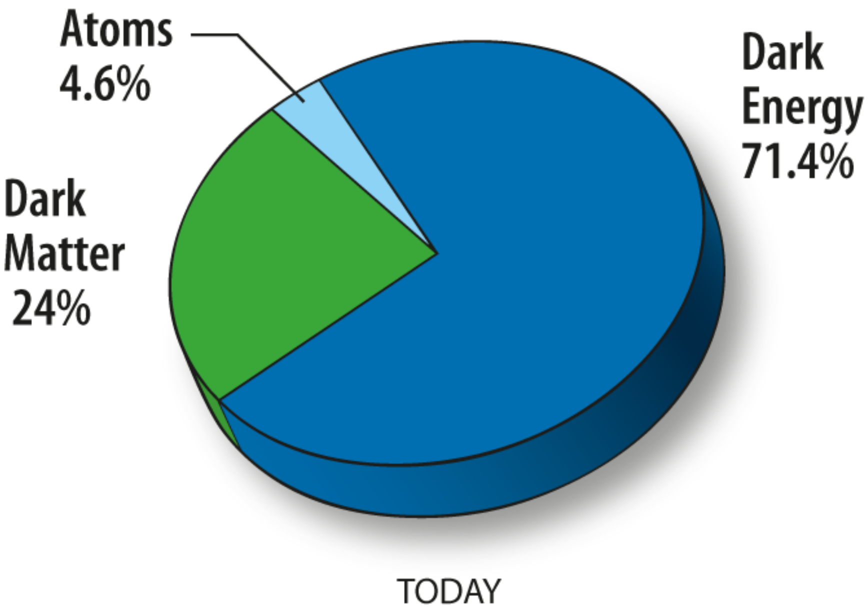
Chandra, Galaxy Clusters and Cosmology

Steve Allen (Stanford/SLAC)



NASA/ESA

In collaboration with:

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Adam Wright (MSOE)
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+ many more ...

Clusters as cosmological probes

Wu et al. 2011 Visualization: R. Kaehler

By comparing the observed internal structure and evolution of galaxy clusters with cosmological model predictions, we can constrain the properties of dark matter and dark energy, as well as gravity, neutrinos, inflation …

Method 1: The cluster gas mass fraction, f_{gas}

IDEA: Galaxy clusters are so large that their matter content should provide an approximately fair sample of matter content of Universe.

i.e.

$$f_{\text{gas}} = \frac{M_{\text{gas}}}{M_{\text{total}}} \sim \frac{\Omega_b}{\Omega_m}$$

Chandra
(+ weak lensing data)

In slightly more detail:

BBNS/CMB

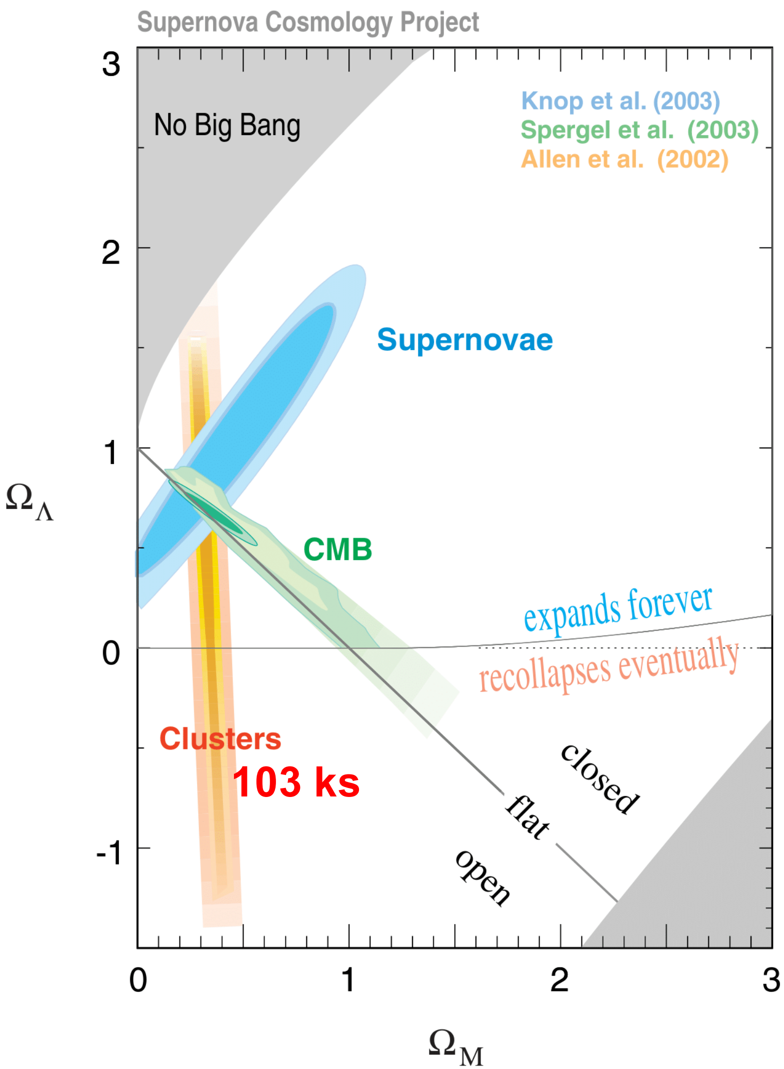
$$f_{\text{gas}}^{\text{ref}}(z) \propto Y(z) \left(\frac{\Omega_b}{\Omega_m}\right) \left[\frac{d_A^{\text{ref}}(z)}{d_A(z)}\right]^{1.5}$$

