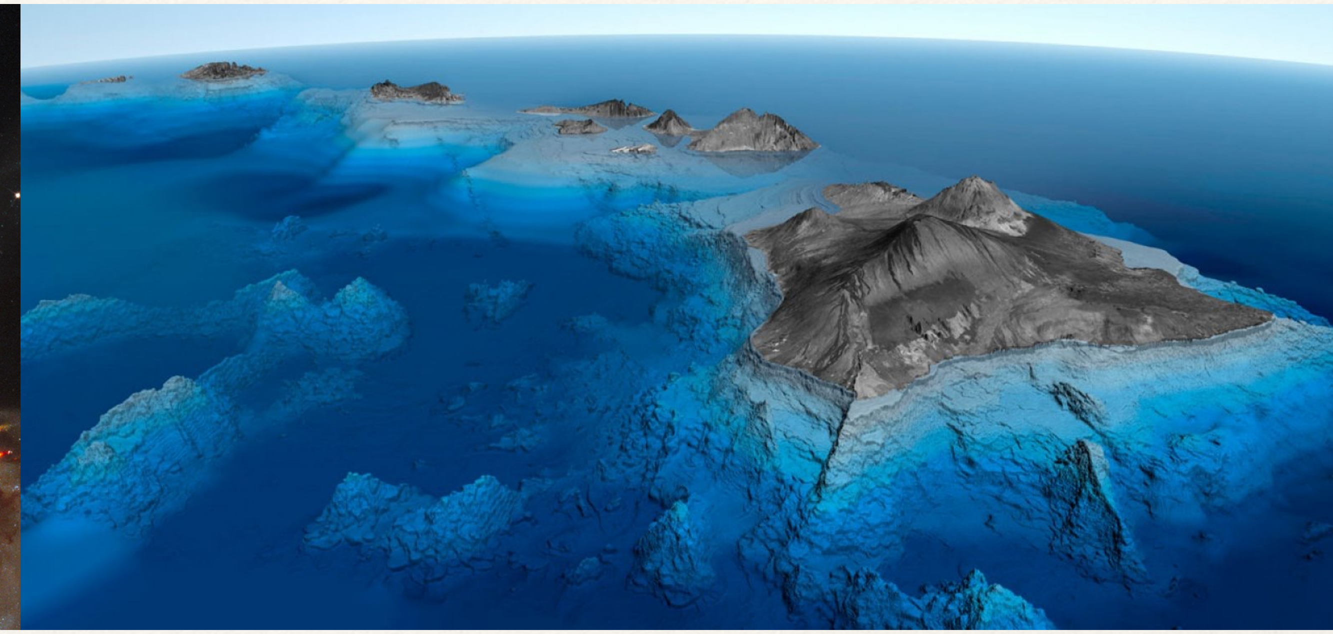

Getting to know the "island universes" out there.

