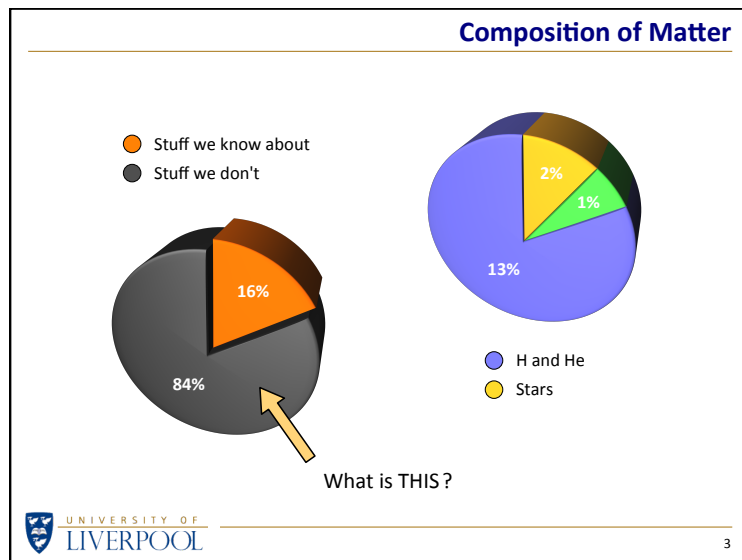
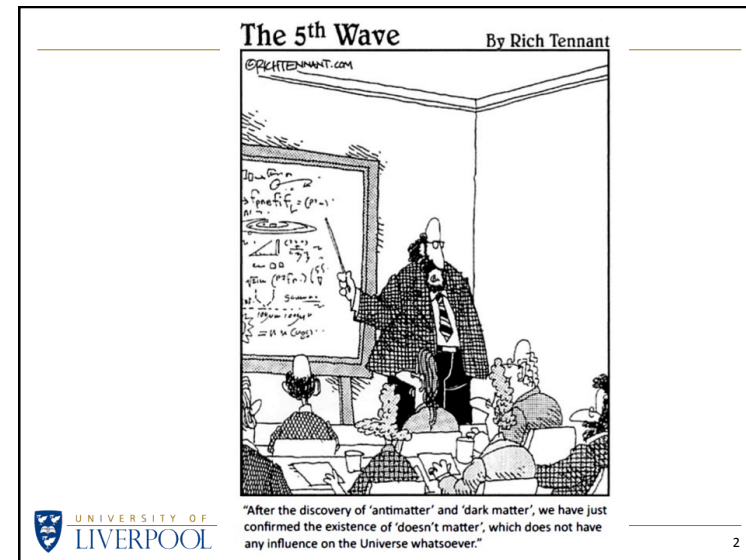


Dark Matter – Why Is It Dark? Does It Matter?



Dark Matter

Why is it dark?	matter and light
What is the evidence?	galaxies in clusters stars in galaxies gravitational lensing cosmic background
What is it?	MACHOs WIMPs
Does it matter?	cosmic evolution

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Dark Matter – Why Is It Dark? Does It Matter?

Why Is It Dark?

Simple answer

It's dark because it's not light

More useful answer

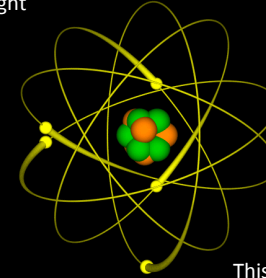
It does not behave the same way as 'ordinary' matter, which

- interacts through the electromagnetic force
- emits and absorbs electromagnetic waves (light)
- can be detected through its interaction with light

Dark matter does none of these

'Ordinary' Matter

Everything we see around us
is made from atoms that
emit or absorb light



This is how we visualise
atoms with electrons buzzing
around a nucleus like bees



What Is the Evidence? #1

Galaxies in Clusters

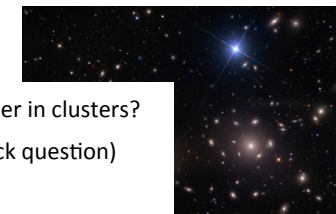
What holds galaxies together in clusters?

