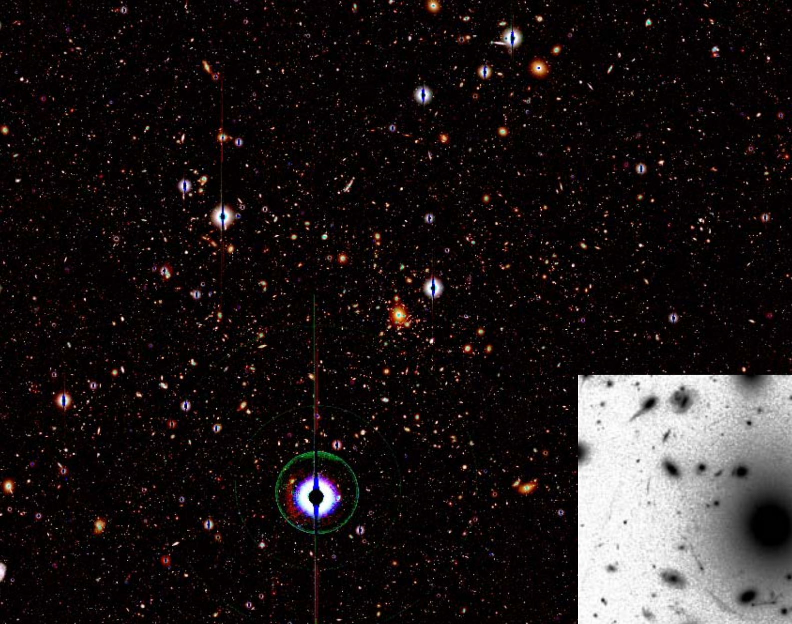
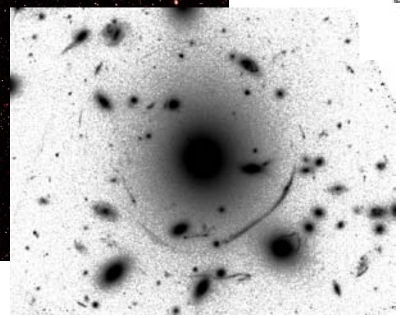
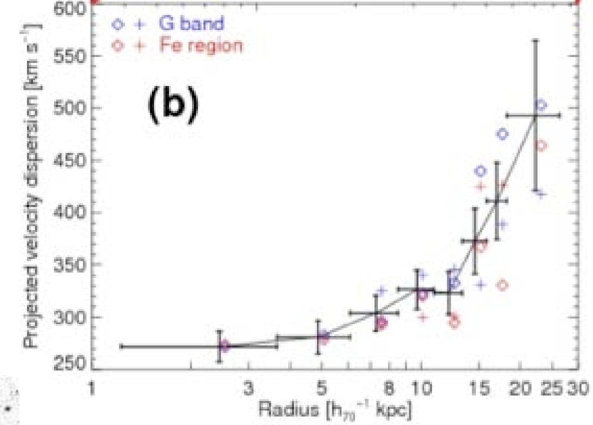
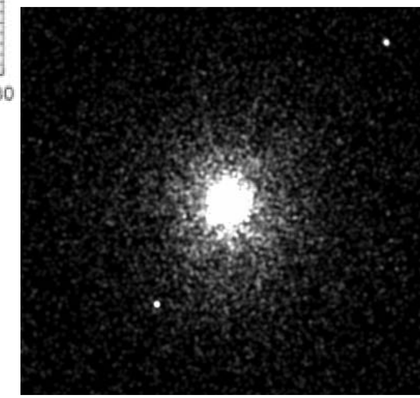






Observing the Dark Matter Profile of Galaxy Clusters from kpc to Mpc Scales

Drew Newman

California Institute of Technology

Kochi, 31 August 2010

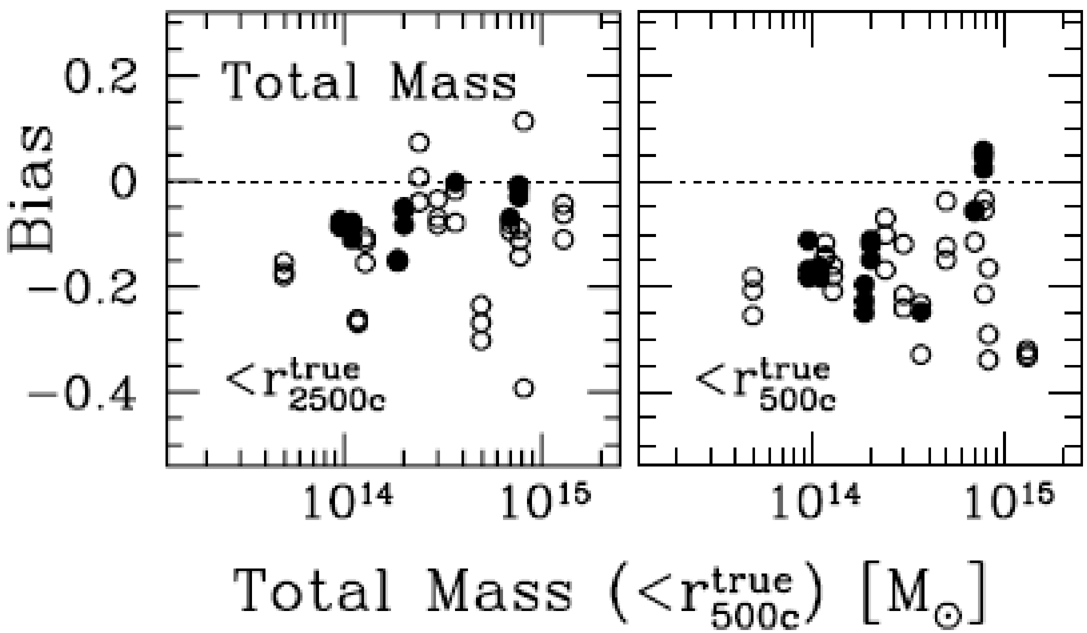
In collaboration with Richard Ellis, Tommaso Treu (UCSB), David Sand (CfA)

Outline

- Motivate detailed studies of galaxy cluster mass profiles
  - Relevance for dark energy/dark matter
- Introduce observational program to combine
  - strong and weak gravitational lensing,
  - X-ray,
  - and stellar kinematics

  to measure precise luminous and DM profiles in a sample of relaxed clusters from ~2 kpc – ~2 Mpc.
- Illustration of method in Abell 383
- Comparison to simulation results
- Conclusions

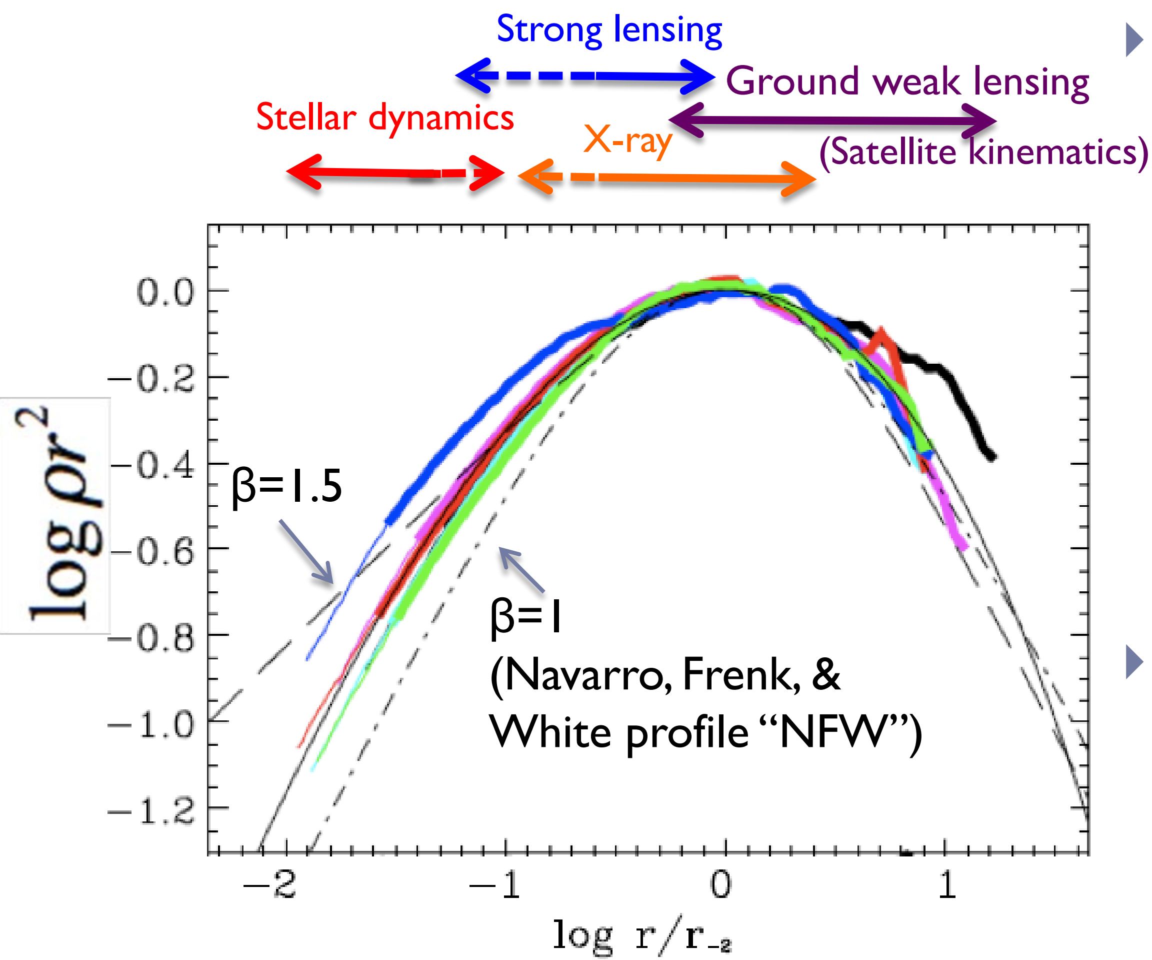
Combining Cluster Mass Probes



Nagai et al 2007

- "Cluster counting" techniques to constrain *w*(*t*) require high-precision absolute calibration
  - Understanding systematics requires comparing independent techniques
  - Interpretation often depends on an assumed DM profile → needs to be tested
- Example: how close is the ICM to hydrostatic equilibrium?
- Projection effects very different for lensing (2D) versus X-ray or dynamics (3D)

