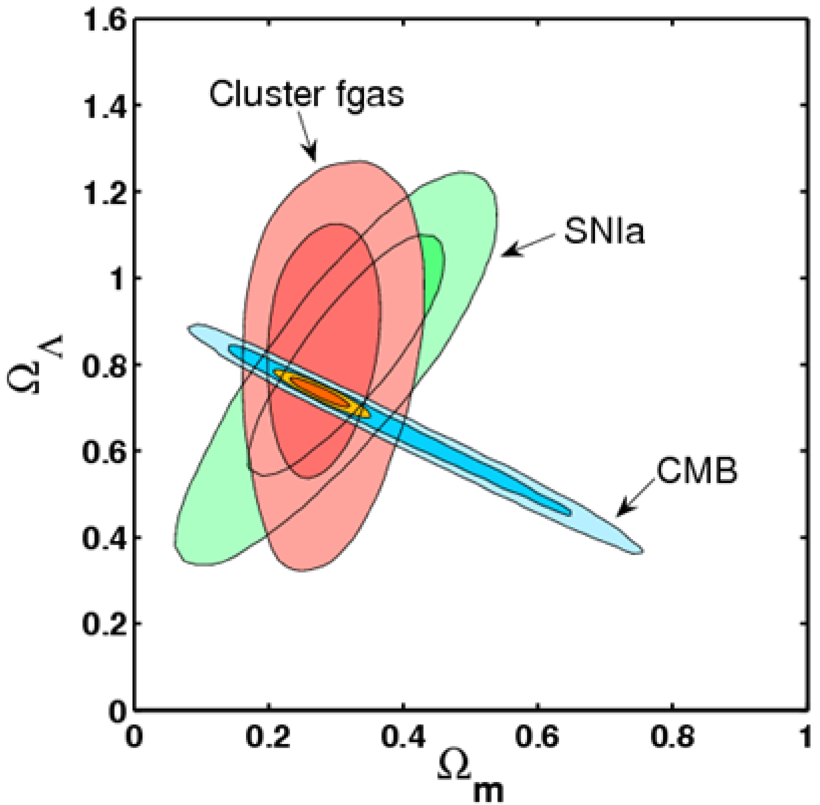
Evolution of Large Scale Stucture in the Universe

Steve Allen (Stanford)

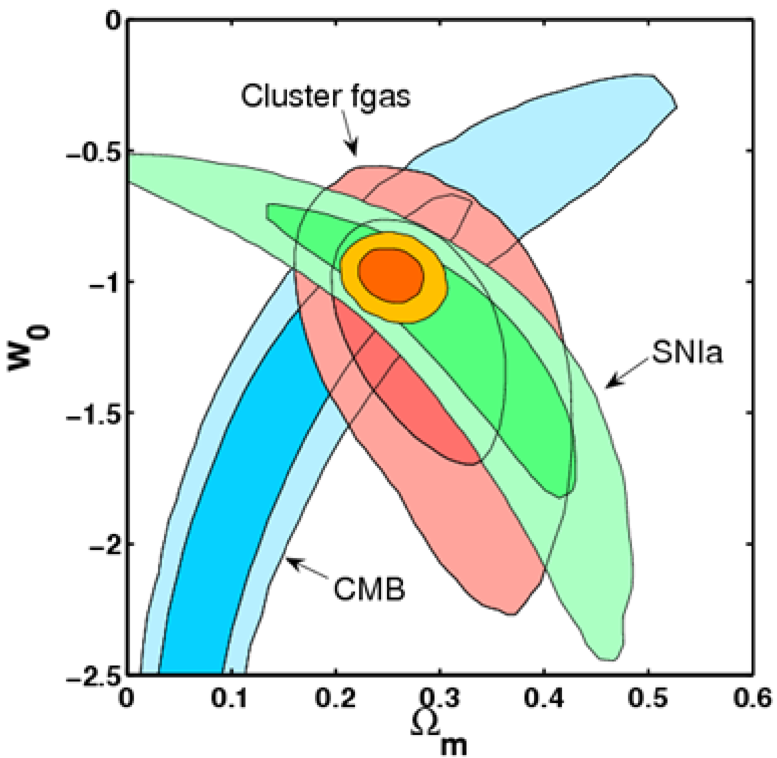


Other Panel Members:

David Rapetti (Stanford)
Alexey Vikhlinin (CfA)
Mark Bautz (MIT)
Max Bonamente (UAH)
Jack Burns (Colorado)
Eugene Churazov (MPA)
Joe Mohr (UIUC)
Daisuke Nagai (Caltech)
Richard Mushotzky (GSFC)
Adam Stanford (LLNL)

Key Question

What are the natures of dark matter and dark energy and how do they shape the structure and evolution of the Universe?



