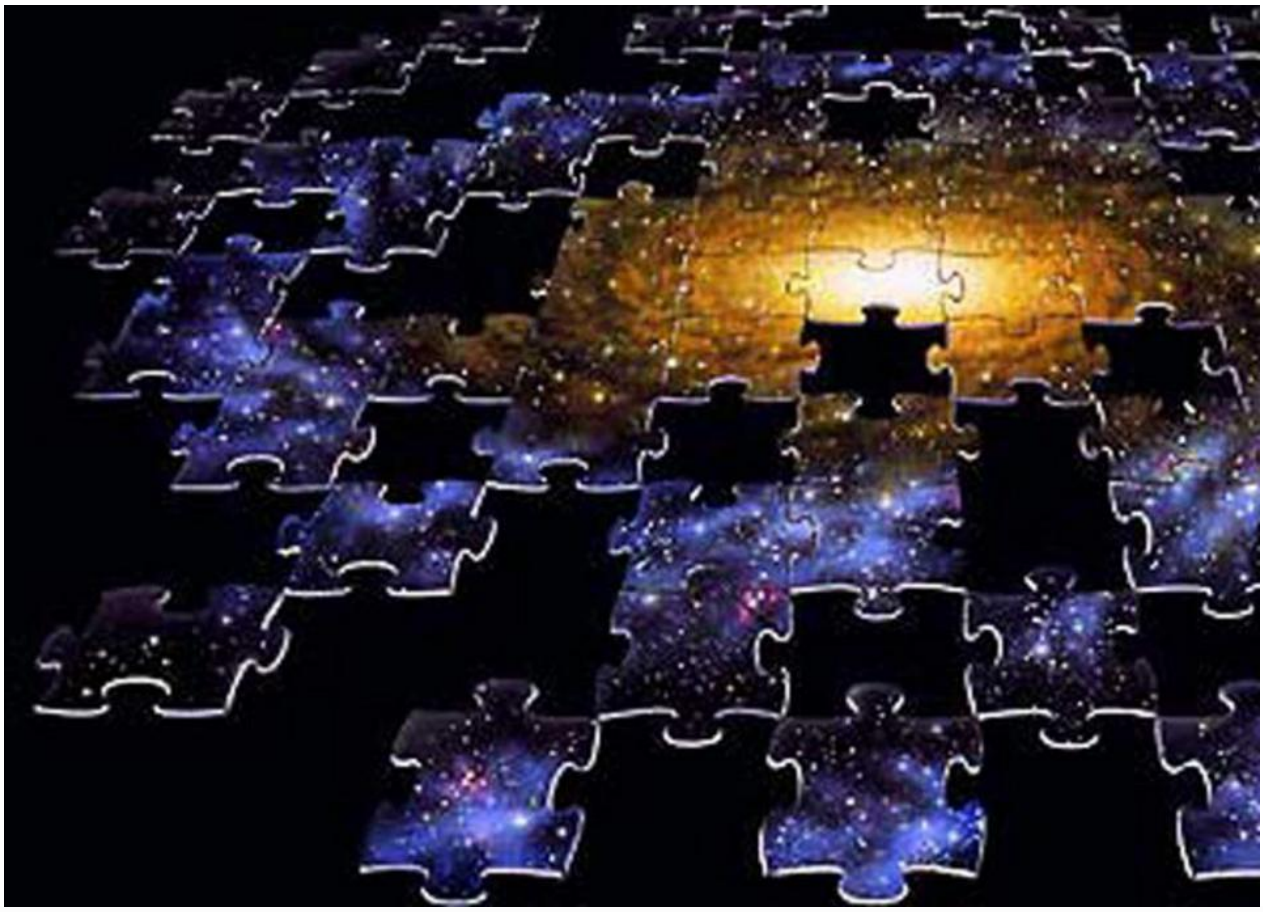
SCIENCE

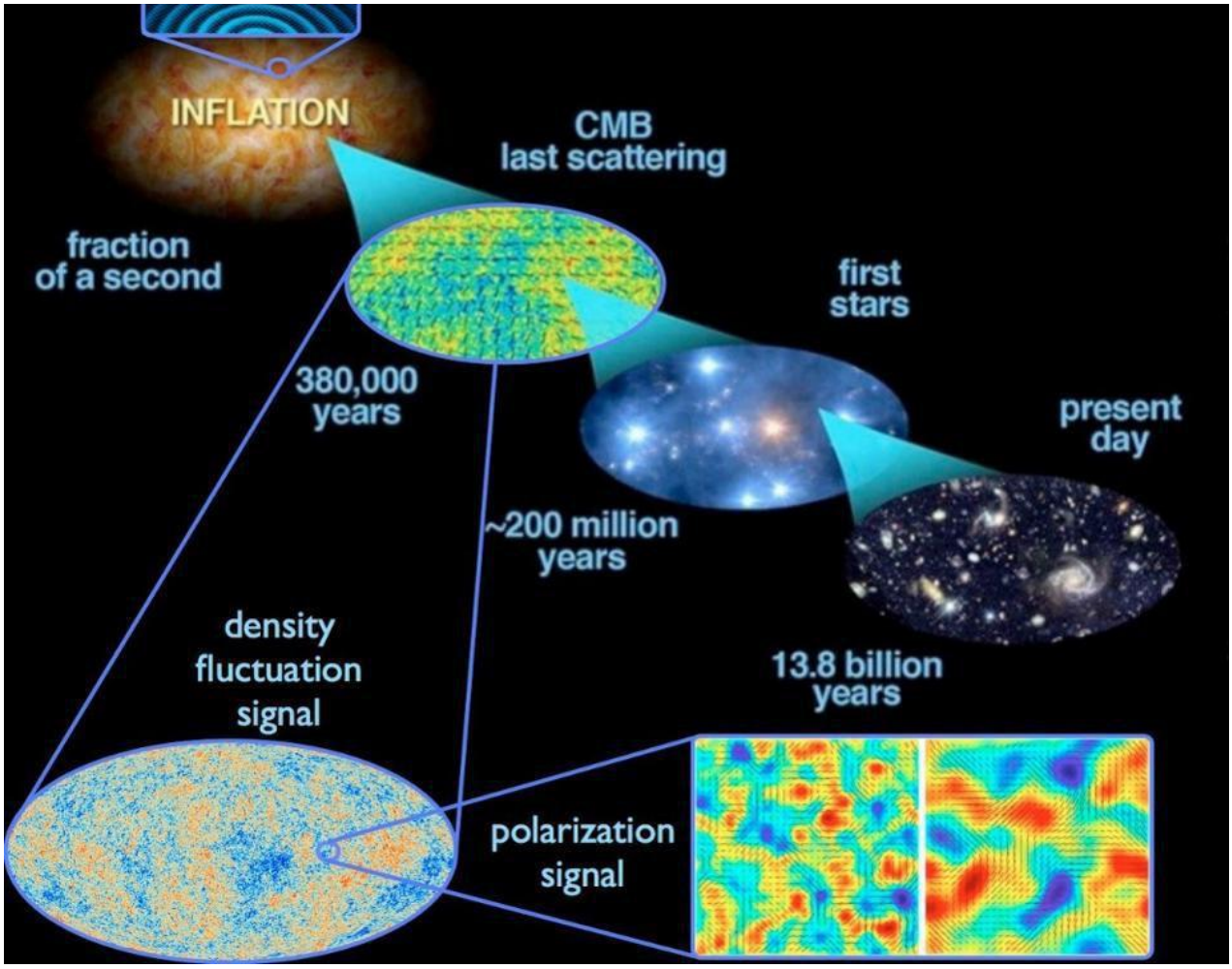
5 Puzzles About The Universe That Keep Scientists Up At Night

Ethan Siegel
Senior Contributor
Starts With A Bang
Contributor Group
Apr 19, 2021,02:00am EDT



