Precise measurement of dark matter distribution with strong and weak gravitational lensing

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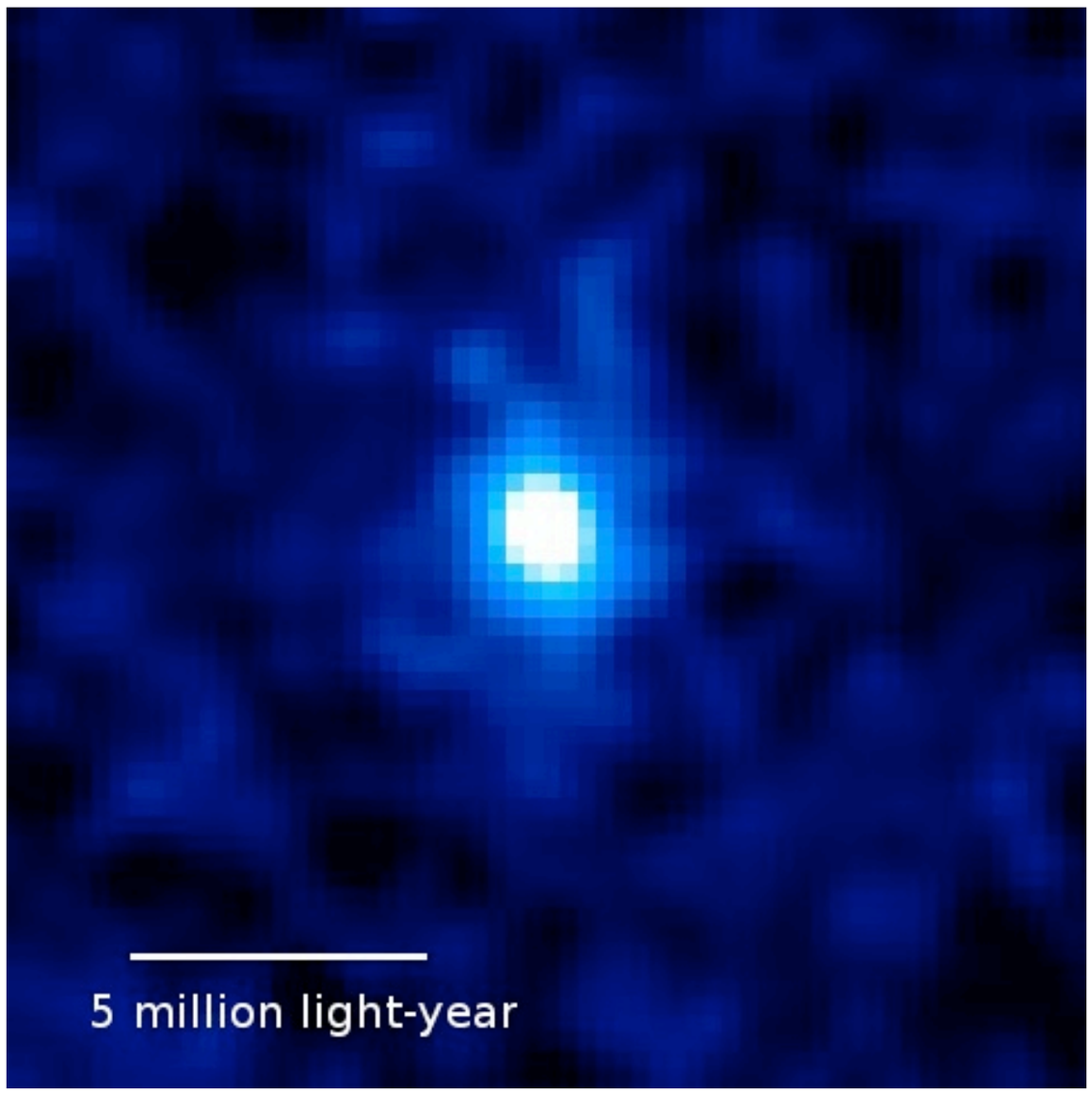


2012/2/29 Subaru UM@NAOJ

This talk is based on:

"Combined strong and weak lensing analysis of 28 clusters from Sloan Giant Arcs Survey"

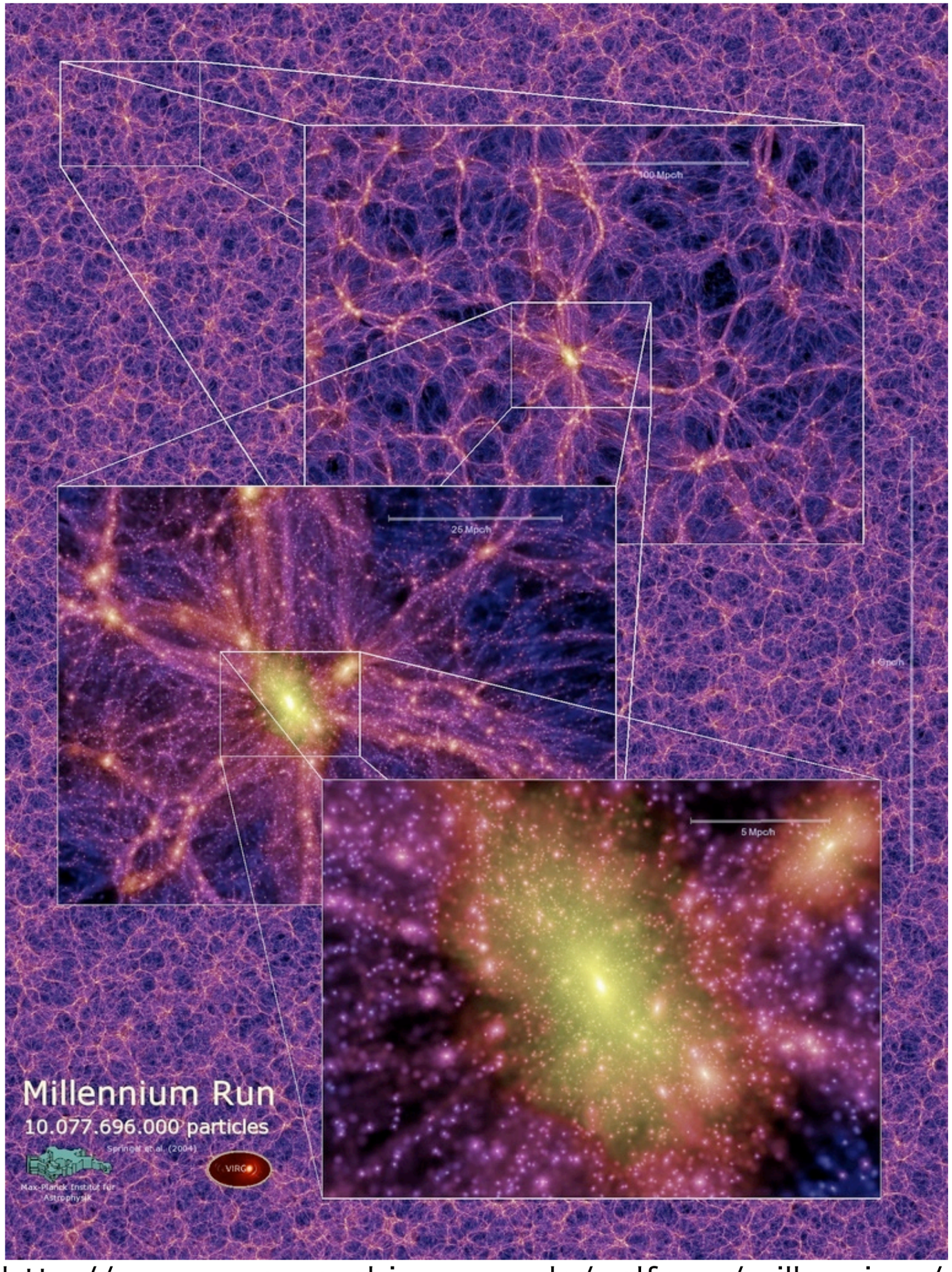
Oguri et al., MNRAS, 420, 3213 (2012) [arXiv:1109.2594]

Collaborators:

Matt Bayliss (Chicago → Harvard)
Håkon Dahle (Oslo)
Keren Sharon (Chicago)
Mike Gladders (Chicago)
Priya Natarajan (Yale)
Joe Hennawi (MPIA)
Ben Koester (Chicago)

