# Cosmological Studies
# With A Large-Area X-ray Telescope

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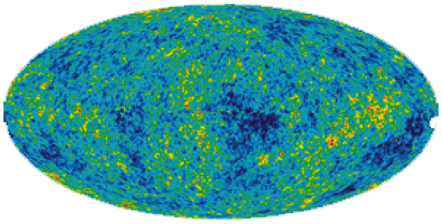

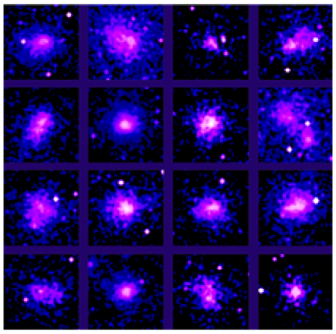

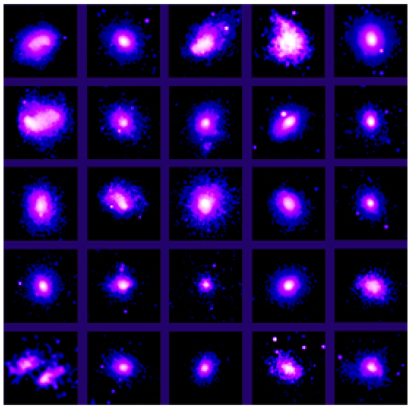

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## 1 X-ray cluster cosmology

Clusters of galaxies are a very promising cosmological tools, in particular because X-ray, SZ and optical and near-infrared data can be combined to minimize systematic errors in identifying and characterizing the cluster population. Mass selection systematics are smallest for X-ray or SZ selection, and there is concrete hope for further reduction in these uncertainties in the near future. X-ray astronomy in particular has played an important role in establishing the current cosmological paradigm. In the early 1990s, X-ray measurements of the baryonic mass fraction in nearby galaxy clusters, coupled with improved measurements of the Universal mean baryon density, provided some of the first compelling evidence that we live in a low density Universe [1]. Starting with early 1990's, X-ray measurements of the local number density of clusters and its evolution have also consistently pointed out towards a low-density Universe and a relatively low value of amplitude of matter fluctuations, $\sigma_8$, [2–7], a result since confirmed by cosmic microwave background (CMB) studies, cosmic shear, and other experiments [8–12].

Robust and precise understanding of dark matter and dark energy and how they shape the structure and evolution of our Universe can be obtained only through multiple, independent tests. The next generation of X-ray observatories will, among many other things, provide powerful, new tools to probe the structure and mass-energy content of the Universe. These tools will be highly complementary to the best other planned cosmological experiments (Planck, JDEM, LSST). In particular, the unique capabilities of the International X-ray Observatory (IXO) will allow the fullest possible exploitation of forthcoming cluster surveys made at X-ray and other wavelengths, and enable the tightest possible control of systematic uncertainties. Together, a powerful X-ray observatory and these other experiments should enable a quantum leap in our understanding of the Universe.

Cosmological studies in X-rays use observations of galaxy clusters. X-ray data for clusters are crucial since ~ 85% of the baryons within them are in the form of hot X-ray emitting gas. Precise measurements of the X-ray brightness and temperature of this gas permit two powerful and independent types of cosmological tests.

Firstly, observations with a powerful X-ray observatory such as IXO will constrain the growth of cosmic structure, primarily by providing accurate measurements for high-redshift galaxy clusters detected in new, large X-ray and SZ surveys. The eROSITA or proposed WFXT X-ray missions, for example, will discover ~ a few × $10^5$ clusters within $z \lesssim 2$, but provide only limited information on the individual properties of high-$z$ objects. Utilizing its much greater collecting area and improved spatial and spectral resolution, IXO will provide precise X-ray mass proxies for a complete subset of these clusters, enabling a much tighter coupling between the survey fluxes and theoretically predicted mass function [13, 14]. This will dramatically enhance the power of these surveys to constrain cosmological parameters [15, 16]. A large catalog of serendipitously discovered clusters will further extend our knowledge of clusters to fainter X-ray fluxes and higher redshifts, beyond $z = 2$.

