Dark Matter Overview

Gopolang Mohlabeng

McDonald Institute Astroparticle physics Summer Workshop

5th EIEIOO

5 May 2023

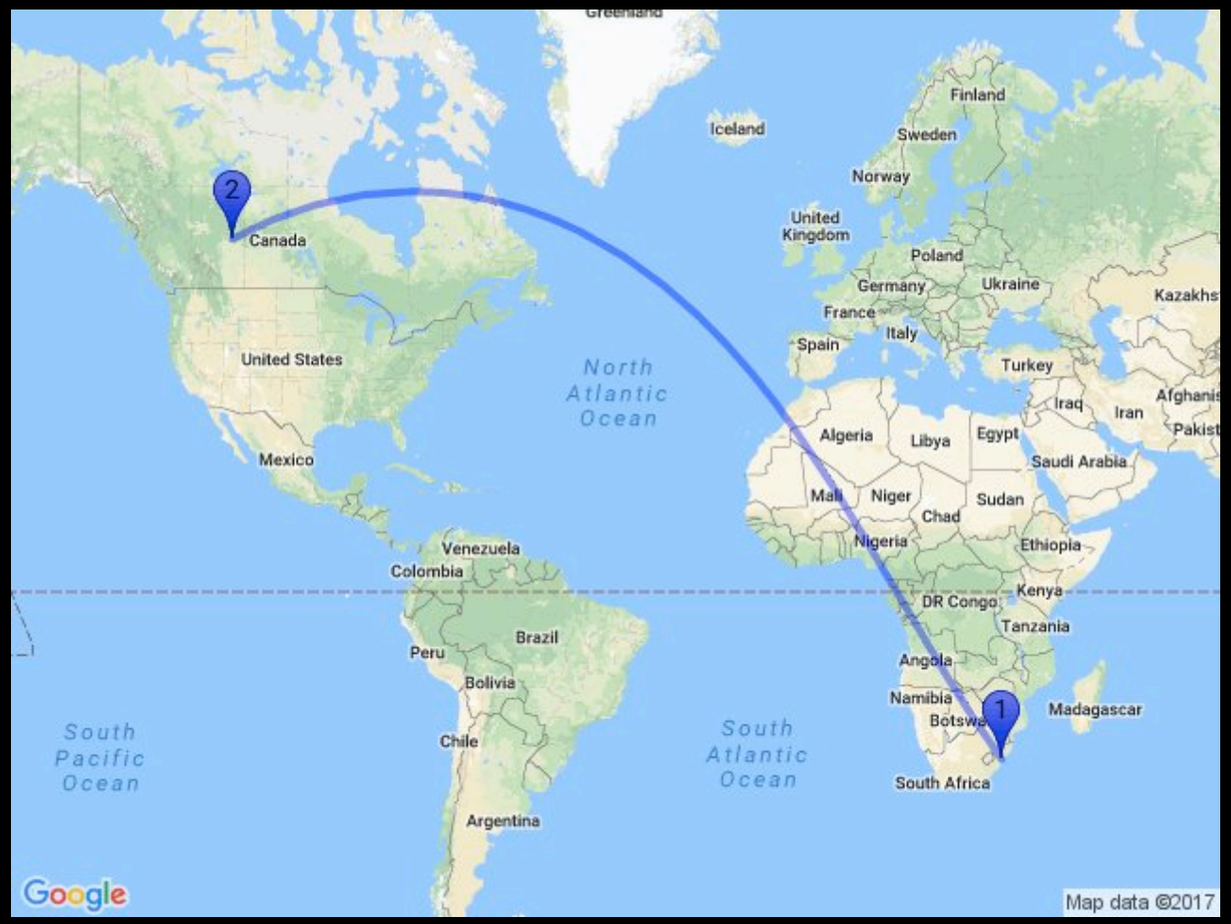
Who am I?

My name is Dr. Gopolang Mohlabeng

I am from South Africa

2010: Undergrad, Physics -
University of Cape Town

2017: PhD Physics -
University of Kansas



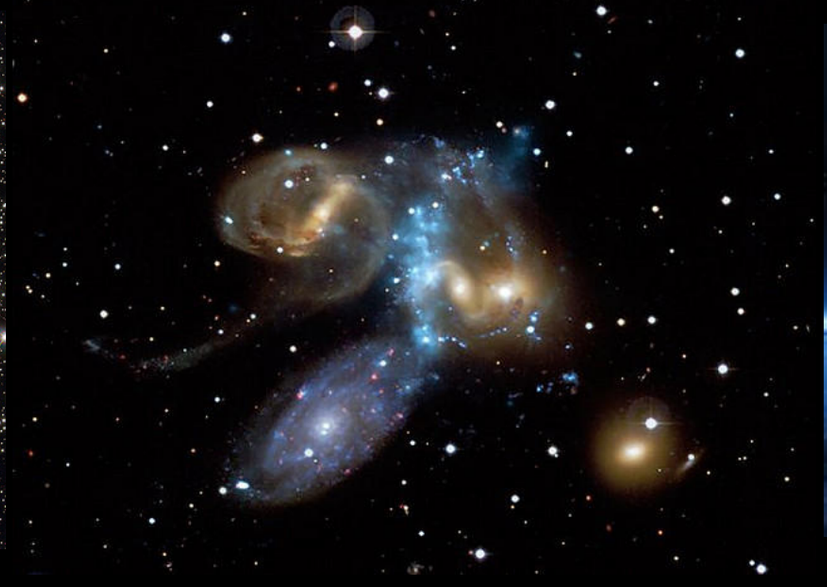
What I do: Postdoctoral Researcher at University of California, Irvine

Assistant professor at Simon Fraser University, Fall 2023

Area of expertise: Dark matter theorist

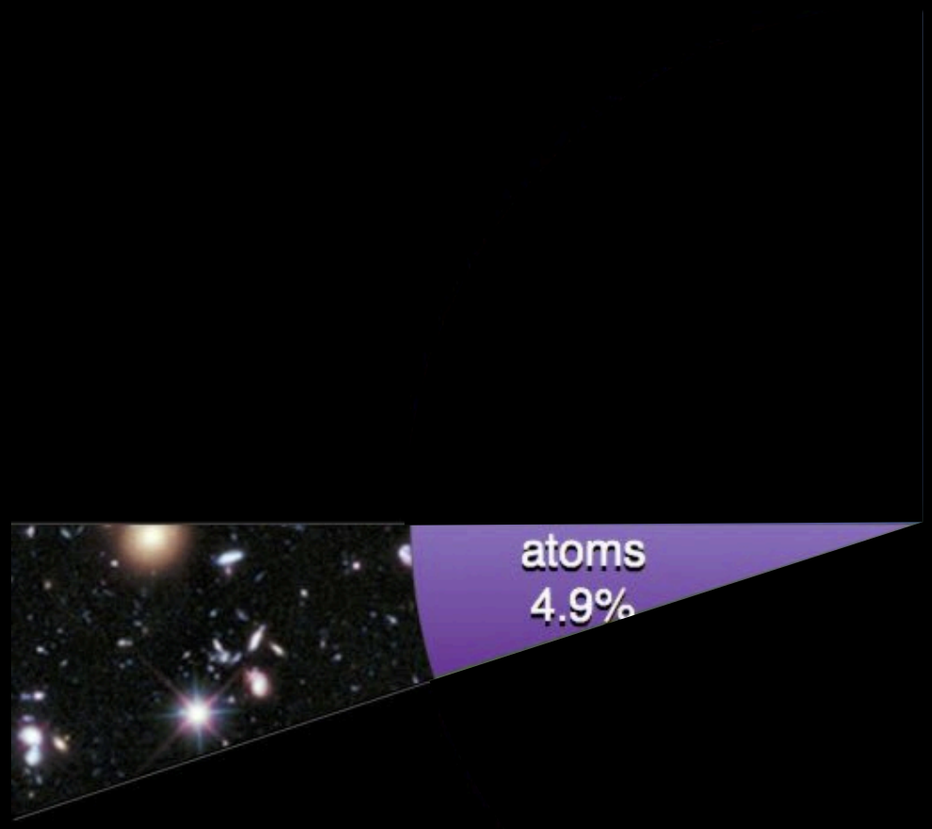
Build DM theories and compare them to data

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

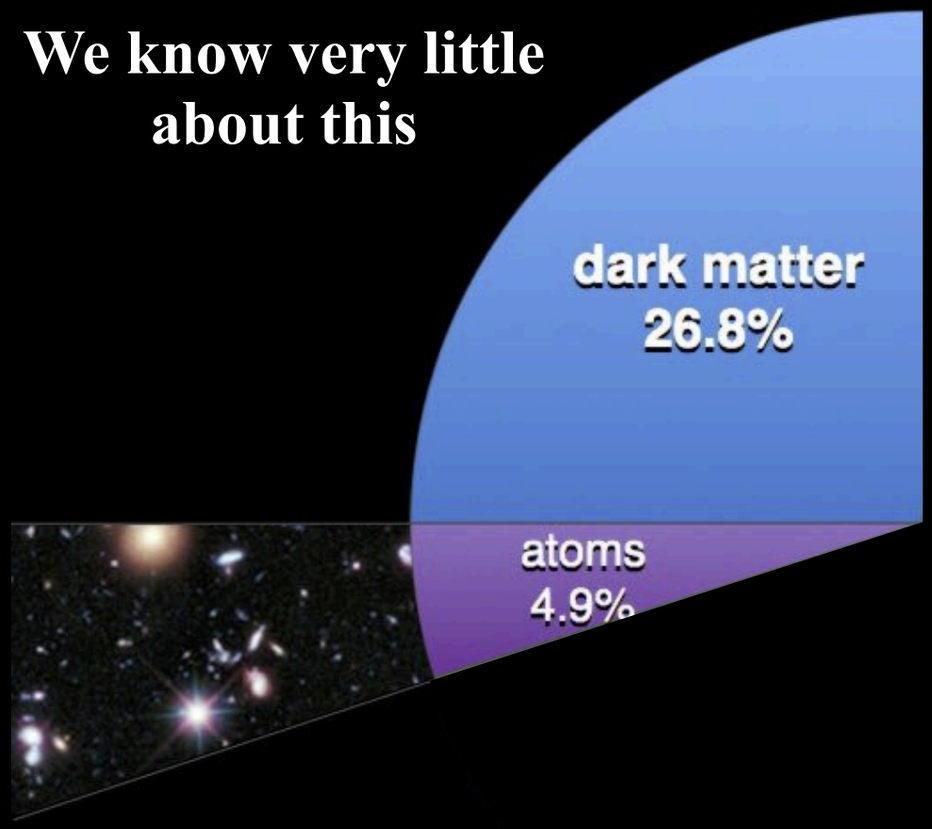


We don’t know what all this other stuff is

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

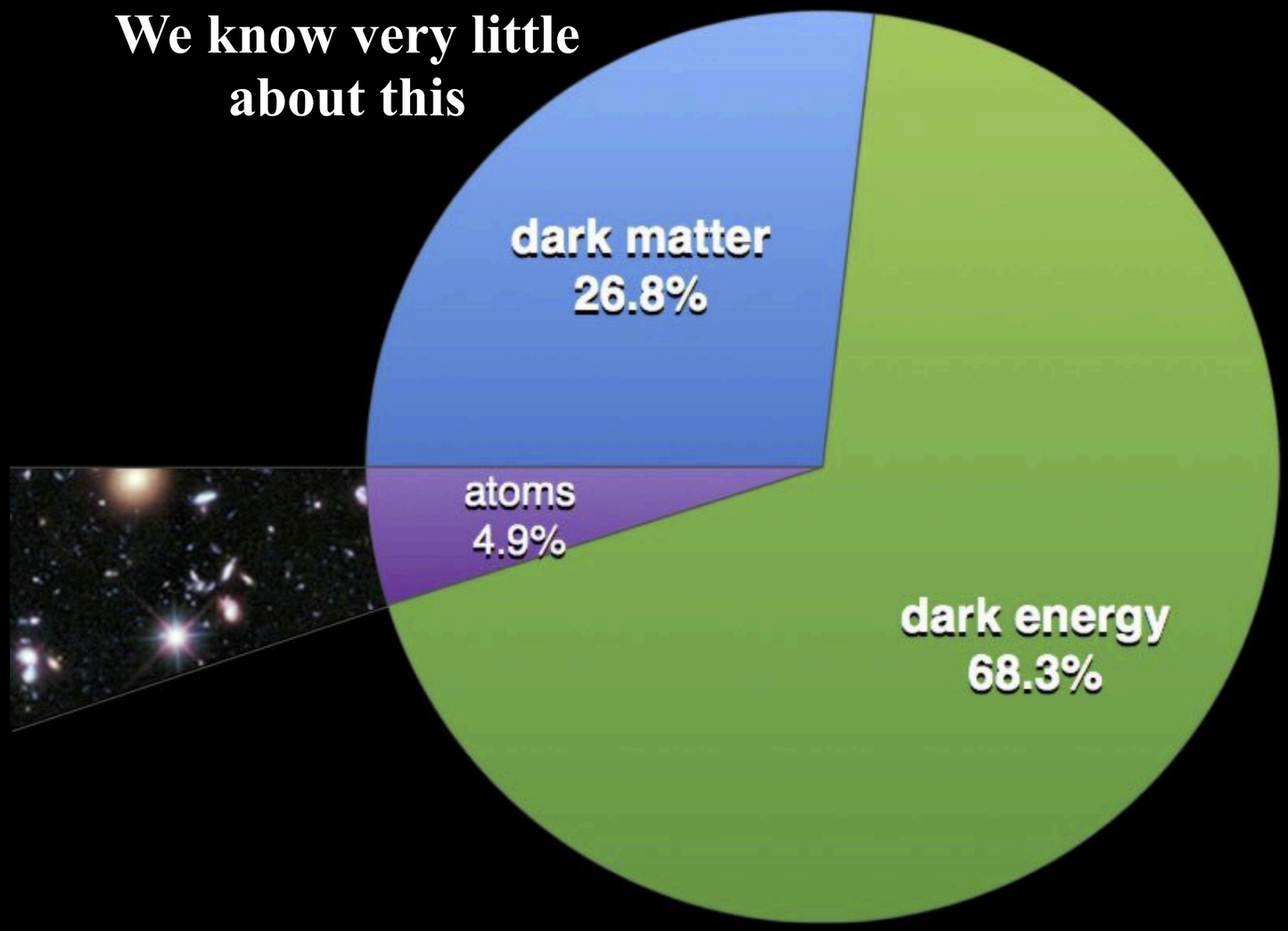
A very large component of our universe is “Dark”

We know very little about this



A very large component of our universe is “Dark”

