K. C. Schwab, *Nature* **443**, 193 (2006).
3. O. Arcizet et al., *Phys. Rev. Lett.* **97**, 133601 (2006).
4. R. G. Knobel, A. N. Cleland, *Nature* **424**, 291 (2003).
5. M. D. LaHaye et al., *Science* **304**, 74 (2004).
6. D. Mozyrsky, I. Martin, *Phys. Rev. Lett.* **89**, 018301 (2002); D. Mozyrsky, I. Martin, M. B. Hastings, *Phys. Rev. Lett.* **92**, 018303 (2004).
7. A. D. Armour, M. P. Blencowe, Y. Zhang, *Phys. Rev. B* **69**, 125313 (2004).
8. M. P. Blencowe, J. Imbers, A. D. Armour, *New J. Phys.* **7**, 236 (2005); A. A. Clerk, S. Bennett, *New J. Phys.* **7**, 238 (2005).
9. H. Hirakawa, S. Hiramatsu, Y. Ogawa, *Phys. Lett.* **63A**, 199 (1977).
10. C. Höhberger Metzger, K. Karral, *Nature* **432**, 1002 (2004).
11. I. Martin et al., *Phys. Rev. B* **69**, 125339 (2004).
12. D. A. Rodrigues, J. Imbers, A. D. Armour, http://arxiv.org/abs/cond-mat/0608166; S. D. Bennett, A. A. Clerk, http://arxiv.org/abs/cond-mat/0609329.

# Collision between galaxy clusters unveils striking evidence of dark matter

**The nonbaryonic matter generally assumed to dominate large aggregates of stars and gas almost always shares a common center of mass with the ordinary matter we can see. But a titanic collision can force them apart.**

**Cosmology's** widely accepted "concordance model" presumes that some still unknown form of dark matter overwhelms the cosmic abundance of ordinary baryonic matter by a factor of about six. Powerful evidence of dark matter has been accumulating since the 1930s from an impressive variety of observational realms: gas temperature and the random motion of galaxies in large galaxy clusters, galaxy rotation, the distribution of clusters, the abundances of the lightest elements, the anisotropy of the microwave background, and the redshifts of distant supernovae.

In all those cases, the reasoning that leads to dark matter assumes that gravitation on galactic and larger scales is correctly described by general relativity and, in the nonrelativistic limit, by Newtonian gravity. But some cosmologists argue that imagining modifications of general relativity on large scales is no more speculative than postulating dark matter in the absence of laboratory evidence. Mordehai Milgrom's 23-year-old phenomenological modification of Newtonian dynamics (MOND) has had considerable success in describing the rotation of galaxies without requiring them to be enveloped in dark-matter halos. And two years ago, Jacob Bekenstein incorporated MOND into a full-blown covariant field theory.[1]

Now however, dark-matter skeptics must contend with what appears to be a persuasively iconic manifestation of dark matter (see figures 1 and 2). Douglas Clowe (now at Ohio University) and coworkers have analyzed new optical and x-ray observations to conclude that the dominant dark matter in a pair of large galaxy clusters emerging from a recent collision is clearly offset from the hot, ionized intergalactic gas that dominates the clusters' baryonic mass.[2] Furthermore, they find that the dark matter, unlike the gas, seems unaffected by the titanic collision. That is—just as the concordance model would have it—dark-matter particles hardly ever scatter off one another.

In a large cluster, hot intergalactic plasma, visible in x rays (figure 2), is known to exceed the stellar mass of the largely gasless constituent galaxies themselves (seen in figure 1) by a factor of about six or seven. But how would one trace the dark matter, which trumps both stars and gas but shines at no wavelength? That's done by noting its gravitational-lensing distortion of the background galaxies in figure 1, far behind the two clusters emerging from their head-on encounter.

## The virtues of collision

Ordinarily in a cluster, as in an individual galaxy, the dark and baryonic matter share a common center of mass. But colliding clusters offer a unique prospect of seeing the two pulled apart. The cluster pair studied by Clowe and company is especially well suited to the purpose. It was discovered first in 1995 as an extended x-ray source in the southern constellation Carina and named 1E0657–558.

