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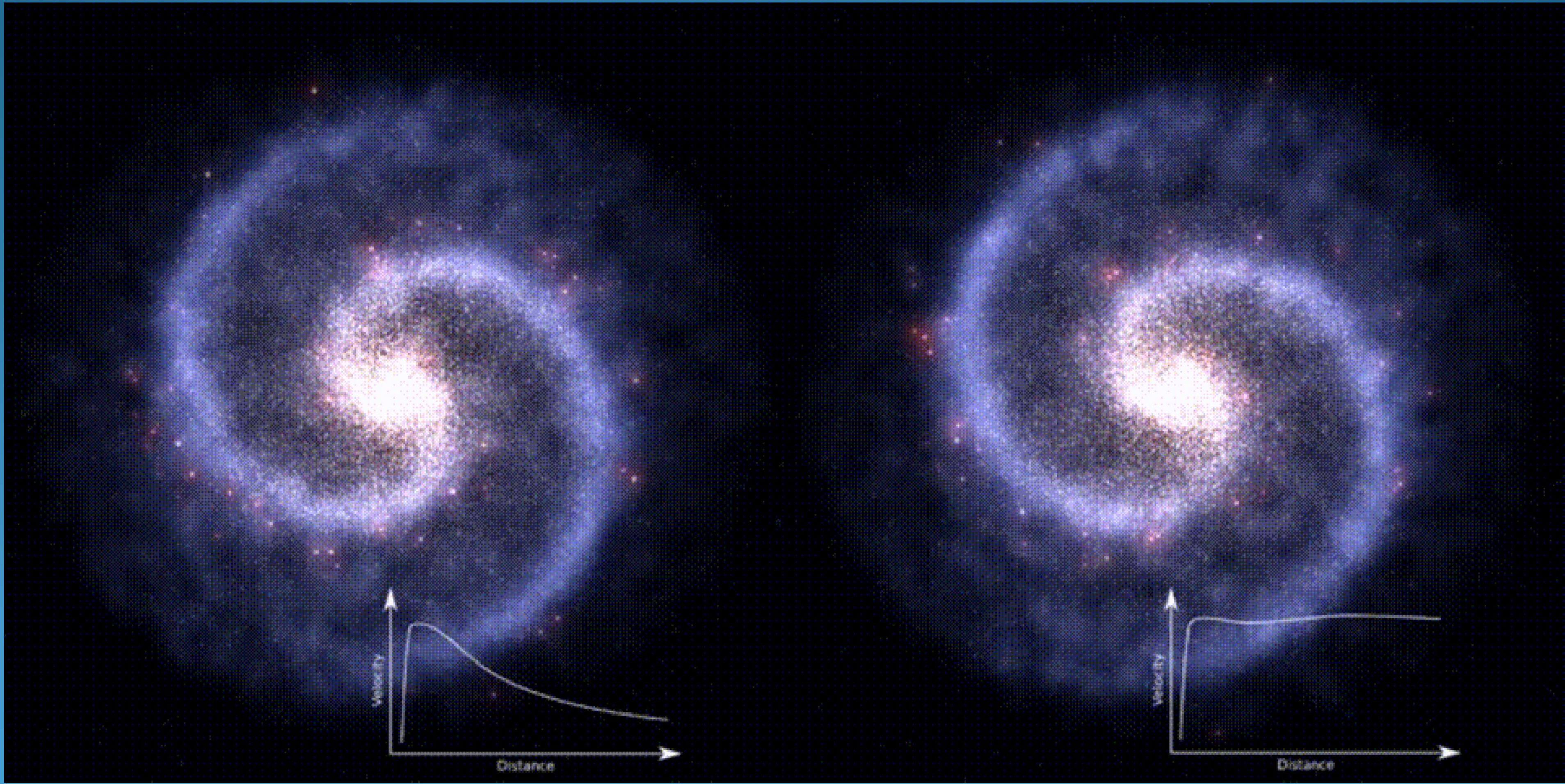
What is the Universe made of?

November 2022



What is the Universe made of?

What is the universe made of?

What is "stuff"?

Why do we need Dark Matter?

Who discovered it/made it up & why

What is it?

Is it real? - *Alternate theories*

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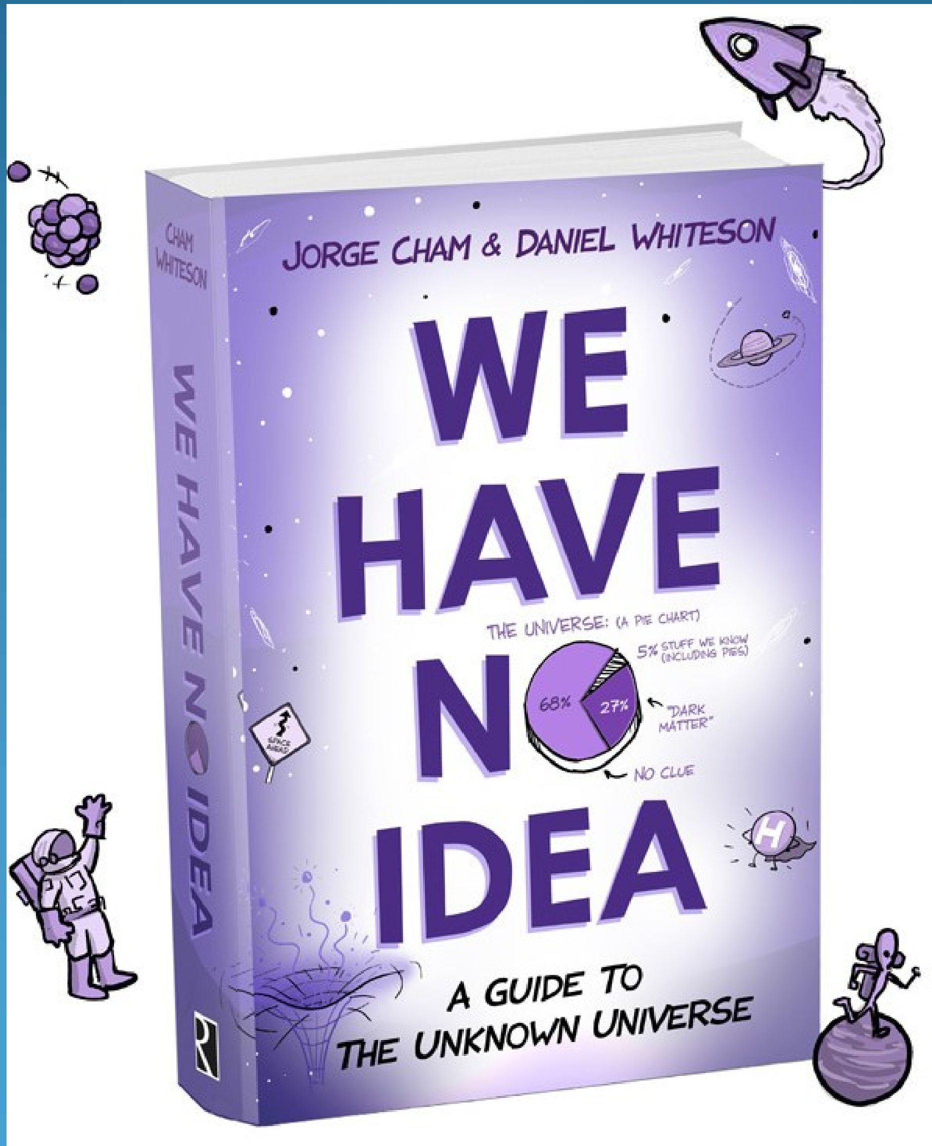
Dark Matter

The ultimate reference book about the universe



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What is the Universe made of?

When Einstein was developing his relativity theories he assumed that the universe was static.

Willem de Sitter assumed an expanding universe driven by the cosmological constant causing expansion to accelerate.

Georges Lemaitre thought that Einstein's assumed static universe was unstable and favoured an expanding model – with a definite beginning.

Alexander Friedmann, in 1927, proposed an expanding universe but one dominated by matter. Thus expansion would slow as matter is diluted.

Edwin Hubble provided data, in 1929, that showed that nebulae are much further away than thought and that the universe is expanding.

This view of a matter dominated expanding universe was the favoured view for the next number of decades.

