

Cosmology with Galaxy Clusters (I)

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DARK, KIPAC, Brahe, and me

Copenhagen

Tycho Brahe: first truly observational cosmologist

Brahe program at DARK: to promote international collaborations in cosmology

Brahe

me

Stanford

What I do

- what I mainly do: cluster weak lensing
- why: accurate cluster masses very important for cluster cosmology
- my main collaborators are: Steve Allen (KIPAC), Adam Mantz (KIPAC → KICP Chicago), Doug Applegate (KIPAC → Bonn), Pat Kelly (KIPAC → UC Berkeley), Marusa Bradac (KIPAC → UC Davis), and others
- together, we: use the most massive clusters known for cluster cosmology (and finding the highest-redshift galaxies)
- also, we: are preparing for the Large Synoptic Survey Telescope (LSST)

- I did my undergrad in: Bonn (with Peter)
- I did my PhD at: MPA Garching

Galaxy Clusters: the largest objects in the Universe

Wu, Hahn & Wechsler 2011



signposts of (dark) matter: observations of their distribution, structure and evolution → nature of dark matter, dark energy, gravity, neutrino properties, inflation ...

Why Clusters?

advantages:

- big → easy to find !
- there's lots of them → **statistically very powerful**
- sensitive to both *geometry* of Universe and *structure growth*
- provide several cosmological tests
- accessible at multiple wavelengths
- long-standing history as cosmological probes

challenges:

- cluster astrophysics difficult to fully model
- embedded in LSS → projection effects

As probes of dark matter

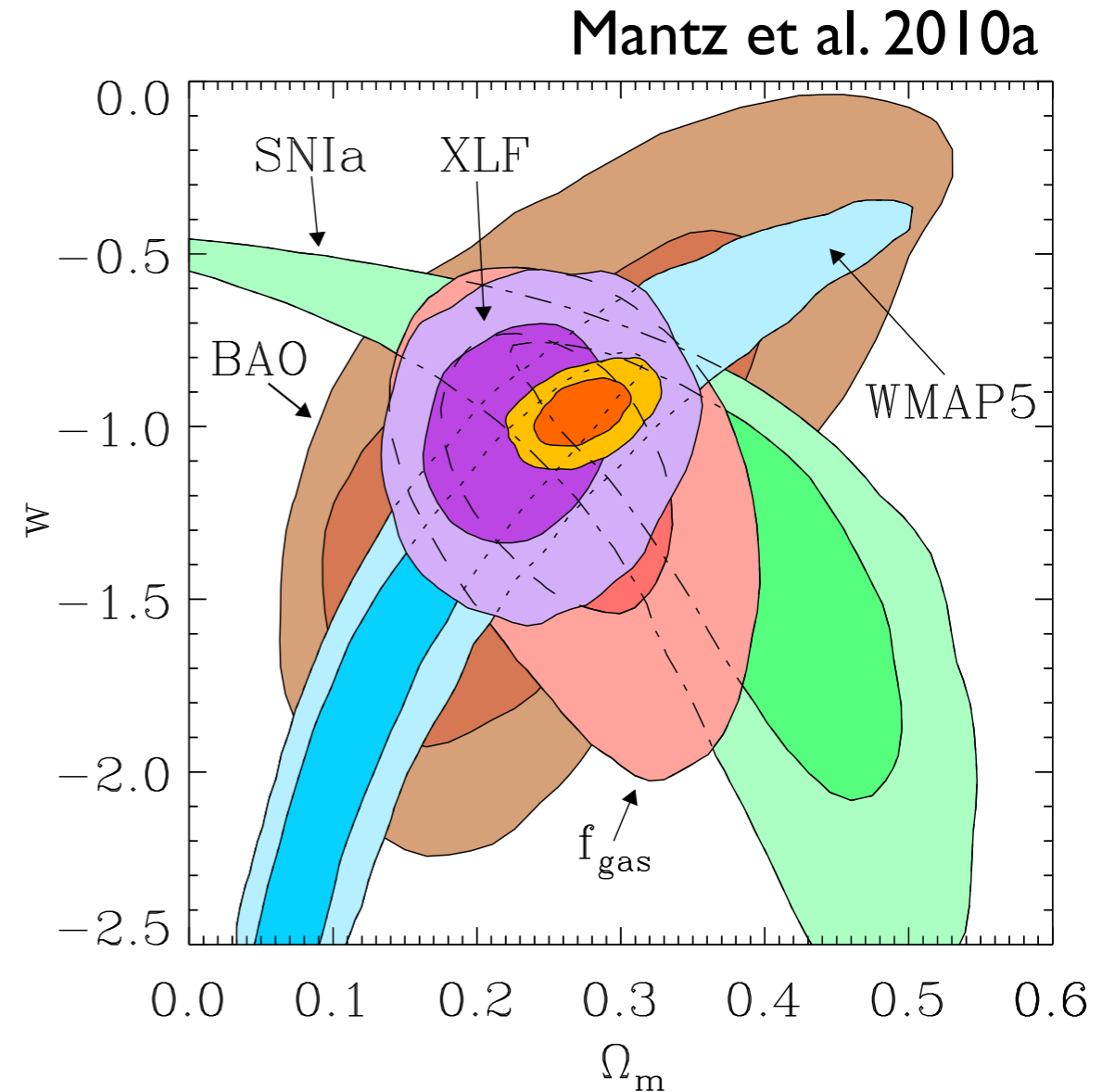
- 1930s: first sign for dark matter: velocity dispersion of Coma cluster (Zwicky 1933)
- 1980s: discovery of gravitationally lensed arcs (Lynds & Petrosian 1986; Soucail 1987)
- 2000s: cluster mergers yield “direct evidence for dark matter”: Bullet Cluster (Clowe et al. 2004, 2006, Bradac et al. 2006); MACS0025 (Bradac et al. 2008)



As probes of dark energy, GR, and more

- early 1990s: evidence for low matter density
(White et al. 1993)
- late 1990s: discovery of massive clusters at high redshifts
(Donahue et al. 1998; Bahcall & Fan 1998)
- 2010: competitive (and independent) constraints on dark energy, modified gravity, neutrino masses, non-Gaussianity
(Mantz et al. 2010a, Rapetti et al. 2009, 2010, 2013, Shandera et al. 2013, Vikhlinin et al. 2009, Rozo et al. 2010, Sehgal et al. 2011, Benson et al. 2013)

→ *cluster mass function*



Clusters are versatile laboratories

Part I: cluster structure

- merging clusters as probe of dark matter
- cluster cores as probe of dark matter
- cosmology with the baryonic mass fraction

Part II:

- cosmology with the cluster mass function

Further reading:

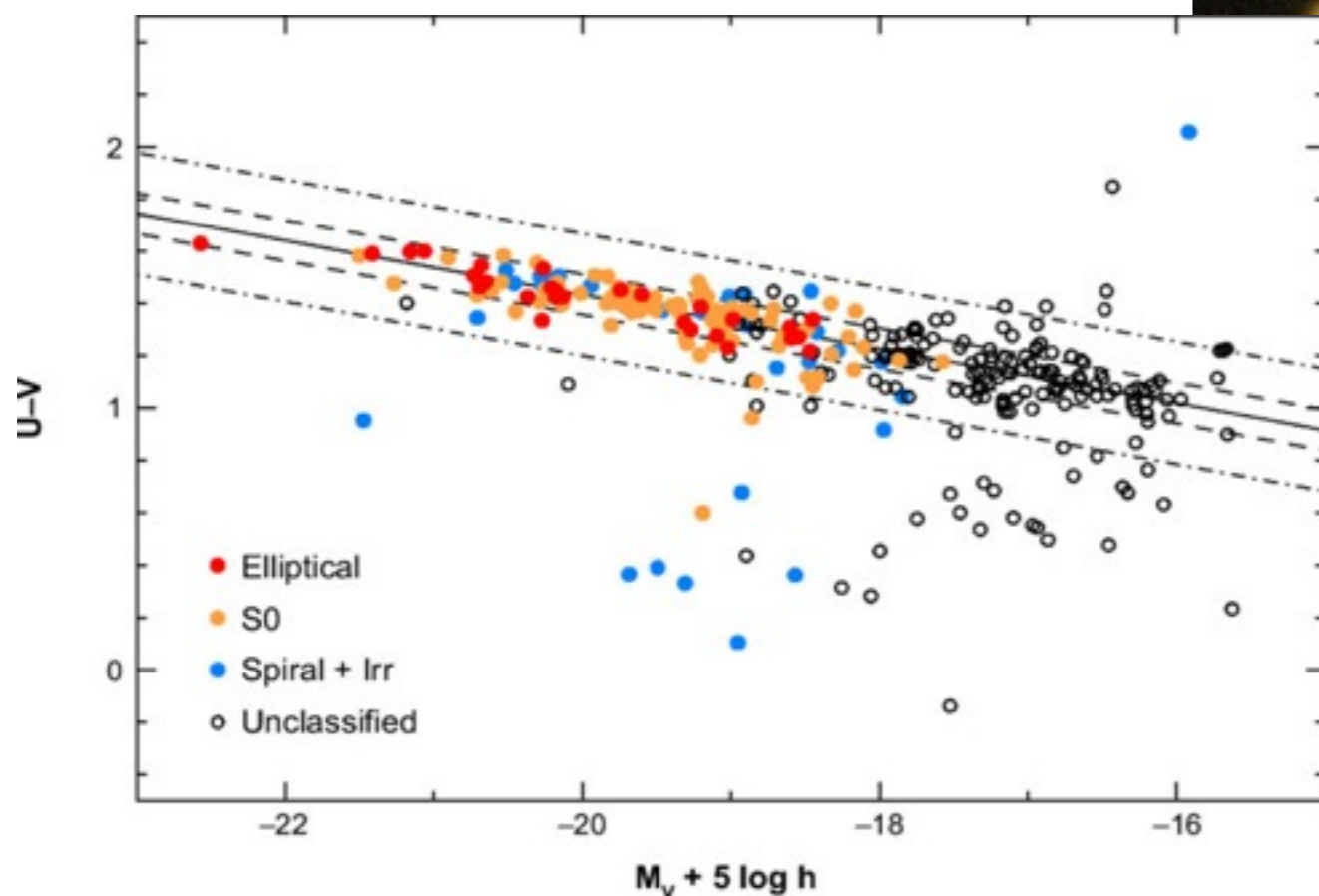
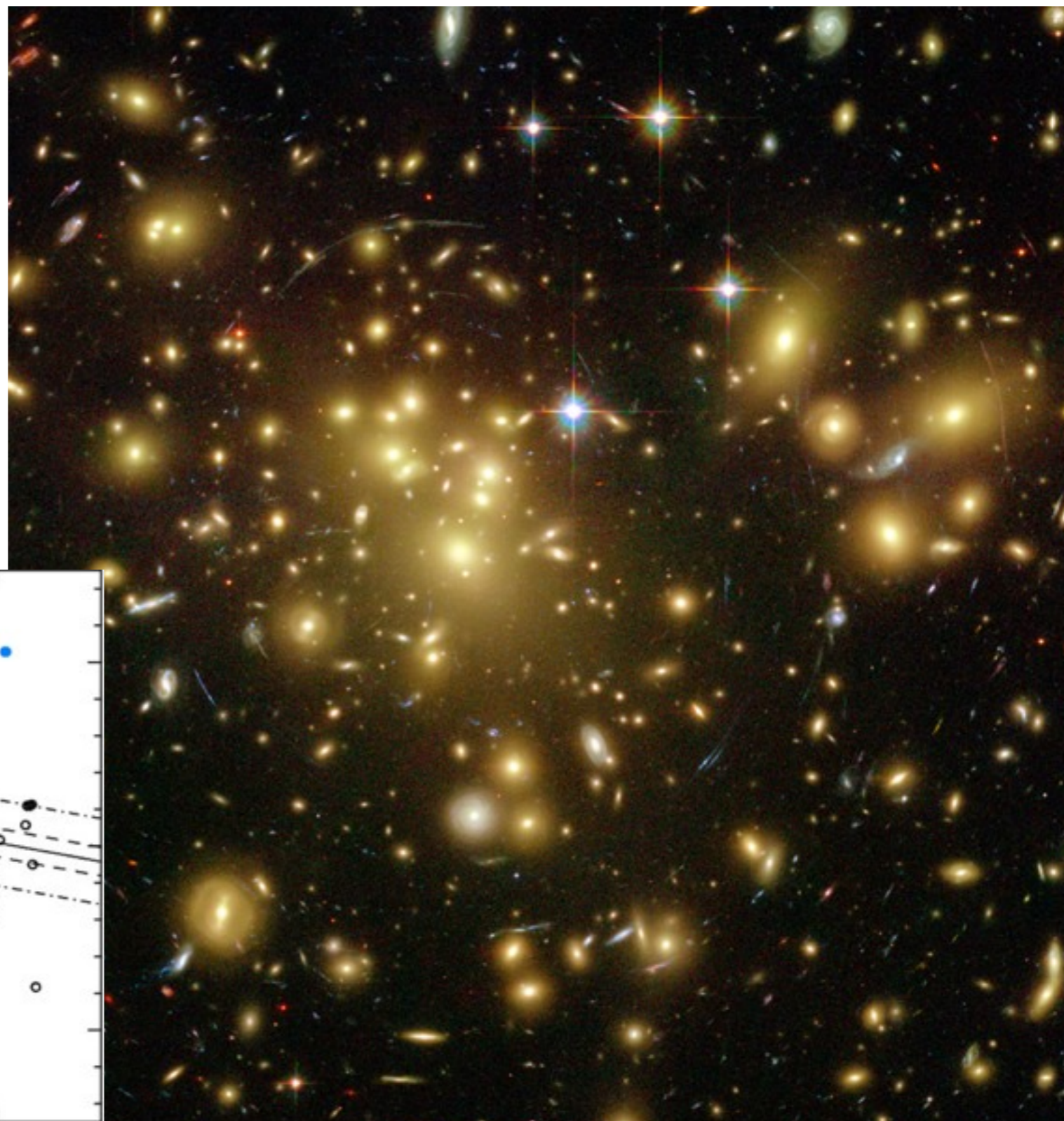
- Allen, Evrard & Mantz: [Cosmological Parameters from Observations of Galaxy Clusters](#), 2011, ARAA
- Voit: [Tracing cosmic evolution with clusters of galaxies](#), 2005, RvMP

What are clusters?

