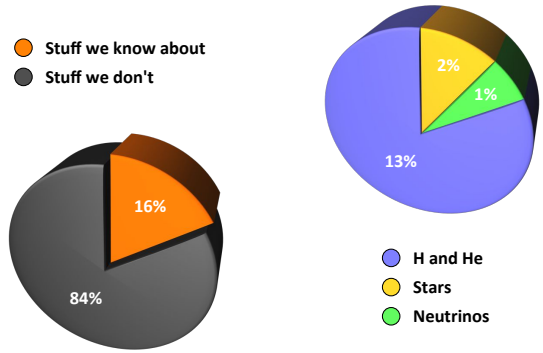
Composition of Matter



Dark Matter / Introduction 2

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 3

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

Dark Matter / Why Is It Dark? 4

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!

What Is the Evidence? #1

Galaxies in Clusters

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

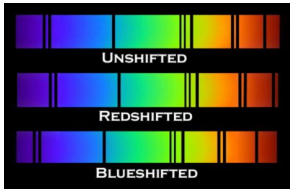
It's as if there is some additional mass, that is not luminous, that is providing the extra gravity that is needed to keep the cluster intact, binding the galaxies together.

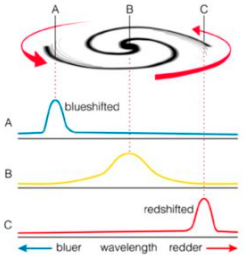
Let's call this … "**Dark Matter**" … that sounds pretty cool.