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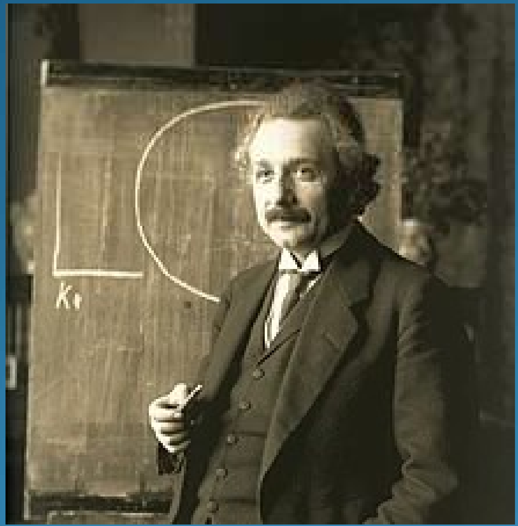
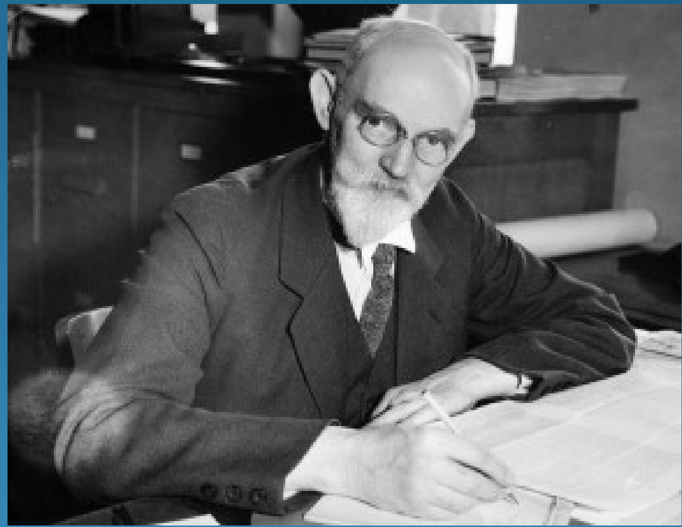
What is the Universe made of?

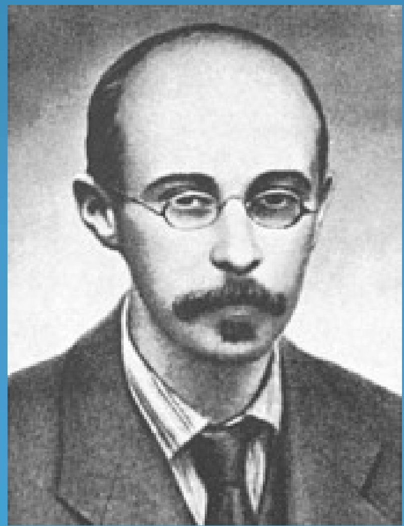


Albert Einstein



Willem de Sitter

George Lemaitre



Alexander Friedmann

Edwin Hubble

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What is the Universe made of?

In the mid 1950s if you asked the question “What are the main components of the universe” the answer would have been:-

“Stars, planets, interstellar gas and dust and photons” (EMR).
In the late 60s cosmic rays were added to the mix

The big question was then what is it’s geometry.

Is there enough stuff so that gravitational force will stop the expansion and pull everything back together again

or

will the expansion go on for ever.

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Dark Matter

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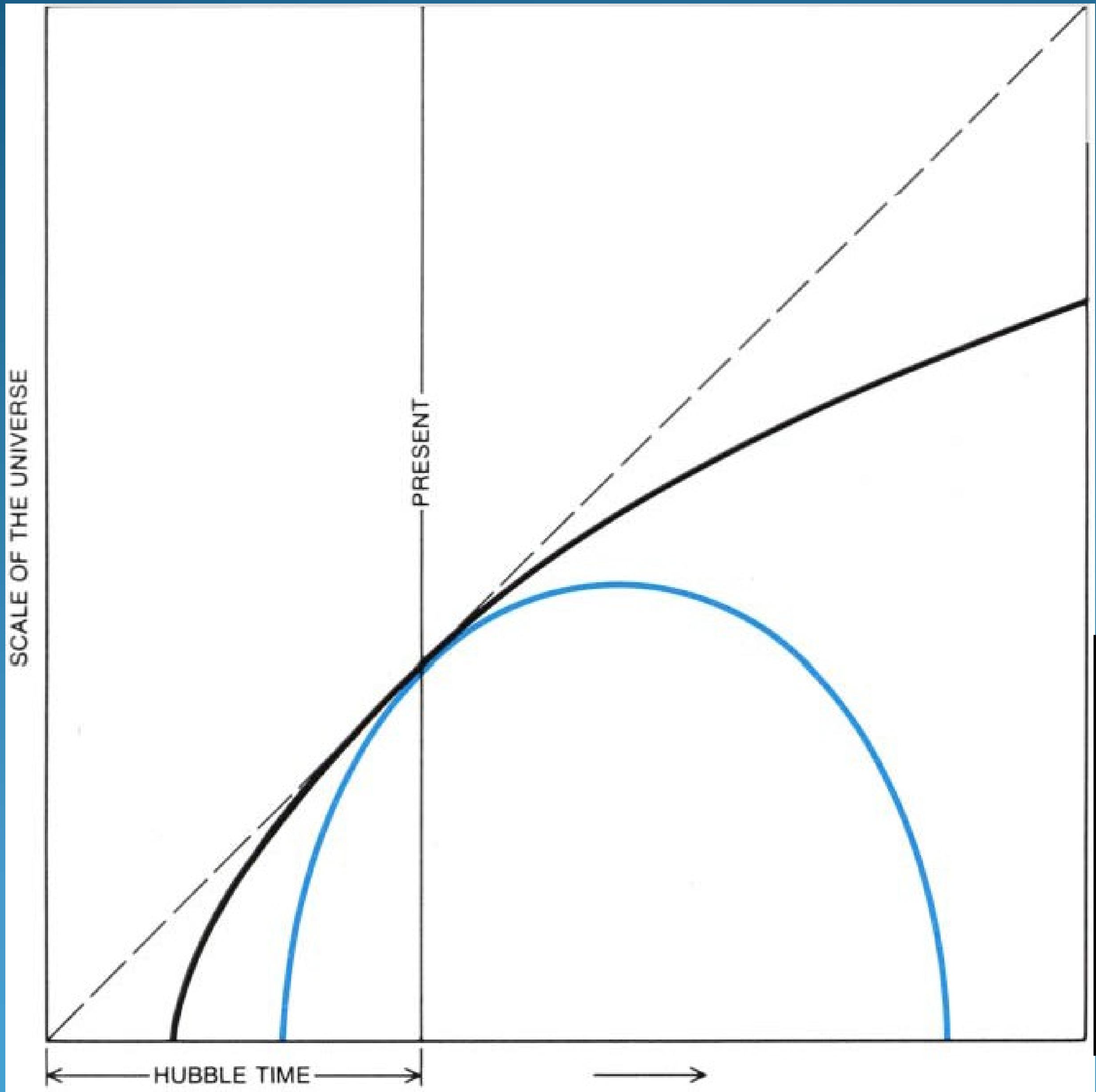

The question is summed up in this diagram

MODELS OF COSMIC EVOLUTION

Will the Universe Expand Forever?

SciAm; March 1976

What is the Universe made of?

In the mid 50s some experiments “showed” that expansion at the far reaches of the Universe was slowing.

Allan R. Sandage, 1956

The redness, and presumably the speed of recession, of most galaxies increases regularly with distance. The most distant galaxies observed appear to depart from this law, a fact of deep meaning for cosmology.............

If the expansion of the universe is decelerating at the rate our present data suggest, the expansion will eventually stop and contraction will begin. If it returns to a super dense state and explodes again, then in the next cycle of oscillation, some 15 billion years hence, we may all find ourselves again pursuing our present tasks.
Although no final answers have yet emerged, big steps have been taken since 1928 toward the solution to the cosmological problem, and there is hope that it may now be within our grasp

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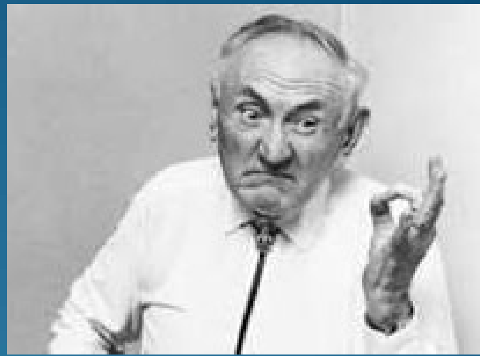
Dark Matter



However, as far back as 1933 there were questions being asked about is what we see all there is.

Fritz Zwicky, a Swiss astronomer working in the US, was examining the Coma galaxy cluster – over 1,000 galaxies ~336 Mly away.

He discovered a gravitational anomaly. The gravitational mass of what he could see didn't explain the rotational velocity of the cluster.

He referred to the missing stuff as ***Dunkle Materie***

He calculated the gravitational mass of the galaxies within the cluster from the observed rotational velocities. The result was a value at least 400 times greater than expected from their luminosity.

Does this then mean that most stuff was dark/invisible?

At the time it was considered to be a curiosity but, as there were many uncertainties in the calculations the concept not taken seriously.

