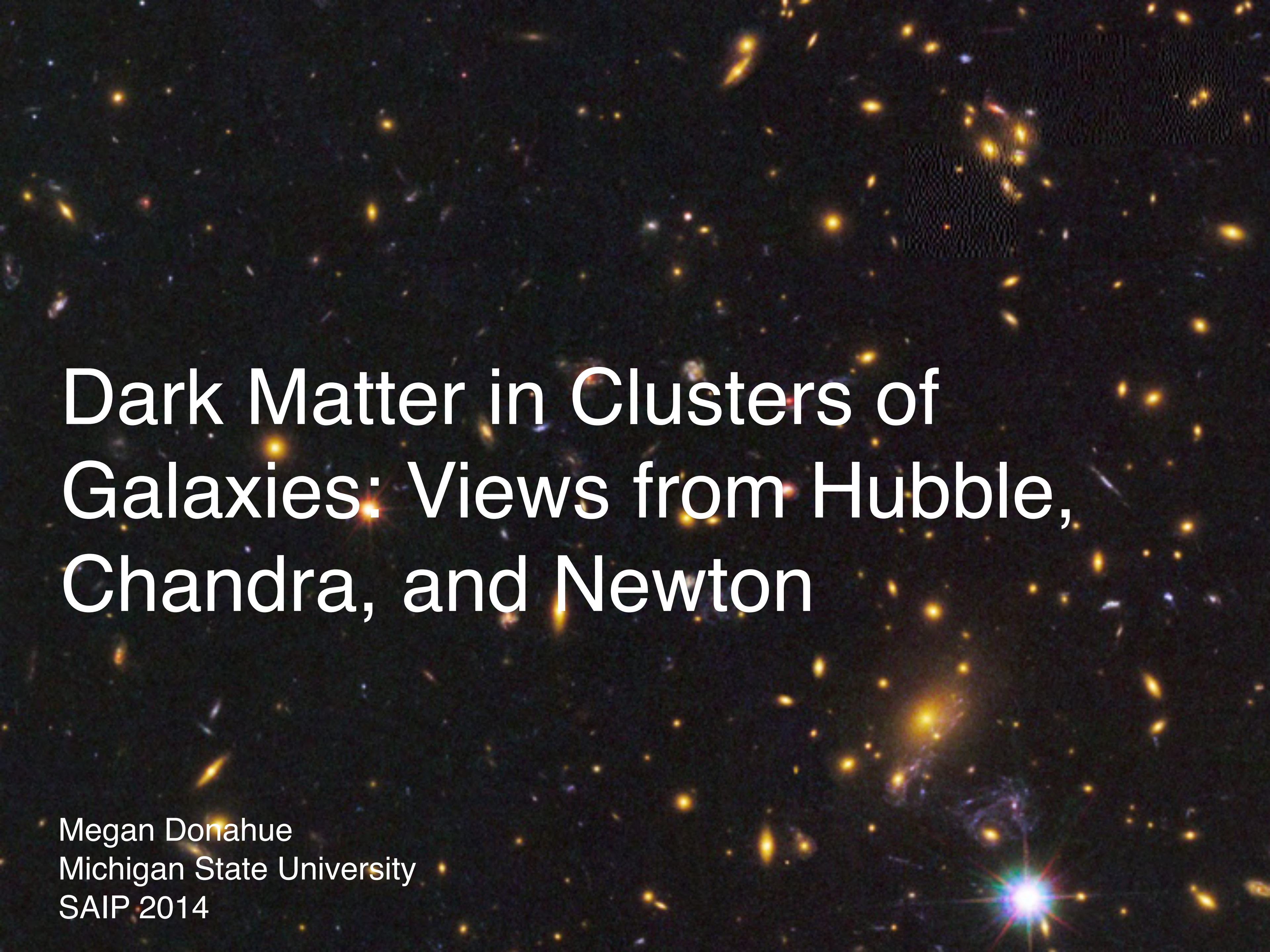
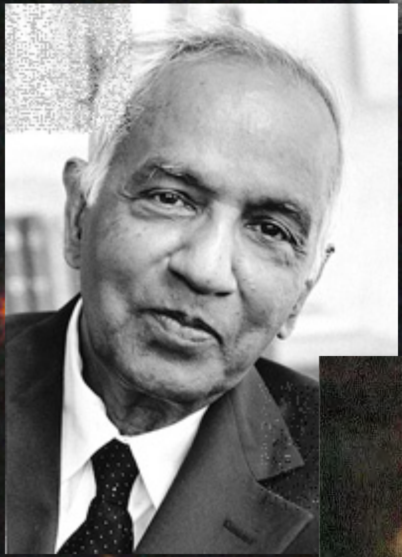


Dark Matter in Clusters of Galaxies: Views from Hubble, Chandra, and Newton

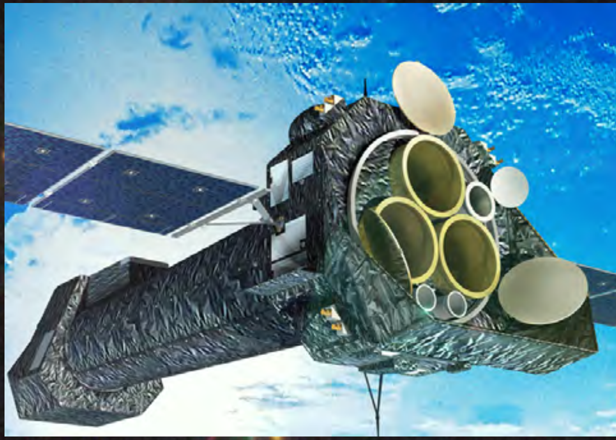
Megan Donahue
Michigan State University
SAIP 2014

Hubble

Chandra

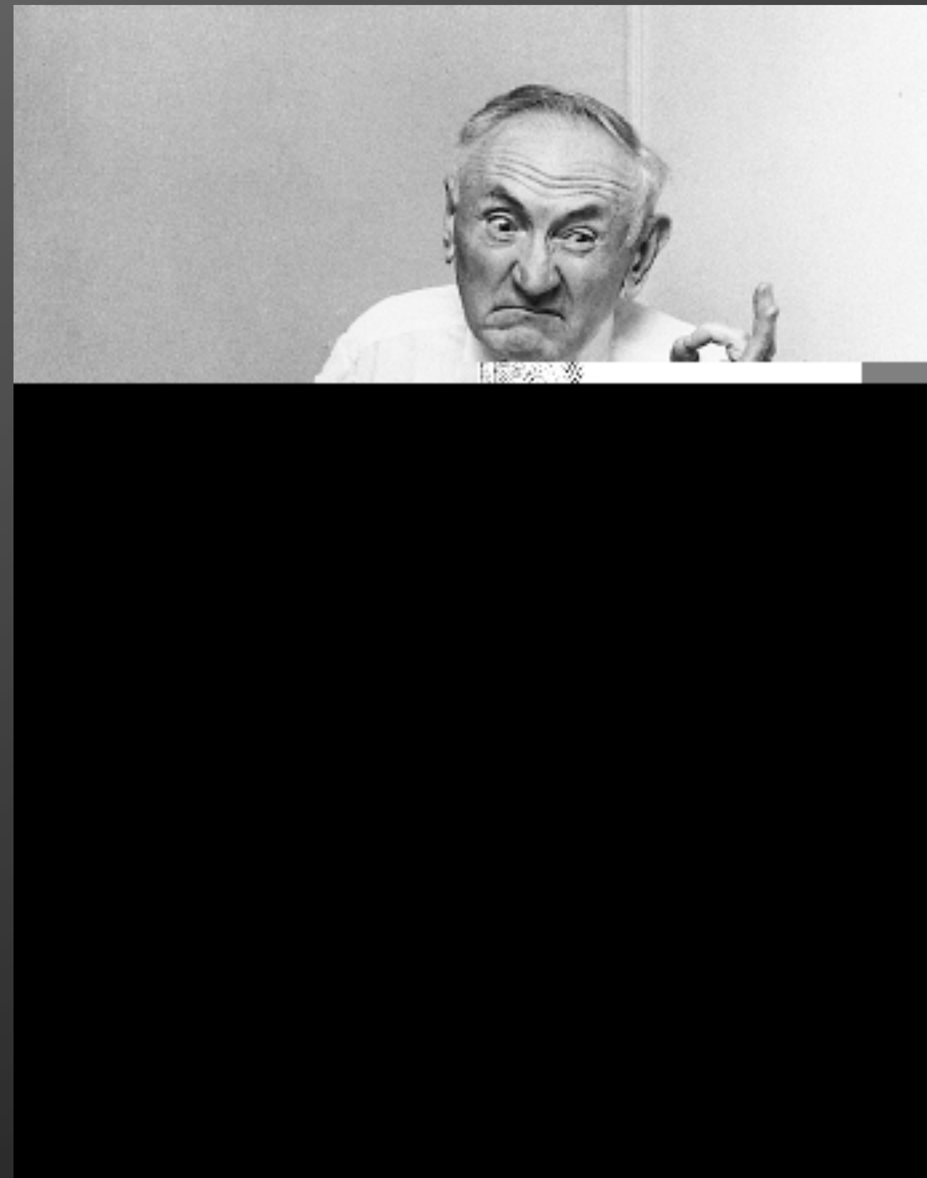


Newton



Megan Donahue
Michigan State University
SAIP 2014

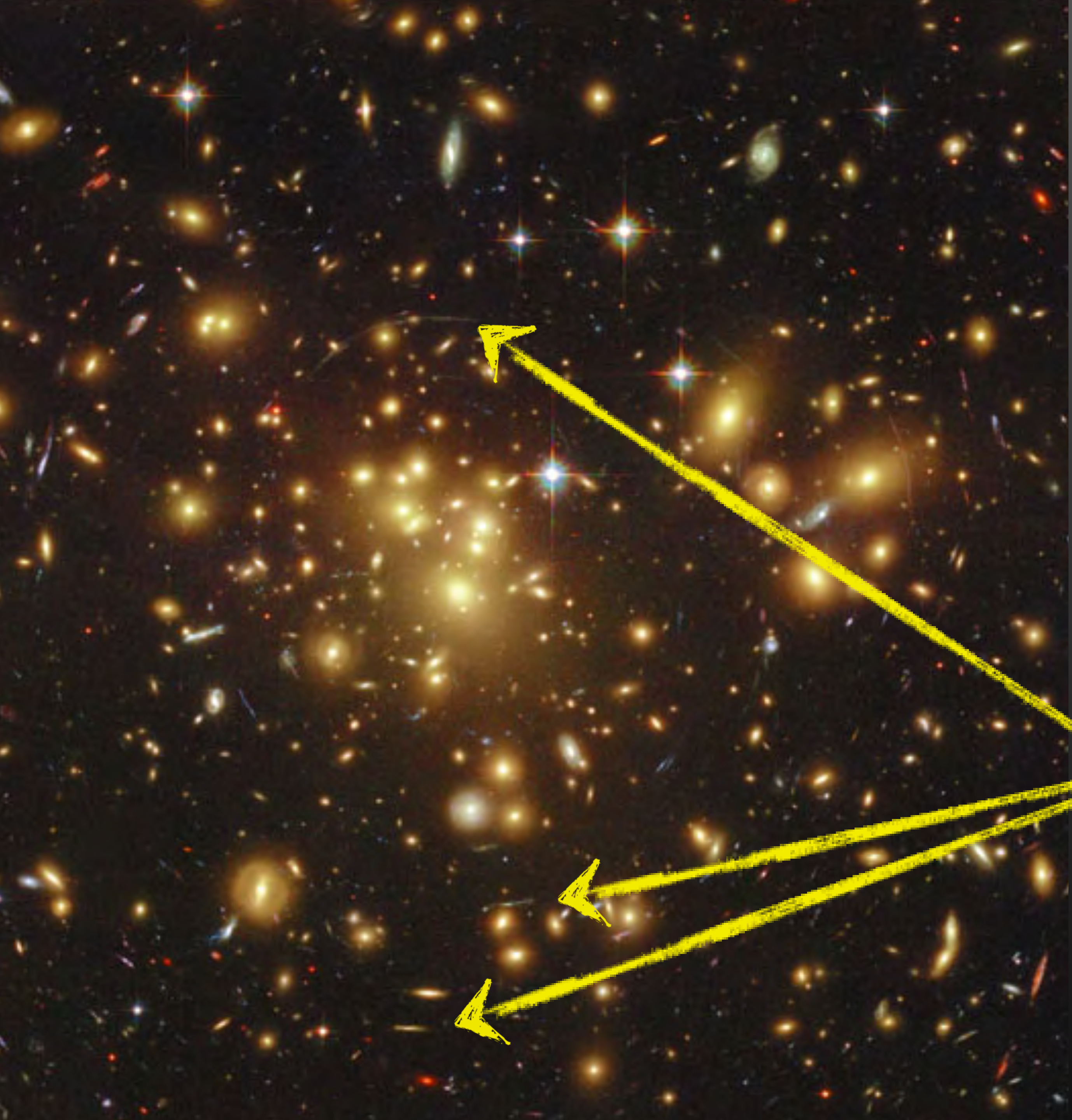
Dark Matter



Fritz Zwicky (1898-1974)

Radial velocities and locations of galaxies in clusters :
50x more gravitating mass than in stars.

Abell 1689



Gravitational lensing of background galaxies: lensing mass is 50 times that in stars.

