Ofer Firstenberg

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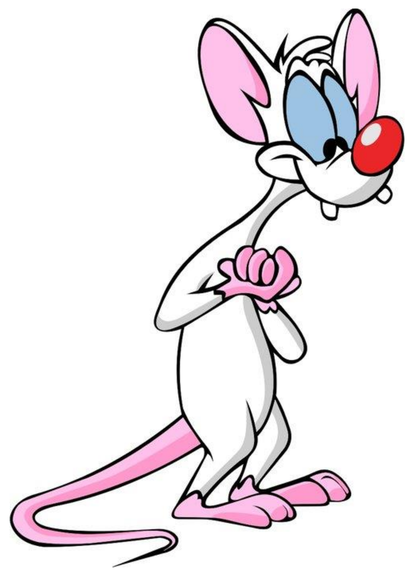
Photon-Photon Interactions

Photons, the fundamental particles of light, do not interact with one another in everyday life. These interactions only exist inside "nonlinear" optical materials and require a huge number of photons to be meaningful. In our lab, we realize a medium that pushes nonlinear optics to its extreme (quantum) limit, where the photon-photon interaction is strong on the level of individual photons.

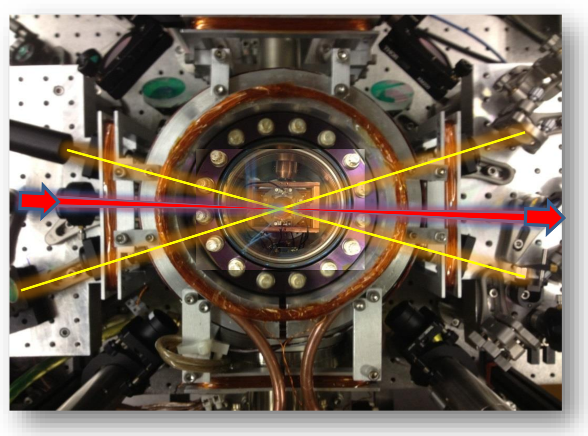


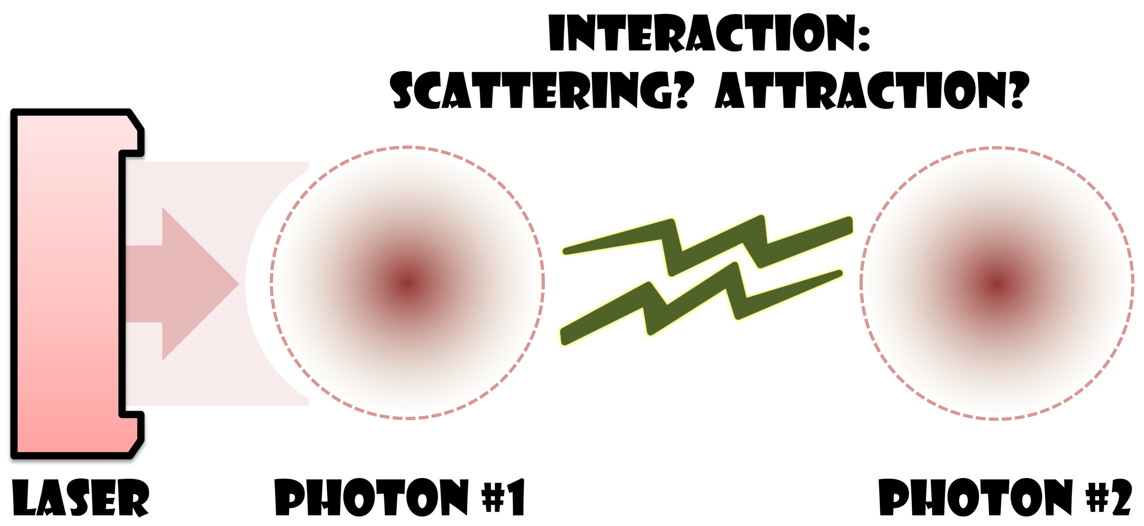
Gee, Prof. Brain, what do you want to do tonight?"

