Multiwavelength Observations of Clusters of Galaxies

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Outline

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1. Introduction
   - What good are clusters of galaxies?
   - Physics with clusters of galaxies
2. Understanding Relaxed Clusters
   - Mass Measurement Techniques at Many Wavelengths
   - CCCP Survey
   - Joint Analysis of Cluster Observations
   - Evidence for Non-hydrostatic Gas
3. Dark Matter and Violent Mergers
   - The Bullet and MACS Clusters
   - Abell 520
   - Chain of slingshots or something more exotic?

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Evolution of Structure in the Universe

Current structure formation picture

- We live in an accelerating universe ($\Omega_m \sim \frac{1}{4}$, $\Omega_\Lambda \sim \frac{3}{4}$)
- Early on, this universe was hot, dense, and nearly (but not perfectly) uniform
- After matter decoupled from radiation, small density perturbations grew nonlinearly
- Smaller objects formed first, and then grew hierarchically into larger and larger structures
- Clusters of galaxies, the most massive collapsed structures, tell us about the composition and fate of matter in the universe

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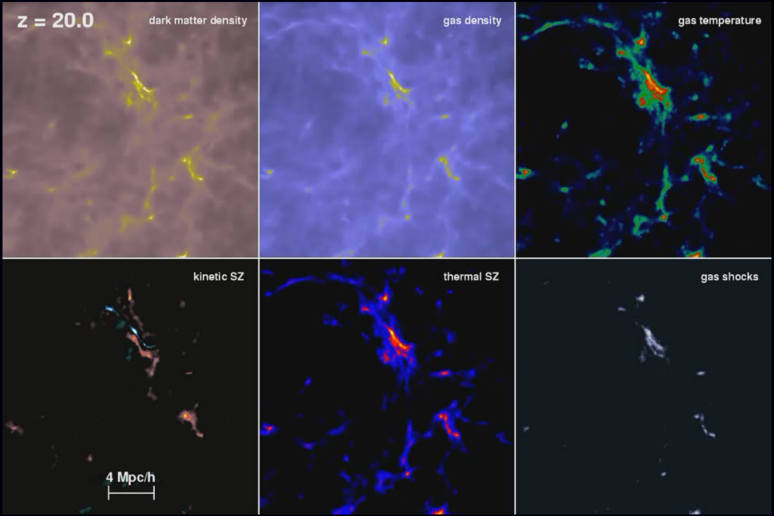
Collapse of a rich cluster of galaxies

Starting 200 million years after the big bang



Courtesy Volker Springel, MPA Garching

Composition a Typical Clusters of Galaxies at $z \approx 0$

Mass budget of a typical rich cluster:

- 5% stars
  - Typically in galaxies with older (red) stellar populations
  - Star-forming (blue) galaxies on the outskirts
  - Occasionally, gas cools enough to form stars at the core
- 15% plasma
  - Largely thermal electron population
  - Bremsstrahlung at 1-10 keV
  - Nonthermal contributions: turbulence, shocks, cosmic rays
- 80% dark matter
  - Favored candidate: SUSY relic or axion (CDM)
  - Neutrinos (HDM), substellar bodies (MACHOS) disfavored
  - Very resistant to alternative theories of gravity

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The Physics of Clusters of Galaxies

Clusters lie at the intersection of several unsolved problems in astrophysics

Through clusters we can address vital questions:

- Fundamental cosmological parameters
- The nature of dark matter
- The physics of cooling and heating in astrophysical plasmas

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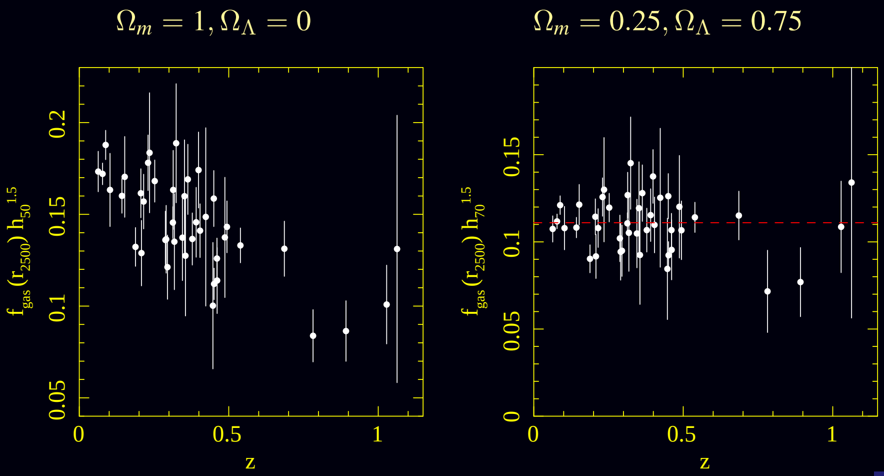
Cosmology with Clusters of Galaxies

Allen et al. 2007



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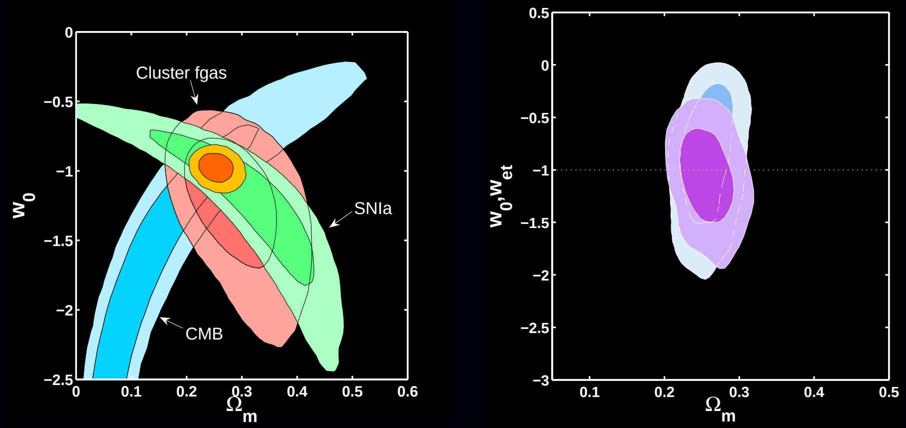
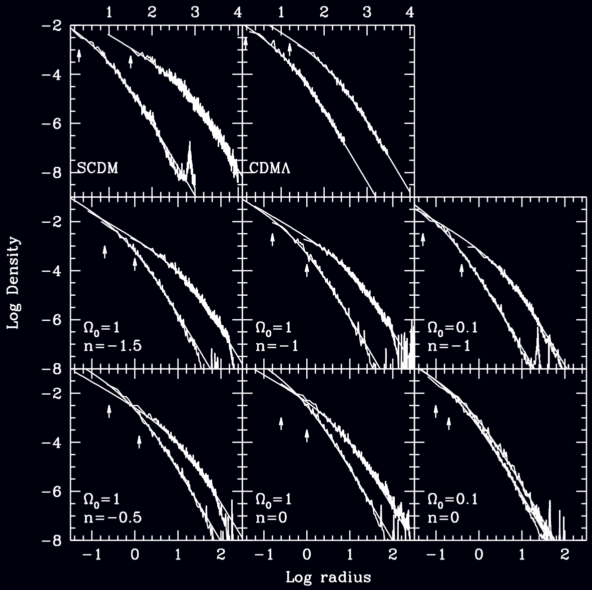
Allen et al. 2007