Abell 1689

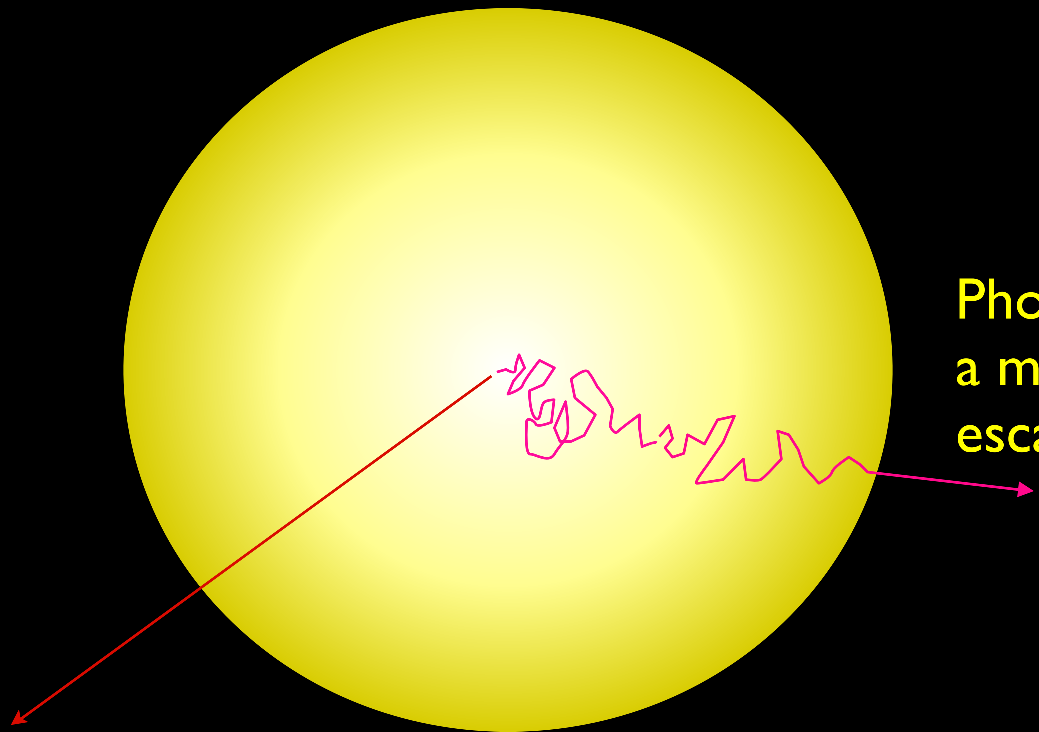

Gravitational confinement of the hot intergalactic plasma:
7x the mass of the hot gas.
X-ray image of Abell 1689

Two Basic Options

1. Ordinary Dark Matter

2. Exotic Dark Matter (WIMPS)
   – Weakly Interacting Massive Particles

Weakly interacting

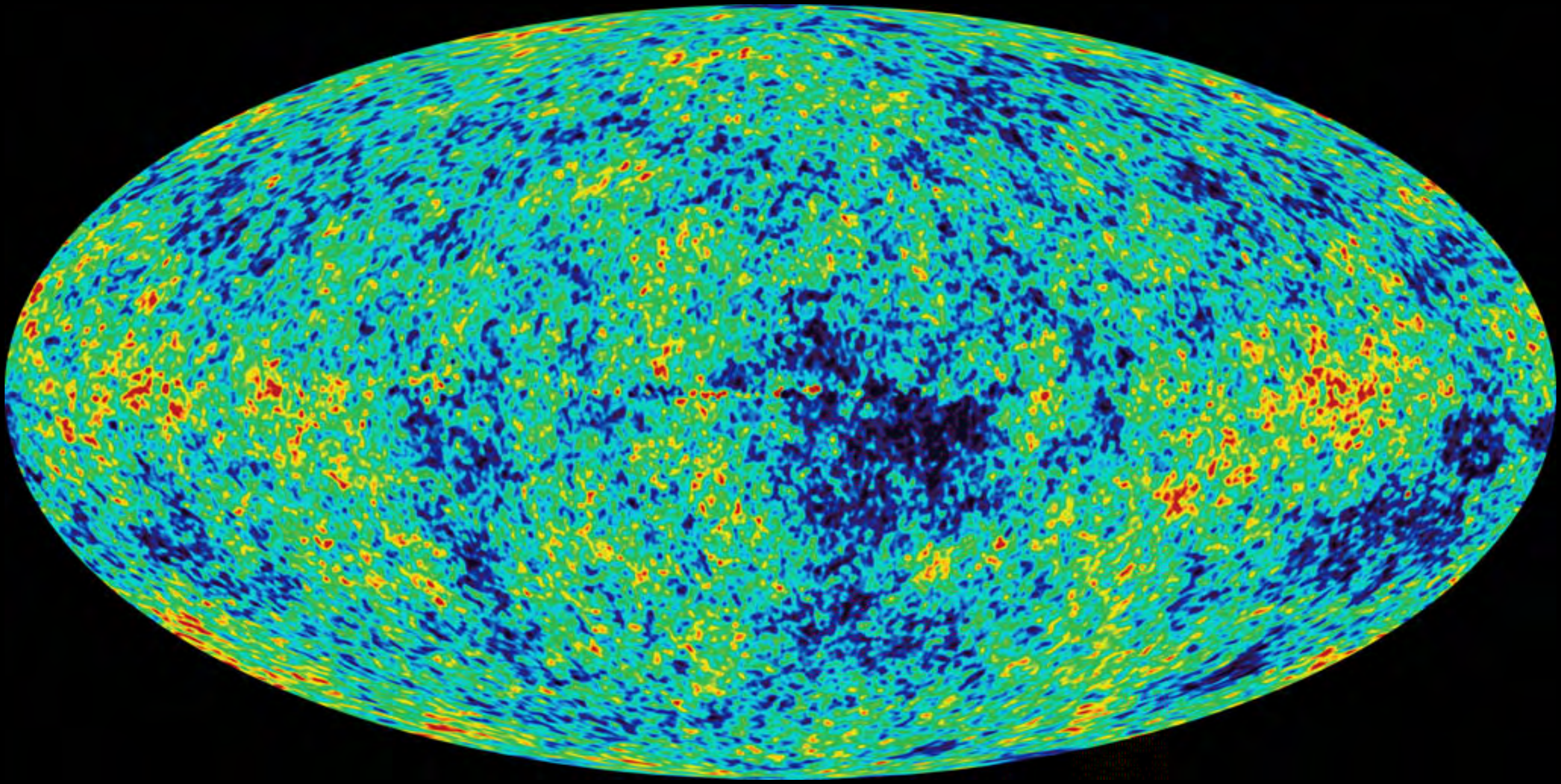


Photons take about a million years to escape

Neutrinos take about 2 seconds

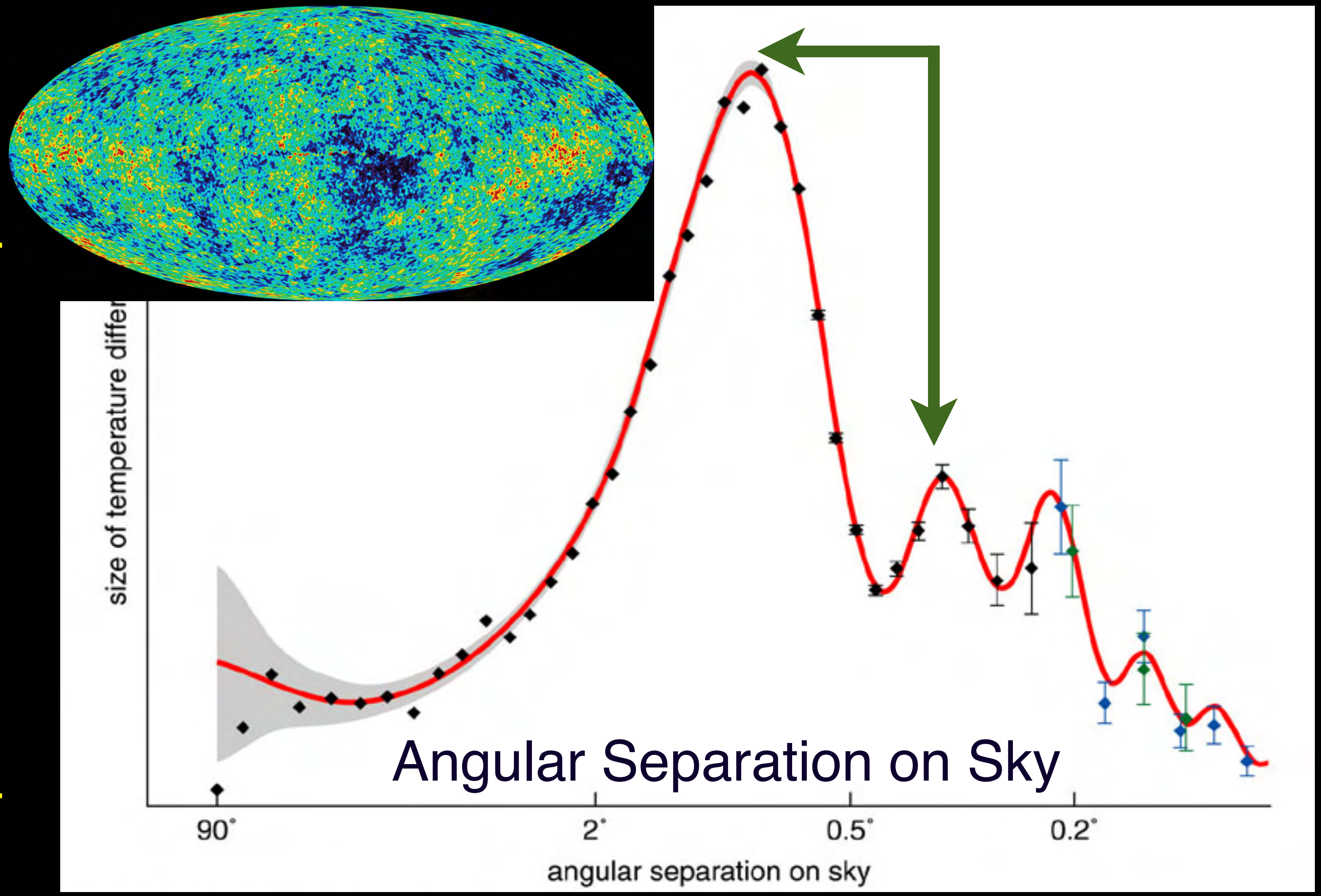
Nuclear fusion reactions in the Sun's core create both photons and (weakly-interacting) neutrinos.

Baryon Baby Pictures



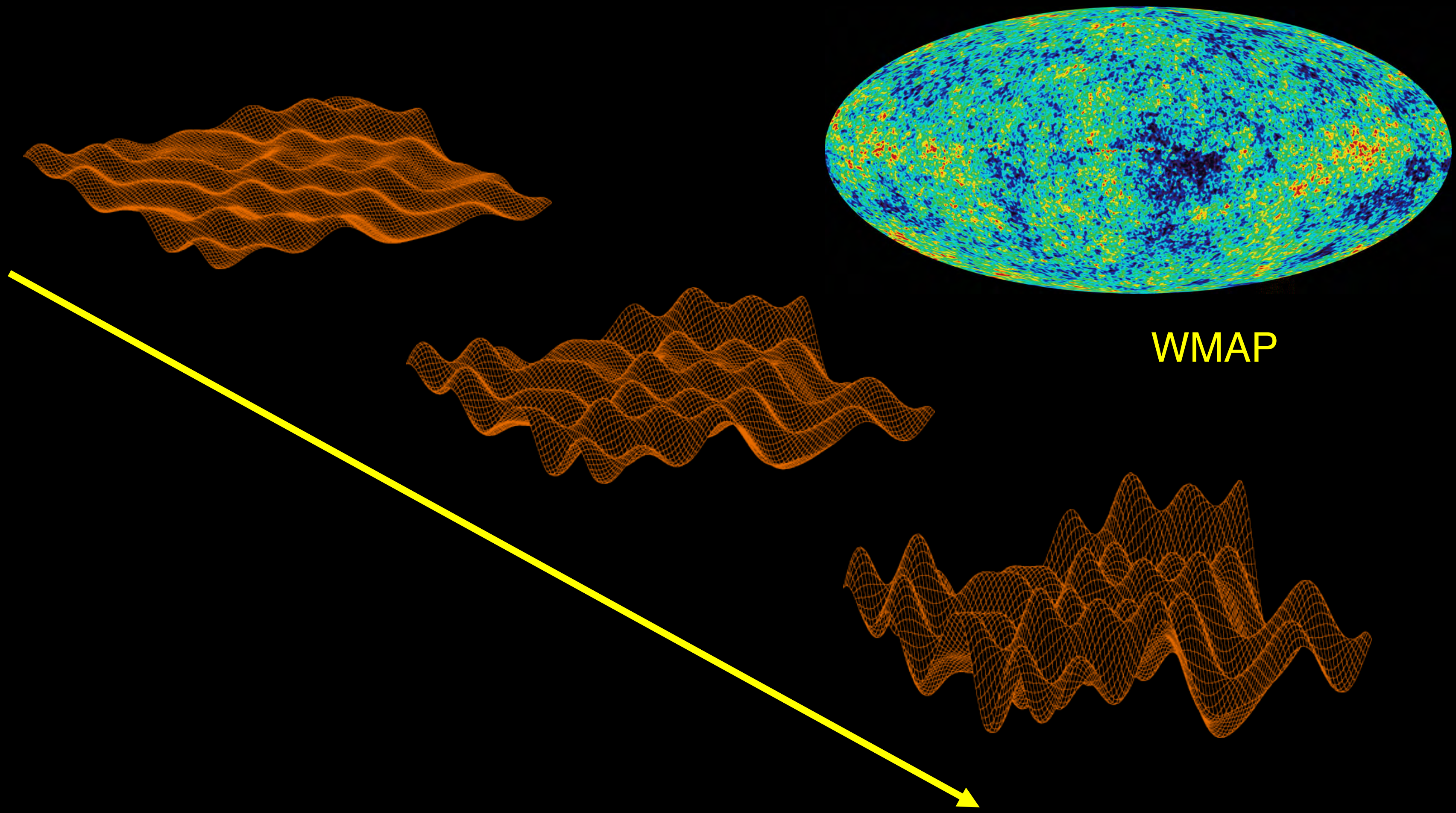
Wilkinson Microwave Anisotropy Probe (WMAP)

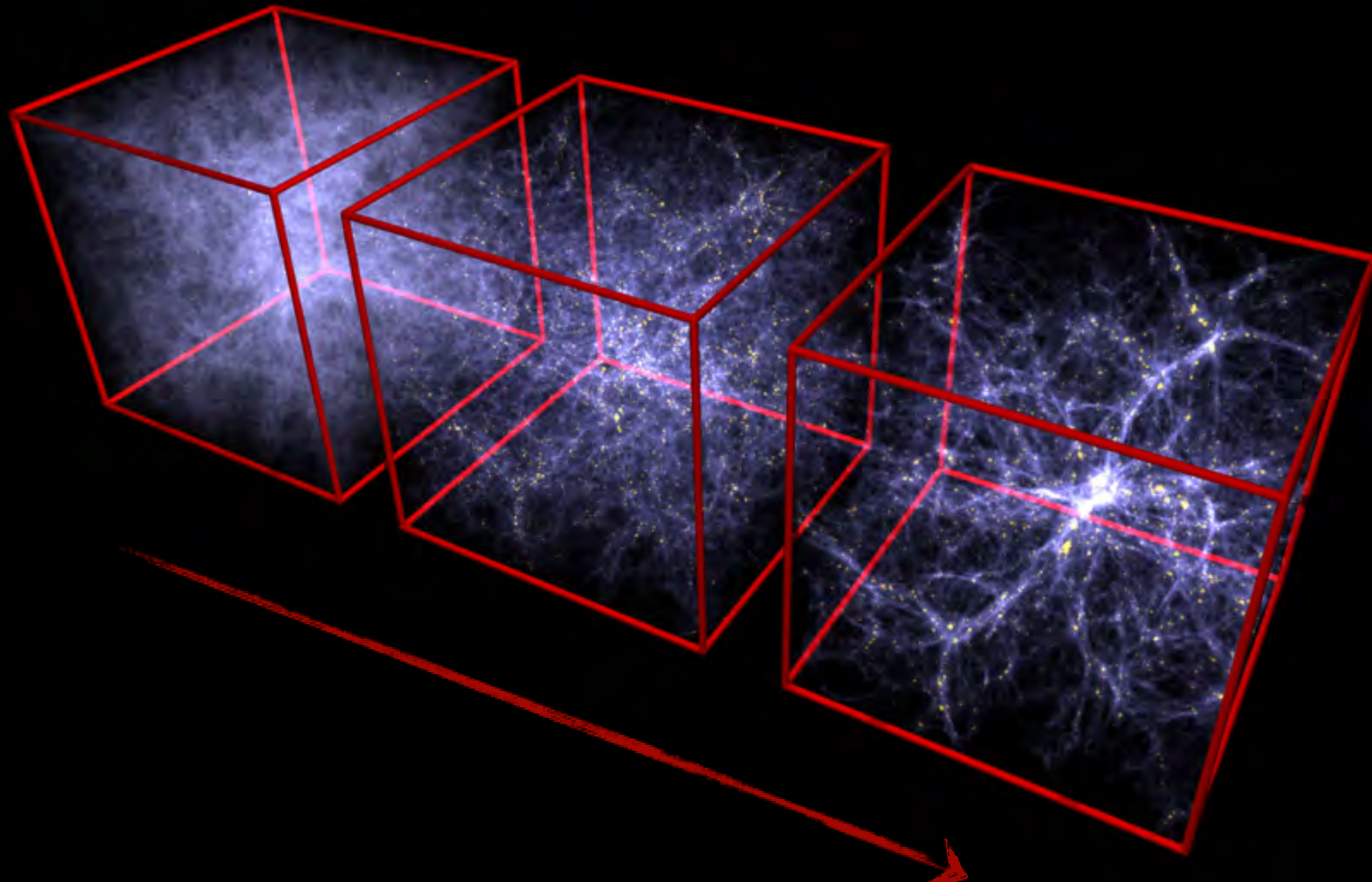
Cosmic Microwave Background



The relative heights of odd and even peaks of the power spectrum tells us that the density of baryons are ~ 4.4% of the total mass-energy density of the universe.