Observed

Depletion factor (simulations)

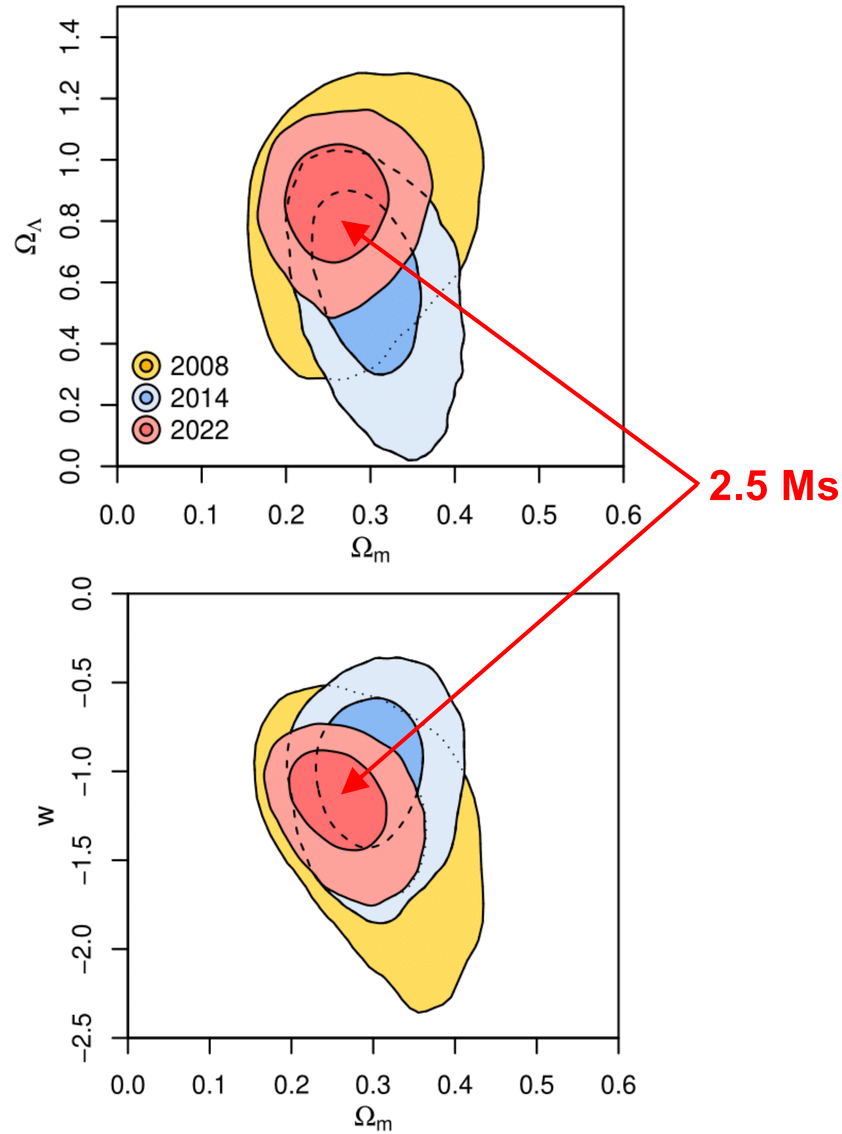
Cosmological sensitivity (matter density, dark energy)