Cluster of galaxies

- most massive virialized objects in the universe
- structure mostly determined by the dynamics of dark matter
- can be a good site to test structure formation models



http://www.mpa-garching.mpg.de/galform/millennium/

Expected mass distribution in ΛCDM

Cuspy

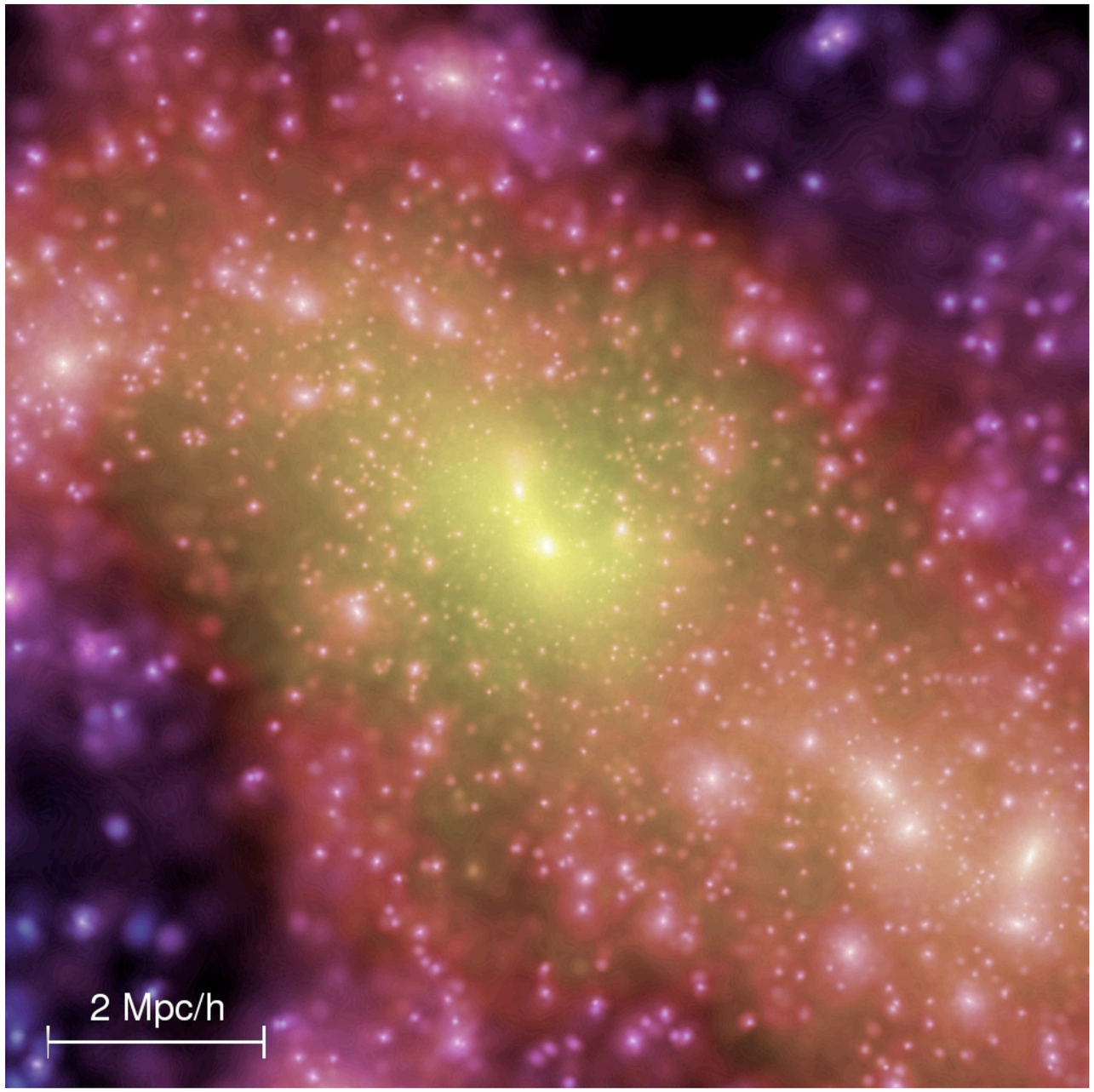
so-called NFW profile, slope gets shallower toward the center

Concentration

correlated with mass, more massive halos are less concentrated

Triaxial

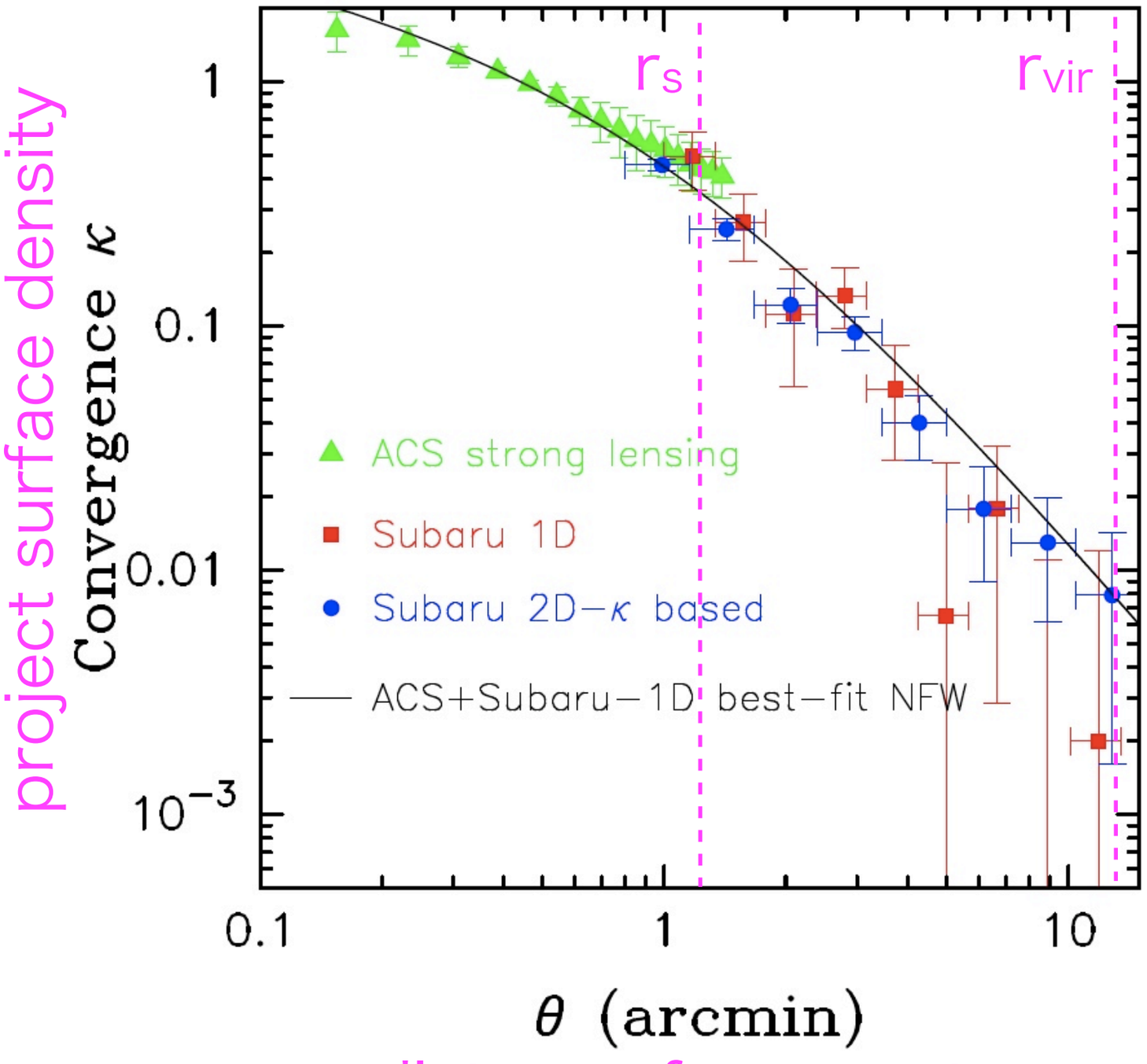
not spherical, highly elongated



http://www.mpa-garching.mpg.de/galform/millennium/

Anomalously high concentration?

Umetsu, Takada & Broadhurst (2007)



- lensing analysis of Abell 1689

  $c_{vir} \sim r_{vir}/r_s \sim 12$

- much larger than typical c_{vir}(~4), may hard to reconcile with ΛCDM

- controversial

→ other clusters?

Sloan Giant Arcs Survey (SGAS)

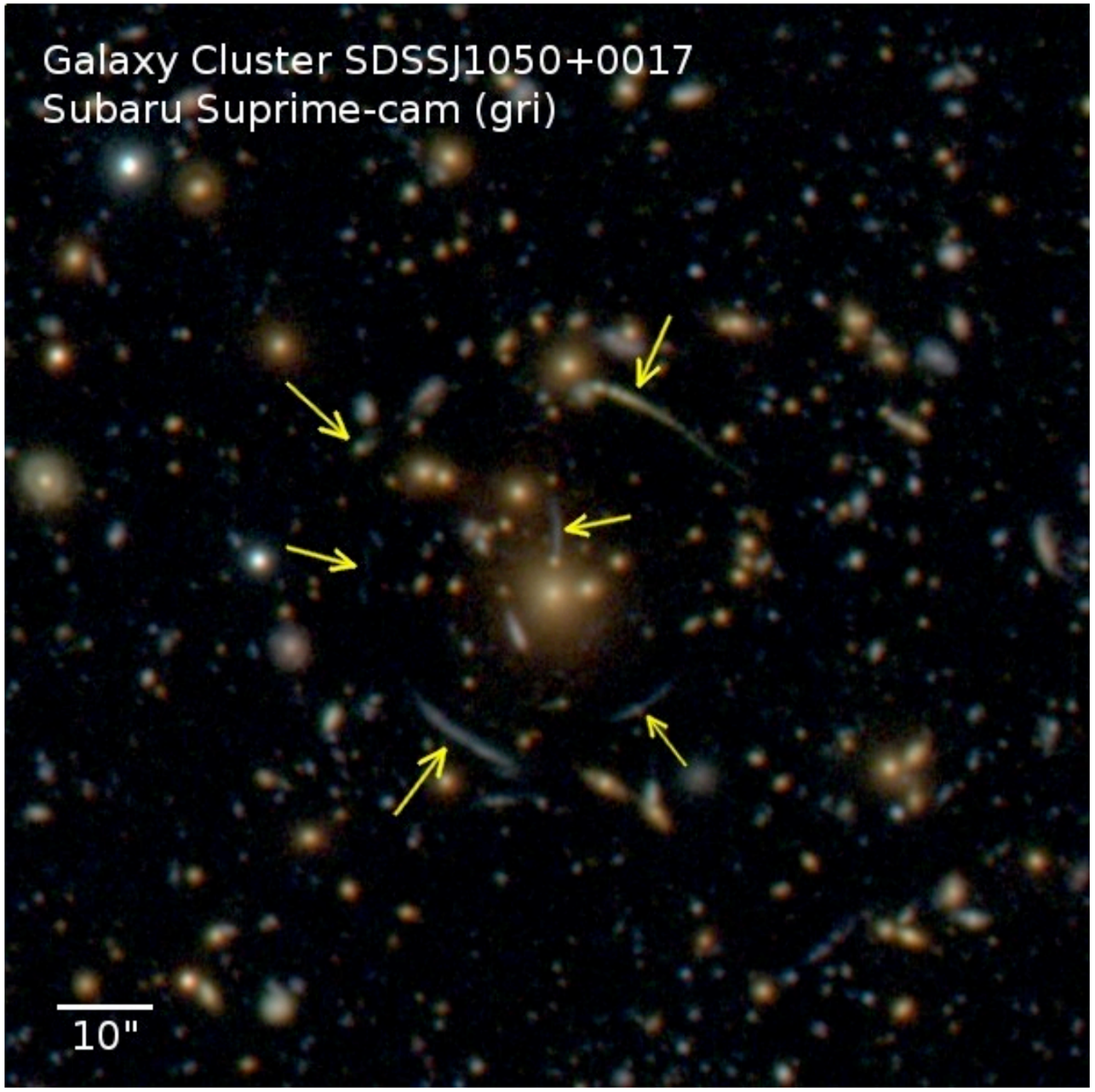
Hennawi et al. (2008), Bayliss et al. (2011)
Gladders et al., in prep.

