Merging Galaxy Clusters as Dark Matter Colliders

David Wittman

University of California, Davis & Instituto de Astrofísica, Lisbon

with Will Dawson (LLNL), **Nate Golovich**, **Karen Ng**, **Bryant Benson**, James Jee & Maruša Bradač (UC Davis), Annika Peter (Ohio State), Julian Merten (Caltech/JPL), Reinout van Weeren (CfA), Andra Stroe (Leiden), David Sobral (U. Lisbon), Marcus Brüggen (Hamburg), James Bullock & Manoj Kaplinghat (UC Irvine)

MERGING CLUSTER COLLABORATION

Galaxy Clusters: More Than Meets the Eye

By mass:

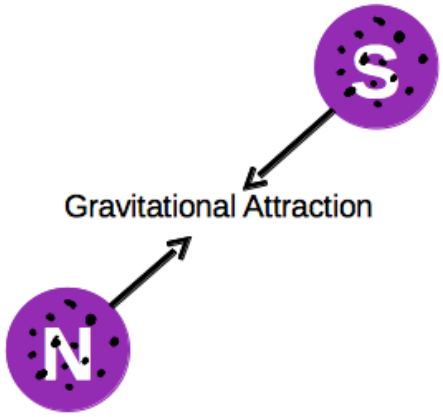
- 3% galaxies
- 15% gas

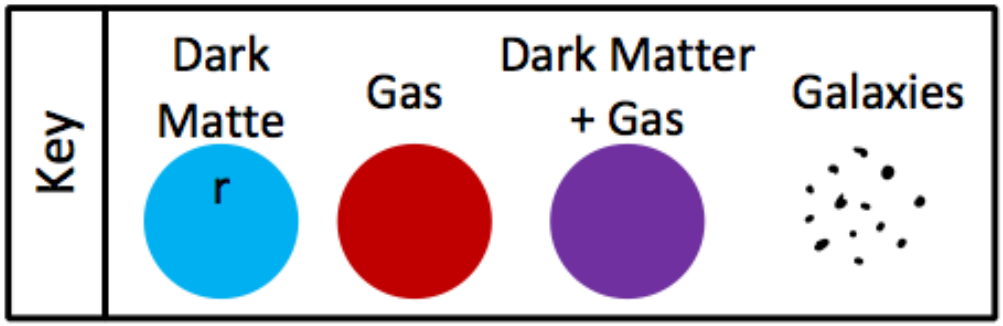
Galaxy Clusters: More Than Meets the Eye

By mass:

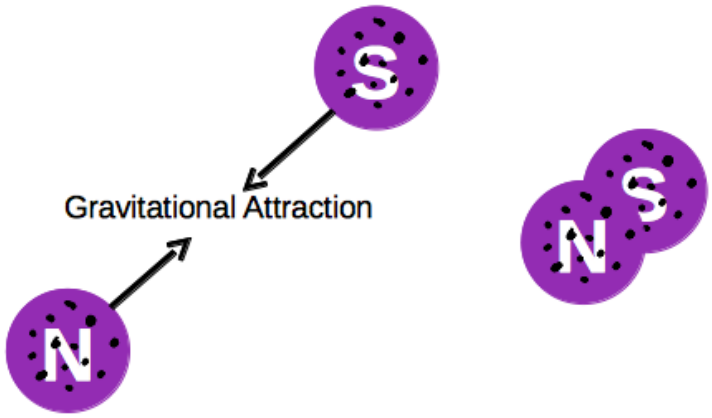
- 3% galaxies
- 15% gas
- 82% dark matter

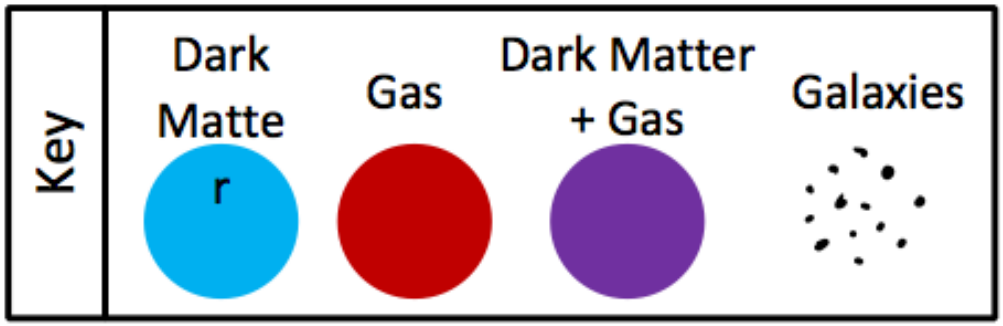
Anatomy of a Merger



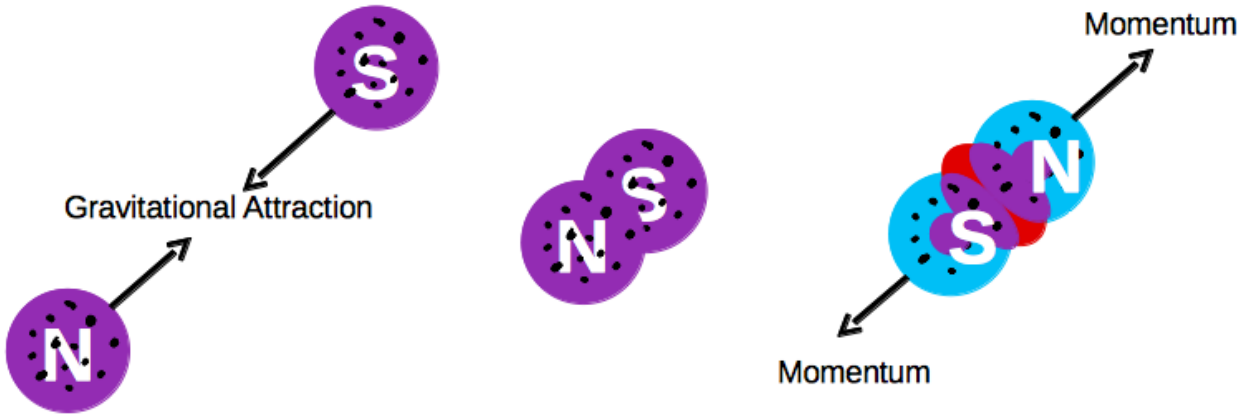


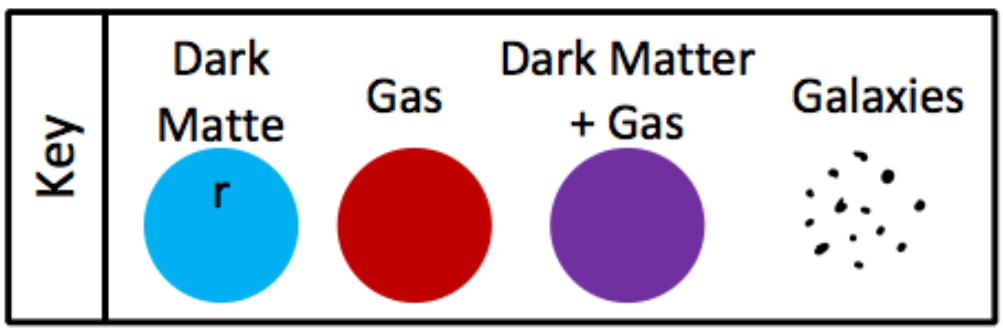
Anatomy of a Merger



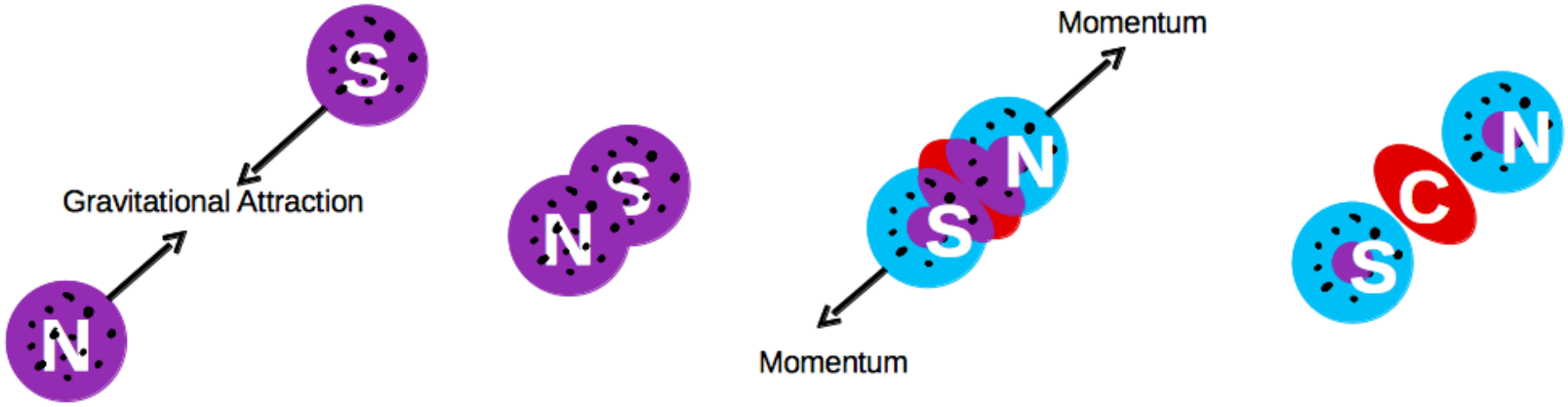


Anatomy of a Merger

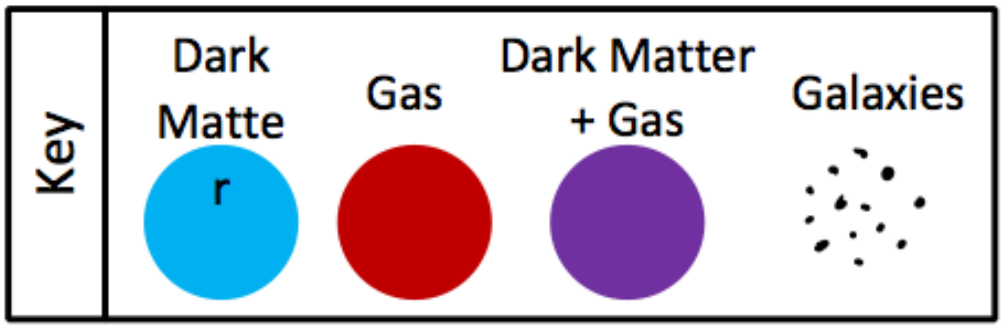




Anatomy of a Merger



a *dissociative* merger

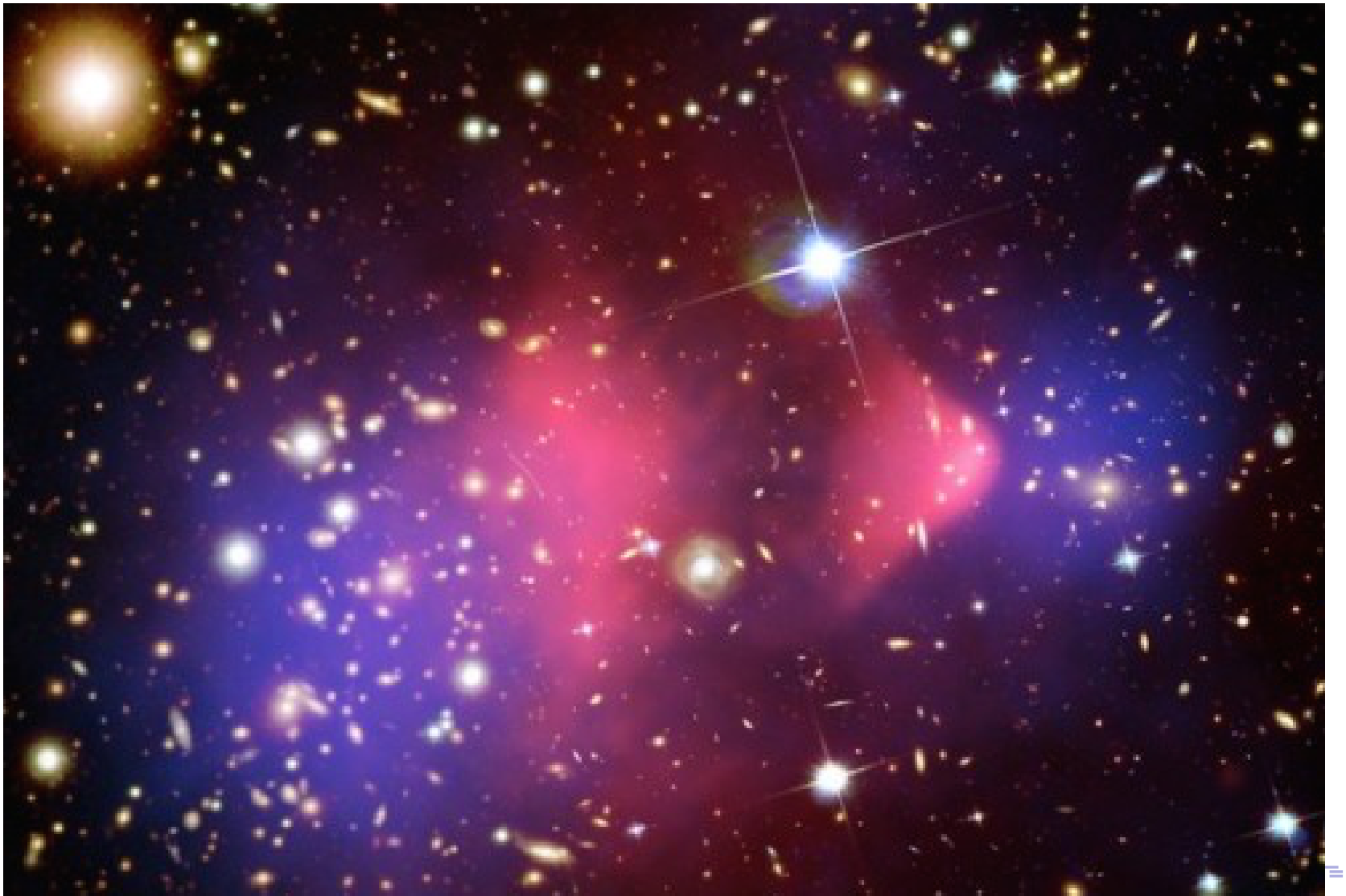


A long time ago in a galaxy cluster
far, far away....