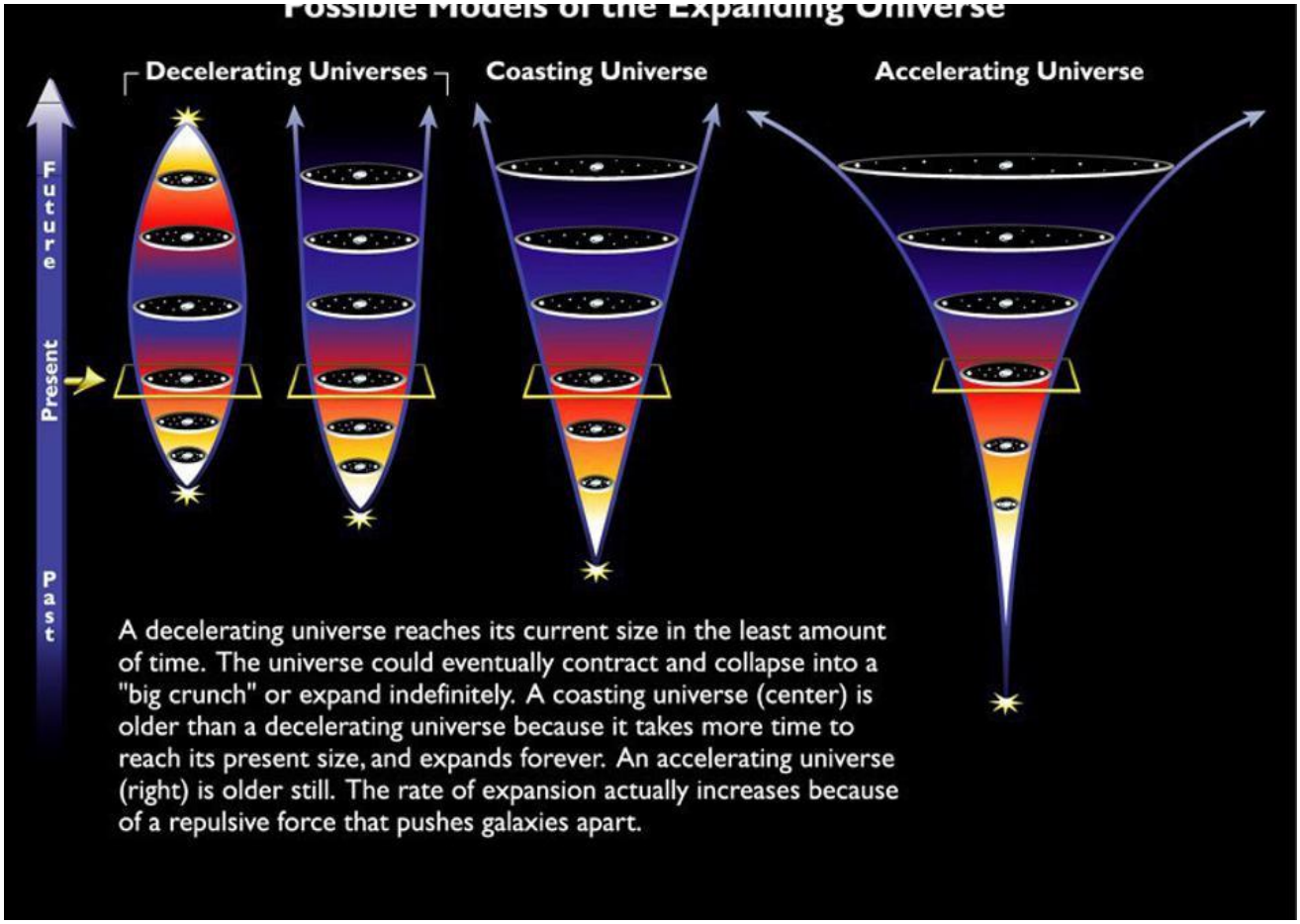
We can explain an enormous amount about our Universe with our prevailing theories. But other mysteries, like dark matter, dark energy, the matter-antimatter asymmetry, and the hierarchy problem remain unresolved. So long as there are mysteries at the frontiers, there will be a reason to continue our scientific journey. -

Despite our vast cosmic knowledge, enormous unknowns remain.



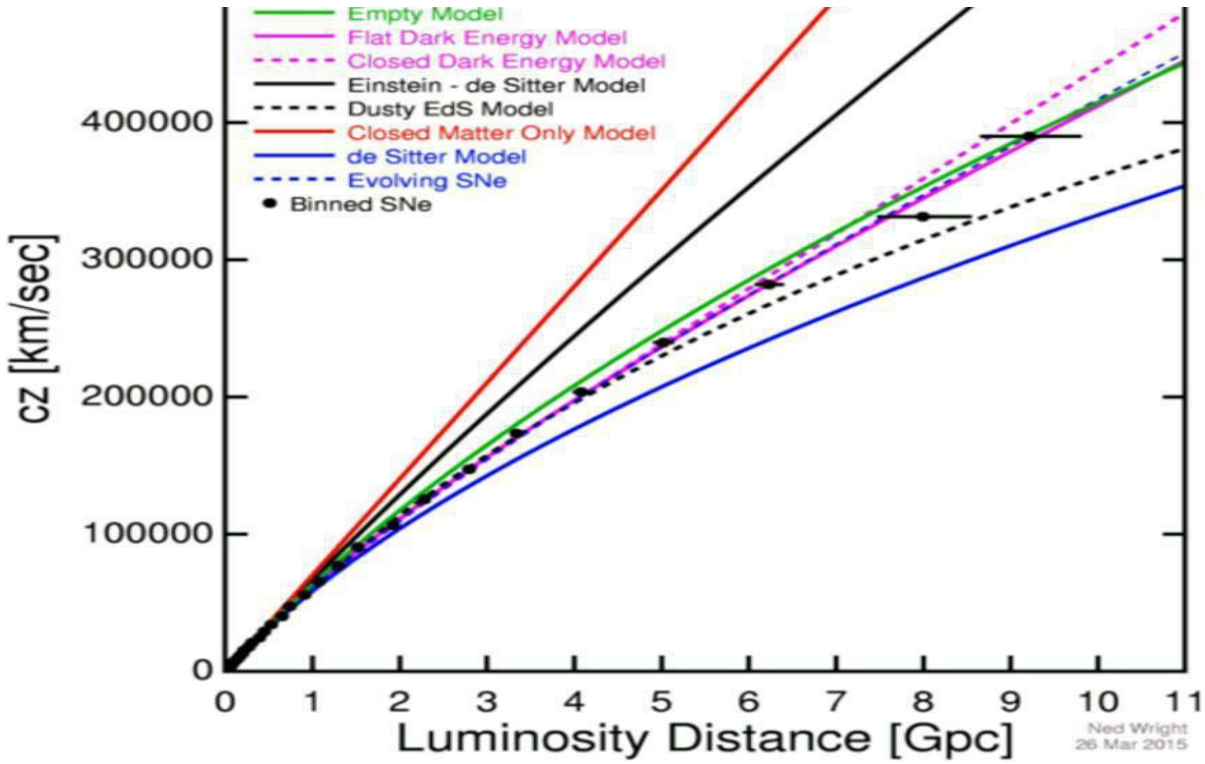
The quantum fluctuations inherent to space, stretched across the Universe during cosmic inflation, gave rise to the density fluctuations imprinted in the cosmic microwave background, which in turn gave rise to the stars, galaxies, and other large-scale structure in the Universe today. This is the best picture we have of how the entire Universe behaves, where inflation precedes and sets up the Big Bang.

These five existential physics puzzles still elude explanation.



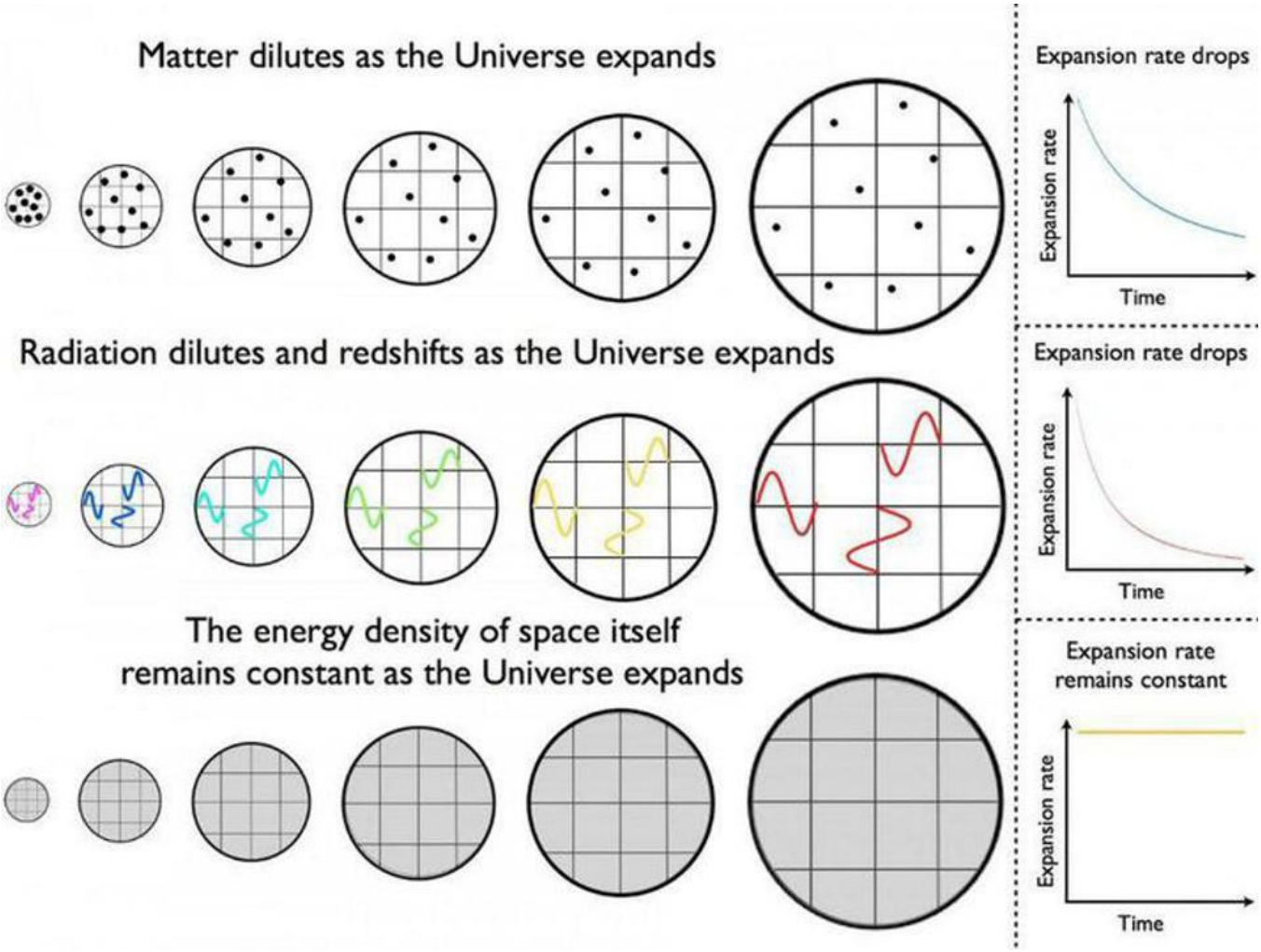
Possible fates of the expanding Universe. Notice the differences of different models in the past; only a Universe with dark energy matches our observations, and the dark energy-dominated solution came from de Sitter all the way back in 1917.

