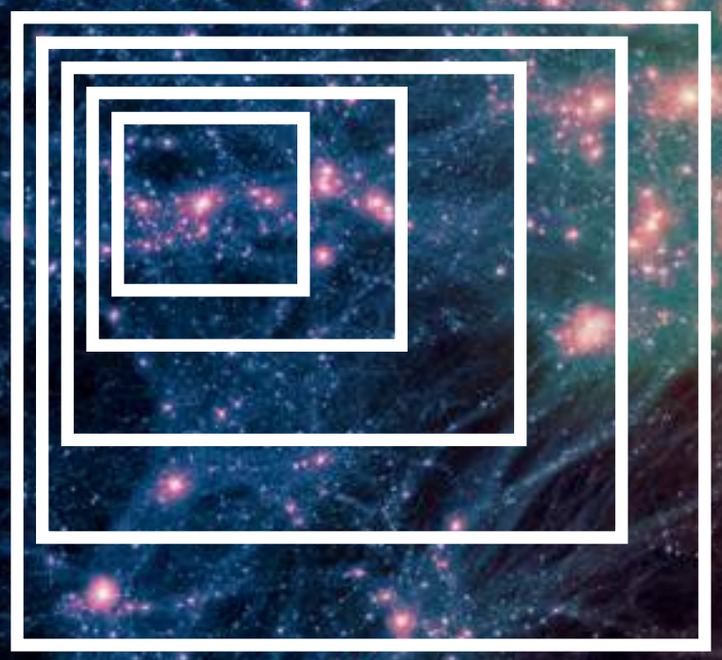
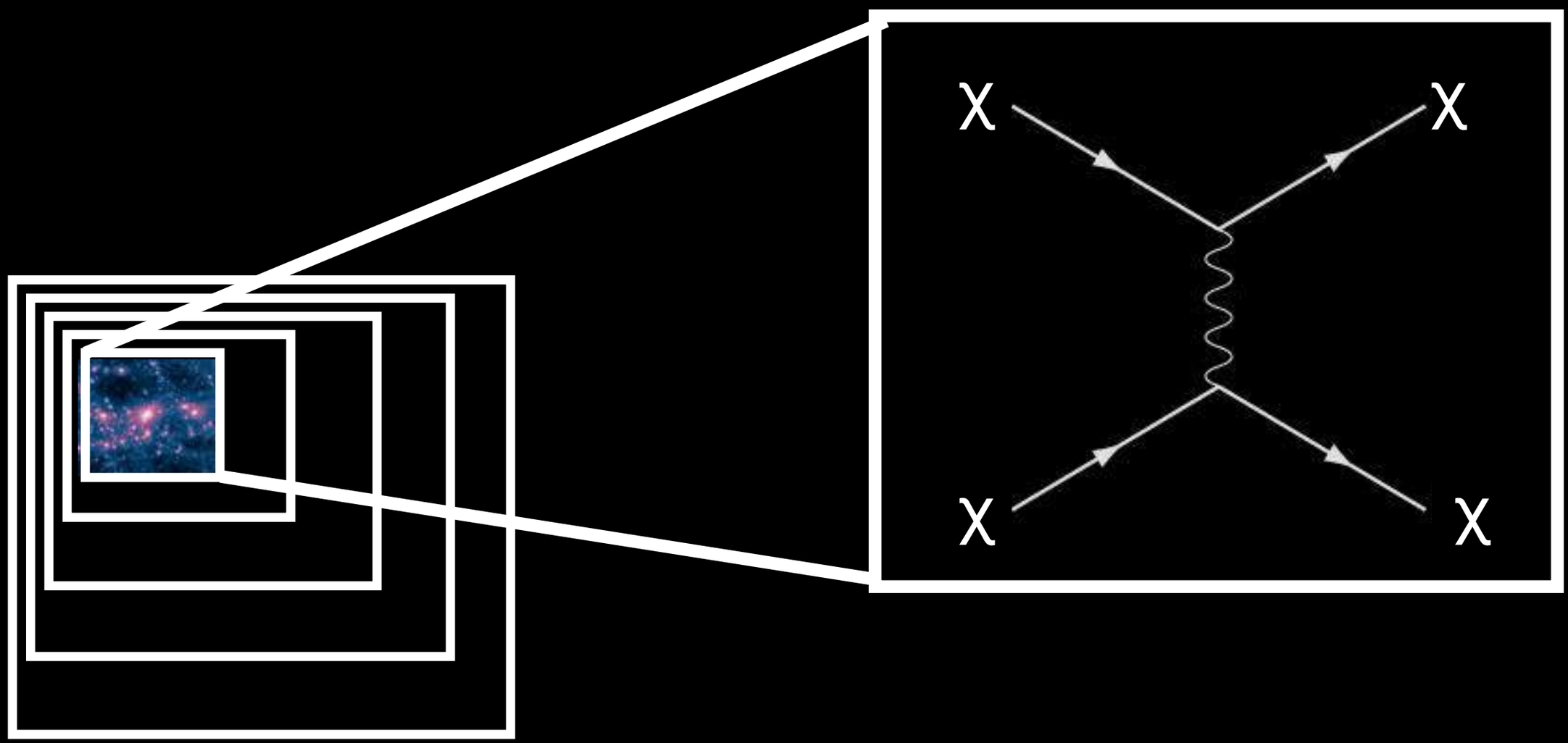
# WHAT IS THE NATURE OF DARK MATTER?

# USING THE LIGHT TO SEE THE DARK



Illustris Simulation

# USING THE LIGHT TO SEE THE DARK *INTERACTIONS*



WHAT IS DARK MATTER?

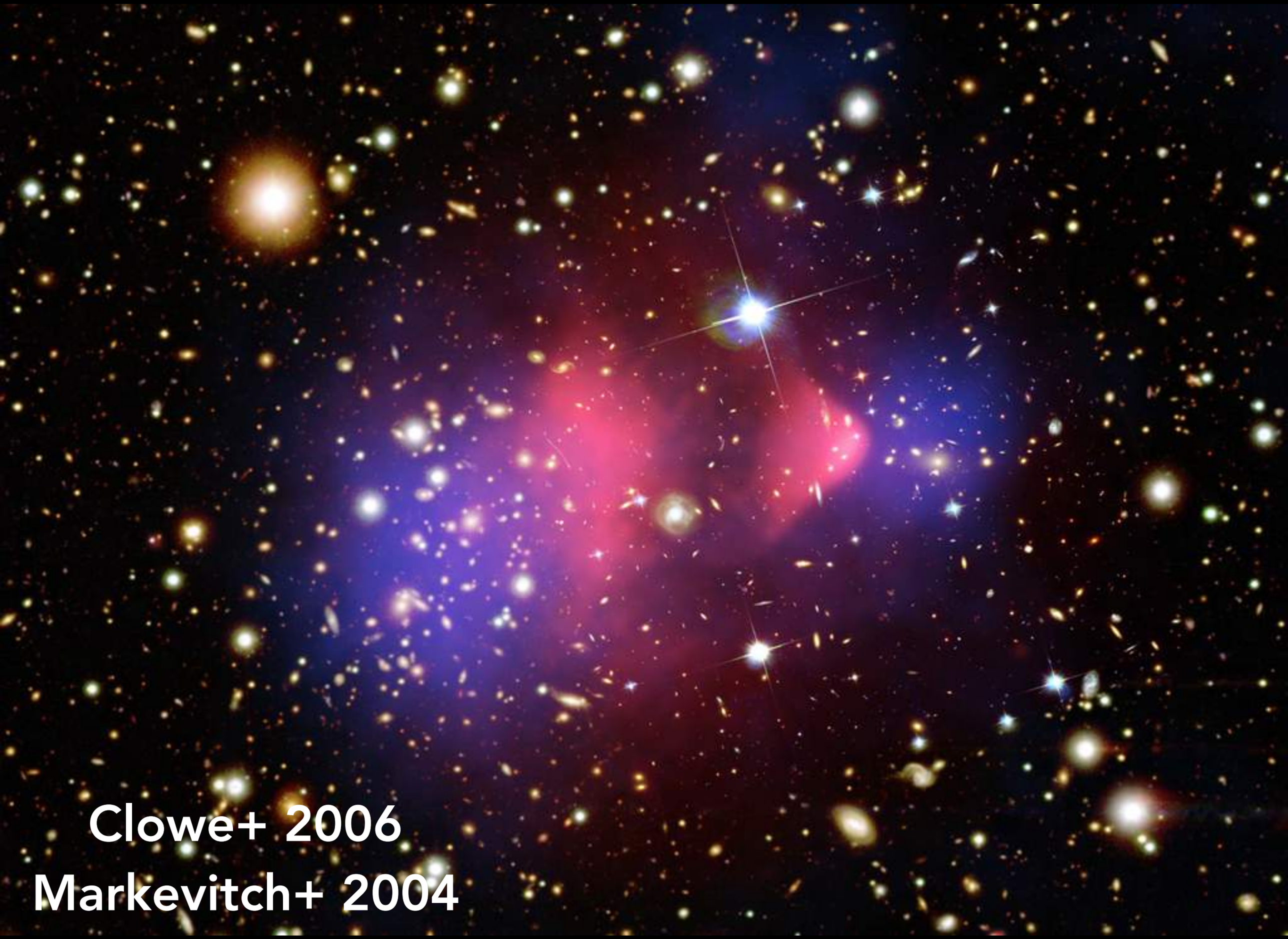
PHYSICAL MODEL OF SIDM

PREDICTED SIGNATURE OF SIDM

CAN WEAK OR STRONG LENSING HELP?

# GRAVITATIONAL LENSING PROBES OF SIDM

DR DAVID HARVEY. EPFL


Clowe+ 2006
Markevitch+ 2004

# BULLET CLUSTERS ARE EVERYWHERE AND CAN BE STACKED

Massey+ 2010

$$\sigma_{\rm DM}/\mathbf{m} < \mathbf{0.02}\mathrm{cm}^{\mathbf{2}}/\mathrm{g}$$

Miralde-Escude 2002

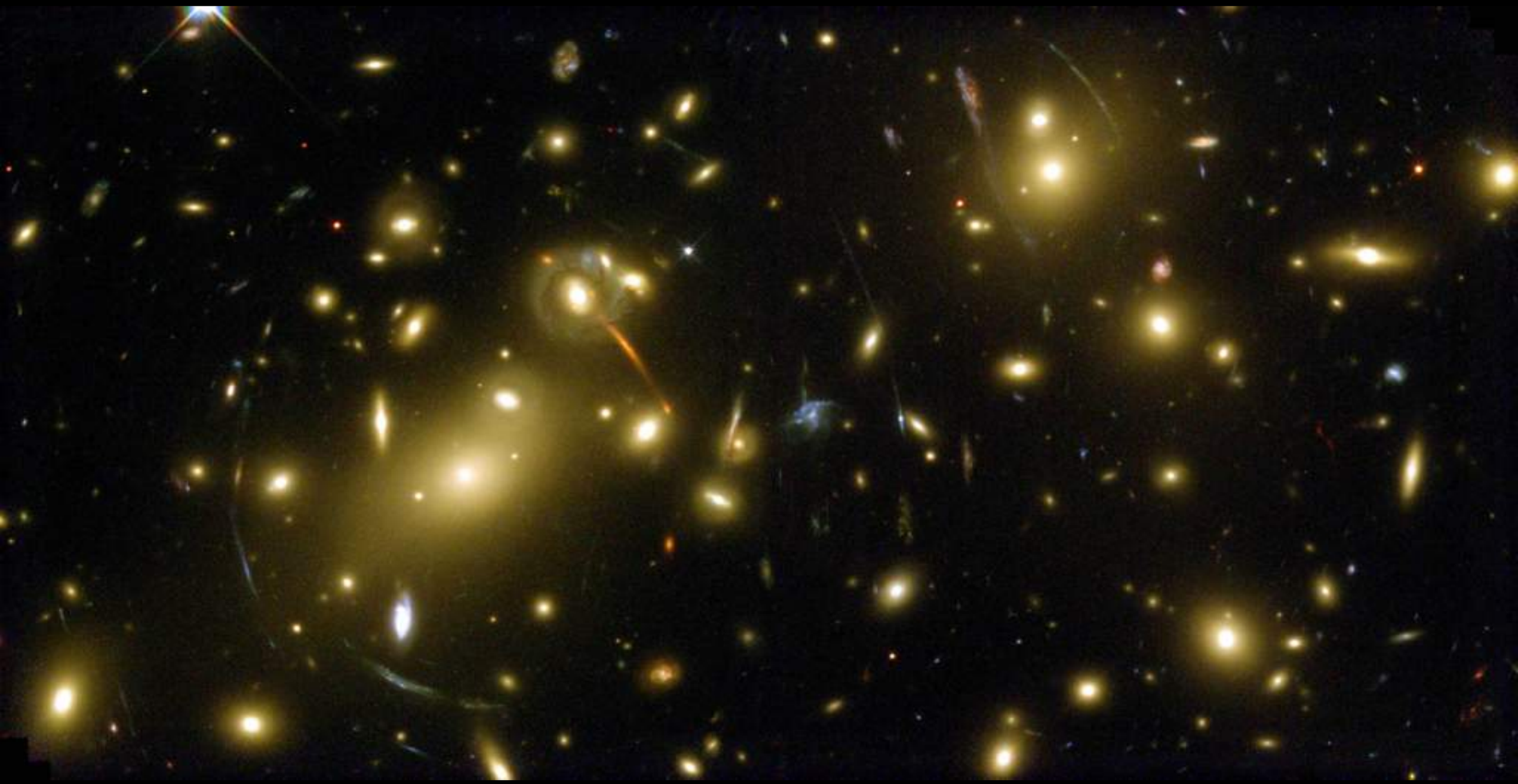
# HIGH RESOLUTION SIMULATIONS REIGNITE SIDM

