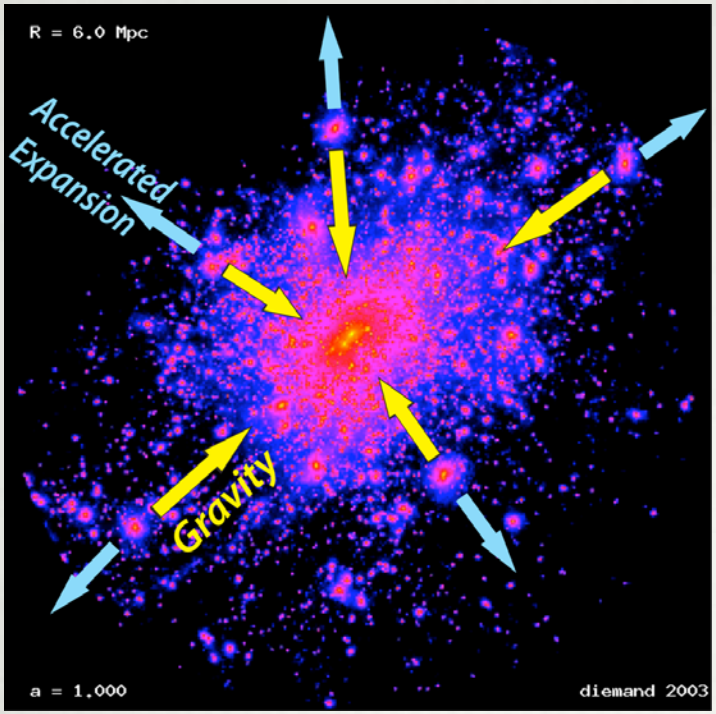
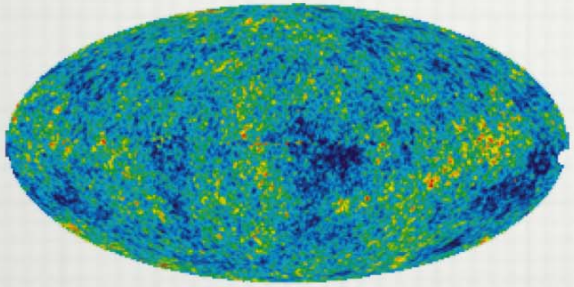
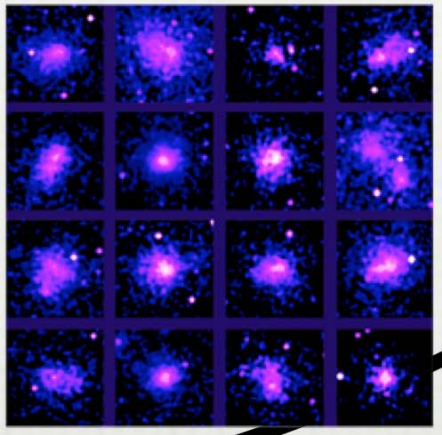
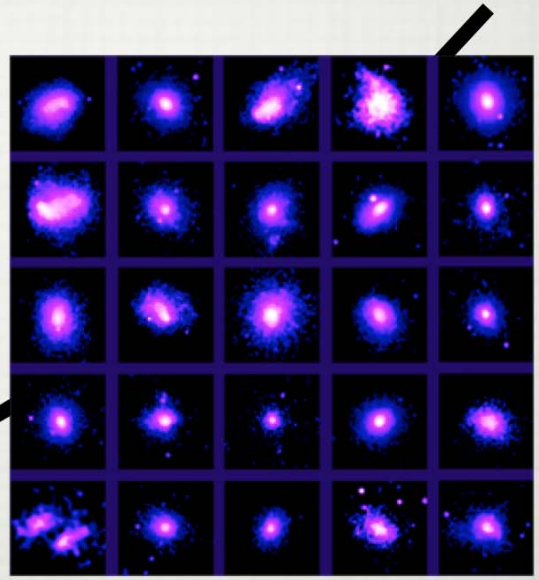