Cosmological measurements with $f_{gas}(z)$

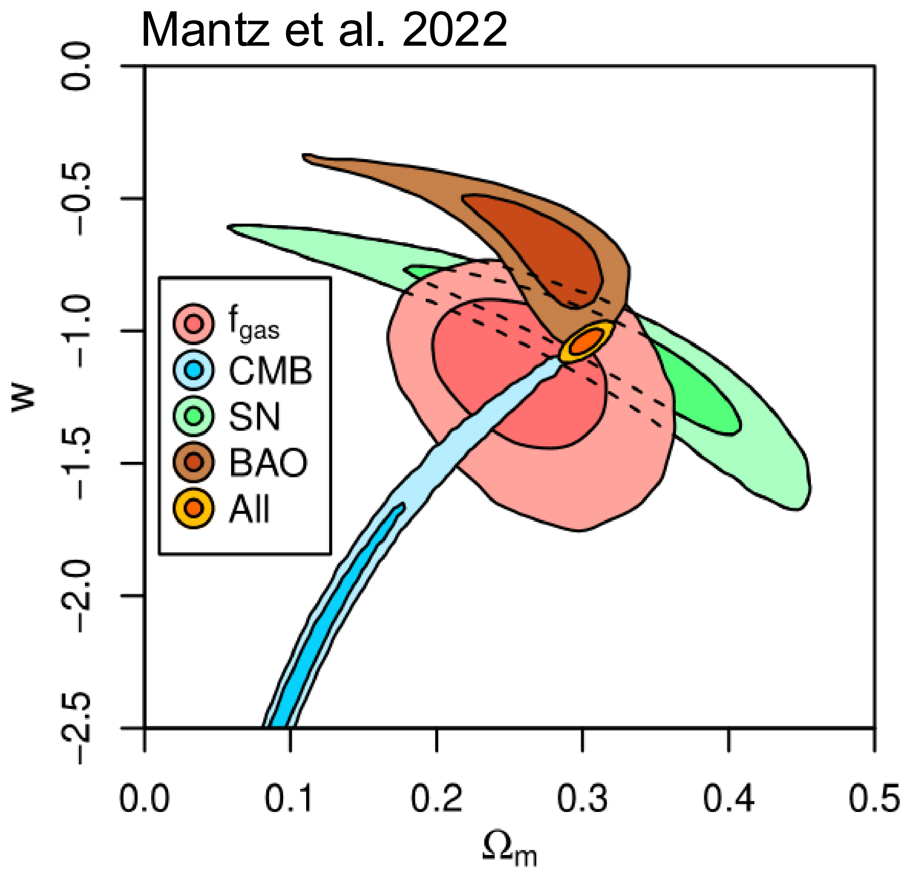


Perlmutter et al. 2003

Mantz et al. 2022



Latest $f_{gas}(z)$ constraints in multi-probe context



fgas(z) measurements continue to provide competitive, independent constraints on dark energy, complementary to other leading probes.