Vogelsberger+ 2012

Rocha+ 2013

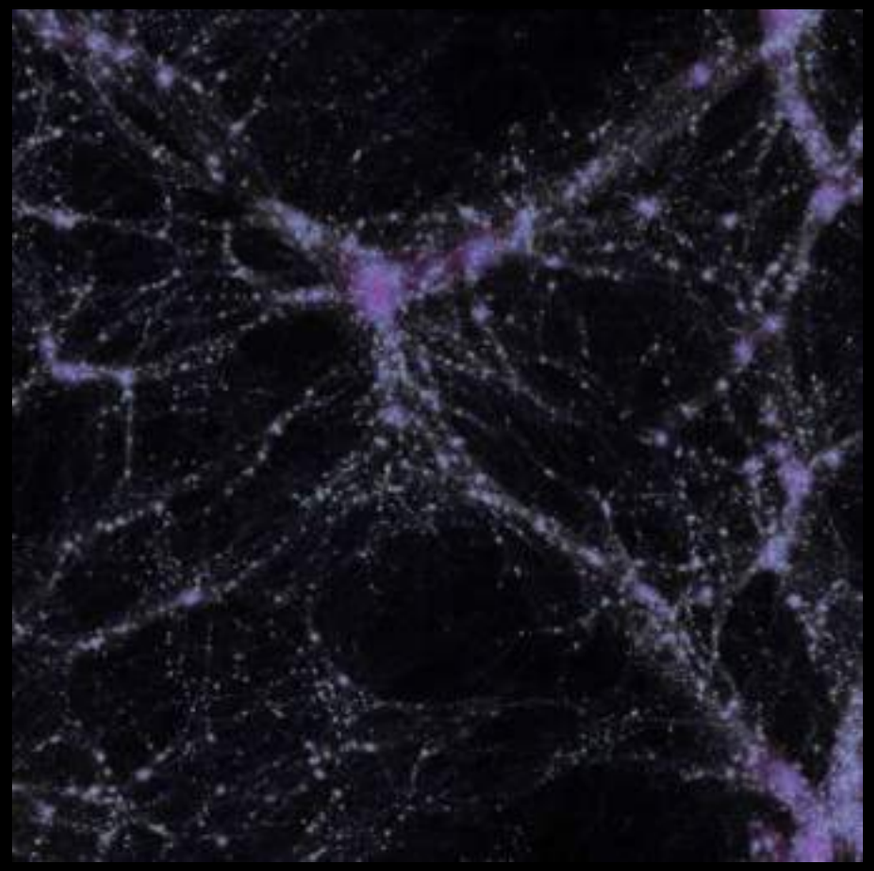
Peter+ 2013

# WEAK AND STRONG GRAVITATIONAL LENSING STUDY DIFFERENT ASPECTS OF DARK MATTER

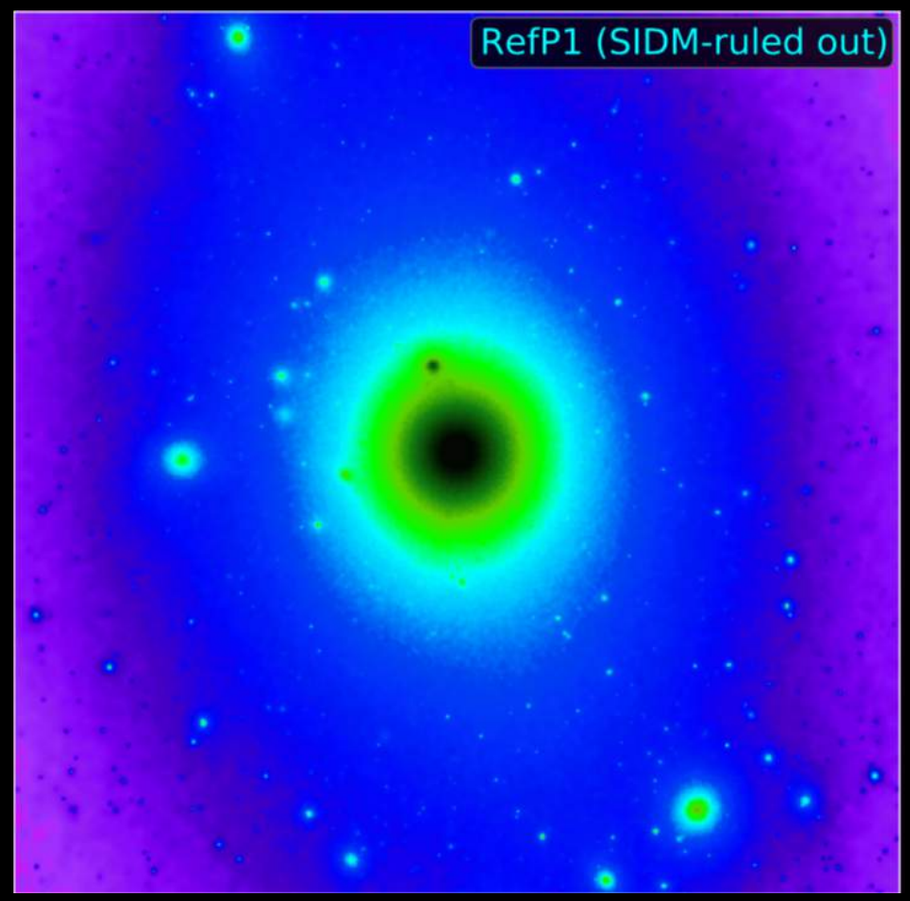


# WHAT ARE THE SIDM SIGNATURES AND HOW CAN LENSING HELP US?

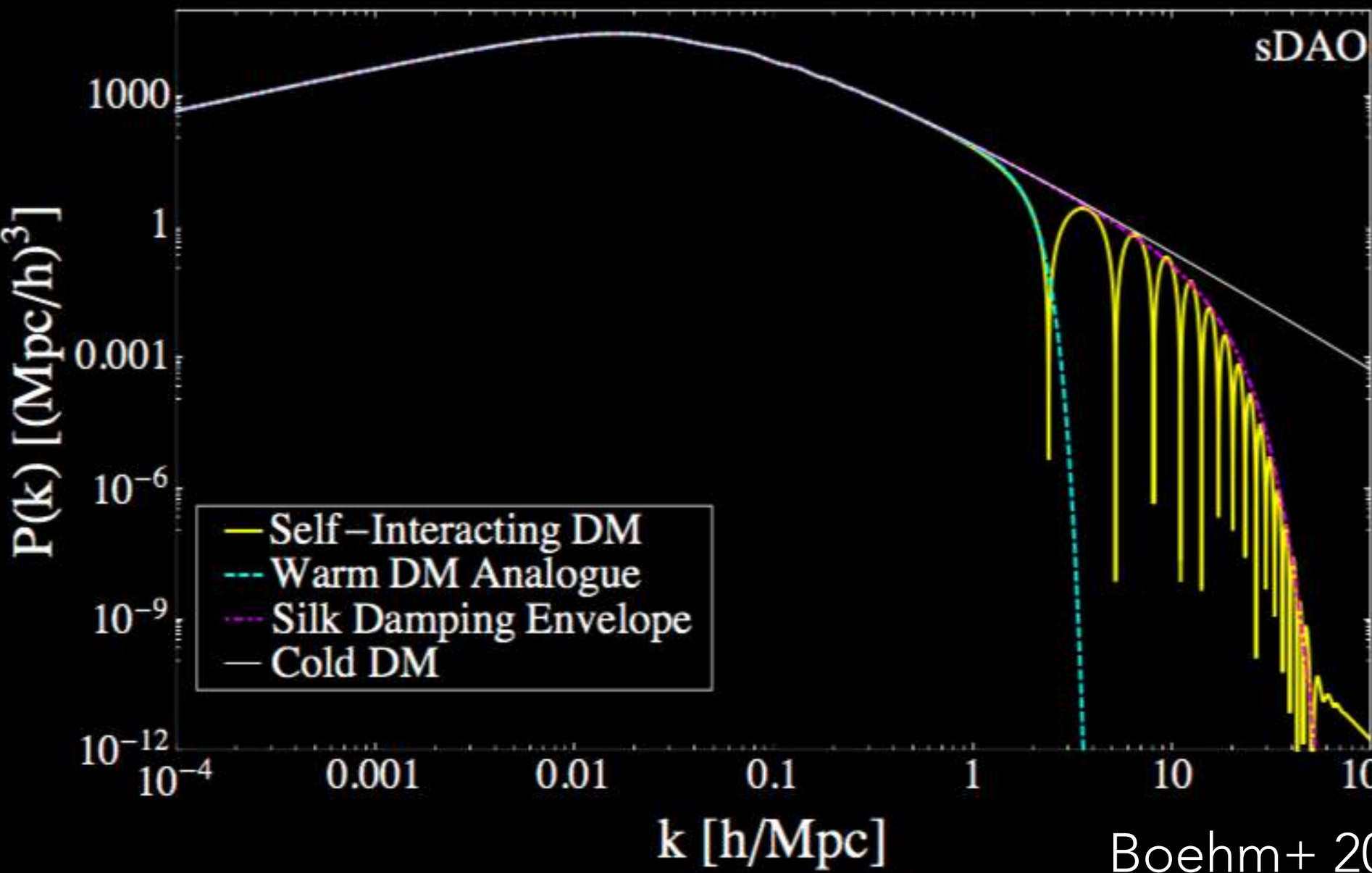
## LARGE SCALE



## SMALL (ISH) SCALE



# TWO MAIN LARGE SCALE MANIFESTATIONS OF DARK PHOTON MODEL

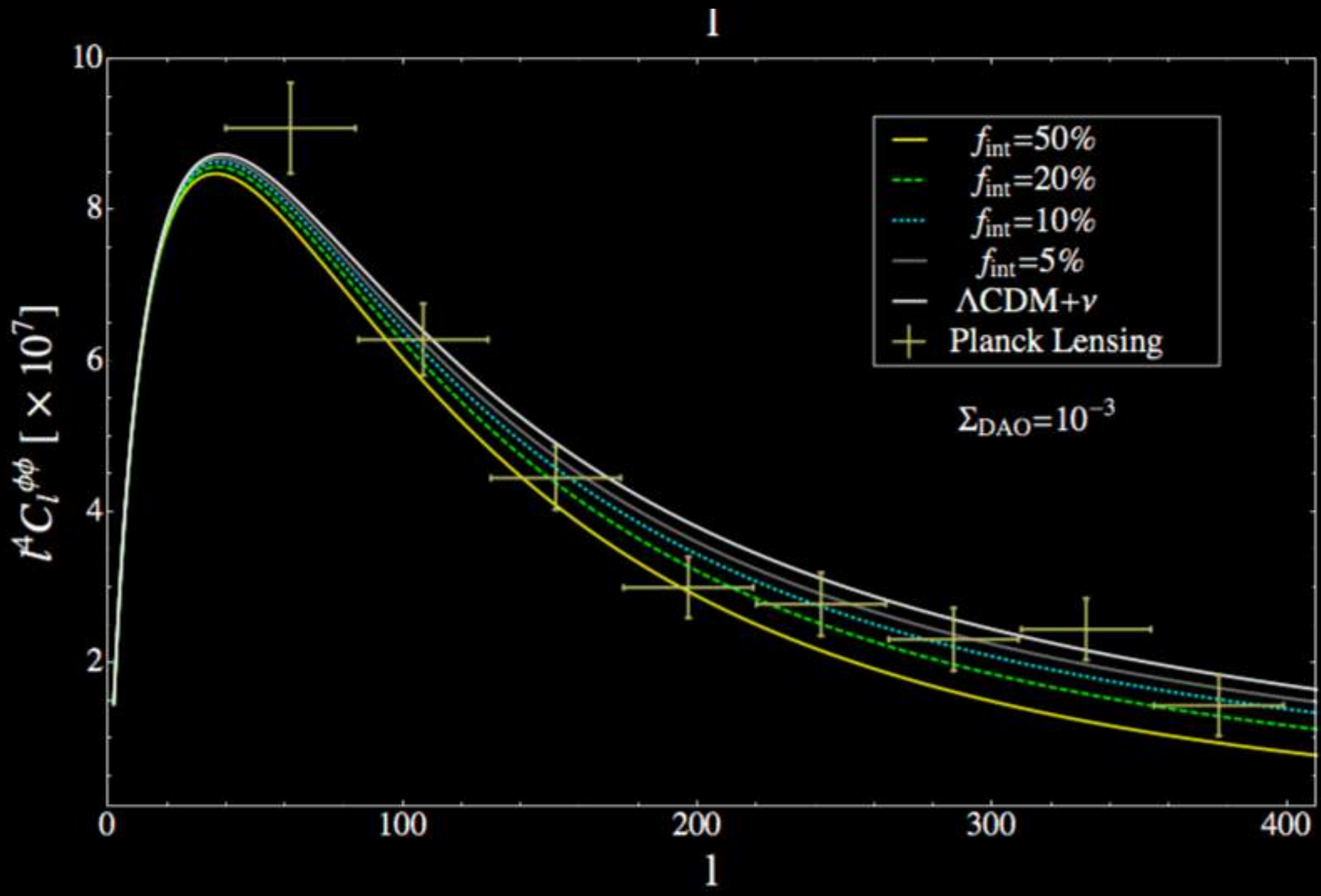



Boehm+ 2002

Cyr-Racine+ 2012

Buckley+ 2014

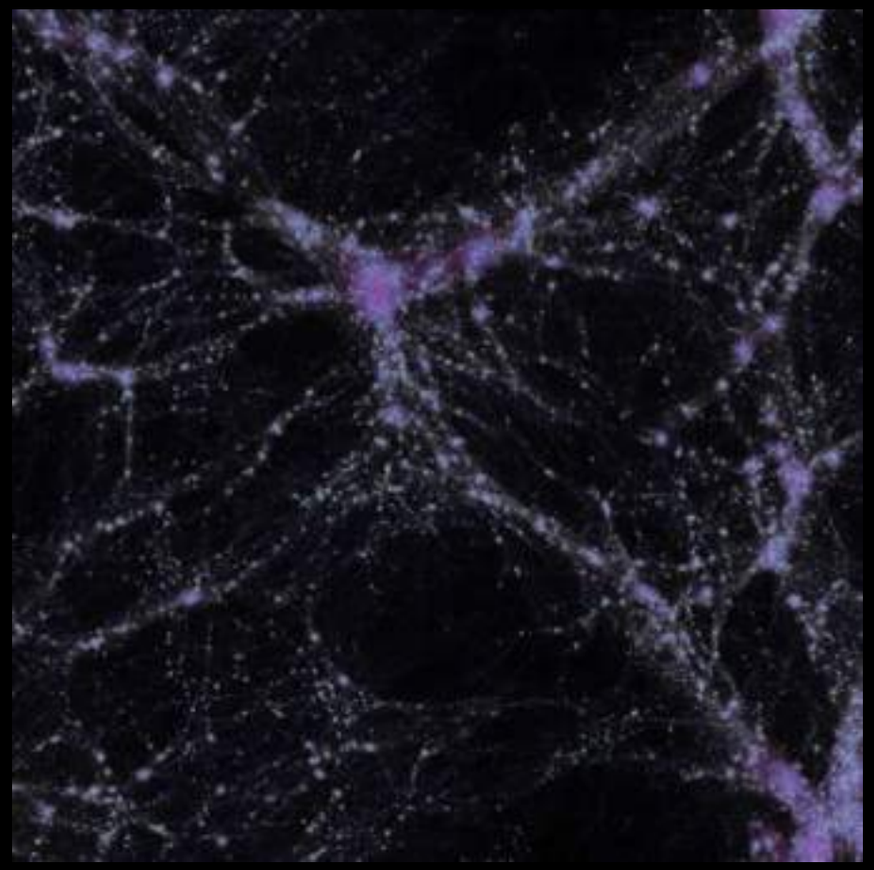
# CMB LENSING CAN CONSTRAIN DAO'S



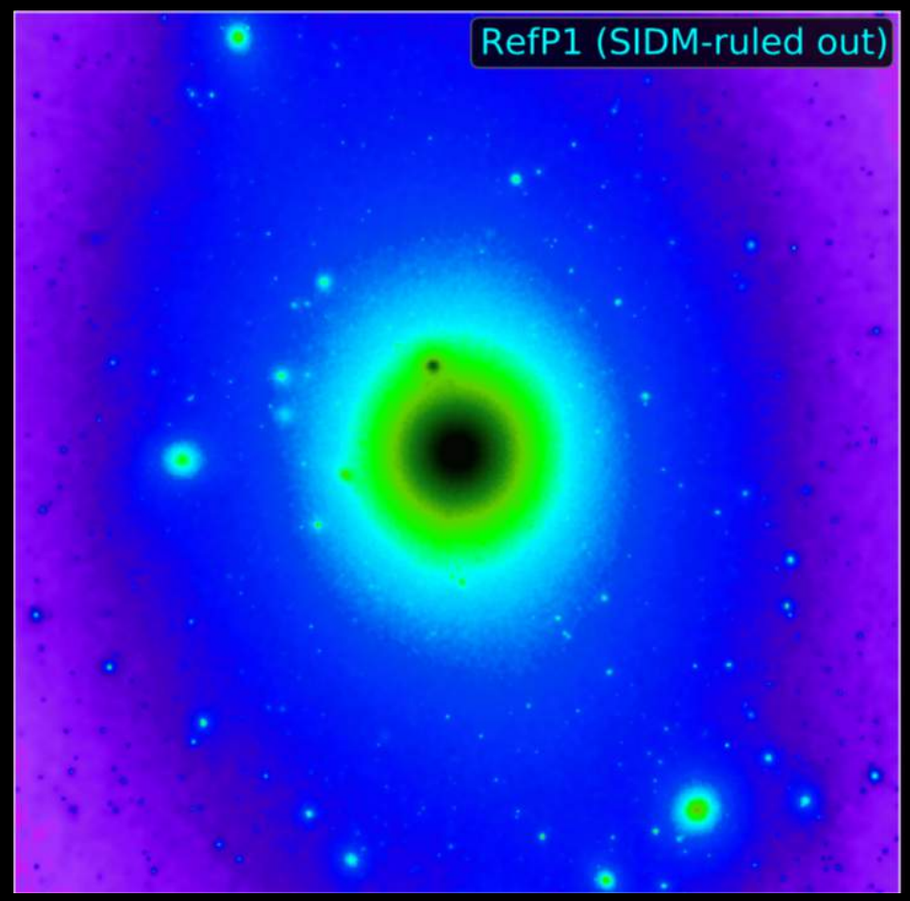

Cyr-Racine+ 2013

