Galaxy Cluster Astrophysics - Highlights and Challenges

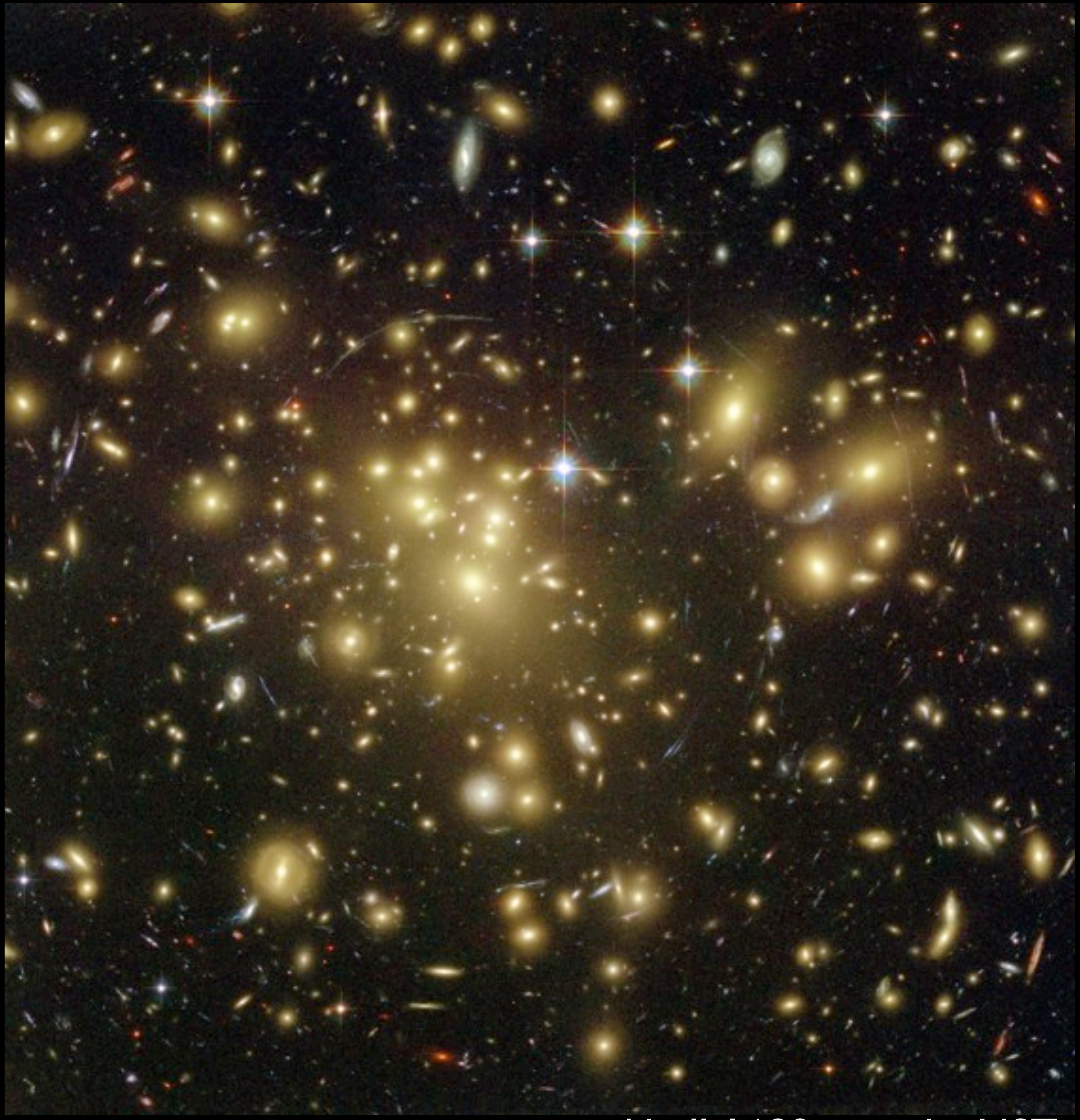
Ben Maughan
University of Bristol

Overview

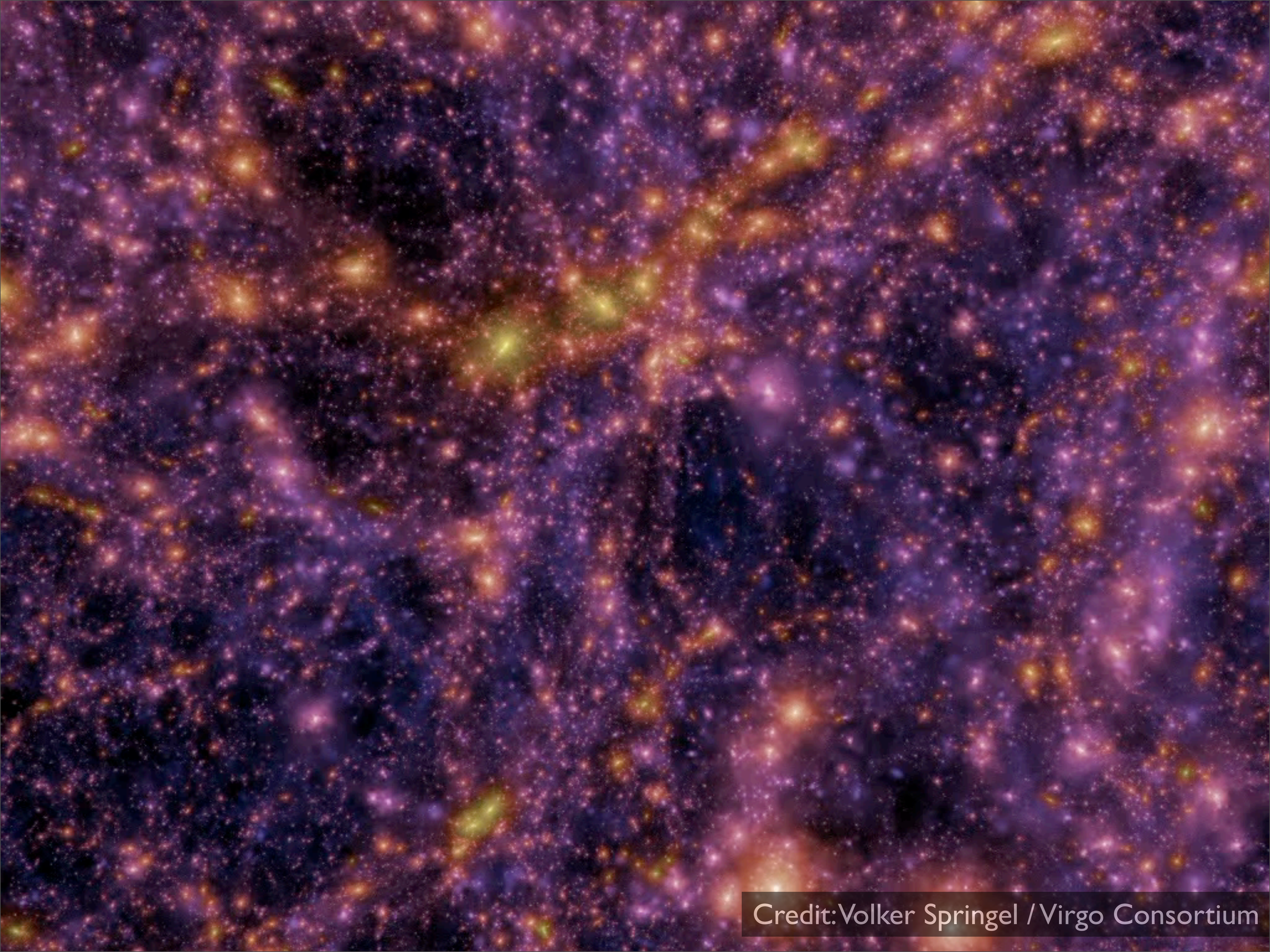
- ★ Introduction to galaxy clusters
- ★ Clusters as laboratories
  - ‣ study dark matter
  - ‣ plasma physics
  - ‣ heating, cooling and feedback
- ★ Cosmology with clusters
  - ‣ standard buckets
  - ‣ cluster surveys

Clusters of Galaxies

- ★ Messier first noted in 19th C that nebulae clustered together on sky
- ★ Later surveys (e.g. Abell) found many thousands of galaxy clusters
- ★ Clusters contain 100's of galaxies
- ★ Dominated by ellipticals, with the most massive residing at centre



Abell 1689 - credit: HST

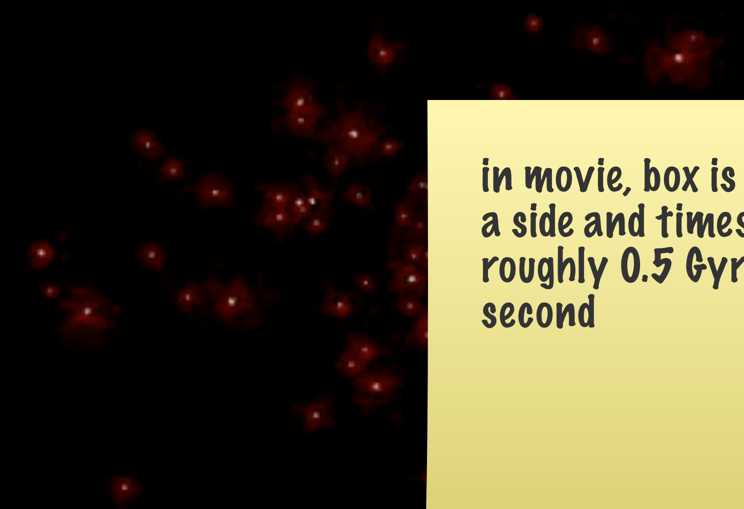


Credit: Volker Springel / Virgo Consortium

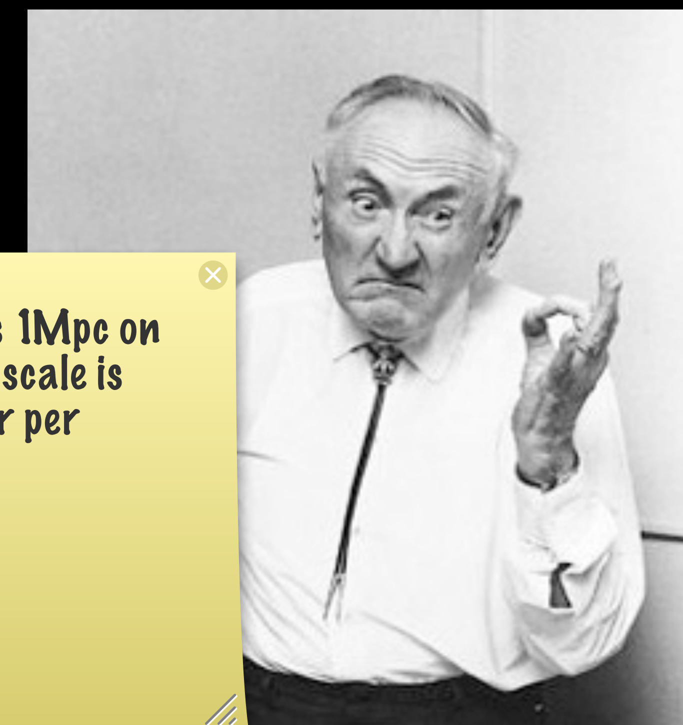
Discovery of Dark Matter

- ★ 1933: Zwicky measured redshifts of galaxies in Coma cluster
- ★ Found a broad range of velocities
- ★ Apply virial theorem
  - 100x mass visible in all stars in all galaxies
  - dark matter
- ★ Later confirmed by galaxy rotation curves