Galaxies I

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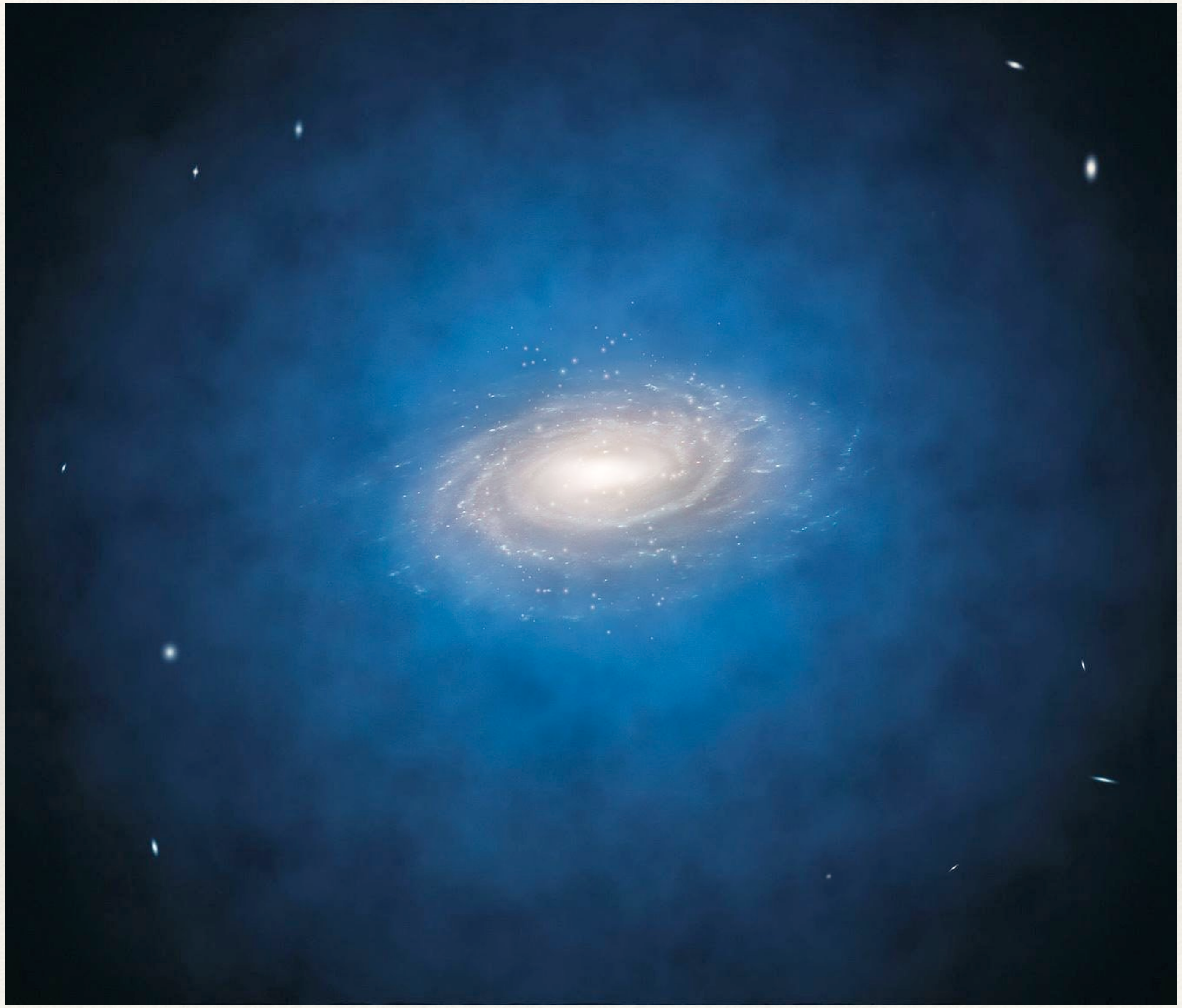
Outline for Today