- based on optical (red-sequence) clusters from the Sloan Digital Sky Survey
- look for strong lenses by visual inspection of SDSS or follow-up images
- >40 clusters with prominent giant arcs discovered, extensive arc spectroscopy w/ Gemini/GMOS

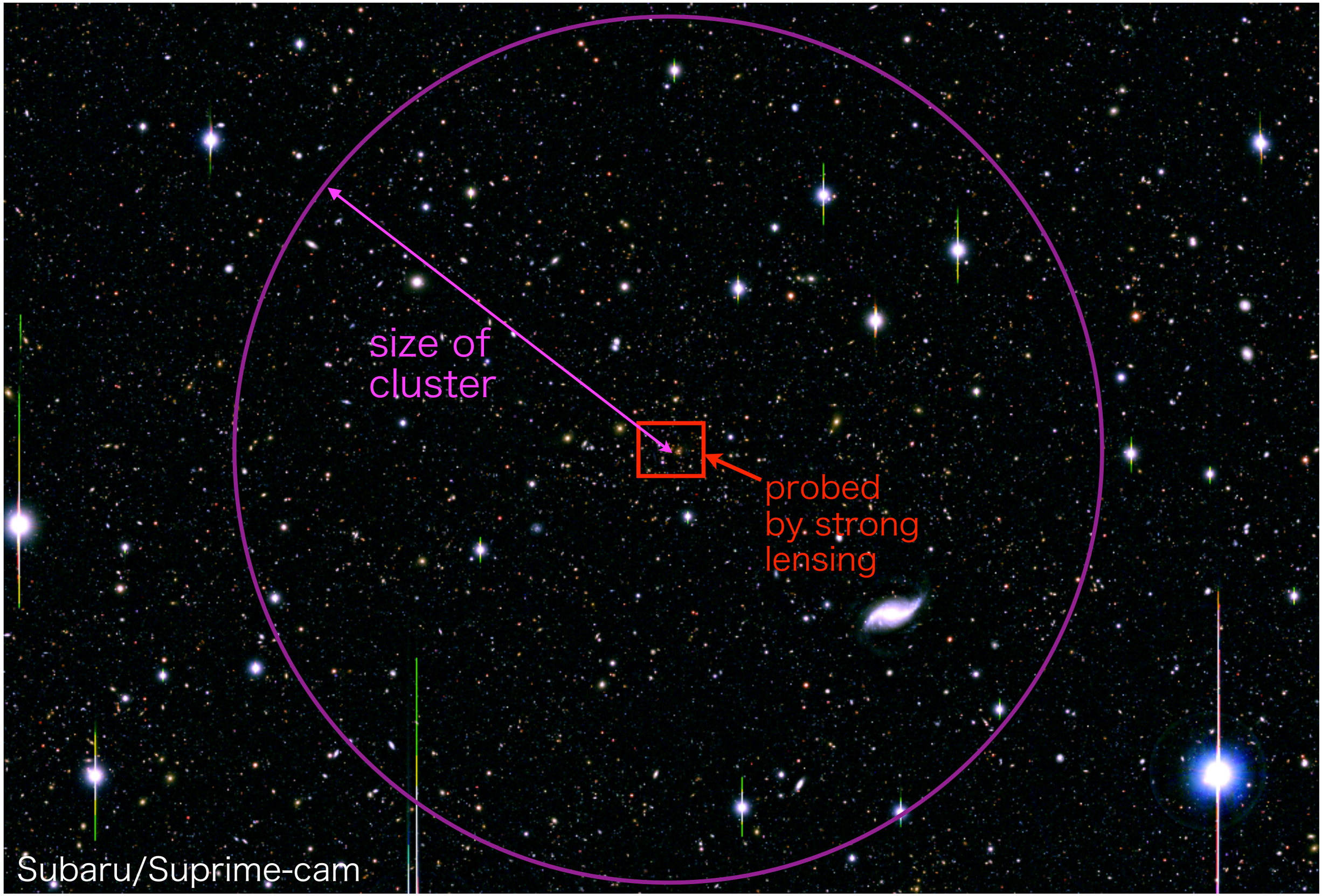
Strong gravitational lensing

- strong deflections of light rays which produce multiple images or highly elongated shapes of galaxies

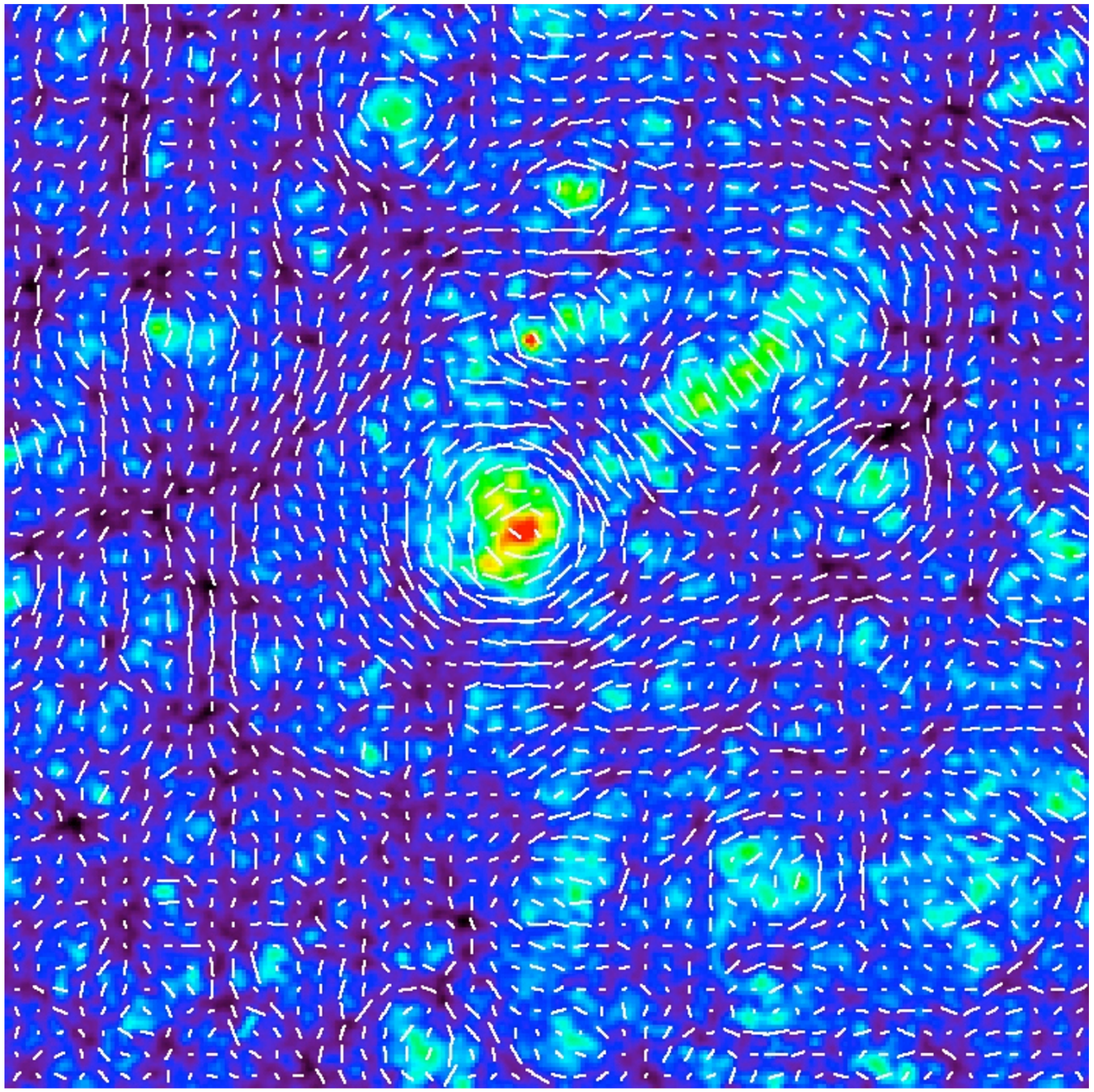
- provide a robust core mass measurement of clusters (w/ redshift info)



Cluster is much bigger...



