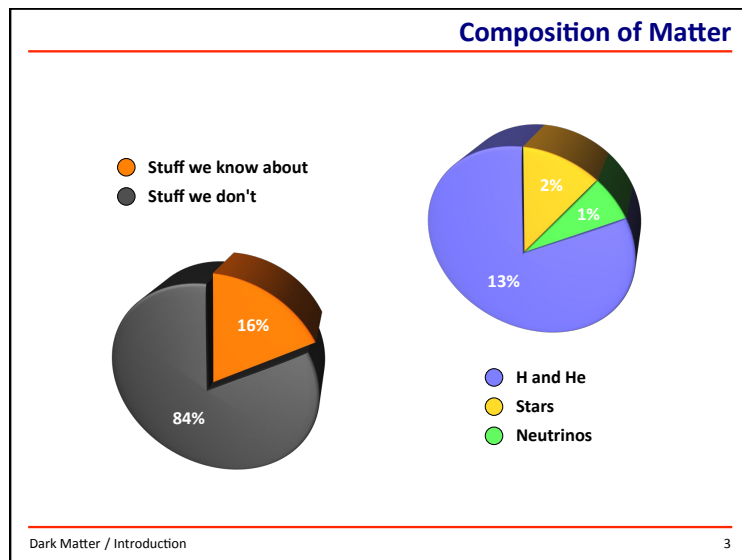
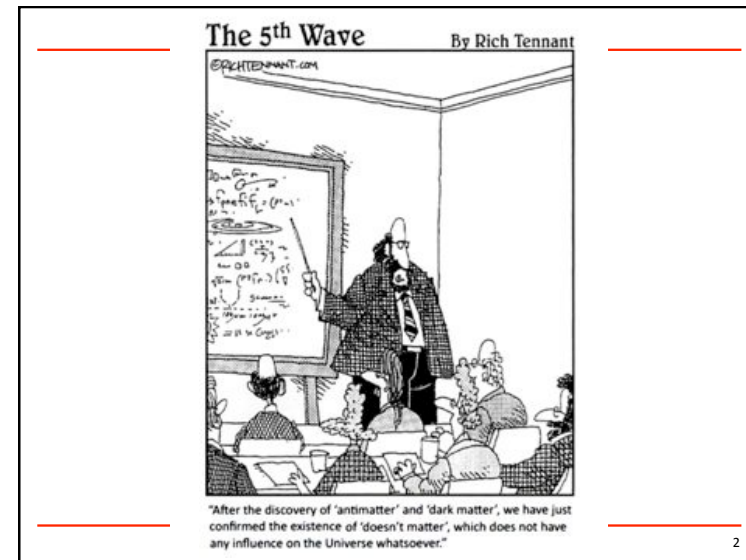


# Dark Matter – Why Is It Dark? Does It Matter?



### 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

Dark Matter / Introduction 4

# 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



## 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)



## 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!



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

## 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.

Dark Matter / Evidence / Galaxies In Clusters

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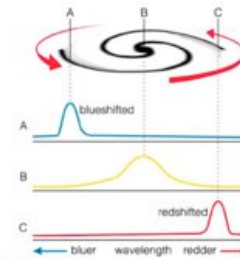
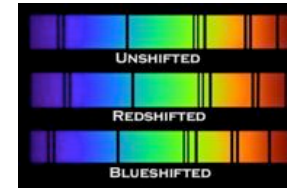
## What Is the Evidence? #2