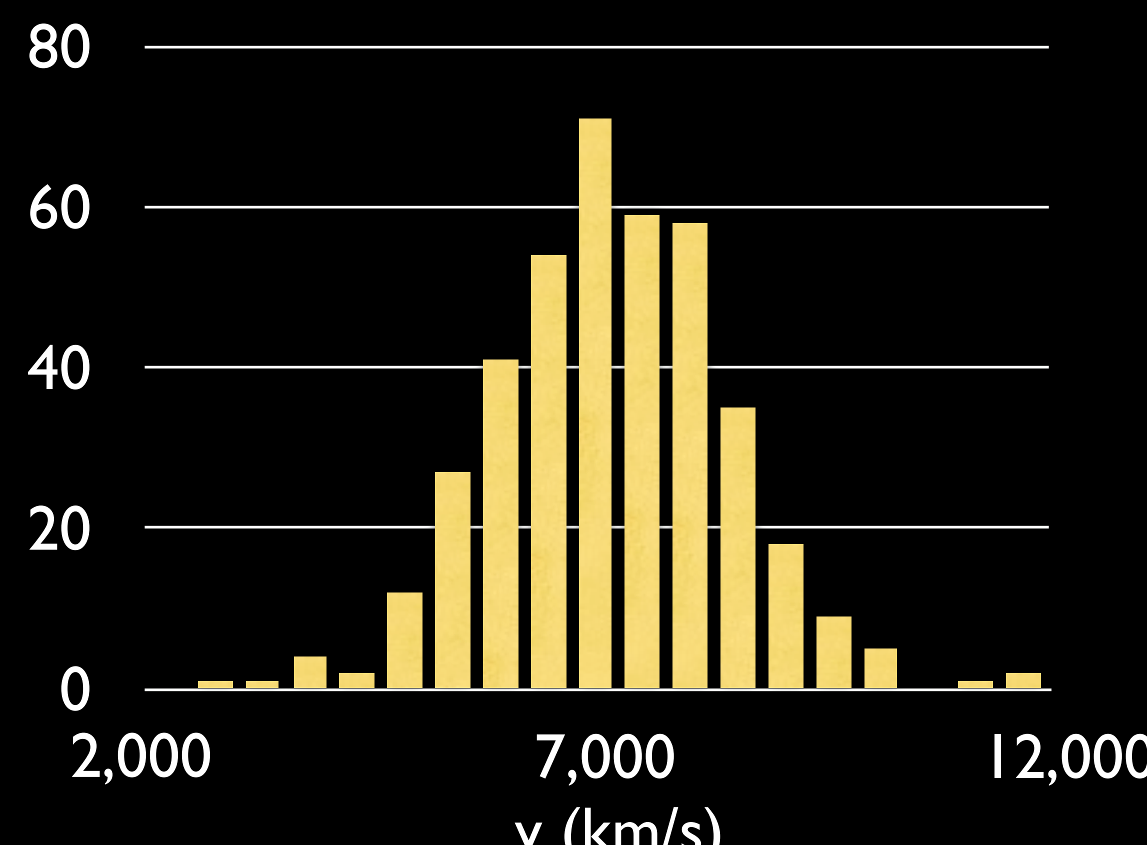
Credit: B Berring



in movie, box is 1Mpc on a side and timescale is roughly 0.5 Gyr per second

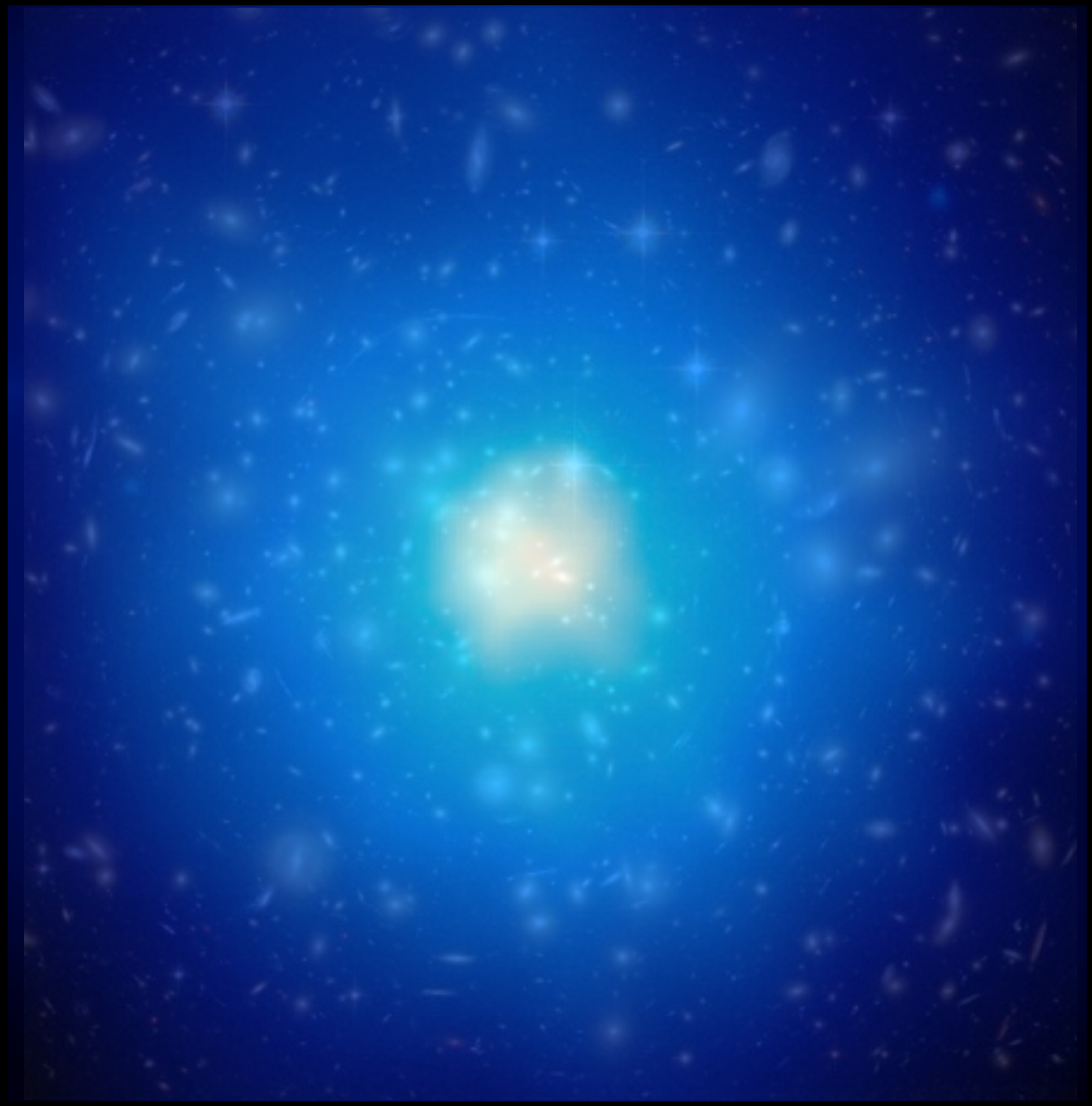


Fritz Zwicky



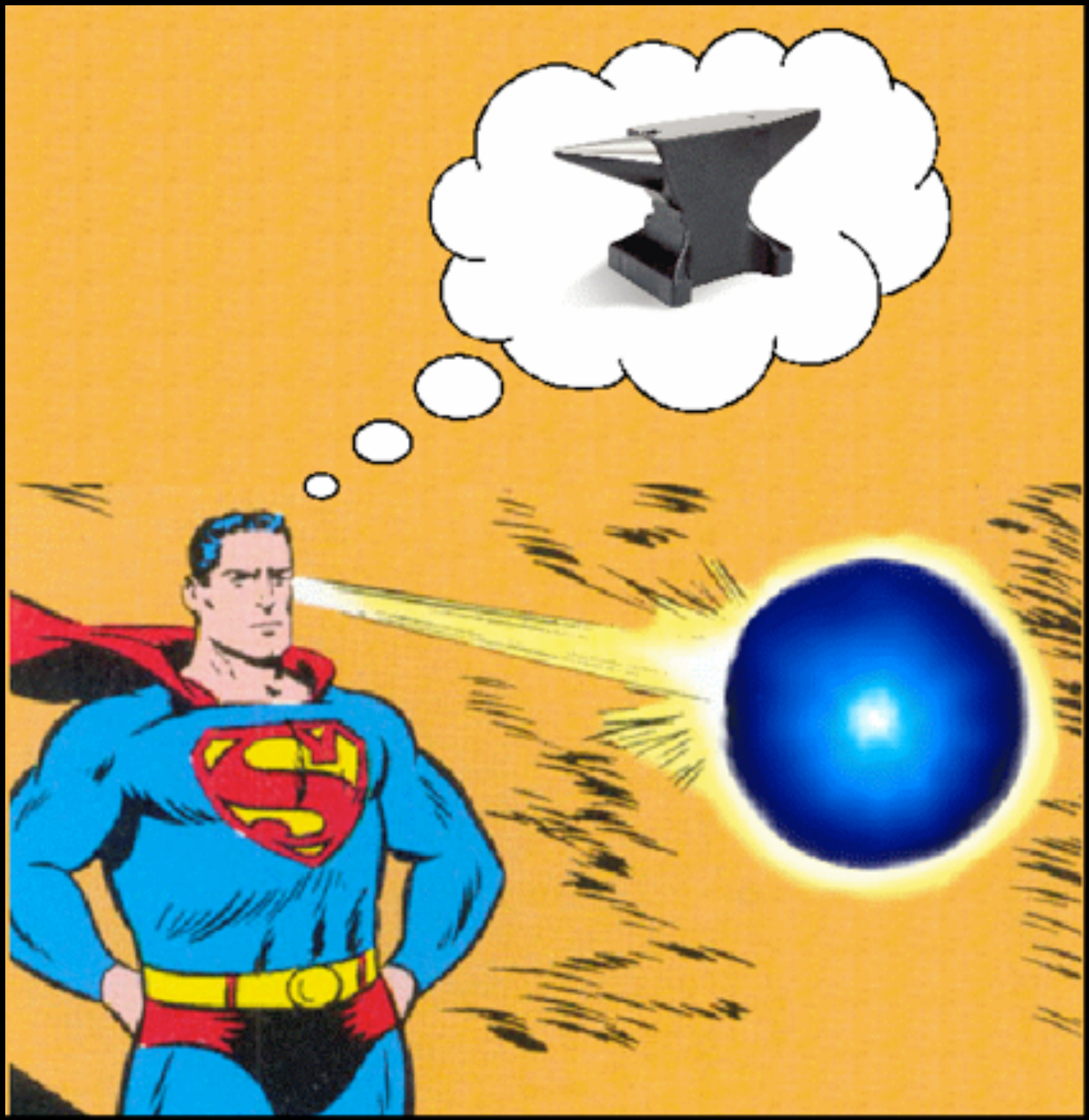
X-ray View of Galaxy Clusters

- ★ Galaxy clusters among brightest X-ray sources
- ★ Bremsstrahlung emission from ~10^8K plasma
  - ‣ $\varepsilon_\nu \propto \rho^2 T^{1/2}$
- ★ Gas optically thin so see all emission from cluster in projection - not just a surface
- ★ X-ray images and spectra give temperature, density, luminosity and ion abundance
- ★ 5x more mass in gas than in stars



X-ray Mass Measurements

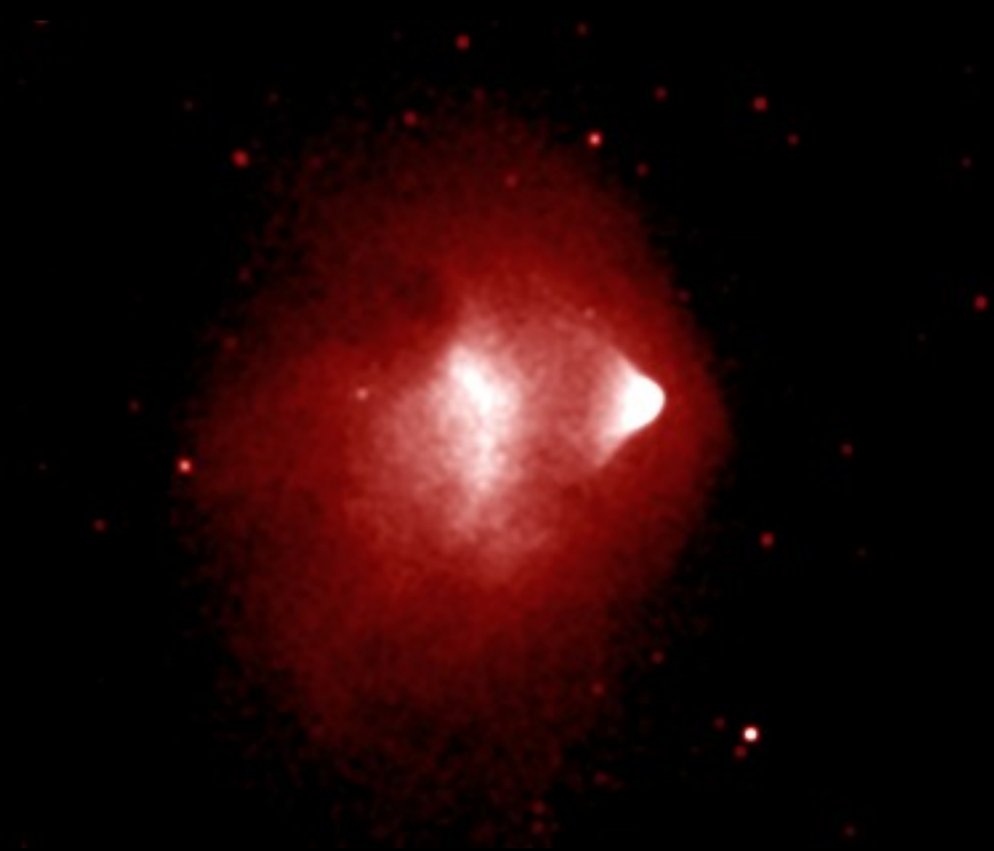
- ★ Temperature of gas gives very good measurement of total mass
  - gives KE of gas particles
  - use virial theorem
- ★ Gas mass & luminosity also expected to scale simply with mass
- ★ For most accurate masses, measure pressure profile and assume hydrostatic eqm
  - need high-quality data for relaxed clusters

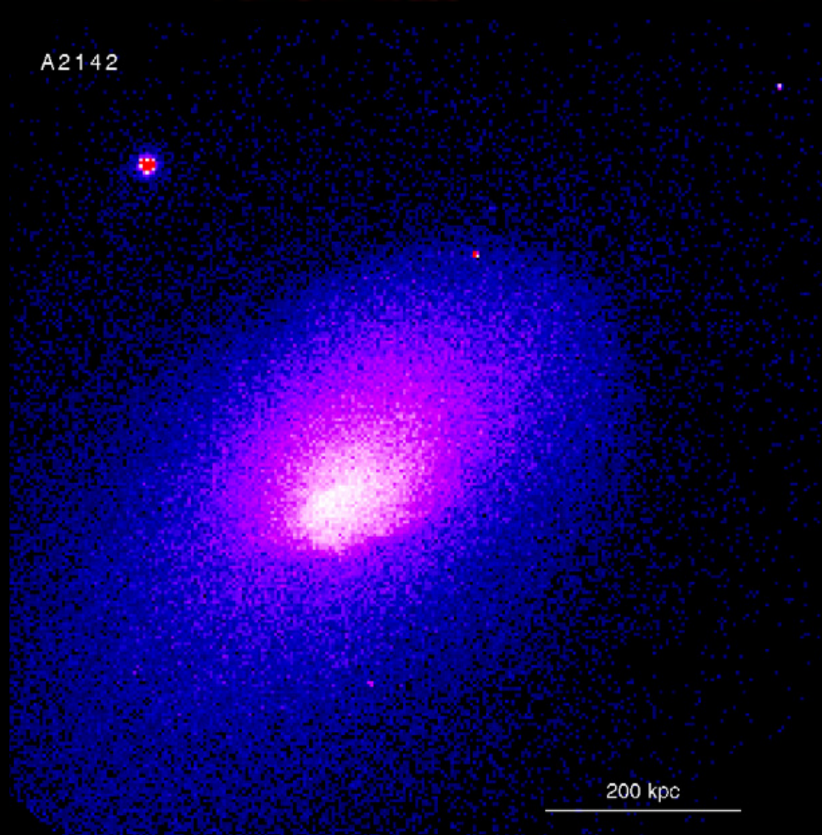


Overview

- ★ Introduction to galaxy clusters
- ★ Clusters as laboratories
  - ‣ study dark matter
  - ‣ plasma physics
  - ‣ heating, cooling and feedback
- ★ Cosmology with clusters
  - ‣ standard buckets
  - ‣ cluster surveys