Growth by Gravity





Models show that gravity of dark matter pulls mass into denser regions – universe grows lumpier with time

The Bullet Cluster

The Bullet Cluster

Two Basic Options

Not enough baryons!

1. Ordinary Dark Matter

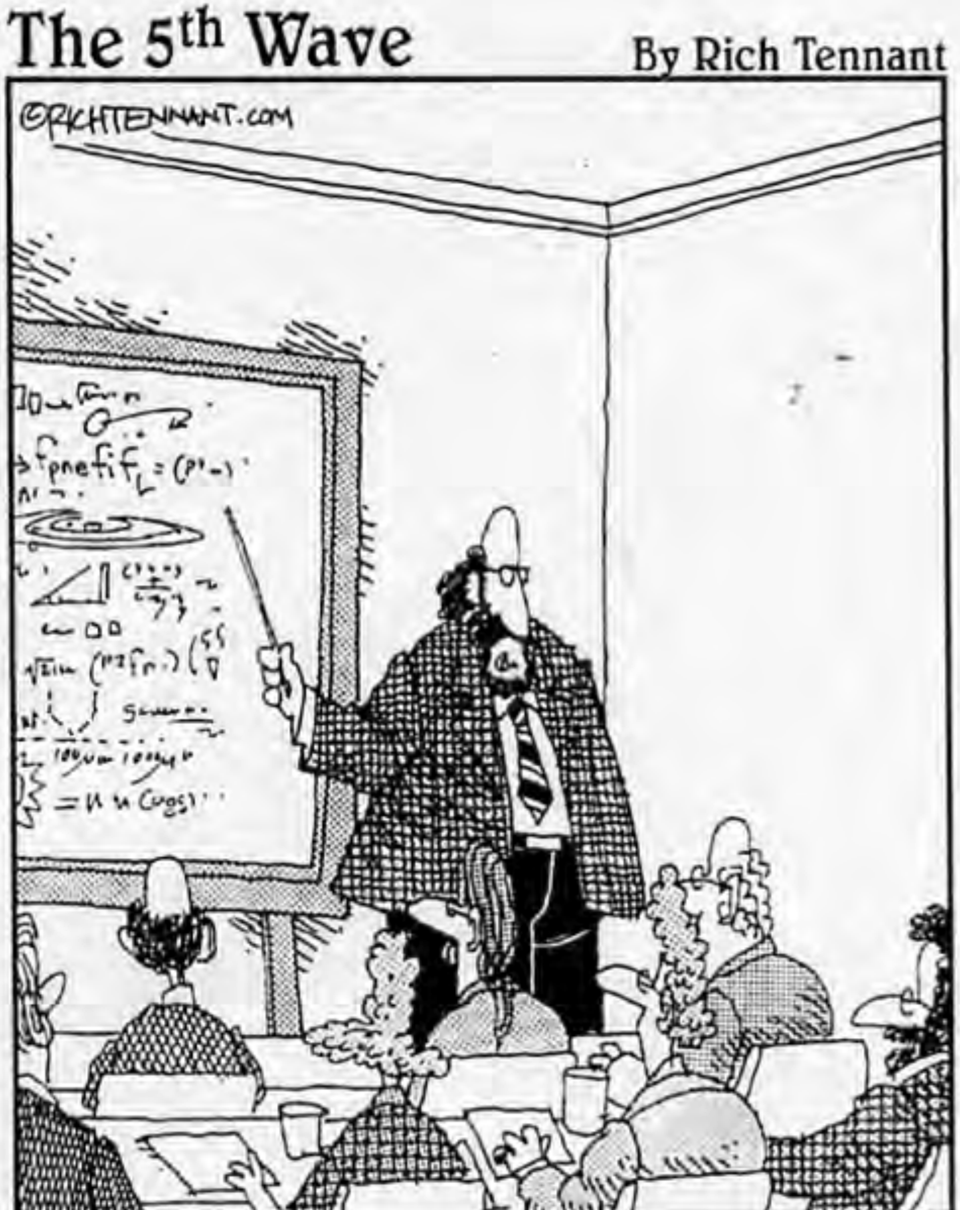
Baryon-only dark matter fails to reproduce the patterns of hot/cold spots in the Cosmic Microwave Background.

(Primordial deuterium abundance is very sensitive to the amount of ordinary matter. There is too much deuterium in primordial gas clouds for dark matter to be ordinary.)

2. Extraordinary Dark Matter (WIMPS)

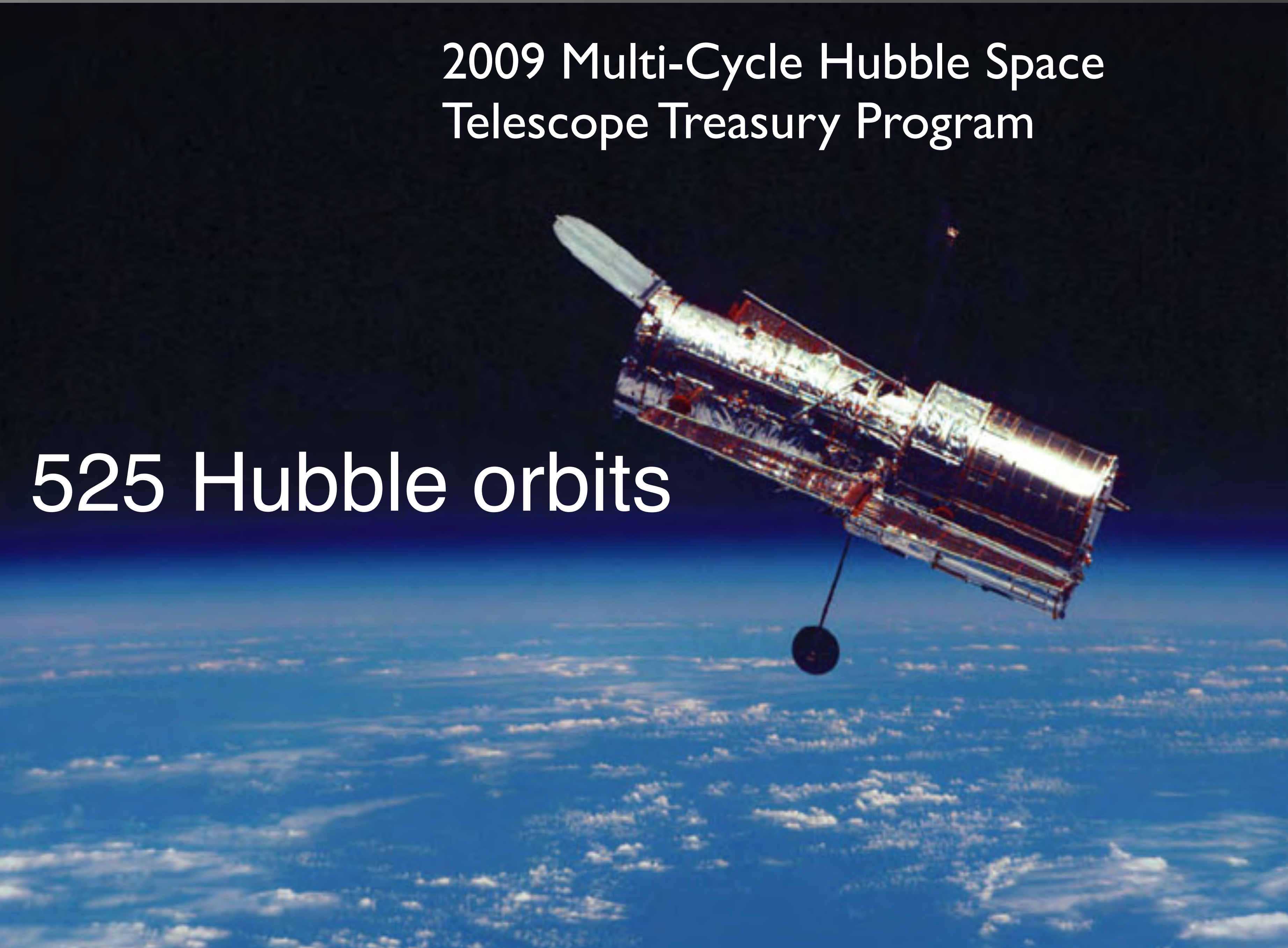
– Weakly Interacting Massive Particles

The Best Bet



"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have

"After the discovery of 'antimatter' and 'dark matter', we have just confirmed the existence of 'doesn't matter', which does not have any influence on the Universe whatsoever."


2009 Multi-Cycle Hubble Space
Telescope Treasury Program
525 Hubble orbits

CLASH:
Cluster Lensing And Supernova survey with Hubble

Scientific goals: to place new constraints on the fundamental components of the cosmos: dark matter, dark energy, and baryons.

To accomplish this, we are observing 25 galaxy clusters as cosmic lenses to probe dark matter and to magnify distant galaxies.

Multiple observation epochs enable a $z > 1$ SN search in the surrounding field (where lensing magnification is low).

The CLASH Science Team: ~60 researchers, 30 institutions, 12 countries

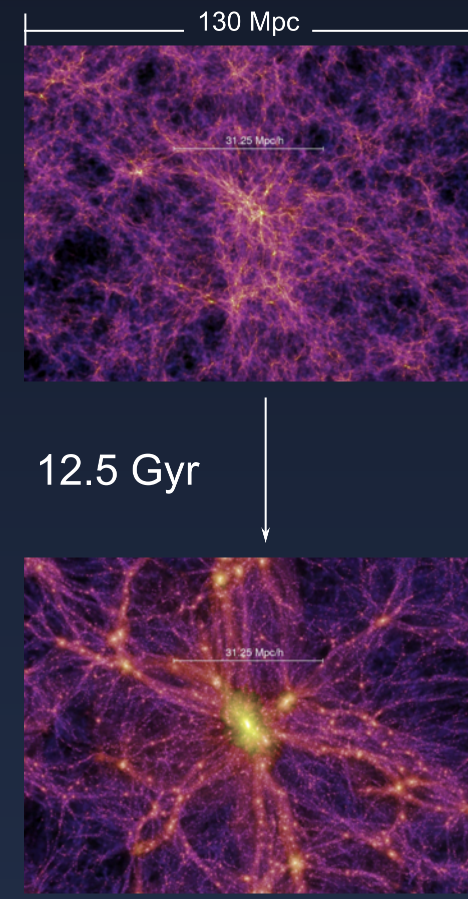
Marc Postman, P.I.	Space Telescope Science Institute (STScI)	Ofer Lahav	UCL
Begona Ascaso	UC Davis	Ruth Lazkoz	Univ. of the Basque Country
Italo Balestra	Max Plank Institute (MPE)	Doron Lemze	JHU
Matthias Bartelmann	Universität Heidelberg	Dan Maoz	Tel Aviv University
Narciso "Txitxo" Benitez	Instituto de Astrofisica de Andalucia (IAA)	Curtis McCully	Rutgers University
Andrea Biviano	INAF - OATS	Elinor Medezinski	JHU
Rychard Bouwens	Leiden University	Peter Melchior	The Ohio State University
Larry Bradley	STScI	Massimo Meneghetti	INAF / Osservatorio Astronomico di Bologna
Thomas Broadhurst	Univ. of the Basque Country	Amata Mercurio	INAF / OAC
Dan Coe	STScI	Julian Merten	JPL / Caltech
Thomas Connor	Michigan State University	Anna Monna	Univ. Sternwarte Munchen / MPE
Mauricio Carrasco	Universidad Catolica de Chile	Alberto Molino	IAA
Nicole Czakon	California Institute of Technology / ASIAA	John Moustakas	Siena College
Megan Donahue	Michigan State University	Leonidas Moustakas	JPL / Caltech
Kevin Fogarty	Johns Hopkins University (JHU)	Mario Nonimo	INAF / Osservatorio Astronomico di Bologna
Holland Ford	JHU	Brandon Patel	Rutgers University
Jorge Gonzalez	Universidad Catolica de Chile	Enikö Regös	European Laboratory for Particle Physics (CERN)
Or Graur	JHU	Adam Riess	STScI / JHU
Genevieve Graves	University of California, Berkeley	Steve Rodney	JHU
Øle Host	DARK Cosmology Centre	Piero Rosati	European Southern Observatory
Claudio Grillo	DARK Cosmology Centre	Jack Sayers	Caltech
Sunil Golwala	California Institute of Technology (Caltech)	Irene Sendra	Univ of Basque Country
Aaron Hoffer	Michigan State University	Stella Seitz	Universitas Sternwarte München
Leopoldo Infante	Universidad Católica de Chile	Seth Siegel	Caltech
Saurubh Jha	Rutgers University	Renske Smit	Leiden University
Yolanda Jimenez-Teja	IAA	Leonardo Ubeda	STScI
Stéphanie Jouvel	Univ. College London (UCL) / Barcelona	Keiichi Umetsu	Academia Sinica, Institute of Astronomy & Astrophysics
Daniel Kelson	Carnegie Institute of Washington	Arjen van der Wel	Max Planck Institüt für Astronomie
Anton Koekemoer	STScI	Bingxiao Xu	JHU
Ulricke Kuchner	Universität Wein	Wei Zheng	JHU
		Bodo Ziegler	Universität Wein
		Adi Zitrin	Caltech

Post-doctoral fellow

Fundamental Questions for Today: Clusters of Galaxies

How does matter behave in deep gravitational potentials?

- Does dark matter act like the dark matter in simulations?
- How are baryonic matter and DM related?
- Do real dark matter halos have the same shape and concentration as simulated halos?