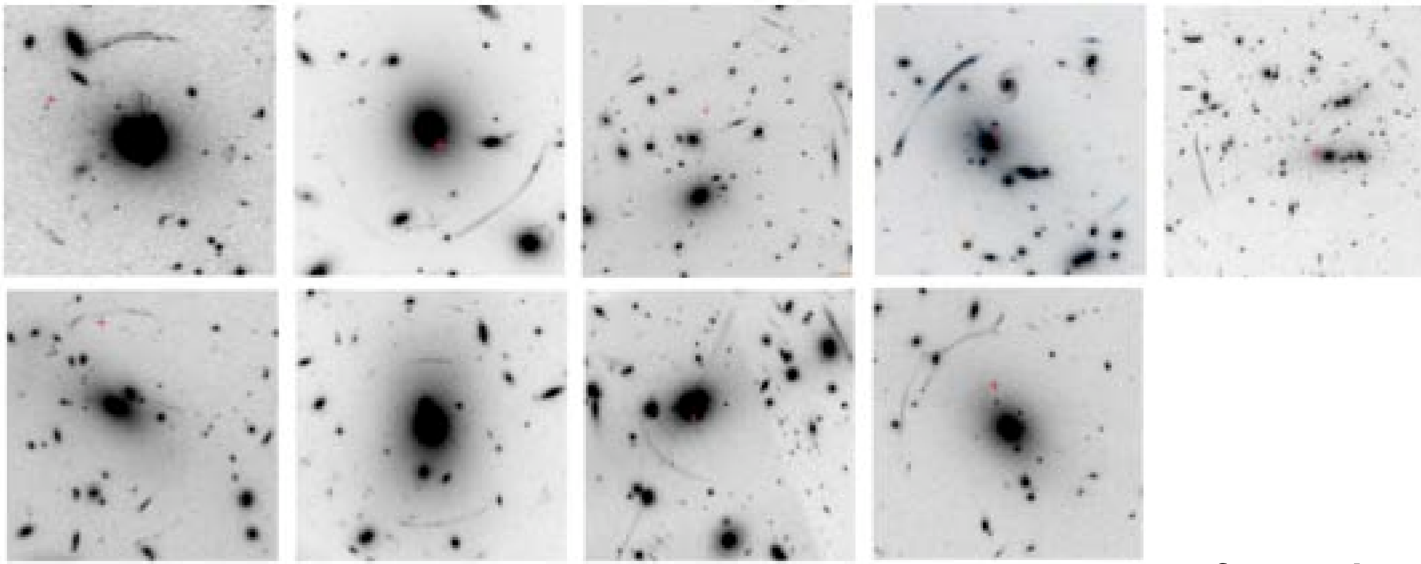
Combining Cluster Mass Probes



Navarro et al 2010
Aquarius (galaxy) halos

- Dark matter (DM) halo profiles probe nature of DM and its interactions with baryons
  - Comprehensive observational tests require *large dynamic range*
  - and *ability to separate baryonic and DM components*
- Inner log slope β of the DM density (**$\rho_{DM} \sim r^{-\beta}$ for small *r***) is sensitive test
  - *N*-body simulations: β= 1-1.5 for DM-only halos

Observational Program



Goal: Measure mass profiles in relaxed clusters from kpc—Mpc scales for dark and luminous components separately via

- Strong lensing
- Stellar kinematics in cD galaxy
- Weak lensing
- X-ray

for a sample of 9 clusters

Sand '04,'08

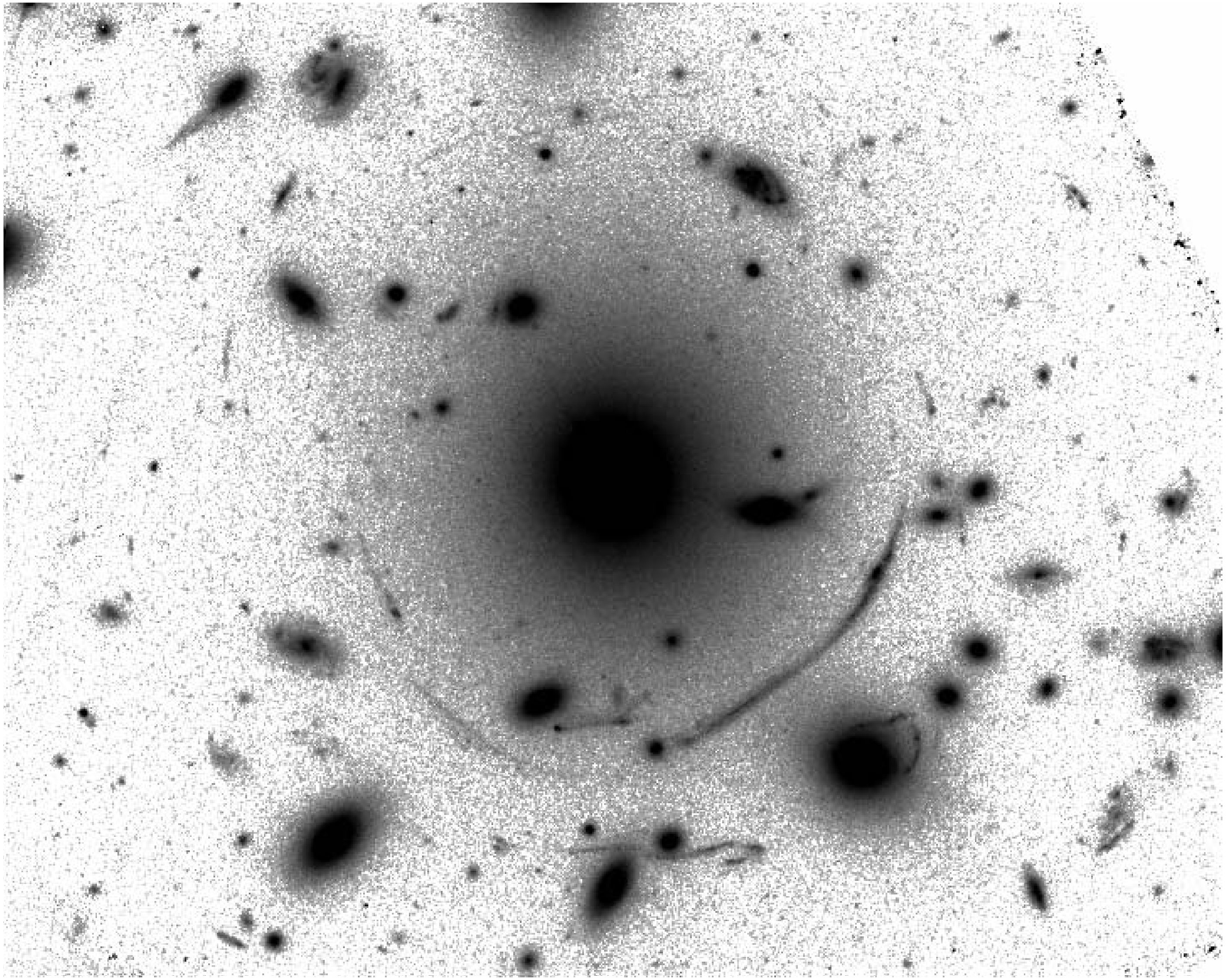
Newman+ '09 Abell 611

Rest of talk:

Newman+ in prep Abell 383

Abell 383

- Relaxed cluster at $z=0.19$
- Regular optical and X-ray morphology
- Cool core
- Very low substructure fraction
- Nearly circular in projection