Gravity (no, it wasn't a trick question)

Gravity depends on mass

Mass can be estimated from luminosity:

- Measure the galaxy brightness
- If we understand stars, then...
 - we know the number of stars (roughly)
 - we know the mass of all the stars (roughly)
 - we know the mass of the galaxy (roughly)



Dark Matter – Why Is It Dark? Does It Matter?

What Is the Evidence? #1

Galaxies in Clusters

Do this for all the galaxies in the cluster
We now have an estimate of the mass
... and hence the gravity

As early as the 1930s it was realised that the gravity calculated in this way is **not enough** to keep the cluster together – the galaxies should have drifted apart long ago.

Something is wrong!



What Is the Evidence? #1

Galaxies in Clusters

Using the luminosity to find the mass seems to underestimate the mass by a huge factor.

It's as if there is some additional mass, that is not luminous, that is providing the extra gravity that is needed to keep the cluster intact, binding the galaxies together.

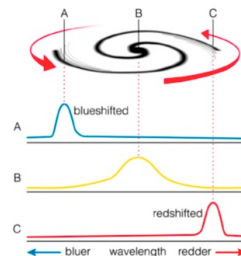
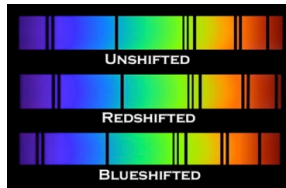
Let's call this ... "**Dark Matter**" ... that sounds pretty cool.



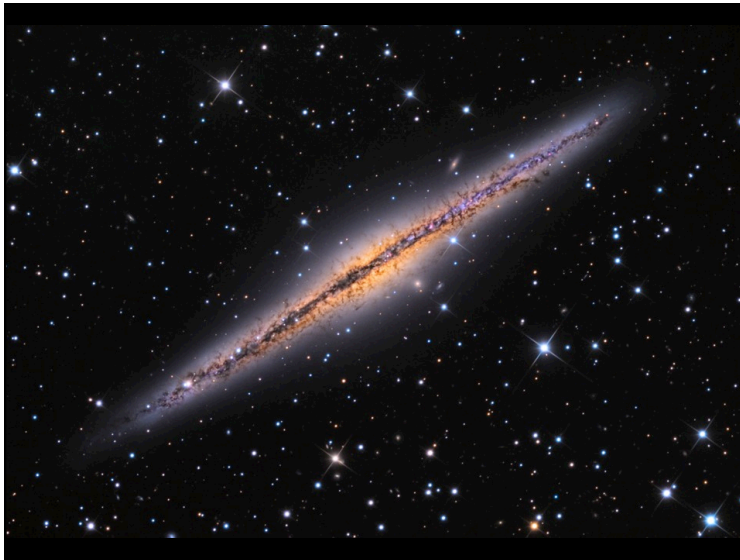
What Is the Evidence? #2

Stars in Galaxies

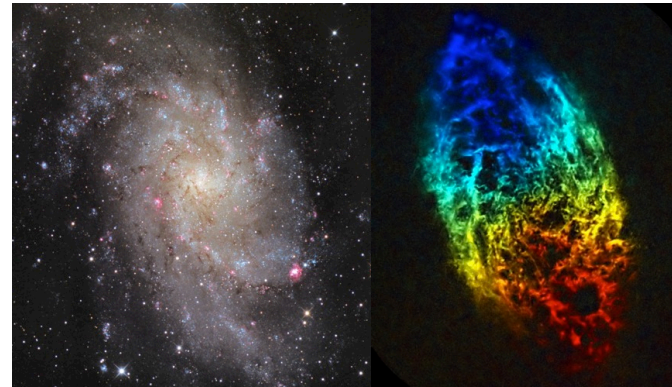
All galaxies rotate
How fast are the stars moving?
Use the Doppler effect



Dark Matter – Why Is It Dark? Does It Matter?