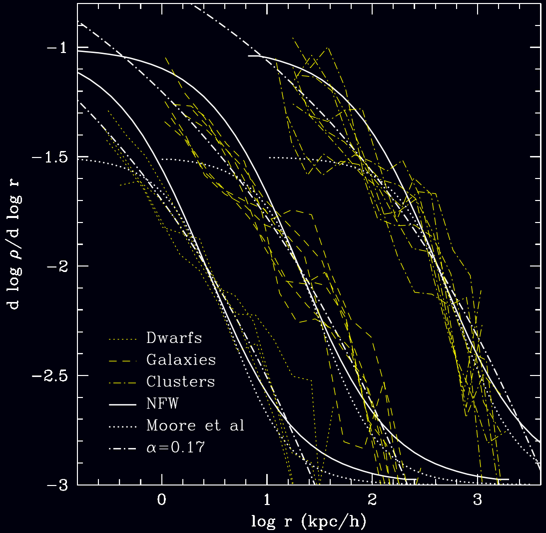
Canonical Cold Dark Matter

Navarro et al. 1997, Ghigna et al. 2001, and others



Canonical Cold Dark Matter

Higher resolution: Navarro et al. 2004, Merritt et al. 2005



$$\rho_{\rm dm} \propto r^{-n}(r_{200}+cr)^{n-3}$$

n is the "slope"
c is the concentration
$n \approx 1 - 1.5$ depending on size of structure
Flat cores ($n = 0$) do not occur in CDM

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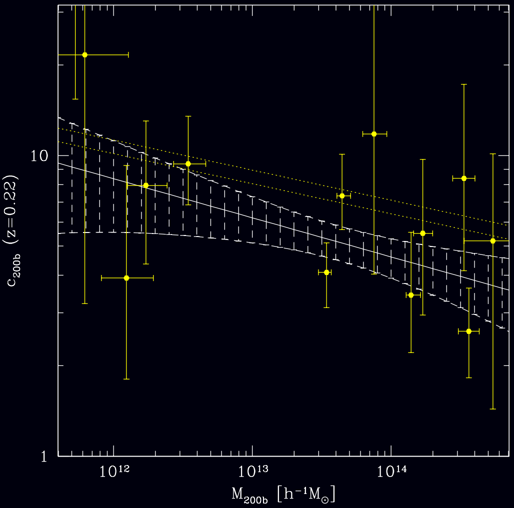
Mass-concentration relation

From gravitational lensing; Mandelbaum, Seljak, & Hirata 2008

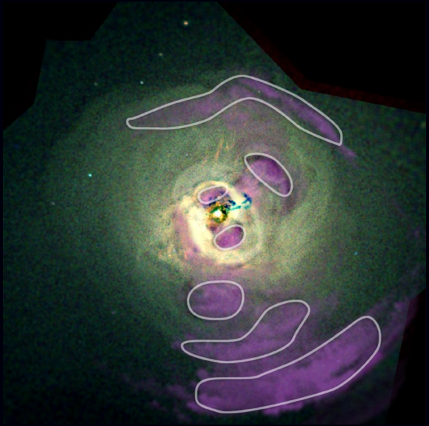


M-c relation is potentially powerful cosmological discriminant

However, precision in c is currently the limiting factor for cosmological tests

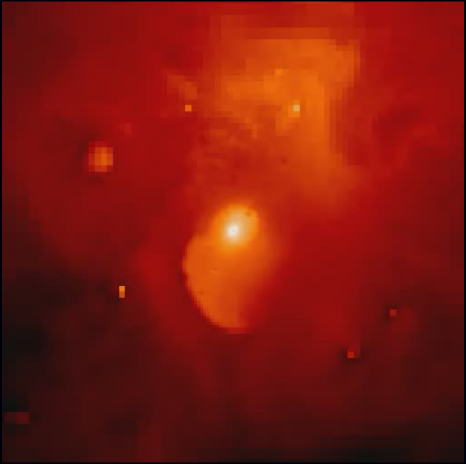
Cooling and Heating of the Intracluster Plasma

Perseus cluster, Fabian et al. 2005



Cooling and Heating of the Intracluster Plasma

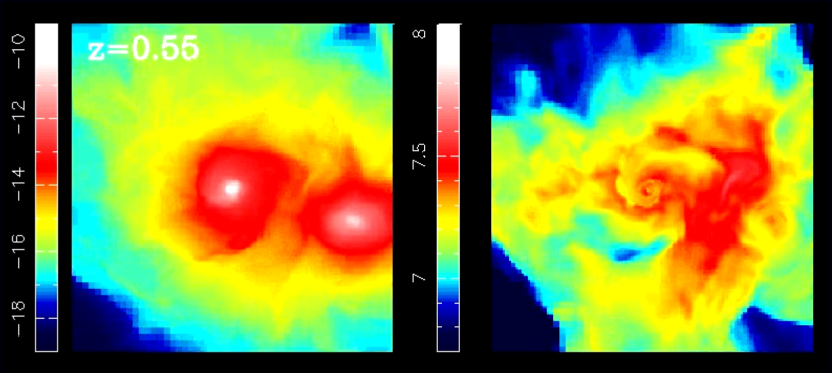
Simulating feedback from active galactic nuclei



Courtesy Markus Brueggen, Jacobs University Bremen

Disturbances due to shocks and cold fronts

Disruptions of the intracluster medium by the hierarchical structure formation process



Courtesy Daisuke Nagai

Physics with clusters of galaxies

- With clusters we can get at dark matter and dark energy.
- To do this, we need to understand the evolution of galaxies and the intracluster plasma along the way

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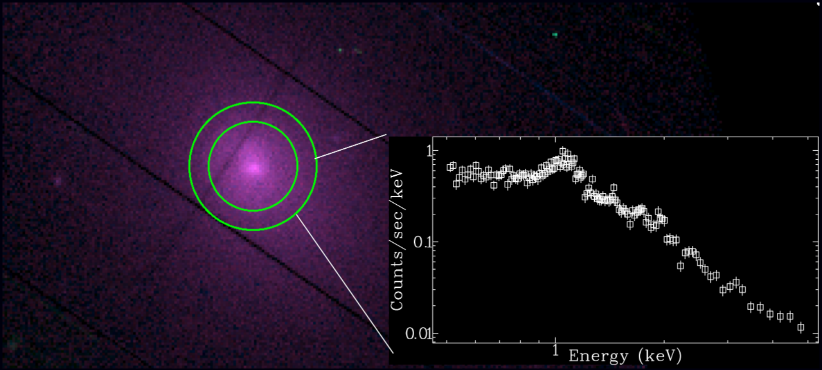
Hydrodynamics