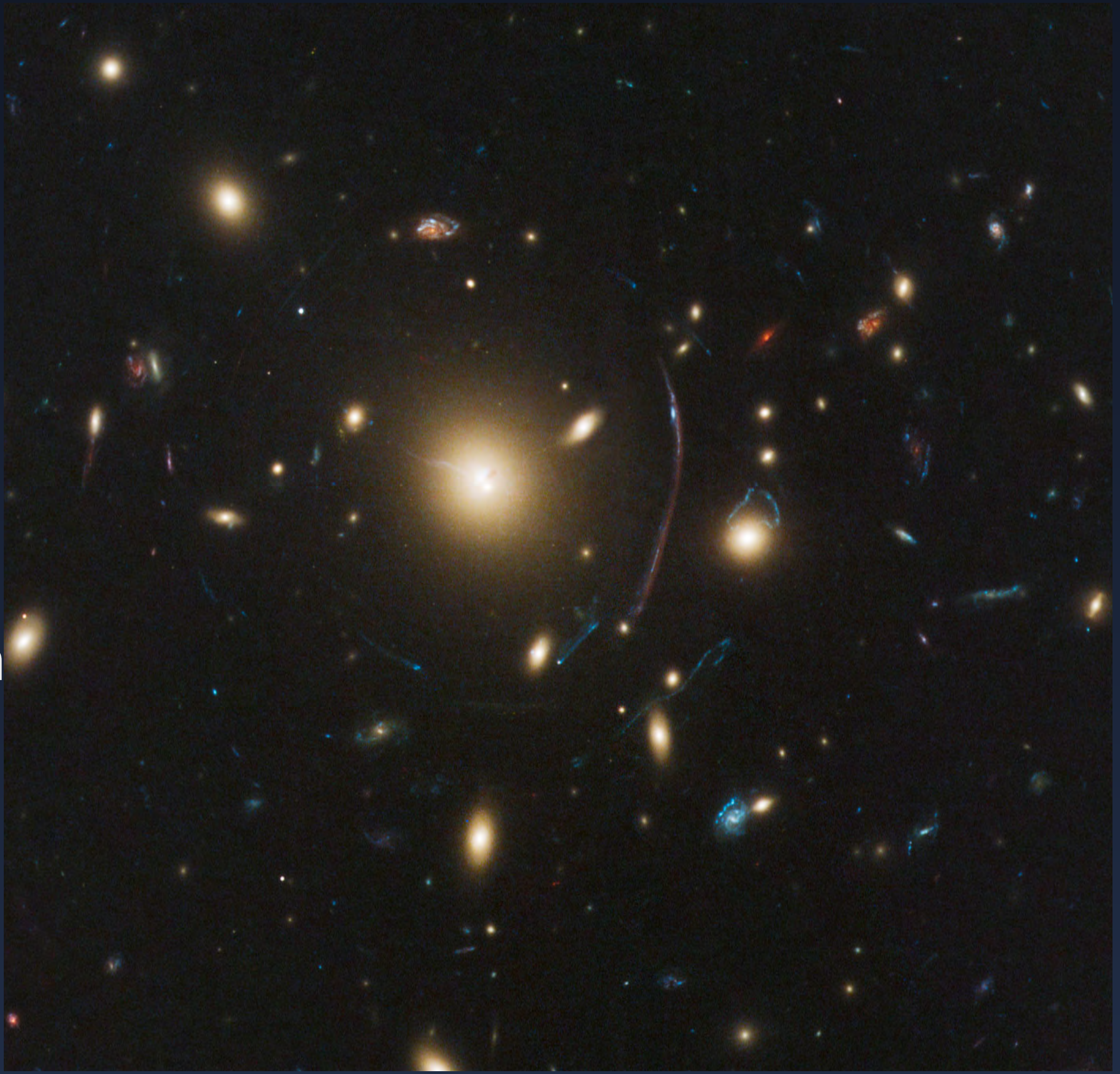
"Millennium" simulation of DM
Springel et al. 2005

Gravitational Lensing

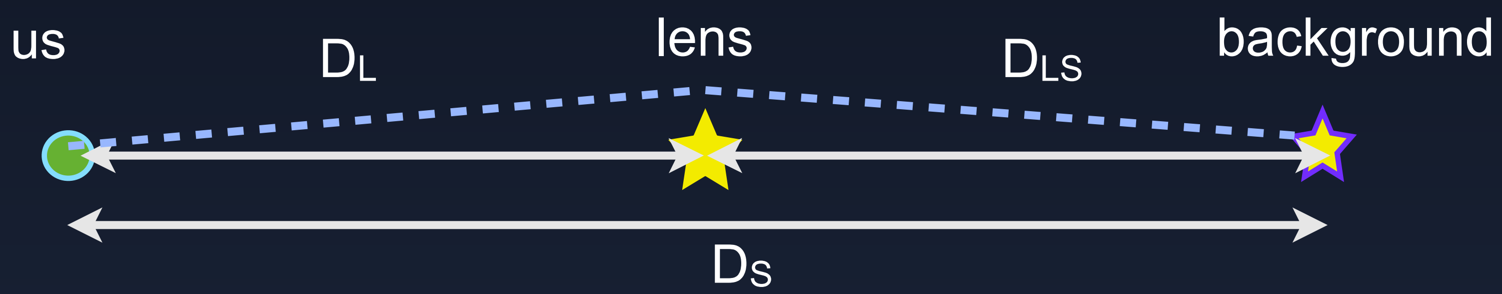
Clusters of galaxies are ~85% dark matter.

~10^{14-15} solar masses

Gravitational lensing distortion by the cluster provides:
1. the mass distribution in the cluster
2. a boosted view of the high redshift universe



Abell 383 (z = 0.225)

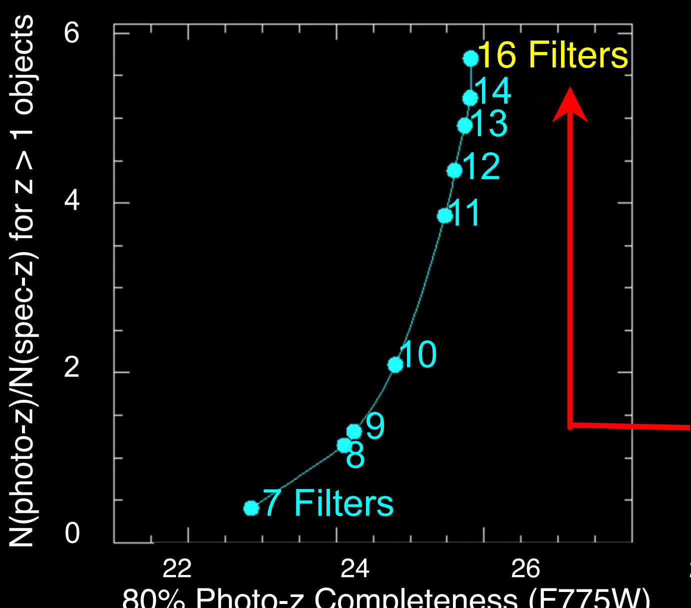


The Einstein Radius (lens approximated as an isothermal sphere with $v^2 \sim GM/r$)

$$\theta_{\mathrm{E}} = \frac{4\pi \langle v_{\parallel}^2 \rangle}{c^2} \frac{D_{\mathrm{LS}}}{D_{\mathrm{S}}}$$

The more massive the object, the larger the deflection: bigger “Einstein radii” , more mass along the line of sight.

CLASH: Deep, multi-wavelength HST imaging is a unique scientific asset for cluster studies

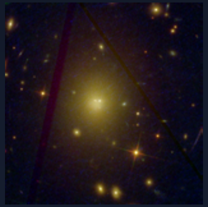


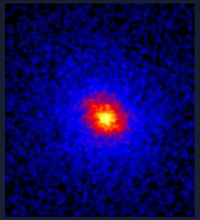
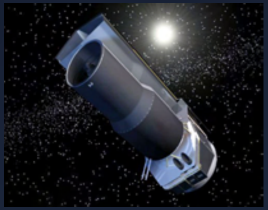
Contiguous 16-band imaging from HST from 225 nm to 1.6 microns: one of the richest data sets on clusters ever collected.

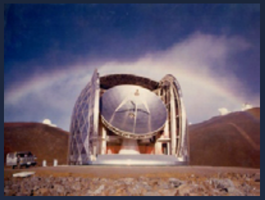
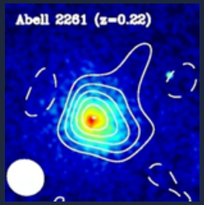
CLASH photometric redshifts can be obtained for ~6x as many z > 1 objects as could be obtained using spectrographs on 10-meter class ground-based facilities. Most of the strongly lensed objects we use to trace dark matter are fainter than ground-based spectroscopic limits.

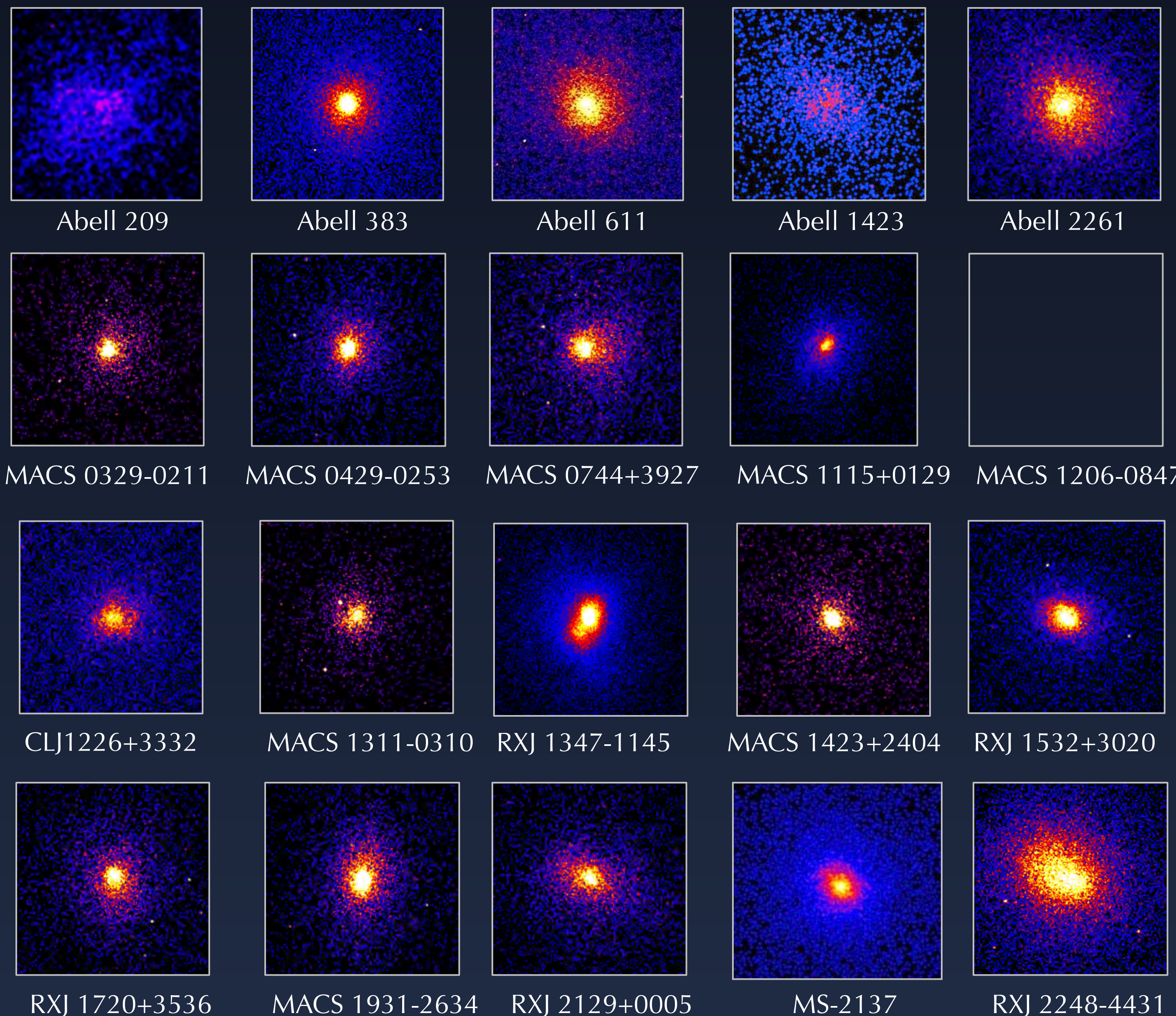
Comprehensive Multi-wavelength Coverage

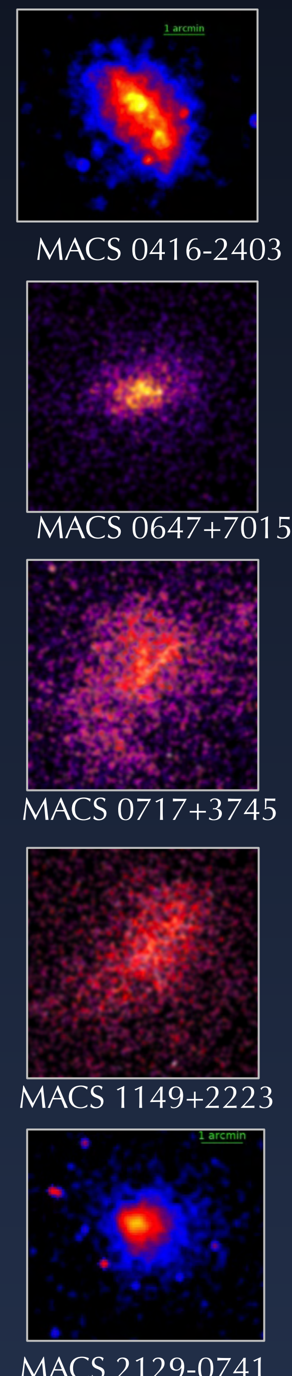
- HST 524 orbits: 25 clusters, each imaged in 16 passbands. (0.23 – 1.6 μm)
  ~20 orbits per cluster.
  Completed last summer.
- Spitzer Space Telescope archival and new cycle 8 data (3.6, 4.5 μm)
- Chandra x-ray and XMM Observatory archival data (0.5 – 7 keV), new XMM (PIs Ettori and Donahue)
- SZE observations (Bolocam, Mustang) to augment existing data (sub-mm)
- VLT, LBT, Magellan, MMT, Palomar Spectroscopy
- Subaru Telescope wide-field imaging (0.4 – 0.9 μm)

