How to See Invisible Matter

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Interactive content

You are invited to go to

www.menti.com

and enter code

262943

Goal

We can't see Dark Matter. But can we nevertheless figure out where in the Universe it is located?

Cosmology

Cosmology is the study of the Universe on the largest scales.

Some parts of cosmology are easy, because we can ignore all the small-scale details . . .

Pillars of Cosmology

There is strong evidence that:

- The Universe is more-or-less the same everywhere and we are not in a 'special' location.
- Einstein's theory ('General Relativity') correctly describes how gravity works.
- The overall geometry of the Universe is 'flat': keep going in a straight line and you won't return home.
- There was a Big Bang - an initial uniformly dense and hot state - and the Universe has been expanding and cooling ever since.

What does the Universe contain?

Go to `www.menti.com` (code 262943) and choose one possibility:

1. Left-over light from the Big Bang, the 'cosmic background radiation', dominates all other forms of energy
2. About 75% hydrogen, 24% helium, 1% everything else
3. 5% gas and stars; the rest we don't really know

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Contents of the Universe (remember mass = energy!)

- 0.01% light
- 5% ‘normal’ matter - stars and gas
- 26% Dark Matter - some form of matter that doesn’t interact with light.
- 69% Dark Energy - ? - mass of empty space?

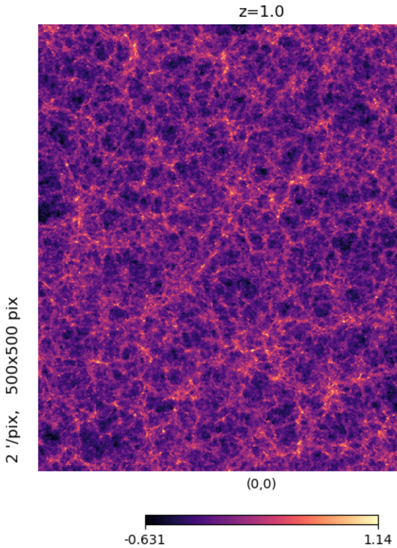
What is Dark Matter?

- We don't know ...
- Range of possible particle masses covers 78 orders of magnitudes ...
- No interaction with light, so dark and invisible.
- Particle physicists have been searching for years - no luck ...
- But like all forms of mass/energy, it interacts via gravity.

Simulations

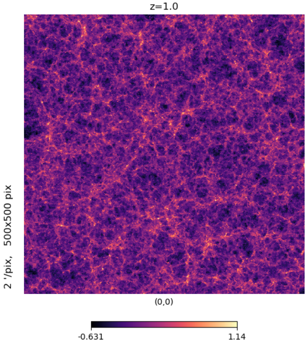
- We can run computer simulations in which we follow the trajectories of dark matter particles under the influence of gravity.
- I ran a simulation - using software ‘PKDGRAV3’ - following one billion dark matter ‘lumps’ from the beginning of time to today.

Simulation result - note log scale



Simulation result

- The dark matter clusters into large ‘halos’ - the densest areas in the picture.
- Hydrogen gas is pulled into the densest halos, where it forms galaxies.
- Also there are ‘filaments’ of dark matter joining the halos, so we get a ‘cosmic web’.



Why are there no dark matter galaxies and stars?

Go to `www.menti.com` (code 262943) and choose one possibility:

1. Dark matter particles move too fast - near the speed of light.
2. Dark matter can't cool down by emitting light.
3. Gravity acts only weakly on dark matter.

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Goal

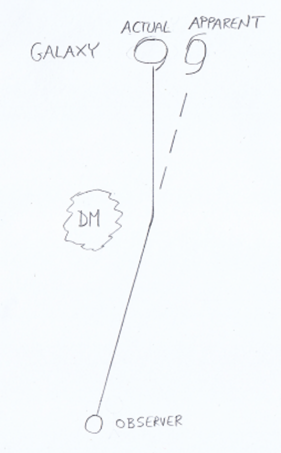
- We want to map the distribution of dark matter on cosmological scales.
- We can't see dark matter . . .
- . . . but we can infer its location from its gravitational impact on light from distant galaxies.
- Our main tool is 'weak lensing' (WL)

Weak lensing

- The gravity of dark matter bends spacetime and hence bends the trajectory of light from distant galaxies.
- This has three effects on the appearance of distant galaxies.

The effects of bending light

- Light gets deflected by the dark matter. . .
- . . . which moves the image of the galaxy on the sky . . .
- . . . and distorts it (makes it flatter i.e. ellipses become more eccentric) . . .
- . . . and can magnify it.



Which lensing effect is the practical one to study?

Go to `www.menti.com` (code 262943) and choose one possibility:

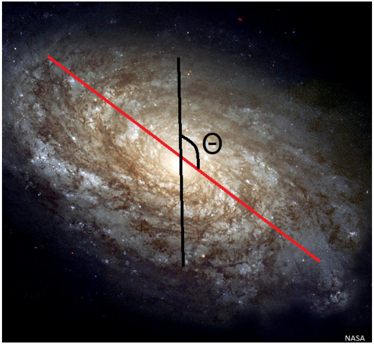
1. The change in location
2. The change in shape (eccentricity)
3. The change in brightness

Which lensing effect is the practical one to study?