Cluster Mergers

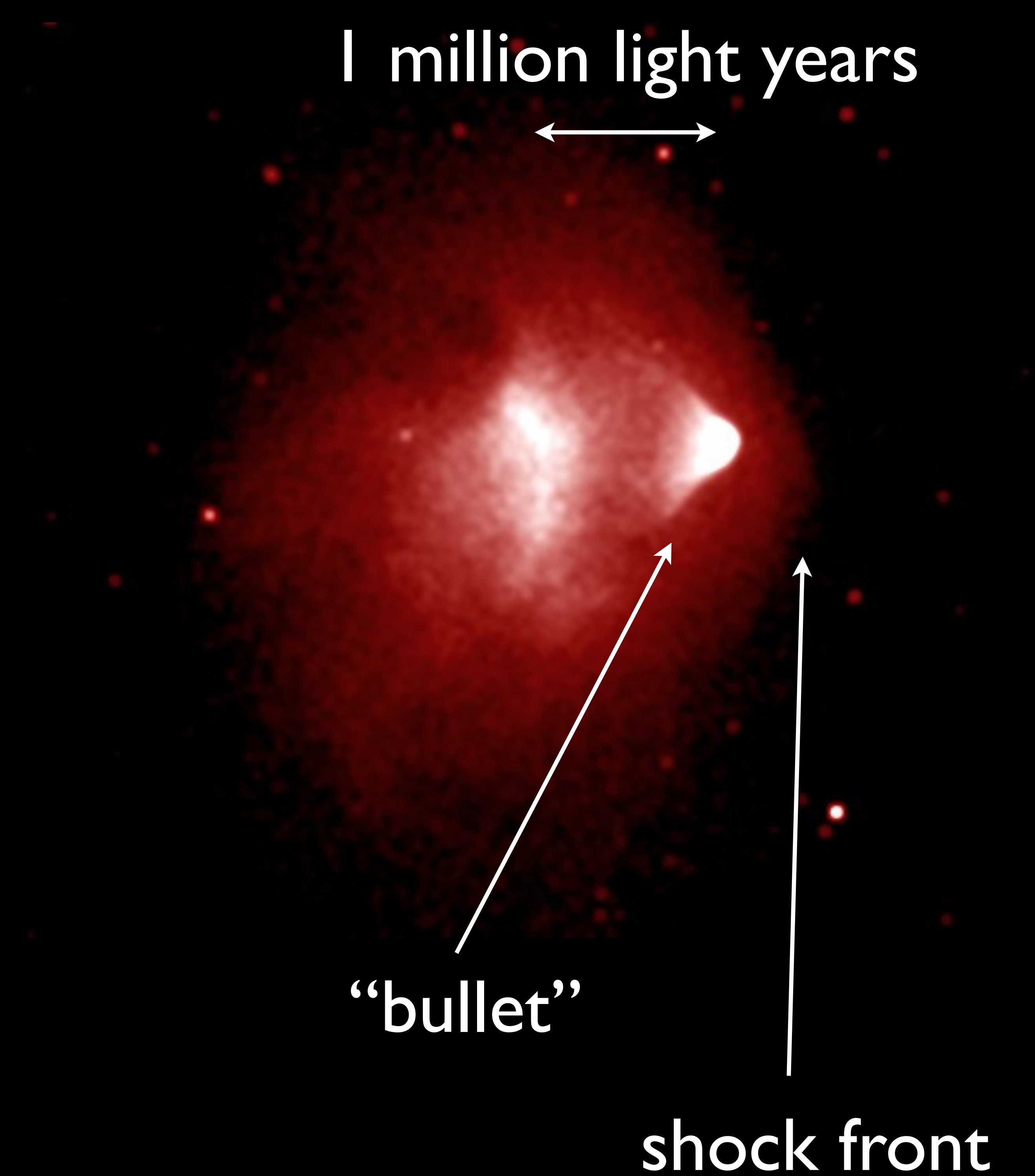




- ★ Clusters grow via mergers of smaller systems
- ★ Major mergers are most energetic events since big bang
    - involving kinetic energies of $\sim 10^{58}$ J
- ★ Energy is dissipated by shocks and turbulence
    - heats gas to virial equilibrium with new potential
- ★ Mergers produce shock fronts and cold fronts

Bullet Cluster

- ★ Bullet cluster is high energy merger between two clusters
- ★ X-ray data show “bullet” travelling at 5,000 km/s
- ★ Can do interesting plasma physics by measuring stability of bullet and properties of shock front
- ★ Also study dark matter properties



Markevitch+ (2004)

Shock Physics

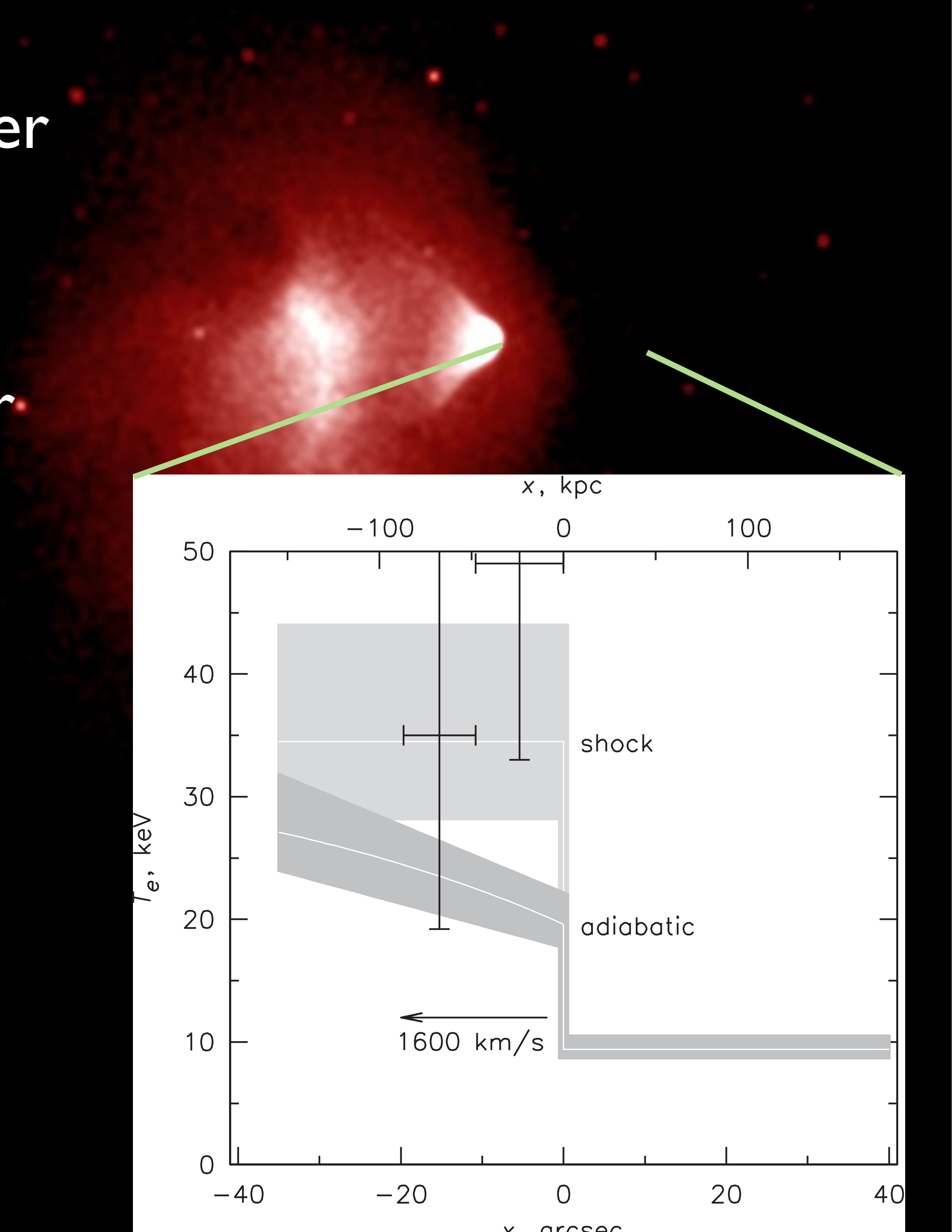
★ In shock front in plasma, slower protons experience shock

- electrons don't notice
- equilibrate adiabatically over time

★ X-ray spectrum measures electron temperature

★ Observed temperature jump much sharper than adiabatic heating

- how do electrons and protons equilibrate so quickly?

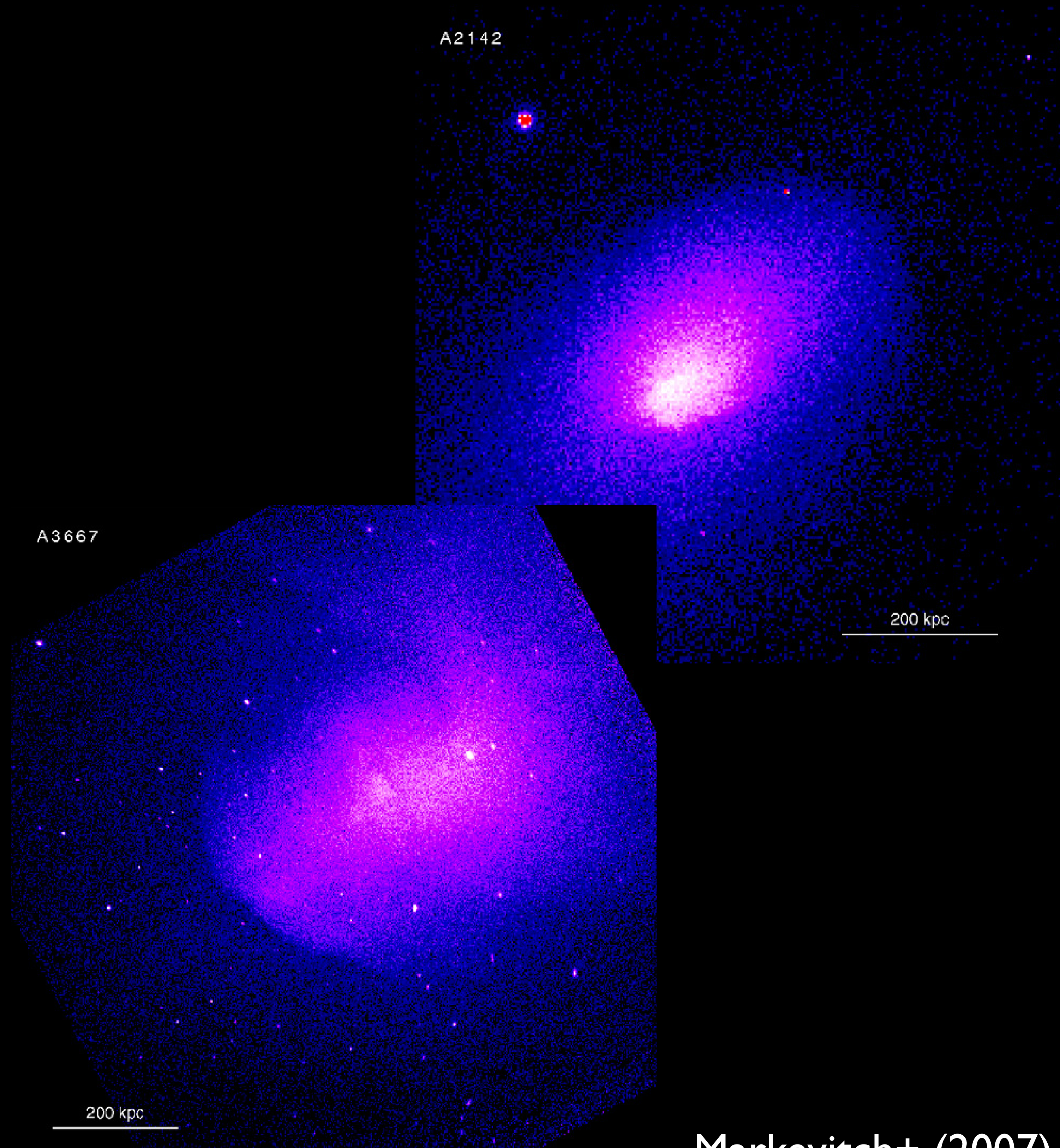


Cold Fronts

★ Chandra X-ray observatory discovered sharp edges in cluster images

- look like shocks
- gas pressure constant across edge so not shocks

★ Cold fronts - cold dense bodies of gas moving through hotter, thinner cluster gas



Markevitch+ (2007)

Cold Fronts

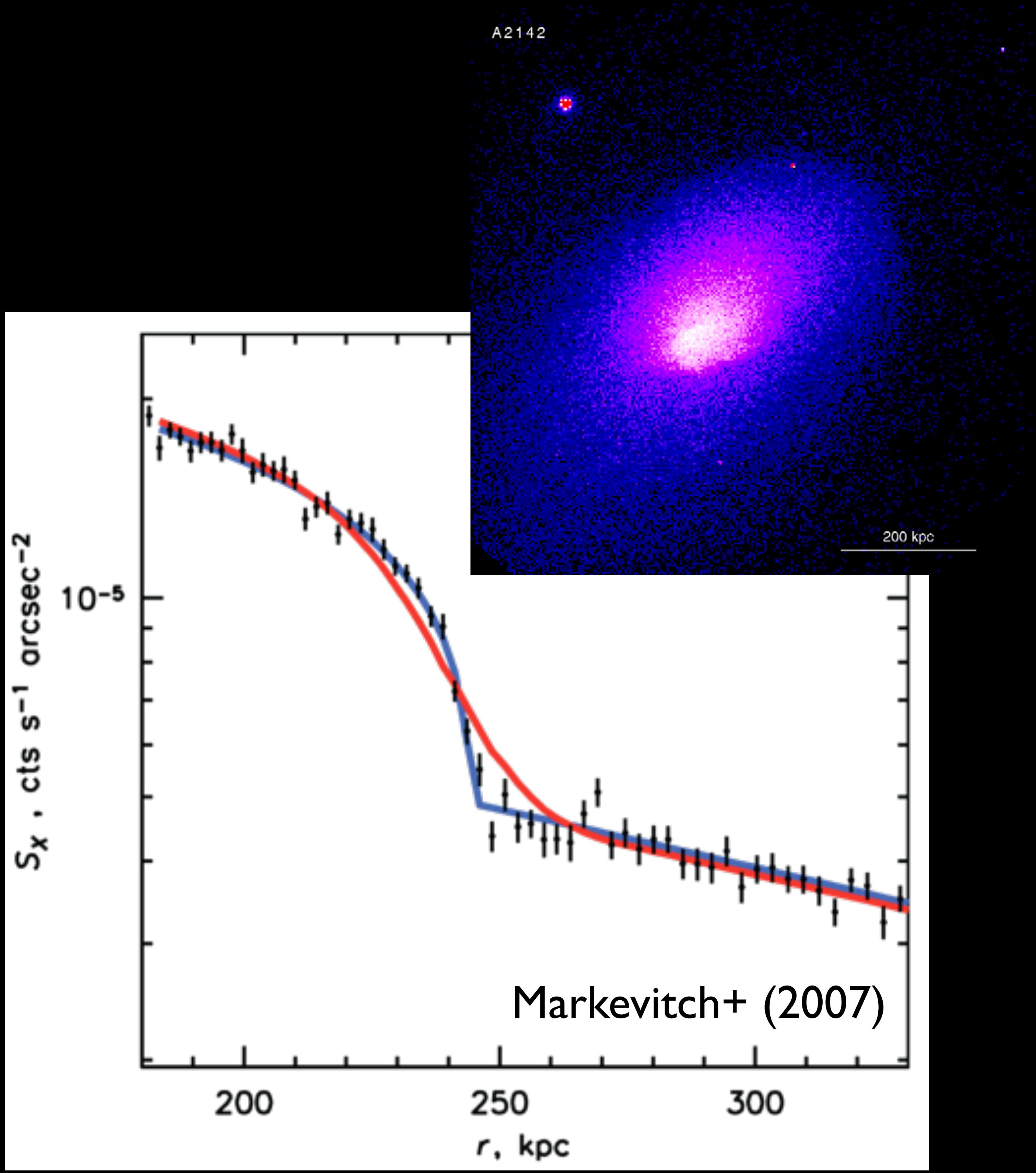
★ Cold fronts are extremely sharp contact discontinuities between hot/thin and cold/dense gas