### Stars in Galaxies

All galaxies rotate

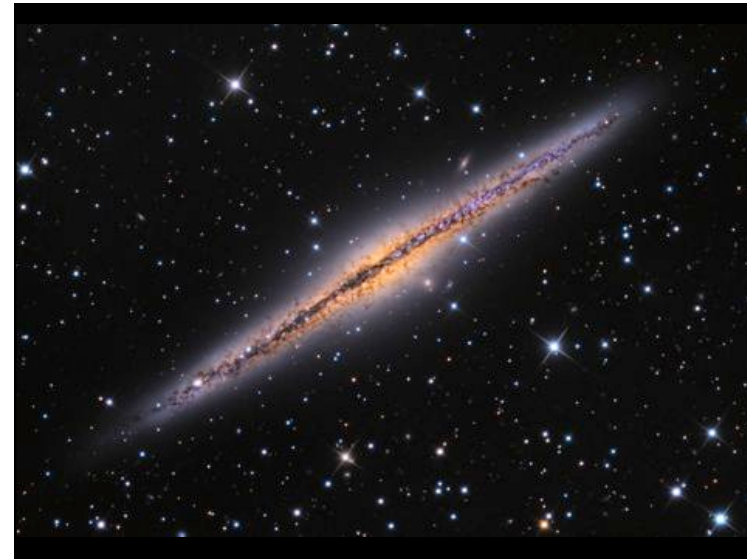
How fast are the stars moving?

Use the Doppler effect



Dark Matter / Evidence / Stars In Galaxies

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

## What Is the Evidence? #2



Dark Matter / Evidence / Stars In Galaxies

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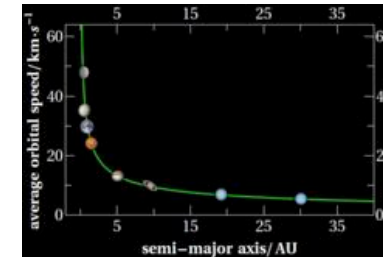
## What Is the Evidence? #2

### Stars in Galaxies

What do we expect to see for the orbital velocity?

How should it vary for stars further from the centre?

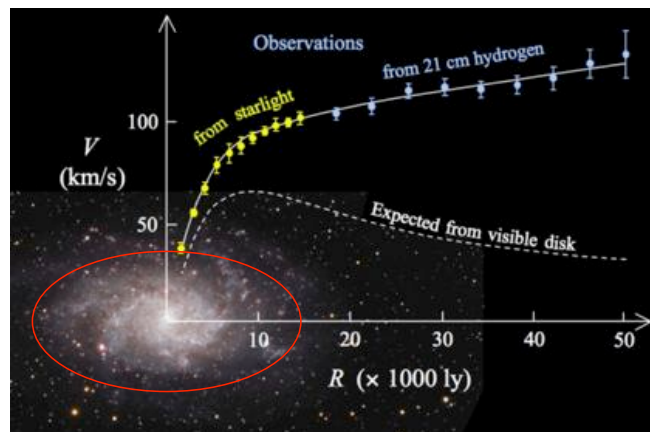
If all the mass keeping an object in orbit is *inside* the orbit...



Dark Matter / Evidence / Stars In Galaxies / Rotation Curves

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## What Is the Evidence? #2



Dark Matter / Evidence / Stars In Galaxies / Rotation Curves

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## 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?

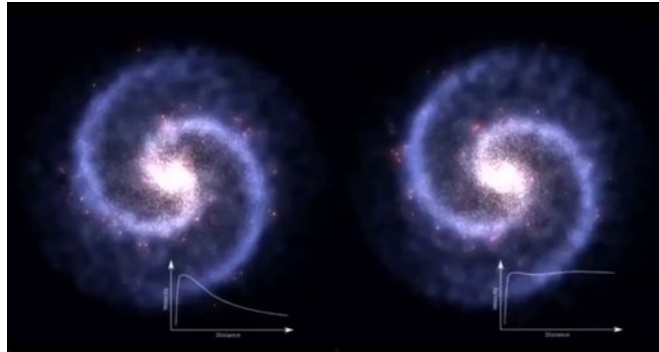
Dark Matter / Evidence / Stars In Galaxies / Rotation Curves

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

## What Is the Evidence? #2



Without dark matter

With dark matter

Dark Matter / Evidence / Stars In Galaxies / Rotation Curves

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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