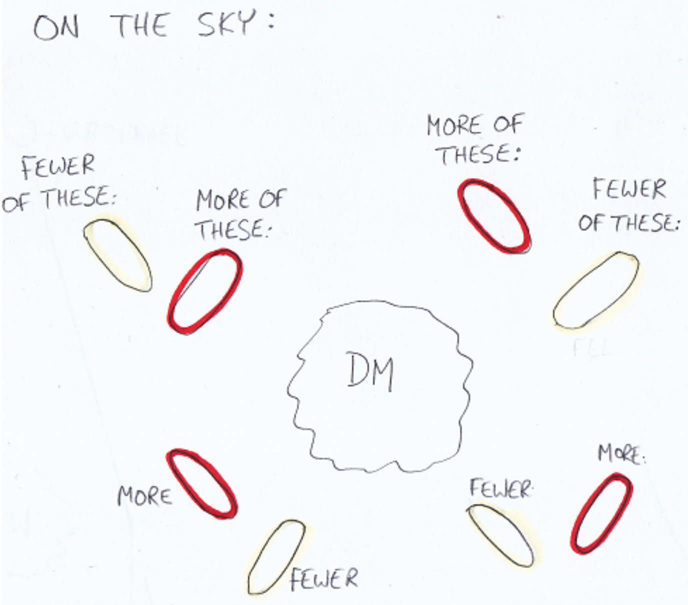
1. The change in location
2. The change in shape (eccentricity) ✓
3. The change in brightness

That's crazy!

- The effect on shapes must be minuscule!
- It is - it's just at the edge of detectability.
- But with shapes we at least know the **distribution** of shapes before the effect of lensing.
- For example, the 'angle Θ of major axis' should be uniformly distributed.



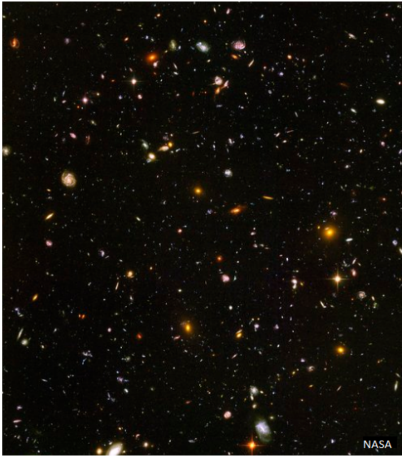
Weak lensing



Weak lensing

So if we see such a quadrupole bias in the shapes, we can infer that there is dark matter in the centre of the picture.

Strong lensing versus Weak lensing



Low signal-to-noise ratio

- The effect on the shapes of galaxies is about 1% of the intrinsic scatter in the shapes themselves.
- In other words, the **signal** is 1% of the **noise**.
- So the SNR (signal-to-noise ratio) is about 0.01 - that's very low!
- Only way to overcome this is with *lots* of data.

SNR = 0.01 - how many data points needed?

Go to `www.menti.com` (code 262943) and choose one possibility:

1. 100
2. 1,000
3. 10,000

SNR $= 0.01$ - how many data points needed?

1. 100
2. 1,000
3. 10,000 ✓

How to get so much data?

- Fortunately there are **lots** of galaxies! We just have to photograph them all . . .
- There have been several *weak lensing surveys* taking long exposure photographs of large areas of the sky.
- For example, the DES project covered one-eighth of the sky; each part of this area was photographed for about 75 minutes.
- It currently has a catalogue of the shapes of 100,000,000 galaxies.

It's all statistics

- Analysing so much low-SNR data requires careful statistical treatment.
- We usually work within the framework of *Bayesian* statistics.

What does Bayes's Theorem say?

Go to `www.menti.com` (code 262943) and choose one possibility:

1. Posterior proportional to Likelihood times Prior
2. Likelihood proportional to Posterior times Prior
3. Prior proportional to Likelihood times Posterior

What does Bayes's Theorem say?

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2. Likelihood proportional to Posterior times Prior
3. Prior proportional to Likelihood times Posterior

What does Bayes's Theorem say?

The *posterior* probability of a parameter depends both on:

- the *likelihood* of seeing the observed data (given the parameter), and
- the *prior* probability of the parameter (before the experiment started).

Bayes example

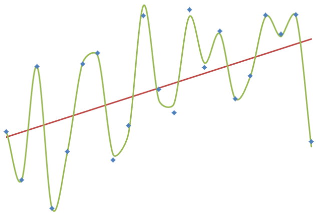
- Strangely-shaped trees? Or old glass?
- Both explanations fit the picture equally well (same *likelihood*)!
- But old glass is more common than strange trees (has more *prior* probability).
- So we conclude 'old glass' has more *posterior* probability.

Bayes and Weak Lensing

In weak lensing we seek an answer - i.e. a map of the dark matter - that both:

- is consistent with the observed galaxy shapes, and
- has a high prior probability (i.e. is physically plausible).

If we don't insist on the latter condition then we end up just fitting noise.

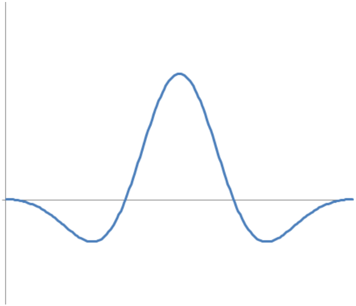


Priors by machine learning

- One way to get a prior is to let a machine learn by looking at many simulations . . .
- . . . similar to how machines can learn to recognise (and generate new) celebrity faces.
- My colleagues Niall Jeffrey is working on this.

GLIMPSE algorithm

- I'm currently using the GLIMPSE algorithm (Lanusse et al. arXiv:1603.01599)
- This algorithm assigns a high prior probability to patterns in the dark matter density that are combinations of a small number of *wavelets*.
- A wavelet is a cosine wave that has been smoothly truncated at each end.



GLIMPSE result