

# 1 The Missing Baryon Problem: Investigating missing matter using 2 the Universe's first picture

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## 5 1 The Cosmic Microwave Background

6 [h]

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8 Fifty five years after its accidental discovery, the first image of a baby universe has still not given up all its  
9 secrets. The afterglow of the Big Bang, known as the Cosmic Microwave Background (CMB), is the only faint  
10 remnant of the early universe currently still visible in the sky, and it has been central in ushering in a golden age  
11 of cosmology.

12 The CMB is made up of very low power microwaves, and its characteristic splotches provide key insights  
13 into conditions in the early universe, allow astronomers to determine characteristics, such as the relative propor-  
14 tions of matter, dark matter and dark energy, and other fundamental parameters. To date, they yield the most  
15 precise measures of the age, geometry and composition of the universe we have.

16 In more recent years, a number of experiments have been done specifically to examine the properties of  
17 the CMB, including the Atacama Cosmology Telescope in the mountains of Chile, the South Pole Telescope,  
18 and the European Space Agency's *Planck* Satellite. These experiments have broadened the scope of the original  
19 detection, leading to the collection of an unprecedented amount of data, and applications across a number of areas

20 of astronomy.

## 21 **2 The Missing Baryon Problem**

22 The CMB has allowed scientists to determine with a very high level of confidence the composition of the universe.  
23 The universe is broadly comprised of light, regular matter, and the infamous dark matter and dark energy, the  
24 precise ratios of which are very tightly constrained.

25 However when astronomers look at the sky, and measure the amount of matter they see with telescopes, it  
26 becomes apparent that only about half of the universe's regular matter - known as 'baryons' - is present in the  
27 light emitted from stars and galaxies. This begs the question, where is all the missing matter?

28 It was clear that the matter must be there, since it is very clear to discern between dark matter and baryons  
29 in physical models. The universe could not have evolved to be what we see today if that fraction wasn't correct.  
30 But it was also apparent that only about 10 percent of baryons exist in galaxies themselves, with some 30 to 40  
31 percent existing in gas clouds surrounding galaxies. This still leaves a large fraction unaccounted for.

32 A possible answer comes from simulations - when astronomers model the behaviour of the very early  
33 universe, they notice that when galaxies form, long string like filaments form between them, creating a picture not  
34 unlike those seen in the brain with neurons.

35 [h]

36 These filaments contain very small amounts of matter, superheated to temperatures between thousands and  
37 millions of degrees, and spread out over the vast reaches of space. The combination of its speed and the distances  
38 over which it is spread makes these filaments very sparse - only a few atoms per cubic meter.

39 Detecting these filaments has proven to be a difficult task, since the scarcity of the gas makes it very unlikely

40 that there will be any observable signal. The only possible method of direct detection of this matter involves using  
41 a quasar, a galaxy with a very active super-massive black hole at its centre, as a backlight. Unfortunately this is  
42 an incredibly rare event, since it requires us to find just such an object, and for its beam to pass through both a  
43 filament and a telescope that is observing the sky and can see the object.

### 44 **3 A new use for the oldest light in the universe**

45 One possible solution is to use the CMB itself. At a fundamental level, the CMB is just light, sitting at the edge  
46 of the observable universe, and light is interactive. It is distorted by the matter in between it and our detectors in  
47 a number of different ways.

48 Scientists appeal first to a phenomenon known as Compton Scattering. The subject of the 1927 Nobel Prize,  
49 and named after its discoverer, Arthur Holly Compton, this effect describes how light can exchange some of its  
50 energy with electrons, and vice versa. Since there is hot gas in between the CMB and us, there will be sections  
51 of the sky which will have absorbed some energy from the intervening gas, and look more energetic than its  
52 surroundings.

53 A second possible tool for analysis is to take advantage of the distortion that matter makes in space-time, an  
54 effect known as Gravitational Lensing. This distortion leaves characteristic traces in the light that we see, making  
55 it appear rotated when we compare it to the background light.

56 On their own, the signals obtained by these techniques are too small for us to detect for a single filament,  
57 there is just not enough matter. We can however, use this fact to our advantage, since by definition, the noise in  
58 the signal is random. This means that if you add up enough of it, it will eventually zero out. Conversely, the  
59 signals we are looking for should stack on top of each other. Therefore, we can make a direct detection if we add  
60 multiple images on top of each other. We expect the noise to cancel out, leaving just the signal.

## 61 4 Tracing the Large Scale Structure

62 With this in mind, scientists know that they must use locations where they expect to find the missing matter in  
63 order to make a detection of any kind. To do so, they look to comprehensive galaxy surveys, such as the Sloan  
64 Digital Sky Survey (SDSS) and the Dark Energy Survey (DES), which have created some of the most detailed  
65 three-dimensional maps of the universe we have to date.

66 They then search for a very particular type of galaxy, one that is said to trace the underlying dark matter,  
67 since it is the dark matter that governs the evolution of the large scale structure of the universe. These galaxies are  
68 known as Luminous Red Galaxies, and are some of the largest and oldest galaxies in the sky.

69 Once the galaxies are located, they are paired up based on whether they are likely to have a filament con-  
70 necting them, and located in the CMB. The signals are then stacked on top of each other, hopefully revealing the  
71 missing baryons.

72 Citation of Einstein's paper <sup>1</sup>.

74 1. Einstein, A. Zur Elektrodynamik bewegter Körper. (German) [On the electrodynamics of moving bodies].  
75 *Annalen der Physik* **322**, 891–921 (1905).