What do they tell us about dark matter?

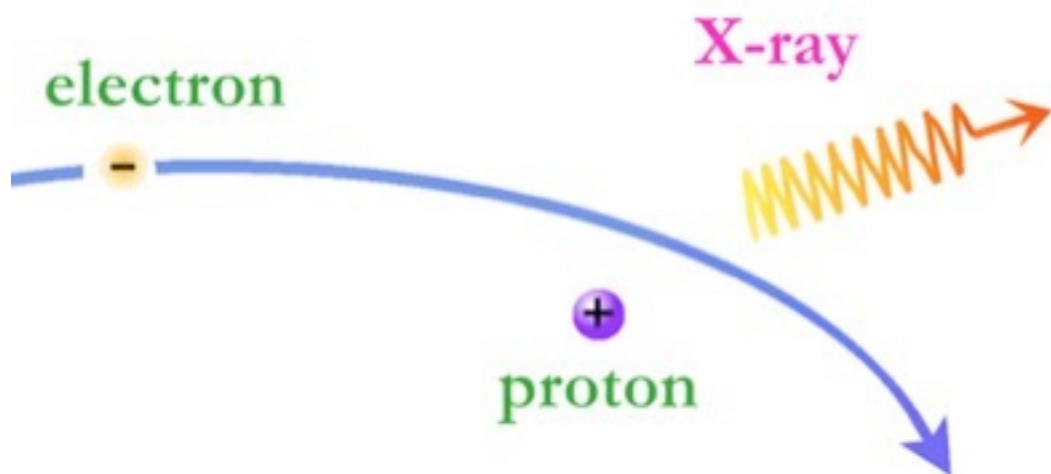
What are clusters ? (I) The light side - galaxies

- a cluster contains hundreds to thousands of galaxies
- each galaxy contains 10^8 to 10^{11} stars
- cluster galaxies have mostly stopped forming stars \rightarrow form the “red sequence”



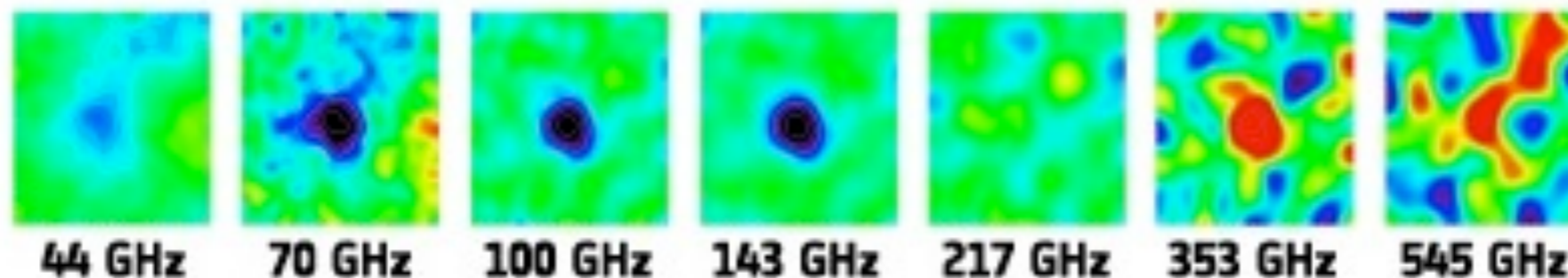
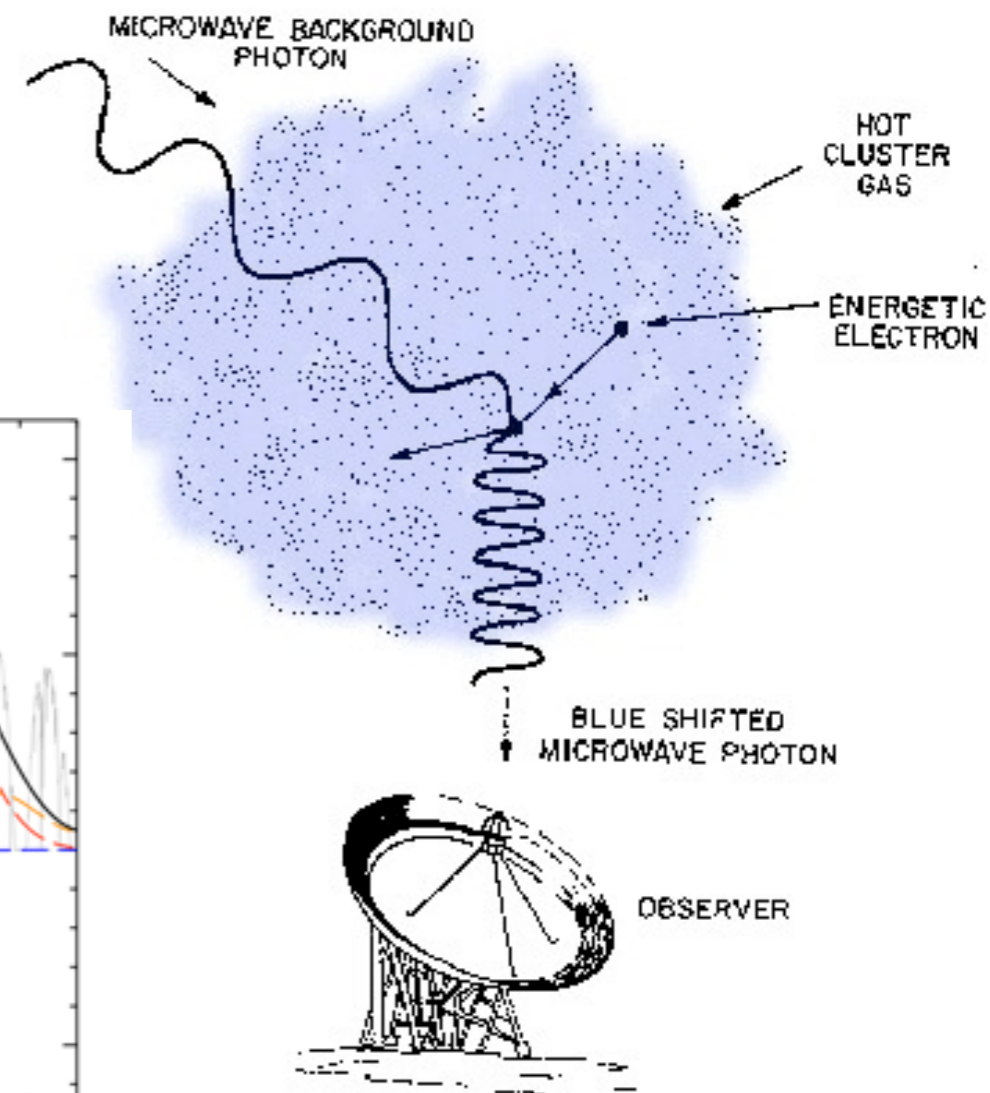
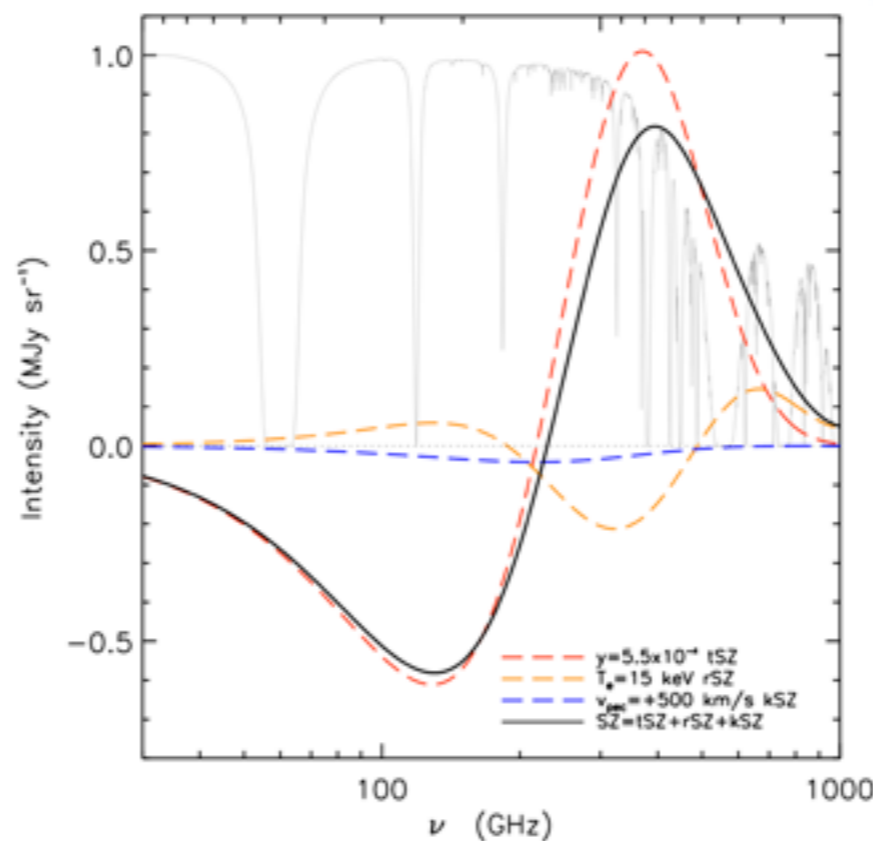
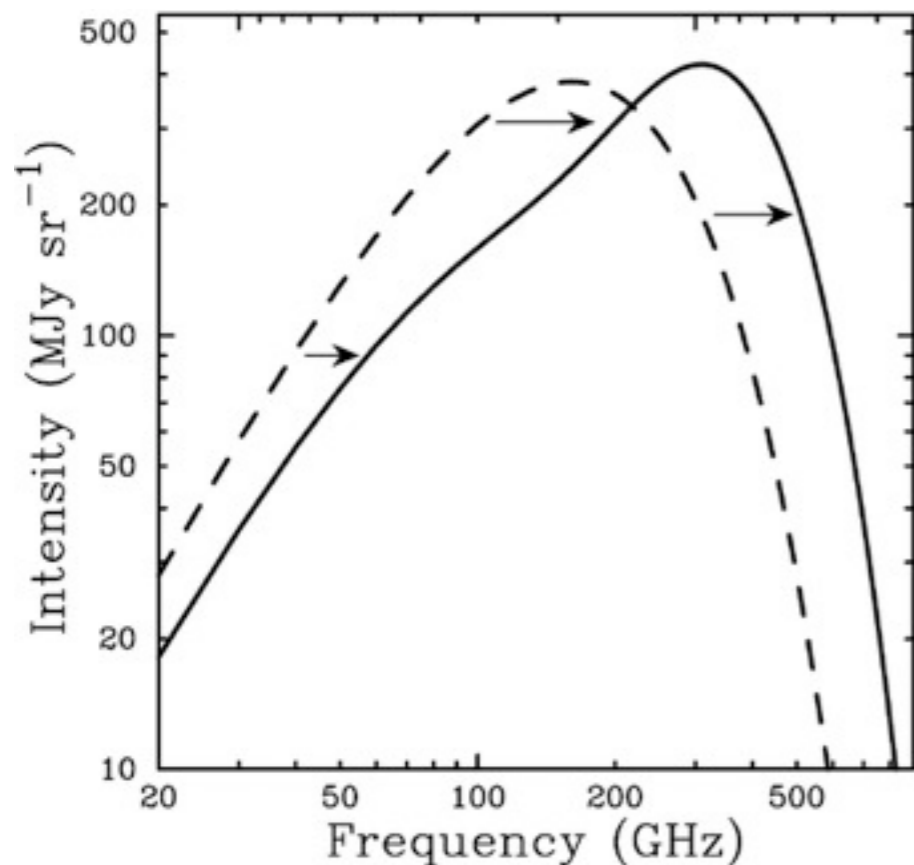
What are clusters ? (2) The hot side - gas

- ~6 more baryonic mass in the form of hot gas than in stars
- gas was shock-heated during cluster formation to high temperatures (10^7 - 10^8 K)
- shines in X-rays via bremsstrahlung



What are clusters ? (2) The hot side - gas

- Sunyaev-Zel'dovich effect: inverse Compton scattering of CMB photons in hot cluster gas
- tell-tale shift in CMB spectrum



What are clusters ? (3) The dark side

- how to measure *total* mass in clusters?

