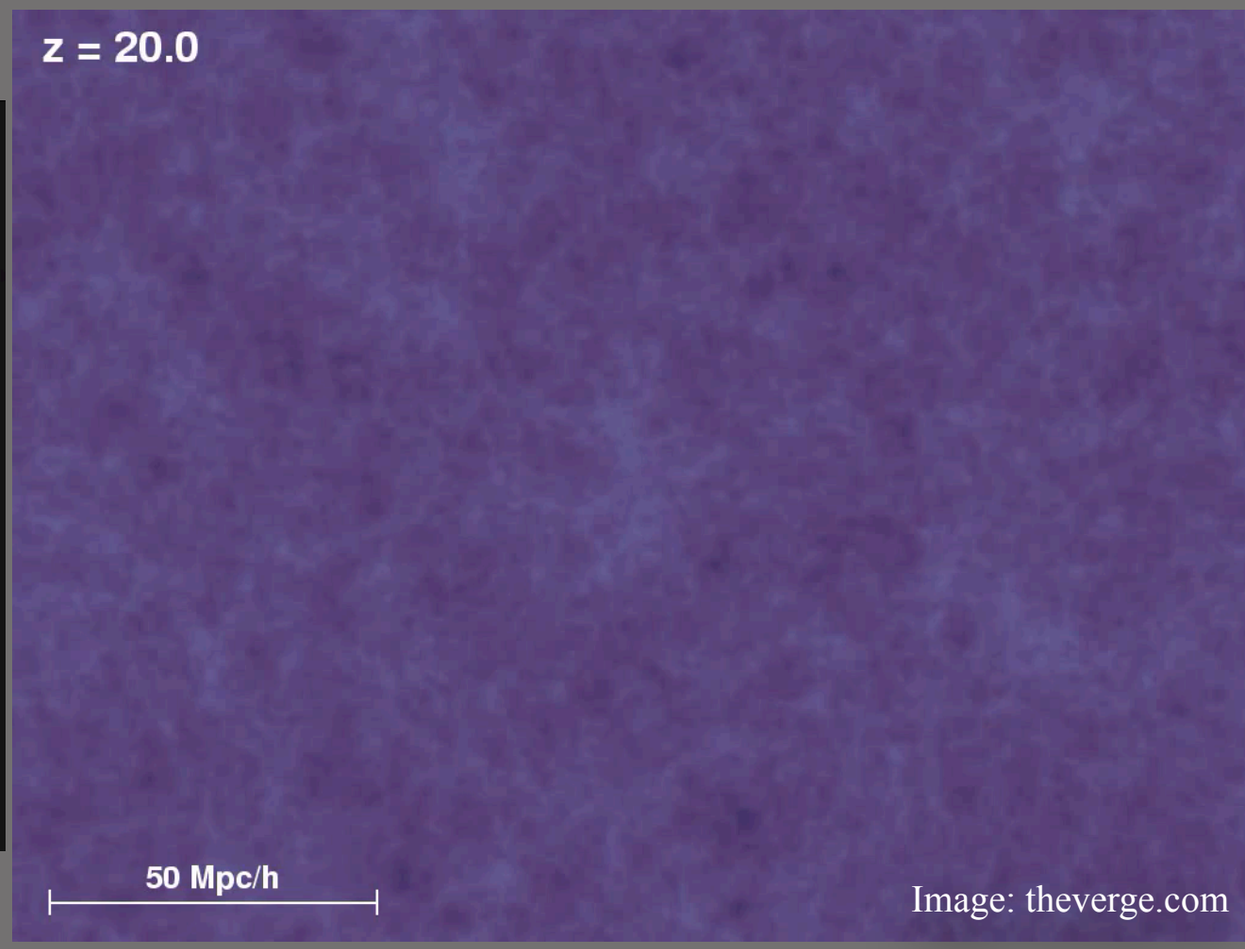


Image: einstein.stanford.edu

Cosmic glue that forms life

Structure Formation

Data



Simulation

What do we (don't) know about DM?

Inconvenient Truth about dark matter

It cannot be part of the standard model of particle physics

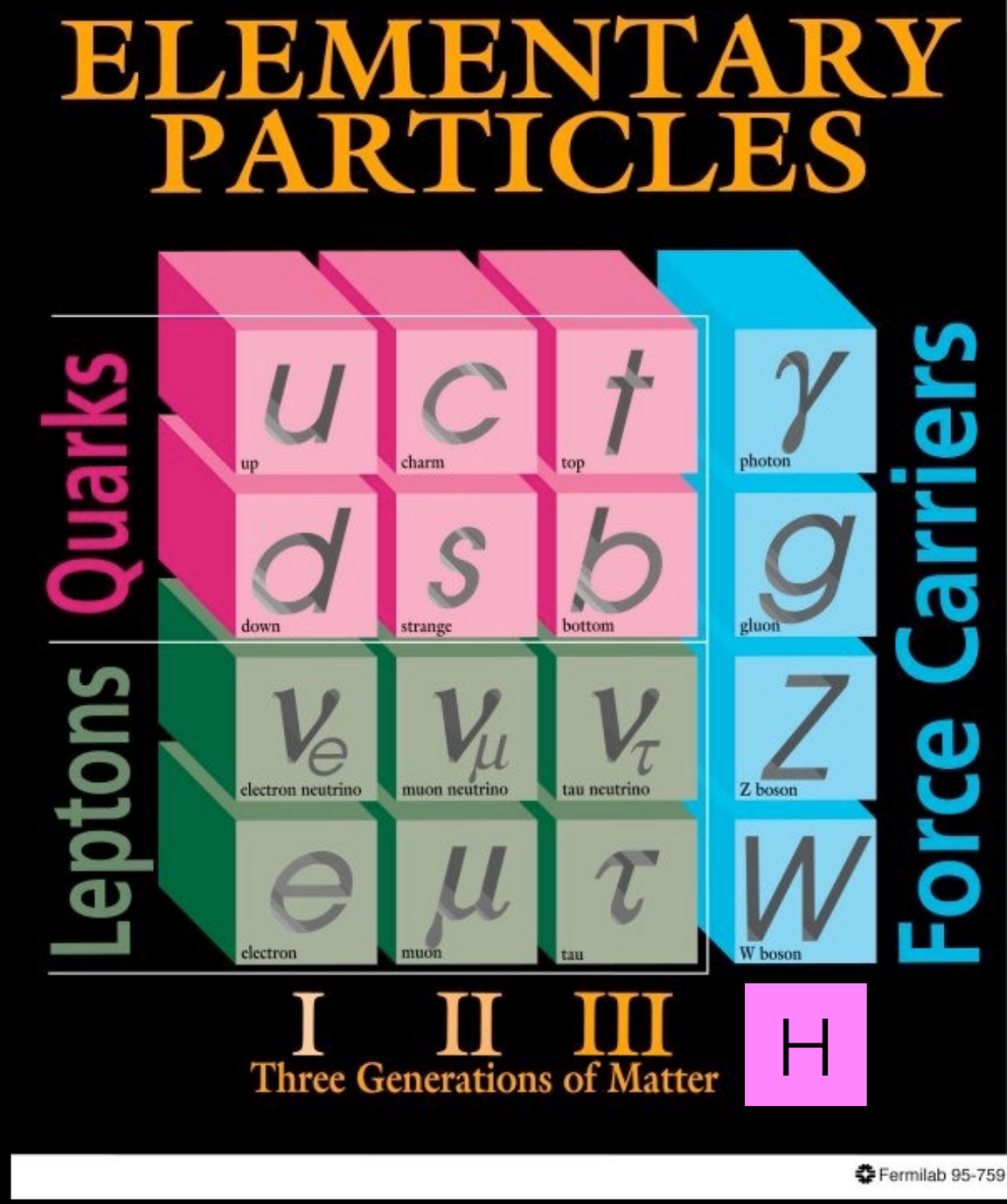
1. Mass = ???
2. Spin = ???
3. Decays = ???
4. Interactions = ***Gravity***, ???
5. Elementary = ???
6. …