The second type of cosmological test possible at X-rays is primarily geometric and, like type Ia supernovae (SNIa), constrains the expansion history of the Universe, measuring distance-redshift relation, $d(z)$. Here, the constraints will primarily come from measurements of the X-ray emitting gas mass fraction, $f_{\rm gas}$, in the largest, most dynamically relaxed galaxy clusters: $f_{\rm gas}$ is a theoretically-predicted and observationally-verified 'standard quantity' associated with large clusters (see [17] and references therein). Additional, independent constraining power will also be obtained from the combination of X-ray observations with measurements of the SZ effect in the same clusters.

The ability of IXO to measure the primary X-ray observables (X-ray brightness, temperature, metallicity and, for the first time, velocity structure in high-$z$ objects) to exquisite precision in a large subset of high-redshift clusters will, when coupled with external information from state-of-the-art hydrodynamical simulations, gravitational lensing studies and follow-up SZ observations, enable the tightest possible control of systematic uncertainties in all cosmological measurements using galaxy clusters.

## 2 Measuring the growth of cosmic structure

The main techniques proposed to study growth of cosmic structure in future cosmological experiments are 1) measuring the evolution of the mass function of galaxy clusters; 2) wide-area cosmic shear surveys; and 3) using redshift-space distortions in the galaxy-galaxy correlation function. The cosmic shear method is currently the only growth of structure component of the proposed JDEM mission. At present, the constraints on dark energy from cosmic shear and redshift-space distortions are weak. In contrast, the constraints from X-ray studies of the cluster mass function are relatively strong and developing rapidly. The dominant systematic effects in the X-ray method are clear and ways to address them have been identified and are being vigorously pursued using e.g. follow-up gravitational lensing studies, SZ observations, and hydrodynamical simulations.

Recent X-ray studies of the evolution of the cluster mass function using the *Chandra* X-ray Observatory to follow up ROSAT X-ray selected clusters, have convincingly demonstrated that the growth of cosmic structure has slowed down at $z < 1$, due to the effects of dark energy. These measurements have been used to improve the determination of the equation state parameter [16] and to place first constraints on possible departures from General Relativity [18]. With IXO, working in concert with other mutli-wavelength facilities to exploit new cluster surveys, it will be possible to make similar measurements out to redshifts $z \sim 2$, providing a unique and critical insight into cosmic structure growth.

***2.1 The basics of cluster mass function measurements*** The mass function of galaxy clusters, $n(M)$, is an exponentially sensitive indicator of the linear density perturbation amplitude at the $\sim 10\,h^{-1}$ Mpc scale. Given precise cluster masses, the perturbation growth factor in a given redshift bin can be recovered to 1% accuracy from a sample of only 100 clusters in the $10^{14}$ – $10^{15}$ solar mass range (for fixed values of all other cosmological parameters). This high sensitivity is the main reason why 'counting clusters' provides such an attractive technique for studying the growth of structure.

At present, cluster surveys provide a degenerate combination of constraints on the growth of mass perturbations and the overall geometric properties of the Universe. [This is simply because the volume elements and masses derived from observations are both a function of $d(z)$]. However, looking ahead a decade from now, we can expect techniques such as SNIa, BAO and the X-ray $f_{\rm gas}(z)$ method to have measured $d(z)$ with sufficient precision that the evolution of the cluster mass function will become an essentially 'pure' growth of structure test. At this point, precise mass function measurements will bring unique degeneracy-breaking power, powerfully and straightforwardly enabling significant improvements in constraining the evolution of the dark energy equation of state and in helping to distinguish the origin of cosmic acceleration.