I. kinematics of cluster galaxies

- measure velocity dispersion along the line of sight

with some simplifying assumptions (spherical symmetry, isolation, virialization):

$$M = c \frac{\sigma_{1D}^2 r}{G} \quad c \sim 3$$

- more general: Jeans equation

$$M(r) = -\frac{r\sigma_r^2}{G} \left[\frac{d \ln \rho}{d \ln r} + \frac{d \ln \sigma_r^2}{d \ln r} + 2\beta \right]$$

takes anisotropic velocity structure, density and velocity dispersion profiles into account

- disadvantages: requires large number of redshifts + assumption of dynamical equilibrium; galaxy relaxation timescale long

What are clusters ? (3) The dark side

- how to measure *total* mass in clusters?

2. X-ray hydrostatic mass estimates

$$M(r) = -\frac{r kT}{G\mu m_p} \left[\frac{d \ln \rho}{d \ln r} + \frac{d \ln T}{d \ln r} \right]$$

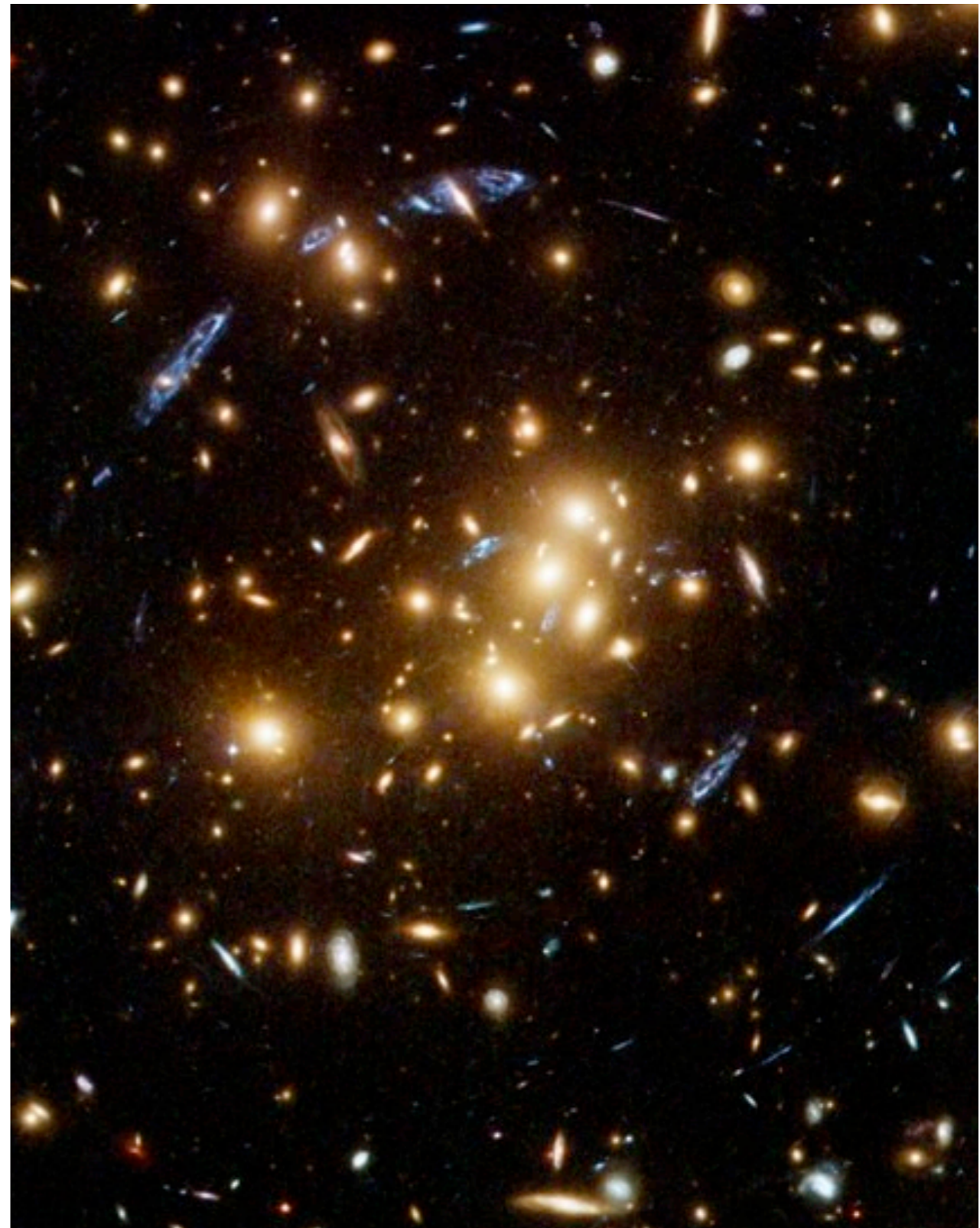
- advantages: for relaxed clusters, relatively precise measurement (scatter $\lesssim 10\%$); relatively insensitive to triaxiality
- disadvantages: can only be applied to relaxed clusters; (unknown) bias due to residual gas motion; sensitive to temperature calibration uncertainty of X-ray satellites

What are clusters ? (3) The dark side

- how to measure *total* mass in clusters?

3. **gravitational lensing**

- advantages:
 - measures total mass directly
 - does not require spherical symmetry
- disadvantages:
 - strong lensing confined to cluster core
 - weak lensing noisy



What are clusters ? (3) The dark side

- measuring *total* mass in clusters:

→ clusters contain $\sim 10\times$ more mass than contained in stars and X-ray gas

→ one of the clearest signs for **dark matter**

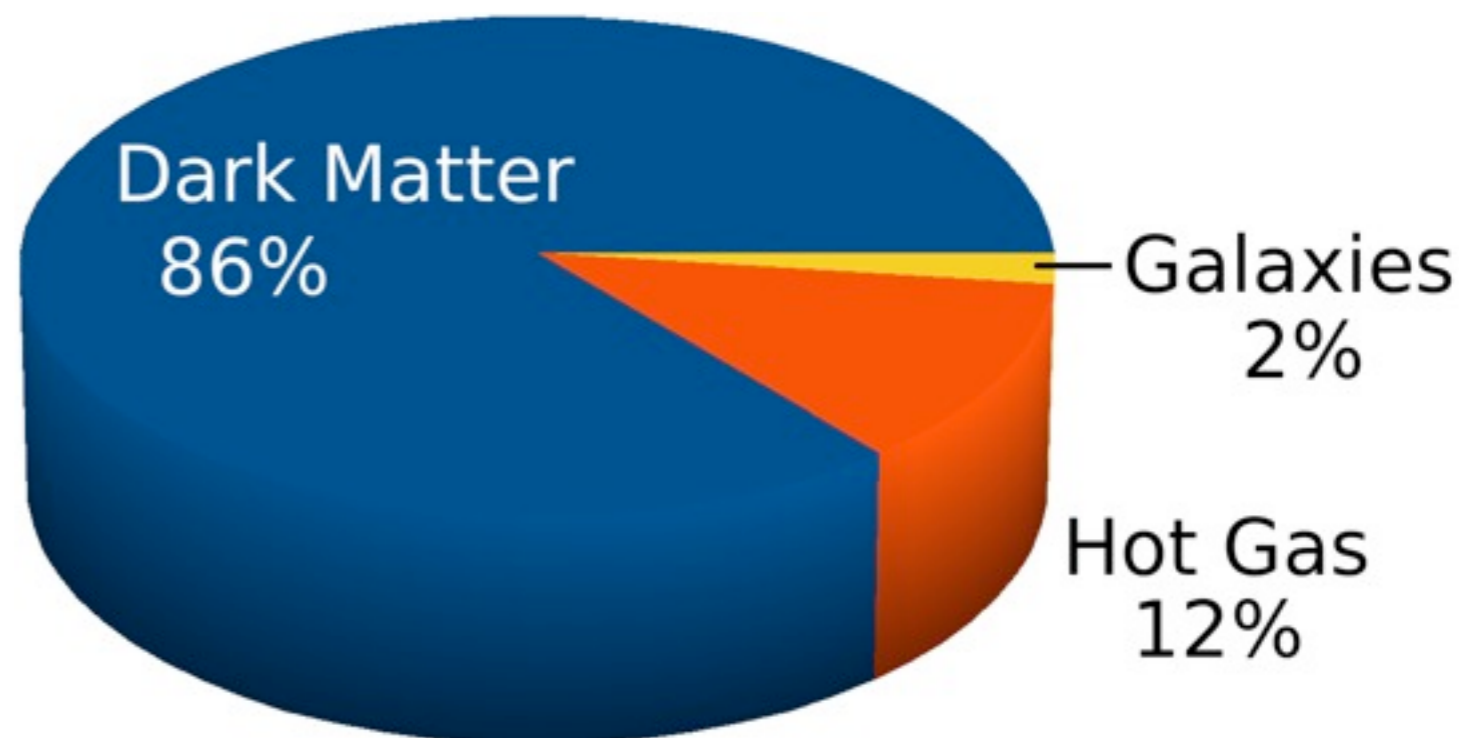
typical cluster properties:

$$M \gtrsim 10^{14} M_{\odot}$$

$$kT \gtrsim 10^7 \text{ K}$$

$$R \gtrsim 1 \text{ Mpc}$$

$$\sigma_v \gtrsim 700 \text{ km/s}$$



Multi-wavelength cluster studies

clusters best studied with complementary observations:

- lensing measures total mass:
 - strong lensing at the core
 - weak lensing at larger radii
- X-rays see majority of baryonic matter
 - baryons expected to trace total mass
 - gas falls into potential well
 - is compressed and heated