At a distance from us of about 5 billion light-years, the two cluster centers have separated by 2 million light-years since they passed through each other "only" 100 million years ago. The well-defined bow shock front visible on the

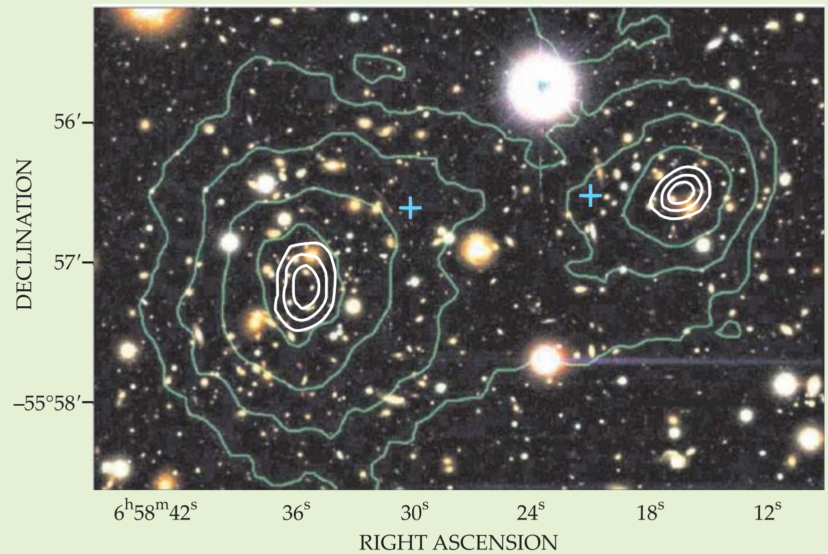


**Figure 1. Deep optical image** of the galaxy cluster 1E0657–558, which is actually a separating pair of large clusters that collided 100 million years ago. Many background galaxies are also visible. (The large bright dots are foreground stars.) The contour lines indicate the density distribution of the system's total baryonic plus nonbaryonic mass, as measured by gravitational-lensing distortion of the background galaxies. That distribution shows two peaks close to the core galaxy concentrations of the two recently collided clusters. The outermost of the white contours delimit the positions of those peaks with 99.7% confidence. The two total-mass peaks turn out to be offset by eight standard deviations from the two blue crosses that mark the centers of the hot intergalactic plasma concentrations revealed by the x-ray images in figure 2—even though the plasma far outweighs the galaxies. (Adapted from ref. 2.)

x-ray image of the plasma associated with the right-hand cluster in figure 2 lets one determine how fast the two clusters are separating. And it earns them the collective nickname "bullet cluster." Happily for observers, its two constituent clusters are passing through each other more or less in the plane perpendicular to the line of sight.

Arguing that in a collision between clusters the intergalactic plasma would be dramatically slowed down while the dark matter (and even the galaxies themselves) speed on largely unscathed, Clowe and coworkers in 2003 sought to demonstrate that separation. Using archival optical and x-ray data from the bullet-cluster field, they achieved a suggestive but statistically inconclusive result.[3] The limiting observational factor was the number of background galaxies whose gravitational-lensing distortions could be imaged clearly enough to contribute to mapping the bullet cluster's total distribution of mass, visible and invisible.

So the group was given observing time on the *Hubble Space Telescope* and two telescopes in Chile to take very deep exposures of the bullet cluster that would treble the number of useable background galaxies. The group also availed itself of new *Chandra X-Ray Observatory* images of the cluster provided by the group's Harvard–Smithsonian Center for Astrophysics contingent, led by Maxim Markevitch.

## Clear offsets

The contour lines in both figures indicate the bullet cluster's overall distribution of baryonic plus dark matter, as determined by the lensing distortion of distant background galaxies. The total dark mass revealed by the lensing is about seven times the cluster's baryonic mass. Figure 1 shows the optical images of the bullet-cluster galaxies as well as background galaxies and a few intruding foreground stars. The two peaks of the bimodal total-mass distribution coincide well with the two concentrations of galaxies that mark the cores of the recently collided clusters.

Figure 2, which shows *Chandra's* x-ray image of the intergalactic plasma of the two clusters, looks quite different. In consequence of the collision, the plasma appears to have fallen behind the dominant dark matter and the con-

