Cosmic Particle Accelerator: Constraining Properties of Dark Matter Using Colliding Galaxy Clusters

M. James Jee (Yonsei University/UC Davis)

CosKASI, April 20, 2017

OUTLINE

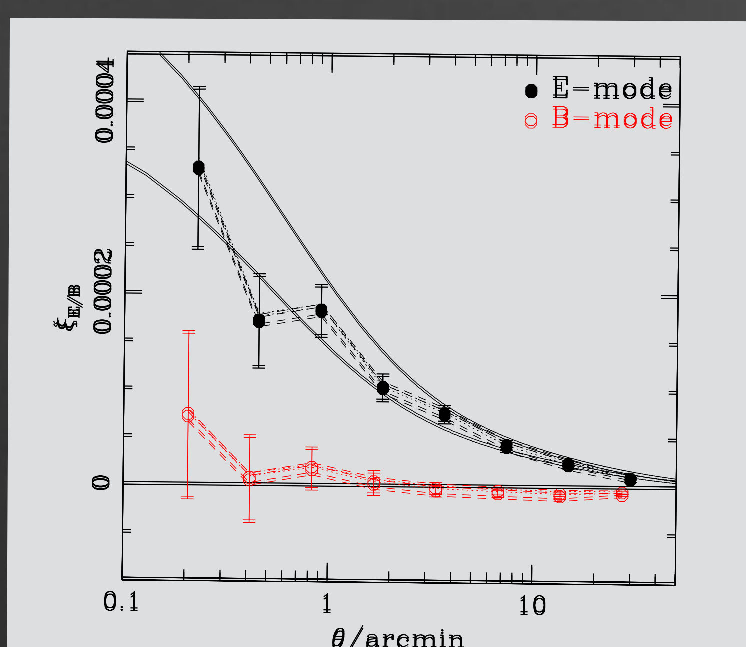
- Introduction: Weak-Lensing for Dummies
- Is Lensing Really in Tension with CMB?
- How Can We Use Colliding Clusters as Cosmic Particle Accelerators?
- Conclusions

Cosmic Shear Made Easy

Observation

Galaxies Distorted

Big Bang



Analysis

You Estimate:

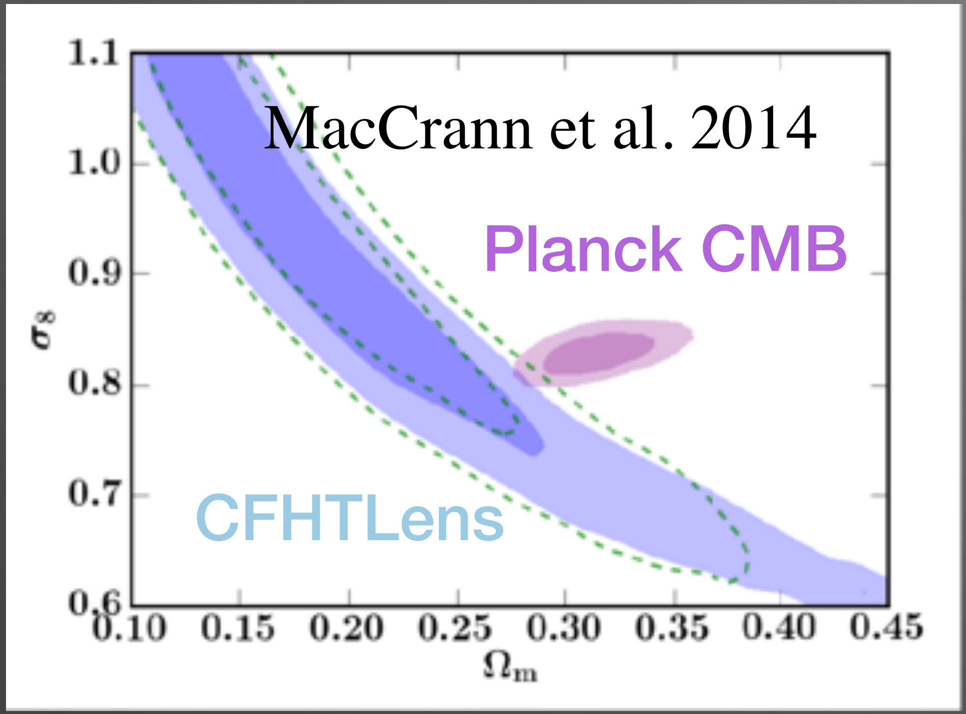
- Velocity of the Stone
- Mass of the Stone
- Size of the Stone
- Time since the Impact
- Height of the Girl

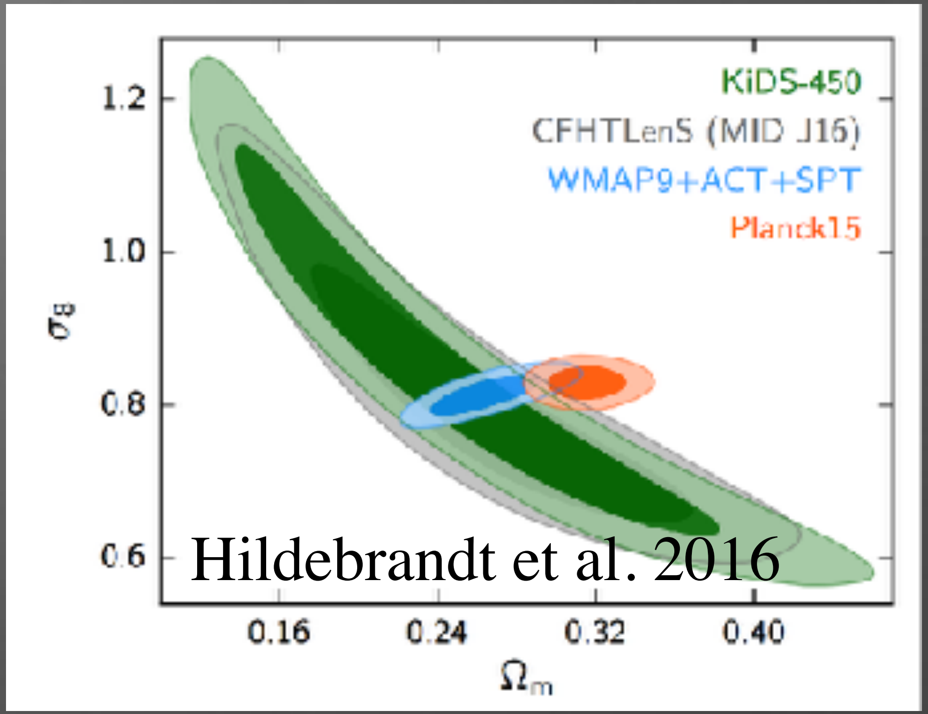
Cosmology

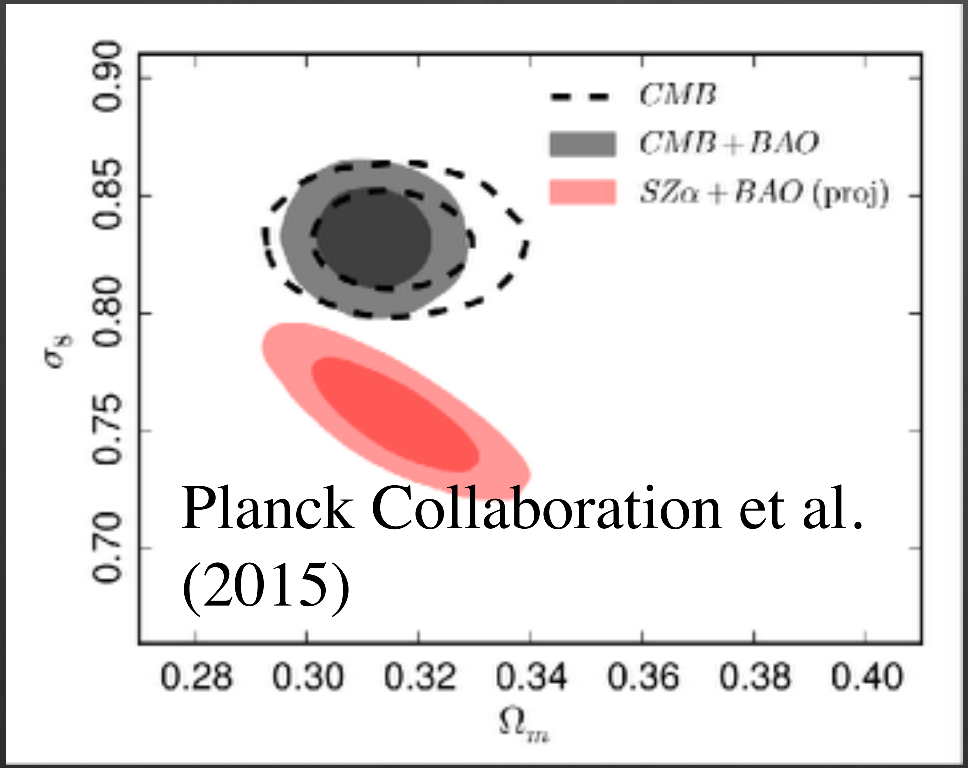
OUTLINE

- Introduction: Weak-Lensing for Dummies
- Is Lensing Really in Tension with CMB?
- How Can We Use Colliding Clusters as Cosmic Particle Accelerators?
- Conclusions

Cosmic Shear vs. CMB



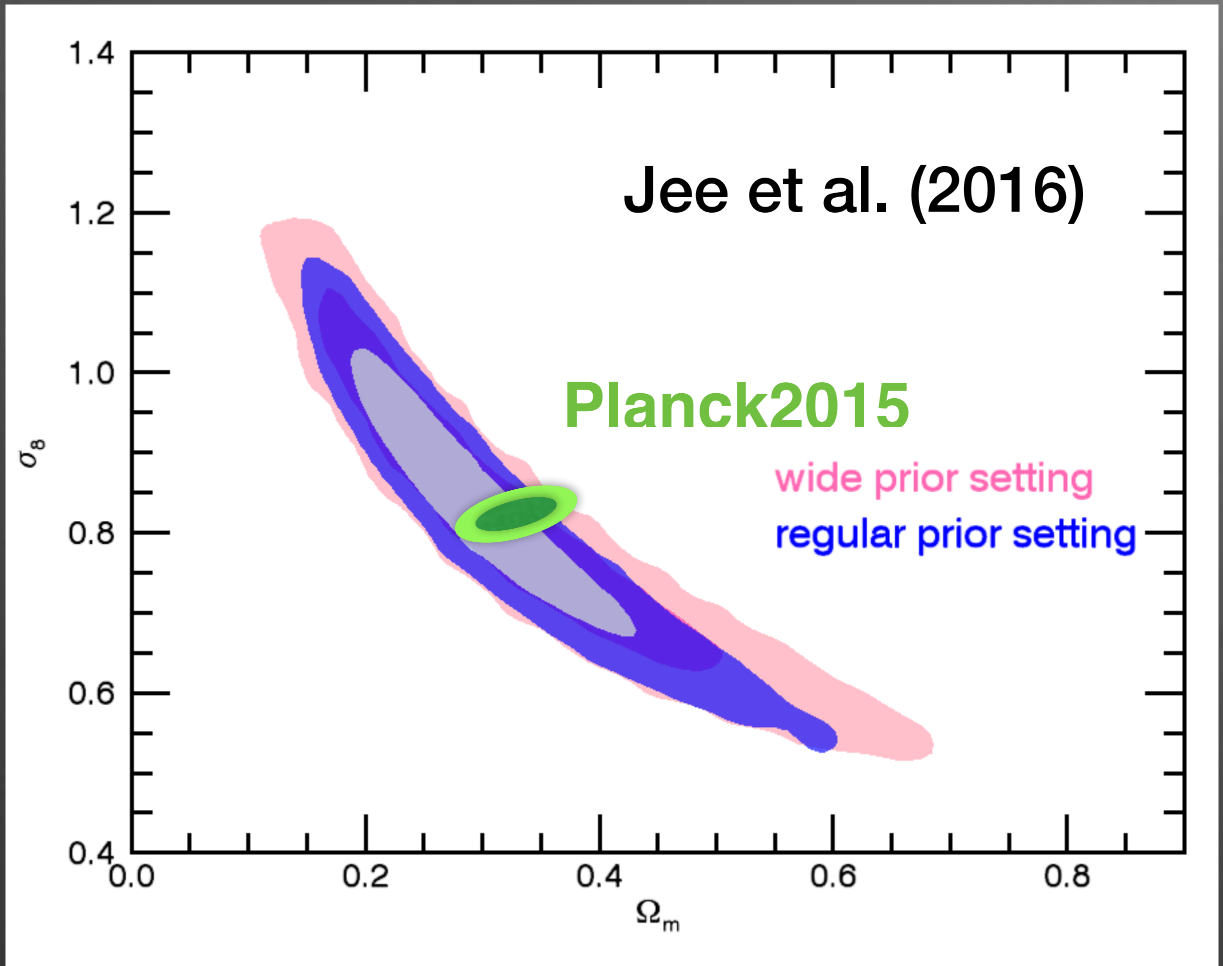




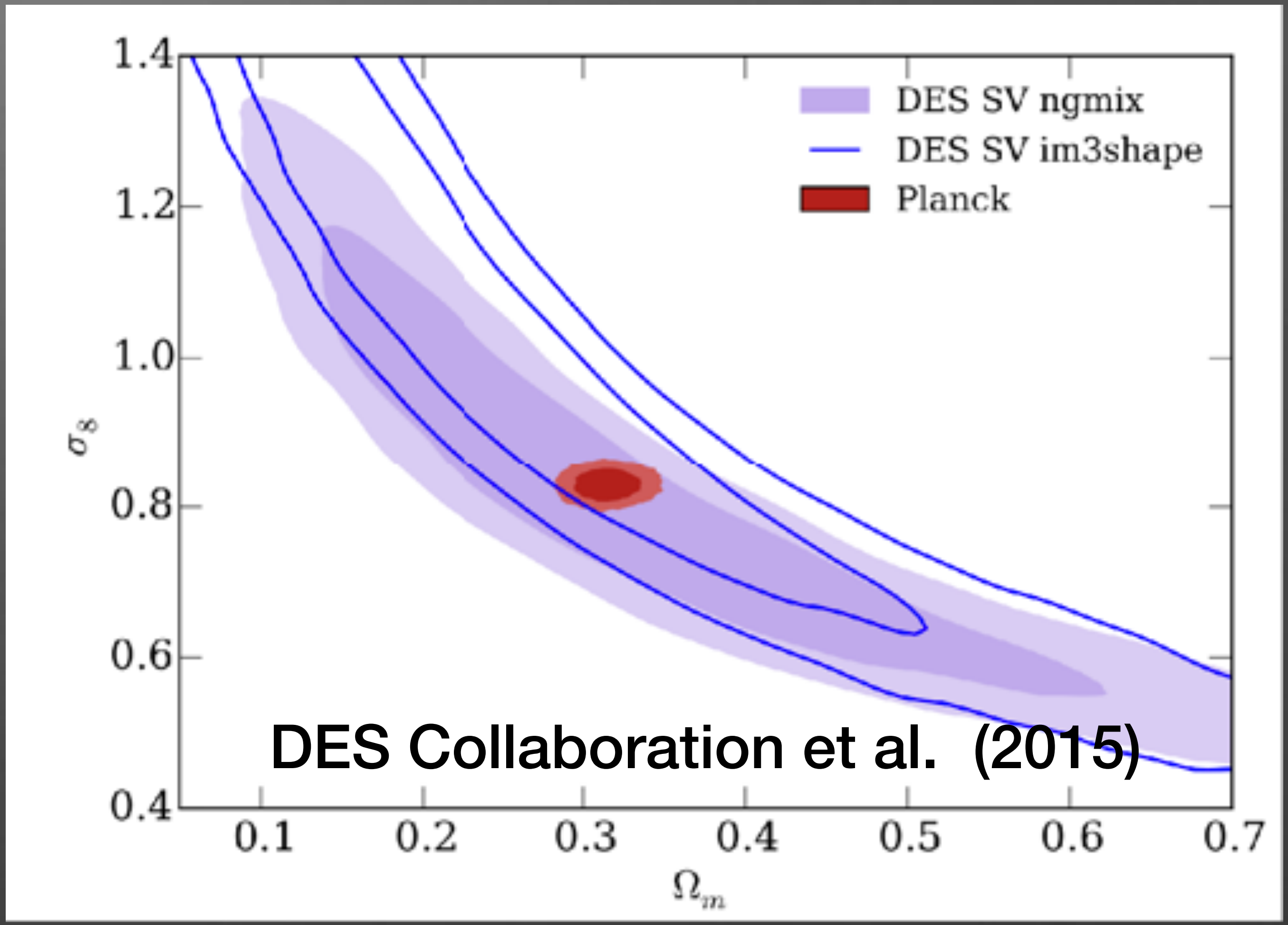
"Low-z vs. High-z Tension"