MACS J0911.2+1746
z=0.505



red sequence galaxies



lensing map



X-ray flux



MACSJ0025.4-1222

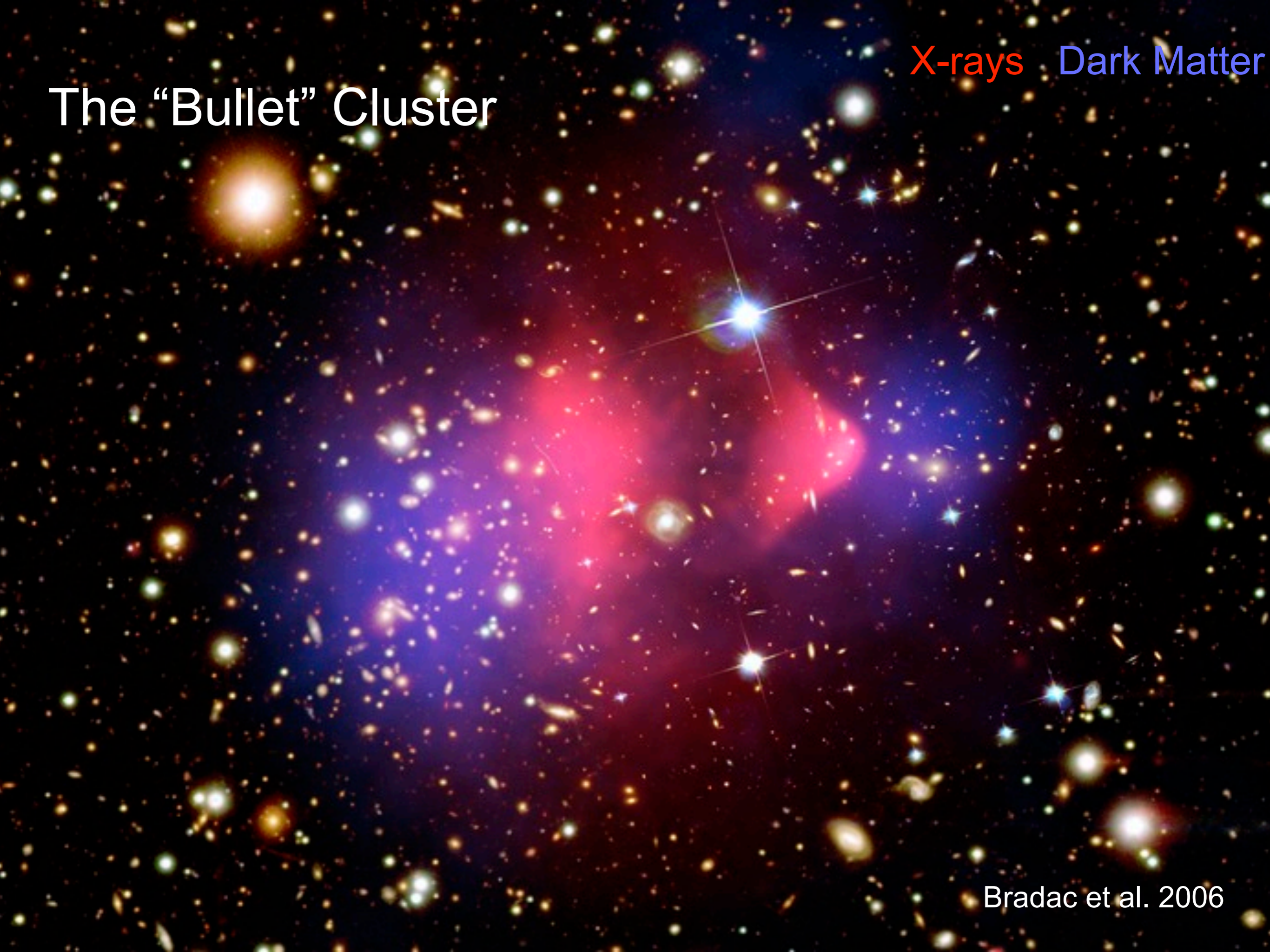


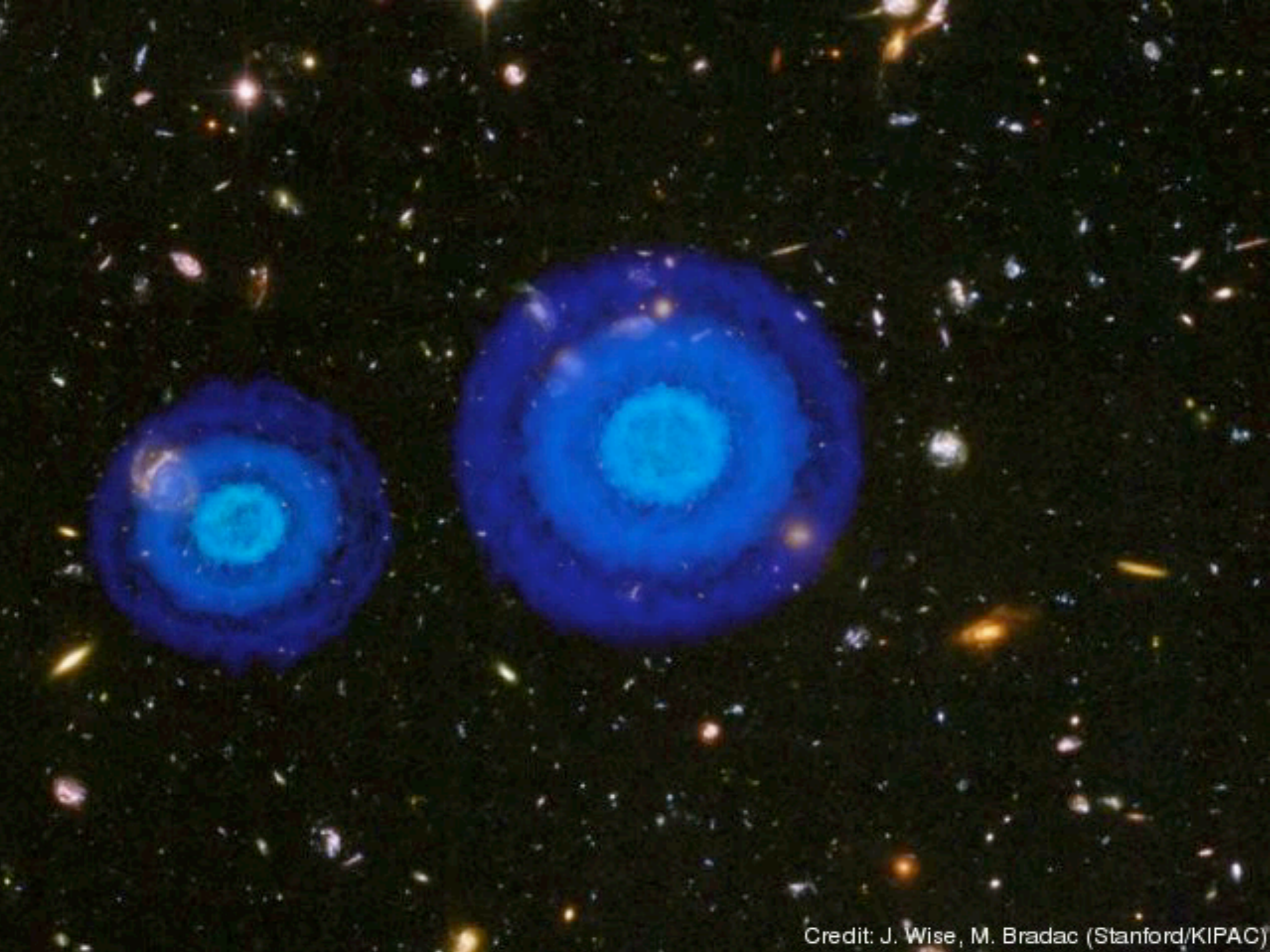
Optical X-ray Lensing

Bradac et al. 2008

The "Bullet" Cluster

X-rays Dark Matter





Credit: J. Wise, M. Bradac (Stanford/KIPAC)

- very hard to explain without (cold, nearly collisionless) dark matter
- “Direct proof of dark matter”
- dark matter coincides with galaxies
 - both (nearly) collisionless
- gas separated from dark matter
 - inelastic collision
- head-on collision of two clusters
 - dark matter and galaxies “fly through”
 - gas “sticks”
- several such clusters confirmed

Self-Interacting Dark Matter (I)

- standard model assumes CDM is collisionless
- what if DM has a finite cross section?
 - ▶ DM particles would scatter off each other
 - ▶ inelastic collision
- to see “Bullet Cluster” configuration, each DM particle cannot have scattered more than once during merger:

$$\tau = \frac{\text{area for interaction}}{\text{area of cluster}} = \frac{n \sigma}{M/\Sigma} = \Sigma \frac{\sigma}{m} < 1$$

projected surface mass density (from lensing): $\Sigma = M/A$

number of DM particles: $n = M/m$

- limit from MACS0025: $\frac{\sigma}{m} < 4 \text{ cm}^2 \text{ g}^{-1}$

(Bradac et al. 2008)

Or ...?

A520 - “cosmic trainwreck”
does it have a “dark core” (a
DM peak without galaxies)?

- Mahdavi et al. 2007 - yes!

$$\frac{\sigma}{m} = (3.8 \pm 1.1) \text{ cm}^2 \text{ g}^{-1}$$

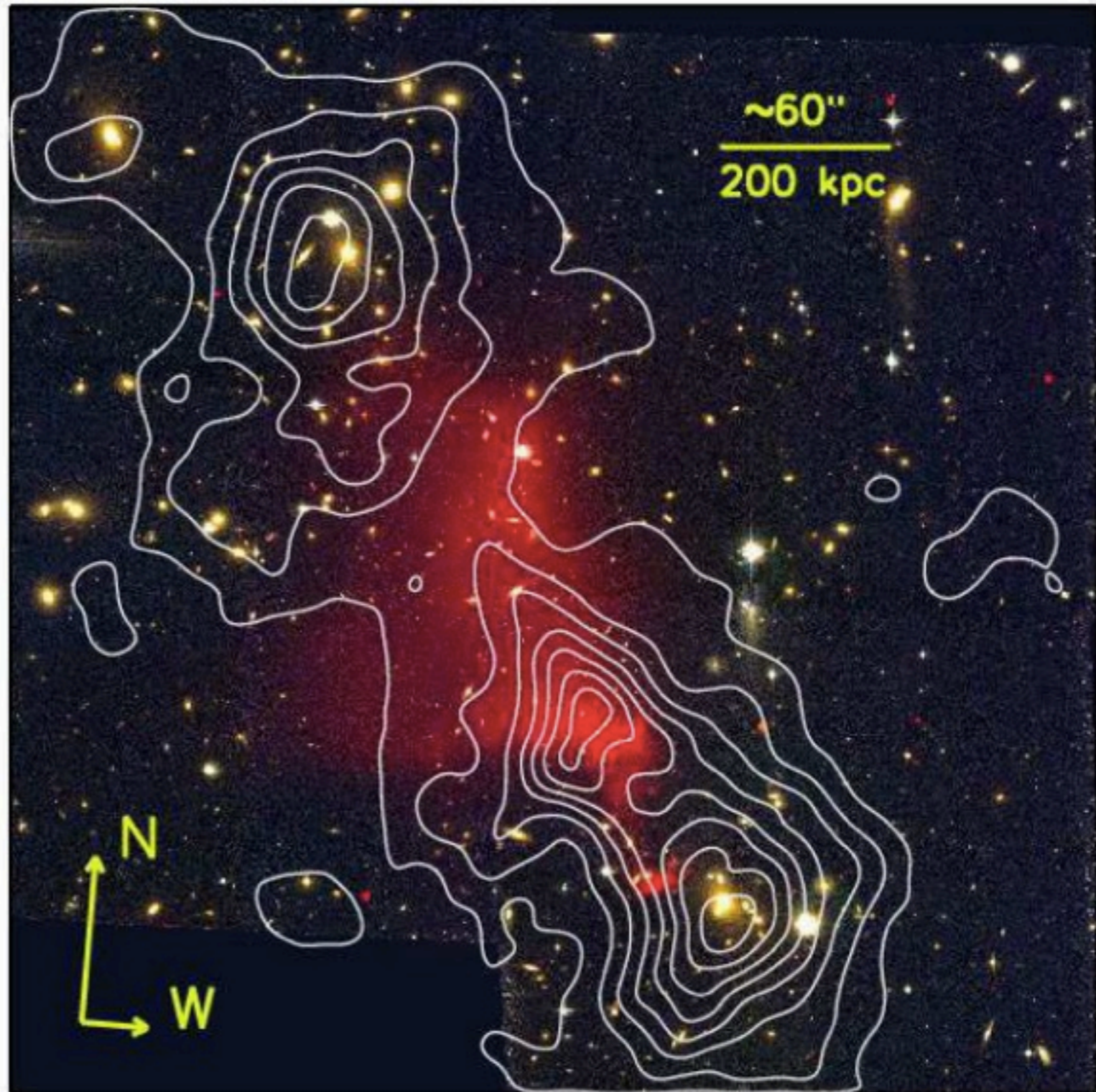
- Jee et al. 2012 - yes!!!

$\sigma/m=1$ ruled out at 6σ

- Clowe et al. 2012 - no

- Jee et al. 2014 - yes!(?)

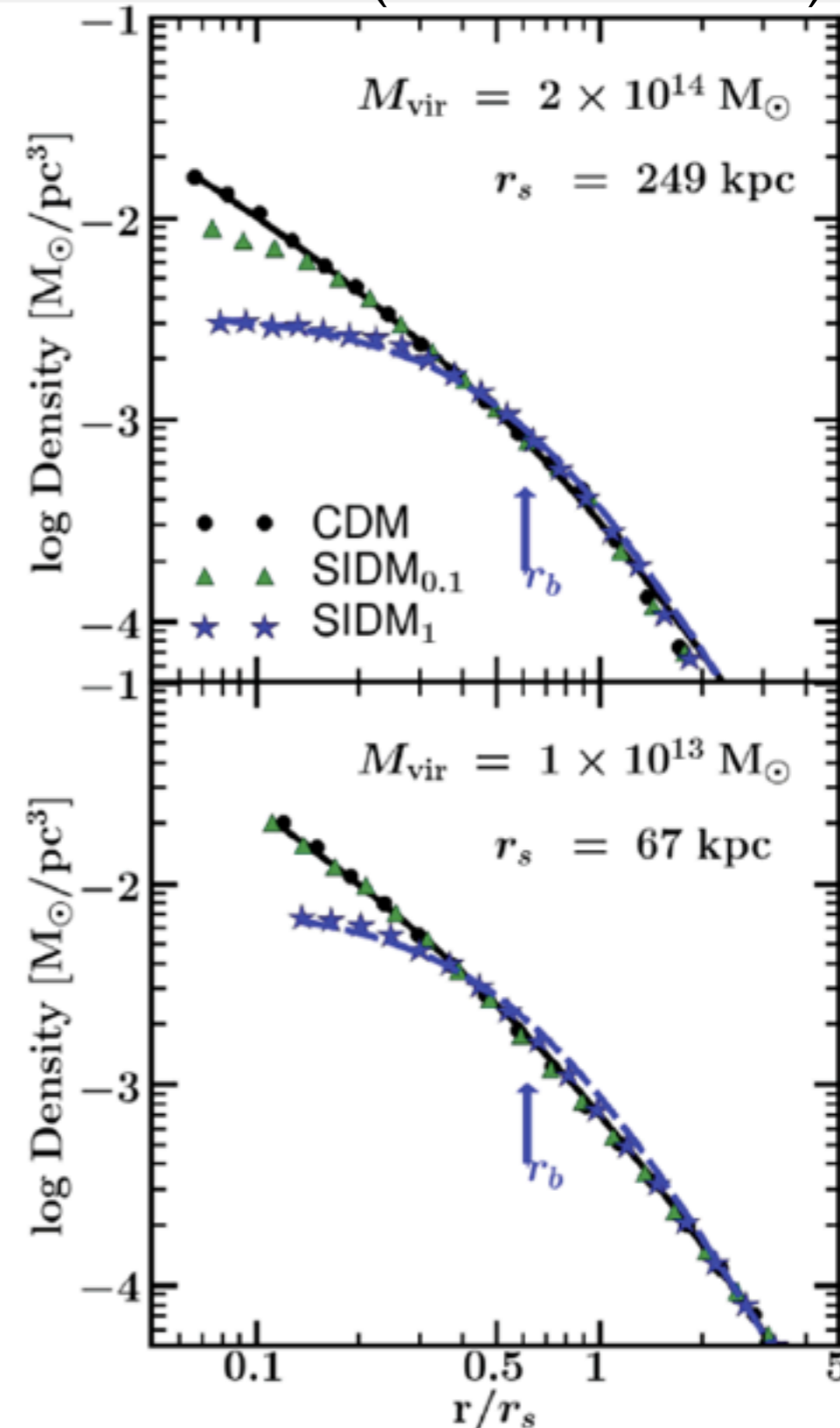
$$\frac{\sigma}{m} = (0.43 - 0.94) \text{ cm}^2 \text{ g}^{-1}$$