DARK ENERGY STUDIES WITH *CHANDRA*

A.VIKHLININ







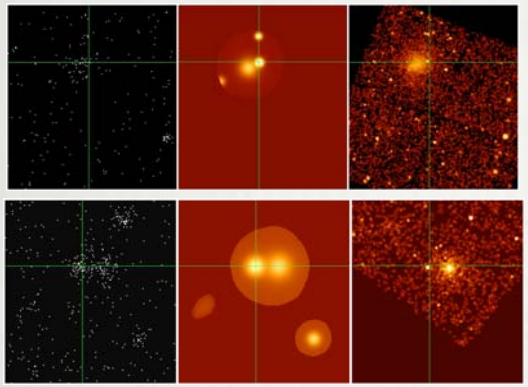
Dark Energy fraction

Time

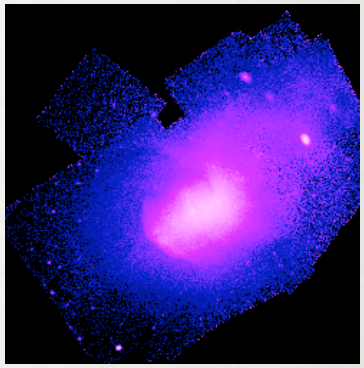
$z = 1000$ $z = 0.5$ $z = 0$

X-RAY COSMOLOGY: CURRENT STATE

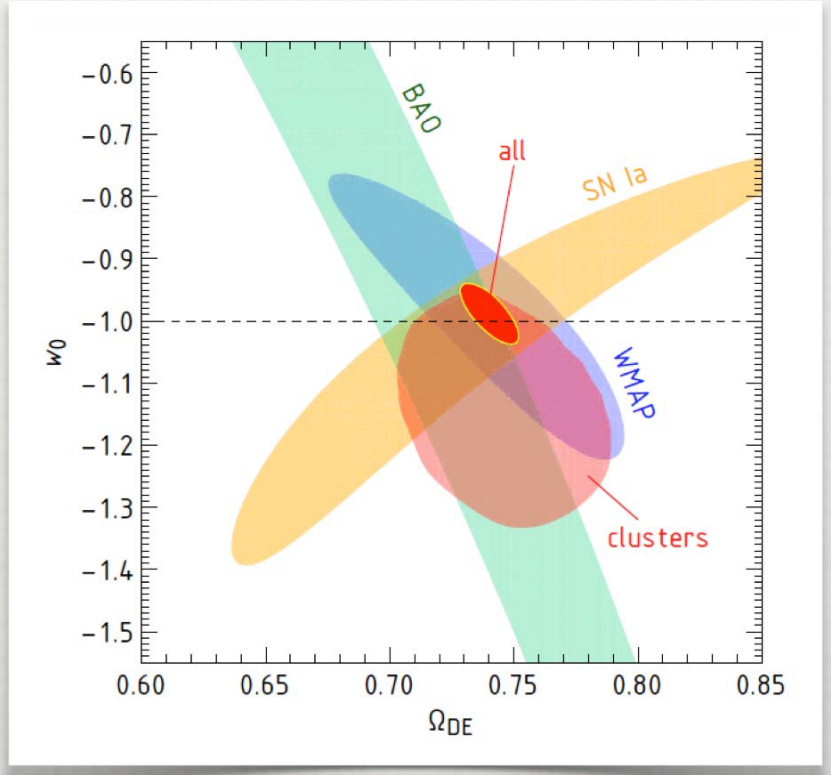
Cluster samples: *ROSAT*



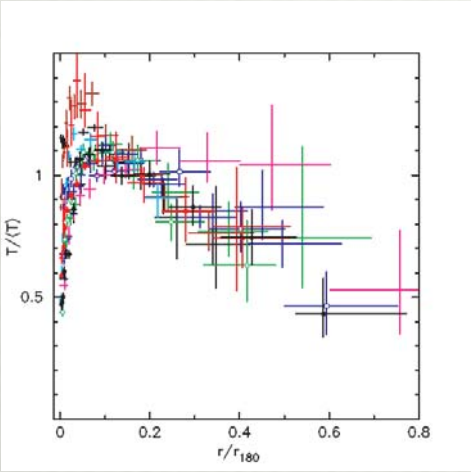
Cluster physics:
Chandra & simulations



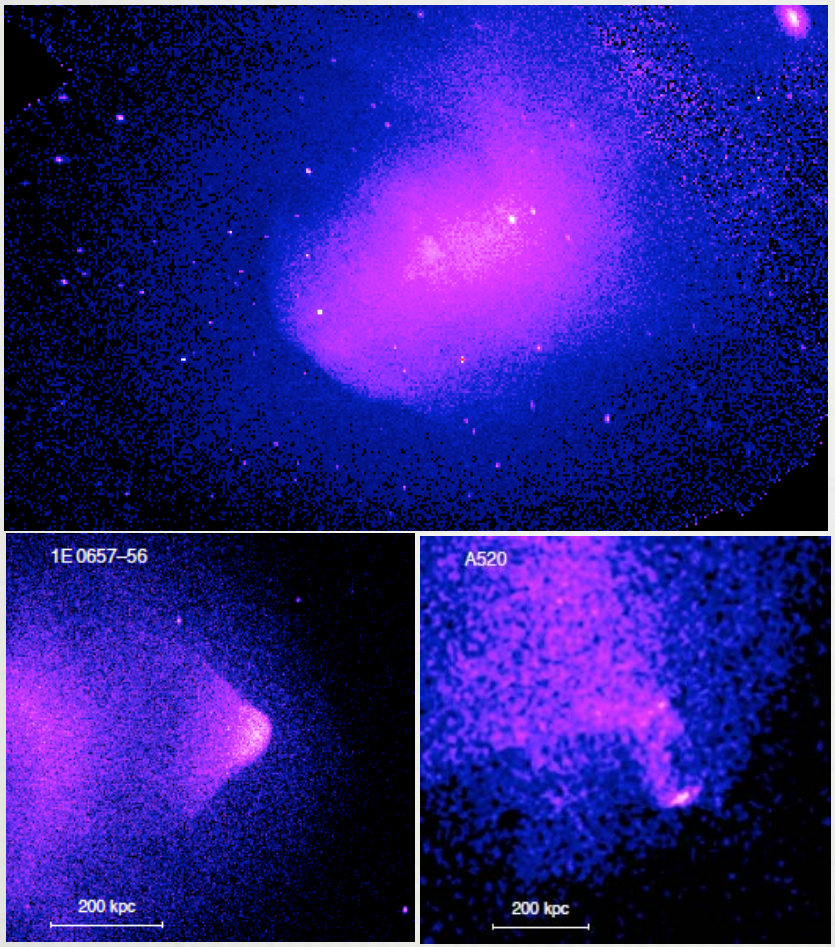
Dark Energy
constraints

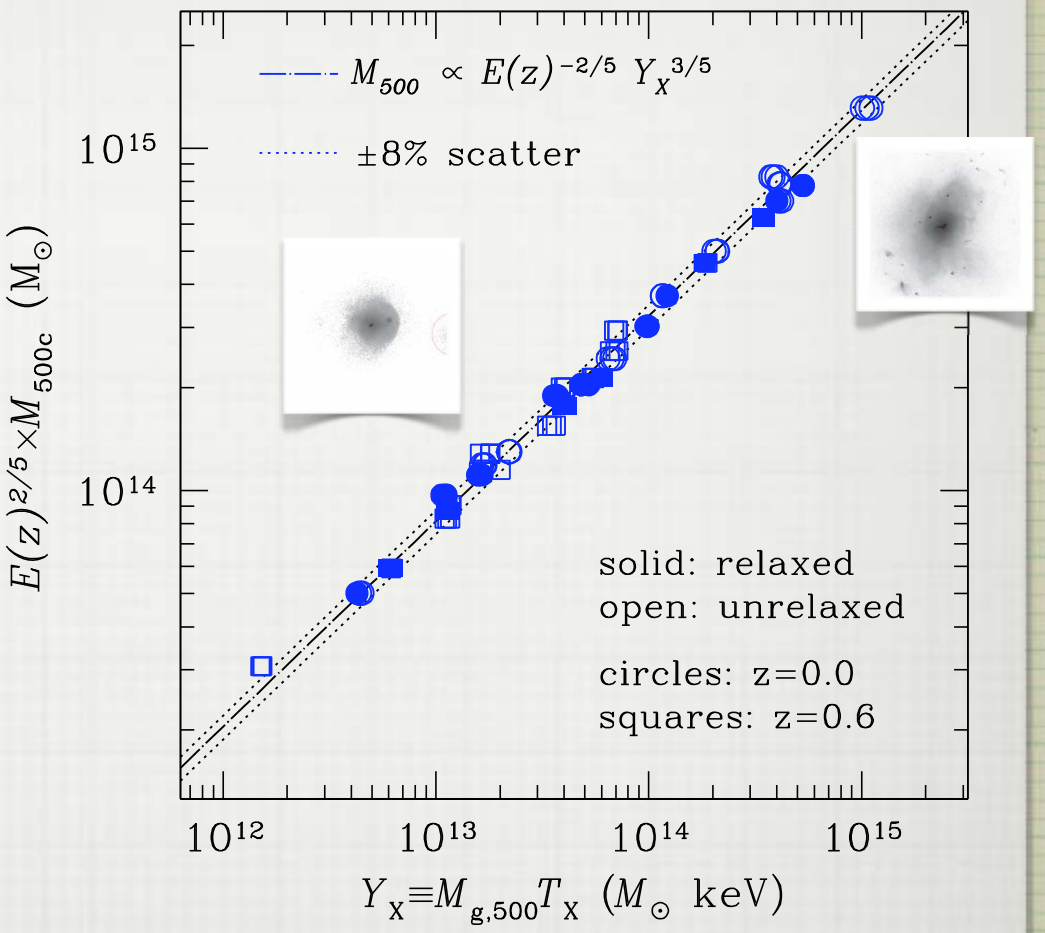


Detailed properties:
Chandra & *XMM*



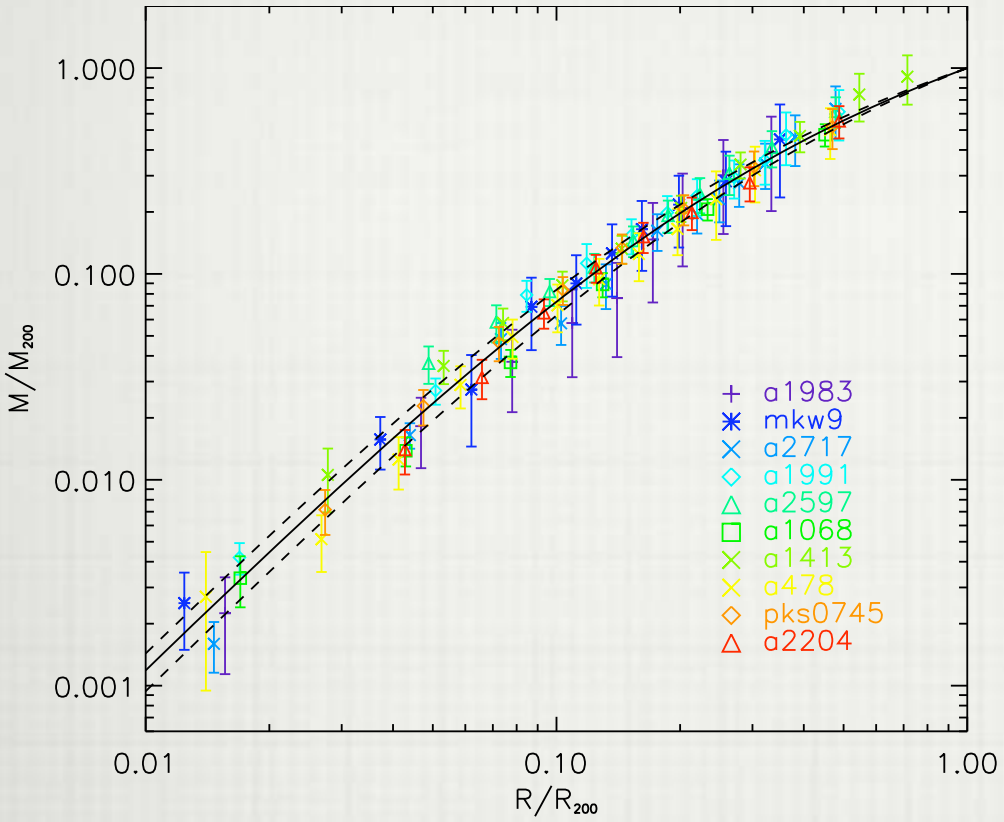
PHYSICS: *CHANDRA* AND MODELS

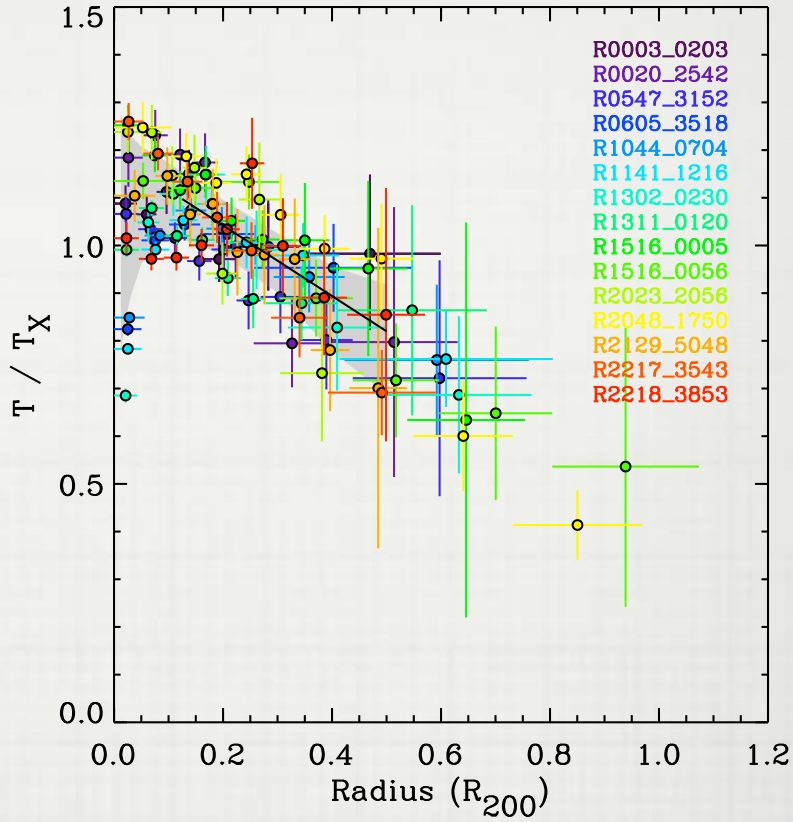




- Direct observational constraints on ICM physics
- Advances in computer modeling
- Identification of robust mass indicators

DETAILED DATA: *CHANDRA & XMM*

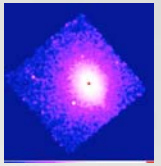


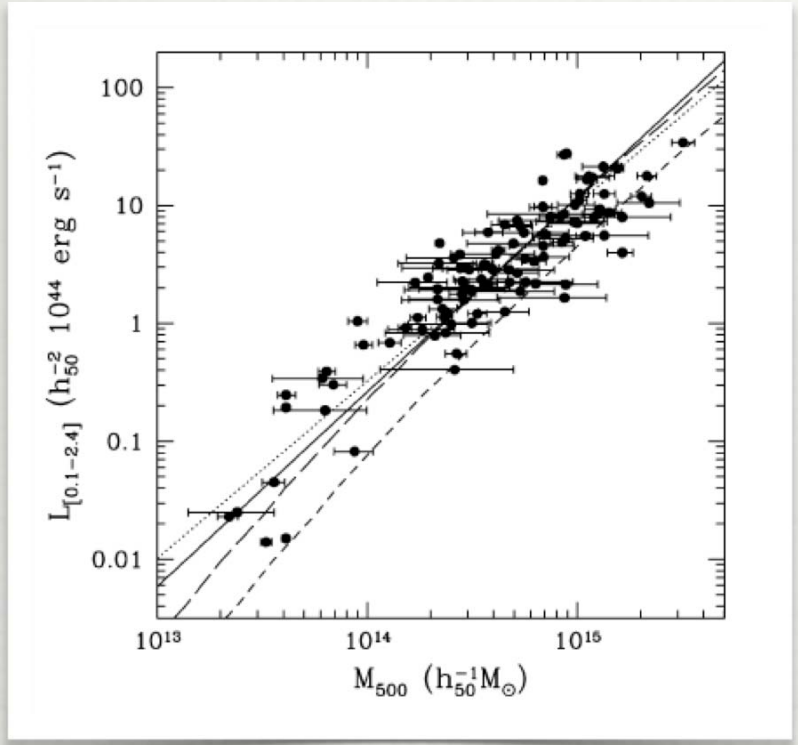


- **Detailed *T*(*r*), *ρ*(*r*) measurements**

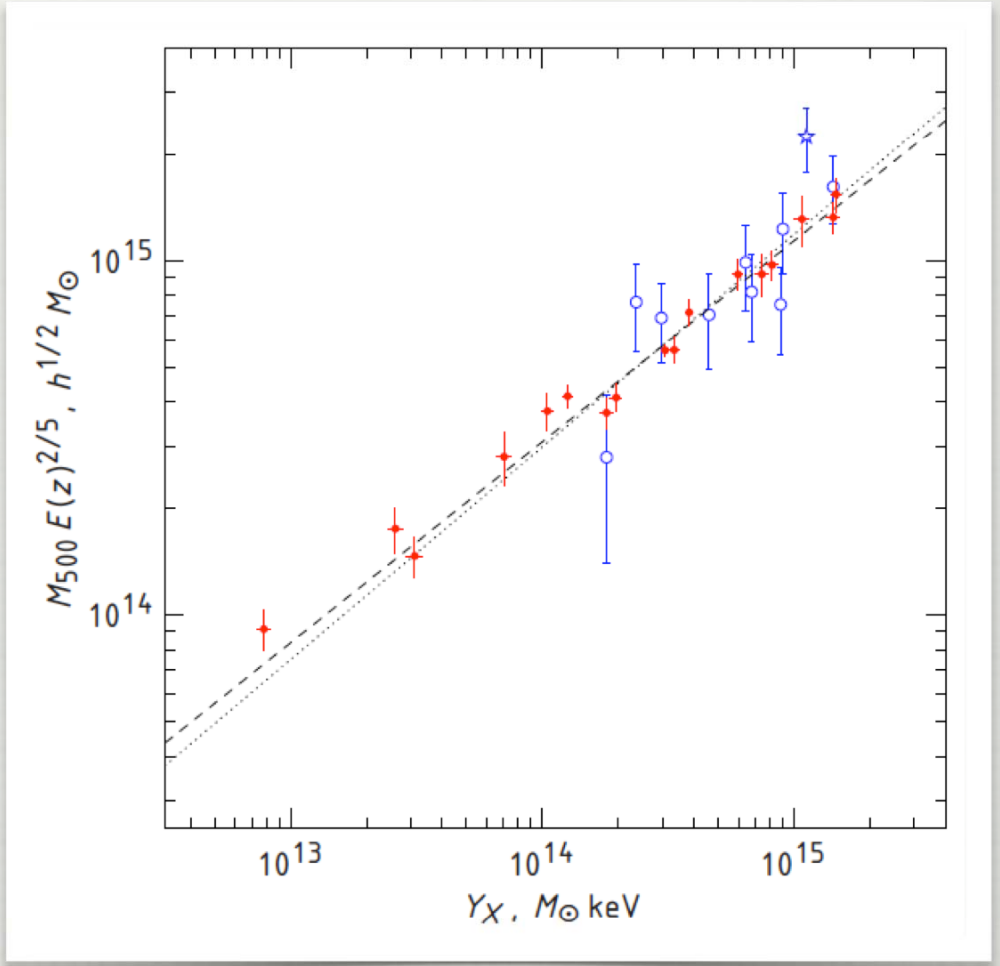
Pointecouteau '05, Pratt et al. '07

MASS CALIBRATION



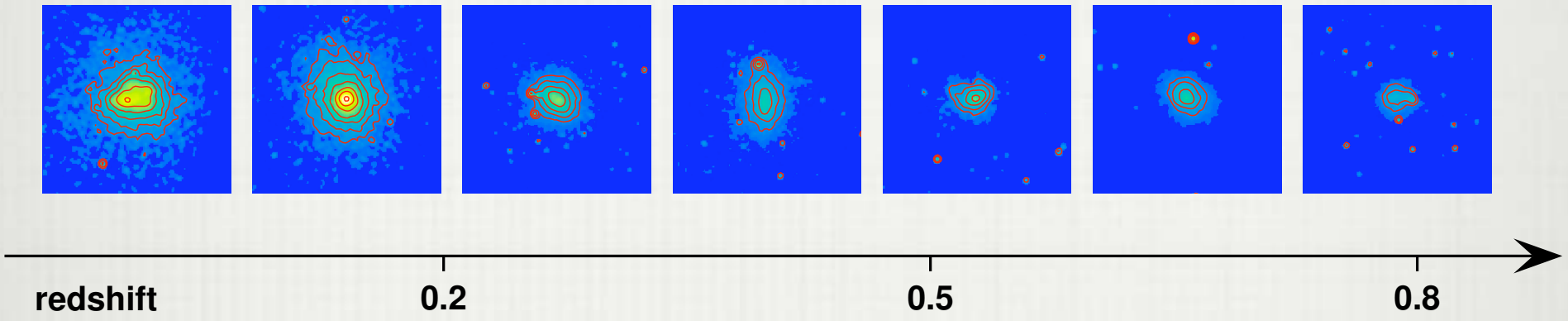


Before *Chandra*



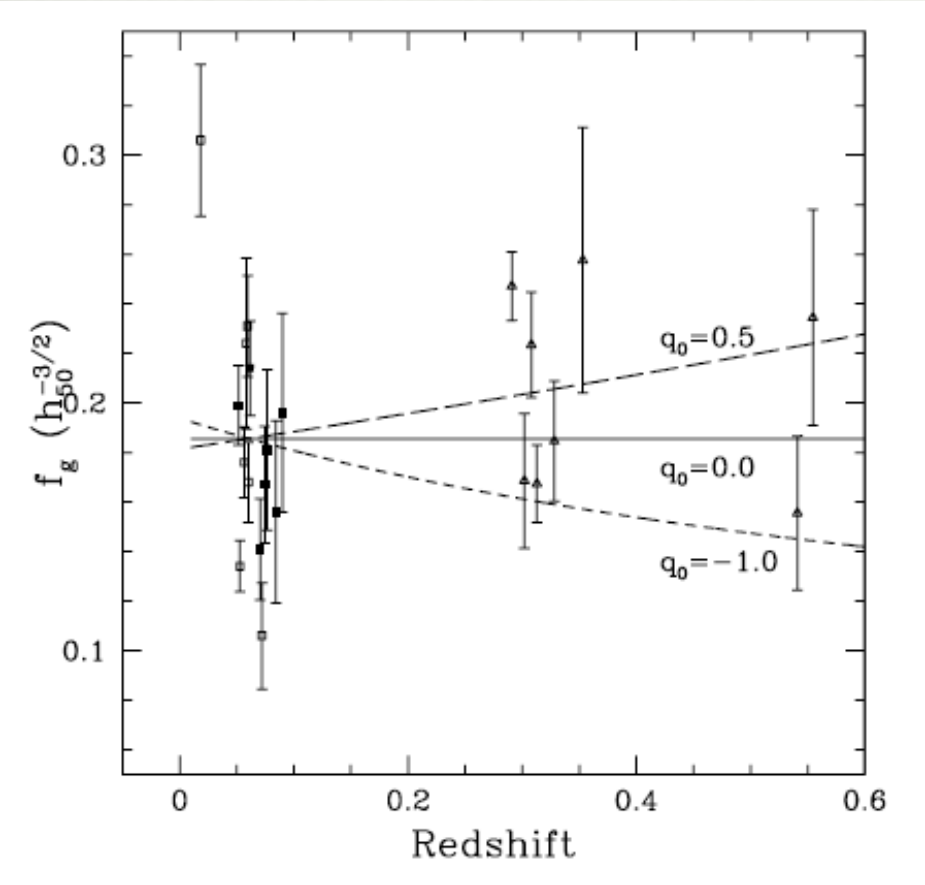
• – *Chandra*, hydrostatic ○ – Weak lensing, Hoekstra '07