- New Physics?
- Systematics

Other Cosmic Shear Studies



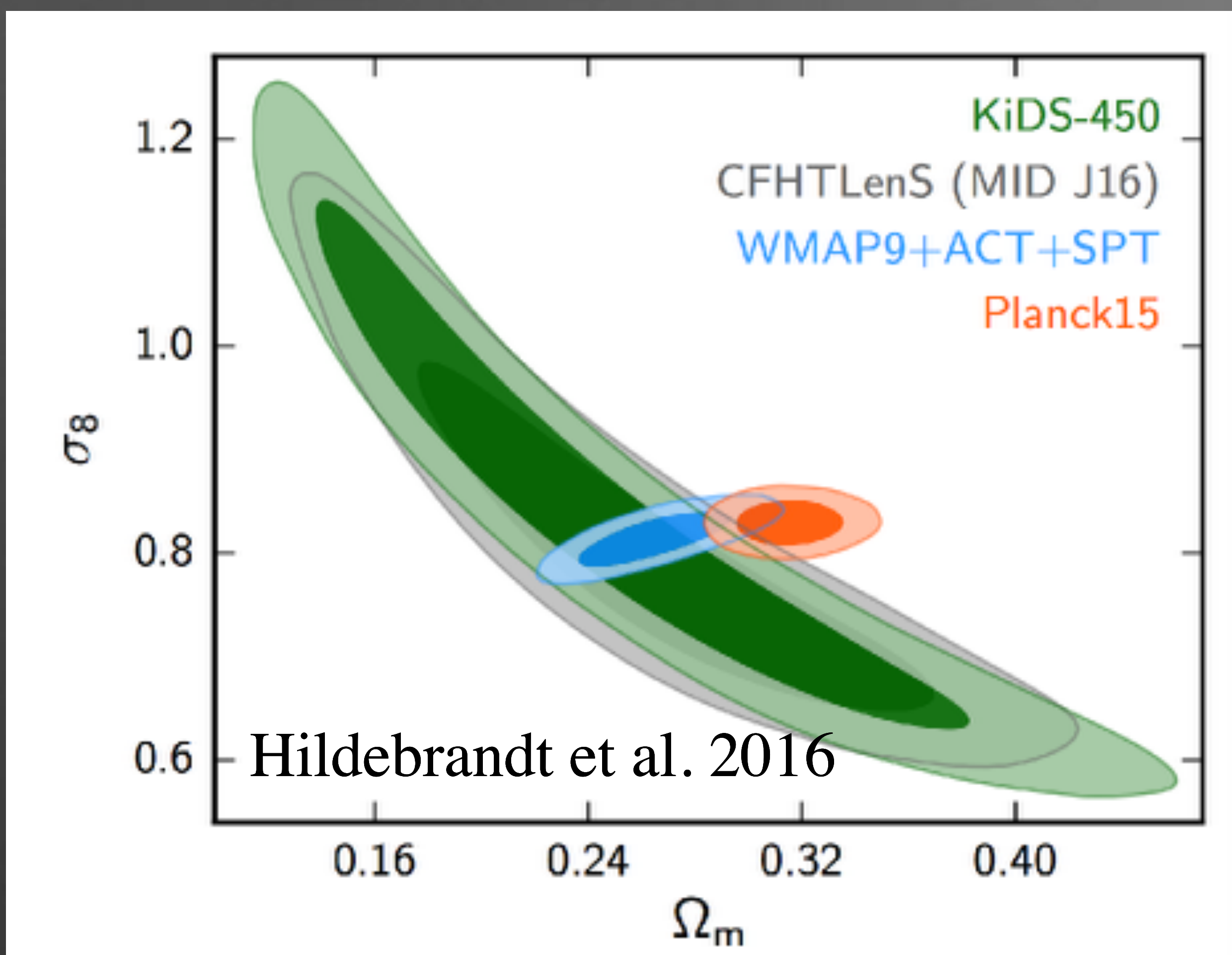
Deep Lens Survey



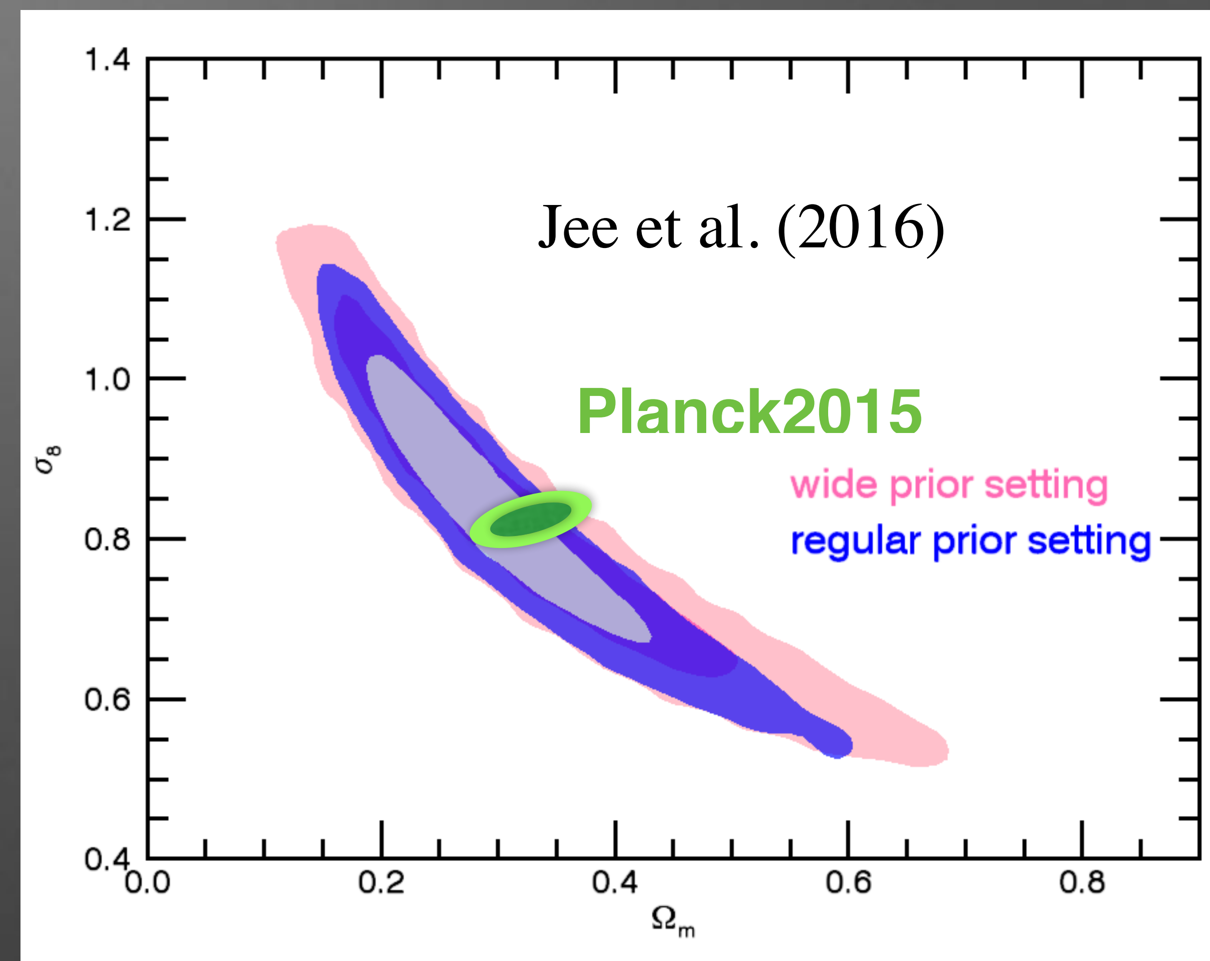
Dark Energy Survey

What is going on?

European Lensing



American Lensing



If European lensing is correct,

American lensing is in trouble. However, physics may be in deeper trouble.

If American lensing is correct,

European lensing is in trouble. However, LCDM is still safe.

Two Major Systematics in Weak-Lensing

1. Photometric Redshift

2. Shear Systematics

Photometric Redshift

Deep Lens Survey

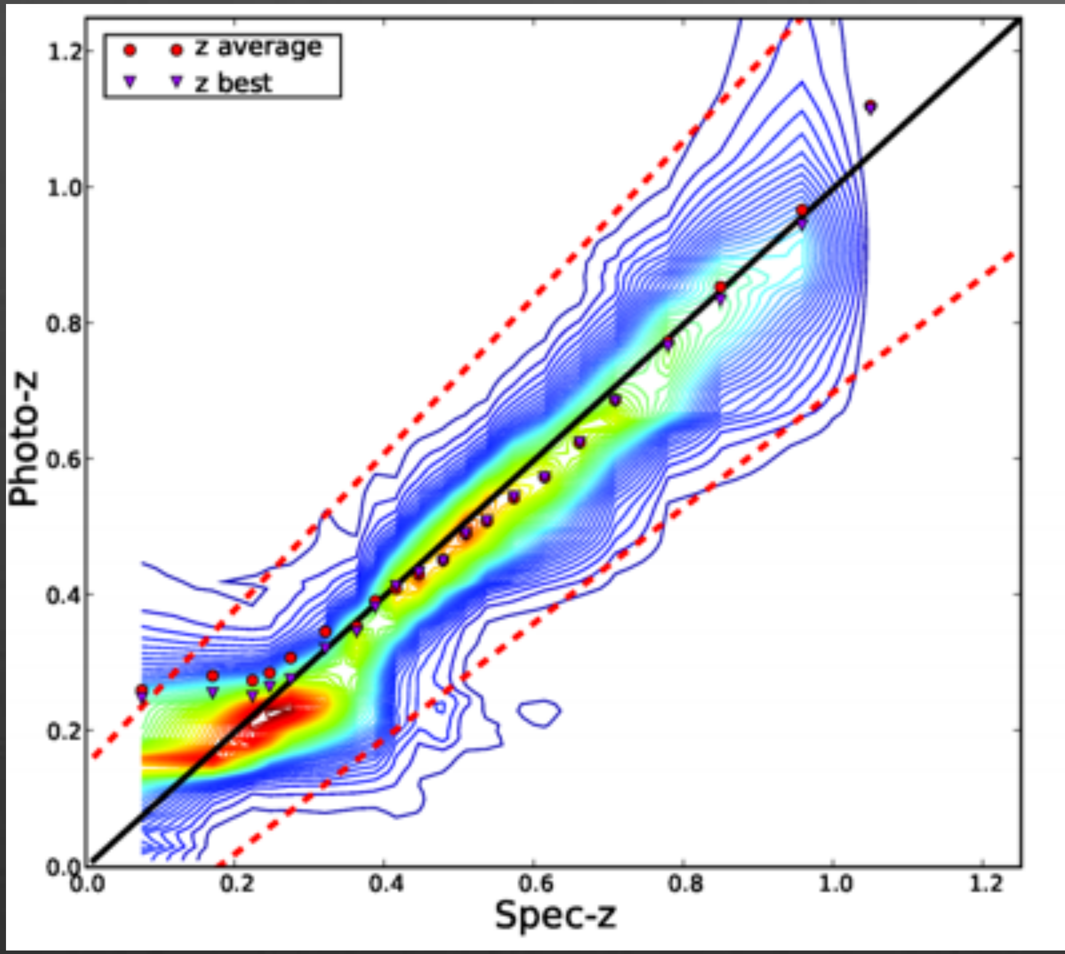
Filters: B,V,R,z

Depth: ~27th

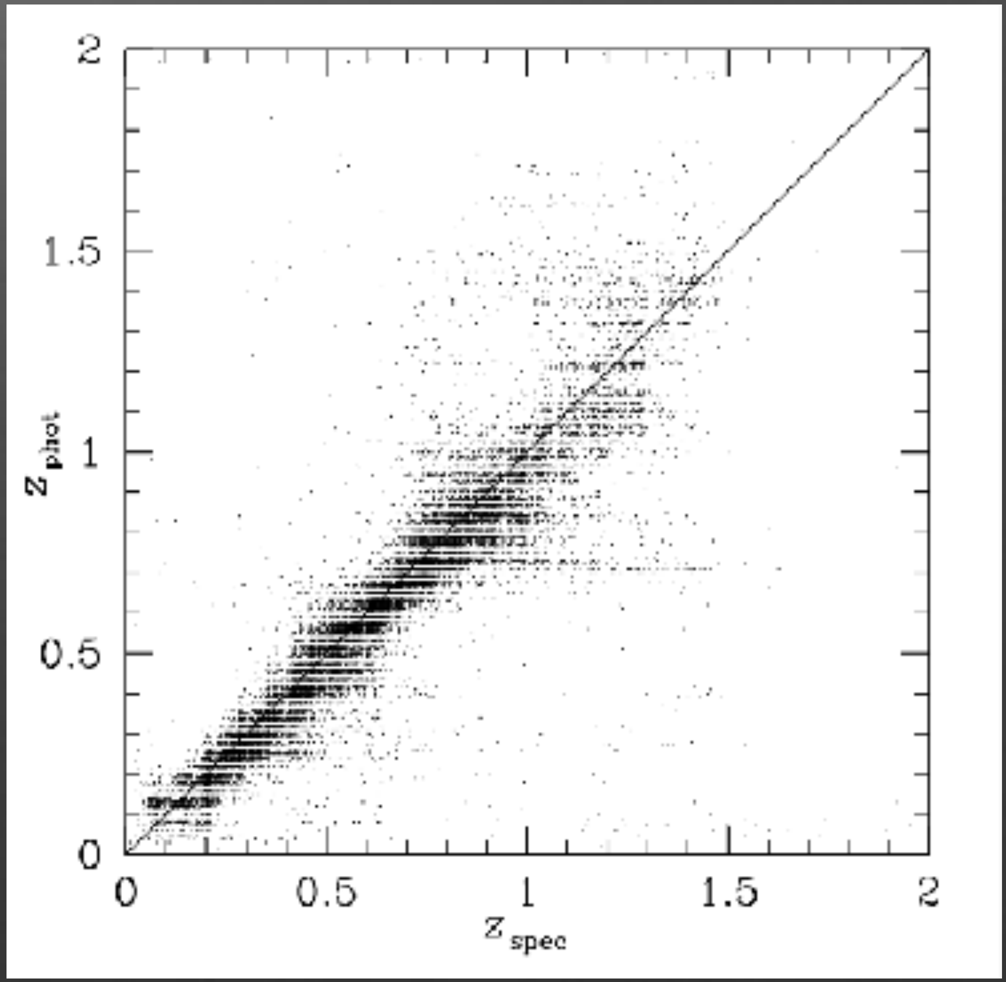
CFHTLens

Filters: u,g,r,i,z

Depth: ~25.5th

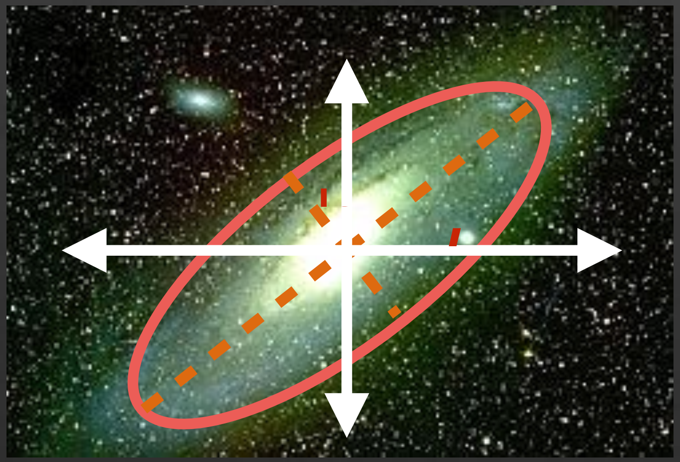


Schmidt & Thorman (2012)



Hildebrandt et al. (2011)

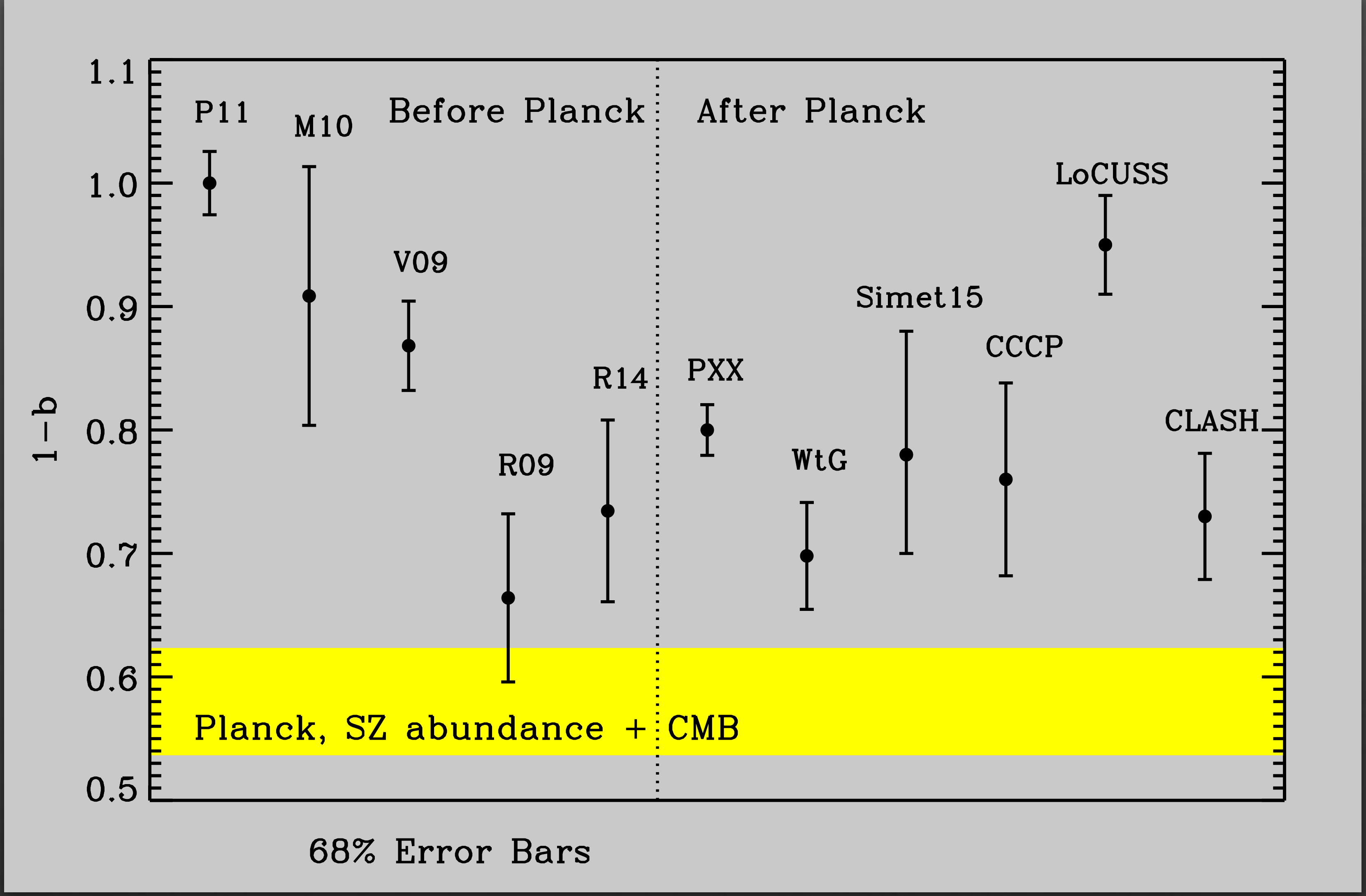
Shear Systematics



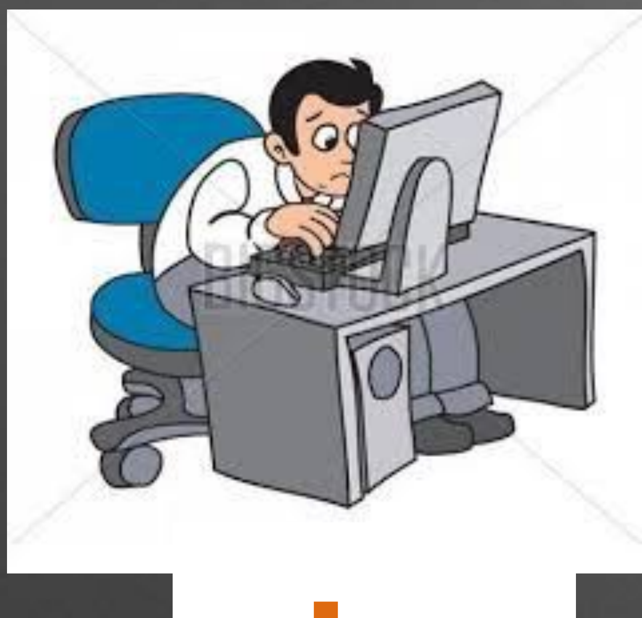
$$\longrightarrow \quad \langle \epsilon \rangle = \frac{\gamma}{1-\kappa}$$

