This uncertainty is exacerbated by the fact that it's also unclear how far away these mergers occurred. The expansion of the Universe implies that the measured oscillation frequencies differ from those that are emitted at the source, but inferring one from the other requires knowledge of the separation between source and detector. And it's impossible to determine the equation of state accurately without knowing the emitted frequencies.

Although bold statements about the equation of state are not immediately forthcoming from this work, Chirenti and colleagues' findings are certainly cause for excitement. Binary neutron-star mergers are prime candidates for being detected through the gravitational waves they generate. Observations of these waves would provide precisely the details that are missing from the authors' study. Gravitational-wave observatories, such as the United States' Laser Interferometer Gravitational-Wave Observatory, Europe's Virgo interferometer and Japan's Kamioka Gravitational Wave Detector (KAGRA), measure the signal before the collision, which should enable estimates of both the distance to the source and the masses of the neutron stars before they collided. Combining these measurements with Chirenti and colleagues' γ-ray observations would allow extremely precise inferences to be made about the nuclear equation of state.

But the future is even brighter. If confirmed independently through observations with a higher signal-to-noise ratio than those reported, these quasiperiodic oscillations would offer a new focus for gravitational-wave observatories. Although the first binary neutron-star merger[6] observed in gravitational waves was whoppingly 'loud', it wasn't loud enough to guarantee that the gravitational waves from these post-merger oscillations will be detectable. But they should be there, and they should be observable by dedicated next-generation observatories, such as Australia's newly proposed Neutron Star Extreme Matter Observatory[12], or third-generation gravitational-wave detectors, such as Cosmic Explorer[13] in the United States, or Europe's Einstein Telescope[14]. Chirenti and colleagues' savvy discovery will help these instruments to analyse matter that is key to one of the great unsolved problems in nuclear physics.

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Microbiology

Asgard archaeal microbes reveal their inner secrets

Jan Löwe

A microorganism that is a proposed relative of our cellular ancestors has been grown successfully in the laboratory. Its internal architecture offers clues to the early evolution of eukaryotic cells. **See p.332**

The nucleus-containing cells of animals, plants and fungi, called eukaryotic cells, arose during evolution through the merging of cells of two types of microorganism — archaea and bacteria — in a process termed eukaryogenesis. How exactly this happened remains enigmatic. The discovery of DNA sequences from a group of microbes called Asgard archaea revealed them to be the best candidates for the archaeal lineage related to the one involved in eukaryogenesis[1]. However, Asgard archaea have proved very difficult to grow in the laboratory. On page 332, Rodrigues-Oliviera *et al.*[2] report successful culture of the Asgard organism *Lokiarchaeum ossiferum*, the second to have been grown in a laboratory so far. *Prometheoarchaeum syntrophicum* was the first[3], but certain details of the intracellular organization of those archaea could not be established.

The cells reported by Rodrigues-Oliviera and colleagues have many surface protrusions and constrictions (Fig. 1), something that is predicted by arguably the most compelling theory of eukaryogenesis, called the inside-out model[4], which proposes that eukaryogenesis occurred through the engulfment of a bacterium by the cell membrane of an archaeal cell. Rodrigues-Oliviera *et al.* used atomic-structure determination of large molecules analysed directly in cells by electron microscopy to identify the *Lokiarchaeum ossiferum* in samples of a culture enriched for these Asgard archaea.

The authors also visualized intracellular protein filaments, which are very similar to key F-actin protein filaments of a eukaryotic internal structure called the cytoskeleton. Although it had been predicted[5] that Asgard archaea would contain a more-complex cytoskeleton than those of bacteria and other archaea, seeing these filaments in cells is nevertheless a triumph made possible by genomics, painstaking microbiology and the advancing field of structural cell biology that uses imaging by cryo-electron tomography (cryo-ET). An understanding of eukaryogenesis might not be as far off as was once thought.

The evolution of complex life from simpler forms is an important feature of biology. Eukaryotes are the most complex multicellular organisms on Earth. Their cells contain a DNA-filled nucleus, energy-providing organelles such as mitochondria, an intracellular membrane network that includes the endoplasmic reticulum and a complex cytoskeleton, which at its core has filaments made of the proteins actin and tubulin. Mitochondrial origins have been traced to a group of bacteria called alphaproteobacteria[6]. Analysis using a phylogenetic approach revealed that the cell that took up the alphaproteobacterium was of archaeal origin[7].