Shapes of relaxed clusters - SIDM (II)

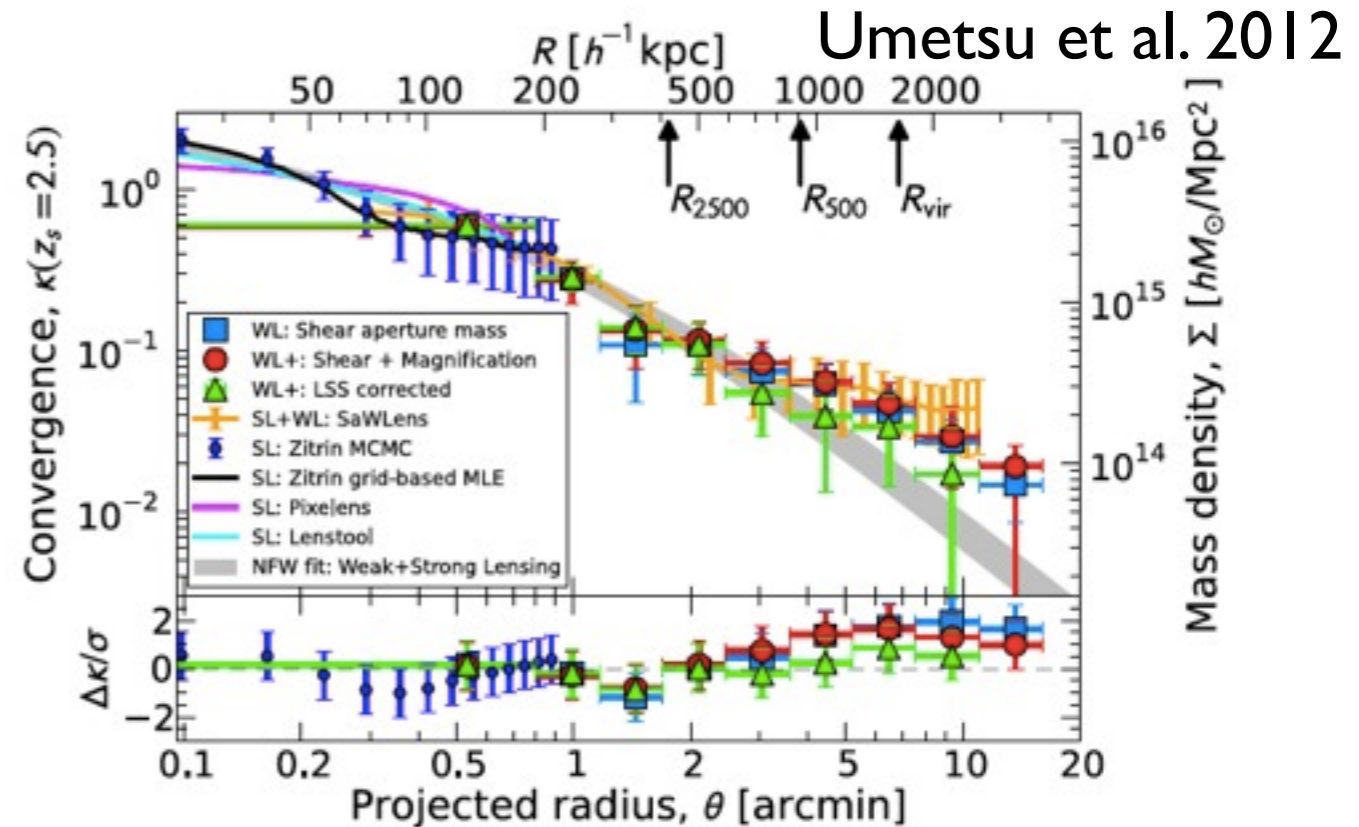
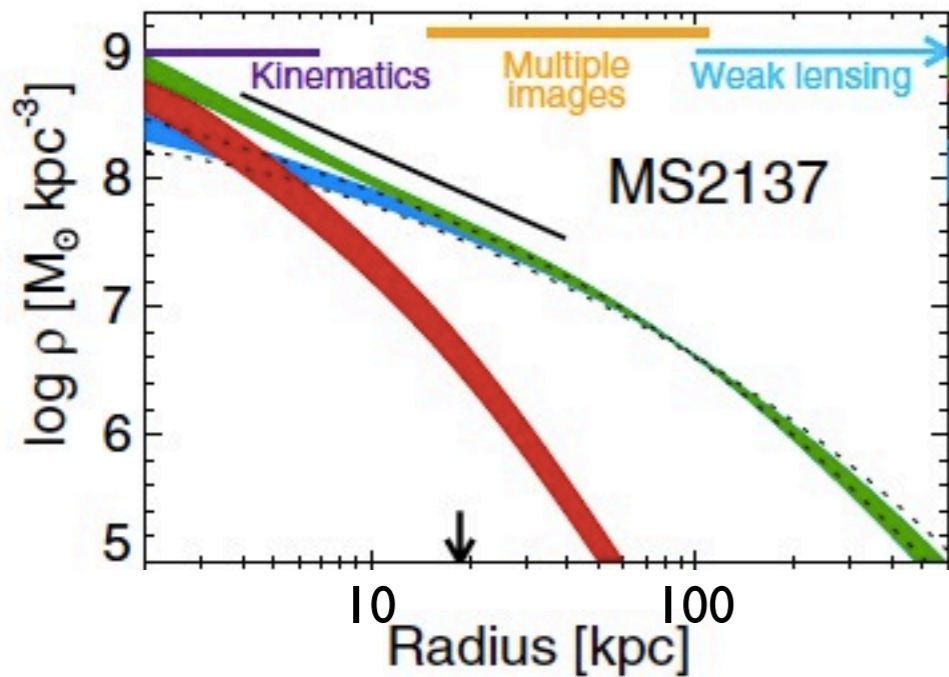
(Rocha et al. 2013)

- N-body simulations of (collisionless) CDM predict universal equilibrium density profile
Navarro, Frenk & White 1997
- if DM collisional: particles scatter away from highest-density regions
→ halos form “cores”, central profile shallower than NFW
- SIDM originally considered to explain alleged cores in low surface brightness galaxies
- can test with clusters?



Shapes of relaxed clusters - SIDM (II)

- to accurately measure (triaxial) density profiles, need to combine several measurements to probe large radial range and break model degeneracies



- Dark matter (gNFW)
- Dark matter (cNFW)
- Stars (BCG)
- Total mass

► DM profiles shallower than NFW; total mass profiles consistent with NFW

Newman et al. 2013

► kinematics of central galaxy necessary to test core

► SIDM? unclear → *need to understand baryonic physics at cluster cores!*

Summary so far

- clusters provide some of the most compelling evidence
 - for the existence of dark matter
 - for the cold, collisionless nature of dark matter
- how to further improve constraints on SIDM?
 - merging clusters: no meaningful way of combining multiple “Bullet Clusters”
 - “Bulleticity”: identify samples of minor mergers, measure offset between stars and dark matter statistically (Massey et al. 2011)
 - relaxed clusters: measure central densities (also ellipticity profiles)
 - need to understand baryonic physics at cluster core

The baryonic mass fraction (f_{gas}) test

Cosmology and Astrophysics from Relaxed Galaxy Clusters II: Cosmological Constraints

A. B. Mantz,^{1,2*} S. W. Allen,^{3,4,5} R. G. Morris,^{3,5} D. A. Rapetti,⁶
D. E. Applegate,⁷ P. L. Kelly,⁸ A. von der Linden,^{3,4,6} R. W. Schmidt⁹

Mantz et al., submitted (M14);
Allen et al. 2002, 2004, 2008; Ettori et al. 2003, 2009;
White et al. 1993; White & Frenk 1991; ...

The baryonic mass fraction (f_{gas}) test - Ω_m

- basic idea (White & Frenk 2011): clusters are so large that their matter content provides a \sim fair sample of the matter content of the Universe
- baryonic mass mostly in X-ray-emitting hot gas

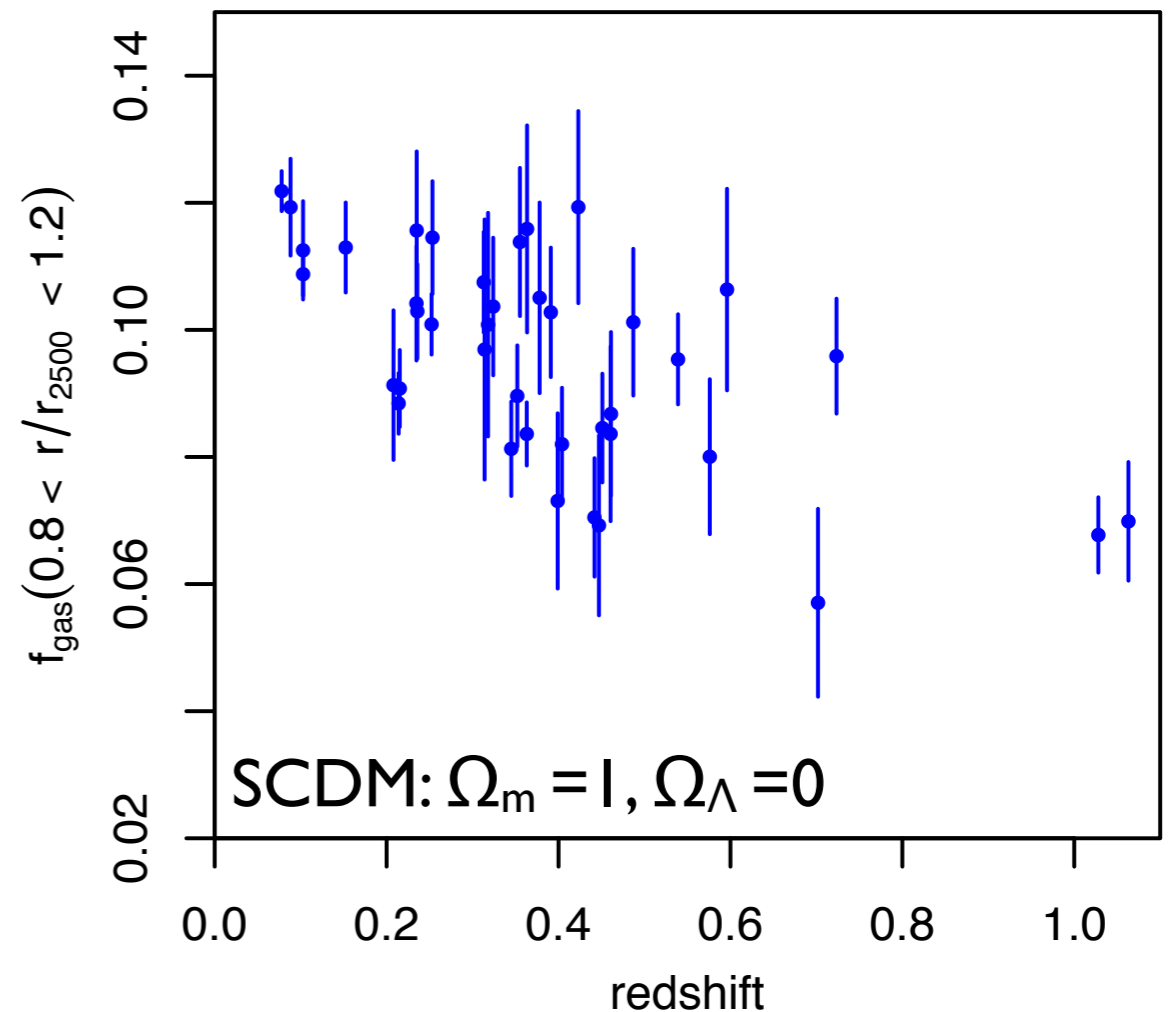
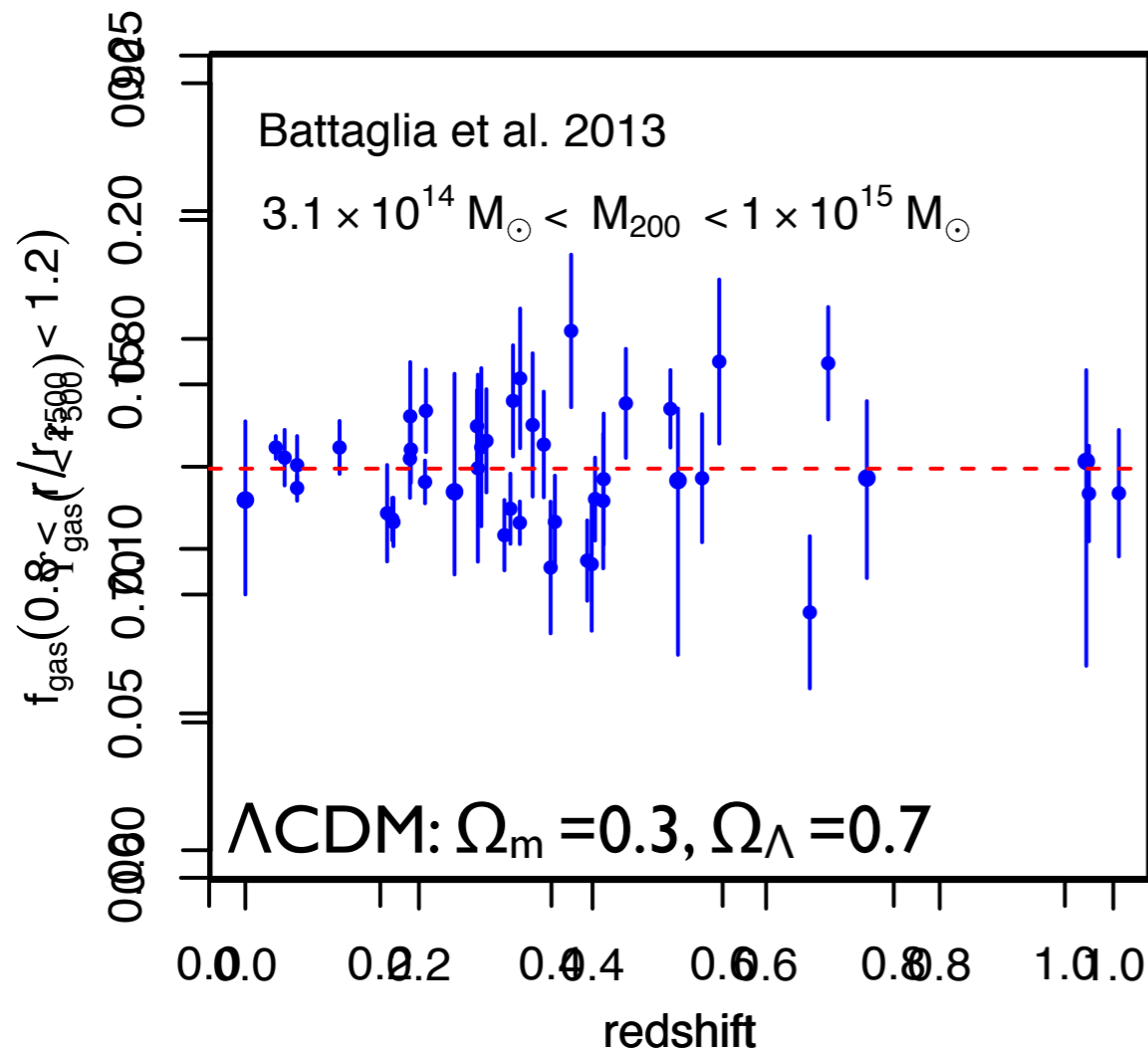
$$f_{gas} = \frac{M_{gas}}{M_{tot}} = \Upsilon \frac{\Omega_b}{\Omega_m}$$