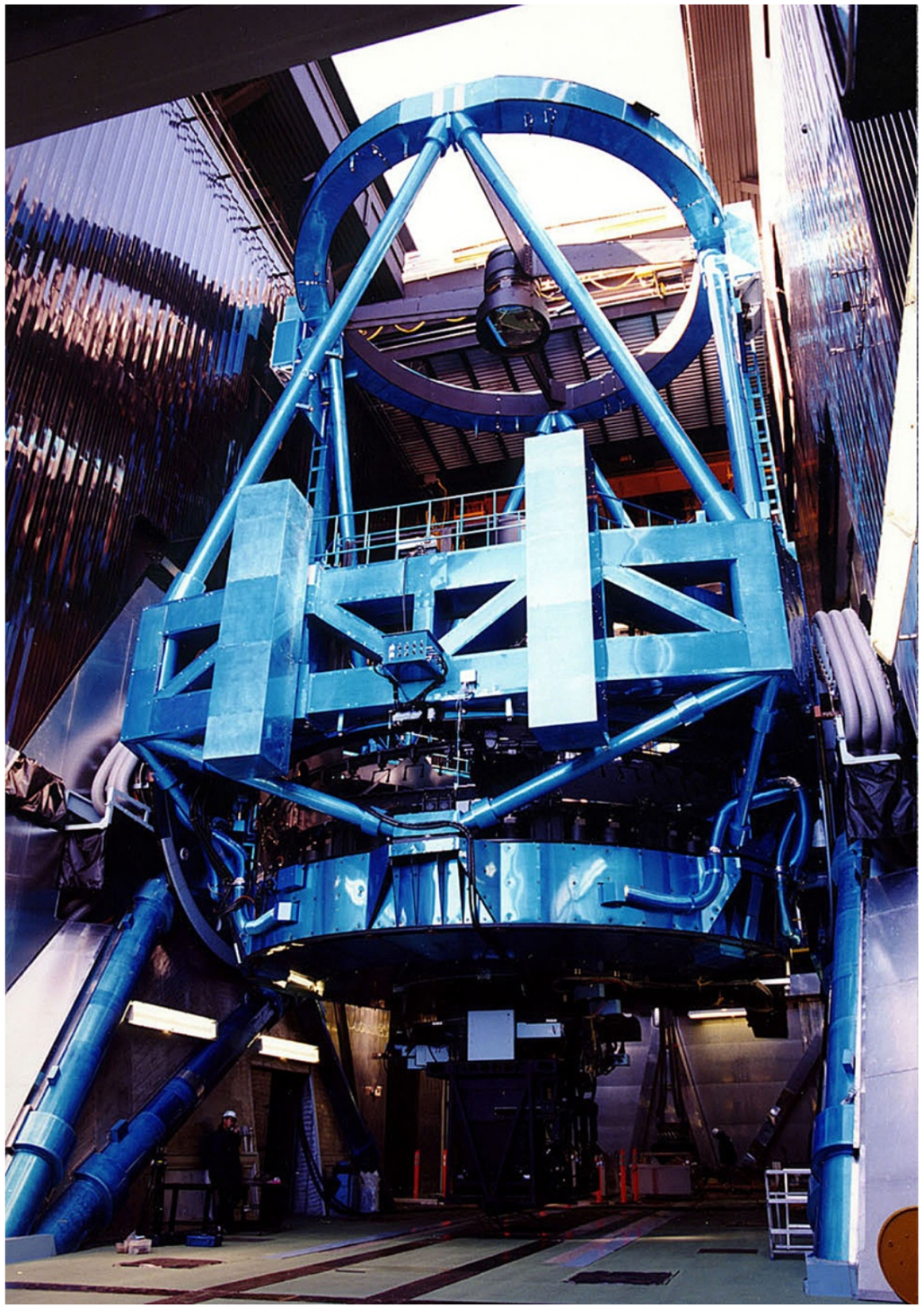
Weak gravitational lensing



(simulation by T. Hamana)

- coherent distortions of shapes of background galaxies
- measured by averaging many galaxies' shapes
- can measure cluster mass profiles out to virial radius

Subaru/Suprime-cam follow-up



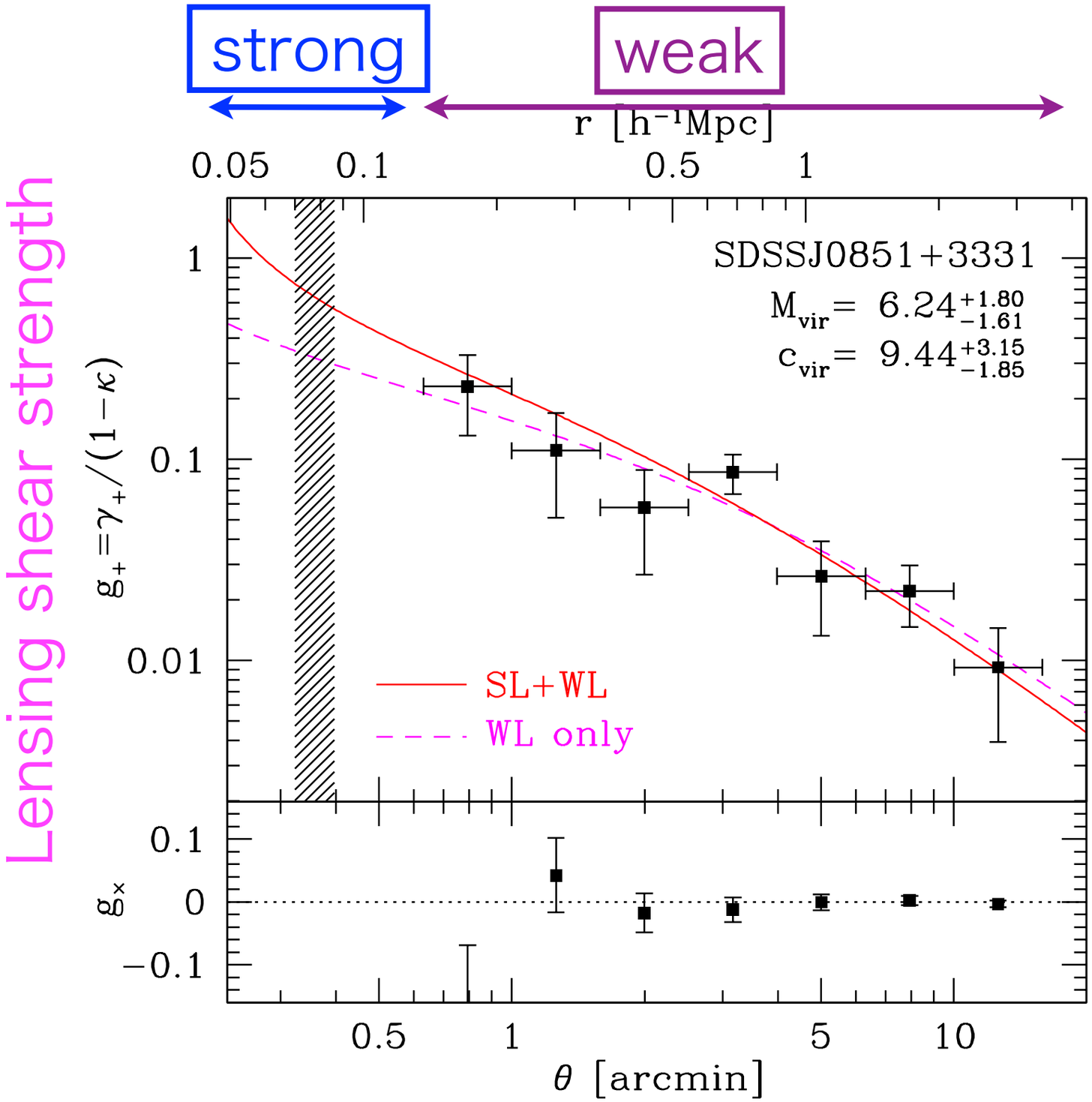
- world best telescope for cluster weak lensing!