1.) Why won't gravitation stop the Universe's expansion?



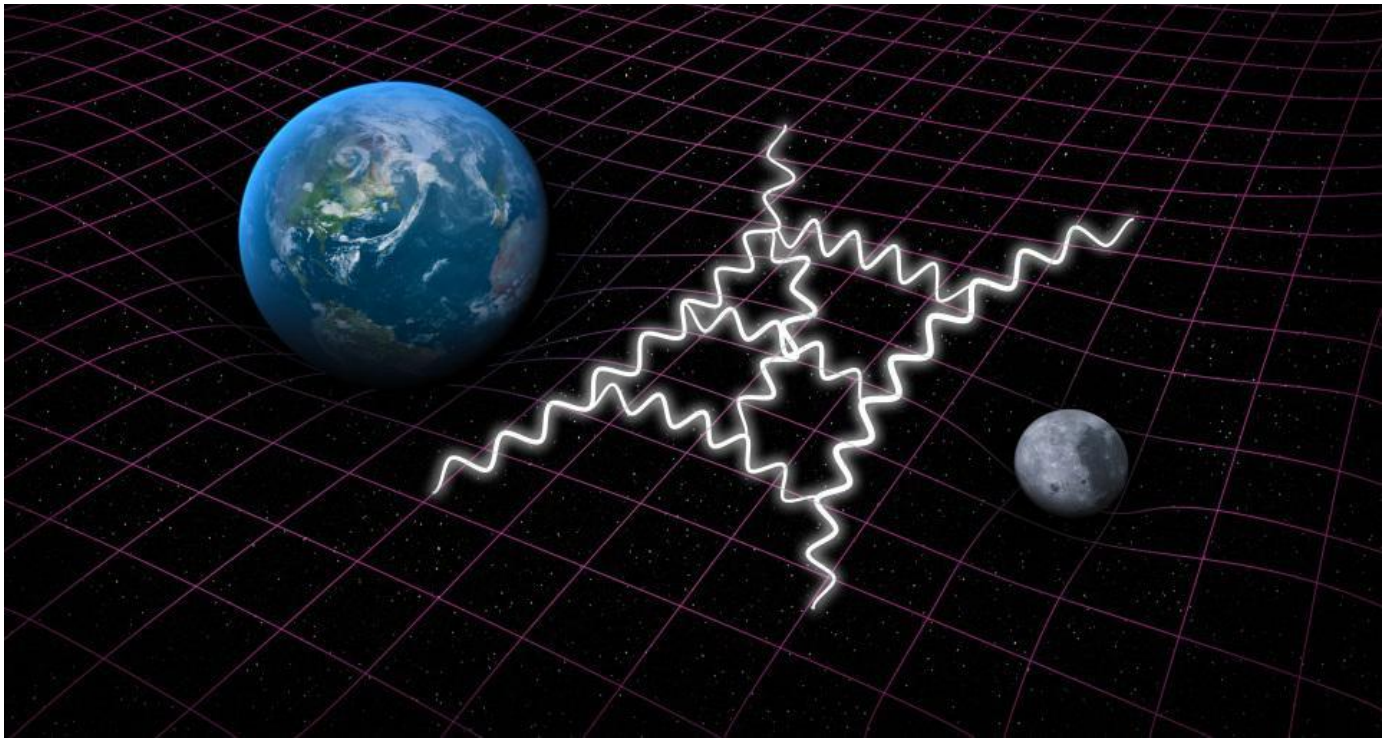
When we plot out all the different objects we've measured at large distances versus their redshifts, we find that the Universe cannot be made of matter-and-radiation only, but must include a form of dark energy: consistent with a cosmological constant, or an energy inherent to the fabric of space itself. Note the fit to the purple, solid line, and how models without dark energy (green, black and solid blue) do not match our observations.

Somehow, there's a non-zero, positive energy inherent to space: dark energy.



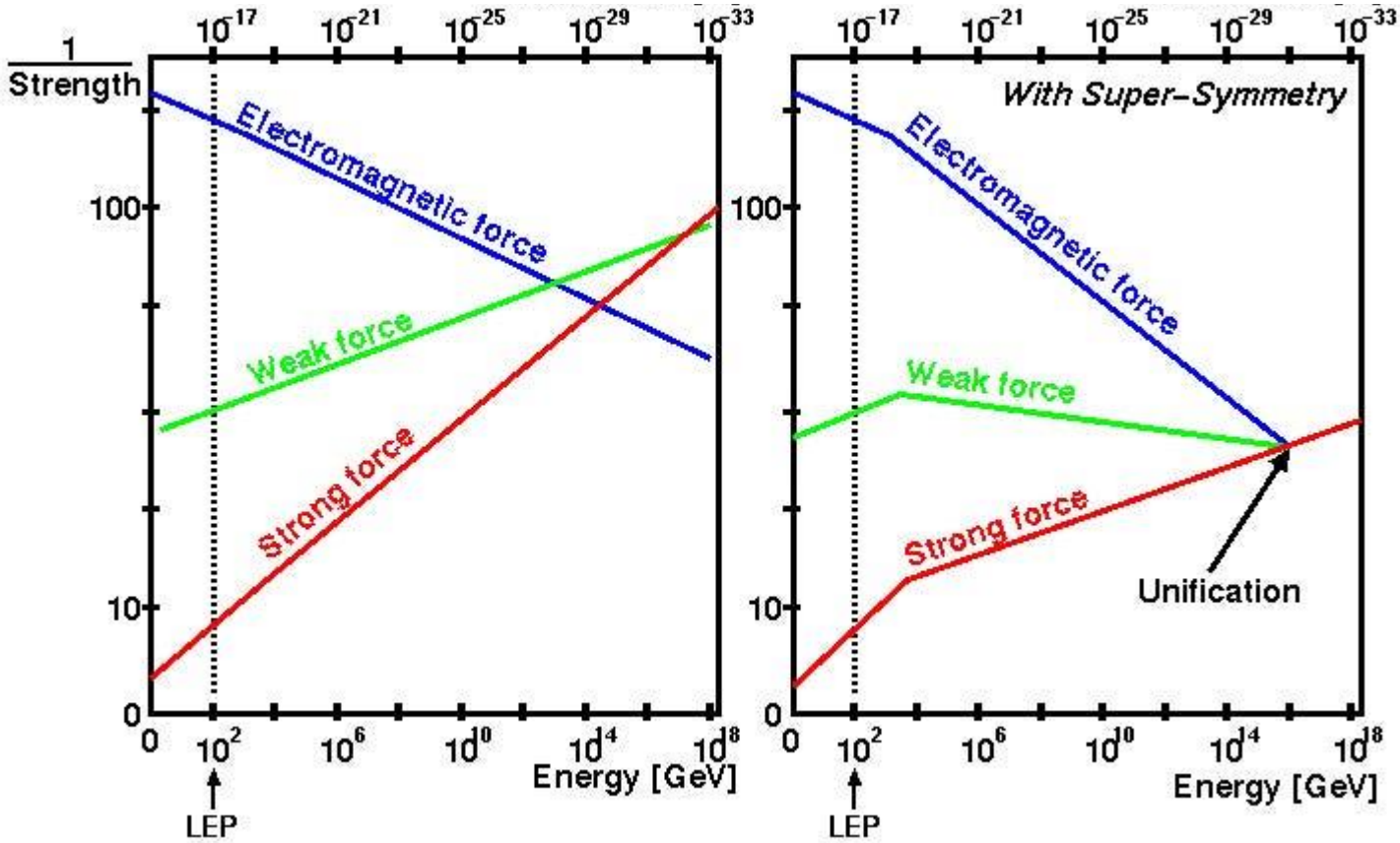
While matter (both normal and dark) and radiation become less dense as the Universe expands owing to its increasing volume, dark energy, and also the field energy during inflation, is a form of energy inherent to space itself. As new space gets created in the expanding Universe, the dark energy density remains constant

It accelerates the Universe's expansion, but its existence and magnitude are unexplained.



