Nancy Aggarwal,
Physics PhD Candidate

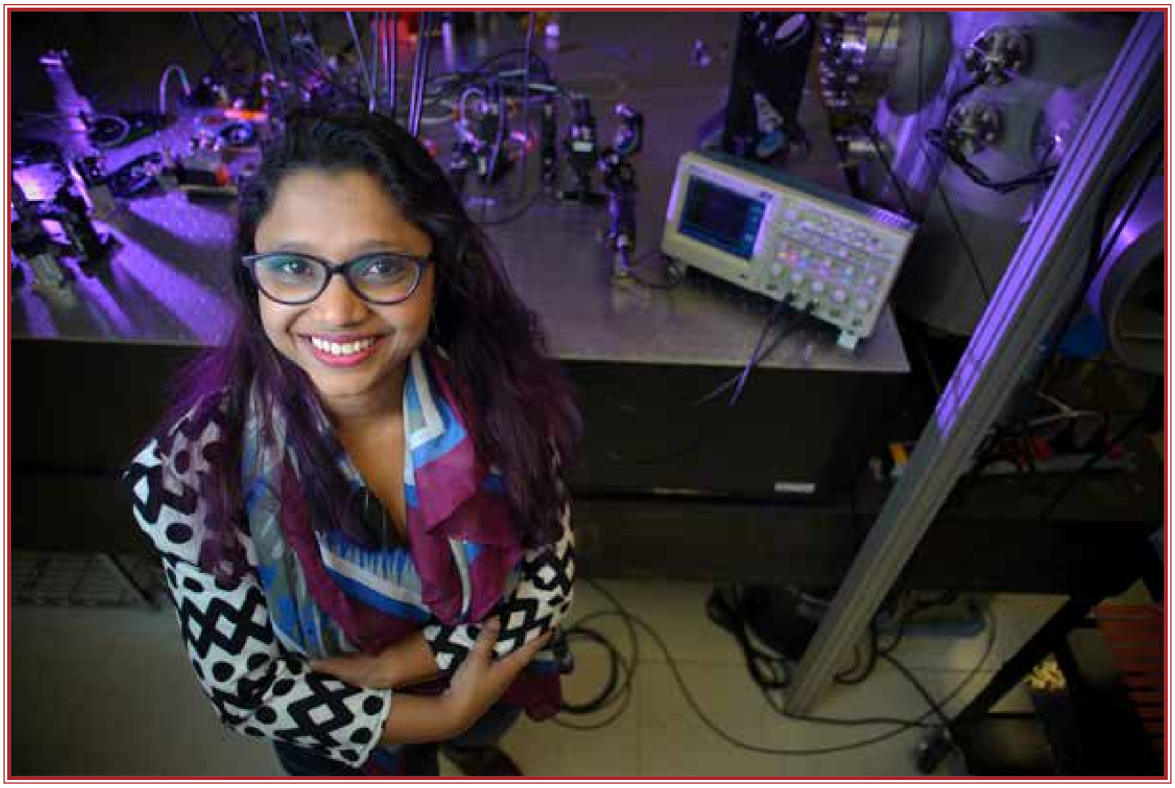
Squeezing Uncertainty

by William A. Rutter SB '16

In September 2015, the Laser Interferometer Gravitational Observatory (LIGO) caught gravitational waves passing through the earth. A true feat of experimentation, the discovery astounded and invigorated the worldwide physics community.

It was, however, simply the next chapter in a larger story for **Nancy Aggarwal**, a PhD candidate in physics at the Massachusetts Institute of Technology. Hailing from India, Aggarwal graduated from the Indian Institute of Technology (IIT), Bombay, in 2011. At IIT, Aggarwal's high school love for math and physics translated predictably well into university—"I was that kid who didn't like anything else!"—and she immediately began pursuing a degree in physics. Although not much of a tinkerer prior to college, she nevertheless decided to explore experimental physics. "All of my classmates, everyone was doing theoretical physics," says Aggarwal. "I think I took it as a challenge."

But she observed a profound gender bias in her college cohort. "People know how to solder things, people have worked with Lego® bricks," she says. "I wasn't really doing that when I was a kid, and I saw it was the same for other women around me." So Aggarwal began mentoring women in science and technology, saying, "Hey—*you* can do this. This is not something that has to be only men." She decided experimental physics' hands-on culture would allow her to further blaze the path. She remembers thinking "I want to change the face of this—I want to be that woman who's interested in robotics and who's interested



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in making things with her hands." Committed to experimental physics, Aggarwal moved to MIT's Kavli Institute post-graduation. Since then she has worked with Professor Nergis Mavalvala, studying and designing quantum-optical systems to further improve the sensitivity of the LIGO observatories.