  ‣ e.g. surface brightness profile across front in A2141

★ Expect conduction to blur out front on scales of ~10s kpc

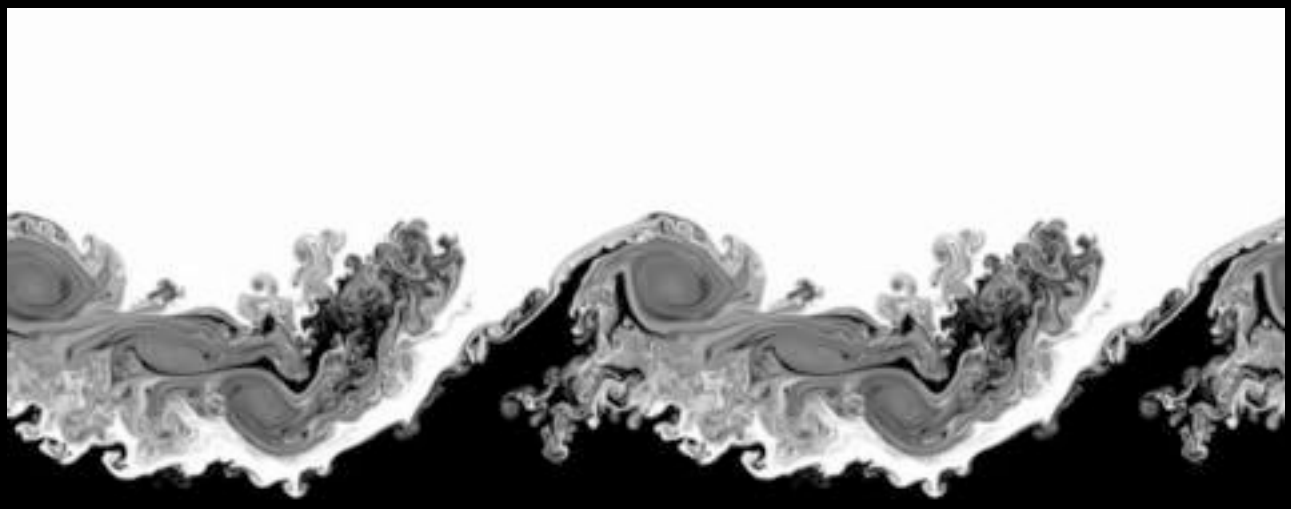
★ Front is too sharp

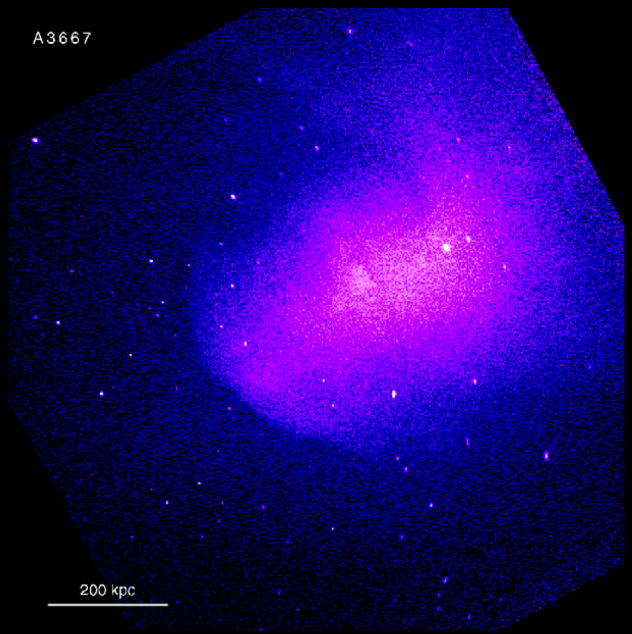
  ‣ conduction is suppressed

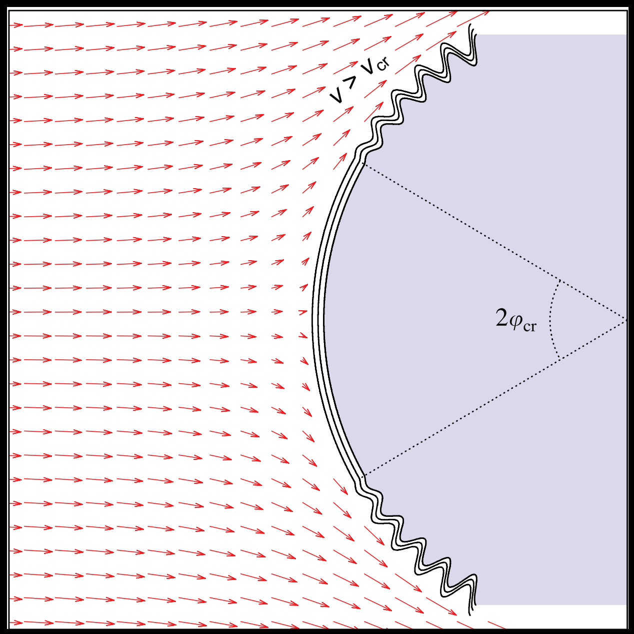


Markevitch+ (2007)

Cold Front Instabilities







Markevitch+ (2007)

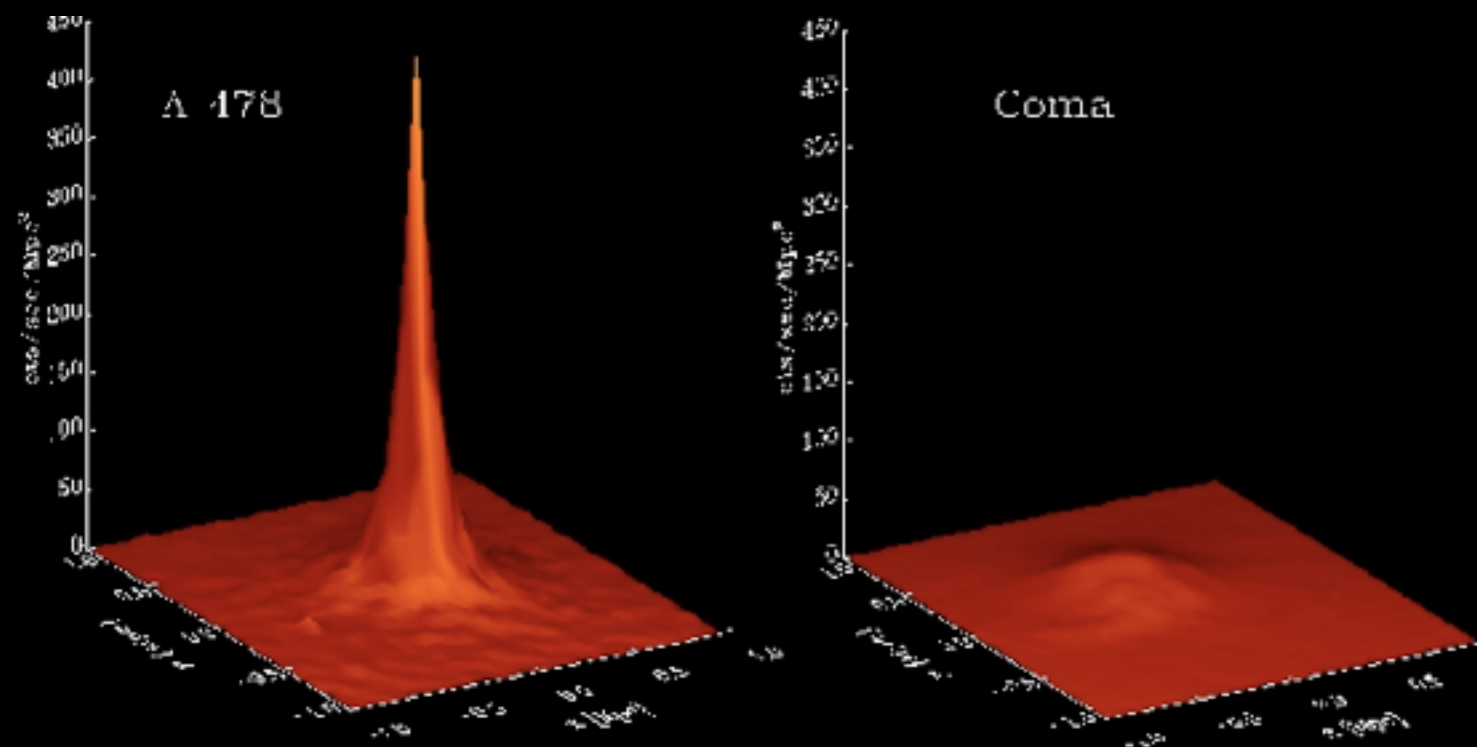
- ★ Expect Kelvin-Helmholtz instabilities to disrupt cold fronts as gas layers shear across each other
- ★ Observed fronts stable over range of angles
  - instabilities supressed
- ★ Magnetic fields and/or viscosity likely responsible
- ★ Magnetic draping can create layer of parallel field along interface

Challenges

- ★ How are conduction and instabilities suppressed?
- ★ What is role of magnetic fields on the cluster plasma?
- ★ What is the nature of viscosity in the cluster plasma?

Cooling in Clusters

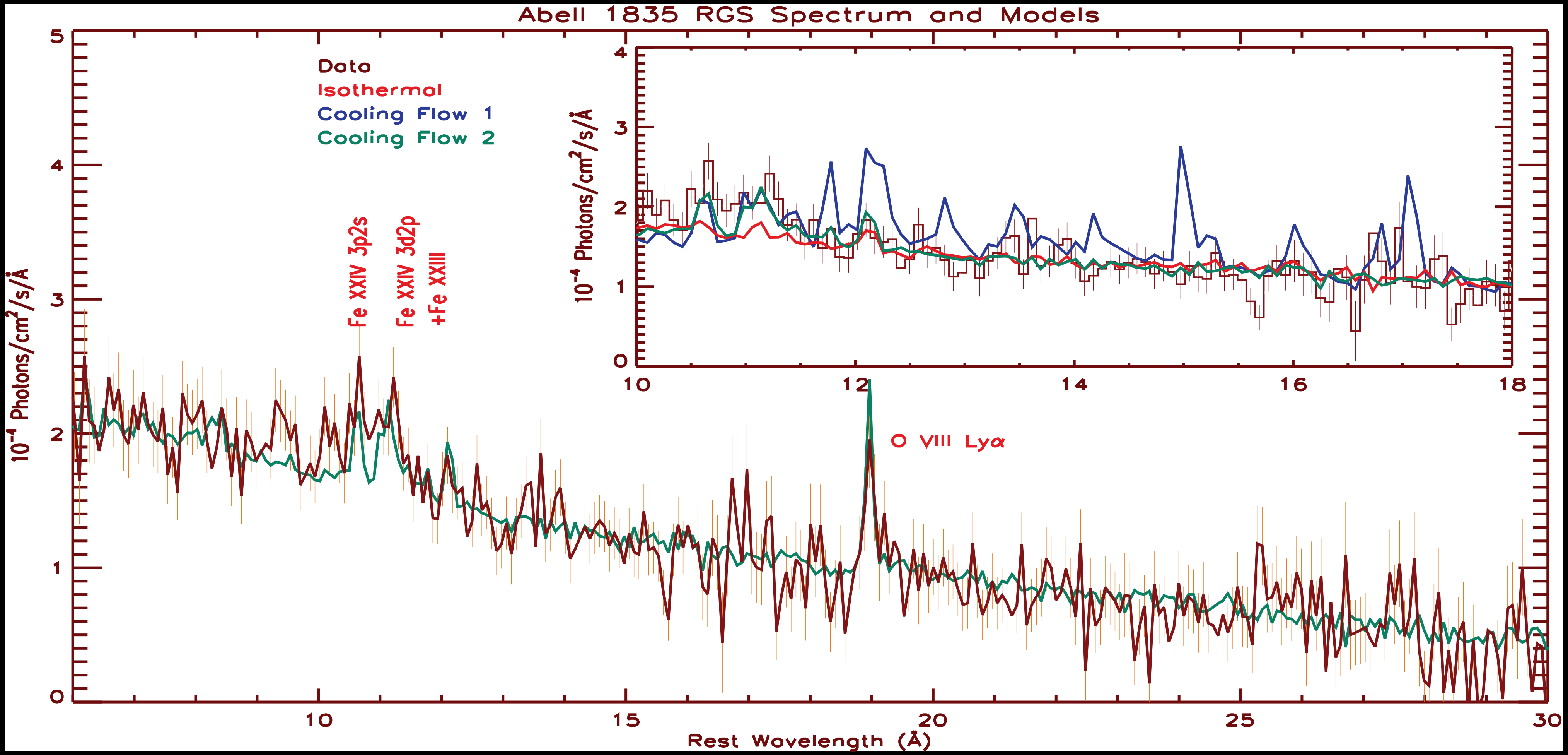
- ★ X-ray emissivity ~ρ_{gas}^2 so dense core gas cools efficiently
  - ‣ condenses and cools further - runaway "cool core"
- ★ Gas expected to cool and condense onto central cluster galaxy, fueling star formation
  - ‣ enhanced star formation not observed
  - ‣ where does gas go?



Fabian+ (1994)

Cooling in Clusters

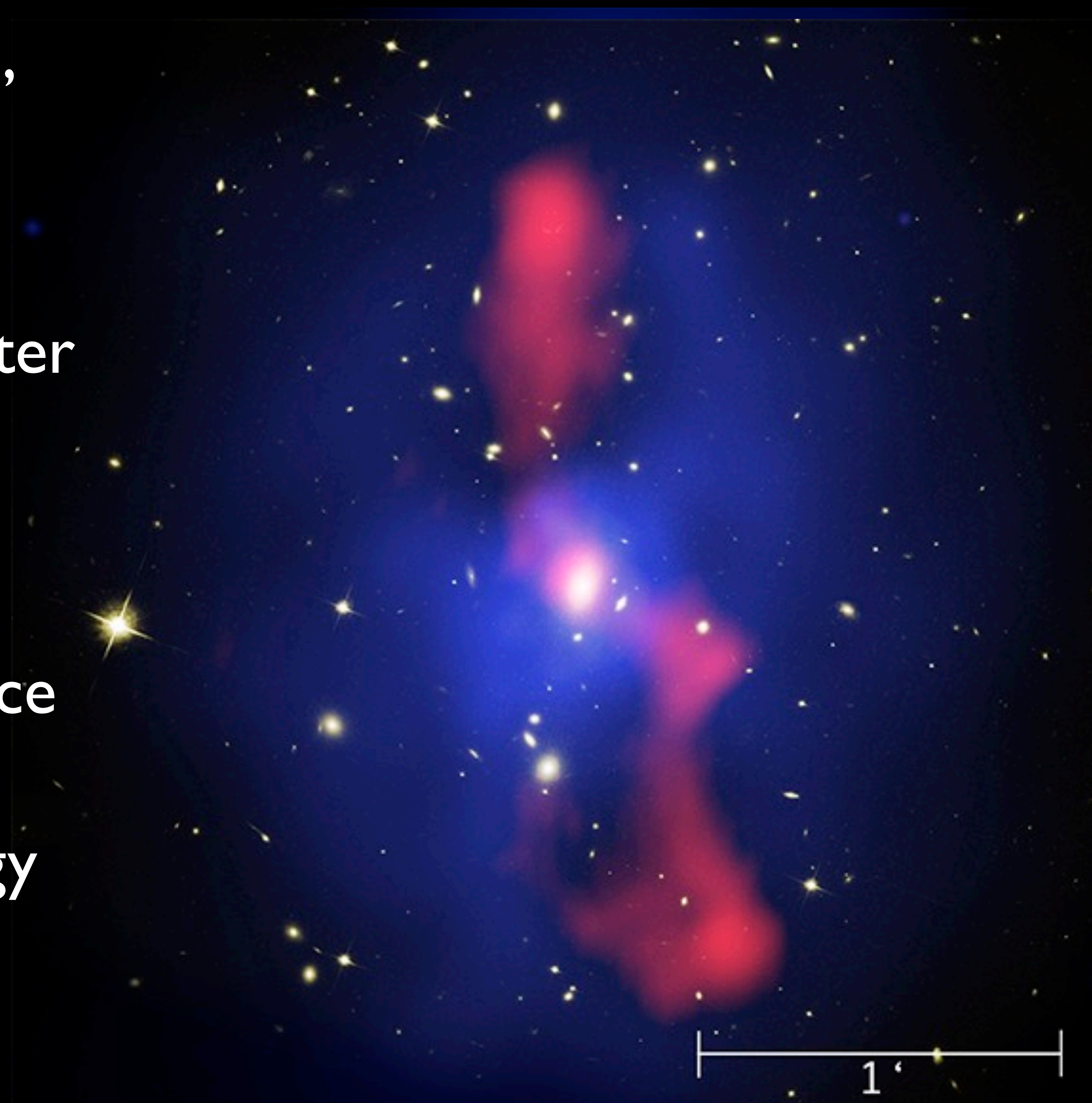
- ★ Asking the wrong question!
- ★ High resolution X-ray spectra from XMM showed that emission lines expected from very cool gas not seen
- ★ What prevents the gas from cooling?