What Is the Evidence? #2

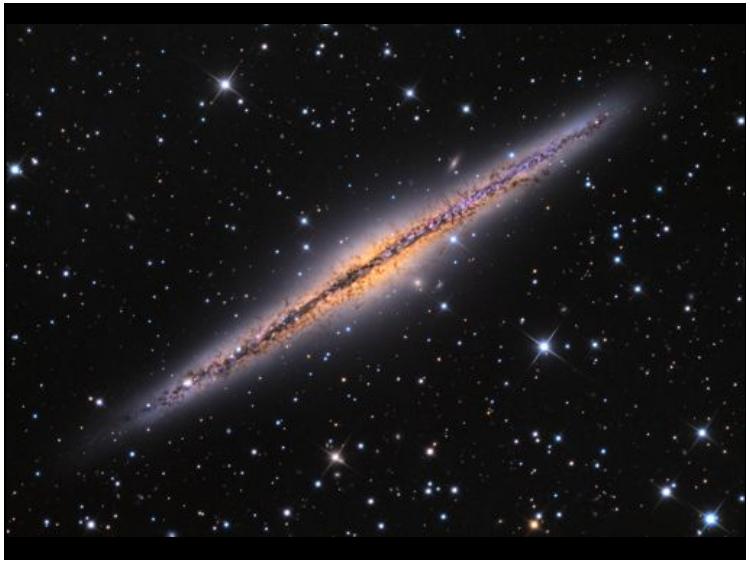
Stars in Galaxies

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

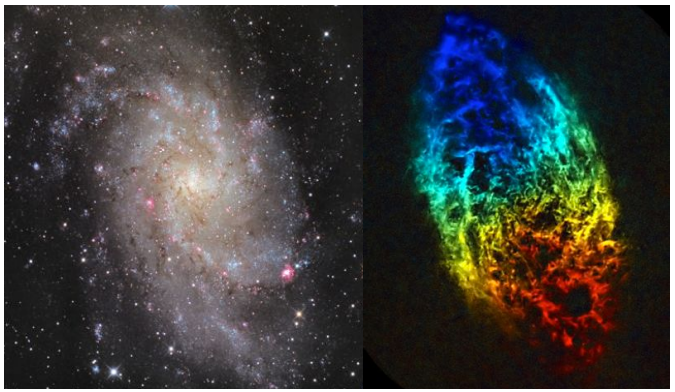




Dark Matter / Evidence / Stars In Galaxies 9



What Is the Evidence? #2



Dark Matter / Evidence / Stars In Galaxies 12

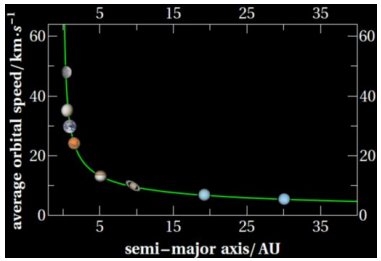
What Is the Evidence? #2

Stars in Galaxies

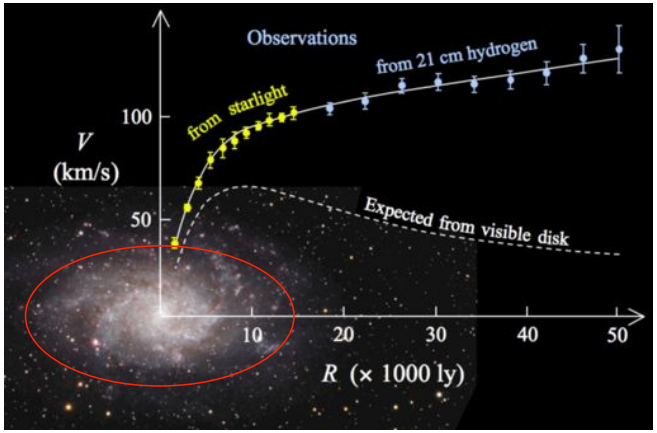
What do we expect to see for the orbital velocity?

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



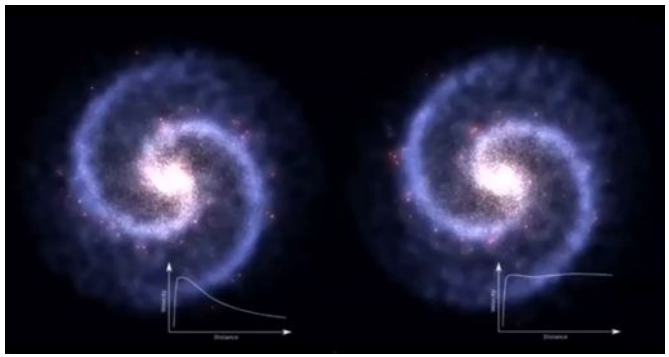
What Is the Evidence? #2

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?