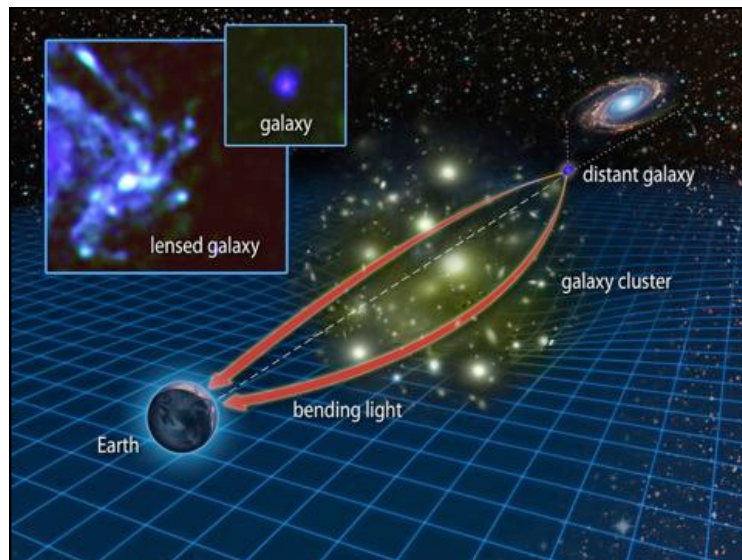
But dark matter does not interact with light, right?

It does not emit or absorb light, that is true

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

Dark Matter / Evidence / Gravitational Lensing

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## Gravitational Lensing

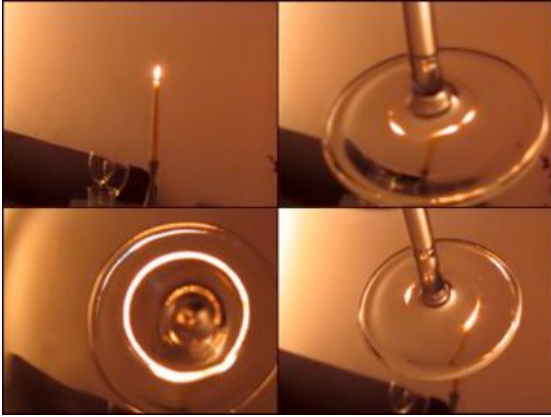


Dark Matter / Evidence / Gravitational Lensing

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

## Gravitational Lensing



Dark Matter / Evidence / Gravitational Lensing

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## What Is the Evidence? #3

### Gravitational Lensing

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

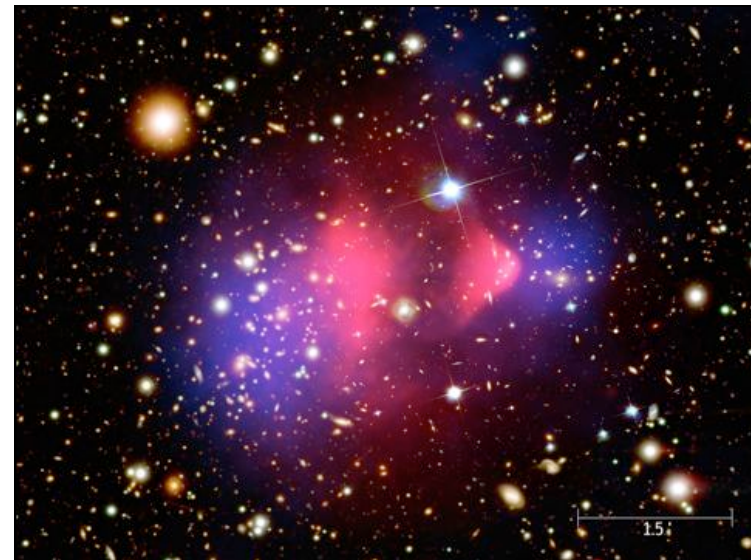
We find this is more than we can see in the lens

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?