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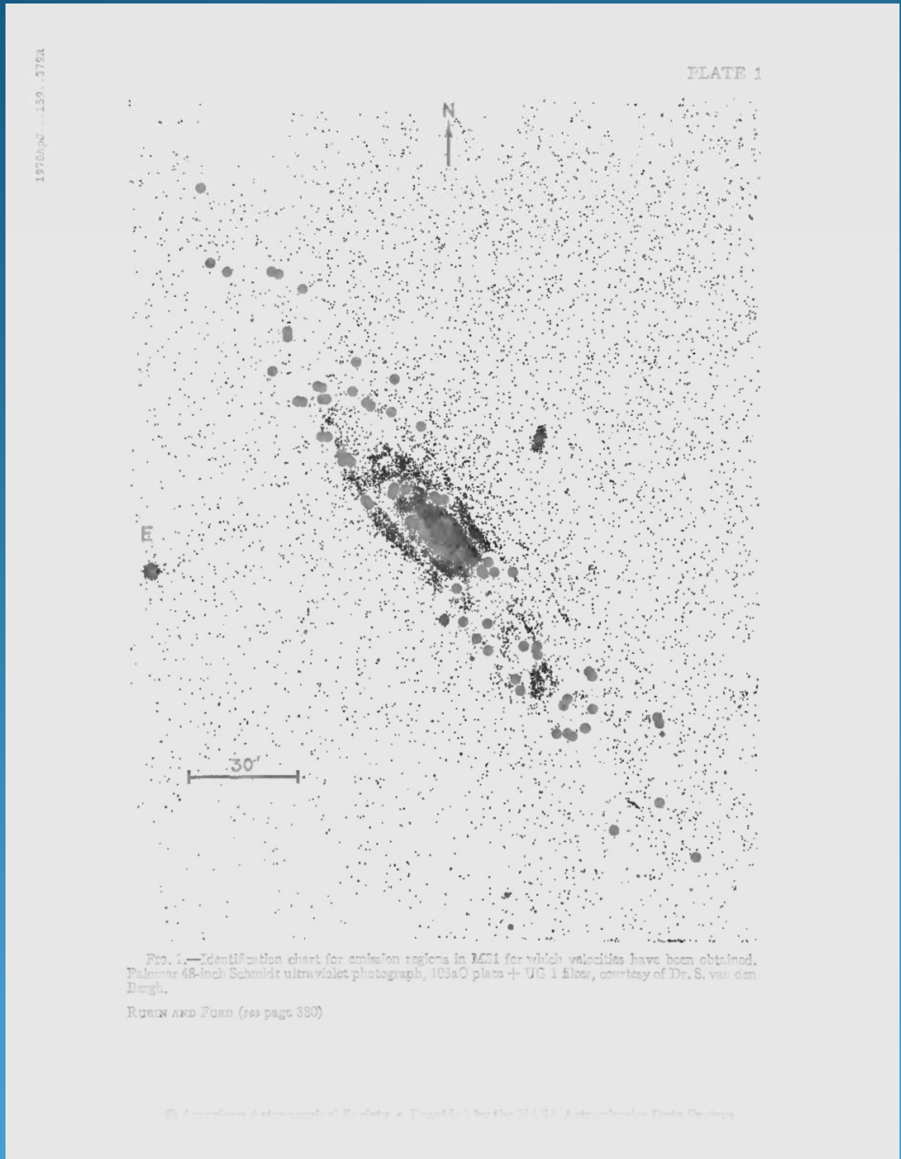
Dark Matter



Rotation of the Andromeda nebula from a spectroscopic survey of emission regions; Rubin & Ford, Astrophysical Journal, Feb 1970

Vera Rubin was interested in galactic astronomy.

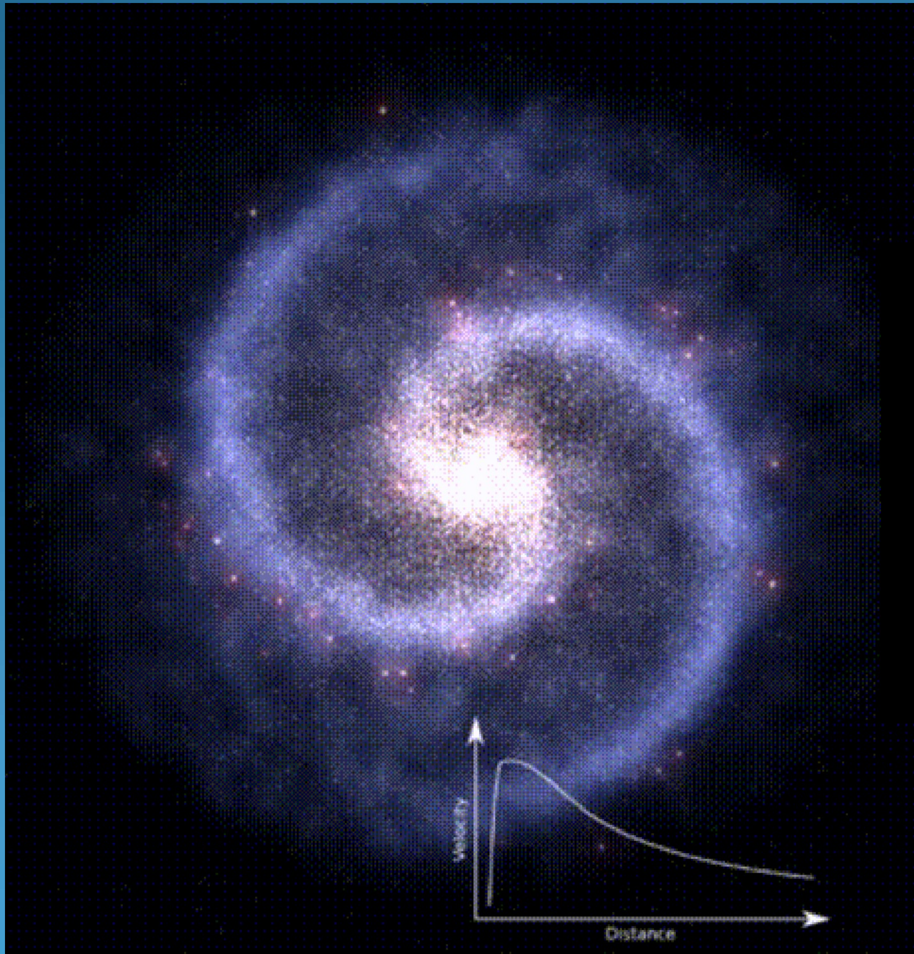
In 1965, along with Kent Ford, who had the best spectroscope at the time, they started to investigate quasars.

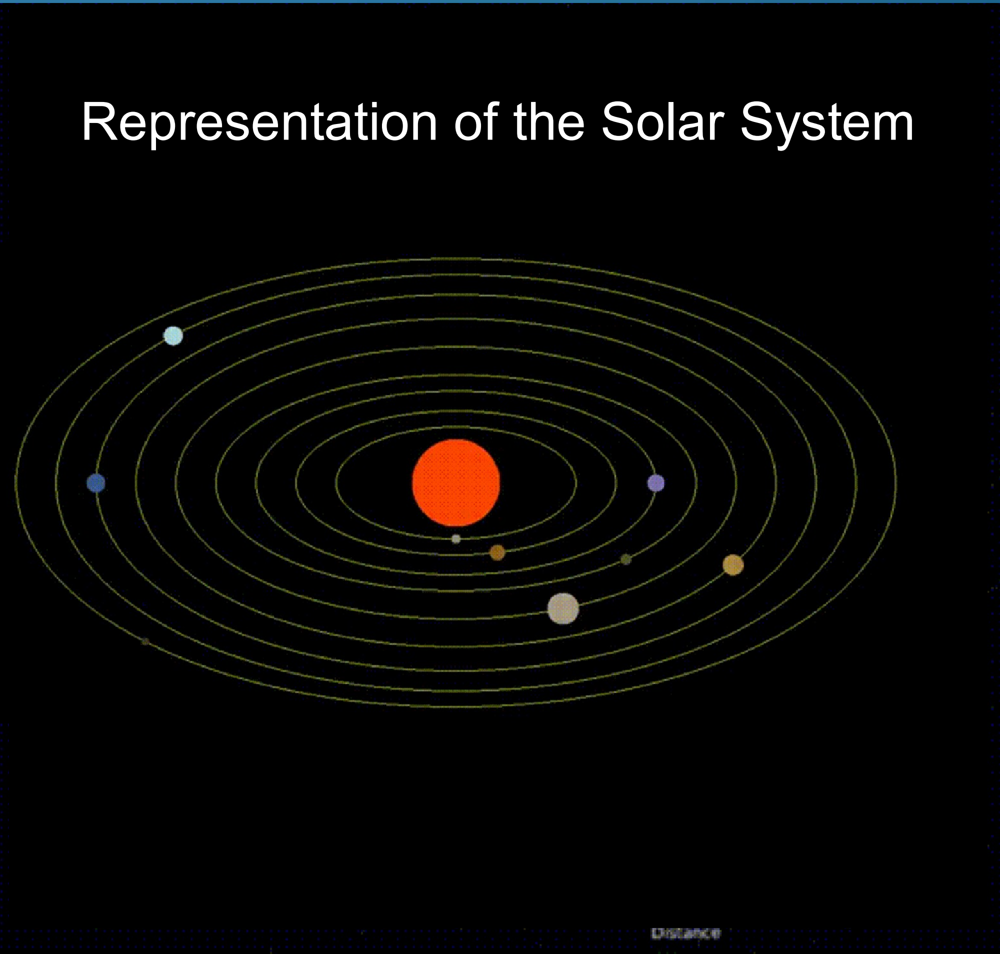
But, with quasars only being discovered in 1963, the field was crowded so they turned their attention to investigate the rotational speed of the Andromeda galaxy (M31).