While matter (both normal and dark) and radiation become less dense as the Universe expands owing to its increasing volume, dark energy, and also the field energy during inflation, is a form of energy inherent to space itself. As new space gets created in the expanding Universe, the dark energy density remains constant.

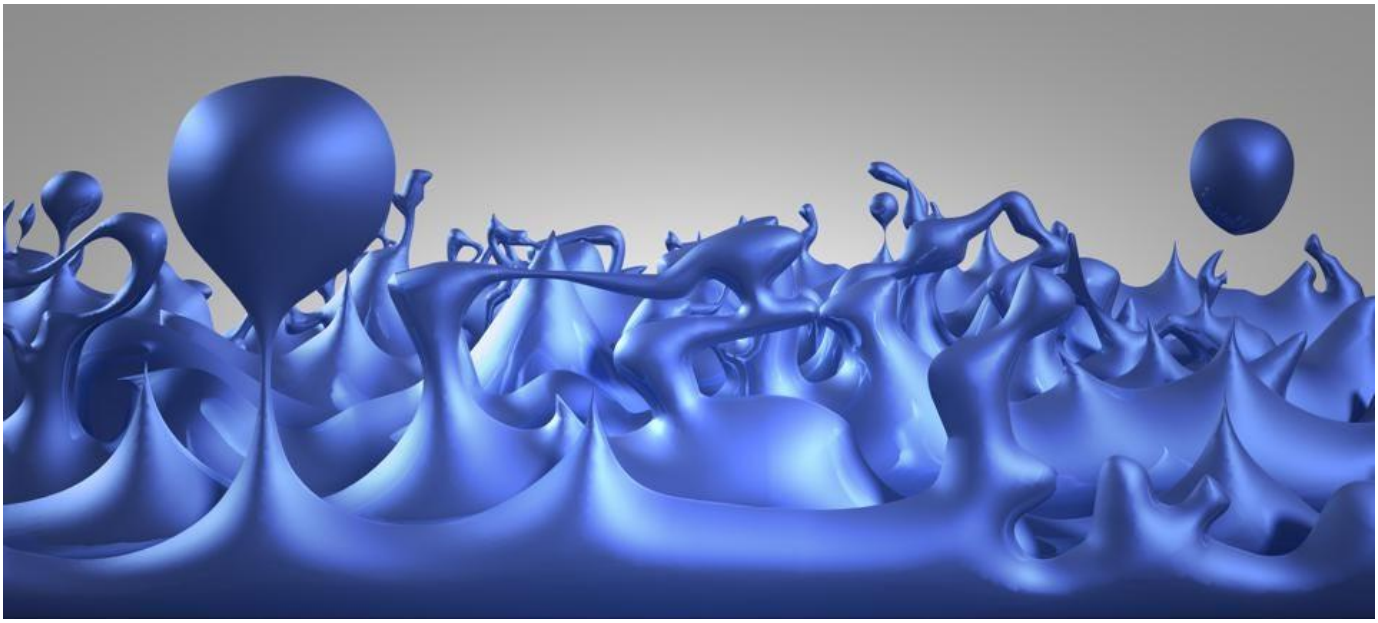
2.) Is gravity truly a quantum force of nature?



When you view the coupling constants as a function of energy on a log-log scale, they appear to nearly miss one another, at left. If you add in the supersymmetric

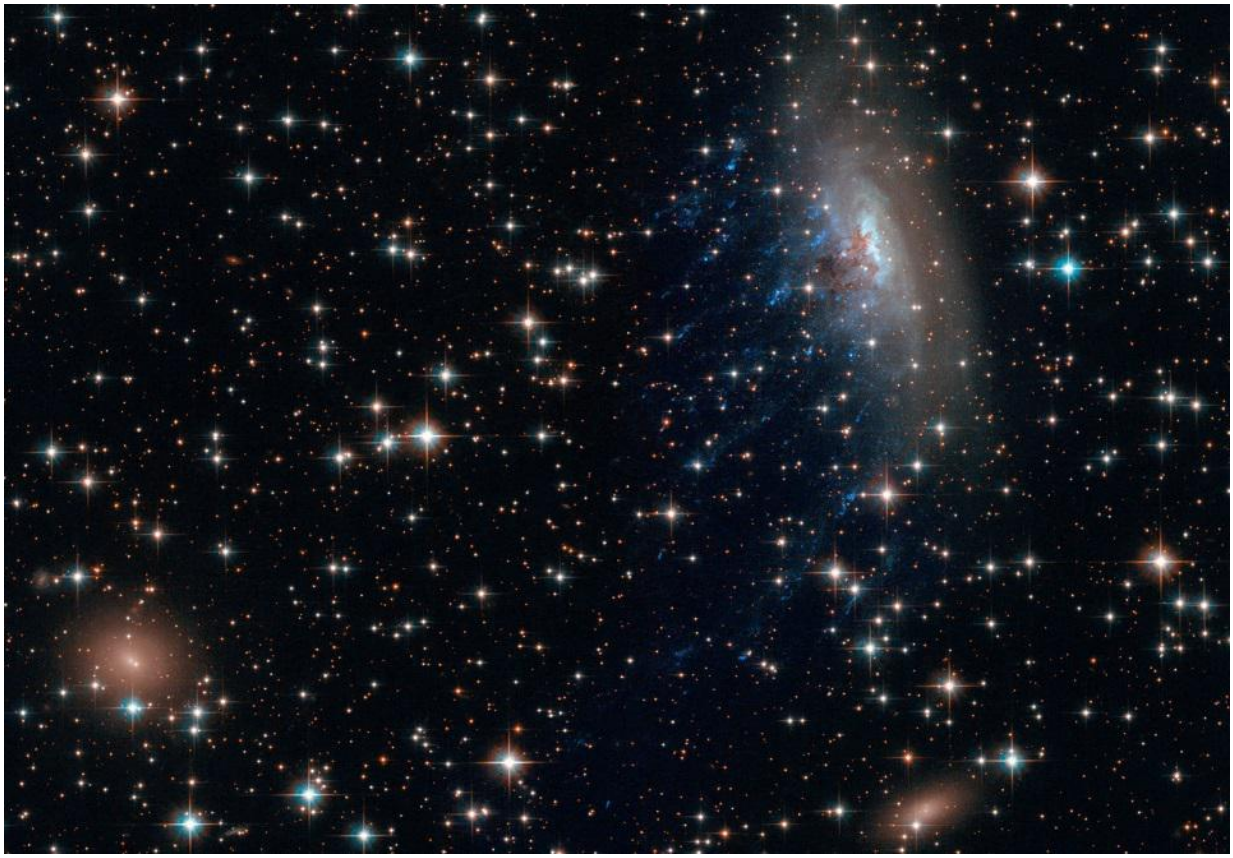
particles as predicted, the constants meet (or come much closer to meeting) at ~10^15 GeV, or the traditional grand unification scale. It is unknown whether, or how, gravitational coupling runs with energy.

At higher energies — and shorter distances — the fundamental quantum interactions change in strength.



