Understanding X-ray Cavities

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Abstract

X-ray observations have shown that the wholesale cooling of the universe is being offset by mechanical heating from active galactic nuclei(AGN). Feedback and heating from AGN are considered a prime candidate for solving the "cooling flow" problem in the hot gas of galaxy clusters. Recent observations using Chandra telescope has produced detection of X-ray surface brightness depressions known as "cavities" or "bubbles" in many of these systems, interpreted as buoyantly rising bubbles created by AGN outbursts. Studies of such cavities in clusters suggest that the outburst energy required to inflate these cavities would be sufficient to balance cooling. The pressure from these cavities have a one-to-one correlation with the luminosity of the clusters. We have created simulations by imagining bubbles by varying their radii and distance from the AGN center using different theoretical models and experimental data of X-ray cavities. We then looked at their pressure and corresponding luminosity of the clusters and found a similar correlation which implies that correlation is rather a property of the gas cluster. So, the objects that we observe as cavities might be just numerical noise in the telescope data as the pressure-luminosity one-to-one correlation is not a cavity specific property. We have also observed that scatter is dependent on the bubble geometry. From previous experimental observations we have also noticed correlation between radii and distance from AGN center. We have imposed theoretical constraints to explain this phenomena as well.

Background

After the end of cosmic inflation, hot atmospheres are expected to cool and to form stars. However, we don't see as many galaxies in the universe as we would expect due to the cooling. This is known as the "cooling flow" problem. X-ray observations have shown that the wholesale cooling of the universe is being offset by mechanical heating from active galactic nuclei. Feedback and heating from active galactic nuclei (AGNs) are considered a prime candidate for solving the "cooling flow" problem in the hot gas of galaxy clusters. Recent observations using Chandra telescope has produced detection of X-ray surface brightness depressions known as "cavities" or "bubbles" in many of these systems, interpreted as buoyantly rising bubbles created by AGN outbursts. Studies of such cavities in clusters suggest that the outburst energy required to inflate these cavities would be sufficient to balance cooling. The only way to detect these cavities is by looking at telescope data and smoothening it till someone gets a clear image. Which can be a problem since these cavities are simply light depressions and numerical noise in data can easily be perceived as cavities. In previously published works (Hlavacek-Larrondo, 2014) we see a very distinct one to one correlation between the luminosity of these cavities and their pressure. Our goal is to recreate the relationship and analyze the factors that motivates the scatter.

Method

We created simulations to recreate one-to-one pressure luminosity relationship by using real pressure and luminosity profile from 6 clusters. We assumed random bubbles at different distance and of different radii and plotted the pressure of the simulated cavities against their corresponding luminosity. We further constrained them based on the visibility of the cavities at different redshift. We also analytically looked at how the pressure of these cavities and their luminosity.

Based on experimental results of cavity detection, there is a strong correlation between the radii of the detected cavities and the distant at which they are found. We explored the correlation using different thermodynamic models to find the best fitting model which can explain the relation using average temperature and density profiles for a standard galaxy cluster.

Results

The pressure of a cavity is defined as Enthalpy per unit rise time. Assuming that the cavity is filled with a relativistic fluid, Enthalpy, E = PV where V is the volume of the bubble. For the simplicity of calculation, we have assumed the cavities are spheres hence the volume, $V = \frac{4}{3}\pi r^3$ for some radius r. And the rise time is defined as $t_{\text{rise}} = d\sqrt{\frac{SC_D}{2gV}}$ where d is the distance from the jet, S is the cross section, C_D is the drag and g is the local gravity. The local gravity can be defined as $g = \frac{GM_d}{d^2}$ where

$$M_{\text{cl}}(\le d) = -\frac{kT}{\mu m_p G}\left(\frac{d\ln\rho_{\text{gas}}(r)}{dlnr} + \frac{d\ln T}{d\ln r}\right)d\,(\text{Diehl, 2006}).$$

Using density and temperature profiles from Abell 85, Abell 479, Abell 1795, Abell 1835, Abell 2199, Abell 4059, we calculated the pressure of the cavity assuming arbitrary cavity radius and imagining cavities different distances. We constrained them depending on visibility of clusters at different redshifts and allowing maximum radius to be equal to the distance from AGN center. The increasing size of the data points is used to show the increasing radius.