They did this by measuring the rotational speed, using the HII spectral line, at 67 different positions in M31.

Dark Matter

What they expected to see





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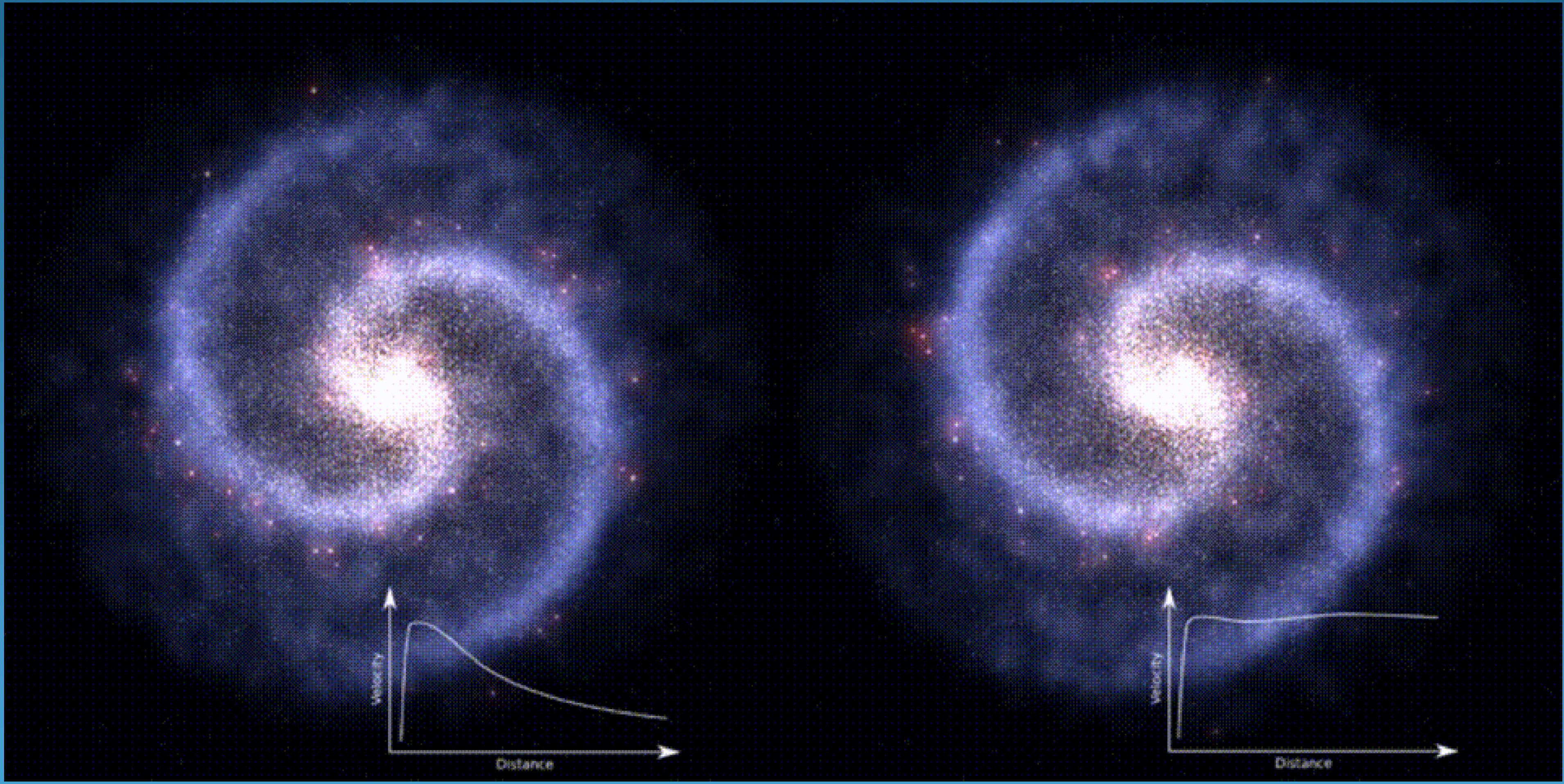
What they actually saw



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They continued their investigations and published a number of papers.

In one published in 1980 entitled:- *Rotational properties of 21 Sc galaxies with a large range of luminosities and radii; Rubin, Ford and Thonnard; The Astrophysical Journal*

the authors posed a number of questions in the conclusion including:-

- Does the common form for the Sc rotation curves mean that all Sc galaxies, small or large, sit in generally similar potential wells, in which the optical galaxy defines only that region in which matter happens to be luminous?

-Is the luminous matter only a minor component of the total galaxy mass?

Note:- Sc Galaxy: Weak or no bulge, open spiral structure, very knotty appearance. Eg the Pinwheel galaxy

Dark Matter

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-Is the luminous matter only a minor component of the total galaxy mass?

However, because she was a woman she wasn't considered for a Nobel.

From "We're sorry, Vera Rubin" SciAm; Oct 2019.
Rubin did nothing short of systematically verify the existence of dark matter...... She wasn't the first to find evidence of dark matter, but she was the one to demonstrate its presence convincingly, which resulted in a paradigm shift in our understanding of the cosmos.

What is "stuff"

"Stuff" is the technical term for everything that you can see/touch/or otherwise experience.

All the stuff we can directly experience is made up of just a few components, known as baryonic matter.:-
Baryonic matter includes Atoms, which are made of neutrons and protons, which are in turn made of quarks.

Other particles and forces, eg electrons, are part of "Stuff" but are non-baryonic.

Usually we only hear about protons and neutrons, and not the plethora of other baryons. The reason is that all the other baryons exist for only a fraction of a millisecond before they decay – they spontaneously transform into other particles. Just as the heavier leptons (the muon and tau) decay into other particles, so do most baryons.

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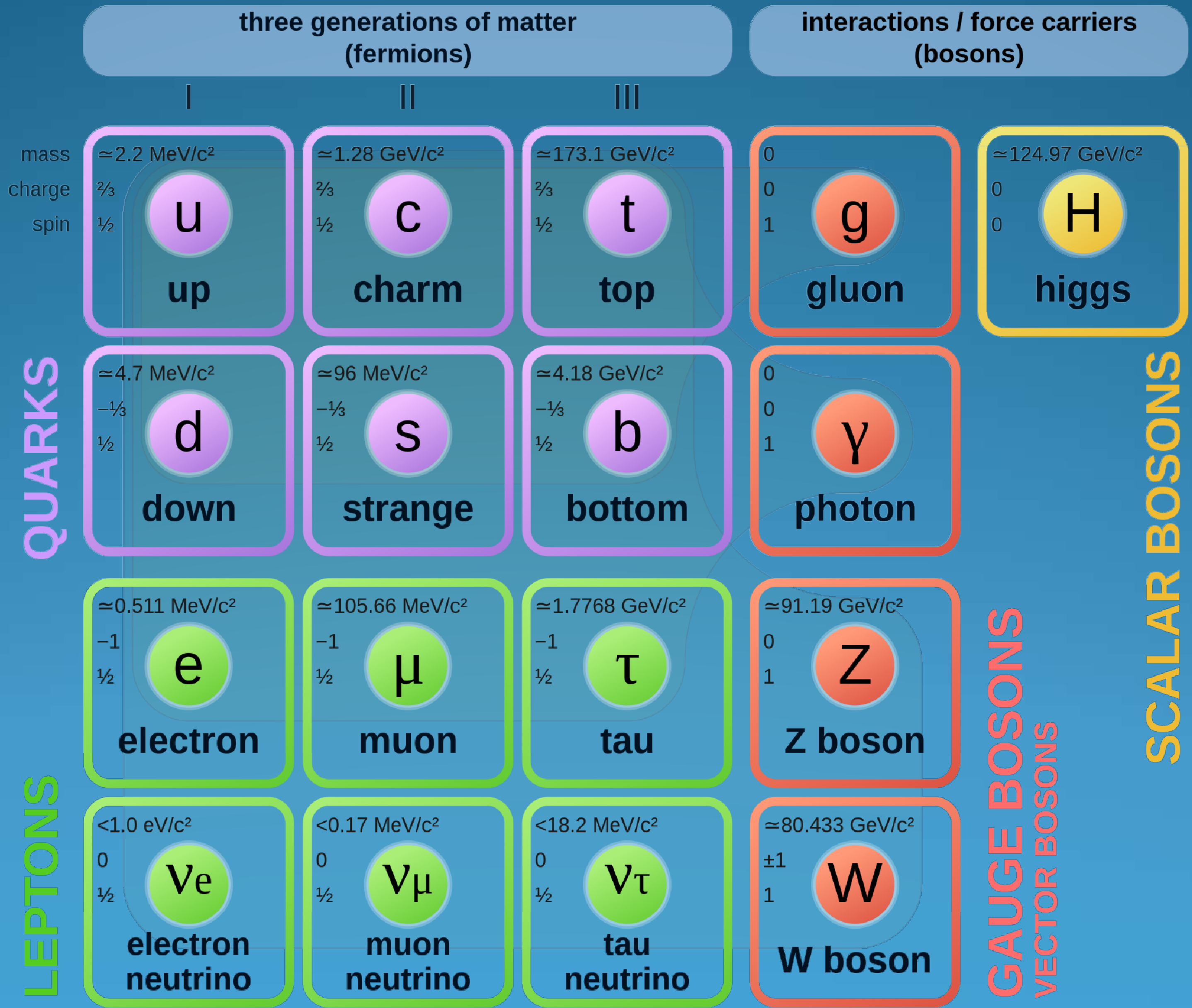
What is the Universe made of?