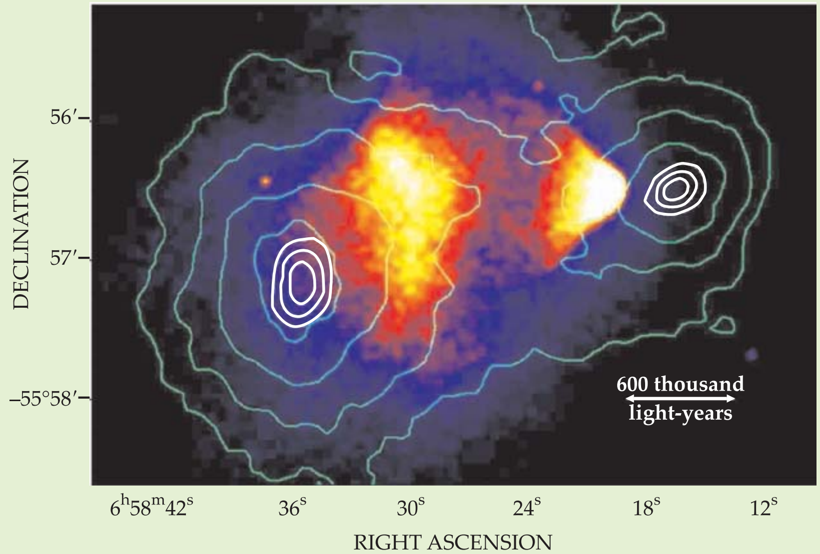


**Figure 2. X-ray image of the same field** as figure 1 reveals the two concentrations of hot intergalactic plasma that dominate the baryonic mass of the two colliding galaxy clusters. The superimposed total-mass contour lines from figure 1 show that the collision retarded the plasma relative to the total masses and the constituent galaxies of the two clusters as they passed through each other. The plasma concentration on the right still exhibits a prominent bow shock front from the encounter. (Adapted from ref. 2.)

stituent galaxies. That makes sense: The galaxies themselves occupy so little of a large cluster's volume that they approximate a collisionless gas. The dark matter is also thought to be almost collisionless. Cosmologists and particle theorists generally assume that its constituent particles, whatever they turn out to be, are Big Bang relics with minuscule collision cross sections characteristic of the weak interactions. The plasma, on the other hand, is far from collisionless, as witness the striking bow shock front.

The principal claim of the new bullet-cluster paper is that, for each of the postcollision clusters, the peak concentration of baryonic matter, dominated by plasma shining in x rays, is offset from the peak of the subcluster's total mass by a robust eight standard deviations. Those offsets are manifested in figure 1 by the clear displacements of the two blue crosses, which represent the peaks of the x-ray brightness in figure 2, from the lensing peaks. The core concentrations of galaxies, on the other hand, lie very close to the lensing peaks.

How can one be sure that the collisionless invisible matter revealed by the lensing isn't baryonic—say, a large population of brown dwarfs? That interpretation of the lensing result is dismissed because so much baryonic matter, if it were typical, would far exceed the cosmic baryon allotment dictated by the theory of Big Bang nucleosynthesis. The conclusion that baryons account for only about 15% of cosmic mass comes mostly from applying the theory to the observed abundance of primordial deuterium (see PHYSICS TODAY, August 1996, page 17).

## The lensing analysis

The overall mass density in the new analysis is determined by what's called weak gravitational lensing. When a background galaxy is closely aligned with the observer's line of sight to the central peak of a strong compact lens, the background object can be grossly and unmistakably distorted (see the article by Leon Koopmans and Roger Blandford in PHYSICS TODAY, June 2004, page 45). In that case, called strong lensing, a single distorted galaxy image can provide unambiguous information about the foreground lensing system.

In weak lensing, however, images of less well-aligned background galaxies are elongated to elliptical shapes that are not beyond the bounds of true galaxy shapes. In that case one learns about the lensing system only from a statistical analysis of many background galaxies that looks for a systematic anisotropy in what should otherwise be a random distribution of ellipticity directions. Gravitational lensing by a point source elongates an image in the direction normal to its direction from the source on the plane of the sky.

Clowe and coworkers deduced the projection of the bullet cluster's overall mass density on the celestial sphere from the so-called gravitational shear field of nonrandom orientations of apparently elliptical background galaxies. Because the two-dimensional mass density thus derived integrates over any lensing foreground or background masses along the line of sight, one might worry that one (or both) of the cluster's two apparent mass peaks could be an artifact due to unrelated galaxies or gas along the sight line. The paper raises the issue but concludes that such artifacts are extremely unlikely. Furthermore, the group's follow-up strong-lensing analysis of selected background galaxies, which is somewhat less sensitive to interlopers along the line of sight, supports the conclusions of the weak-lensing paper.[4]

## A circular argument?

Clowe and company call the lensing result "a direct empirical proof of the existence of dark matter." But if the purpose is to present evidence against nonstandard gravity as a plausible alternative to dark matter, the argument might seem circular. Isn't the group basing its conclusions on lensing analyses that presume the correctness of general relativity?

"In fact, our conclusion that the baryon peaks are offset from the total-matter peaks relies only on very general assumptions about gravity that are obeyed by MOND and other plausible alternatives," says Clowe. "Any nonstandard gravitational force that points back to its source and scales with mass can't reproduce our lensing results without invoking preponderant concentrations of unseen matter. Our demonstration of dark matter doesn't preclude nonstandard theories of gravity, but it does remove their primary motivation."