- Υ : depletion factor, can be well modeled by hydrodynamical simulations (outside cluster core)
- measure M_{gas} and M_{tot} from X-ray observations of most massive, most relaxed clusters (to apply hydrostatic equilibrium)
- with minimal external datasets ($\Omega_b h^2$ from BBN, h), clusters can sensitively constrain Ω_m
- White (1993): $\Omega_m \sim 0.3$ (problem with then-paradigm, $\Omega_m = \Omega_0 = 1$)

The baryonic mass fraction (f_{gas}) test - Ω_Λ

- for the most massive clusters, f_{gas} is a standard quantity (constant with mass and time/redshift)
- measurement depends on cluster distance as $f_{gas} \propto d^{3/2}$ (combination of angular diameter and luminosity distances)

observations:



The baryonic mass fraction (f_{gas}) test - Ω_Λ

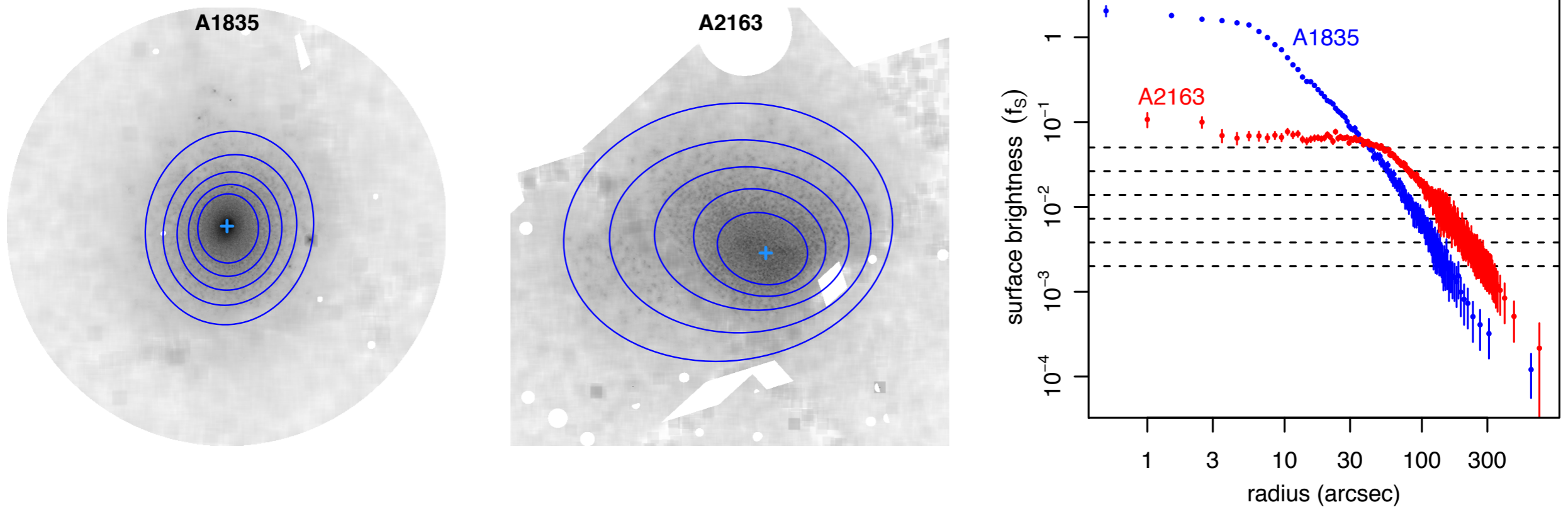
- for the most massive clusters, f_{gas} is a standard quantity (constant with mass and time/redshift)
- measurement depends on cluster distance as $f_{\text{gas}} \propto d^{3/2}$ (combination of angular diameter and luminosity distances)

$$f_{\text{gas}}^{\text{ref}}(z) = \Upsilon \left(\frac{\Omega_b}{\Omega_m} \right) \left[\frac{d_{\text{ref}}(z)}{d(z)} \right]^{3/2}$$

- f_{gas} is measured in a reference cosmology
- cosmology dependence is part of the model fitted to the data

Observations

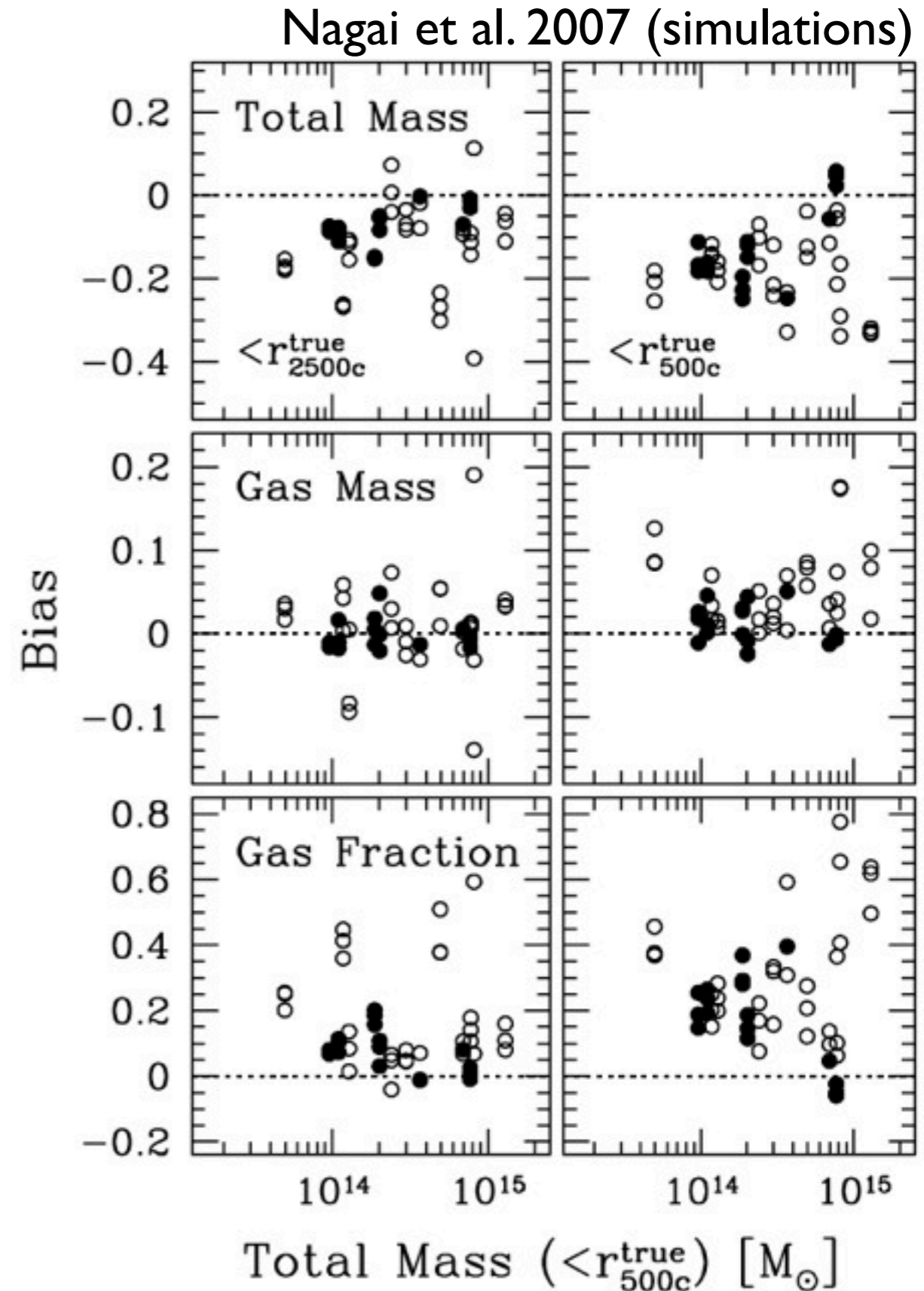
- measurement best done on most massive ($kT > 5\text{keV}$), most dynamically relaxed clusters
- searched through $>20\text{Ms}$ of Chandra data (~ 350 clusters)



- identify most relaxed clusters through morphological features (peak brightness, isophote symmetry, isophote alignment)
- final sample: 40 clusters $0 < z < 1.1$; 3.1 Ms of Chandra data

Measurements

- M_{gas} :
 - X-ray emission \propto (gas density)²
 - robust, relatively simple measurement from X-ray imaging
 - (NB: can be reliably measured on any cluster, not just relaxed)
- M_{tot} :
 - assume hydrostatic equilibrium
 - can only be applied to relaxed clusters
 - requires density and temperature profiles
 - subject to hydrostatic bias



Hydrostatic bias and calibration uncertainties

- have to assume hydrostatic equilibrium and spherical symmetry
 - ▶ expect biased measurements due to non-thermal pressure support, ~20% overall, 5-10% even in dynamically relaxed clusters
 - calibration by simulations sensitive to details of astrophysics
- practical problem:
 - X-ray temperature estimates very difficult to calibrate (for $T > 2\text{keV}$)
 - Chandra and XMM T and M_{HE} masses systematically offset (20-30%)
- need to account for mass calibration, $K = M_{\text{true}} / M_{\text{HE}}$

$$f_{\text{gas}}^{\text{ref}}(z) = K \Upsilon \left(\frac{\Omega_{\text{b}}}{\Omega_{\text{m}}} \right) \left[\frac{d_{\text{ref}}(z)}{d(z)} \right]^{3/2}$$

- weak lensing to the rescue! *Weighing the Giants* project (tomorrow)