We know very little about this



We know almost nothing about this

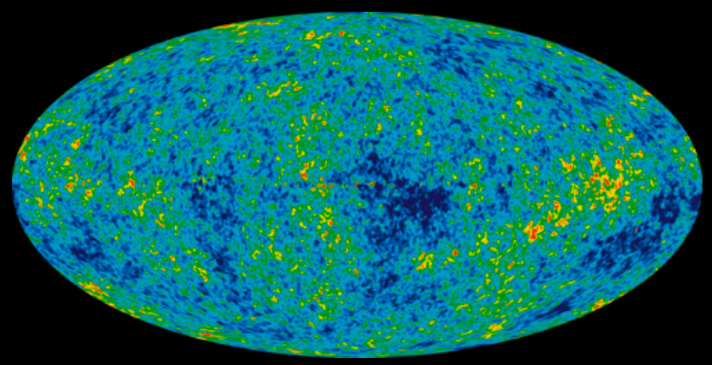
What we will cover in this lecture

1. How do we know dark matter exists?

What galaxies tell us

What clusters of galaxies tell us

What an infant Universe tells us

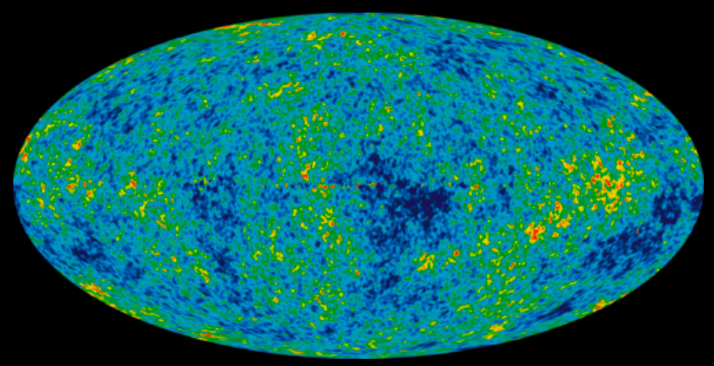


1. How do we know dark matter exists?

What galaxies tell us

What clusters of galaxies tell us

What an infant Universe tells us



governed by gravity

2. What we (don’t) know about DM?

What DM could be

3. How do we find DM?

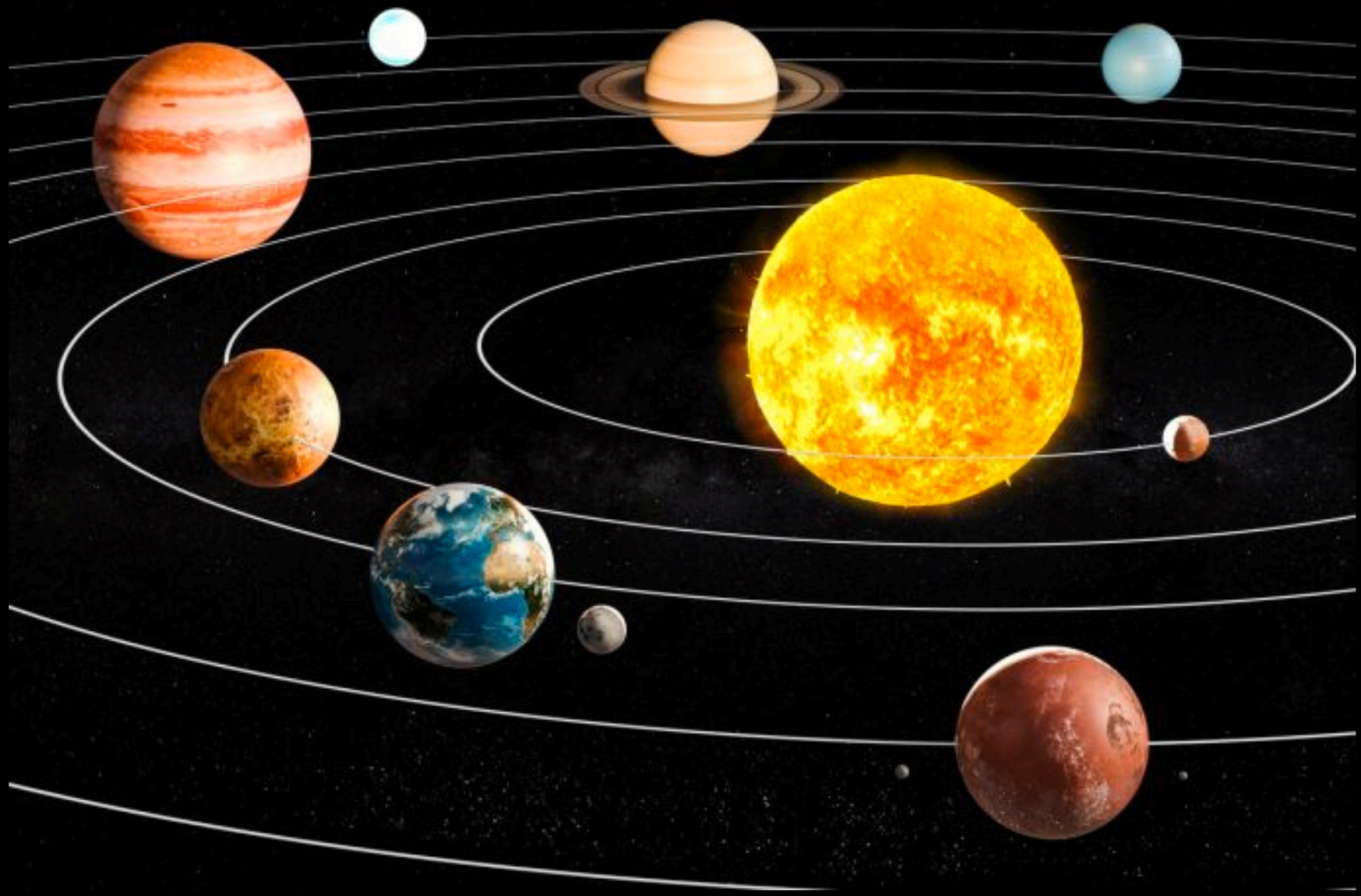
In the sky

In the laboratory

Deep underground

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

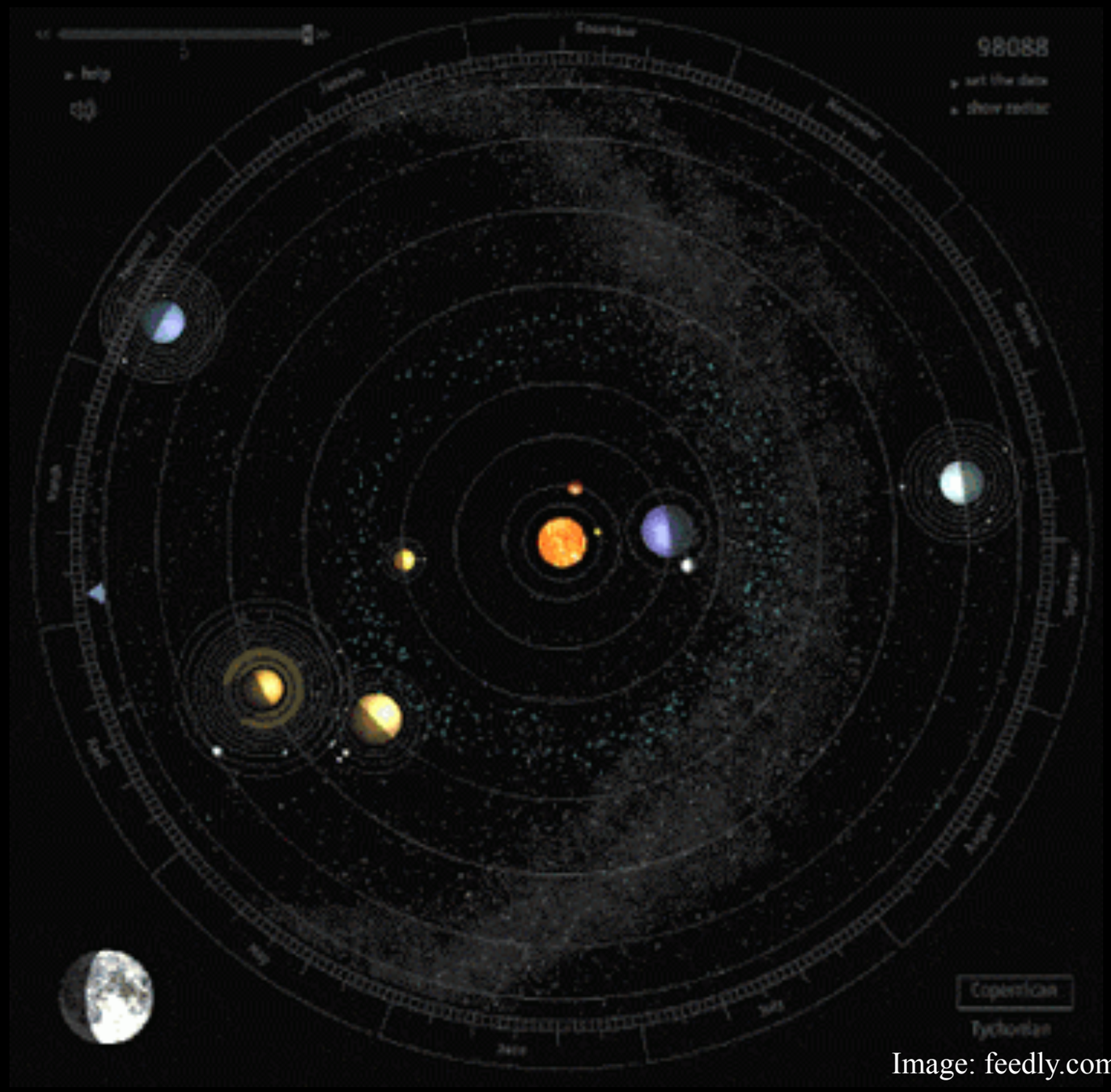


Image: feedly.com

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

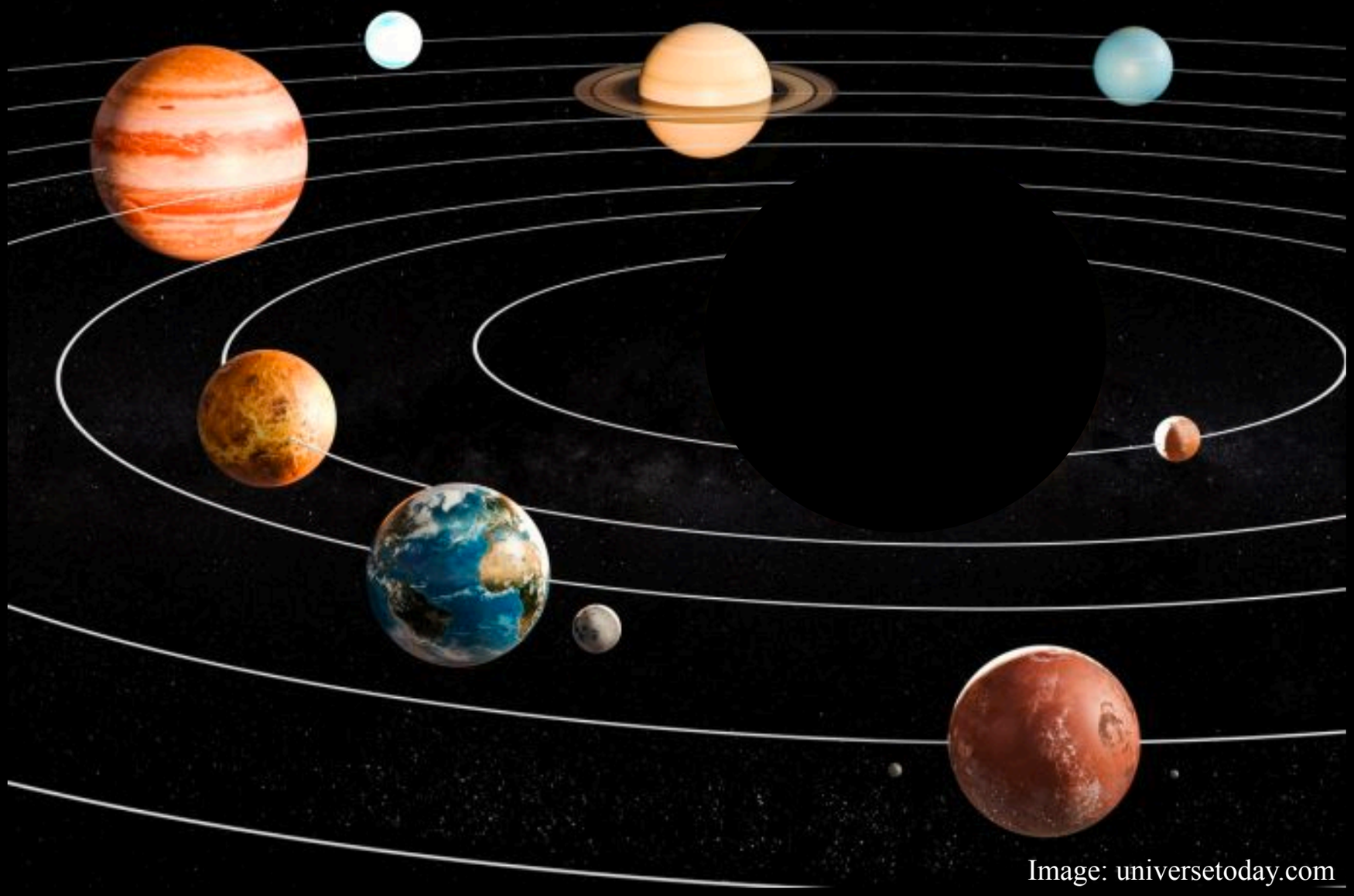


Image: universetoday.com

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

2×10^{30} kg

Early evidence

1884 - Lord Kelvin

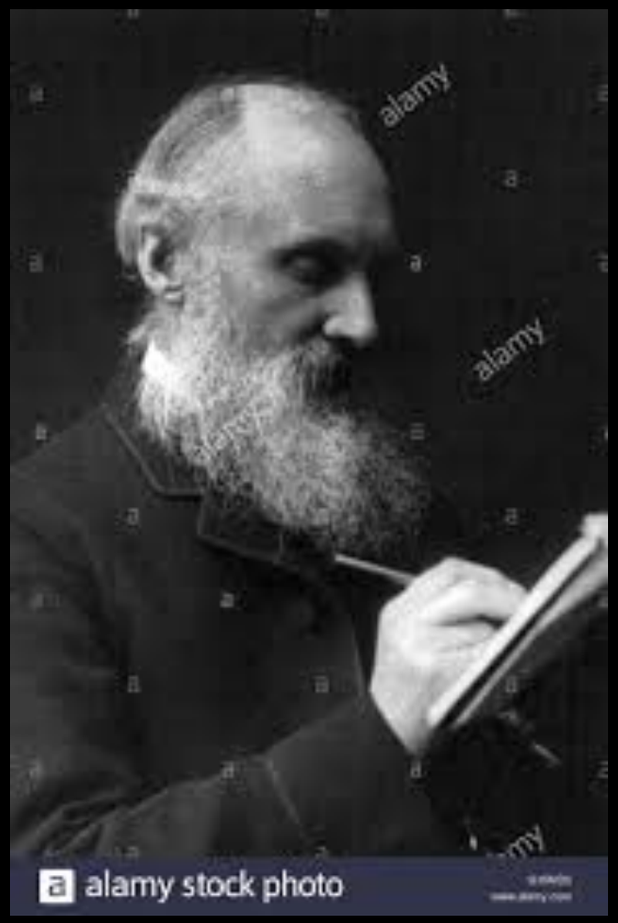


Image: alamy.com

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

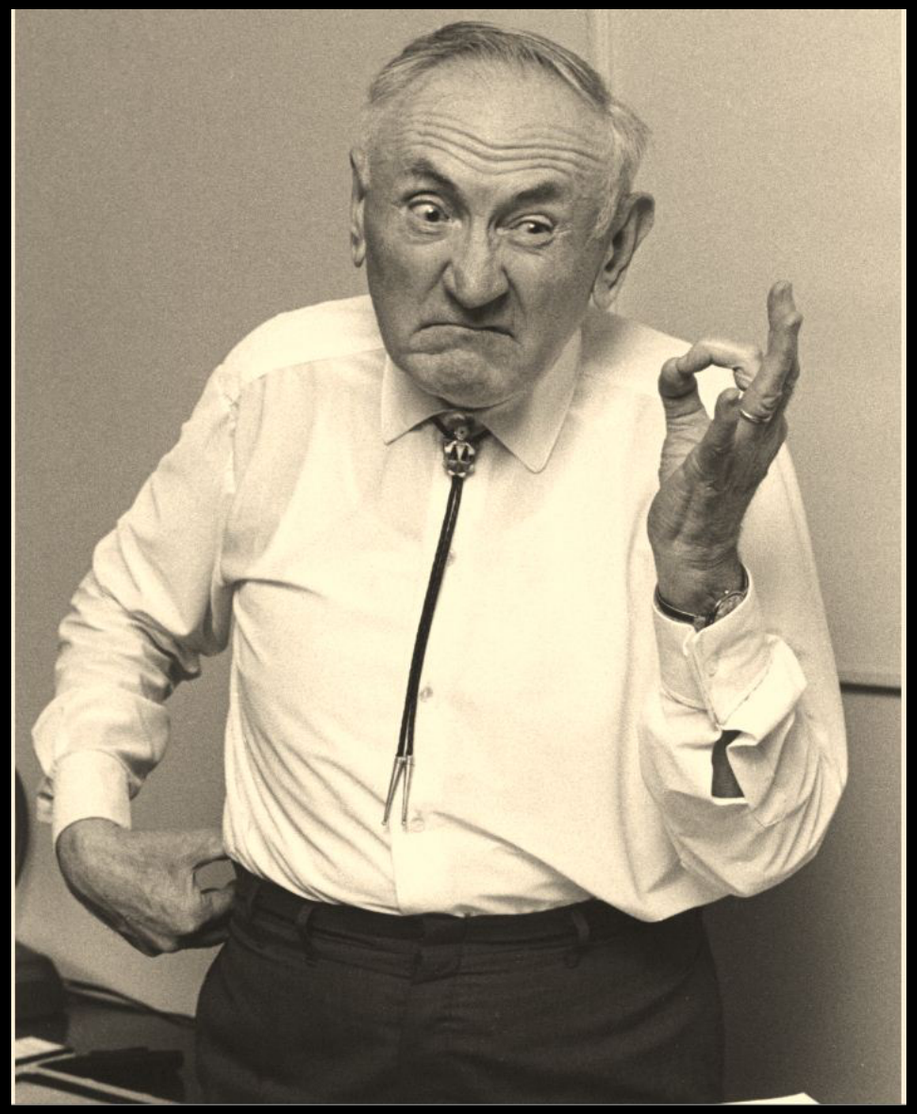


Image: Caltech Archives

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

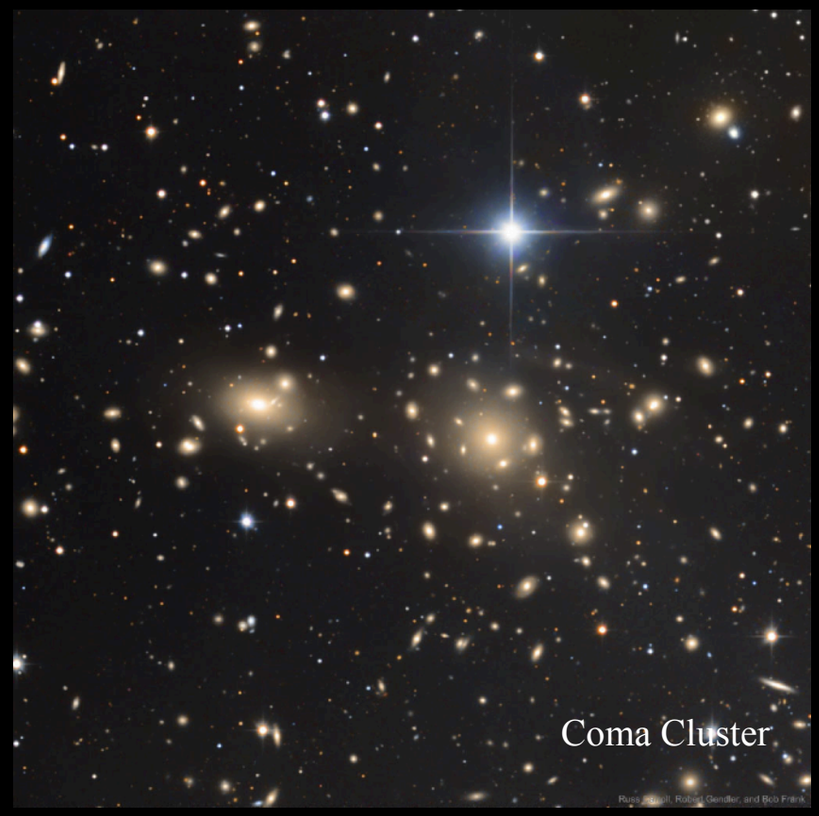


Image: NASA APoD

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

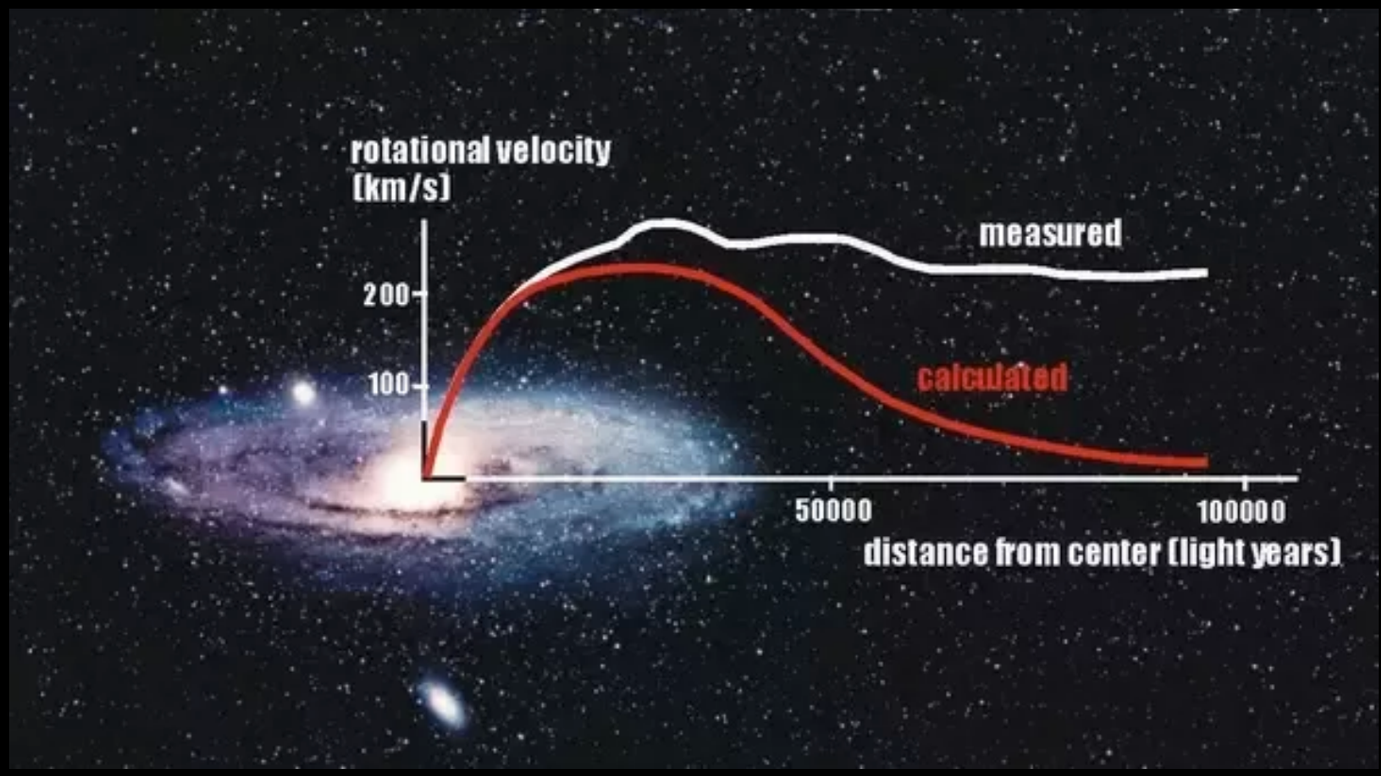
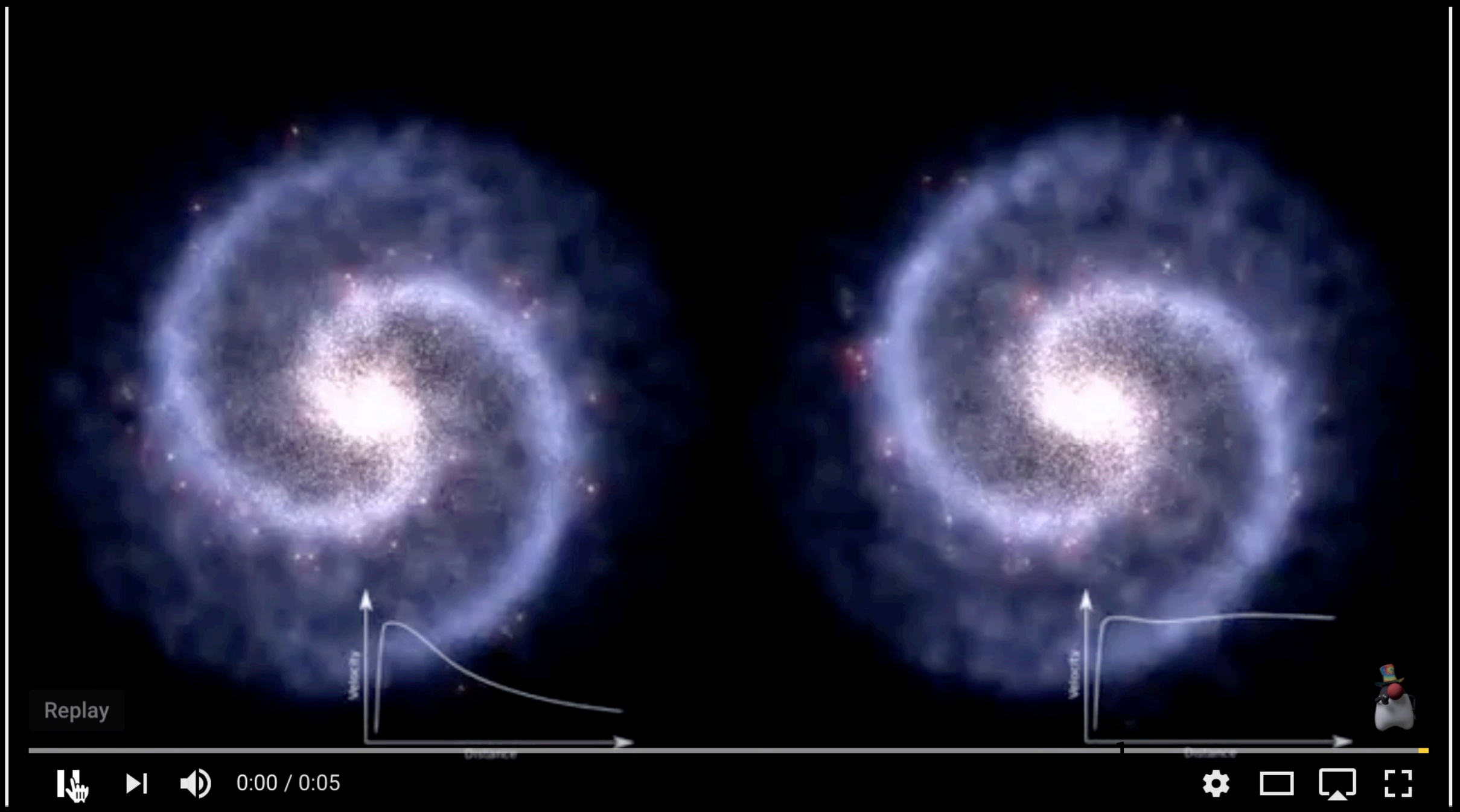


Image: quora.com

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

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

What do galaxies tell us about DM?