X-ray observations



X-ray spectra → X-ray temperatures

$$\frac{1}{\rho_g}\frac{d}{dr}\left(\frac{\rho_g kT}{\mu m_p}\right) = -\frac{G(M_d + M_g + M_s)}{r^2}.$$

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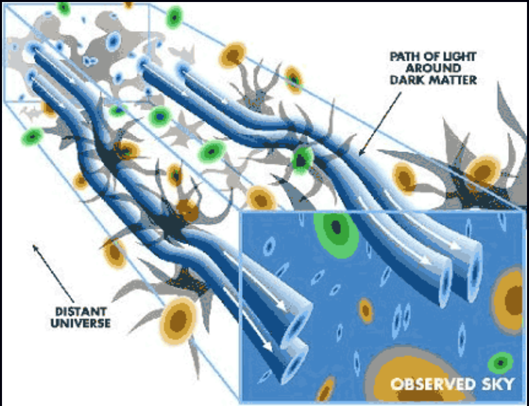
Weak gravitational lensing

Optical observations



From Wittman et al. (2000)

Shear profile:

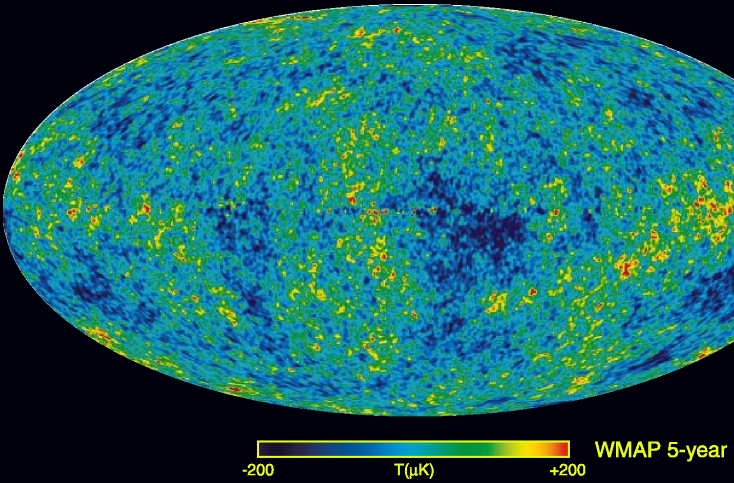
$$\langle g_T \rangle(R) = \frac{\bar{\kappa}(< R) - \kappa(R)}{1 - \kappa(R)}$$

$$\kappa(R) = \frac{\Sigma(R)}{\Sigma_{\rm crit}}$$

Kaiser, Squires, & Broadhurst (KSB) shear measurement technique

Sunyaev-Zel’dovich Effect

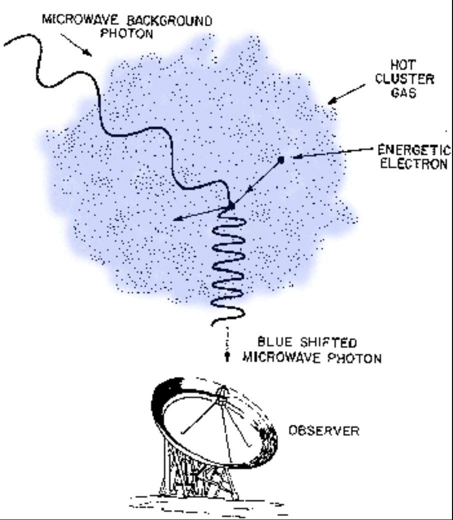
Radio observations



Courtesy WMAP Science Team

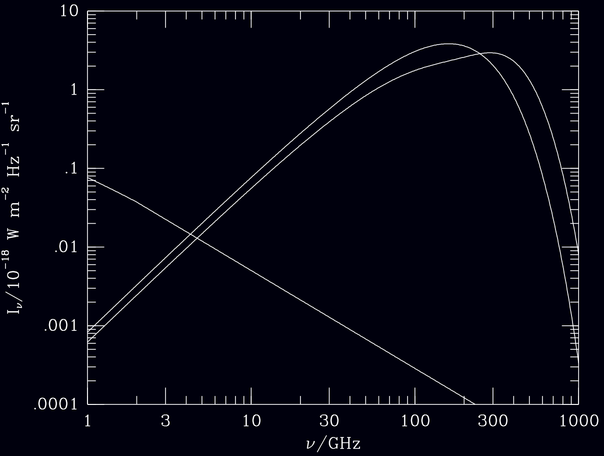
Sunyaev-Zel'dovich Effect

Radio observations



Courtesy L. Van Speybroeck / U. Chicago

Radio: Sunyaev-Zel'dovich Effect



$$\Delta T/T_{\mathrm{CMB}} \approx 2y$$

$$y = \int \frac{P\sigma_T}{m_e c^2} dl$$

$$= \int \frac{\sigma_T}{\rho_g} \int \frac{GM\rho_g}{m_e c^2 r^2} dl$$

From Birkinshaw (1998)

Canadian Cluster Comparison Project

Mahdavi, Hoekstra, Babul; (UVic); Henry (IfA); Sievers (CITA)

Canadian Cluster Comparison Project

Detailed study of ≈ 30 massive clusters ($kT > 5$ keV)

- Data sources:
  - X-rays: archival and proprietary Chandra and XMM-Newton data
  - Optical: CFHT/Gemini/HST for weak lensing and spectroscopy
  - Radio: Cosmic Background Imager
- Project goals:
  - Relaxed systems: Dark matter profiles from simultaneous modeling of all data at all wavelengths
  - Merging systems: Maps of X-ray / Lensing offsets, comparison with our own N-body "collider"
  - Study nonthermal contributors to plasma equation of state

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Joint Analysis of Cluster Observations

Mahdavi et al. 2007a

1. New physical insights
   - Combining X-ray, lensing, and SZ data breaks degeneracies in the structural parameter of the gravitational potential
   - Study the covariance of all astrophysical parameters (gas metallicty, dark matter slope, mass-to-light ratio . . .)
2. Designed to deal with real data
   - First time real X-ray, lensing, and SZ data are jointly fit
   - Models are projected and convolved with instrumental response
3. Modular, state-of-the-art codebase
   - Easily handle new astrophysics (e.g. turbulence, cooling/heating)
   - Includes new distributed minimization algorithms (Hrothgar)
   - Can run on (for large data sets, requires) Beowulf clusters