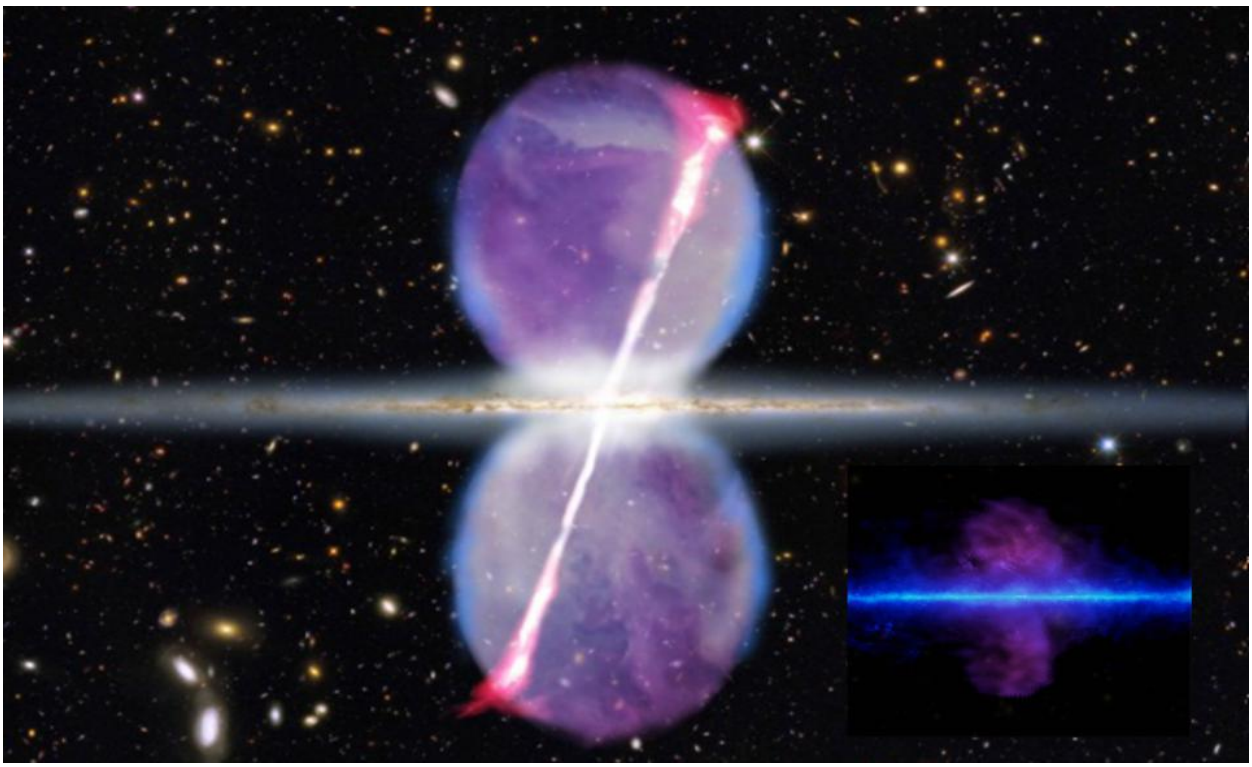
Quantum gravity tries to combine Einstein's general theory of relativity with quantum mechanics. Quantum corrections to classical gravity are visualized as loop diagrams, as the one shown here in white. The hypothetical contributions of these quantum corrections have never been observed or measured.

Does gravity exhibits analogous quantum effects? We don't know.



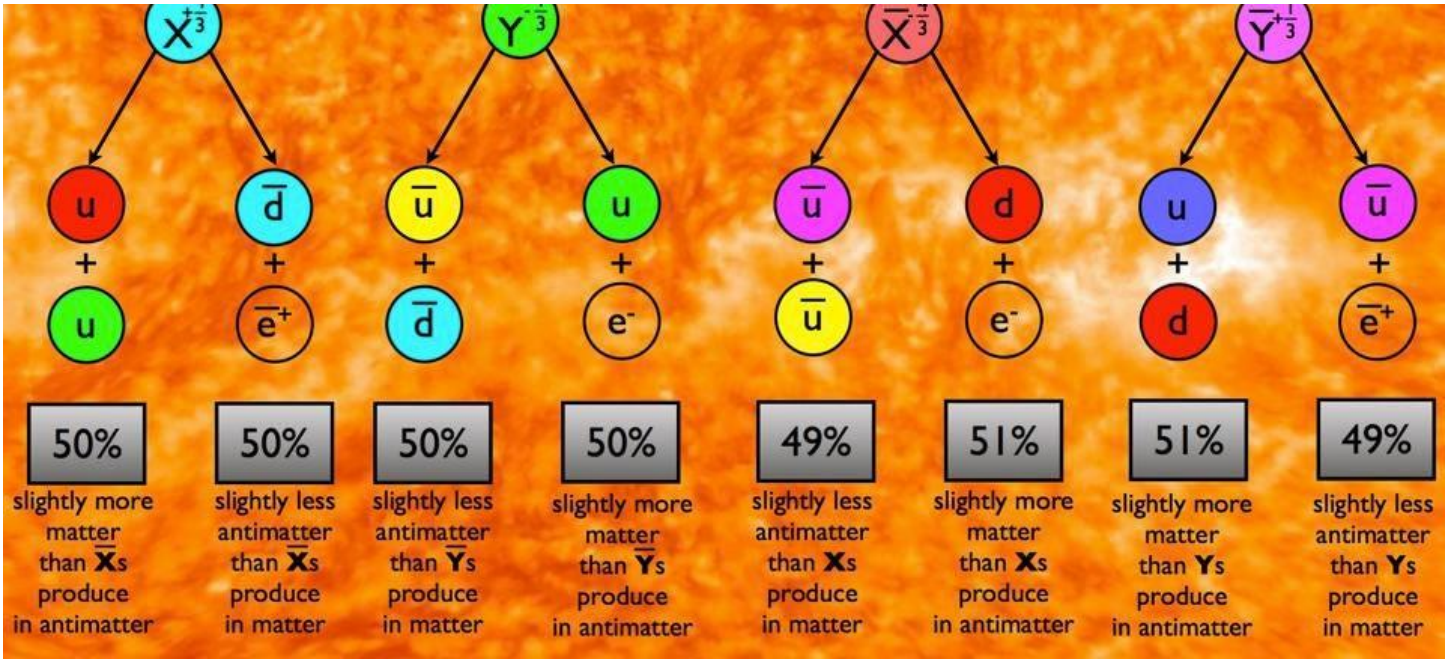
On all scales in the Universe, from our local neighborhood to the interstellar medium to individual galaxies to clusters to filaments and the great cosmic web, everything we observe appears to be made out of normal matter and not antimatter. This is an unexplained mystery.

3.) Why is the Universe filled with normal matter, but not antimatter?



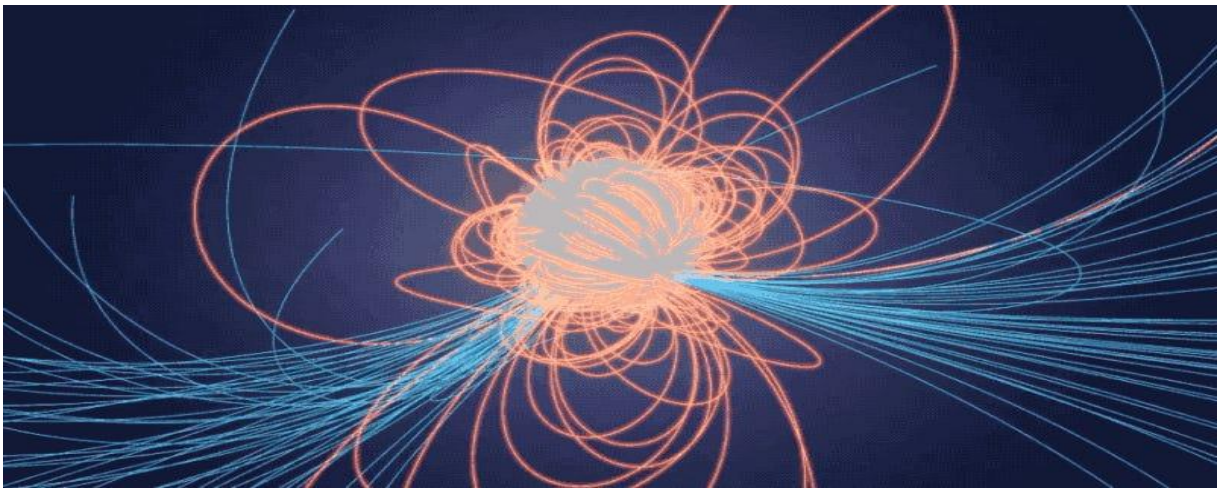
In the main image, our galaxy's antimatter jets are illustrated, blowing 'Fermi bubbles' in the halo of gas surrounding our galaxy. In the small, inset image, actual Fermi data shows the gamma-ray emissions resulting from this process, with the red-and-blueshifts indicating that one jet is more pointed towards us and the other an equivalent amount away from us. Fewer than one part in one million of the particles emitted from the galactic center are antimatter.

Antimatter only exists in tiny amounts; all stars and galaxies consist of normal matter.