The discovery of Asgard archaea only seven years ago[1] revealed non-eukaryotic organisms that are the most closely related in DNA sequence to eukaryotes. In fact, the relationship is so close that we cannot exclude the possibility that eukaryotes emerged directly from one of the Asgard lineages[5]. Or, in other words, the tree of life might have only two branches, bacteria and archaea[7] — with us humans merely a twig on the archaeal branch.

The closeness is reflected by Asgard archaea having many eukaryotic signature proteins (ESPs), proteins that are found almost exclusively in eukaryotes and are often associated with uniquely eukaryotic processes such as intracellular trafficking — the movement of cargo between membrane-bound

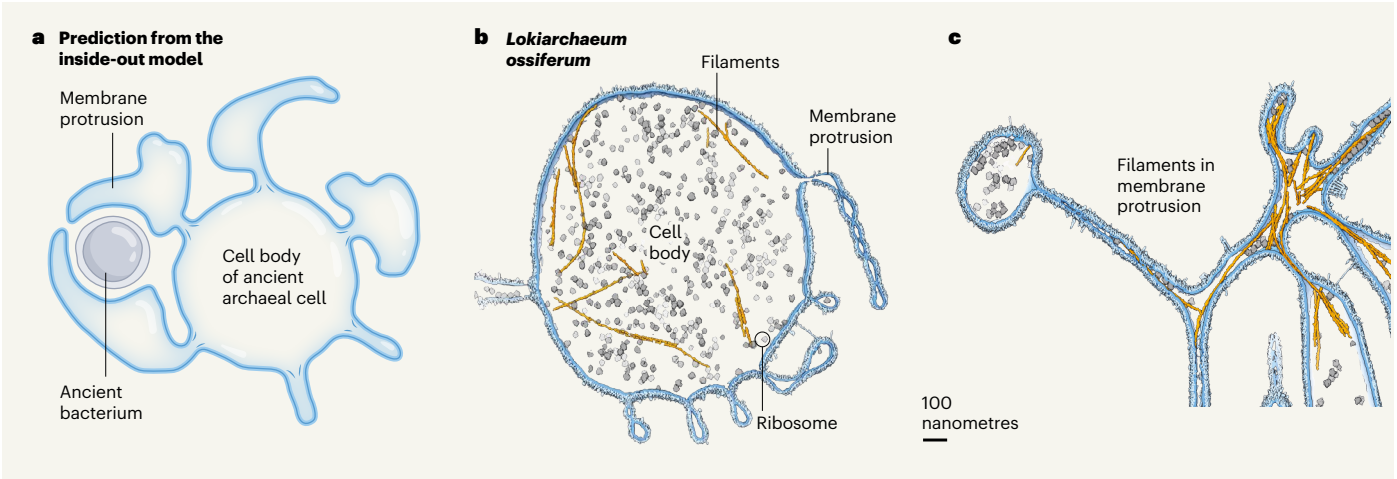

Figure 1 | Asgard archaeal cells. a, The 'inside-out' model[3] offers a proposal for how eukaryotic cells (the nucleus-containing cells of animals, plants and fungi) arose. The model suggests that they formed when two types of microbial cell — an archaeal cell and a bacterium — merged when the bacterium was taken inside the archaeal cell through engulfment by membrane protrusions of the archaeon. The depiction shown is based on drawings of these proposed cellular interactions made when the model was proposed[4]. **b**, Rodrigues-Oliviera *et al.*[2] report the laboratory culture and imaging of a type of archaeal cell (an Asgard archaeal cell) that is closely related to eukaryotic cells. These *Lokiarchaeum ossiferum* cells show the membrane protrusions predicted by the inside-out model. The identification of filaments that look like structures called F-actin filaments found in eukaryotic cells reveal the archaeal cell's close evolutionary relationship to eukaryotes. The archaeal cells were identified in the samples by structural analysis of a cellular component — the ribosome. **c**, The presence of filaments in membrane protrusions of *L. ossiferum* echoes an arrangement found in eukaryotic cells.

compartments. For example, many Asgard organisms contain eukaryote-like components of the ESCRT machinery that is involved in intracellular trafficking in eukaryotic cells, and components of the ubiquitin system that degrade proteins in eukaryotes. Most Asgard archaea also contain cytoskeletal proteins such as actin and actin modulators, which are similar to those that drive cell dynamics in eukaryotes. Although bacteria and non-Asgard archaea also contain cytoskeletons, these are more distantly related to eukaryotic cytoskeletons, and their modulators are different[8].

After the discovery[1] of the Lokiarchaeota (the first known Asgard archaea) using a metagenomics approach, many more Asgard archaea were identified[9]. Surprisingly, these organisms inhabit ecological niches that are neither extreme nor rare, and they might have been expected to be found much earlier, given that they are, essentially, everywhere. We just did not know they existed because they are not abundant, not associated with disease and generally slow growing. It seems they are not much in the way of anything else.