ScienceNews
INDEPENDENT JOURNALISM SINCE 1921

ALL TOPICS LIFE HU

NEWS SPACE

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**

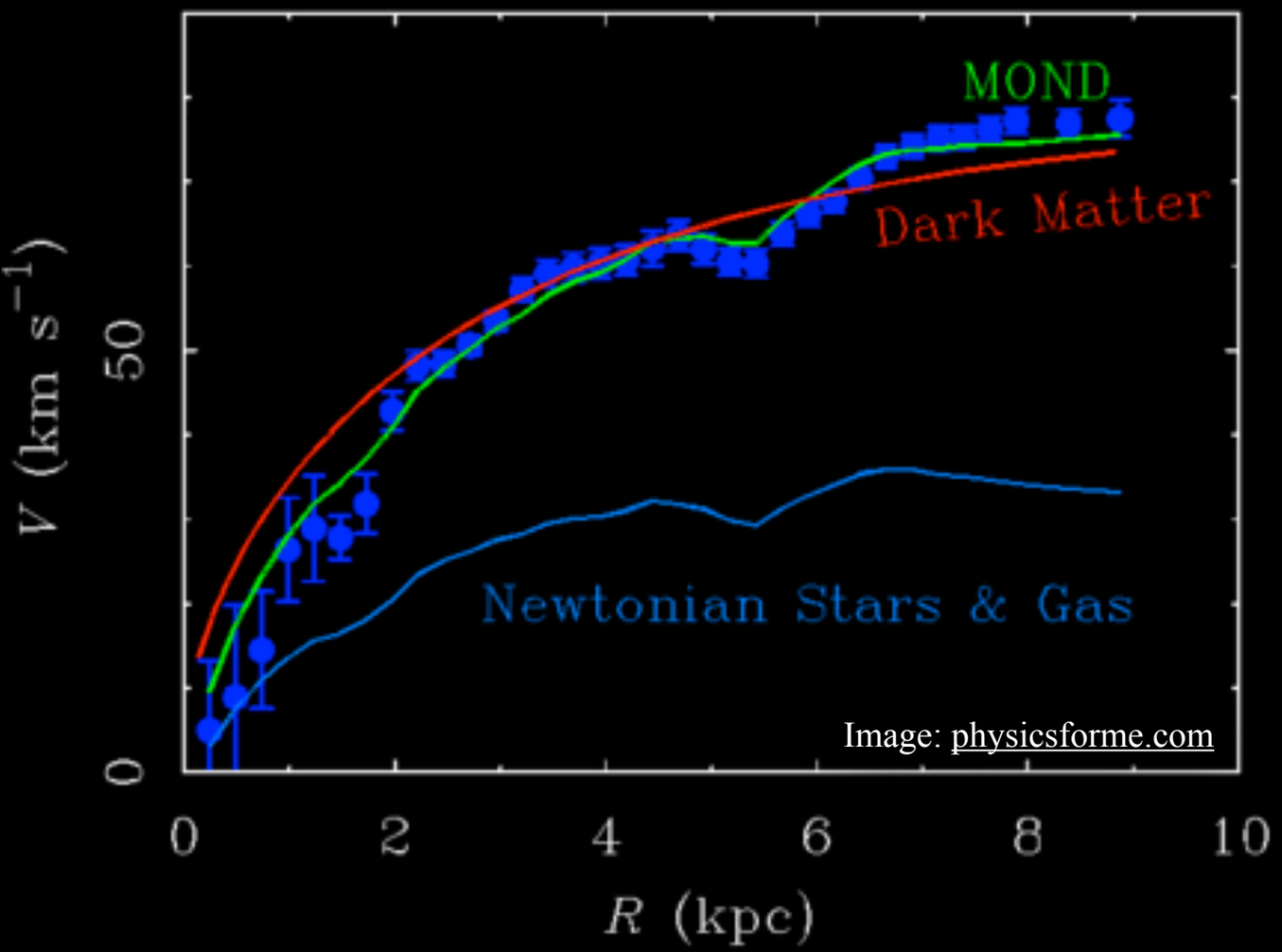


Image: physicsforme.com

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

Lets look scales larger than galaxies

Gravity can also bend light coming from distant objects

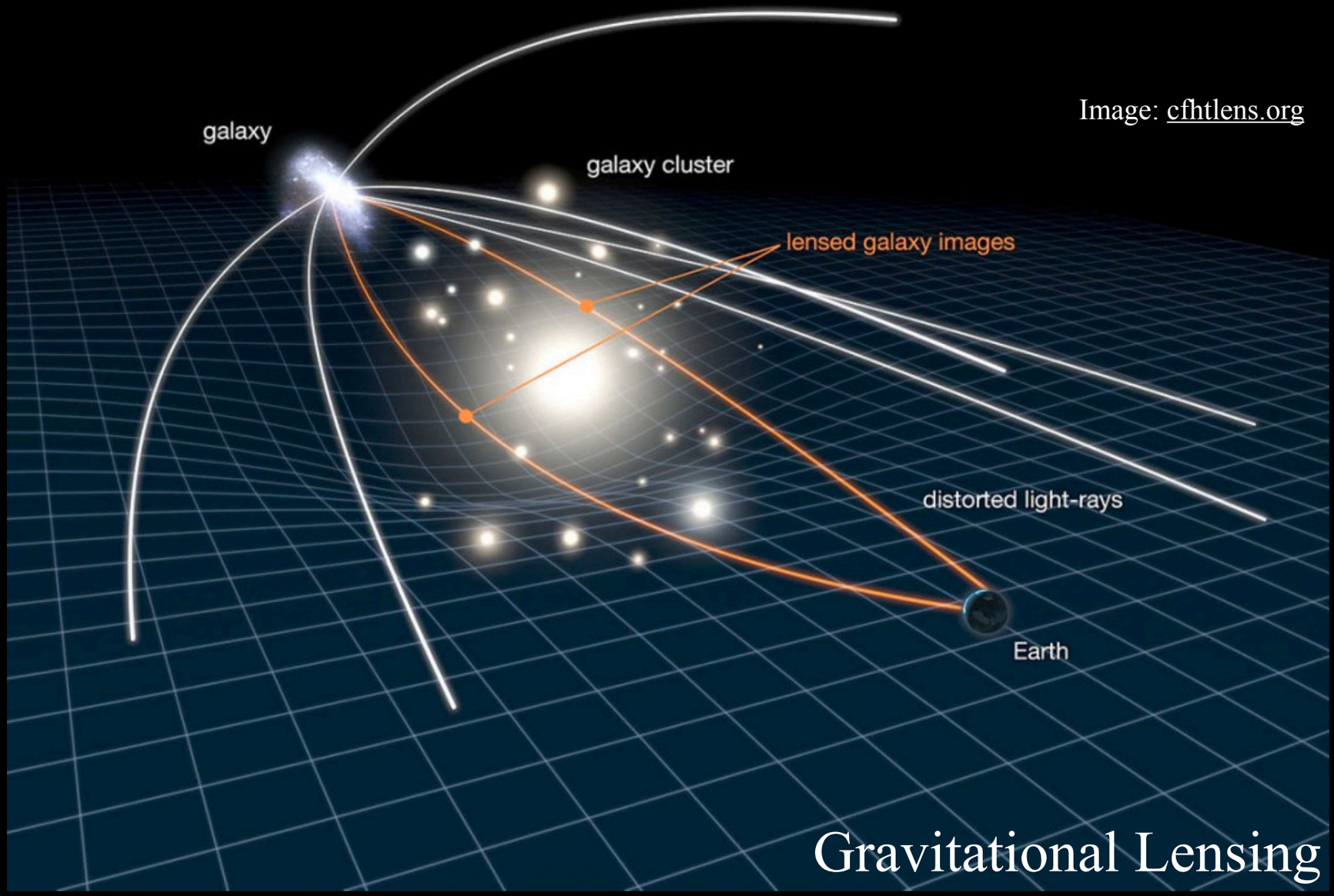


Image: cfhtlens.org

Light from galaxy is bent by gravitational field of galaxy cluster

Lets look scales larger than galaxies

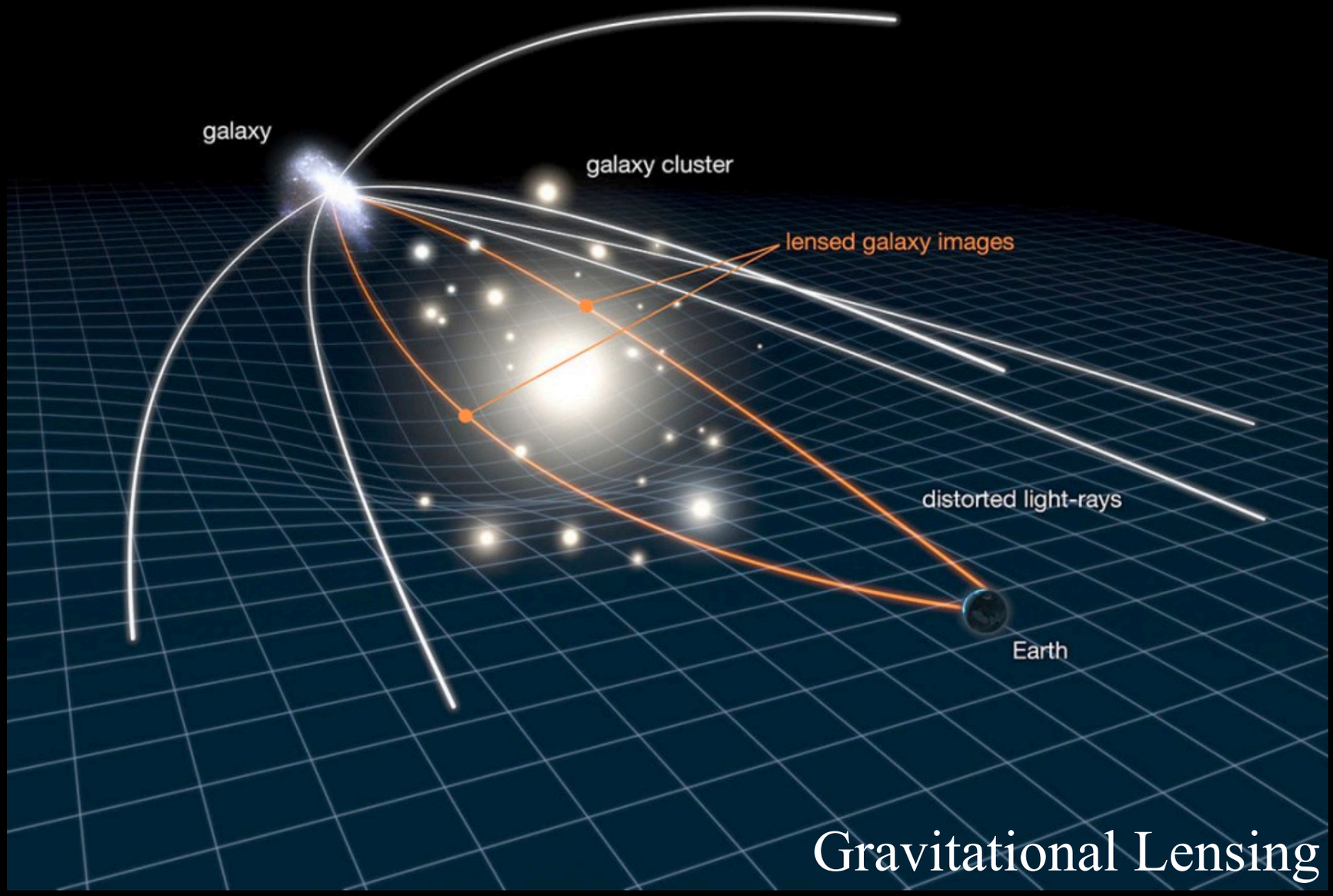
We see this Gravitational bending of light (lensing) in our telescopes

Image: slate.com

Gravitationally lensed object

Lets look 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?

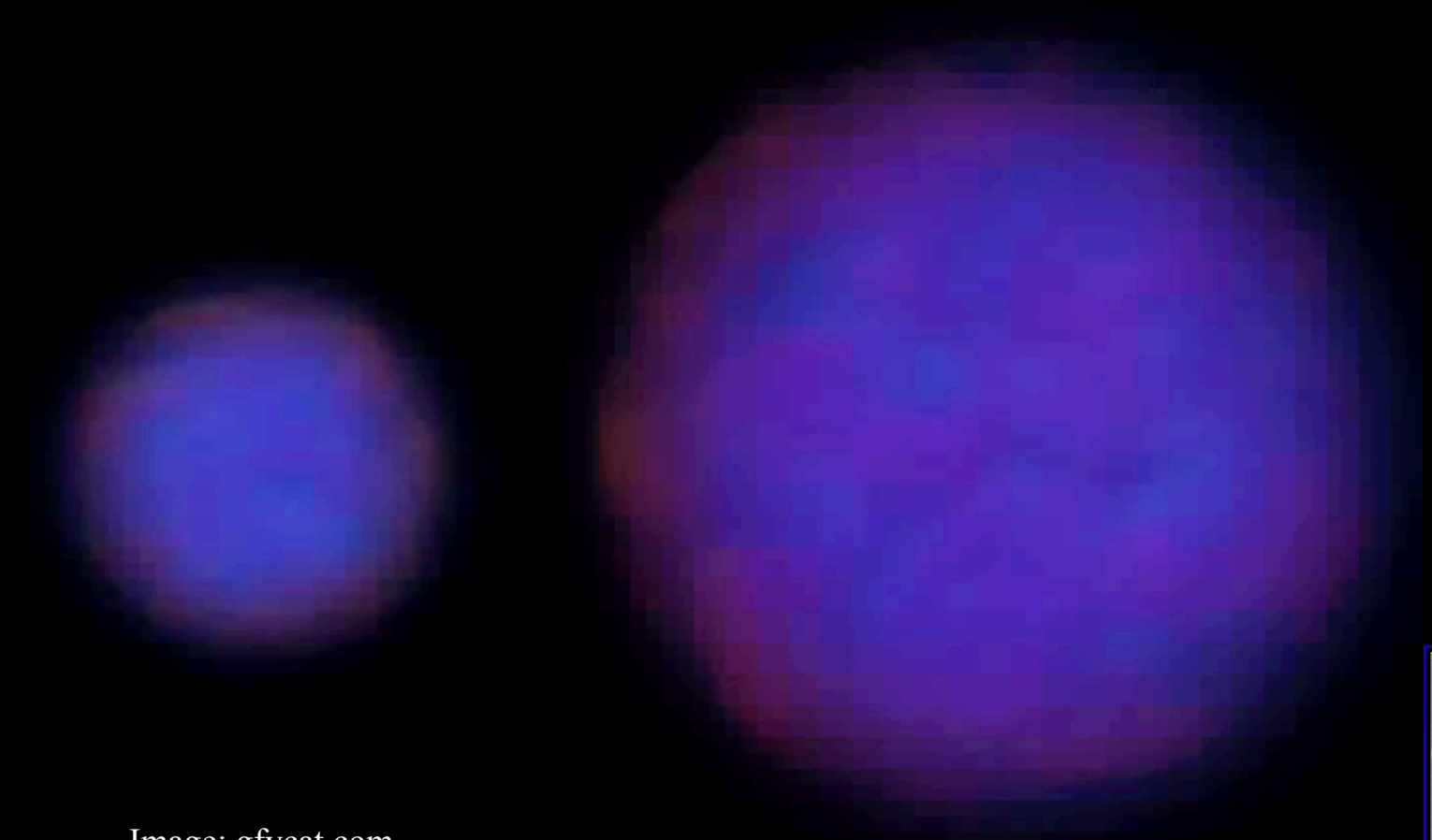


Image: gfycat.com

Visible Matter

Dark Matter

Gravitational Lens

DARK MATTER

Most of the universe can't even be bothered to interact with you.

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 does an infant universe tell us?

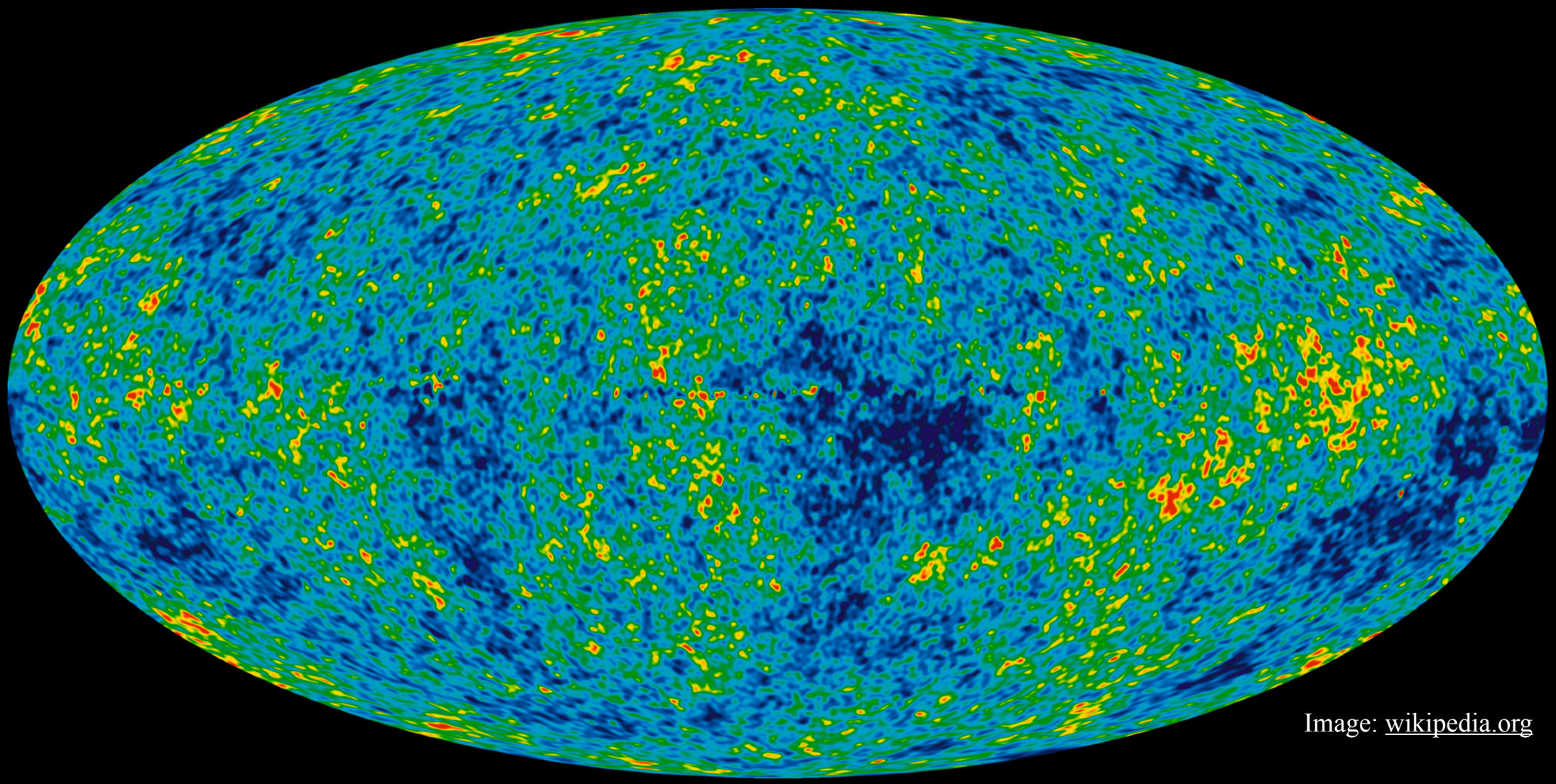


Image: wikipedia.org

- Random temperature fluctuations give rise to DM clumps
- Information is carried by photons which escape and reach us now

What does an infant universe tell us?

We call these photons Cosmic Microwave Background Radiation

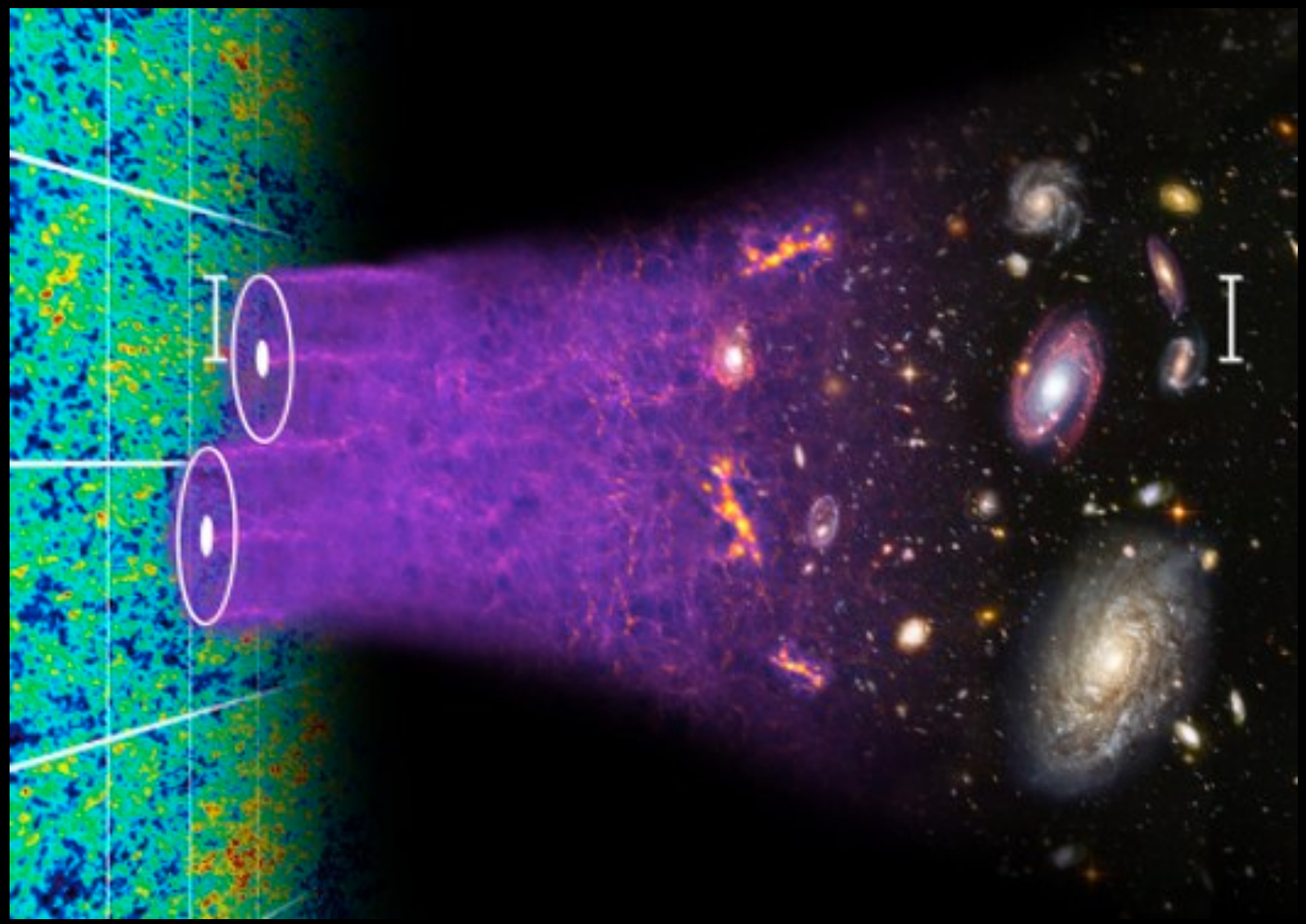


Image: medium.com

CMB gives us whole picture of our Universe

What does an infant universe tell us?