Nuisance parameters and priors

- marginalize over systematic uncertainties

- depletion factor

$$\Upsilon(z) = \Upsilon_0(1 + \Upsilon_1 z) \quad \Upsilon_0 = 0.85 \pm 0.09$$

$$\Upsilon_1 = 0.00 \pm 0.05$$

uniform priors, taken from current hydrodynamical simulations

- mass calibration

$$K = 0.90 \pm 0.09$$

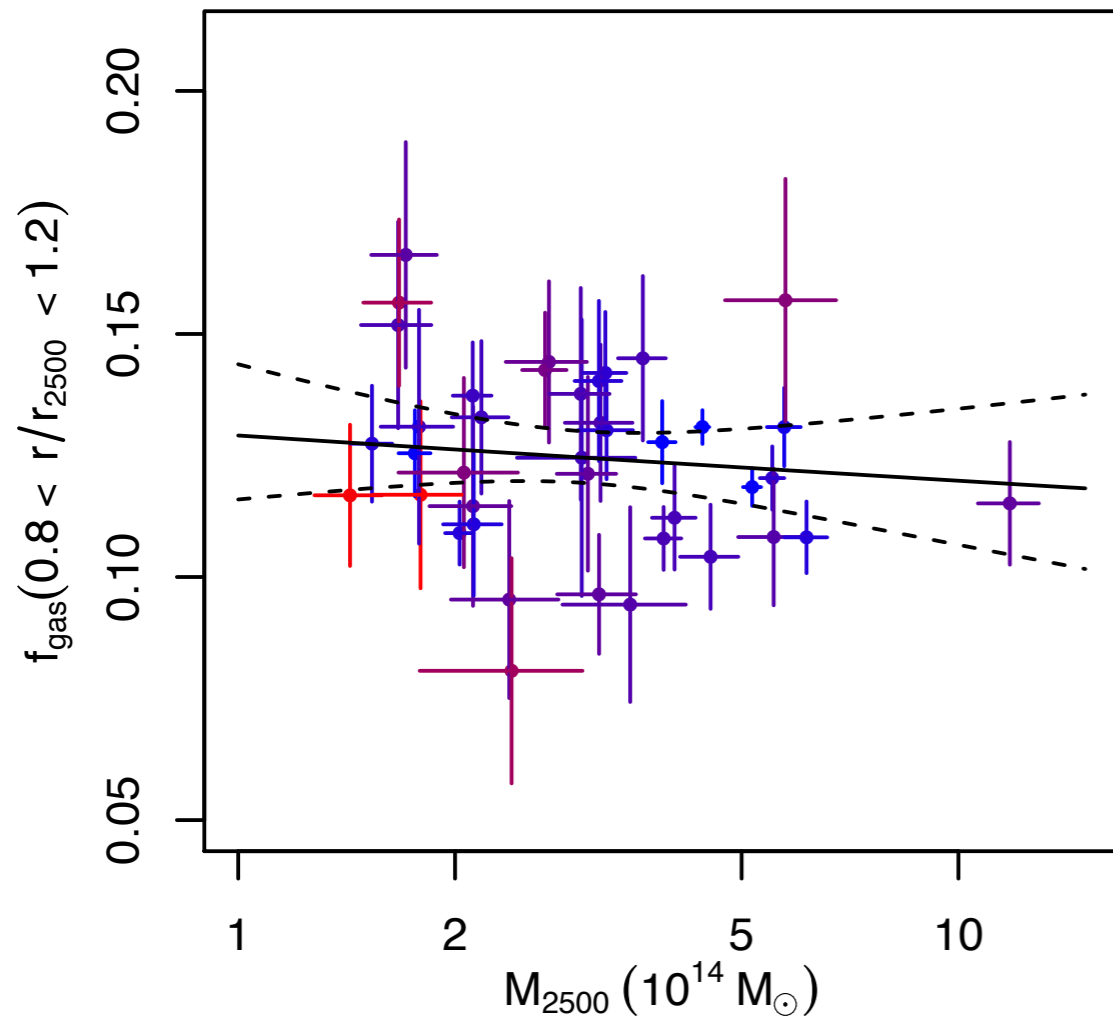
Gaussian prior from weak lensing masses (Applegate et al. in prep.)

- (Gaussian) priors from other measurements:

$$\Omega_b h^2 = 0.02202 \pm 0.00045 \quad (\text{BBN; Cooke et al. 2014})$$

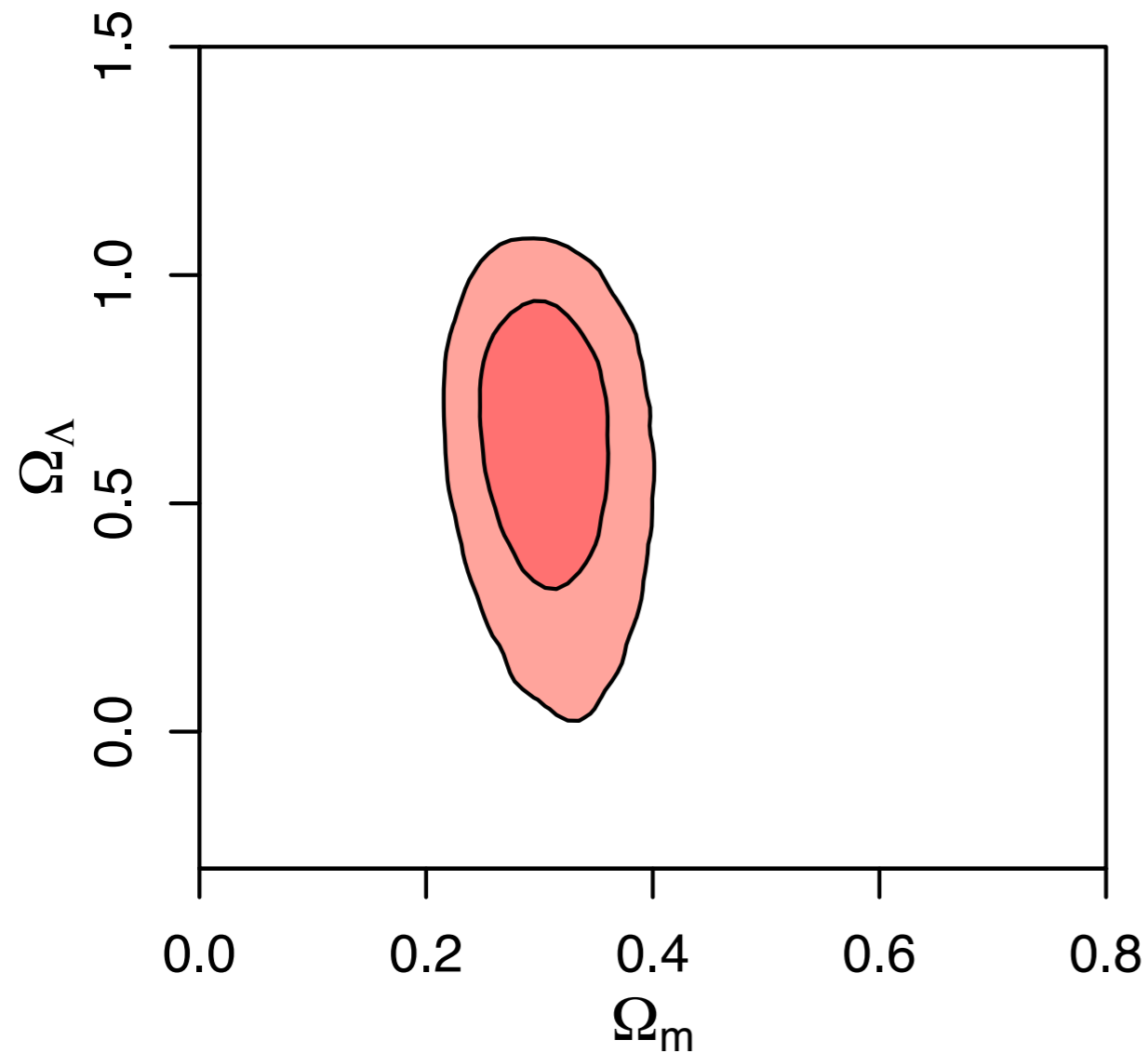
$$h = 0.738 \pm 0.024 \quad (\text{Cepheids; Riess et al. 2011})$$

Results - scatter in f_{gas}



- intrinsic scatter in f_{gas} : $(7.4 \pm 2.4)\%$
- (4.9% in distance)
- this is very small!
- no mass-dependence
- f_{gas} can be used as standard quantity
- M_{gas} is a good low-scatter mass proxy

Results - Λ CDM

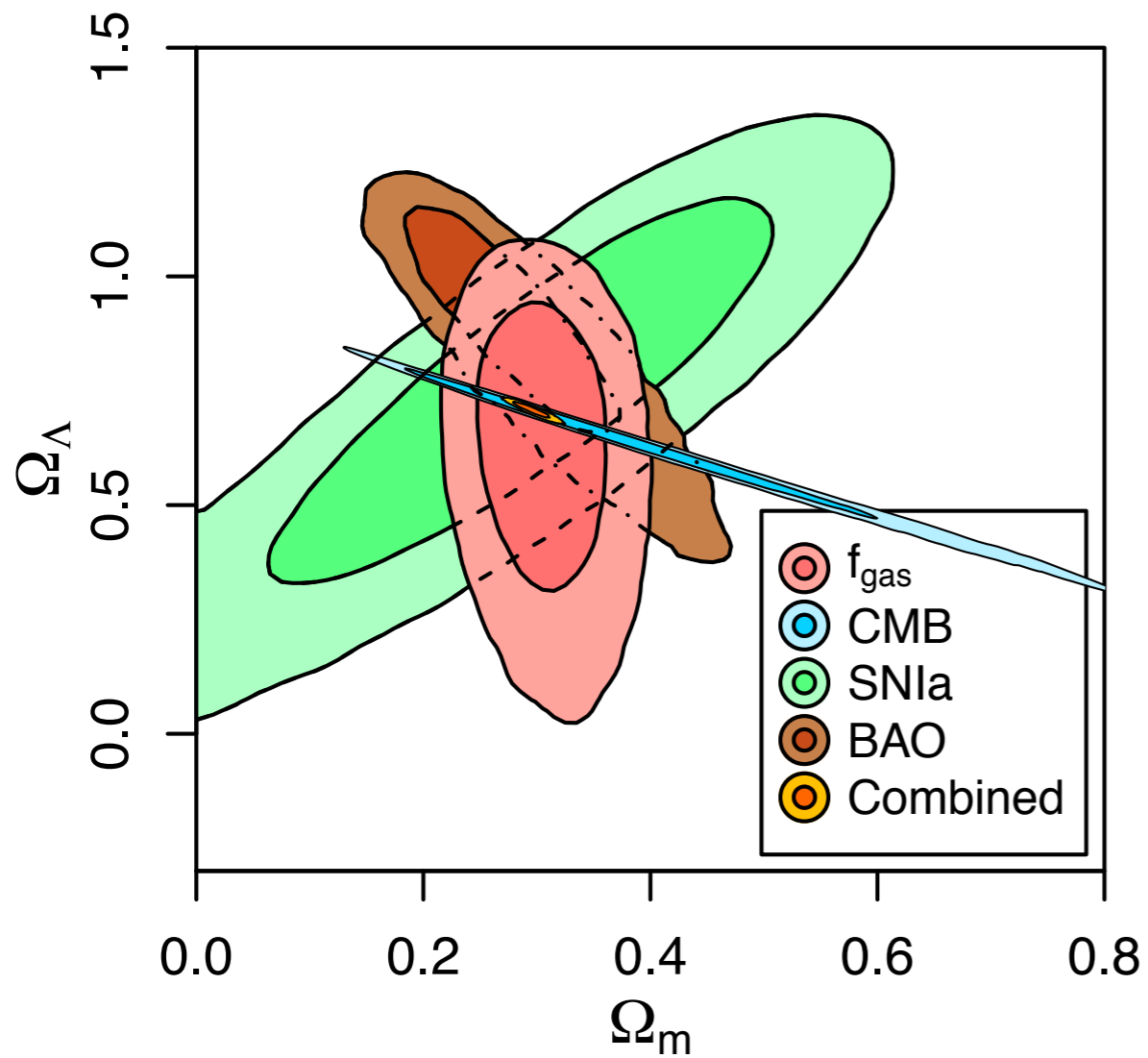


$$\Omega_m = 0.29 \pm 0.04$$

$$\Omega_\Lambda = 0.63 \pm 0.19$$

- constraint on Ω_m limited by mass calibration K (only 12 relaxed clusters with lensing data)
- constraint on Ω_Λ limited by number of high-redshift clusters