What Is the Evidence? #2



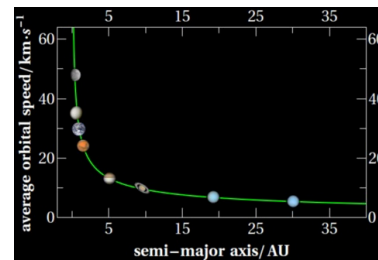
What Is the Evidence? #2

Stars in Galaxies

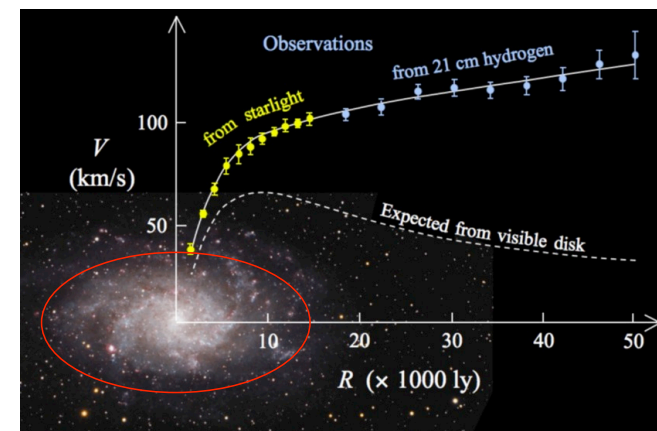
What do we expect to see for the orbital velocity?

How should it vary for stars further from the centre?

If all the mass keeping
an object in orbit is
inside the orbit...



What Is the Evidence? #2



Dark Matter – Why Is It Dark? Does It Matter?

What Is the Evidence? #2

Stars in Galaxies

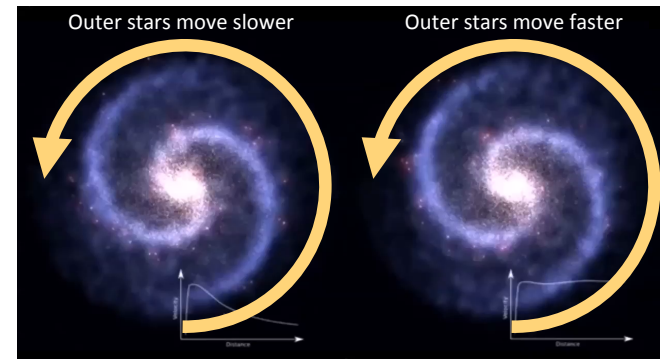
It's as if there is some additional mass, that is not luminous, that is providing the extra gravity that is needed to keep the stars (or gas) orbiting at high velocities, even a long way outside the visible "edge" of the galaxy.

"Dark Matter" again?



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What Is the Evidence? #2



Without dark matter

With dark matter



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What Is the Evidence? #3

Gravitational Lensing

This body of evidence is quite unlike the previous two

We can calculate mass from its gravitational effect,

... not on galaxies in a cluster, or stars in a galaxy

... but on light itself

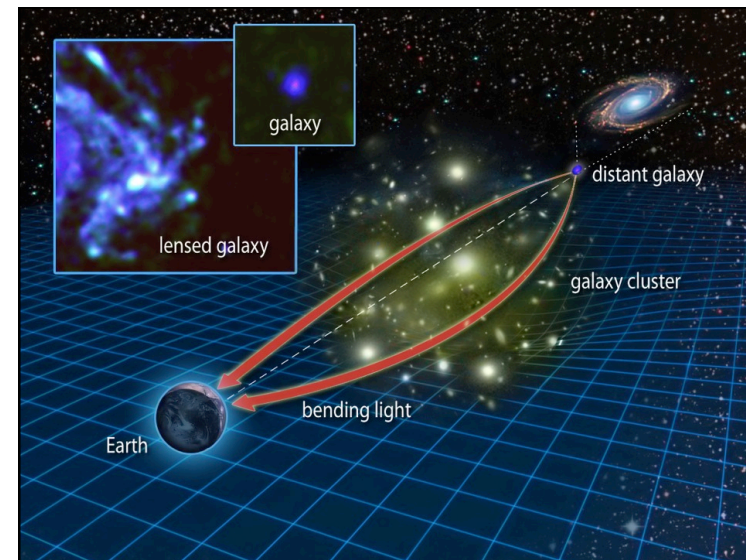
But dark matter does not interact with light, right?