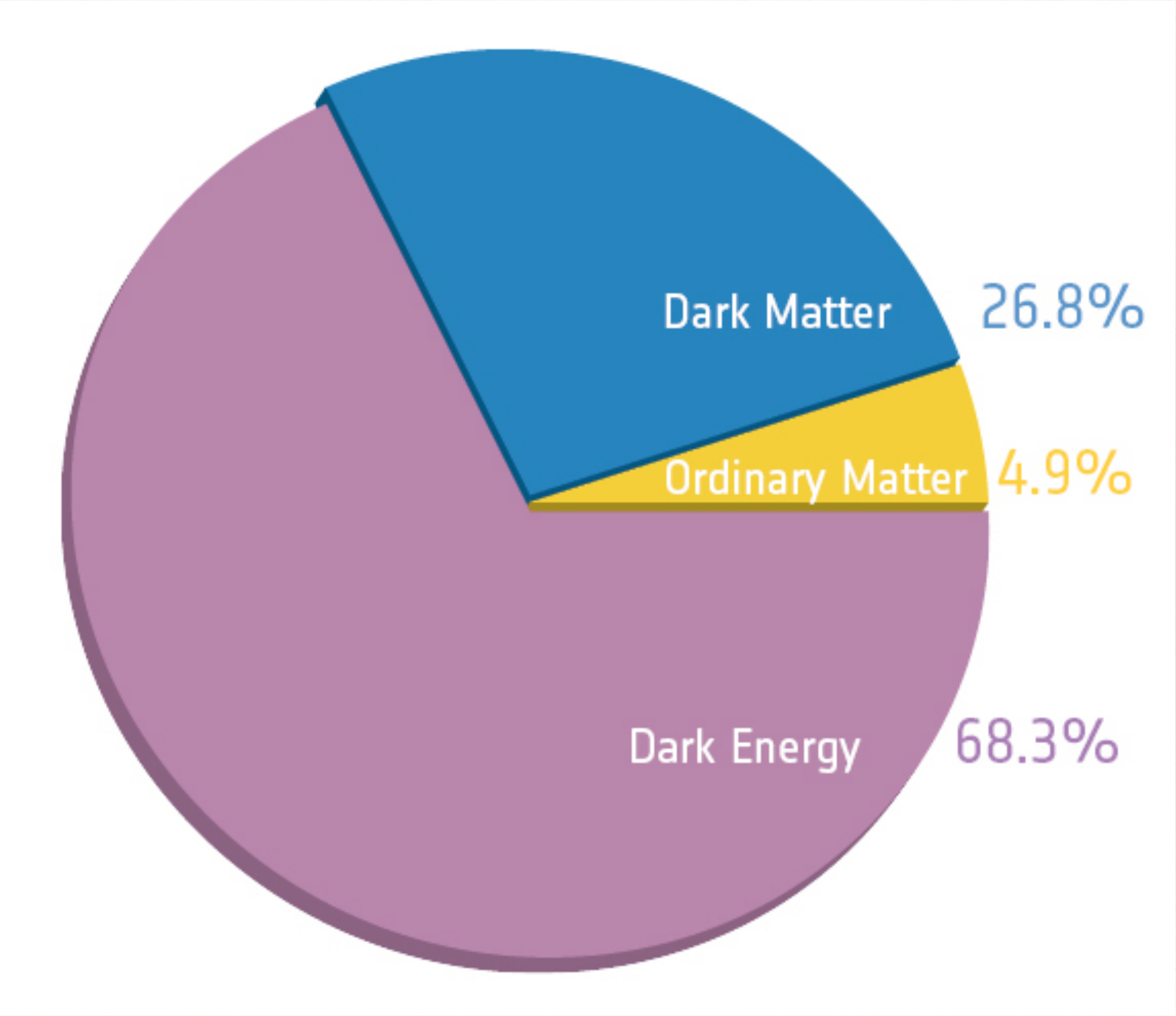
- Building Blocks - Dark Matter:
  - Kinematics
  - Gravitational Lensing
  - Total masses of galaxies



Artist's impression of the dark matter halo around a Milky Way type galaxy (Credit: ESO/L. Calçada)

Building Blocks - Dark Matter

- Motivation: dark matter dominates mass in Universe
- How is dark matter distributed, both within and between galaxies?
- May provide information on the nature of dark matter