Standard Model of Elementary Particles



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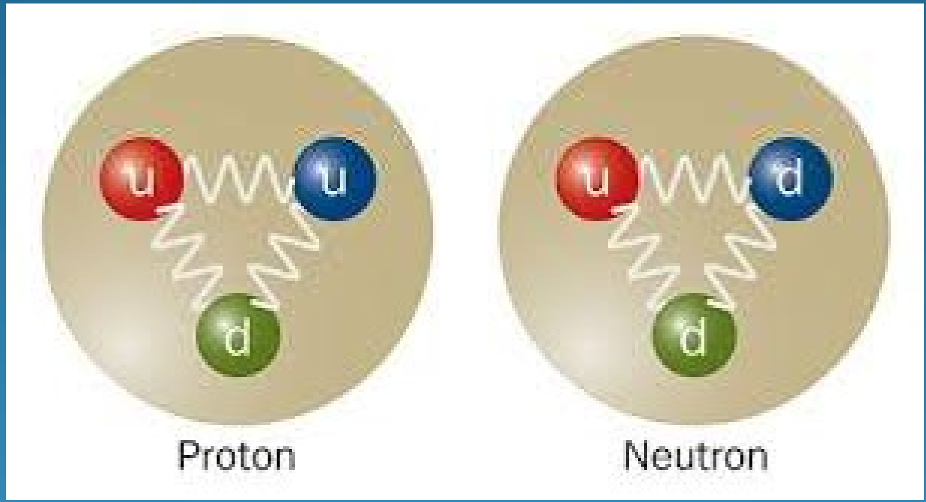
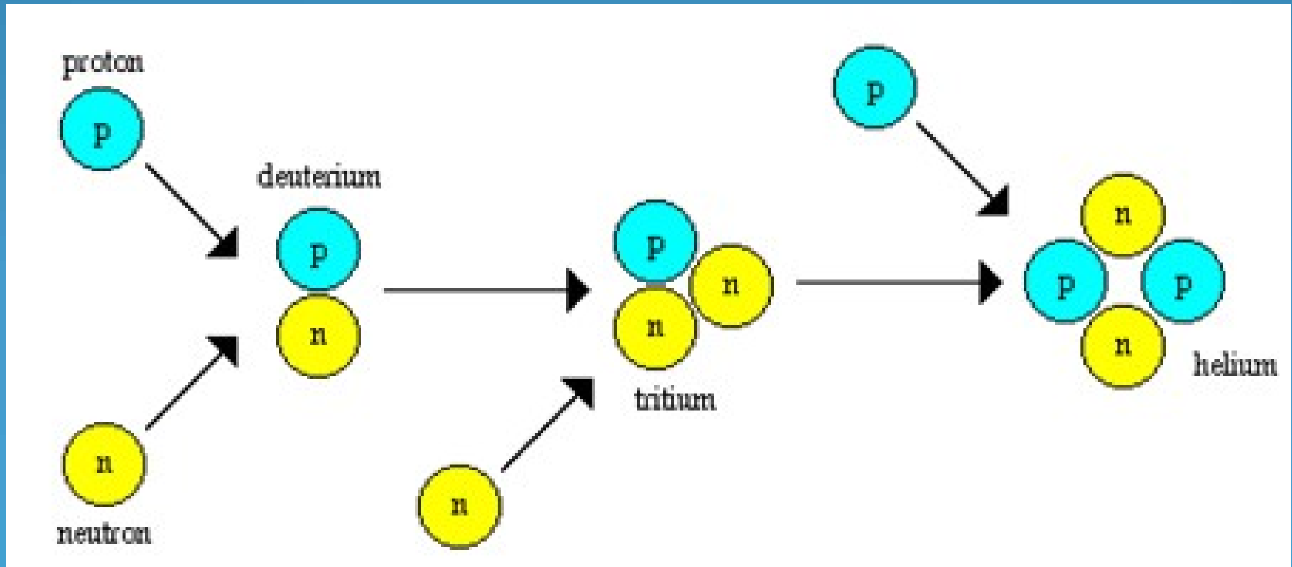
What is the Universe made of?





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What is the Universe made of?

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Abundance – Universe

(73% H and 25% He)

Element	Symbol	Atomic Number	Protons	Neutrons	Electrons
Hydrogen	H	1	1	0	1
Helium	He	2	2	2	2
Oxygen	O	8	8	8	8
Carbon	C	6	6	6	6
Neon	Ne	10	10	10	10
Iron	Fe	26	26	30	26
Nitrogen	N	7	7	7	7

Abundance - Earth

Element	Symbol	Atomic Number	Protons	Neutrons	Electrons
Oxygen	O	8	8	8	8
Silicon	Si	14	14	14	14
Aluminium	Al	13	13	14	13
Iron	Fe	26	26	30	26
Calcium	Ca	20	20	20	20
Sodium	Na	11	11	12	11
Magnesium	Mg	12	12	12	12

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What is the Universe made of?

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Periodic Table of the Elements :

Atomic Number = number of protons in the atom

Group → / Period ↓	1	2		3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																		2 He
2	3 Li	4 Be												5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg												13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca		21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr		39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	*	71 Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	**	103 Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
			*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb		
			**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No		

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What is the Universe made of?

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The current favoured model has calculated that, in terms of matter (ignoring Dark Energy that is, which is a whole other subject!):

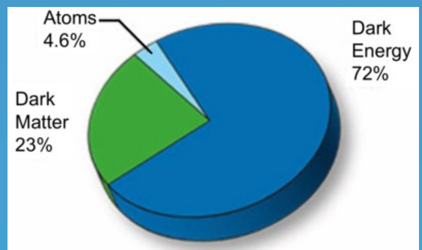
Normal or Baryonic Matter, ie stuff we can see/touch/smell/etc only comprises some