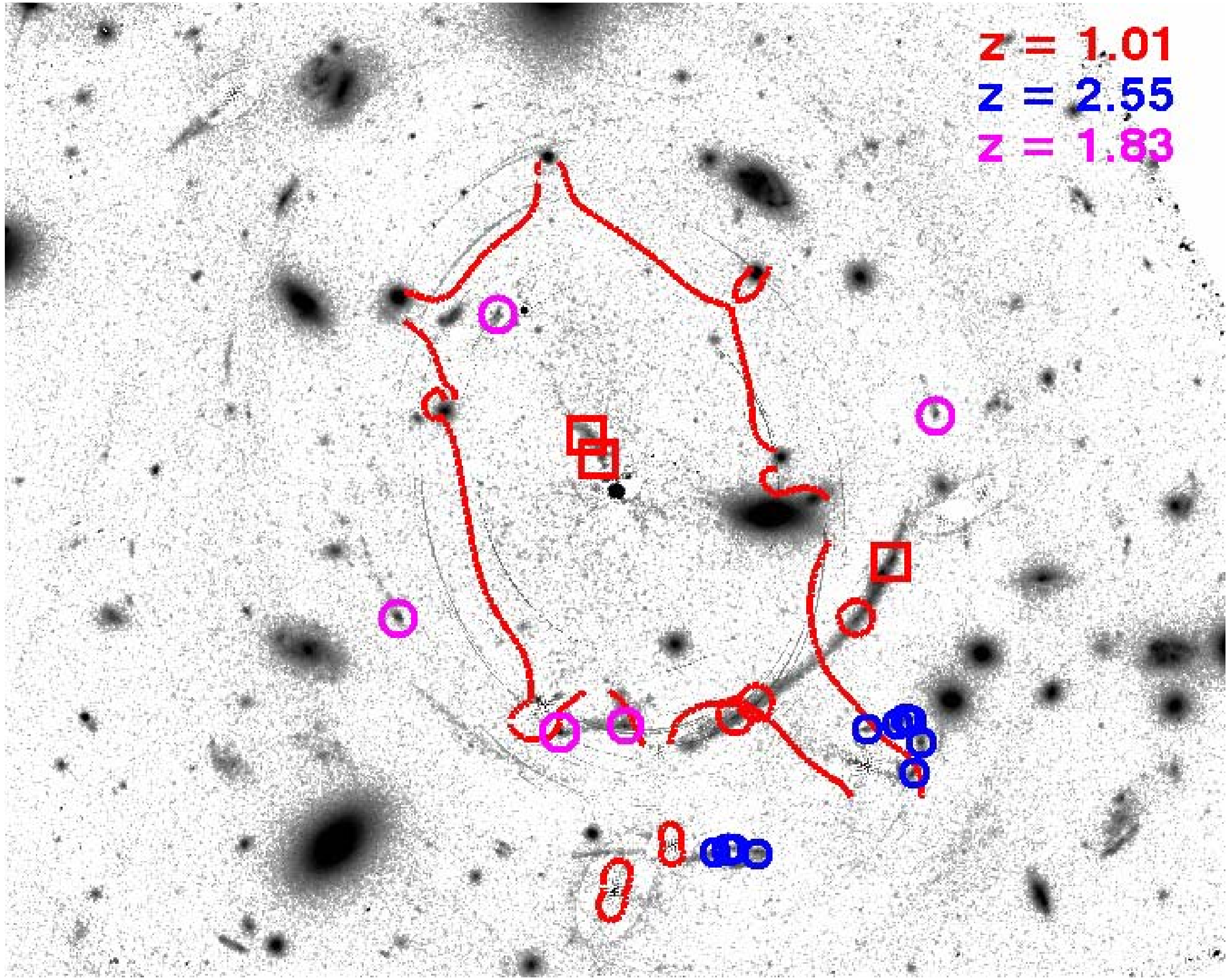


Abell 383: Strong lensing

3 multiply-imaged galaxies with spectroscopic z

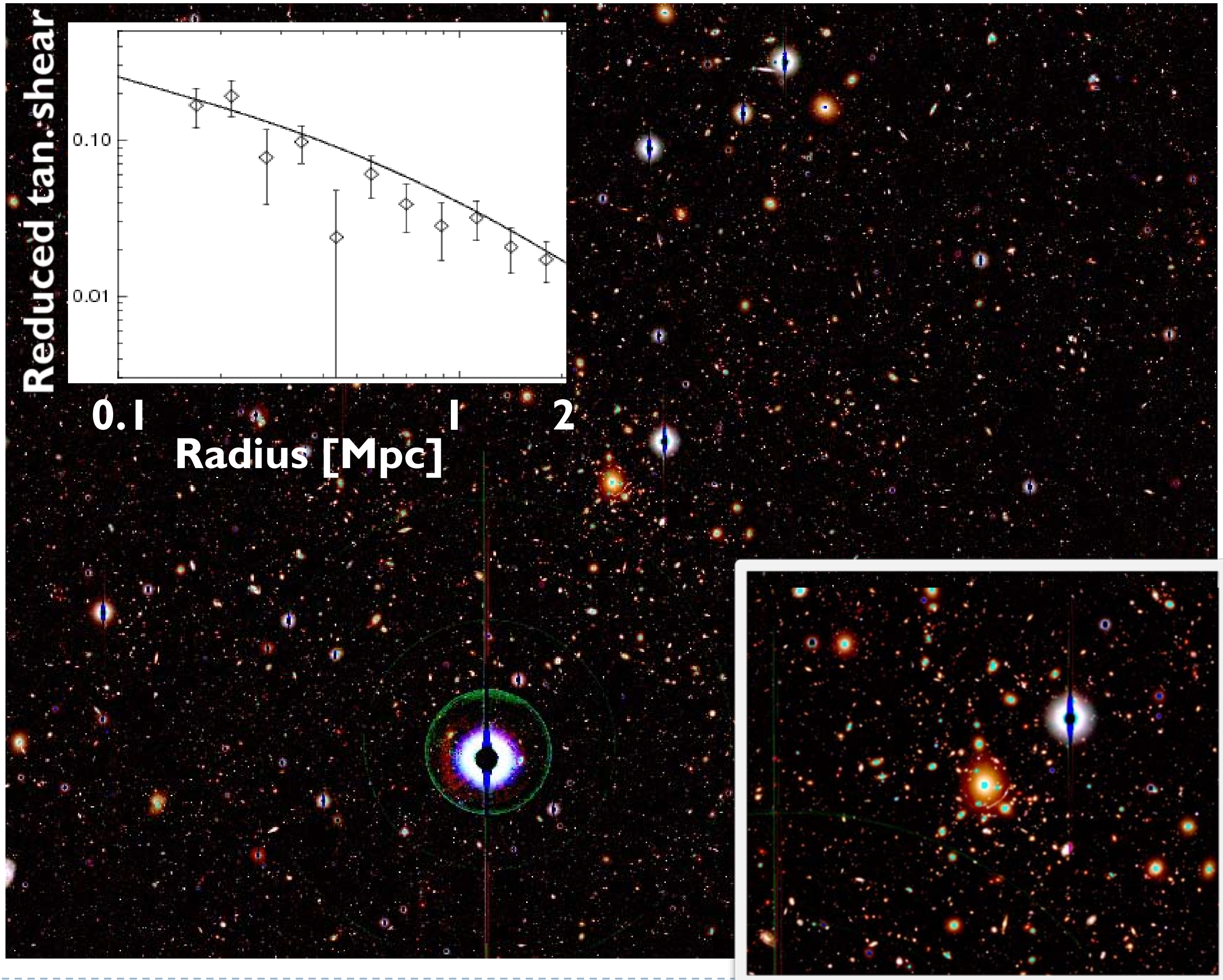
21 images of 7 sources

Constrains projected mass on ~10-70 kpc scales

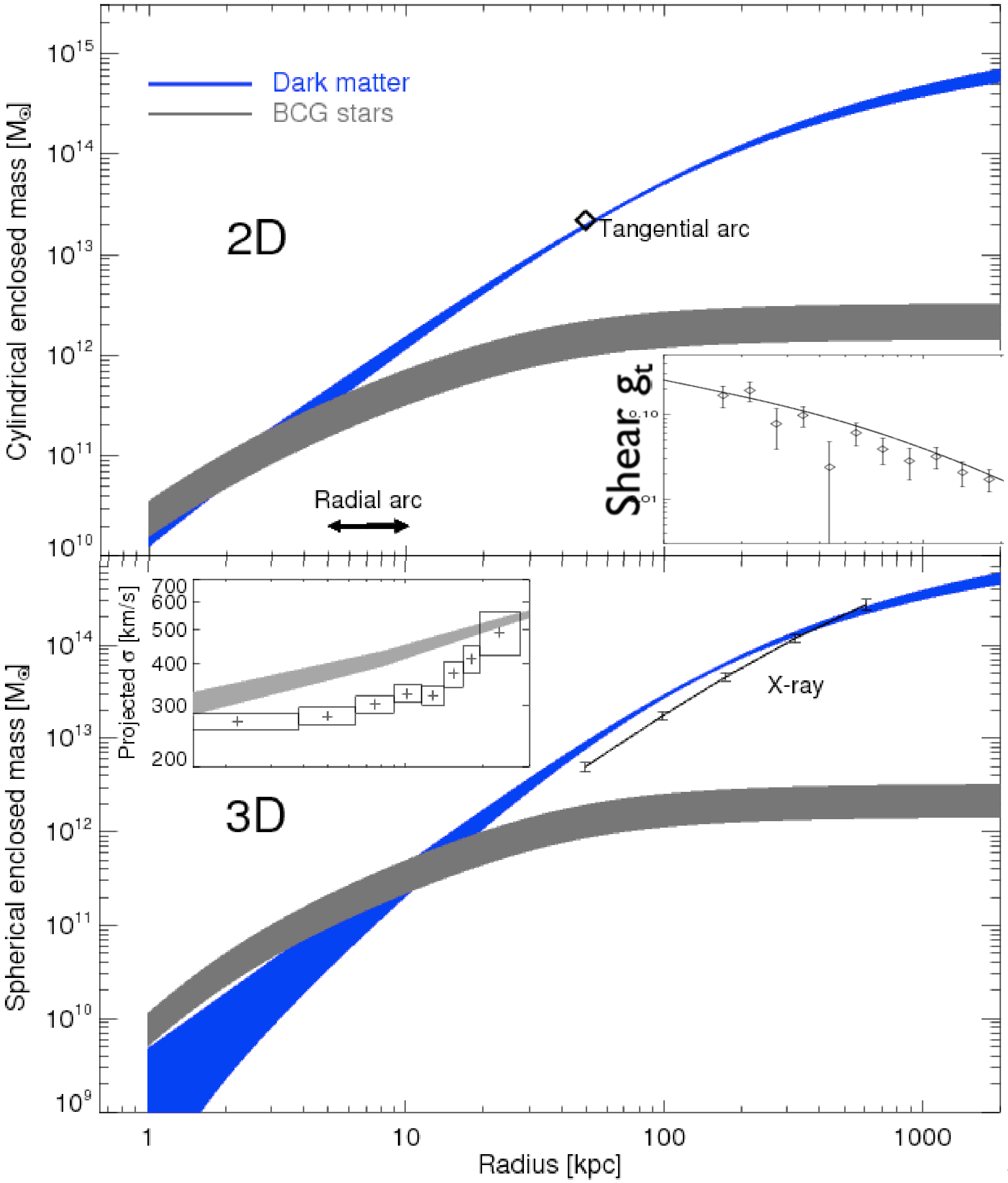


Abell 383: Weak lensing

- *BVRiz* Subaru Suprime-Cam imaging over 30'
- Shear measured in *R* band (0.56" seeing, KSB); surface density ~25 arcmin^{-2}
- Calibrated against STEP2 simulations
- Photo-z's to remove cluster/foreground