One of the most interesting applications for growth of structure data is in testing theories that attempt to explain cosmic acceleration by modifying the standard rules of gravity (General Relativity) on large scales. In general, modifications to GR will affect theoretical predictions for the cluster mass function by changing both the growth rate of linear perturbations and modifying the process of non-linear collapse. The process of non-linear collapse is already well calibrated for GR-based dark energy models [14]. As the field of research matures, we can expect that the calibration will also become similarly robust for other interesting non-GR models. The combination of precise X-ray and lensing, as well as SZ and optical-dynamical, measurements of the baryonic and dark matter distributions in individual clusters will also aid in probing modified gravity theories on Megaparsec scales because in non-GR theories, dynamic and weak lensing mass estimated in general are not expected to yield the same value.

***2.2 Strategy for mass function measurements*** Systematic, not statistical, uncertainties provide the limiting factor in cosmological measurements based on the cluster mass function. The cluster catalog provided by future X-ray survey missions will be very large and, due to the strengths of X-ray techniques, should have excellent purity and completeness. The primary need will be the accurate calibration of cluster masses. Mass uncertainties are generally of two kinds: 1) systematic *average* biases in the derived masses; and 2) *scatter* in the mass measurements for individual clusters. Both sources of uncertainty are damaging. For example, systematic uncertainties of ±10% in the mean cluster mass at a given redshift automatically lead to ±3% uncertainties in the growth factor.

No single cluster mass measurement technique can address both uncertainties. However, the *combination* of X-ray and lensing methods provides an approach that is both bias-free and has minimal intrinsic scatter, and is also insensitive to detailed physics of cluster formation.

X-ray hydrostatic analyses can provide low-scatter, and even relatively low-bias, mass estimates for the most dynamically relaxed clusters. However, for most systems, systematic scatter and biases in hydrostatic mass estimates are expected at the $20 - 30\%$ level. Although IXO will be able to measure and/or eliminate some such sources of uncertainty (e.g., by measuring bulk motions and turbulence in the intracluster medium via high-resolution X-ray spectroscopy), controlling them at the few percent level from X-ray data alone would appear to be impossible. However, *one does not require hydrostatic X-ray mass estimates for cluster mass function work*. High-resolution cosmological simulations have shown that the parameter $Y_X = T \times M_{\rm gas}$, where $T$ is the average temperature derived from the X-ray spectrum and $M_{\rm gas}$ the gas mass derived from the X-ray surface brightness profile, provides a high-quality proxy for the total mass. The simulations, using different codes, with or without including non-gravitational heating and cooling of the cluster gas, and with different numerical techniques for treating these effects, all show that $M_{\rm tot} \propto Y_X^{\alpha}$, with $\lesssim 10\%$ scatter and a slope very close to the prediction of self-similar theory, $\alpha = 3/5$ (see [15] and later works). The low scatter in the $M_{\rm tot} - Y_X$ relation is therefore a very *robust* theoretical prediction, and the only prediction we need to implement the test outlined below. The minimal scatter in the $M_{\rm tot} - Y_X$ (and also $M_{\rm tot} - M_{\rm gas}$) relations is confirmed by Chandra observations (e.g., [17, 19]).

Weak lensing techniques have a lower limit on the accuracy of mass measurements for individual clusters of $20 - 30\%$, due to projection effects. This scatter is too large for "precision cosmology" with the cluster mass function. However, *on average*, weak lensing masses are free of bias [20]. By combining the X-ray and lensing approaches, and drawing on their individual strengths, one can obtain mass measurements for samples of clusters that are both low in intrinsic scatter and are bias free.

Once the systematic scatter in the X-ray mass proxy has been reduced to $\lesssim 10\%$, it will have only a small effect on cosmological measurements from the cluster mass function. The dominant uncertainties are then associated with the weak lensing data and establishing the *normalization* of the $M_{\rm tot} - Y_X$ relation in each redshift bin.