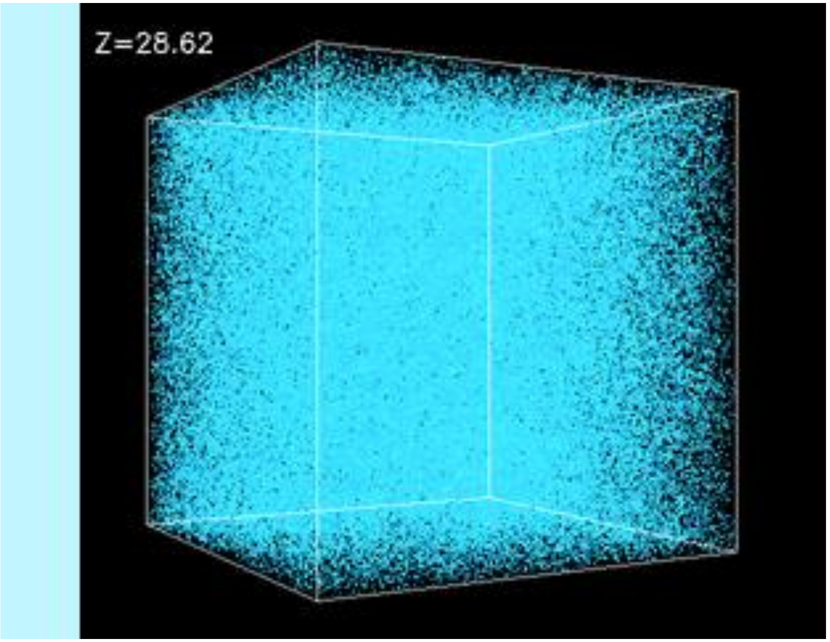
The **simplicity** of the method is a (substantial) **strength**.

The combination of these constraints remains consistent with standard ΛCDM (w = -1).

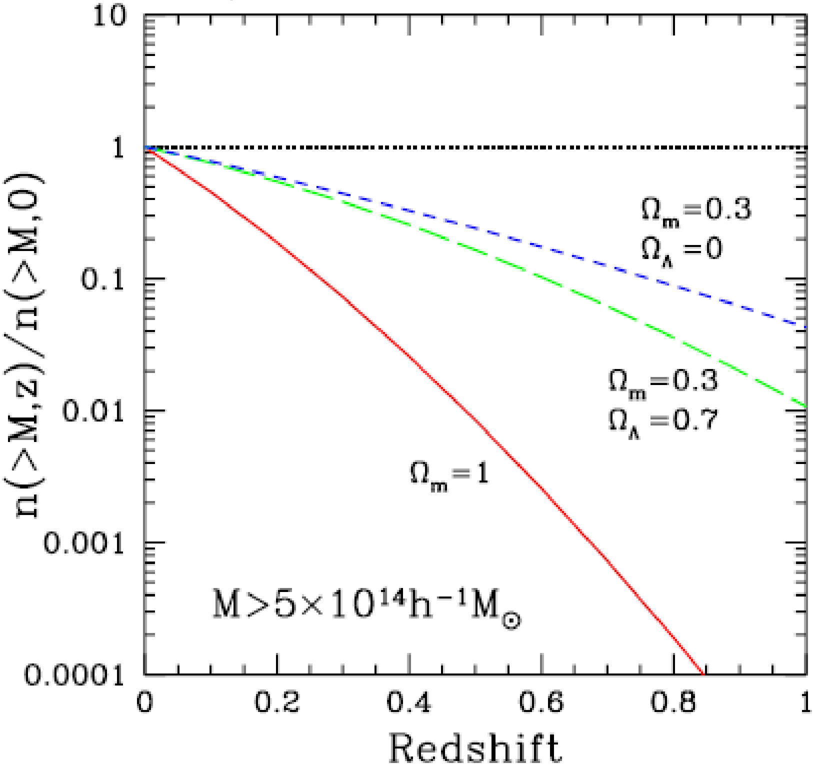
For the latest updates see posters 04-01 and 04-02 by Anthony Flores and Haley Stueber et al.

Method 2: cosmology with cluster counts

Kravtsov et al.



Borgani et al. 2004



IDEA: Measurements of number counts of galaxy clusters as a function of mass and redshift provide powerful constraints on cosmological parameters ("... could emerge as the most powerful cosmological probe", DOE Cosmic Visions Dark Energy Science report, arXiv:1604.07626)

Requirements for cosmology with cluster counts

[THEORY] The predicted mass function of clusters, n(M,z), as a function of cosmological parameters (σ_8,Ω_m,w etc).