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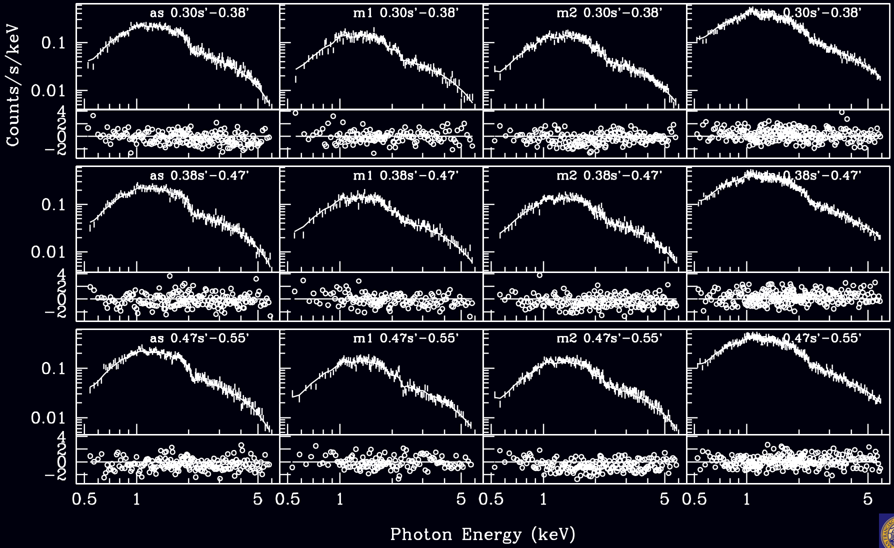
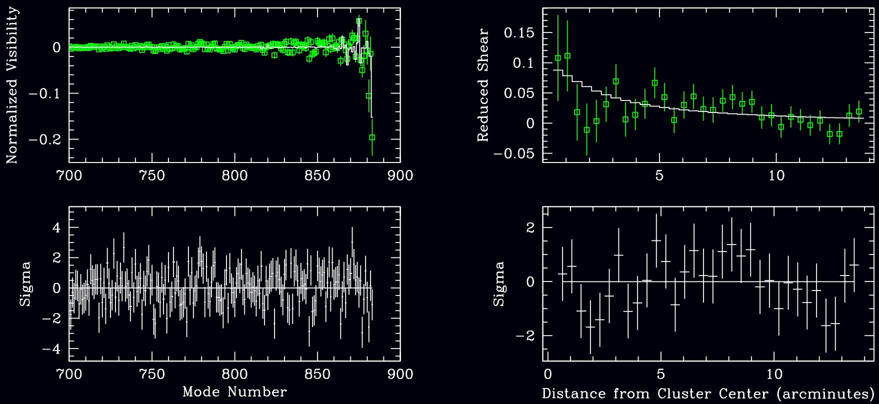
Application to the Abell 478 Cluster of Galaxies

3% of Abell 478 X-ray data is shown

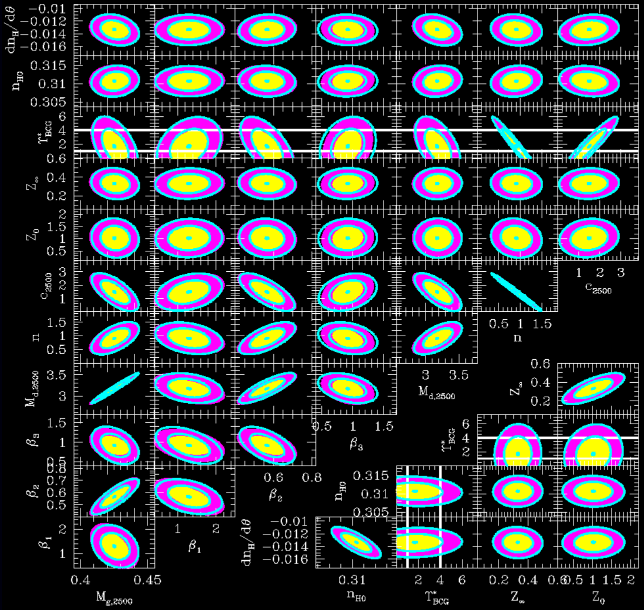


Fit results: SZ and lensing data

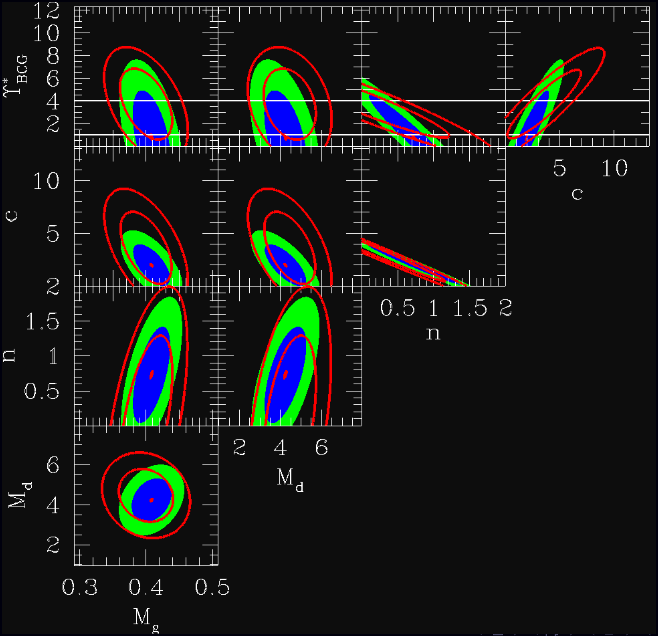


→ The same physical model fits the lensing, X-ray, and SZ data self-consistently.

Covariance of all cluster observables

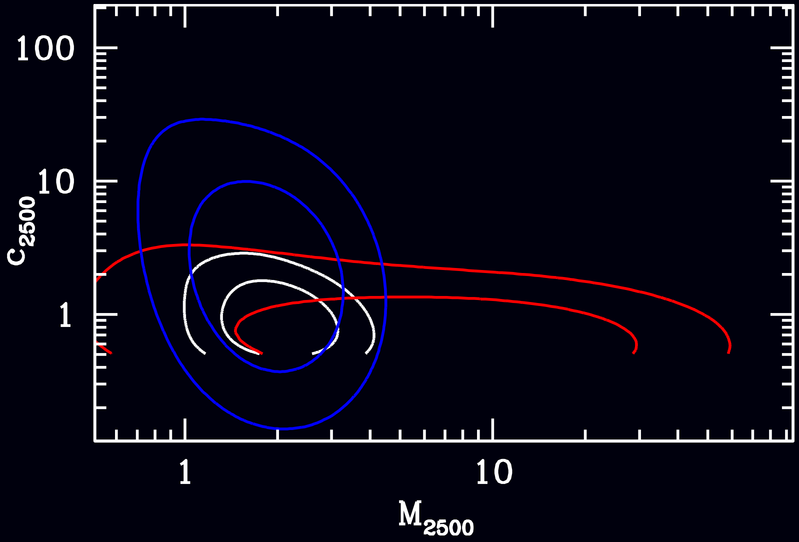


Covariance of dark matter parameters



Covariance of dark matter parameters

Using only SZ and Weak lensing, gas mass fixed at X-ray value



Conditions for correctness of joint analysis

- Error in dark matter concentration can be halved via joint analysis
- Relevant for high redshift survey: SZ + WL only require the X-ray surface brightness
- But there are caveats...
- Reliance on hydrostatic analysis
- Theory says gas should be nonhydrostatic
- But are there “more hydrostatic” regions within a cluster?
  - Interior disturbed by cooling gas
  - Exterior incompletely thermalized due to bulk motions