Abell 383: Lensing Only



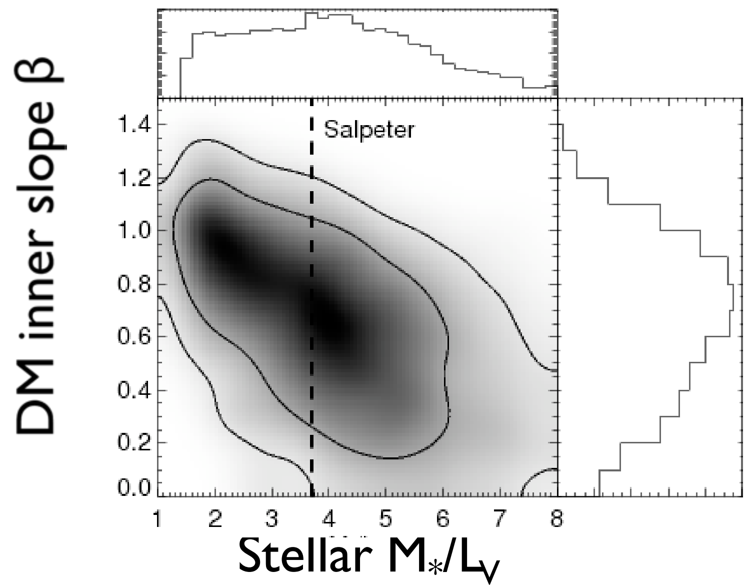
Mass model

(1) gNFW DM halo (elliptical)

$$\rho_{DM}(r) = \frac{\rho_0}{(r/r_s)^{\beta}(1+r/r_s)^{3-\beta}}$$

Note: $\rho_{DM} \sim r^{-\beta}$ as $r \rightarrow 0$

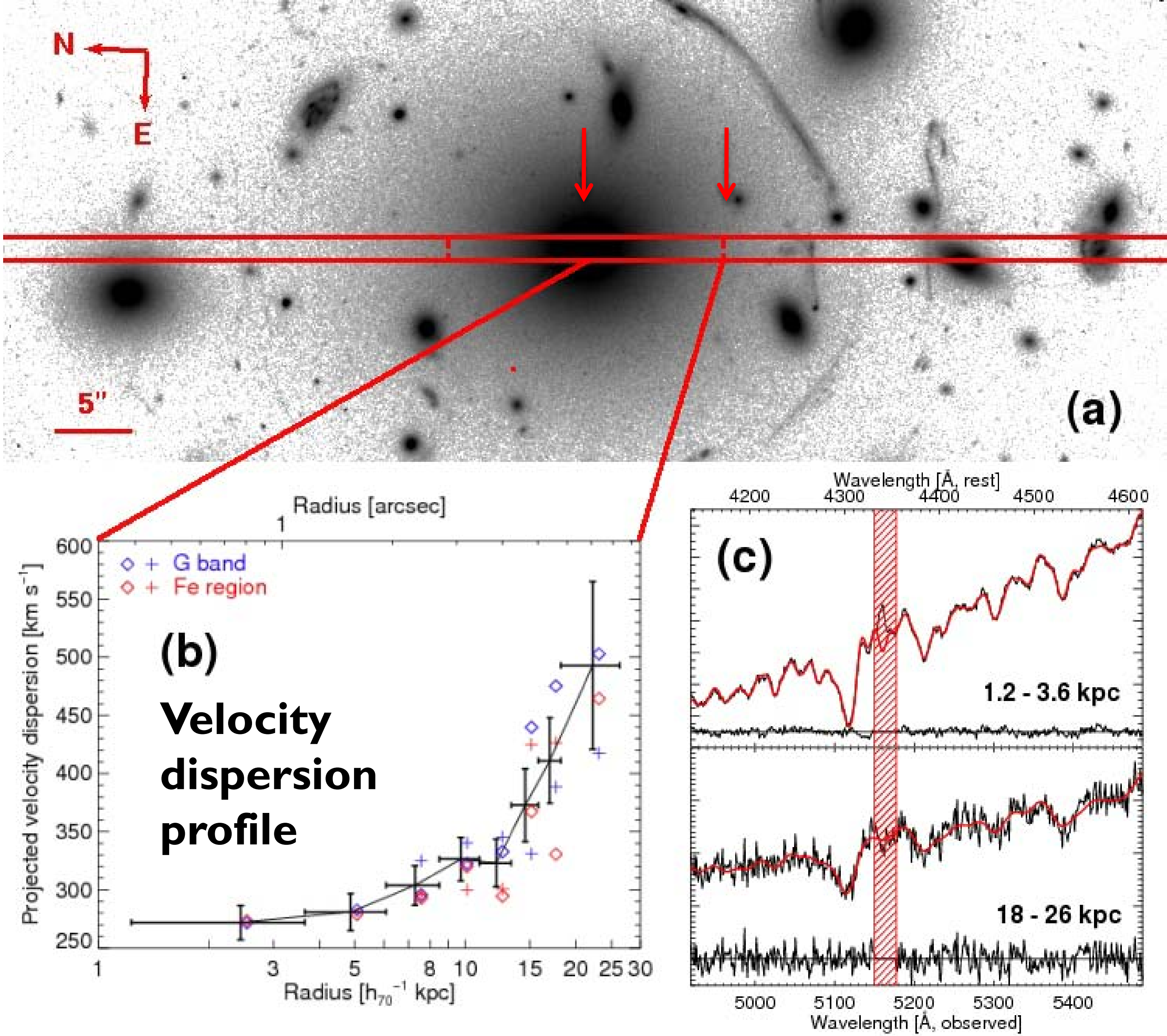
(2) Stellar mass in central cD galaxy following *HST* surface photometry



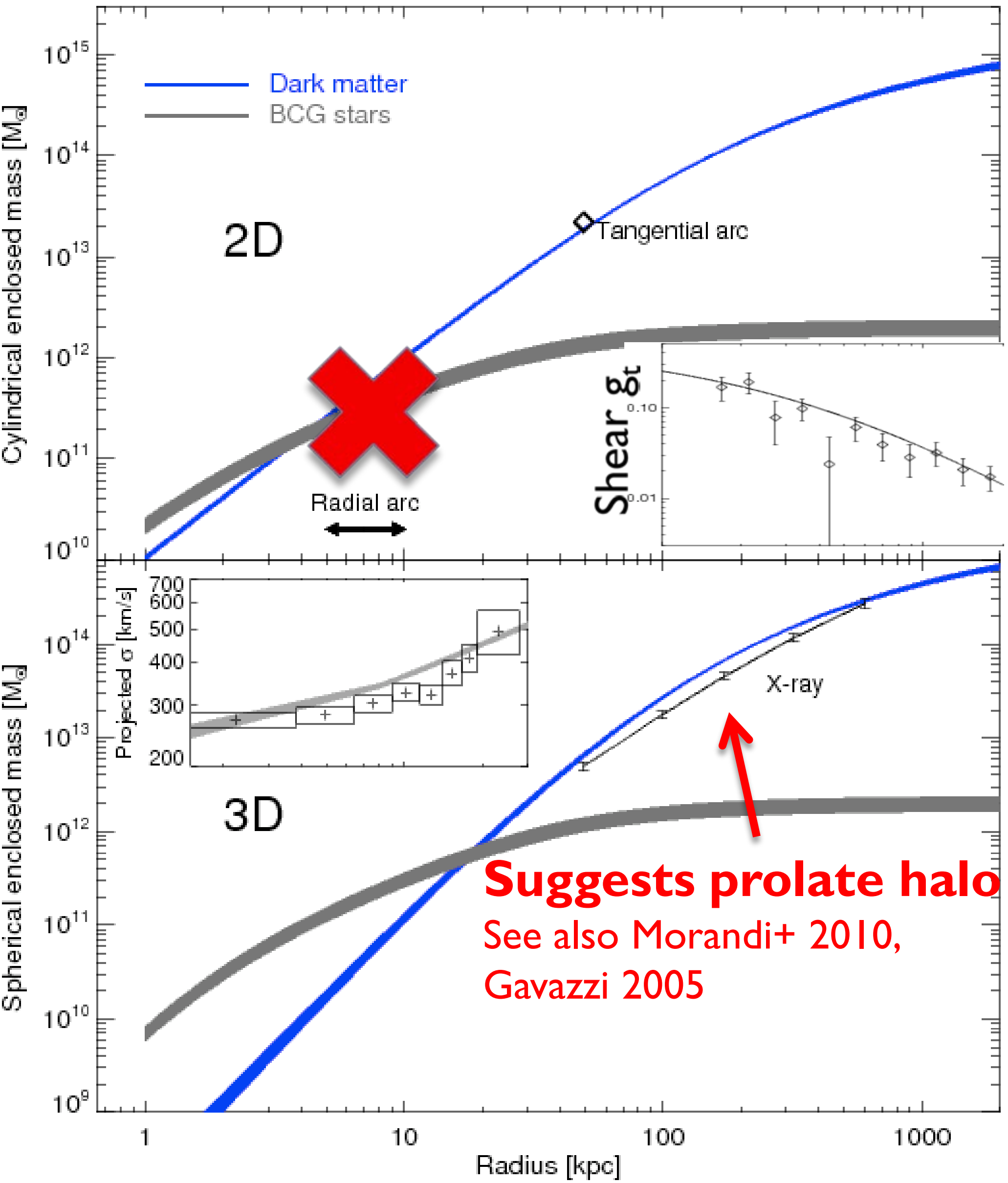
Excellent fits to lensing possible – but little information on inner DM profile