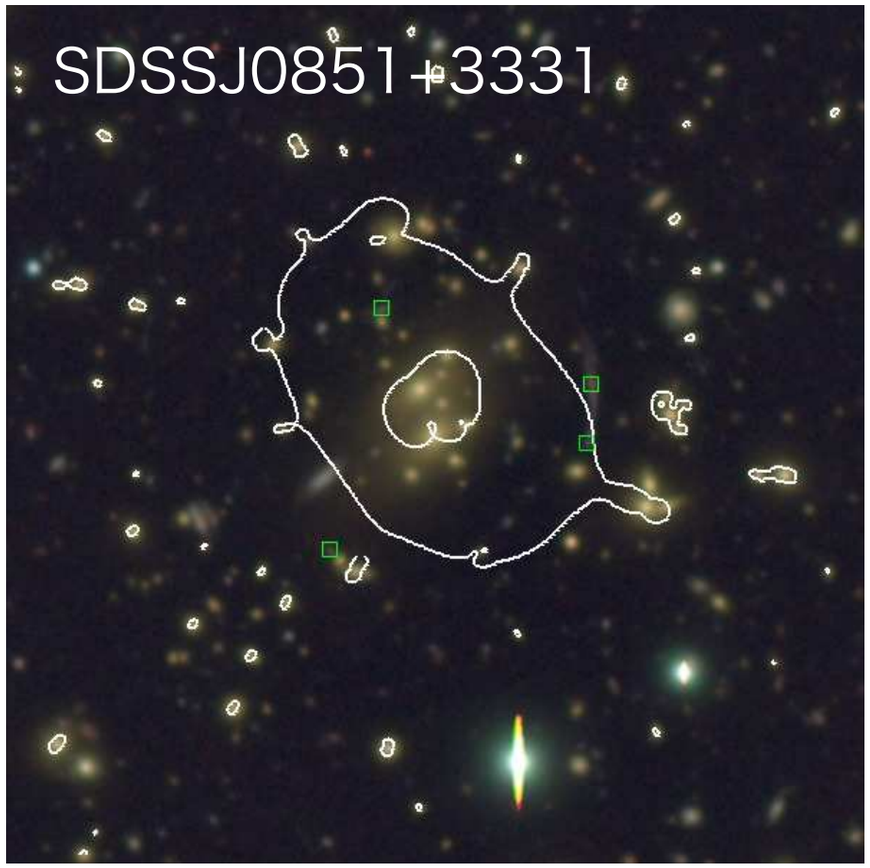
- gri-band imaging
  (g ~ 20min, r ~ 40min, i ~ 30min)

- ~7 nights allocated from 2007 to 2011 (PI: M. Oguri) [Thank you!]

→ strong+weak lensing analysis for ~30 clusters

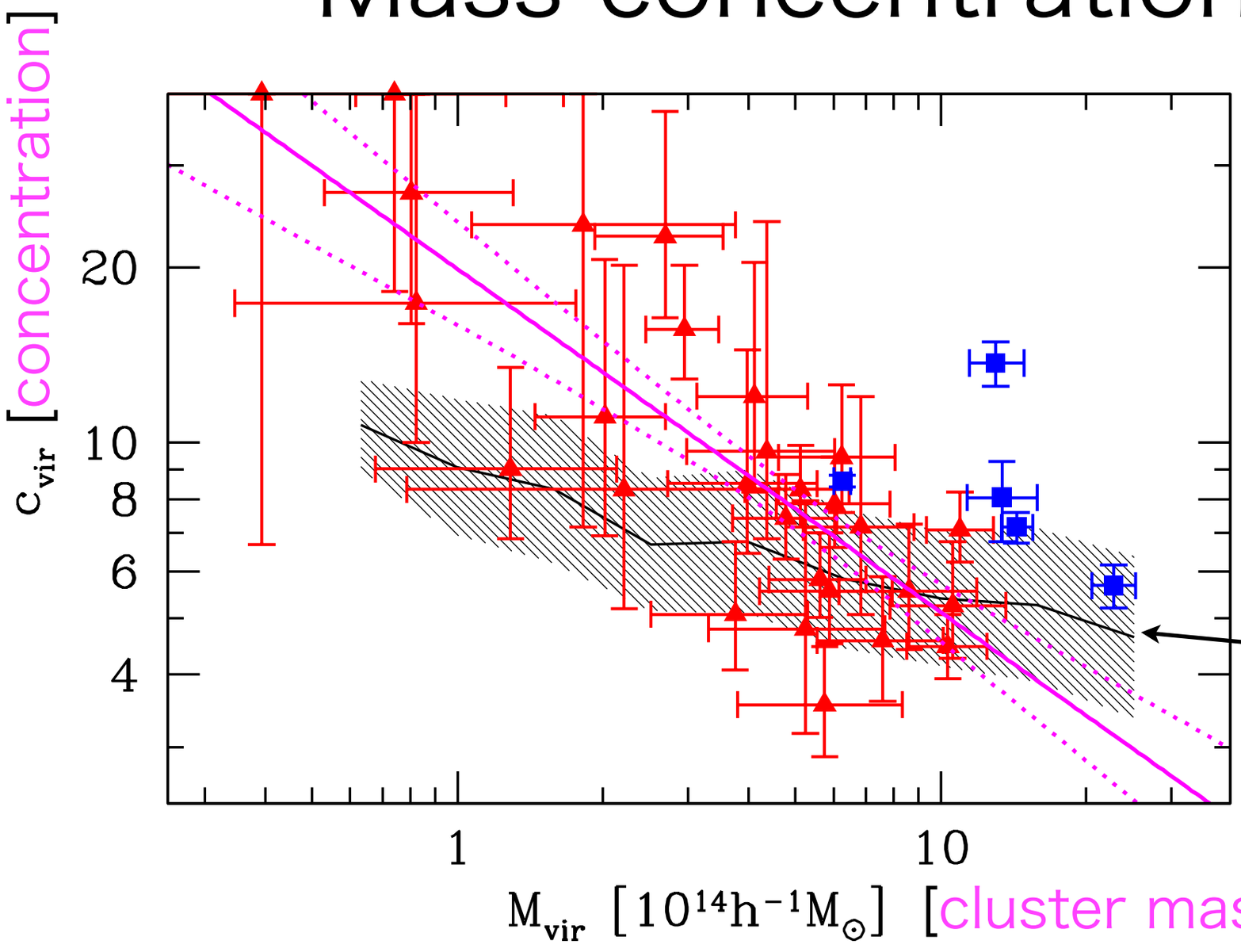
Example of strong+weak lensing analysis





- Strong and weak lensing results are complementary, leading to robust profile observation

Mass-concentration relation



our sample

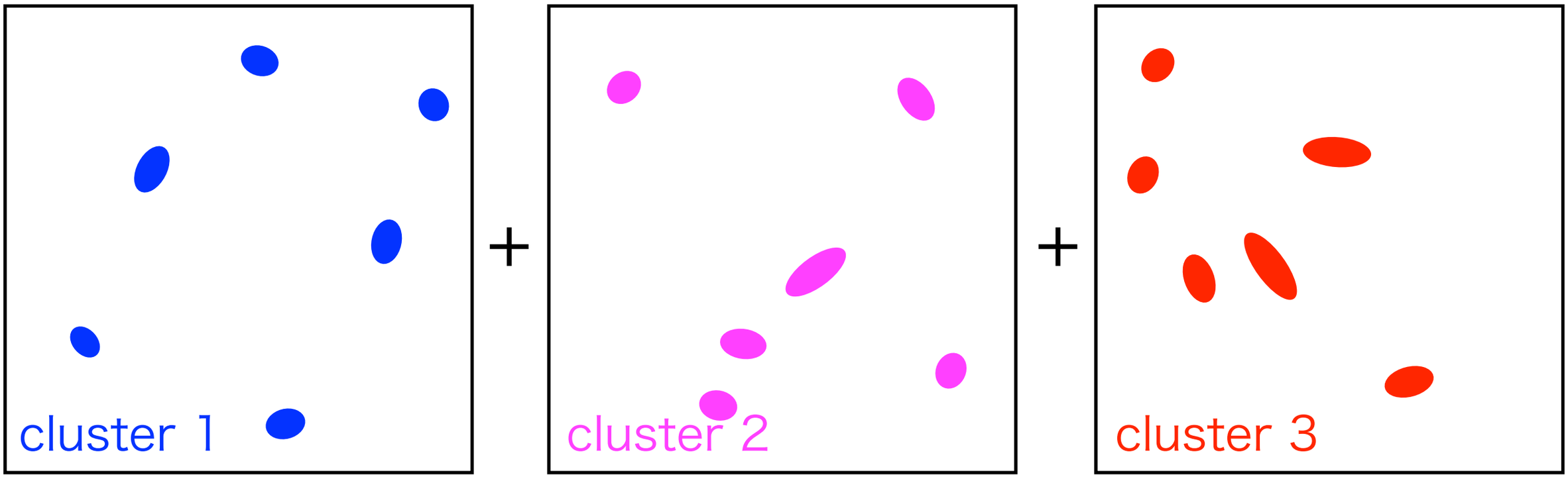
from literature

(Umetsu et al. 2011;
Zitrin et al. 2011)

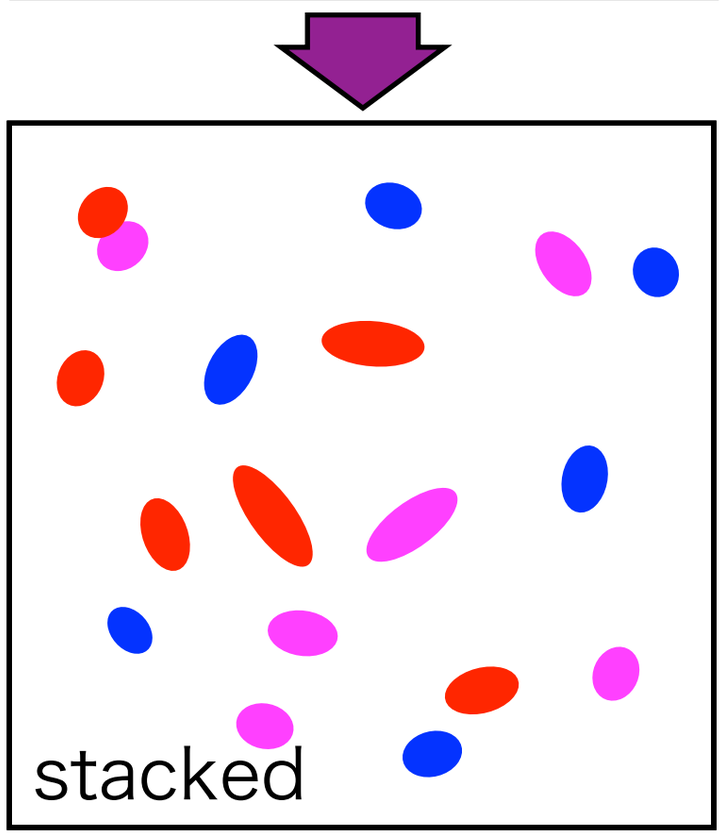
ΛCDM prediction
w/ lensing bias
+ triaxiality