Petersen+ (2001)

Heating Clusters

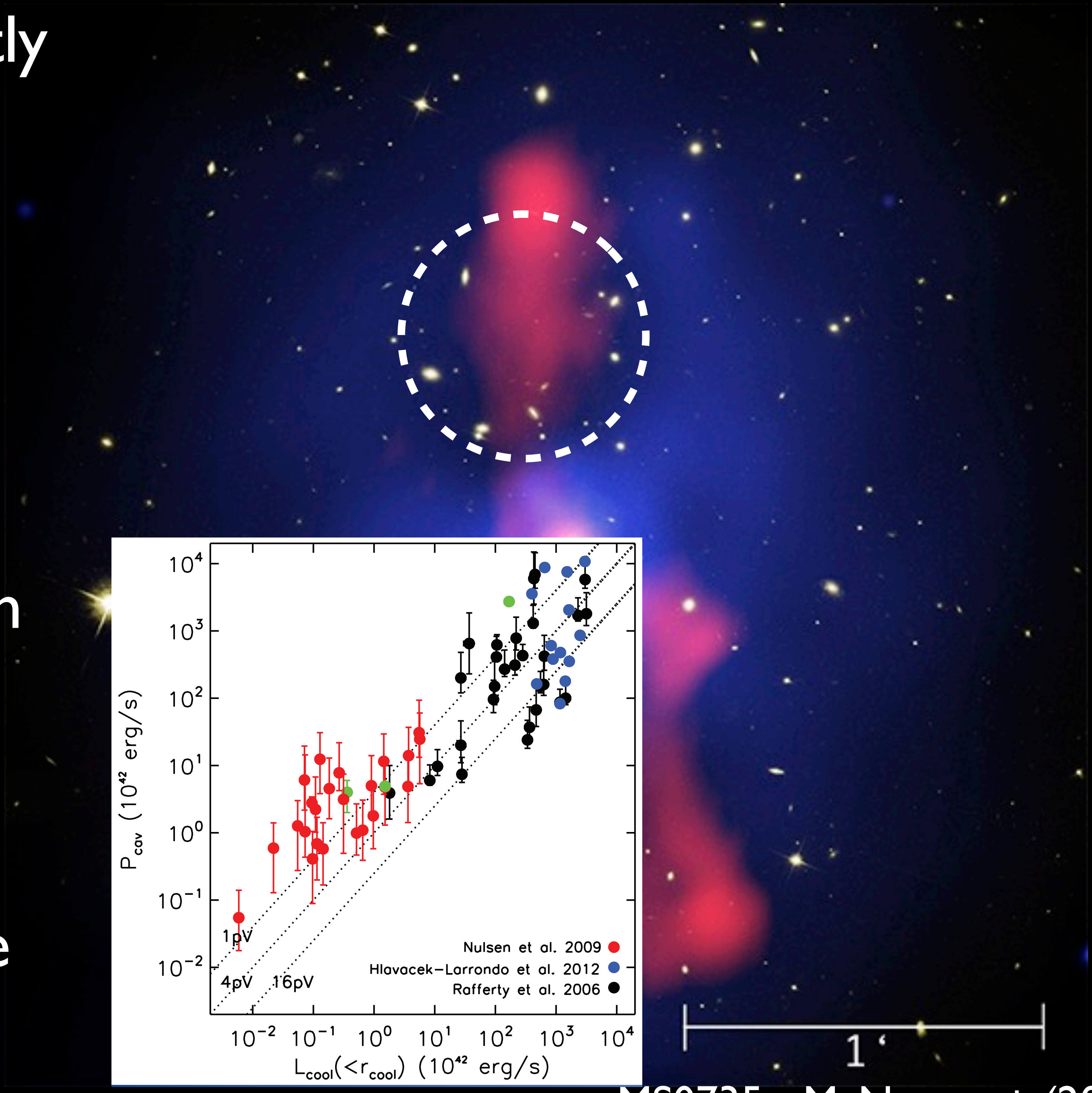
- ★ After healthy debate, general consesus is active galactic nuclei
- ★ AGN jets observed interacting with cluster gas
  - ‣ inflate bubbles
- ★ Energy provided by jets enough to balance heating
- ★ How does the energy get into the gas?



MS0735 - McNamara+ (2007)

Effervescent Heating

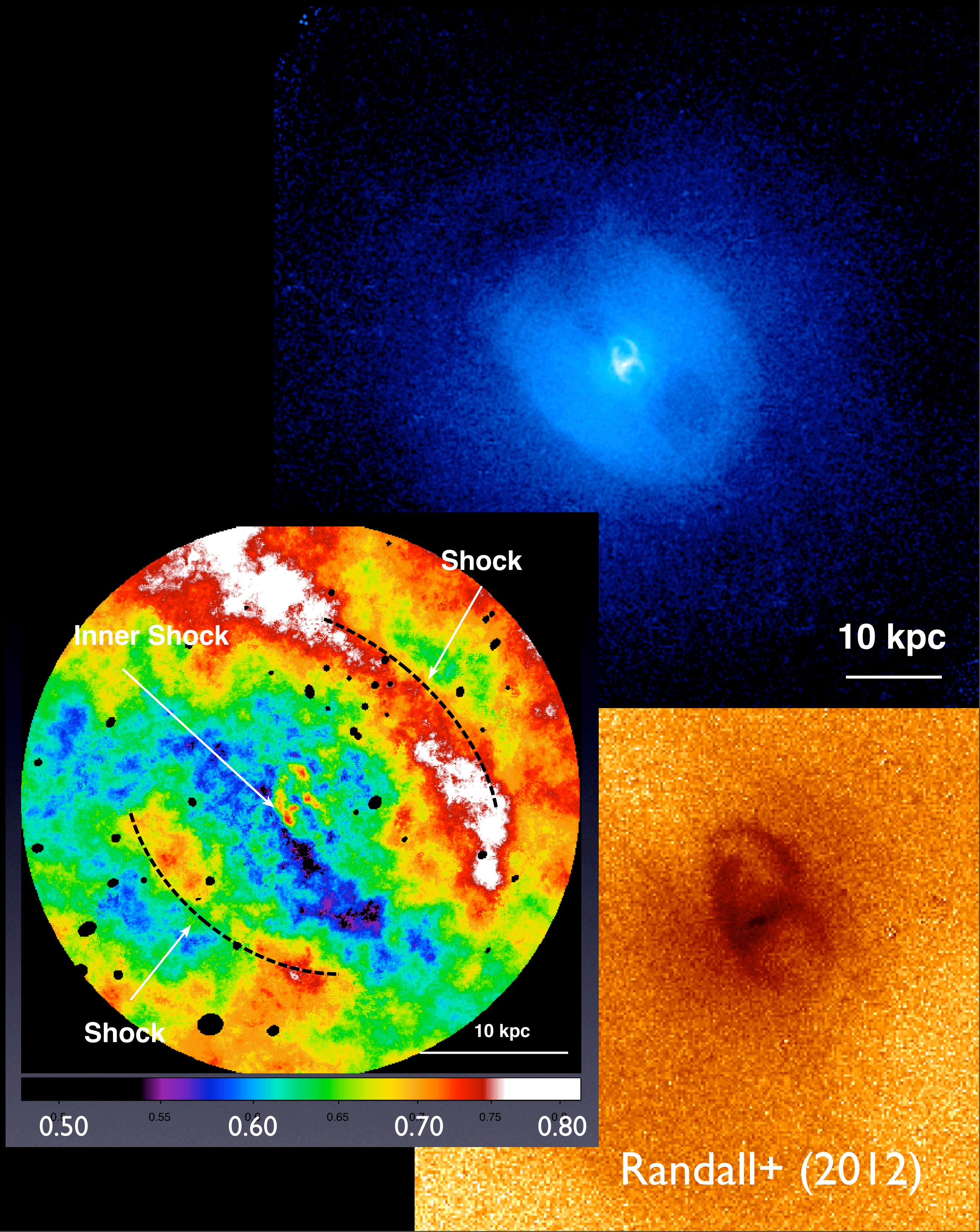
- ★ Bubbles rise buoyantly and gas falls in to replace them
  - loses PE
- ★ Energy required to inflate bubble is transferred to gas
- ★ Estimate energy from PdV work done
  - enough to balance cooling
- ★ Difficult to heat core regions this way



MS0735 - McNamara+ (2007)

Shock Heating

- ★ Shock fronts associated with AGN seen in handful of clusters
- ★ X-ray image of NGC 5813 shows 3 generations of bubbles and shocks
- ★ Temperature and density jumps across shocks give
  - energy input from shock
  - velocity of shock
- ★ Rate of heating from shocks alone balances cooling



Randall+ (2012)

Challenges

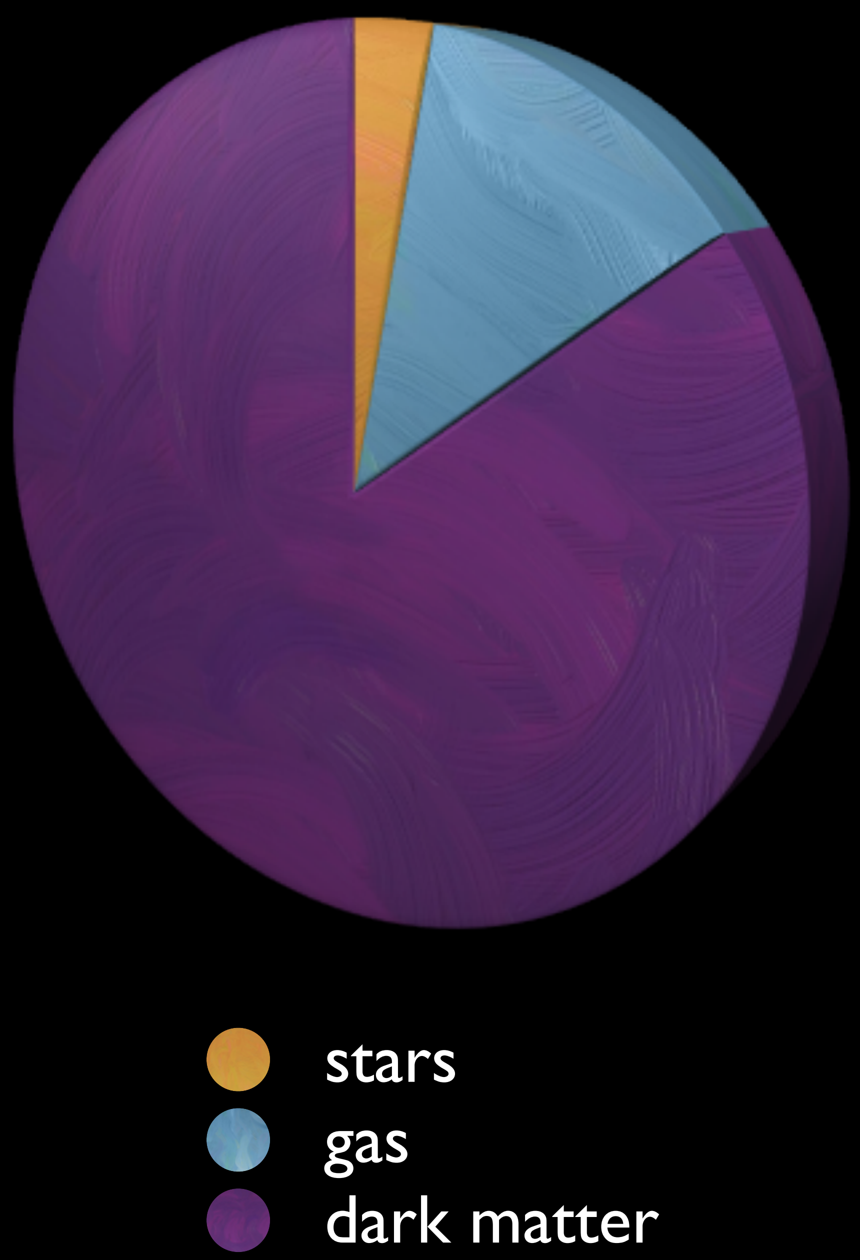
- ★ Is NCG 5813 unusual?
  - ‣ can shocks alone provide heating in most systems?
  - ‣ does effervescent heating contribute significantly?
- ★ What feedback processes link the heating and cooling?
- ★ What is effect on galaxy formation and evolution?