# WHAT ARE THE SIDM SIGNATURES AND HOW CAN LENSING HELP US?

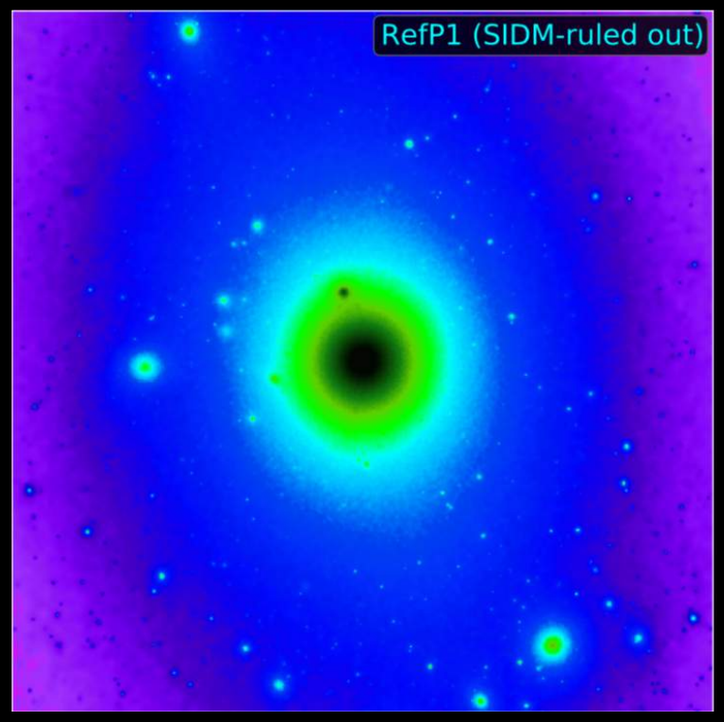
## LARGE SCALE



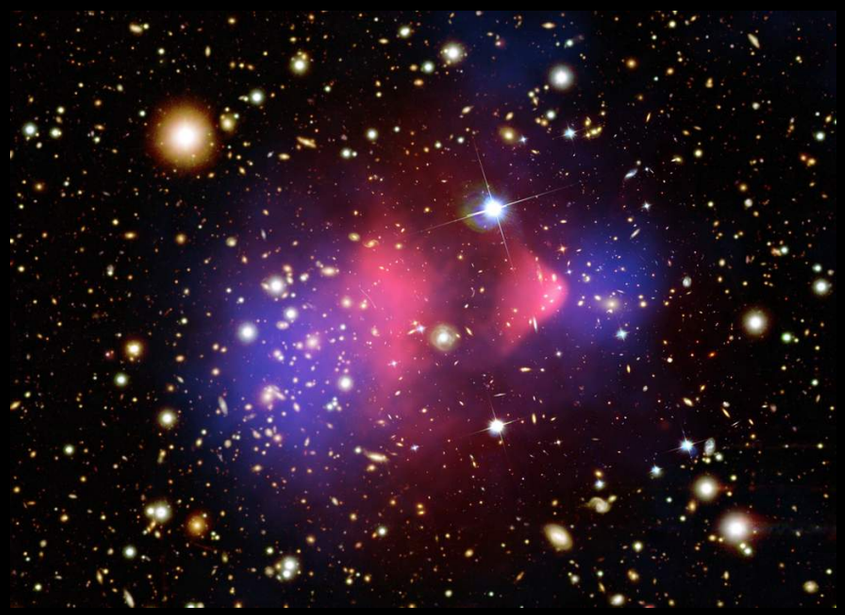
## SMALL (ISH) SCALE



# OBSERVING SIDM IN GALAXY CLUSTERS

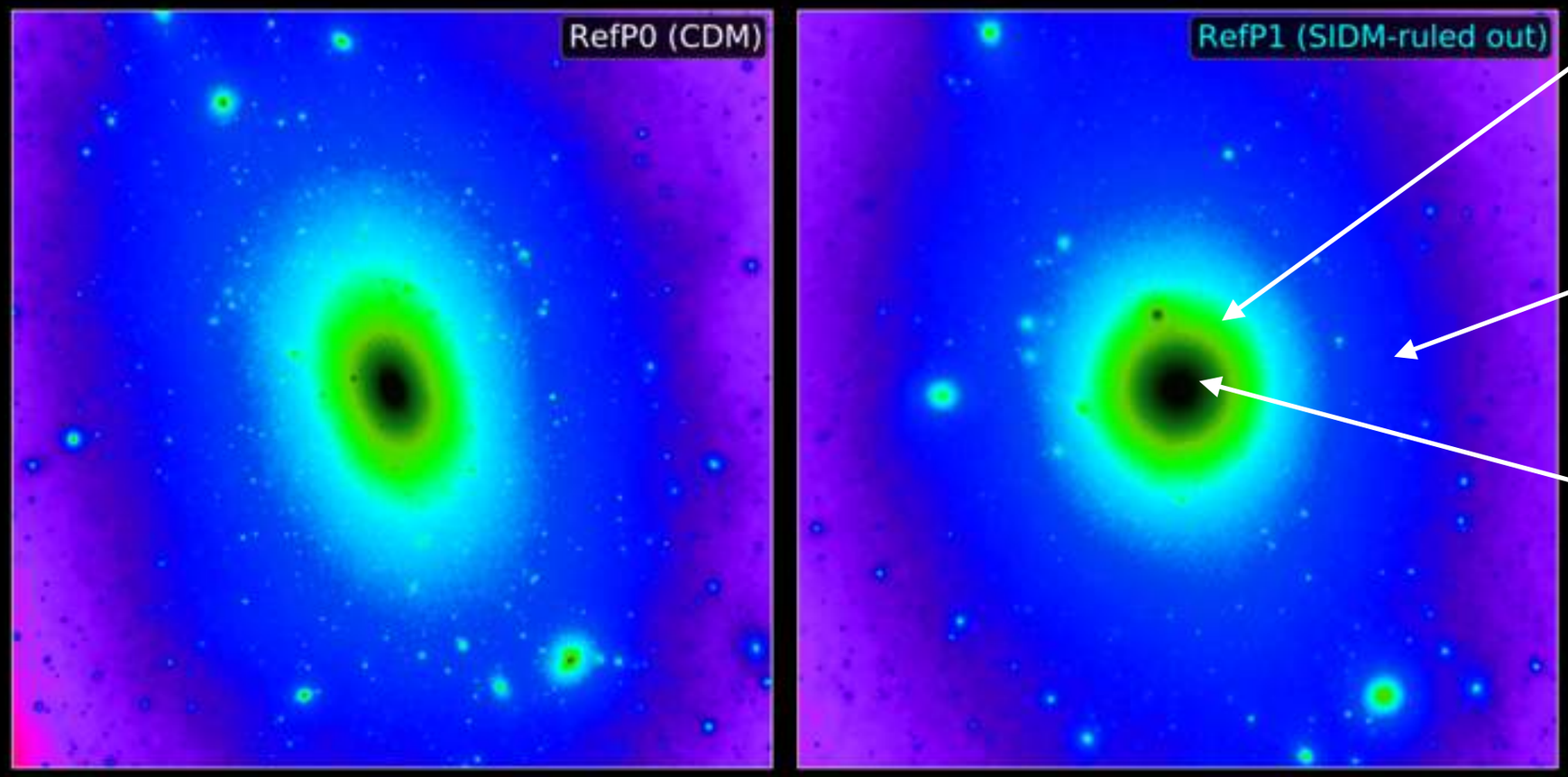



## RELAXED CLUSTERS



## MERGING CLUSTERS

# STATISTICAL PROPERTIES OF RELAXED SIDM HALOES ARE DIFFERENT OF THAT TO CDM

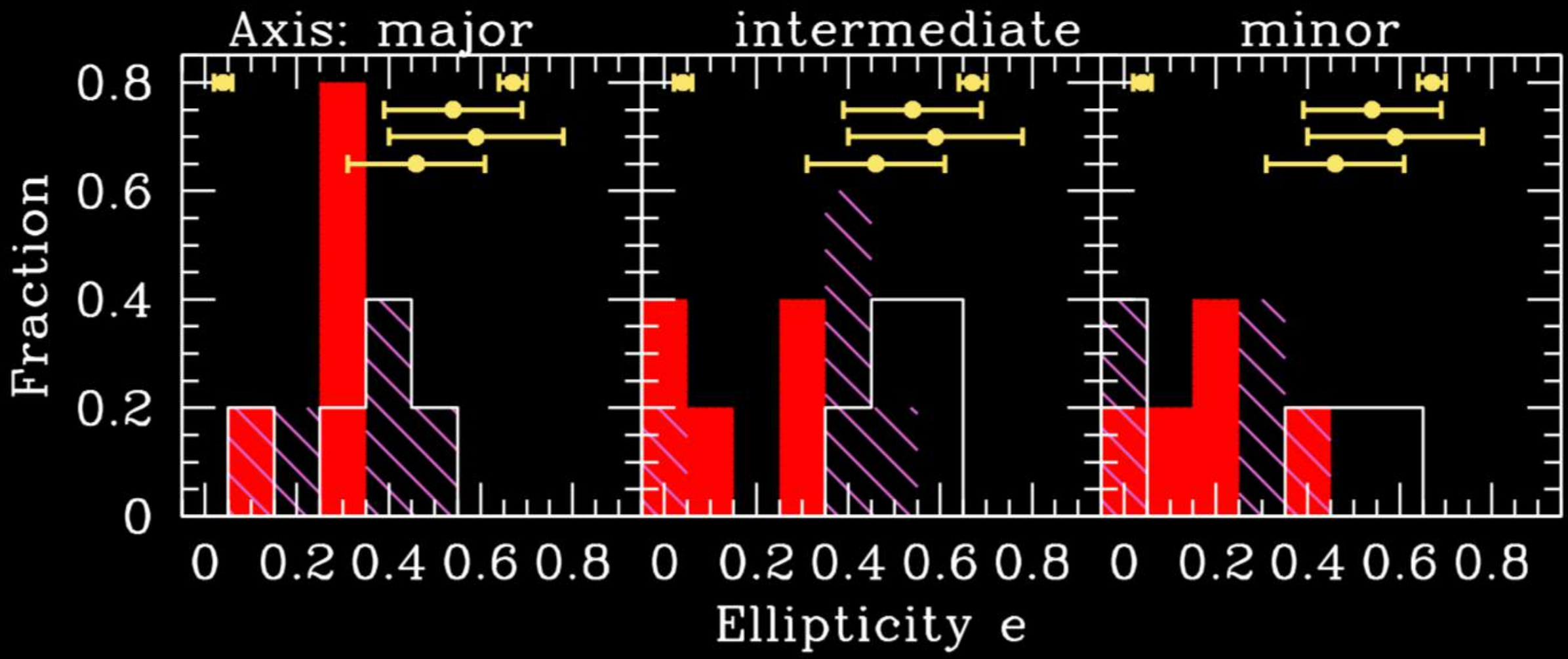



Vogelsberger+ 12′

# CLUSTER SPHERICITY CONSISTENT WITH $\mathbf{1 cm^2/g}$

Peter+ 2013

**Observations**



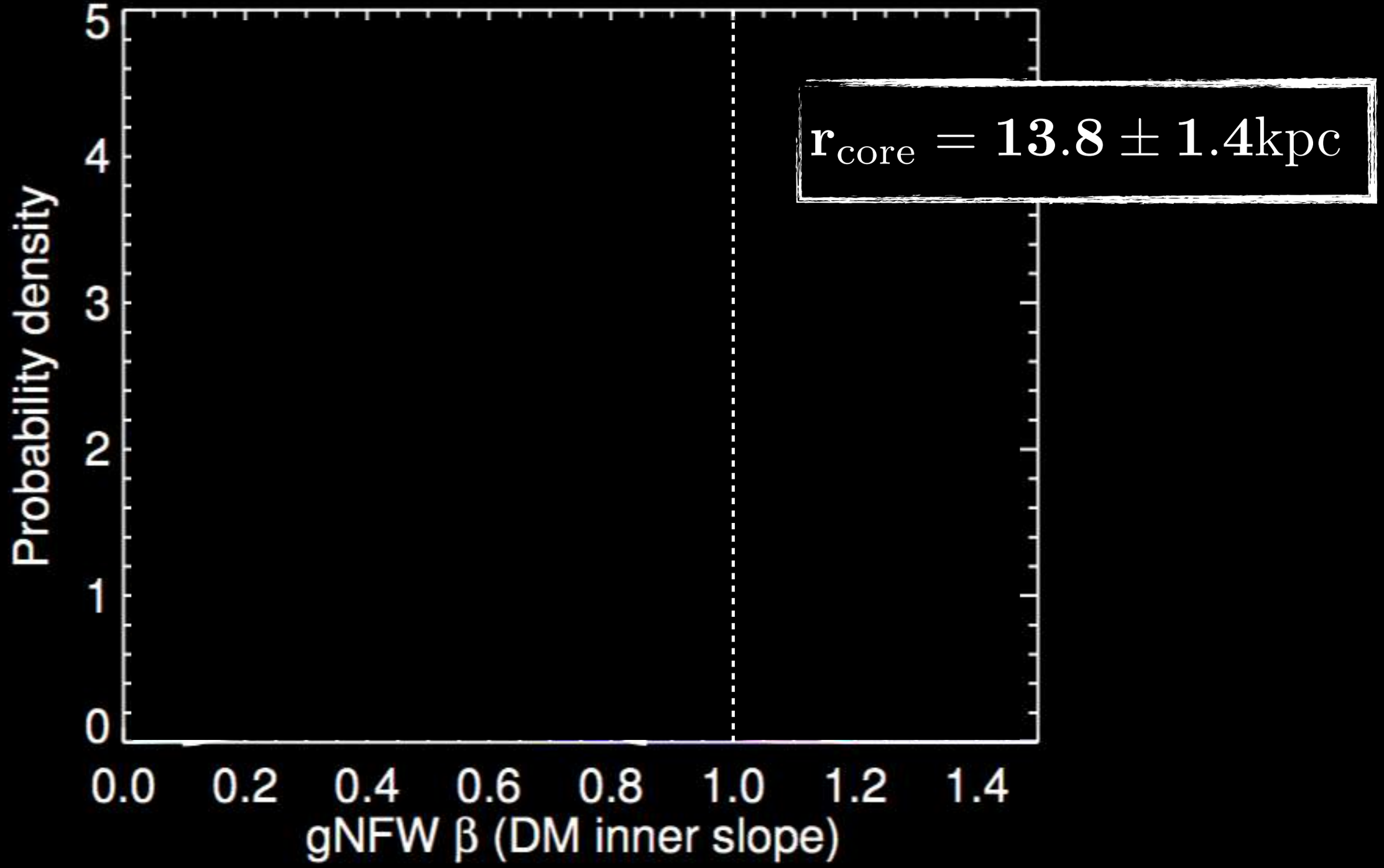

$\mathbf{1 cm^2/g}$ $\mathbf{0.1 cm^2/g}$ **CDM**

# PROBING SUBSTRUCTURE AND WOBBLING THROUGH GALAXY-GALAXY STRONG LENSING

(see L. Williams talk)