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

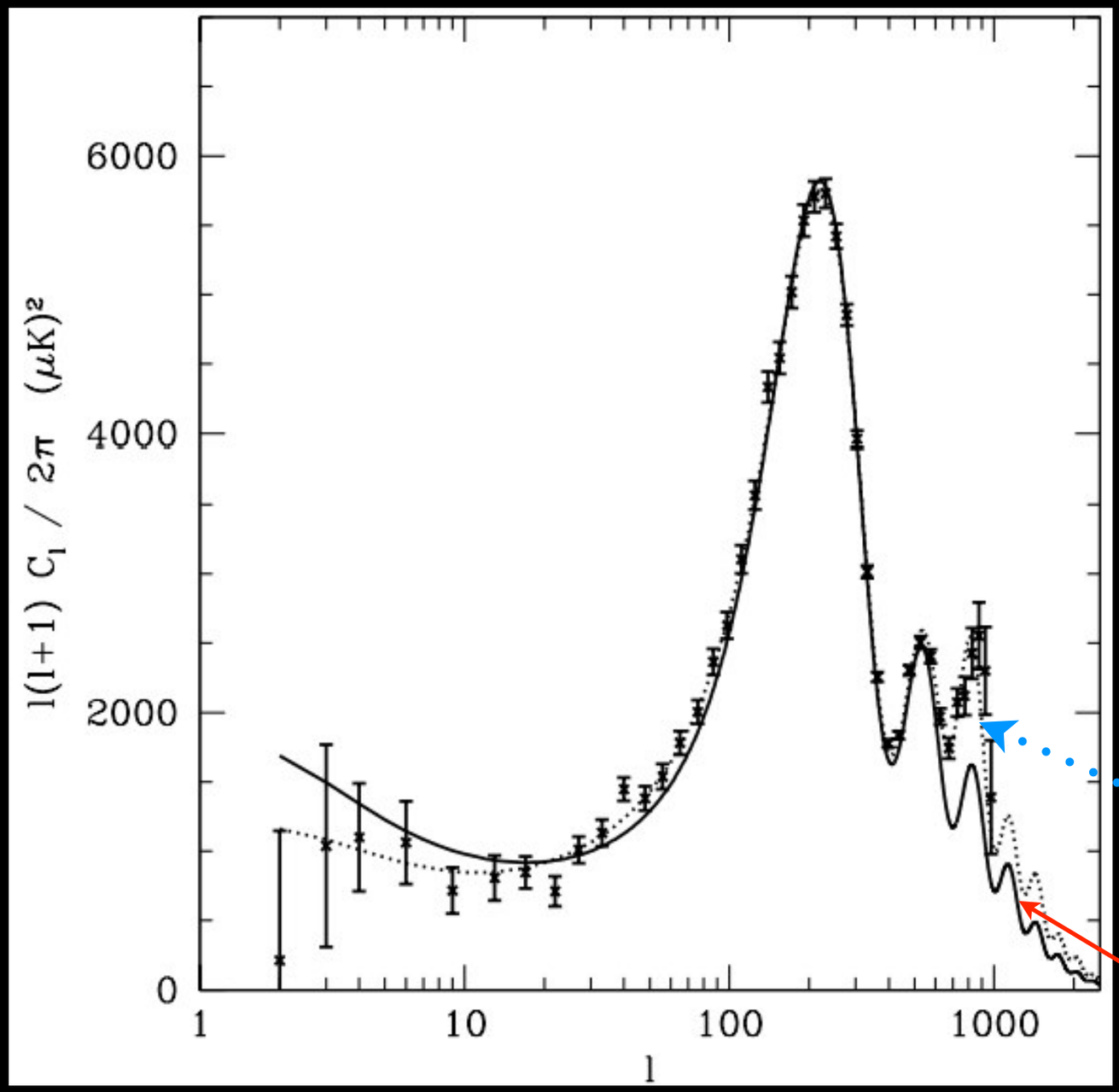
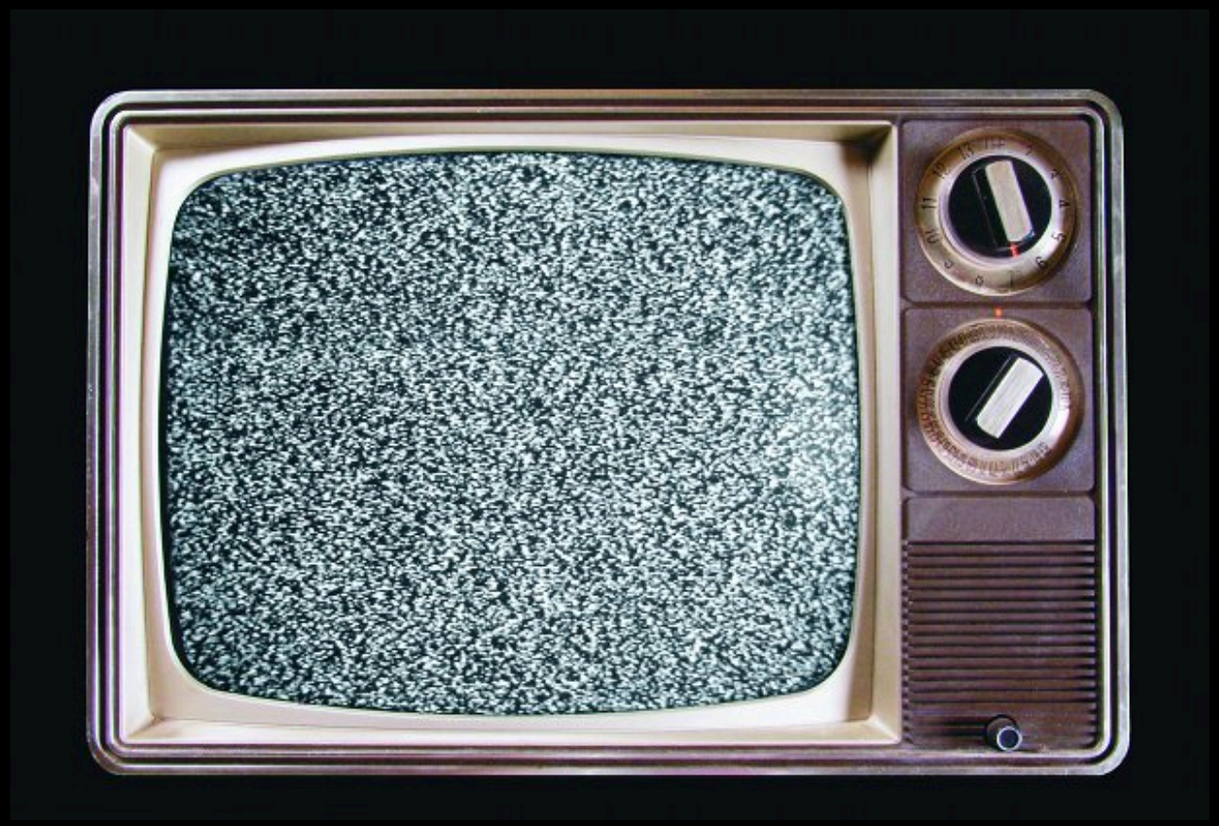


Image: Sean Carrol

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

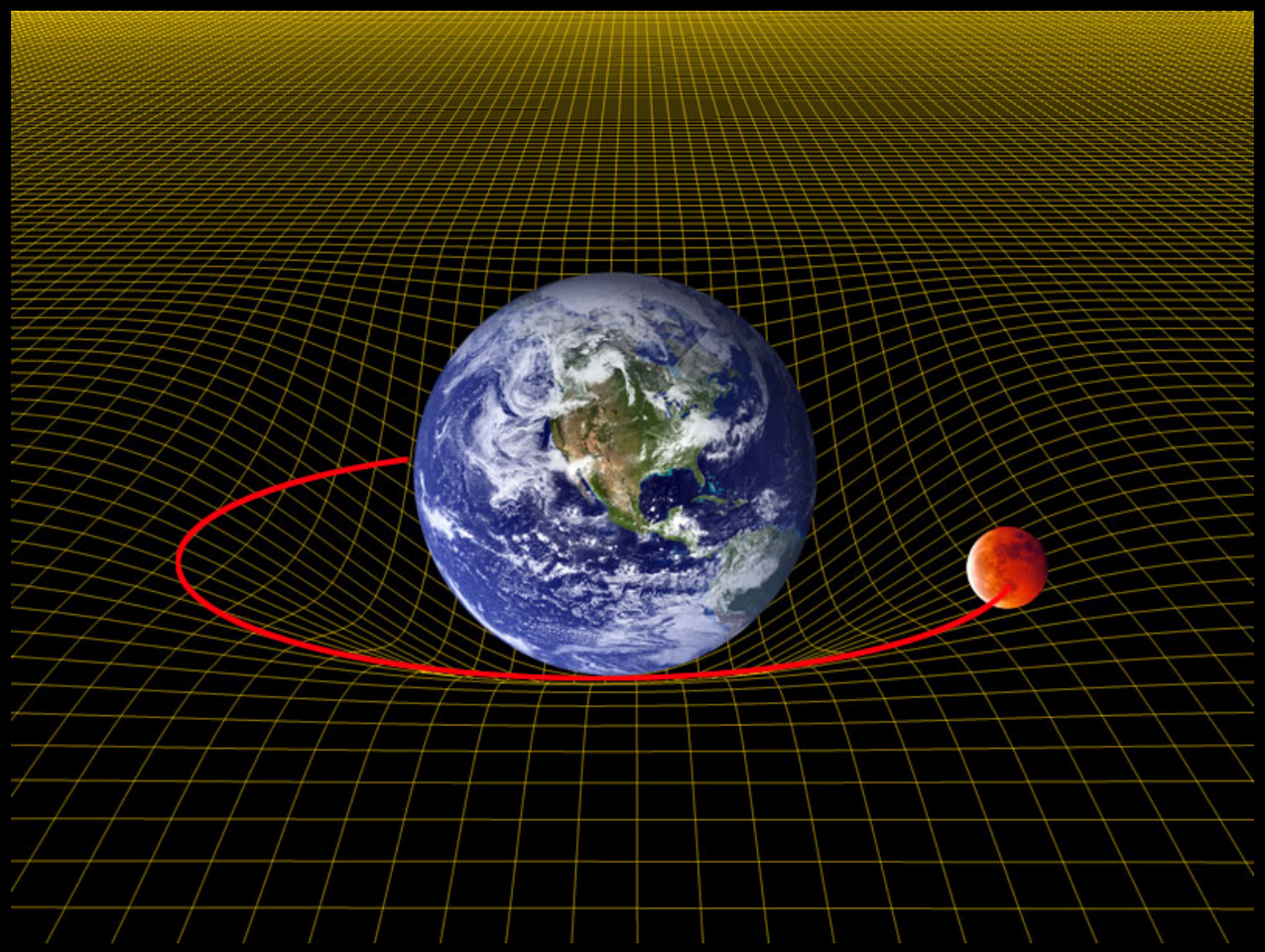
Why does dark matter Matter?

- 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.

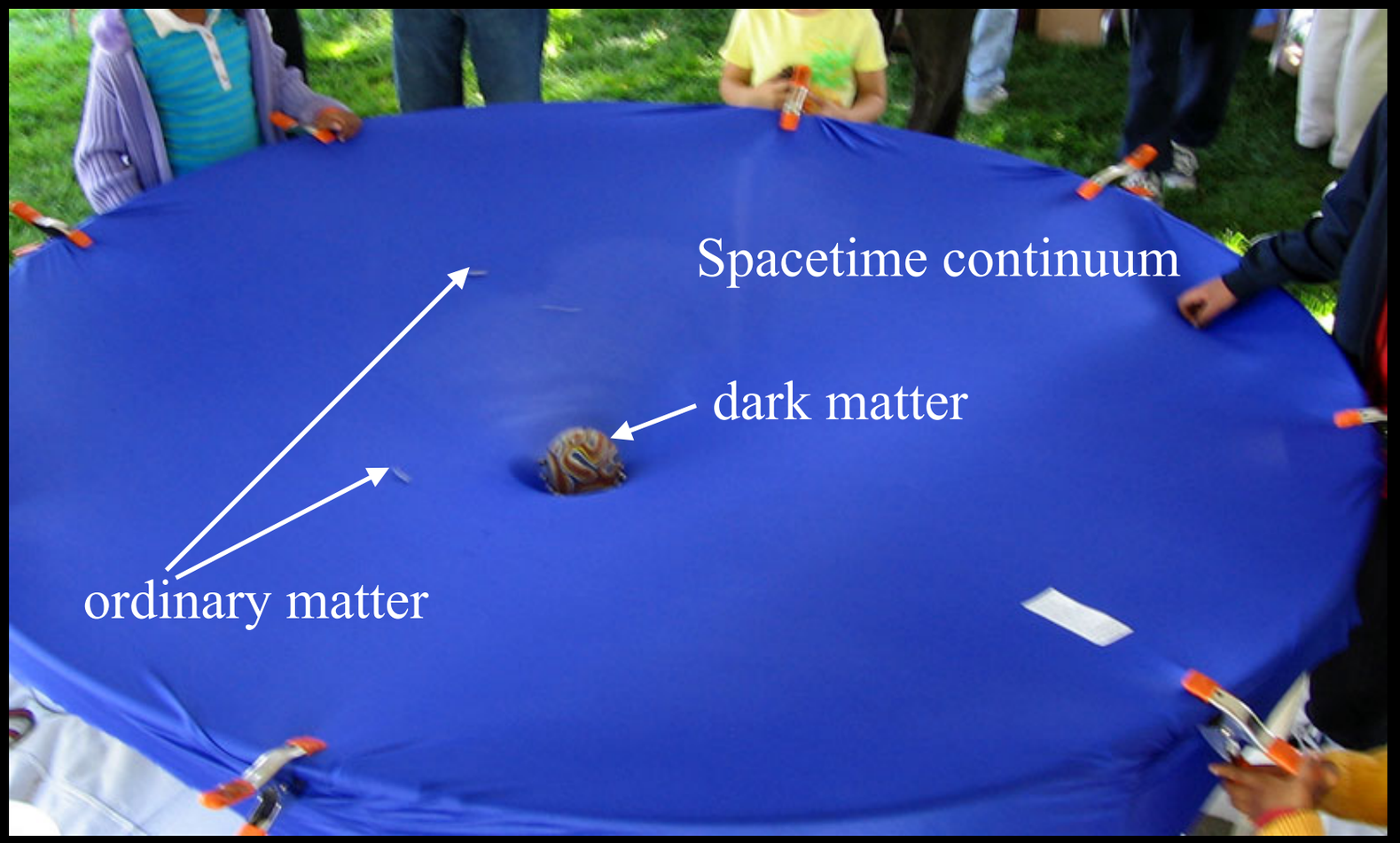
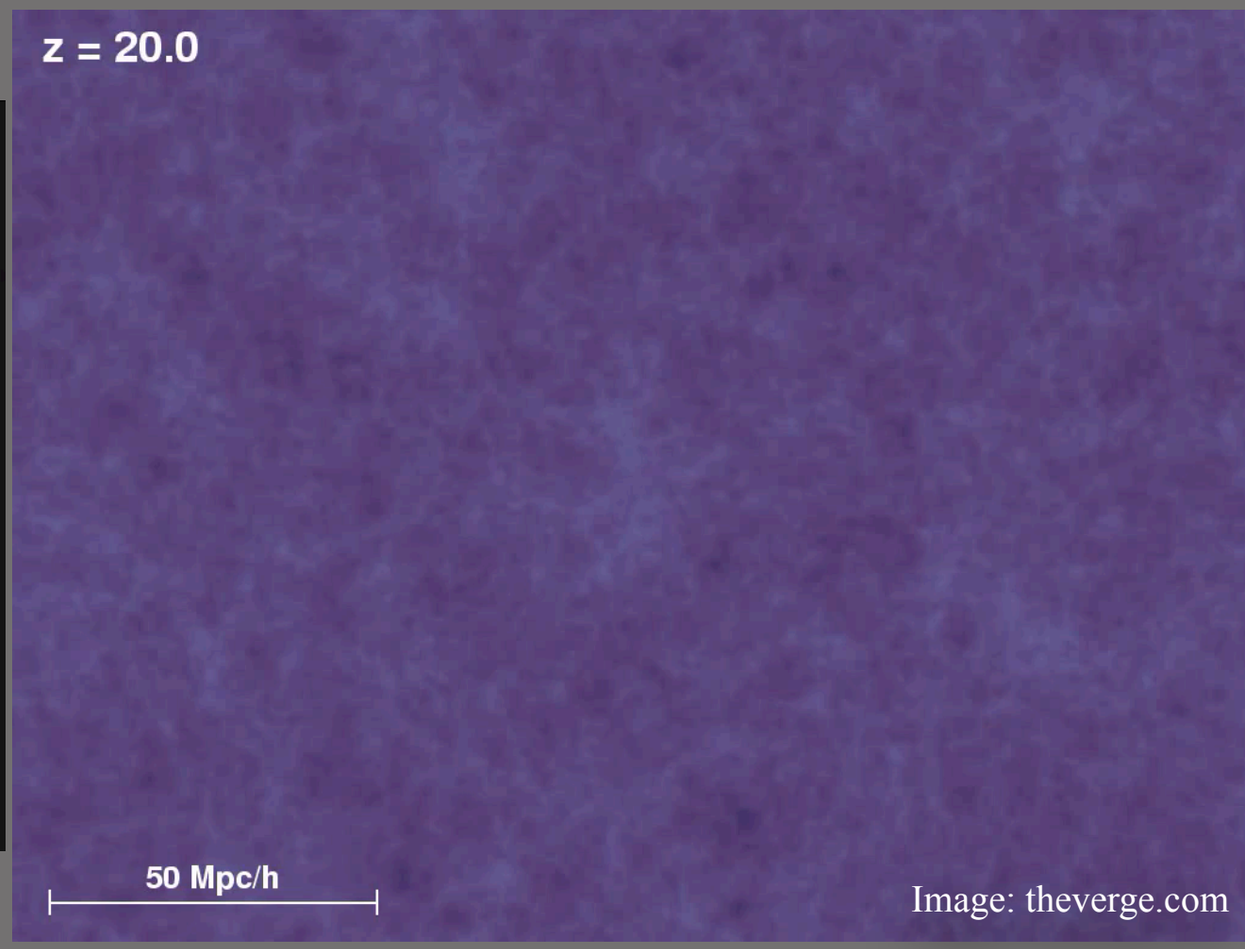


Image: einstein.stanford.edu

Cosmic glue that forms life

Structure Formation

Data



Simulation

Inconvenient Truth about dark matter

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

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

What do I mean by a particle?