Hydrostatic Bias

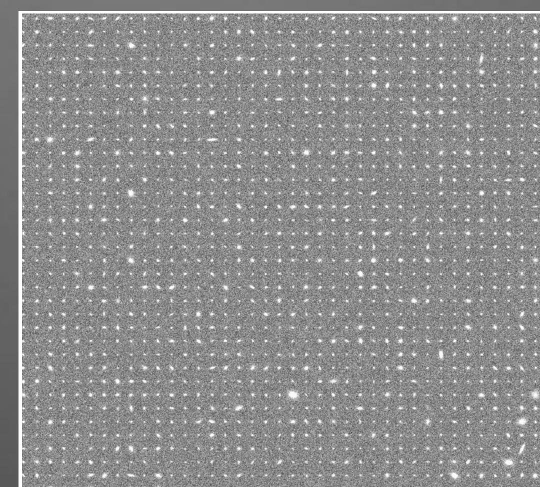
$$1 - b = \frac{M_{SZ}}{M_{true}}$$



BLIND SHEAR CHALLENGE



Analyze



~1 million galaxy images

Download

upload

feedback

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **450,** 2963–3007 (2015) doi:10.1093/mnras/stv781

GREAT3 results – I. Systematic errors in shear estimation and the impact of real galaxy morphology

Rachel Mandelbaum,[1★] Barnaby Rowe,[2★] Robert Armstrong,[3] Deborah Bard,[4,5] Emmanuel Bertin,[6] James Bosch,[3] Dominique Boutigny,[5,7] Frederic Courbin,[8] William A. Dawson,[9] Annamaria Donnarumma,[6] Ian Fenech Conti,[10] Raphaël Gavazzi,[6] Marc Gentile,[8] Mandeep S. S. Gill,[4,5] David W. Hogg,[11] Eric M. Huff,[12] M. James Jee,[13] Tomasz Kacprzak,[2,14] Martin Kilbinger,[15] Thibault Kuntzer,[8] Dustin Lang,[1] Wentao Luo,[16] Marisa C. March,[17] Philip J. Marshall,[4] Joshua E. Meyers,[4] Lance Miller,[18] Hironao Miyatake,[3,19] Reiko Nakajima,[20] Fred Maurice Ngolé Mboula,[15] Guldariya Nurbaeva,[8] Yuki Okura,[21] Stéphane Paulin-Henriksson,[15] Jason Rhodes,[22,23] Michael D. Schneider,[9] Huanyuan Shan,[8] Erin S. Sheldon,[24] Melanie Simet,[1] Jean-Luc Starck,[15] Florent Sureau,[15] Malte Tewes,[20] Kristian Zarb Adami,[10,18] Jun Zhang[25] and Joe Zuntz[26]

Affiliations are listed at the end of the paper

Accepted 2015 April 8. Received 2015 April 2; in original form 2014 December 4

ABSTRACT

We present first results from the third GRavitational lEnsing Accuracy Testing (GREAT3) challenge, the third in a sequence of challenges for testing methods of inferring weak gravitational lensing shear distortions from simulated galaxy images. GREAT3 was divided into experiments to test three specific questions, and included simulated space- and ground-based data with constant or cosmologically varying shear fields. The simplest (control) experiment included parametric galaxies with a realistic distribution of signal-to-noise, size, and ellipticity, and a complex point spread function (PSF). The other experiments tested the additional

Table 2. Table summarizing the methods used by teams that participated in the challenge, including basic information such as team name; class (overall type of method); weighting scheme; calibration philosophy (discussed in the text); and number of branches entered in the challenge ($N_{\rm branch}$). 'Limitations' refers to types of data to which the implementation used here is not applicable without significant further development. 'Rank' is the leaderboard ranking for those that received points ('-' for those that did not, and 'N/A' for those that were ineligible due to participation of a GREAT3 EC member). 'exact PSF?' indicates whether they used the exact PSF or an approximation to it (e.g. sums of Gaussians). 'New software' indicates whether the software used to analyse the GREAT3 simulations was newly developed ('yes'), included some existing infrastructure with new software of non-trivial complexity ('some'), or was entirely pre-existing ('no'). Finally, we show the approximate processing time per galaxy per exposure (on a single core) for science-quality shear estimates. Several fields are discussed in detail in Section 3.

Team	Class	Weighting scheme	Calibration philosophy	Limitations	$N_{\rm branch}$	Rank	Exact PSF?	New software	Time per galaxy
Amalgam@IAP	Maximum likelihood	Inverse variance	Ellipticity penalty	None	16	2	Yes	Some	0.1–1 s
BAMPenn	Bayesian Fourier	Implicit	$p(\varepsilon)$ from deep data	Variable shear	2	-	Yes	Yes	<1 s
EPFL_gfit	Maximum likelihood	Constant + rejection	None	None	8	6	Yes	Yes	1–3 s
CEA-EPFL	Maximum likelihood	Various	None	None	20	3	Yes	Yes	1–3 s
CEA_denoise	Moments	Constant	None	None	8	-	Yes	No	0.03 s
CMU experimenters	Stacking	Constant	External simulations	Variable shear	2	N/A	Yes	Some	0.03 s
COGS (IM3SHAPE)	Maximum likelihood	Constant	External simulations	None	12	N/A	Yes	Yes	1 s
E-HOLICS	Moments	Constant + rejection	External simulations	None	12	8	Yes	No	1–3 s
EPFL_HNN	Neural network	Constant	None	None	7	-	Yes	Yes	2–3 s
EPFL_KSB	Moments	Inverse variance	None	None	4	-	Yes	No	0.001–0.002 s
EPFL_MLP / EPFL_MLP_FIT	Neural network	Constant	None	None	5	-	Yes	Yes	2–3 s
FDNT	Fourier moments	Inverse variance	External simulations	None	12	N/A	Yes	Some	∼1 s
Fourier_Quad	Fourier moments	Various	None	None	6	5	Yes	No	0.001–0.002 s
HSC/LSST-HSM	Moments	Inverse variance	External simulations	None	4	N/A	Yes	Some	0.05 s
MBI	Bayesian hierarchical	Implicit	Inferred $p(\varepsilon)$	Variable shear, PSF	4	9	No	Some	10 s
MaltaOx (LENSFIT)	Partially Bayesian	Inverse variance	Self-calibration	None	3	7	Yes	Some	0.05 s
MegaLUT	Supervised ML	Constant + rejection	External simulations	None	16	4	Yes	Some	0.02 s
MetaCalibration	Moments + self-calibration	Inverse variance	Self-calibration	Variable shear	1	N/A	Yes	Yes	0.3 s
Wentao_Luo	Moments	Inverse variance	None	None	4	-	Yes	Yes	1–2 s
ess	Bayesian model-fitting	Implicit	$p(\varepsilon)$ from deep data	Variable shear	2	-	No	Yes	1 s
sFIT	Maximum likelihood	Inverse variance	External simulations (iterative)	None	20	1	Yes	Yes	0.8 s

Summary of Part 1

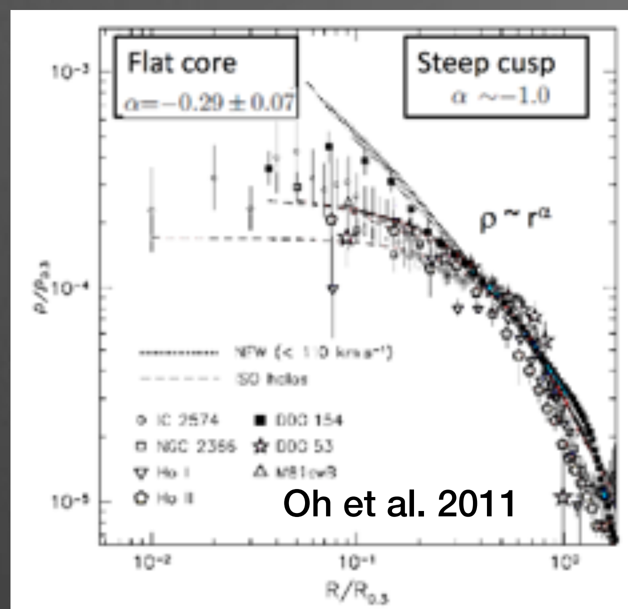
- Some European cosmic shear results are in tension with the PLANCK-CMB results.
- Some American cosmic shear results are in no tension with the PLANCK-CMB results.
- The discrepancy may arise from systematics.
- Both CFHTLens and DLS photo-z results are in reasonable agreement with the spec-z data.
- The photo-z accuracy of faint sources is currently unknown for both surveys.

OUTLINE

- Introduction: Weak-Lensing for Dummies
- Is Lensing Really in Tension with CMB?
- How Can We Use Colliding Clusters as Cosmic Particle Accelerators?
- Conclusions

SIDM Motivation

Core-Cusp Problem:



Missing Satellite Problem:

Tully-Fisher ZP problem:

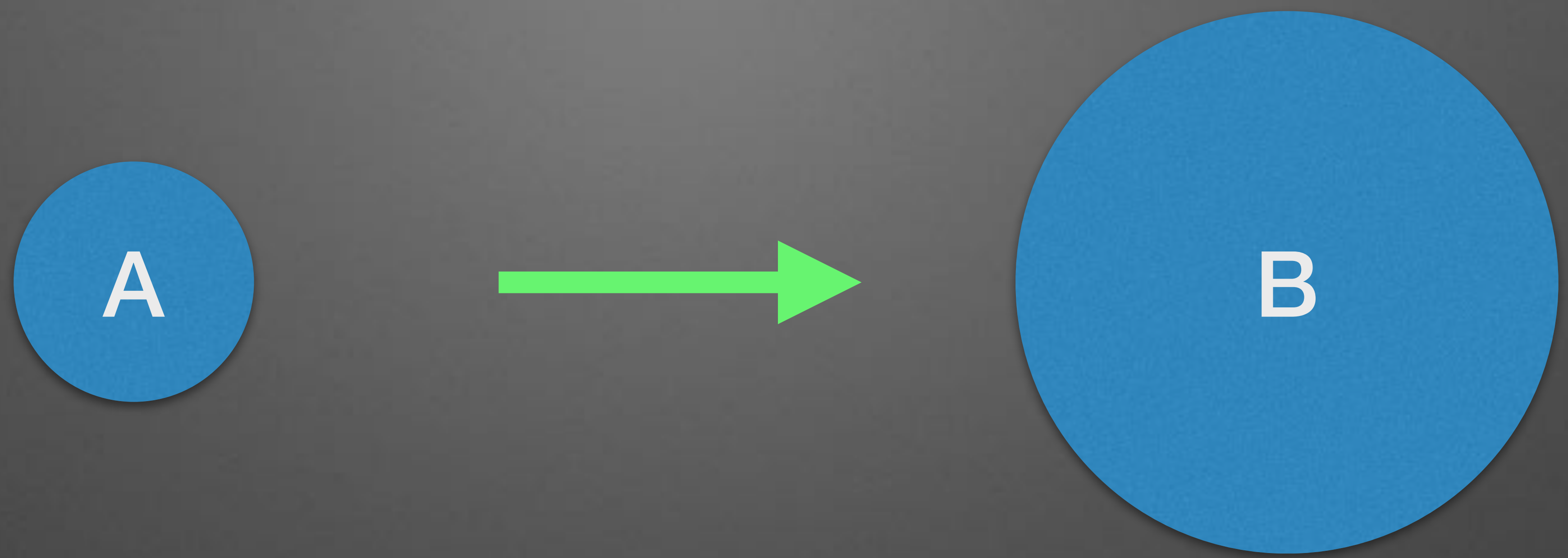
Requires c~7

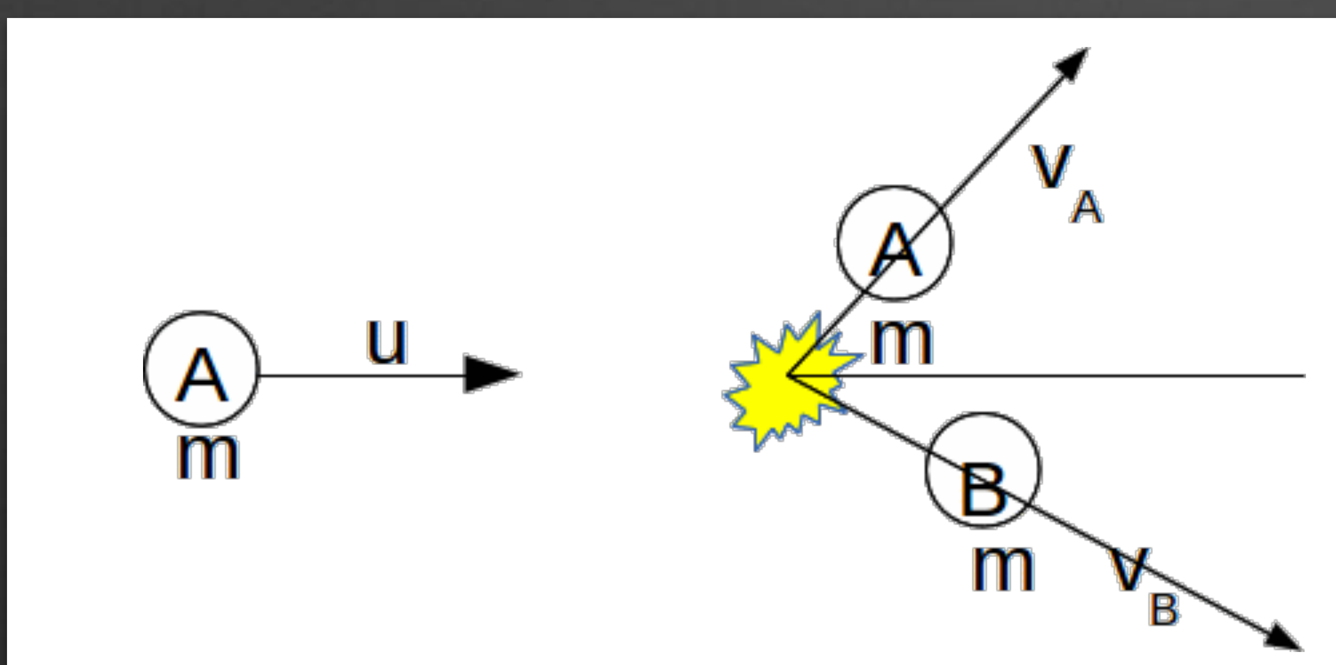
Simulations show c~20

Bar Stability:

Stable bars mean the core density is low.

Consequences of SIDM in Merging





1. Evaporation
2. Slow down

Evaporation Argument

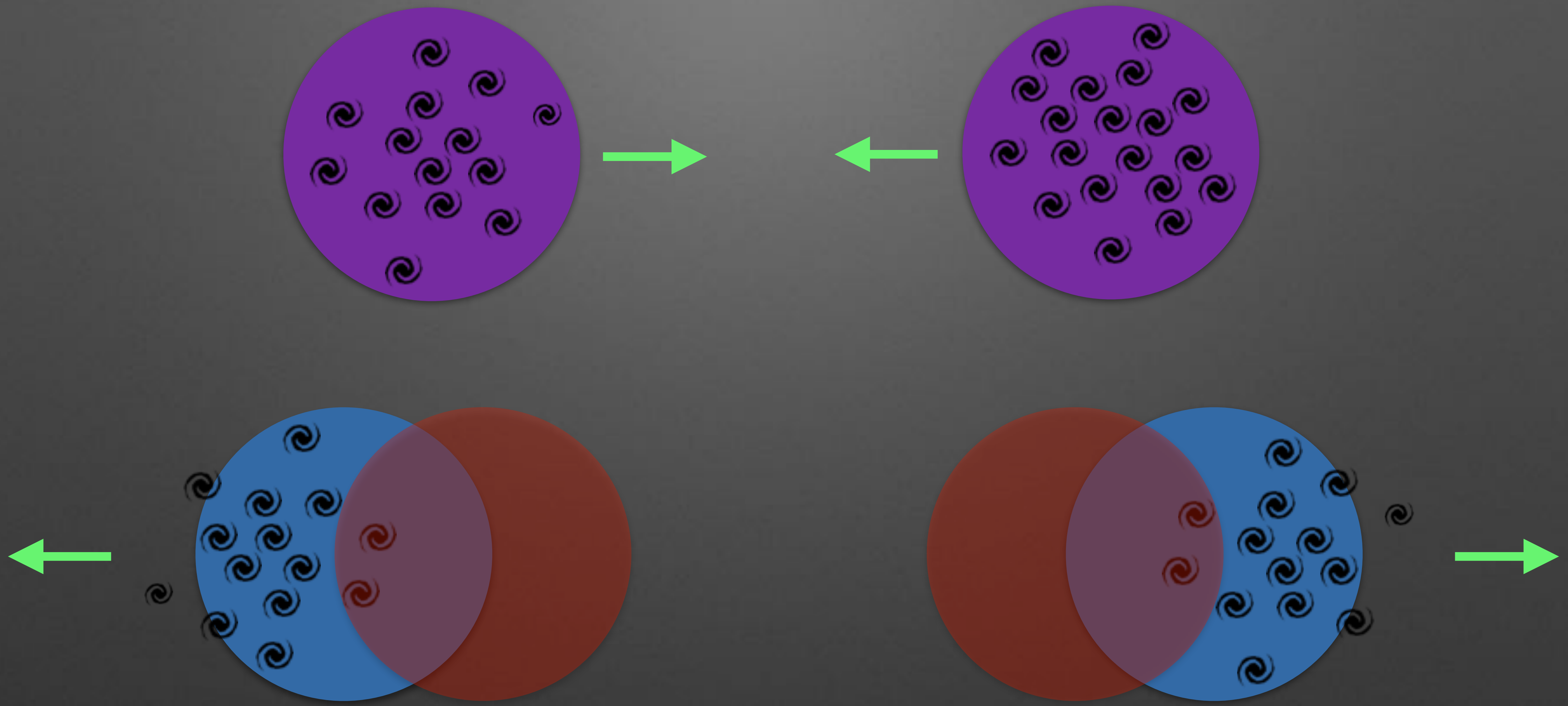
Markevitch et al. (2004) suggest

that from the survival of the subhalo

$$\frac{\sigma}{m} < 1\mathrm{cm}^2/g$$

However, this only provides an upper limit.