If it is a particle must be **a new particle**

Physics beyond the Standard Model

(Lecture by Prof. Ilic)

- The Standard Model of particle physics has nothing with the right properties to be dark matter:
  - Photons, leptons, hadrons, and W bosons all shine too brightly.
  - Neutrinos are too light.
  - Z and Higgs bosons are too short-lived.
- Dark matter is a manifestation of physics beyond the Standard Model.
- We have **lots** of ideas for what it *could* be.



Dark Matter Questionnaire

- ☐ Mass
- ☐ Spin
- ☐ Stable?
  - ☐ Yes ☐ No

Couplings:

- ☑ Gravity
- ☐ Weak Interaction?
- ☐ Higgs?
- ☐ Quarks / Gluons?
- ☐ Leptons?

☐ Thermal Relic?

☐ Yes ☐ No

What is Dark Matter made of?

We simply have no idea.

We DO know:

- It must be cold (non-relativistic) at the time of structure formation
- It must be super long-lived or completely stable
- It must be some new state lying beyond the SM

Non-EM interacting
Non-QCD interacting

Dark Matter should be described by a quantum field corresponding to a definite spin, uncharged under $U(1)_{EM}$ or $SU(3)_C$.

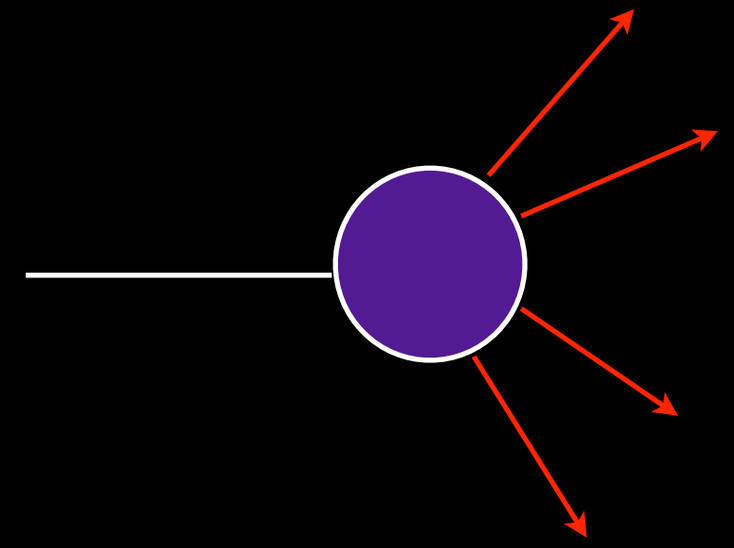
(So: no tree-level interactions with gluons or photons).

- It **may** interact with the SM through some new force

Dark Matter Stability

- One of the mysteries of dark matter is why it is very massive but (at least to very good approximation) stable.

- This is actually telling us something very important about how it can interact with the Standard Model.



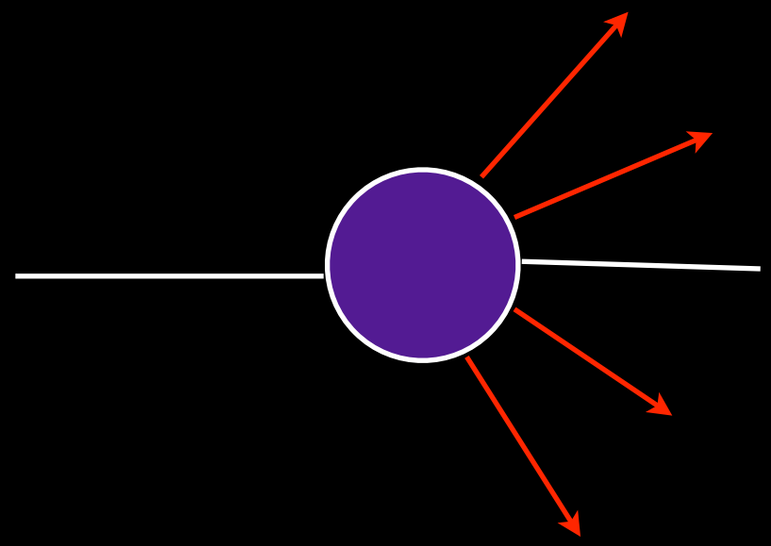
χ decays.

- We need a symmetry (at least approximately) to prevent dark matter particles from decaying.

- The simplest example is a new kind of parity (a Z_2 discrete symmetry), under which the dark matter transforms, but the Standard Model does not.

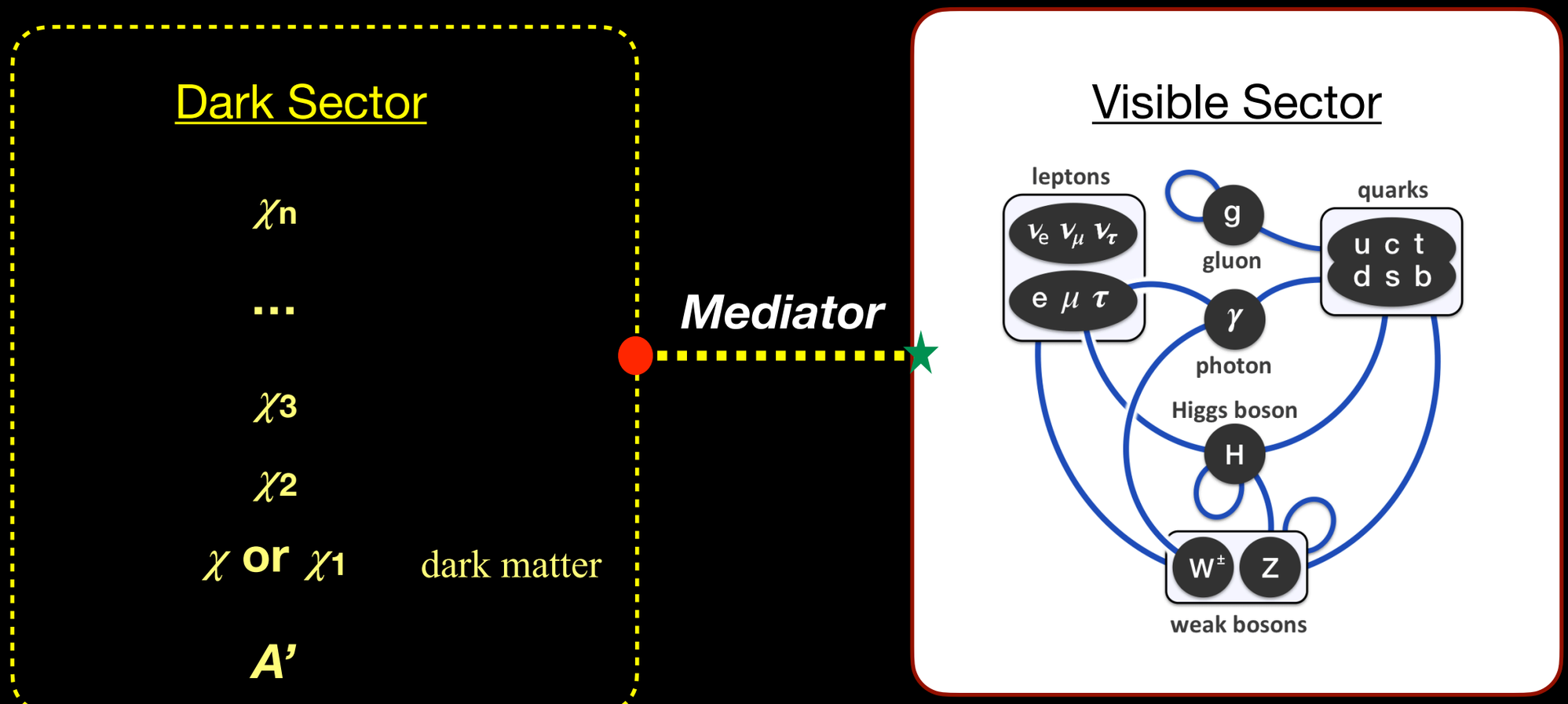
Z_2: $\chi \to -\chi$ $\qquad$ $\mathrm{SM} \to +\mathrm{SM}$