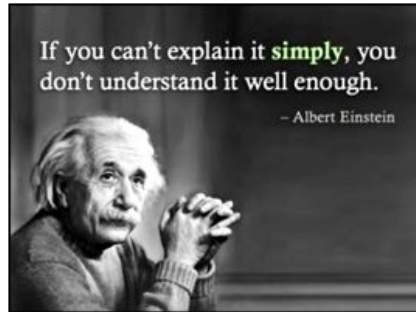
Dark Matter / Evidence / Gravitational Lensing

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

## What Is the Evidence? #4



Dark Matter / Evidence / Cosmic Microwave Background

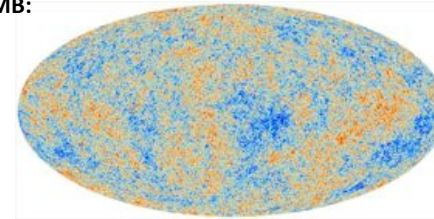
25

## What Is the Evidence? #4

### Cosmic Microwave Background

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

The CMB:

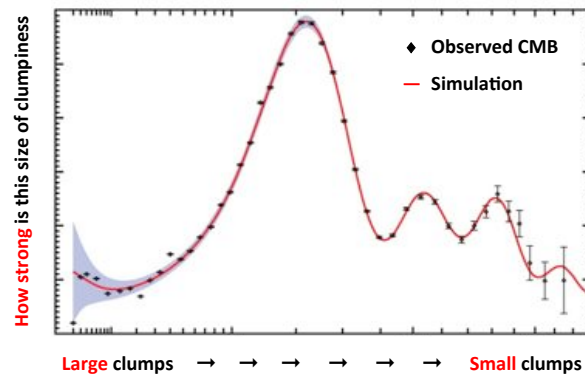


The degree of granularity – the "clumpiness" – depends on the relative amounts of ordinary matter and dark matter

Dark Matter / Evidence / Cosmic Microwave Background

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## Quantifying the Clumpiness



Dark Matter / Evidence / Cosmic Microwave Background

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## 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

Dark Matter / What Is It?

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

## Galaxy Halo



Dark Matter / What Is It? / MACHOs / Halo

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## MACHOs

### MACHOs

Massive Astrophysical Compact Halo Objects

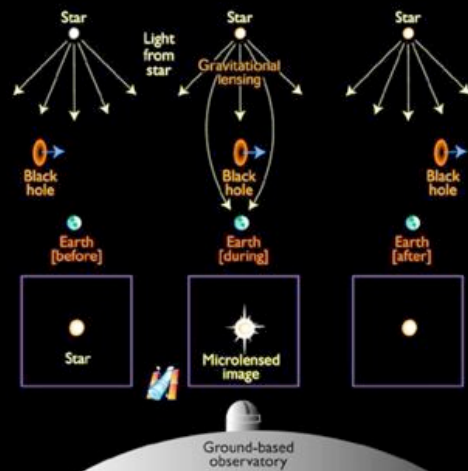
Bodies composed of 'normal' matter that emits no light  
Black holes, neutron stars, white dwarf stars

How can they be detected? Gravitational microlensing

Dark Matter / What Is It? / MACHOs

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## Gravitational Microlensing by Black Hole



## 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

Dark Matter / What Is It? / MACHOs

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

## WIMPs

### WIMPs

**Weakly Interacting Massive Particles**

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

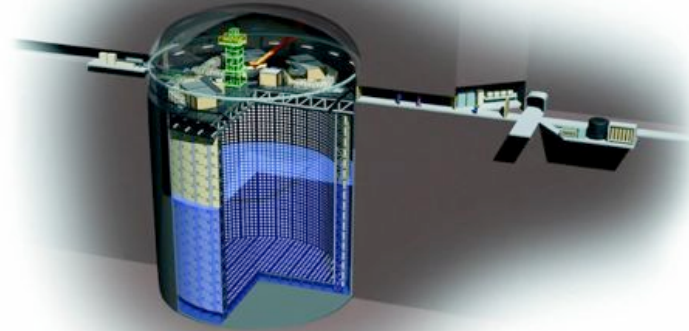
**Born in the Big Bang (see "The Beginning of Everything")  
Annihilation of DM and anti-DM particles now very rare**