Drag Argument



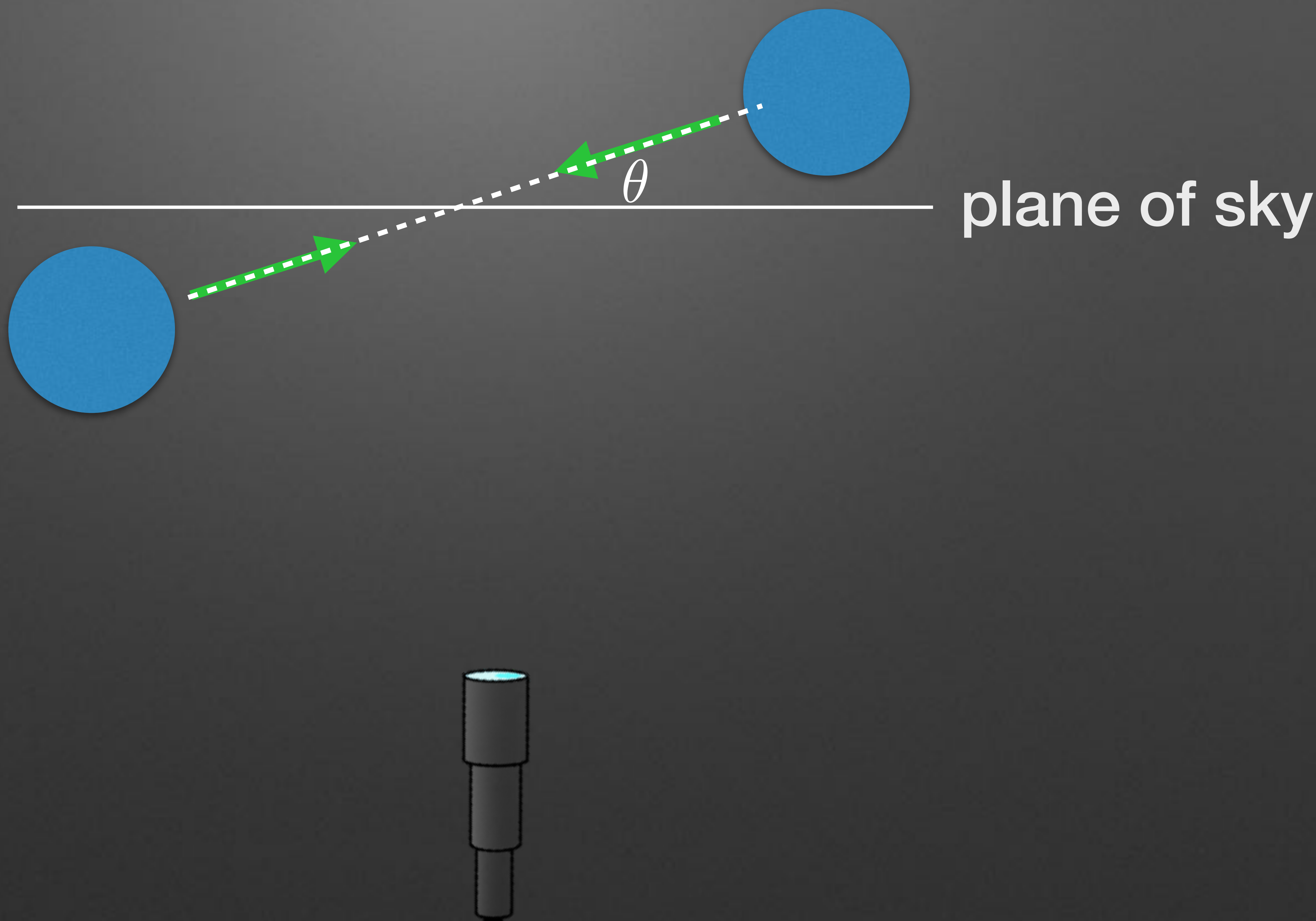
How did it happen?

Damages, Tire Tracks, Orientations, Debris, etc.

Some Practical Issues

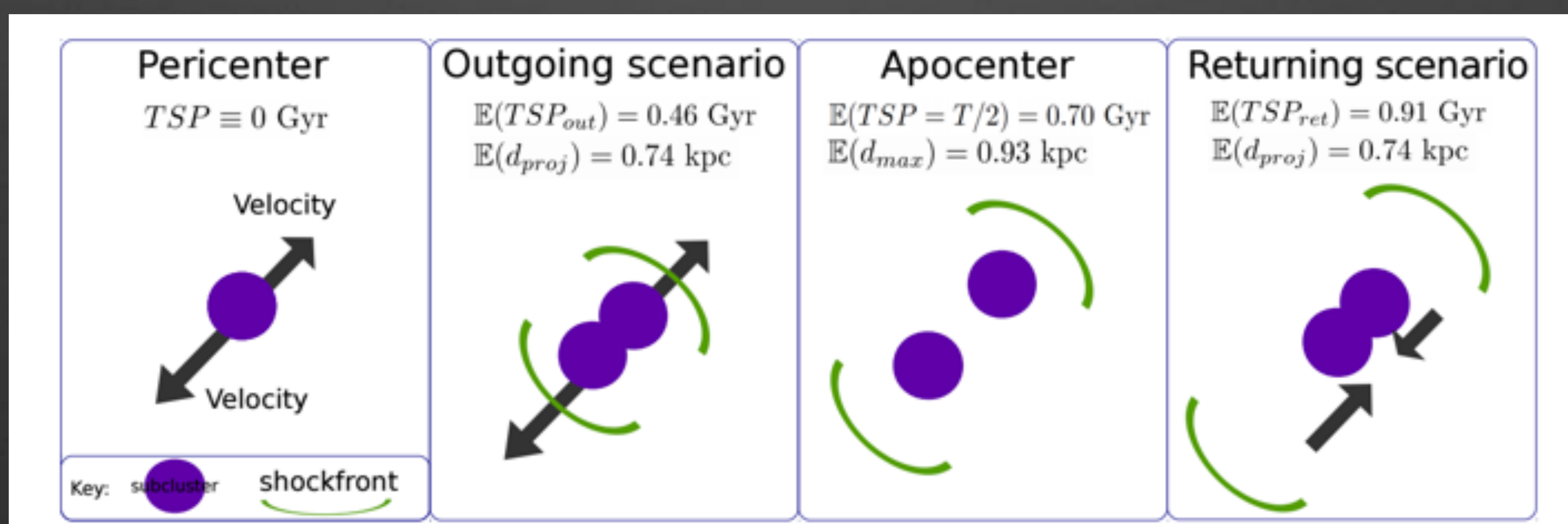
- Viewing angle (merger geometry) is unknown.
- Collision velocity is uncertain.
- Stage of merger is ambiguous.
- Impact parameter has to be inferred.
- Weak-lensing is noisy.

Viewing Angle-Collision Speed Degeneracy

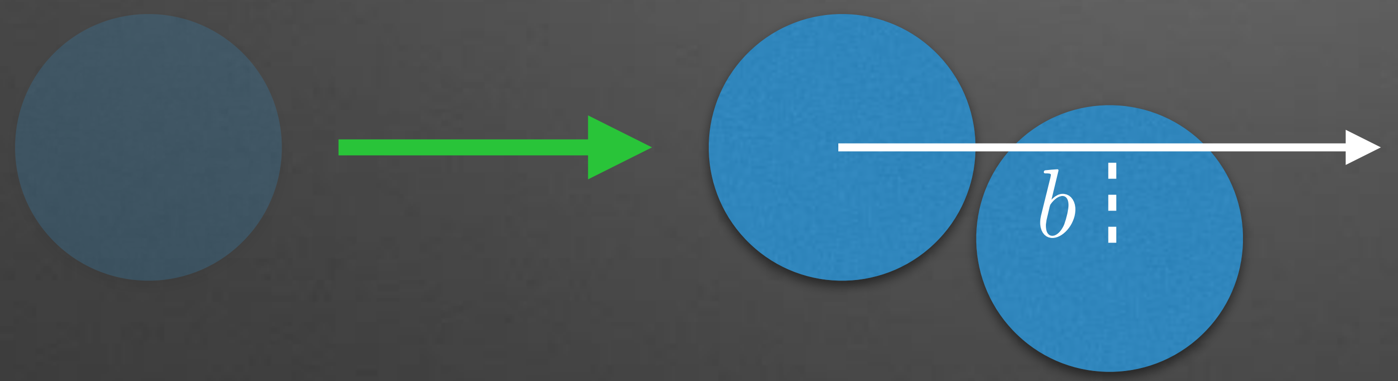


Merger Stage Ambiguity

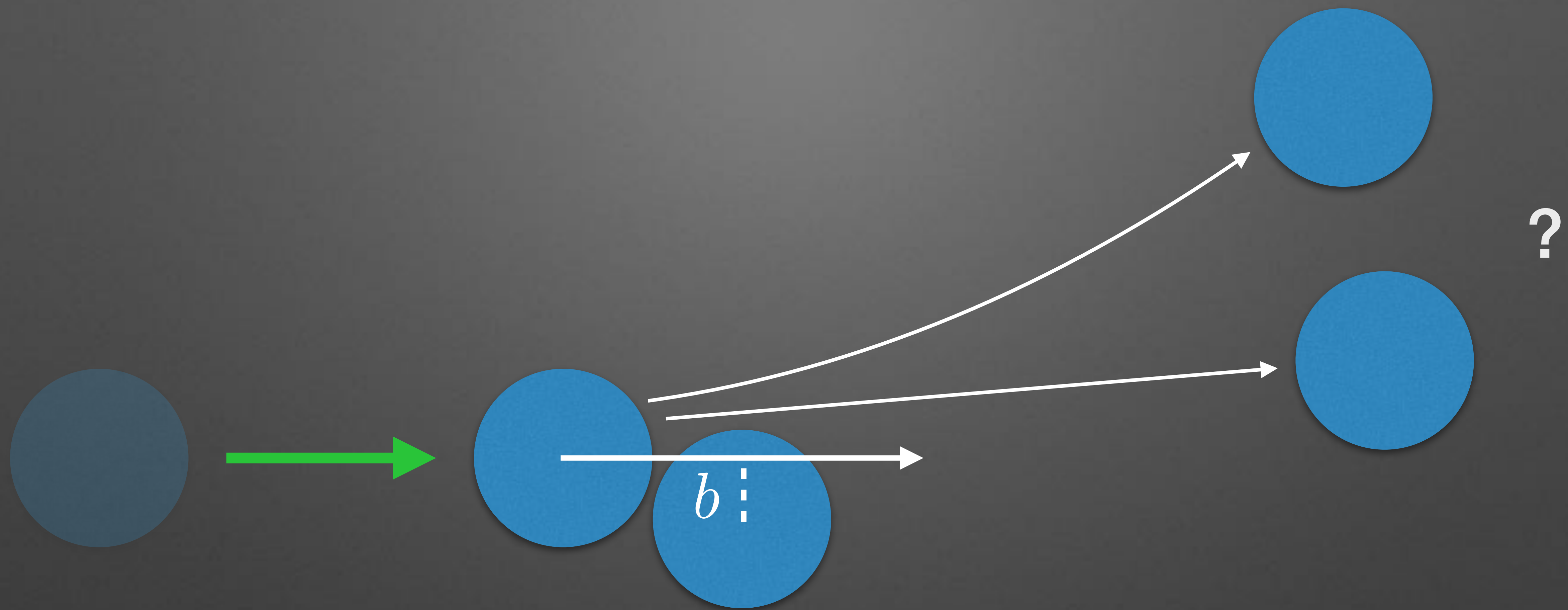
"El Gordo"



Impact Parameter Uncertainty

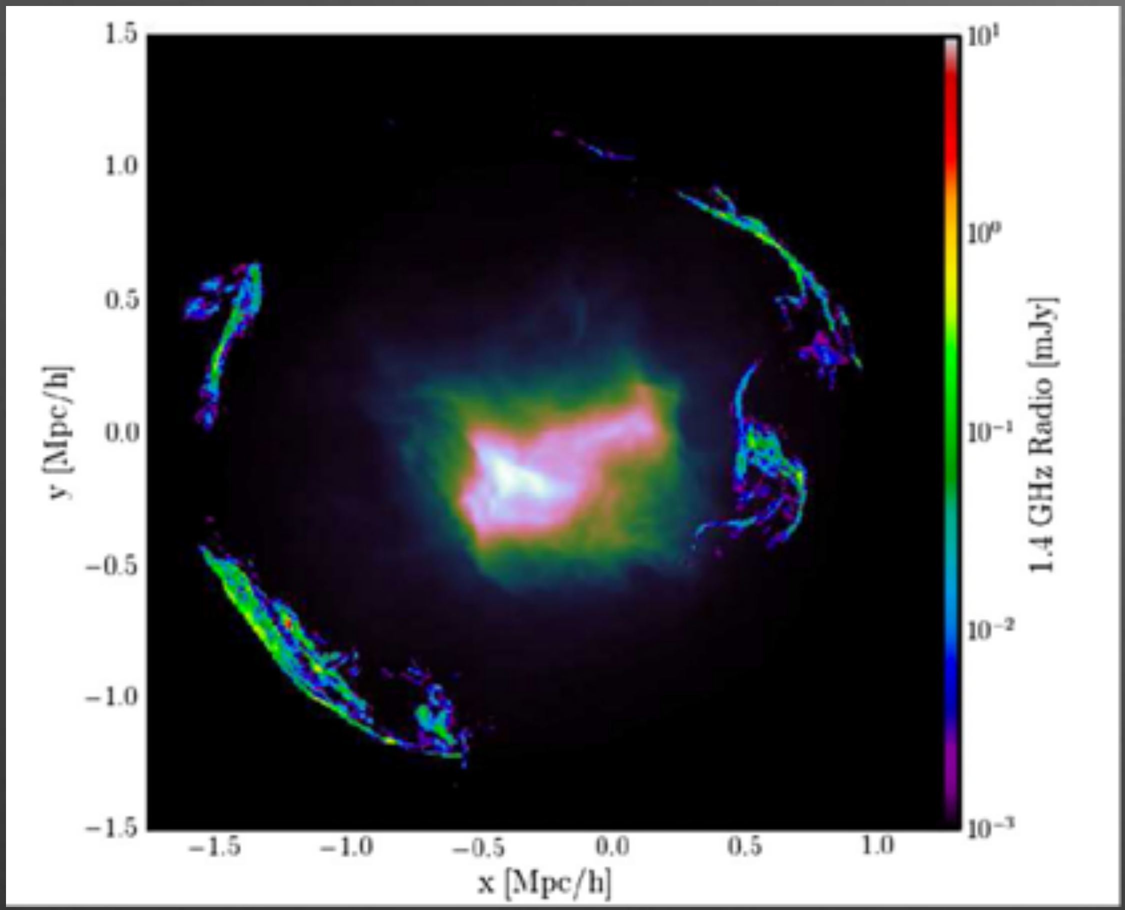


Impact Parameter Uncertainty

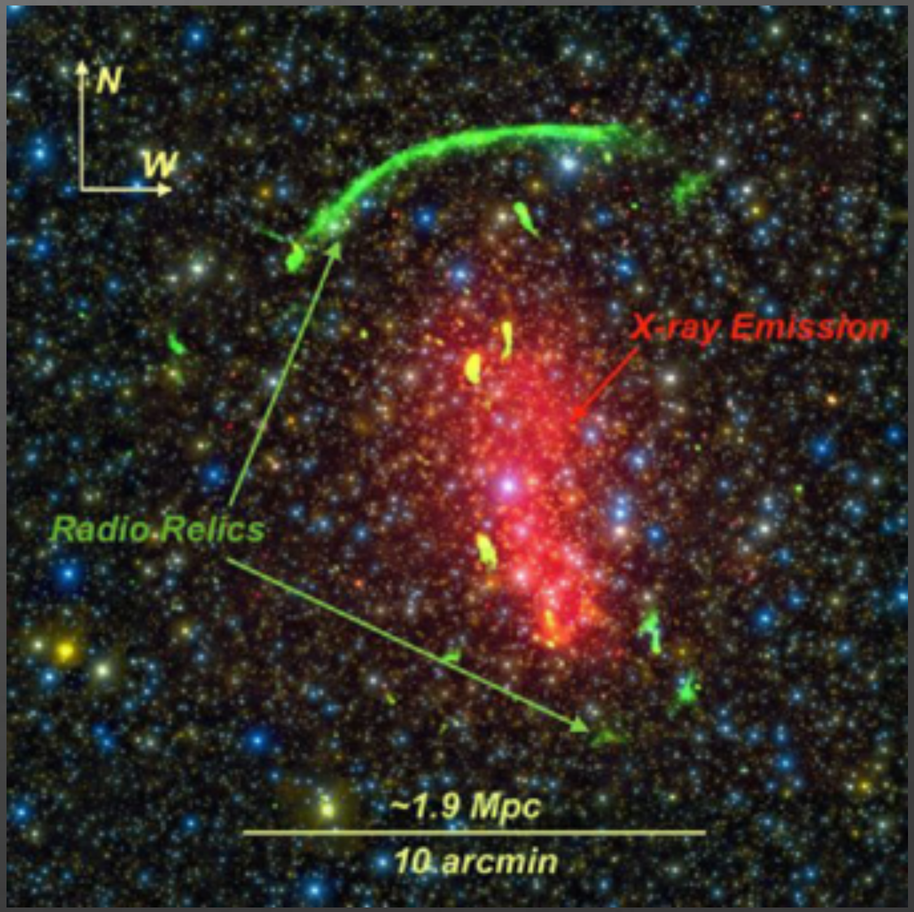


Degenerate with collision velocity, viewing angle, and offset interpretation.

Radio Relics

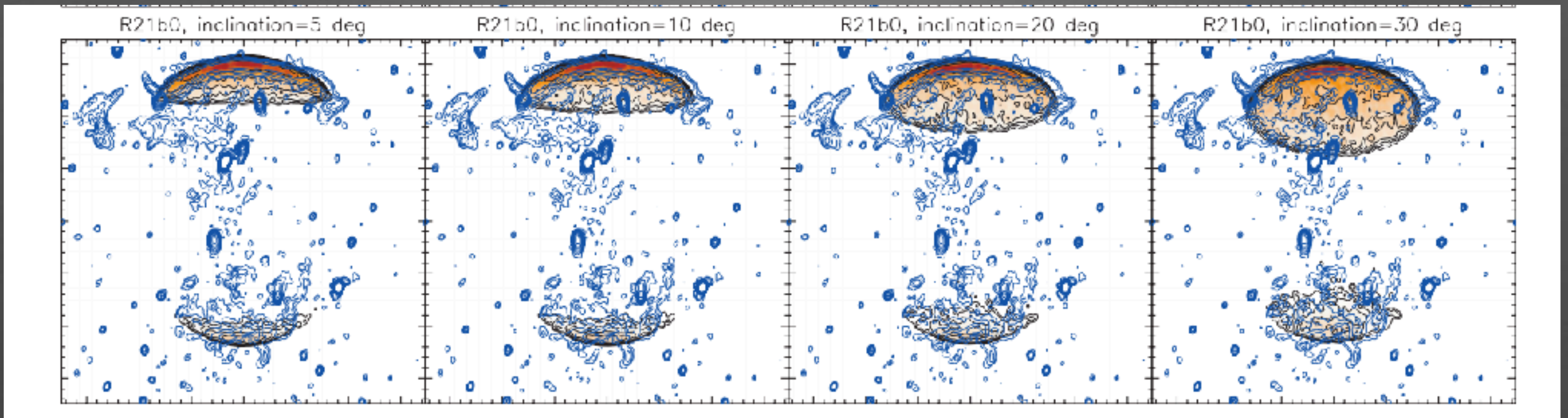


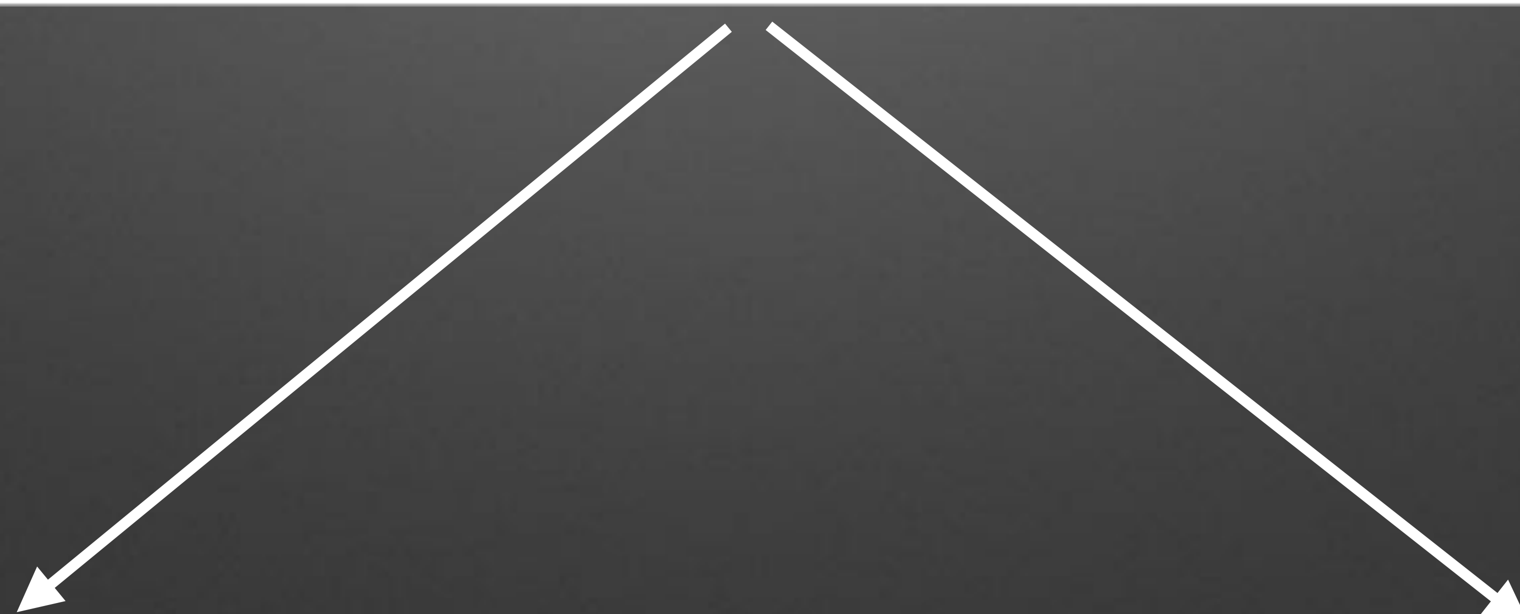
Skillman et al. (2013)



van Wereen et al. (2010)