GEOMETRIC TEST WITH $f_{gas}(z)$

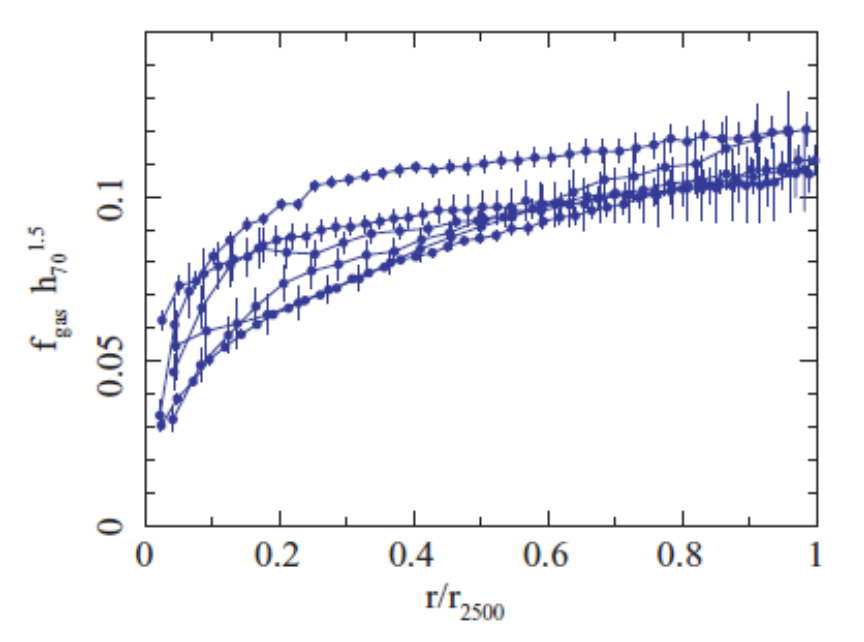


- $f_{gas}(z)$ gives $d(z)$
- $f_{gas}(0)$ is a test for Ω_M

GEOMETRIC TEST WITH $f_{gas}(z)$

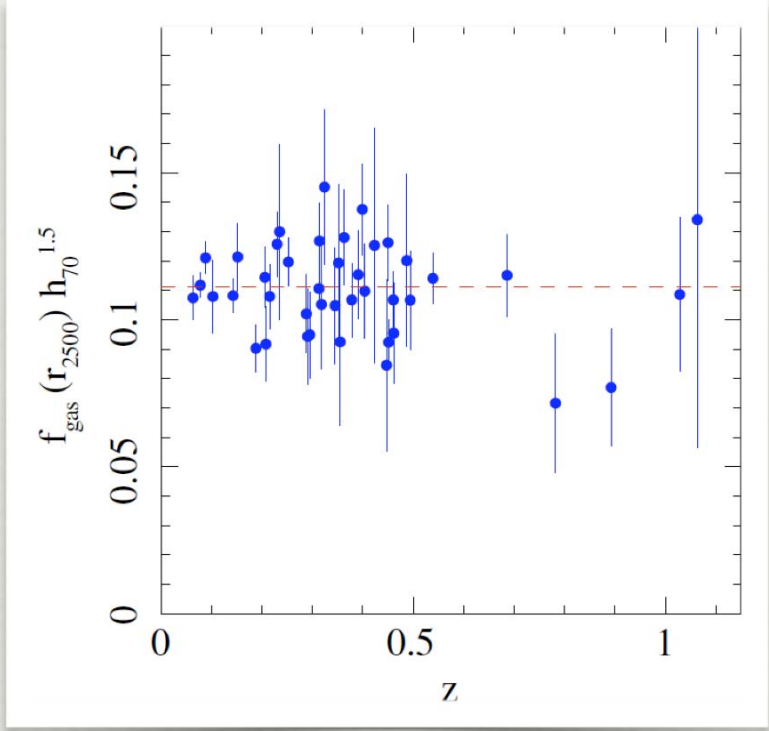


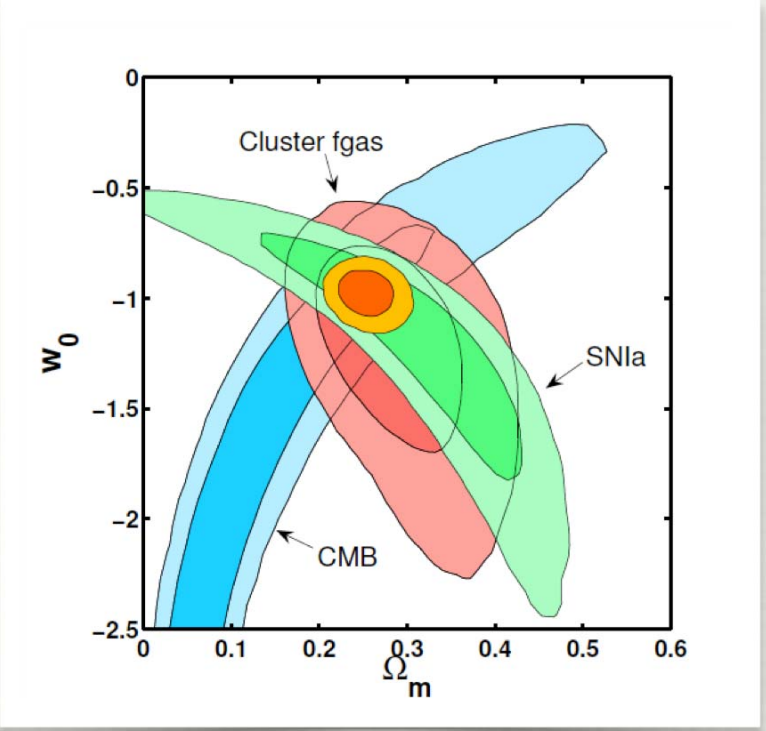
Before *Chandra*



Sample results from Allen et al.

GEOMETRIC TEST WITH $f_{gas}(z)$

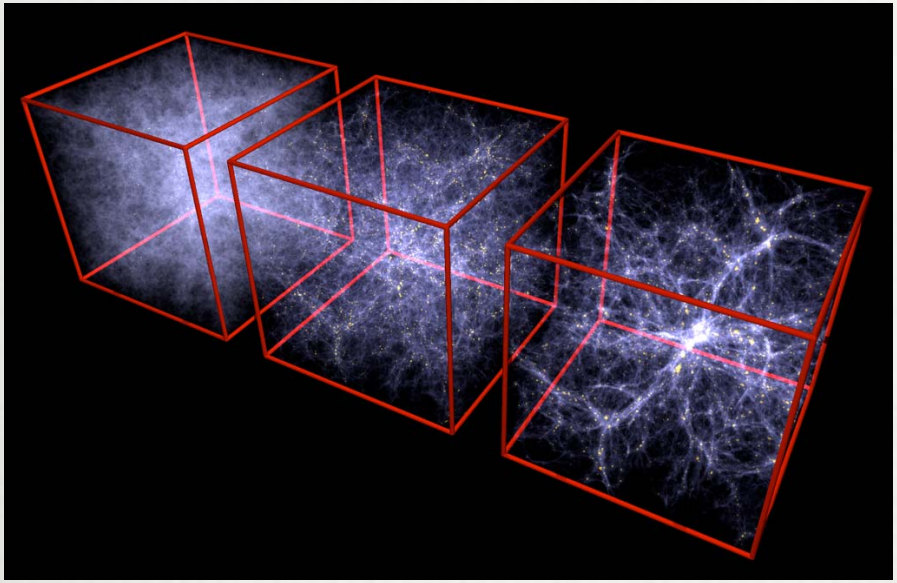




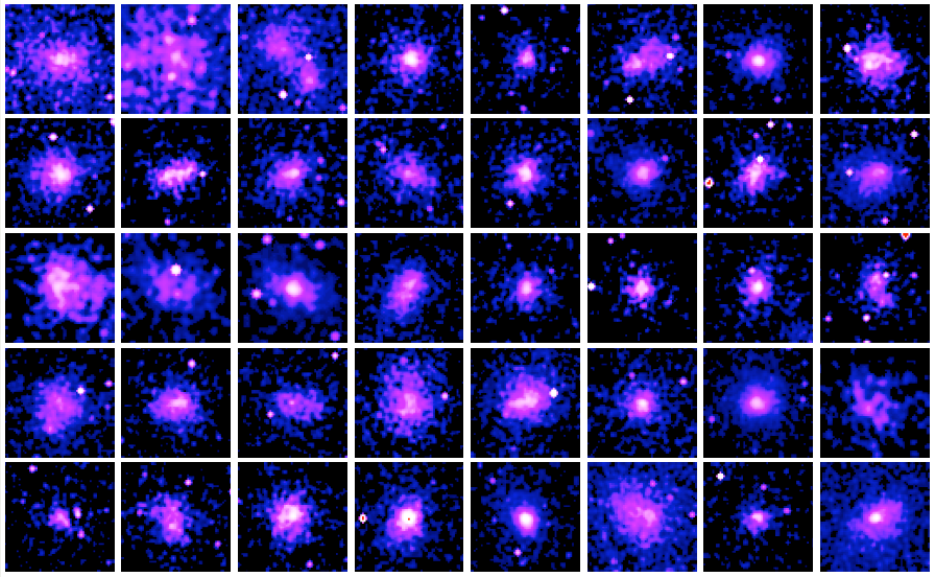
- Independent geometric confirmation of accelerated expansion
- Constraints on equation of state

Allen et al.

GROWTH OF STRUCTURE TEST



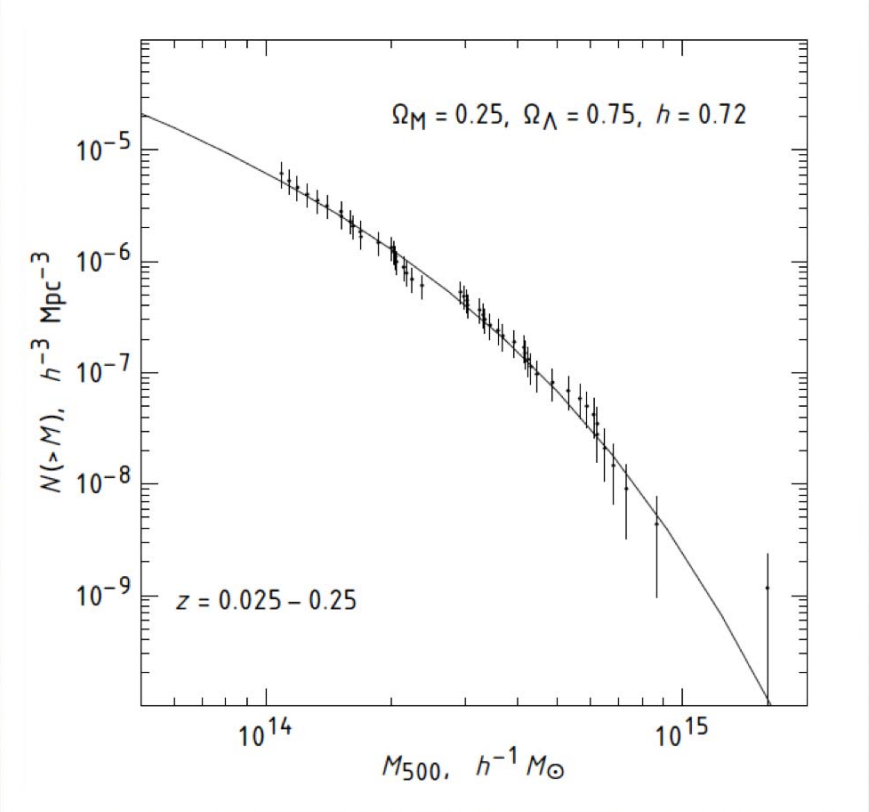
Numerical simulations

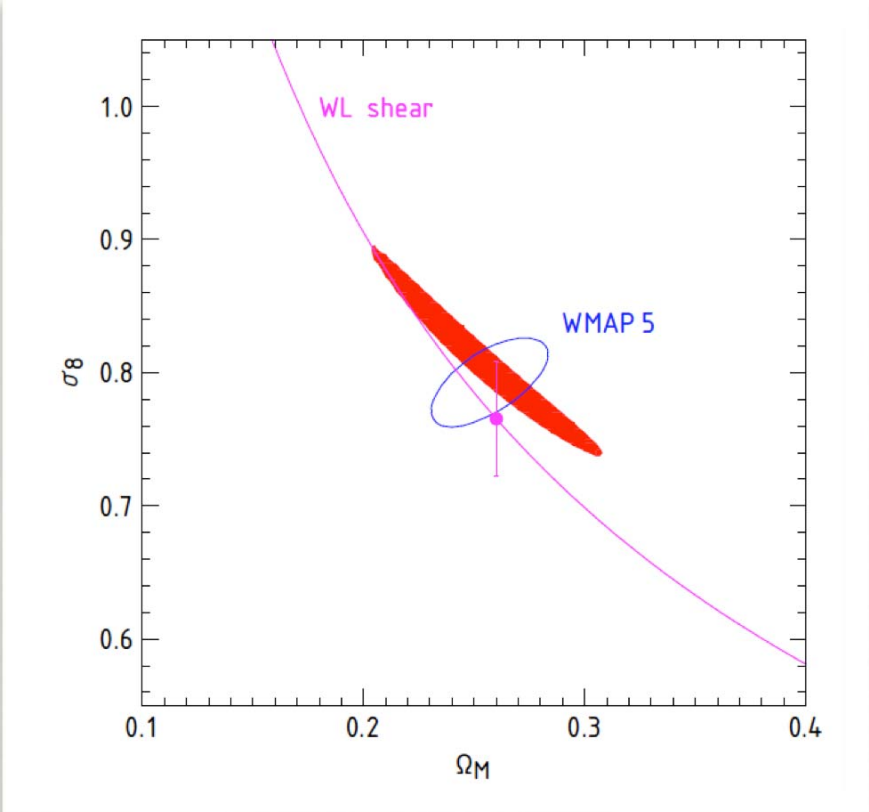


Chandra images of high-z clusters

- Measure how accelerated expansion stifles growth of structures
- Use clusters as "sensors" of structure

CLUSTER MASS FUNCTION TEST

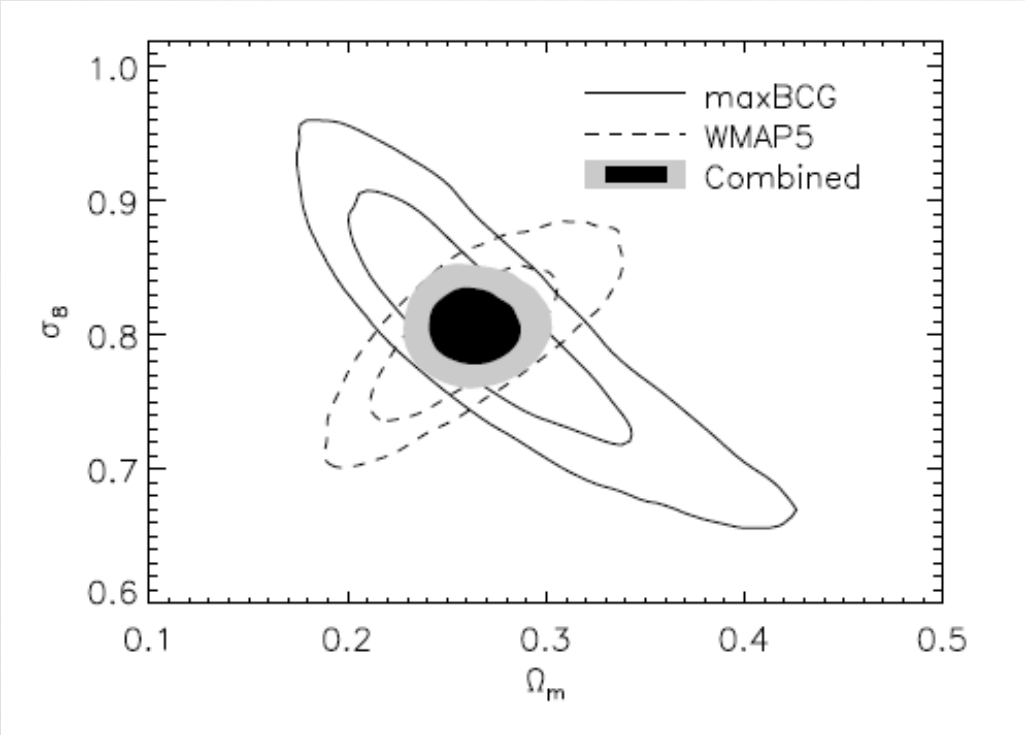




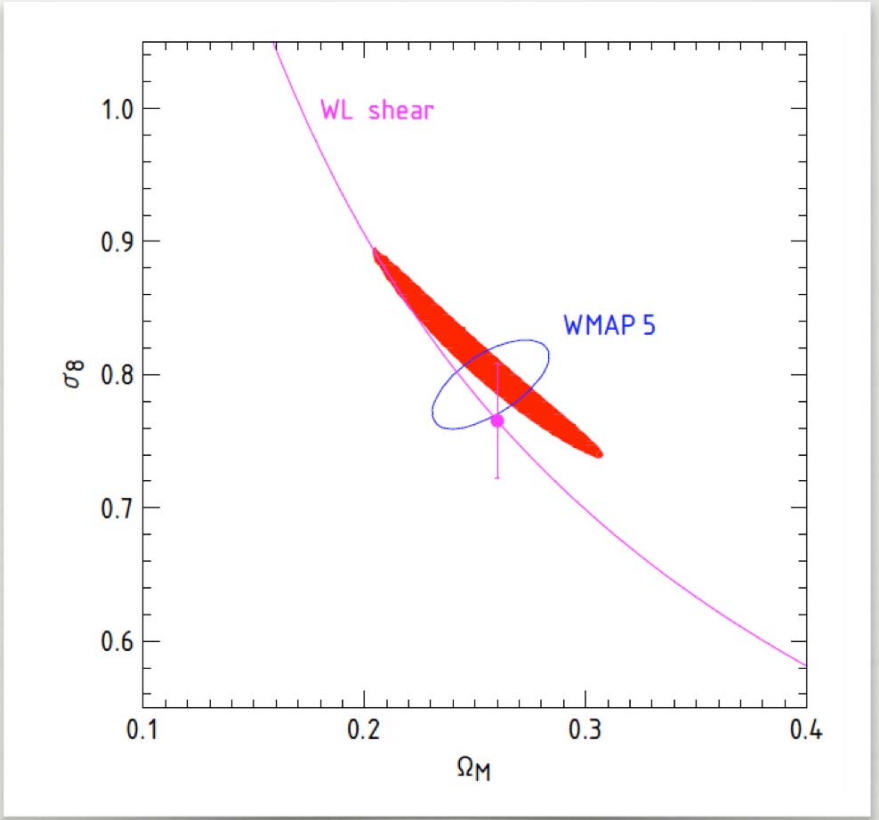
- **50 clusters $\Longrightarrow$ σ_8 to ±1.5% (±3% sys)**