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

Dark Matter / What Is It? / WIMPs

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## Super-Kamiokande



Dark Matter / What Is It? / WIMPs / Detection / Super-Kamiokande

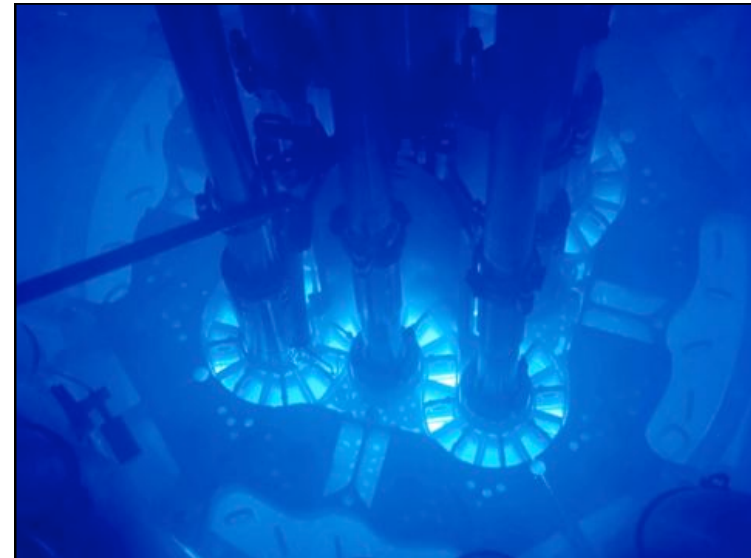
34

## Cerenkov Radiation

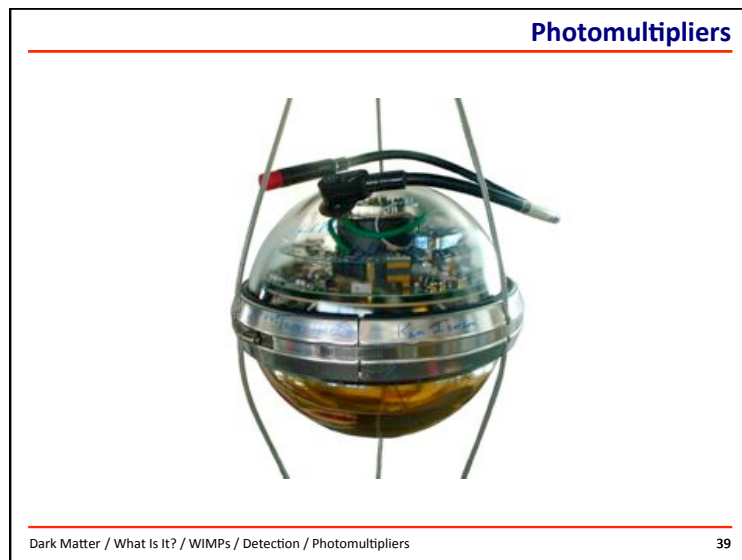
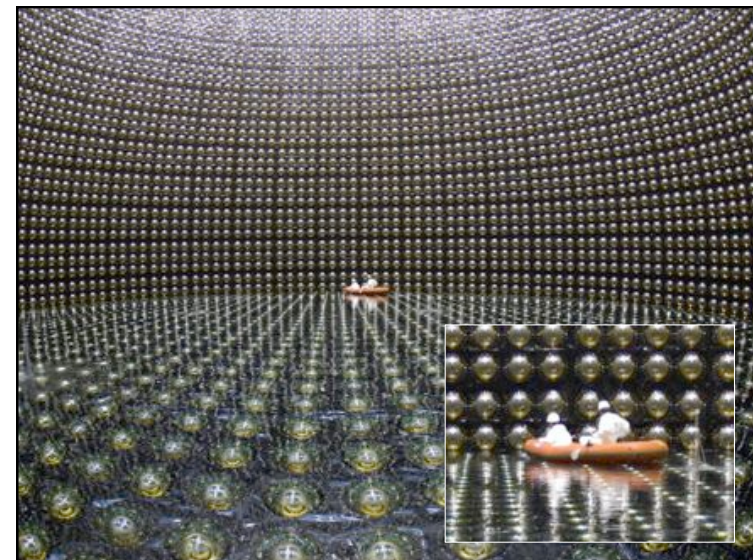
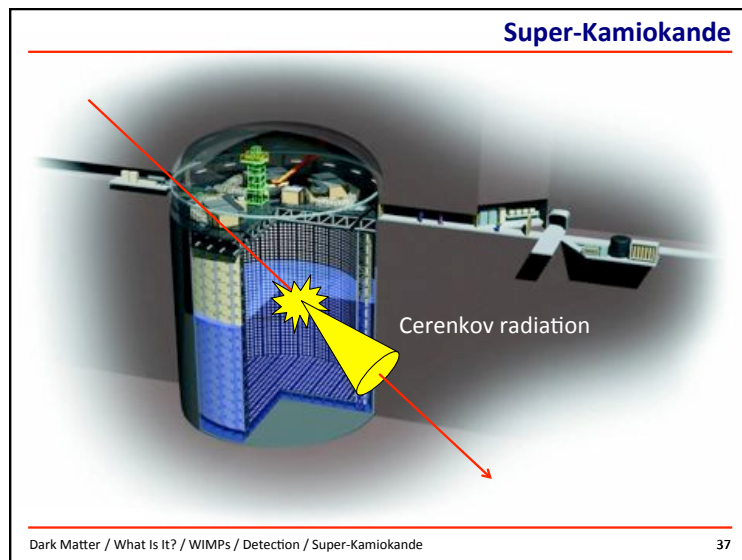


Dark Matter / What Is It? / WIMPs / Detection / Cerenkov

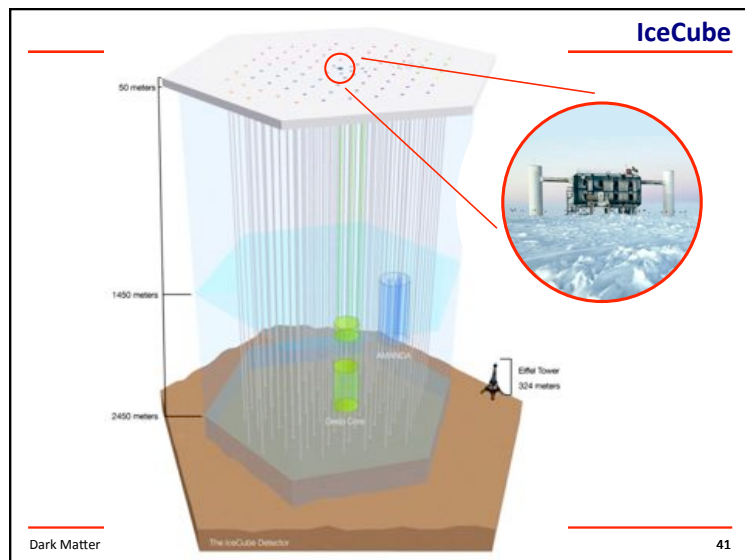
35



# 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

Dark Matter / What Is It? / WIMPs / Detection 42



## Cerenkov Telescope Array

The illustration shows the Cerenkov Telescope Array (CTA) in a desert landscape. The array consists of many large, dish-shaped telescopes arranged in a circular pattern. The telescopes are mounted on a central platform and are pointed towards the sky. The background shows a clear blue sky and a desert landscape with some rocky hills in the distance.