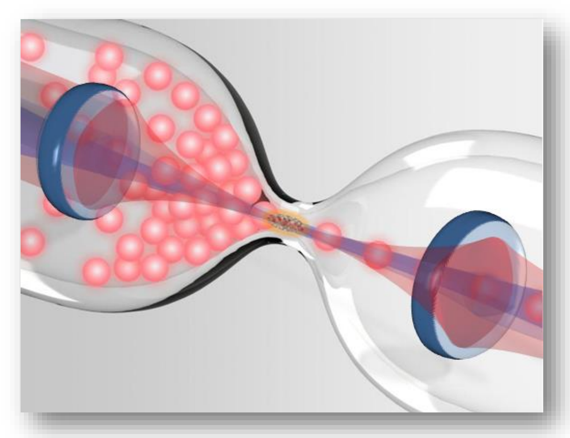
The same thing we do every night, Research Scholar Pinky — try to take over the world!

How are we going to do that, Brain?

We'll make two photons INTERACT!! Turning all the light in the world into.... Hoo-Haa-Haa!!!





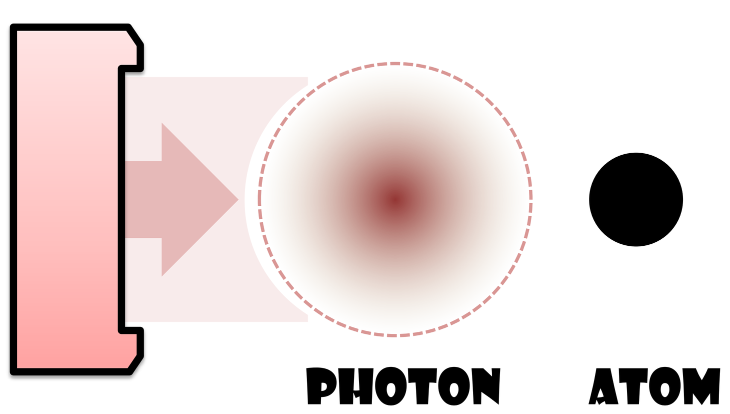


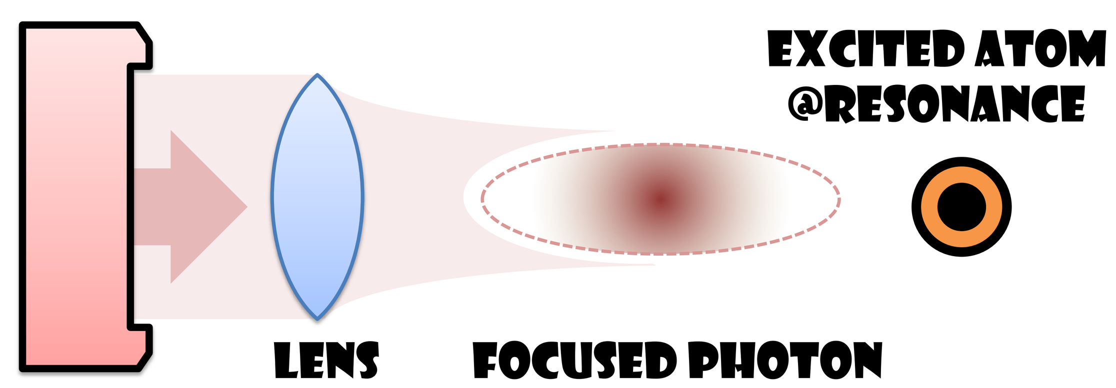
Brain, photons usually do not interact

They do interact with ATOMS, Pinky!