Metcalfe & Zhao 2002

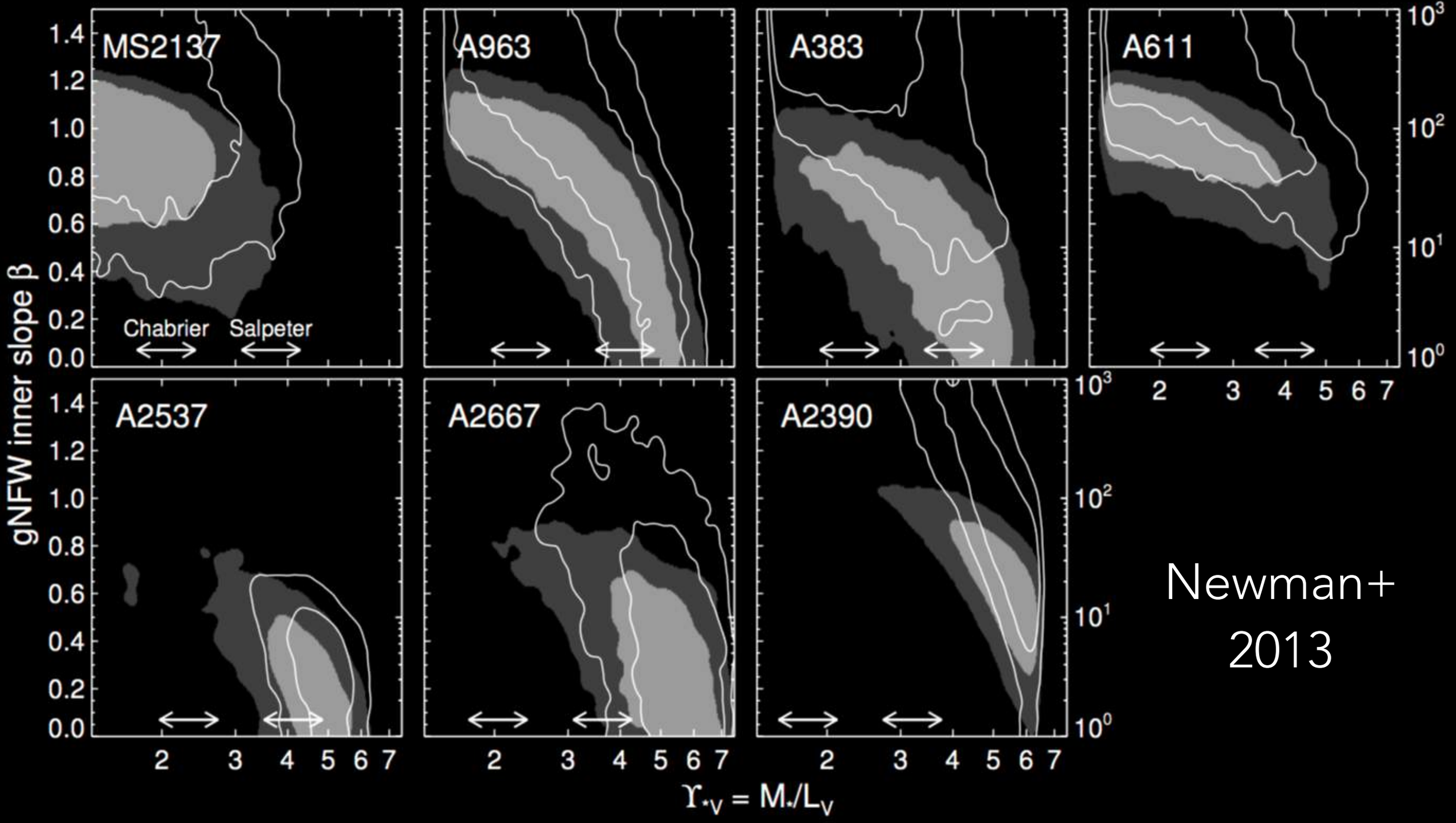
# EVIDENCE FOR CORES IN GALAXY CLUSTERS




$$\mathbf{r_{core} = 13.8 \pm 1.4 kpc}$$

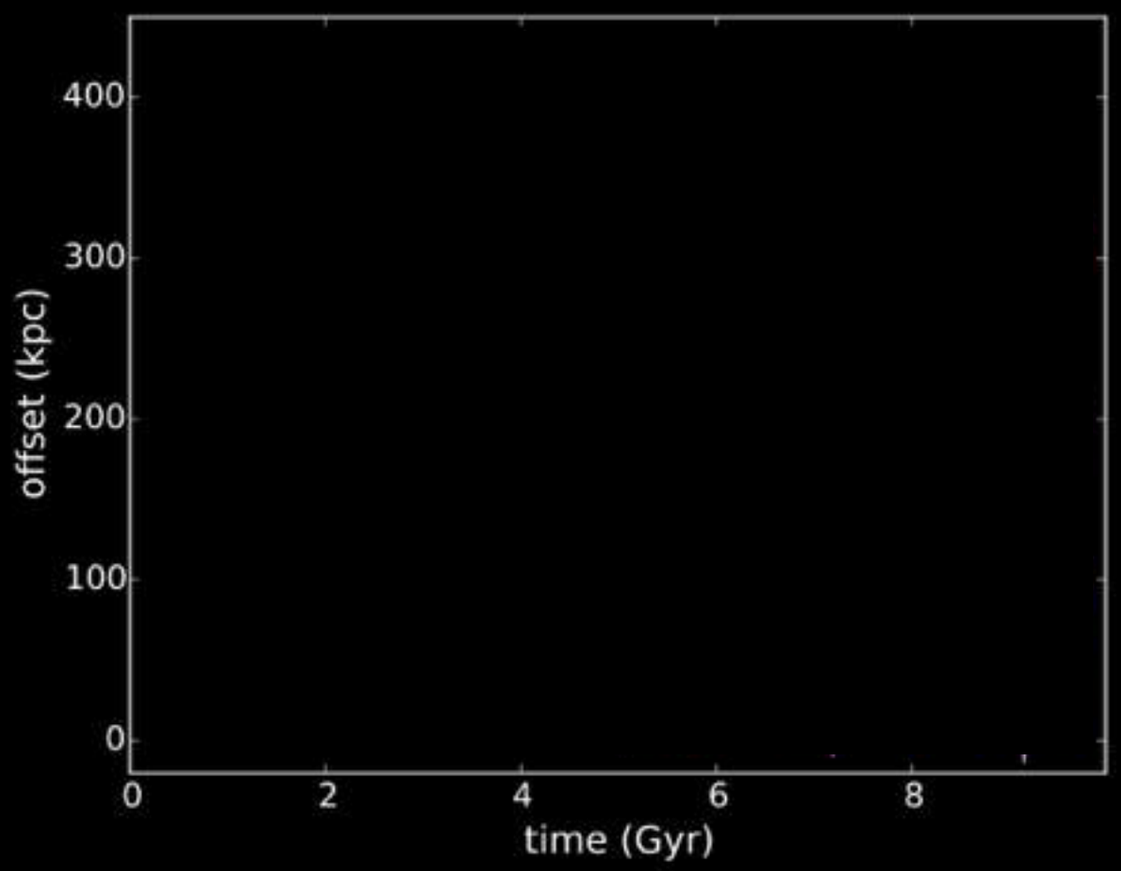
Newman+ 2013

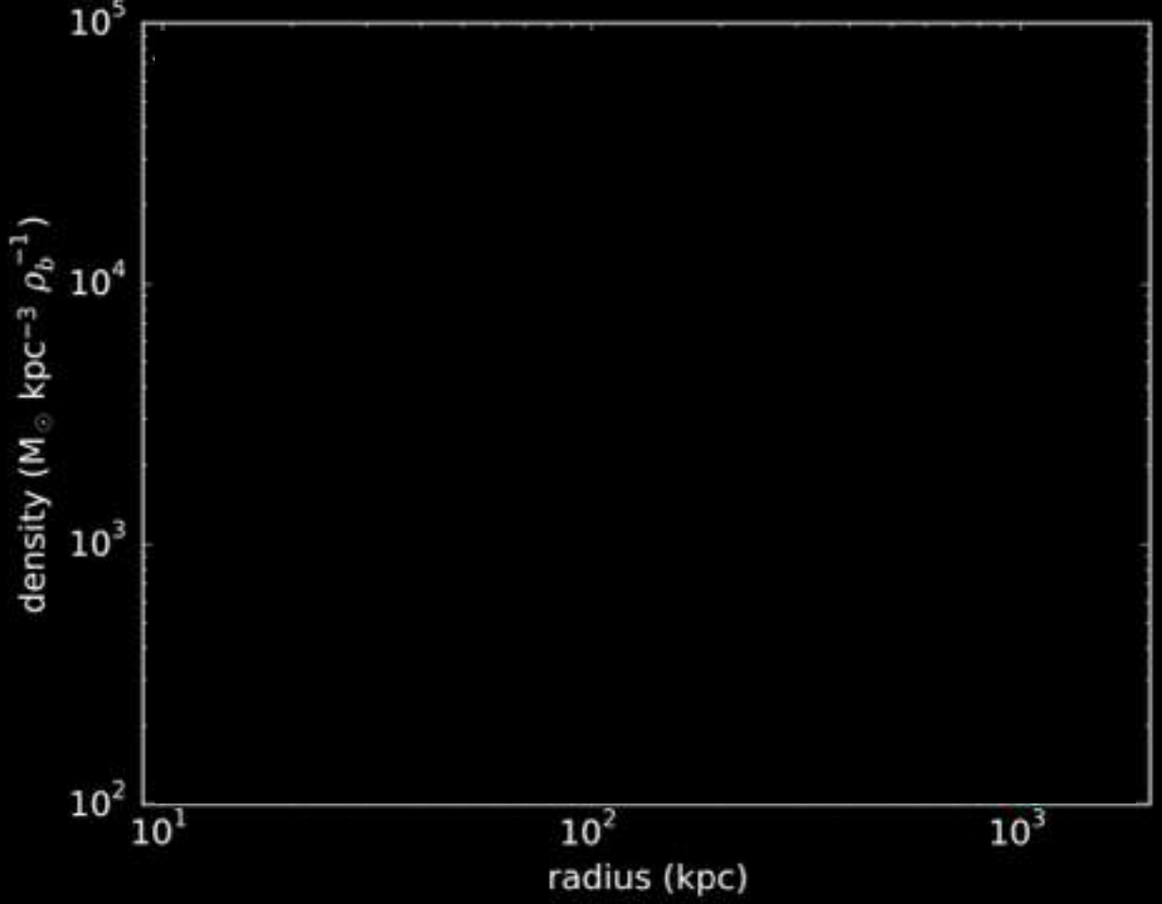
# DEGENERACIES BETWEEN DENSITY SLOPE AND MASS TO LIGHT RATIO