What Is the Evidence? #2

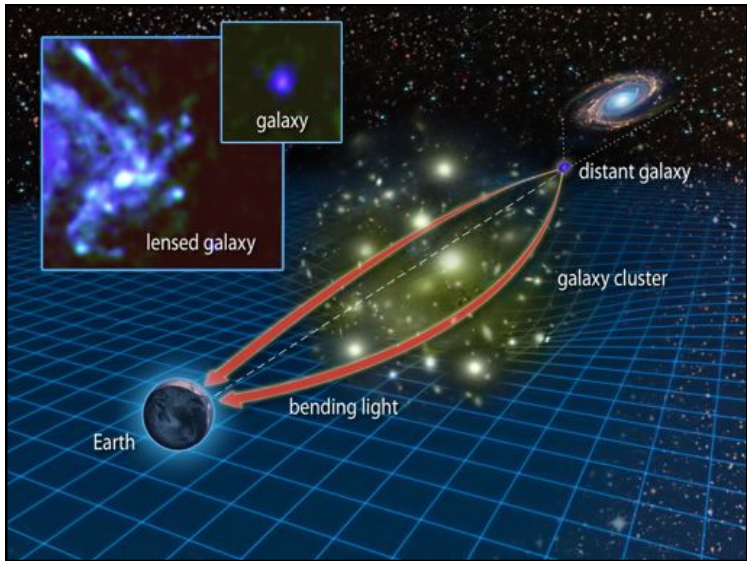


Without dark matter **With dark matter**

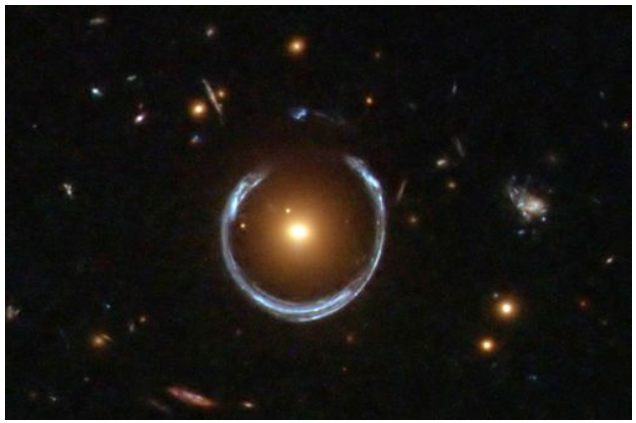
What Is the Evidence? #3

Gravitational Lensing

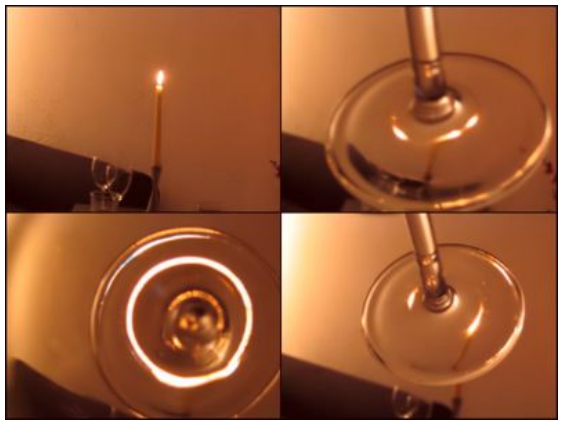
- This body of evidence is quite unlike the previous two
- We can calculate mass from its gravitational effect,
  - … not on galaxies in a cluster, or stars in a galaxy
  - … but on light itself
- But dark matter does not interact with light, right?
- It does not emit or absorb light, that is true
- However, dark matter has mass ⇒ gravity ⇒ bend light

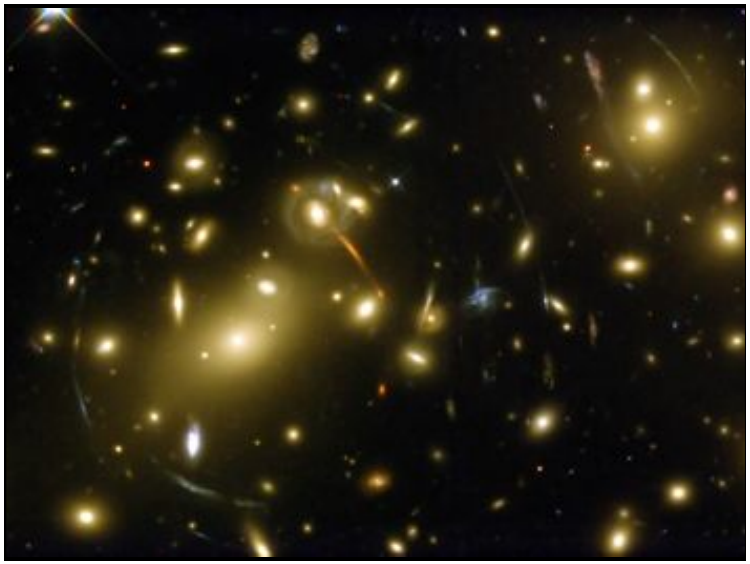


Gravitational Lensing



Gravitational Lensing



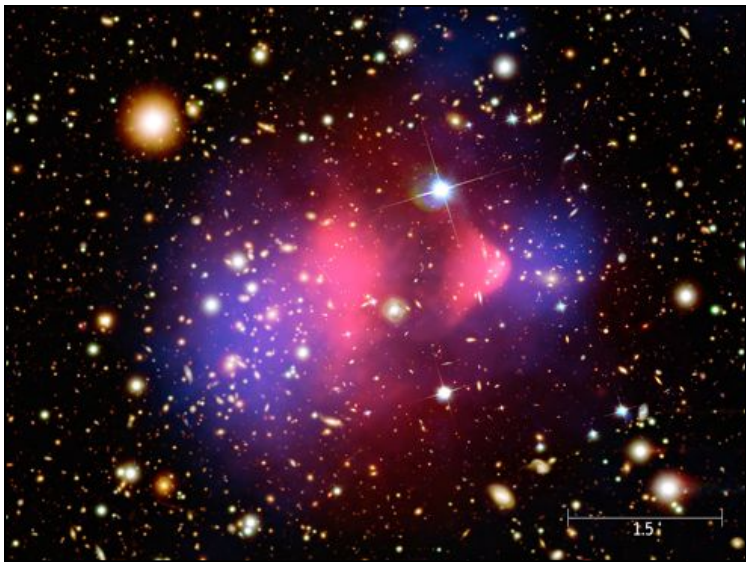


What Is the Evidence? #3

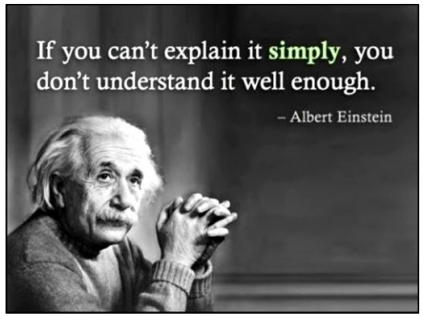
Gravitational Lensing

- **The (distorted) images ⇒ 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 22