But the probability for a single photon to excite a single atom is super-ultra small

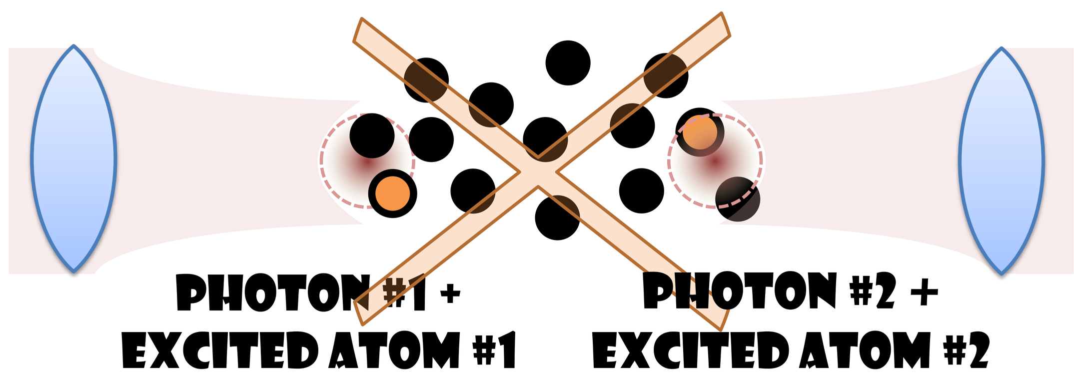
(1) We use narrowband lasers and strong atomic resonances
(2) We focus the photons to make their electric field stronger





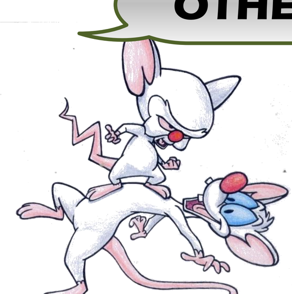
Seems like the excitation probability is still only a few percent ... we should use MORE ATOMS!

WRONG [1], Brain. This helps LINEAR processes, but not NONLINEAR processes



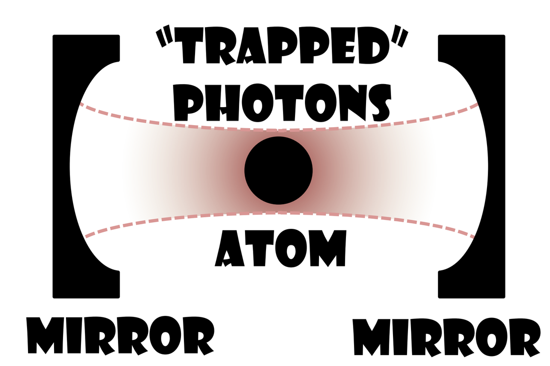
We could confine the photons along the beam's direction using CAVITIES

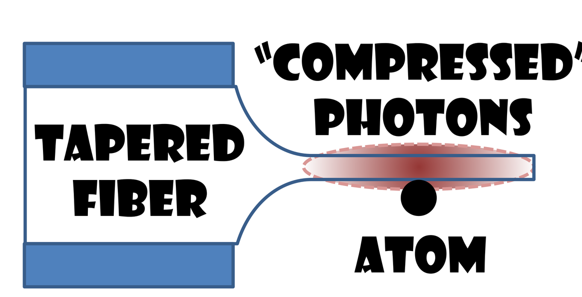
OTHERS already tried that [2]



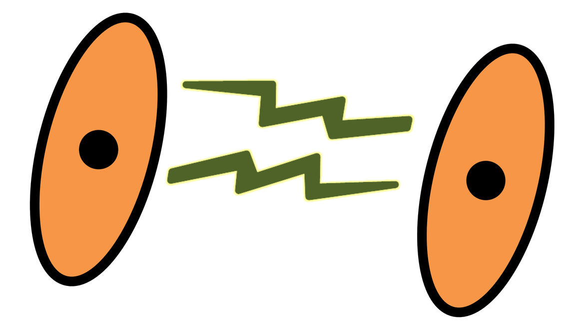
So confine the photons transversely using SUB-WAVELENGTH structures

Others did that too [3]