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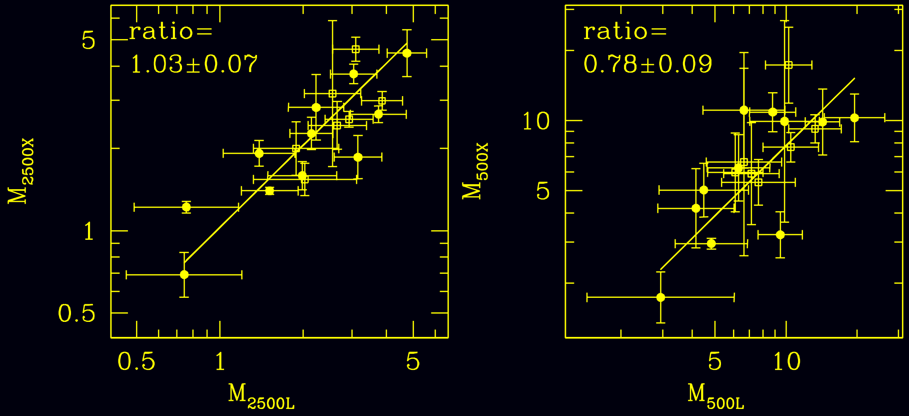
Evidence for Non-hydrostatic Gas

A dramatic first result for the JACO+CCCP survey

Comparison of Weak Lensing and X-ray derived masses

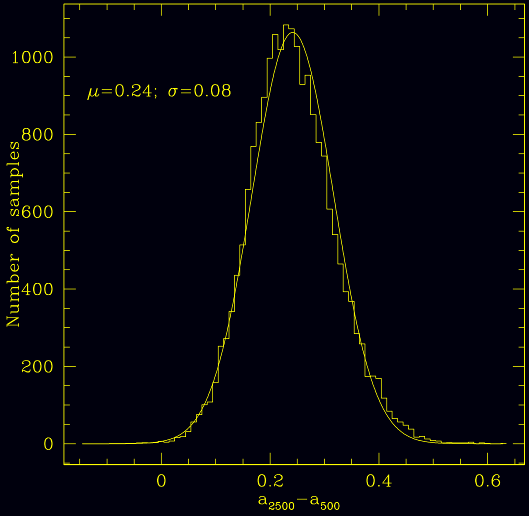
$$M(r_\Delta) = 4\pi\Delta r_\Delta^3 \rho_c/3$$



Evidence for Non-hydrostatic Gas

Properly taking data covariance into account

- 1.03 ± 0.07 (r_{2500}) and 0.78 ± 0.09 (r_{500}) are correlated
- Data used for M_{2500} goes into M_{500} as well.



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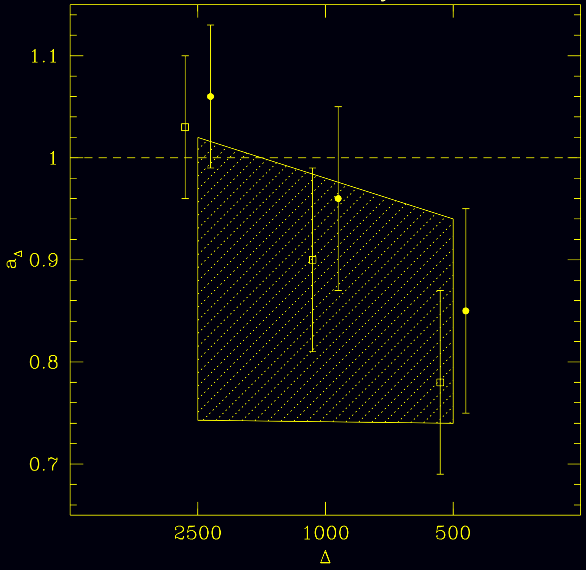
Comparison with N-body work

X-ray and “true” masses agree at r_{2500}, disagree at r_{500}

Consistent with recent N-body simulations involving bulk motions:



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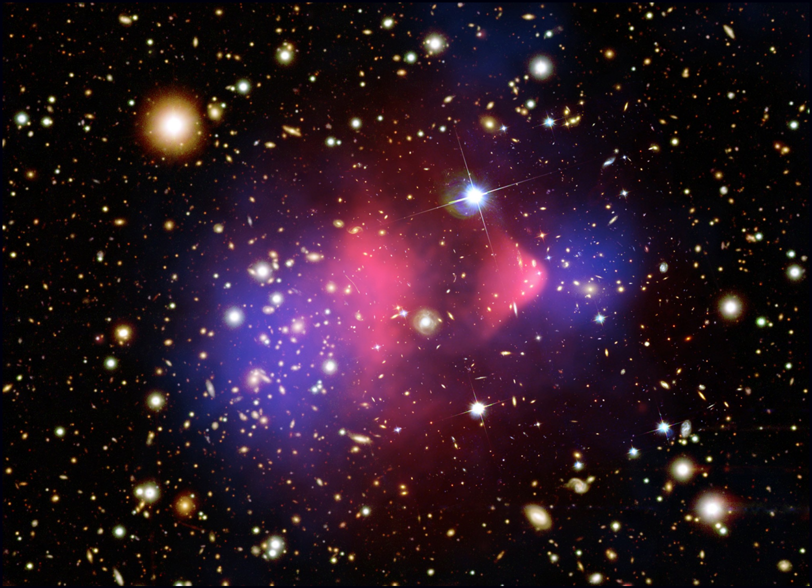
The Bullet Cluster