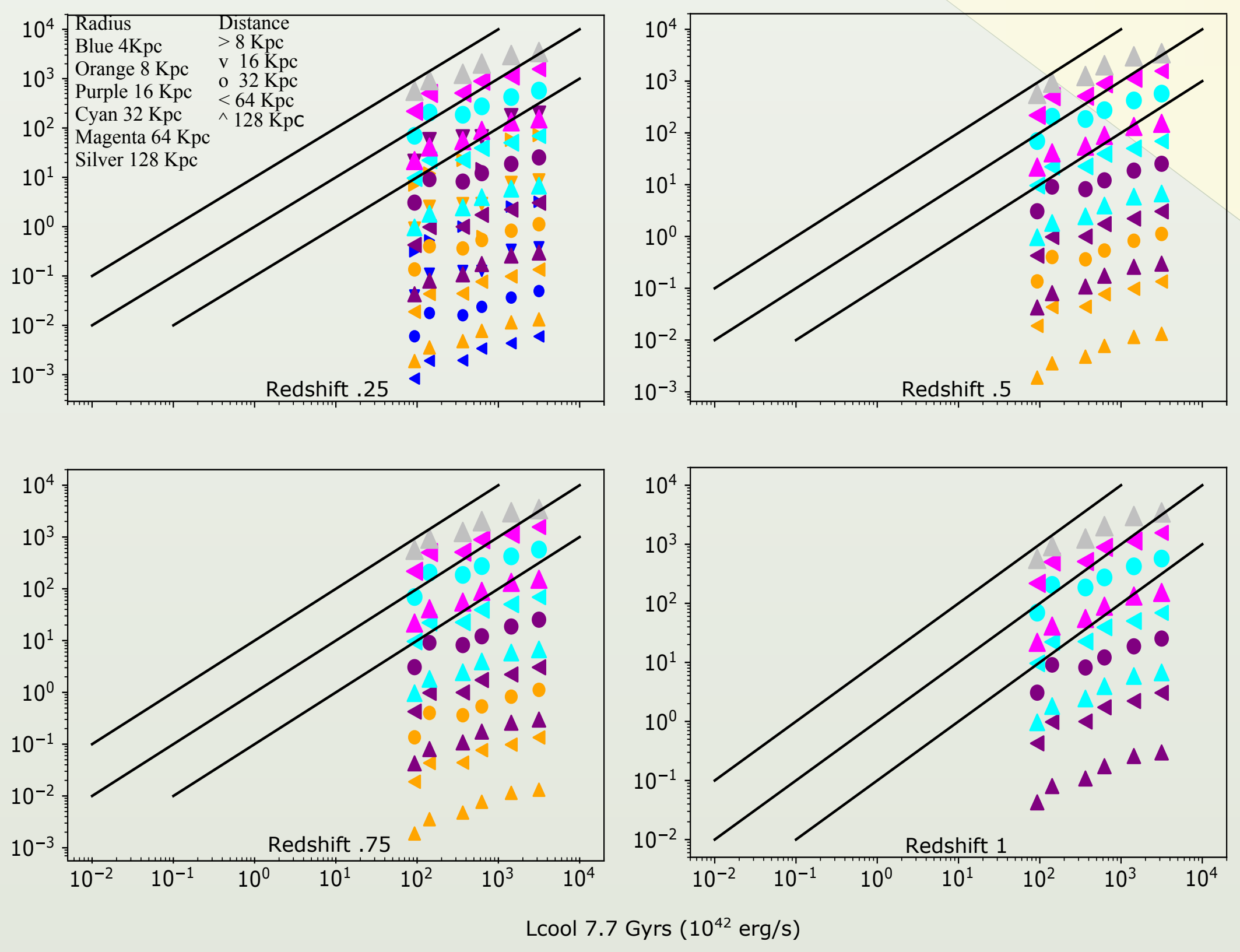

Figure 1: Cavity pressure vs cooling luminosity for X-ray cavities of difference radius and located at different distances at different redshifts in Abell 85, Abell 479, Abell 1795, Abell 1835, Abell 2199, Abell 4059

We also analytically explored the pressure luminosity relationship. From Kravtsov (2012), the luminosity of X-ray cavity can be written as:

$$L_{\text{cool}} \propto \rho_g^2 T^{\frac{1}{2}} V \propto \frac{M_g^2}{V} T^{\frac{1}{2}},$$

where, $M_g(< d) = 4\pi\rho_{g*} d^3 \int_0^1 x^2 \tilde{\rho}g(x)\,d\,x \propto M(< d)$. Assuming $r^2 d \sim V$,

$$L_{\text{bol}} \propto \frac{M(< d)^2}{V} T^{1/2} \approx \frac{\rho^{1/2}}{T^{1/2}} P_{\text{cav}} \propto \left(\frac{d}{V}\right)^{\frac{1}{2}} P_{\text{cav}}$$

We further looked at previous observations to find at what distance and of what size most of the cavities are. We found that that all the cavities in the previously published works are within a small error bar(~10-1/2) of the one-to-one line. So, we further explored how we can theoretically explain this phenomena. We used a theoretical model for density and temperature profile for our theoretical approximation. The temperature for a standard galaxy cluster can be written as:

$$\frac{T(r)}{T_{mg}} = 1.35\,\frac{(r/0.045)^{1.9}+0.45}{(r/0.045)^{1.9}+1}\,\frac{1}{(1+(r/0.6)^2)^{0.45}}\ \text{(Vikhlinin, 2006)}$$

We calculated the entropy using the slope for entropy vs radius linear relation to be 1.05 ± 0.14 (Babyk, 2018) and calculated the density from entropy. Then, we imagined what the radius would be as a function of the distance if we assumed PV is constant in the system. We also explored the same correlation if the system is adiabatic and assumed for the adiabatic system PV^{Γ} is constant with $\Gamma = 4/3$. We also looked at what highest slope we can possibly get in an adiabatic system for a constantly rising bubble using continuously inflated hydrodynamic bubble theory where the radius is defined as:

$$r = \left(\frac{3\dot{E}_0 r}{4\pi\eta p_0 c_s}\right)^{1/3}\left[1+\left(\frac{r}{r_c}\right)^2\right]^{\beta/2\Gamma}$$

(Diehl, 2006) where r_c is the core radius and $\beta = 1/2$. We also examined this relation if the noise to signal ratio is kept constant. In that case the distance vs radius relation is driven by keeping ρr^2 constant.

For a bubble starting at radius .1, located at distance 1, we get:

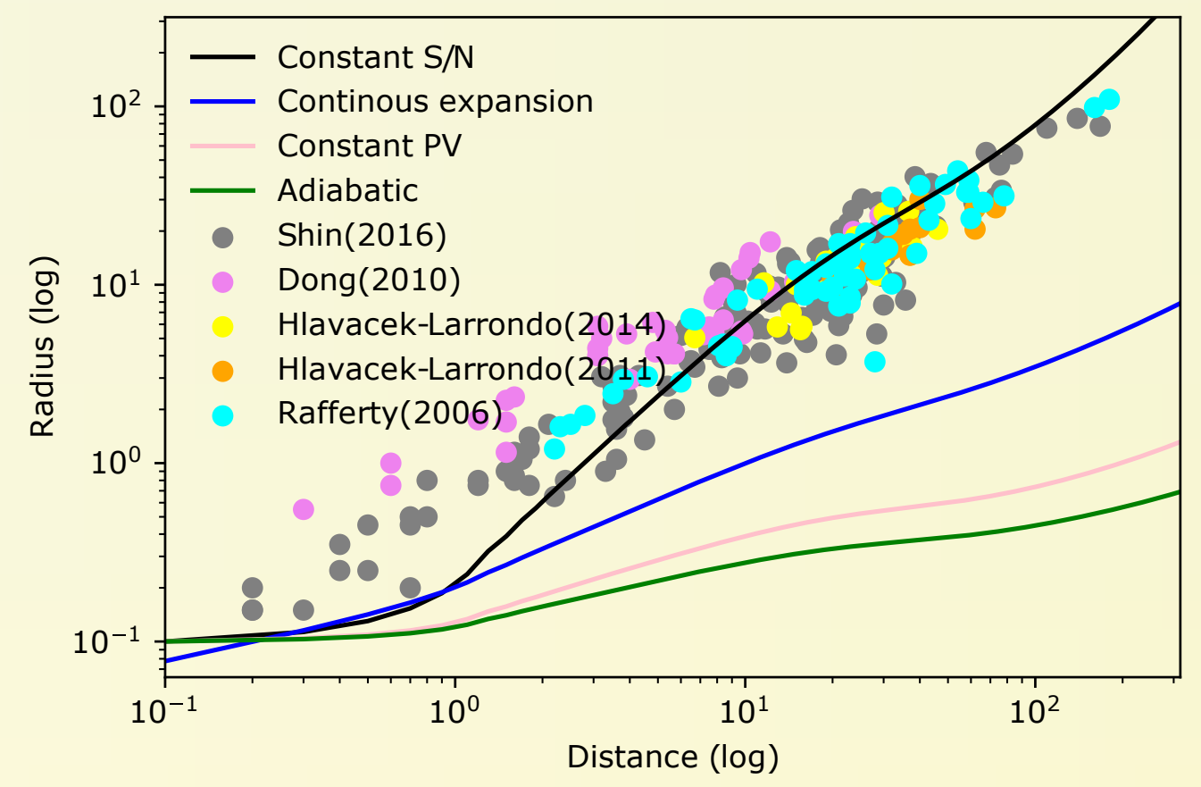

Figure 2: Experimental data of cavities detected at different radius and distances with theoretical curves for constant signal noise ratio, constant PV, constant PVΓ, constantly rising hydrodynamic bubble

The distance vs radius relation in the experimental data can also be potentially driven by the angle at which a telescope is observing cavities. The inclination angle of observation can push the slope of the curves to further left and therefore we can recreate the experimental correlation in radius and distance. After constraining the radius of the cavity as a function of distance, we again looked at the pressure vs luminosity correlation to examine the scatter of the correlation:

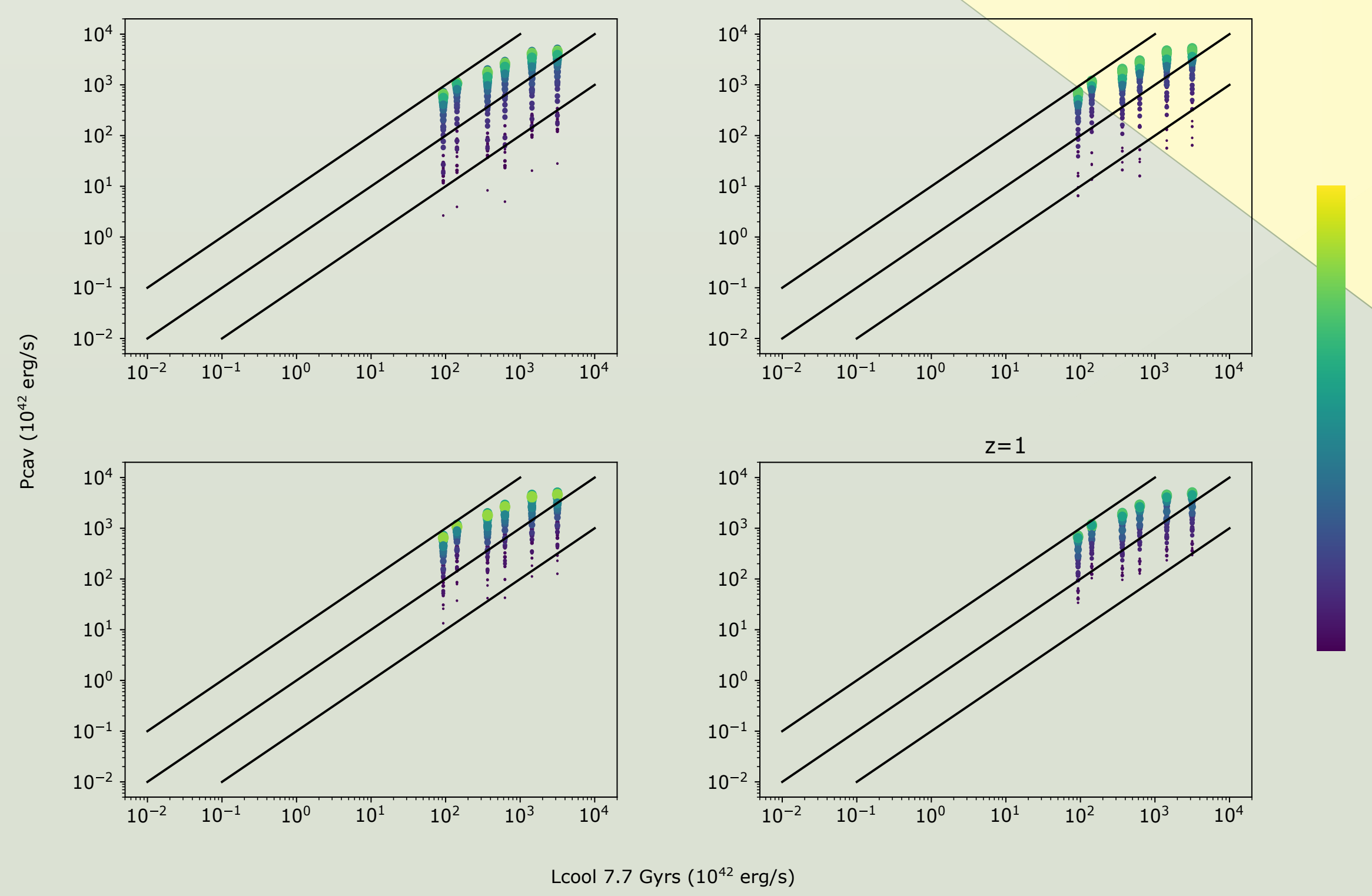

Figure 3: Cavity pressure vs cooling luminosity for X-ray cavities after constraining radius and distances at different redshifts in Abell 85, Abell 479, Abell 1795, Abell 1835, Abell 2199, Abell 4059

Conclusions

Our simulations show that we can create the relationship between luminosity and pressure of the cavity at random places in the galaxy cluster as we have shown that some of the simulated data lies on the one-to-one line found in previously published work (fig 1). This means the correlation is rather a property of the AGN and not the cavities. Furthermore, the radius of the cavity and the distance where the cavity is located drives the scatter. Even though the constant PV, adiabatic expansion curve seem to have a lower slope from the theoretical data, if we take telescope bias into account, the curves will get steeper and therefore overlap with the experimental data. Also, from our observations we have found that, the scatter can be driven by signal to noise ratio. As the cavities are light depression, they show up as dips in the luminosity. However, if there is too much noise then the light depression would seem like a noise and therefore can easily be undetectable.

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