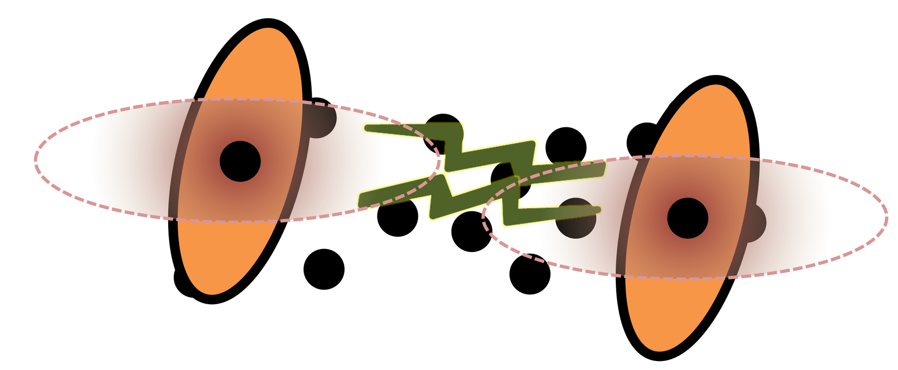
Use two atoms that strongly interact



Electron in a "Rydberg" state: Orbital radius of ~1 micrometer

Effectively two antennas that interact 10^{12} times stronger than non-excited atoms