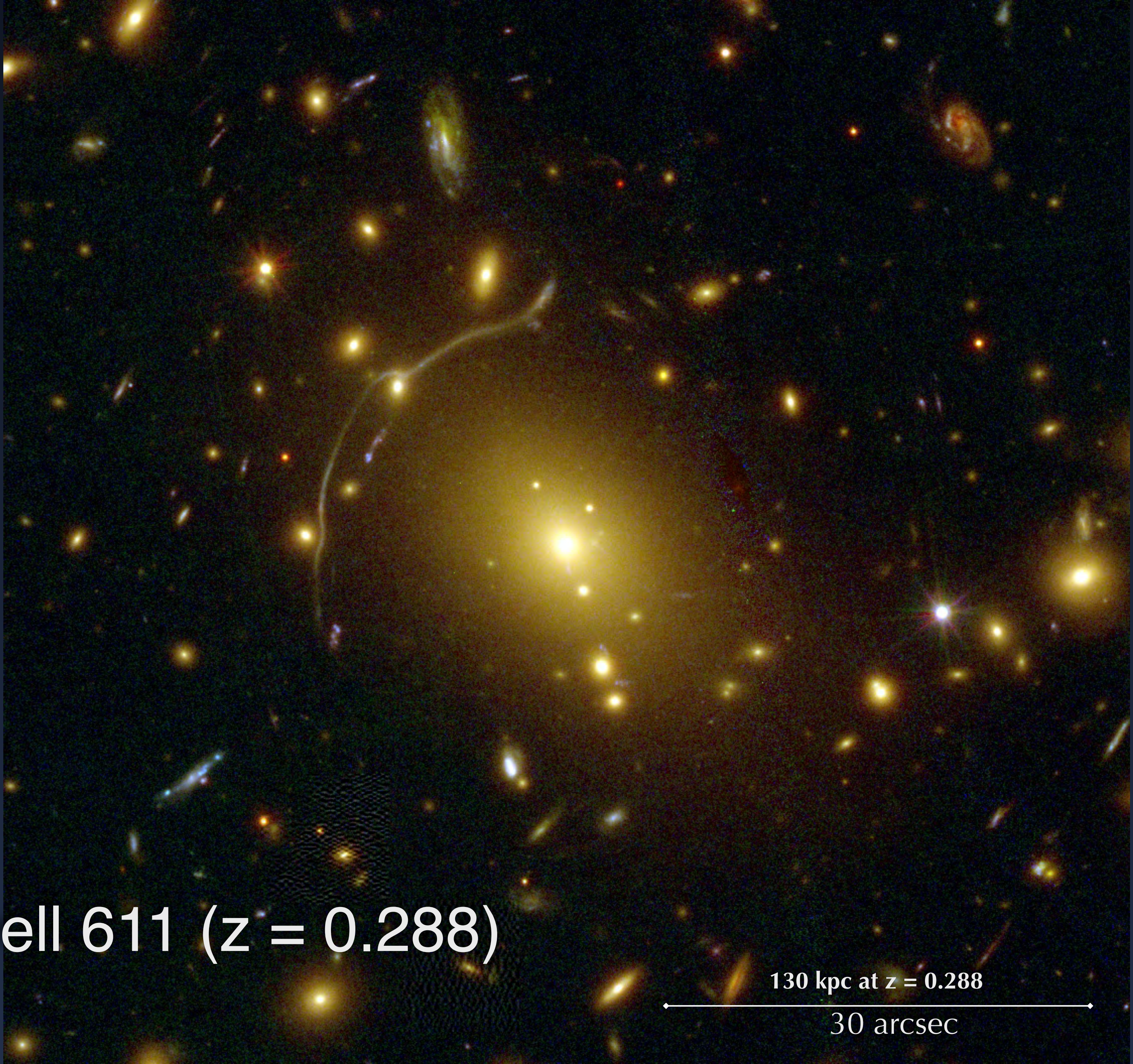



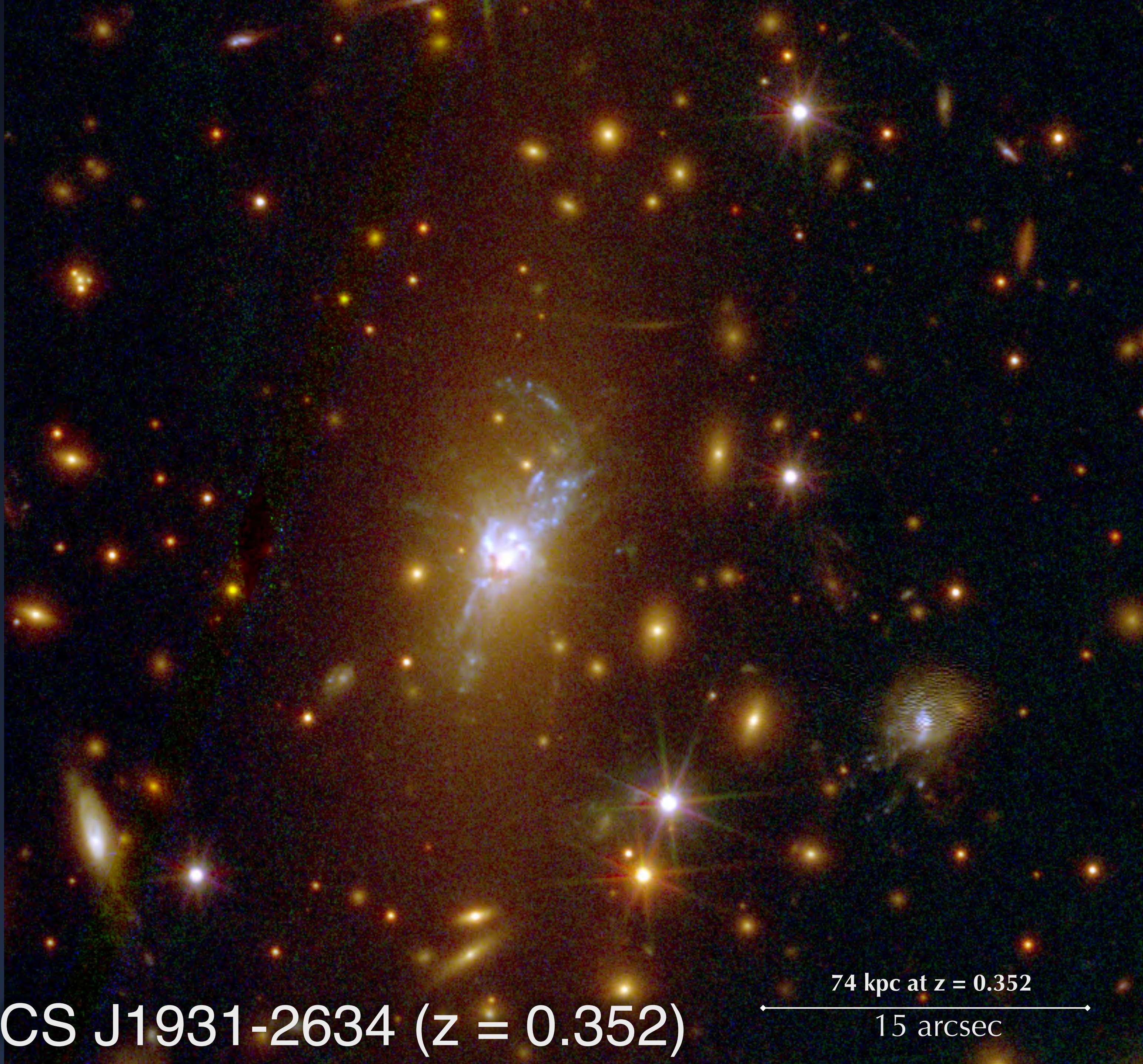





X-ray images of the 25 CLASH clusters. 20 are selected to be "relaxed" clusters (based on their x-ray properties only). 5 (last column) are selected specifically because they are strongly lensing $\theta_E > 35''$. **All CLASH clusters have Tx > 5 keV.**



Abell 611 (z = 0.288)



MACS J1931-2634 (z = 0.352)

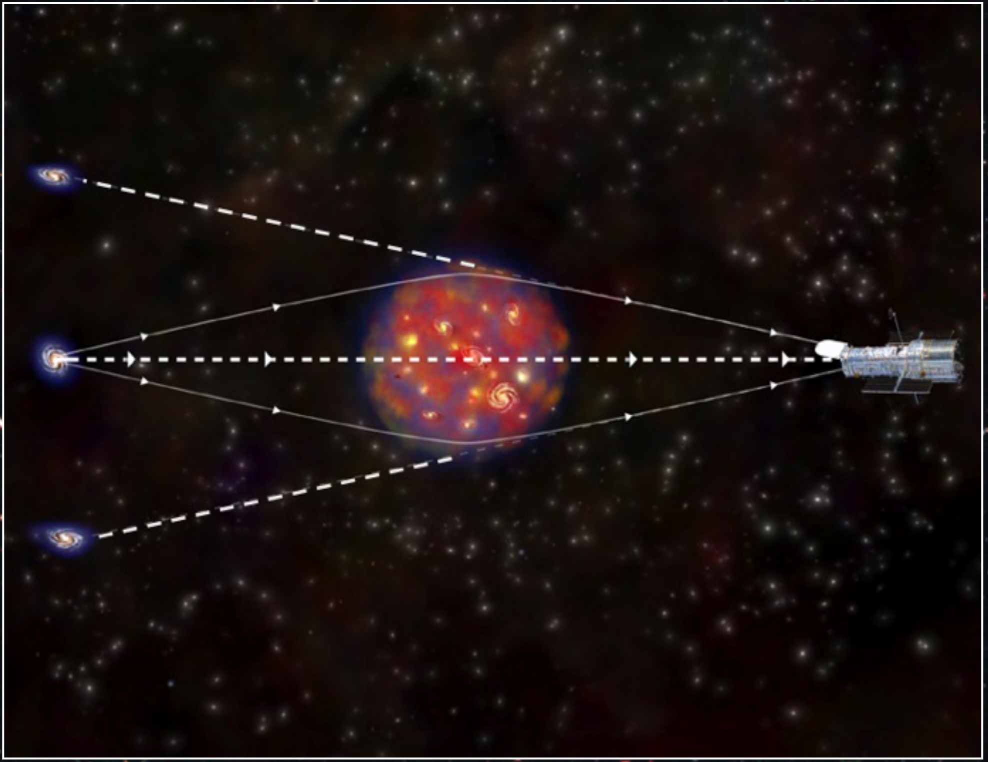
The CLASH (HST) Gallery

The final HST observation for CLASH was on 9-July-2013 … 963 days, 15 hrs, 31 min after first obs.

Galaxy Clusters as Cosmic Telescopes

Strong Lensing:

- Galaxy cluster mass density deforms local space-time.
- Pure geometrical effect with no dependence on photon energy.
- Provides large areas of high magnification ($\mu \sim 10$).
- Amplifies both galaxy flux and size while conserving surface brightness.
- Can have multiply-imaged background galaxies.



Weak Lensing:

- Beyond regions of critical mass surface density, the galaxy distortions are subtle and are only detected statistically.
- No multiply imaged sources.
- Probes large-scale mass distribution.

CLASH Clusters make HST a Super Space Telescope

HST, enhanced

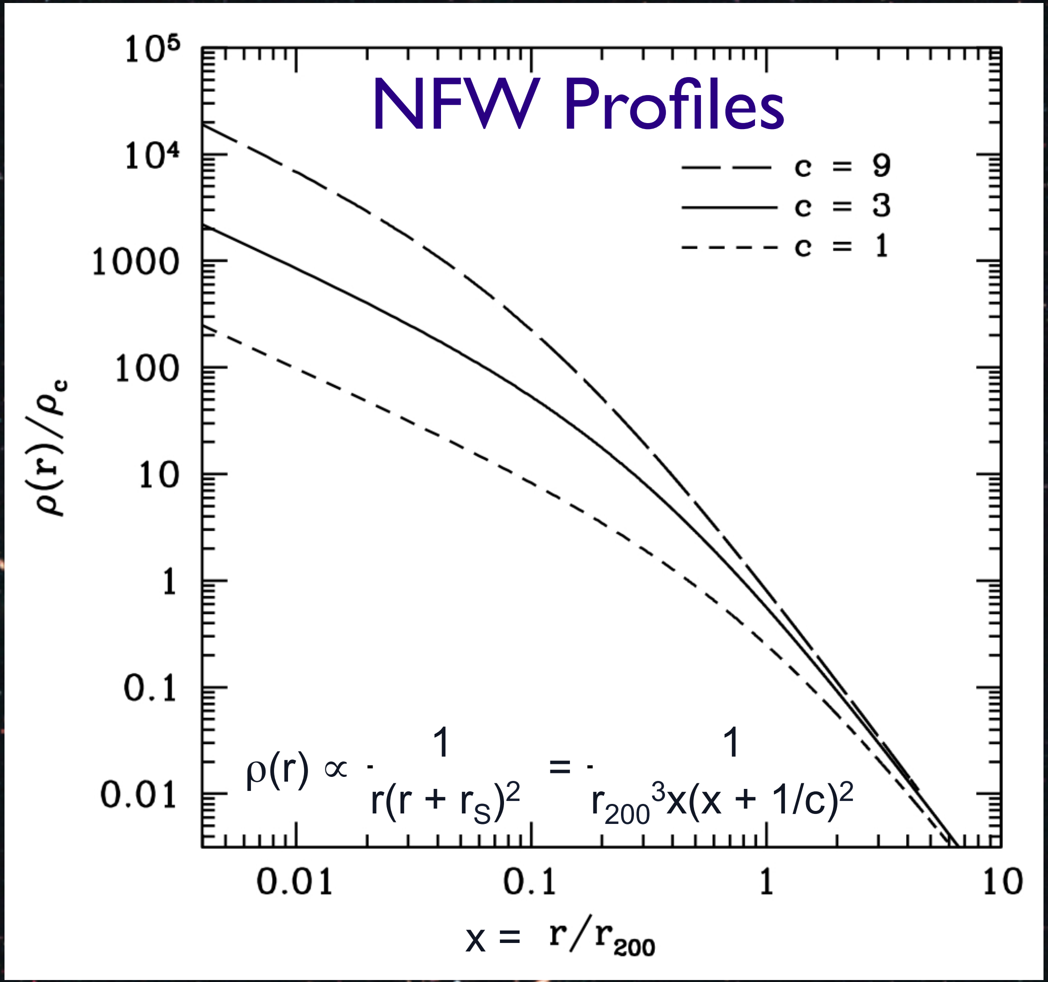
(legally)

Testing "cold" dark matter:

The matter distribution in CLASH clusters

Background: On average, all clusters are:
85% Dark Matter
13% Hot gas (x-ray)
2% Stars

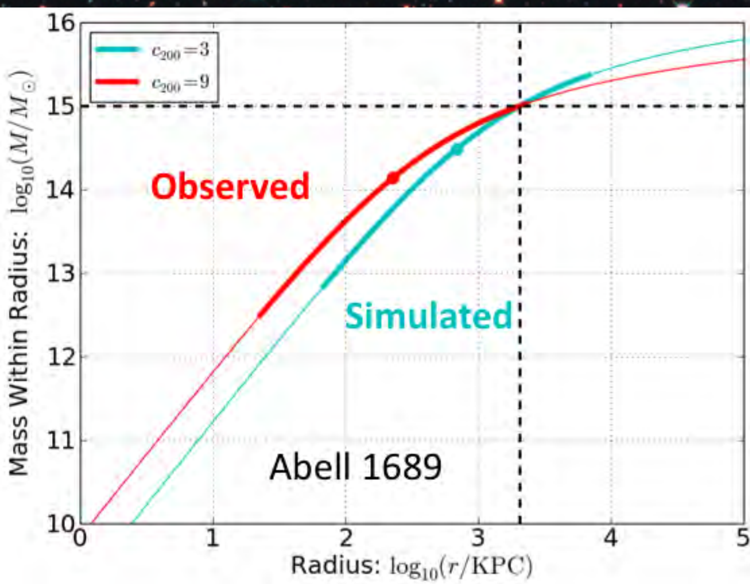
Prediction of Cold Dark Matter simulations: all mass profiles have similar shapes.

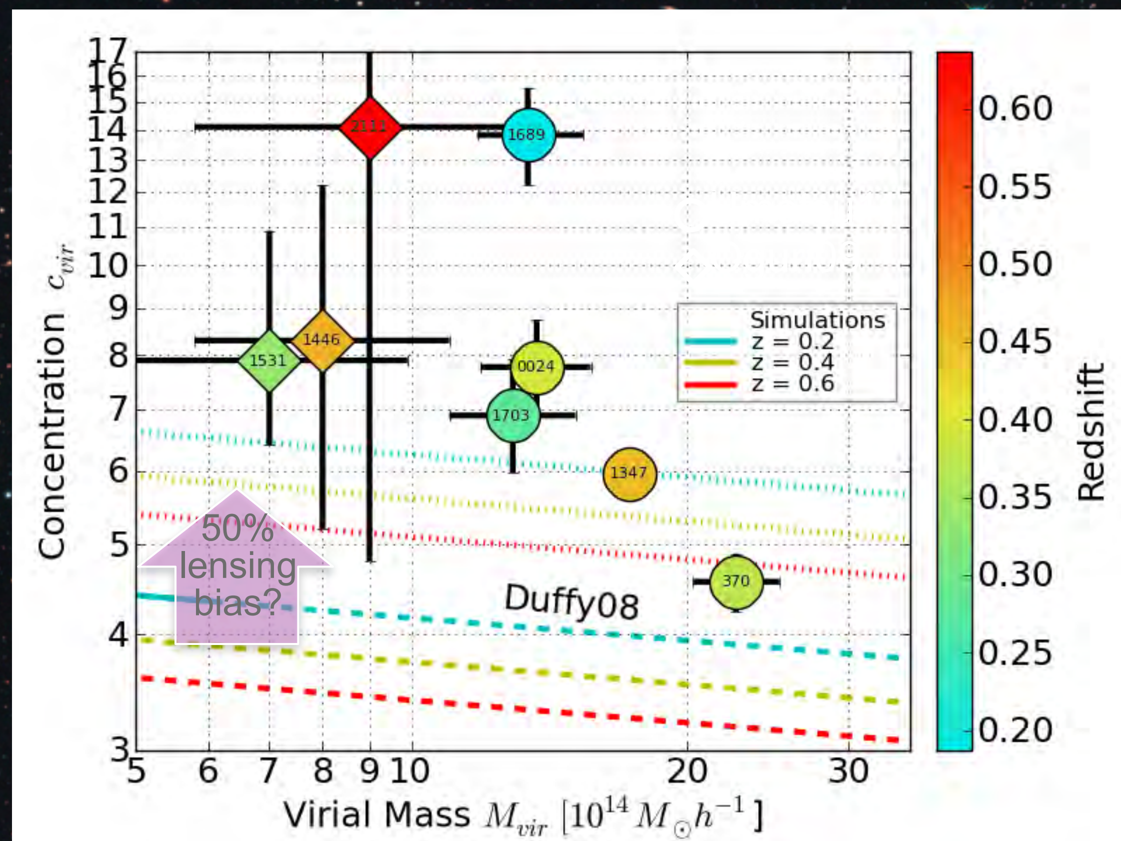


Shapes of DM halos in ΛCDM simulations all exhibit a steeper slope as radius increases with a roll-over defined by a characteristic scale or central concentration, $c = r_s/r_{virial}$

Why were the few well-studied cluster lensing mass profiles more concentrated than the mass profiles of simulated clusters?