Building blocks of life

Standard Model of Particle Physics

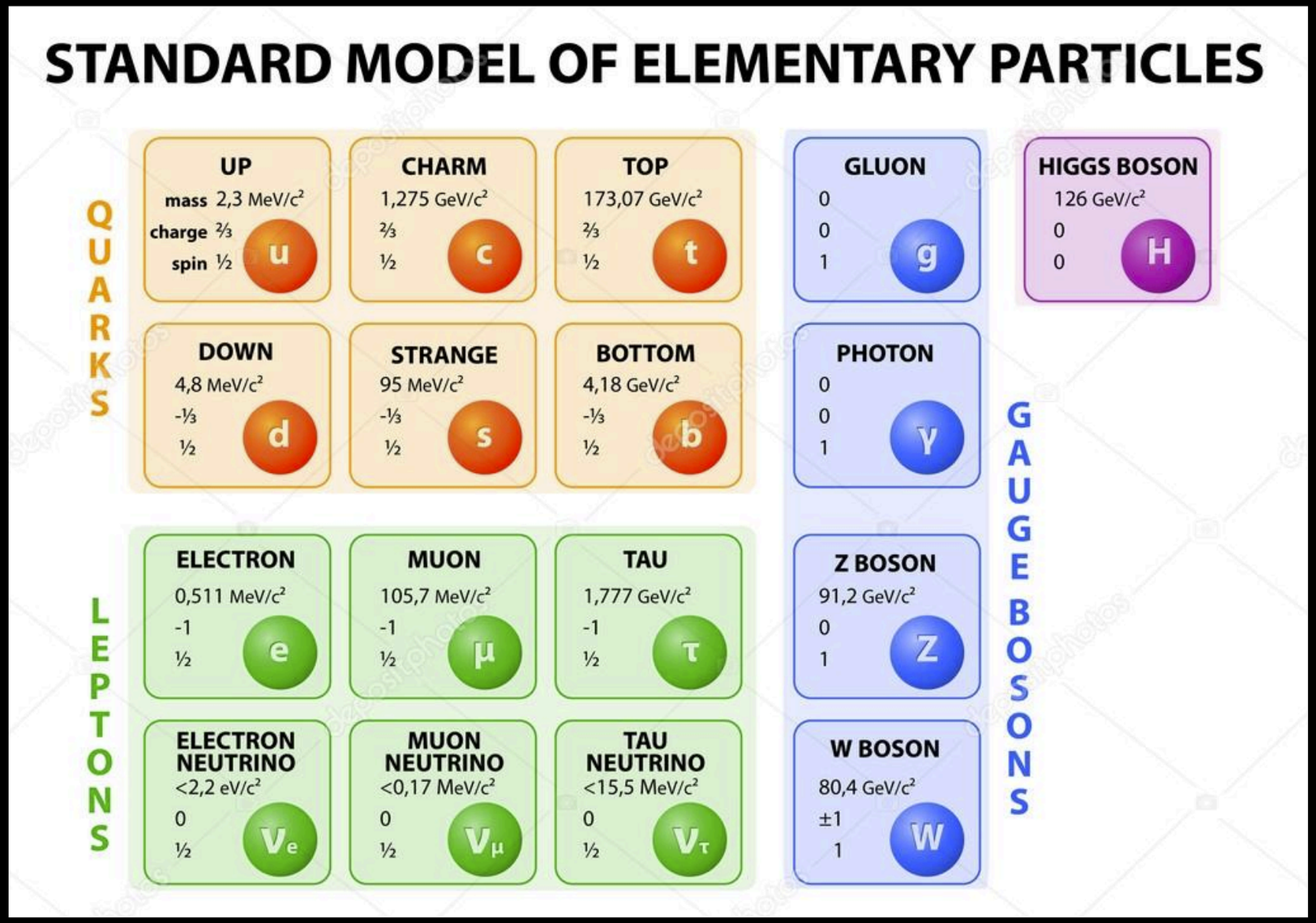


Image: 123rf.com

Building blocks of life

Standard Model of Particle Physics

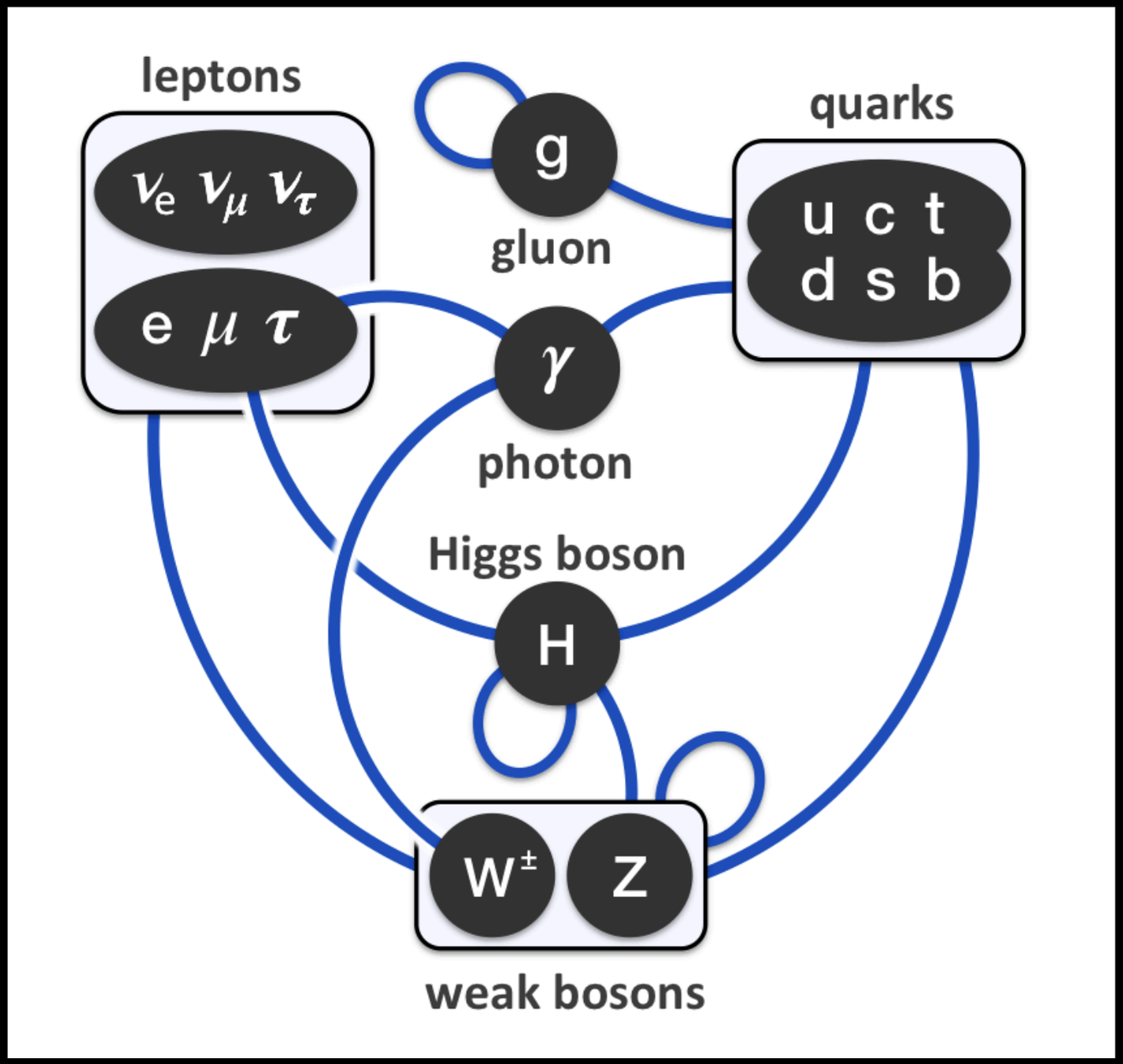
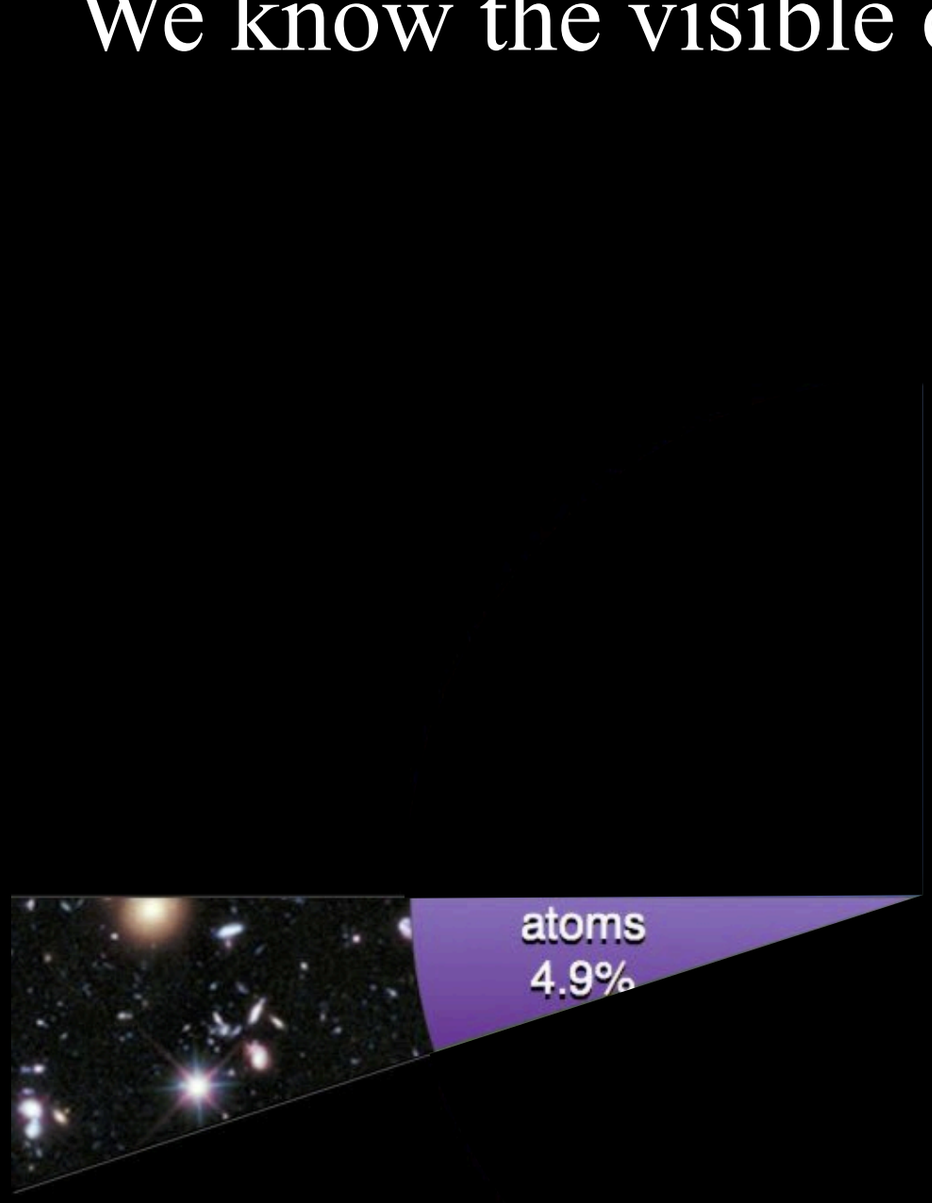
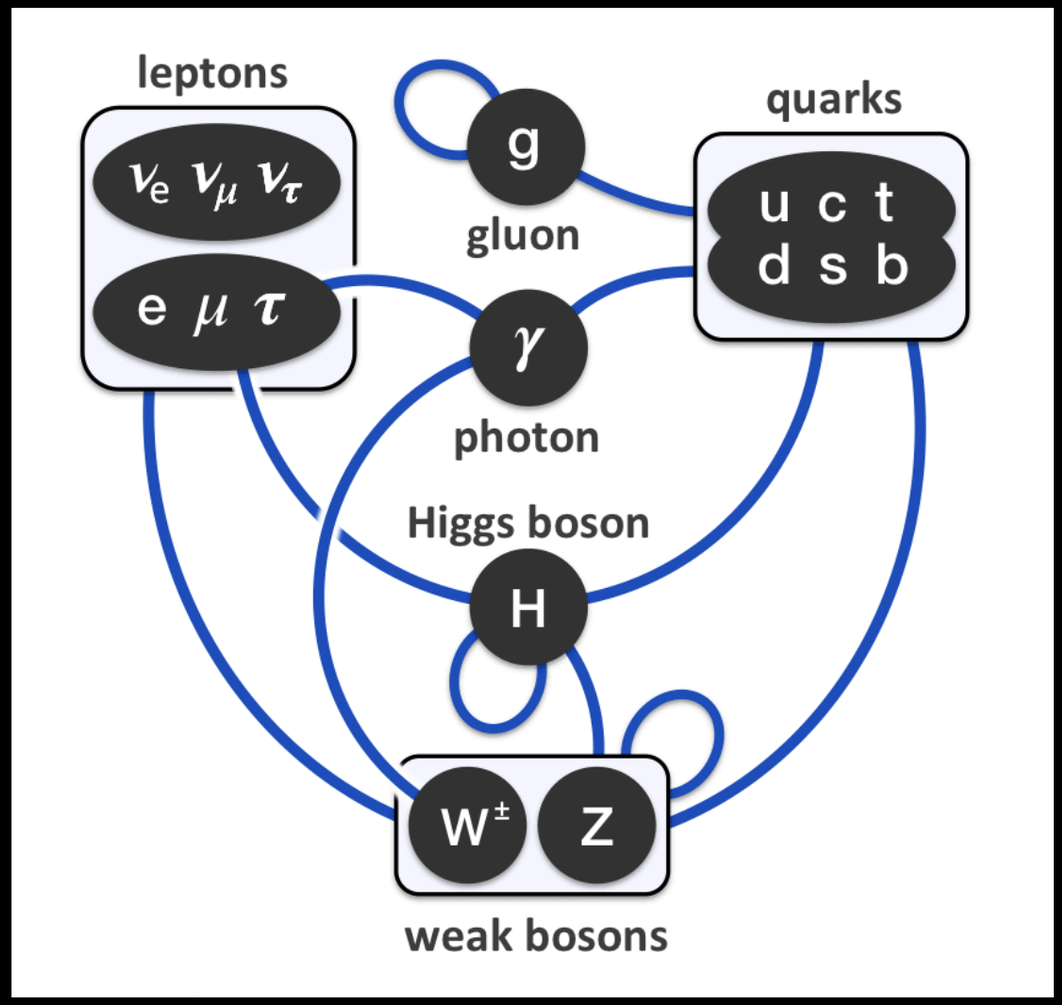


Image: blogs.scientificamerican.com

The Standard Model is complete

We know the visible component very well





The Standard Model is complete

What is the Dark Matter sector 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

- It may interact with the SM through some new force

By coincidence, 20-30 years ago, a solution to another fundamental problem resulted in a perfect dark matter candidate

Weakly-Interacting Massive Particles

Dark matter connected to SM through "Weak" force

Carried by known force carriers W & Z bosons

$$\left.\begin{aligned} \langle \sigma v \rangle &\sim \frac{\alpha^2}{M_W^2} \\ \Omega h^2 &\sim \frac{0.1 \text{ pb}}{\langle \sigma v \rangle} = 0.12 \end{aligned}\right\} \text{WIMP Miracle}$$

Dark matter mass Range ~ 1 - 1000 GeV

By coincidence, 20-30 years ago, a solution to another fundamental problem resulted in a perfect dark matter candidate

Weakly-Interacting Massive Particles

Dark matter connected to SM through "Weak" force

Carried by known force carriers W & Z bosons

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{M_W^2}$$

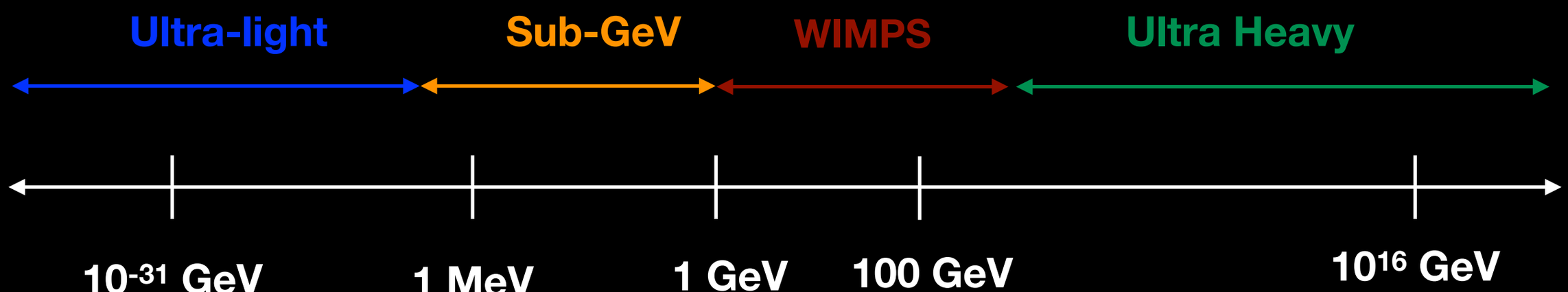
$$\Omega h^2 \sim \frac{0.1 \text{ pb}}{\langle \sigma v \rangle} = 0.12$$

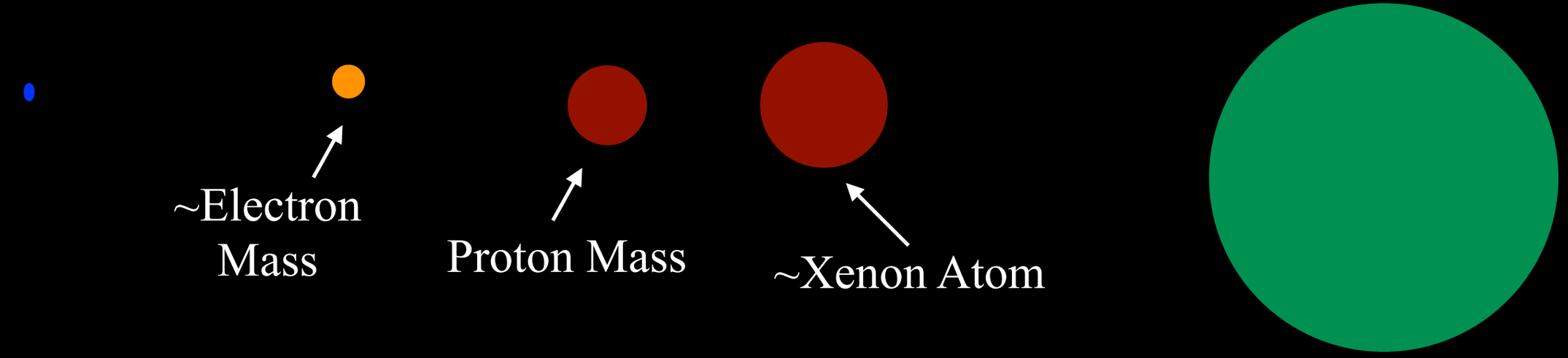
WIMP Miracle

Dark matter mass Range ~ 1 - 1000 GeV

Is this a big number?

Range of possibilities is VAST





Primordial Blackholes - much heavier than Ultra heavy

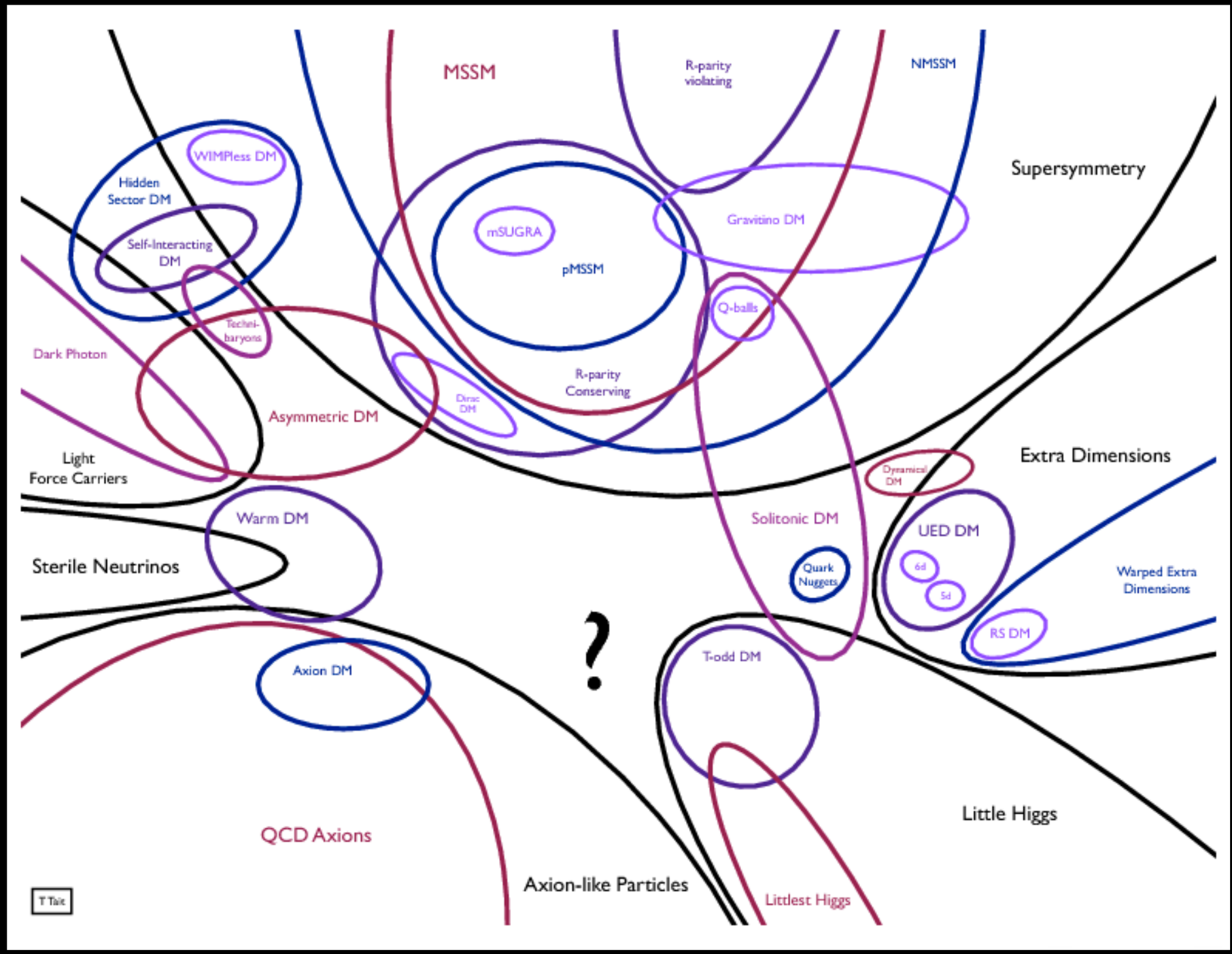


Image: ps.uci.edu

Range of possibilities is VAST

How do we find these new particles?