Dark Matter / What Is It? / WIMPs / Detection / CTA 44

# 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 gas  $\Rightarrow$  acoustic shock wave

Dark Matter / What Is It? / WIMPs / Detection / Experiments

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## WIMP Detection

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

**CRESST** in Gran Sasso, Italy

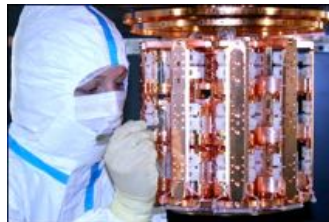
**DAMA** in Italy

**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

Dark Matter / What Is It? / WIMPs / Detection / Experiments

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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

Dark Matter / What Is It? / Alternatives

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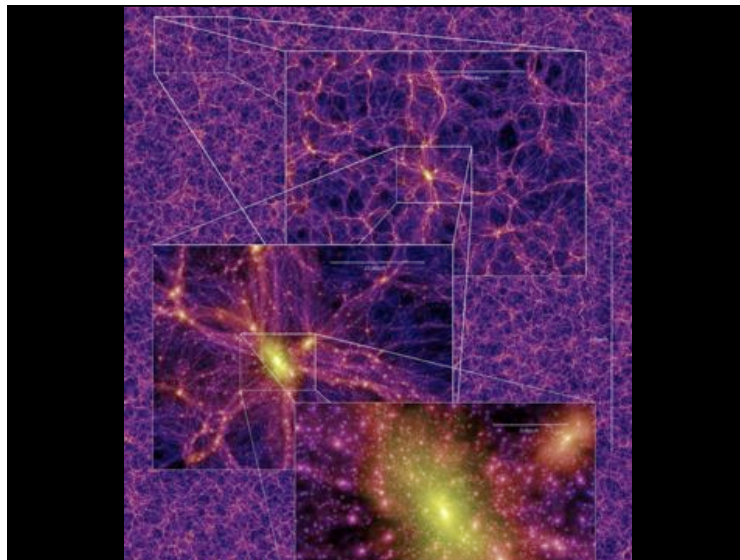
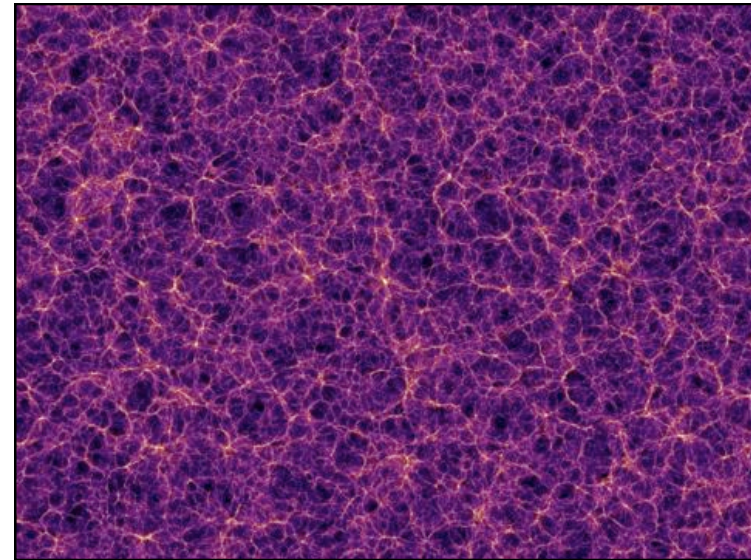
# Dark Matter – Why Is It Dark? Does It Matter?

## Does It Matter?

### What are the consequences?

Simulations  $\Rightarrow$  galaxy distributions similar to observations

Without dark matter, matter doesn't "clump" enough



## Dark Matter

Why Is It Dark?

Does It Matter?

<http://www.liv.ac.uk/~sdb/Talks>

Dr Steve Barrett

4 Nov 2015