2009 ApJ 692 1060

CLUSTER MASS FUNCTION TEST



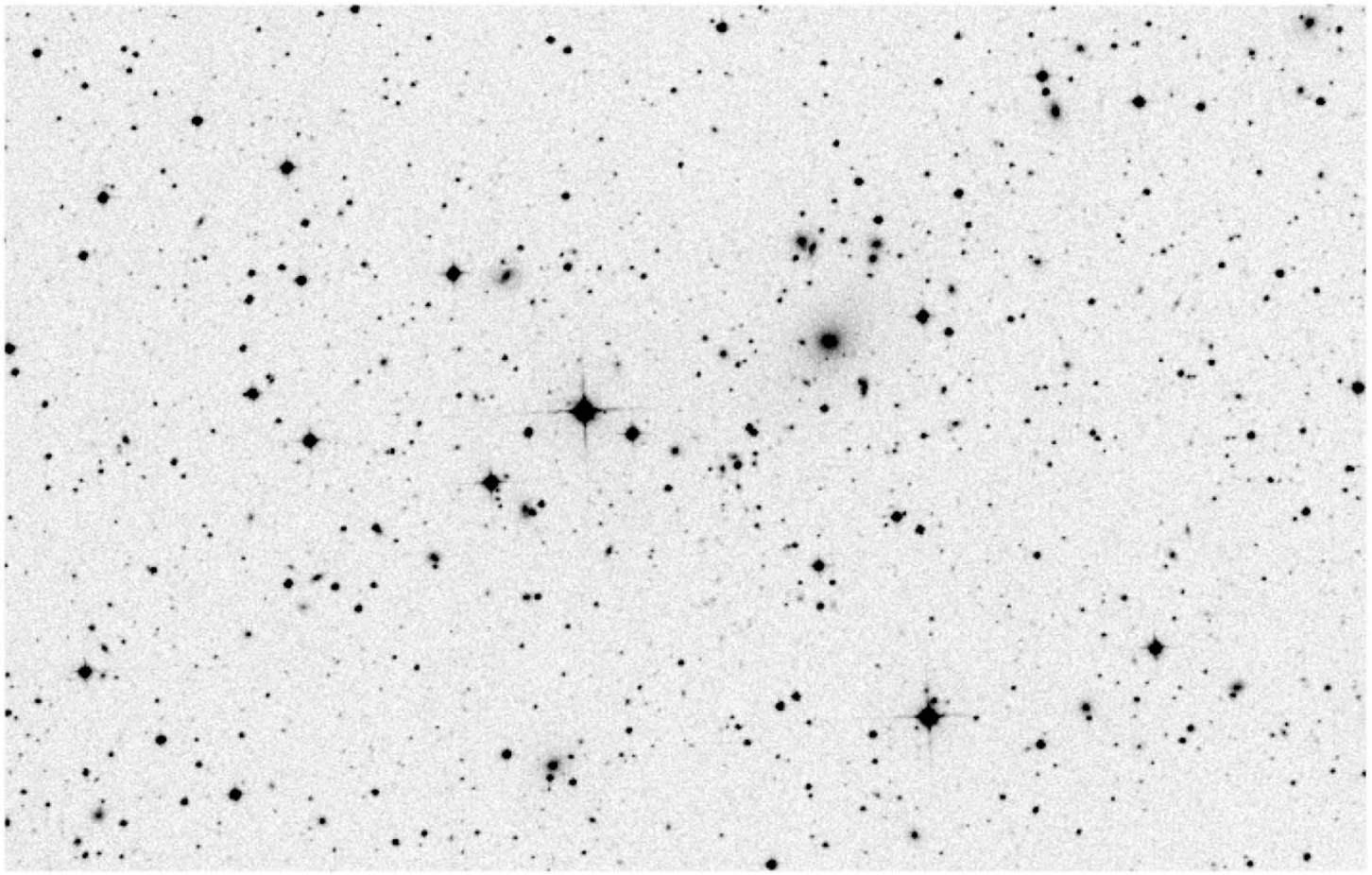
SDSS results, Rozo et al.



- **X-rays: 50 clusters $\Longrightarrow$ σ_8 to ±1.5% (±3% sys)**
- **SDSS: 10,000+ clusters $\Longrightarrow$ σ_8 to ±3.3%**

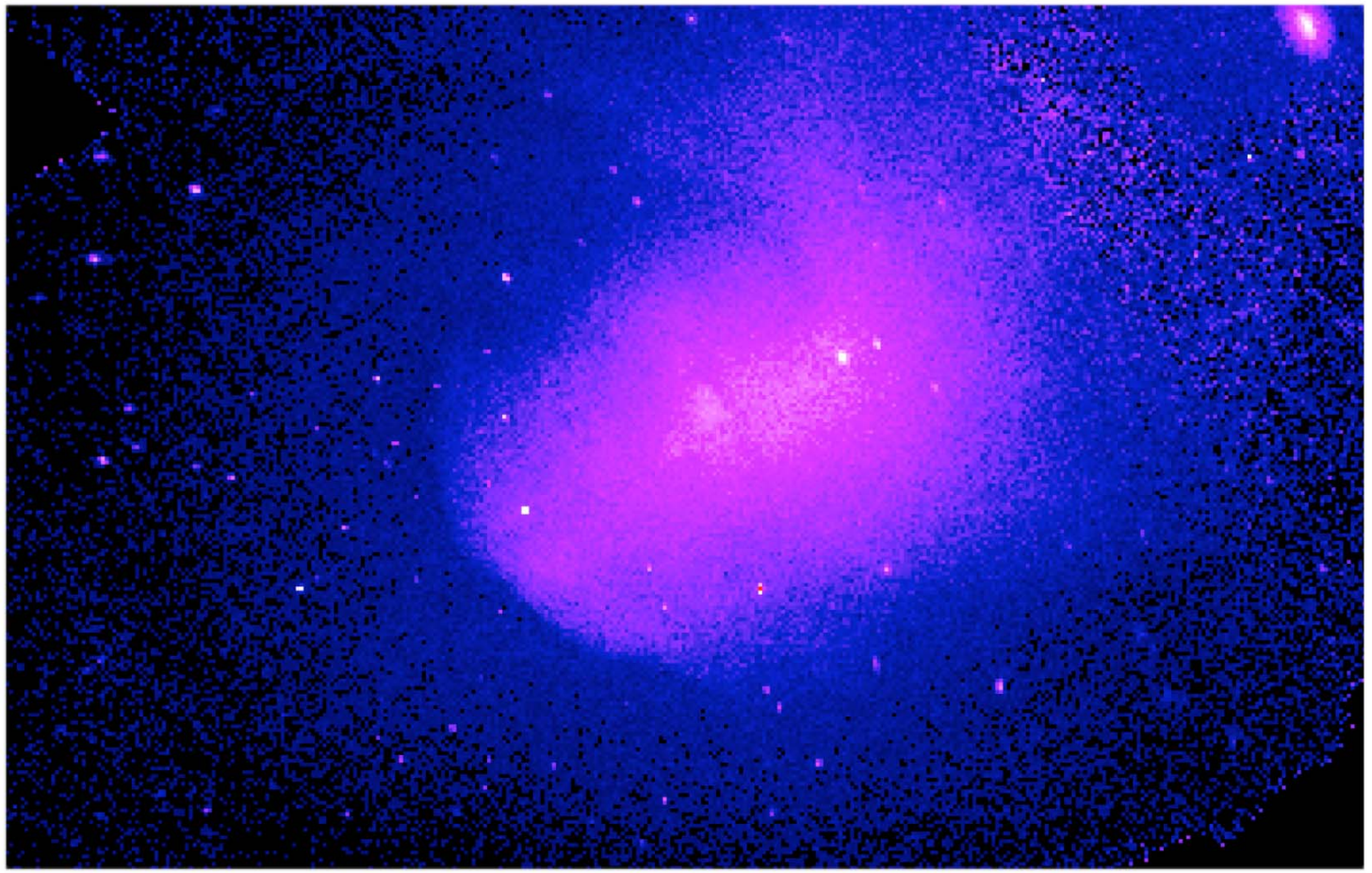
2009 ApJ 692 1060

WHY X-RAYS?



A3667, optical image

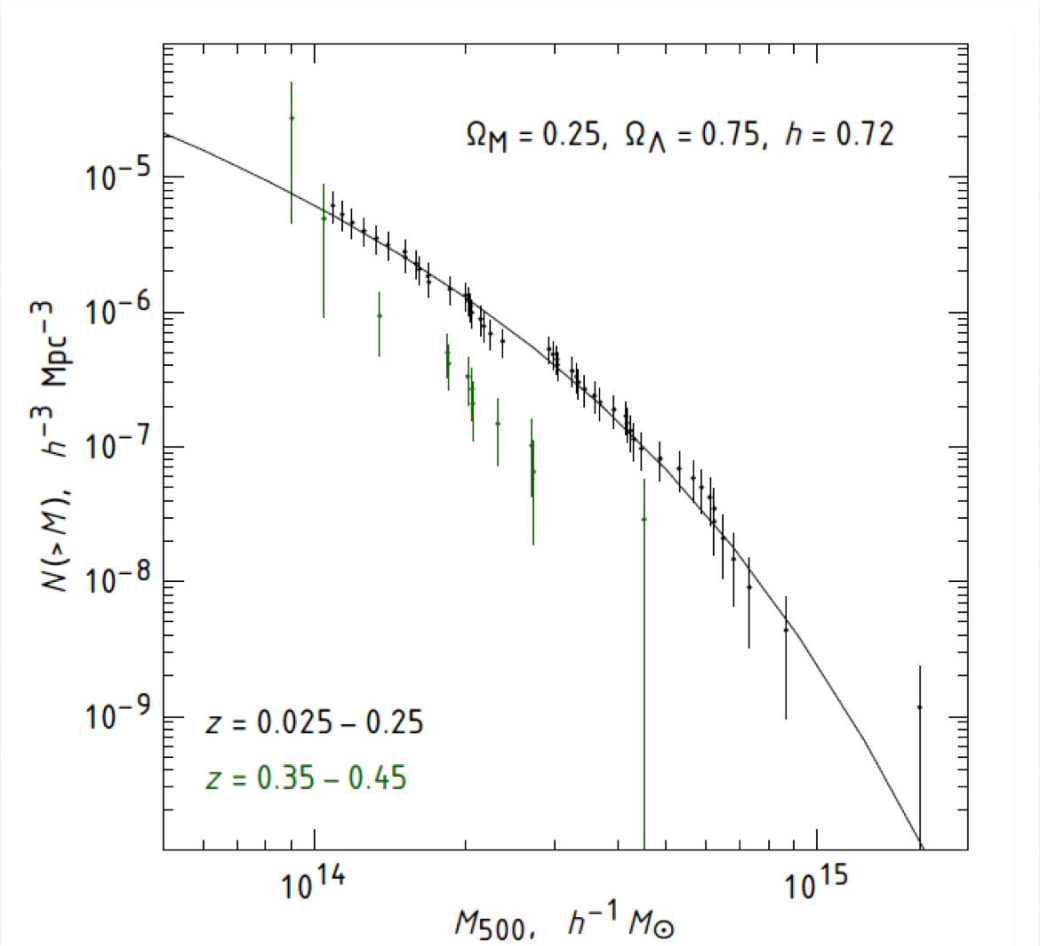
WHY X-RAYS?



- Observe dominant baryonic component
- Detectable with very few photons — $N_{phot} \ll N_{gal}$
- Detectable to high z