Viewing Angle Constraint with Radio Relic



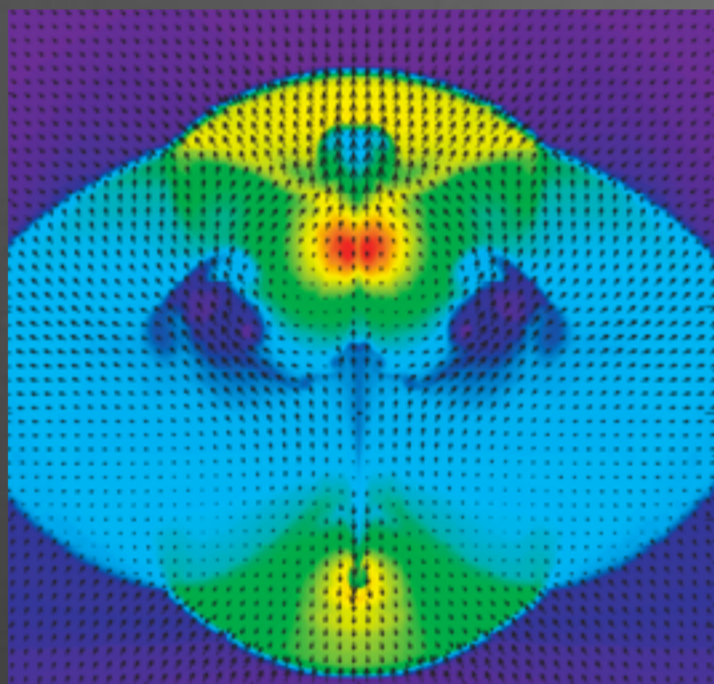


Thickness of Relic

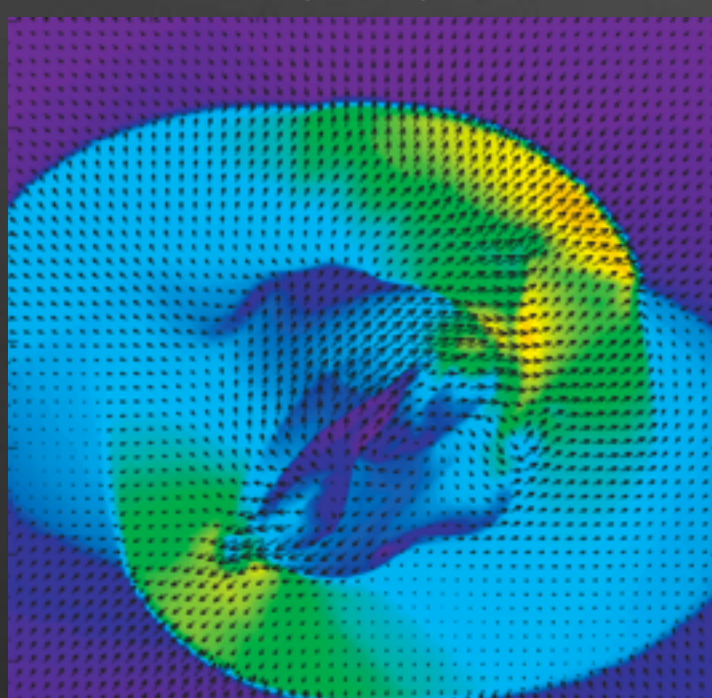
Polarization Fraction

Impact Parameter Constraint

van Wereen et al. (2011)



b=0

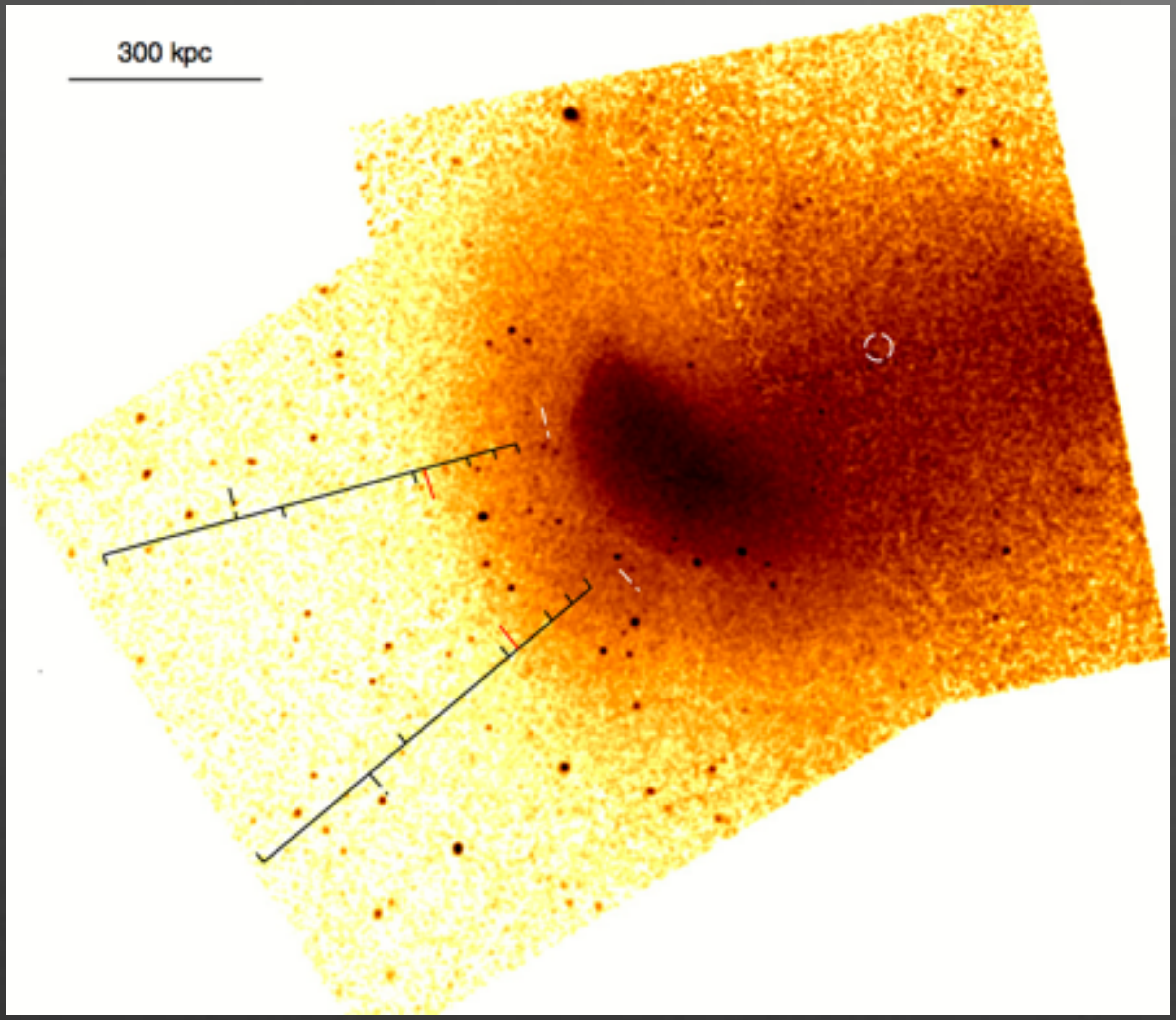


b~400 kpc

Radio relics and X-ray galaxy offsets constrain impact parameters.

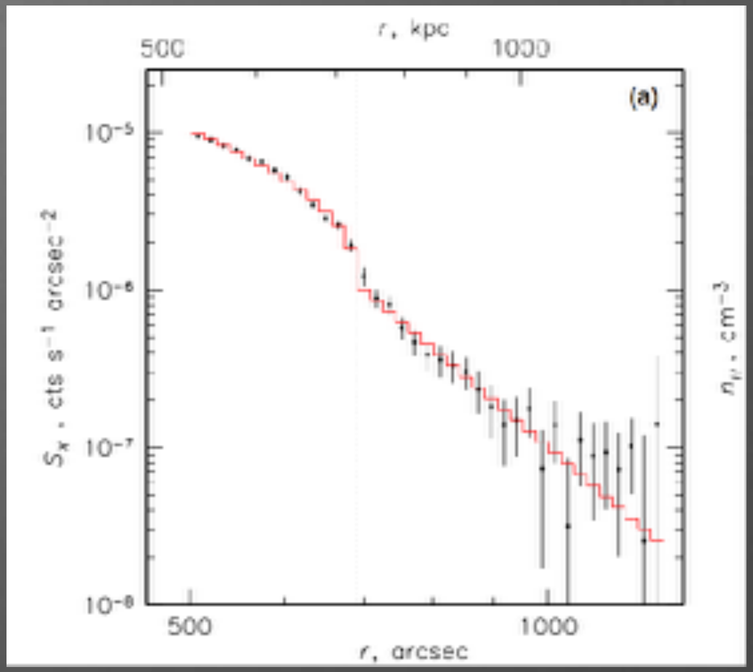
Collision Velocity Constrain (X-ray)

A754

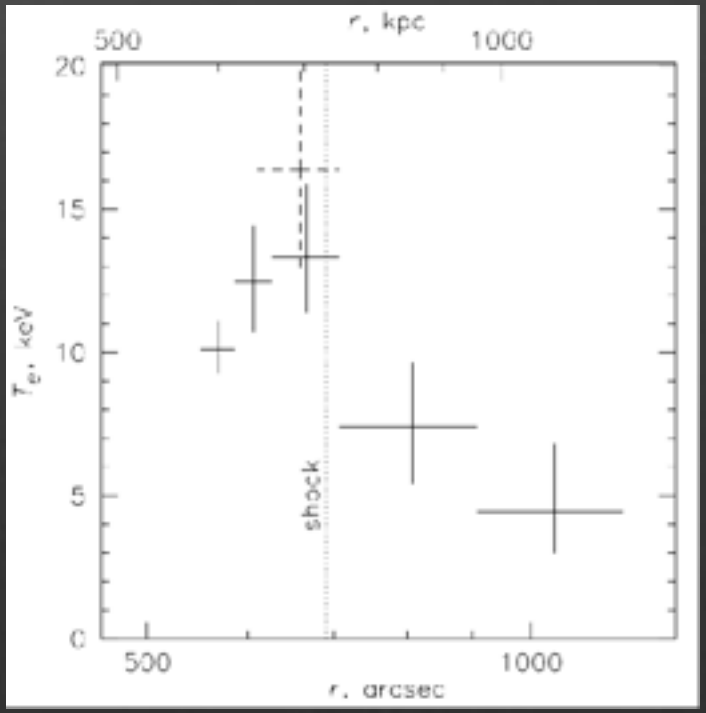


Marcario et al. (2011)

Surface Brightness

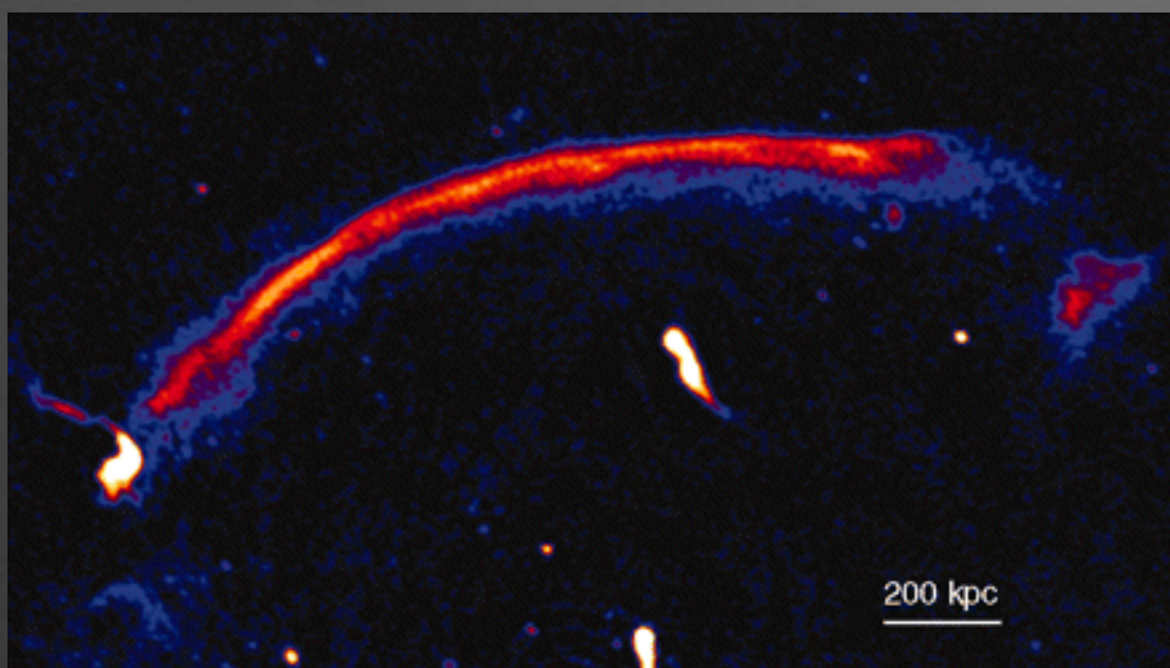


Temperature

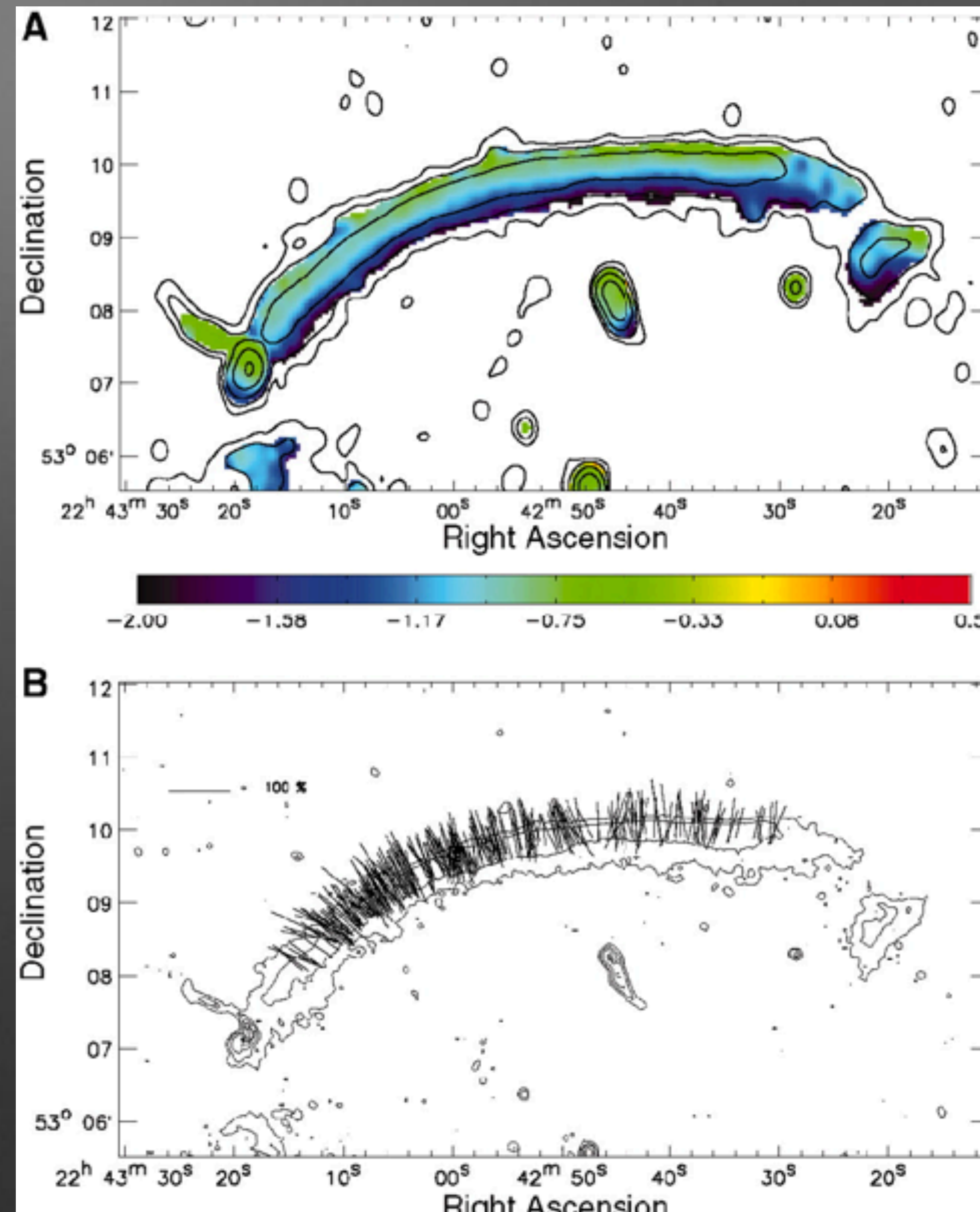


Collision Velocity Constrain (Radio)

"Sausage"