Background and motivation

X-ray observations of galaxy clusters have played a crucial role in establishing the current cosmological paradigm.

Early 1990s: Ω_m~0.3. Cluster baryon fraction (e.g. White et al. '93)

Early 2000s: σ_8~0.75 for Ω_m~0.3. XLF/XTF (many references),

Initially controversial, but now confirmed by several independent routes.

Determining the natures of dark matter and dark energy remain major goals of Physics and Astrophysics. We require multiple, independent means to test their properties so as to ensure precise, robust results.

IXO will provide powerful new X-ray tools to probe the mass-energy content and evolution of the Universe. Competitive with and highly complementary to Planck, JDEM, LSST and eROSITA.

Cosmology with IXO

1) The expansion history: constraints on Ω_m and dark energy (Ω_{de},w) from measurements of the apparent evolution of the baryonic mass fraction in the largest relaxed clusters (+SZ follow-up).

2) The growth of cosmic structure: constraints on Ω_m, dark energy, and the amplitude of matter fluctuations σ_8 from the evolution of the cluster mass function.

3) The nature of dark matter: constraints on self-interaction cross section from inner density profiles of relaxed clusters, the separation of dark and baryonic matter in merging clusters. Also evolution of the concentration-mass relation and searches for dark matter annihilation lines.

Con-X will provide a quantum leap in constraining power and, in combination with hydrodynamical simulations, SZ and gravitational lensing observations, the tightest possible control of systematics.

IXO capabilities vs. Con-X

The improved capabilities of IXO are good news for cosmological studies.

Improvement in spatial resolution → Better removal of AGN, better identification of relaxed clusters.

Larger FOV → can fit whole cluster in single pointing even at modest redshifts. Better background subtraction at high-z.

Increased collecting area → shorter exposure times (20Ms→15Ms?)

Note: 10-40 keV data not critical to cosmological studies, but will improve knowledge of non-thermal emission and CR pressure with deeper exposures.

Possible observing plan

IXO hardware (throughput, FOV, spatial and spectral resolution) is remarkably well-suited to cosmological studies.

STAGE 1:

Short 1-10ks exposures of few thousand hottest, X-ray brightest (highest SZ flux) clusters detected in precursor surveys like eROSITA (~10 Ms total).

→ mass proxy information for growth of structure test: core-excluded Lx, gas mass, Yx (product of gas mass and mean temperature) within r500.