What Is the Evidence? #4



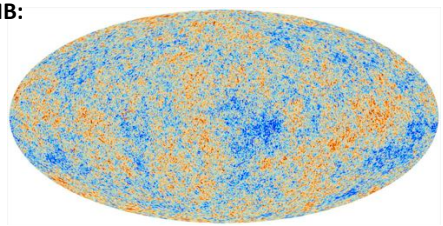
Dark Matter / Evidence / Cosmic Microwave Background 24

What Is the Evidence? #4

Cosmic Microwave Background

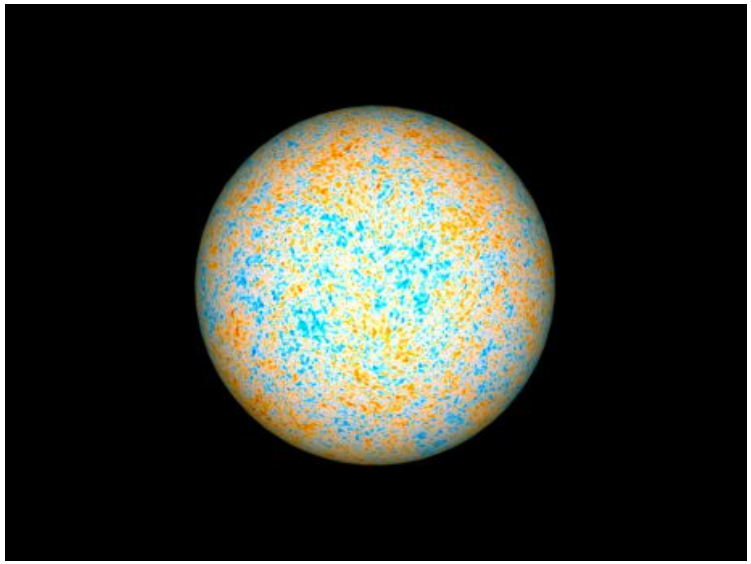
The fourth and final strand of evidence is not easy to explain

The CMB:

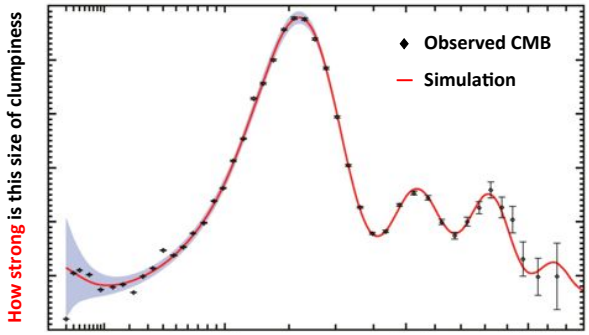


The degree of granularity – the "clumpiness" – depends on the relative amounts of ordinary matter and dark matter

Dark Matter / Evidence / Cosmic Microwave Background 25



Quantifying the Clumpiness



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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? 28