It does not emit or absorb light, that is true

However, dark matter has mass $\Rightarrow$ gravity $\Rightarrow$ bend light

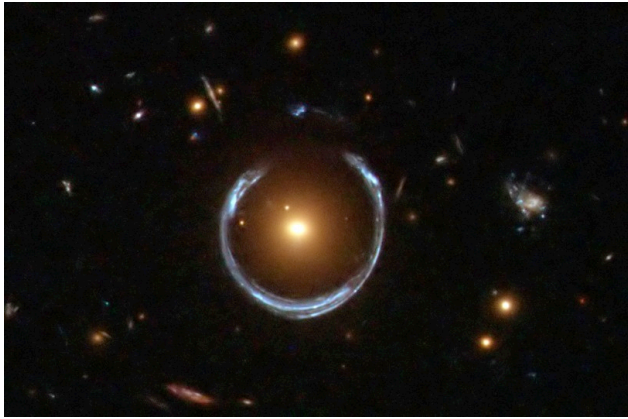


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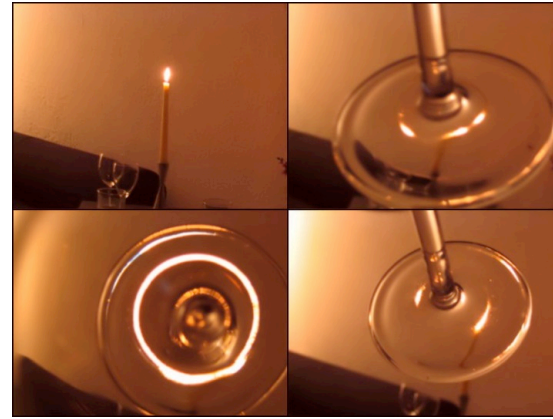


Dark Matter – Why Is It Dark? Does It Matter?

Gravitational Lensing



Gravitational Lensing



What Is the Evidence? #3

Gravitational Lensing

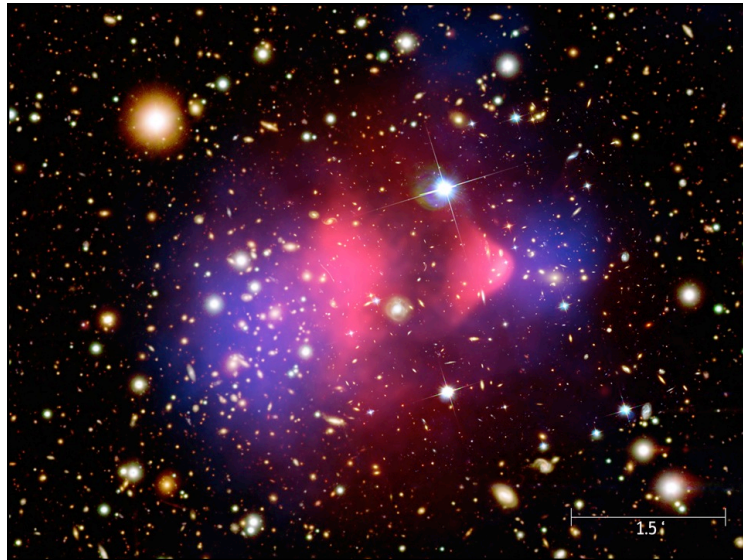
The (distorted) images $\Rightarrow$ the mass distribution in the 'lens'

We find this is more than we can see in the lens

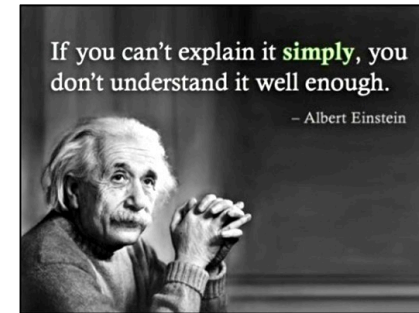
It's as if there is some additional mass, that is not luminous, that is providing the extra gravity that is needed to bend the light and produce the distorted images.

"Dark Matter" again?

Dark Matter – Why Is It Dark? Does It Matter?