- This symmetry requires the dark matter to couple in pairs to SM fields, and prevents decay processes from happening.



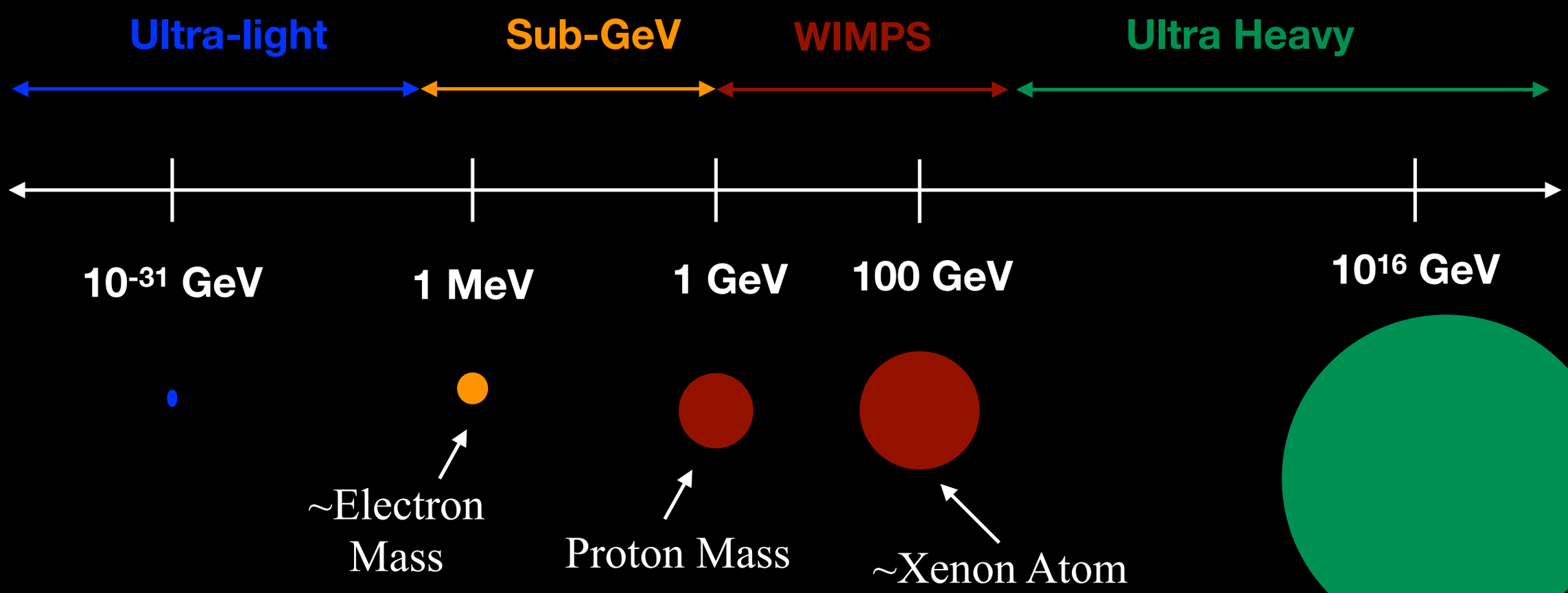
The number of χ's is conserved.

Dark Matter and the Dark Sector



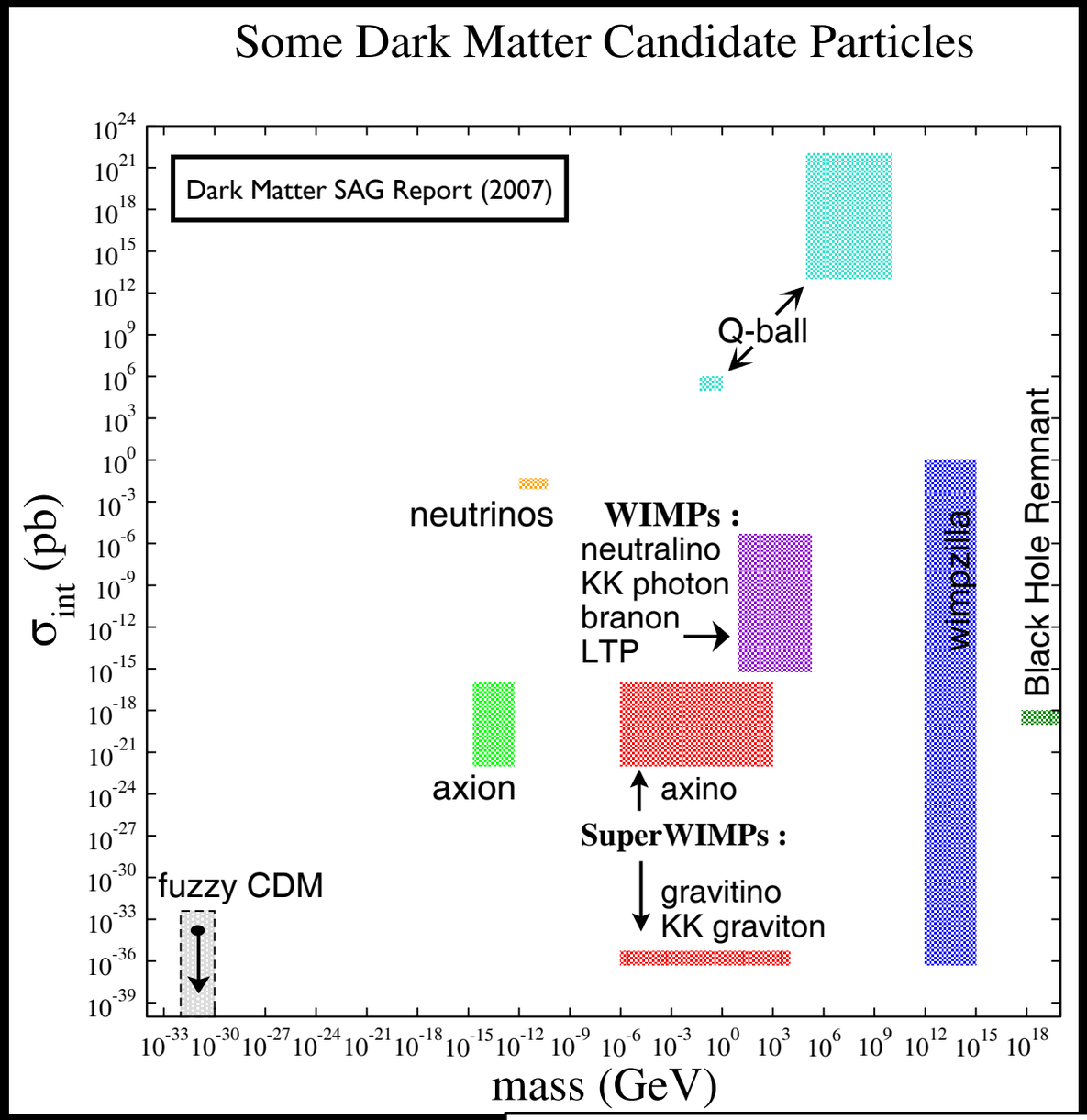
A dark sector is a group of related particles, one of which is dark matter