Overview

- ★ Introduction to galaxy clusters
- ★ Clusters as laboratories
  - study dark matter
  - plasma physics
  - heating, cooling and feedback
- ★ Cosmology with clusters
  - standard buckets
  - cluster surveys

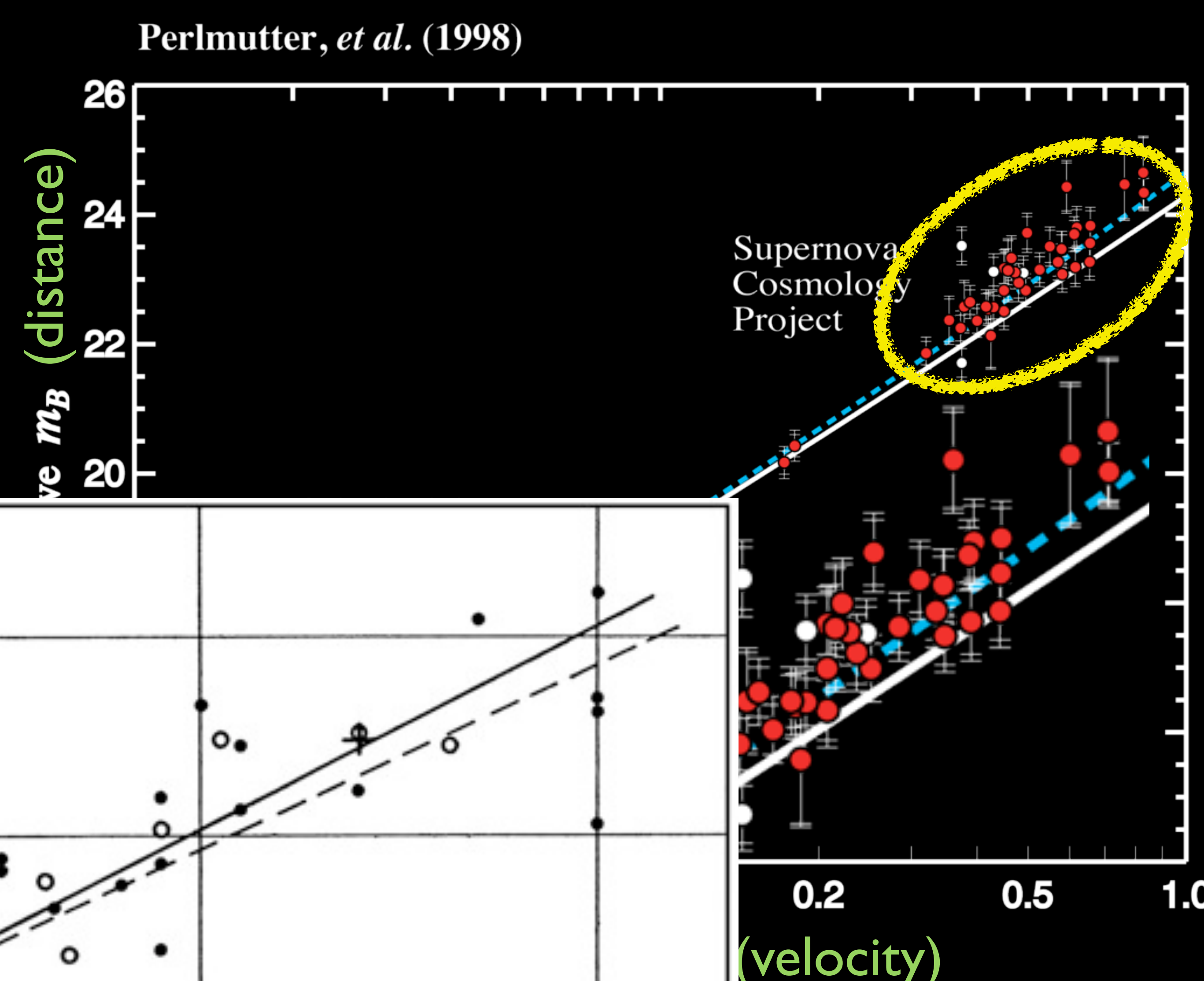
Clusters and Cosmology

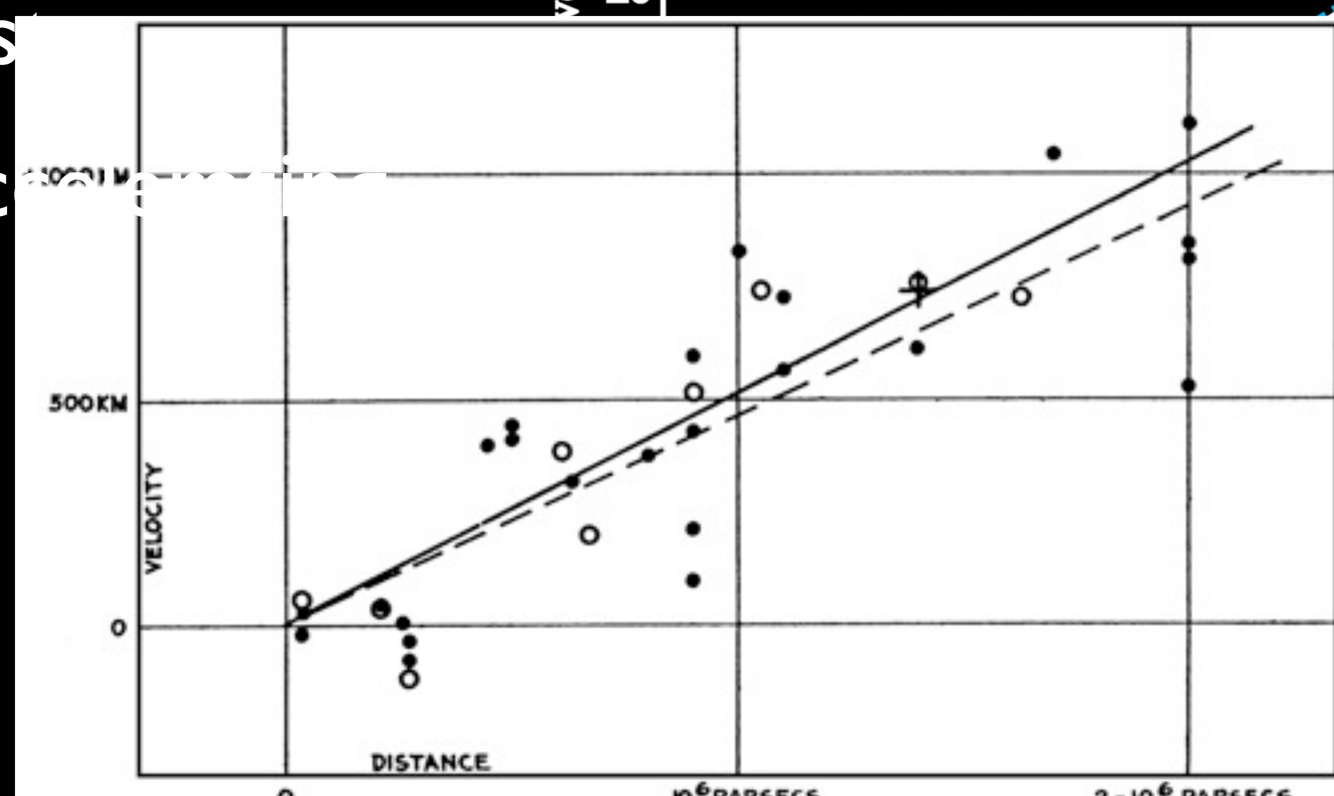
- ★ 1993: White et al; Galaxy clusters large enough to represent universe
- ★ Fraction of normal matter in cluster should match universe as a whole
- ★ Most recent measurements:
  - 3% stars, 12% gas, 85% dark matter
- ★ 5 times as much dark matter as normal matter in the universe
- ★ Use the fraction of mass in baryons (stars + gas) as standard bucket



Dark Energy Discovery

- ★ 1998: use supernovae as standard candles to extend Hubble's law to high-z
- ★ Distant SN receding more slowly than expected
  - Universe was expanding slower in pas
  - expansion ac
- ★ Dark energy





Standard Buckets

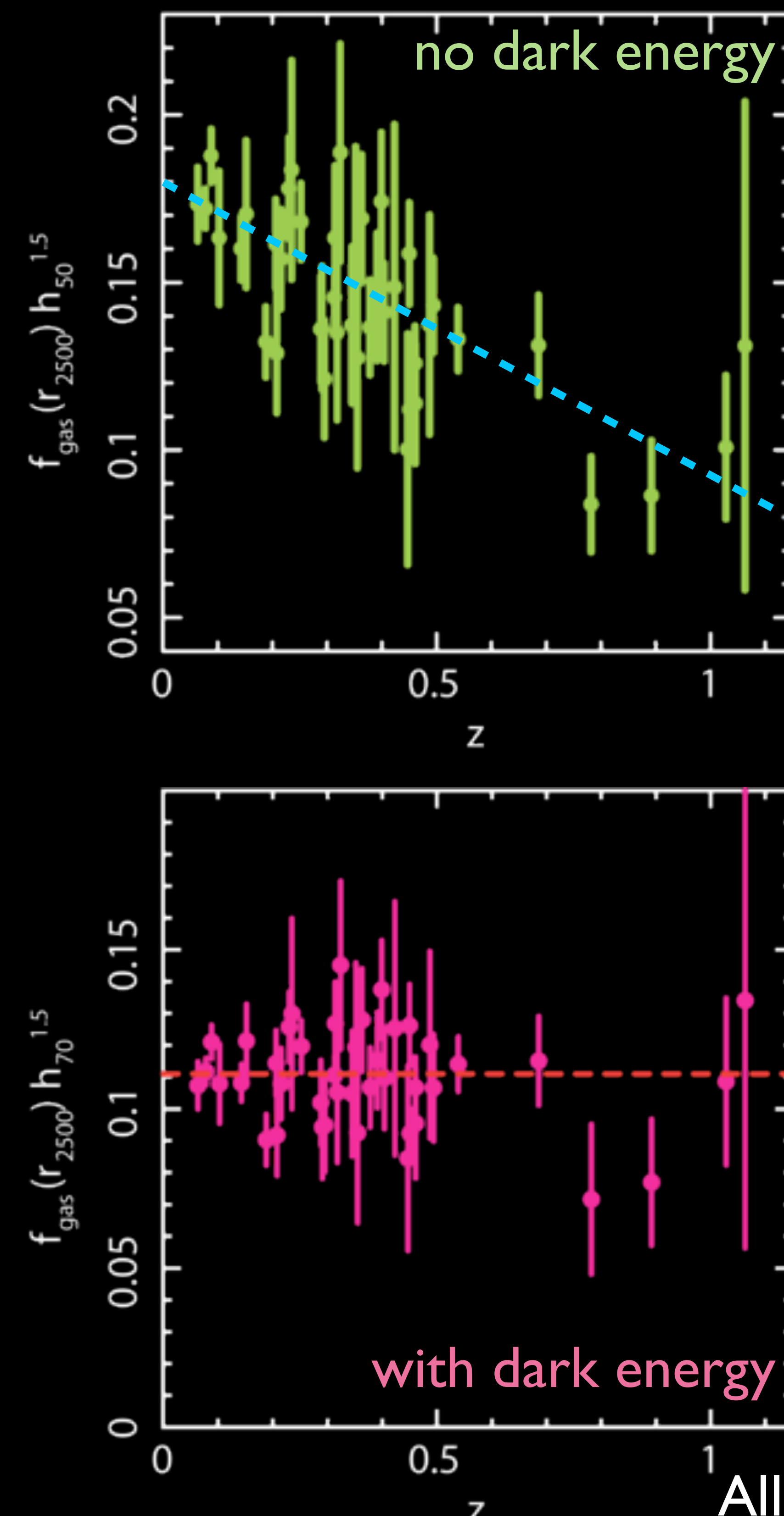
- ★ Galaxy clusters are representative objects
  - expect all clusters to have same ratio of baryonic/dark matter
  - gas fraction (fgas)
- ★ To calculate fgas from X-ray data need to know distance to cluster

$$f_{gas} = \frac{M_{gas}}{M_{tot}} \propto d_L d_A^{1/2}$$

  - or, if know fgas can calculate distance

fgas Evolution

- ★ 2008: Allen et al. measured fgas for clusters at different redshifts
- ★ Used X-ray observations to measure amount of normal and dark matter
- ★ Tested which cosmological model gives "correct" fgas
  - i.e. gives same fgas at all distances
- ★ Cluster data require dark energy
  - high-z clusters vital



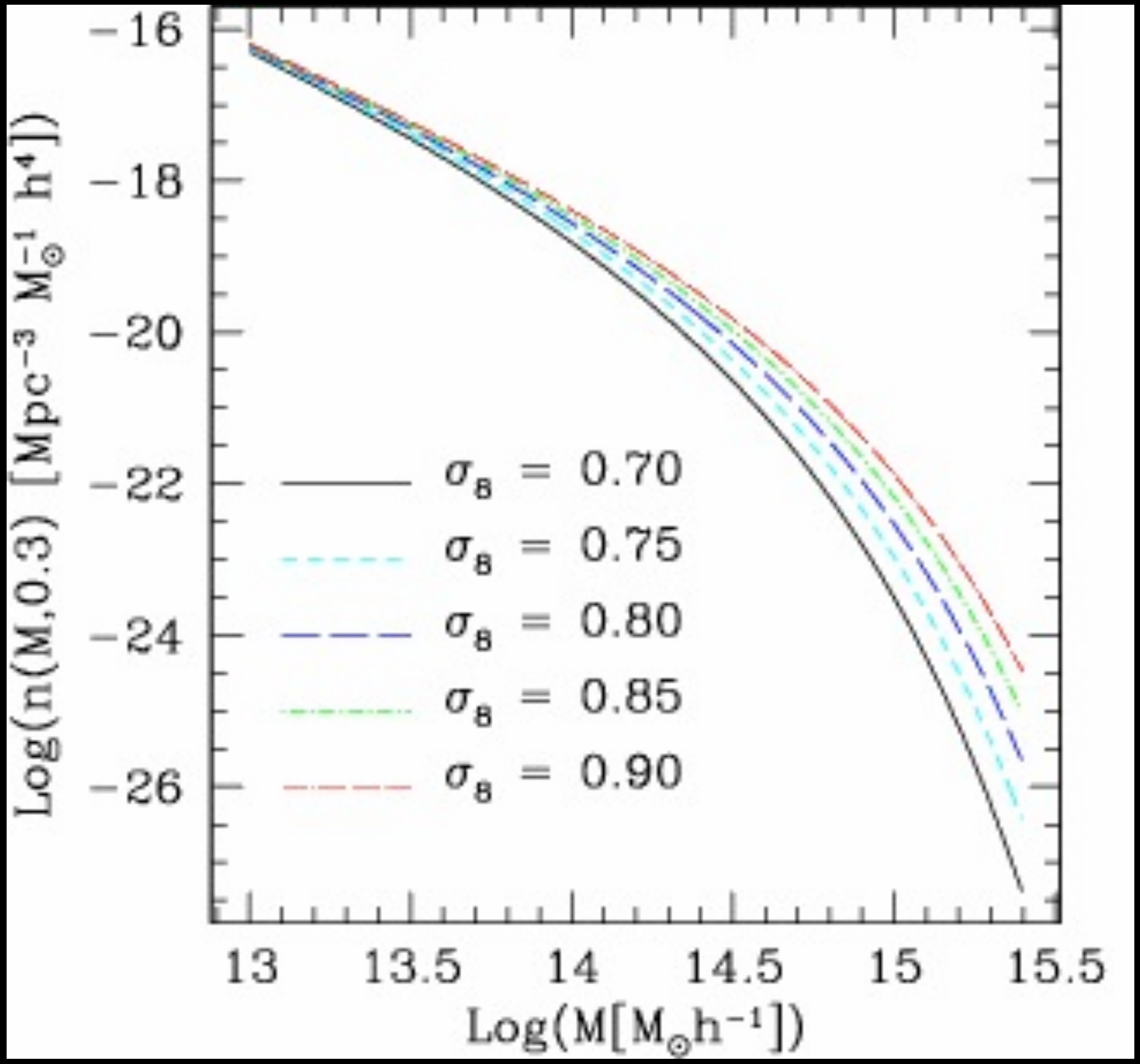
Allen+ (2008)

Challenges

- ★ Measuring cluster masses is hard (and even harder at high-z)
  - ‣ are clusters relaxed?
  - ‣ are X-ray masses biased?
  - ‣ comparisons of masses estimated with different techniques needed
- ★ Can we add many more distant clusters?