In a dense medium, a photon would always excite an atom

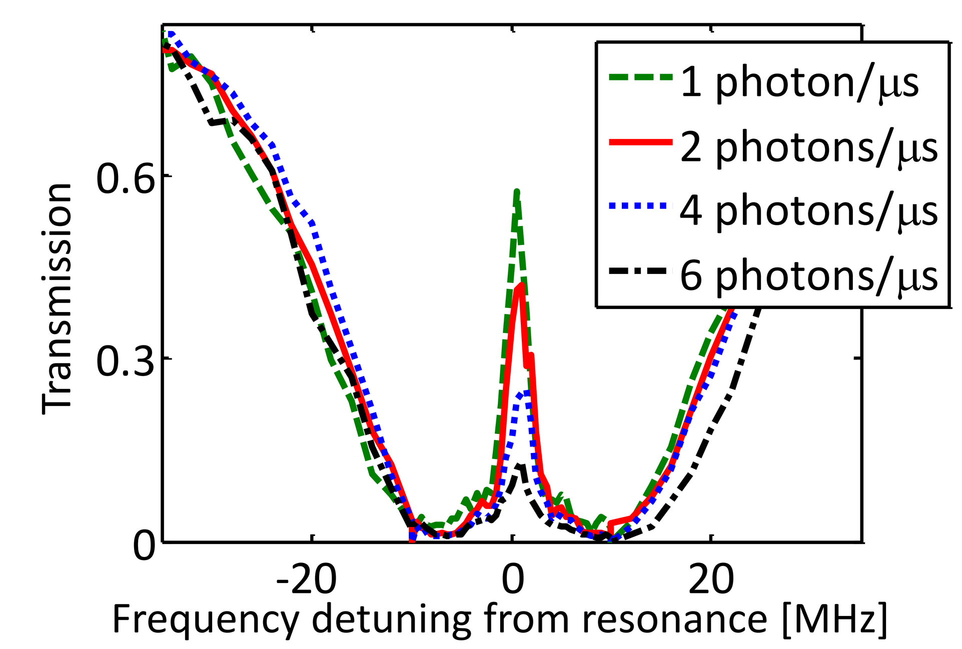


Photons propagate slowly while exciting Rydberg states

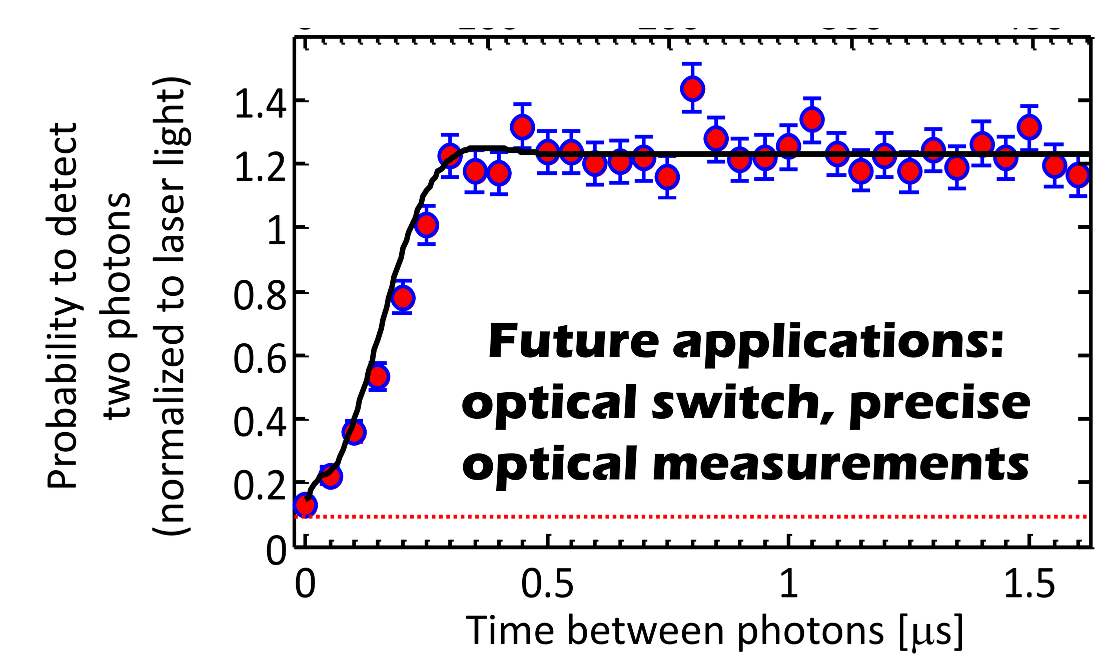
They become "Rydberg polaritons" [4] – hybrids of light and Rydberg excitations, affected by the Rydberg-Rydberg interaction

Photon-photon scattering

Nonlinearity: the transmission through the medium changes in the presence of another photon