Galaxy Halo

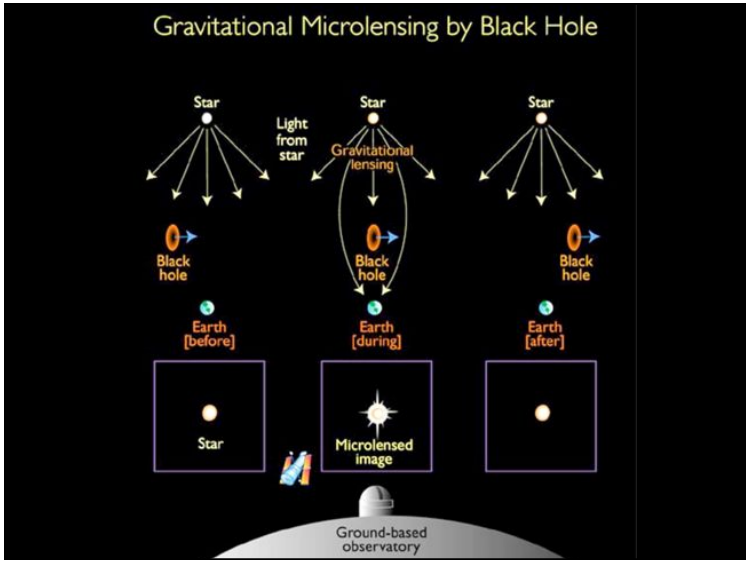
MACHOs

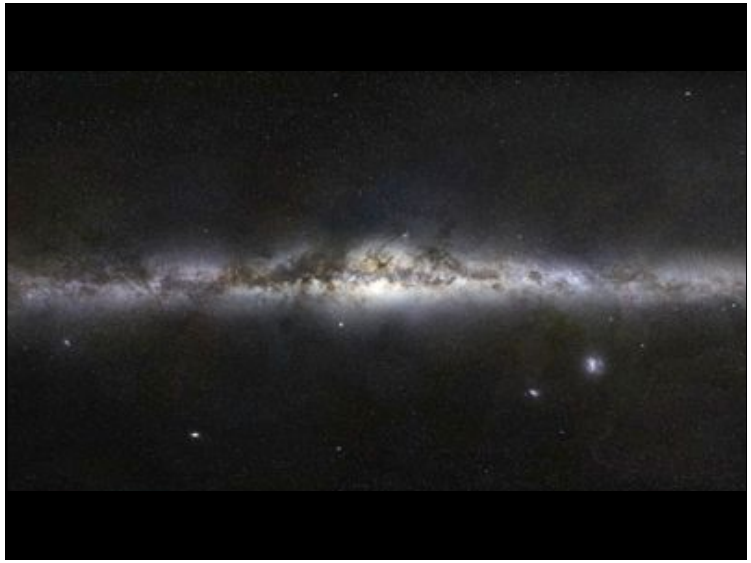
MACHOs

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





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

WIMPs

WIMPs

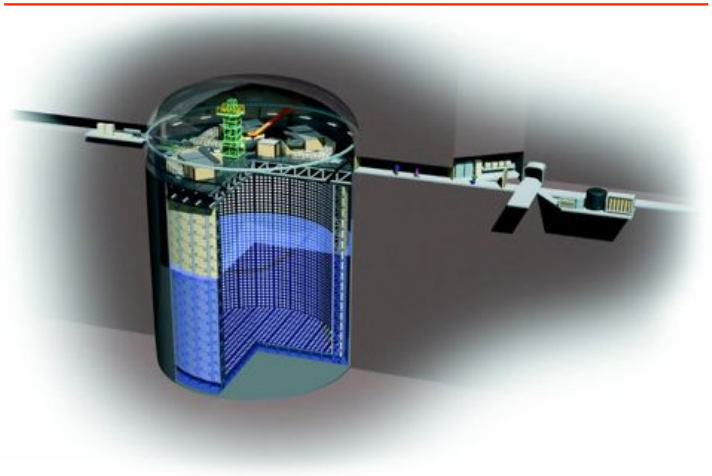
Weakly Interacting Massive Particles

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

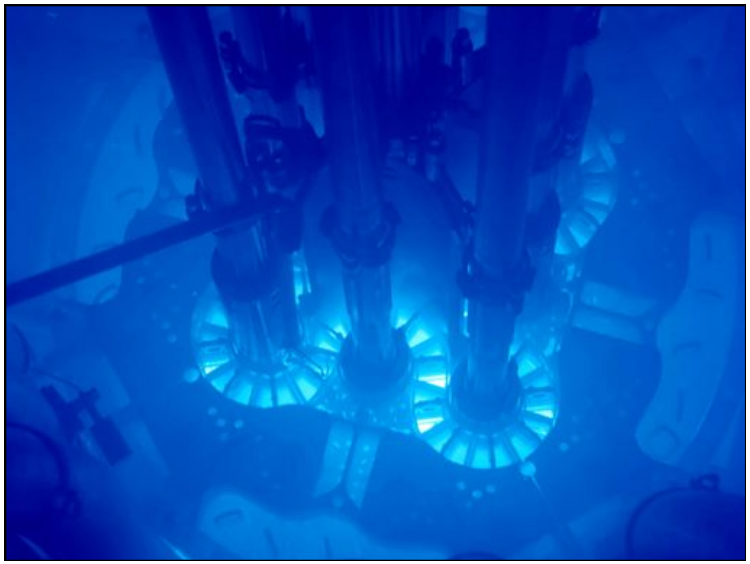
Born in the Big Bang (see "The Beginning of Everything")
Annihilation of DM and anti-DM particles now very rare