It took many years for the first Asgard organisms to be cultured[3]. *Prometheoarchaeum syntrophicum* grows together with other prokaryotic organisms (that is, other bacteria and archaea, which lack a nucleus) in a system that offers shared nutritional and other potential benefits (syntrophy). Imaging showed the cells to have membrane-enclosed protrusions, in support of the inside-out theory, but it was impossible to determine much else.

Rodrigues-Oliviera *et al.* set out to change this situation. Starting with a sediment sample that contained around 4% Asgard archaea, the authors tried a range of conditions to enrich and culture these organisms. Using a minimal medium of nutrients, antibiotics and oxygen-depleted (anaerobic) conditions, the authors finally grew *L. ossiferum* to 80% enrichment (that is, it represented 80% of the organisms present). These are regarded as 'fast' Asgard — yet their slow generation time of 7–14 days gives an indication of the difficulties the researchers encountered. Notably, *L. ossiferum* also grew in syntrophy with other species, some of them bacterial.

Having an enriched culture enabled the sequencing of the approximately six-million-base-pair genome of *L. ossiferum* to high standards. This is crucial because, only a few years ago, the existence of Asgard organisms was questioned because the metagenomic methods available for sequencing at the time found no evidence of them. No such doubts can persist now.

The authors then examined the cells of *L. ossiferum*. The cells are too small for most light-microscopy methods, so Rodrigues-Oliviera and colleagues turned to cryo-ET to produce 3D maps of the cells at molecular resolutions of 3–5 nanometres. But how could one be sure of which cells to look at in a sample that is not uniformly one species? This is where the work becomes particularly ingenious. The authors solved the structure of a large cellular component — the ribosome — to determine which of the cells are Asgard, as indicated by segments in their ribosomal RNA that provide a hallmark. This is a beautiful use of the concept of visual proteomics, as envisaged nearly two decades ago[10].

The maps of the architecture of *L. ossiferum* reveal many features that will keep scientists busy. The cell membrane has many protrusions, and is not strengthened by a cell wall or any ordered surface-layer structure, and its surface is rough, most probably because of proteins that stick out. The DNA is confined to the cell bodies (it is not in the protrusions), as predicted by the inside-out model. And the gorgeous maps enable viewers to see many filaments, in both the cell bodies and the protrusions (Fig. 1). Using cryo-ET and an averaging method, the authors could identify a double-helical structure in the filaments that is strikingly similar to the arrangement in eukaryotic F-actin filaments.

The finding that the second Asgard organism imaged also has surface protrusions supports the inside-out theory of eukaryogenesis. The localization of the F-actin filaments in *L. ossiferum* might suggest that the filaments have a role in the shaping of membranes, although this needs to be confirmed.

No intracellular membranes were found, which is surprising given the presence of ESPs that relate to intracellular membrane trafficking, such as GTPases, Sec24 and ESCRT proteins. One could speculate that these ESPs are instead involved in vesicular transport into and out of the Asgard cells. Such transport might be required between *L. ossiferum* cells and also between them and their syntrophic companions, as predicted by the inside-out model. These proteins might also modulate the membrane locally to enable protrusion.

The finding of syntrophy could indicate that Asgard organisms prefer, or require, a 'social' lifestyle. It suggests that cell-merging events could be frequent. For example, it might be possible to find merged cells that are different from those that led to eukaryotes — we might just have to look harder. What also lies ahead

is to establish Asgard model organisms with genetic and imaging potential. In the meantime, we should marvel at the beauty of a new world that has been discovered.

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Particle physics

Nuclear reaction rules out neutrino hypothesis

Jun Cao

An anomalous measurement from a nuclear reactor triggered a three-year campaign to find an elusive particle called the sterile neutrino. The search shows definitively that sterile neutrinos don't exist — but the anomaly persists. **See p.257**

Neutrinos are among the most abundant elementary particles in the Universe, but they have zero electric charge and interact only weakly with matter, so are difficult to detect in experiments. They have therefore been implicated as the reason behind some of the key gaps in our current understanding of the Universe. The long-held idea[1] that there are only three types of neutrino was challenged in 1996 (ref. 2) by evidence suggesting the possibility of a fourth type, called the sterile neutrino. Further support for this proposal came in 2011 (ref. 3), when the total number (the flux) of antineutrinos — the antimatter counterpart of neutrinos — produced in a nuclear reactor differed significantly from that predicted. A dedicated search ensued. And now, on page 257, the STEREO collaboration[4] confirms the flux anomaly, but reports that this discrepancy cannot be explained by the existence of a sterile neutrino.