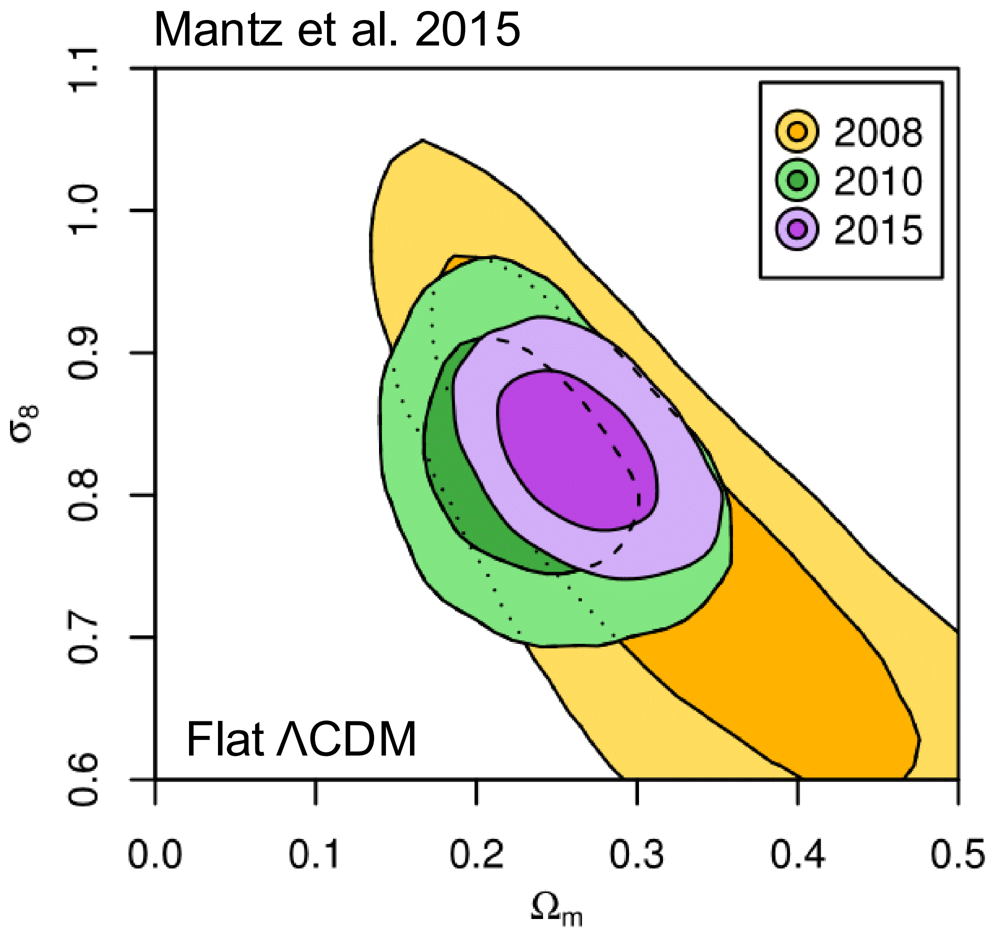
[CLUSTER SURVEY] A large, clean, complete cluster survey with a well-defined selection function.

Here, catalogs based on the ROSAT All-Sky Survey (RASS) proved **foundational** (exquisite purity and completeness). Work to develop next generation mm-wavelength (SZ; Planck, SPT, ACT) and X-ray (eROSITA) catalogs advancing rapidly (but still work to do!)

[MASS-OBSERVABLE RELATION] Well-calibrated scaling relation(s) linking survey observable (e.g. Lx, richness, SZ flux) to M,z.

Chandra provides low-scatter mass proxies (M_{gas},Tx,Yx) which precisely measure the relative masses of individual clusters (with independent weak lensing data providing robust absolute mass calibration for ensemble).