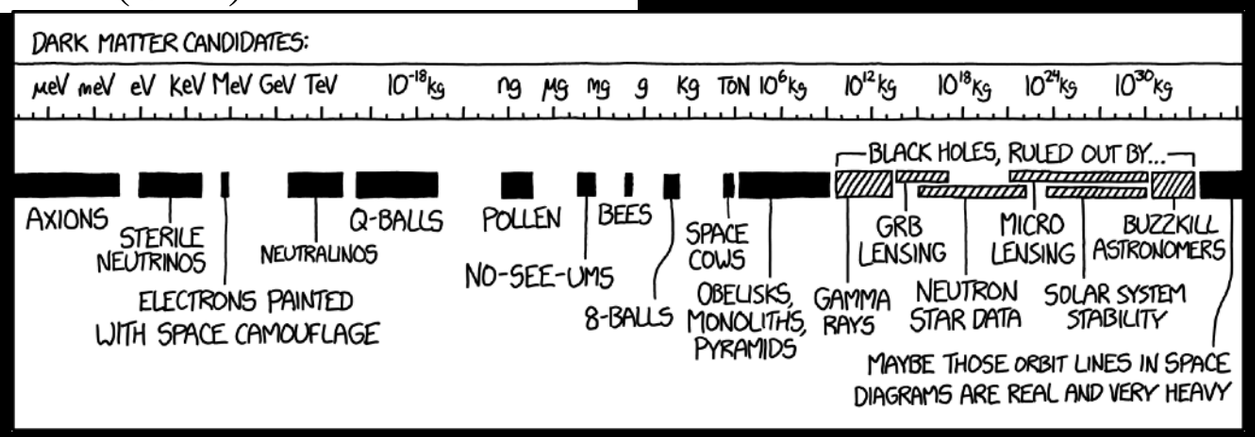
Range of Dark Matter Possibilities is VAST