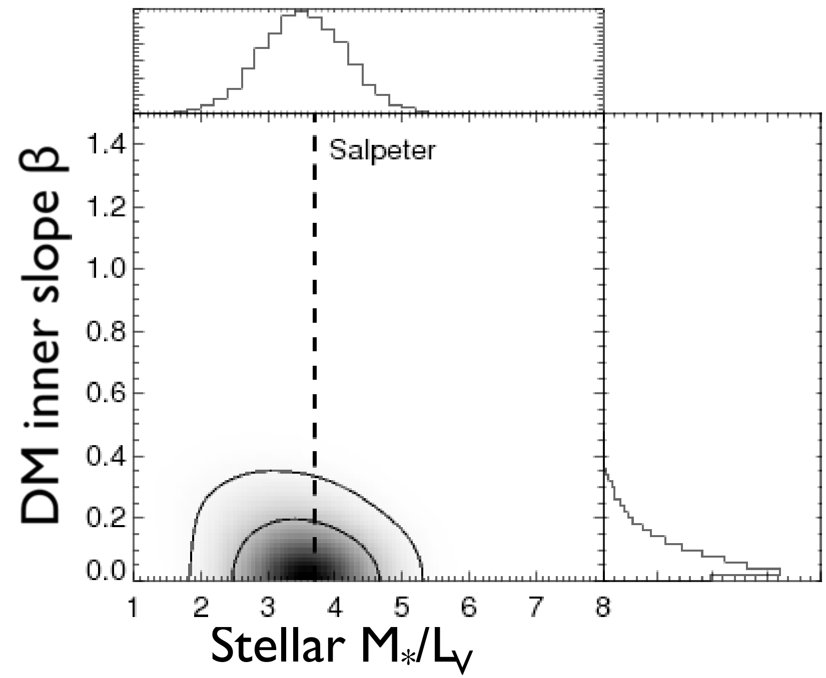
Abell 383: Stellar kinematics

New 6.3 hr Keck/LRIS spectrum of cD galaxy → very extended velocity dispersion profile rising to R=26 kpc



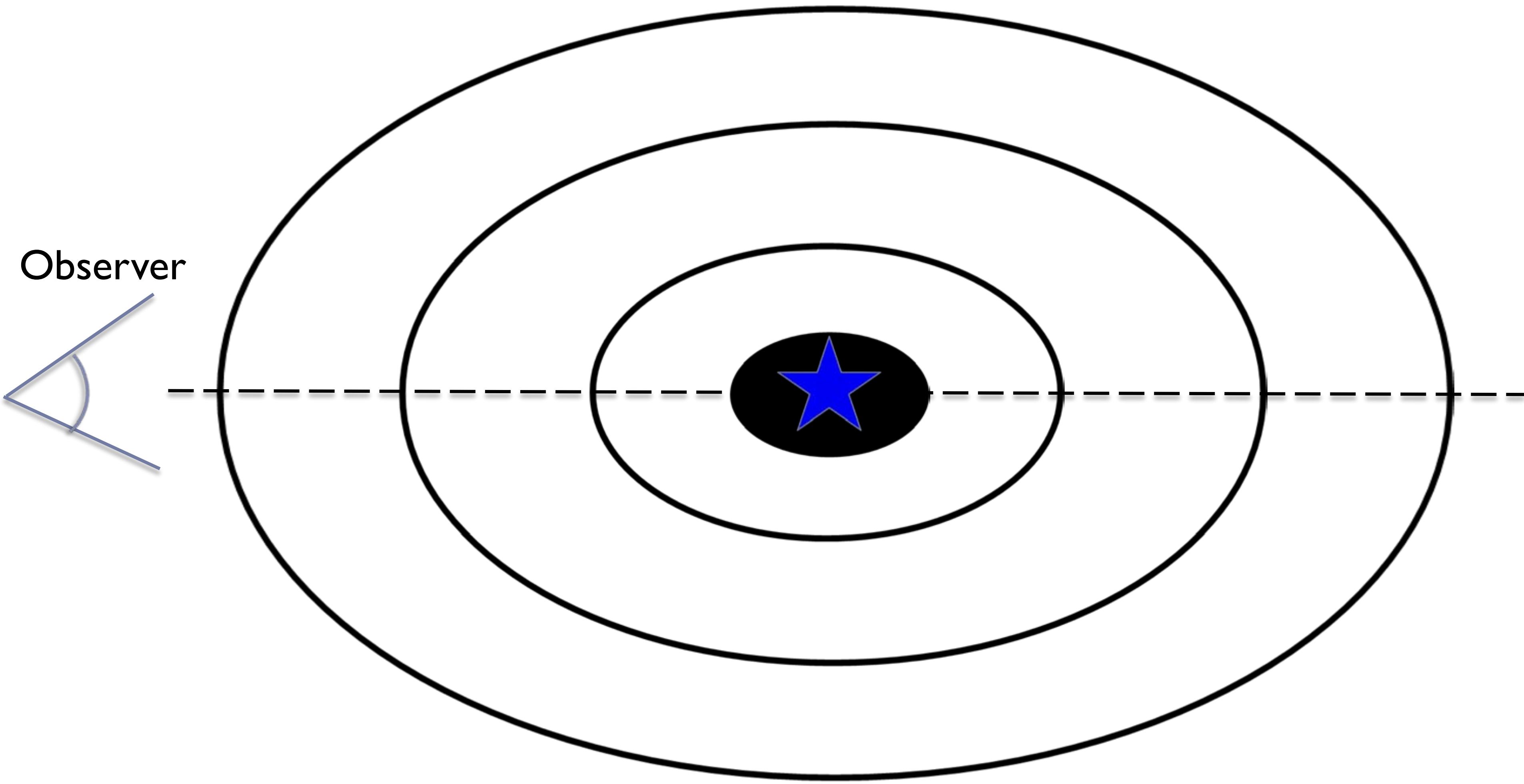
Abell 383: Lensing + Stellar kinematics





- Velocity dispersions nearly fit, if β< 0.2 – but strong lensing features not reproduced very well
- Lensing + X-ray → prolate halo elongated along line of sight