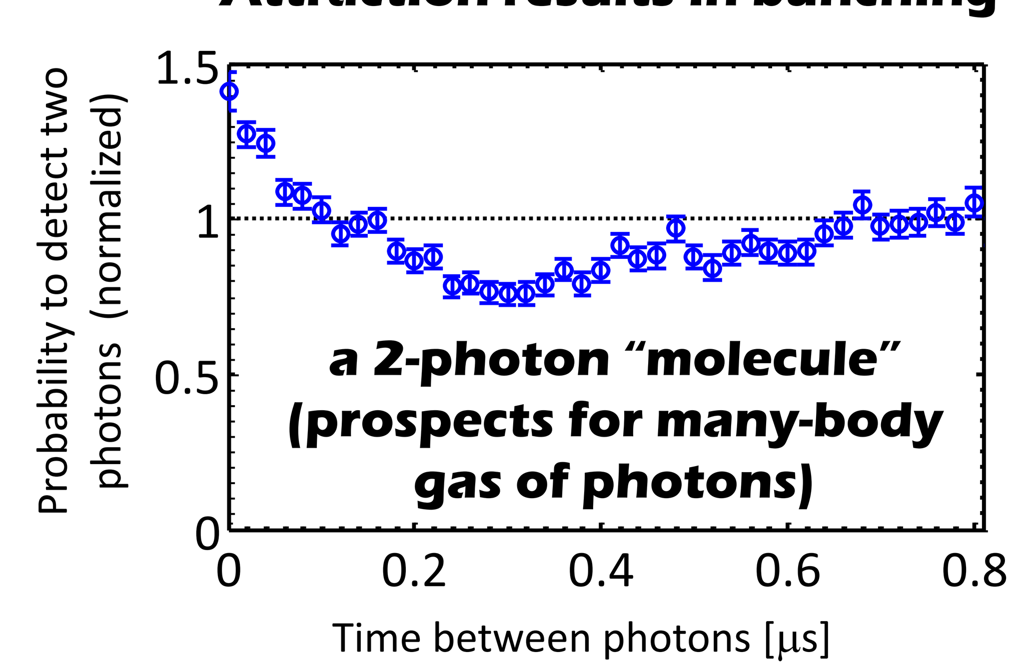


Probability that two photons exit the medium together reduced to 10% ("anti-bunching") [5]

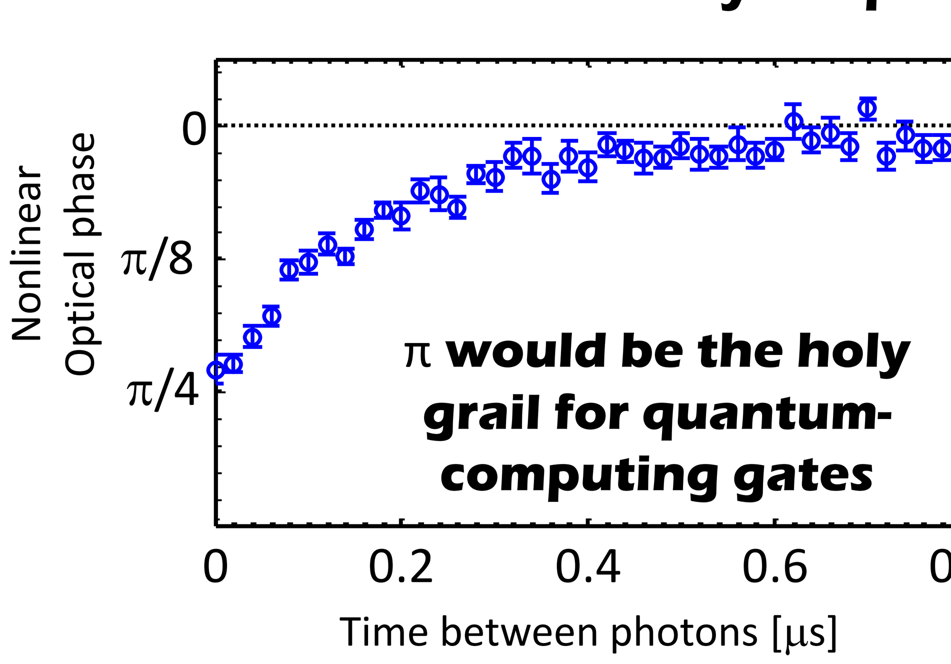


Photon-photon attraction

Attraction results in bunching



Conservative forces modify the phase



[1] The probability that a single photon will excite one of those many atoms can indeed be made high, but it does not guarantee that two photons excite the SAME atom, and so does not promise interaction BETWEEN THE PHOTONS

[2] Kimble (Caltech), Rempe (MPQ, Garching), Imamoglu (ETH), Vuckovic (Stanford), ...

[3] Lukin (Harvard), Rauschenbeutel (Mainz), Kimble (Caltech), Martinis (Santa Barbara), ...

[4] Theory: Lukin (Harvard), Gorshkov (Caltech), Pohl (MPQ, Dresden), Fleischhauer (Kaiserslautern) Otterbach (Harvard), Kurizki (Weizmann), Petrosyan (Crete), Büchler (Stuttgart) Experiments: Adams (Durham), Pfau (Stuttgart), Kuzmich (Georgia Tech), Grangier (Paris), Saffman, Walker (Madison)

[5] Peyronel, Firstenberg, Liang, Hofferberth, Gorshkov, Pohl, Lukin, Vuletic, "Quantum nonlinear optics with single photons enabled by strongly interacting atoms," Nature (London) 488, 57-60 (2012)