What Is the Evidence? #4

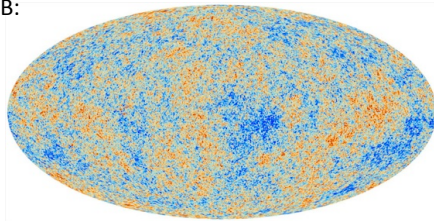


What Is the Evidence? #4

Cosmic Microwave Background

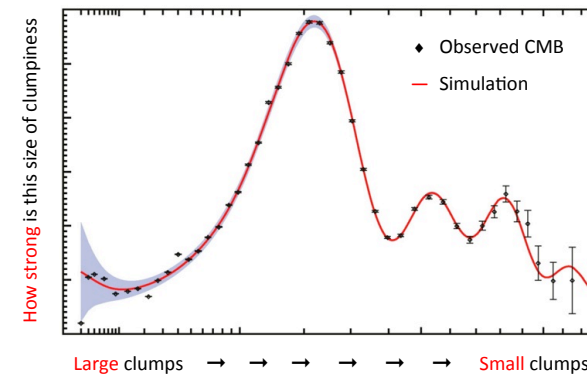
The fourth and final strand of evidence is not easy to explain

The CMB:



The degree of granularity – the "clumpiness" – depends on the relative amounts of ordinary matter and dark matter

Quantifying the Clumpiness



Dark Matter – Why Is It Dark? Does It Matter?

What Is It?

OK, I'm convinced.

There's a lot of evidence that there is something dark out there.
But... what *is* it?

There are two main candidates for the composition of DM...

MACHOs

Massive Astrophysical Compact Halo Objects

WIMPs

Weakly Interacting Massive Particles

Galaxy Halo



MACHOs

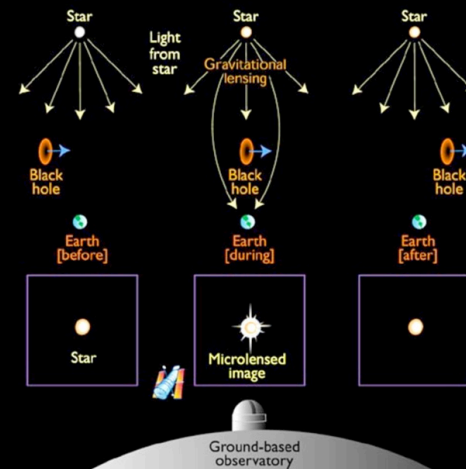
MACHOs

Massive Astrophysical Compact Halo Objects

Bodies composed of 'normal' matter that emits no light
Black holes, neutron stars, white dwarf stars

How can they be detected? Gravitational microlensing

Gravitational Microlensing by Black Hole



Dark Matter – Why Is It Dark? Does It Matter?

MACHOs

MACHOs

Massive Astrophysical Compact Halo Objects

Bodies composed of 'normal' matter that emits no light
Black holes, neutron stars, white dwarf stars

How can they be detected? Gravitational microlensing

At most, MACHOs account for a few % of Dark Matter



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WIMPs

WIMPs

Weakly Interacting Massive Particles

Interact through gravity, but not electromagnetism
Similar to neutrinos, but much much heavier and slower

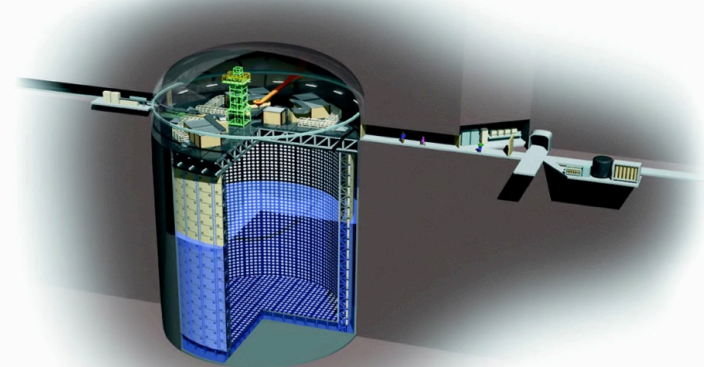
Born in the Big Bang (see "The Beginning of Everything")
Annihilation of DM and anti-DM particles now very rare

WIMPs could be captured by the Sun
... and annihilate with each other to make neutrinos