Observational calibration of the $M_{\rm tot} - Y_X$ relation is essential. These cannot (currently) be predicted by theory with percent level accuracy. The necessary weak lensing measurements will come from survey data collected by ground and space-based projects like Pan-STARRS, DES, LSST, JDEM and JWST, but also from targeted ground- and space-based observations. The capabilities of 6m-class telescopes such as Magellan or Subaru are adequate for average weak lensing measurements out to $z \sim 1$; beyond that, some kind of space-based data will be required. It could be either JWST pointings or survey data from JDEM or EUCLID. Assuming that the weak lensing data will provide $M_{\rm tot}$ with 30% scatter and minimal average bias, then by observing ~ 100 clusters in each redshift bin we will normalize the $Y_X - M$ relation at that redshift to ~ 3%. Given 3% accuracy in the normalization of the $Y_X - M$ relation, one can derive the linear perturbation amplitude at this redshift to 1% accuracy. If one were to conservatively assume a factor of two degradation in these measurements (representing a 'pessimistic' scenario), then the same data will still constrain the linear perturbation amplitude to 2% accuracy at each redshift.

Both the weak lensing and X-ray components are essential to this work. If one has only weak lensing masses for the clusters, one cannot accurately reconstruct the mass functions because of the large and unavoidable ~ 30% scatter in the individual mass measurements. Conversely, if one has only precise, X-ray measured $Y_X$ or $M_{\rm gas}$ parameters, it would be hard to control systematic biases in the mass at the level sufficient for the 1–2% growth measurements. Only the combination of the two techniques circumvents these problems.

***2.3 The cluster samples*** Future, scheduled X-ray and SZ surveys will easily provide the samples of clusters required for this work. For example, eROSITA will carry out a sensitive all-sky X-ray survey that will detect ~ 200,000 clusters, and this sample will have > 100 clusters per $\Delta z = 0.1$ bin out to $z = 1.5$. The serendipitous cluster catalog constructed by IXO will probe two orders of magnitude lower in X-ray flux over a smaller area and, together with SZ experiments, extend the target list to $z = 2$ and beyond. Proposed next-generation X-ray survey missions like WFXT would extend these surveys yet further.

Selecting 100 massive, X-ray bright clusters in each $\Delta z = 0.1$ redshift bin spanning the range $0 < z < 2$ gives a sample of 2000 clusters requiring weak lensing and X-ray followup. Precise spectroscopic redshifts will automatically be provided for each cluster by the X-ray observations, but can also be obtained in a dedicated optical followup program.

The effective area of the survey-optimized X-ray telescopes telescopes will be insufficient to measure $Y_X$, even with deep pointed observations, for clusters at $z \geq 0.8$. At higher redshifts, the required $Y_X$ measurements will only be possible with a powerful observatory such as IXO. Detailed exposure time estimates show that ≈ 10 Msec of IXO observing time will be required to carry out this program. This is moderate, but by no means prohibitive, investment of observing time over the lifetime of the mission, and will provide a cosmological measurement of fundamental importance. The expected, reconstructed structure growth history is illustrated in Fig. 1. The redshift range of $0 < z < 2$ spans the entire epoch of accelerated expansion. At the highest $z$, these studies will dovetail into planned Ly-$\alpha$ forest observations.

***2.4 Expected results from the $G(z)$ measurement*** Growth of structure, $G(z)$, data are highly complementary to cosmological expansion history measurements in constraining, for example, the dark energy equation of state. For illustration, we have computed the combined constraints from a SNAP-like SNIa experiment (adopted from [21]) together with the $G(z)$ data from the combined X-ray+weak lensing studies discussed above. The results are shown in Fig.2. Because the distance- and growth-based constraints are nearly orthogonal, their combination improves the equation of state uncertainties by a factor of 2.5. Cluster growth of structure data will provide a vital complement to the JDEM mission, especially if that mission emphasizes $d(z)$ measurements.