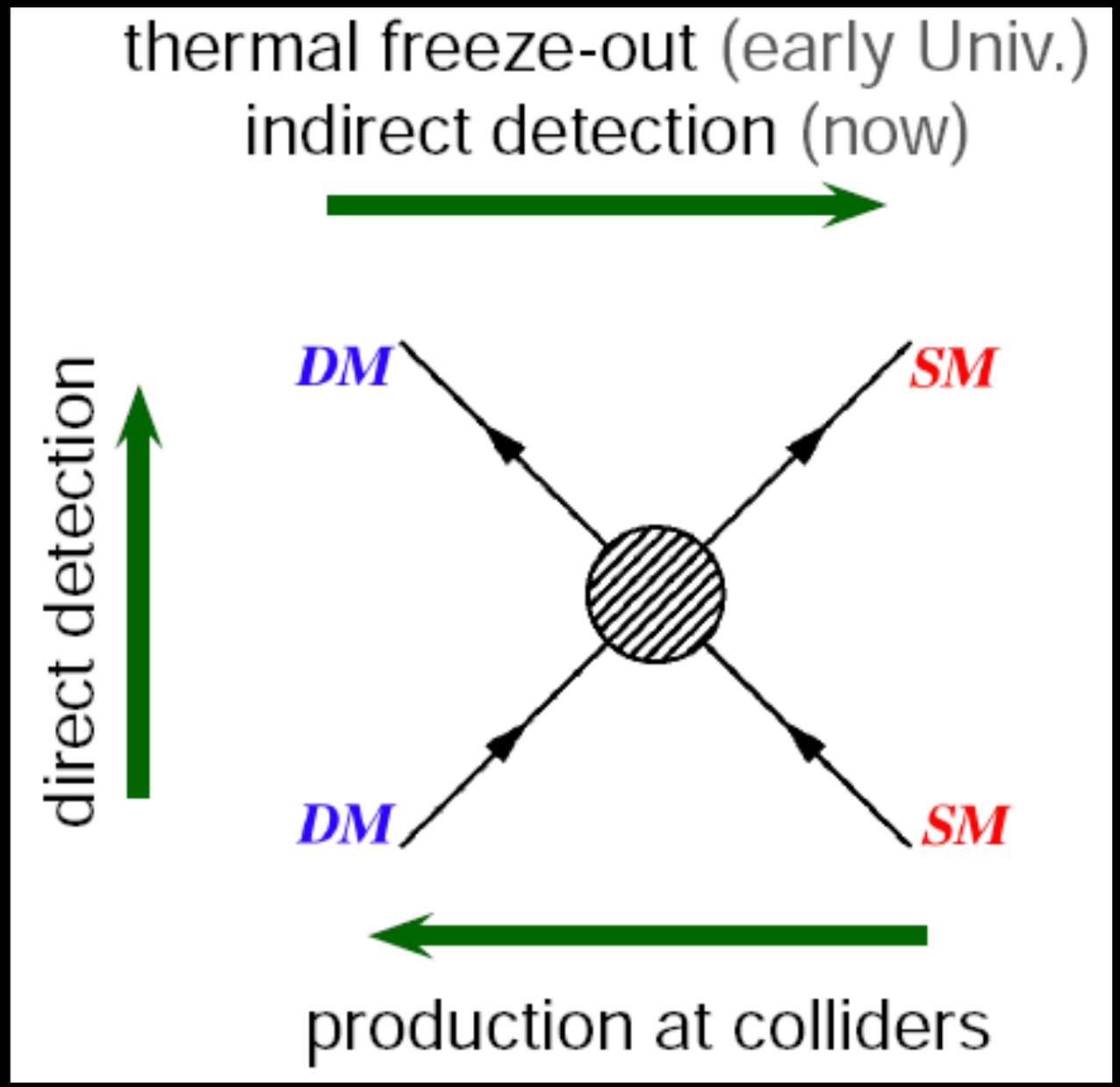


Image: cosmo17.in2p3.fr

In the Sky

At Colliders

In underground detectors

In the sky

In Dark matter dense regions like the Galactic center:

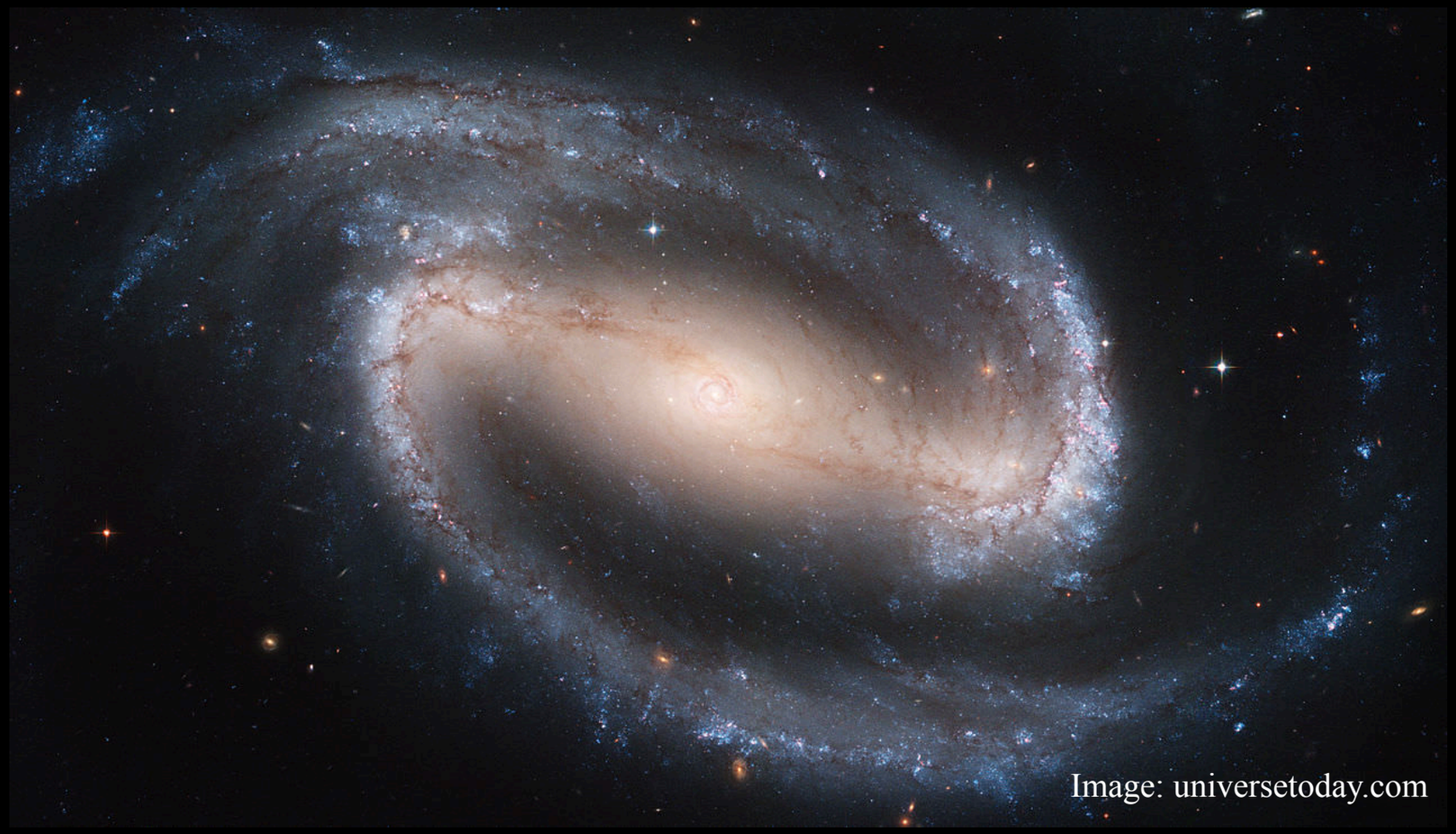


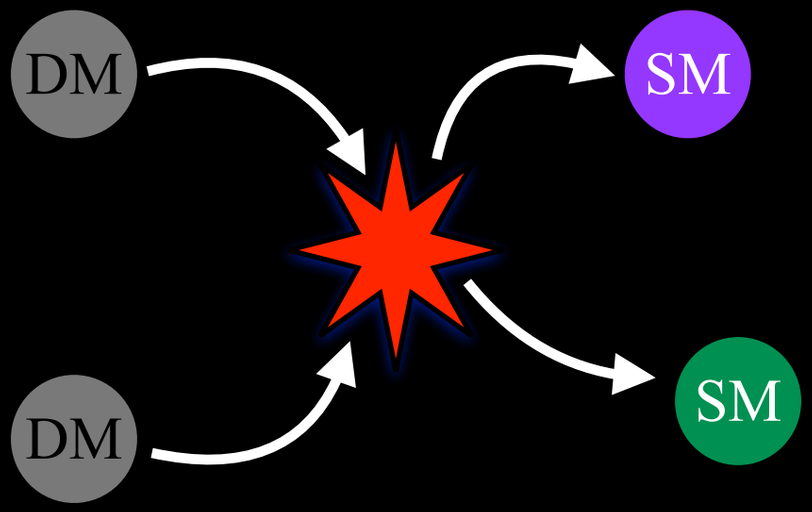
Image: universetoday.com

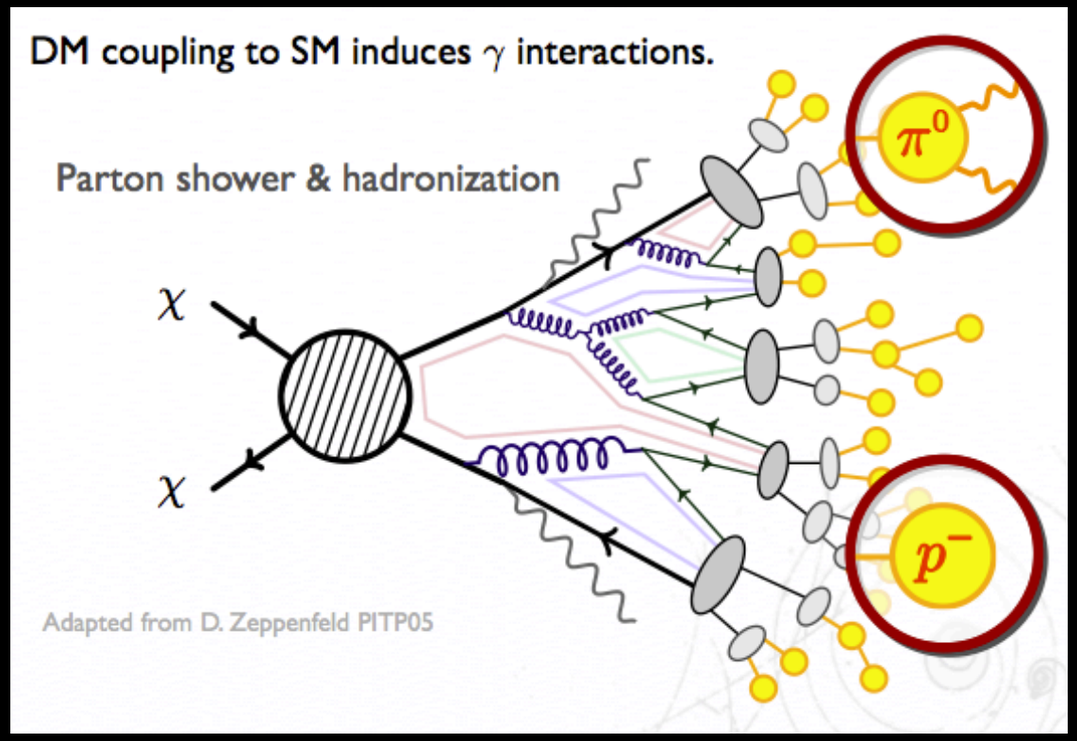
Dark matter particles find each other and annihilate into SM particles

Dark matter particles may decay into SM particles

Indirect Detection

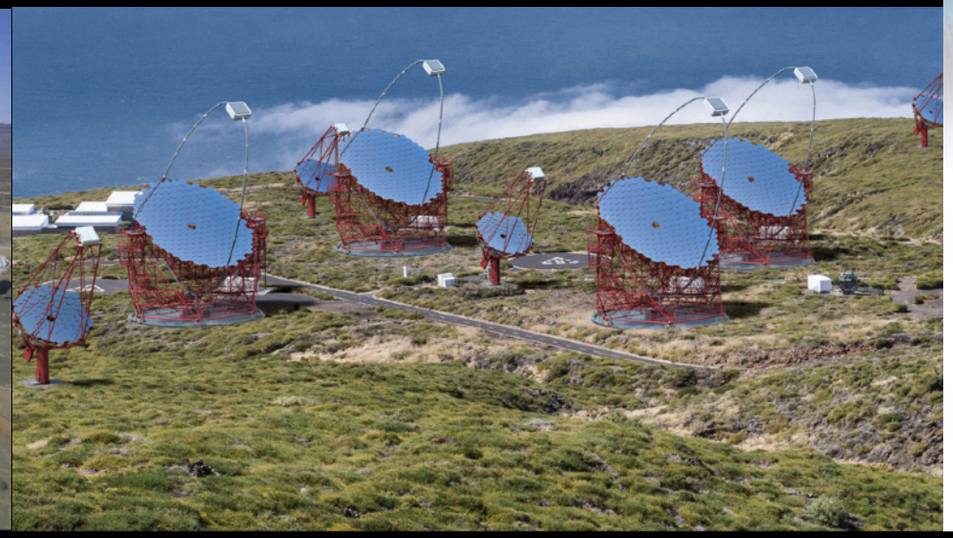
Dark Matter annihilates / decays into SM particles



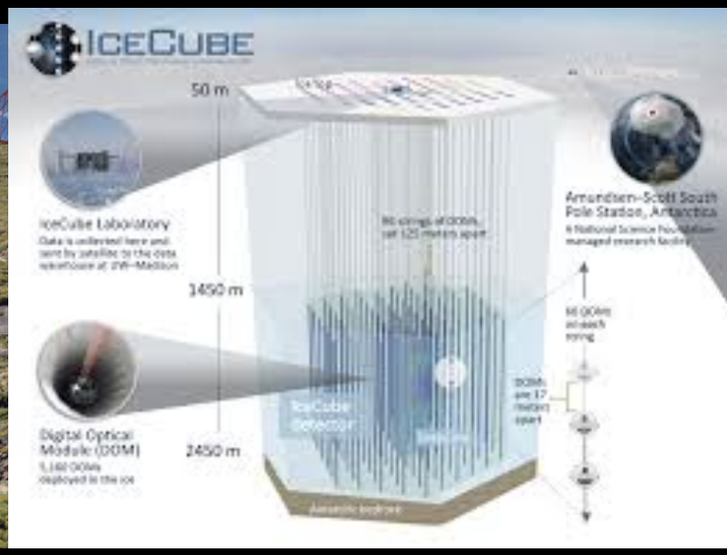


Square Kilometer Array

H.E.S.S / Cherenkov Telescope Array

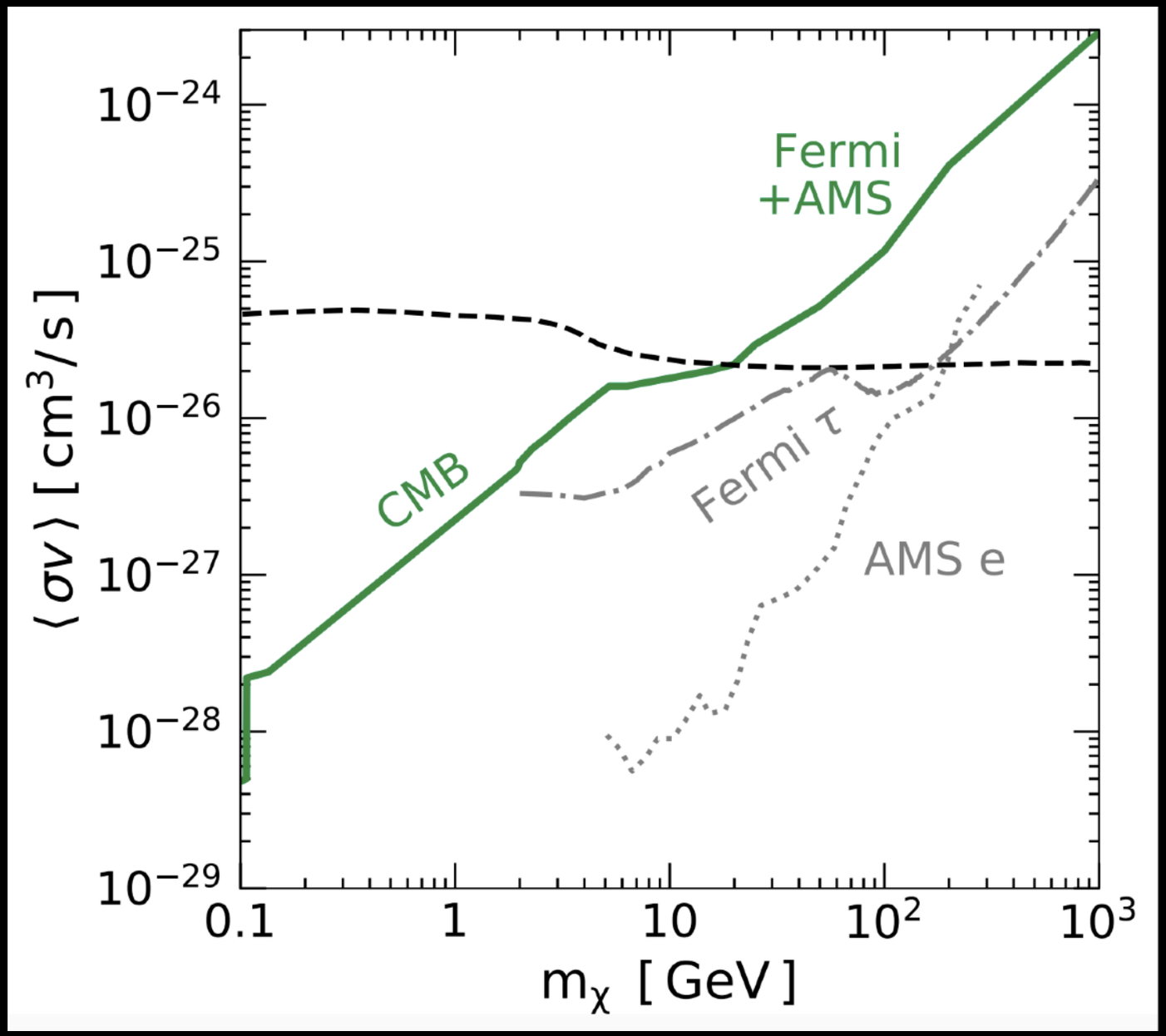


IceCUBE neutrino observatory



Indirect Detection

$$\frac{d\phi}{dE_\gamma} \sim \left(\frac{\langle\sigma v\rangle}{8\pi}\frac{dN_\gamma}{dE_\gamma}\frac{1}{m_\chi^2}\right)\int_{\Delta\Omega}\int_{l.o.s}\rho_\chi^2(l)dld\Omega$$