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Super-Kamiokande



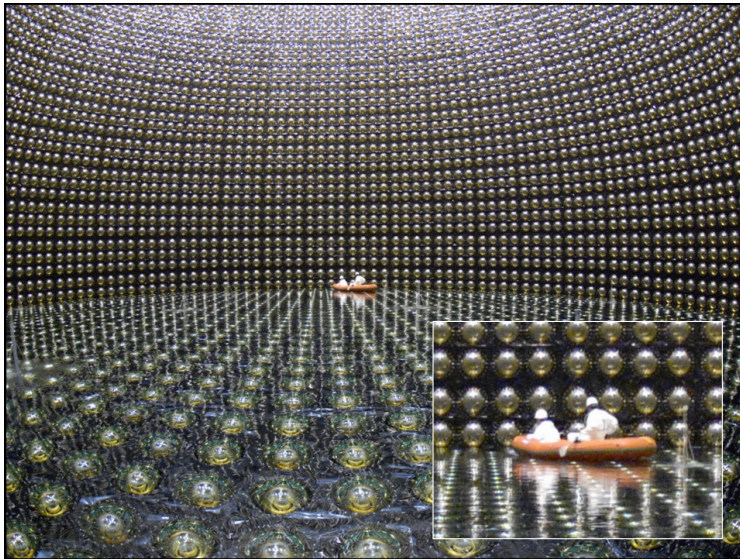
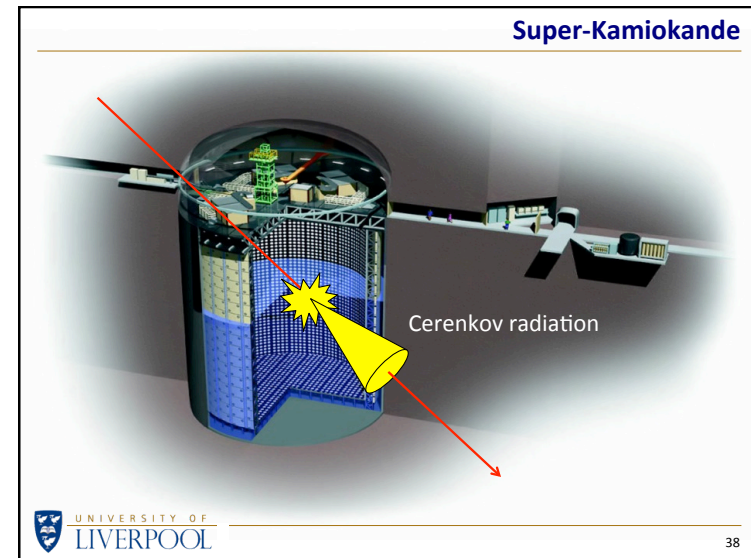
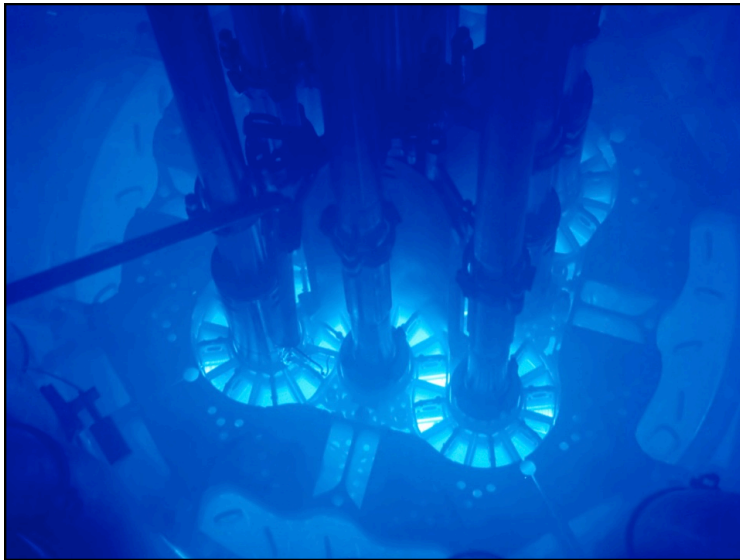
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Cerenkov Radiation