- mass dependence of c_{vir} detected
- slope too steep? ($c_{vir} \propto M_{vir}^{-0.59\pm0.12}$) (cf. Okabe et al. 2010)
- c_{vir} consistent w/ theoretical prediction at high mass
- low mass excess probably due to baryon cooling

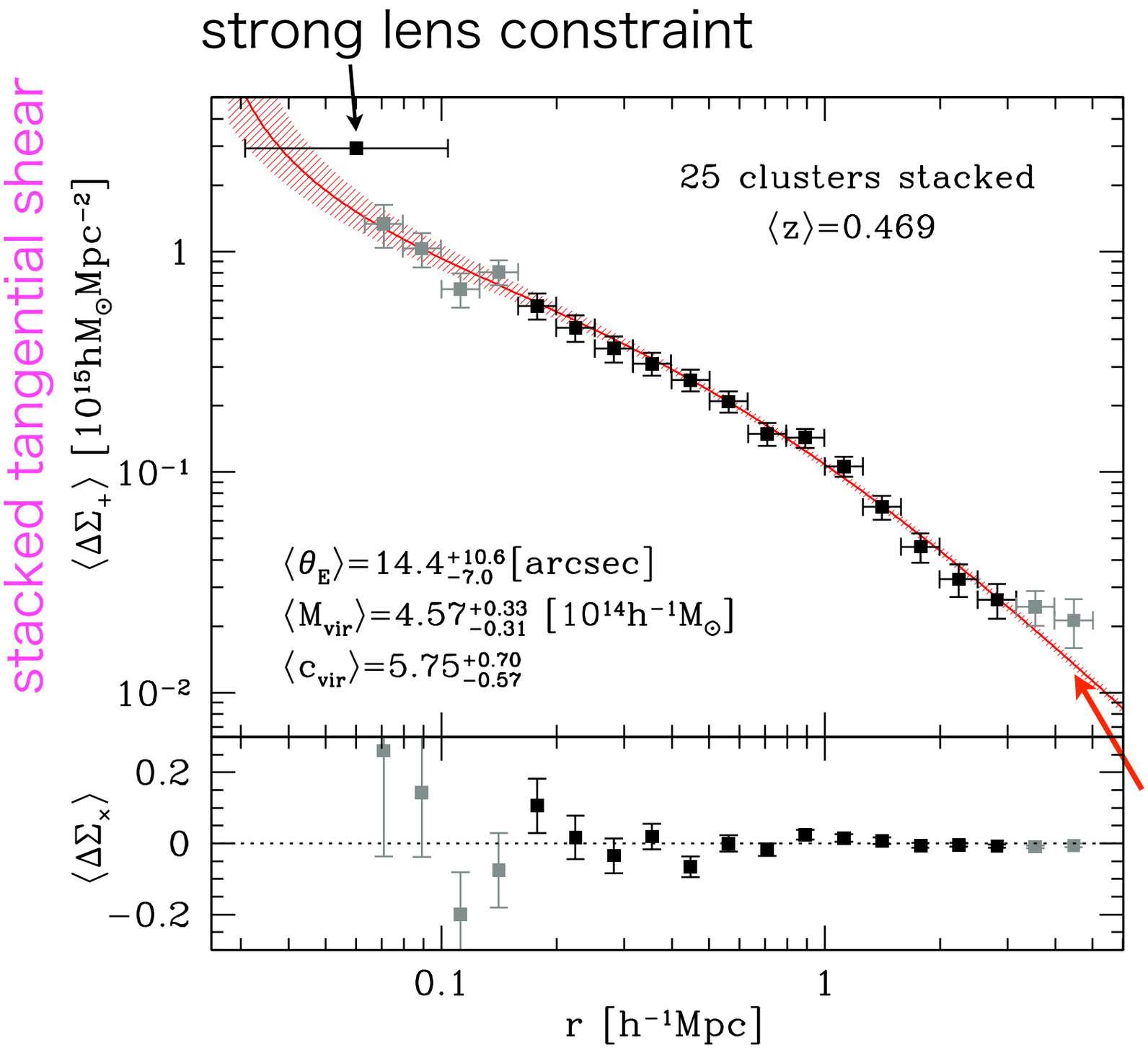
Stacked lensing analysis



- combine weak lensing shear measurements for many clusters
- higher S/N, leading to accurate mean profile measurement