Cluster Mass Function

- ★ Clusters form from densest peaks in early Universe
  - affected by density distribution and expansion rate of Universe
- ★ Shape and evolution of mass function sensitive to cosmology
  - number density vs mass
- ★ Need well-defined surveys to detect clusters to high-z and compute volumes for number densities



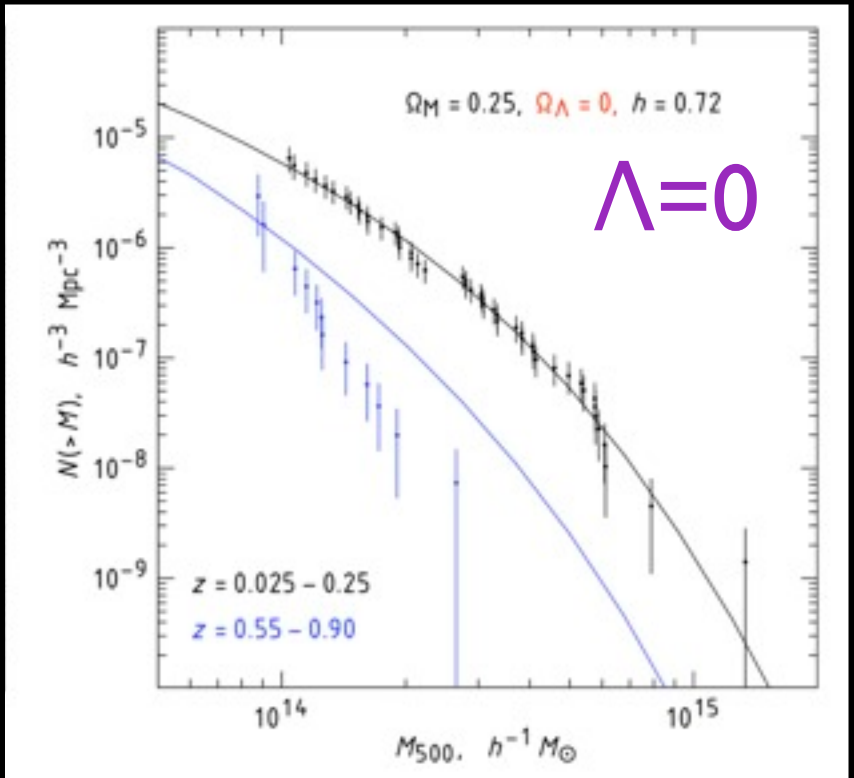
Fedeli+ (2008)

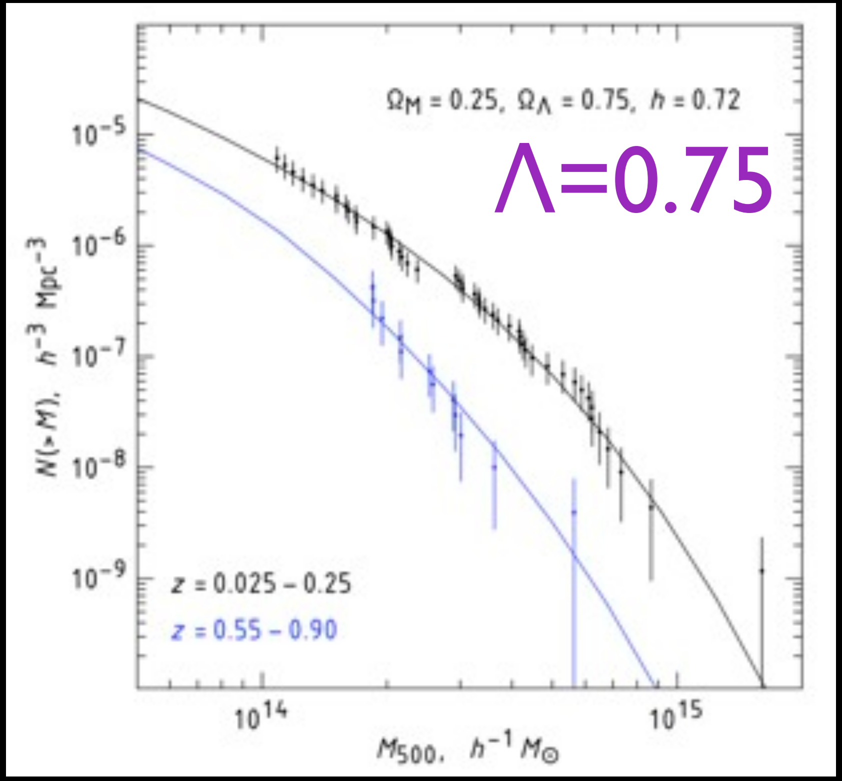
Cluster Surveys

- ★ Galaxy overdensities
  - very large samples, redshift information
  - projection effects give false positives
- ★ X-ray
  - unambiguous detection, good mass indicators
  - need follow up for redshifts
- ★ Sunyaev-Zel'dovich effect (decrement in CMB due to scattering by cluster gas)
  - redshift independent, v large samples to high-z
  - limited to high mass clusters, need redshifts

Mass Function Evolution

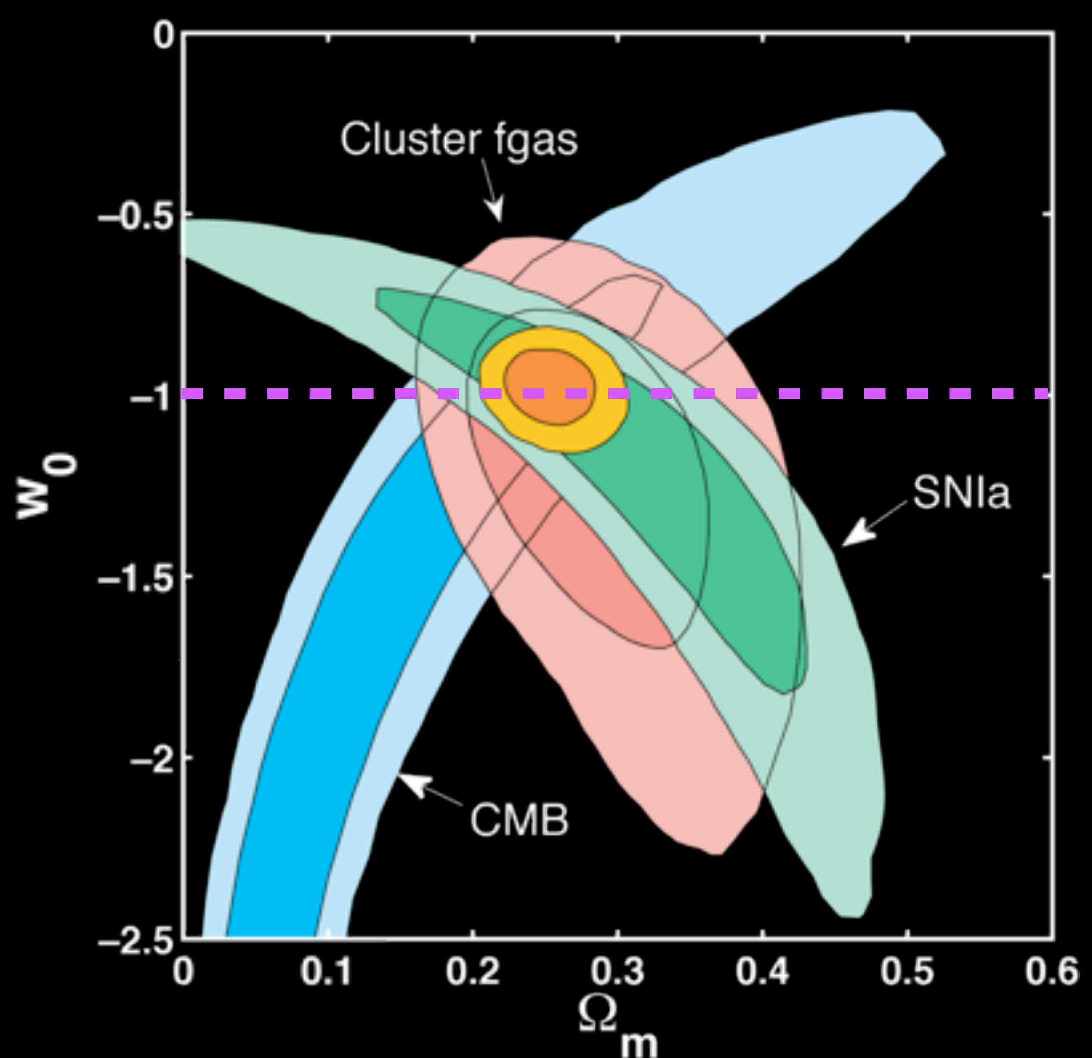
- ★ Vikhlinin+ (2009) used X-ray cluster survey to measure mass function evolution
  - ‣ 49 clusters at <z>=0.05
  - ‣ 37 clusters at <z>=0.55
- ★ Dark energy required
- ★ Need to measure evolution of mass function to probe dark energy
  - ‣ high-z clusters vital



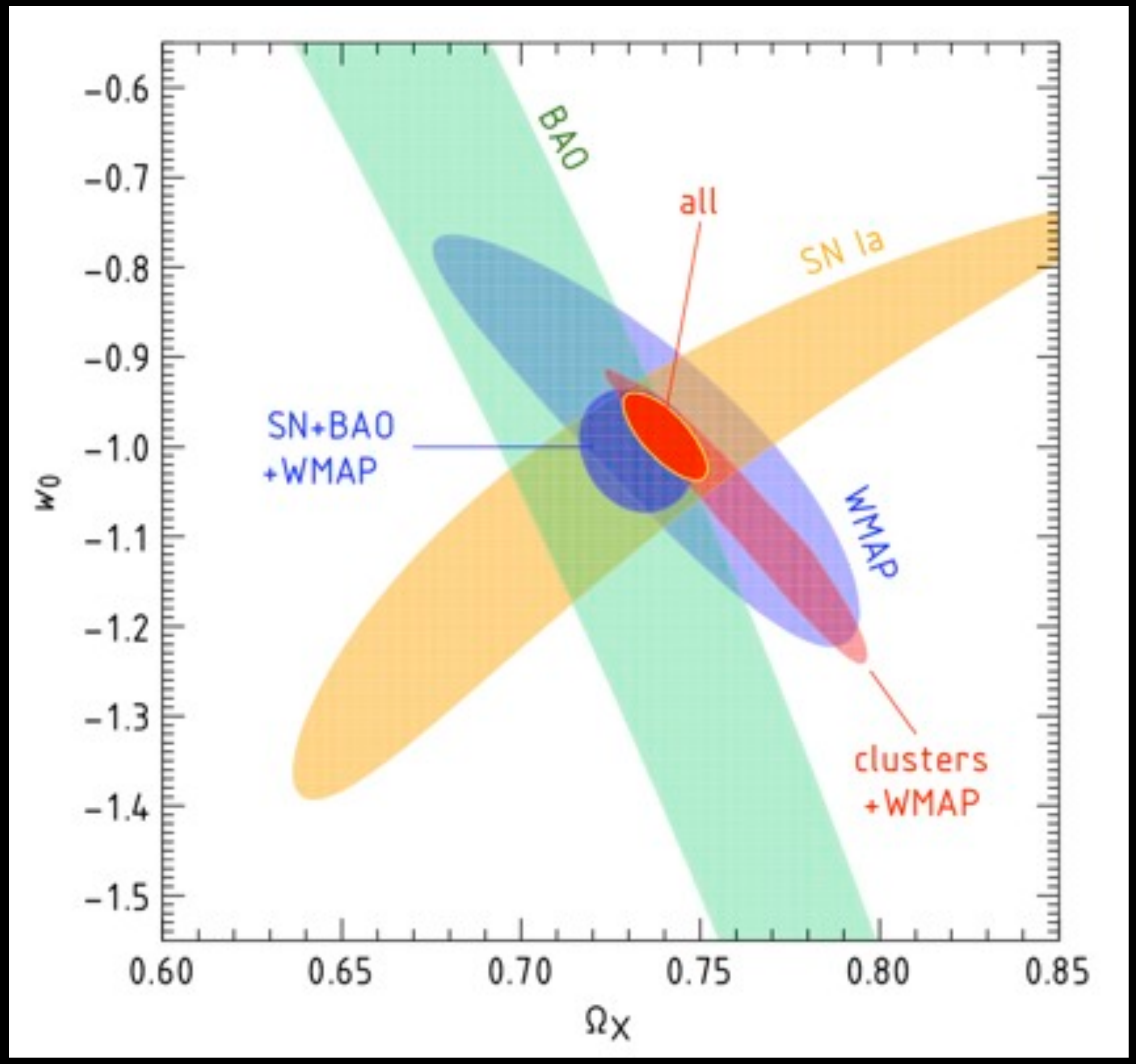


Combined Cosmology

- ★ Cluster constraints on cosmological parameters are competitive with, and complementary to, other methods



standard bucket



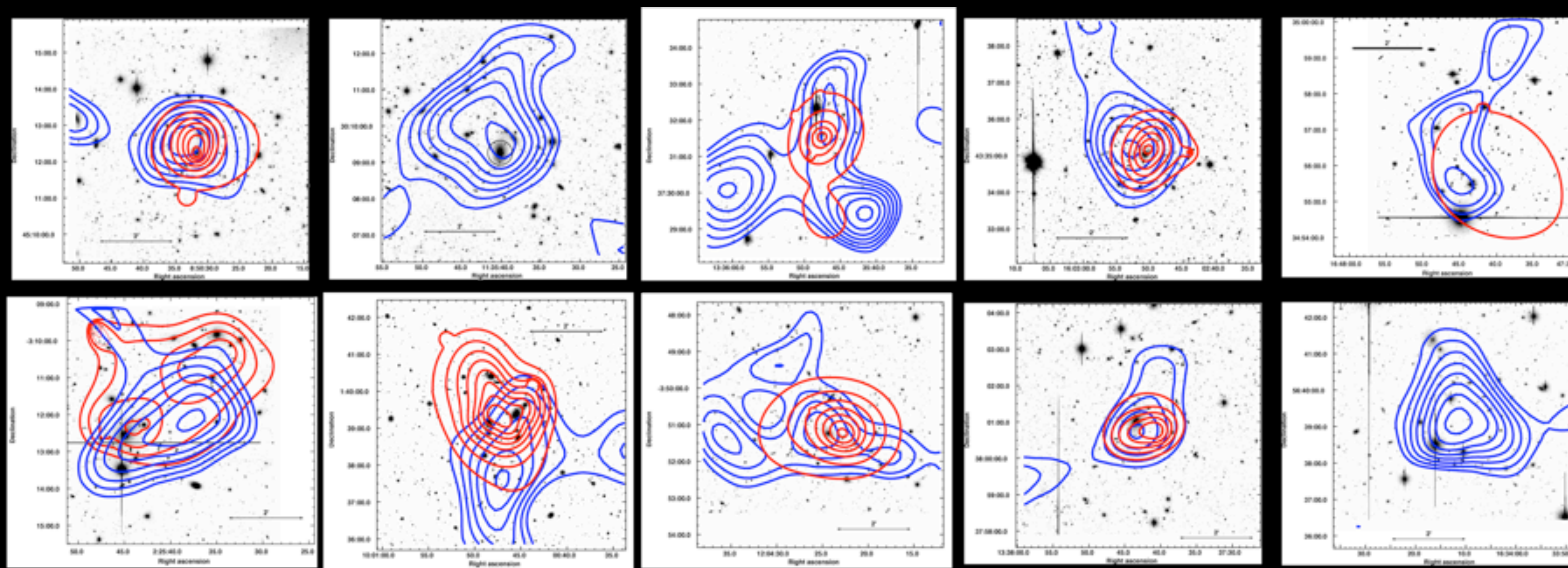
mass function

Challenges

- ★ Need cheap, reliable cluster masses to high-z
  - ‣ calibrate observables like X-ray luminosity, SZ flux, N galaxies against mass for full range of cluster masses, types, redshifts
- ★ Need to understand how clusters are detected (or not) by surveys
  - ‣ all survey methods have flaws
  - ‣ need to know how detection property relates to cluster mass, and how much scatter
- ★ Next generation surveys in all bands underway (inc Sussex)