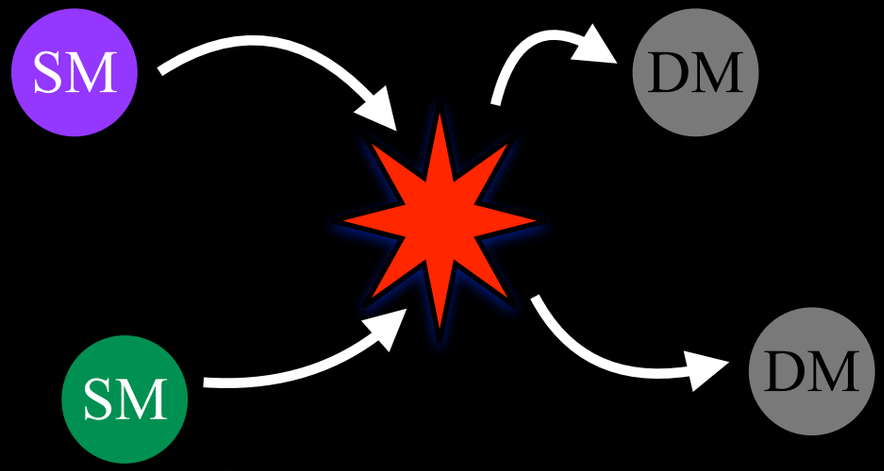


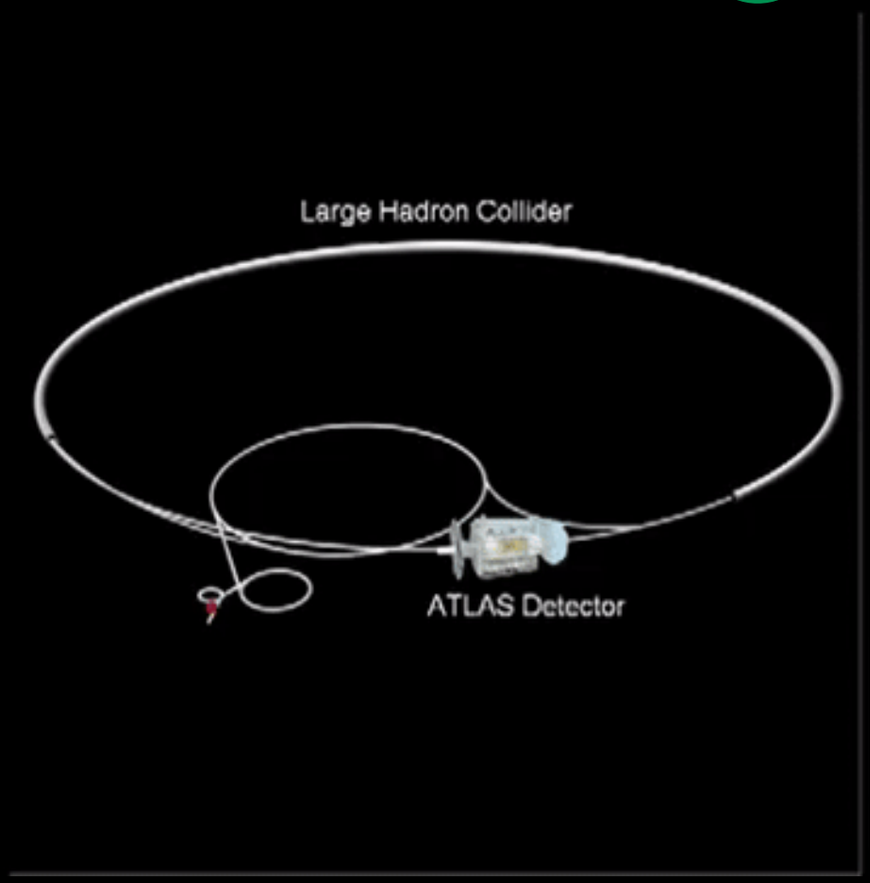
Leane et al, Phys.Rev.D 98 (2018) 2

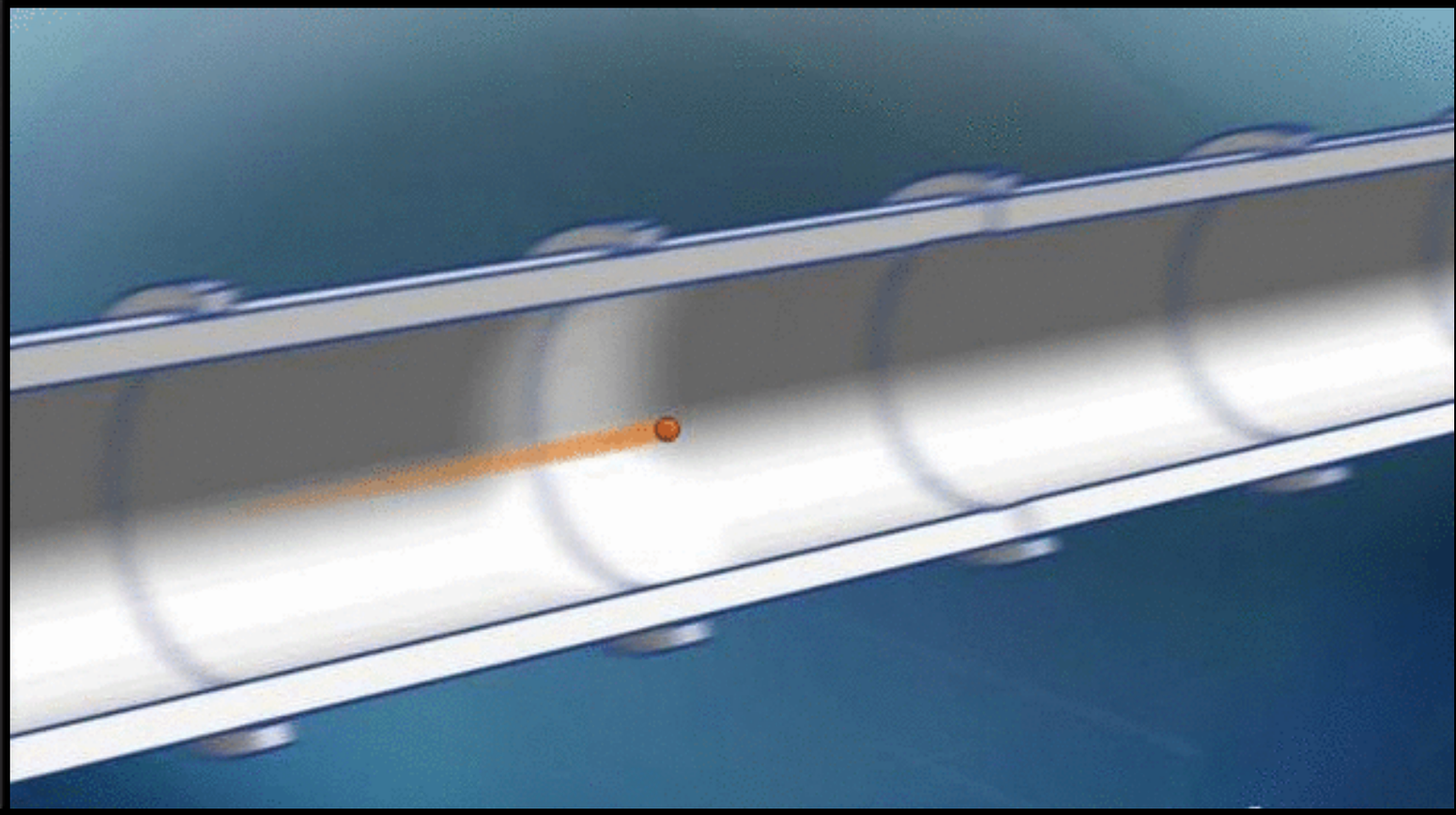
See lecture by C. Cappiello

Production at Colliders/Accelerators

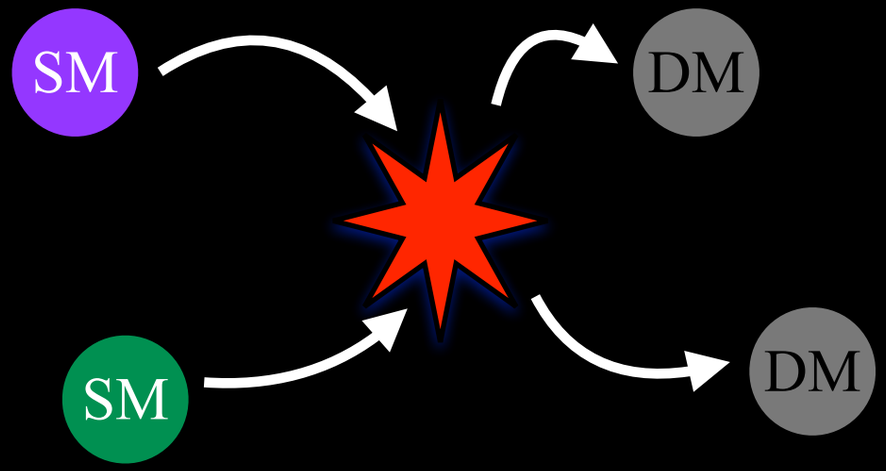
Collide SM particles to produce dark matter in the Laboratory







Production at Colliders/Accelerators



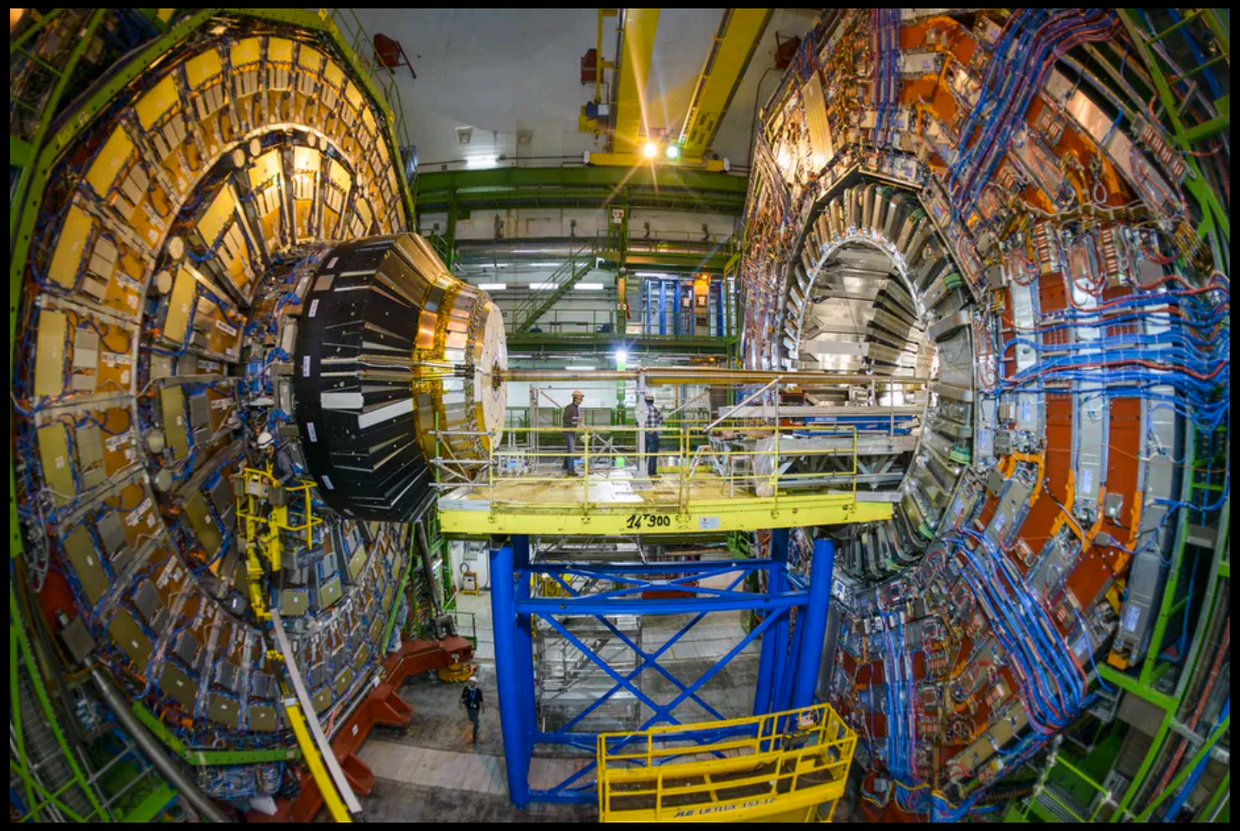


Image: theconversation.com

High/low energy colliders

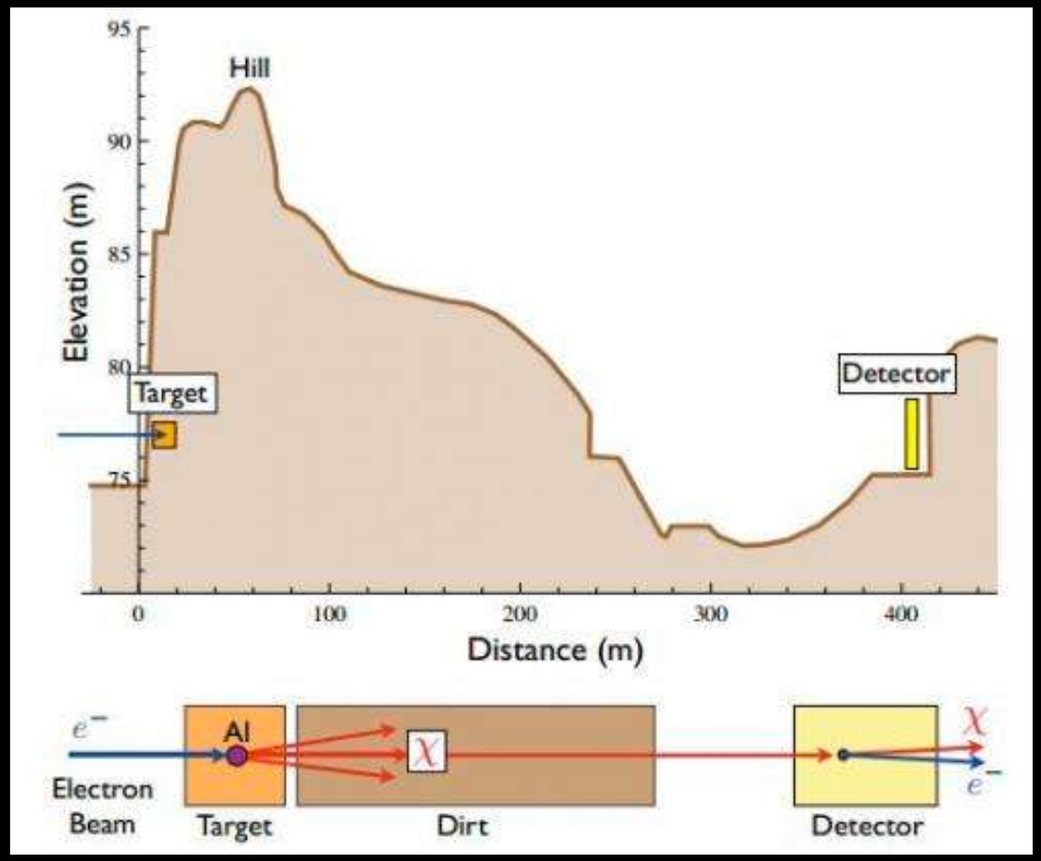


Image: phys.org

Fixed target experiments

Direct Detection

Milky way is surrounded by ‘spherical’ halo of DM

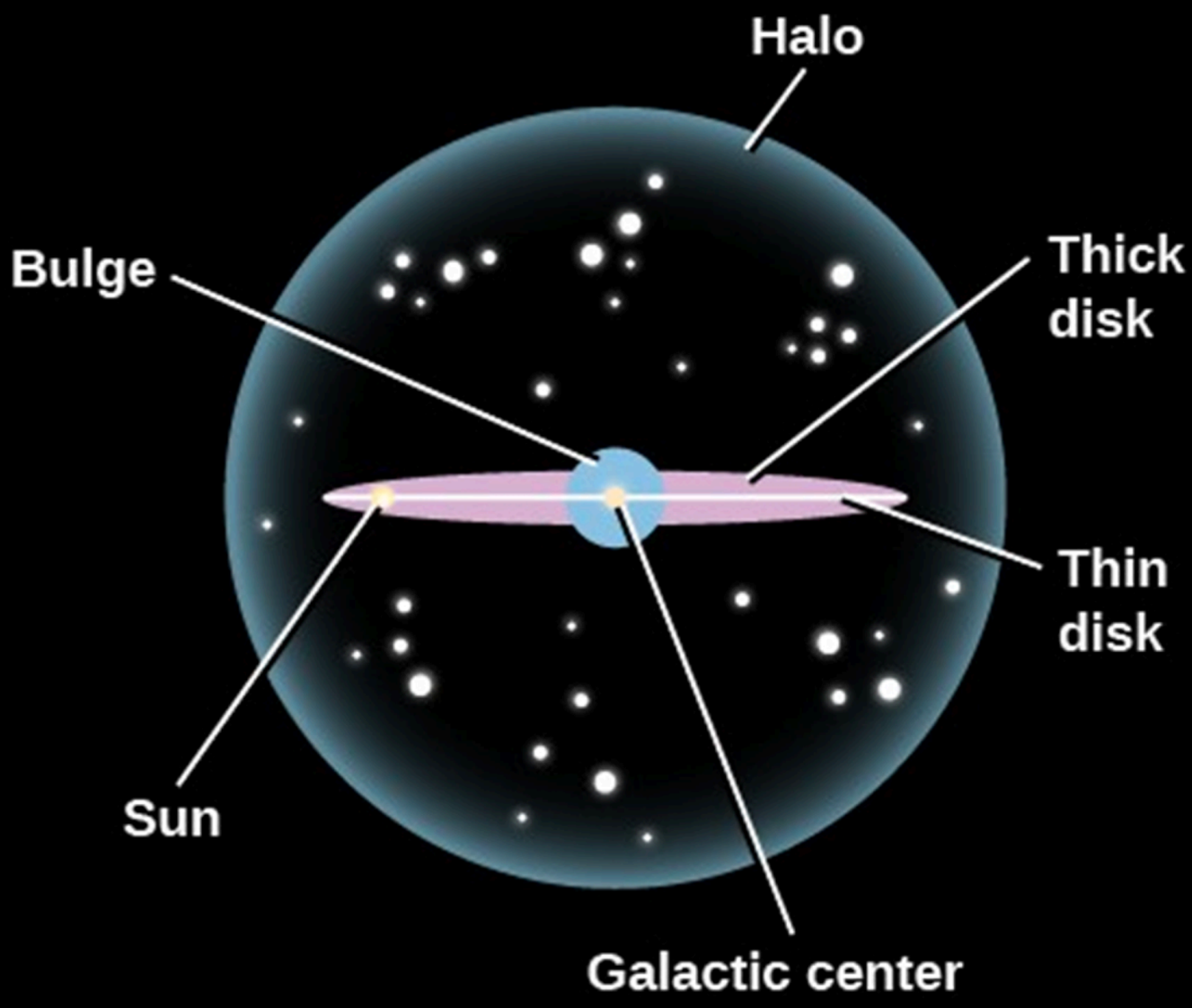


Image: evolution.calpoly.edu

Direct Detection

As sun moves around galaxy, solar system gets hit by dark matter wind

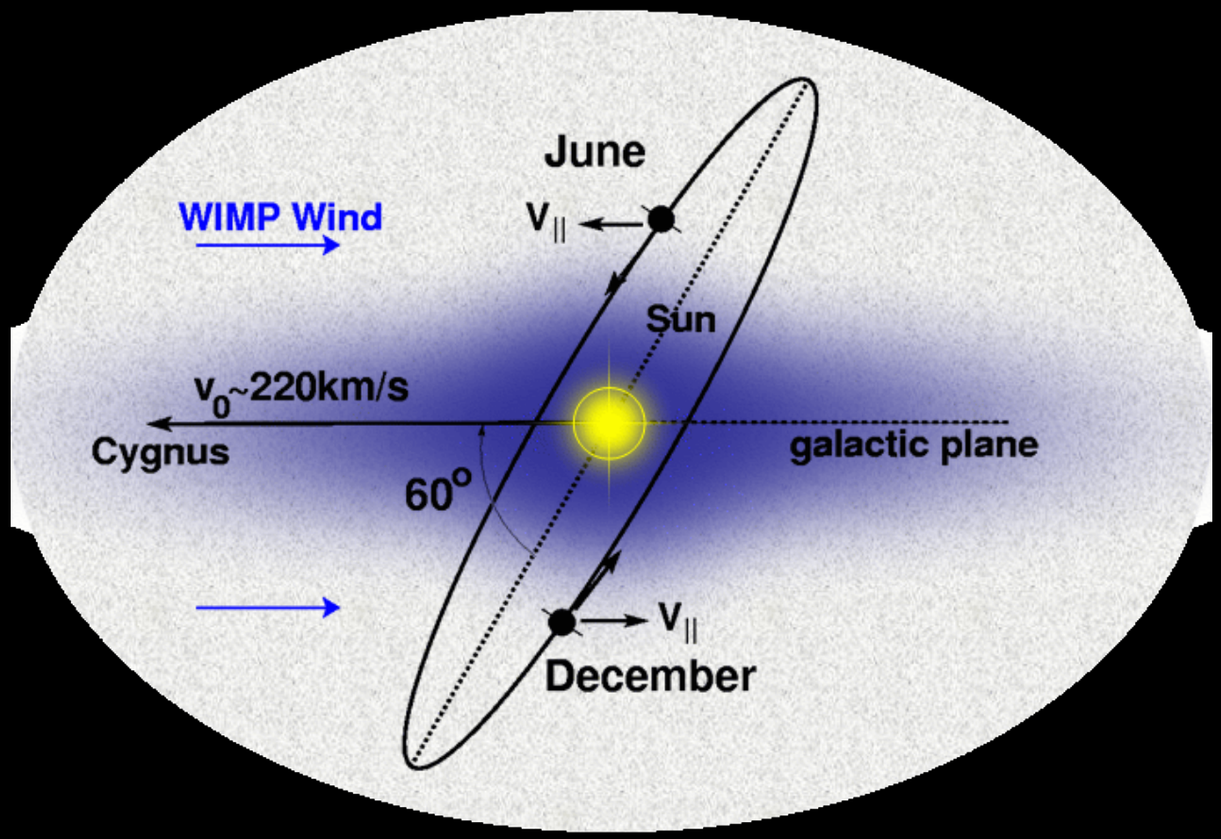


Image: quantumdiaries.org

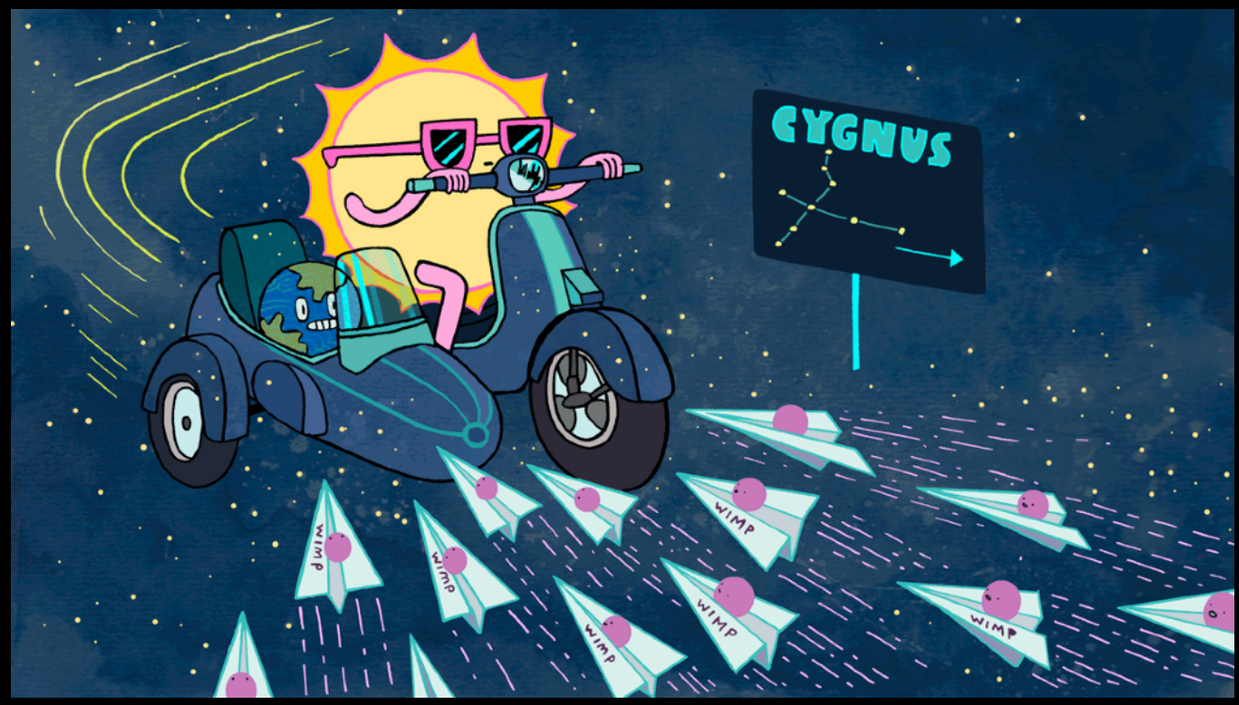


Image: symmetrymagazine.org

Build a detector in a quiet place and patiently wait for dark matter to come knocking