But some cosmologists argue that invoking dark energy—even more mysterious than the putative dark matter—to explain the observed acceleration of cosmic expansion is an even stronger motivation for seeking a new theory of gravity. Does Bekenstein's modification of general relativity generate anisotropic lensing effects that could explain away the bullet-cluster offset without dark matter? "We won't know until someone does the full calculation for this very asymmetric system," says Bekenstein. "The closest anyone has come is a new approximation by Garry Angus,[5] which fails to reproduce the offset without dark matter." But Angus argues that the dark matter could conceivably be nothing more mysterious than moderately heavy neutrinos. Princeton University theorist Jeremiah Ostriker concludes that "the bullet-cluster observations really do make a strong case against nonstandard gravity."

## How collisionless

In the concordance model, dark matter that is cold (nonrelativistic) and essentially collisionless is essential for explaining the evolution from the almost perfectly homogeneous cosmos evinced by the microwave background to today's profusion of galaxy clusters. A useful measure of collisionality is $\sigma/m$, a system's collision cross section per unit mass. For hydrogen gas, it's of order $10^8$ $cm^2/g$ (a square angstrom per atom). For the weakly interacting dark-matter particles most often proposed by particle theorists, it would be much less than 1 $cm^2/g$.

Computer models of galaxy formation with collisionless cold dark matter have been complicated by two problems—perhaps minor, but persistent. They predict intragalactic mass distributions that are too peaked at the centers, and they predict too many small satellites surrounding large galaxies. Princeton theorists David Spergel and Paul Steinhardt argued in 1999 that both problems go away if dark-matter particles have $\sigma/m$ anywhere from 0.5 to 500 $cm^2/g$. Now Clowe and company have excluded most of that range. From the bullet-cluster observations, they were able to set an upper limit of 1 $cm^2/g$. That means a typical dark-matter particle in the inner precincts of a galaxy would suffer at most one or two collisions every ten billion years.

**Bertram Schwarzschild**

## References


1. J. D. Bekenstein, *Phys. Rev. D* **70**, 083509 (2004).
2. D. Clowe, M. Bradac, A. Gonzalez, M. Markevitch, S. W. Randall, C. Jones, D. Zaritsky, *Astrophys. J. Lett.* **648**, L109 (2006).
3. D. Clowe, A. Gonzalez, M. Markevitch, *Astrophys. J.* **604**, 596 (2004).
4. M. Bradac et al., *Astrophys. J.* (in press); available at http://arxiv.org/abs/astro-ph/0608408.
5. G. W. Angus, H. Shan, H. Zhao, B. Famaey, available at http://arxiv.org/abs/astro-ph/0609125.


# physics update

Supplementary material related to these items can be found at www.physicstoday.org.

**Acoustic nanocavities.** Phonons pulsed at around 100 GHz, with wavelengths of a few nanometers, have been confined in the same kind of resonant cavity used in photonics. A collaboration of physicists in France and Argentina used a superlattice made of carefully grown alternating layers of gallium arsenide and aluminum arsenide, materials with different acoustic impedances—the acoustic analog of refractive index for light. Two sets of multilayers in the superlattice act as Bragg mirrors for phonons, while a single nanometer-thick layer of GaAs in the center serves as the cavity. A femtosecond laser focused on the bottom of the stack generates the high-frequency sound, which is reflected multiple times through the nanocavity. After some delay, narrow phonon wavepackets at certain allowable sharp frequencies are detected by a laser probing the top of the device. Bernard Jusserand (CNRS and University of Paris VI and VII) says that he and his colleagues hope to reach the terahertz acoustic range. The researchers think that a new field of nanophononics has been inaugurated and that the acoustical properties of semiconductor nanodevices will play important roles. One envisaged use is high-frequency modulation of the flow of charges or light in small spaces. Another is for novel forms of tomography that could image the interior of opaque solids. (A. Huynh et al., *Phys. Rev. Lett.* **97**, 115502, 2006.)

—PFS

**Repairing a cell's cancer defenses** looks possible now that scientists have determined how mutations prevent a tumor-suppressing protein from doing its job. In healthy cells, the protein p53 monitors the transcription of genetic information from DNA to RNA. When p53 detects DNA damage or incipient cancer, it blocks DNA replication and kills the cancer cells. Mutated p53, which turns up in half of all human cancers, is powerless to prevent errors from propagating and resulting tumor cells from proliferating. Now, Andreas Joerger, Hwee Ching Ang, and Alan Fersht of Cambridge University in England have used x-ray crystallography to identify structural changes caused by the mutations. Overall, a substantial fraction of the mutations don't prevent p53 from folding or from binding to DNA. Rather, the