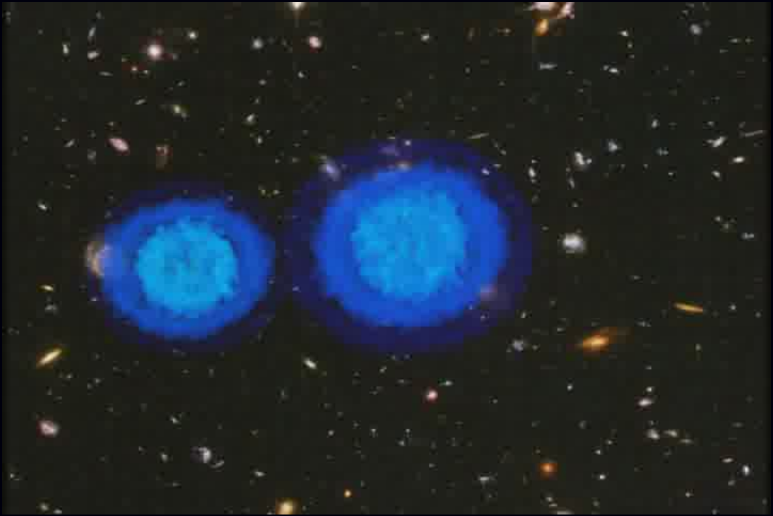
Clowe et al. 2006



The MACS Extreme Merger

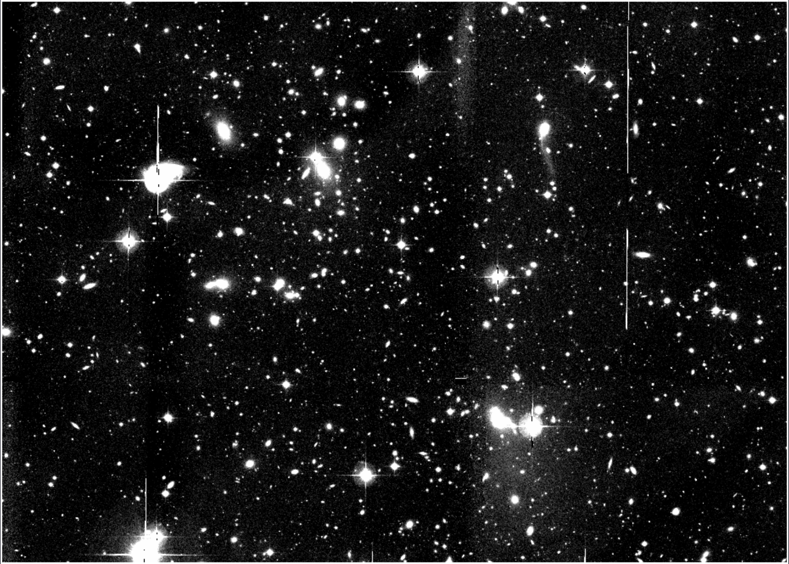
Bradač et al. 2008

Simulation of bullet cluster collision

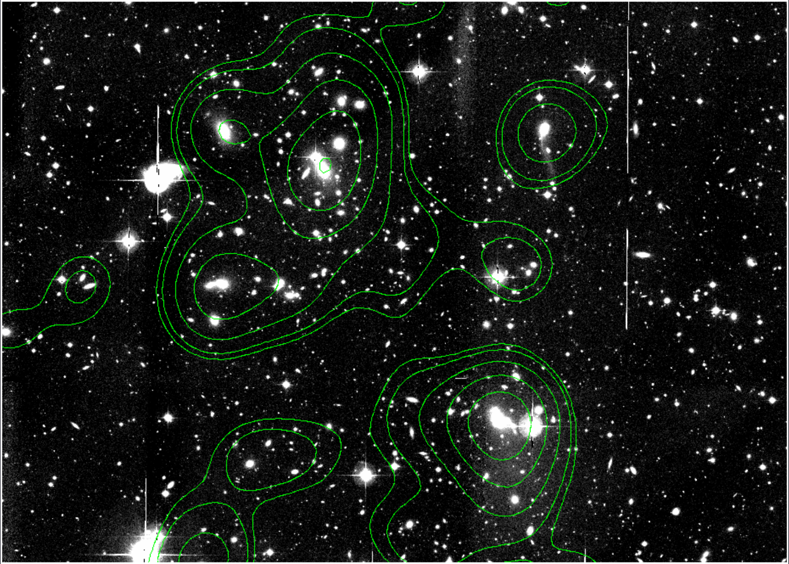


Courtesy KIPAC/John Wise

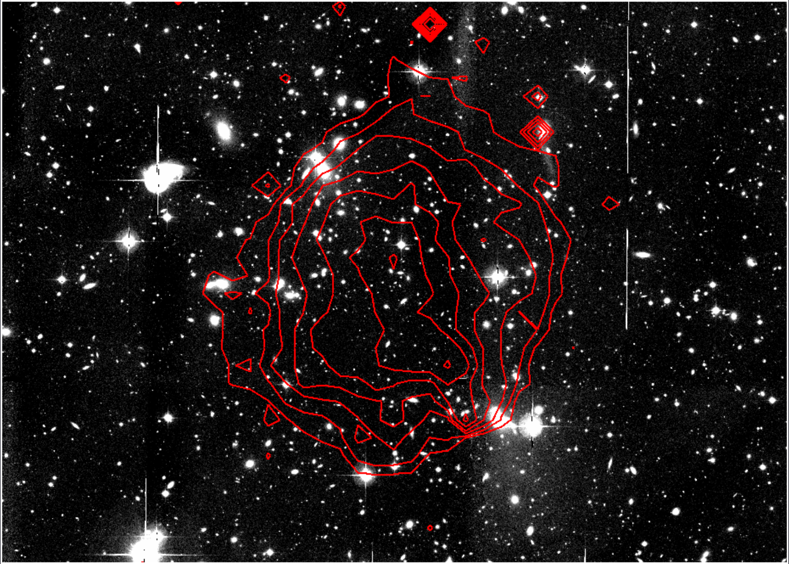
Abell 520, CFHT optical image



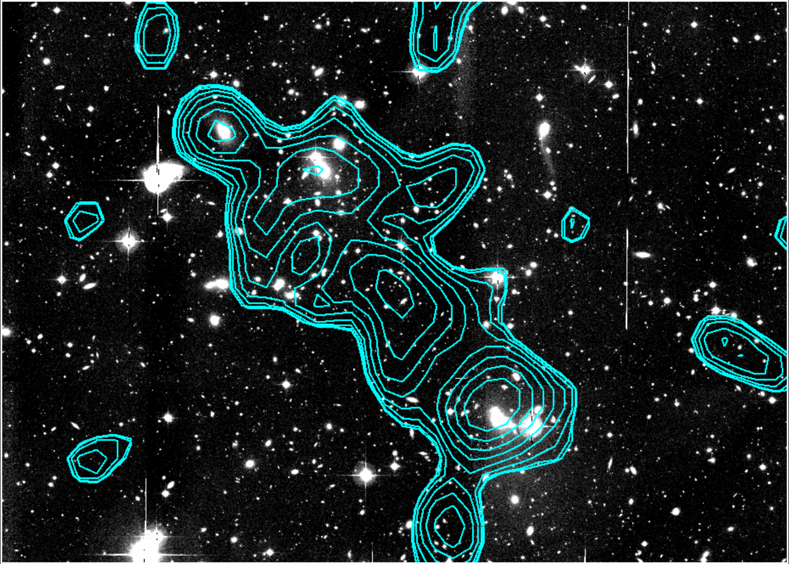
Abell 520, red light (likely members)