Primordial Blackholes - much heavier than Ultra heavy

Wide Ranging Parameters

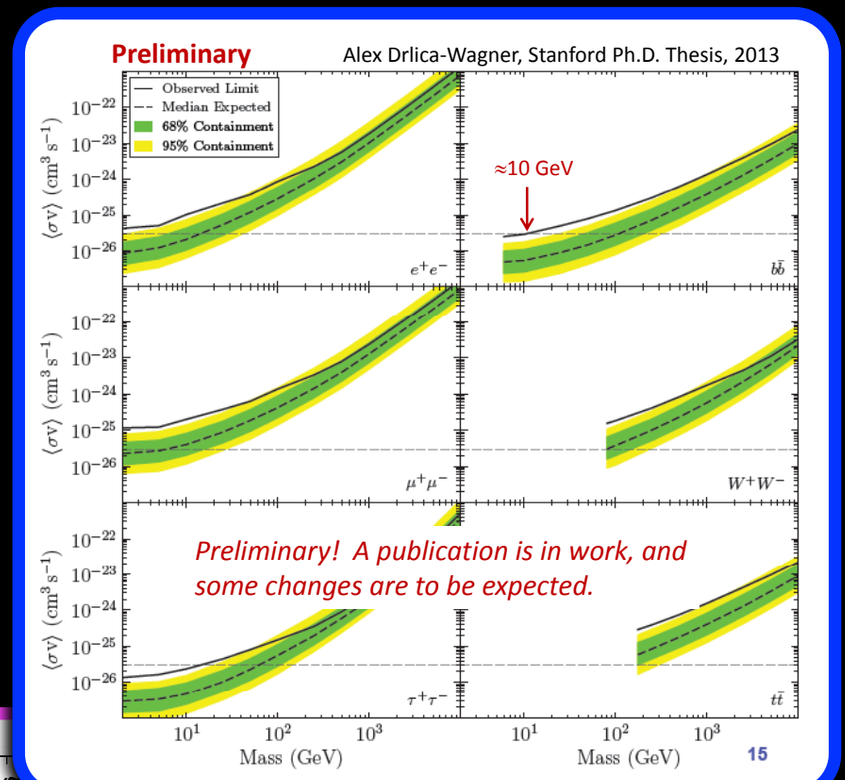


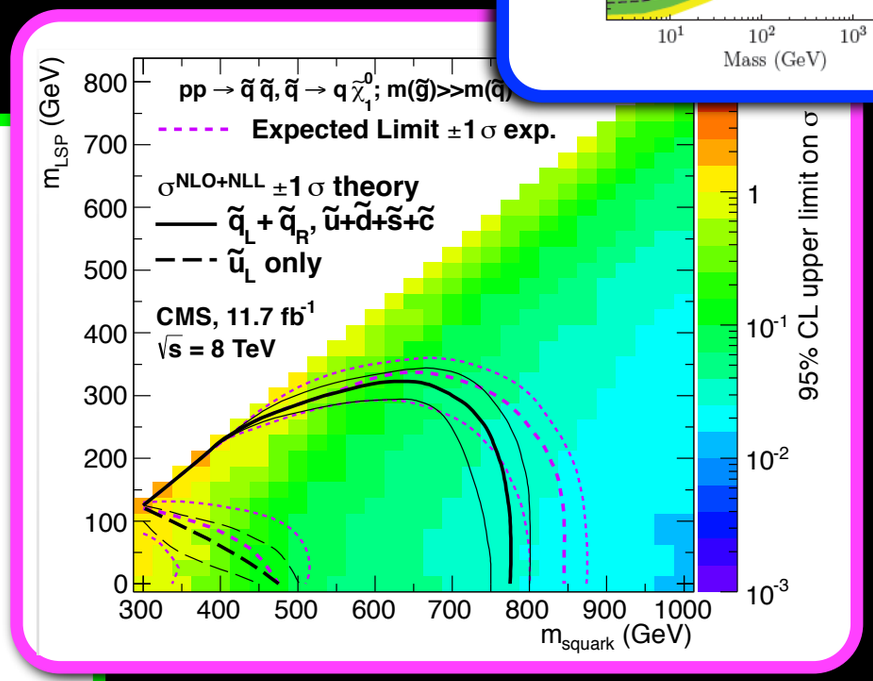


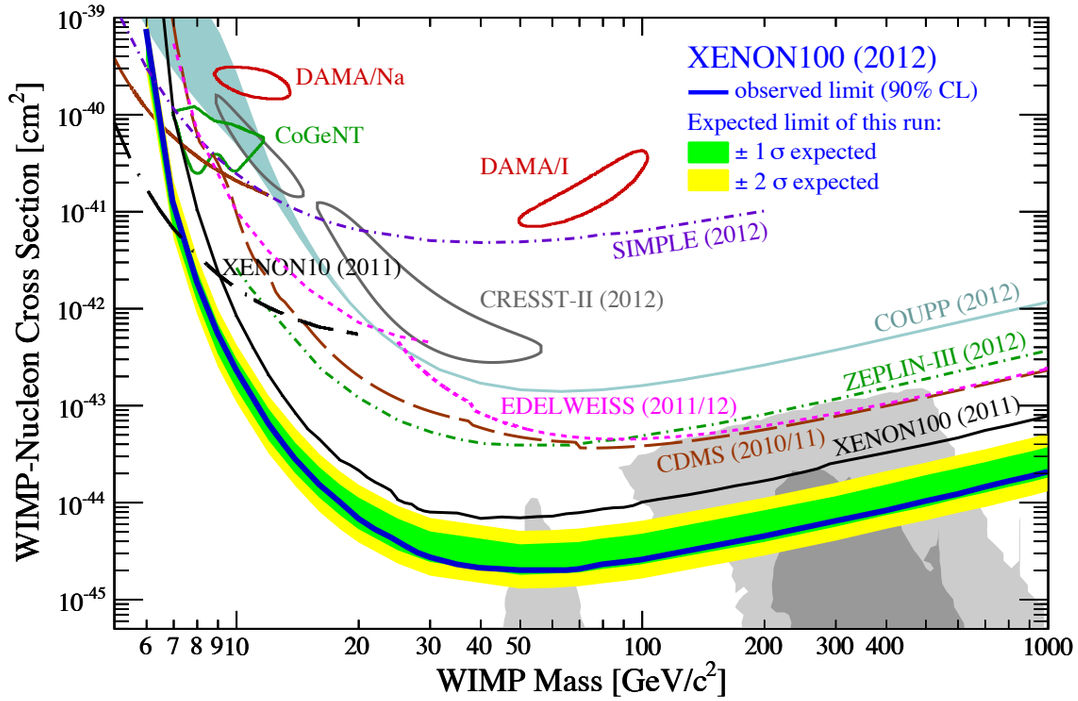
We Need Theories

Searches for dark matter and dark sectors of all kinds put limits on different observables. Without some kind of theoretical structure, we can't compare them.

We need to know how they fit together, and whether there are ideas out there worth testing by a given experiment.







Range of Possible Theories is VAST

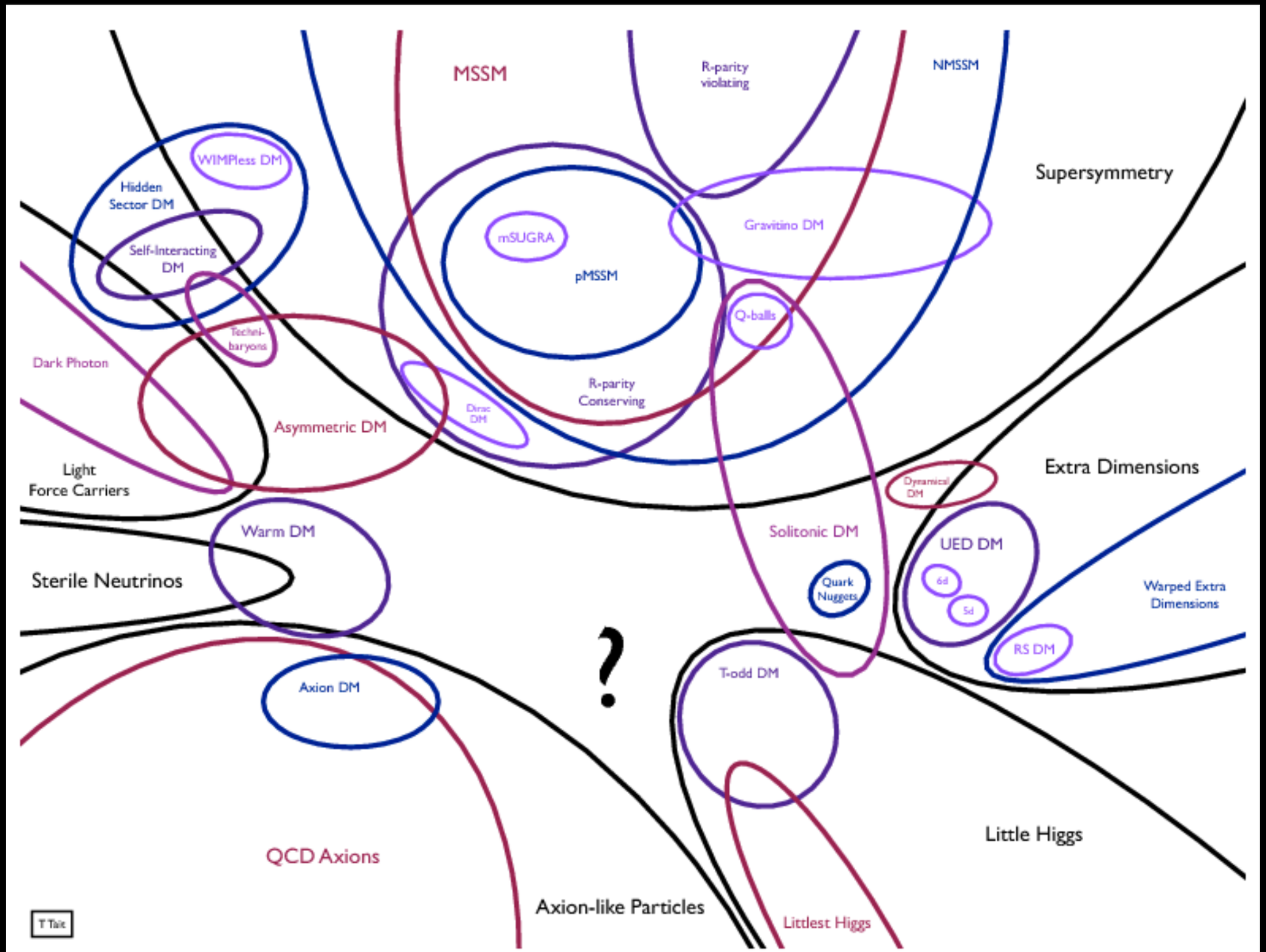
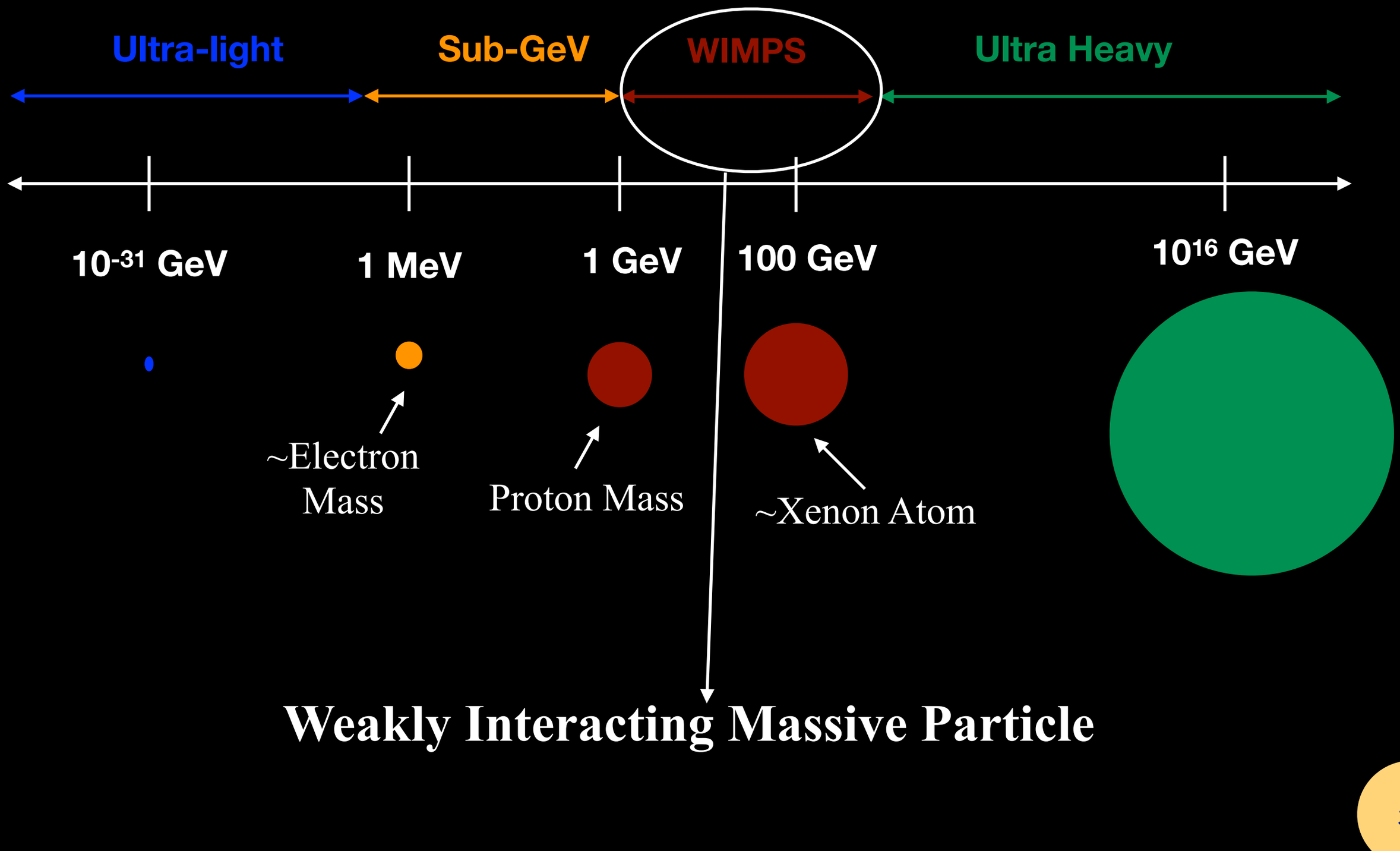