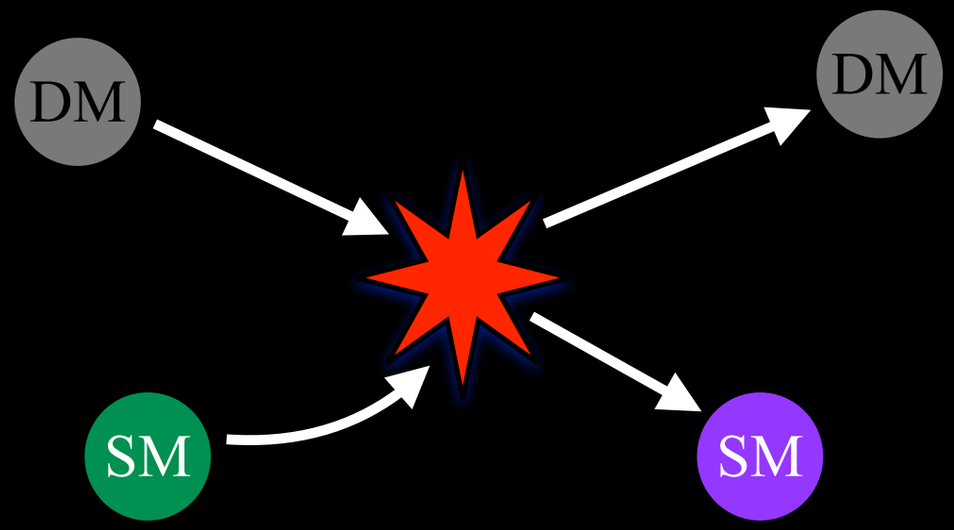
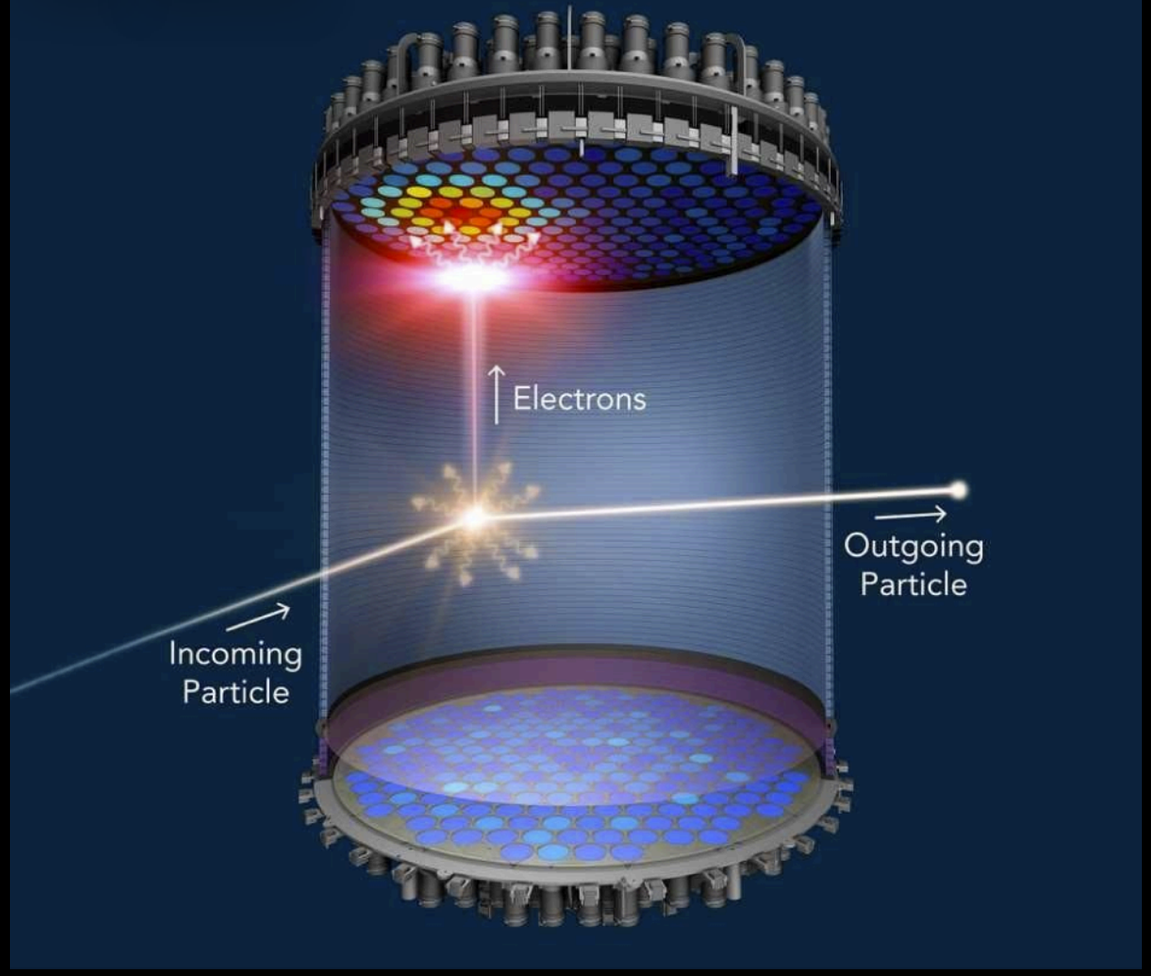


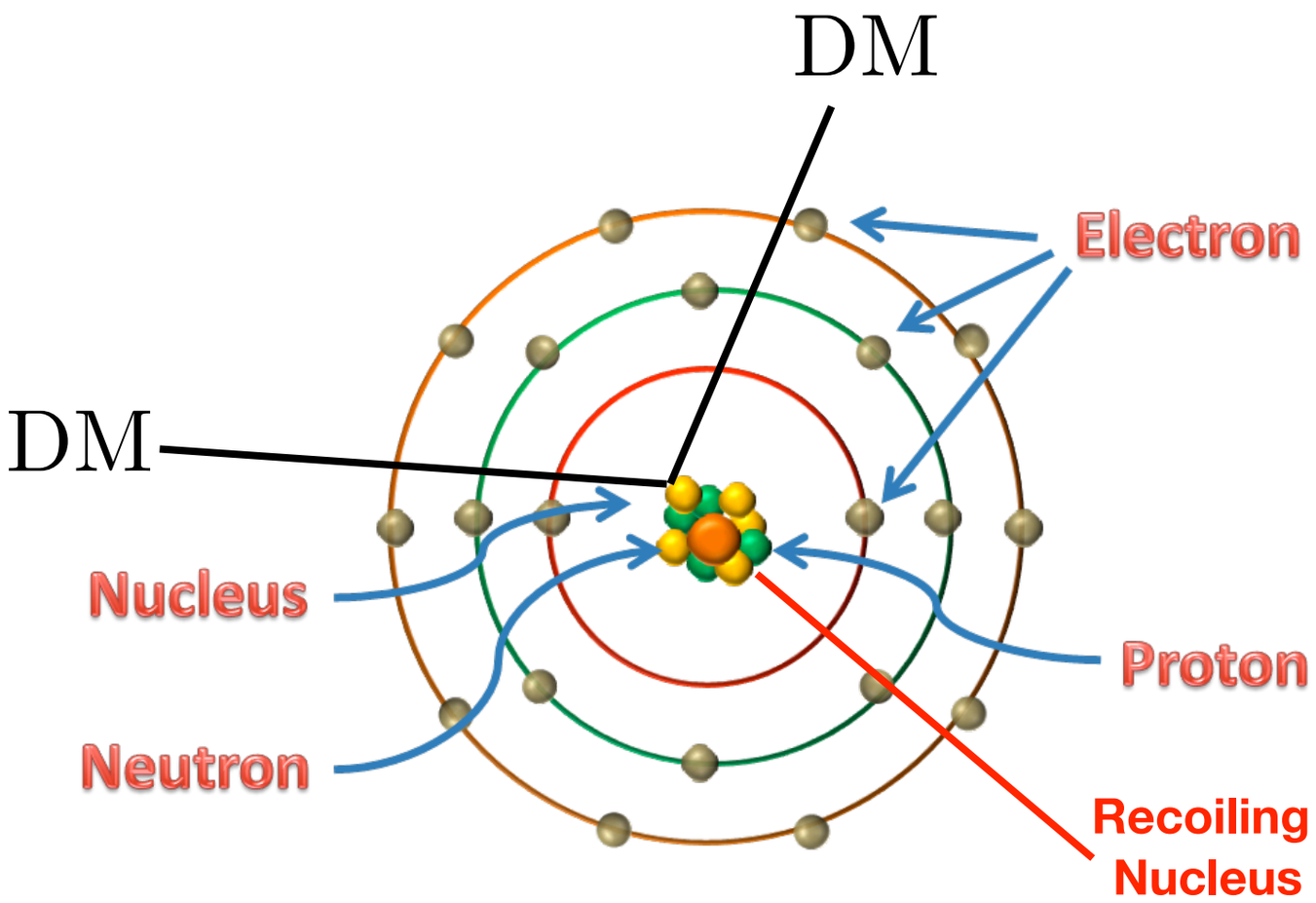
Image: forbes.com



Dark matter hits a nucleus causing a recoil

recoil nucleus is detected and kinematic information used to get dark matter properties

Nuclear Scattering

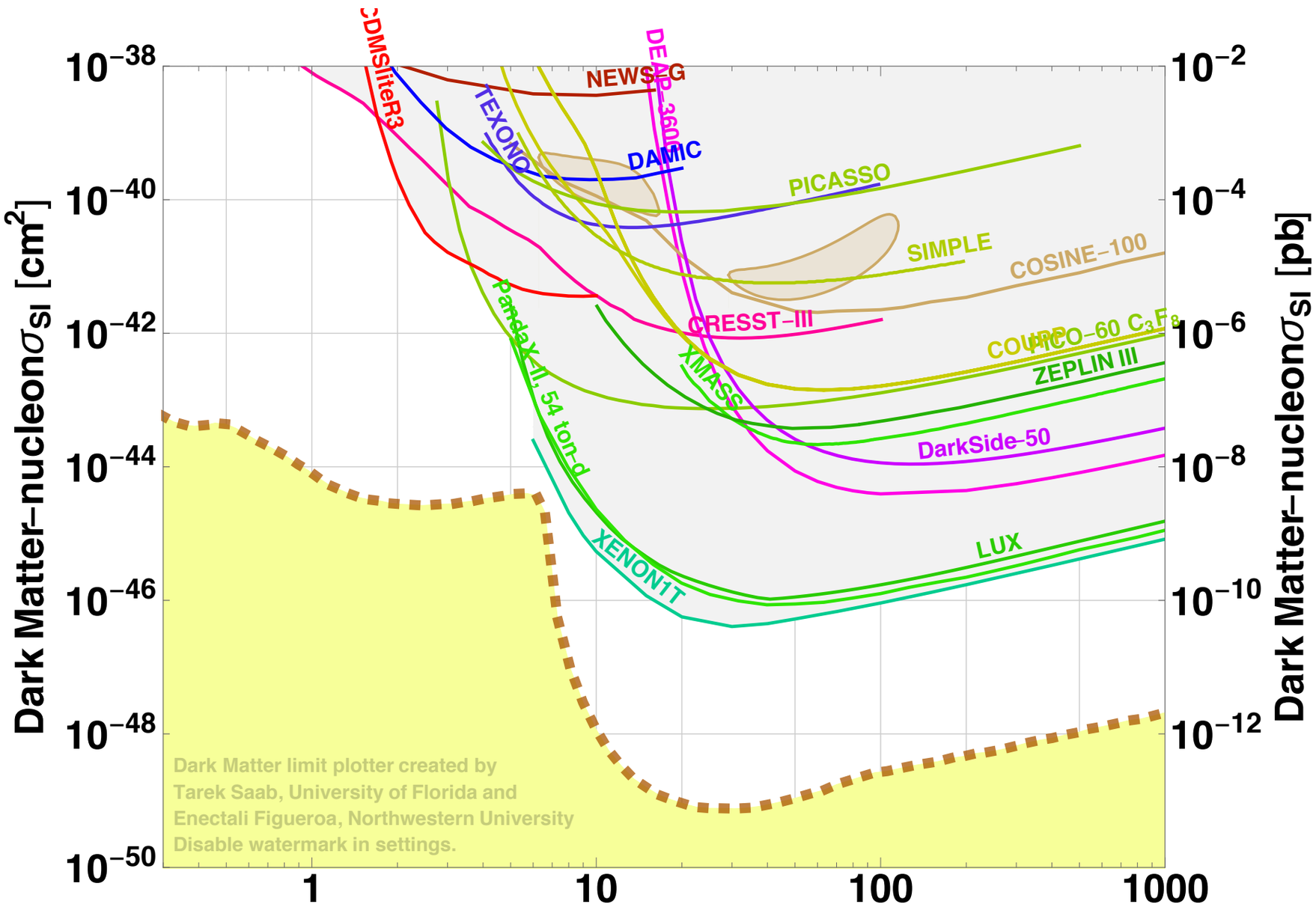


pijaeducation.com

$$\frac{dR}{dE_R} \sim N_T \Delta T \frac{\sigma_{\chi N}}{2\mu^2} |F(E_R)|^2 \frac{\rho_\chi}{m_\chi} \int_{v_{min}}^{\inf} \frac{f(v)}{v} dv$$

Nuclear Scattering

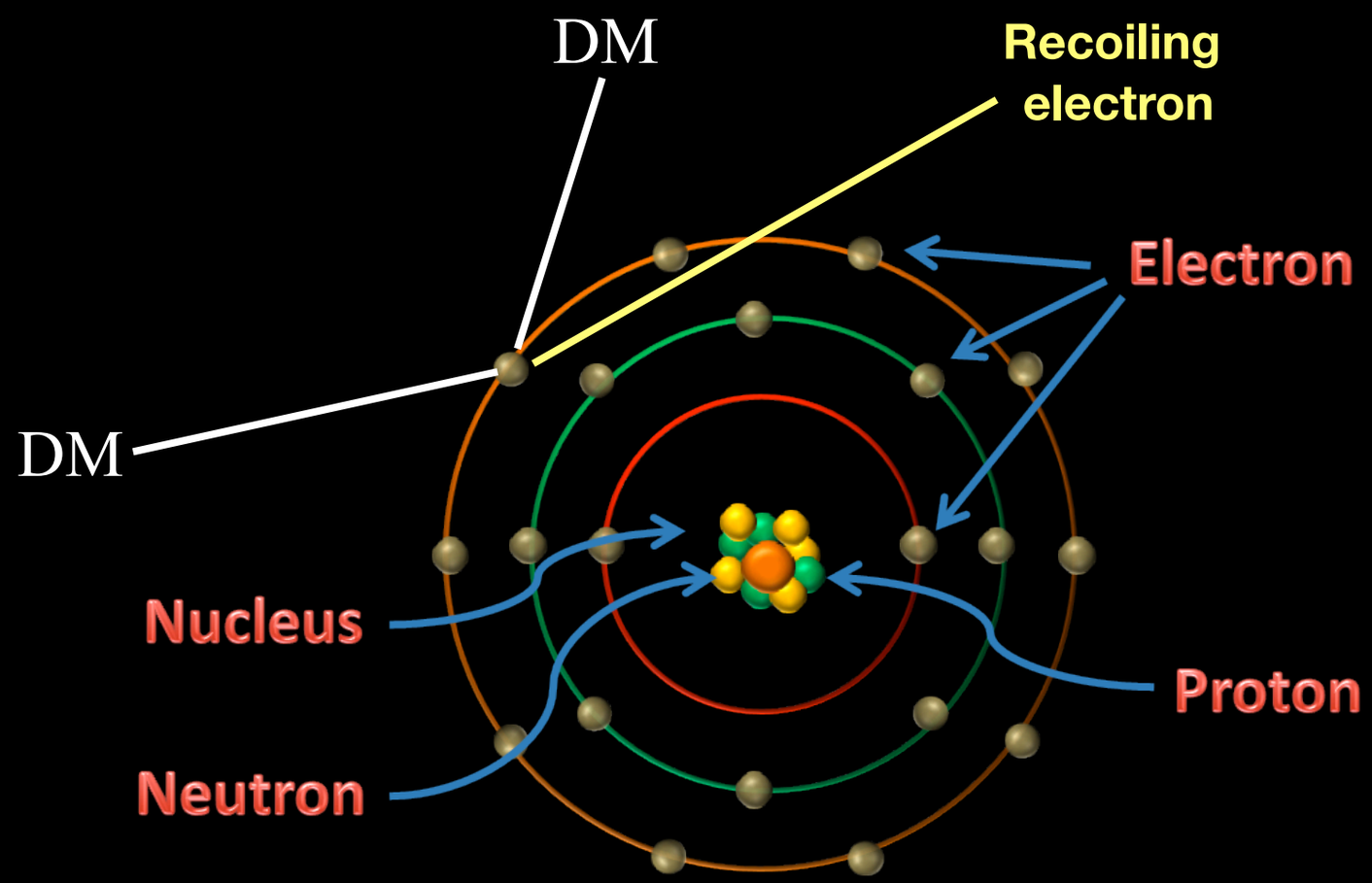
$$\frac{dR}{dE_R} \sim N_T \Delta T \frac{\sigma_{\chi N}}{2\mu^2} |F(E_R)|^2 \frac{\rho_\chi}{m_\chi} \int_{v_{min}}^{\inf} \frac{f(v)}{v} dv$$



See lecture by C. Cappiello

supercdms.slac.stanford.edu/dark-matter-limit-plotter

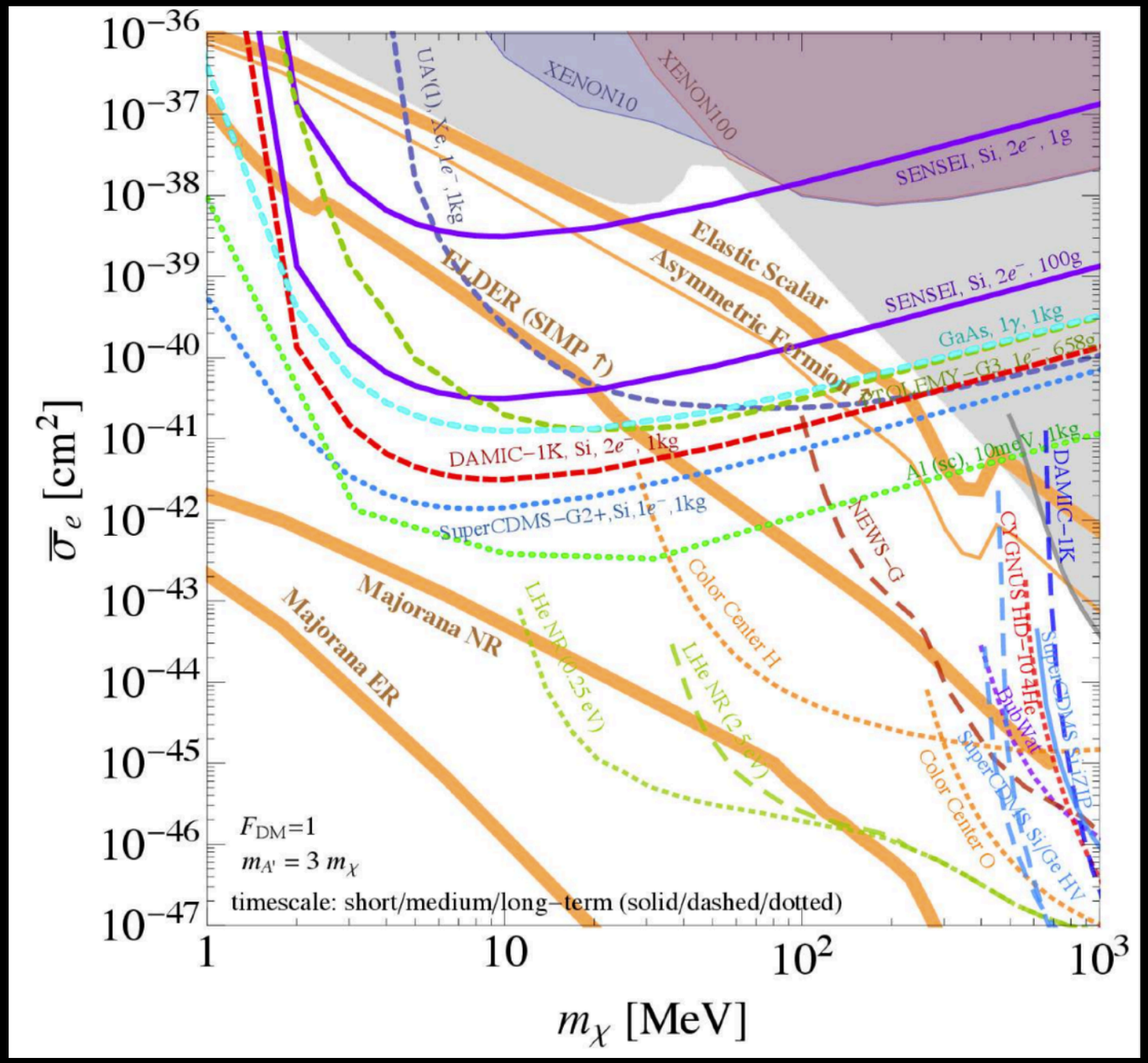
Electron Scattering



$$\frac{dR}{dlnE_R} \sim N_T \Delta T \frac{\rho_\chi}{m_\chi} \frac{\bar{\sigma}_e}{8\mu^2} \int q dq |f_{ion}^{nl}|^2 |F_{DM}(q)|^2 \int_{v_{min}}^{\inf} \frac{f(v)}{v} dv$$

Electron Scattering

$$\frac{dR}{dlnE_R} \sim N_T \Delta T \frac{\rho_\chi}{m_\chi} \frac{\bar{\sigma}_e}{8\mu^2} \int qdq |f_{ion}^{nl}|^2 |F_{DM}(q)|^2 \int_{v_{min}}^{\text{inf}} \frac{f(v)}{v} dv$$



US Cosmic Visions Report: **arXiv:1707.04591**

Questions?