– Broadhurst08, Oguri09, Sereno10, Zitrin11a,b



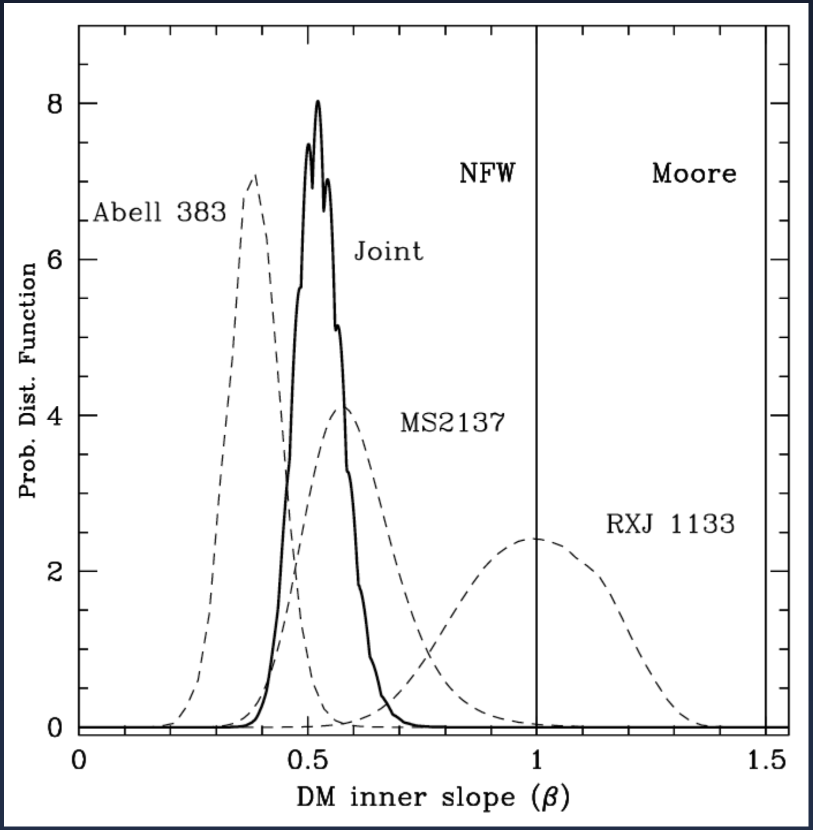


Possible explanations for high observed concentrations

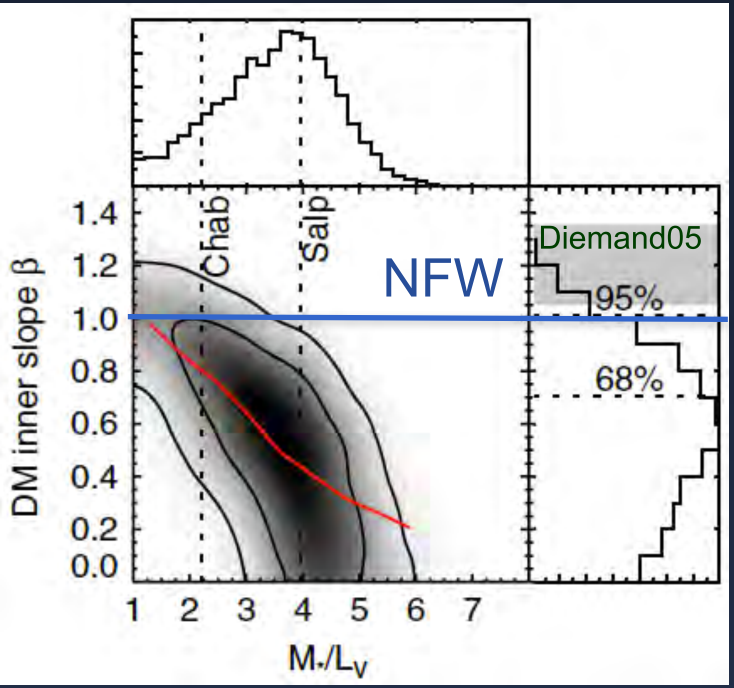
- Lensing selection sample bias.
  - 20 CLASH clusters were chosen independent of lensing appearance.
- Baryons that cool and get more concentrated.
  - Simulations that predict NFW were CDM only.
  - Simulations that include baryons differ on the degree of this effect, maybe only ~30%
- Halo Tri-axiality and Large Scale Structure
- Some fundamental problem with Lambda-CDM?

Problem 2: Well constrained cluster core DM profiles are shallower than simulated clusters

Sand et al. (2004) analyses of 6 clusters including 3 with radial arcs
- HST strong lensing
- Keck long-slit BCG spectroscopy

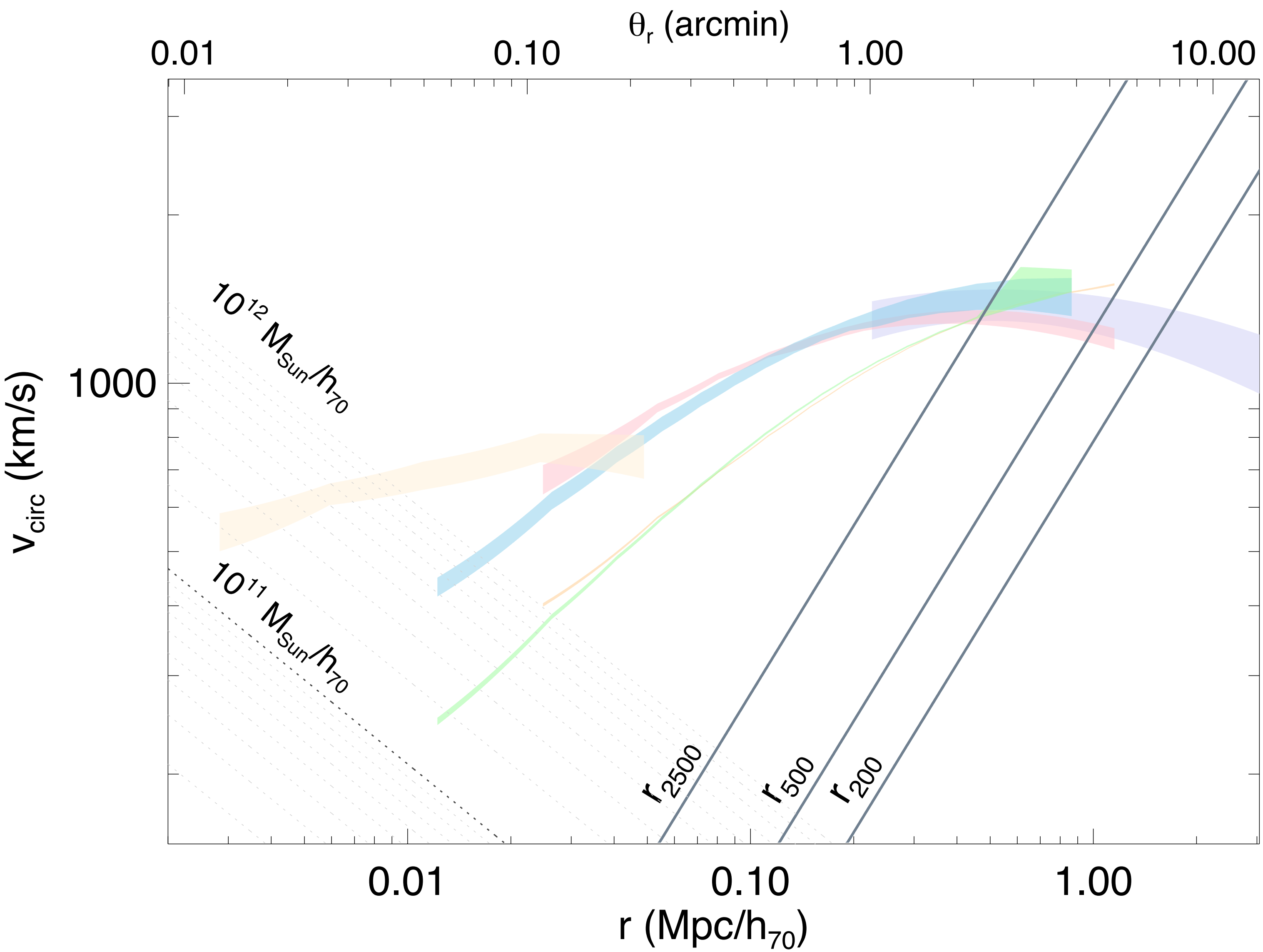


Newman et al. (2011) joint analysis of Abell 383:
- HST strong lensing
- Subaru weak lensing
- Chandra X-ray
- Keck long-slit BCG spectroscopy



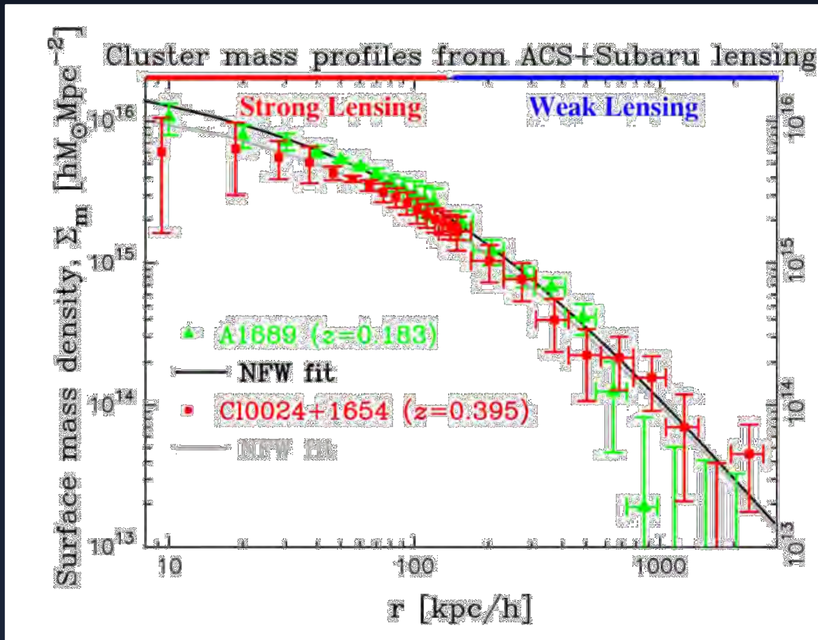
See also Gavazzi03, Sand05, Sand08, Richard09, Newman09

RXJ2129

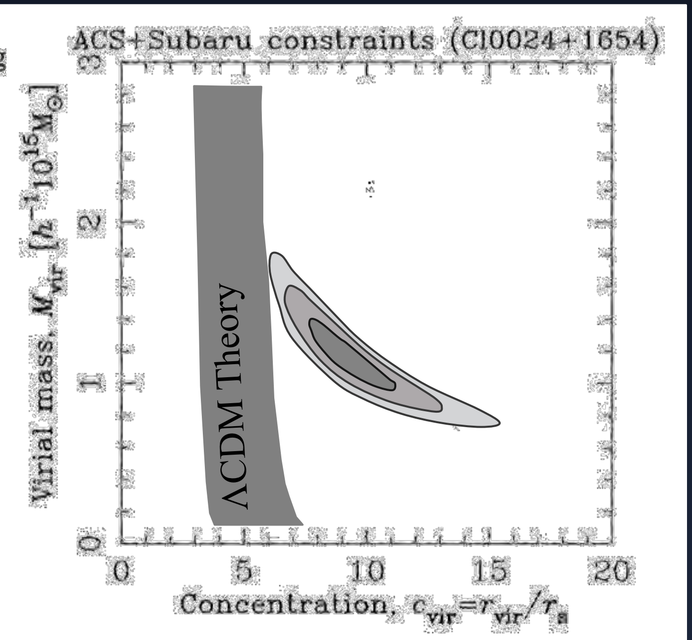


θr (arcmin)
0.01
0.10
1.00
10.00
1000
vcirc (km/s)
10^12 MSun/h70
10^11 MSun/h70
r2500
r500
r200
0.01
0.10
1.00
r (Mpc/h70)

Both Strong & Weak Lensing Measurements Needed for Good Constraints on overall mass profile



Umetsu et al. 2010



LCDM prediction from Duffy et al. 2008

CLASH provides:

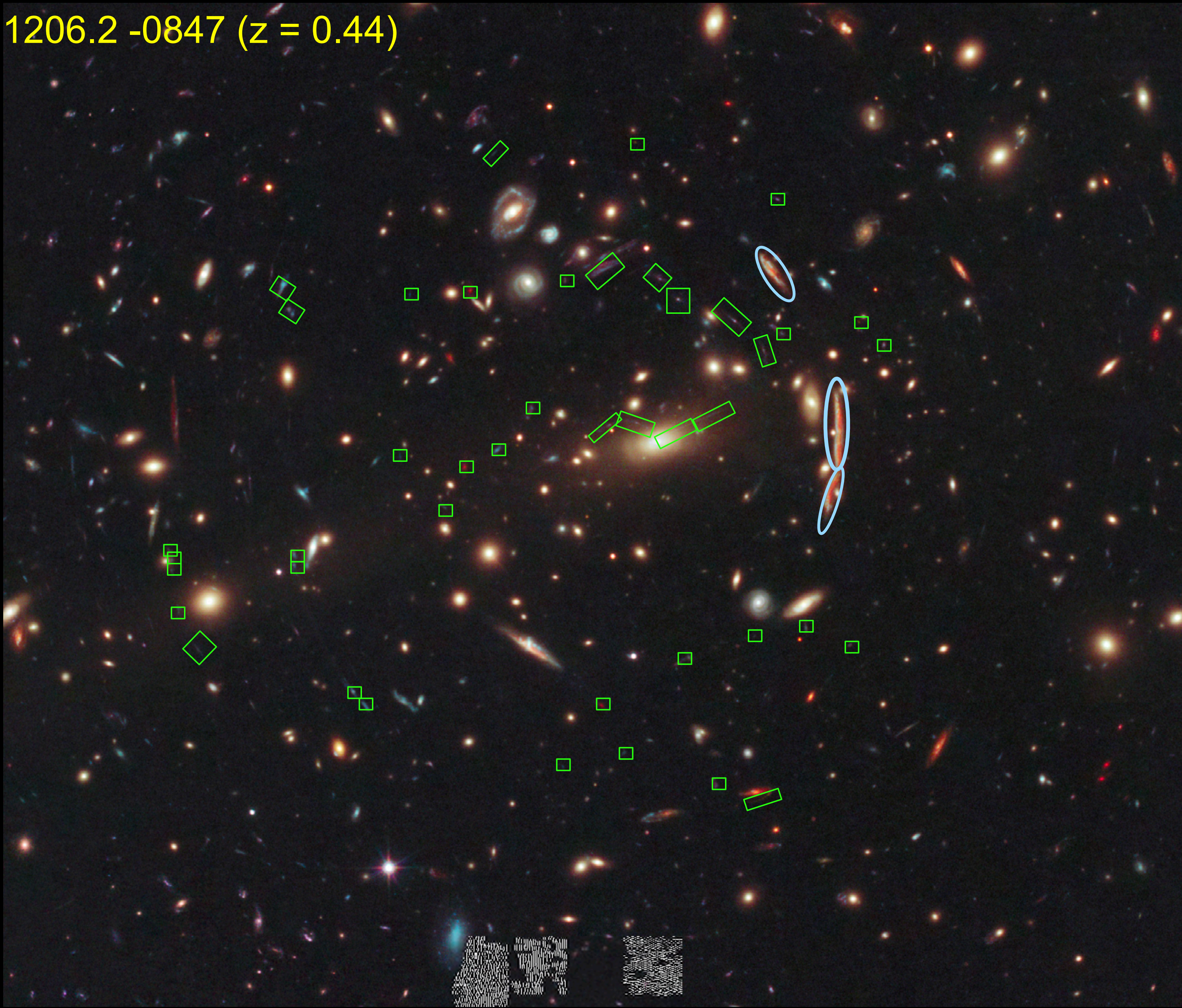
- Three independent lensing constraints with HST: SL, WL, mag bias
- Well-selected cluster sample with minimal lensing bias
- Definitive constraints on the representative equilibrium mass profile shape
- Robust measurement of cluster DM concentrations and their dispersion as a function of cluster mass (and possibly their redshift evolution).
- Excellent mass census of gas, stars AND dark matter for clusters (including dynamical, lensing, x-ray, and SZE for nearly all 25 clusters)

MACS J1206.2 -0847 (z = 0.44)

Previously known multiple images from a lensed galaxy at z=1.03 (Ebeling et al. 2009)

47 newly discovered multiple images from 12 distant lensed objects in CLASH image spanning range: 1.1 < z < 5.8

(Zitrin et al. 2012)

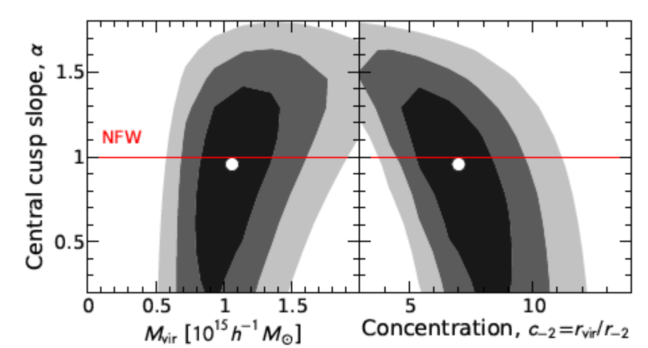


Full 2D Mass Reconstructions:

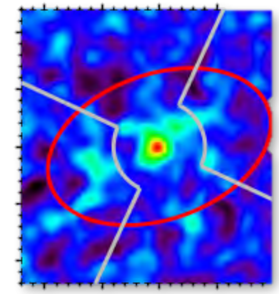
• Such reconstructions have only been applied to single clusters with different combinations of data (e.g., Merten: A2744; Bradac: Bullet Cluster, MACSJ 0025)

• Now >20 CLASH clusters are analyzed with uniform data quality and reconstruction parameters.

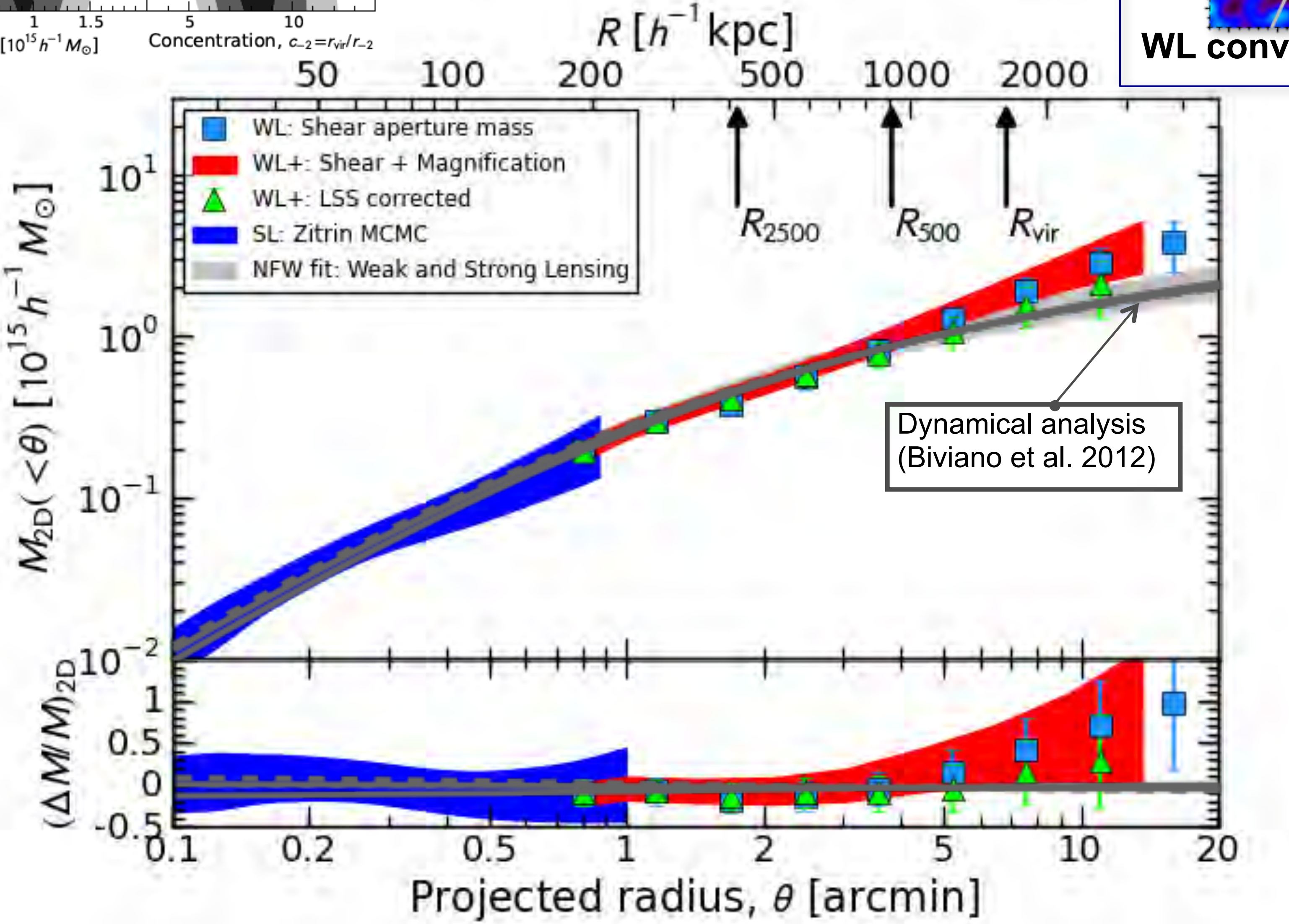
• Each mass model set consists of 2,000 bootstrap



MACS1206 (z=0.45)
Total mass profile from completely independent methods



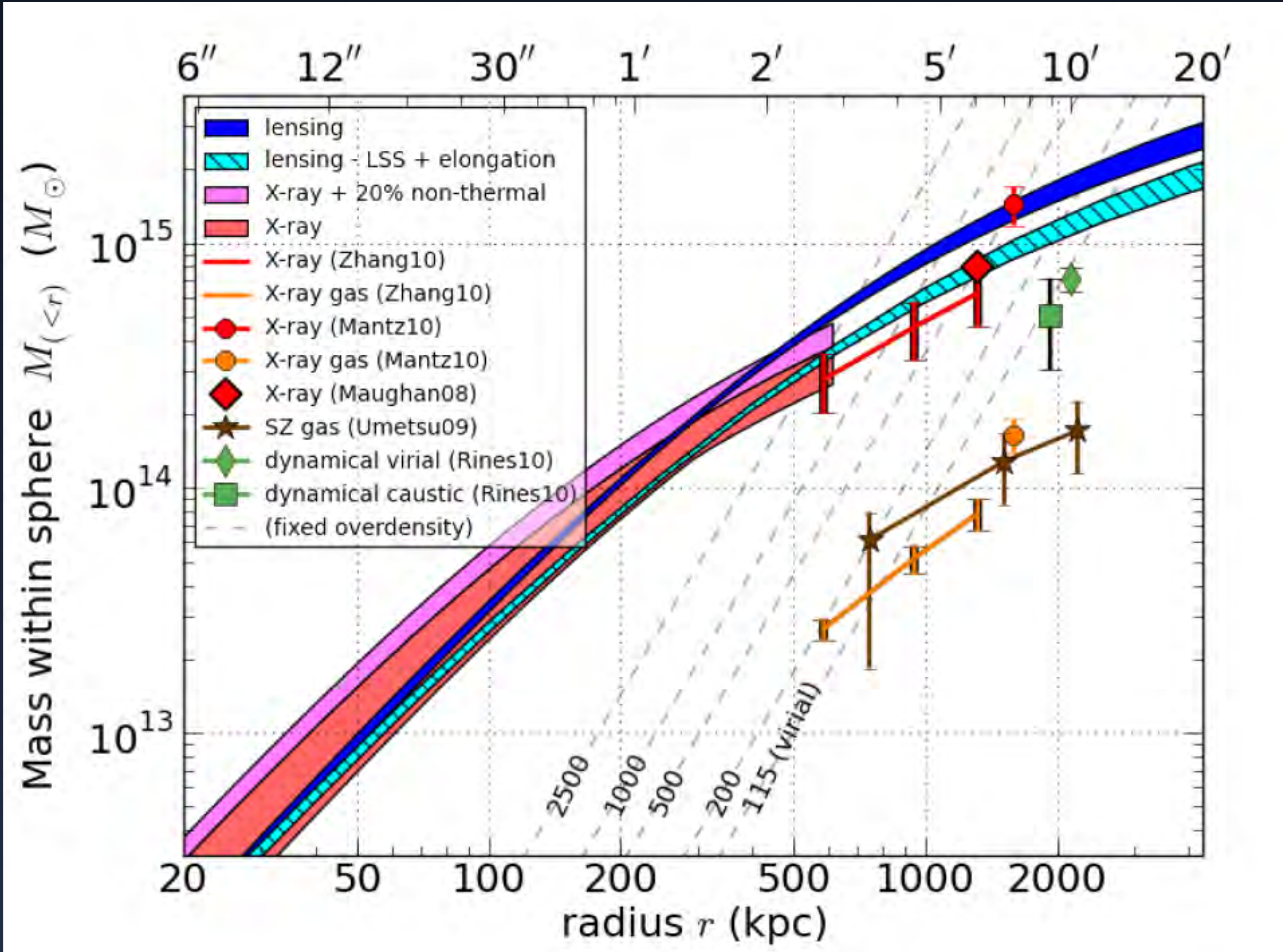
WL convergence



(Umetsu et al. 2012; Biviano et al. 2013)

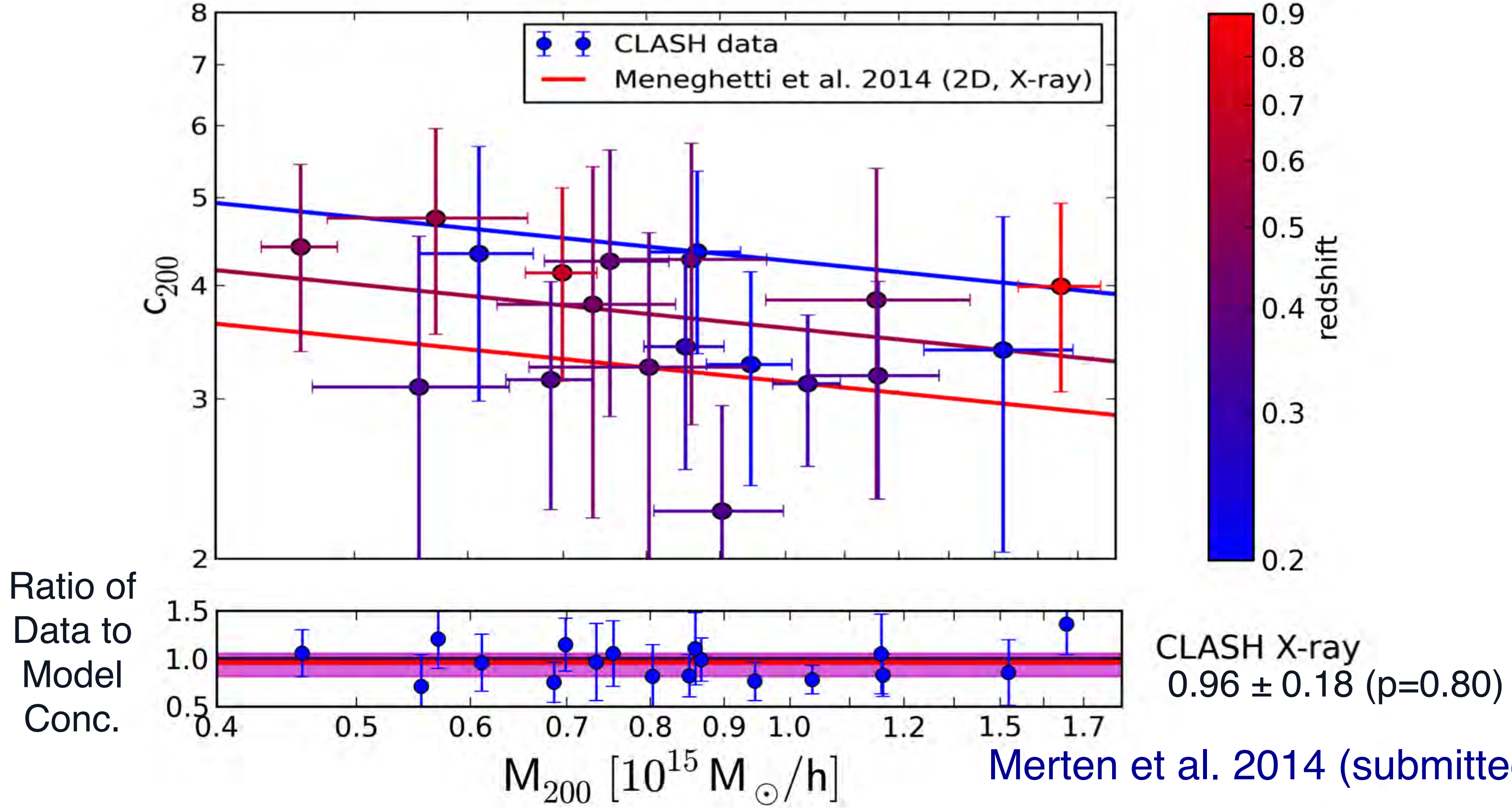
Abell 2261 (z=0.225)