Bullet Cluster

Clowe et al (2006): "A direct empirical proof of the existence of dark matter"

gas (from X-rays); mass (from grav. lensing)



This Is a Dark Matter Collider!

Markevitch et al (2004): ways to limit σ_{SIDM}:

- DM-gas offset
- high velocity of the subcluster
- M/L of subclusters is typical for its redshift
- (DM not displaced from galaxies)

Bottom line: $\sigma_{SIDM} \lesssim 1$ cm^2 gm^{-1} (~ 2 barn/GeV)

Wait, barn/GeV?

Amazingly, DM could self-interact this strongly and still escape detection (to date).

Astrophysics is well-suited to constrain *self*-interactions.[1]

[1] Add another Feynman diagram to your introductions? Coin a new phrase?

Astrophysical hints that $\sigma_{SIDM} \sim 0.1 - 0.5$

- dwarf spheroidal galaxies (dSph) around the Milky Way have much lower central density than predicted by CDM (Boylan-Kolchin et al 2012, Rocha et al 2012)
- stellar kinematics in low surface brightness (LSB) and dwarf galaxies indicate cores rather than cusps (Simon et al 2005; Kuzio de Naray et al 2008; Oh et al 2011, Rocha et al 2012)
- massive galaxy clusters have central density profiles (Newman et al 2012) and ellipticities (Richard et al 2010) more consistent with $\sigma_{SIDM} \sim 0.1 - 0.5$ than with CDM

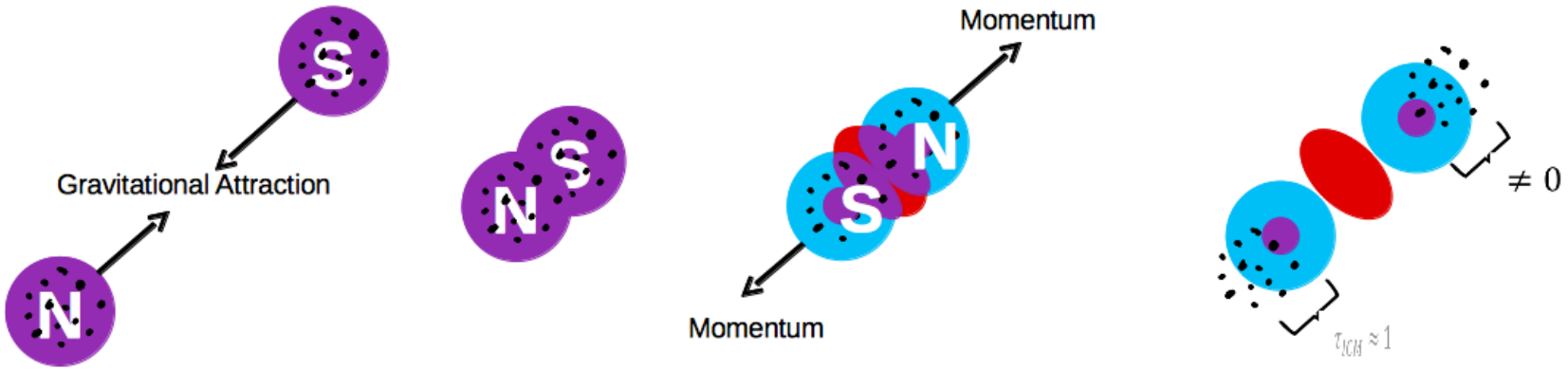
Astrophysical hints that $\sigma_{SIDM} \sim 0.1 - 0.5$

- dwarf spheroidal galaxies (dSph) around the Milky Way have much lower central density than predicted by CDM (Boylan-Kolchin et al 2012, Rocha et al 2012)
- stellar kinematics in low surface brightness (LSB) and dwarf galaxies indicate cores rather than cusps (Simon et al 2005; Kuzio de Naray et al 2008; Oh et al 2011, Rocha et al 2012)
- massive galaxy clusters have central density profiles (Newman et al 2012) and ellipticities (Richard et al 2010) more consistent with $\sigma_{SIDM} \sim 0.1 - 0.5$ than with CDM

Baryonic uncertainties?
Merging clusters provide an independent probe!

Drag-force Approximation

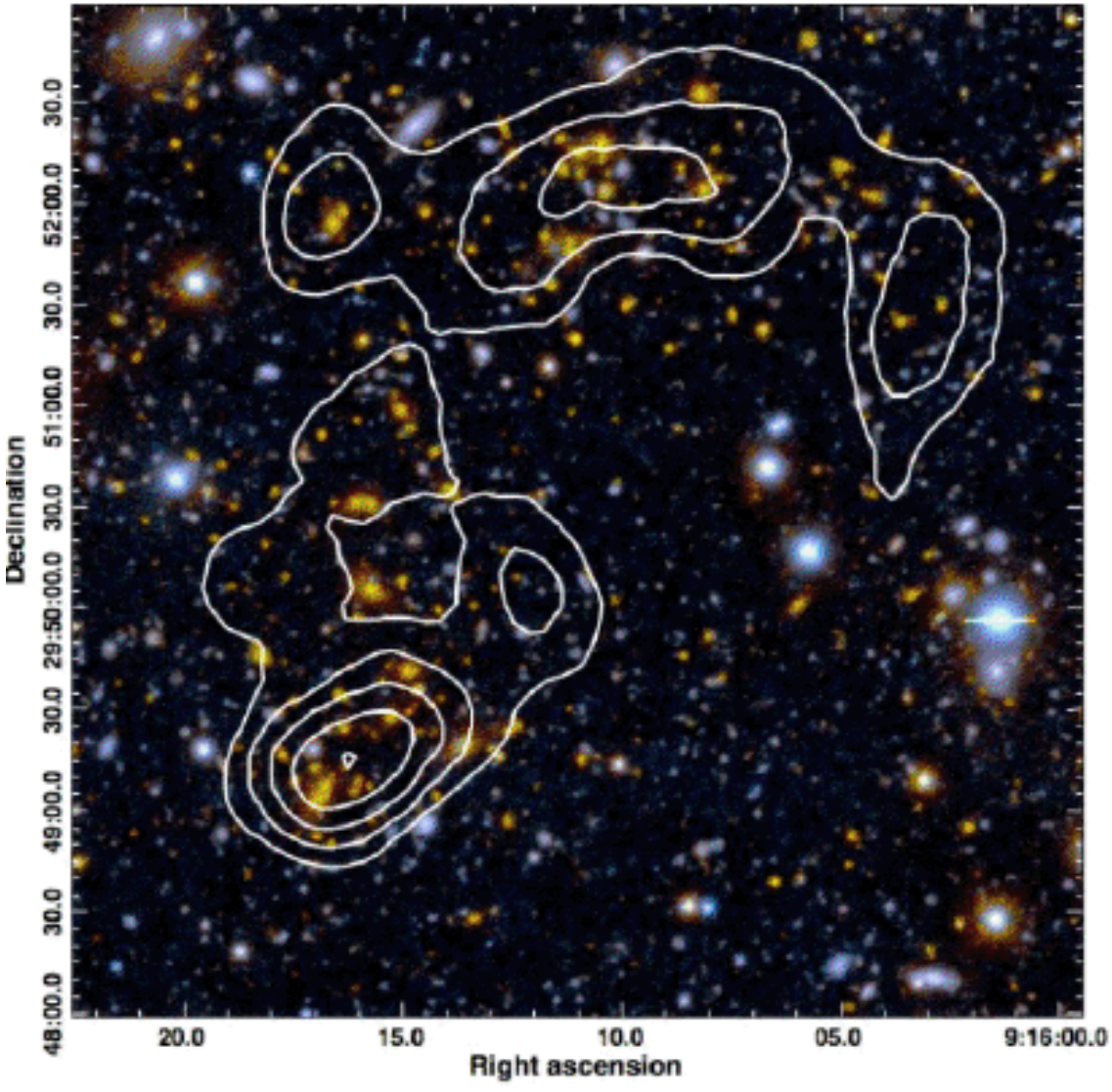
(Frequent Interactions w/Small Momentum Transfer)



Upper limit from Bullet (Randall+08, 68% CL): $\sigma_{SIDM} < 1.25$ cm^2/g.

Alternative scenario: infrequent interactions with large momentum transfer (DM particles can scatter out of halo). Upper limit from Bullet (Randall+08): $\sigma_{SIDM} < 0.7$ cm^2/g.

Musketball Cluster: Older and Slower Than the Bullet



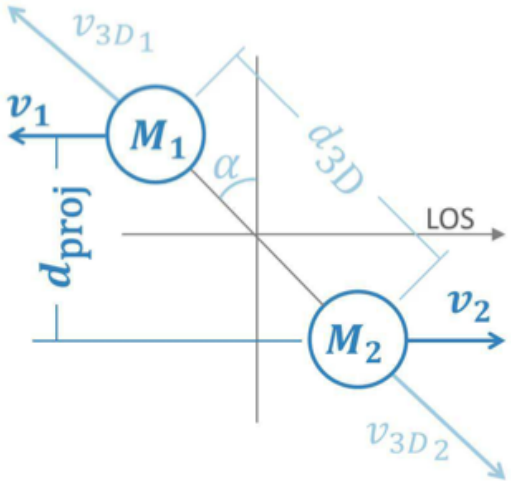
Galaxy density contours for $z_{\mathrm{phot}} \approx 0.53$

Older and Slower...How Do We Know?

Equations of motion require masses (weak lensing) and velocities (galaxy spectroscopy).