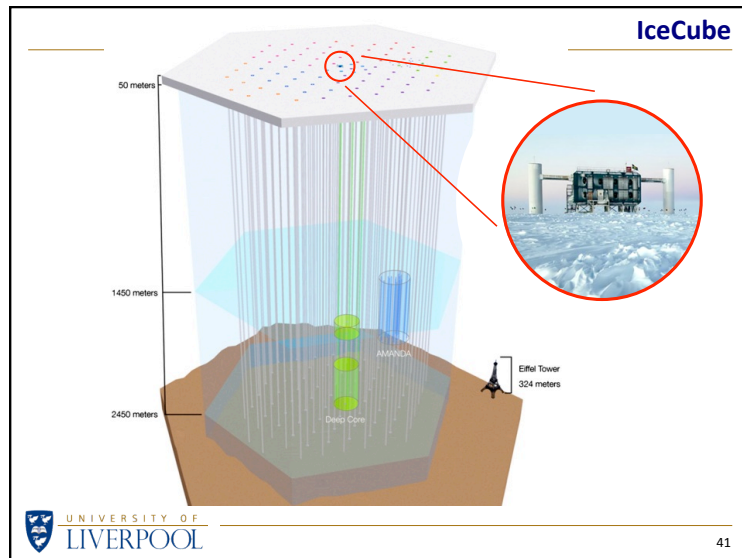


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Dark Matter – Why Is It Dark? Does It Matter?



Dark Matter – Why Is It Dark? Does It Matter?



Gamma Rays

WIMPs

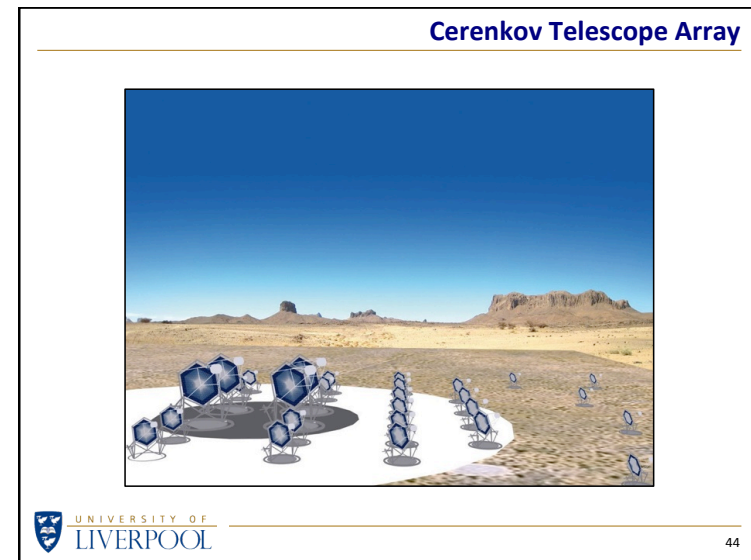
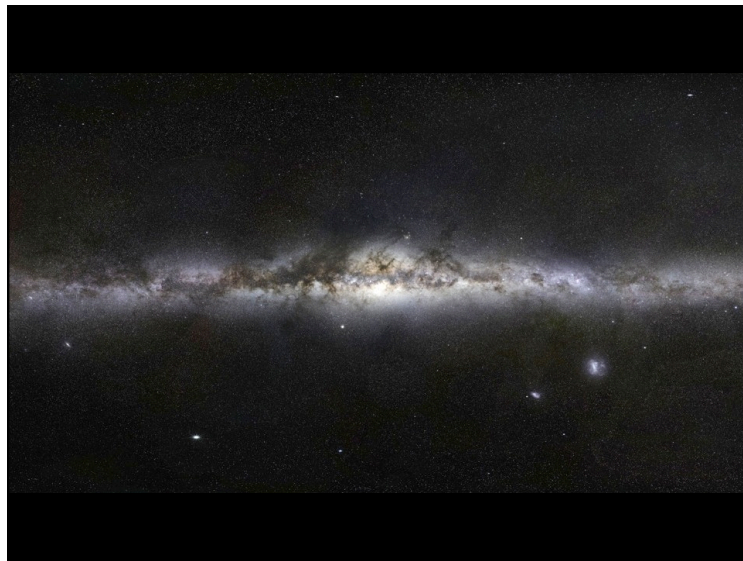
As well as being concentrated (locally) in the Sun ...
there might be a lot of them at the centre of the Milky Way

DM annihilation would produce very energetic gamma rays

There are experiments planned to search for these

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Dark Matter – Why Is It Dark? Does It Matter?