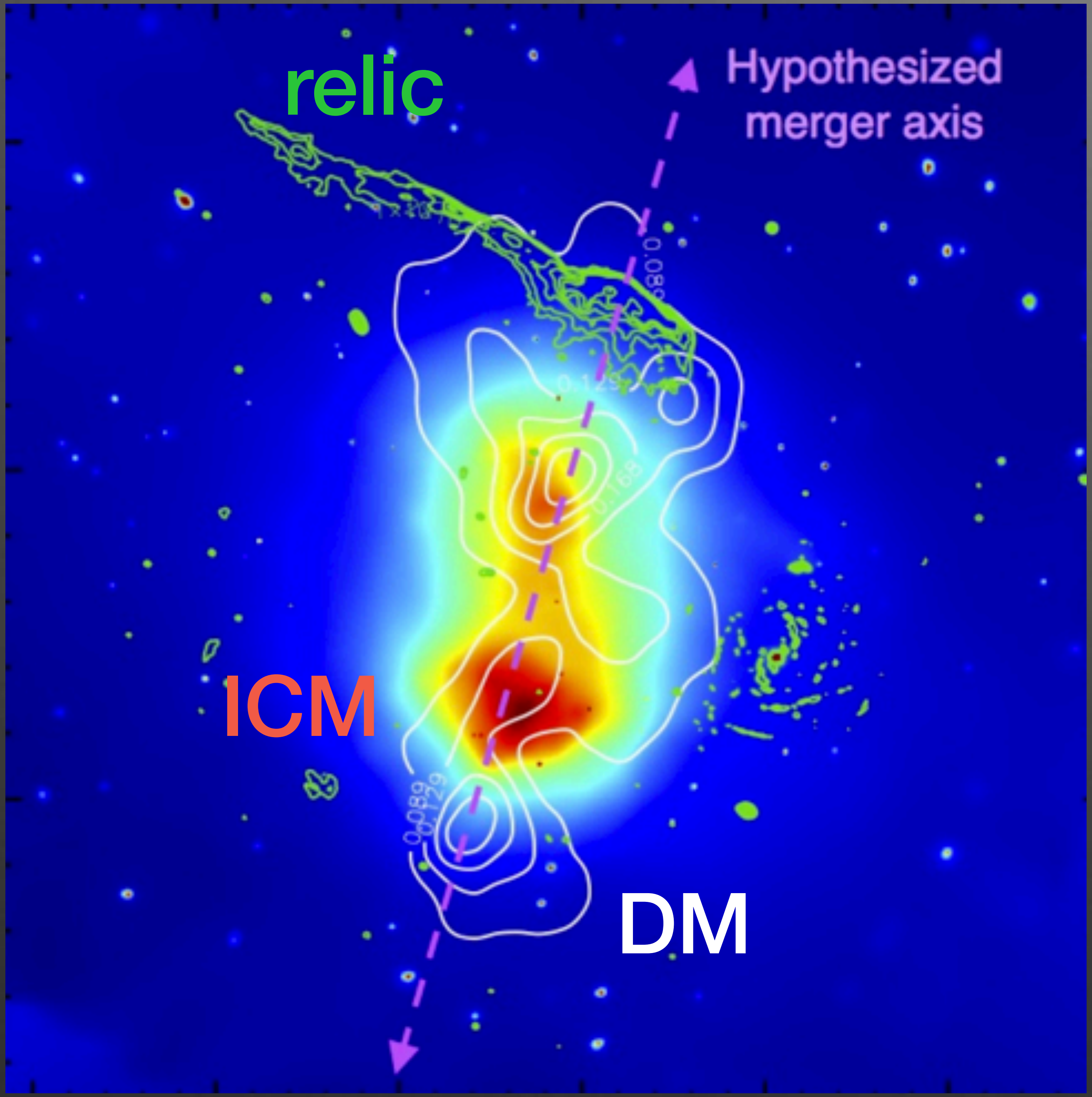


van Wereen et al. (2010)



Resolving the Stage of Mergers

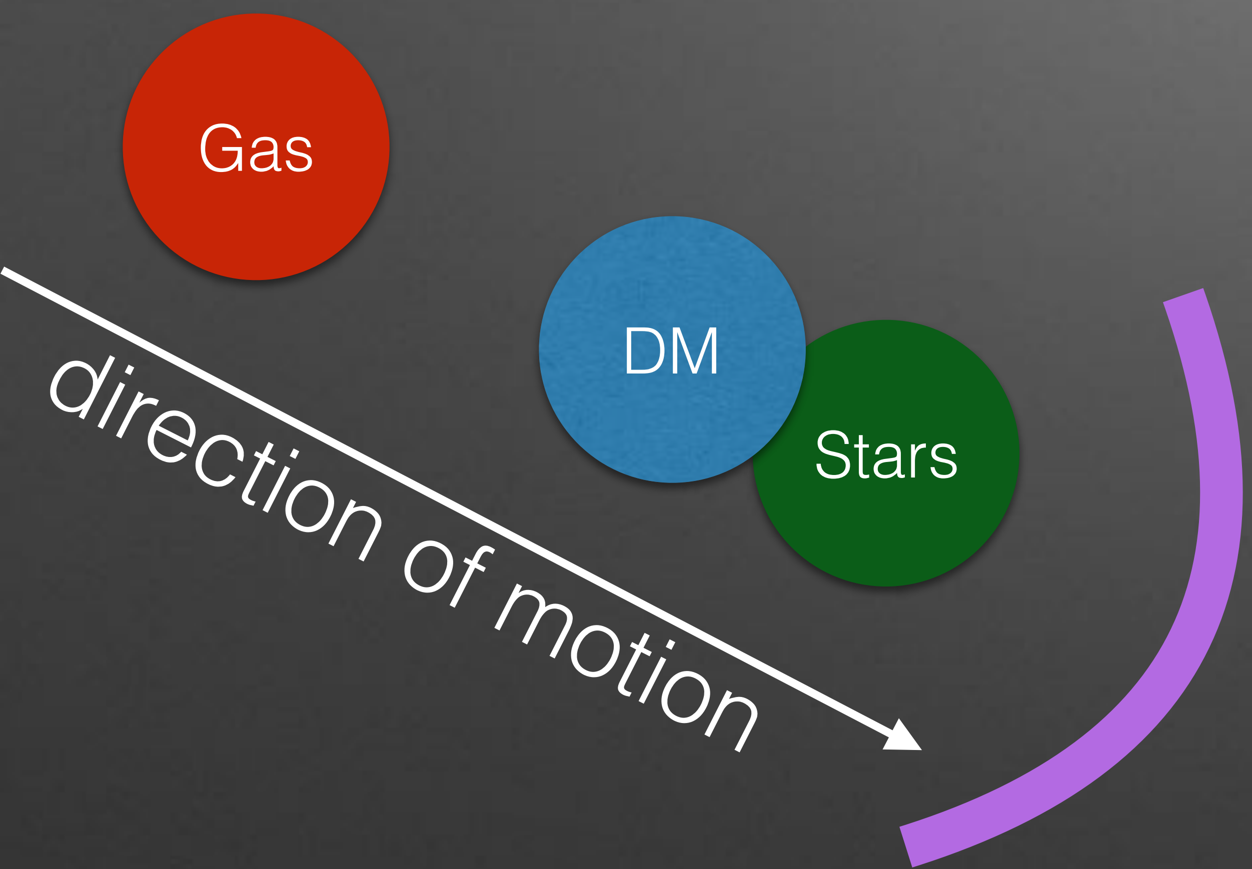
"Toothbrush"



Jee et al. (2016)

- Clear offsets among the relics, x-ray peaks, and mass clumps.
- Offsets between mass and ICM are indicative of the velocity direction.
- The location of relics traces the shock fronts and refines the merger stage.

Essential Components of Merger Scenario Reconstruction



- X-ray: ICM distribution, shock location, collision velocity, impact parameter, etc.
- Radio: relic locations, viewing angle, merger trajectory, collision velocity, impact parameter, etc.
- Optical: galaxy distributions, M/L estimation, etc.
- Weak-lensing: cluster mass, DM distribution, SIDM, etc.
- Numerical simulations: reproduction of observed features, SIDM, etc.

MC²
Merging Cluster Collaboration


Andra Stroe


Marcus Bruggen


James Bullock


Reinout van Wereen


Annika Peter


Natan Golovich


Will Dawson

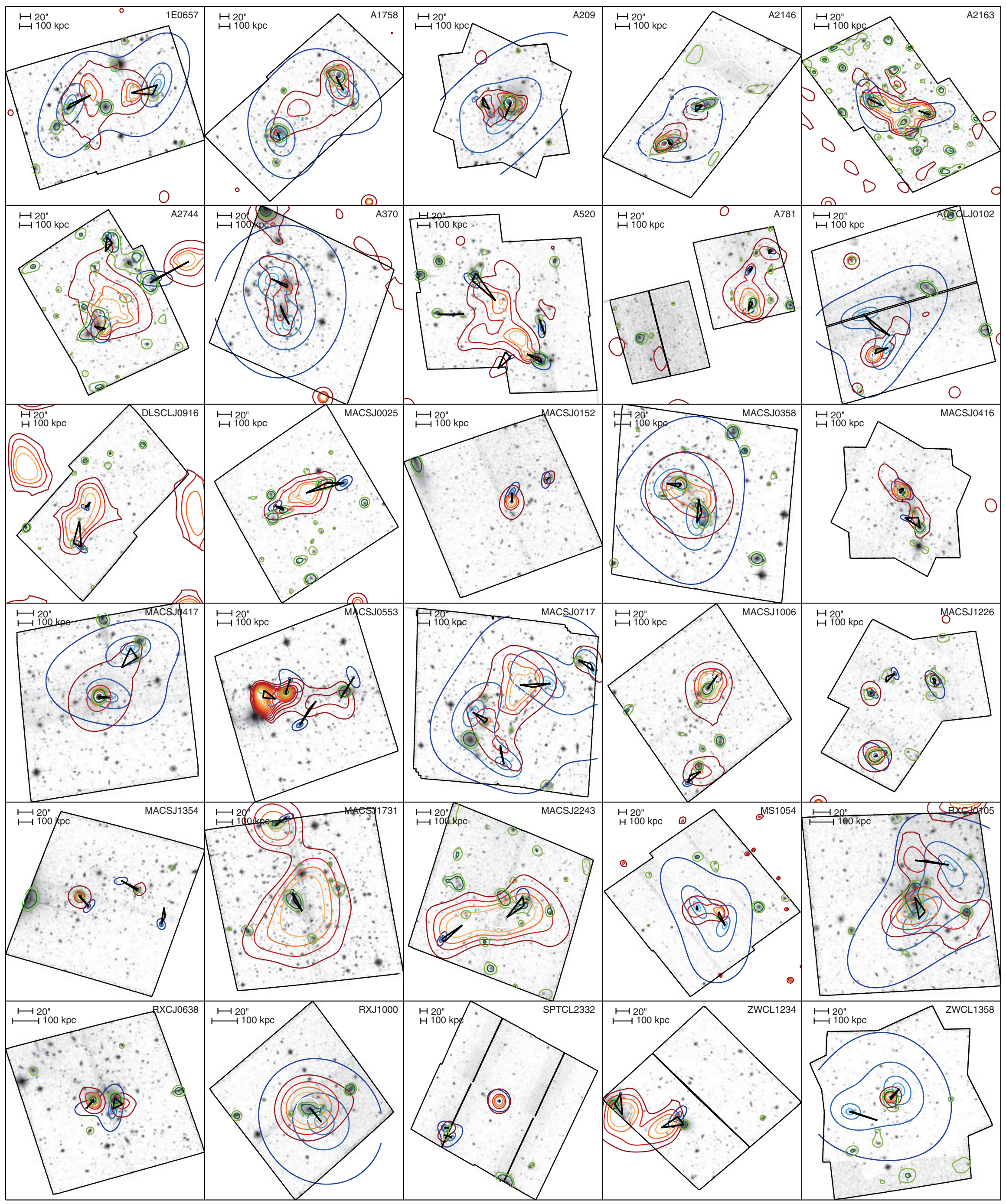

James Jee


Manoj Kaplinghat


Andisheh Mahdavi


Dave Wittman

And many more



Harvey et al. (2015)

The nongravitational interactions of dark matter in colliding galaxy clusters

David Harvey,[1,2]* Richard Massey,[3] Thomas Kitching,[4] Andy Taylor,[2] Eric Tittley[2]

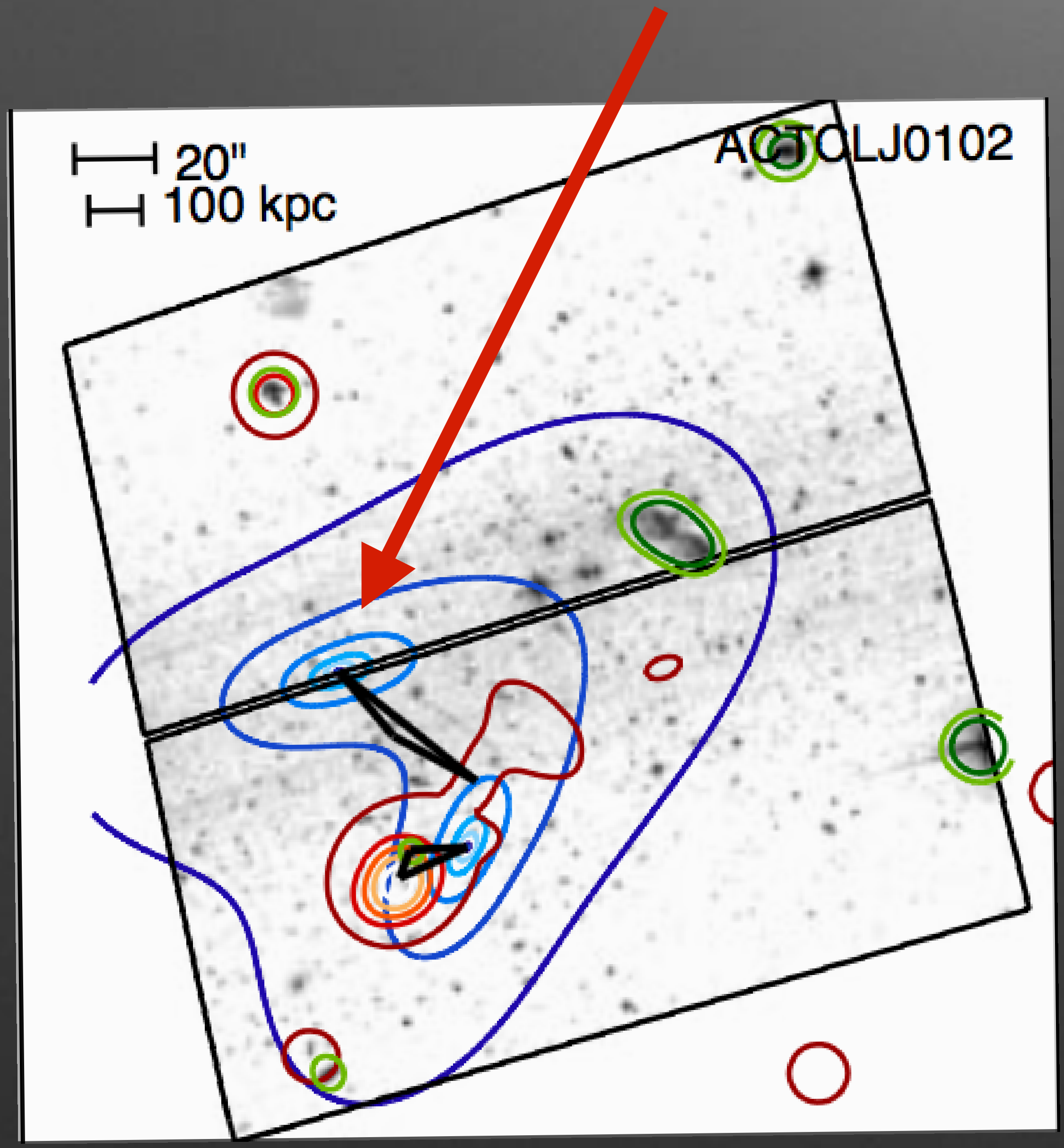
Collisions between galaxy clusters provide a test of the nongravitational forces acting on dark matter. Dark matter's lack of deceleration in the "bullet cluster" collision constrained its self-interaction cross section $\sigma_{DM}/m < 1.25$ square centimeters per gram (cm^2/g) [68% confidence limit (CL)] (σ_{DM}, self-interaction cross section; m, unit mass of dark matter) for long-ranged forces. Using the Chandra and Hubble Space Telescopes, we have now observed 72 collisions, including both major and minor mergers. Combining these measurements statistically, we detect the existence of dark mass at 7.6σ significance. The position of the dark mass has remained closely aligned within 5.8 ± 8.2 kiloparsecs of associated stars, implying a self-interaction cross section $\sigma_{DM}/m < 0.47$ cm^2/g (95% CL) and disfavoring some proposed extensions to the standard model.