A3667, Chandra image

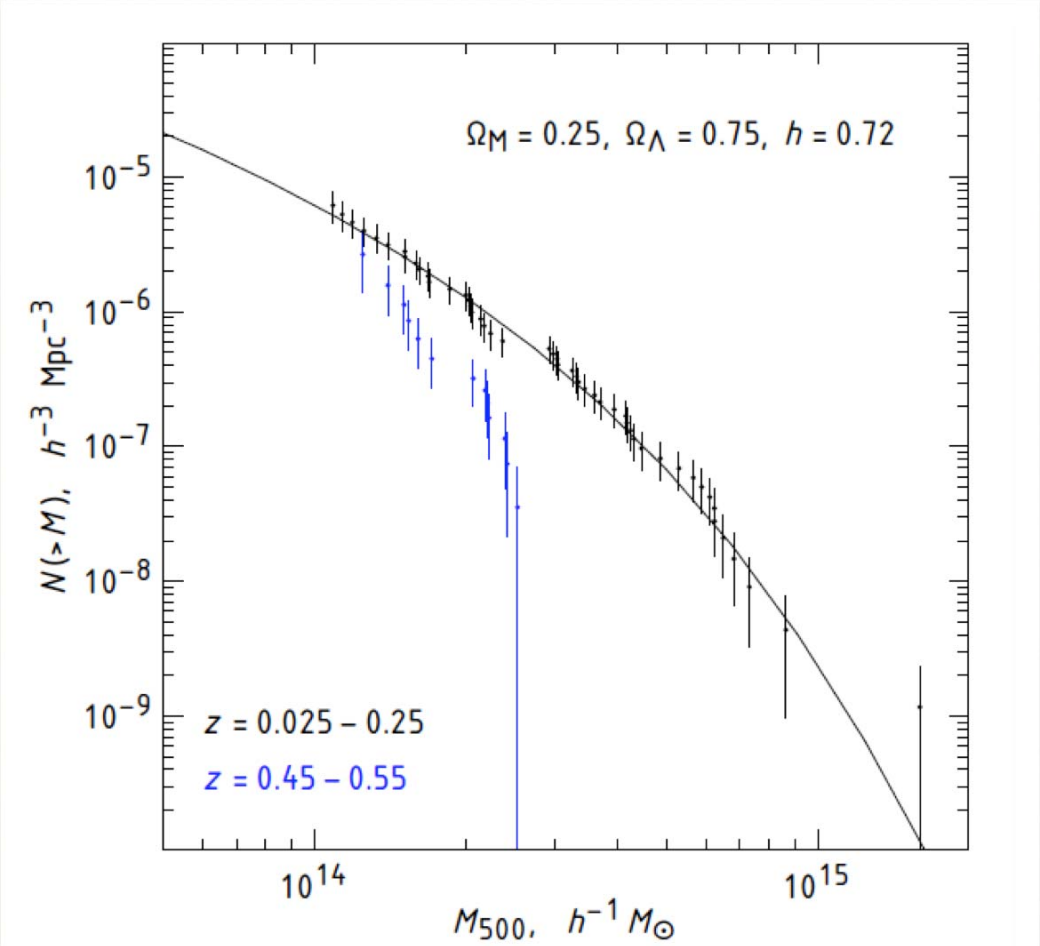
CLUSTER MASS FUNCTION TEST



Measure σ_8 at $z \approx 0$ *and* $z = 0.35–0.45$

2009 ApJ 692 1060

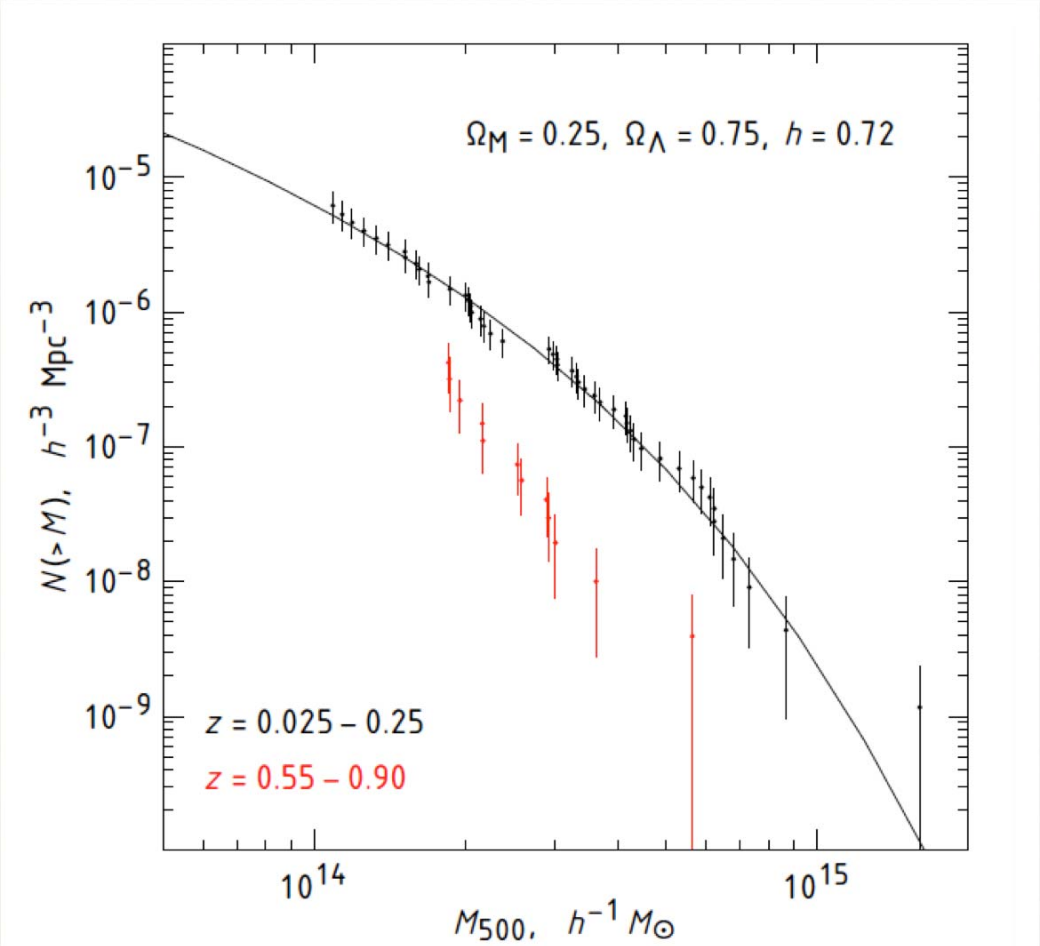
CLUSTER MASS FUNCTION TEST



Measure σ_8 at $z \approx 0$ *and* $z = 0.35–0.45$ *and* $z = 0.45–0.55$

2009 ApJ 692 1060

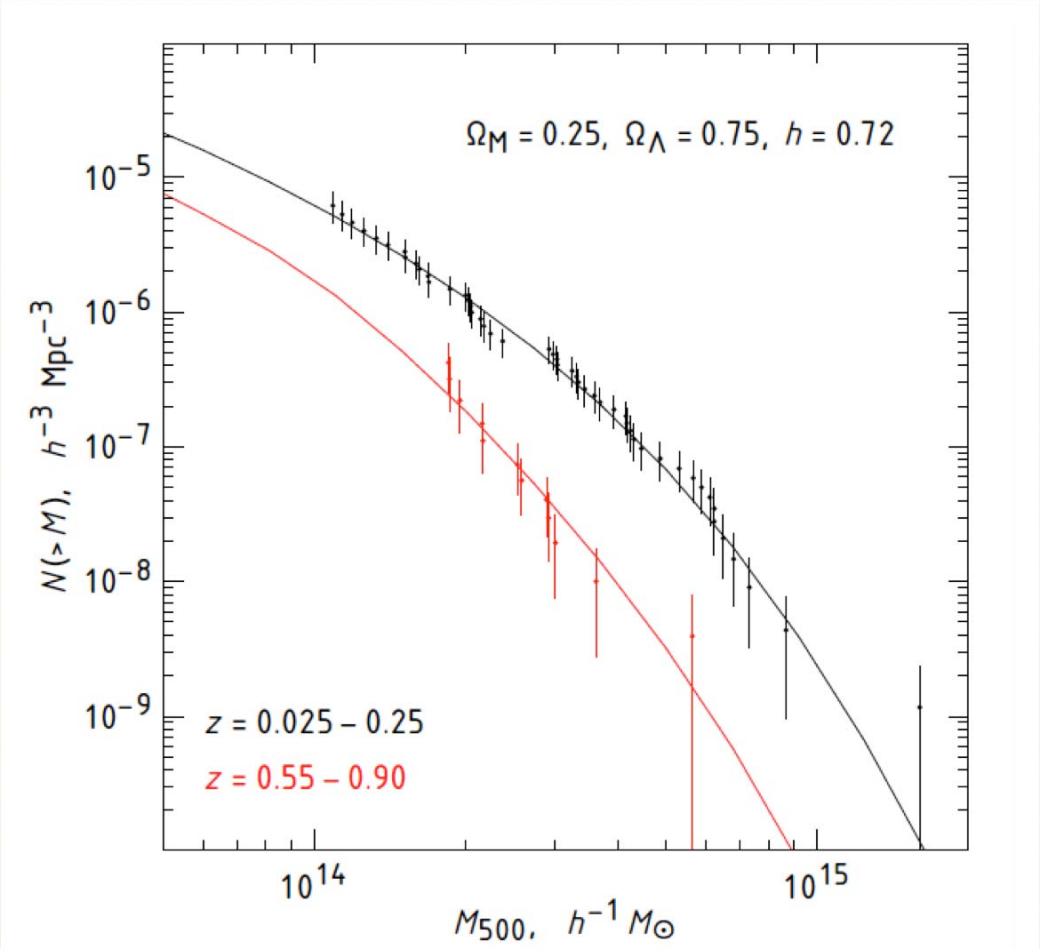
CLUSTER MASS FUNCTION TEST



Measure σ_8 at $z \approx 0$ *and* $z = 0.35–0.45$ *and* $z = 0.45–0.55$ *and* $z = 0.55–0.9$

2009 ApJ 692 1060

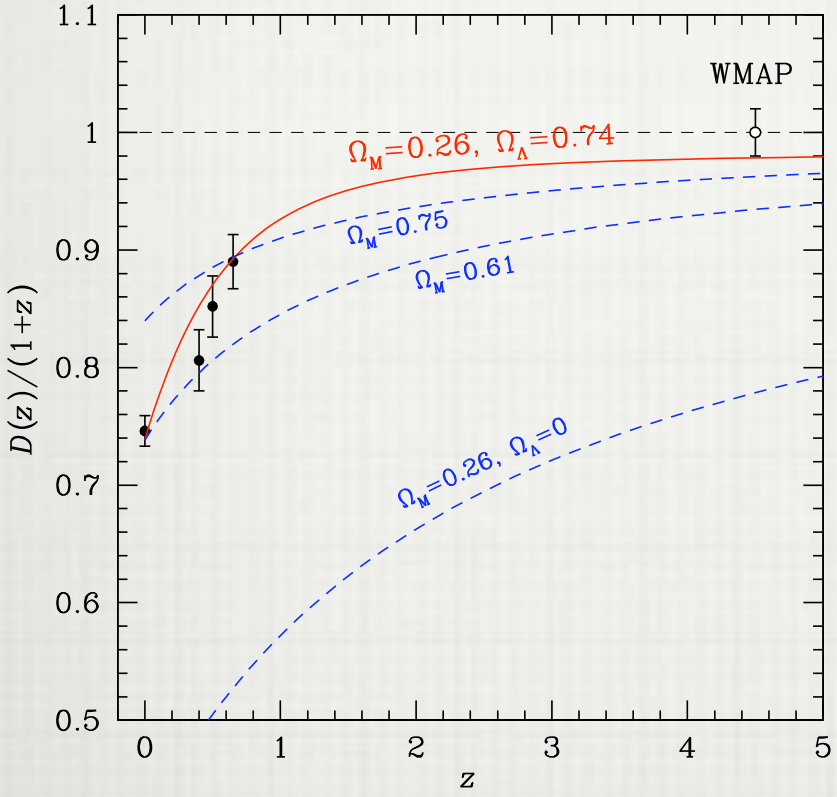
CLUSTER MASS FUNCTION TEST

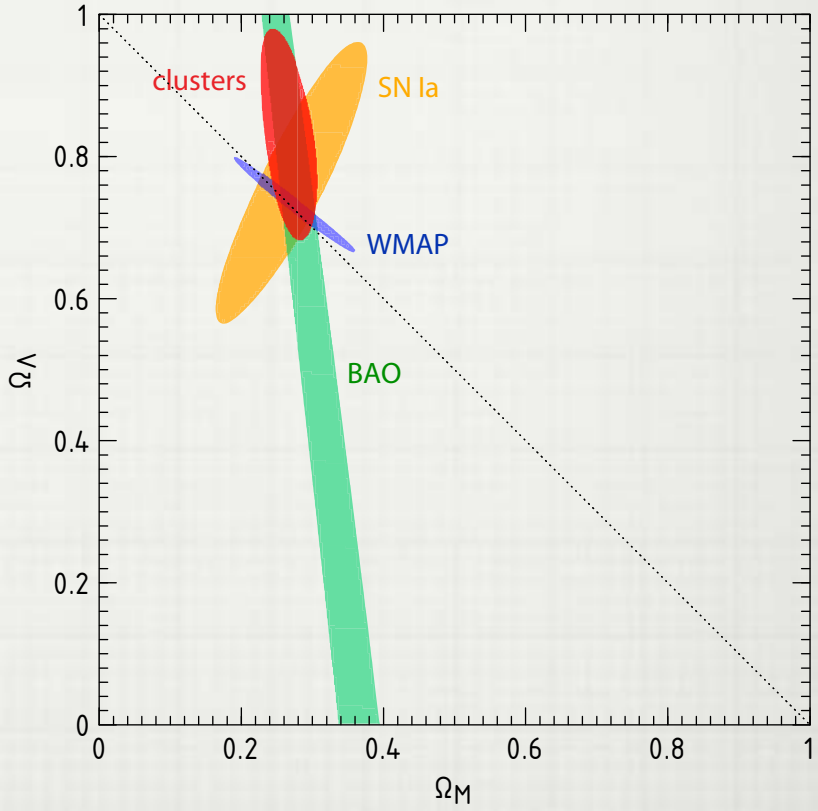


Measure σ_8 at $z \approx 0$ *and* $z = 0.35–0.45$ *and* $z = 0.45–0.55$ *and* $z = 0.55–0.9$