Image: ps.uci.edu

Most searched for Candidate: WIMP



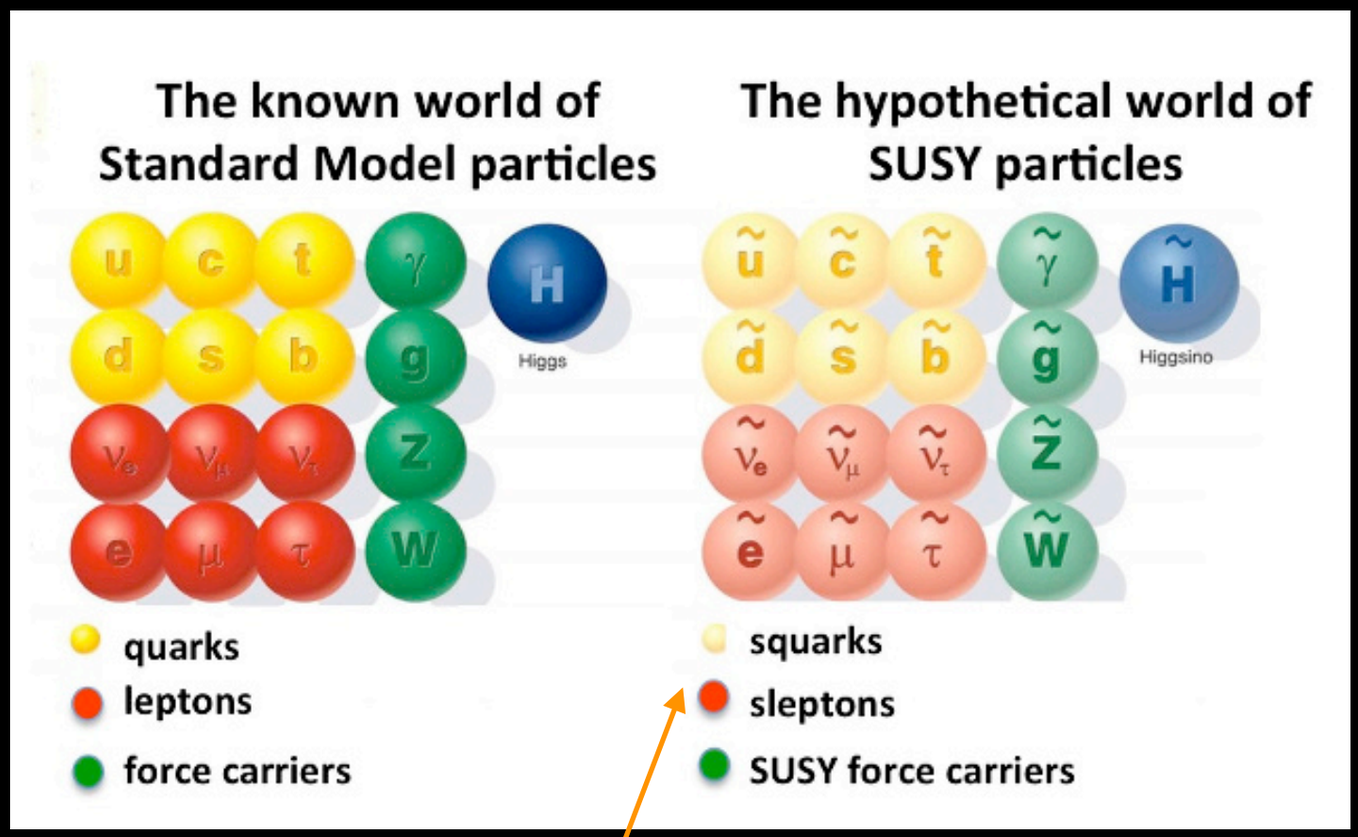
Story starts with Hierarchy Problem

(Lectures by Prof. N. Ilic)