Newman+ 2013

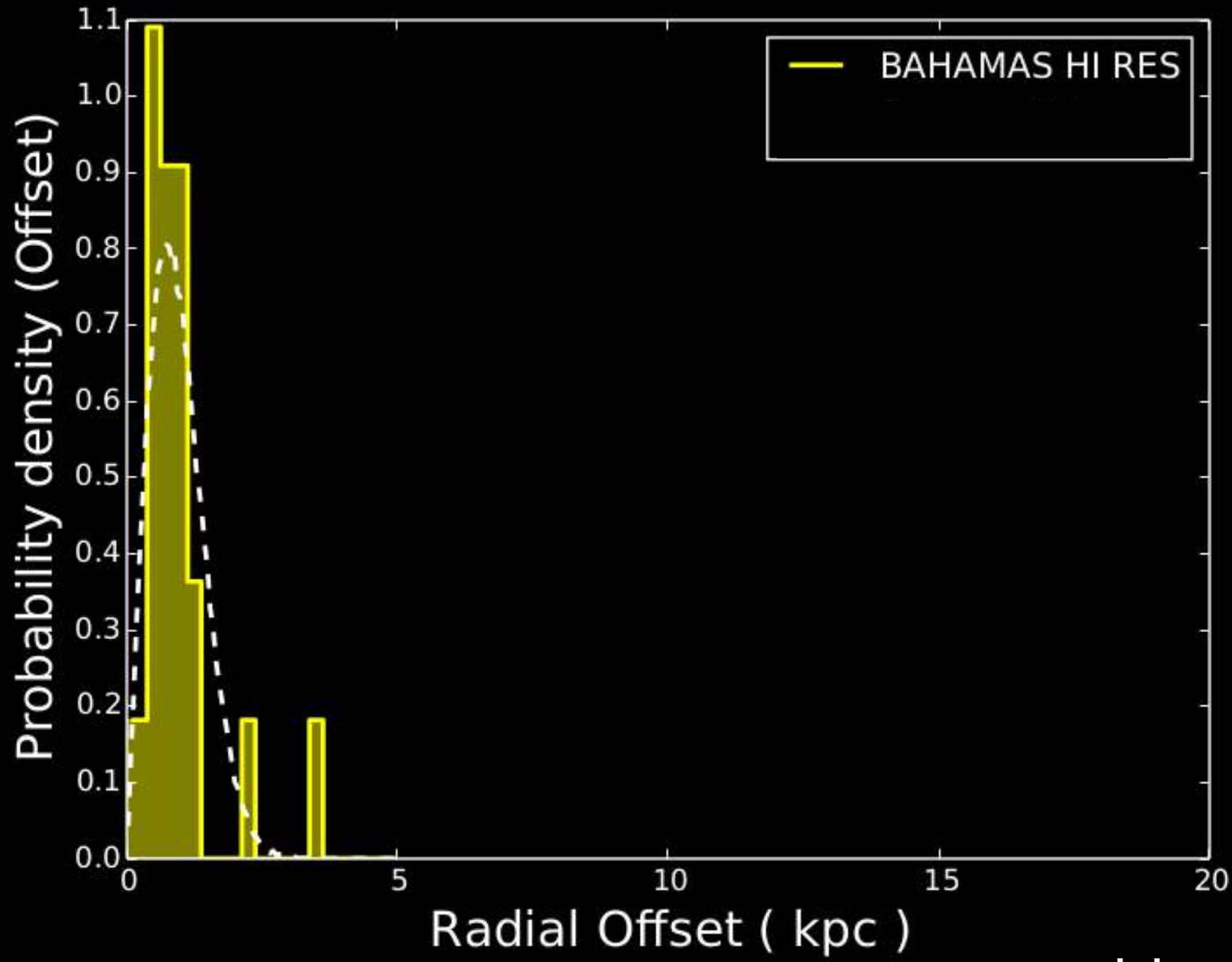
# BRIGHTEST CLUSTER GALAXIES WOBBLE IN THE PRESENCE OF CORED GALAXY CLUSTERS



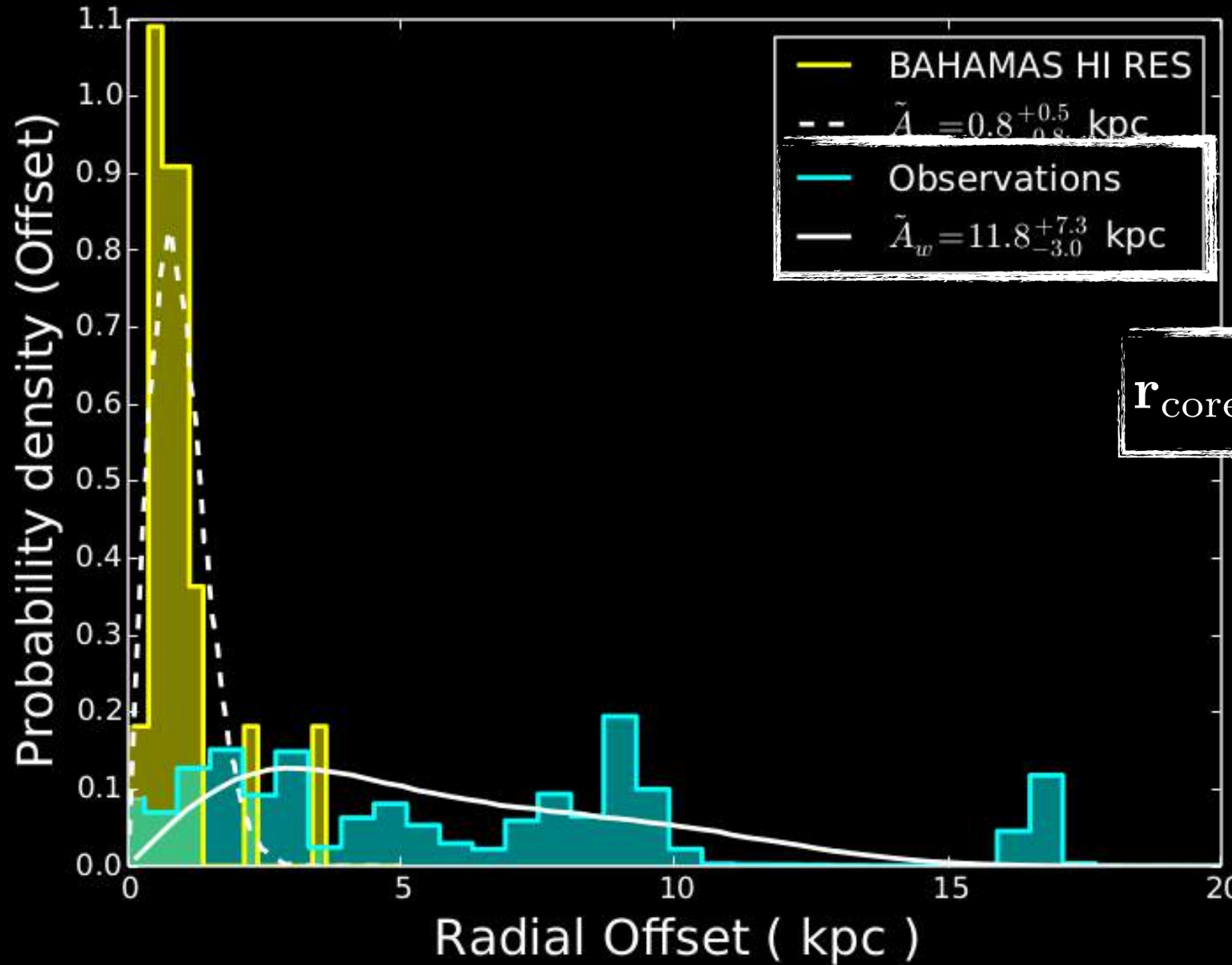

Kim+ 2016

# NO WOBBLING OBSERVED IN STANDARD MODEL DARK MATTER




Harvey+ 2017b

# OBSERVATIONS FAVOUR NON-ZERO WOBBLE AT 3-SIGMA SIGNIFICANCE

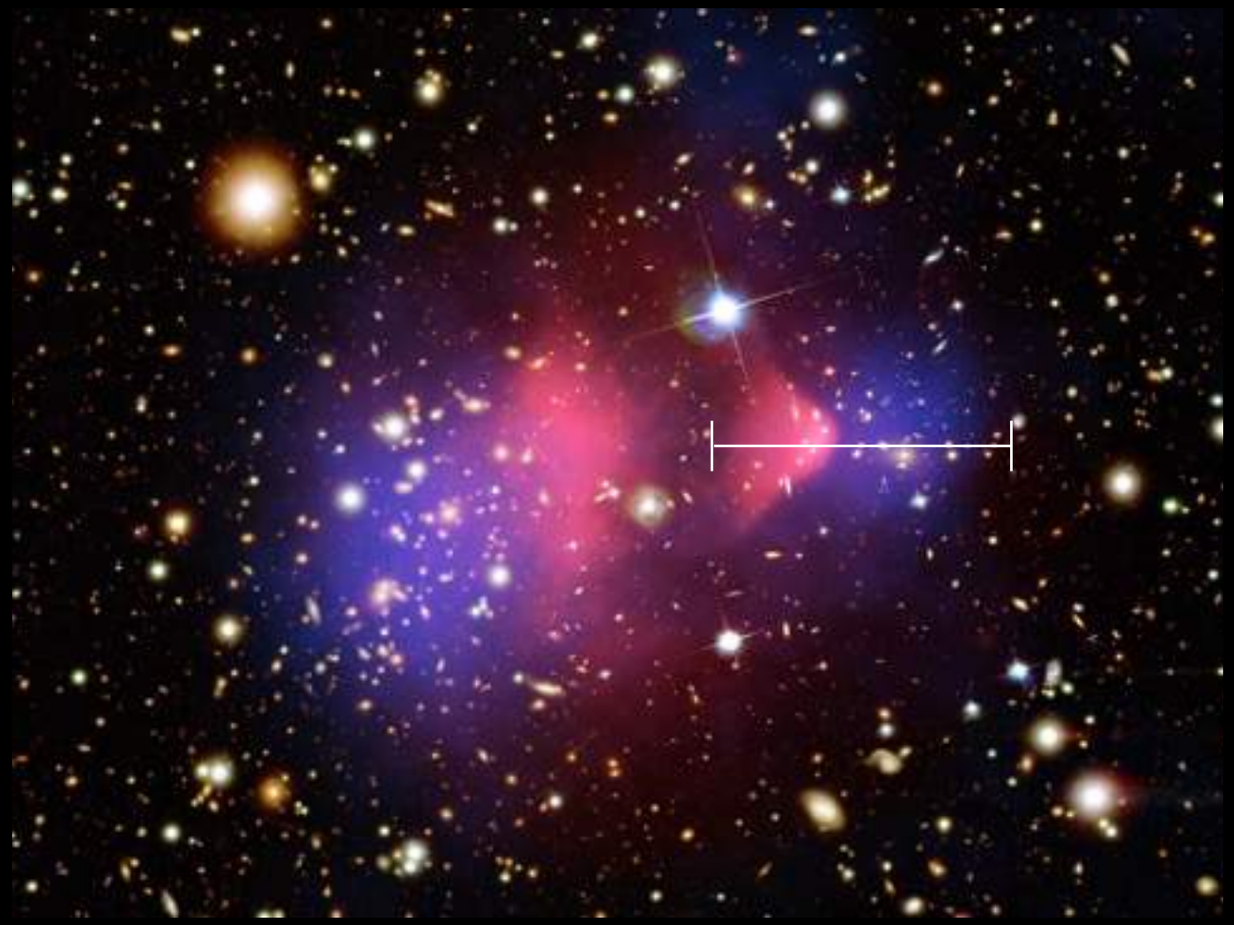



$\mathbf{r_{core} = 13.8 \pm 1.4 kpc}$

Harvey+ 2017b

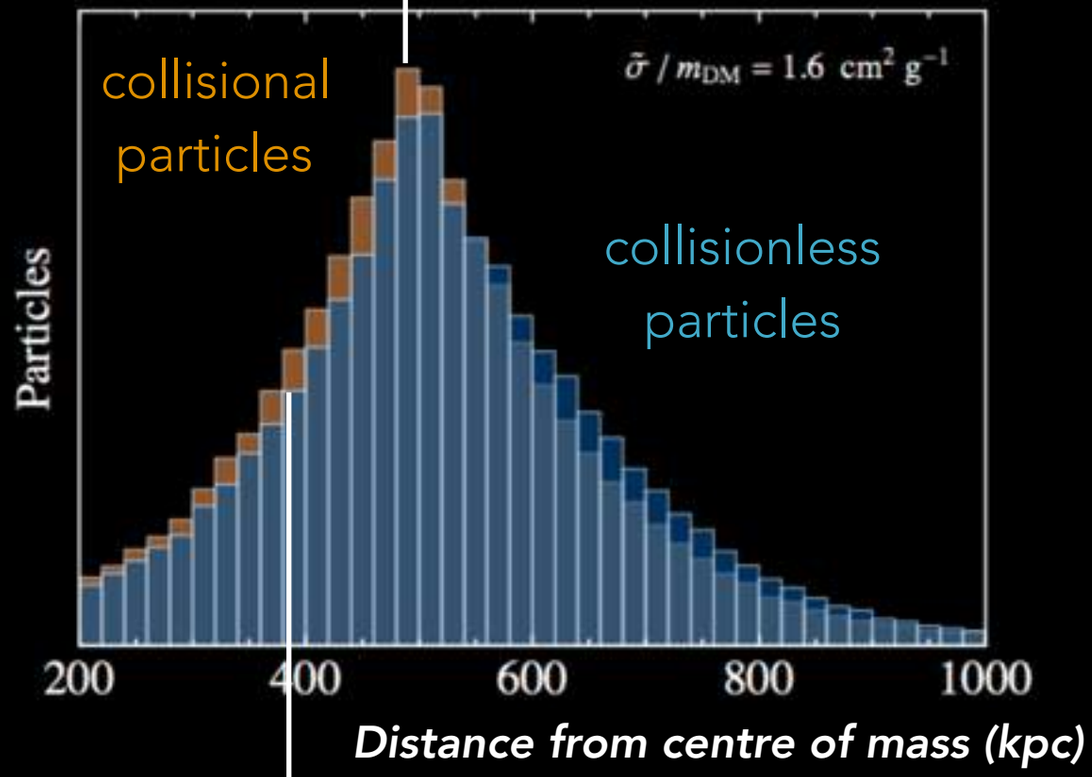
# DYNAMICS OF SELF-INTERACTING DM IN MERGING CLUSTERS

# DYNAMICS OF SELF-INTERACTING DM
# ***CHANGE*** IN MERGING CLUSTERS



Kahlhoefer+ 2014
Kim+ 2016

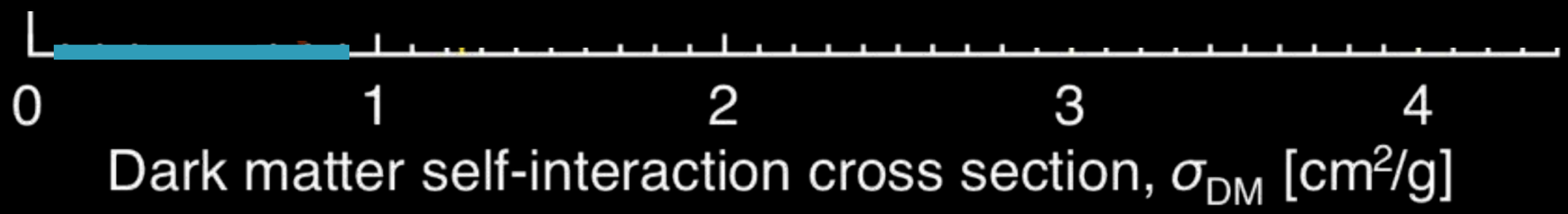
Peak Shift




Trailing dark matter
and mass loss

# THE CROSS-SECTION SCALE

Solves cosmology's "small scale crisis"



# CONSTRAINTS ARE LIMITED WITH SINGLE CLUSTER MERGERS

Markevitch+ 2004
Randall+ 2008

Mertens+ 2011

Bradac+ 2008

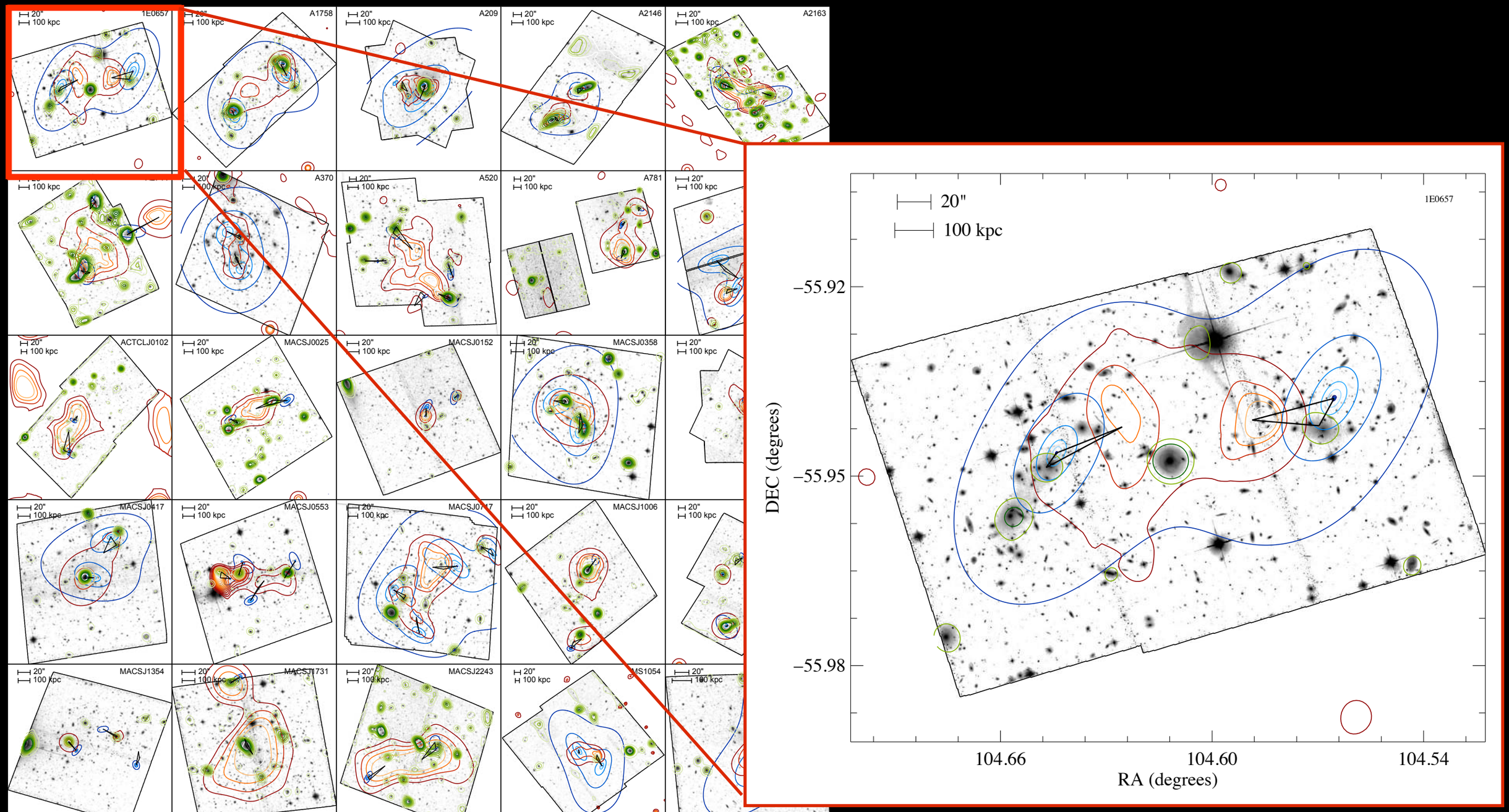
1 barn/GeV

Solves cosmology's "small scale crisis"

0 1 2 3 4

Dark matter self-interaction cross section, $\sigma_{DM}$ [cm$^2$/g]

# EXTENDING THE STUDY TO 30 CLUSTER MERGERS

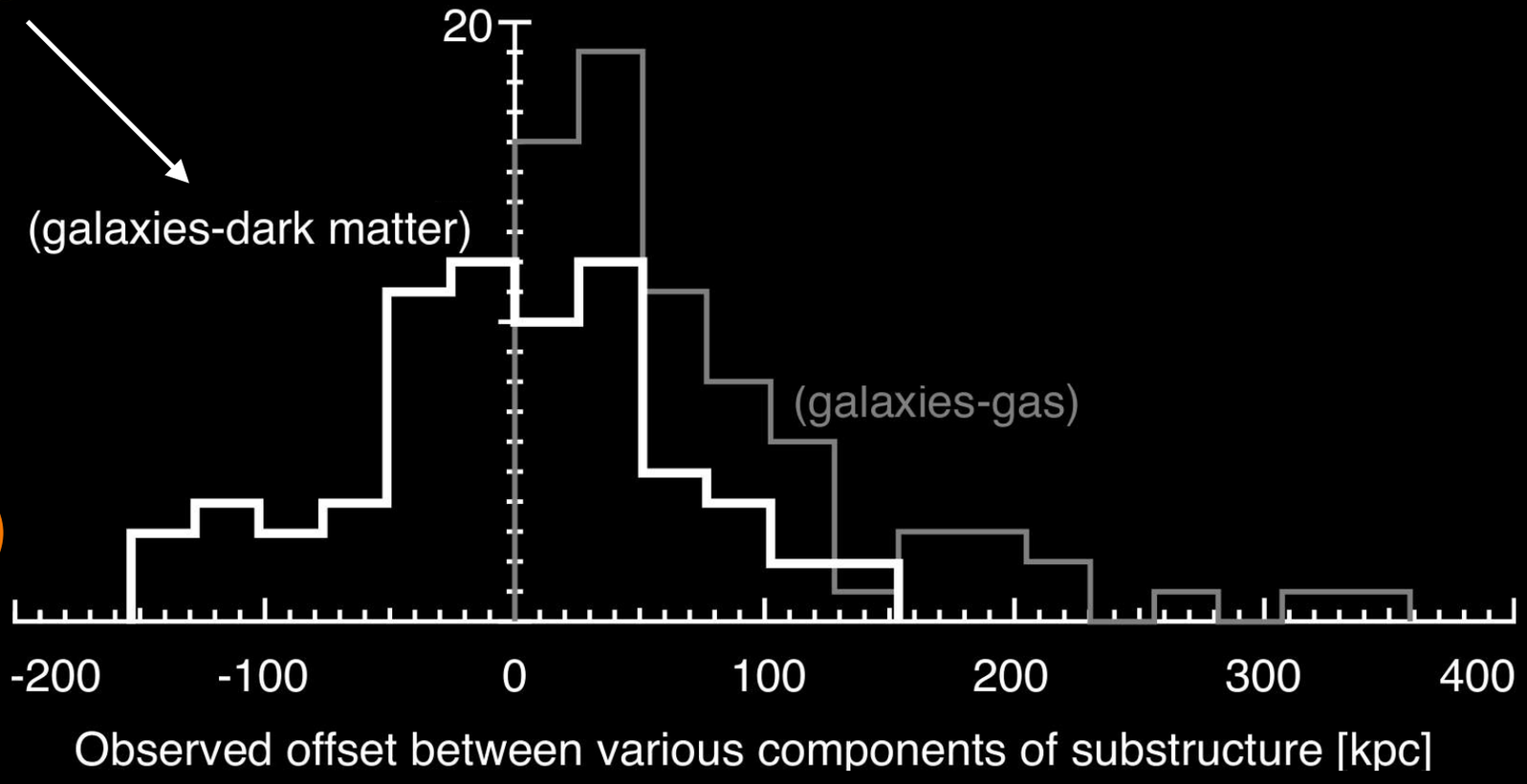



Harvey+ 2015

# DARK MATTER — GALAXY OFFSETS FROM 72 MERGING SYSTEMS

$5.8 \pm 8.2\mathrm{kpc}$

$25 \pm 29\mathrm{kpc}$
(Bullet Cluster)




Harvey+ 2015

# IMPROVING THE CONSTRAINTS ON THE SELF-INTERACTIONS CROSS-SECTION

**0.47** $\mathrm{cm}^2/\mathrm{g}$

Markevitch+ 2004
Randall+ 2008

Mertens+ 2011

Bradac+ 2008

30 Cluster Mergers

1 barn/GeV

Bullet cluster
1E 0657-558

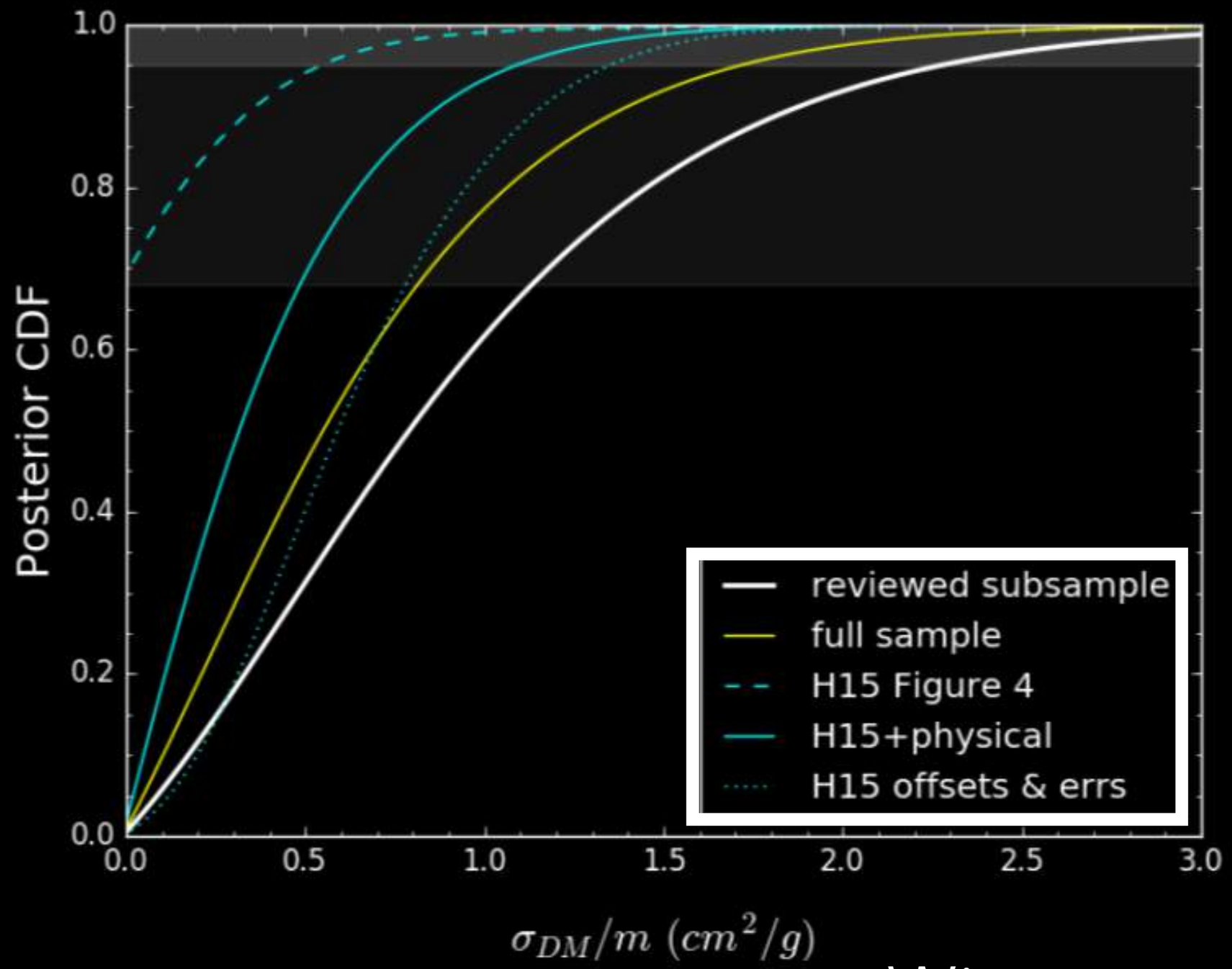
Pandora's cluster
Abell 2744

Baby bullet
MACSJ0025

0 1 2 3 4

Dark matter self-interaction cross section, $\sigma_{DM}$ [$cm^2/g$]