2009 ApJ 692 1060

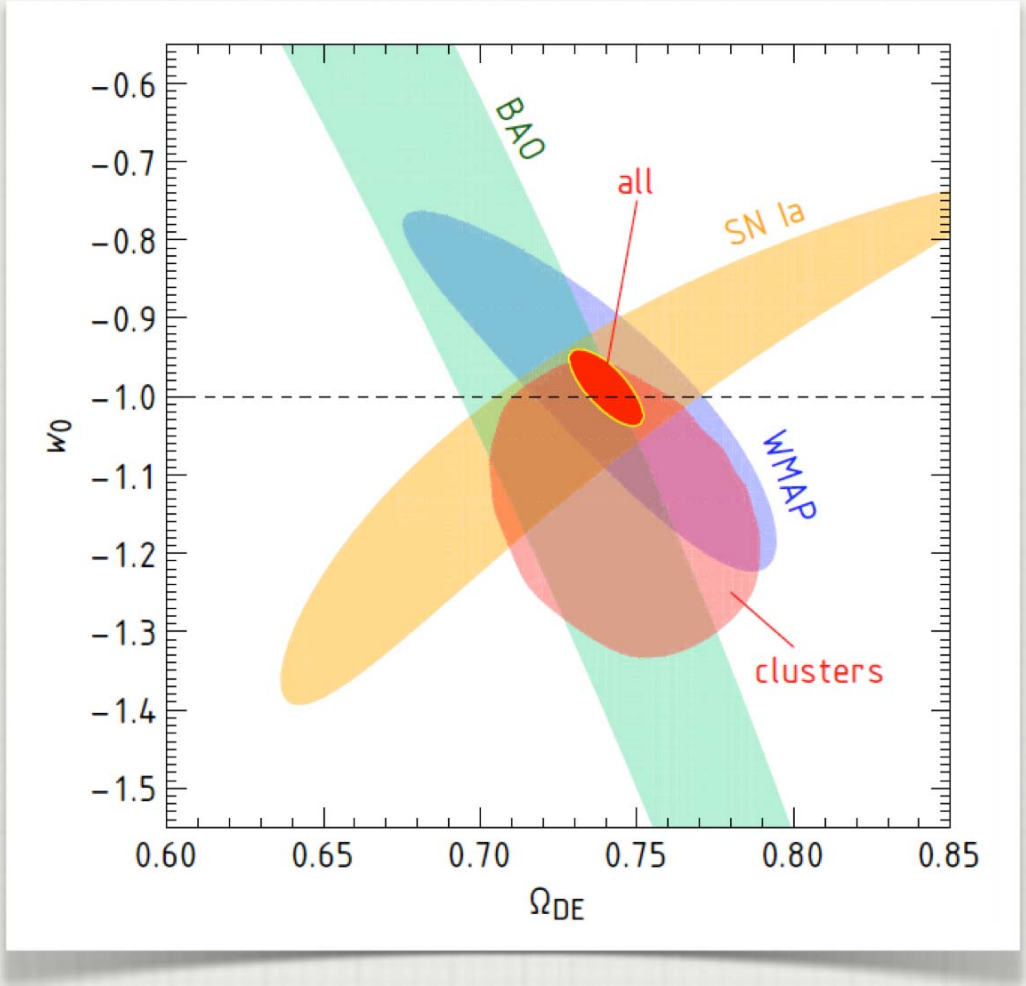
CLUSTERS DETECT Λ & CONSTRAIN *w*





2009 ApJ 692 1060

w_0 FROM COMBINATION OF METHODS

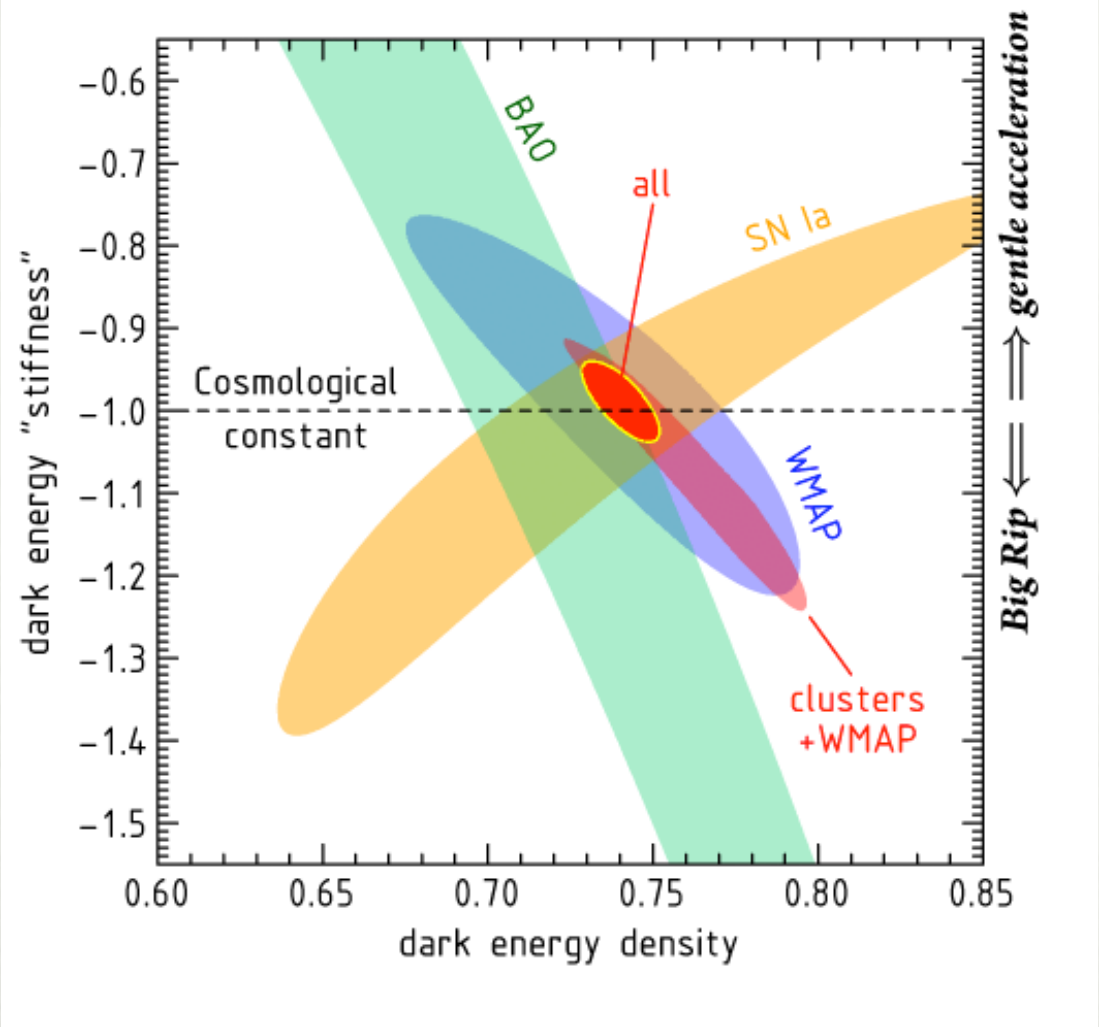


$w_0 = -0.99$ ± 0.045 (stat) (± 0.067 without clusters)

± 0.039 (sys) (± 0.076)

2009 ApJ 692 1060

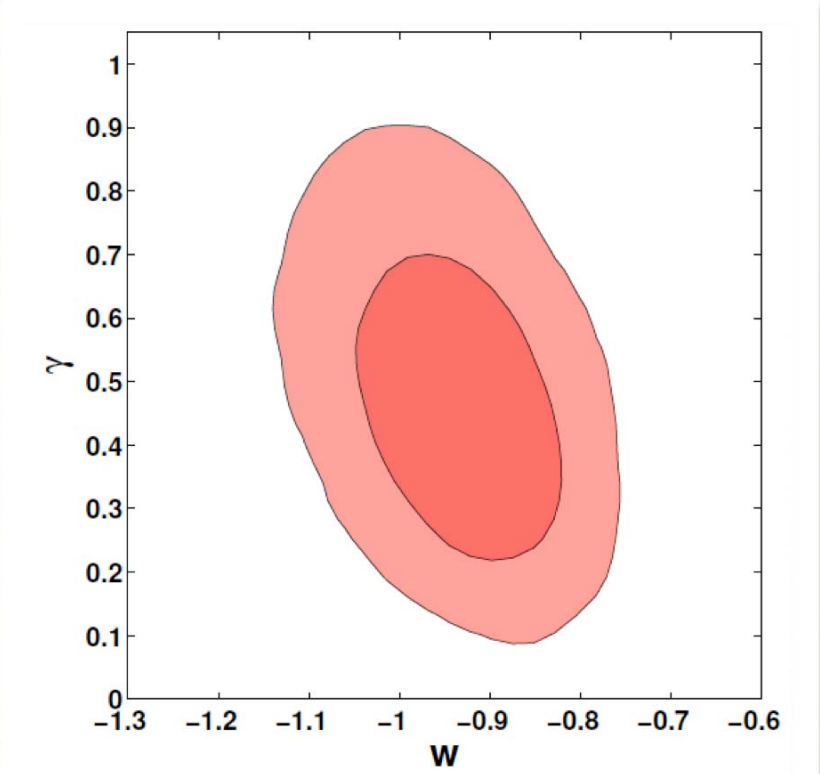
w_0 FROM COMBINATION OF METHODS



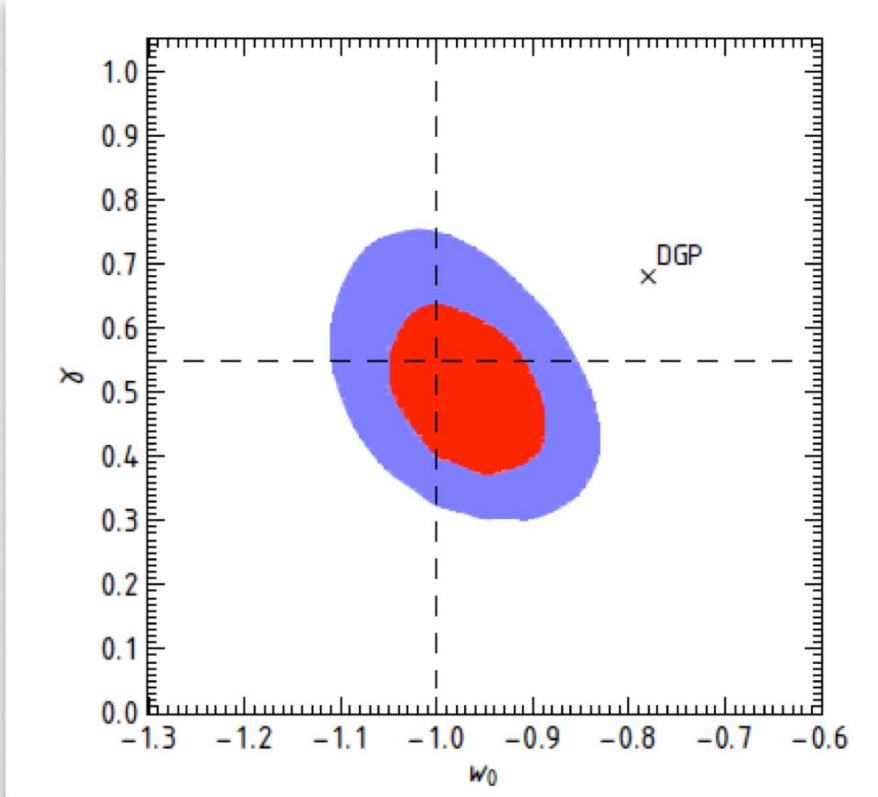
Is Dark Energy dangerous?

TESTING GENERAL RELATIVITY

Rapetti et al., from analysis of X-ray luminosities



400d results

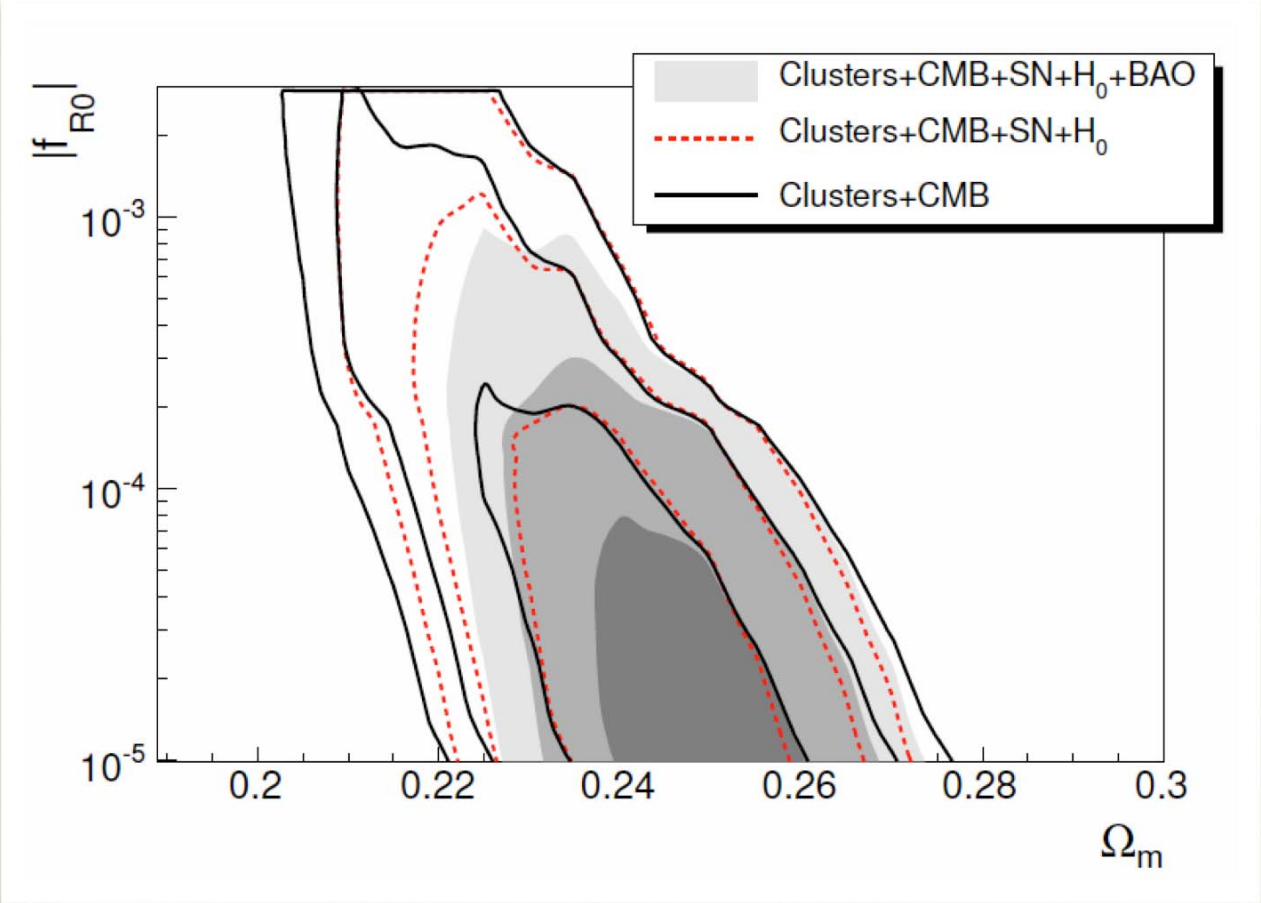


- Growth index, γ:

$$d\ln D/d\ln a = \Omega_M(a)^\gamma$$

- $\gamma \approx 0.55$ for wCDM
- $\gamma = 0.50 \pm 0.08$ measured

TESTING GR: CONSISTENT f(R) MODEL



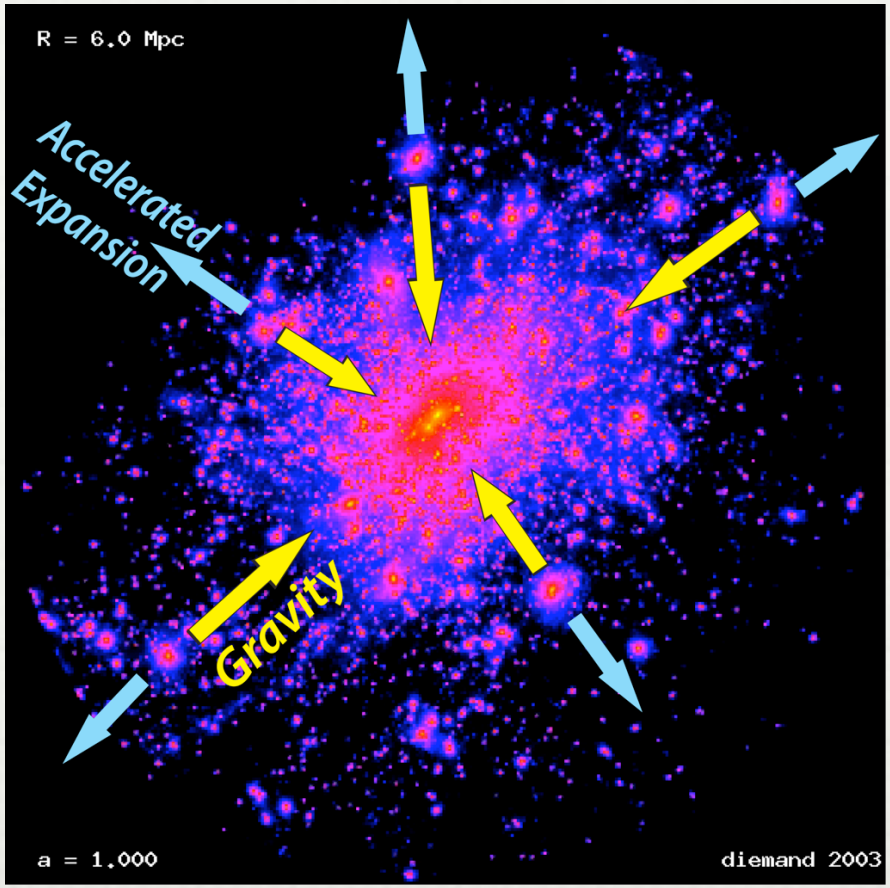
$16\pi G\,\mathcal{L}_g = R + f(R) = R - 16\pi G\rho_\Lambda - f_R \times R_0^2/R$ $\qquad f_R <$ a few $\times 10^{-4}$

Schmidt, Hu & AV, PRD in press.