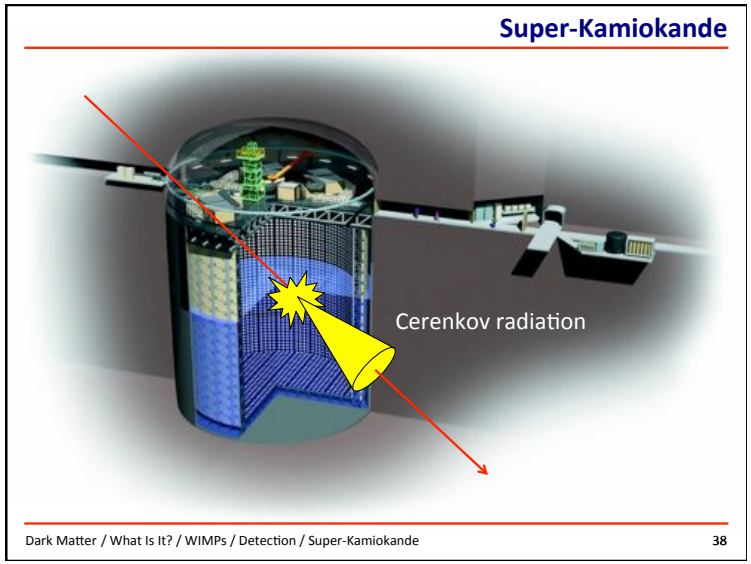
WIMPs could be captured by the Sun
… and annihilate with each other to make neutrinos

Super-Kamiokande



Cerenkov Radiation




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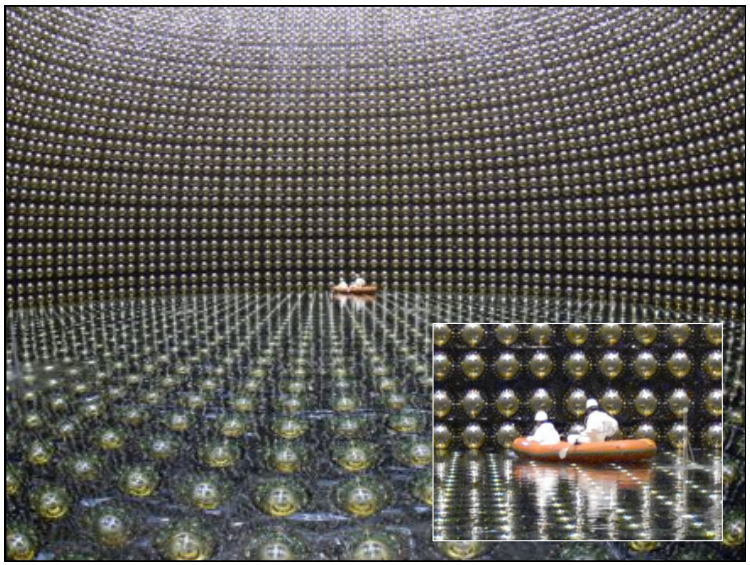

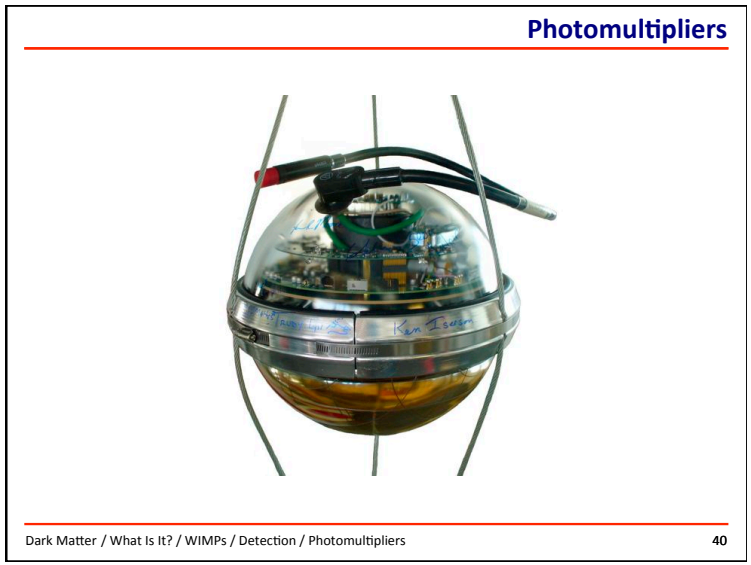
Photomultipliers
Dark Matter / What Is It? / WIMPs / Detection / Photomultipliers
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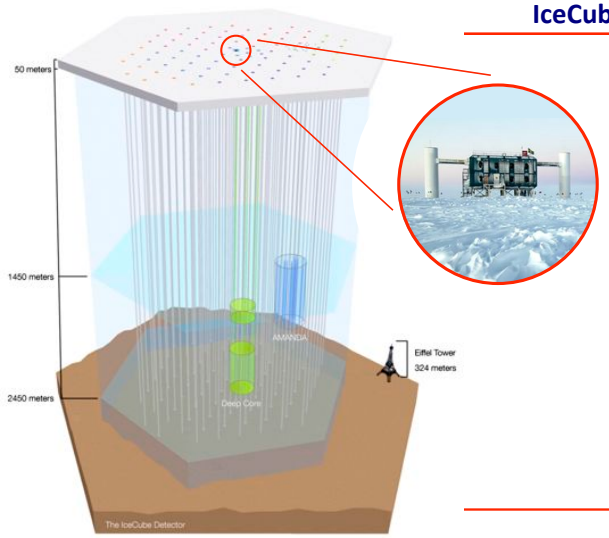
IceCube