Results - Λ CDM



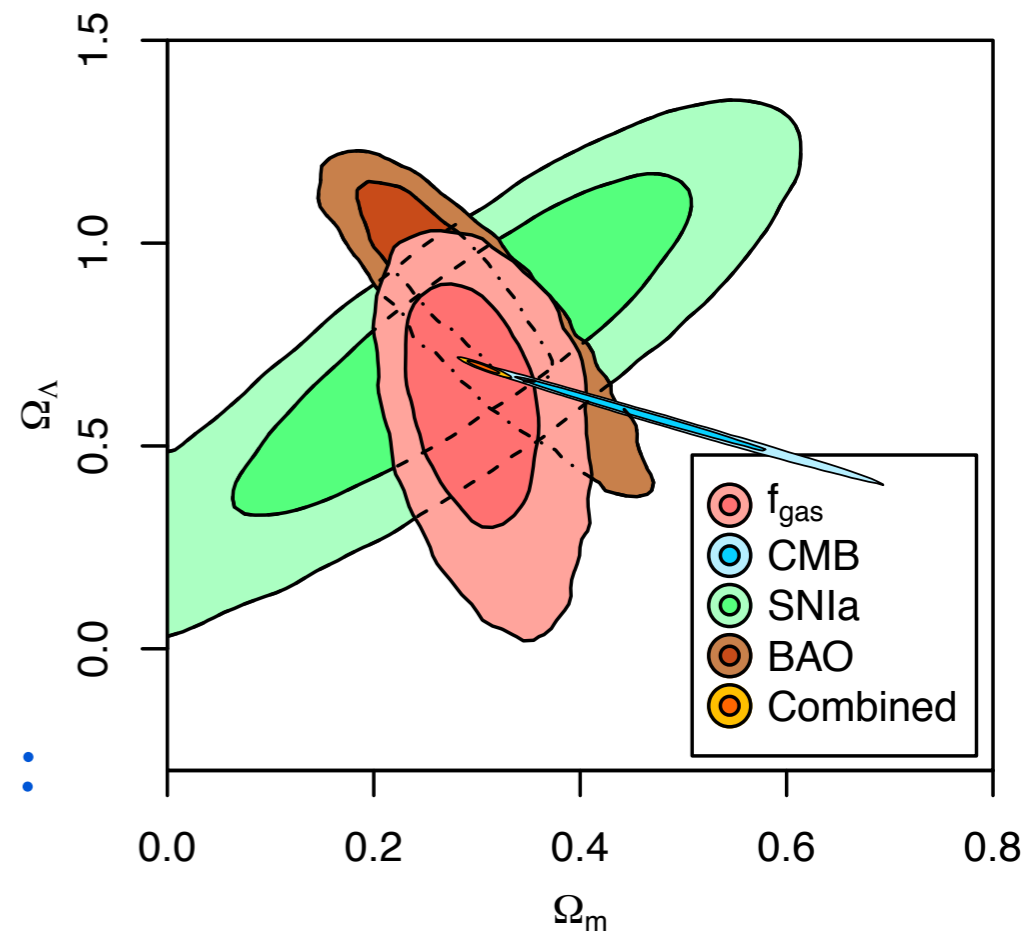
cluster f_{gas}

CMB: WMAP, SPT, ACT

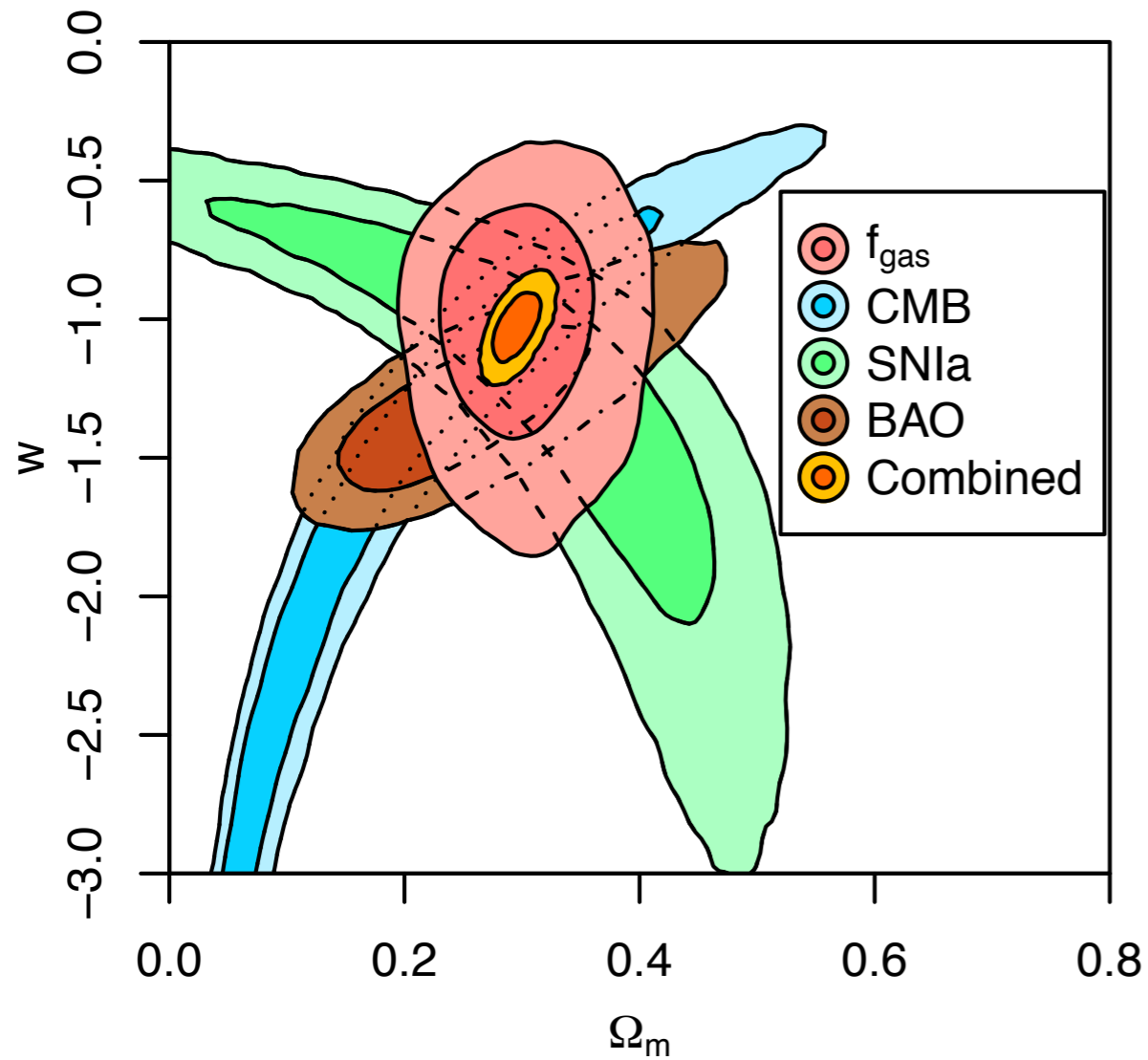
SNIa: Union 2.1

BAO: 6df, SDSS, BOSS

WMAP → Planck :



Results - flat, constant w



f_{gas} constraints:

$$\Omega_m = 0.29 \pm 0.04$$

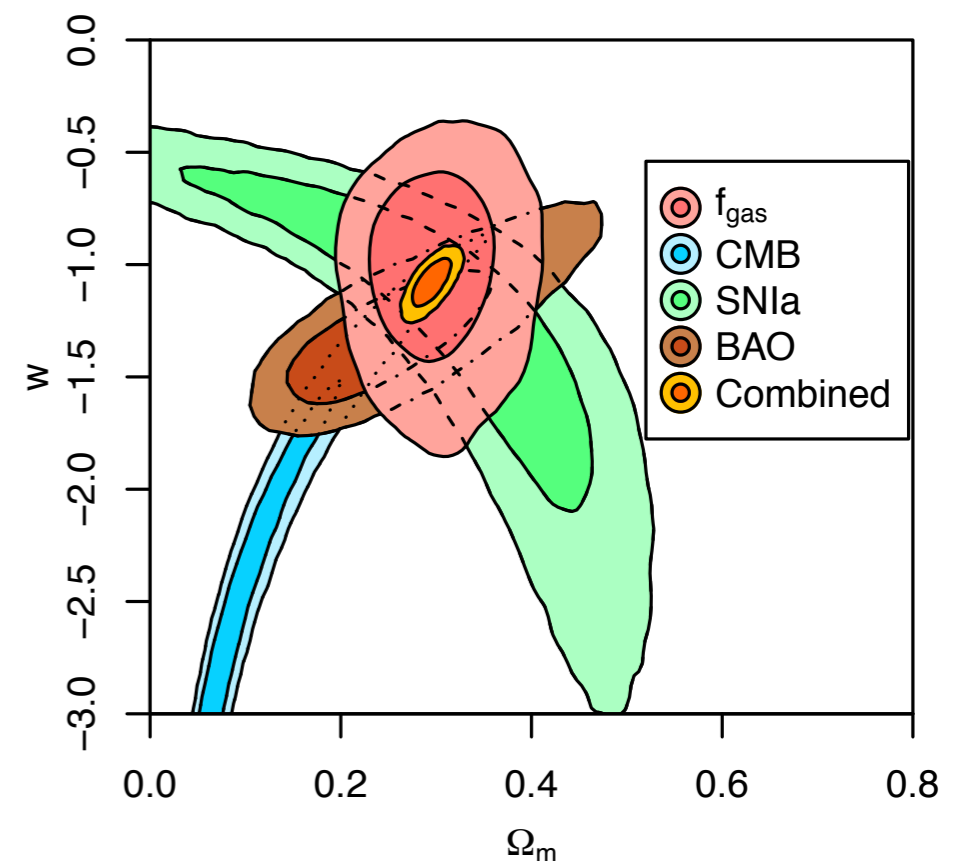
$$w = -0.97 \pm 0.25$$

combined constraints:

$$\Omega_m = 0.296 \pm 0.014$$

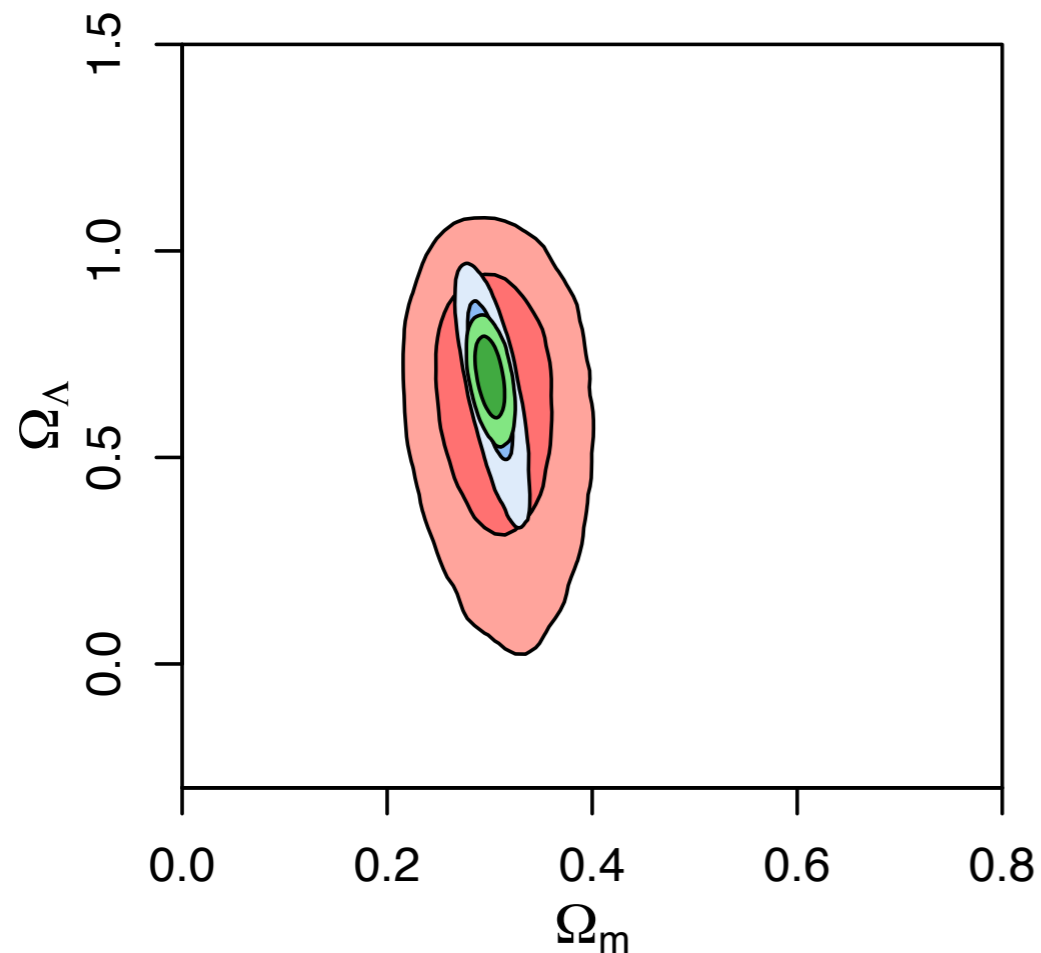
$$w = -1.02 \pm 0.08$$

WMAP \rightarrow Planck :



The road forward

- more lensing data + improved simulations \rightarrow better Ω_m constraints
- more relaxed clusters at $z \gtrsim 0.5 \rightarrow$ better Ω_Λ constraints



40 clusters (current)

\sim 100 clusters

\sim 400 clusters

white paper; Allen et al. 2013

f_{gas} summary

- provides one of the best measures of Ω_m
- is a “standard quantity” and can therefore be used to constrain geometry of Universe (including dark energy)

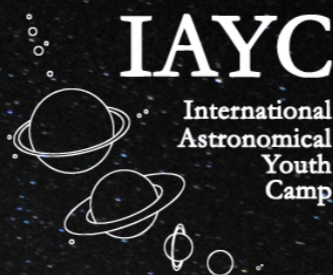
- measuring cluster masses is very important for cluster cosmology
- ... but also very difficult
- multi-wavelength approach: use unbiased, high-scatter weak lensing masses to calibrate low-scatter, biased X-ray mass measures (more on this tomorrow)
- gas mass is a good “mass proxy” - easy to measure, correlates tightly with cluster mass

Plan for tomorrow

- “counting clusters” - cosmology with the cluster mass function
- more on *Weighing the Giants*



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