About 20-30 years ago particle physicists were trying to understand

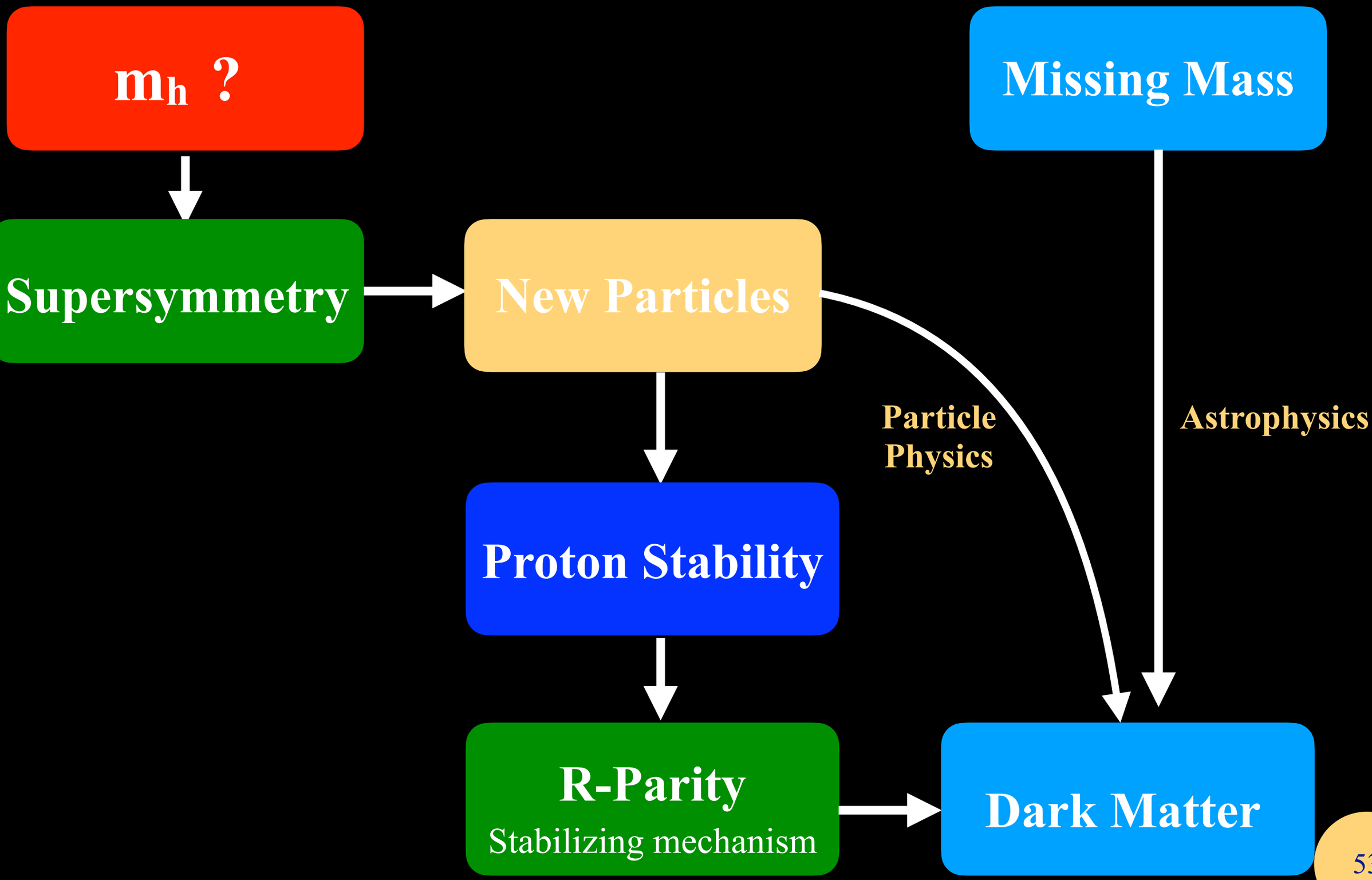
Why is the Higgs mass so small?