X-RAY COSMOLOGY

Fundamental questions about the Universe

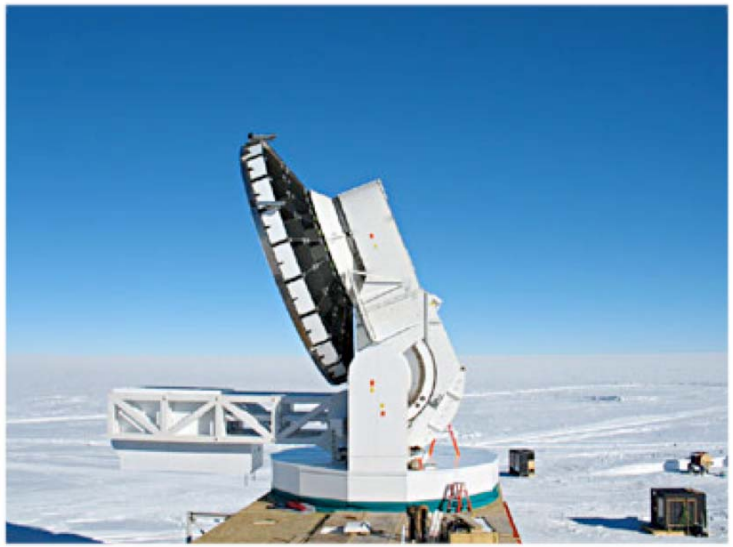
- What is the agent of cosmic acceleration?
- Do we see any departures from General Relativity?
- Are there any departures from "concordance cosmology"?

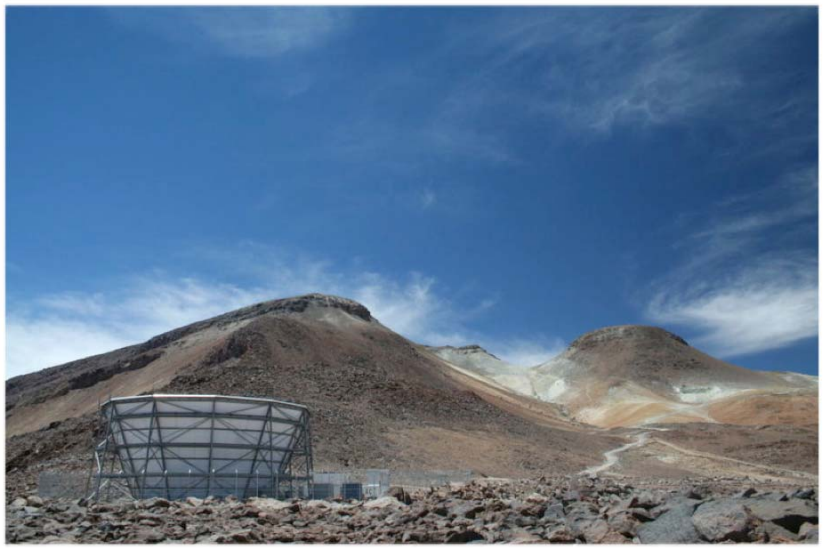


— *and* fundamental astrophysics

- Star formation
- Plasma physics in the intra-cluster medium
- AGN growth and energy feedback, now and in the past
- Recycling of matter through galaxies

FUTURE SAMPLES: SZ

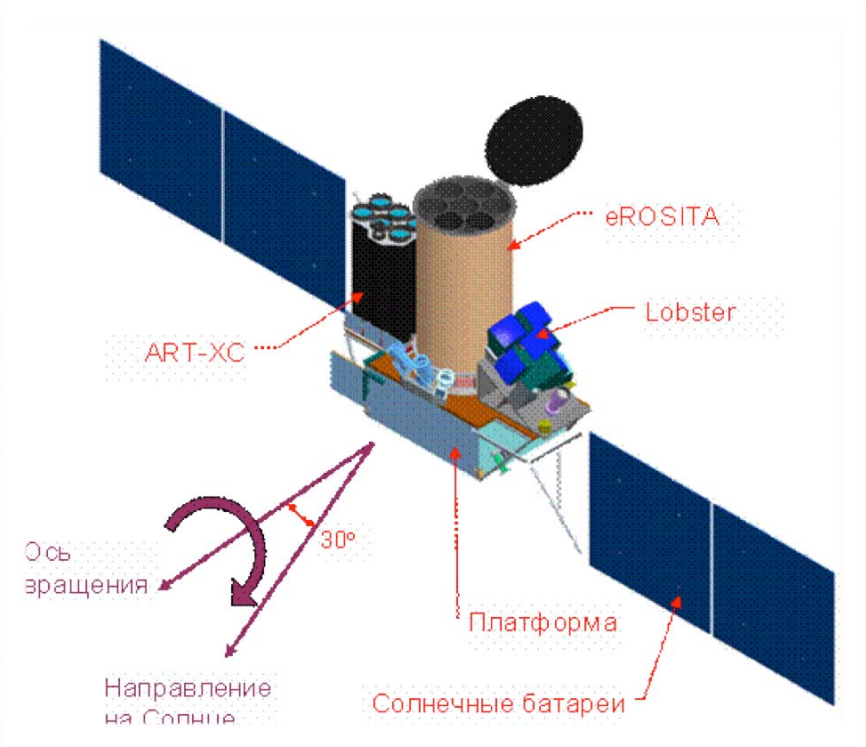




A few × 1,000 deg^2 surveys. 100's of clusters expected

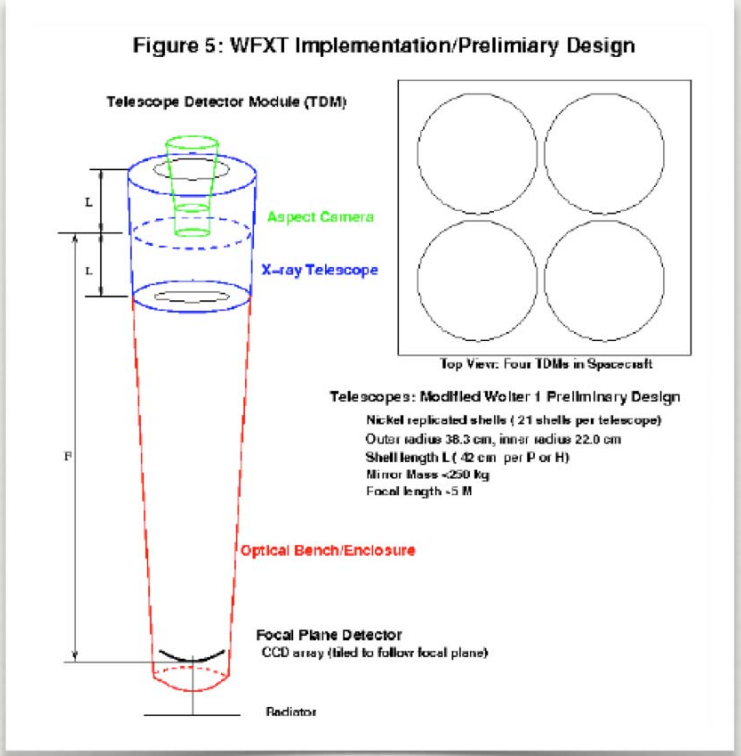
FUTURE SAMPLES: X-RAY

SRG/eRosita



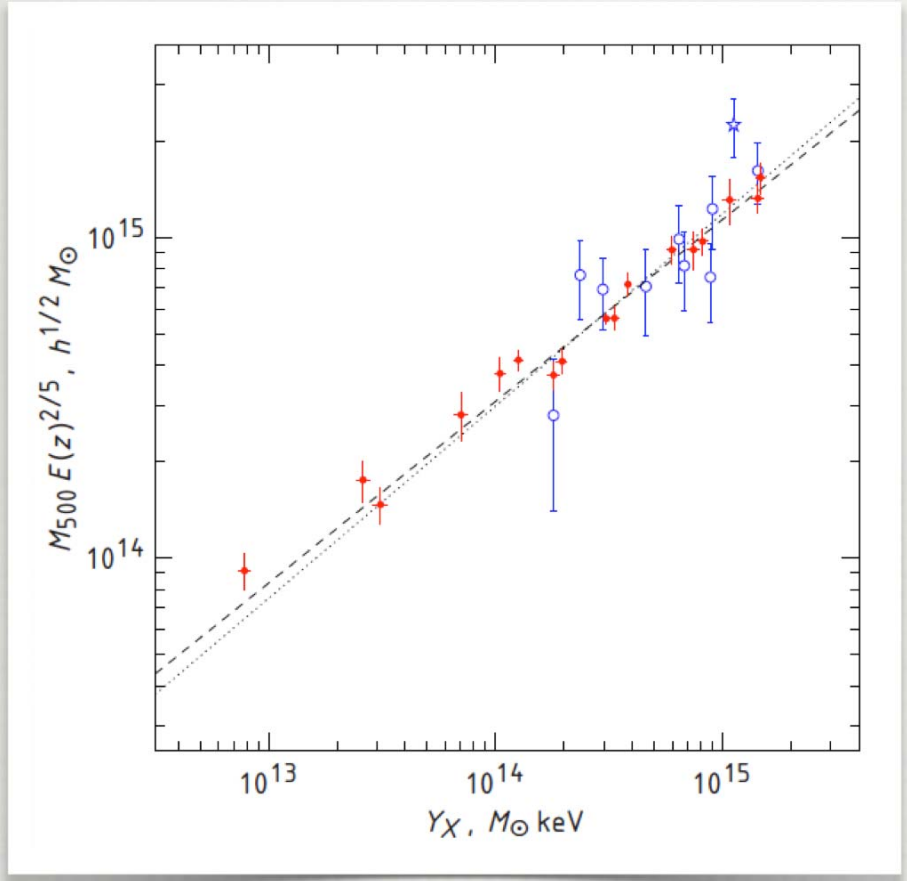
- effective area ~ *XMM-Newton*
- angular resolution better than *ROSAT*
- all-sky survey
- $f_{min} \sim (2–4) \times 10^{-14}$ erg s^{-1} cm^{-2}
- 100,000 – 200,000 clusters, $z_{max} \approx 1.5$

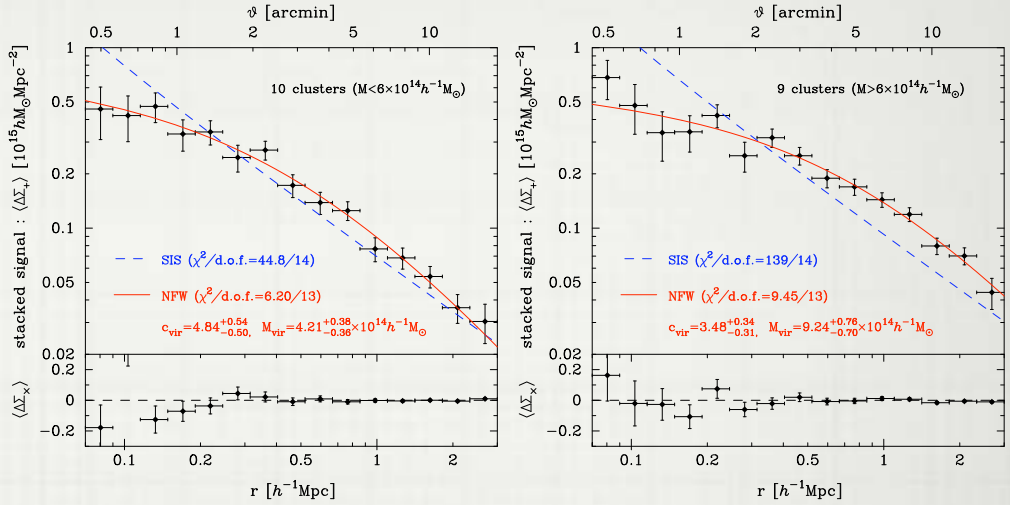
WFXT



- effective area ~ *Con-X*
- angular resolution ~ *XMM-Newton*
- a few $\times 10^3$ deg^2 survey
- $f_{min} \sim 10^{-15}$ erg s^{-1} cm^{-2}
- ~10^6 clusters, $z_{max} > 2$

FUTURE: MORE DIRECT *M*-ESTIMATES



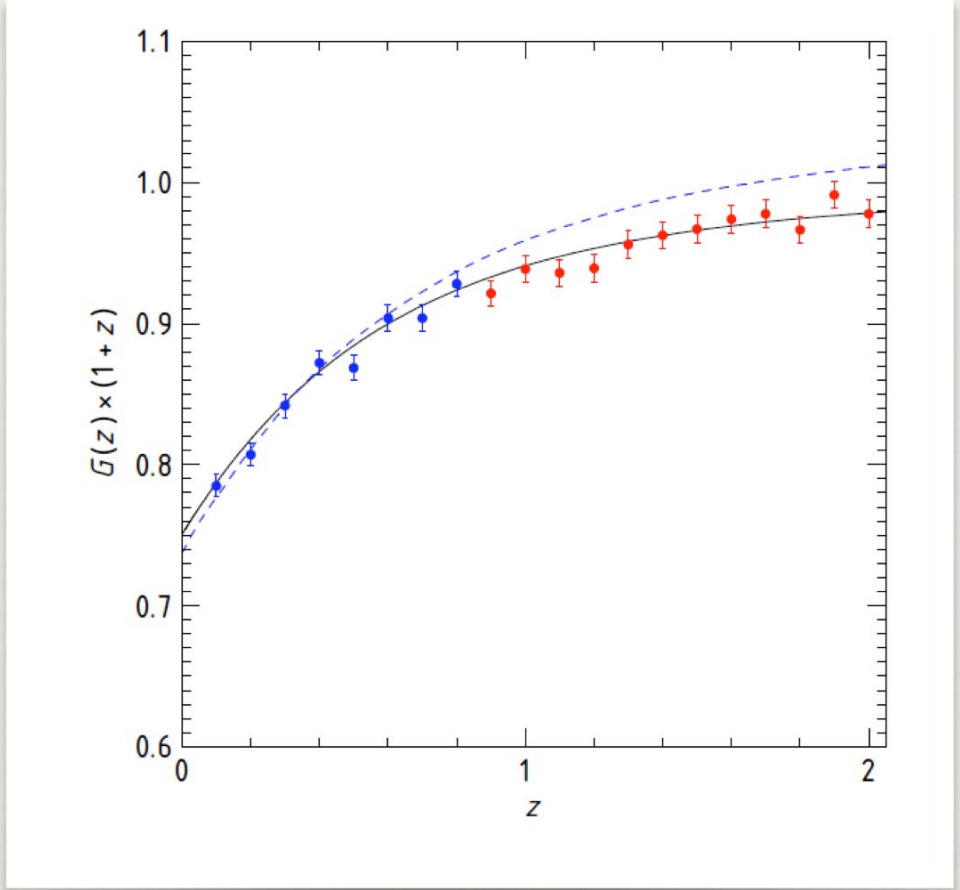


Stacked mass profiles, LoCuSS project,
Okabe etal. '09

- WL – low bias, large scatter; X-rays – low scatter, potential bias
- 100 clusters with Y_X (*IXO*) and M_{WL} $\Longrightarrow$ 3% in M–Y_X, 1% in growth ***per bin***