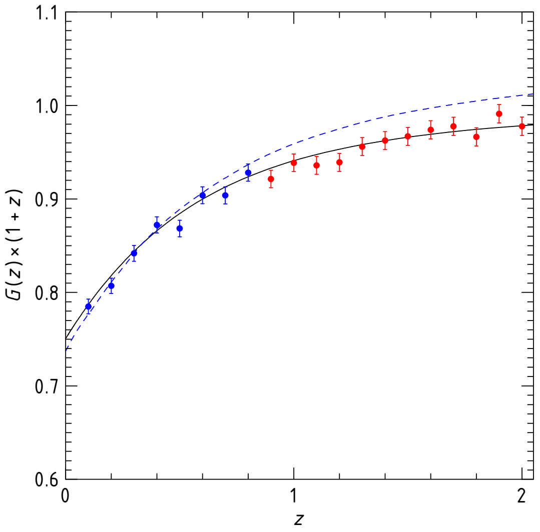

Fig. 1— The normalized growth factor of density perturbations, $G(z)$, constructed from follow-up X-ray and weak lensing observations of 2000 clusters detected in sensitive X-ray surveys. The extension of $G(z)$ measurements to $z = 2.0$ will be possible only with the high sensitivity of IXO. The high-$z$ ($z > 0.8$) data points are crucial for testing non-GR models of cosmic acceleration. For example, the dashed line shows the $G(z)$ function predicted for a DGP model with the same expansion history as the quintessence model depicted by the solid curve.

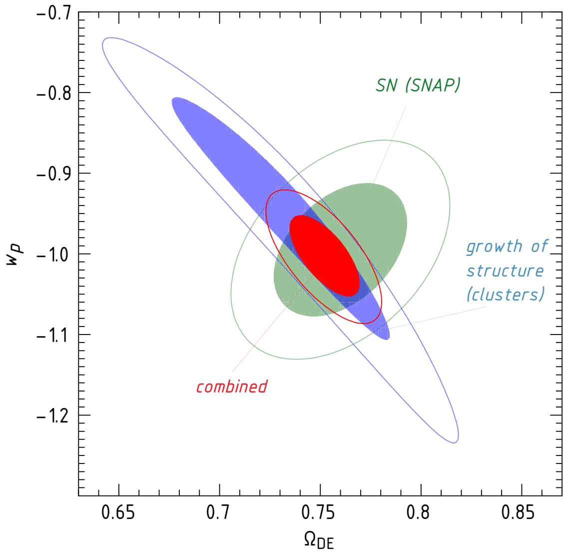

Fig. 2— The improvement in the dark energy equation of state constraints obtained from the combination of distance-based techniques (projected results are shown for the SNAP SNIa experiment), and X-ray growth of structure measurements. Contours show the two-parameter 68% and 95% confidence regions, assuming Planck priors. The combination of SNIa and X-ray growth of structure data improves the equation of state uncertainties by a factor of ~ 2.5. $w_p$ is the value of equation of state at "pivot" redshift, where it is best constrained by the given experiment.

Regardless of the accuracy in the equation of state measurements achieved by JDEM, the next big question will be whether the cosmic acceleration is caused by a physical scalar field or modifications of General Relativity on large scales. The X-ray cluster data will be crucial for testing such models because they, in general, significantly modify the growth factor with respect to GR dark energy models with similar distance-redshift relations. For example, the $d(z)$ relation for a DGP modified gravity model (REF) can be almost indistinguishable from the $d(z)$ of a quintessence model with $w \simeq -0.8$. The growth factor, however, is substantially different, as illustrated by the solid and dashed lines in Fig.1. A DGP-type modification of the growth history will be easily detectable with the proposed IXO measurements at $z > 1$.