$\sigma_{DM}/m < 0.47\ \mathrm{cm}^2/\mathrm{g}$

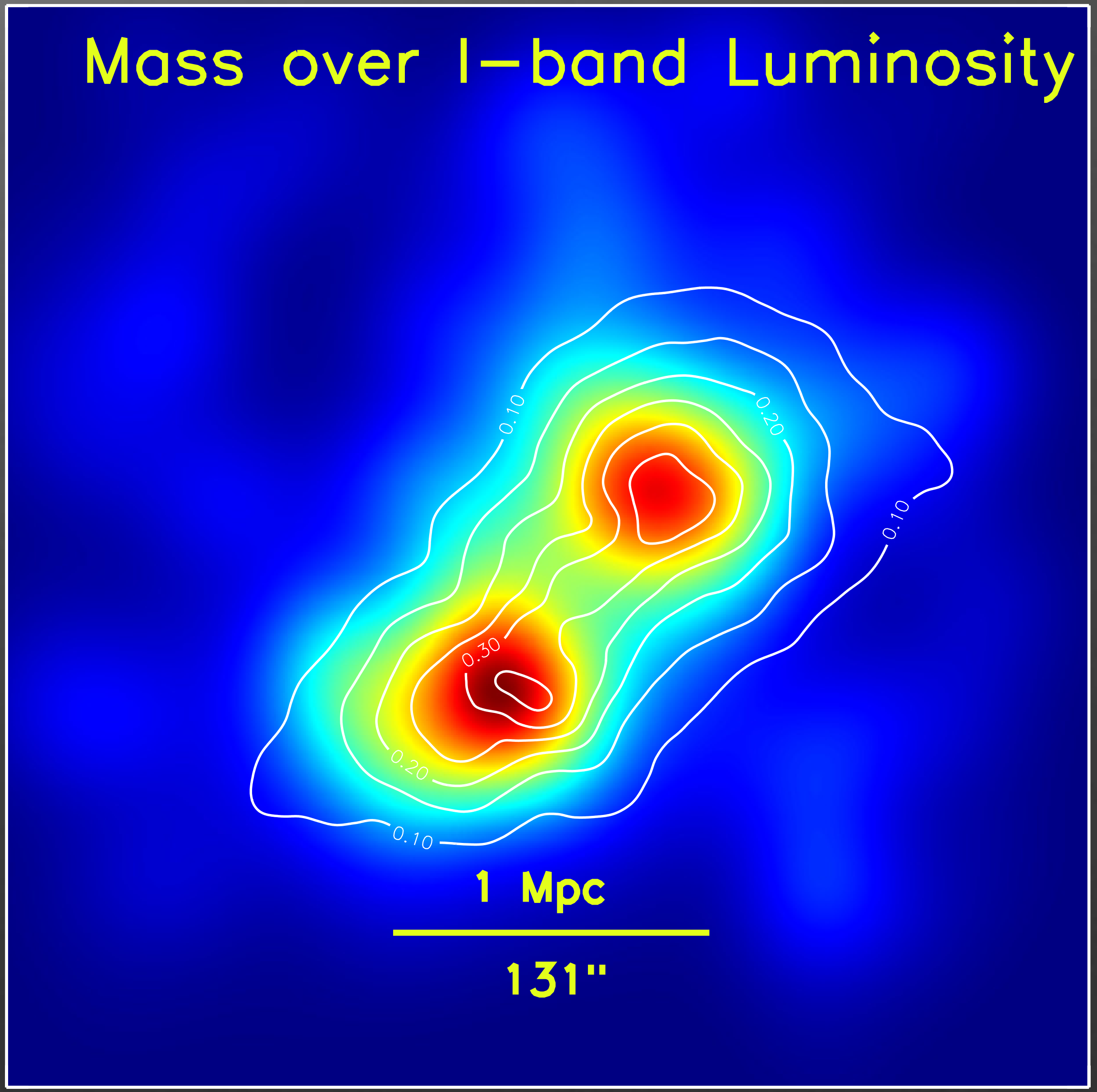
30 merging clusters

Mismeasure of Mergers

a ghost peak



Harvey et al. (2015)



Jee et al. (2014)

DRAFT VERSION JANUARY 23, 2017
Preprint typeset using LaTeX style emulateapj v. 01/23/15

THE MISMEASURE OF MERGERS: REVISED LIMITS ON SELF-INTERACTING DARK MATTER IN MERGING GALAXY CLUSTERS

DAVID WITTMAN[1,2], NATHAN GOLOVICH[1], WILLIAM A. DAWSON[3]

Draft version January 23, 2017

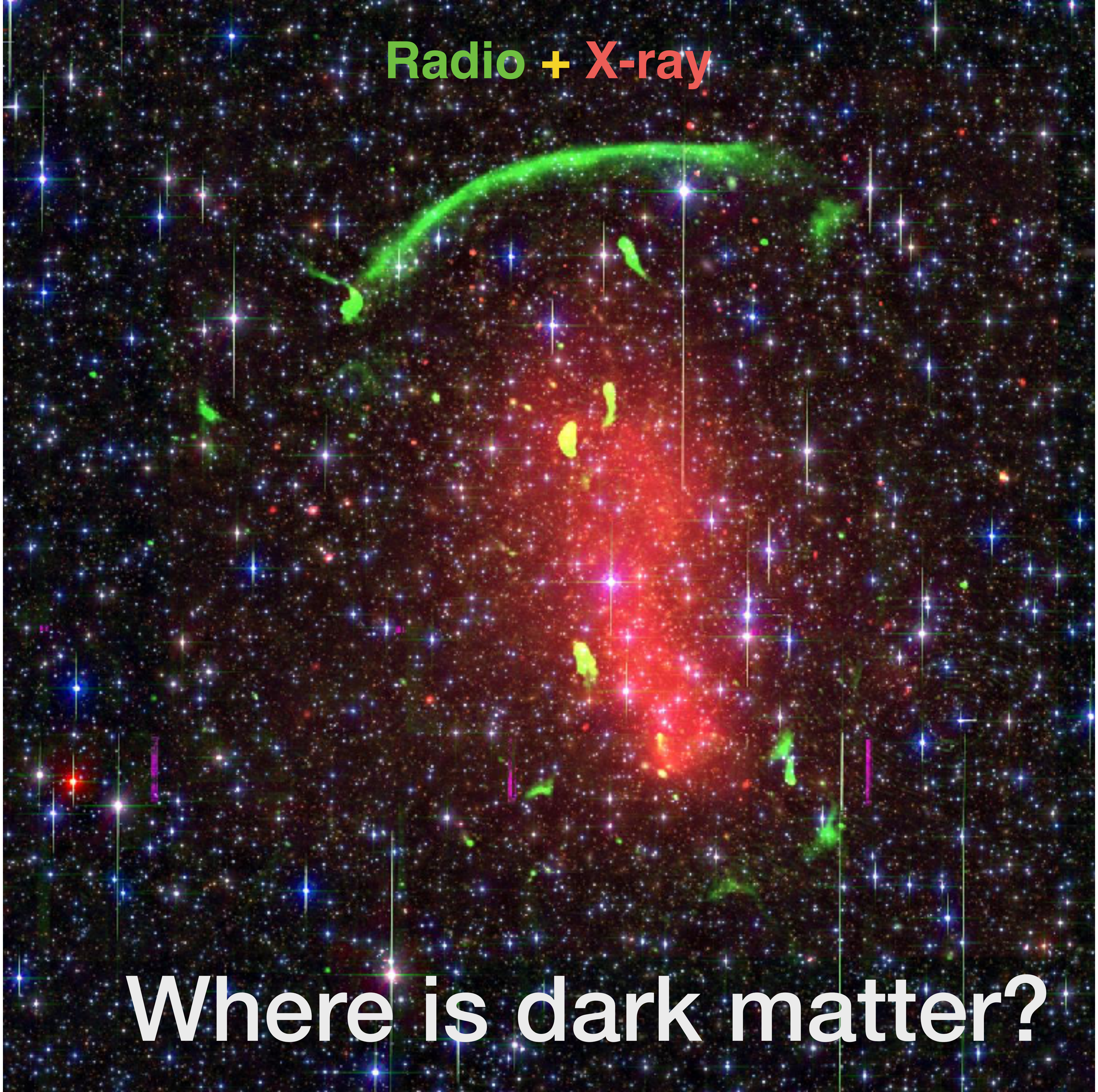
ABSTRACT

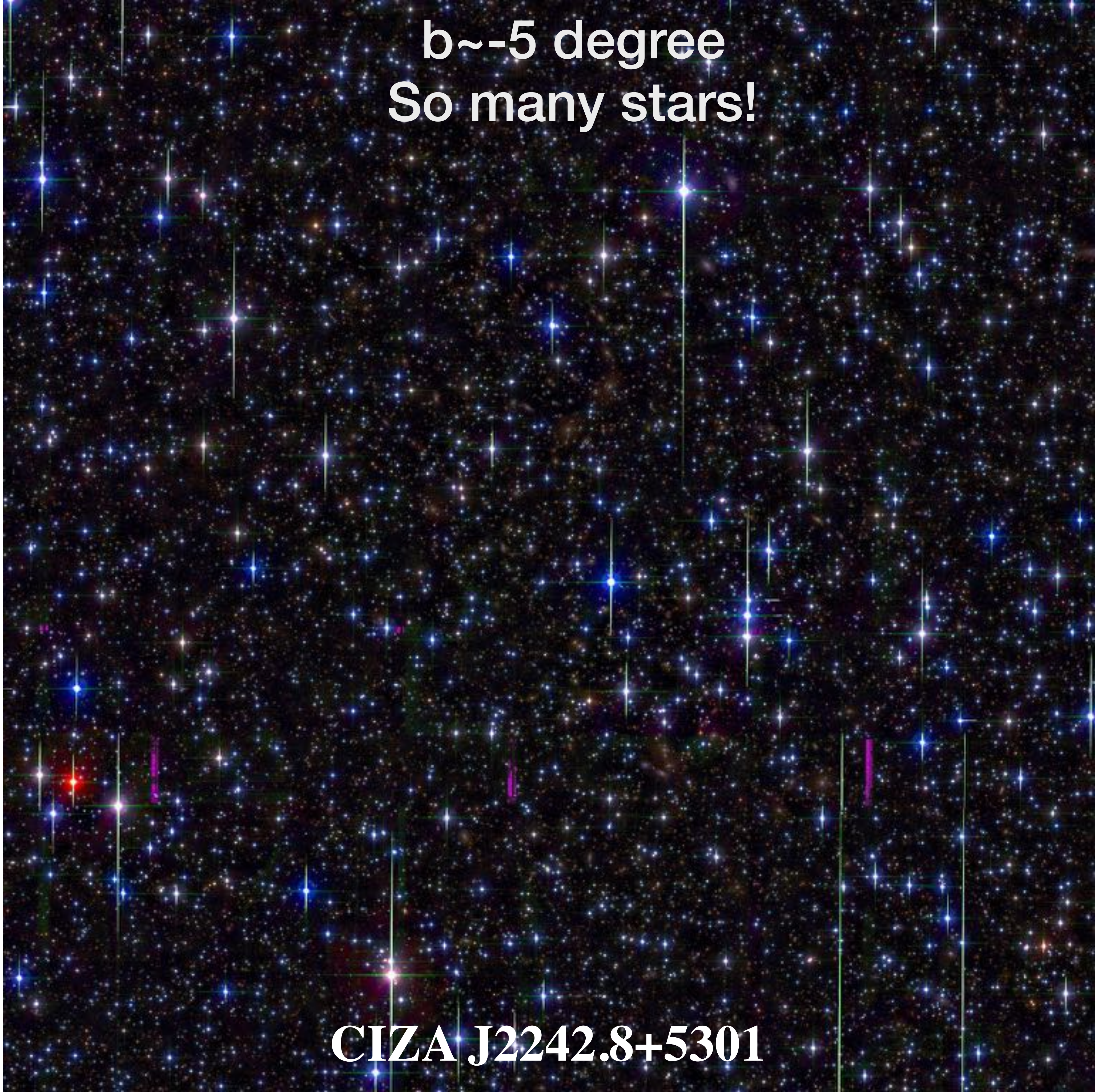
In an influential recent paper, Harvey et al. (2015) derive an upper limit to the self-interaction cross section of dark matter ($\sigma_{\rm DM}/m < 0.47$ cm^2/g at 95% confidence) by averaging the dark matter-galaxy offsets in a sample of merging galaxy clusters. Using much more comprehensive data on the same clusters, we identify several substantial errors in their offset measurements. Correcting these errors relaxes the upper limit on $\sigma_{\rm DM}/m$ to $\lesssim 2$ cm^2/g, if we follow the Harvey et al. (2015) prescription for relating offsets to cross sections. Furthermore, many clusters in the sample violate the assumptions behind this prescription, so even this revised upper limit should be used with caution. Although this particular sample does not tightly constrain self-interacting dark matter models when analyzed this way, we discuss how merger ensembles may be used more effectively in the future.

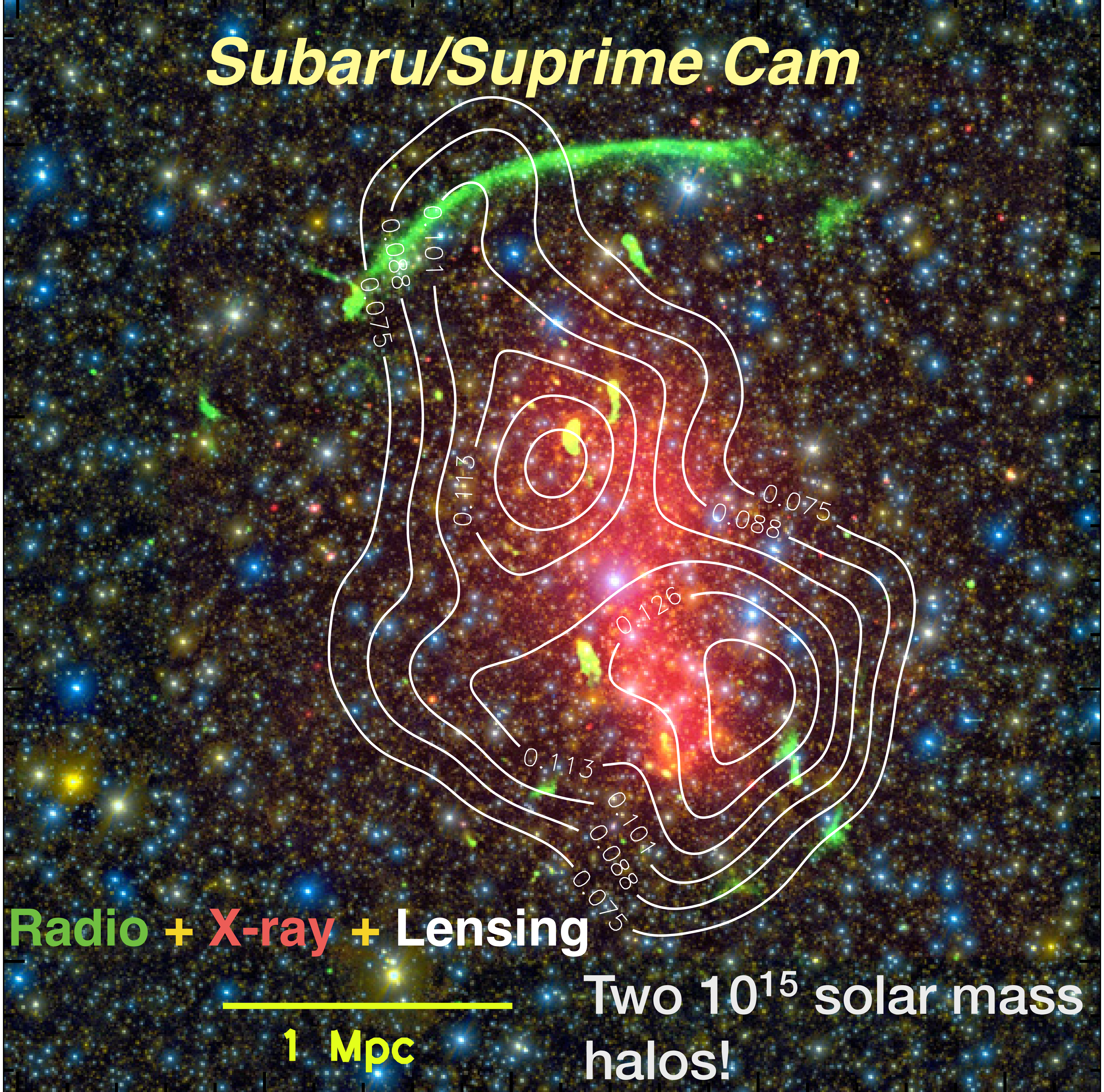
- Questionable WL results for >~10 clusters
- Neglecting the stage of mergers
- Inhomogeneous sample
- No SIDM simulations

$\sigma_{\rm DM}/m < 0.47$ cm^2/g at 95% confidence → $\sigma_{\rm DM}/m$ to $\lesssim 2$ cm^2/g

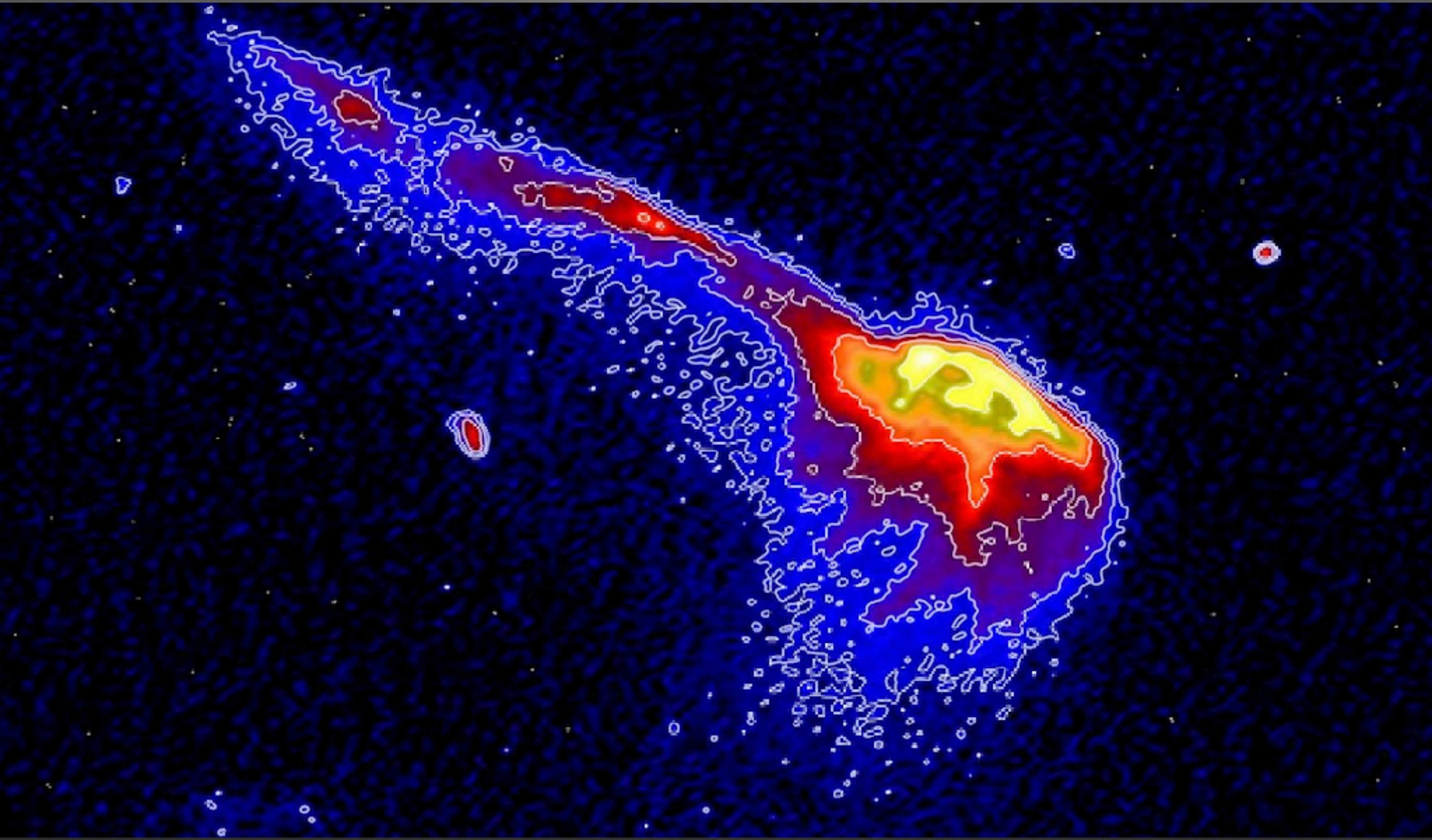
MC^2 Highlights


Radio + X-ray
Where is dark matter?


b~-5 degree
So many stars!
CIZA J2242.8+5301



Subaru/Suprime Cam
0.075
0.088
0.101
0.113
0.126
Radio + X-ray + Lensing
1 Mpc
Two 10^{15} solar mass halos!