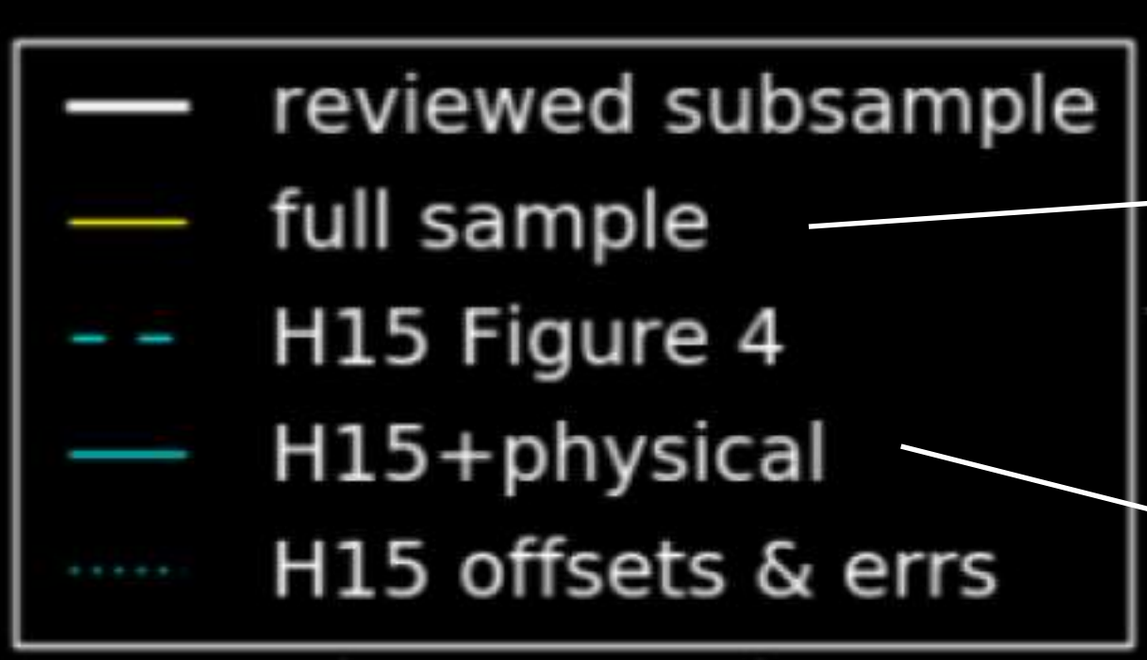
# SYSTEMATICS IN MEASURING AND INTERPRETING OFFSETS




Wittman+ 2017

# HOW SHOULD WE STACK CLUSTERS IN A STATISTICAL FASHION?

Should we pick and select clusters?




Or have predefine selection criterium

Requirement for simulation driven constraints

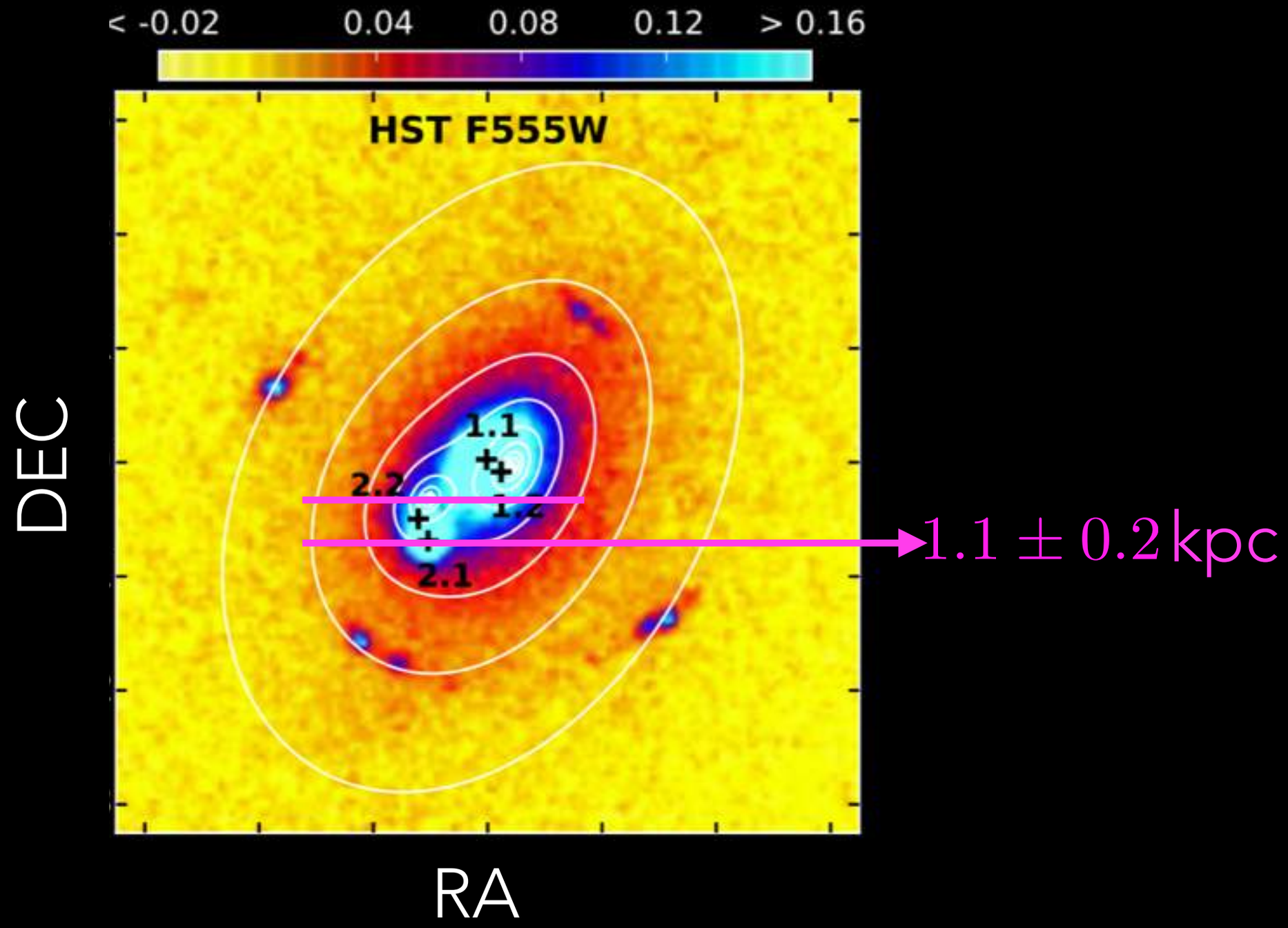
# THE CURIOUS CASE OF A3827

(See R. Massey Talk)

Williams & Saha 2011, MNRAS

Massey+ 2015, MNRAS

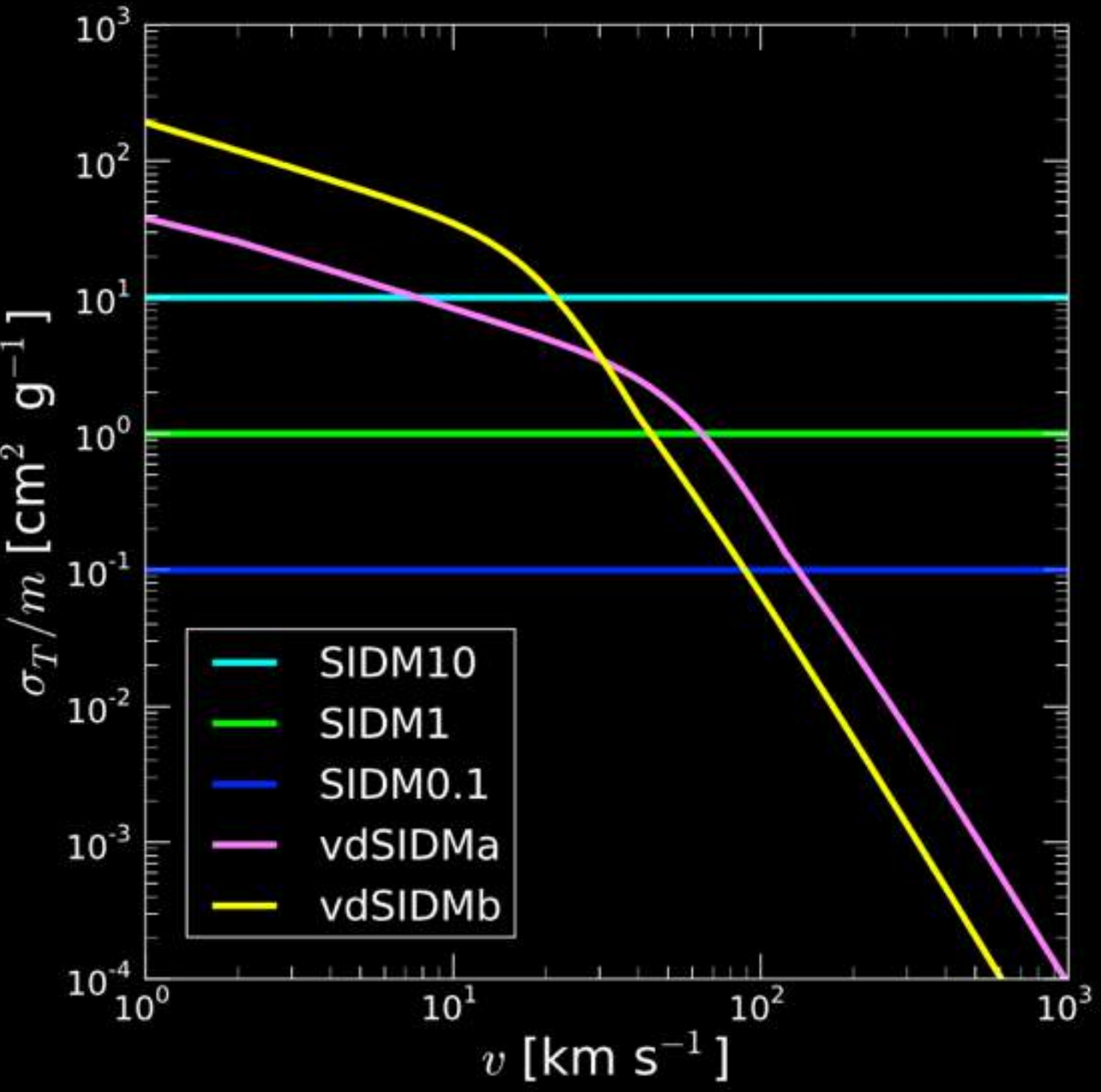
# SIGNS OF PARTICLE DARK MATTER IN SDSSJ1011?




Shu et al 2016

# IS THERE A TENSION BETWEEN CLUSTER MERGER CONSTRAINTS, SDSS1001 & DWARFS?

- Dynamical friction: offsets arise without SIDM?
- Systematics
  - A. Foreground structure
  - B. Source-lens degeneracies
- Velocity dependence



# CLOSING IN ON THE CROSS-SECTION OF DARK MATTER

Markevitch+ 2004
Randall+ 2008

Mertens+ 2011

Bradac+ 2008

Harvey+ 2015

SDSS1001?

30 Cluster Mergers

Bullet cluster
1E 0657-558

Pandora's cluster
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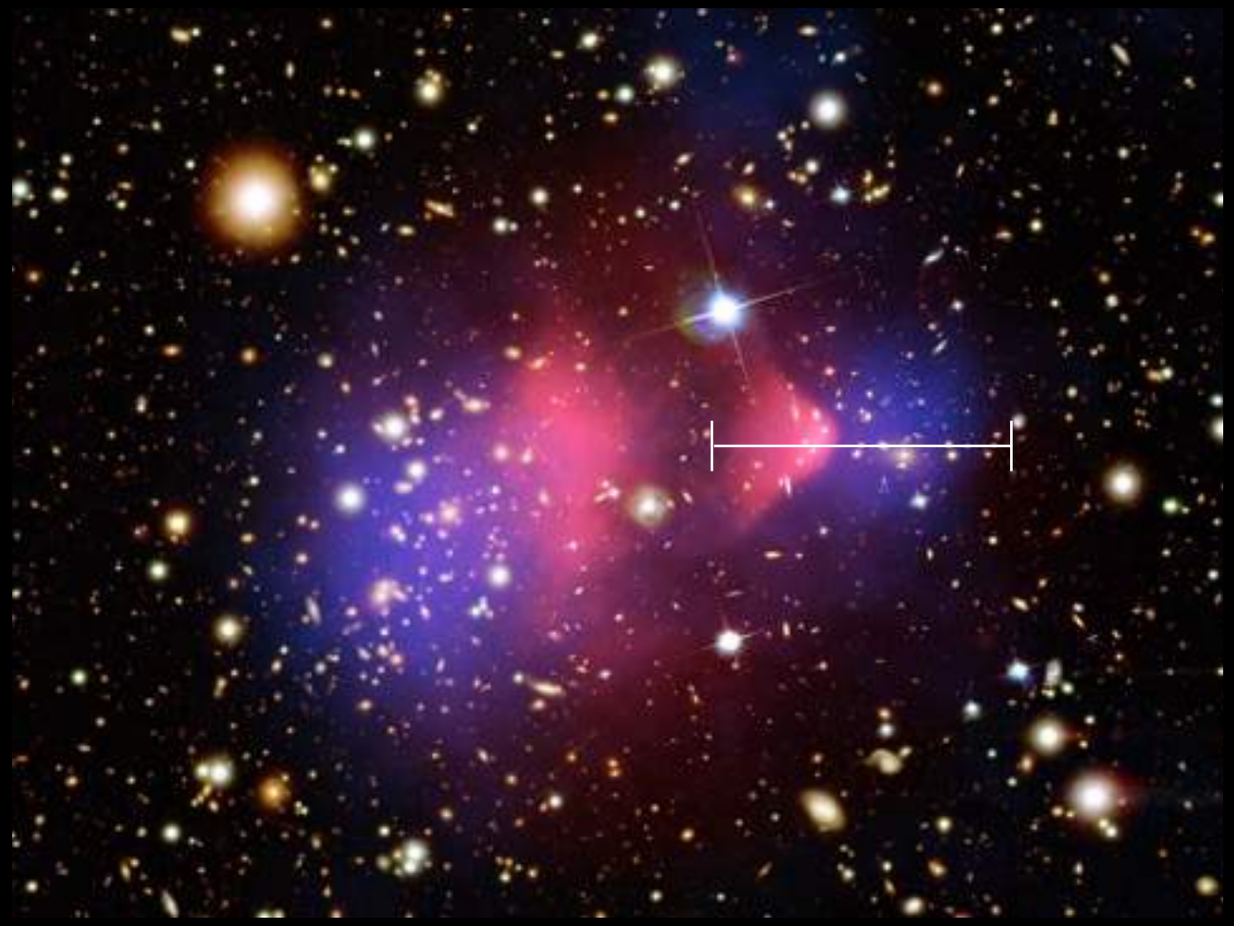
Baby bullet
MACSJ0025

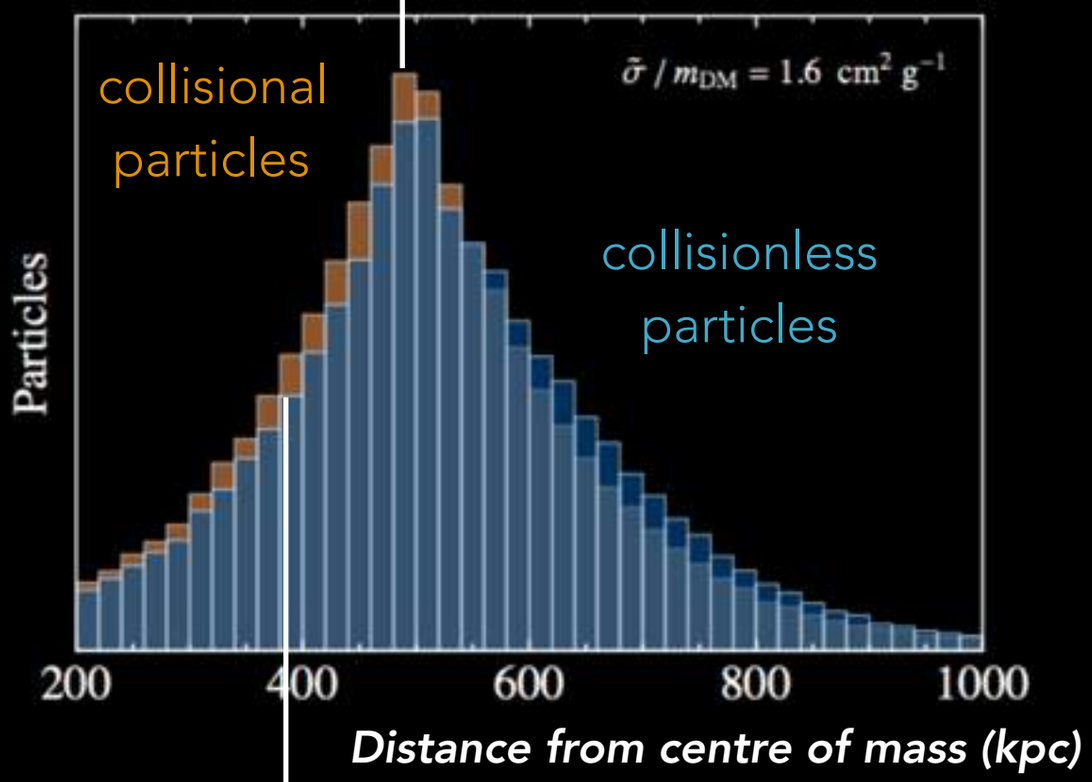
0 1 2 3 4

Dark matter self-interaction cross section, $\sigma_{DM}$ [cm$^2$/g]