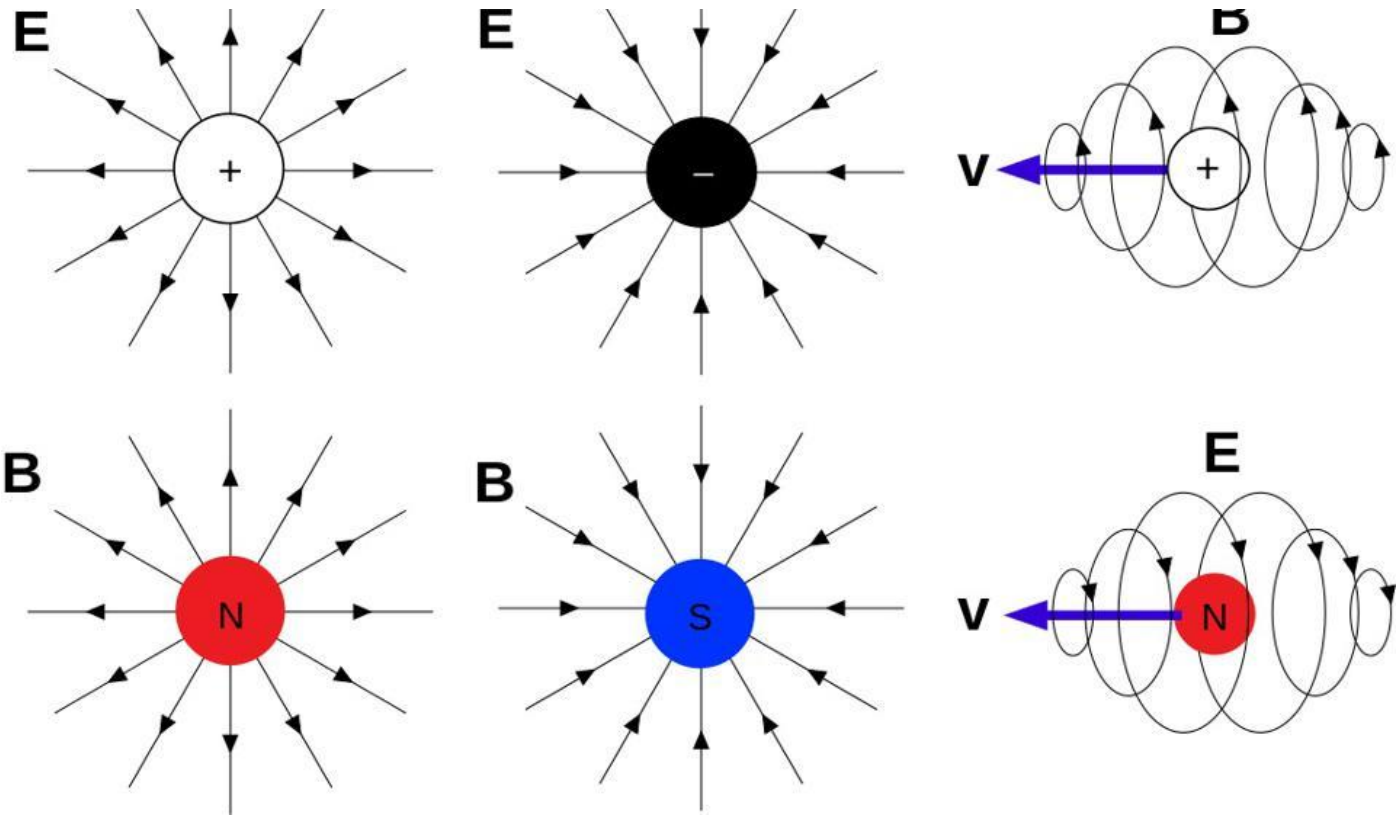
If you create new particles (such as the X and Y here) with antiparticle counterparts, they must conserve CPT, but not necessarily C, P, T, or CP by themselves. If CP is violated, the decay pathways — or the percentage of particles decaying one way versus another — can be different for particles compared to antiparticles, resulting in a net production of matter over antimatter if the conditions are right.

Many theoretical solutions create this cosmic asymmetry, but lack supporting evidence.



The pulsar J0030+0451, based on NICER data, is shown to have 'hot spots' only in its southern hemisphere, which means that a magnetic model involving only a typical magnetic dipole cannot explain what we observe. Here, a large quadrupole, from simulations, is shown to be a far superior fit to the data.

4.) Why do we have electric charges, but not magnetic charges?

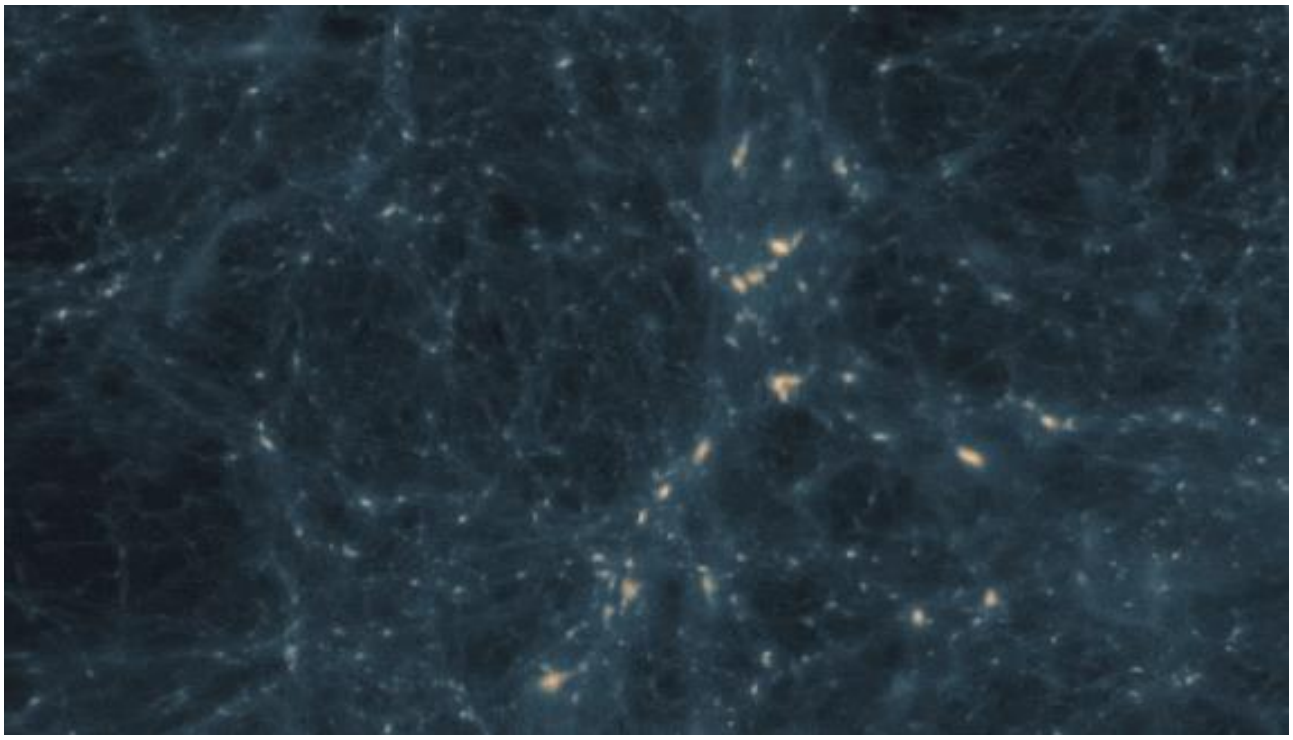


Electromagnetic fields as they would be generated by positive and negative electric charges, both at rest and in motion (top), as well as those that would theoretically be created by magnetic monopoles (bottom), were they to exist. As they don't exist, only the top examples, and not the bottom row, remain physical possiblities.
Isolated magnetic poles don't fundamentally exist; only moving electric charges create magnetism.