A more quantitative demonstration of IXO capabilities in constraining non-GR theories can be based on the so called "growth index", $\gamma$ [22]. For GR and a very wide range of "physical" dark energy models, such as quintessence, $\gamma$ is close to 0.55. Therefore, departures from General Relativity can be searched for by detecting deviations in $\gamma$ from 0.55. For example, $\gamma = 0.68$ is predicted for the DGP model. The projected $G(z)$ measurements in Fig.1 will constrain $\gamma$ to ±0.022 (0.045) using cluster data only, and to ±0.018 (0.034) from combination of the cluster and Planck data, assuming that the masses of light neutrinos are known). The values in parentheses are for the "pessimistic" calibration scenario in which projected uncertainties for mass calibration are degraded by a factor of 2, as discussed above. Huterer & Linder predict [22] that $\gamma$ will be constrained to ±0.044 from combination of the supernovae and weak lensing measurements from a SNAP-type mission combined with Planck CMB priors.

## 3 Probing the expansion history with $f_{\rm gas}(z)$

The ratio of baryonic-to-total mass in clusters should closely match the ratio of the cosmological parameters $\Omega_b/\Omega_m$ because the matter content of the largest clusters of galaxies is expected to provide a fair sample of the matter content of the Universe [1]. The baryonic mass in clusters is dominated by X-ray emitting gas, the mass of which exceeds the mass in stars by a factor of ~ 6, with other sources of baryonic matter being negligible. The combination of X-ray measurements of $f_{\rm gas}$ with optical/near-IR estimates of the stellar mass, and determinations of $\Omega_b$ and $H_0$ from e.g. CMB data, can therefore be used to measure $\Omega_m$.

Measurements of $f_{\rm gas}$ as a function of redshift also probe the acceleration of the Universe. This constraint originates both from the fact that for the largest clusters $f_{\rm gas}$ is predicted to be a near-invariant quantity with minimal intrinsic scatter [23, 24] and from the dependence of the $f_{\rm gas}$ measurements (which are derived from the observed X-ray temperature and density profiles, assuming hydrostatic equilibrium) on the assumed distance to the clusters: $f_{\rm gas} \propto d^{3/2}$. The latest results from this experiment [17] using Chandra data for 42 hot, relaxed clusters, give marginalized constraints of $\Omega_M = 0.28 \pm 0.05$ and $\Omega_\Lambda = 0.86 \pm 0.22$ (Fig.3). The Chandra data confirm that the Universe is accelerating at 99.99% confidence, comparable in significance to the best current SNIa data combined. We emphasize that systematic scatter remains *undetected* in current Chandra $f_{\rm gas}$ data for hot, relaxed clusters, despite a weighted-mean statistical distance error of only 5% [17]. This compares favorably with SNIa, where systematic scatter is detected at the 7% level in the individual distance estimates [25].

The prospects for $f_{\rm gas}$ studies with IXO have been studied in detail in [26]. An investment of ~ 10 Ms of IXO time to measure $f_{\rm gas}$ to 5% (corresponding to 3.3% accuracy in distance) in each of the 500 hottest, most X-ray luminous, dynamically relaxed clusters detected in future cluster surveys, will be sufficient to constrain cosmological parameters with a DETF [21] figure of merit (FoM) of 20–40. This range in FoM spans pessimistic to optimistic assumptions regarding systematic uncertainties [26]. Similar cosmological constraints would also be achievable by observing the best 250 clusters for 40 ks each, on average; such a strategy may prove useful at higher $z$ if the fraction of relaxed clusters is found to drop faster than expected. Gravitational lensing data will again be used to pin-down the mean hydrostatic mass bias in each redshift bin. (These biases are not expected to exceed 10% for the largest, relaxed clusters.)

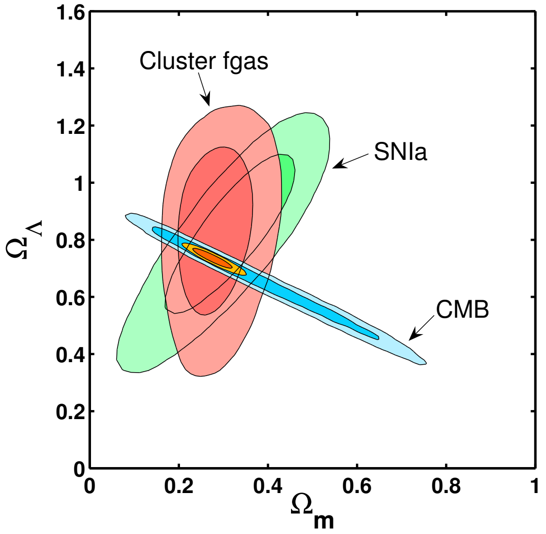

Fig. 3— Constraints on $\Omega_M - \Omega_\Lambda$ from the current *Chandra* $f_{\rm gas}$ measurements.