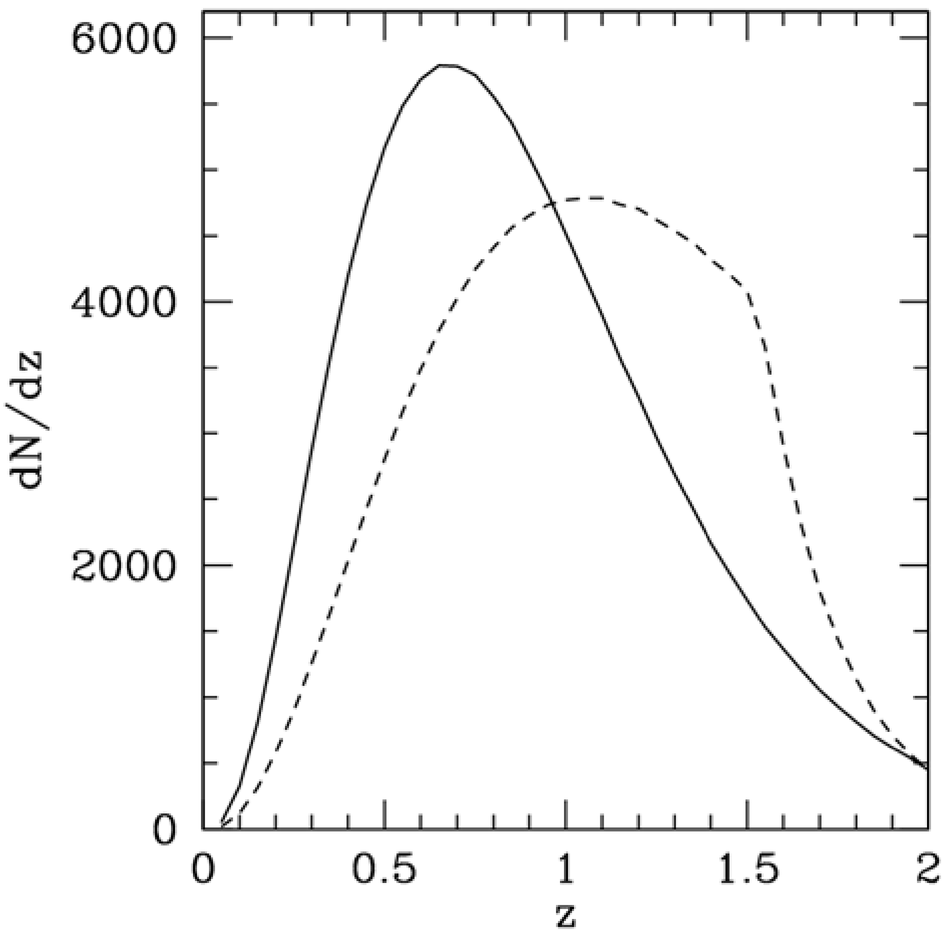
→ identify ~500 most relaxed systems (morphology + velocity width).

STAGE 2:

Average 20ks exposures of ~500 most relaxed clusters (~10 Ms total).

→ sufficient to measure fgas(r) and predict Compton y-parameter at r2500 to ~5% accuracy, corresponding to 3.3% in distance.

Redshift distribution of target clusters



Assume targets provided by eROSITA flux limited X-ray survey.

Solid curve shows >5 keV clusters (same kT range used with present data).

Density of target clusters peaks at z~0.7.