When Aggarwal arrived, LIGO's search had proceeded for eight years without seeing a gravitational wave. Scientists agreed that LIGO's *noise floor*, the point at which internal fluctuations in the detector shroud useful signals, was too high. Important parts of this noise floor come from the quantum mechanics of the lasers LIGO uses to detect gravitational waves. Aggarwal's work focuses on lowering these particular noise sources with quantum states of light called "squeezed states."

Squeezed states are a consequence of the quantum mechanical uncertainty inherent in measuring light. Light has two principle measurable qualities: power, which is essentially brightness, and phase, which describes what point the light currently inhabits in its electromagnetic cycle. Light's inherent uncertainty can

Photo: David Sella

be shared equally between power and phase, as is the case for laser light. In squeezed states, however, careful manipulation has "squeezed" uncertainty from one quality into the other. It is this exchange of uncertainty between power and phase that will prove invaluable for lowering LIGO's noise floor.

One source of quantum noise in LIGO is *shot noise*—the uncertainty in measuring flows of distinct objects solely due to their distinct nature. The laser LIGO uses to detect gravitational waves is a flow of distinct photons, and the resultant shot noise creates uncertainty in the laser's phase. Laser interferometers like LIGO work by measuring phase precisely, so this is a problem.

LIGO could decrease shot noise by increasing its laser power. The more powerful a laser is, the more photons it makes. With more photons, each individual photon is less important to the big picture, washing out shot noise and decreasing phase uncertainty. This solution, however, is not perfect. Increasing laser power comes hand in hand with increasing the power's uncertainty. Greater uncertainty in power leads to greater uncertainty in the bouncing force the laser's photons exert on mirrors in LIGO. This uncertainty in force leads to an uncertainty in the mirrors' movement, as if they are being buffeted by a gale of photons. This mirror movement ultimately raises the noise floor, making it harder to see gravitational waves.

It turns out that this phase versus power uncertainty tradeoff is fundamental to lasers. "There isn't really any getting away with it," says Aggarwal, because it comes down to the same quantum uncertainty that causes squeezed states. But this means that squeezed states can offer a solution: if inserted correctly, squeezed states can exchange power uncertainty with phase uncertainty for the whole LIGO system. By controlling the type of squeezing, scientists can therefore control the uncertainty exchange, even tailoring it for listening at different gravitational wave frequencies.

Here, Aggarwal hopes to contribute. Conventional methods use advanced lenses to generate squeezed states. This only works at certain laser wavelengths, however, constraining the lasers LIGO can use. Further, conventional squeezers require meticulously aligned, room-sized optical setups to operate. Aggarwal wishes to create squeezed states without these lenses.

Aggarwal begins by creating resonance cavities out of two tiny mirrors, suspending one of the mirrors on a thin, spring-like piece of metal. When a laser shines into the resonance cavity, the suspended mirror recoils from photons hitting it, changing the length of the cavity and its corresponding resonance frequency. This effect is analogous to the way a guitar string vibrates at higher frequencies when you move your finger up the fretboard. Any uncertainty in laser power becomes uncertainty in cavity length, and therefore uncertainty in resonance frequency. This frequency uncertainty becomes phase uncertainty as the light leaves the resonance cavity. Overall, the system takes some of the laser's power uncertainty and turns it into phase uncertainty—a squeezed state is born.

Aggarwal's system is noteworthy for two reasons. First, the lensless design means it can create squeezed states at any laser wavelength LIGO could want. Second, Aggarwal's squeezer design lends itself to a convenient, self-contained package. "We have squeezers, but currently they take a room full of space and three PhD students to make," says Aggarwal. By contrast, Aggarwal's squeezer is quite compact—no larger than a piece of carryon luggage. "I could imagine," Aggarwal continues, "putting it in a box and just giving it to LIGO, saying, 'Hey, LIGO, here's this box, and that's your squeezer.' " These words hint at a deeper implication of Aggarwal's work: ease of scaling. As LIGO, propelled by its success, begins to establish further observatories around the world, the convenience and flexibility of Aggarwal's squeezer will allow for expedient implementation of squeezers in new systems.

Still, the work is ultimately very personal for Aggarwal. "I designed and built the entire experiment in an empty room," she says, "from designing shelves to designing very small and precision measurement components." The system is her creation—not only designed with her mind, but also built with her hands. In an intellectual whirlwind of quantum physics and gravitational waves, Aggarwal still challenges that bias against hand-on, practical work she discerned in college. Now a mentor of a different sort, Aggarwal leads by example, squashing both scientific and societal barriers with each squeezed state.