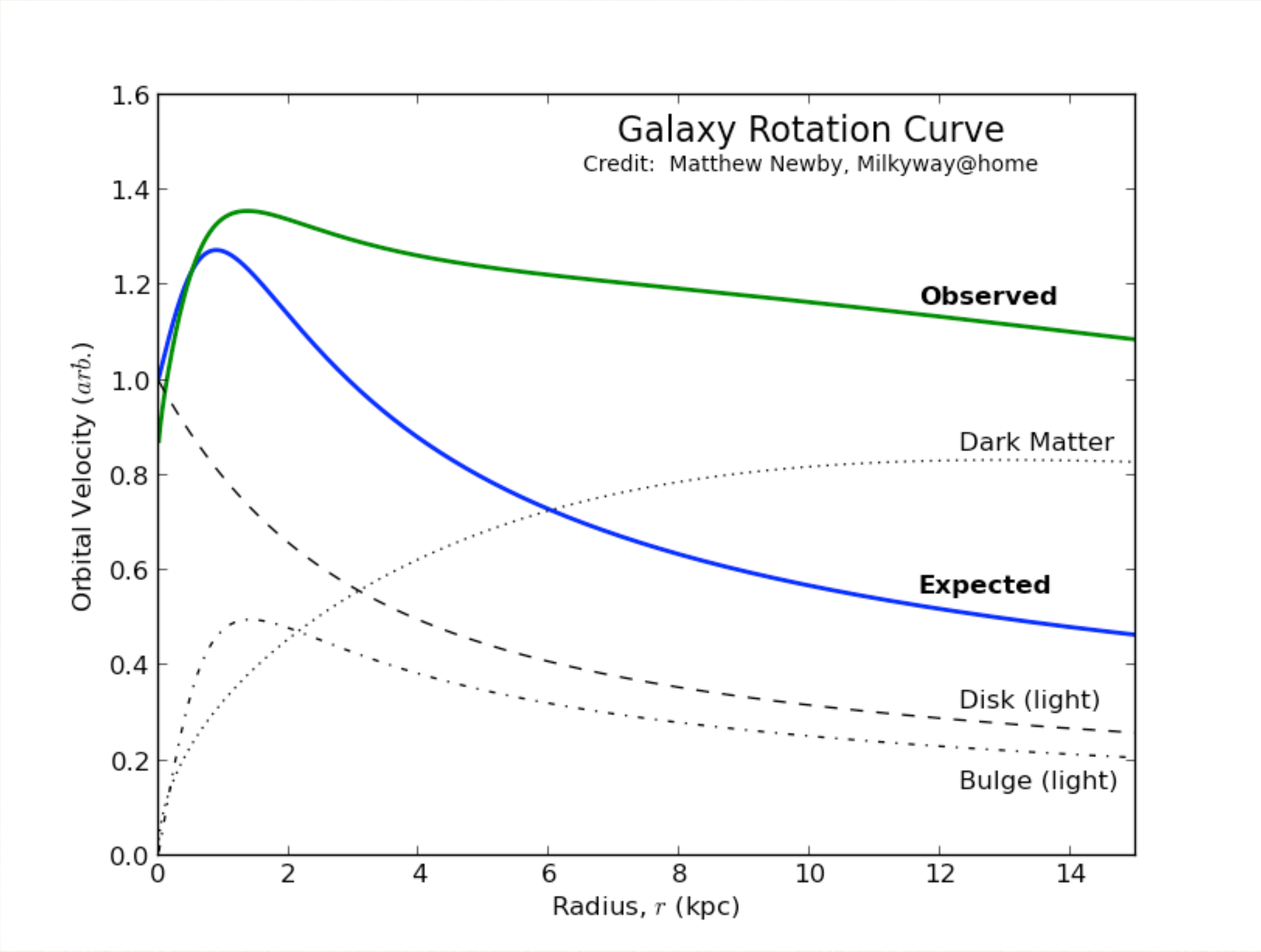


Credit: ESA/Planck Collaboration

Building Blocks - Dark Matter

- Dark matter in spirals
  - Rotation velocity scales with radius and mass enclosed
  - Flat rotation curves imply **M(r) α r**, i.e. significantly more than implied by exponentially declining stellar component
  - want to know how much more, and how DM is distributed --> mass modeling