Abell 520, Chandra X-ray emission

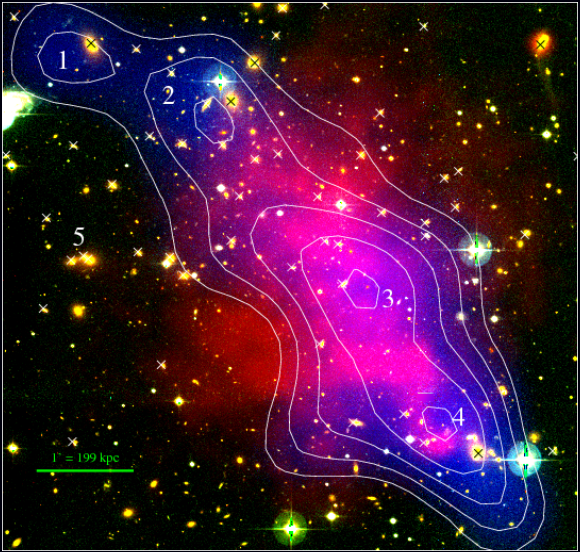


Abell 520, Weak gravitational lensing signal



Abell 520 multiwavelength image

Mahdavi et al. 2007b



$M_{\rm tot}/L_B$

1: 234 ± 62

2: 85 ± 25

3: 721 ± 179

4: 135 ± 25

5: 57 ± 49

$M_{\rm gas}/M_{\rm tot}$

1: < 0.05

2: < 0.12

3: < 0.17

4: < 0.07

5: < 1

Abell 520 Dark Core

How confident are we in the result?

Chance superpositions and other trivial explanations ruled out:

- Redshift measurements for the X-ray gas as well as the galaxies—all coincide
- Lensing signal as a function of magnitude rules out a background cluster (light or dark) beyond $z = 0.7$
- Any normal cluster within $z = 0.7$ would have been detected spectroscopically
- Not an overlap of two NFW or isothermal halos (too much mass)
- Dark matter-only “bridges” of this mass and size do not occur in CDM merger simulations

Bottom line: we are confident in the result at the stated level of 3σ (statistical+systematic) excess M/L

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- Dark matter-only "bridges" of this mass and size do not occur in CDM merger simulations

Bottom line: we are confident in the result at the stated level of 3σ (statistical+systematic) excess M/L

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Abell 520 Dark Core

How confident are we in the result?

Chance superpositions and other trivial explanations ruled out:

- Redshift measurements for the X-ray gas as well as the galaxies—all coincide
- Lensing signal as a function of magnitude rules out a background cluster (light or dark) beyond $z = 0.7$
- Any normal cluster within $z = 0.7$ would have been detected spectroscopically
- Not an overlap of two NFW or isothermal halos (too much mass)
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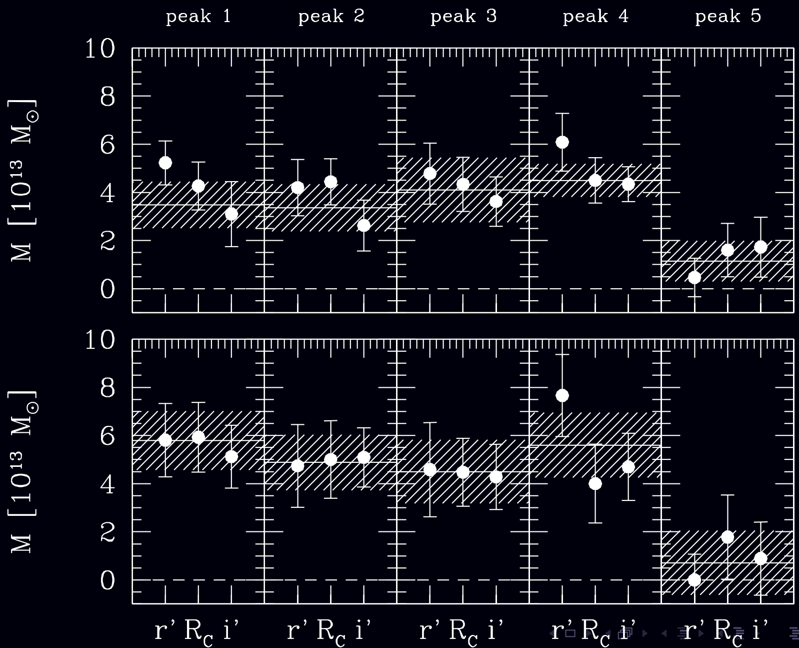
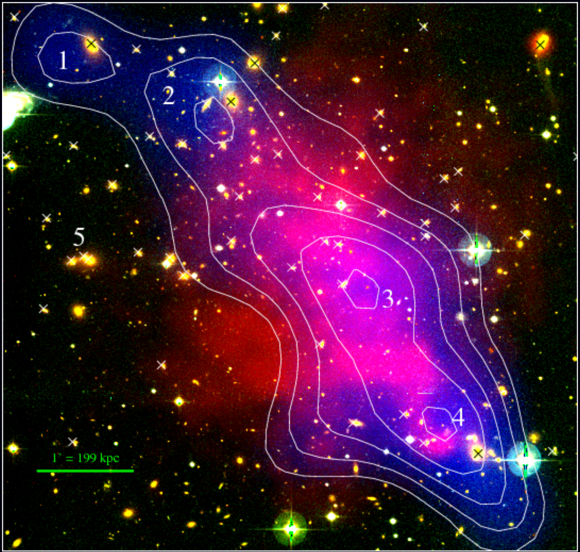
Abell 520, Weak gravitational lensing signal



Abell 520 multiwavelength image

Mahdavi et al. 2007b



$M_{\rm tot}/L_B$

1: 234 ± 62

2: 85 ± 25

3: 721 ± 179

4: 135 ± 25

5: 57 ± 49

$M_{\rm gas}/M_{\rm tot}$

1: < 0.05

2: < 0.12

3: < 0.17

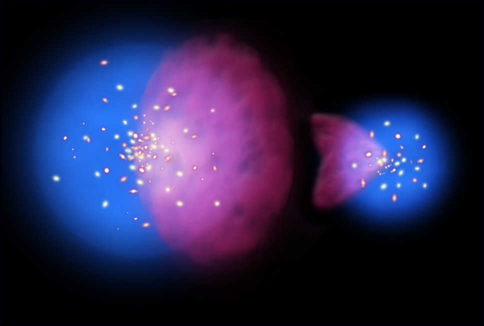
4: < 0.07

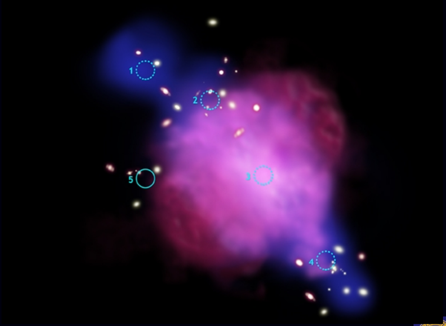
5: < 1

Abell 520 and the Bullet Cluster

They differ in the relative offset of dark matter and galaxies

- In Bullet cluster, mass is where the galaxies are, and vice versa.
- In Abell 520, the core has mass and X-ray but almost no galaxies,
- Peak 5 has galaxies, but little mass (baryon fraction ~ 1).