17%

And Dark Matter makes up the other

83%

Adding in Dark Energy gives



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Dark Matter

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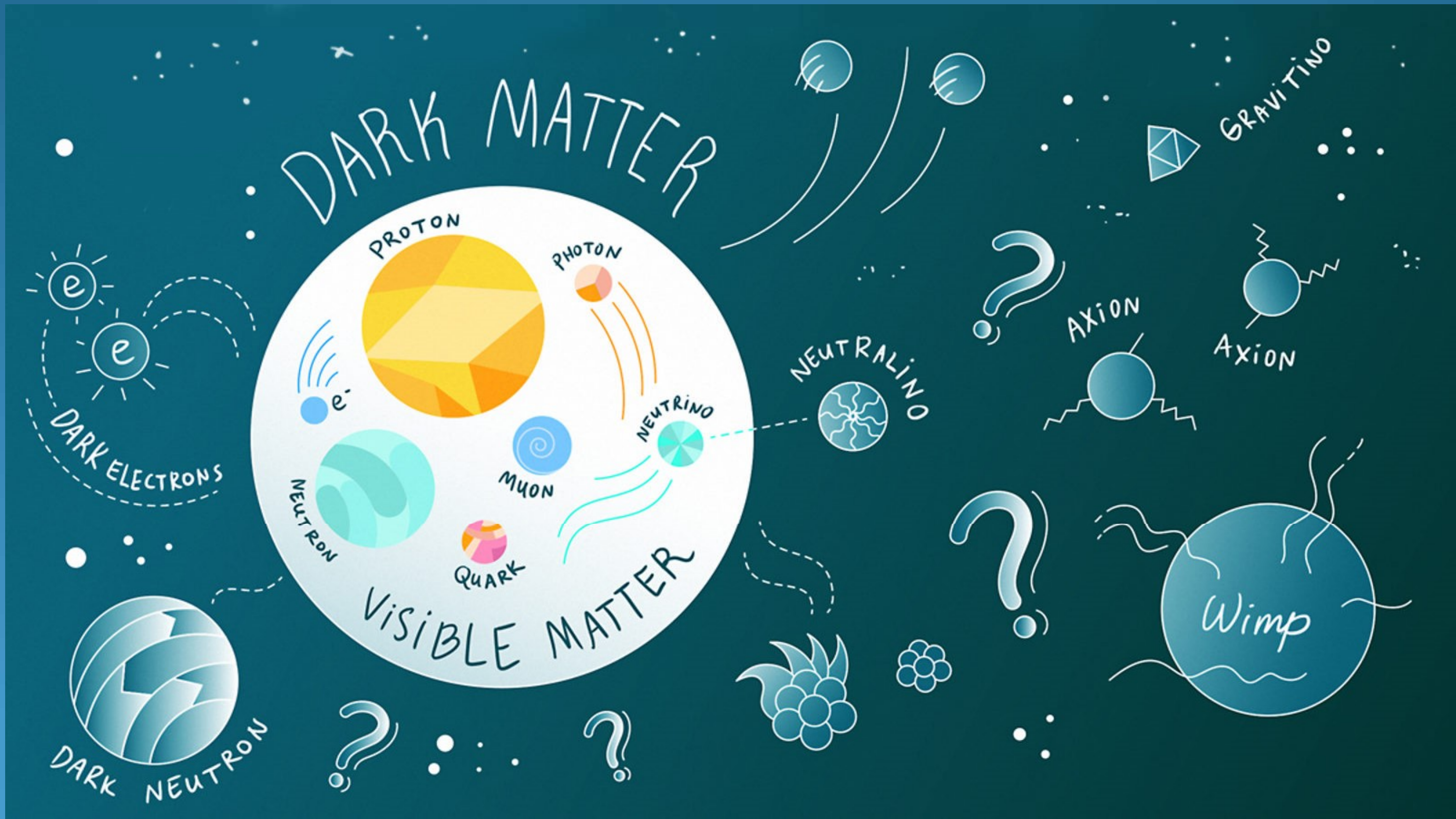
So, we now have the situation where, unlike when I was a lad, most of the stuff in the universe is thought to be something else.



Copyright 2022 Symmetry Magazine : A joint Fermilab/SLAC publication

So, what is it???

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Why do we need Dark Matter?

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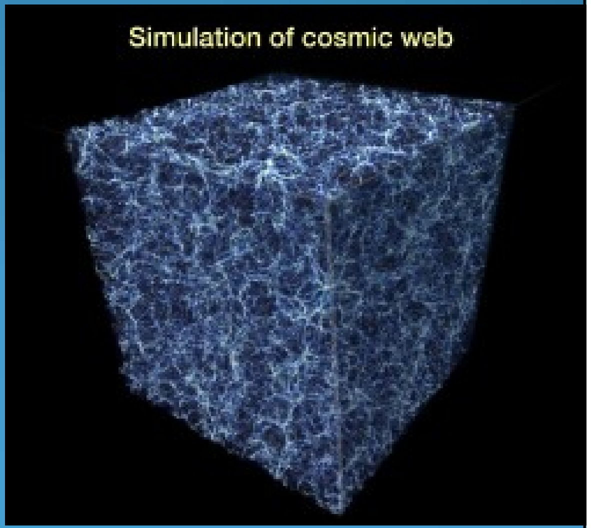
Summary of what we know / think

Dark matter is only detectable by the gravitational force it exerts.

Observations of the motion of galaxies, as noted by Zwicky, Rubin and others, suggest more mass that we can see.

Gravitational lensing, ie the bending of distant light by intervening galaxies etc, also suggests more mass.



It is now thought that Dark Matter in the emerging universe provided a skeleton on which stars/galaxies could grow. Galaxies do not grow randomly but have an underlying structure on which they form.

ie, the gravitational attraction of this DM web concentrated baryonic matter allowing the first stars to form.

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<u>*Dark Matter*</u>

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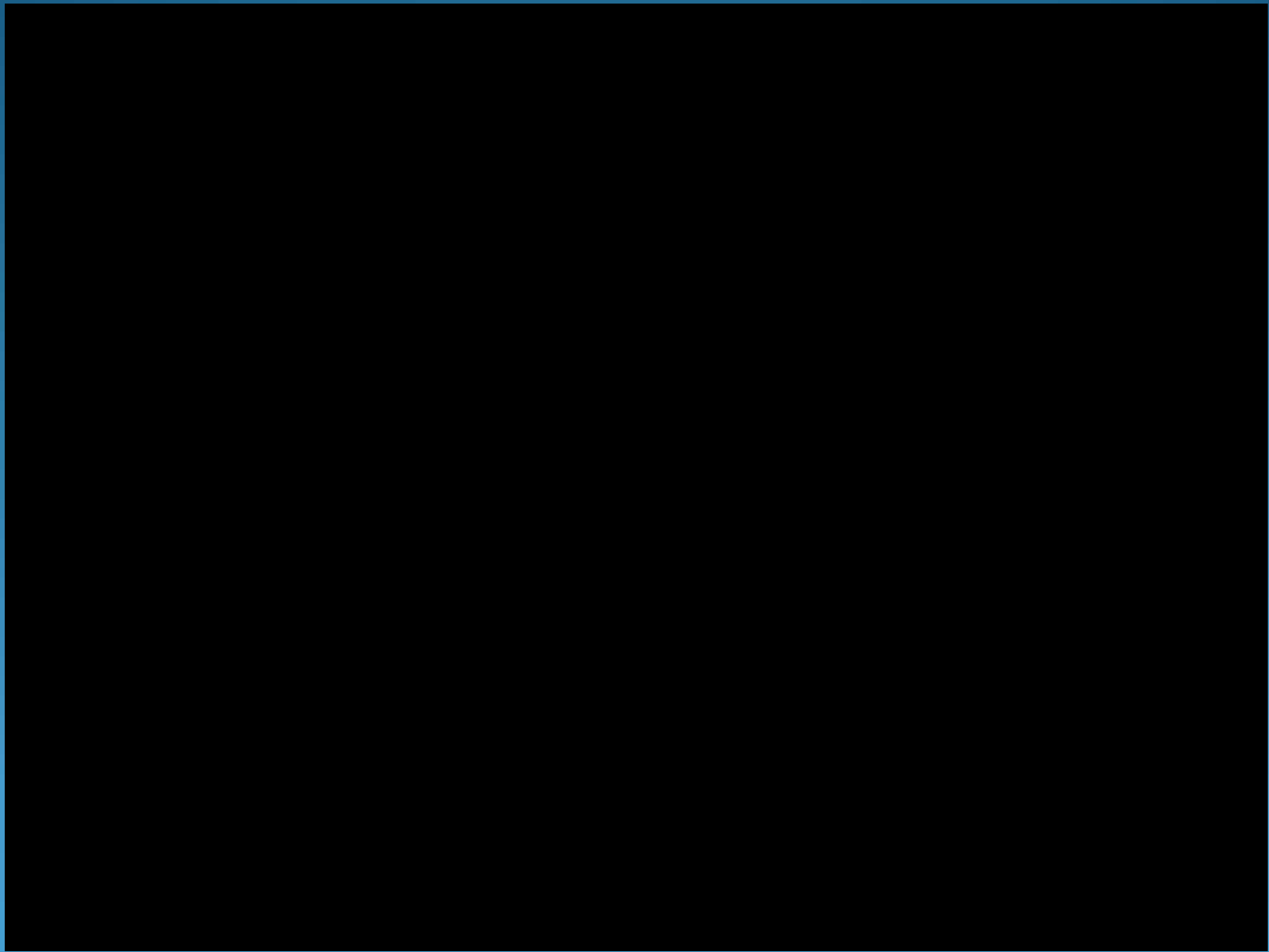

2012 : Hubblecast - Cosmic Dark Matter Web (NASA ESA)

Dark Matter

What we think we know about Dark Matter:-

1 It’s been around for a long time. The heaviest particles tend to break down in time to form lighter particles.
Only the light ones, eg electrons & protons, have very long life spans.
Does this mean that DM is as light as these long lived particles?