Impact of improved mass calibration



Key advances:

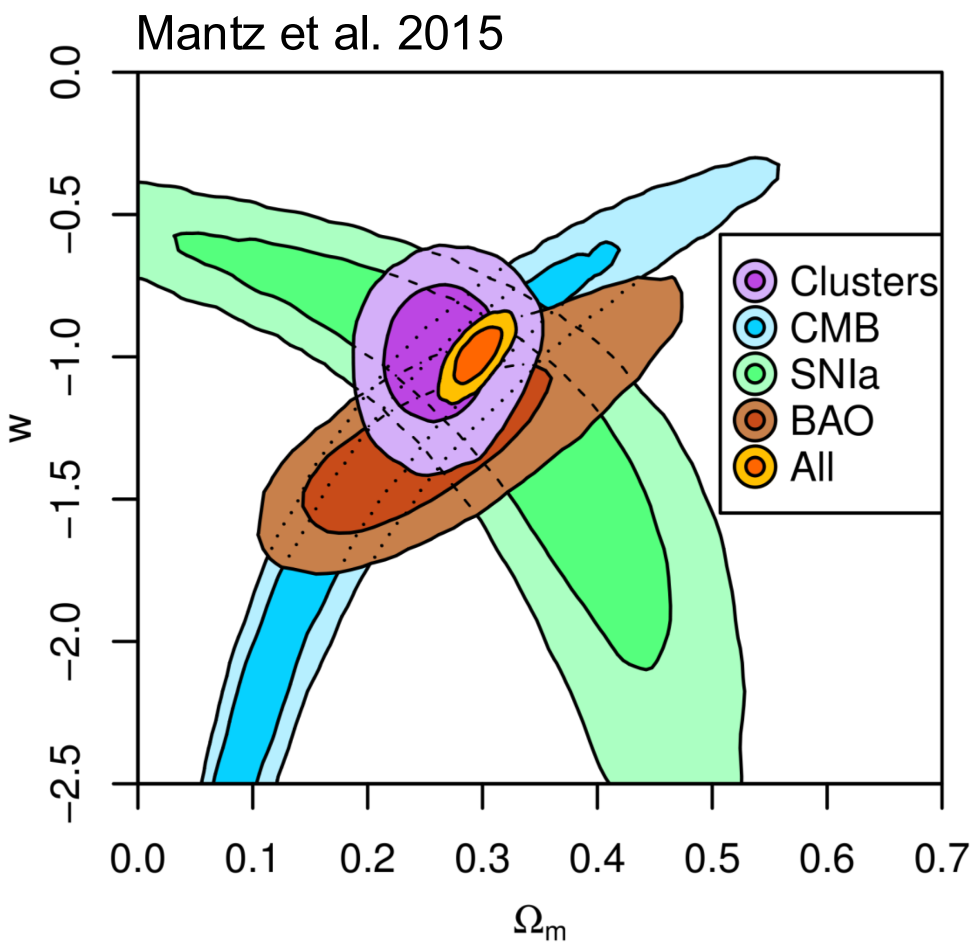
2008 → 2010: inclusion of low-scatter Chandra X-ray mass proxies.

2010 → 2015: inclusion of Weighing the Giants weak lensing mass calibration.

See also Vikhlinin et al. 2009, Mantz et al. 2010, deHaan et al. 2016, Bocquet et al. 2019)

The addition of low-scatter Chandra X-ray mass proxies + WL mass calibration → substantial boost in cosmological constraining power.

Dark energy constraints from cluster counts



Flat, constant w model:

Clusters (Mantz et al. 15)
CMB (WMAP9+SPT+ACT)
SNIa (Suzuki et al. '12)
BAO (Anderson et al. '14)