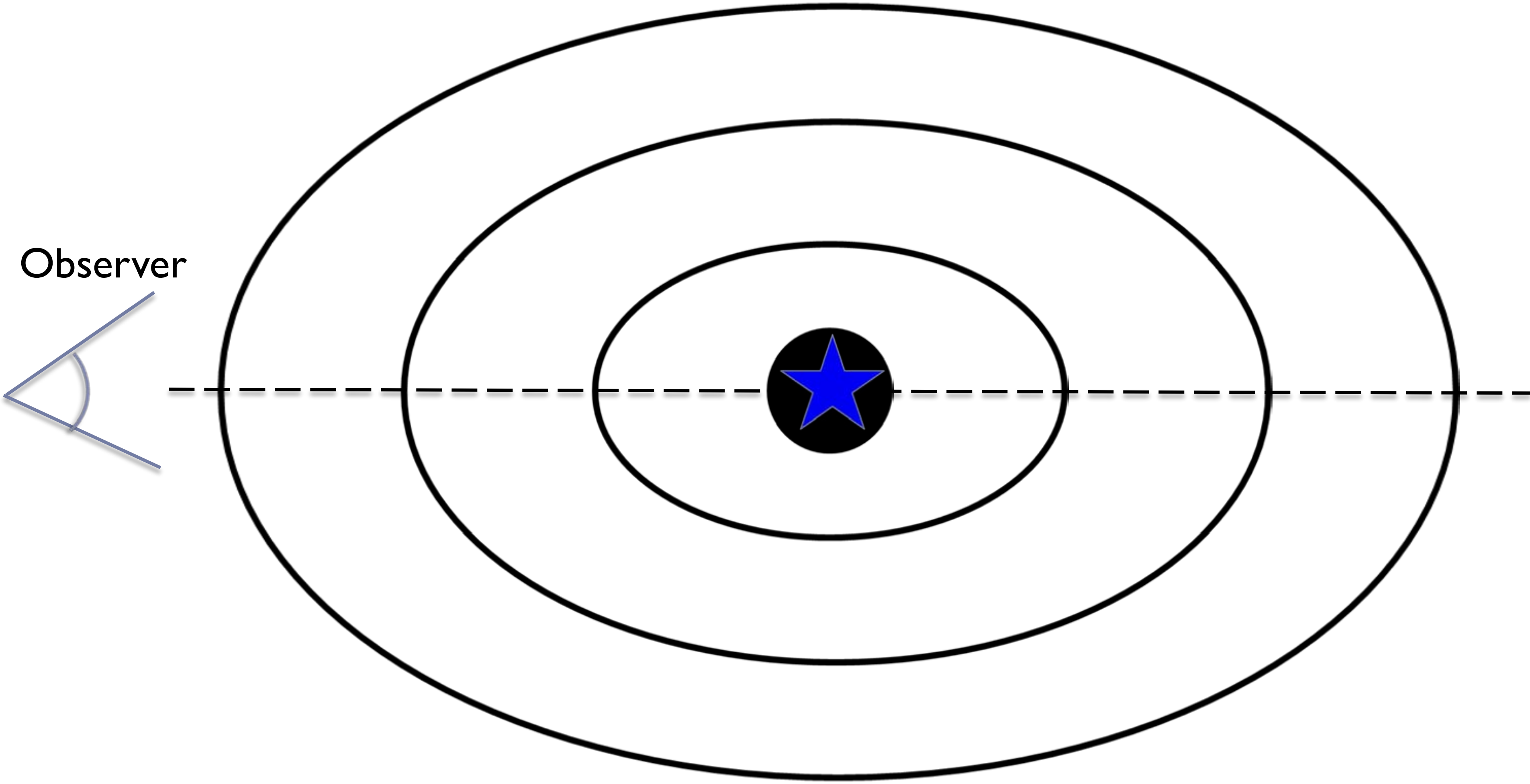
Effects of projection on mass estimates



Halo *and* stars equally elongated along line of sight (prolate)

→ *Can reconcile lensing with X-ray, but not with stellar dynamics*

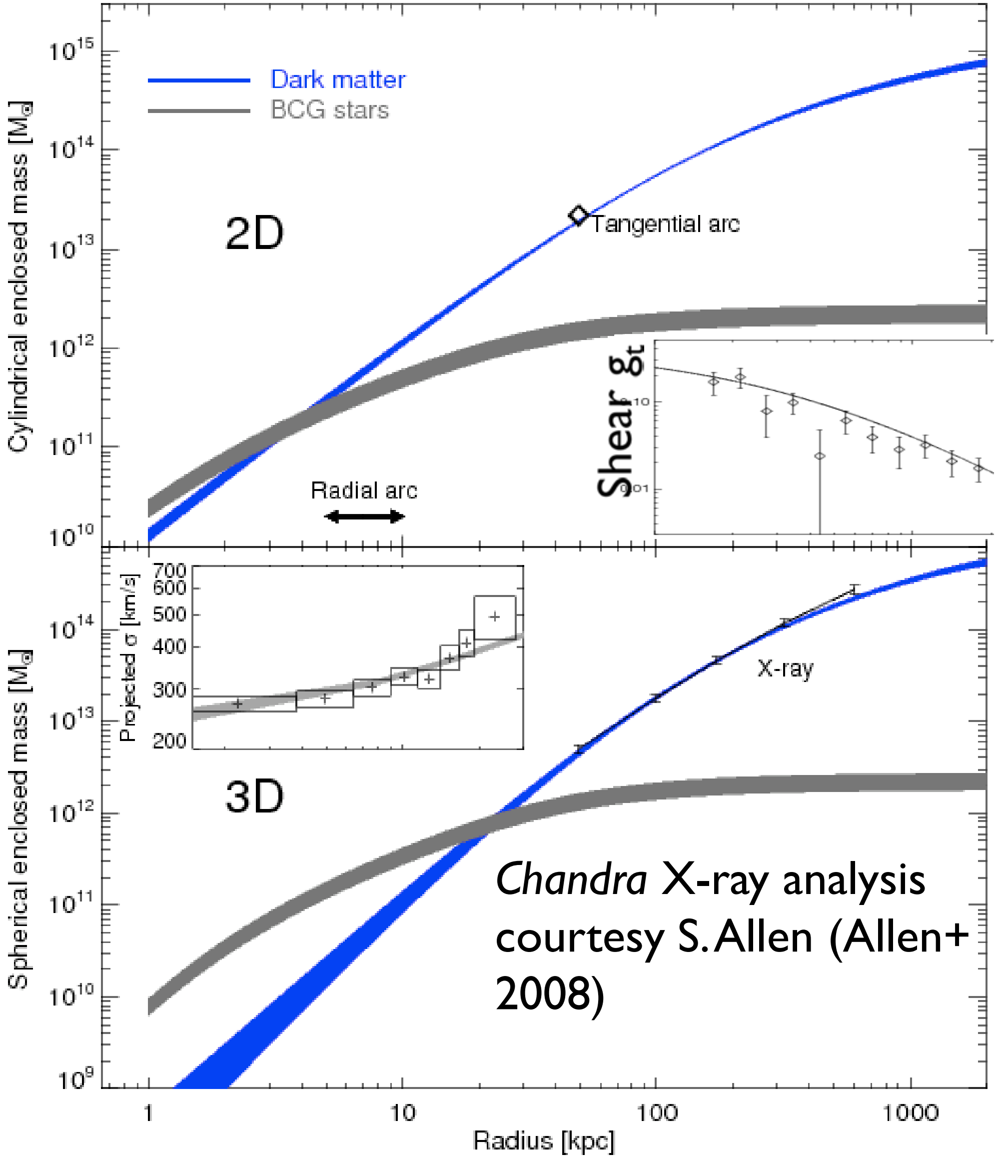
Effects of projection on mass estimates

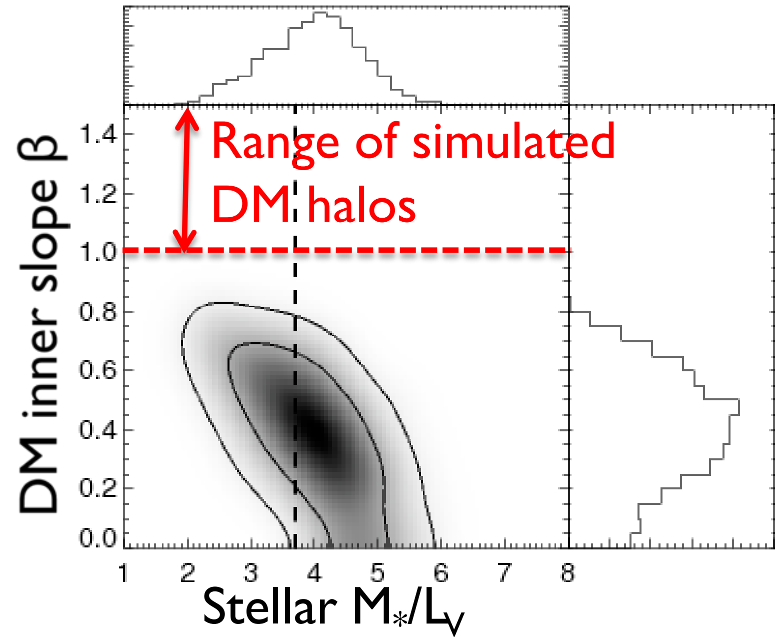


Halo elongated, but stars spherical (limiting case)

→ *Another way (besides a shallow DM slope) to remove mass from center, where it affects stellar dynamics, but keep within the "Einstein cylinder," as lensing requires*