2 It’s key to the evolution of the universe forming the scaffolding on which the galaxies have grown.

3 The presence of non-visible matter is demonstrated by the distortion of light by gravitational lensing and by the rotational speeds of galaxies and galaxy clusters

4 It represents 83% or thereabouts of all matter in the universe which we know from its gravitational effects.

5 Of course, as with ordinary stuff there could well be a host of different DM particles!

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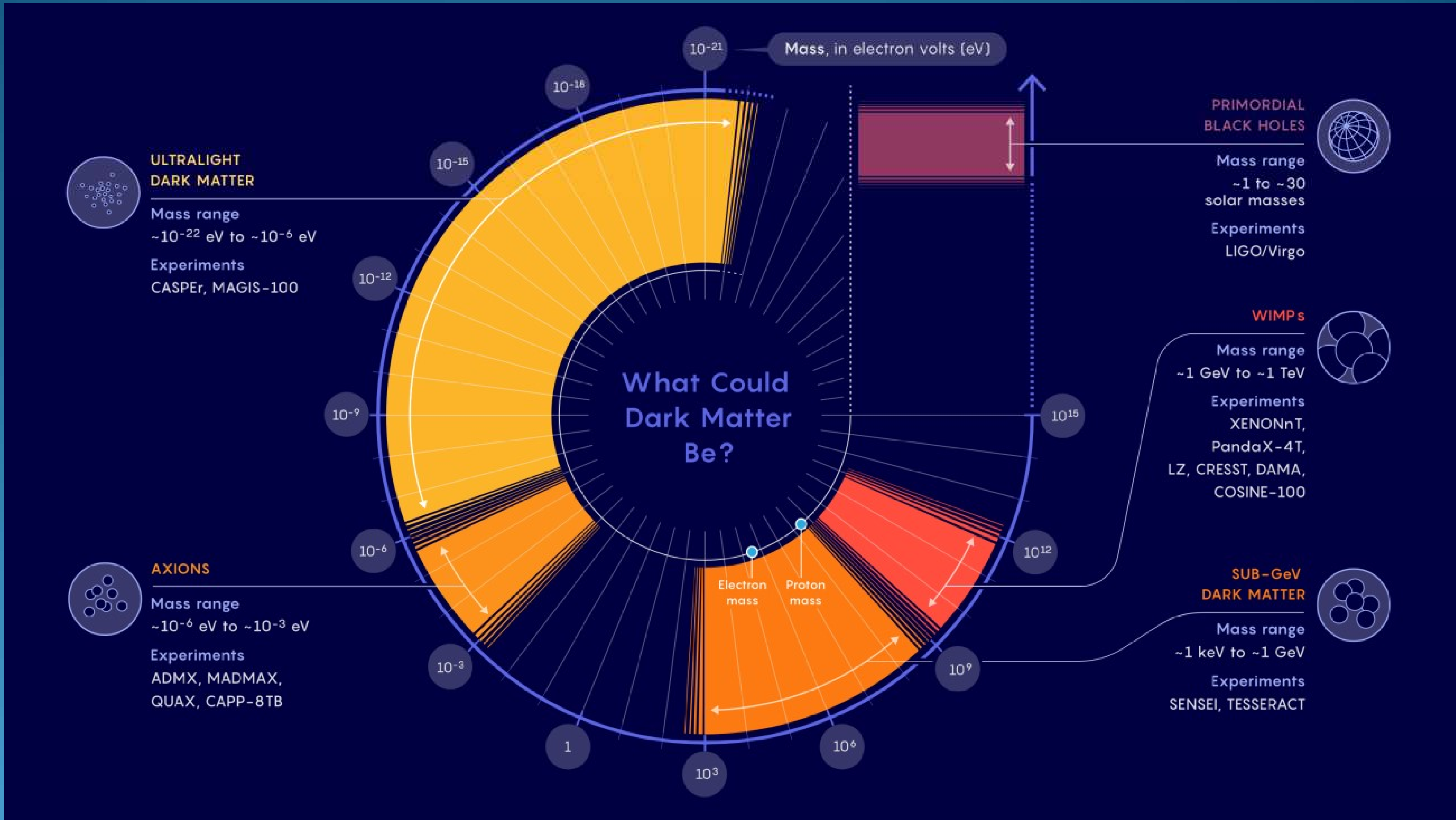
Dark Matter



Dark matter could be made up of particles with a vast range of possible masses.
www.quantamagazine.org/physicists-are-expanding-the-search-for-dark-matter-20201123/

November 2022

Dark Matter

MACHOs (Massive compact halo object)

One of the early candidates for dark matter.

These objects, including neutron stars, brown dwarfs, white dwarfs and possibly primmordial or small black holes, are composed of ordinary matter.

But they could they be invisible as they emit very little to no light.

Gravitational lensing would detect them but current models say that it is unlikely that enough of these dark bodies could accumulate to make up the vast amount of dark matter that exists.

So that's a NO then (probably)

Dark Matter

WIMPs (weakly interacting massive particle)

It would be completely different from the type of matter we know and would interact via gravity or unknown weak forces. Roughly 100,000 of these would pass through every square centimetre of Earth each second, interacting only via the weak force and gravity with surrounding matter.

If WIMPs exist, mathematical modelling shows there must be about five times more of these than normal matter, which coincides with the abundance of dark matter that we observe in the Universe.

They also emerge from the super-symmetry extension of the standard model.

This means we should be able to detect them through their collisions with other “real” particles which would produce observable effects.

Over the last 25+ years that various experiments have been running no confirmed detections have been made.

For example in December 2021 the PandaX experiment, using Xenon and located 1.5 miles underground in China, reported no signals detected.

Dark Matter

Axions

A hypothetical elementary particle first proposed in 1977.

Low-mass, slow-moving particles that don't have a charge and only interact weakly with other matter which makes them difficult to detect.

Axions of a specific mass would be able to explain the invisible nature of dark matter, if they are any lighter or heavier we would be able to see them.

And, if they do exist they would be able to decay into a pair of photons, which means we could detect them by looking for such pairs.

In 2020 the XENON1I experiment, located under Gran Sasso mountain, Italy, thought they had detected solar axions.

However in July, 2022, a new analysis with XENONnT “quashed earlier hints of new particles “.

Dark Matter

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Neutrino

Neutrinos are produced by beta decay, stellar nuclear reactions, nuclear reactors, supernova, when cosmic rays strike an atom etc.

Most neutrinos detected on Earth are from the Sun, around 65 billion per sec per square cm. That 's an awful lot going through us every second, and we don't feel a thing!

For a particle to be considered a dark matter candidate, it must have non-zero mass and no electromagnetic charge.

Neutrinos and neutrino-like particles have these two properties and are of interest .

However, the active neutrinos of the Standard Model are not likely to account for all dark matter due to their low mass.

Thus a sterile neutrino has been proposed, very small mass, electrically neutral and only interacting via the weak force and gravity.

It may be an attractive candidate for DM, but none have been detected yet.

Experiments at CERN and Fermilab colliders have set limits on this hypothetical particle.

But NO detections

Dark Matter

Gravitino

Theories combining general relativity and 'supersymmetry' predict the existence of a particle called the gravitino, the supersymetric partner of the Graviton.

In some models of supergravity, where the gravitino is very light, it could account for dark matter.

The graviton is a hypothetical particle which mediates the gravitational force. This is analogous to the photon mediating EMR.

It would have to be very light and stable, or have a very long life time.

Supersymmetry, which is a successful theory explaining a lot of observations in physics, states that all 'boson' particles have a 'superpartner' – such as the photon, ie the photino.

The LHC has yet to detect any sign of supersymmetry.

Dark Matter

Kalzula-Klein theory

This is built around the existence of an invisible 5th dimension, in addition to the usual 4.

It's a precursor to string theory, predicts the existence of a particle that could be a dark matter particle, which would have the same mass as 550 to 650 protons.

This kind of particle could interact both via electromagnetism and gravity. Although it is in a dimension we cannot see it should be easy to look for in experiments as it should decay into particles we can measure – ie neutrinos and photons – like the LHC.

No sign of Kaluza yet.