# WHAT ARE THE OBSERVATIONAL MANIFESTATIONS OF SELF-INTERACTING DARK MATTER IN COLLIDING CLUSTERS?

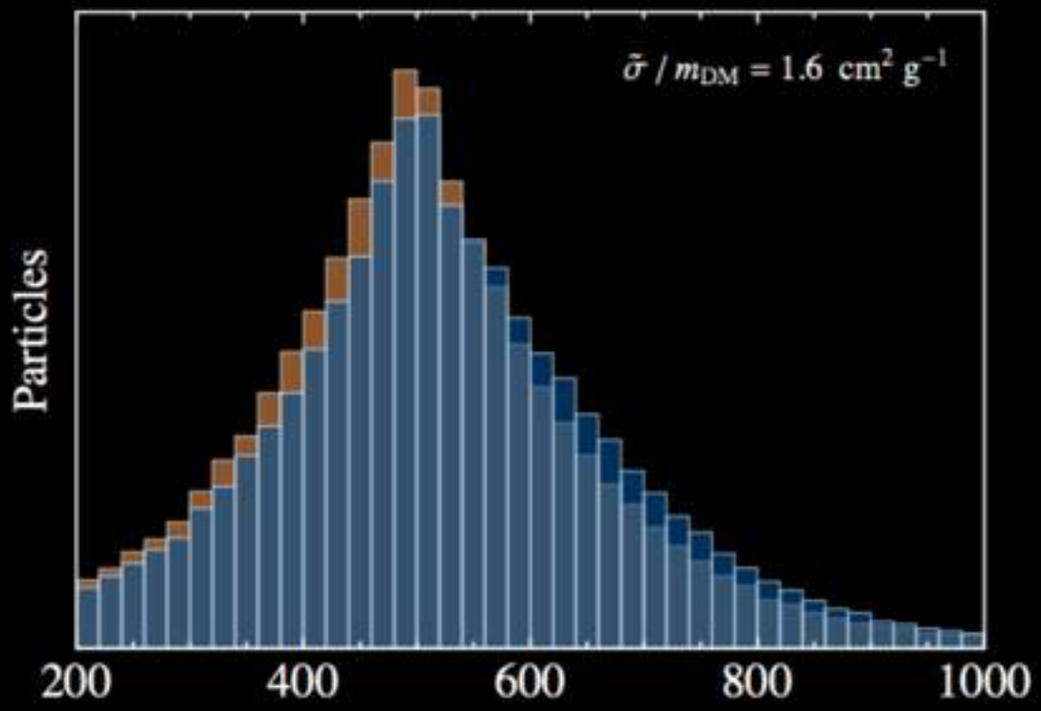


Peak Shift




Trailing dark matter and mass loss

# EXTRACTING THE TRAILING DARK MATTER



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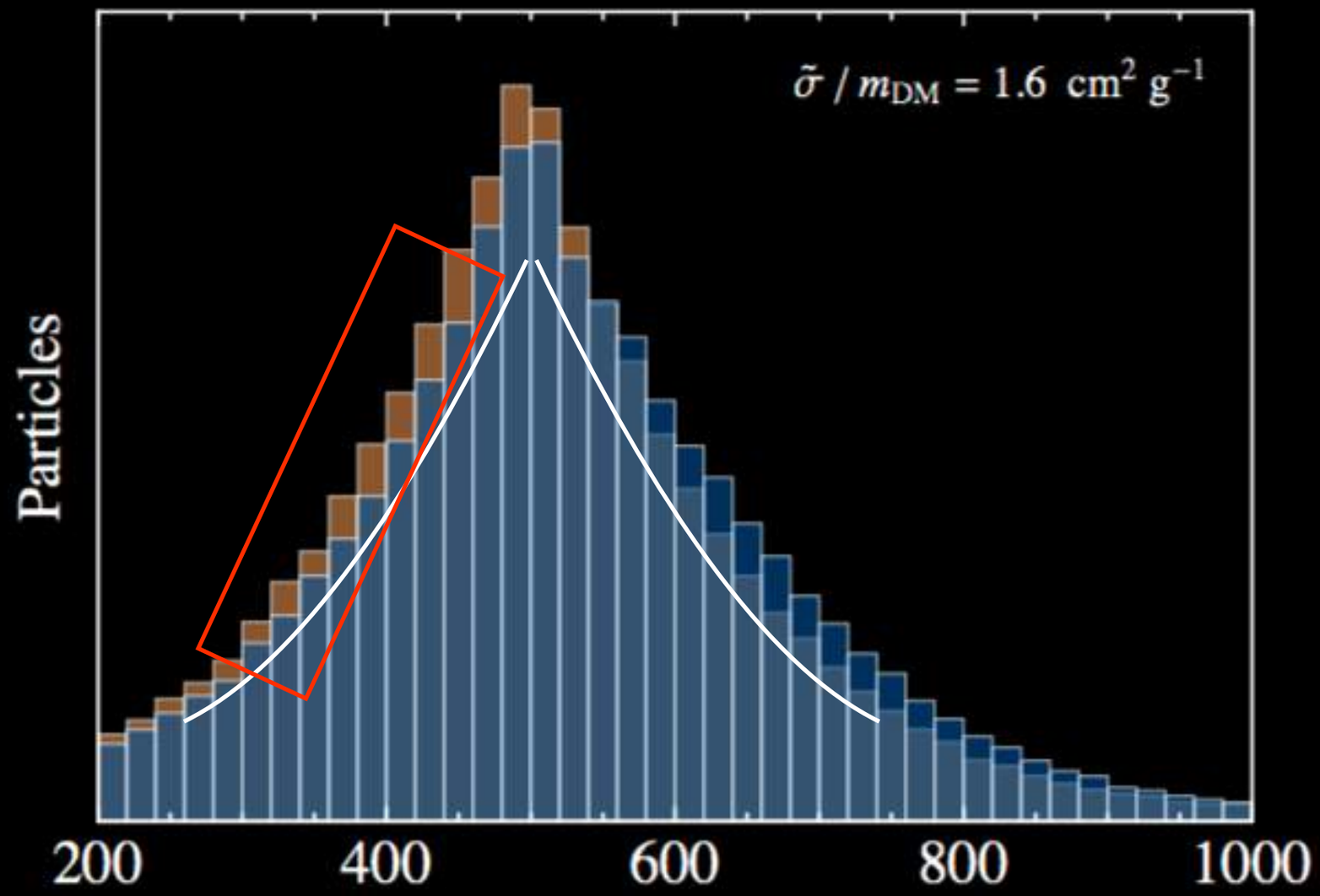
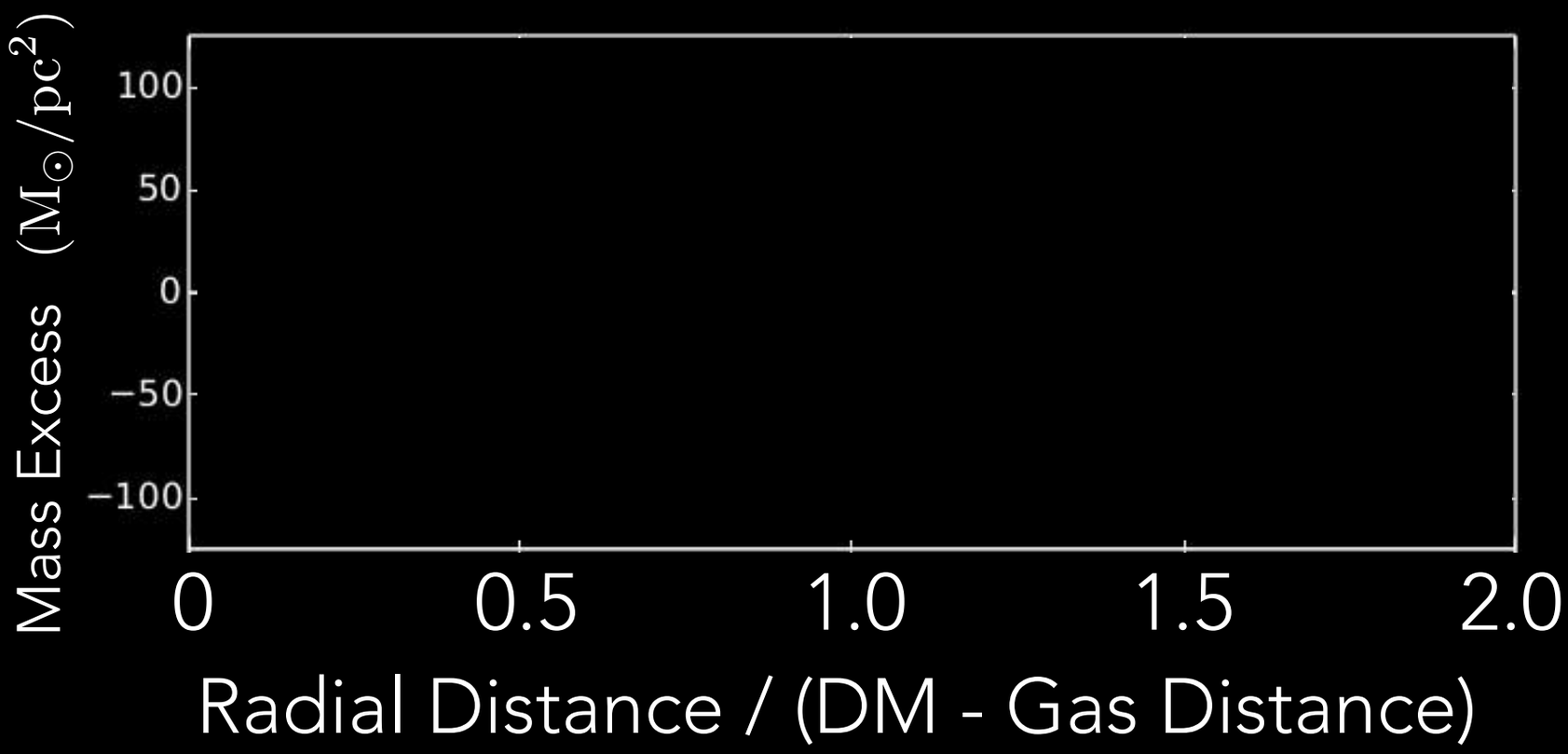
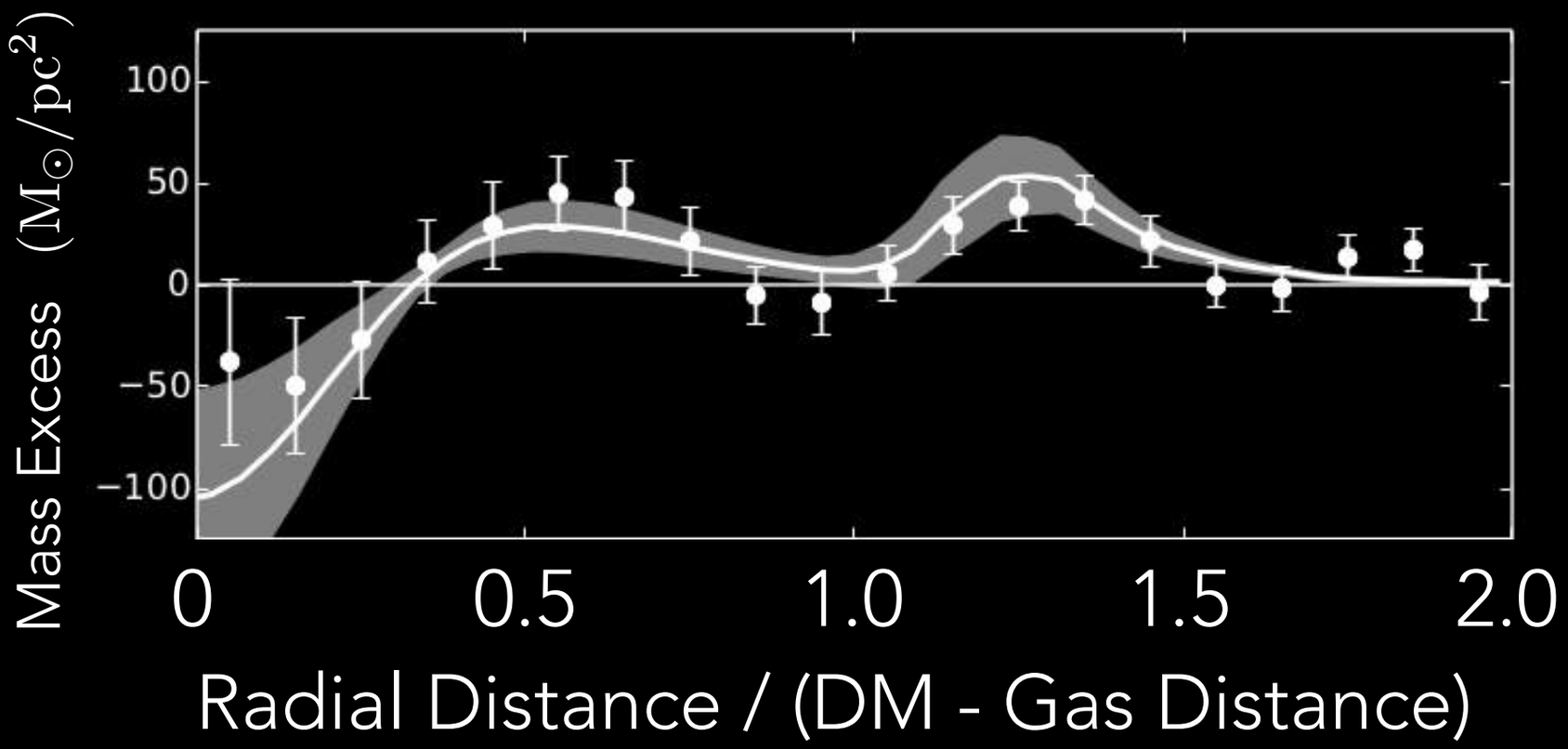