Rapetti, Mantz & Allen '08

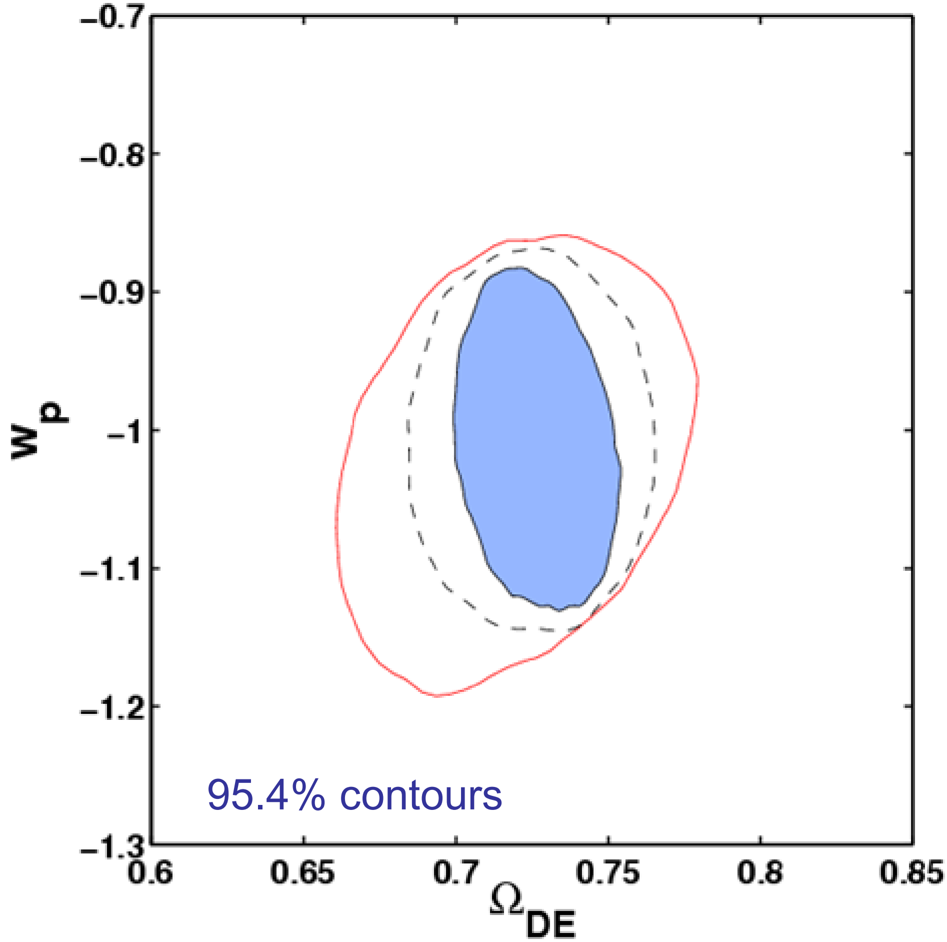
1) The expansion history

Results are presented in the style of the Dark Energy Task Force (DETF) report to allow for direct and easy comparison with other techniques.

Like the DETF, we assume `Planck priors' and present results for `optimistic', `standard' and `pessimistic' systematic allowances. Full MCMC simulations.

Cluster	Parameter	Allowance (optimistic/standard/pessimistic)	Type
f_{gas} EXPERIMENT			
Calibration/Modelling	K	$1.0 \pm 0.02/\pm 0.05/\pm 0.10$	Gaussian
Non-thermal pressure	γ	$0.96 < \gamma < 1.04/0.92 < \gamma < 1.08$	uniform
Gas depletion: norm.	b_0	$0.82 \times (1 \pm 0.02/\pm 0.05/\pm 0.10)$	uniform
Gas depletion: evol. (linear)	α_b	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
Gas depletion: evol. (quadratic)	β_b	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
Stellar mass: norm.	s_0	$0.16 \times (1 \pm 0.02/\pm 0.05/\pm 0.10)$	Gaussian
Stellar mass: evol. (linear)	α_s	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
Stellar mass: evol. (quadratic)	β_s	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform
XSZ EXPERIMENT			
Calibration/Modelling	k_0	$1.0 \pm 0.02/\pm 0.05$	Gaussian
evolution (linear)	α_k	$\pm 0.02/\pm 0.05/\pm 0.10$	uniform

DETF figure of merit



optimistic (blue) standard (dashed)

$FoM=[\sigma(w_p)x\sigma(w_a)]^{-1}$

$w_p=w(a_p)$; minimal $\sigma(w(a))$.

	$\sigma(\Omega_{DE})$	$\sigma(w_p)$	FoM
Optim.	0.009	0.044	38.5
Pessim.	0.023	0.058	25.2

Comparable to constraints for other methods: DETF (opt./pes.)

	Space	Ground
SNIa	27.0 / 19.1	22.2 / 7.9
BAO	42.2 / 19.8	55.2 / 21.5

Rapetti, Mantz & Allen '08

2) The growth of cosmic structure

IXO will powerfully complement new X-ray and SZ cluster surveys.

The uncertainties in cosmological parameters from cluster `growth of structure' work are dominated by uncertainties in the mass-observable relation.