Subaru

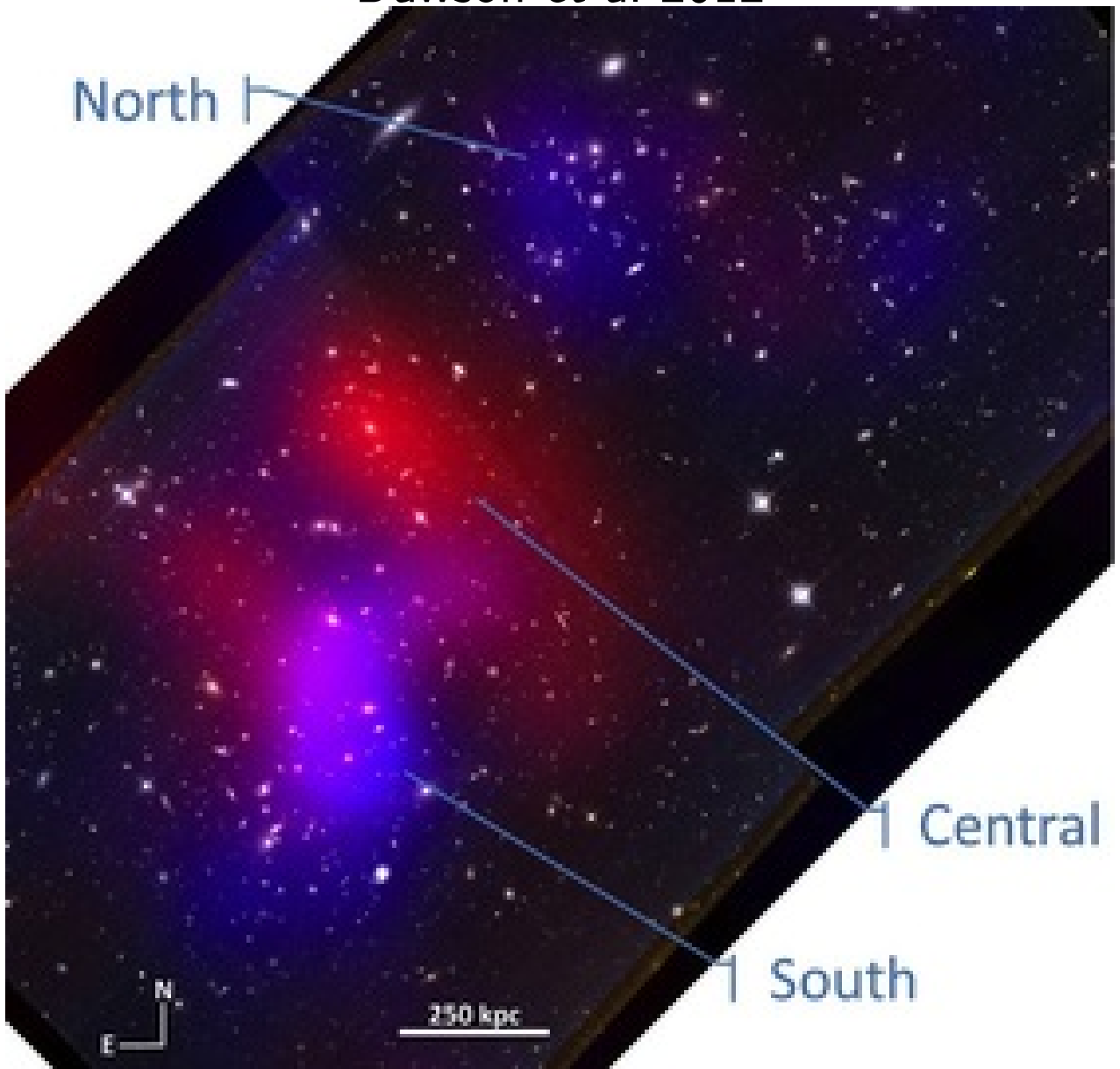
Keck/Deimos



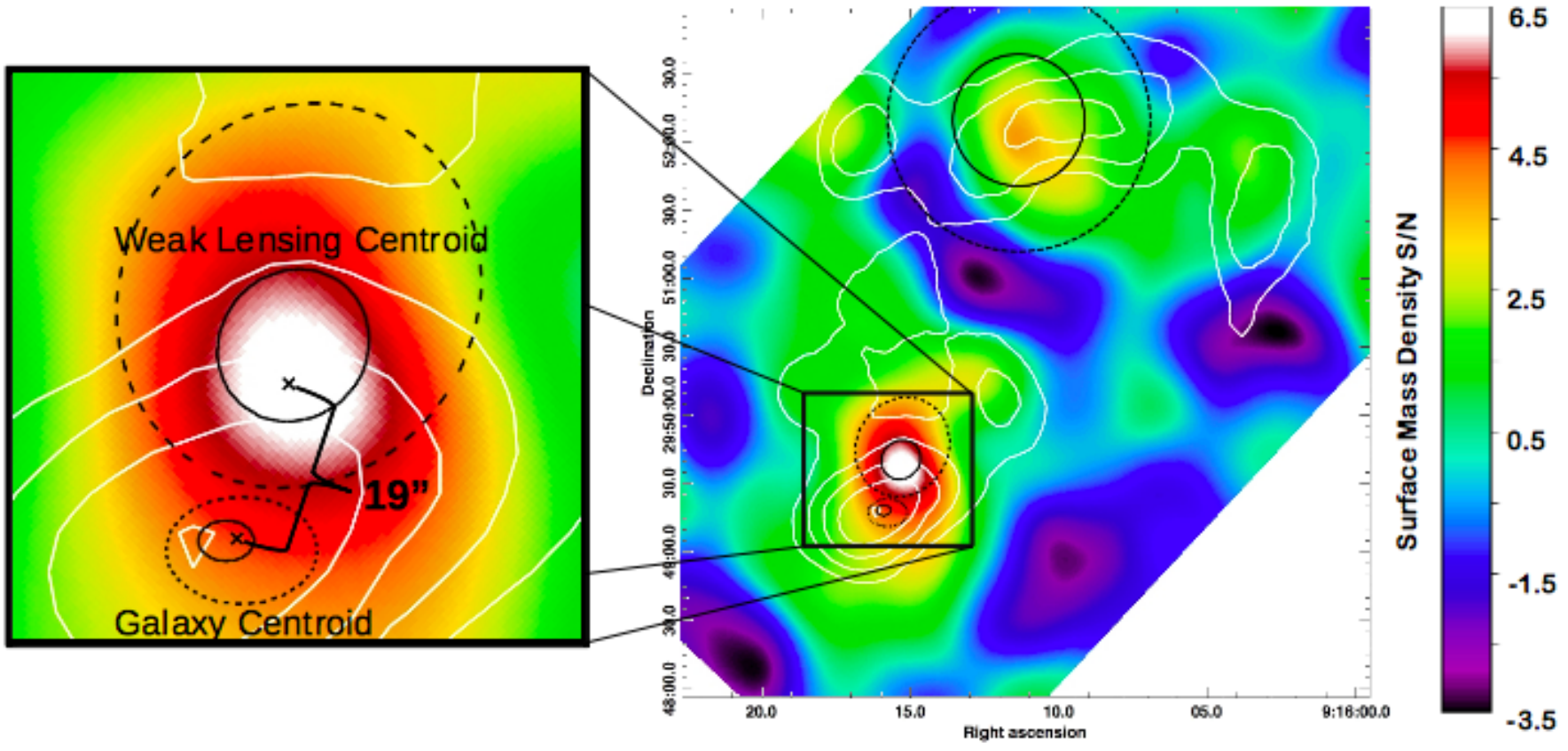
Need to constrain viewing angle and marginalize over uncertainties: Dawson arXiv:1210.0014)

Musketball: Gas Proves It's Post-pericenter

Dawson et al 2012



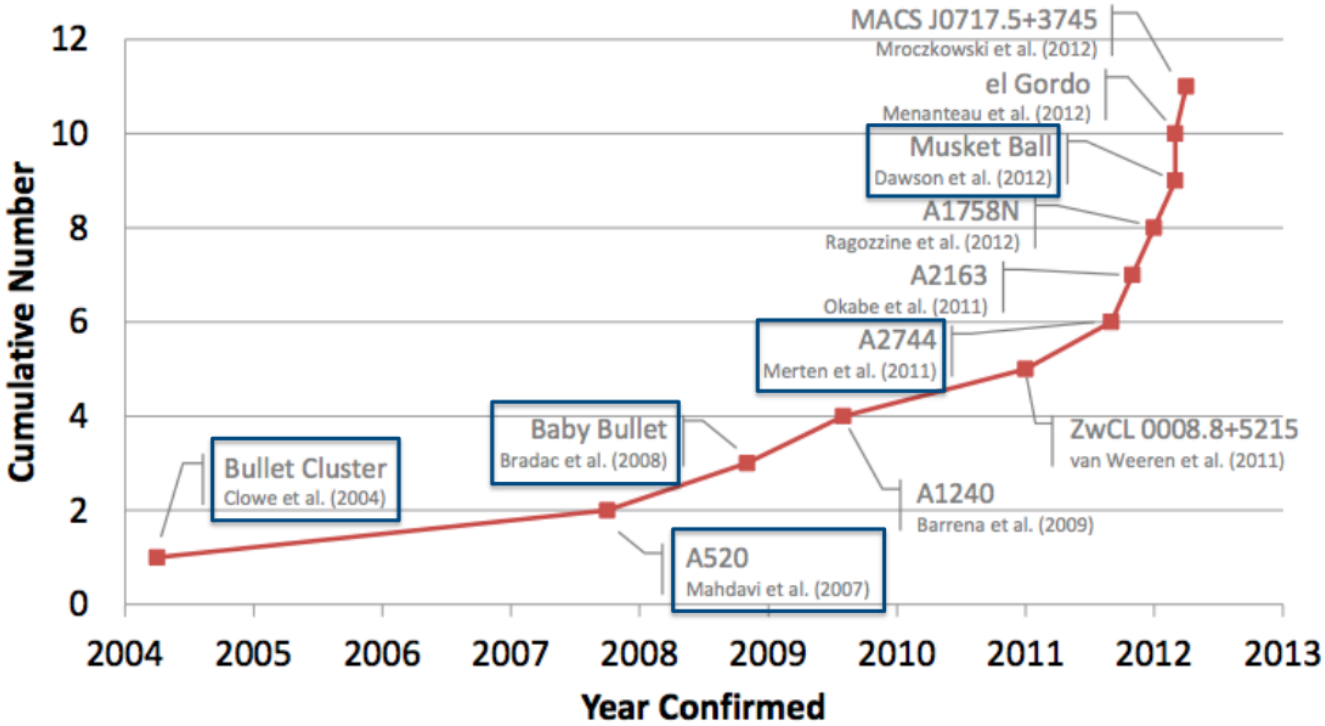
Musketball: The Drag Force Awakens?



Not highly significant, but older may be better...
or at least *different* is better

Challenges/Opportunities

- more dissociative mergers being discovered all the time
- some may be better than others at constraining SIDM
- modeling uncertainties can be substantial in a given system



Merging Cluster Collaboration

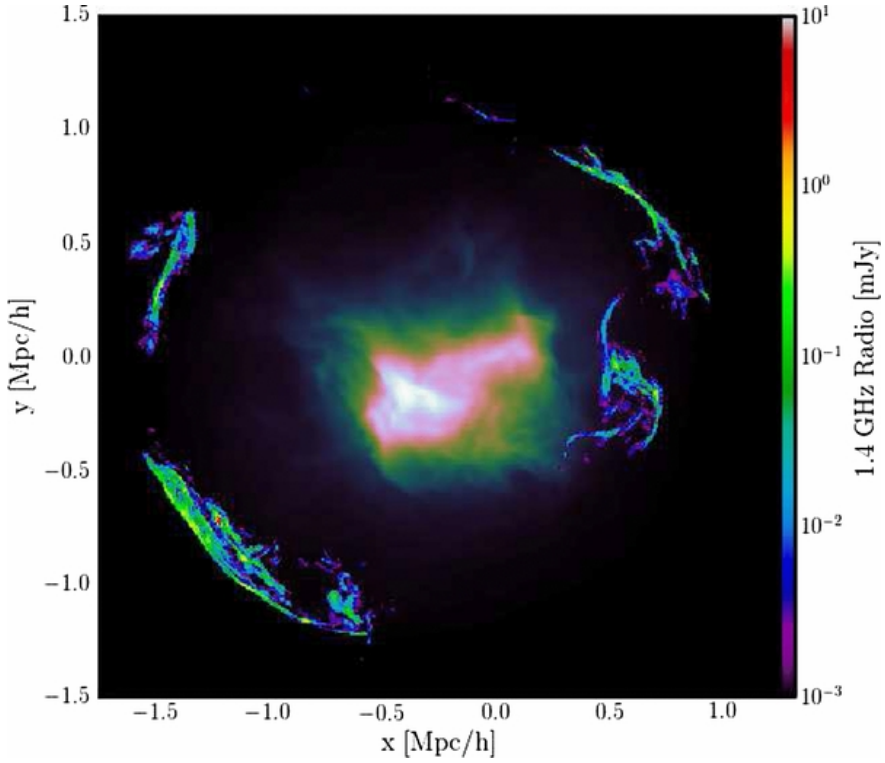
Goal: constrain σ_{SIDM} to within 0.1 $\mathrm{cm}^2\ \mathrm{gm}^{-1}$

- analyzing an *ensemble* of mergers with a range of properties
- simulating mergers much more realistically
- comparing simulations and data as directly as possible
- targeting observations to reduce modeling uncertainties
- and discovering more dissociative mergers

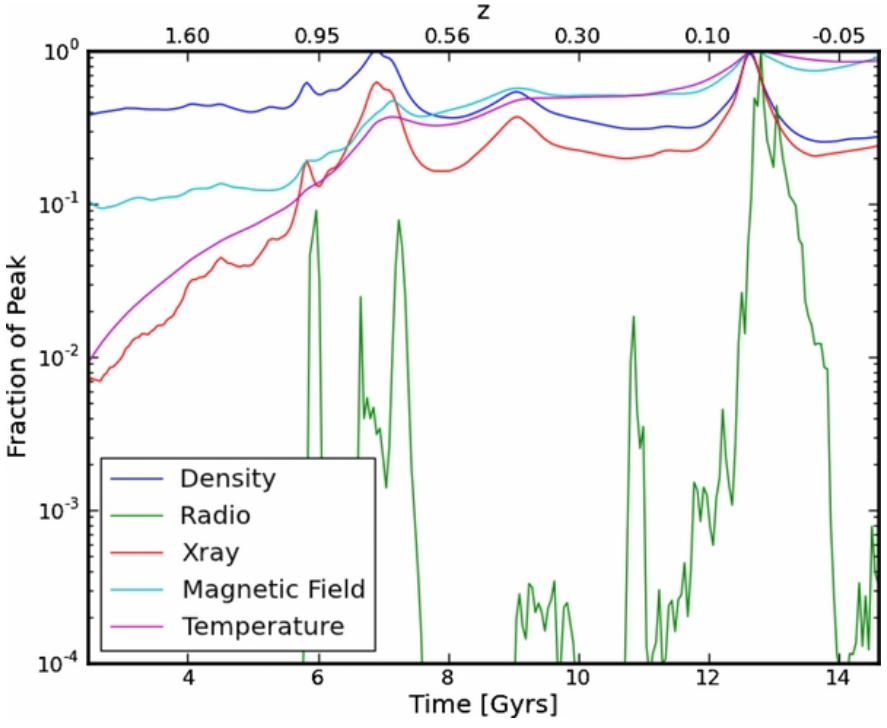
This program will discover or rule out astrophysically interesting SIDM.