# DATA EXCESS ALONG AXIS OF COLLISION



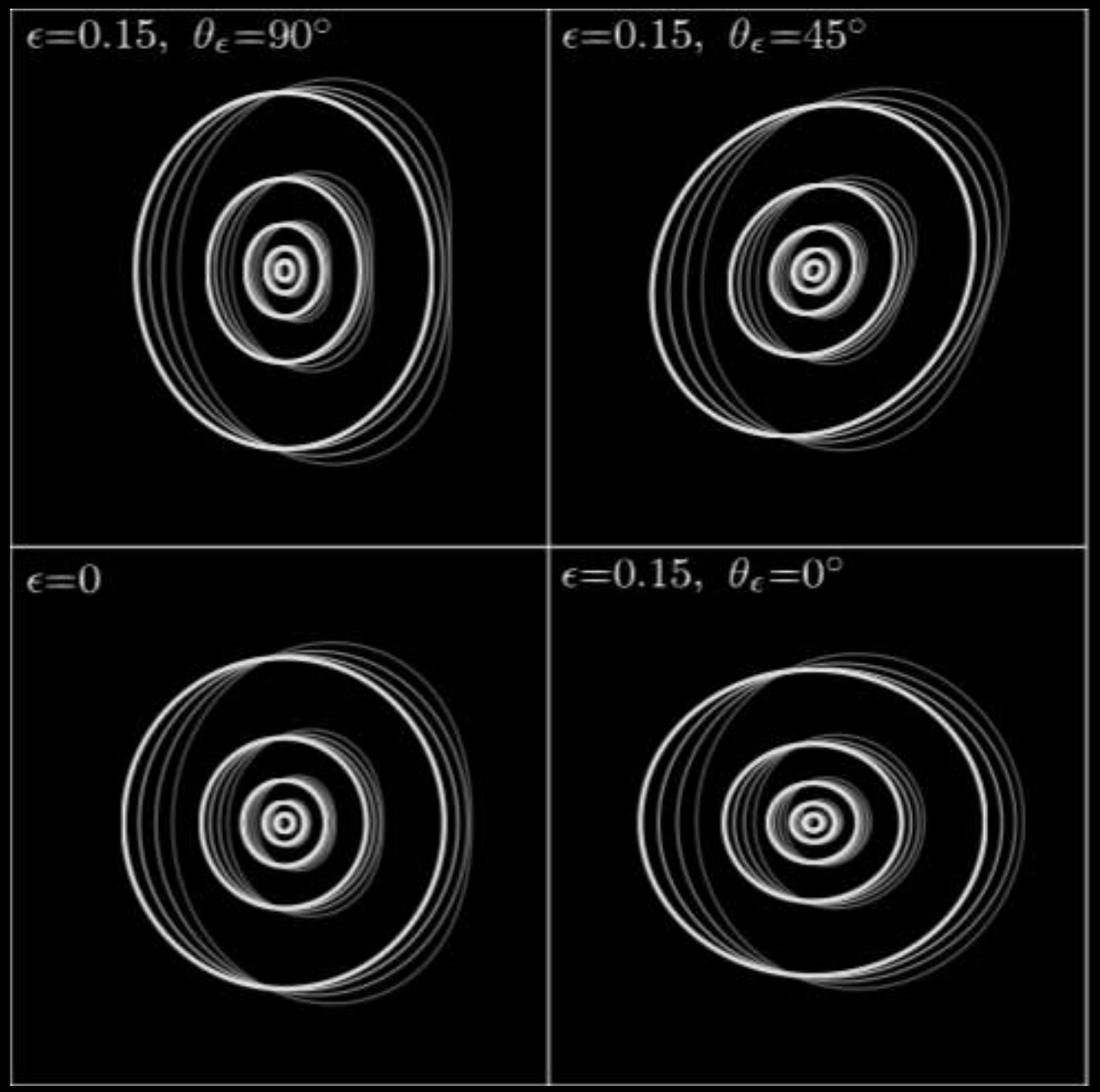

Harvey+ 2017a

# DATA EXCESS ALONG AXIS OF COLLISION EXPLAINED BY ERROR MODEL



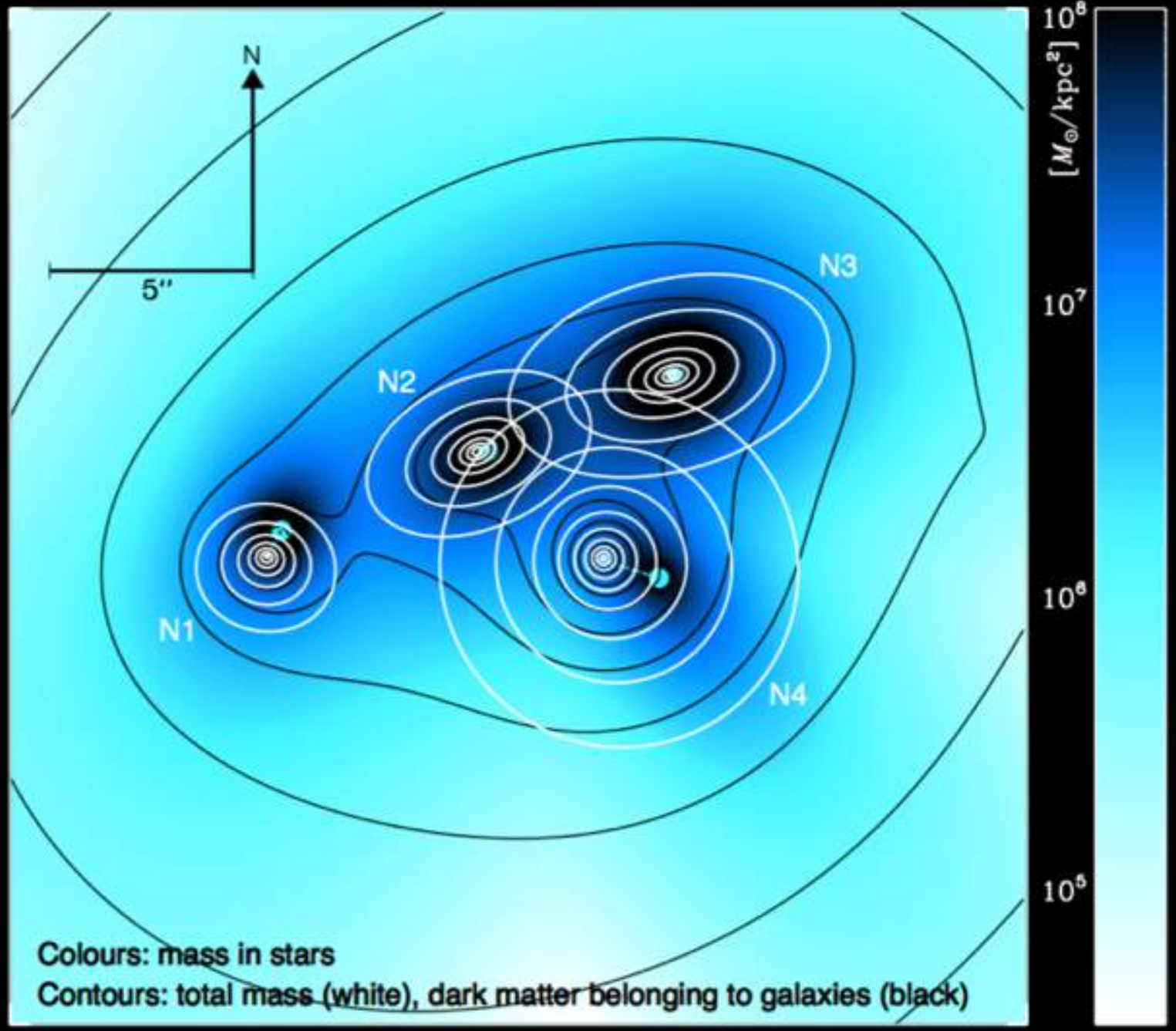

Harvey+ 2017a

# FITTING A SKEWED MASS PROFILE




Taylor+ 2017

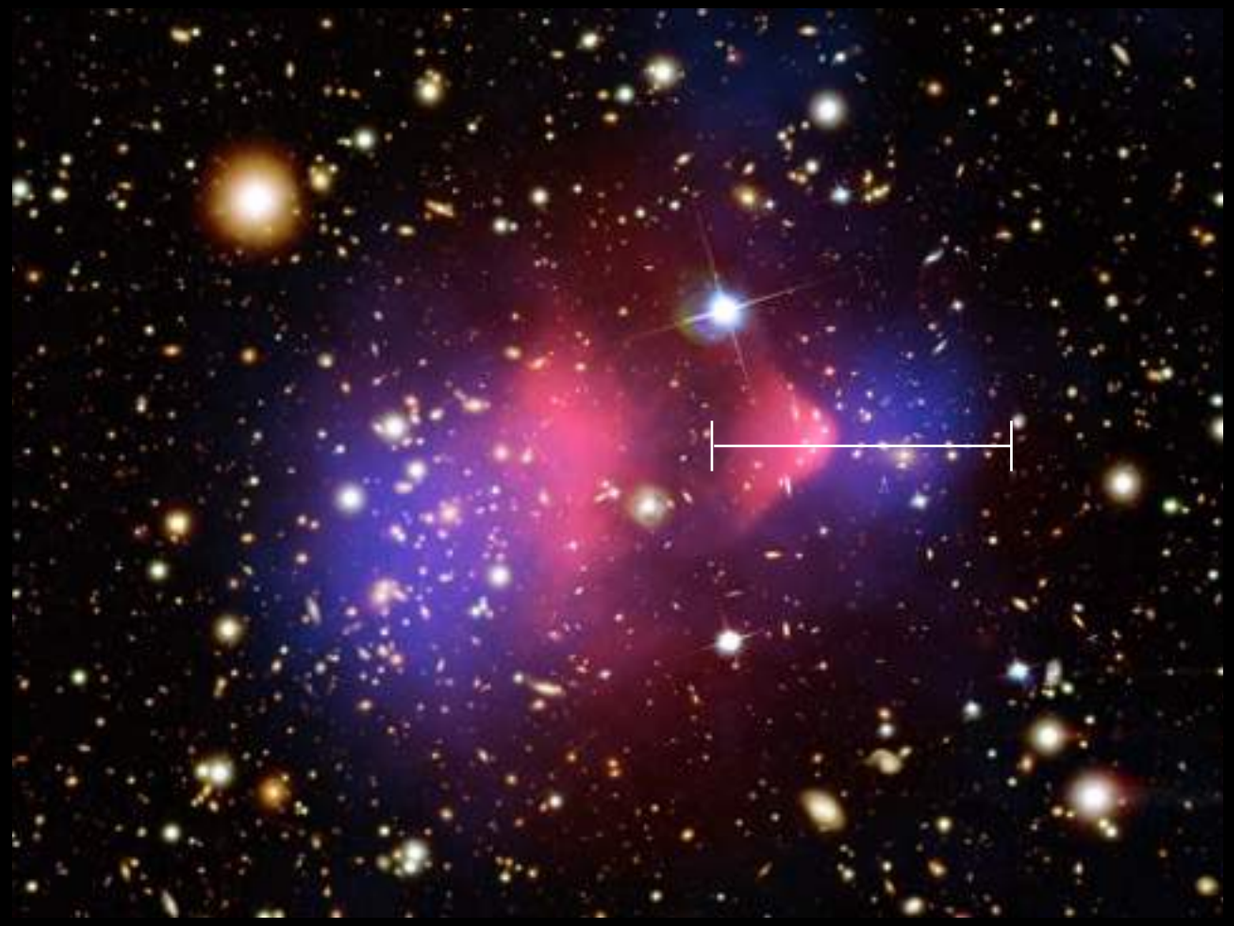
# FIRST APPLICATION TO DATA



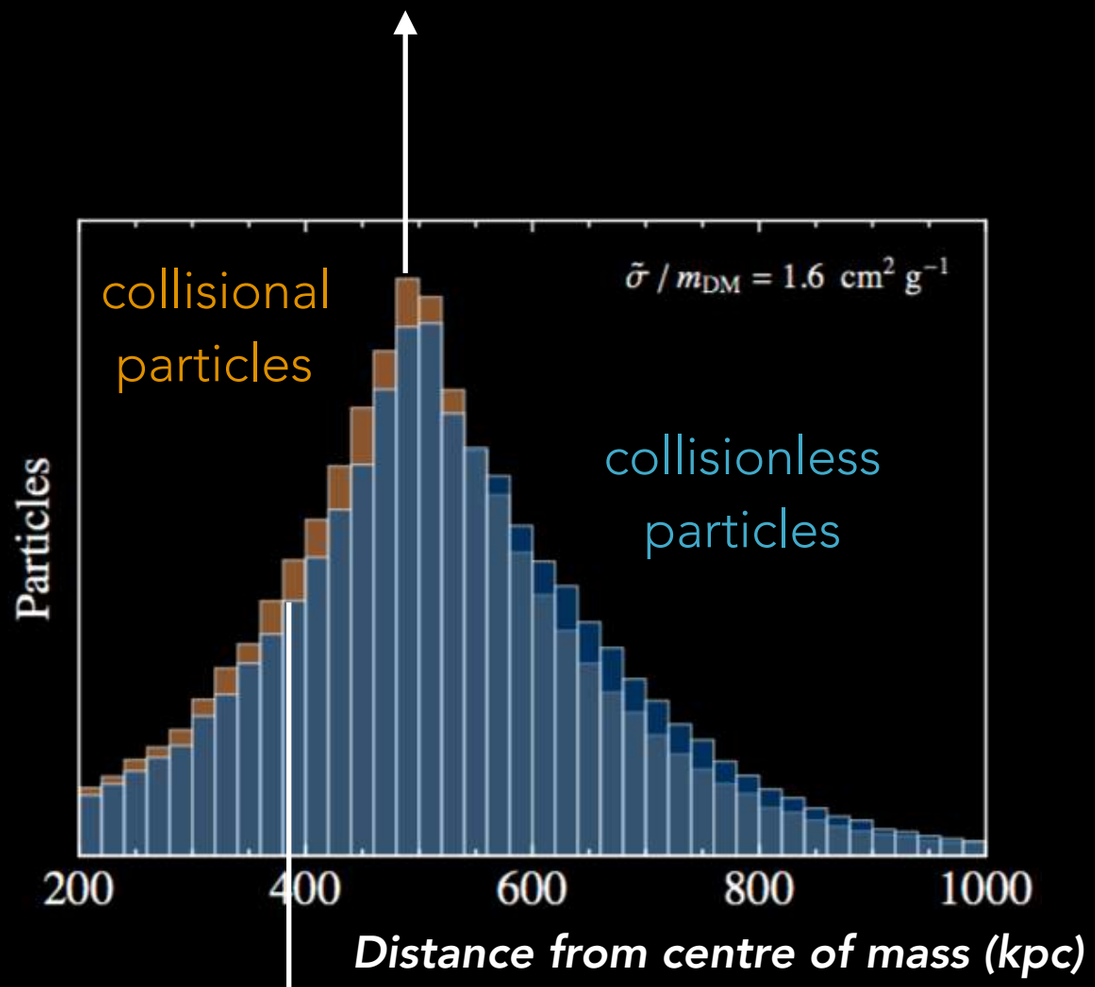

(See R. Massey Talk )

Taylor+ 2017

# WHAT ARE THE OBSERVATIONAL MANIFESTATIONS OF SELF-INTERACTING DARK MATTER IN COLLIDING CLUSTERS?



Peak Shift




Trailing dark matter and mass loss

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Randall+ 2008

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Harvey+ 2015

SDSS1001?

30 Cluster Mergers

Bullet cluster
1E 0657-558

Pandora's cluster
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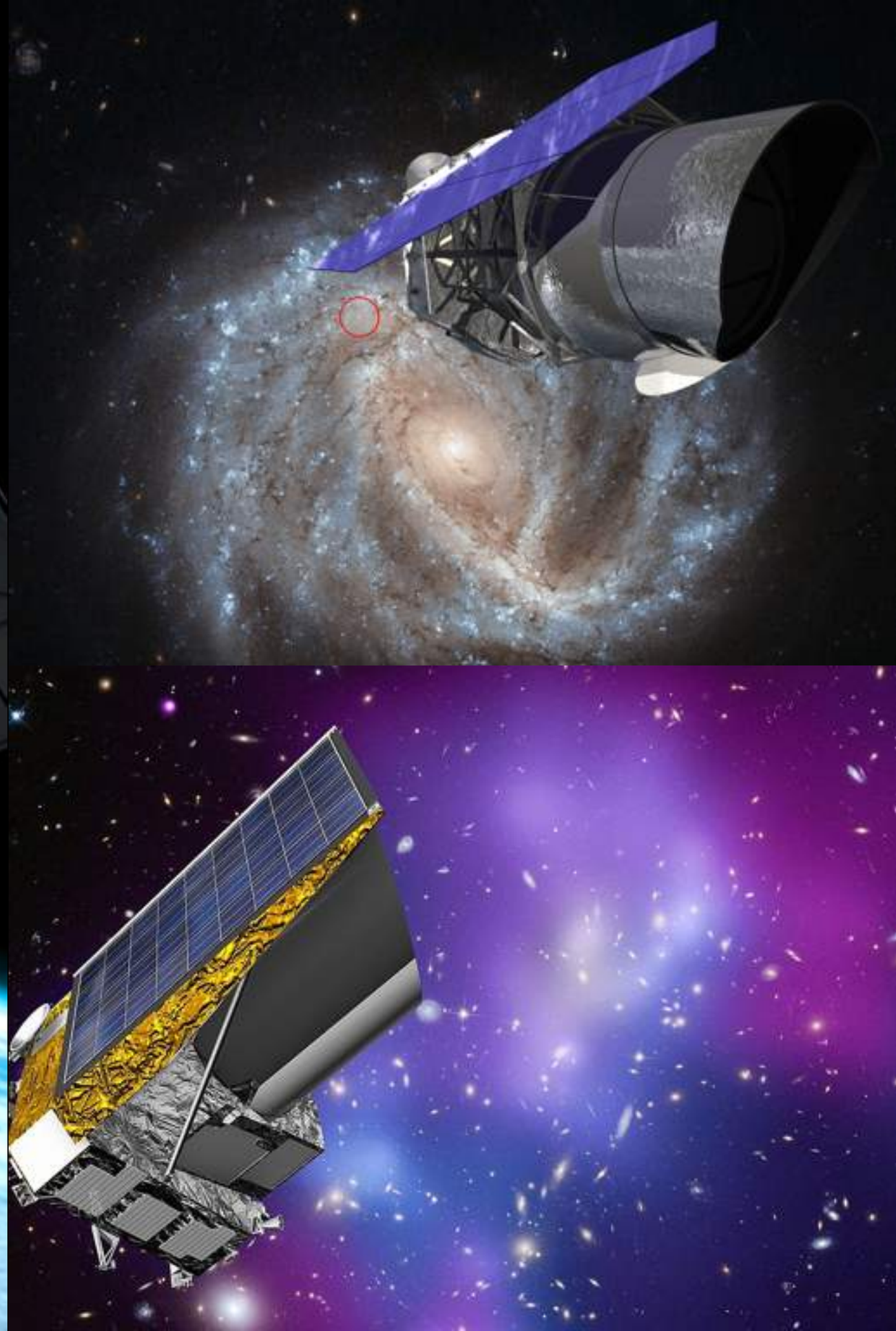
Baby bullet
MACSJ0025

0 1 2 3 4

Dark matter self-interaction cross section, $\sigma_{DM}$ [cm$^2$/g]

THE FUTURE IS DATA RICH

# (See D.Wittman Talk)

DAO's

Mass Function

Cores

Sphericity

Large Scale Structure

Relaxed Clusters

GL PROBES OF SIDM

Merging Clusters

Substructure

Light / Mass Offsets

Skewed Mass Profiles

Mass Loss

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