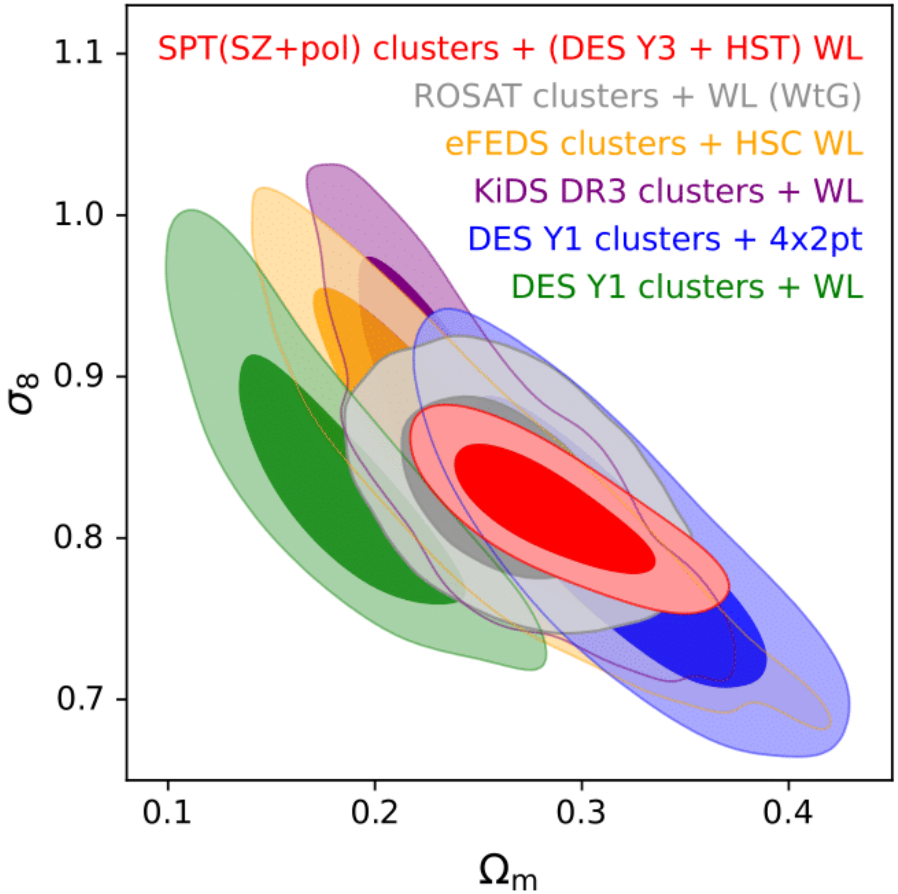
Combined constraint (68%)

$\Omega_m = 0.295 \pm 0.013$
$\sigma_8 = 0.819 \pm 0.026$
$w = -0.99 \pm 0.06$

All 4 independent techniques consistent with cosmological constant.
Cluster constraints (highly) competitive with other leading methods.

Latest cluster count constraints in multi-probe context

Bocquet et al. 2024



The constraints on Ω_m and σ_8 from cluster counts remain competitive with other methods.

No sign of σ_8 tension for clusters vs. primary CMB.

Best constraints on dark energy from cluster counts still from RASS (better coverage of 0<z<0.5 universe when DE dominated expansion – plus exquisite purity, completeness).

Summary and look ahead

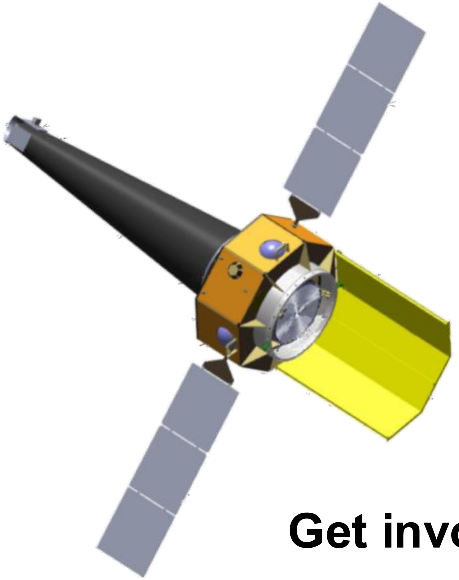
Chandra observations of galaxy clusters played an important role in helping to establish our modern understanding of cosmology and fundamental physics.

Key results included precise, robust measurements of Ω_m and σ_8 and some of the tightest individual constraints on the properties of dark energy.

Progress was rapid in the first 15 years of the mission but then slowed given the large exposure times required to make substantial improvements (requires Ms).

To reaccelerate progress, we need a new mission providing high spatial resolution X-ray imaging but with greater collecting area (~10x Chandra)

The Advanced X-ray Imaging Satellite



One of two Probe concepts (one X-ray, one FIR) selected by NASA for Phase A study (downselect 2026; winner to launch 2032).

Get involved!

https://axis.astro.umd.edu/