What is the Dark Matter?

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Outline

• Evidence for the existence of dark matter
  – Motion of visible matter
  – Cosmological evidence
  – Lensing evidence

• What is this stuff?!?!?!?
  – Theories of dark matter
  – Experimental searches for dark matter
Is There Dark Matter?

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Fathers of Dark Matter

Jacobus Kapteyn
Jan Oort
Fritz Zwicky
Galactic Rotation Curves

Horace Babcock

Vera Rubin and Kent Ford
Rotation Curve of Andromeda

The graph shows the rotational velocity (km/s) plotted against the distance from the center of the galaxy (light years). The measured curve is shown in white, while the calculated curve is in red. The graph indicates a deviation from the expected rotation curve beyond a certain distance from the center, suggesting the presence of dark matter or other gravitational effects.
History of the Universe

- Afterglow Light Pattern 380,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.
- Big Bang Expansion 13.7 billion years
Planck

Multipole moment, $\ell$

Temperature fluctuations [$\mu$K$^2$]

Angular scale
Universal Recipe

- Dark Energy: 68.3%
- Dark Matter: 26.8%
- Ordinary Matter: 4.9%
Structure Formation
Actual Observations (SDSS)
Gravitational Lensing
Gravitational Lensing

Diagram:
- Apparent position
- Position of source
- Electromagnetic waves
- Massive object
- Gravitation field
- Focus
Lensing the CMB
Evidence for Dark Matter

• Dynamics of visible matter
  – Need extra gravity to explain why things haven’t flown apart already

• Cosmology and structure formation
  – Without dark matter, we don’t make seeds for galaxies and clusters fast enough for them to be here now

• Gravitational Lensing
  – We can actually map the mass of structures in the universe, and see that the mass doesn’t always line up with the ordinary matter.
Intermission
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What is the Dark Matter?

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Theories of Dark Matter?
Theories of Dark Matter

• While others exist, there are two big classes of dark matter models: WIMPs and FIMPs.
• WIMP: Weakly Interacting Massive Particle
  – Expected to be much heavier than a proton
  – Expected to interact with some regularity
• FIMP: Feebly Interacting Massive Particle
  – Expected to be much lighter than anything known
  – Expected to interact with extreme rarity
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Dark Matter Production

• WIMPs: interact often, so make a lot
  – Also destroy a lot
  – Rate of destruction sets amount left over
  – This process is called freeze out

• FIMPs: interact very rarely
  – So we don’t make many
  – Almost never destroy them
  – Just the right amount made while the universe is hot
  – Freeze in
Freeze out

• As universe cools, DM is destroyed
• Bubbles = DM particles
  – Can only go away by finding each other
• When the universe is cold compared to the DM mass scale, all the DM should be gone, except...
Freeze out

• As the universe cools, it also expands
  – Eventually, particles so far apart they can’t find each other anymore
Freeze in

- Every so often, a particle gets produced
  - More often when the universe is hotter
- This is like the rare occasions where the pot spits water outside itself from a bubble
- As the pot is turned down, it happens more and more rarely
Theories are all well and good...

But sooner or later someone comes along and wants to know the truth about the universe.
How can we measure the dark matter?

• Three things to try...
  – Detect some interacting with us
  – Detect the results of interactions somewhere else in the neighborhood
  – Make some for ourselves

• Different techniques needed for WIMPs and FIMPs in each of these attempts

• A lot of effort going into all these fronts
WIMP Direct Detection

- Simple, just watch for a WIMP to bounce off something
  - Doesn’t leave much energy behind
  - Other things bounce too
- Characterize the bounce as well as possible
- Bury it deep in a mine
- Calibrate very carefully
FIMP Direct Detection

- FIMPs are so light that they can only convert into photons, nothing else is light enough
- The best way to make this happen is to have them experience a strong magnetic field
- The photon this creates is still very low energy and difficult to detect
- Need to be able to tune the frequency we’re looking for just like you tune a radio
ADMX
WIMP Indirect Detection

• The next technique is to look for the results of DM interactions in the sky
• For WIMPs, this means the results of ongoing (rare) annihilations, producing normal stuff
  – Many different things can be produced, but a few are easier to see than others
• I’ll focus on searching in gamma rays (very energetic photons) and antimatter
FIMP Indirect Detection

• The detection technology for FIMPs is, as usual, rather different
• The photons generated by FIMP decays are so low energy that they can’t be reliably detected
• Instead, we look for ongoing FIMP production somewhere hot and dense
• The sun is a perfect candidate for this
WIMP Production

• WIMP production is driven by Einstein’s famous relation, $E = mc^2$
  – If we put in enough energy, there’s a chance that we can make something more massive that’s going slower than what we put in
  – This is actually the principle that searches for new physics at colliders has been running on forever

• WIMPs are a decent target for this, because their interactions are not so tiny
FIMP Production

• FIMPs couple to two photons
  – One can come from a magnetic field
• Producing a FIMP from a photon is rare
  – We want a strong light source for many chances
• Once made, we need to detect it
  – Convert it back to a photon
  – Need to stop the light from overwhelming our detector though
Light shining through walls
Dark Matter Experiments
THE END OF THE FILM