Coe et al. 2012



CLASH Mass-Concentration Relation

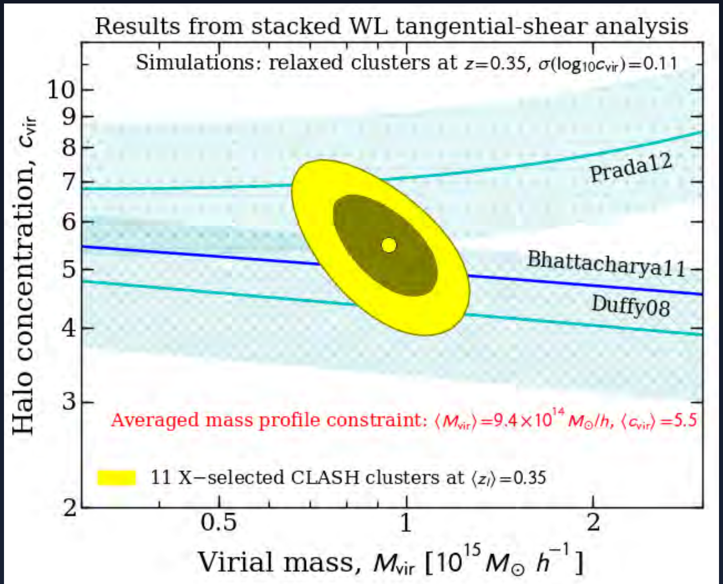
Meneghetti+14 are from Multi-DARK simulations + more gas physics

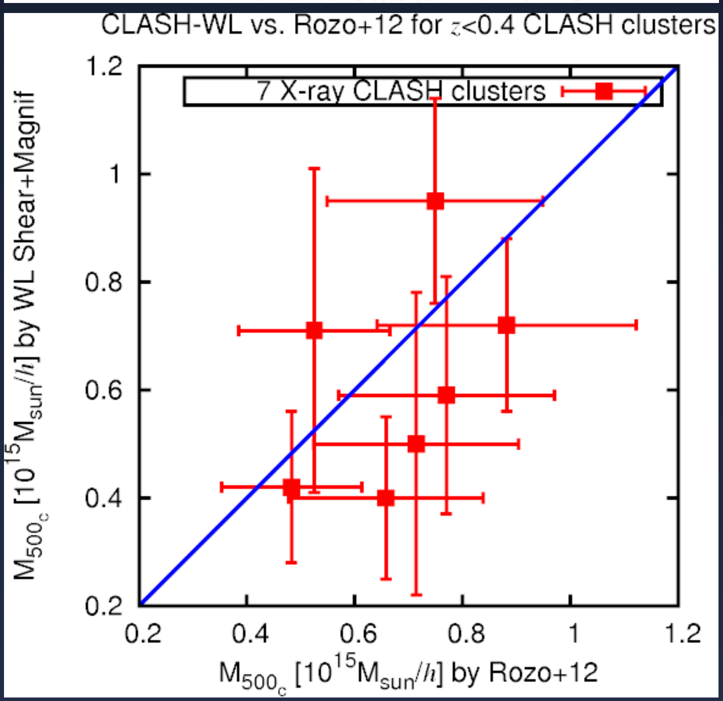


Merten et al. 2014 (submitted)

Tension between previous data and predictions largely a sample selection effect. CLASH M-c relation is fully consistent with LCDM.

Stacked Weak Lensing Analysis





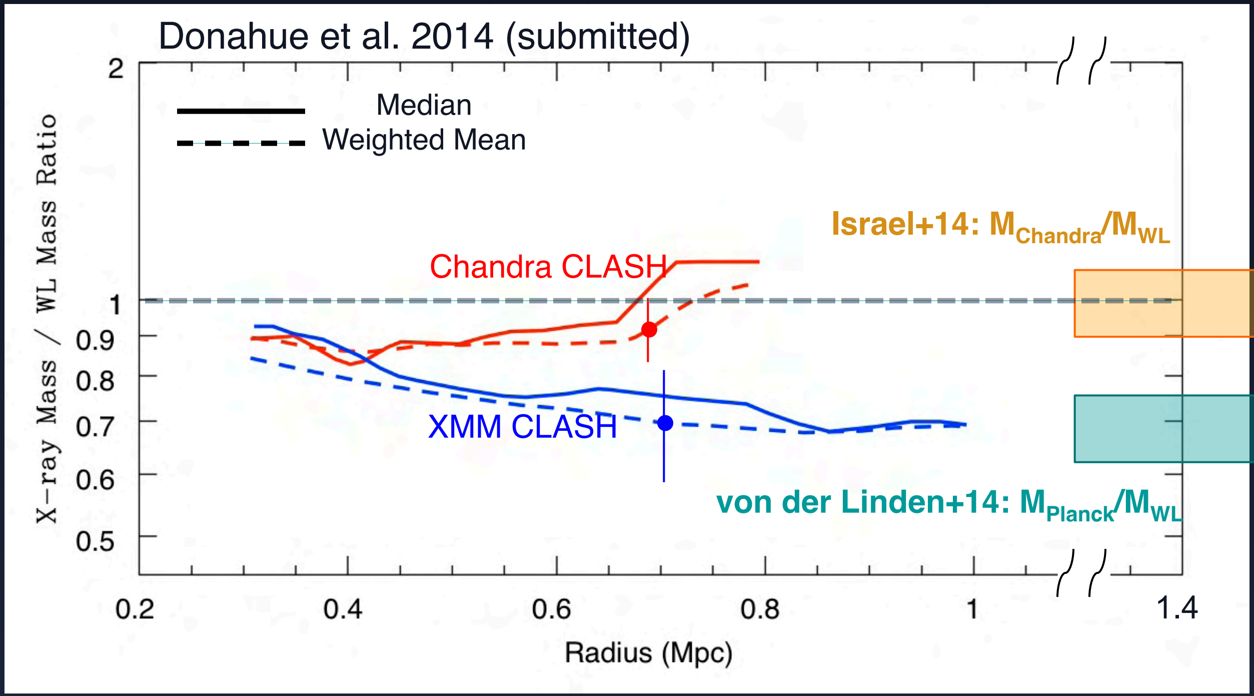
Umetsu et al., 2014, submitted

$\Delta M/M \sim 0.35$ at R500
$\Delta M/M \sim 0.20$ at R200

Calibrating X-ray Mass Profiles

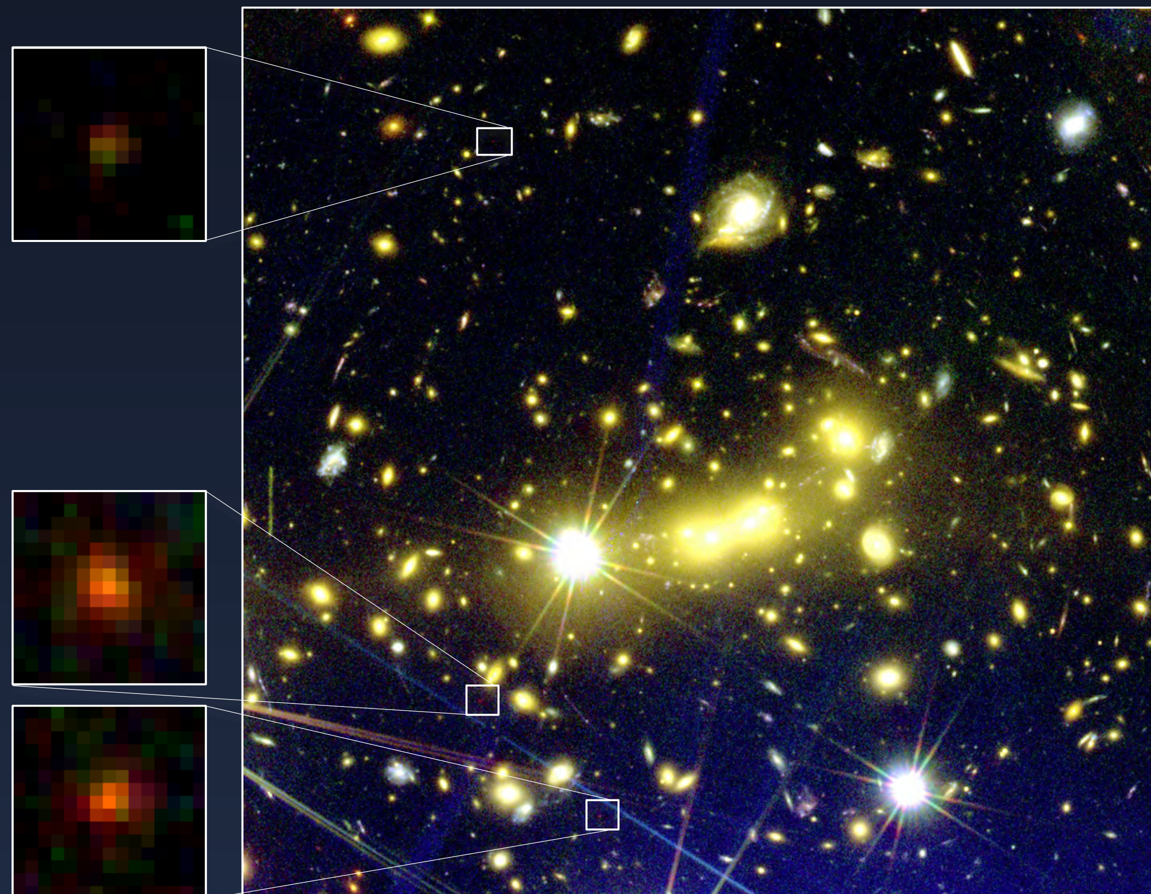
$$\frac{dP_{gas}}{dr} = -\rho_{gas}(r)\frac{GM_{tot}}{r^2}$$

HSE = Hydrostatic Equilibrium



- A systematic difference between XMM and Chandra HSE mass to WL mass ratios exists even after the most recent calibration and PSF corrections are applied.
- These results have implications for resolving the discrepancy between Planck cluster counts and the number of clusters predicted based on Planck CMB cosmological parameters.

Two of the Most Distant Galaxies Known



z = 9.6 object in MACSJ1149+2223

Zheng et al. 2012, Nature, 489, 406

z = 10.8 object in MACSJ0647+7015

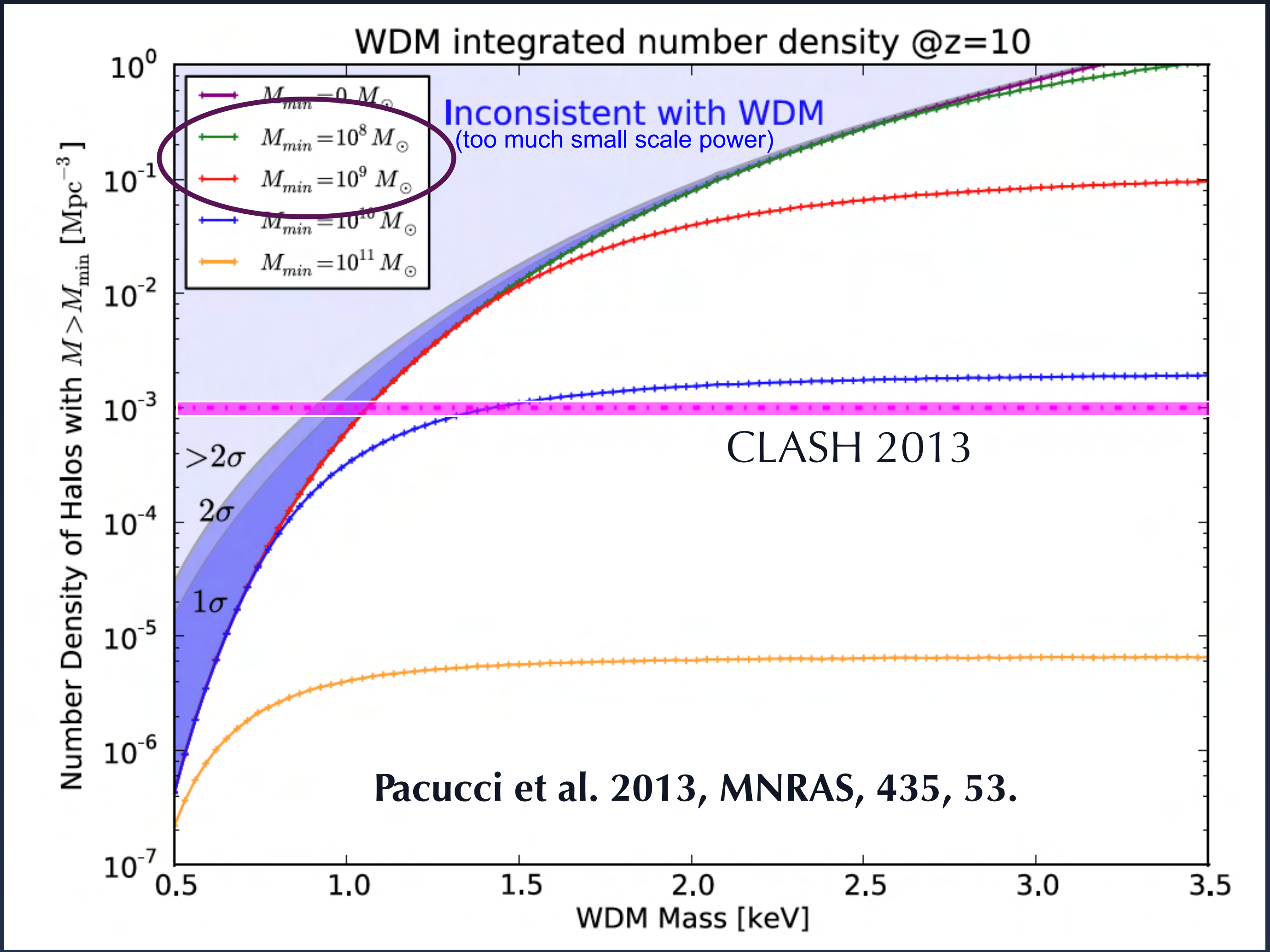
Coe et al. 2013, ApJ, 762, 32

Using CLASH Lensed Galaxies can Constrain Dark Matter Properties

- Finding structures in the early universe places a constraint on the mass of a putative warm dark matter particle.
- Warm Dark Matter (WDM) is a relativistic particle whose mass is expected to be inversely proportional to its free streaming length.

Independent constraint on the nature of DM

- WDM particle mass $m_X > 1.0$ (0.9) keV at 68% (95%)
  - Limit depends only on WDM halo mass function, not on astrophysical modeling.



Pacucci+13: "Even a few galaxies found in such small volumes require a very high number density of collapsed dark matter (DM) haloes. This implies significant primordial power on small scales, allowing these observations to rule out popular alternatives to standard cold dark matter (CDM) models, such as warm dark matter (WDM)."

Summary

- CLASH is making many new and exciting discoveries. Over 50 refereed papers have been published / submitted based on or inspired by CLASH data.
- Joint SL+WL producing precise measurements of mass concentrations. X-ray selection criteria important for unbiased test of LCDM.
- Providing our first look at "JWST's Universe" – the epoch when the Universe was < 500 Myr old.
- Enables new independent constraints on WDM particle mass and DM EoS (pressureless DM is consistent with observational constraints).
- Providing superb mass calibrators for larger cluster surveys:
  - WL + SL + X-ray + SZE + Dynamics
- Plus more science (high redshift galaxies, supernovae, massive galaxy science) than I can discuss in 1 hour!
- The survey is complete. Co-added images available for public download at the STScI MAST website. Mass models are also available.