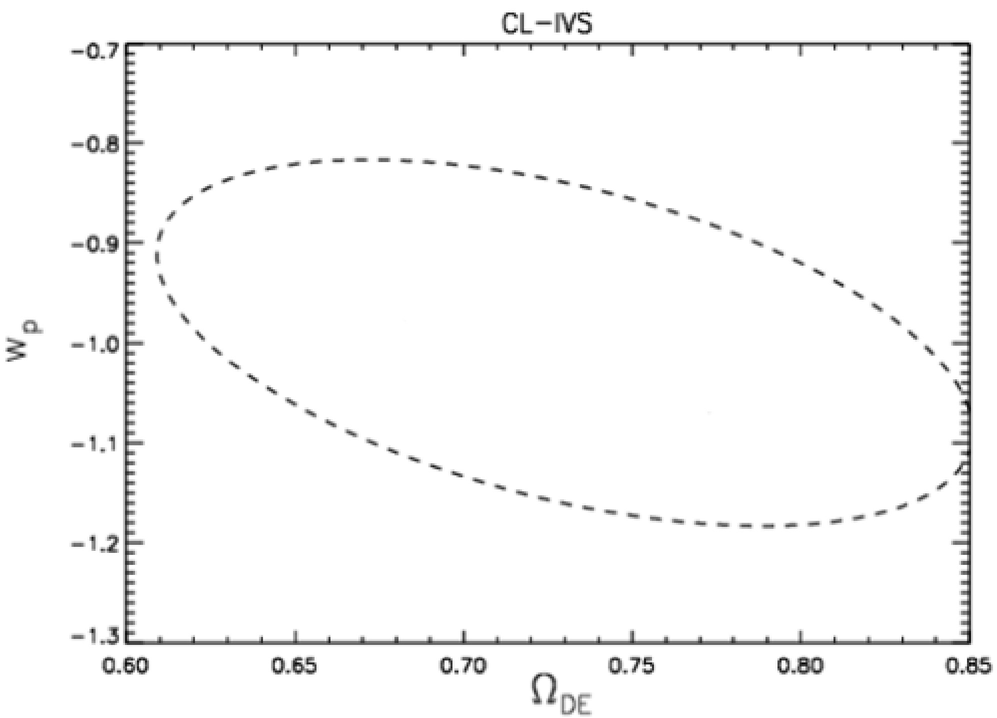
The Dark Energy Task Force (DETF: Albrecht et al '06) consider a future 20000 sq degree X-ray/SZ survey with 30,000 clusters, comparable to that expected from e.g. eROSITA/Spectrum-X-gamma or future large SZ surveys.

They examine the constraints achievable from `growth of structure+spatial clustering' information, both with and without detailed information on the mass-observable relation.

In essence, this shows the difference that IXO follow-up providing precise mass measurements (few % accuracy) for a few % of the survey clusters can make.

Figure of merit (self calibration only)

Option 1: \`Self calibration': marginalize over unknown norm/scatter of mass-observable relation (using priors on form of relation) solving for cosmological parameters using only shape of mass (proxy) function + clustering information.



Dark Energy Task Force:

20000 sq degree X-ray/SZ survey. 30000 clusters with M>2.5e14/h Msun.

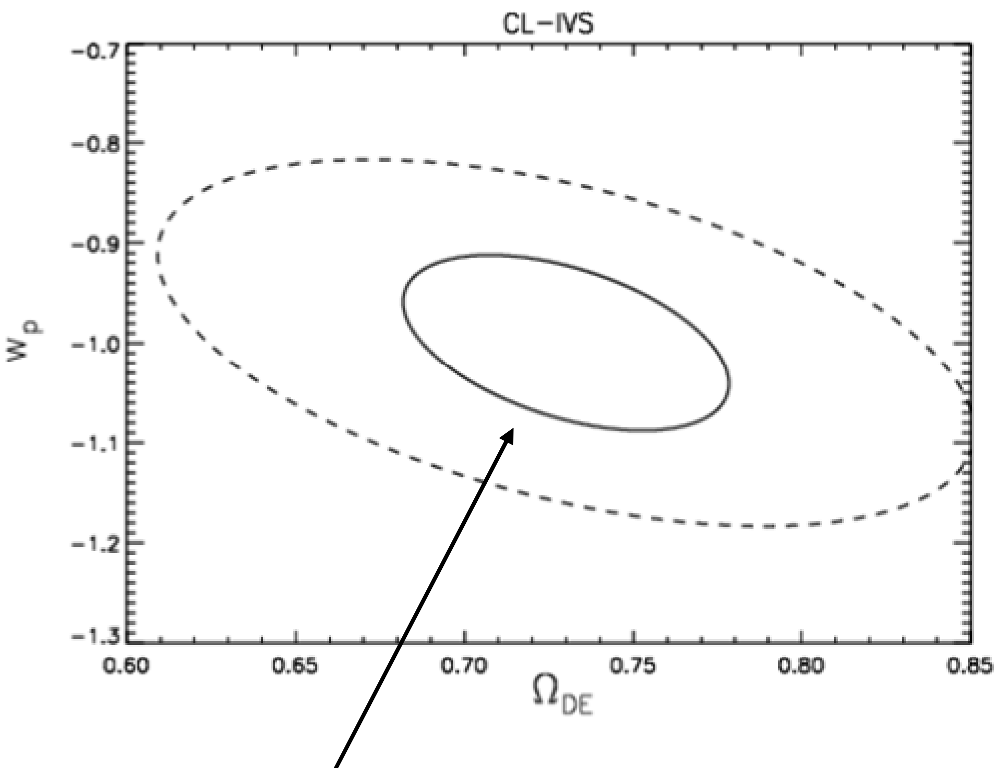
Self calibration only.