A New Trigger: Radio "Relics" Mark Major Mergers

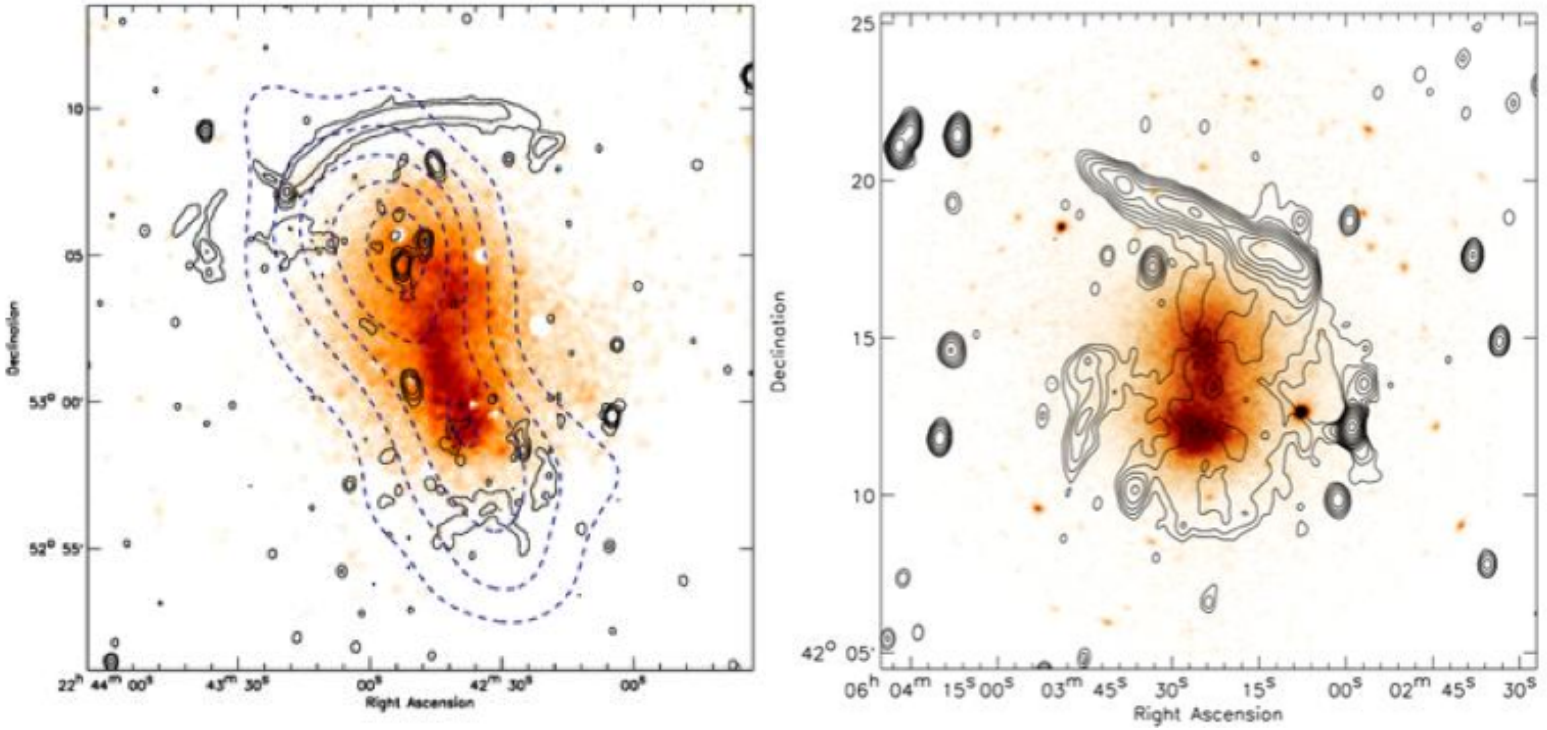
And Constrains the Viewing Geometry



Skillman+2013



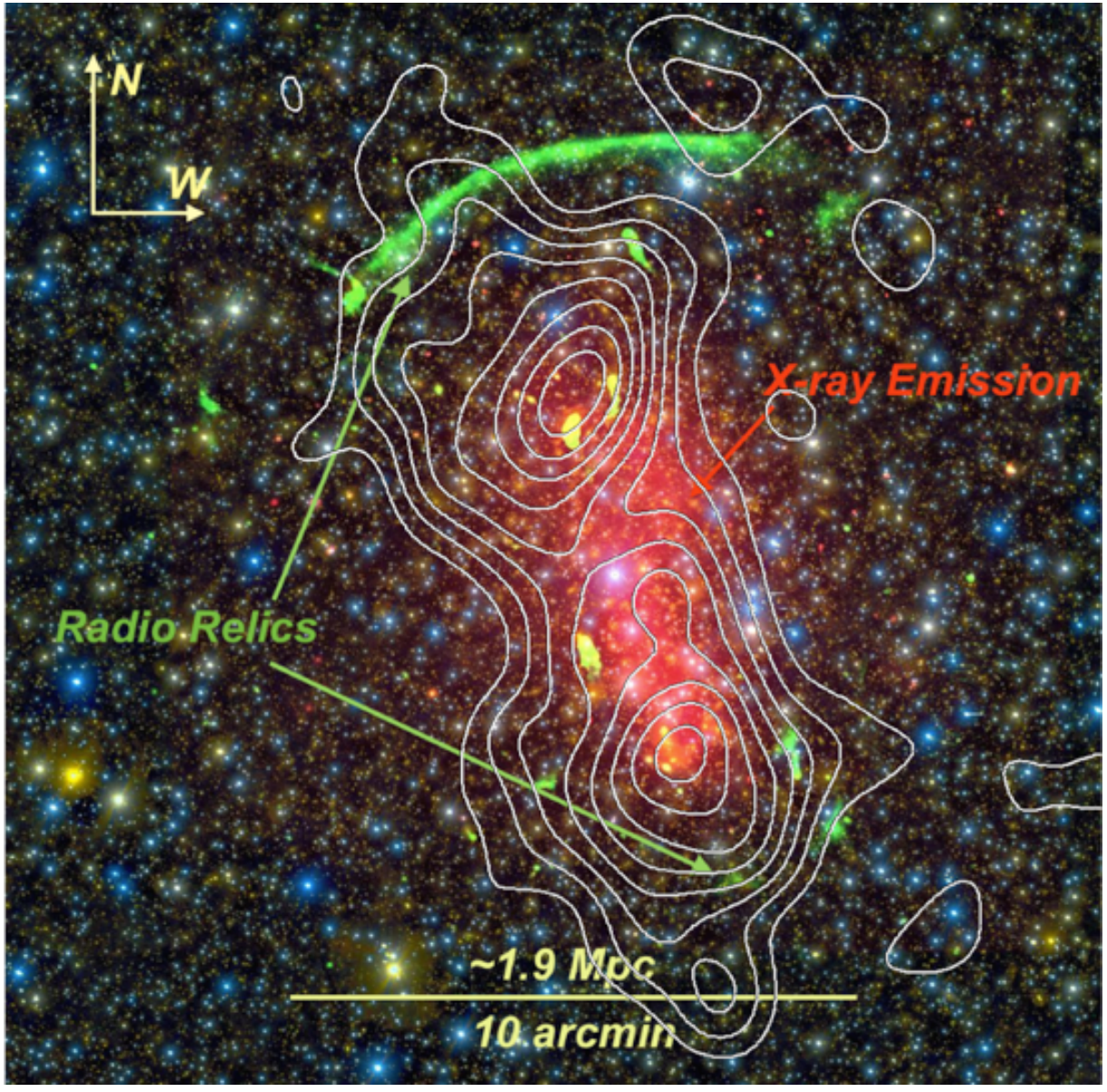
$\sim$ 35 Relic Systems Already Known in Radio Surveys



van Weeren+11

Our task: spectroscopic and weak-lensing surveys to constrain merger dynamics and galaxy-DM offsets; better polarization measurements to constrain viewing angle.

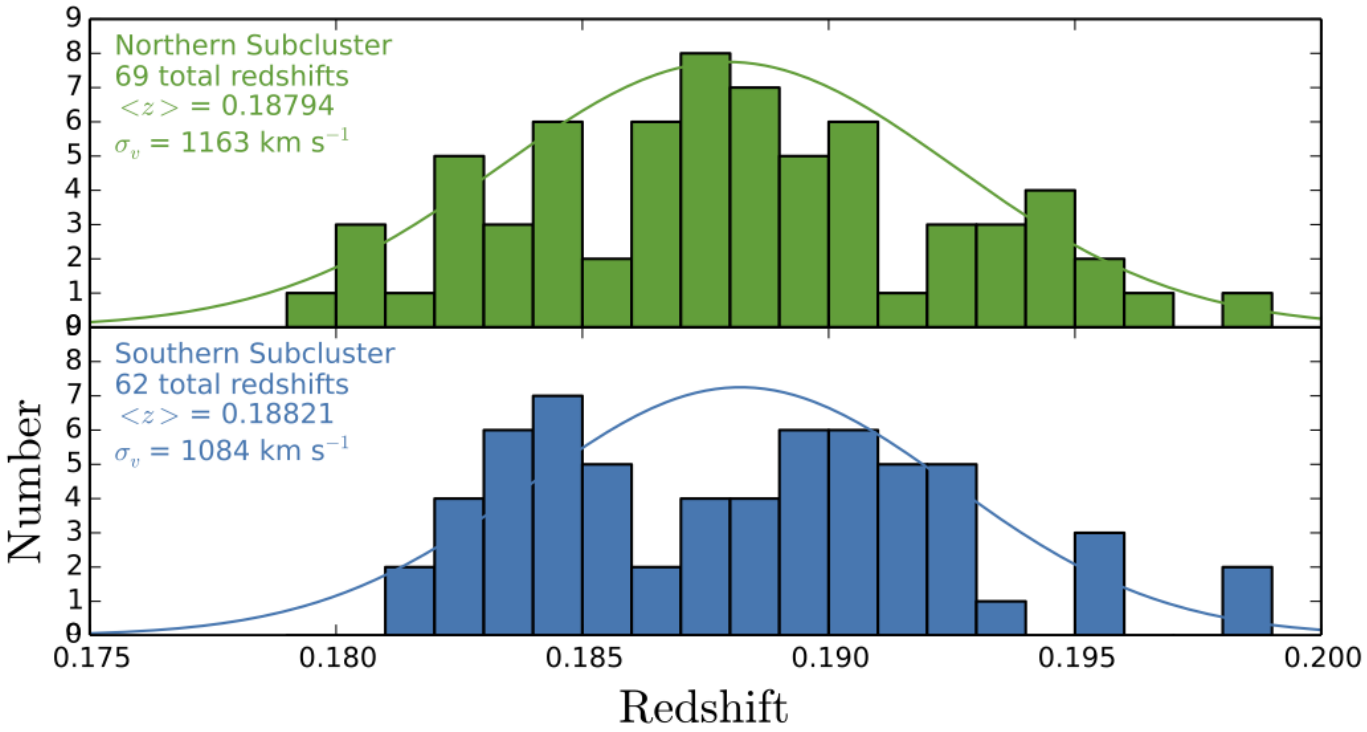
"Sausage" Cluster: **CIZA** J2242.8+5301 ($z = 0.19$)



GMRT 610 Mhz
(van Weeren+ 2010)
Chandra
red sequence galaxies

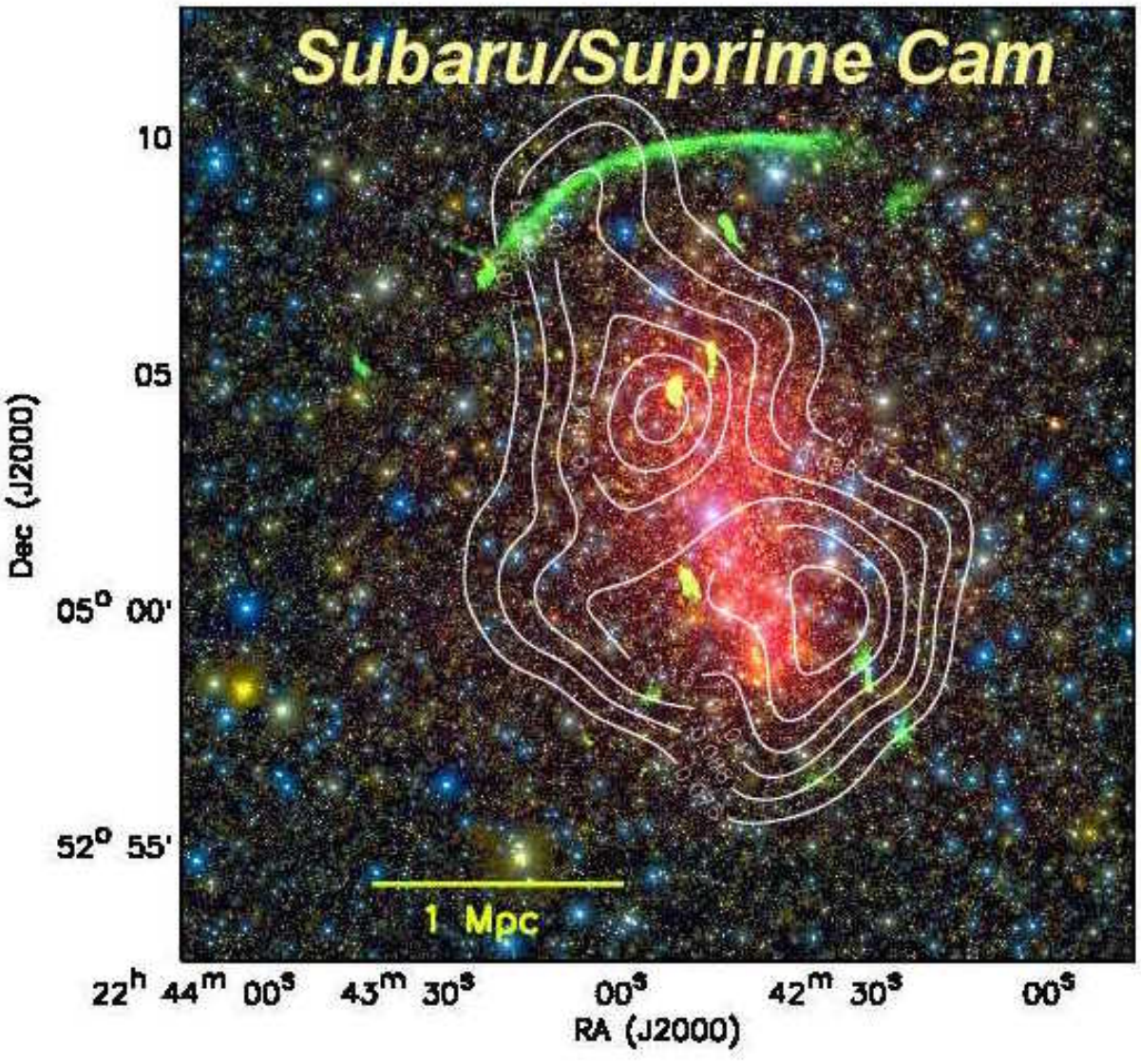
Subaru imaging: MC^2
Jee et al,
arXiv:1410.2898

Sausage: Keck/DEIMOS Spectroscopy



Dawson et al, arXiv:1410.2893: $v_{los} = 69 \pm 190$ km/s!