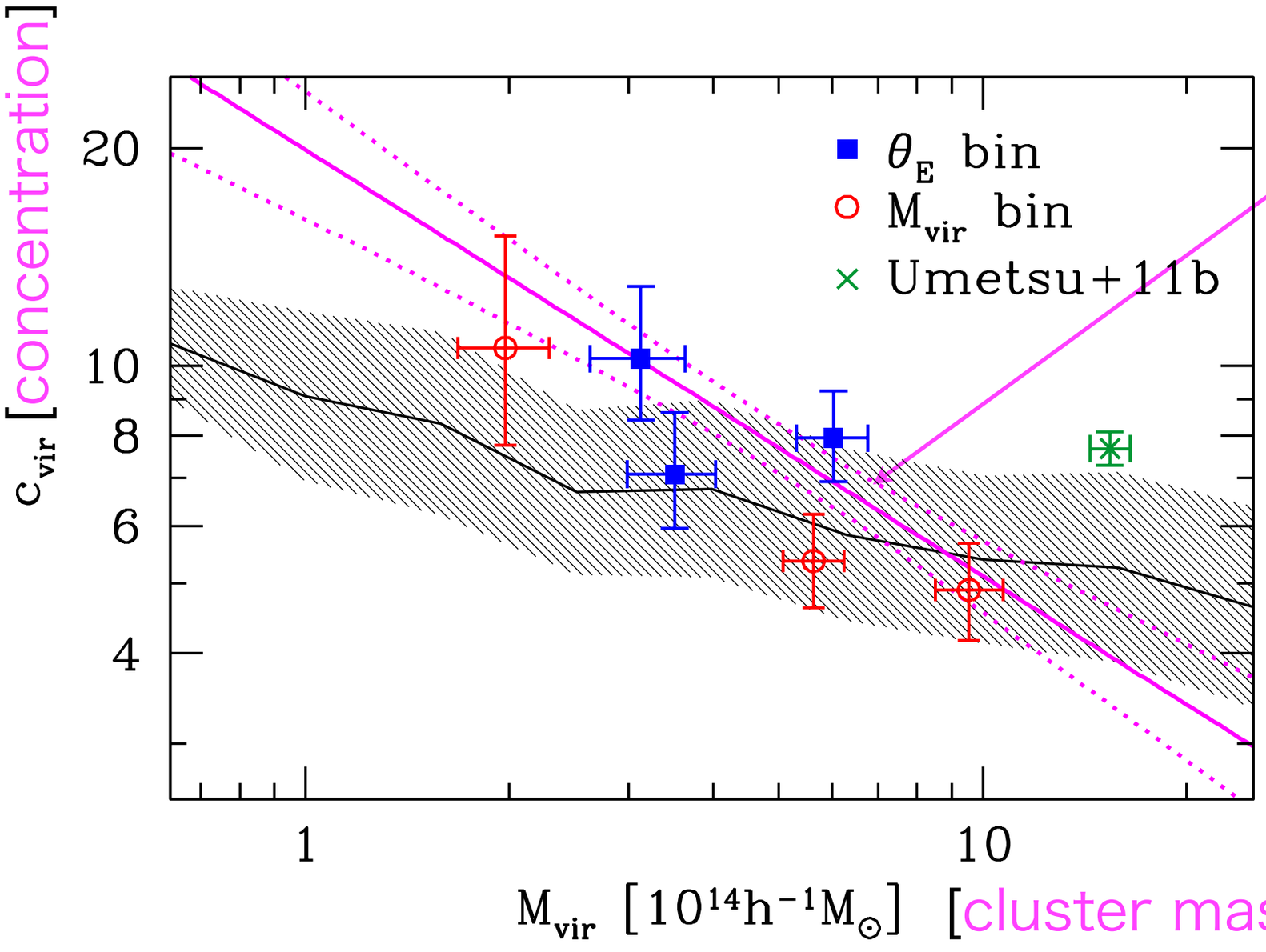


Stacked lensing analysis



- high S/N lensing shear profile by stacking 25 clusters
- follow NFW well

Stacked lensing analysis



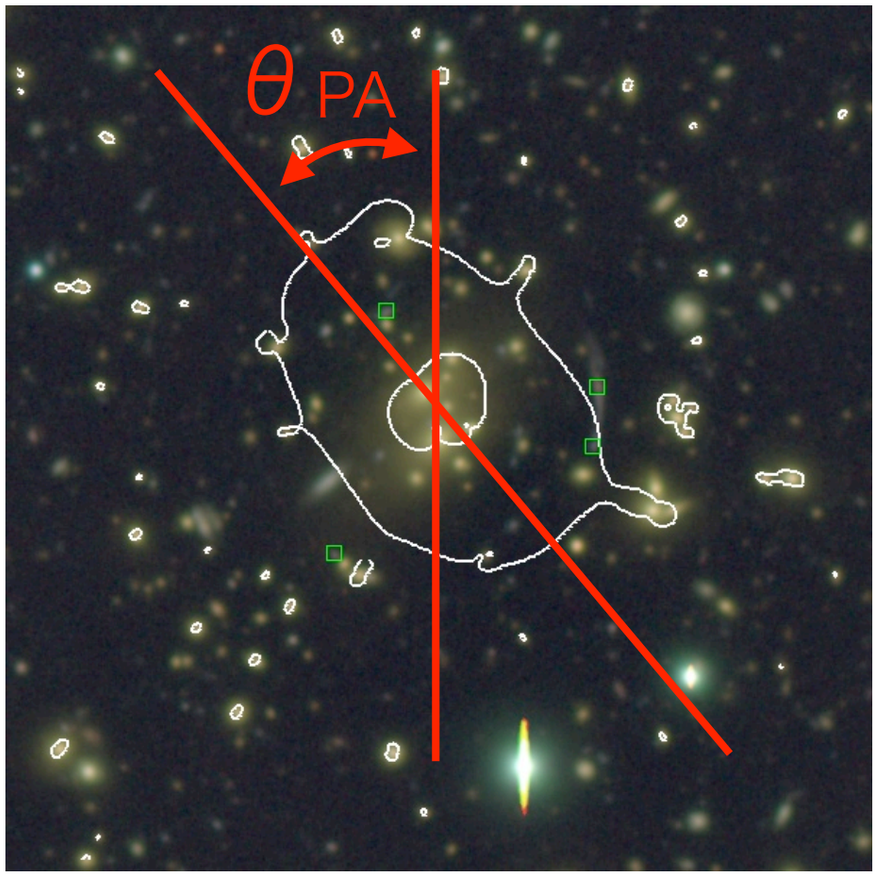
best-fit M-c relation from individual analysis of clusters