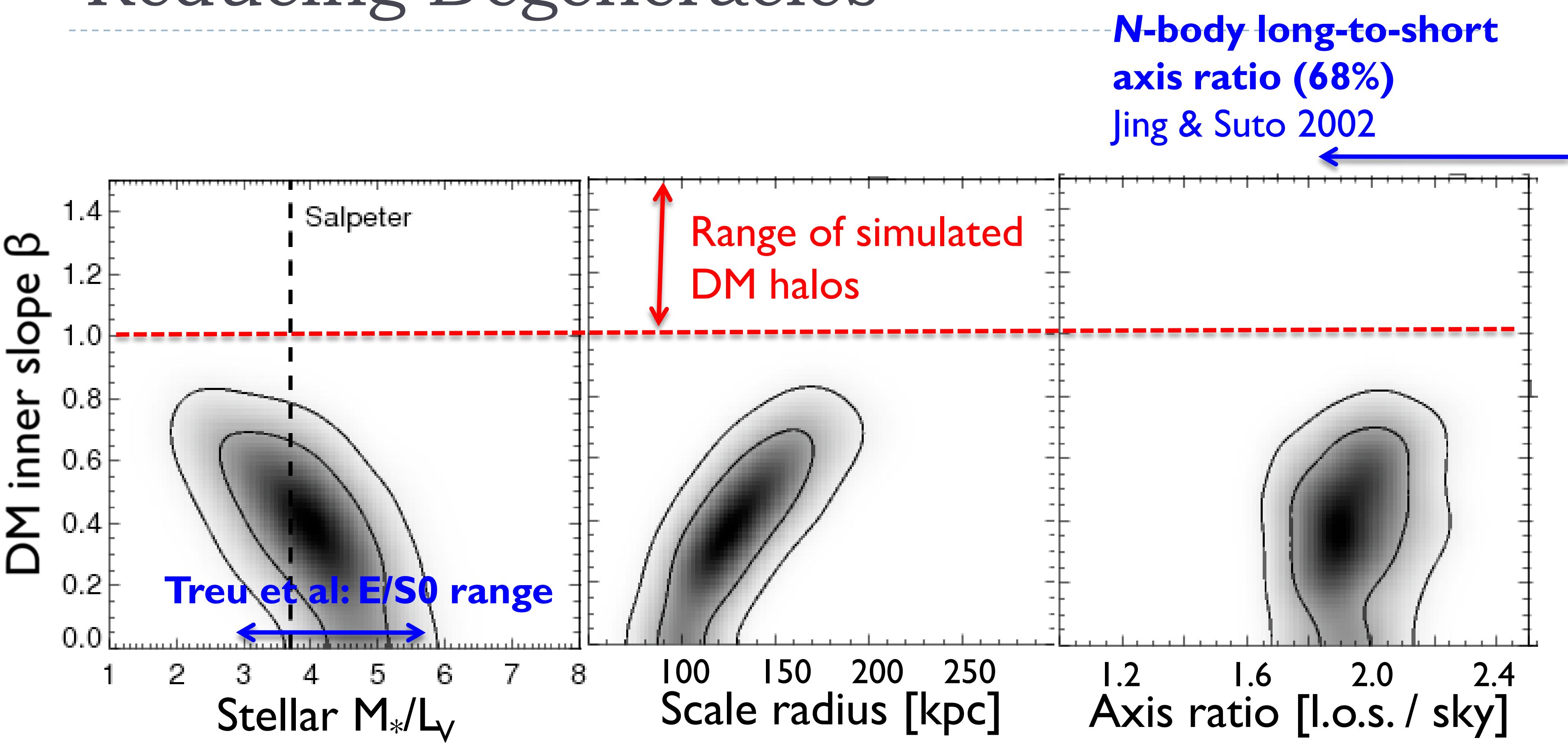
Abell 383: Lensing, X-ray, Kinematics





- Assume ~7% low bias in X-ray masses due to non-thermal support (e.g., Nagai+ 2007, Meneghetti+ 2010) but include uncertainty in this normalization
- Good fit to all data

Reducing Degeneracies



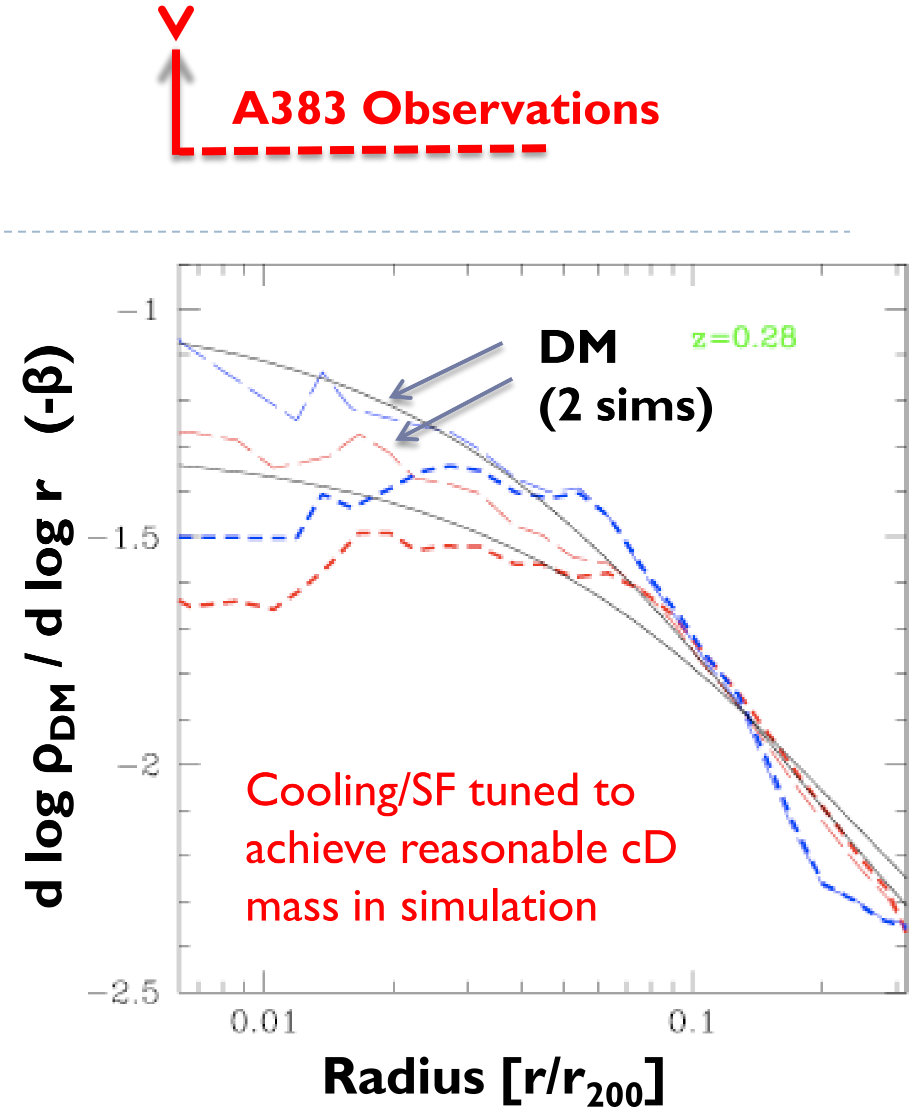
Stellar kinematics

Weak lensing

X-ray

Effect of baryons

- Baryons likely modify the DM profile – not well understood
- Cosmological simulations *of* clusters, including gas physics and feedback, show DM *contraction* → *steeper* cusps with β>1
  - e.g., Gnedin+ 2004, Duffy+ 2010, Sommer-Larsen & Limousin 2009
- Adding baryons exacerbates the discrepancy with observations