Sausage: Weak Lensing Morphology and Masses

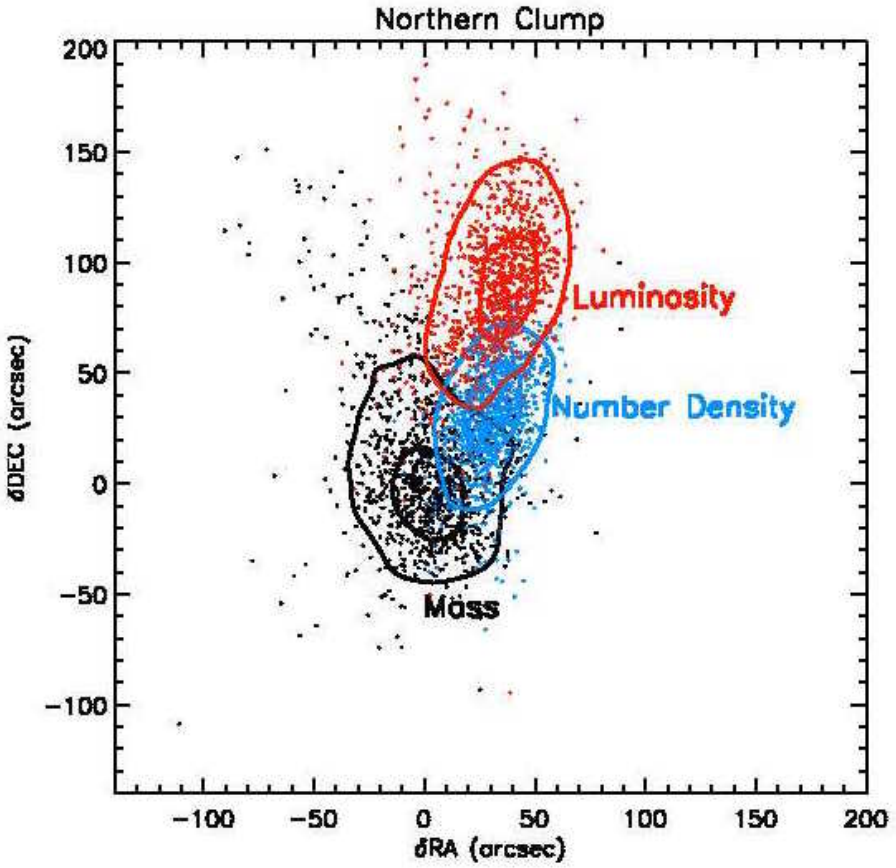


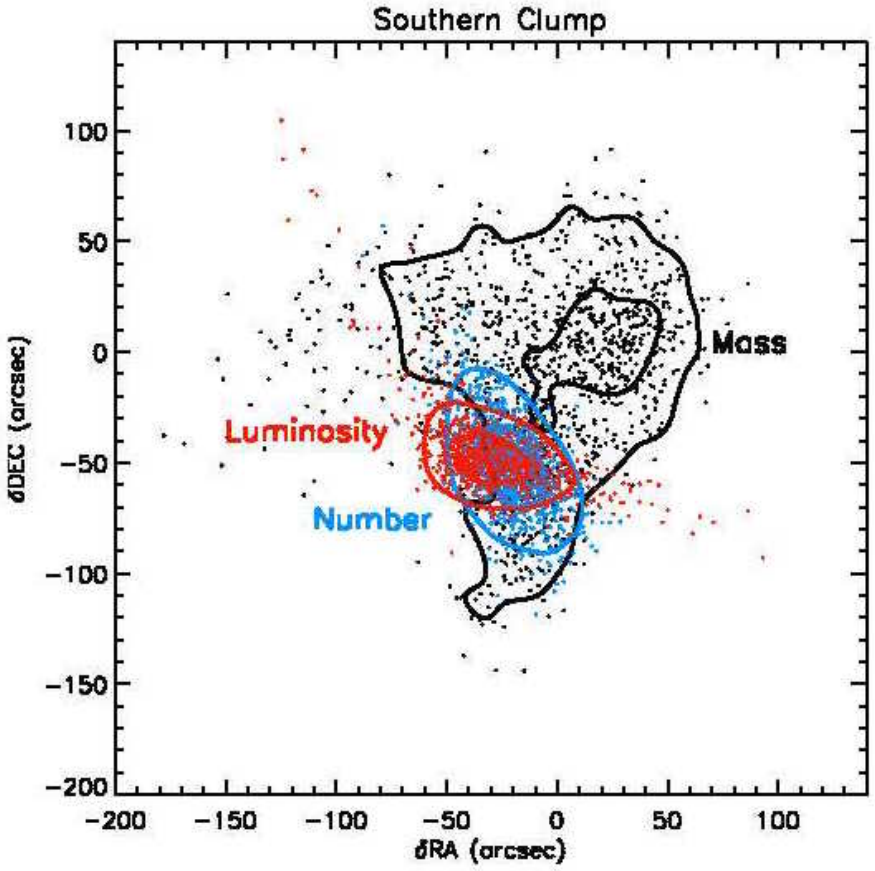
Jee et al, arXiv:1410.2898:

South: $1 \pm 0.2 \times 10^{15} M_{\odot}$

North: $1.1 \pm 0.2 \times 10^{15} M_{\odot}$

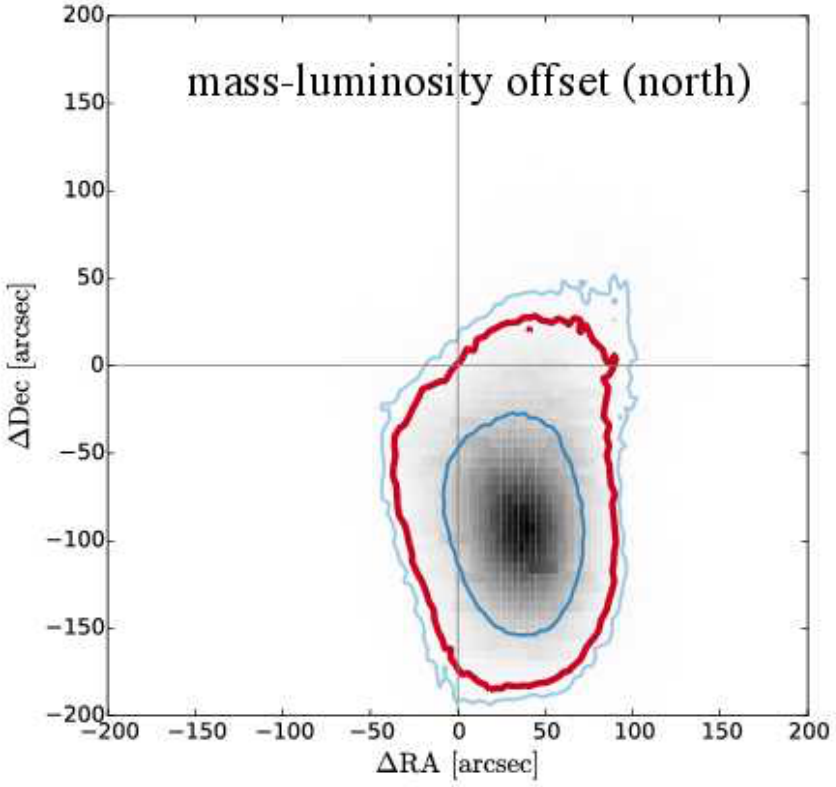
Sausage: Lensing vs Galaxy Centers

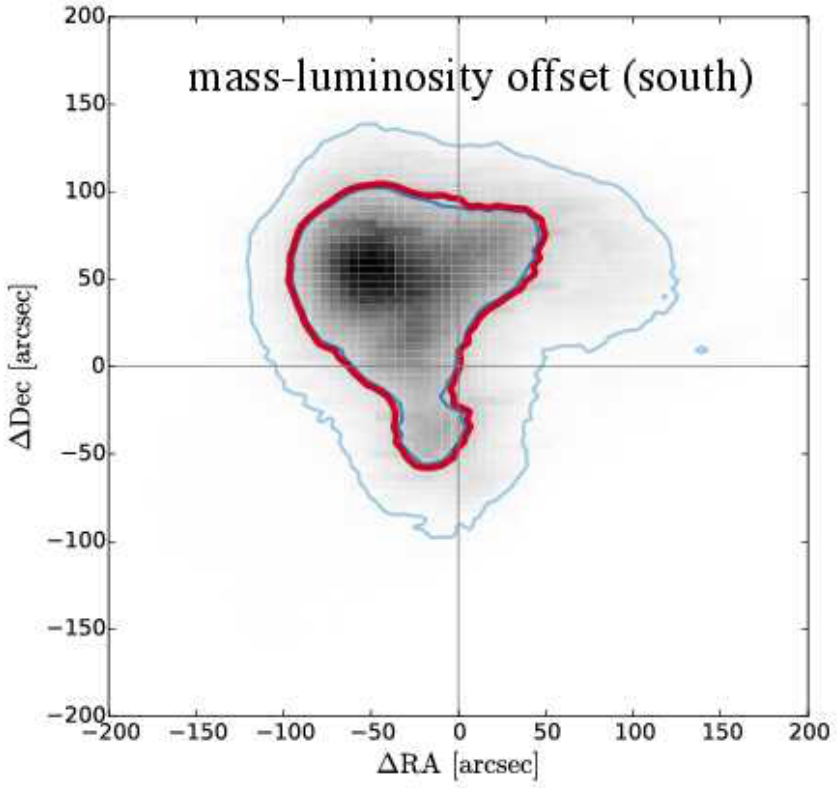




Jee et al, arXiv:1410.2898

Lensing/Galaxy Offsets Are Not Significant

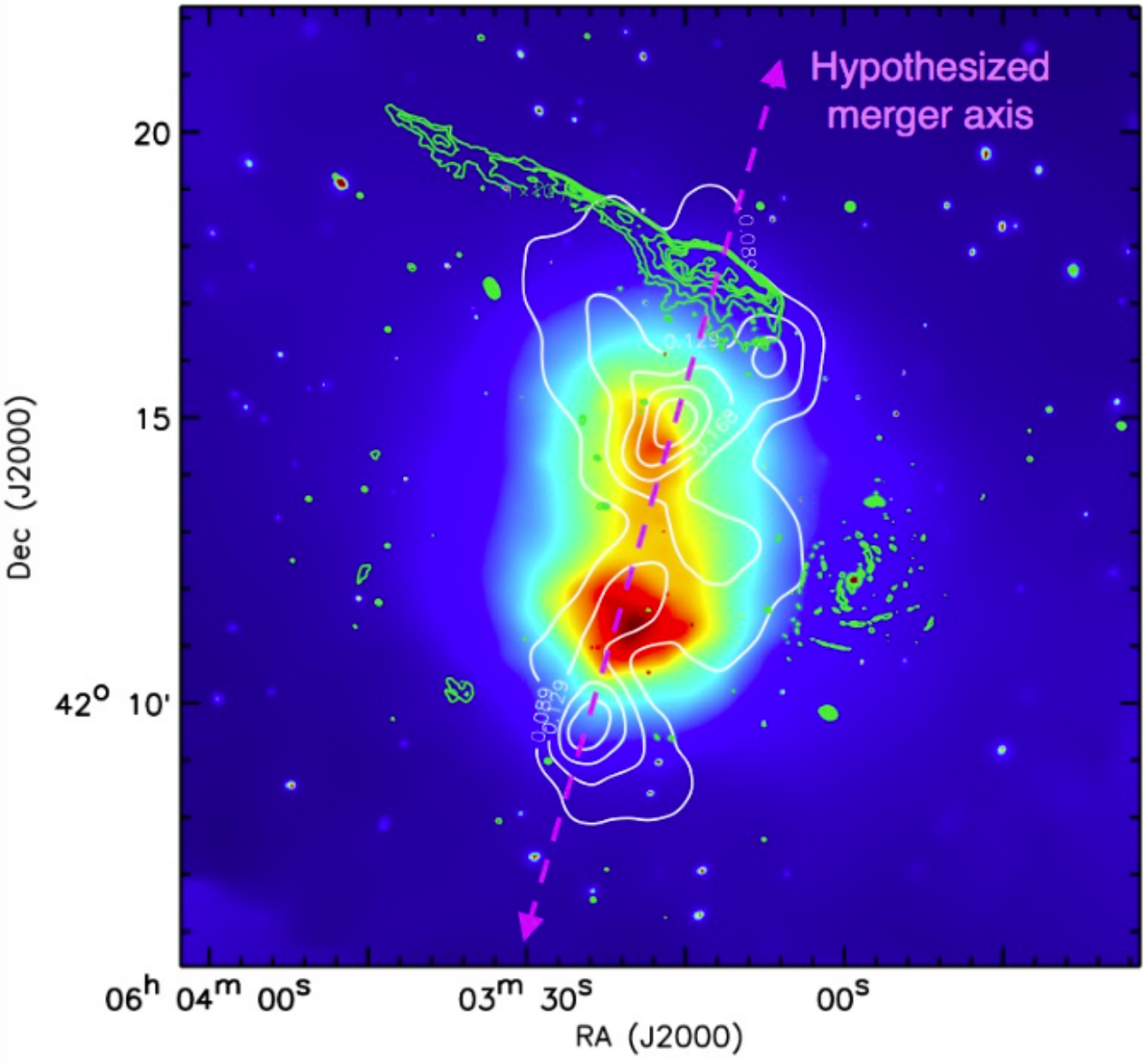




Jee et al, arXiv:1410.2898

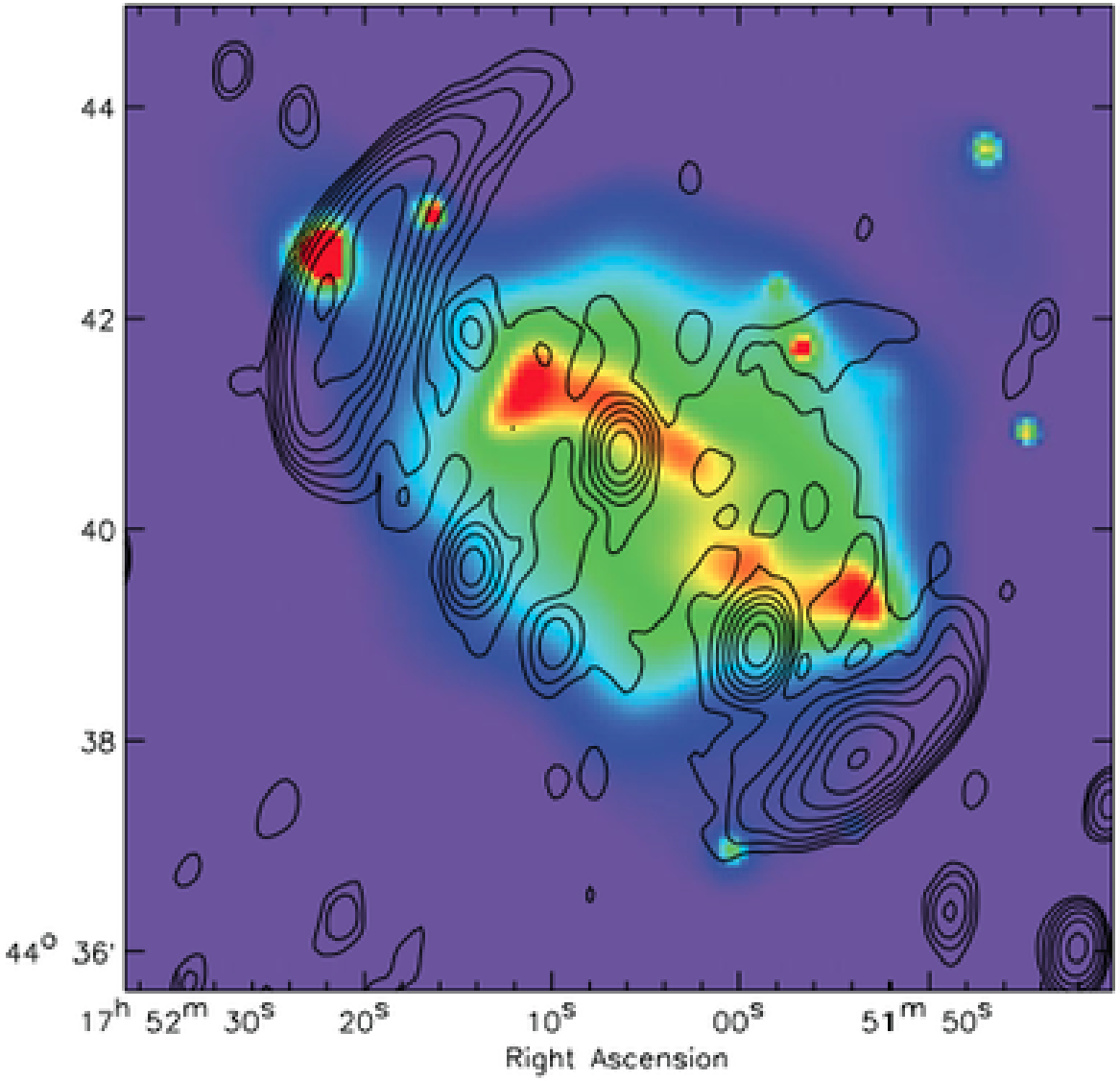
HST lensing data in hand to refine the mass location

We Also Find "Train Wrecks"



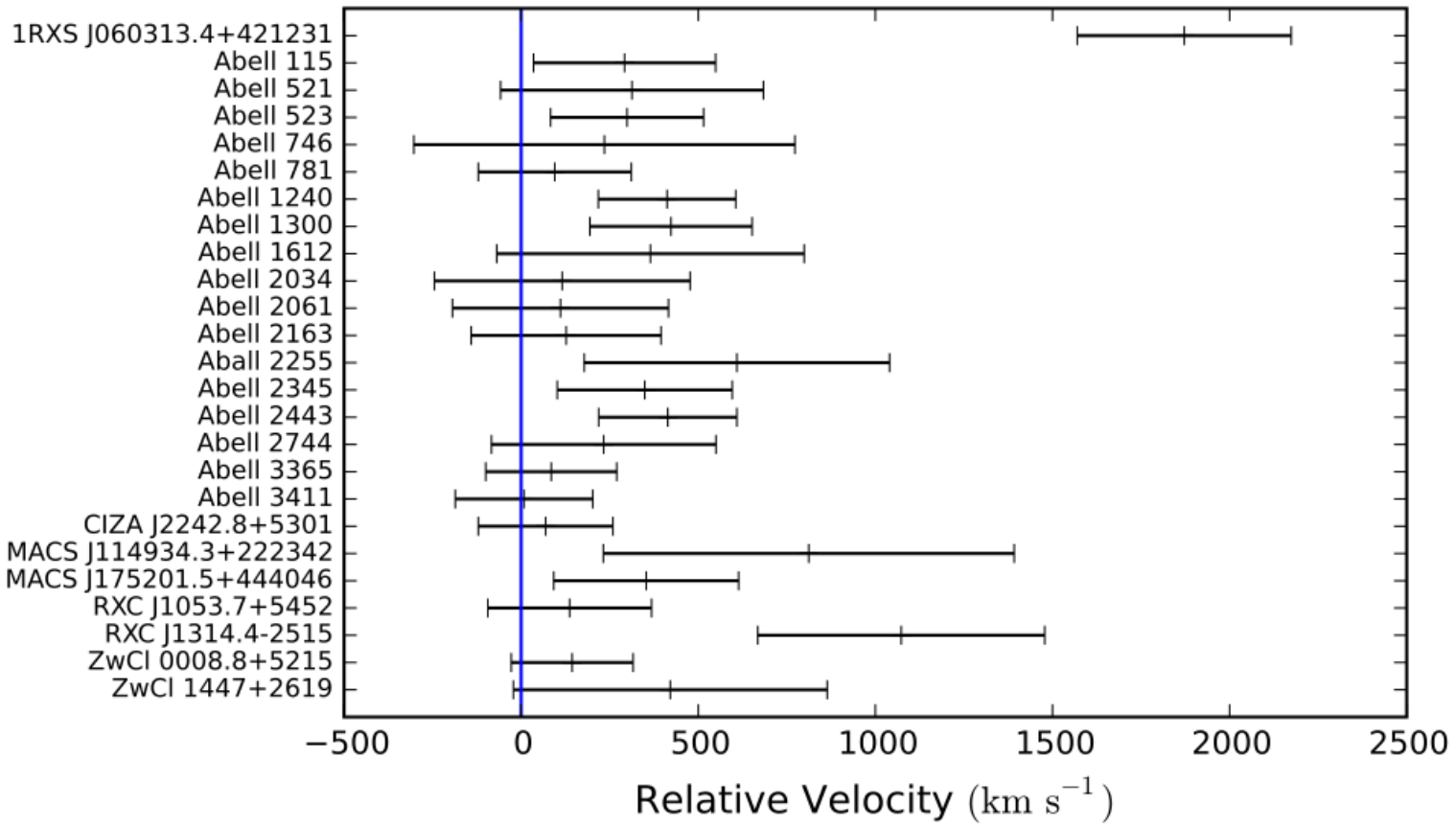
Toothbrush cluster
Xray/mass/radio
Jee+ accepted

MACS J1752+4440: Two Bullets?



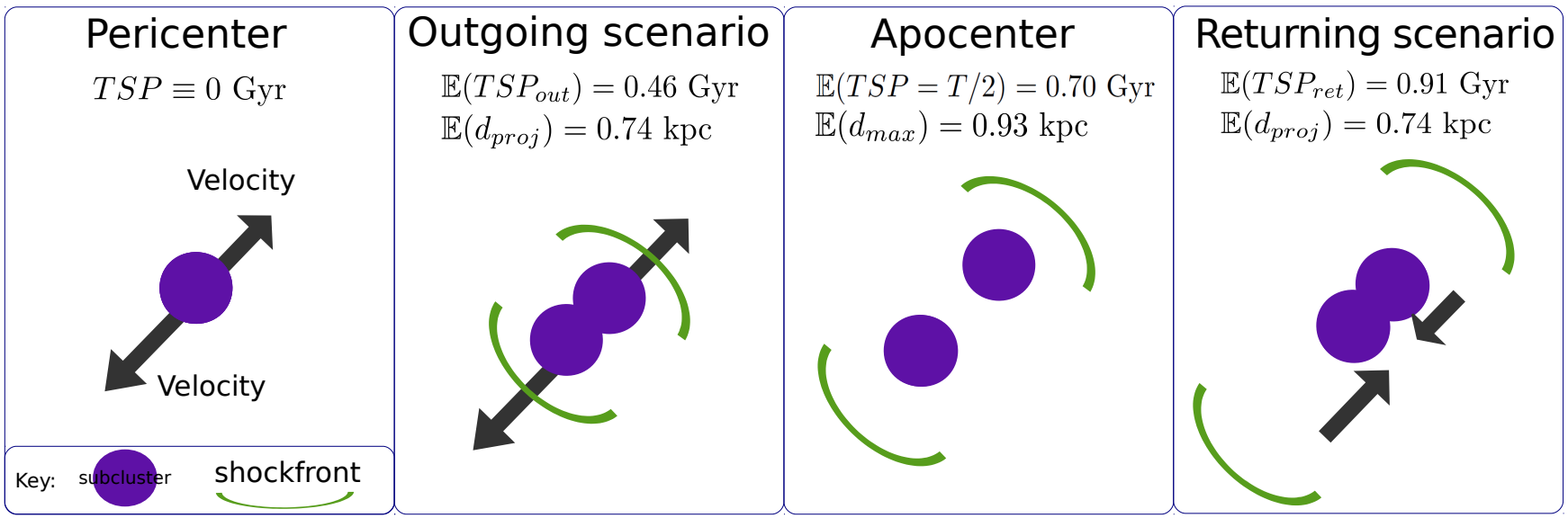
X-ray
WSRT 21cm
(van Weeren+2012)

Sample Overview: $v_{los}(t_{obs})$



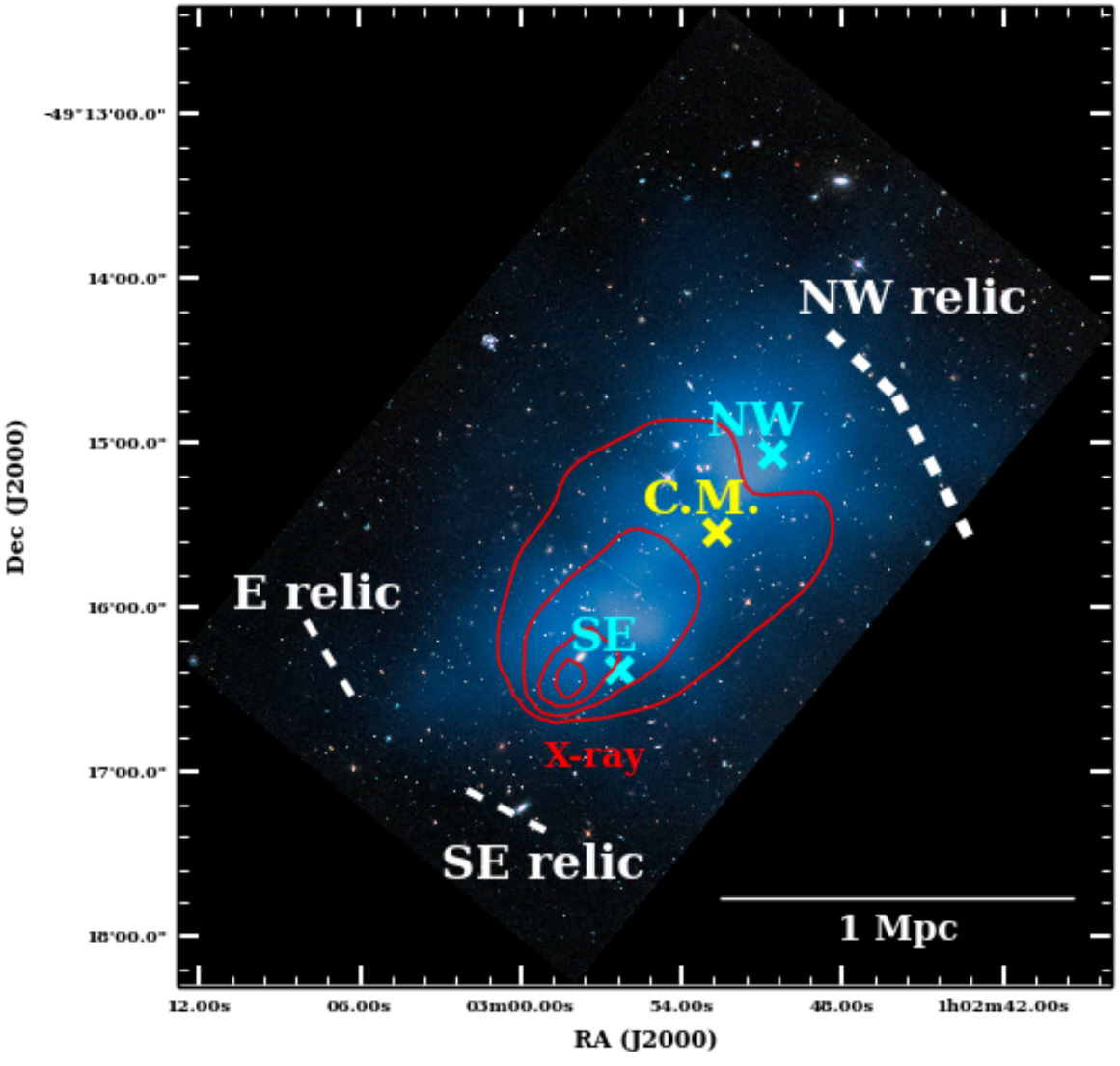
Low v_{los}: merger in plane of sky and/or near turnaround.
Lensing: systems generally quite massive ($\sim 10^{15}$ M$_\odot$)