WIMP Detection

CDMS – Cryogenic Dark Matter Search

GeSi crystals with a superconducting skin
Detect vibrations produced by atom being "kicked" by WIMP

DRIFT – Directional Recoil Identification From Tracks

1000 litres of low pressure gas
An atom hit by a WIMP can recoil by mm, making a track

PICASSO – Project in Canada to Search for Supersymmetric Objects

Freon bubble chamber with 200µm bubbles in gel matrix
WIMPs turn liquid bubble to gas $\Rightarrow$ acoustic shock wave



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WIMP Detection

There are many other attempts to detect DM directly...

CRESST in Gran Sasso, Italy

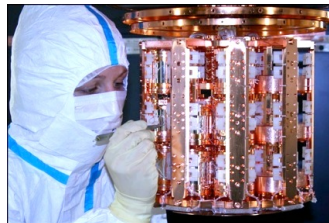
DAMA in Italy

DEAP at SNOLAB, Canada

EDELWEISS in France/Italy

SIMPLE in France

WARP at LNGS, Italy



Many of these experiments have observed "events" ...
... but many are contradictory or not yet confirmed



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Alternatives

There is another possibility ...

- We have misunderstood how gravity works
- Hence we only *seem* to need dark matter

Maybe gravity works differently on the scale of

- The Universe
- The Galaxy
- The Solar System and smaller

There is a theory called Modified Newtonian Dynamics (MOND)

However, it generates more problems of its own



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Dark Matter – Why Is It Dark? Does It Matter?

Does It Matter?

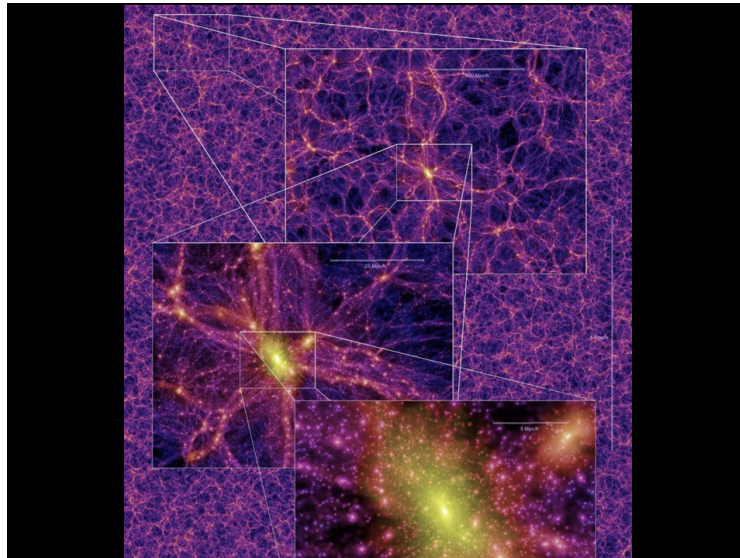
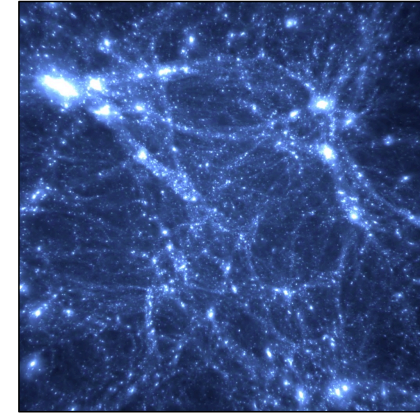
What are the consequences?

Simulations $\Rightarrow$ galaxy distributions similar to observations
Without dark matter, matter doesn't "clump" enough

Cosmic Web

When the very early Universe was the size of a golf ball it had very small variations in density ('dimples')...

...and over billions of years these collapsed into a cosmic web of filaments and voids.



Dark Matter

Why Is It Dark?
Does It Matter?

www.liverpool.ac.uk/~sdb/Talks

Dr Steve Barrett

WU3A 21 Apr 2022