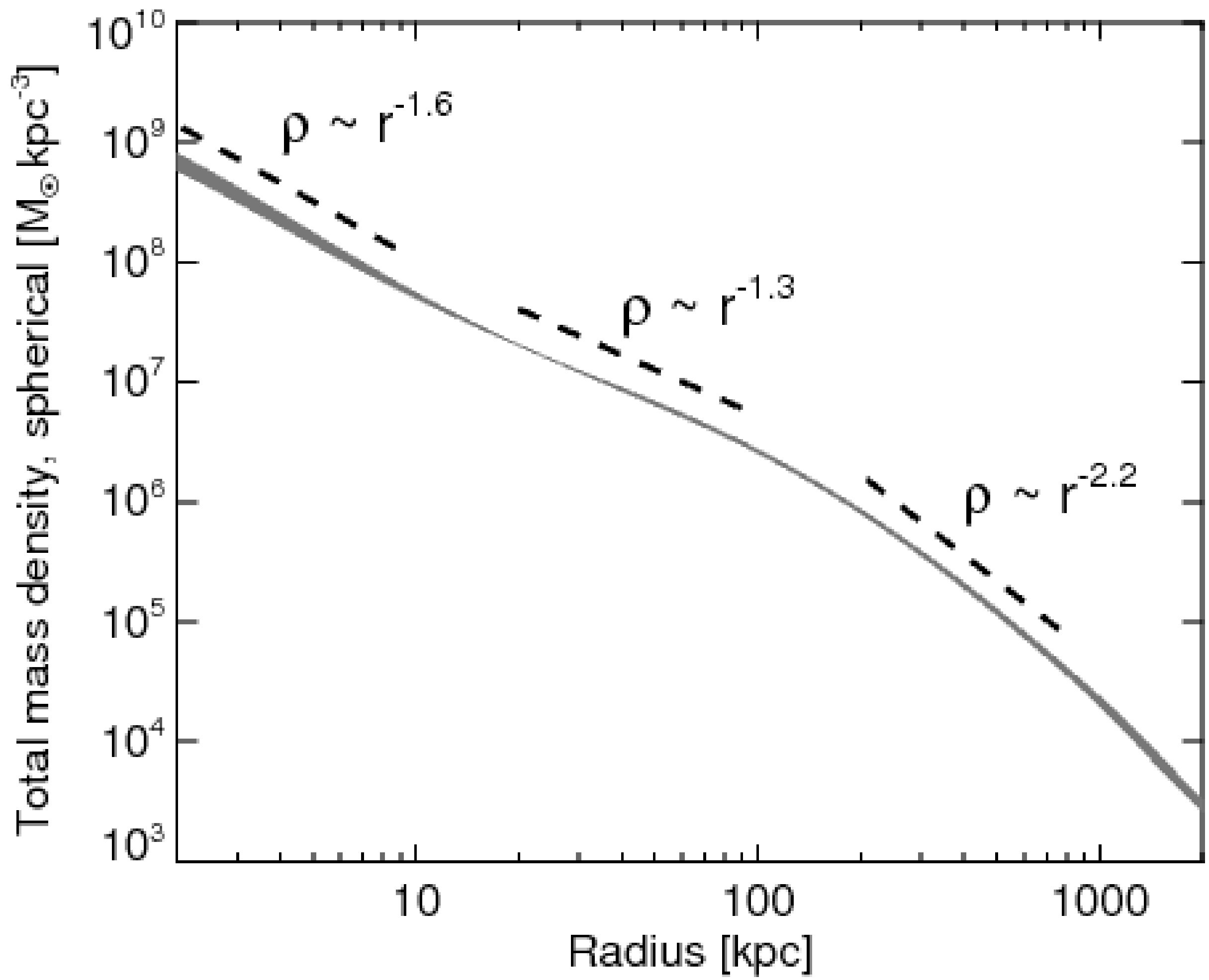


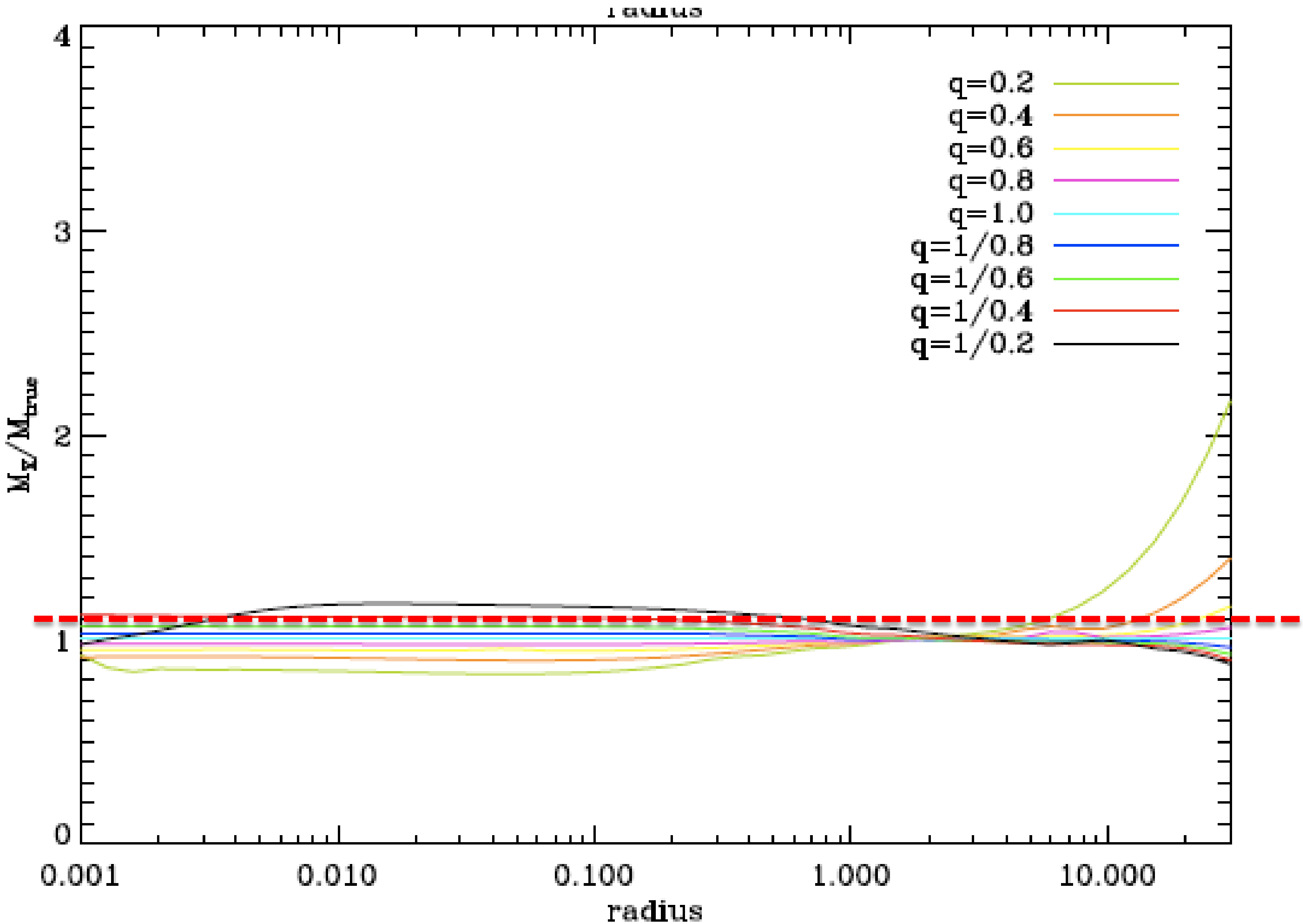
Sommer-Larsen & Limousin 2009

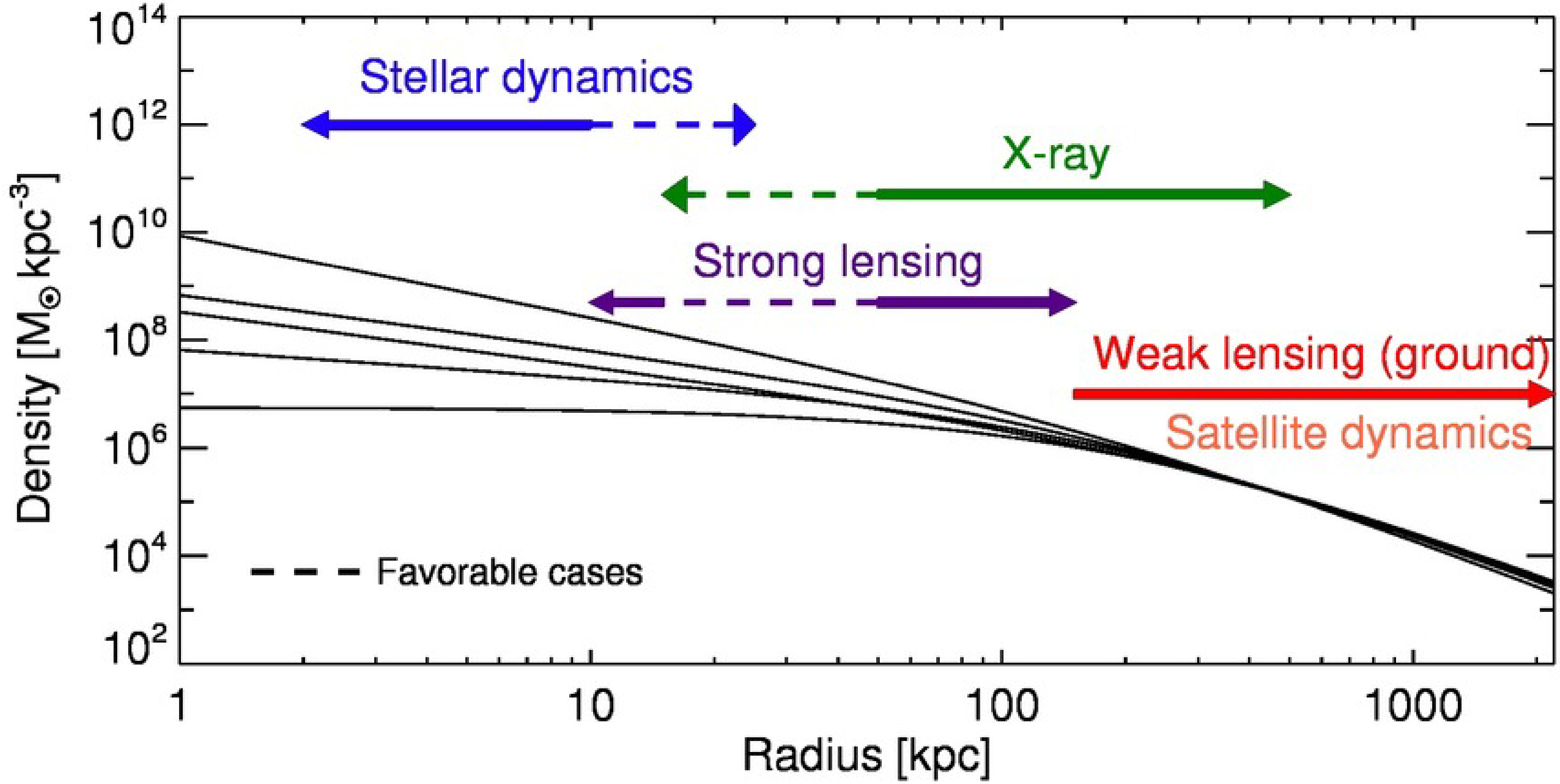
Conclusions and Future Work

- Combining lensing, X-ray, and stellar kinematics is a promising method to constrain
  - DM and stellar density profiles individually
  - Over 3 decades in radius – a similar range to modern simulations
  - The three-dimensional shape of halo
- Application to Abell 383 implies a shallow dark matter cusp with $\beta \approx 0.4 \pm 0.2$
- Unclear how to reconcile with steep DM cusps, even in presence of baryons.
- Future work
  - Extend to a larger sample of 9 clusters
  - Improving models
  - Further modes of comparison to simulations/theory beyond β

Abell 383: Total Mass Density




radius
q=0.2
q=0.4
q=0.6
q=0.8
q=1.0
q=1/0.8
q=1/0.6
q=1/0.4
q=1/0.2
0
1
2
3
4
0.001
0.010
0.100
1.000
10.000
radius



Range of several mass probes illustrated for different DM profiles of same virial mass

Combining mass probes necessary since each

- covers a *limited radial range*
- has its own *systematic uncertainties*

Abell 383: X-ray

- Mass profile from *Chandra* data from Allen et al. 2008
  - Assumes spherical symmetry and hydrostatic equil.
- X-ray masses biased low in simulations – regardless of projection – due to non-thermal support

  e.g., Nagai et al 2007, Lau et al 2009, Meneghetti et al 2010
- Will assume X-ray gives spherical masses with a ~7% low bias but allow scatter in normalization