X-ray Selection Probes Entire Timeline



El Gordo ($z = 0.87$), Jee+14

MCC Analysis, Ng+ 2015



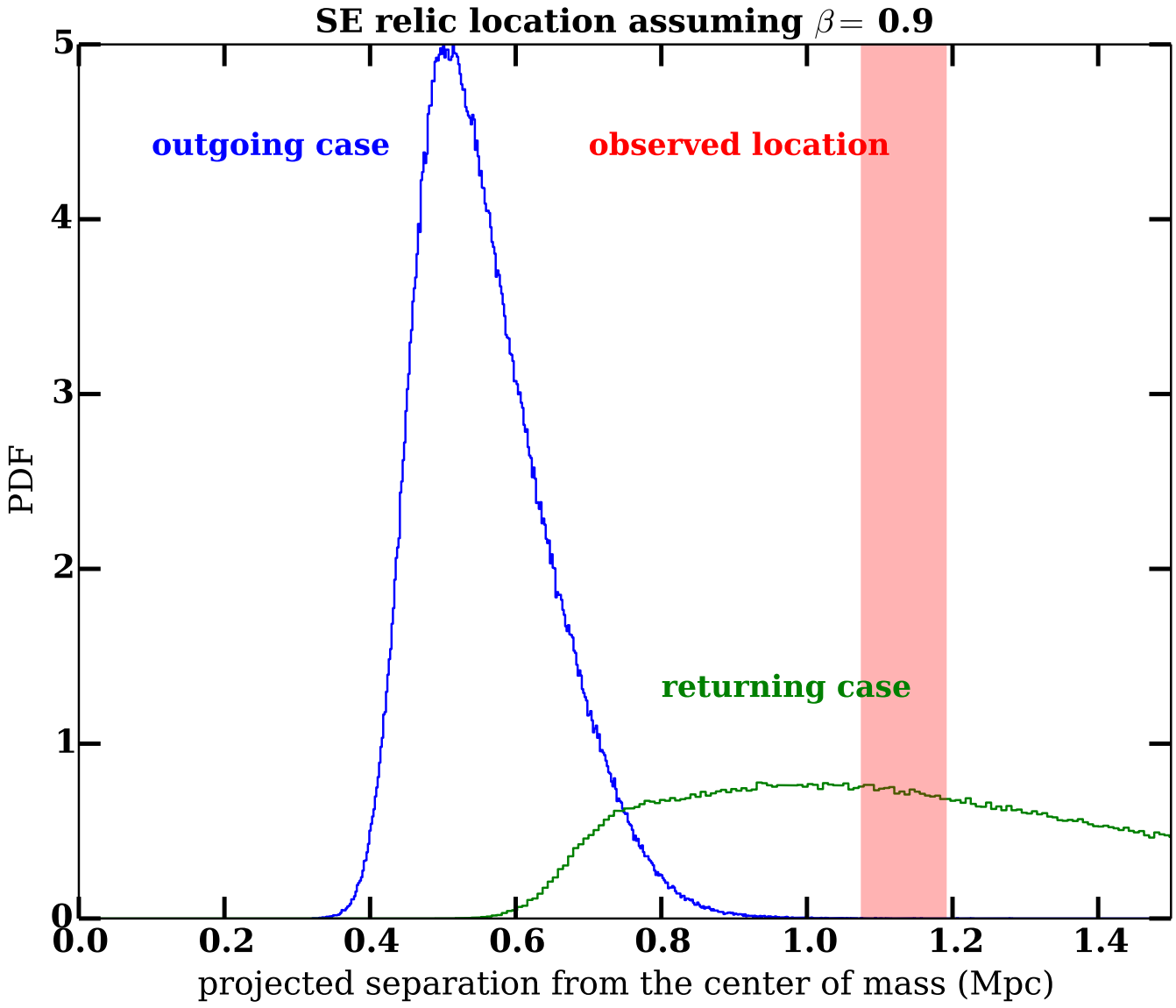
Weak lensing:

SE: $0.8 \pm 0.2 \times 10^{15} M_{\odot}$

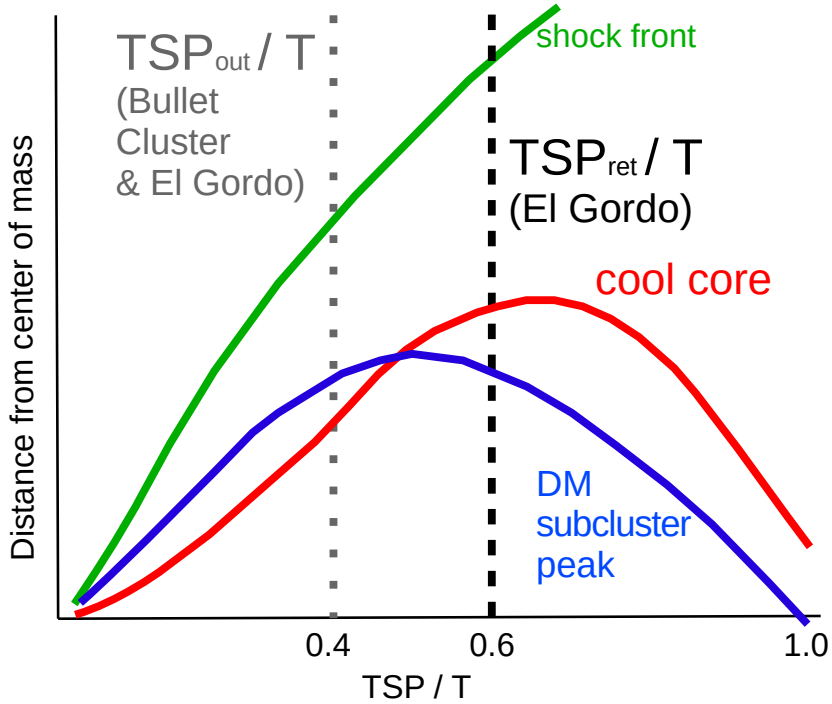
NW: $1.4 \pm 0.2 \times 10^{15} M_{\odot}$

(Jee+14, arXiv:1309.5097)

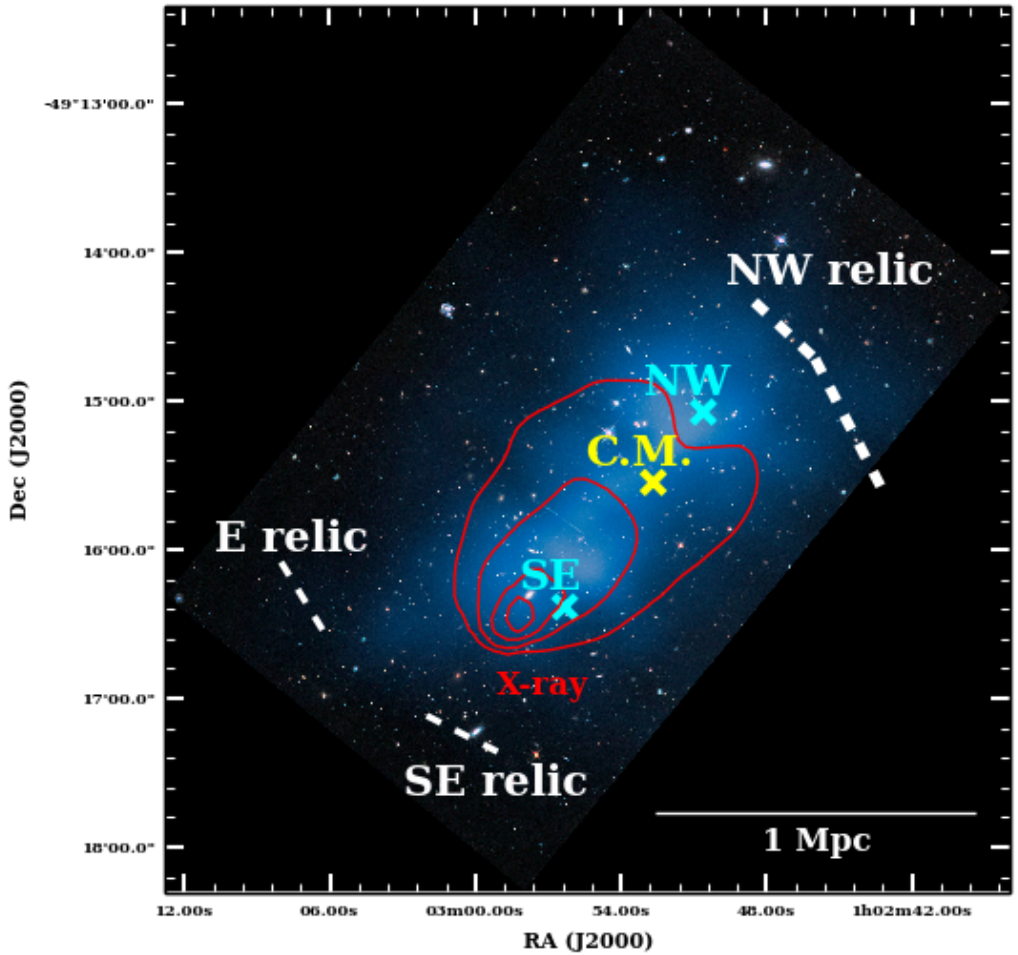
El Gordo: Returning



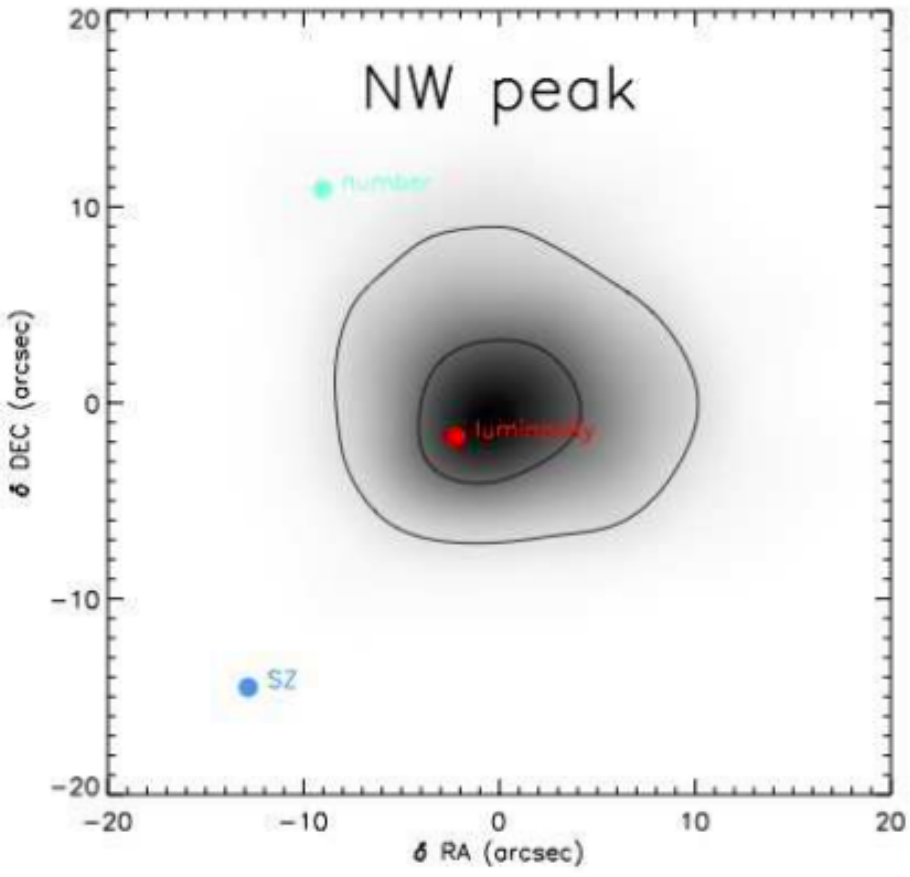
Returning Scenario Supported by Other Evidence

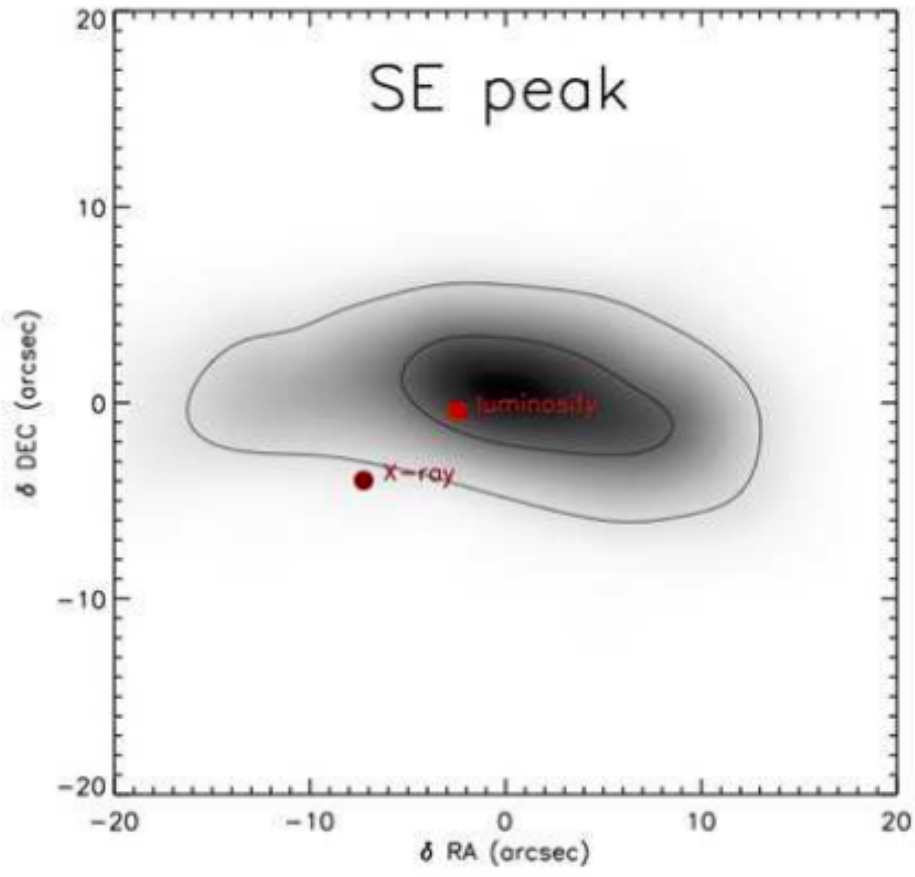


Cartoon based on simulations by Mathis+05



El Gordo: No Galaxy-DM Offset





Jee+14

Chandra/Planck "MC3PO" Sample

Abell 2218

Comprehensive sample of Planck clusters w/disturbed X-ray morphologies $\rightarrow$ broad sample of merger phases (Dawson, Forman, Jones++).