Law of Physics	Standard Form w/o Magnetic Monopoles	With Magnetic Monopoles (simple symmetrization)
Gauss' Law	$\vec{\nabla}\cdot\vec{E}=\frac{\rho}{\epsilon_0}$	$\vec{\nabla}\cdot\vec{E}=\frac{\rho_e}{\epsilon_0}$
Gauss' Law for Magnetism	$\vec{\nabla}\cdot\vec{B}=0$	$\vec{\nabla}\cdot\vec{B}=\mu_0\rho_m$
Faraday's Law of Induction	$\vec{\nabla}\times\vec{E}+\frac{\partial\vec{B}}{\partial t}=0$	$\vec{\nabla}\times\vec{E}+\frac{\partial\vec{B}}{\partial t}=-\mu_0\vec{J}_m$
Ampere's Circuital Law	$\vec{\nabla}\times\vec{B}-\epsilon_0\mu_0\frac{\partial\vec{E}}{\partial t}=\mu_0\vec{J}$	$\vec{\nabla}\times\vec{B}-\mu_0\epsilon_0\frac{\partial\vec{E}}{\partial t}=\mu_0\vec{J}_e$
Lorentz Force Equation	$\vec{F}=q_e(\vec{E}+\vec{v}\times\vec{B})$	$\vec{F}=q_e(\vec{E}+\vec{v}\times\vec{B})+q_m\left(\vec{B}-\vec{v}\times\frac{\vec{E}}{c^2}\right)$

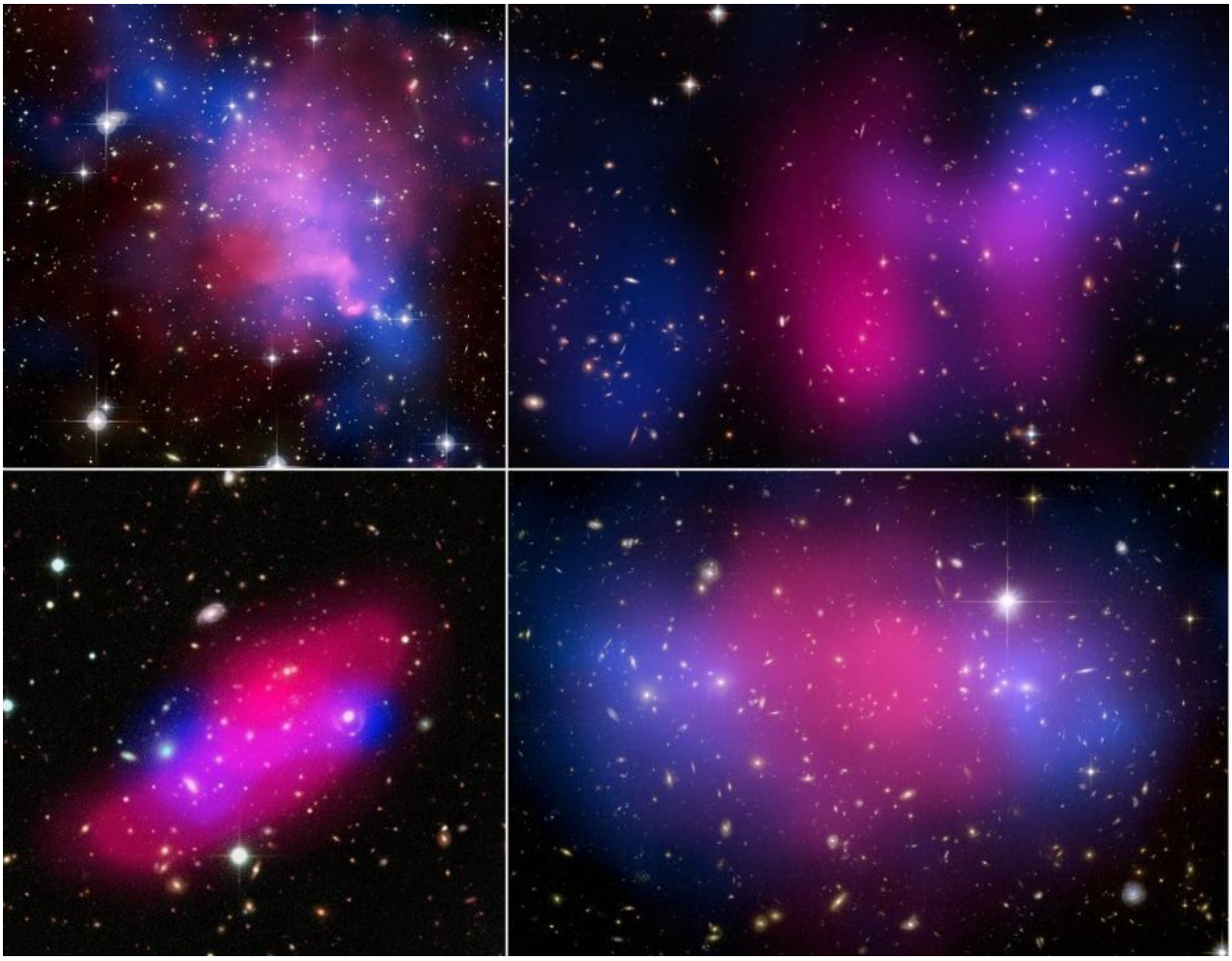
It's possible to write down a variety of equations, like Maxwell's equations, that describe the Universe. We can write them down in a variety of ways, but only by comparing their predictions with physical observations can we draw any conclusion about their validity. It's why the version of Maxwell's equations with magnetic monopoles (right) don't correspond to reality, while the ones without (left) do.

Nature is not symmetric between electricity and magnetism, with no underlying explanation.



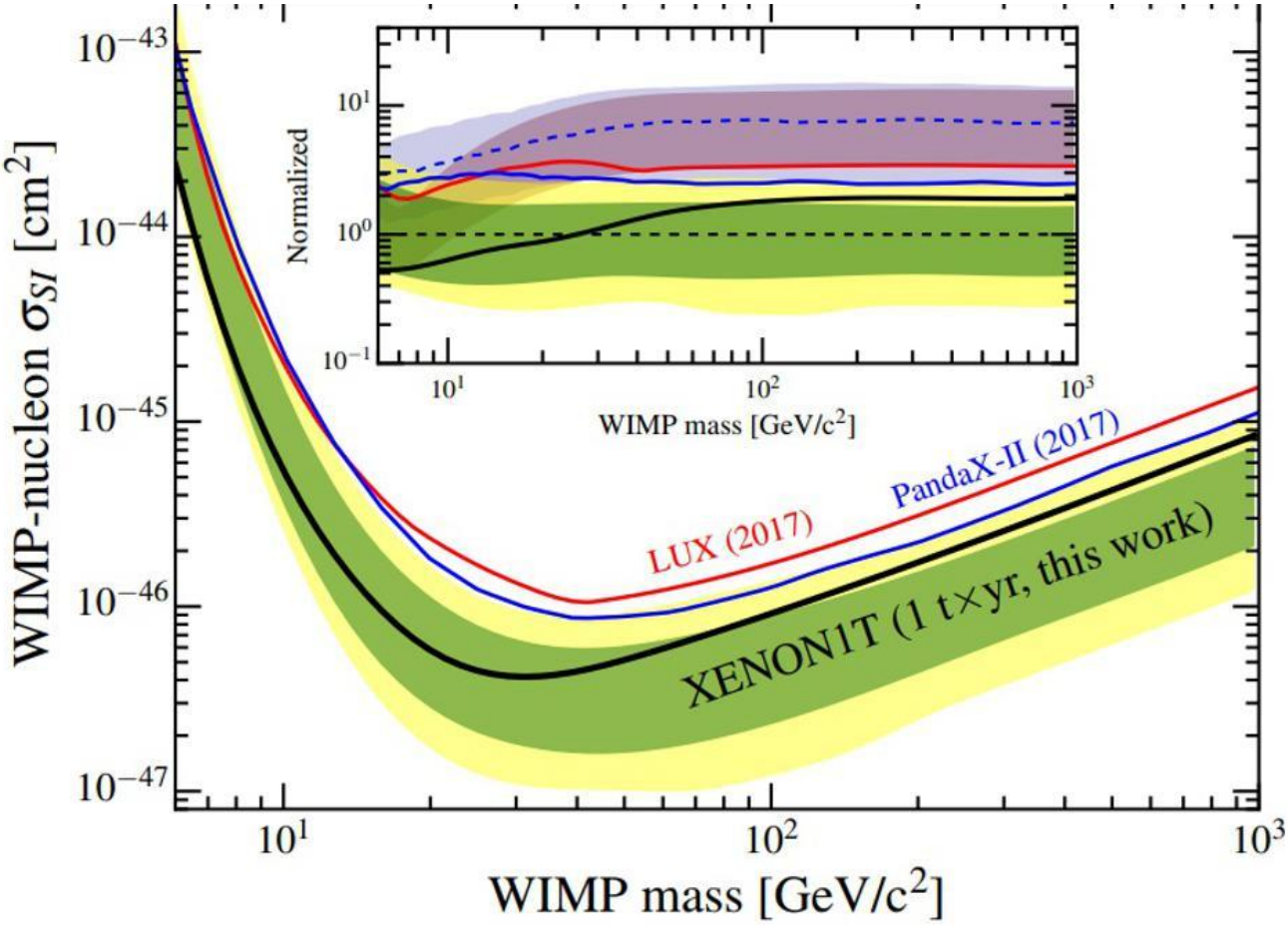
This snippet from a structure-formation simulation, with the expansion of the Universe scaled out, represents billions of years of gravitational growth in a dark matter-rich Universe. Note that filaments and rich clusters, which form at the intersection of filaments, arise primarily due to dark matter; normal matter plays only a minor role.

5.) Will we ever reveal the “matter” behind dark matter?