ΛCDM prediction w/ lensing bias + triaxiality

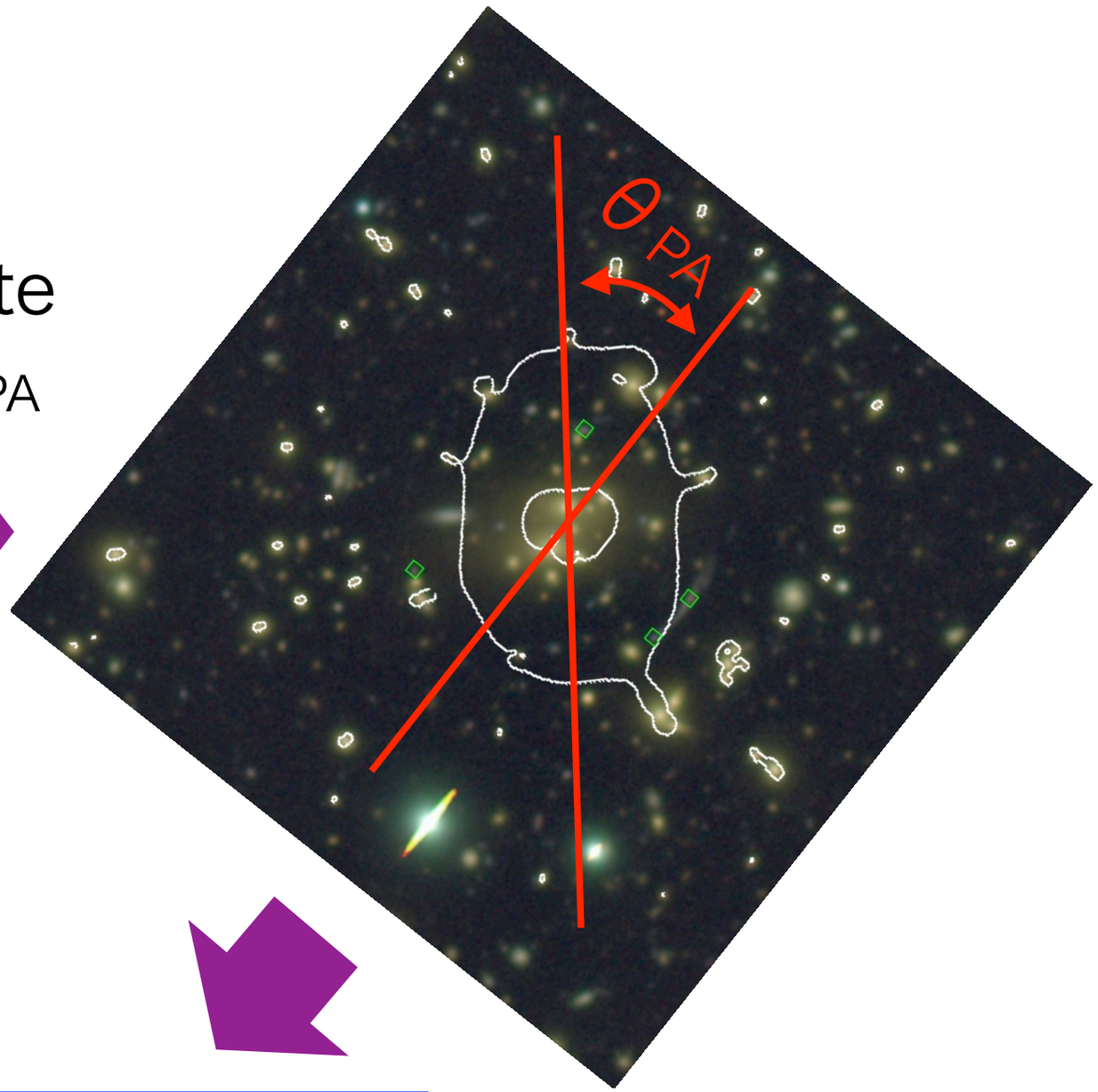
- consistent with individual analysis

Shape: 2D stacking analysis

strong lens modeling



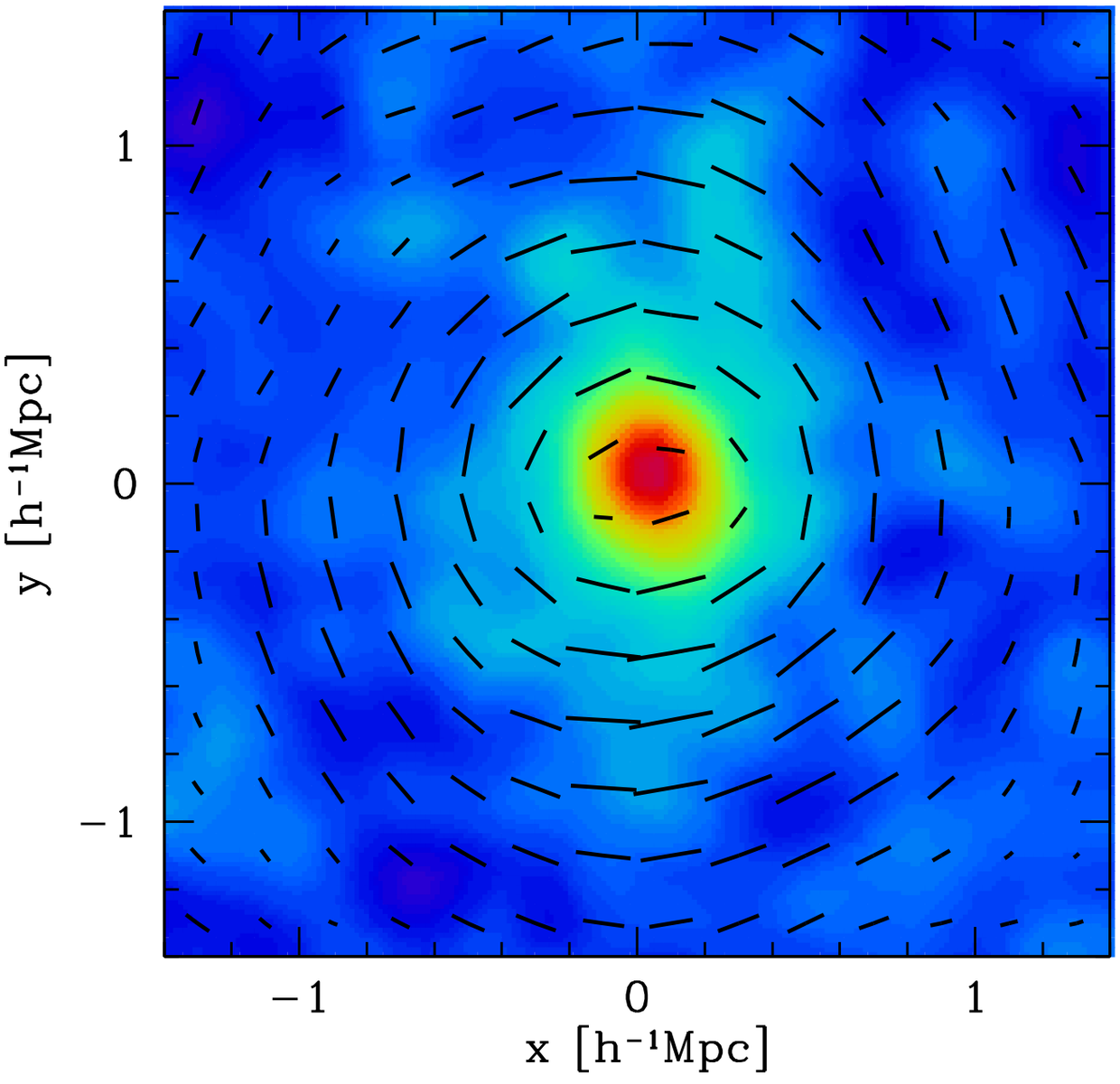
rotate
$-\theta_{\mathrm{PA}}$



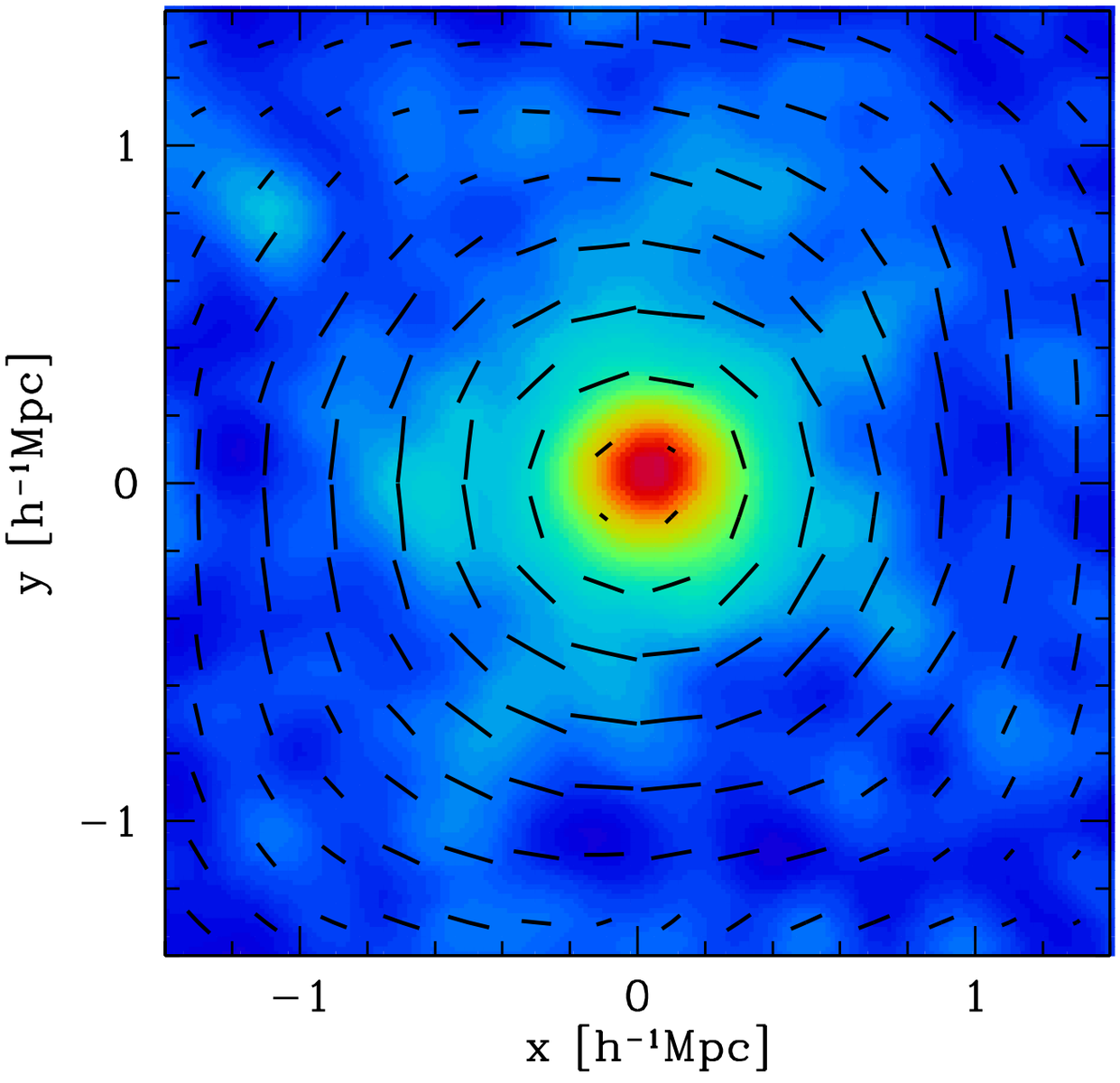
stacked weak
lensing analysis

(No assumption on mass-light alignment!)

Observed stacked 2D weak lensing map

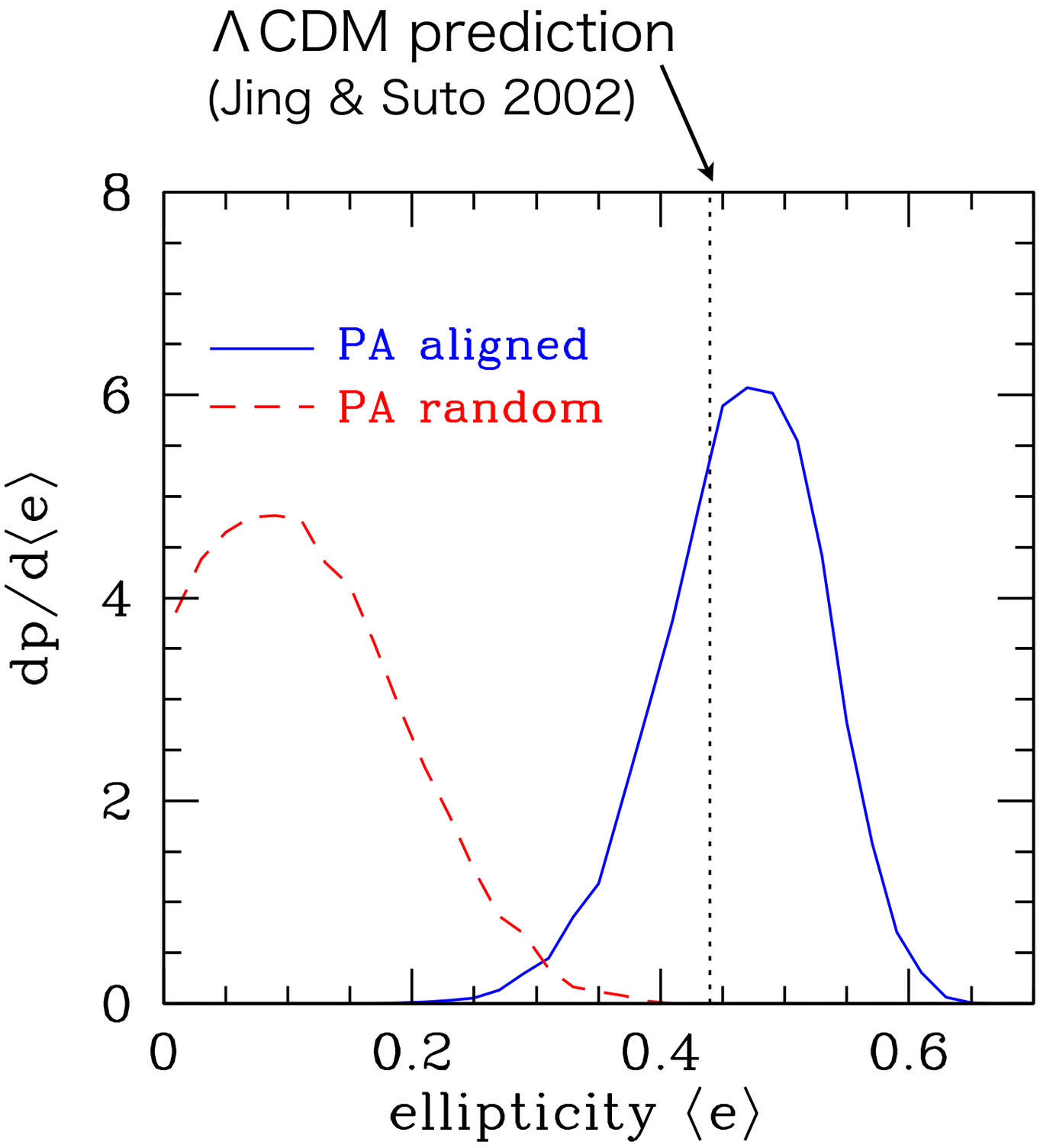


stacking w/ PA aligned



stacking w/ random PA

Constraint on mean ellipticity



Aligned PA:

$e = 0.47 \pm 0.06$

Random PA:

$e < 0.19$

- ellipticity detected at 5σ level
- mean ellipticity consistent w/ ΛCDM

[see also Oguri, Takada, Okabe & Smith (2010)]

Summary: testing halo profiles

- NFW-like radial density profile (r^{-1} inner, r^{-3} outer)
  observed profile consistent with NFW

- concentration (low, correlated with mass)
  steep mass dependence
  consistent with ΛCDM at high mass
  larger c_{vir} at small mass due to baryon cooling

- large non-sphericity (axis ratio a/c ~ 0.4)
  excellent agreement with ΛCDM

ΛCDM works remarkably well at cluster scale!