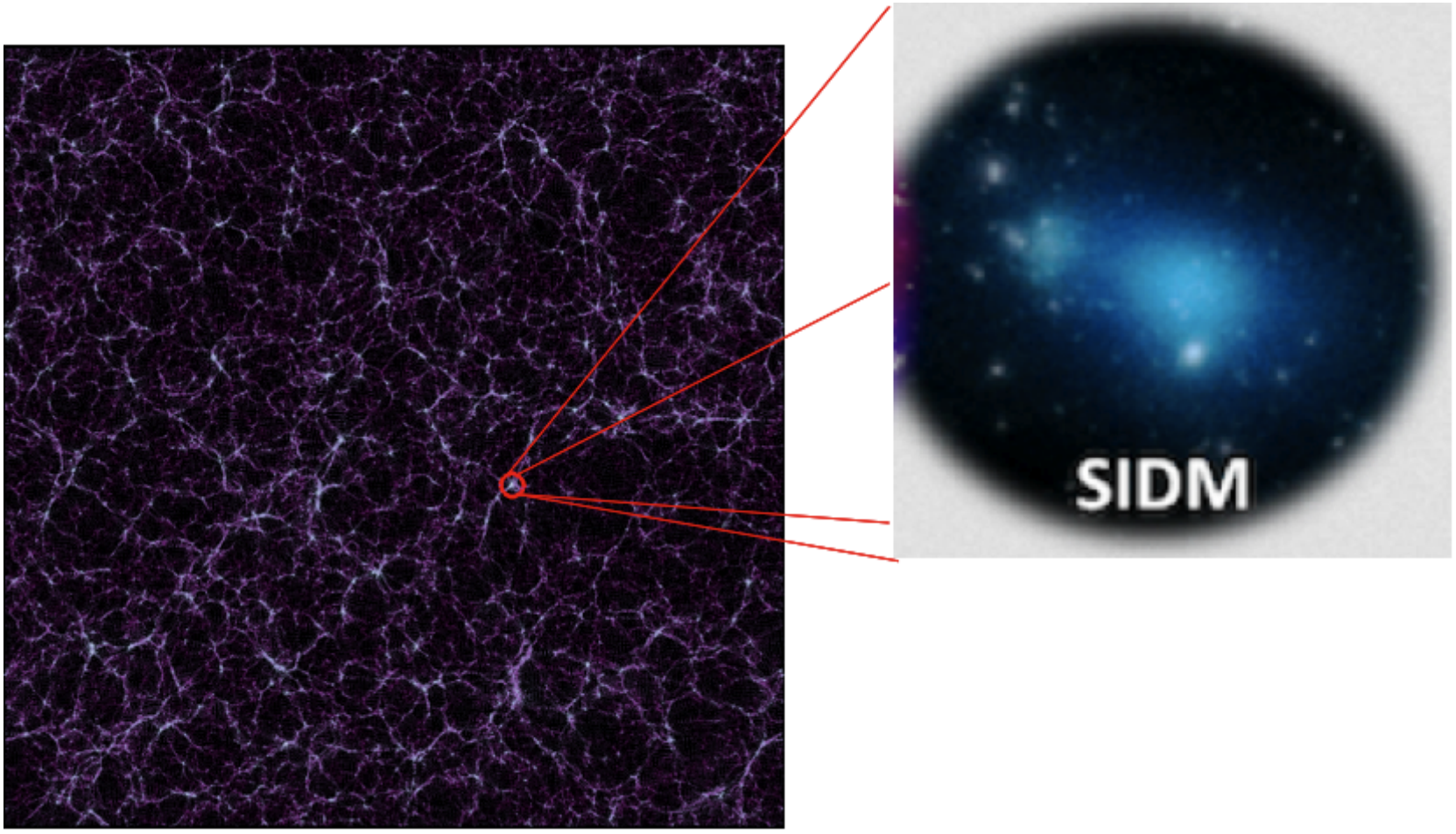
Existing Simulations

Randall et al (2008): n-bodies with a range of σ_{SIDM} confirms $\sigma_{SIDM} \lesssim 1$ for Bullet. BUT:

- "staged" simulations with isolated King profile subclusters: no subhaloes or other structure
- randomly distributed test masses stand in for galaxies
- parameters lack cosmological motivation
- fixed values of observables (mass, α)

Importance Sampling of Cosmological N-bodies

Followed by Resimulation at Higher Resolution

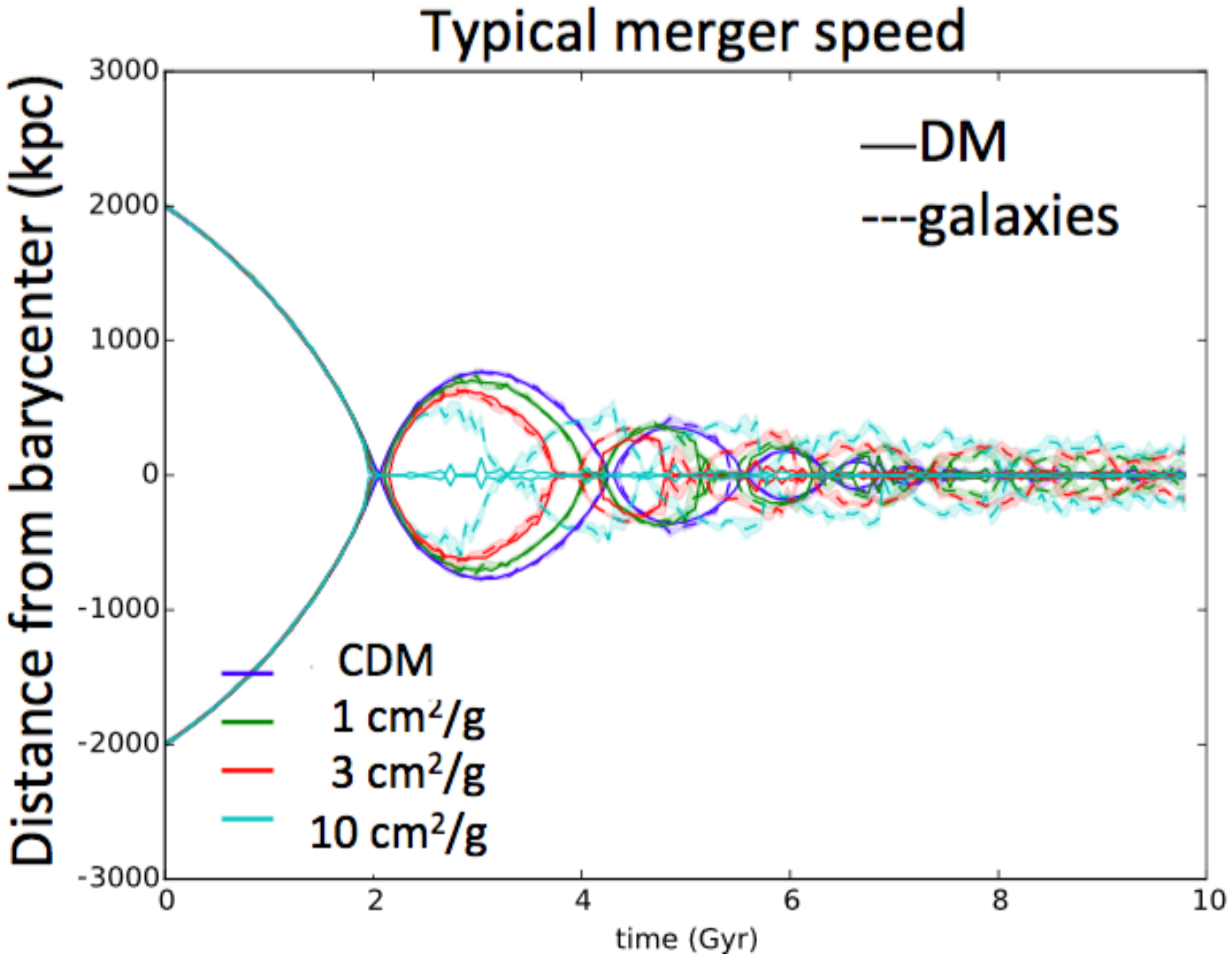


650 h^{-1} Mpc box contains many Musketball analogs

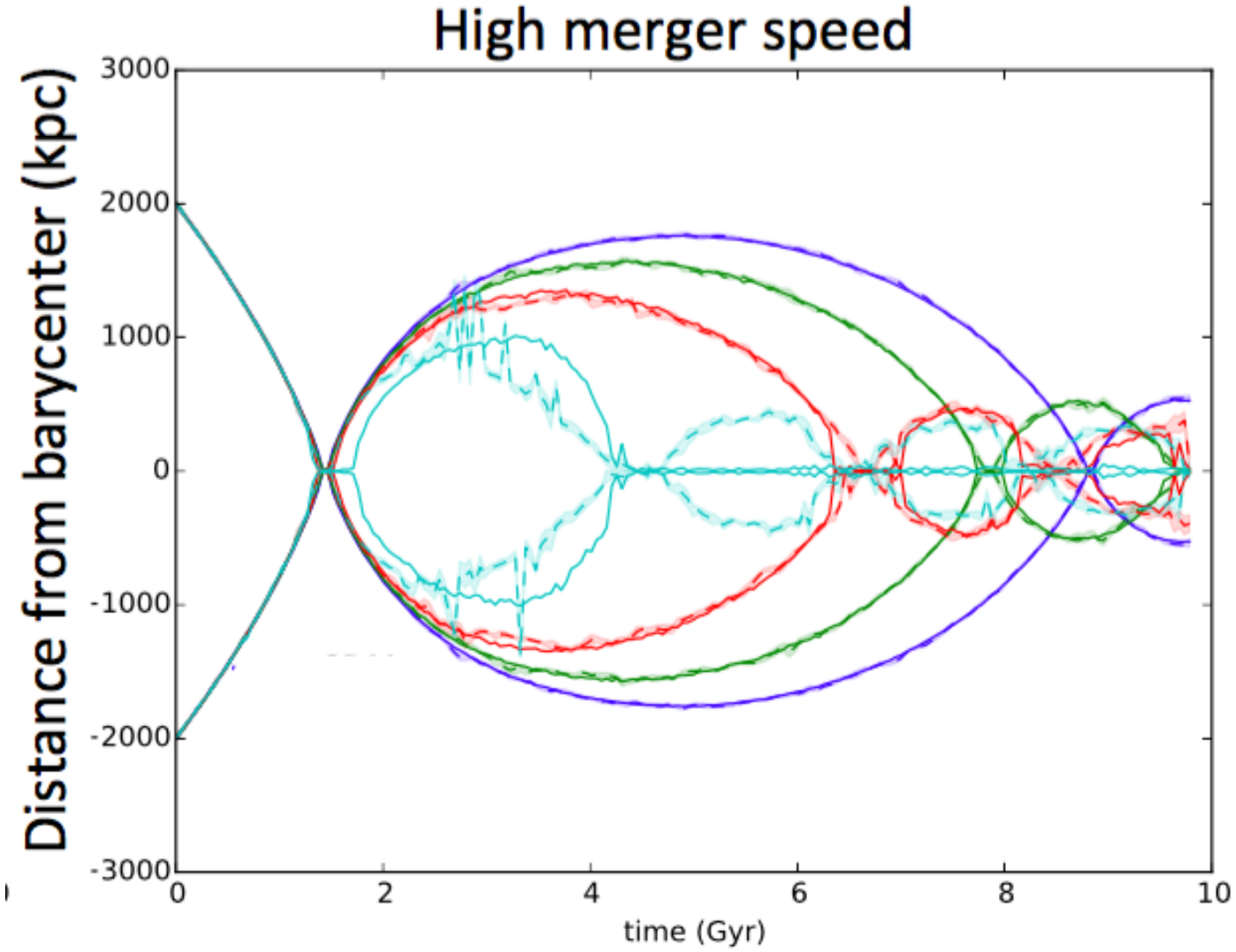
This Two-Step Process Enables:

- merger conditions (impact parameter, velocity, continued mass accretion) faithful to known cosmology
- realistic substructure and galaxy placement
- self-consistency (subcluster profiles will match given value of σ_{SIDM})
- proper marginalization over observational uncertainties (including α)
- targeting new observations that maximally reduce uncertainty

New Sims from Annika Peter/Stacy Kim (OSU)



New Sims from Annika Peter/Stacy Kim (OSU)



Summary

Early results on relics sample (25 mergers):

- relic-selected systems are indeed close to transverse
- tend to be quite massive
- mix of bimodal and more complicated mergers
- WL-galaxy offset measurements in progress

Other MCC work in progress:

- El Gordo is in returning phase
- SIDM simulations by Annika Peter's group (Ohio State)
- MC3PO (Chandra-Planck) sample for add'l merger phases

If $\sigma_{SIDM} \approx 0.1 - 0.5$ MCC will find it.

Extra Slides

Observable vs σ_{SIDM} from Randall+08