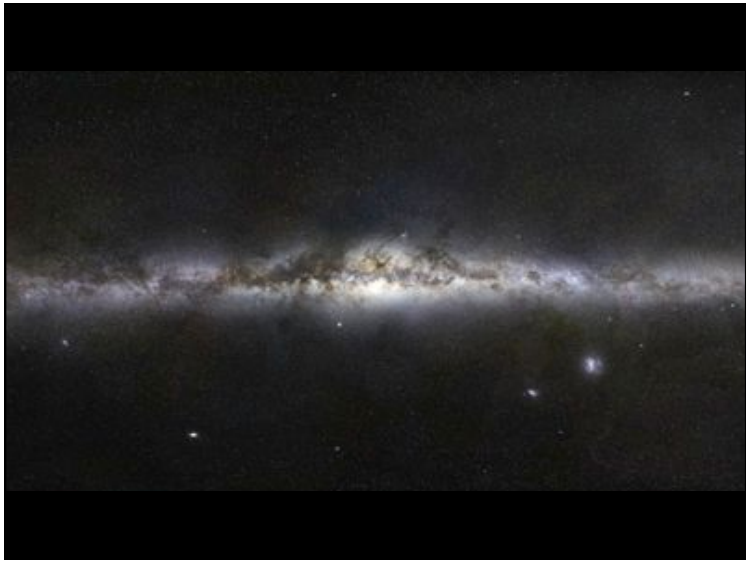
Gamma Rays

WIMPs

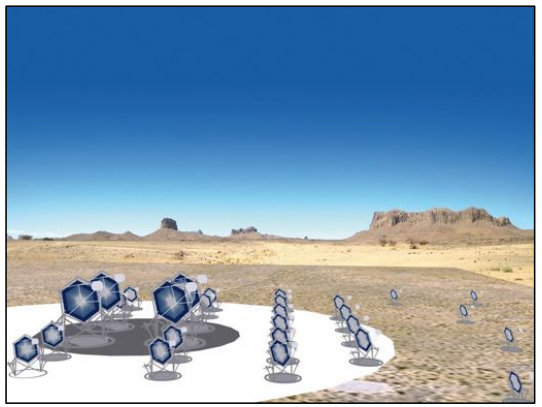
As well as being concentrated (locally) in the Sun …
there might be a lot of them at the centre of the Milky Way

DM annihilation would produce very energetic gamma rays

There are experiments planned to search for these



Cerenkov Telescope Array



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*

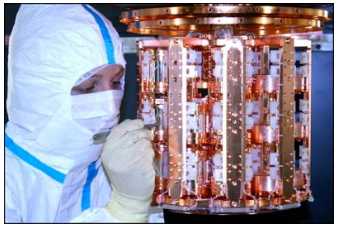
Freon bubble chamber with 200µm bubbles in gel matrix

WIMPs turn liquid bubble gas ⇒ acoustic shock wave

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

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

Does It Matter?

What are the consequences?

- Simulations ⇒ galaxy distributions similar to observations
- Without dark matter, matter doesn't "clump" enough

Dark Matter / Does It Matter? 49