The constraints on the expansion history (see Fig. 4) from the IXO $f_{\rm gas}$ experiment are comparable to, or exceed, those expected for future 'Stage IV' ground and space-based SNIa and BAO experiments [21]. In particular, the $f_{\rm gas}$ data are expected to provide a very precise measurement of the mean matter density, $\Omega_{\rm m}$. Most importantly, the very different natures of the astrophysics and systematics affecting the $f_{\rm gas}$, SNIa and BAO experiments will ensure maximum robustness when the results are combined. The addition of follow-up SZ observations will boost the IXO FoM still further, providing independent

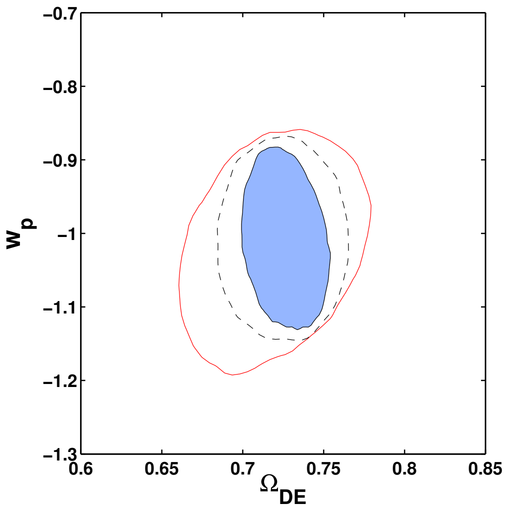

Fig. 4— The projected 95% confidence contours for the IXO $f_{\rm gas}$ experiment in the $\Omega_{\rm DE} - w_p$ plane for the default dark energy model and optimistic (2%; blue, solid contour), standard (5%; dashed contour) and pessimistic (10%; red contour) allowances for systematics. The figure presented in an identical style to the DETF report [21] to allow direct comparison with those results.

constraining power via the classic 'XSZ' experiment that combines X-ray and SZ measurements of the Compton y-parameter [26,27]. Although less intrinsically powerful, than the $f_{\rm gas}$ test, the XSZ experiment rests on different assumptions and has different systematic uncertainties. The optimal IXO observing strategies for both the $f_{\rm gas}$ and XSZ experiments are identical and will use the same X-ray observations of the largest, dynamically relaxed clusters [26].

## 4 Summary

A moderate investment of observing time with the International X-ray Observatory to study high-redshift galaxy clusters detected in future large-scale surveys, will provide cosmological measurements of fundamental importance. IXO observations, combined with lensing follow-up, will measure the perturbation growth factor from $z = 0 - 2$ with an accuracy comparable to, or possibly better than, that expected from observations of cosmic shear with JDEM, and redshift-space distortions with EUCLID. The growth of structure data derived from clusters will significantly improve our knowledge of the dark energy equation of state and will aid in constraining non-GR models for cosmic acceleration. IXO observations of the largest, dynamically relaxed clusters will provide a powerful, independent measurement of the cosmological expansion history using the apparent $f_{\rm gas}(z)$ trend. Systematic and statistical errors from this technique are competitive with SNIa and BAO studies, making the test extremely useful for improving the accuracy and reliability of the geometric cosmological measurements planned for LSST and JDEM. Only by employing a range of powerful, independent approaches, including those discussed here, can robust answers to puzzles as profound as the origin of cosmic acceleration be expected.

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