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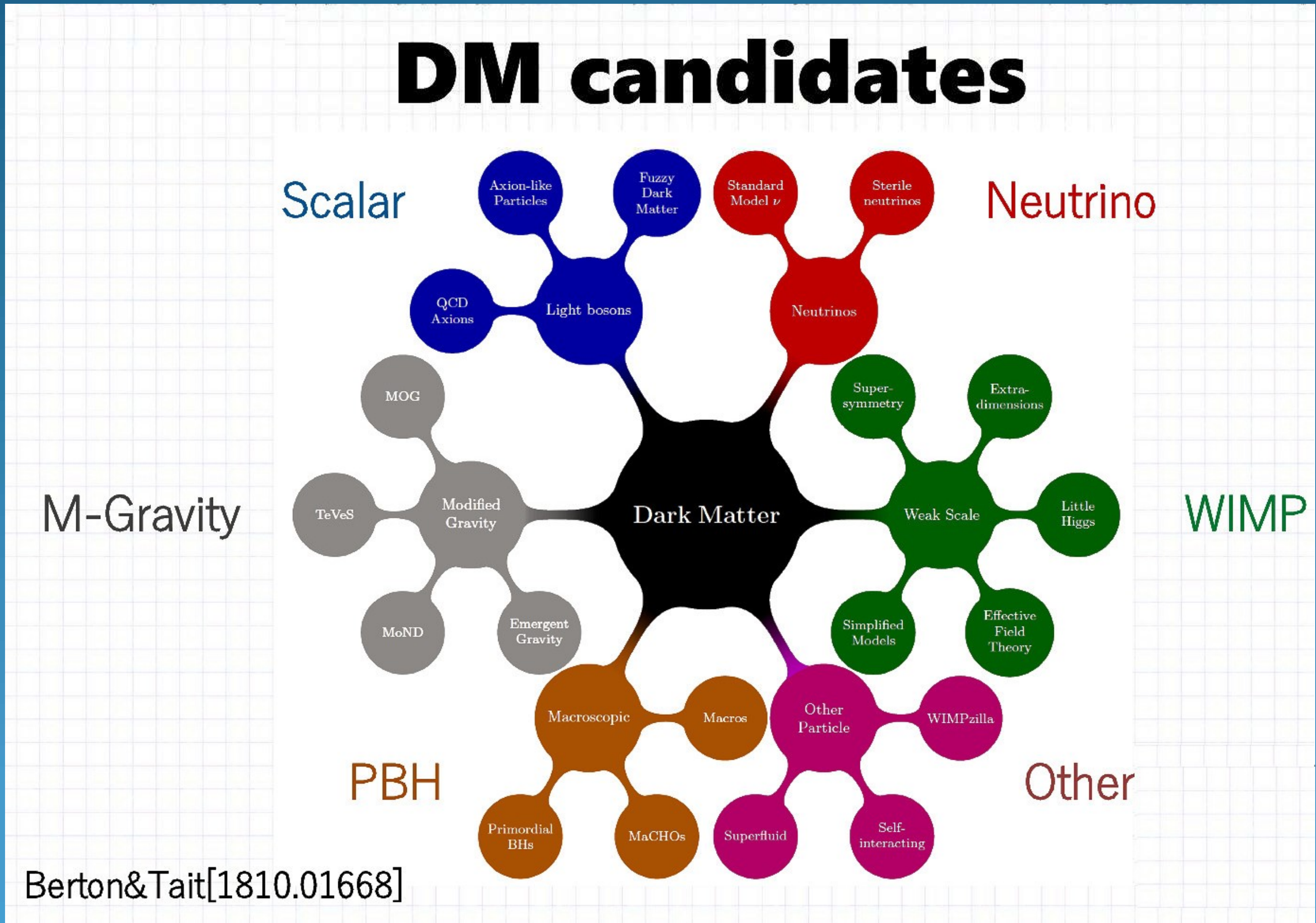
Dark Matter



Phy.org : A new era in the quest for dark matter, University of Amsterdam : 05/10/2018

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Dark Matter

Are there alternatives to the theory of DM that explains the cosmos?

How about Modified Gravity?

This theory attempts to reconcile the observations.

If correct it may also do away with the need for Dark Matter.

Modified Gravity assumes that gravity behaves differently at the very small and very large scales.

Many of the MG theories failed when the speed of gravitational waves were measured in 2017.

One Modified Gravity theory that was compatible with GW speed was MOND (Modified Newtonian dynamics)

Dark Matter

MOND

A hypothesis that modifies Newtonian universal gravitation law to explain the observed properties of galaxies.

It was proposed in 1982 by Moedehai Milgrom, an Israeli physicist.

Basically MOND says that Newton 2nd Law needs to be modified for the very low forces and accelerations on the fringes of galaxies, from:
$F = ma$ to $F = ma^2/a_0$ where a_0= approx 1.2×10^{-10} m/s^2

This rewritten law makes no difference at solar system scales but does at galactic scales, whilst doing away with the need for DM.
A recent paper by Skordos & Klosnik claims that MOND is also compatible with CMB observations. *(https://darkmattercrisis.wordpress.com/2022/04/04/67-mond-for-dummies/)*

An article published in May 2022 reported recent work on the galaxy AGC 114905, a dwarf galaxy around 250 MLy from us, which shows an extremely low rotation curve .

“The very low recorded rotation speed of this galaxy is incompatible with both MOND and the standard approach to dark matter.
However, unlike the theory of dark matter, only MOND is able to circumvent this contradiction,” says ZhaoHong-Sheng, a physicist at St. Andrews University and one of the researchers.
(https://universemagazine.com/en/alternative-theory-of-gravity-questioned-dark-matter/)

Dark Matter

MOND (ctd)

One major criticism of MOND is that it cannot eliminate the need for dark matter, or an equivalent I guess, in all astrophysical systems.

In addition observations made of the Bullet Cluster also pose a “missing mass” problem for MG theories.

In MOND, one would expect the "missing mass" to be centred on regions of visible mass which experience accelerations lower than a_0 .

In ΛCDM, on the other hand, one would expect the dark matter to be significantly offset from the visible mass because the halos of the two colliding clusters would pass through each other whilst the cluster gas would interact and end up at the centre.

An offset is clearly seen in the observations.

How do the Standard & MOND models compare? According to MOND supporters.

scitechdaily.com/dark-matter-may-not-exist-these-physicists-favor-of-a-new-theory-of-gravity/

The standard cosmological model (ΛCDM)

	Clear prior expectation	Not predicted, but follows from theory	Auxiliary assumptions needed, but these have little effect	Auxiliary assumptions needed, but these have a discernible effect	Auxiliary assumptions allow theory to fit any plausible data
Excellent agreement	Gravitational waves travel at c Expansion history at $z \gtrsim 0.2$	Einstein ring radii		⊙ CMB anisotropies	MW escape velocity curve MW-M31 timing argument Galaxy cluster internal dynamics Galaxy two-point correlation function
Works well	Big Bang nucleosynthesis Offset between X-ray and lensing in Bullet Cluster			Hickson Compact Group abundance	
Plausibly works	Weak lensing correlation function		Galaxy cluster mass function at low redshift		Weak lensing by galaxies HSB disc galaxy RCs
Some tension	Number of spiral arms in disc galaxies External field effect			Prevalence of thin disc galaxies Weakly barred M33	LSB disc galaxy RCs Gas-rich galaxy RCs Elliptical galaxy RCs Spheroidal galaxy σ_{LOS} Galaxy group σ_{LOS}
Strong disagreement	No distinct tidal dwarf mass-radius relation Local Group satellite planes El Gordo formation KBC void Local Hubble diagram slope and curvature	Galaxy bar pattern speeds RV of NGC 3109 association	Tidal limit to radii of MW satellites Bar fraction in disc galaxies		

MOND model with hypothetical sterile neutrinos

	Clear prior expectation	Not predicted, but follows from theory	Auxiliary assumptions needed, but these have little effect	Auxiliary assumptions needed, but these have a discernible effect	Auxiliary assumptions allow theory to fit any plausible data
Excellent agreement	LSB disc galaxy RCs No distinct tidal dwarf mass-radius relation External field effect	Galaxy bar pattern speeds ⊙ HSB disc galaxy RCs Elliptical galaxy RCs El Gordo formation		Expansion history at $z \gtrsim 0.2$	Gravitational waves travel at c Einstein ring radii CMB anisotropies
Works well	Tidal limit to radii of MW satellites Freeman limit Weak lensing by galaxies Binary galaxy v_{rel} Galaxy group σ_{LOS}	RV of NGC 3109 association	Weakly barred M33 Exponential profiles of disc galaxies Local Hubble diagram slope and curvature Shell galaxies	Big Bang nucleosynthesis Galaxy cluster internal dynamics Offset between X-ray and lensing in Bullet Cluster	
Plausibly works	Number of spiral arms in disc galaxies Spheroidal galaxy σ_{LOS} KBC void	MW-M31 timing argument	Local Group satellite planes	MW escape velocity curve	
Some tension					
Strong disagreement					

Dark Matter

Other recent reports : *(https://www.quantamagazine.org/brightest-ever-space-explosion-could-help-explain-dark-matter-20221026)*

An exceedingly high energy photon was observed from a recent gamma ray burst. These are thought to be caused by the collapse of a giant star into a black hole or neutron star.

The photon was measured at 18 TeV, 4 times higher than anything seen from a GRB previously and greater than the LHC energies.

The photon shouldn't have survived its journey across the cosmos.

So how did it get here?

One possibility is that, following the GRB, a high-energy photon was converted into an axion-like particle, slightly more massive than Axions, the hypothesized lightweight particles that may explain dark matter.

High-energy photons could be converted into such particles by strong magnetic fields, such as the ones around an imploding star.

The axion-like particle would then travel across the vastness of space unimpeded.

As it arrived at our galaxy, magnetic fields would convert it back into a photon, which would then make its way to Earth.

What now?

So there you have it.

There may be something else there or not.

It may be what has been proposed or not.

To be fair lots of things have been ruled out

But

Despite our investment, both in terms of money and intellectual efforts over many years, for direct or indirect detection,

nothing has been seen (yet)