In 1989, experiments[1] on the Large Electron–Positron Collider (LEP) at CERN, Europe's particle-physics laboratory near Geneva, Switzerland, determined precisely that there were three types (or 'flavours', in particle-physics terms) of neutrino. The three confirmed flavours are the electron neutrino, the muon neutrino and the tau neutrino. Neutrinos are generated when cosmic rays interact with Earth's atmosphere, and also through nuclear fusion occurring in the Sun's core. Experiments designed to detect these atmospheric[5] and solar[6] neutrinos established the curious fact that neutrinos oscillate — they change spontaneously from one flavour to another as they travel.

Neutrino oscillation can occur only if neutrinos have mass, and their mass is difficult to measure. An electron neutrino (or any other flavour) is a quantum mixture of three states that have different masses. When this neutrino moves through space, quantum interference between the three states leads to the periodic flavour transformations that constitute neutrino oscillation.

Although scientists do not know the exact values of the neutrino masses, they can measure the differences between them; these are called 'mass splittings' and are proportional to the oscillation frequencies. The three frequencies corresponding to the three mass splittings have all been observed with various neutrino sources, including solar and atmospheric neutrinos, as well as with sources produced in particle accelerators and nuclear reactors.

An abnormal neutrino oscillation with a new frequency was detected[2] in 1996, triggering the proposal of the sterile neutrino. This hypothetical neutrino should have a much larger mass than those of the other three and yet it was not detected in the LEP experiments. The name comes from the fact that it is not expected to participate in the weak interaction — the interaction between subatomic particles that leads to the radioactive decay of atoms. Certain fundamental-physics theories suggest the existence of the sterile neutrino, and there are experimental hints that support these theories, one of the strongest hints being a result known as the reactor antineutrino anomaly[3].

Electron antineutrinos are produced in abundance by nuclear-fission reactions in the cores of nuclear reactors. This type of

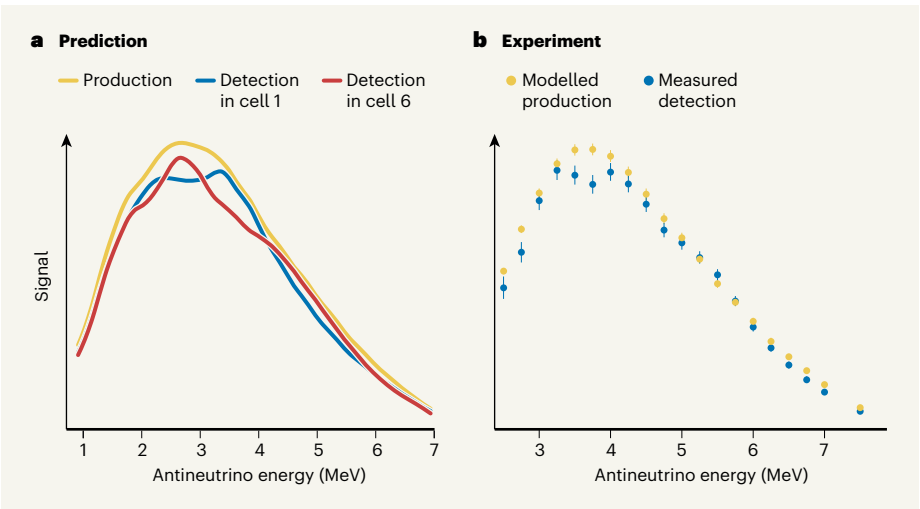

Figure 1 | The search for sterile neutrinos using a nuclear reactor. Neutrinos come in different 'flavours', including electron, muon and tau neutrinos. Electron antineutrinos (the antimatter counterparts of electron neutrinos) are produced in fission reactions in nuclear-reactor cores, and it was previously found[3] that the average number of these particles (their flux), measured by detectors close to such reactors, is about 6% less than that predicted. This anomaly was proposed to result from some neutrinos changing into a hypothetical fourth flavour, known as the sterile neutrino. The STEREO collaboration[4] measured the flux and energy spectra of antineutrinos in 6 detector cells positioned between 9 and 11 metres from a nuclear reactor. **a**, The existence of the sterile neutrino would have resulted in the shape of the detected energy spectra varying between cells. **b**, This spatial variation was not detected, but the authors measured lower flux than that predicted, thus confirming the anomaly, and excluding the possibility that it is caused by a sterile neutrino. (Adapted from Figs 1 and 2 of ref. 4.)