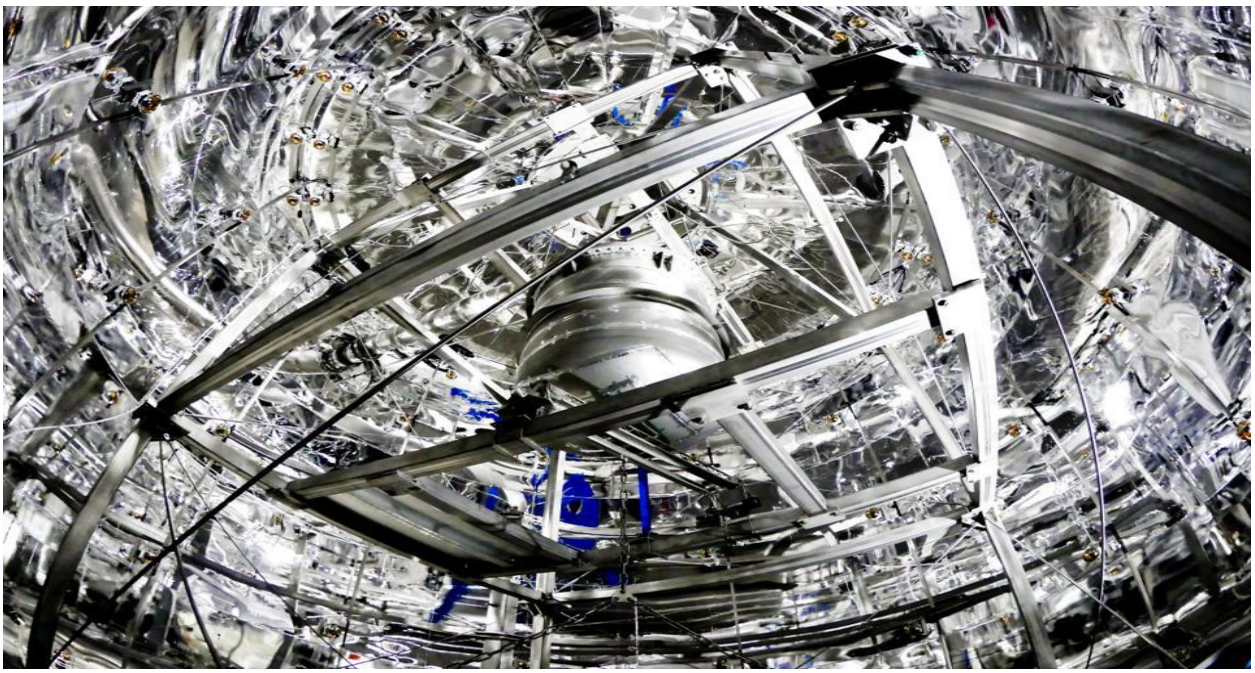
Four colliding galaxy clusters, showing the separation between X-rays (pink) and gravitation (blue), indicative of dark matter. On large scales, cold dark matter is necessary, and no alternative or substitute will do. However, mapping out the X-ray light (pink) is not necessarily a very good indication of the dark matter distribution (blue).

From gravitational lenses to the cosmic web to the CMB, indirect evidence overwhelmingly supports dark matter's presence.



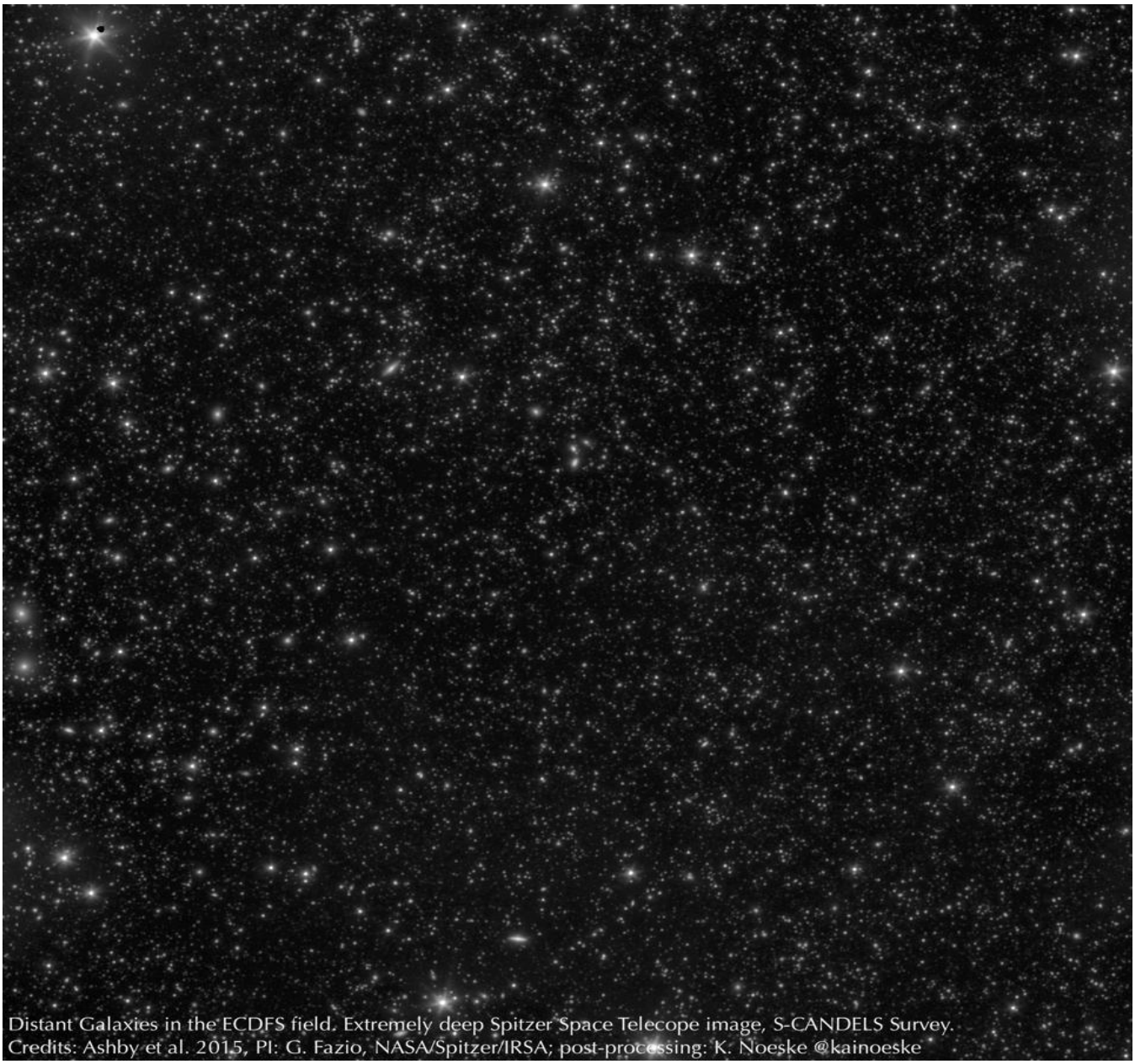
The spin-independent WIMP/nucleon cross-section now gets its most stringent limits from the XENON1T experiment, which has improved over all prior experiments, including LUX. While many may be disappointed that XENON1T didn't robustly find dark matter, we mustn't forget about the other physical processes that XENON1T is sensitive to.

But every direct detection effort continues to fail, with experiments revealing no robust clues.



The XENON1T detector, with its low-background cryostat, is installed in the centre of a large water shield to protect the instrument against cosmic ray backgrounds. This setup enables the scientists working on the XENON1T experiment to greatly reduce their background noise, and more confidently discover the signals from processes they're attempting to study. XENON is not only searching for heavy, WIMP-like dark matter, but other forms of potential dark matter, including light candidates like dark photons and axion-like particles.

Until experiment, observation, and theory all align, these cosmic mysteries will persist.



Every dot of light in this image represents its own galaxy, courtesy of NASA's Spitzer space telescope. By taking infrared observations, Spitzer can see through the light-blocking dust that would obscure many of these galaxies, while simultaneously possessing wide-field views that can reveal how galaxies clump and cluster across cosmic time. This clustering pattern, like many other cosmic lines of evidence, requires dark matter.

Follow me on Twitter. Check out my website or some of my other work here.

Ethan Siegel

I am a Ph.D. astrophysicist, author, and science communicator, who professes physics and astronomy at various colleges. I have won numerous awards for science writing since 2008 for my blog, Starts With A Bang, including the award for best science blog by the Institute of Physics. My two books, Treknology: The Science of Star Trek from Tricorders to Warp Drive, Beyond the Galaxy: How humanity looked beyond our Milky Way and discovered the entire Universe, are available for purchase at Amazon. Follow me on Twitter @startswithabang.