IXO White Paper

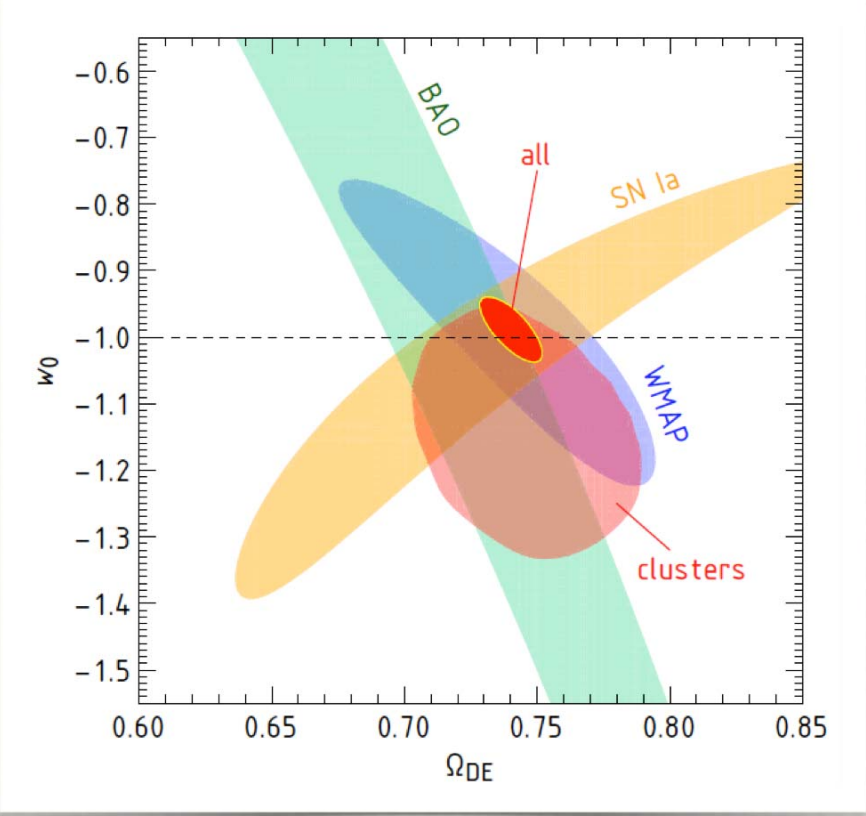
FUTURE: FLAVOR OF RESULTS

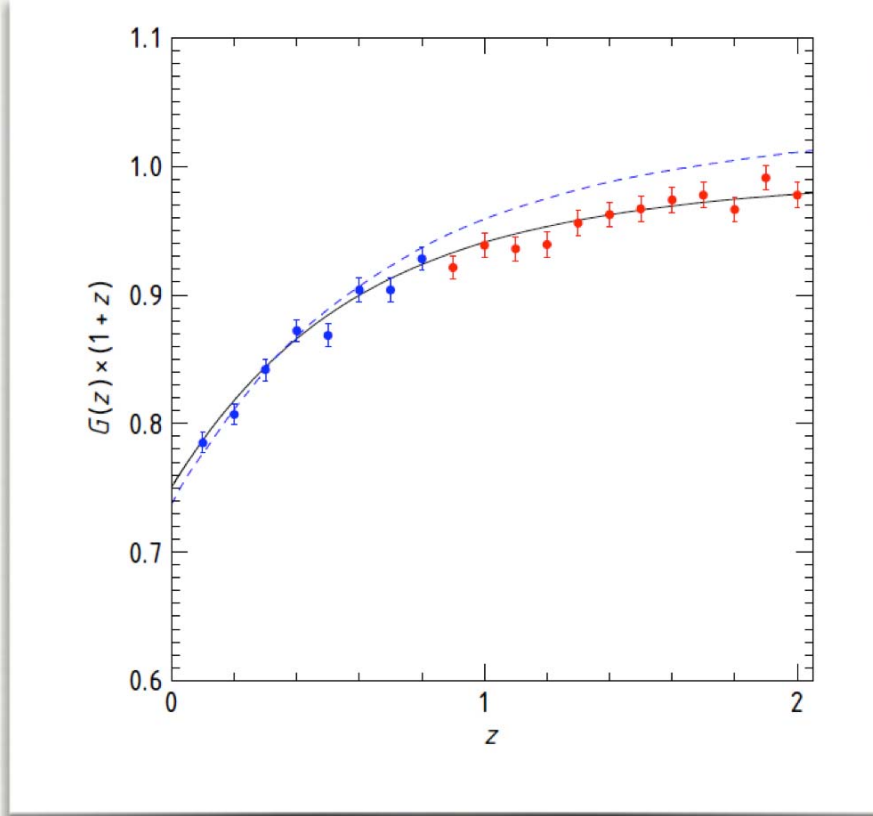


- measure growth(z) to $z \approx 1.5-2$
- test non-GR theories (growth index, γ, to ± 0.02)
- $\times 2$ improvement in w in combination with distance(z)

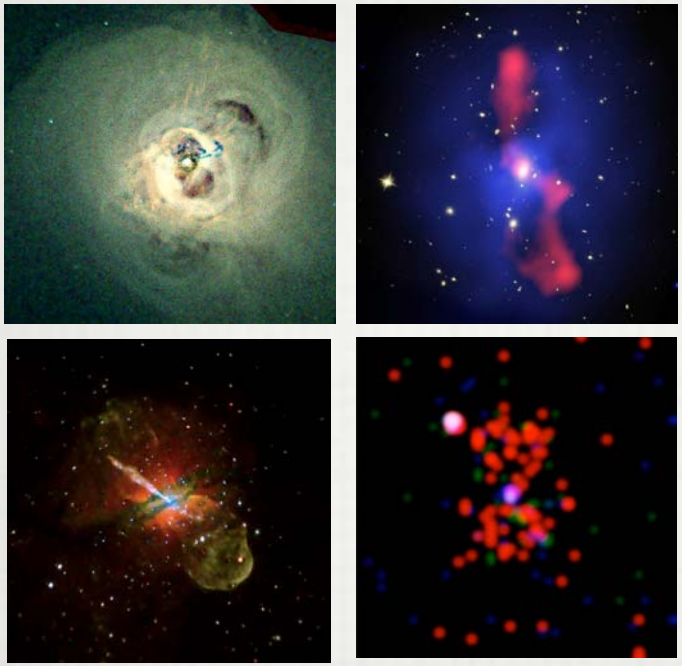
IXO White Paper

THE PRESENT AND THE FUTURE

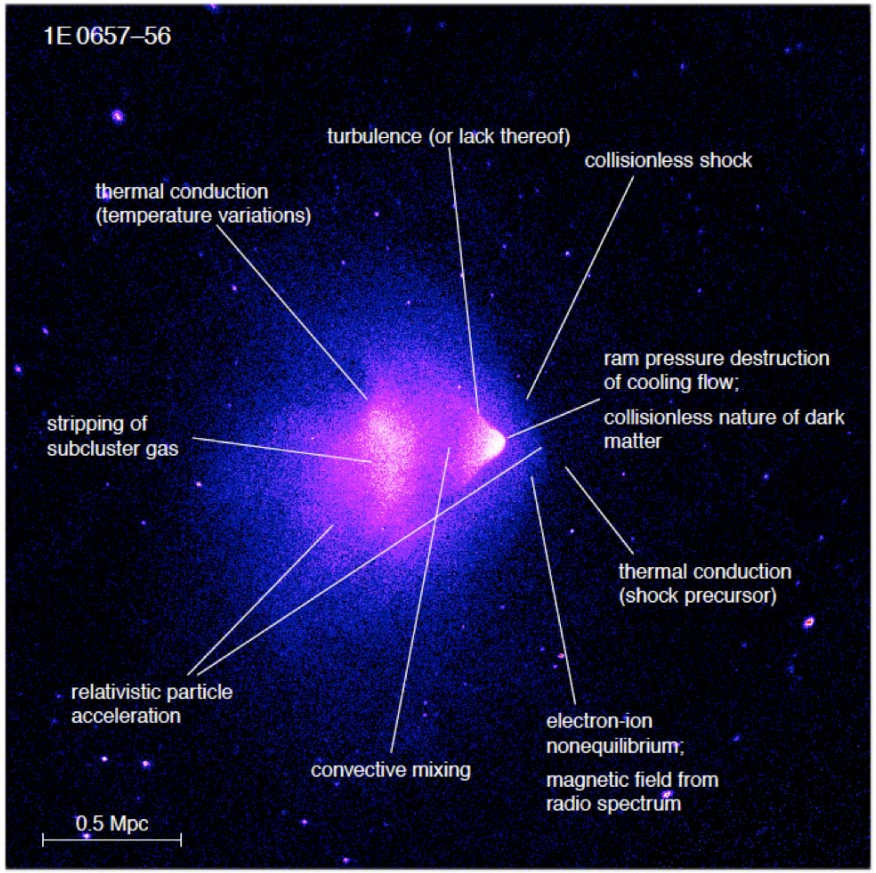




AGN FEEDBACK & NON-EQ PHYSICS

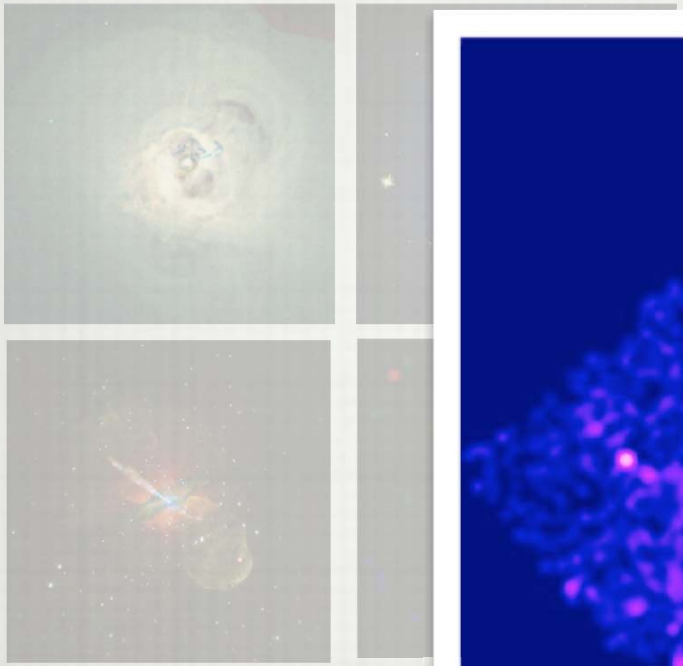


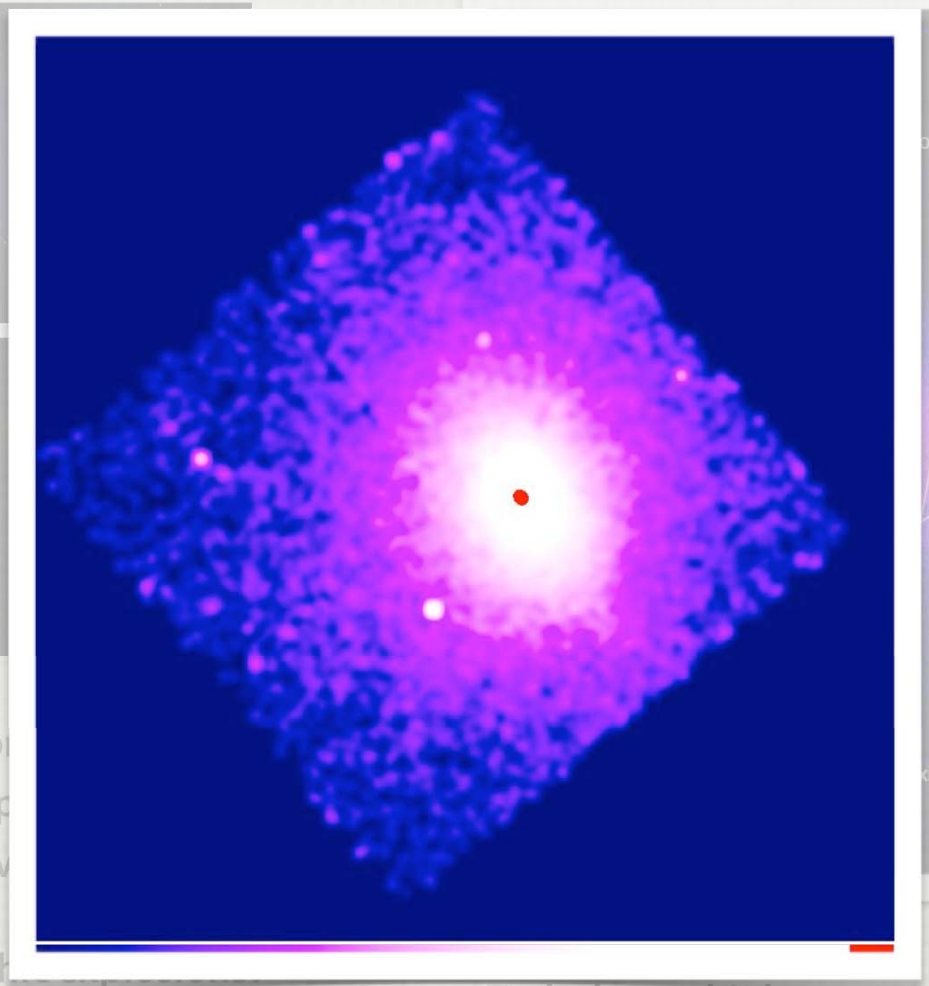
- What it does to star formation?
- How much energy deposited into IGM?
- Ultimate fate of relativistic particles in bubbles?
- Statistics of catastrophic explosions?
- Relation of high-z AGNs to large-scale structure?

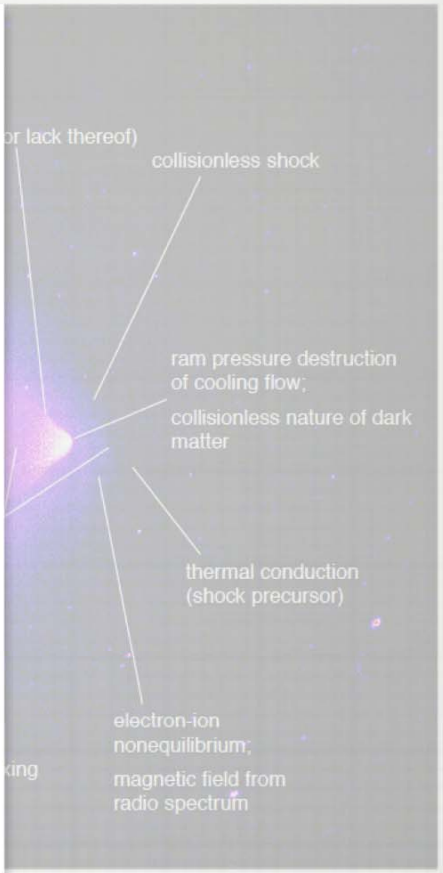


- Turbulence, high-energy particles, magnetic fields
- Effective viscosity
- Stability of small-scale structures
- Transport processes

AGN FEEDBACK & NON-EQ PHYSICS







- What it does to star fo
- How much energy dep
- Ultimate fate of relativ bubbles?
- Statistics of catastroph
- Relation of high-z AGNs to large-scale structure?

- Turbulence, high-energy particles, magnetic fields
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- Stability of small-scale structures
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