The Abell 520 Puzzle

Did the dark matter and galaxies separate during the merger? If so, how?

- Peak is 5σ detection; excess M/L is 3σ. Followup:
  - 18 orbits HST time—just completed!
  - 500ks of Chandra data—in hand
  - Keck DEIMOS spectroscopy—in hand
- If the result is confirmed, two unpalatable choices:
  - Galaxies separated from DM via complex slingshots
  - Dark matter self-interaction partly responsible
    - Implied cross section is 4 ± 1 cm^2/g
    - Still much smaller than coulomb interaction cross-section, ≈ 1200 cm^2/g for 1000 km/s gas collision

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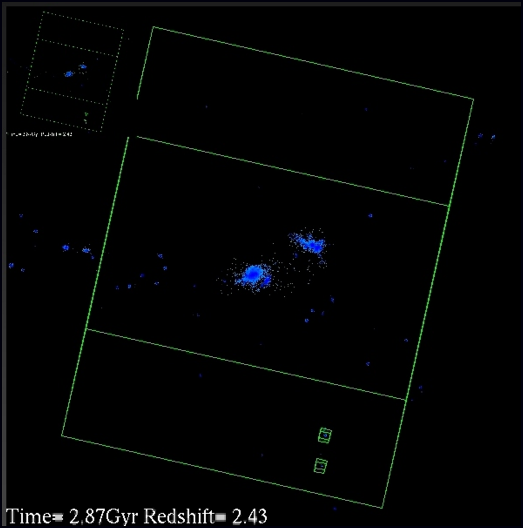
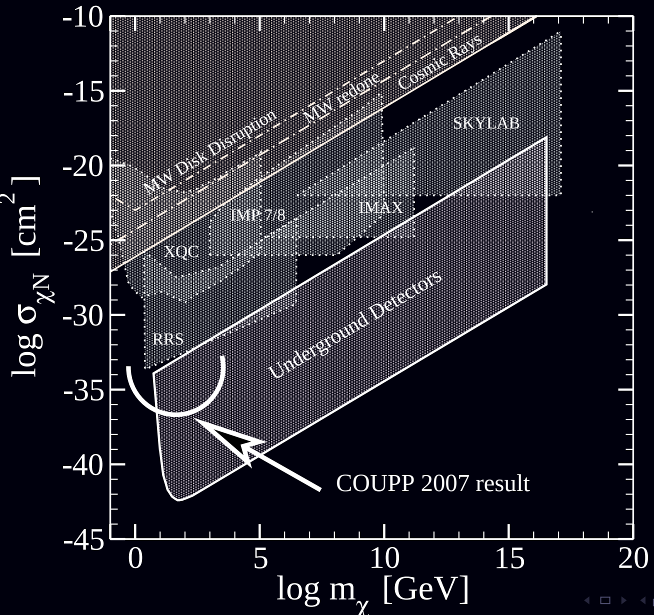
The Abell 520 Puzzle

Chain of slingshots works with the small halo galaxies, not the largest ones



The Abell 520 Puzzle

Dark matter self-interaction: how plausible is it?



Implied $\sigma_{\rm dm}/m_\chi \approx$ 4 cm^2/g

$\approx 7 \times 10^{-24}$ cm^2/GeV

Much larger than limits on dark matter-nucleon cross sections

The Abell 520 Puzzle

Dark matter self-interaction: how plausible is it?

- Fine-tuning required:
  - Need to make self-interaction cross section orders of magnitude larger than nucleon cross section
  - Some simple models exist (e.g. Faraggi & Pospelov 2001)
- Astrophysical constraints on self-interaction:
  - For $\rho \propto r^{-n}$, CDM predicts $n \approx 1$, SIDM $n \approx 0$
  - Observers disagree on the value of n
  - Measurement of n is a key goal of JACO
- Other key problems can be worked out:
  - Do $n = 0$ halos undergo core-collapse? (Kochanek & White 2000)
  - Does the same $\sigma_{\rm dm}$ describe dwarf galaxies and clusters?
    - May require velocity-dependent cross-section (Davé et al. 2001)
- SIDM may be an unlikely possibility, but is interesting and not conclusively ruled out by either data or theory

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Summary

- Clusters of galaxies offer exciting limits on dark matter and dark energy properties
- We will need to learn a lot of baryon physics along the way
- The JACO, CCCP, and LoCuSS projects will offer new constraints on vital astrophysical questions through
  - Joint analysis of lensing, SZ, X-ray, and dynamical data
  - Mass models of relaxed clusters
  - Studies of violent mergers such as Abell 520

Upcoming work

Where are we headed?

Next few years: better dark matter constraints

- Detailed modeling and simulations of Abell 520
- Final constraints from CCCP sample (30 clusters)
- Expansion to larger samples (e.g. LoCUSS, 100 clusters)
- Inclusion of dynamics, triaxiality, nonthermal effects, and strong lensing into JACO codebase

Next decade: era of precision cluster physics

- PAN-STARRS, Large Synoptic Survey Telescope, SNAP: 10^5 clusters of galaxies
- SPT, ACT surveys coordinated with weak lensing and X-ray campaigns
- International X-ray Observatory (IXO): advanced probes of turbulence, cosmic ray heating, bulk motions, and other nonthermal effects

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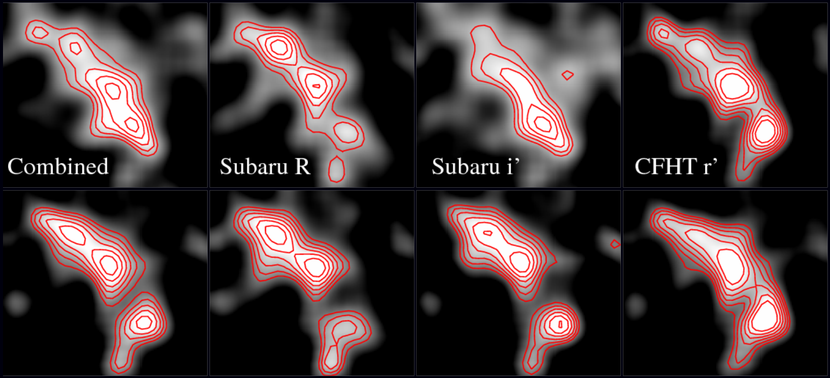

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Independent analysis of the data by Milkeraitis and van Waerbeke