Accuracy: $\sigma(w) \sim \pm 0.08$
DETF FoM ~ 5-10.

Note: Some other studies provide more optimistic projections but self-calibration requires very detailed (sub %) knowledge of survey characteristics to work well.

Figure of merit (including IXO follow-up)

Option 2: Use IXO to measure mass-observable relation for fair sample (few thousand) clusters + calibrate with lensing/simulations. Require IXO throughput and high spatial/spectral resolution to remove AGN and map thermodynamics.



Dark Energy Task Force:

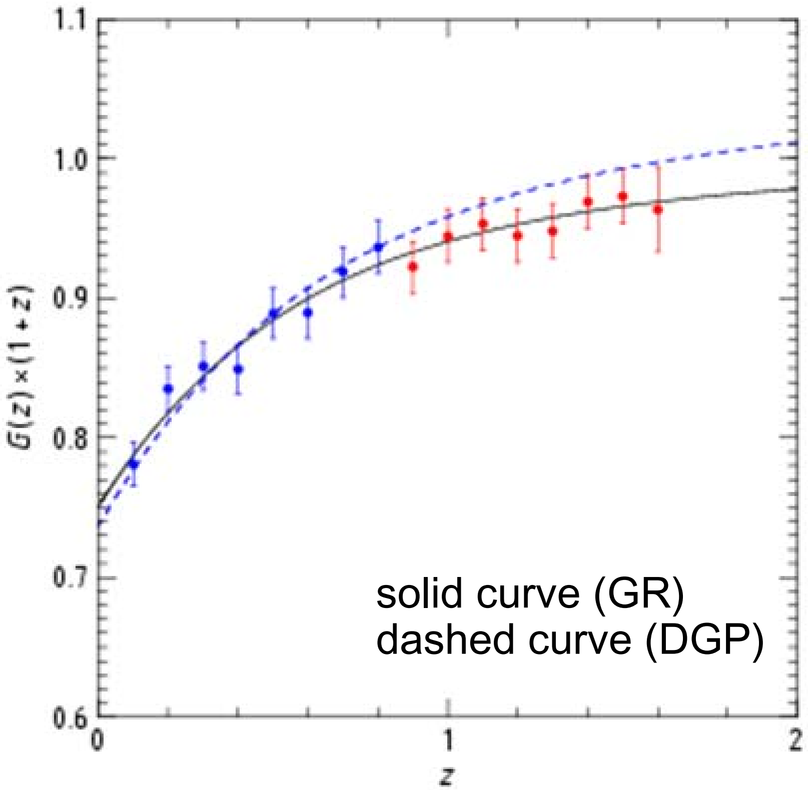
20000 sq degree X-ray/SZ survey. Mass-observable relation calibrated to ~2 % accuracy.

Accuracy: $\sigma(w) <= \pm 0.04$
DETF FoM >=40

Conclude: IXO follow-up of small fair sample of clusters in future X-ray/SZ surveys can dramatically enhance their power to constrain dark energy.

Distinguishing dark energy vs. modified gravity

Even though a dark energy and modified gravity model might share the same expansion history, they would be unlikely to also share the same growth history.



Combination of expansion history and growth of structure constraints offers possibility to distinguish dark energy from modified gravity.

Essential to probe to high-z (only possible with high IXO throughput and excellent PSF).

3) IXO tests of dark matter

Constraints on DM self-interaction cross section from central density profiles in relaxed clusters and separation of dark and baryonic matter in cluster mergers.

MACSJ0025 (z=0.59)
Bradac et al. (2008)

IXO $\rightarrow$ gas velocity measurements and thermodynamic maps

Further DM constraints from evolution of c-M relation and searches for annihilation lines.