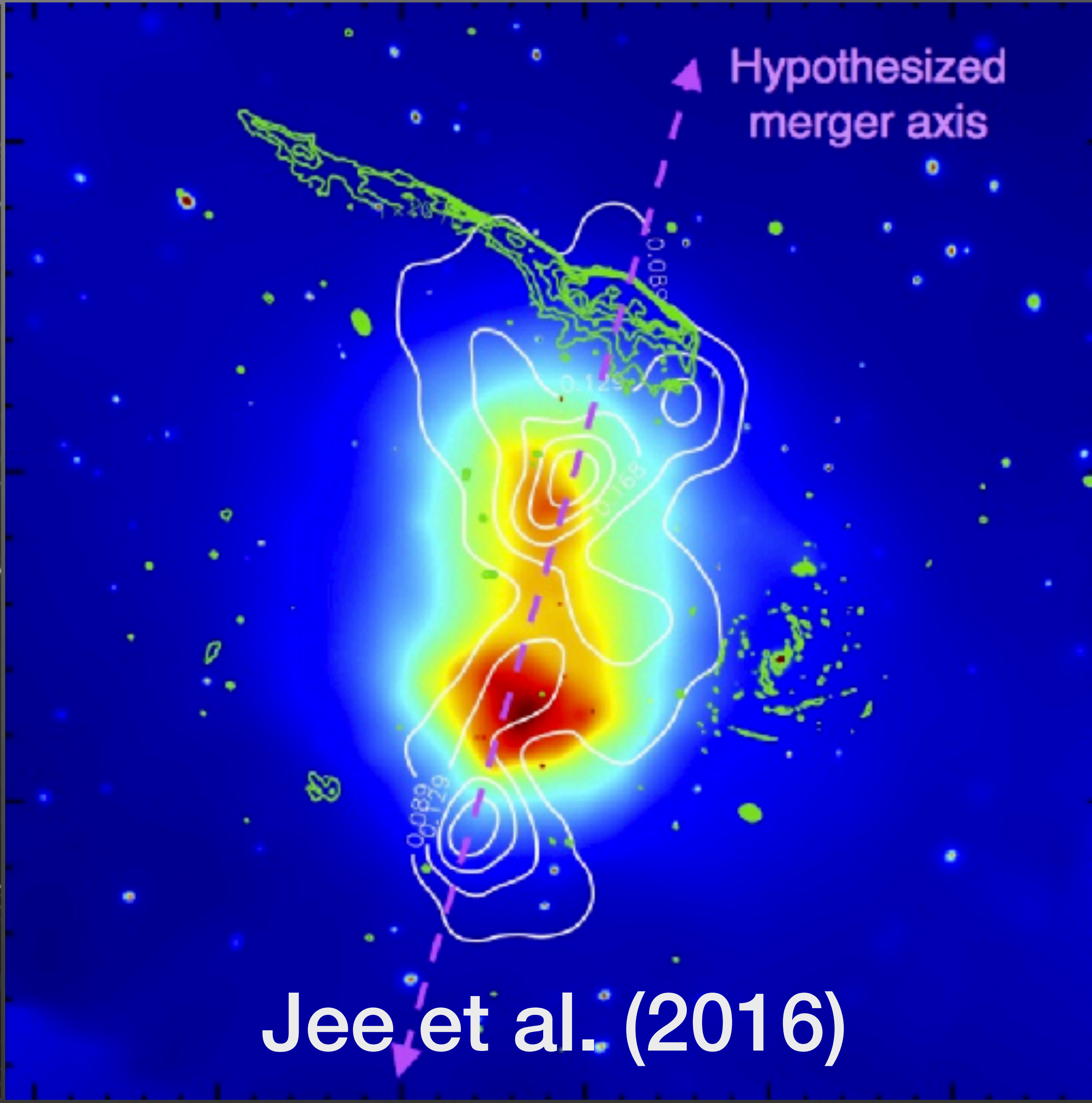


"Toothbrush"

NASA Press Release

"Toothbrush"

NASA Press Release

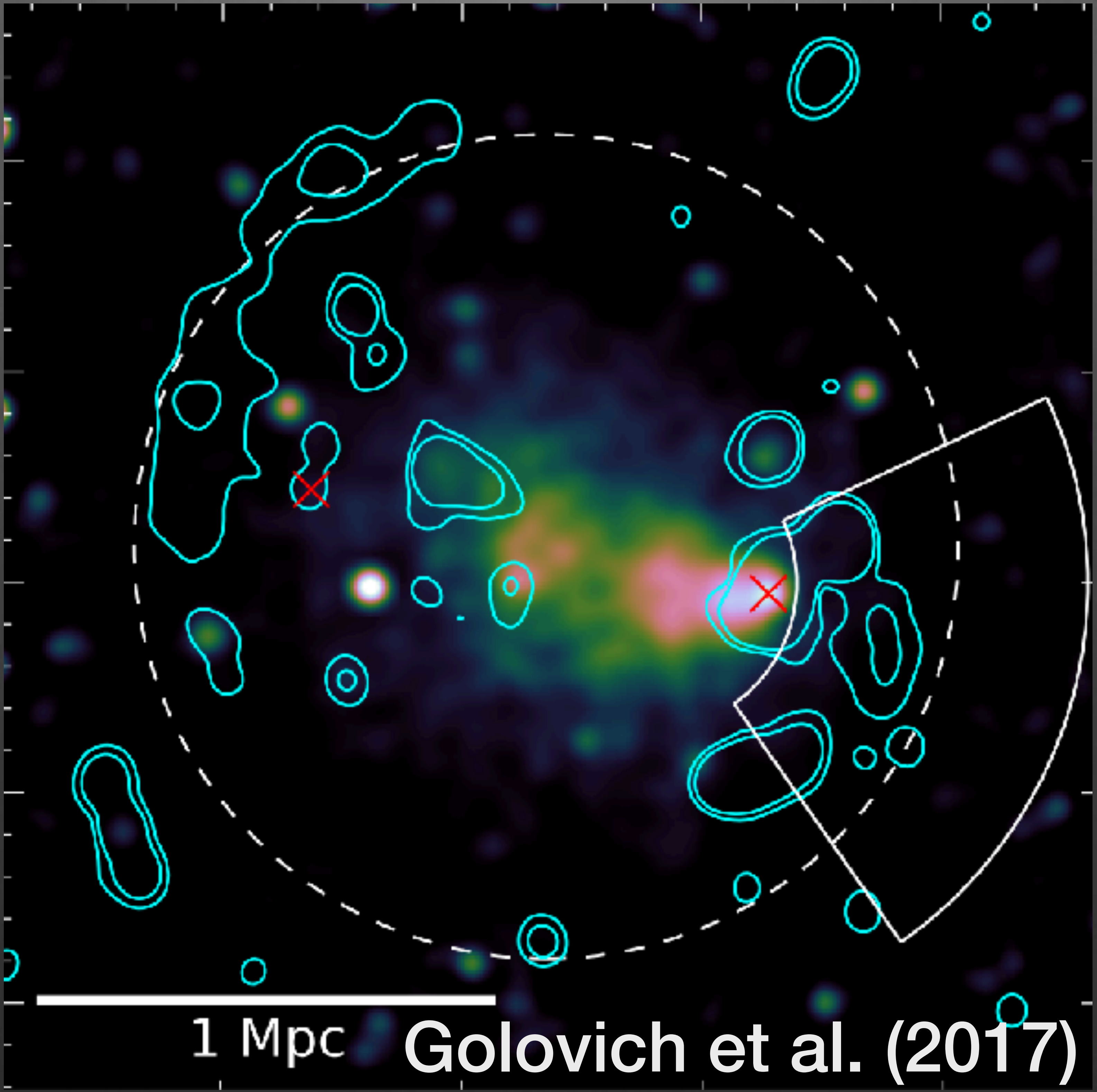


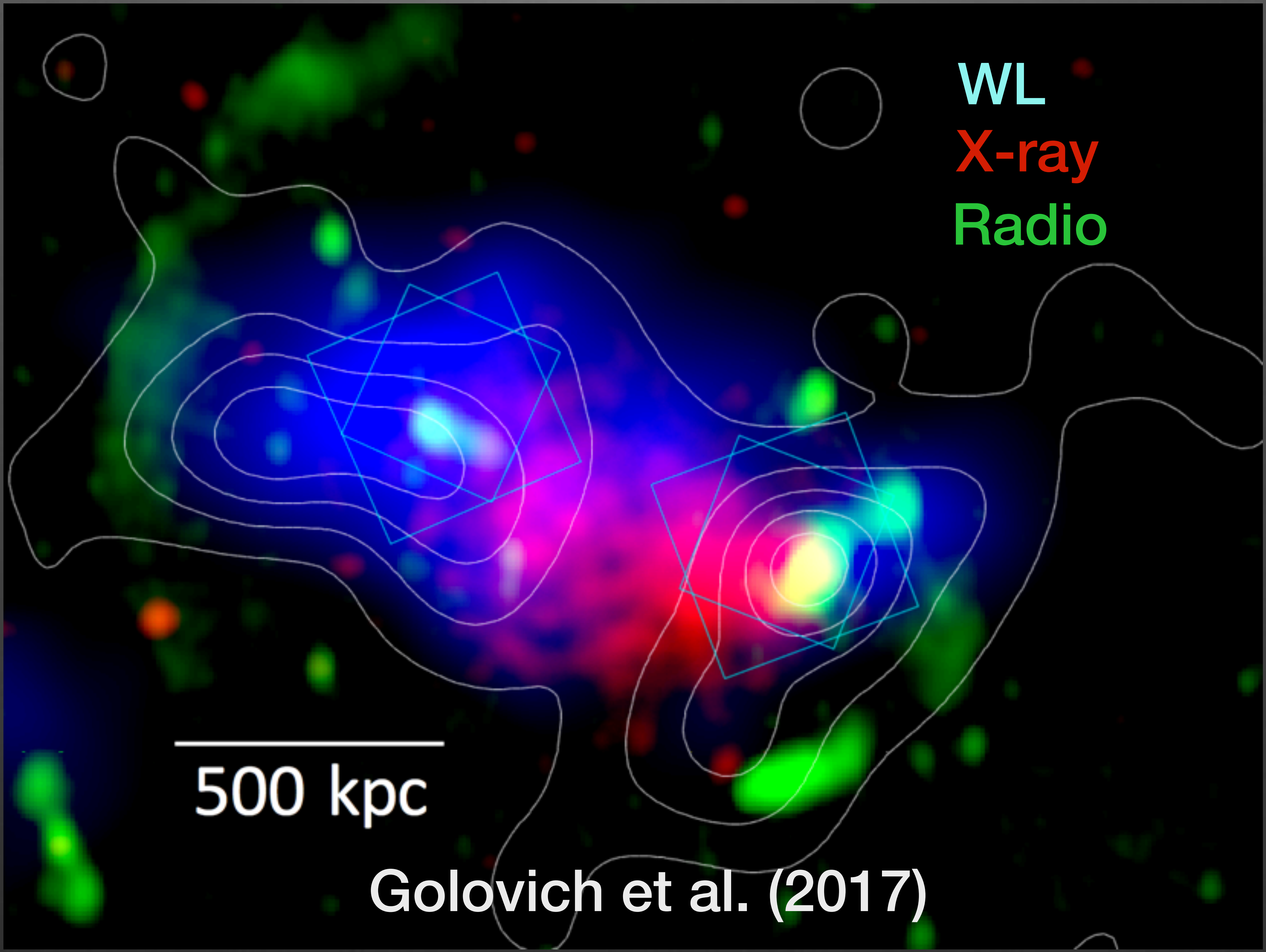
Jee et al. (2016)

b~10 degrees

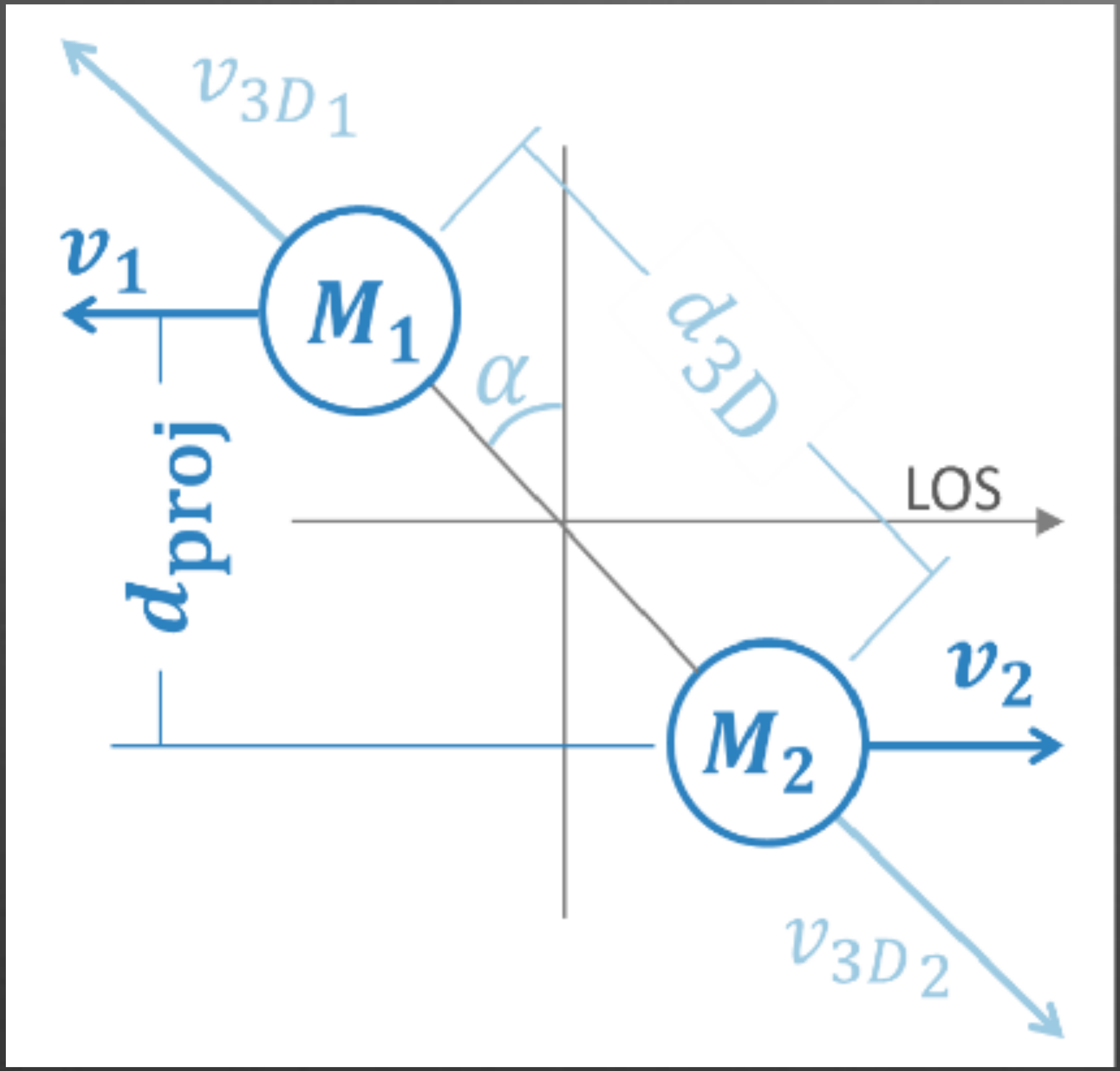
ZwCl 0008+5215

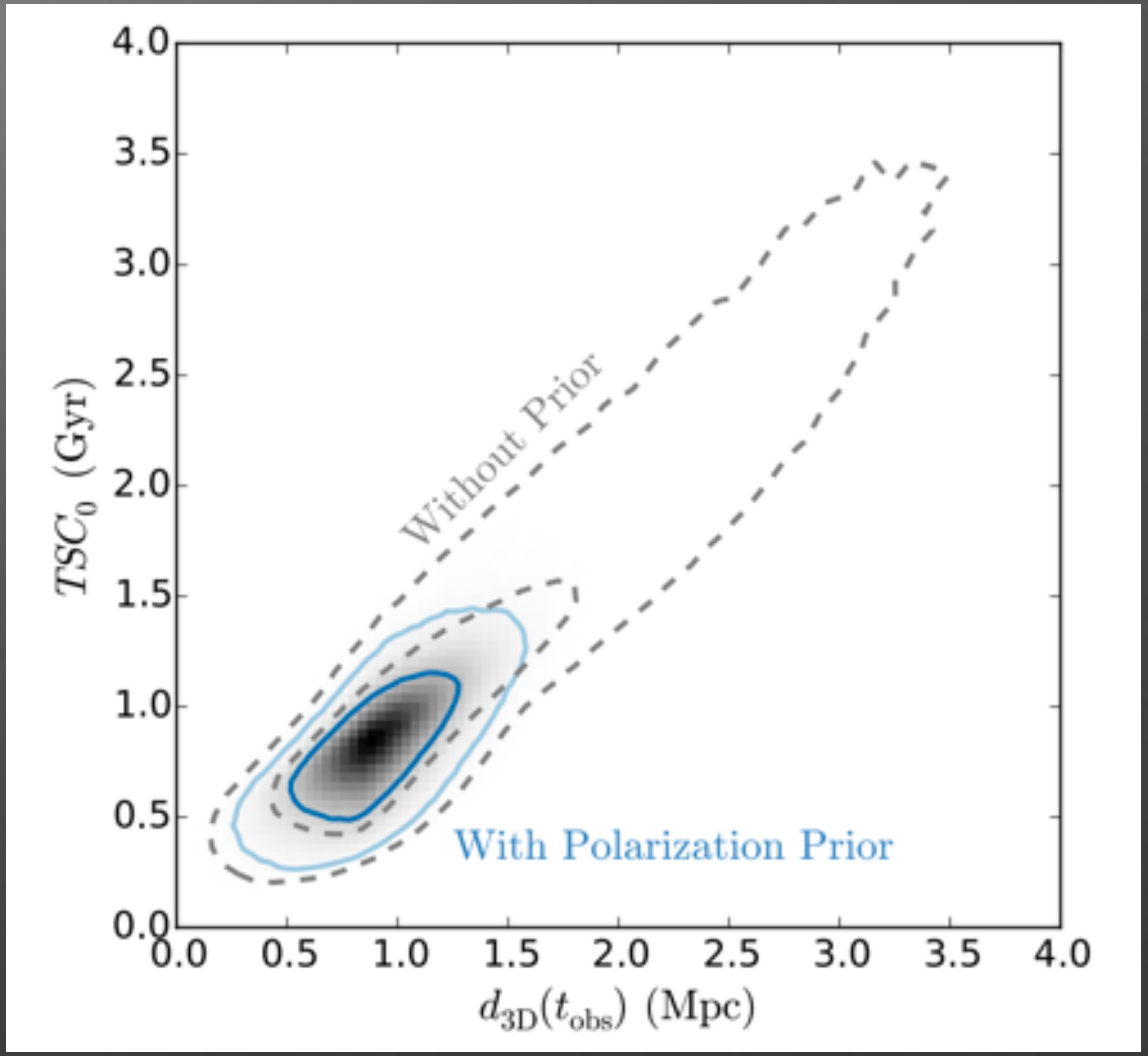
"Old Baby Bullet"




WL
X-ray
Radio
500 kpc
Golovich et al. (2017)

ZwCl 0008+5215
Merger Stage Constraint





Golovich et al. (2017)

Conclusions

Cosmic Shear:

- It is interesting that some cosmic shear studies gives results in tension with the Planck CMB results.
- It is also important to know that not all cosmic shear studies give such tensions.
- It is urgent to resolve discrepancies among different teams.

MC^2:

- Colliding clusters are powerful tools to study properties of dark matter.
- It is important to use multi-band data and high-fidelity simulations to reconstruct merging scenarios.
- We are working on SIDM simulations. Stay tuned.