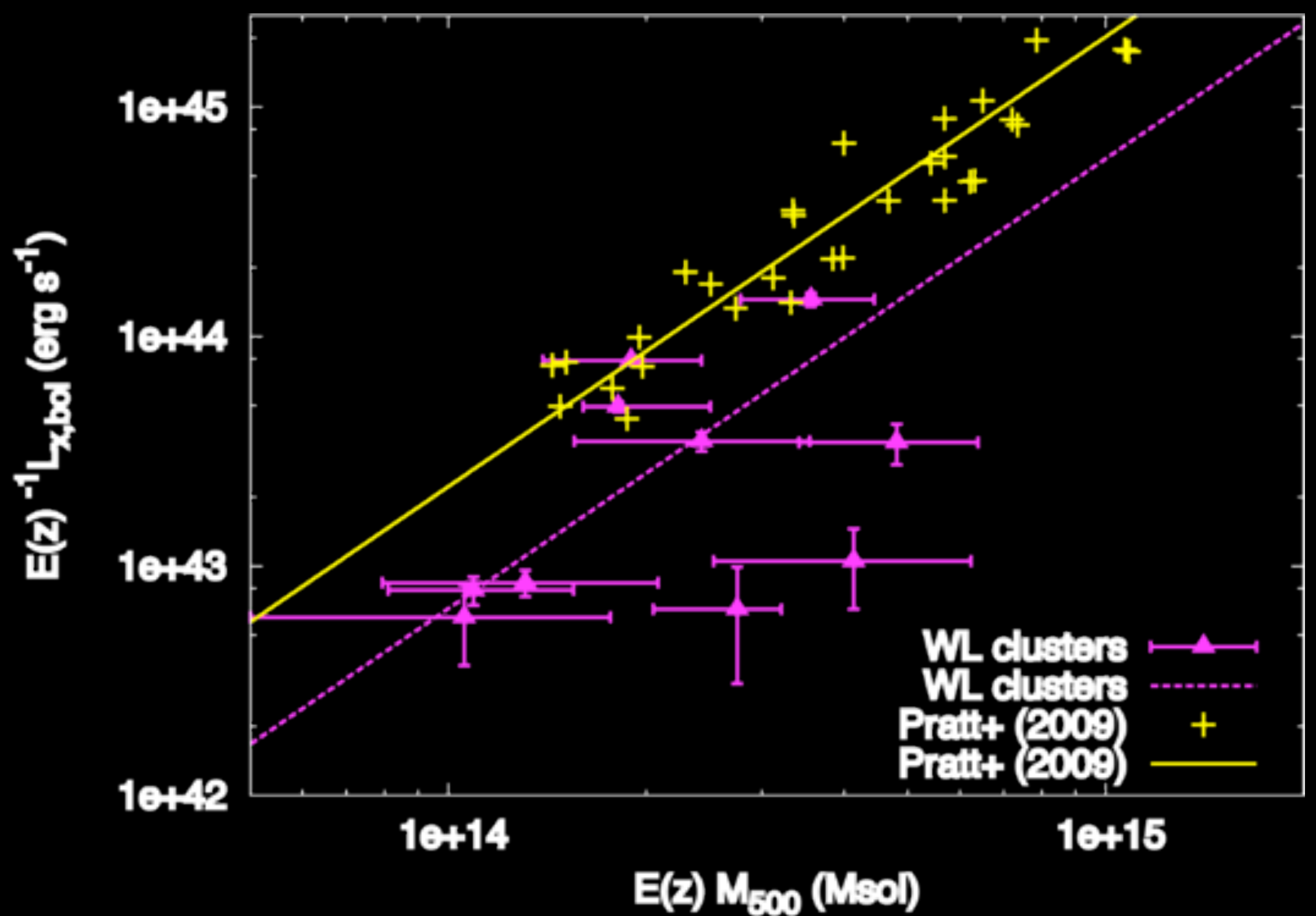
X-ray Properties of WL Selected Clusters

Lensing Selected Clusters



- ★ Several small lensing surveys have been performed
- ★ Looked at X-ray properties of 10 clusters from 17 deg^2 Subaru WL Survey (Giles+ 2012)
- ★ R band Suprime-Cam images with WL and X-ray contours
- ★ 1/7 appears relaxed c.f. ~50% of X-ray selected clusters

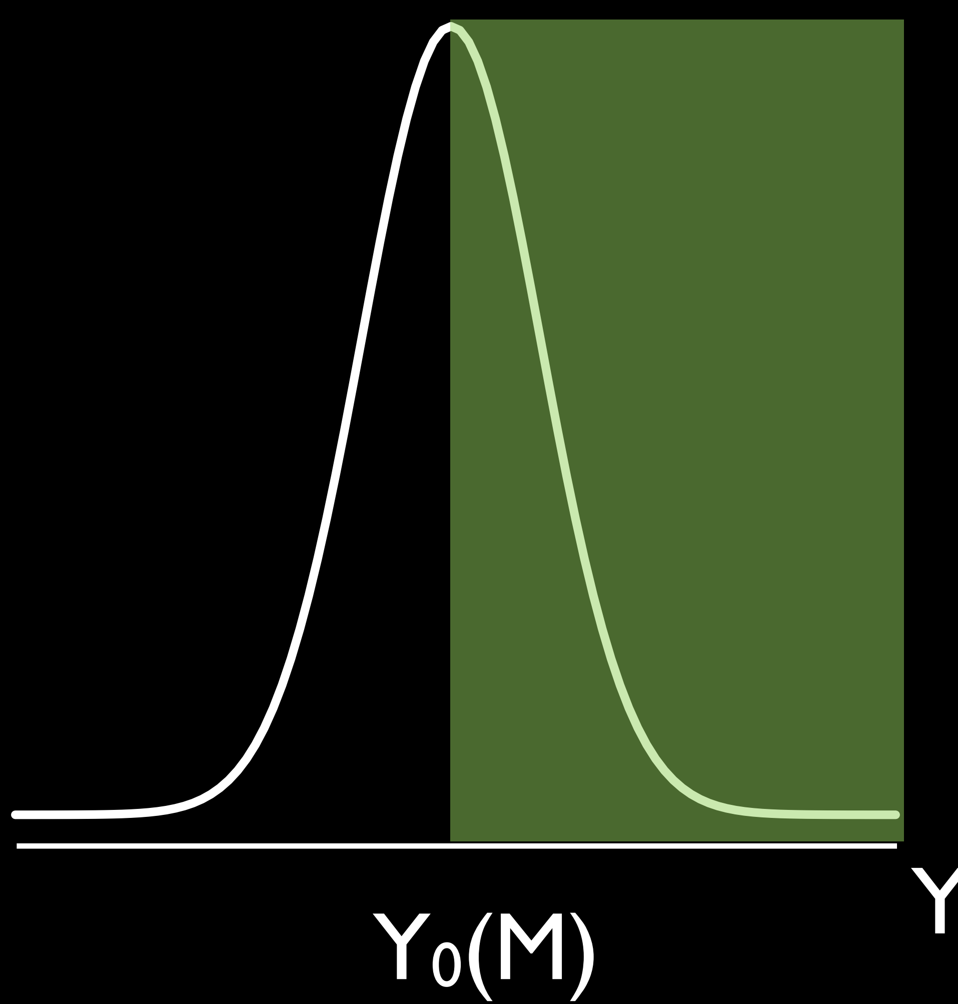
X-ray Luminosity Vs WL Mass



- ★ Compare LM relation for WL selected clusters to X-ray selected (Pratt+ 09)
- ★ Fix WL slope → WL clusters 2.5x fainter (6σ)
  - ‣ clusters fainter and/or WL masses overestimated?

Selection Biases

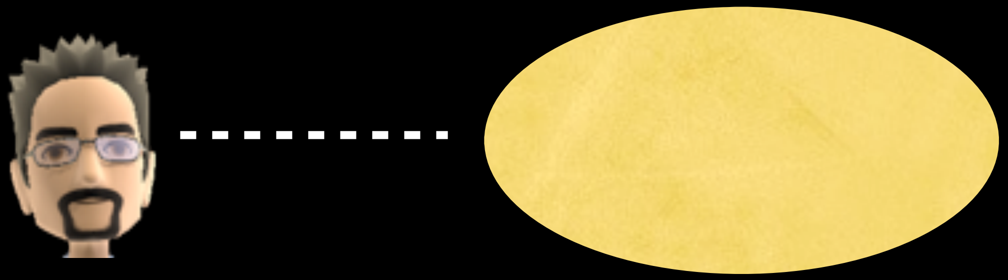
- ★ We detect clusters based on some observable (Y) which has noisy correlation with mass
  - e.g. X-ray luminosity, lensing shear
- ★ Range of possible Y values for a cluster of a given mass
- ★ Clusters with higher than average Y are easier to detect
  - sample biased towards high Y
- ★ Can correct bias if size of scatter and selection function known



Selection Biases

★ Lensing selected clusters biased towards prolate clusters pointing along line of sight

- overestimate lensing mass if assume spherical

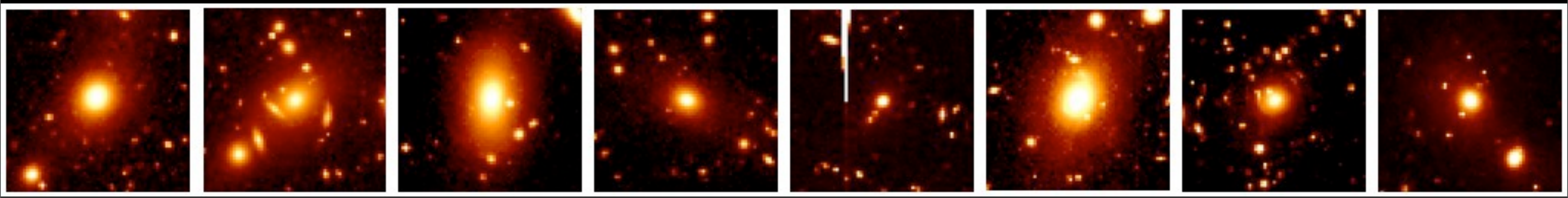


★ Lensing selected clusters biased towards prolate clusters pointing along line of sight

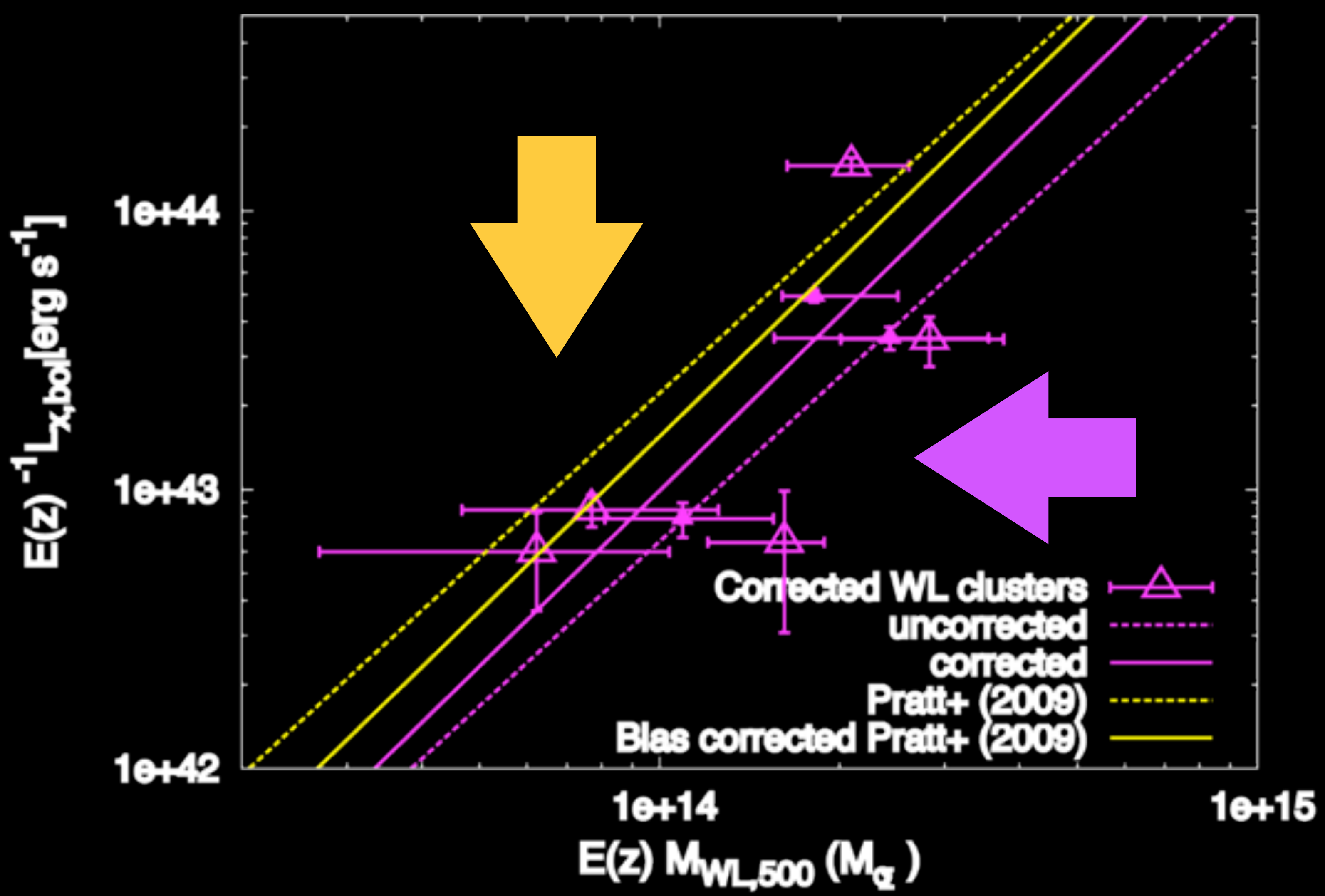
- overestimate lensing mass if assume spherical NFW

★ Use central galaxy ellipticity as proxy for halo orientation

- circular BCG means extended along line of sight



Bias Corrected LM



- ★ Expect Lx biased high for X-ray selected clusters and M biased high for lensing selected clusters
- ★ Correcting for biases improves agreement
- ★ Other plausible bias factors remain

Summary

★ Clusters are laboratories to study unique physics

- WIMPS, plasma physics, heating/cooling, feedback and galaxy formation

★ Clusters are powerful cosmological probes

- standard buckets, mass function

★ Many interesting challenges remain!