Higgs boson has mass of 125 GeV

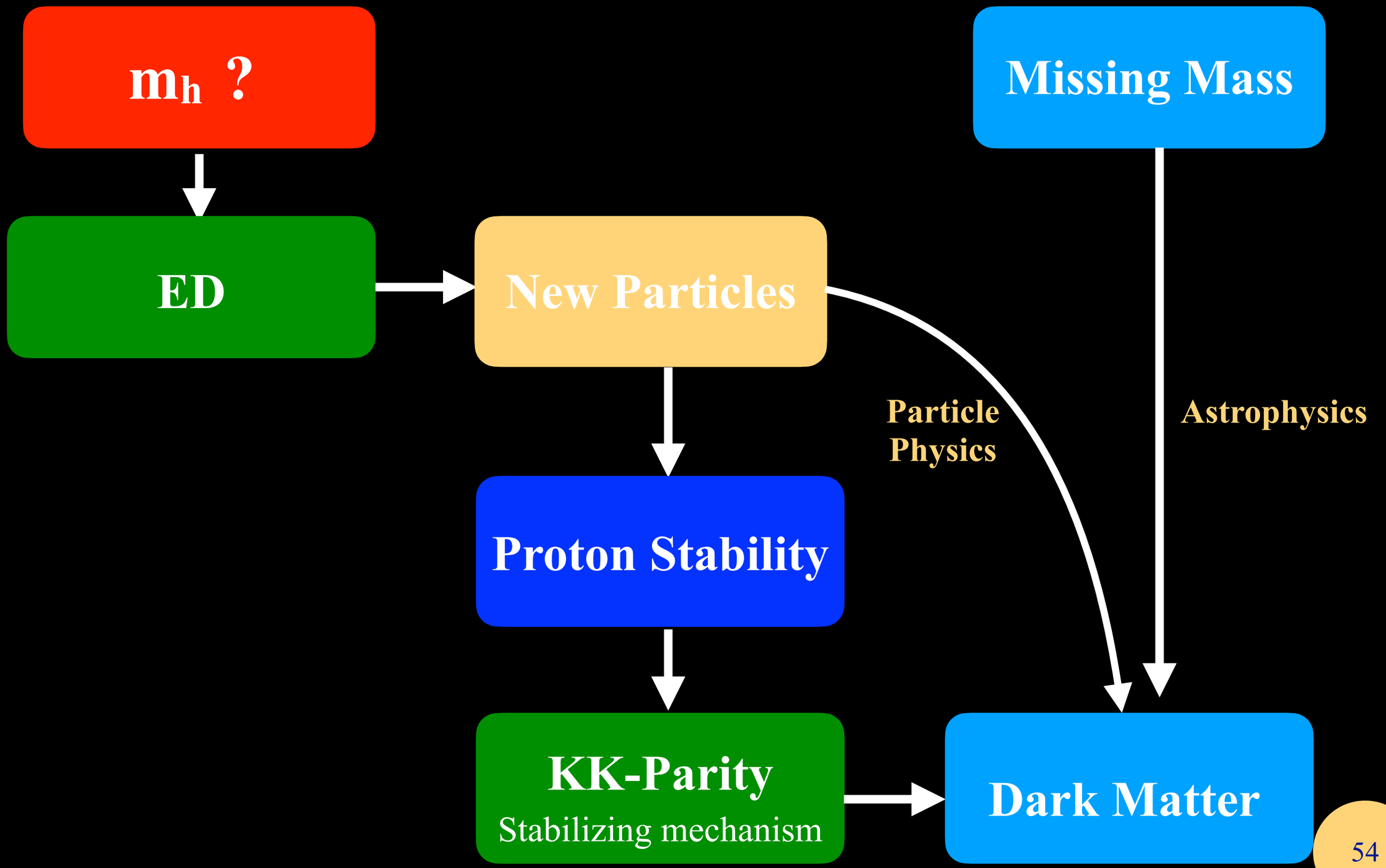


One solution is a new theory called **Supersymmetry**

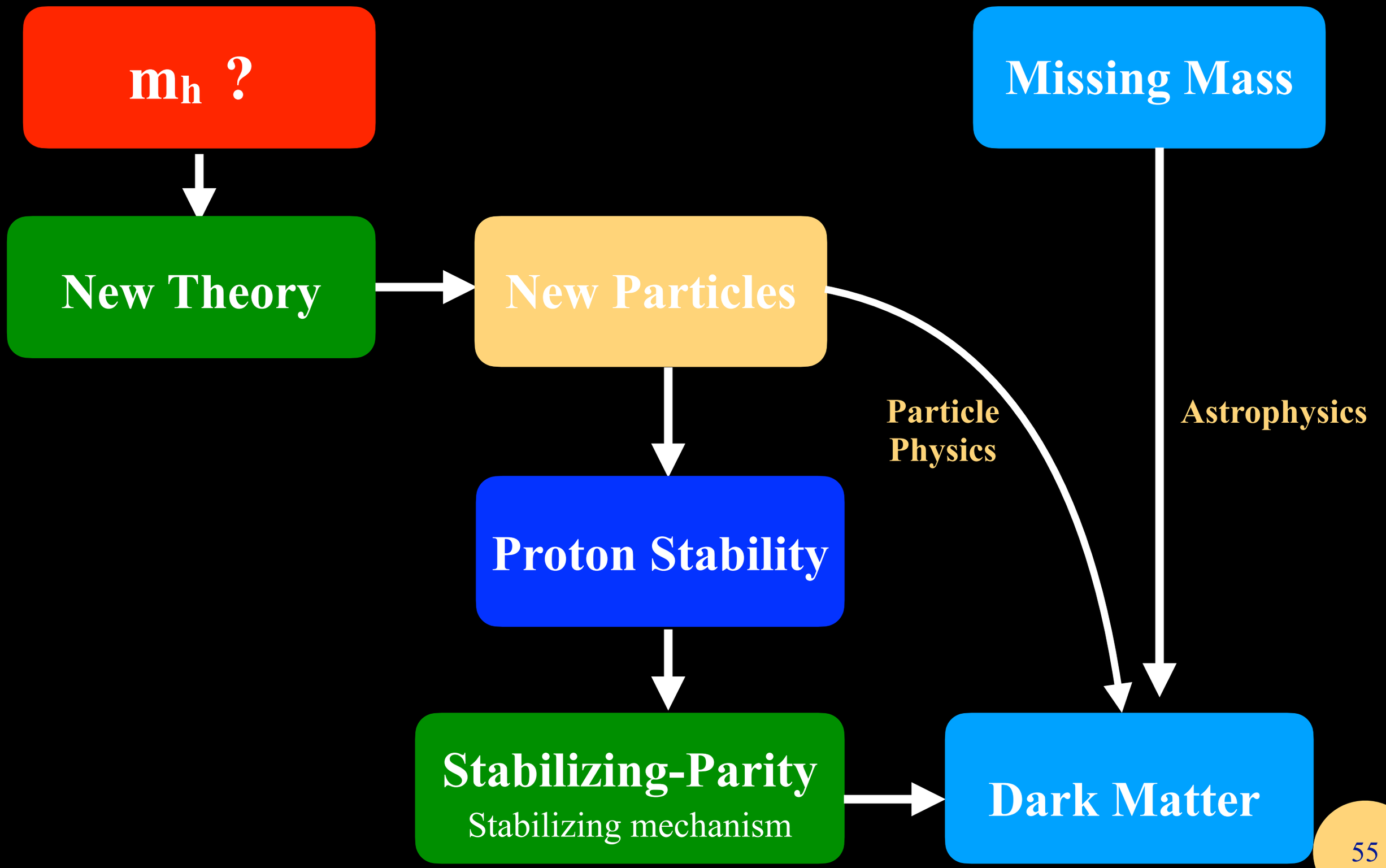
Story so far: Supersymmetry



Another solution: Extra Dimensions



Applies to any solution of hierarchy problem



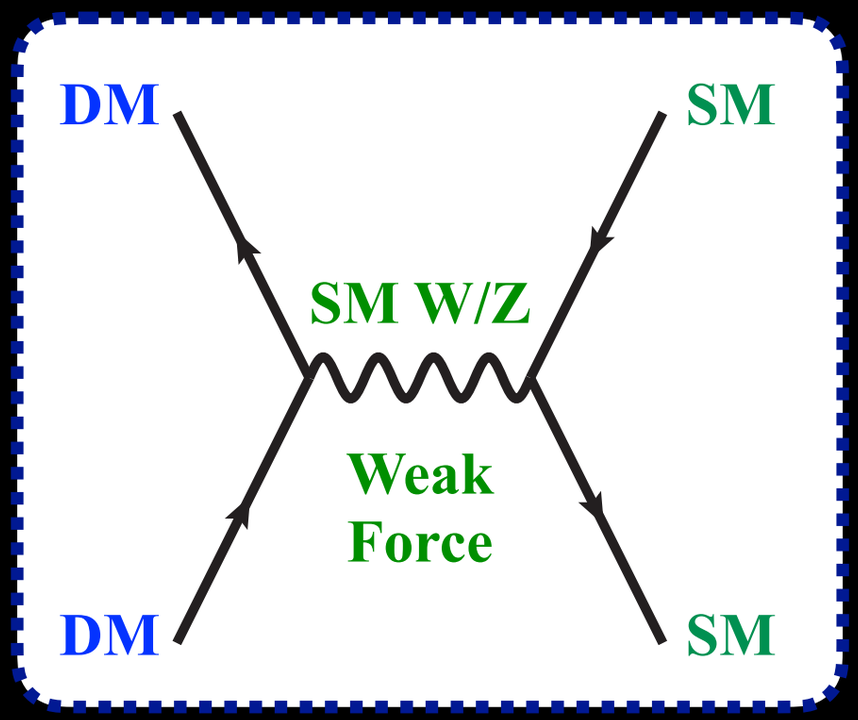
Solving the Hierarchy problem resulted in a perfect class of dark matter candidates called

Weakly-Interacting Massive Particles

"Electroweak" interactions ($W^{\pm}$, Z, h)

"weak-scale" mass
1 - 10 000 GeV

Explains: **Why so much dark matter around**



Dark matter annihilation

Observed **amount of dark matter** today → 'Relic Density'

$$\Omega h^2 \sim \frac{0.1 \text{ pb}}{\langle \sigma v \rangle}$$

Weak scale
annihilation rate

Recap: lecture 1

- We have much astrophysical evidence that dark matter exists

- We do not know what it is, but we know what properties it must have and non of the SM particles fit the profile

- We know that: 1. It must be stable
2. Non relativistic
3. Must not interact via SM charges

- Many possibilities of what DM could be

- Very well motivated possibility called WIMP

Next lecture we will talk about how to detect dark matter

Questions?