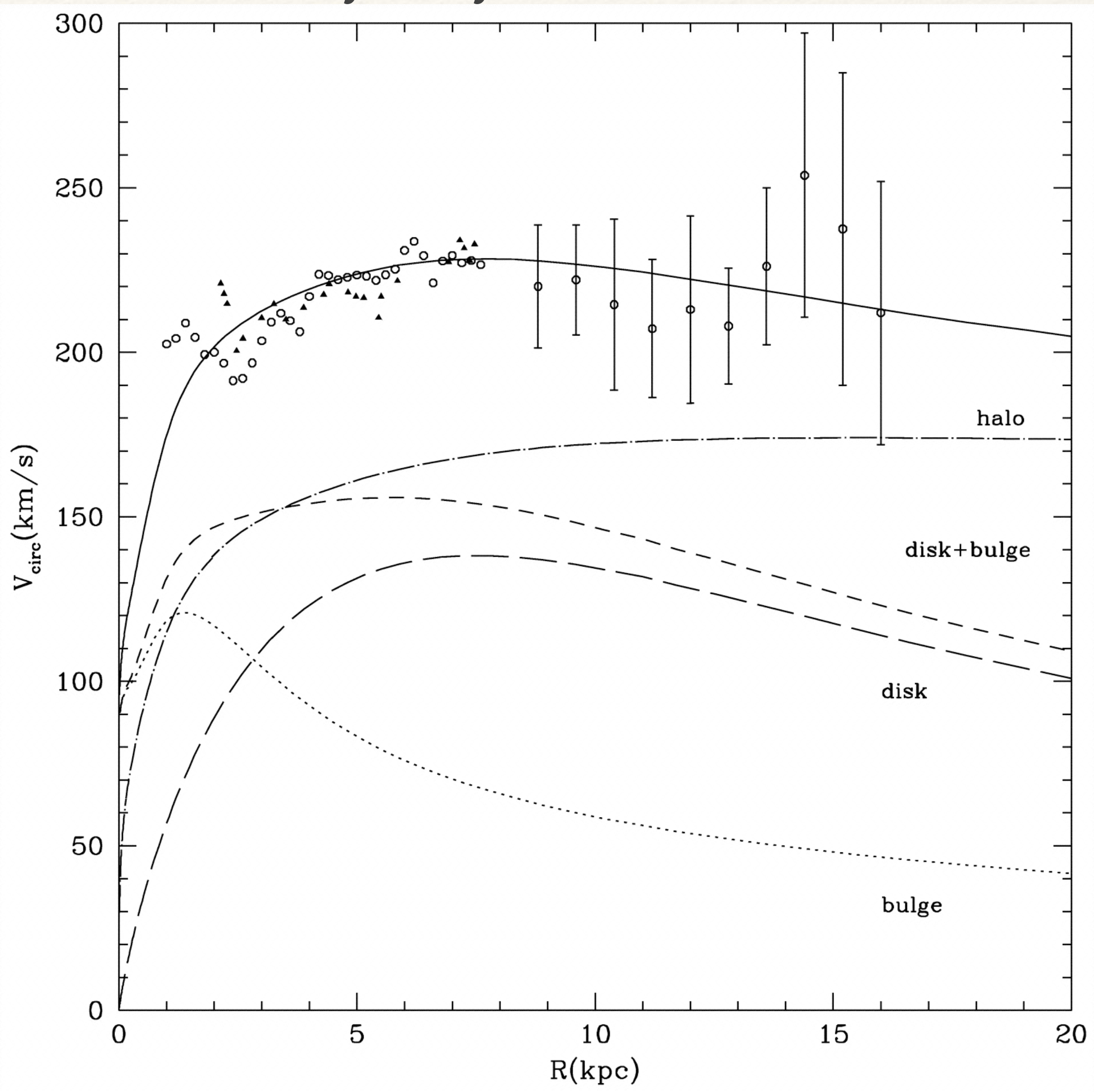
$$v_{rot} \propto \sqrt{\frac{GM(r)}{r}}$$



Building Blocks - Dark Matter

- **Mass Modeling**
  - Compare rotation curve to luminosity profile
  - dark matter fraction depends on the M/L ratio of the stellar population—uncertain due to IMF, etc.
  - Total M/L ~ 10-50 from spiral rotation curves

Milky Way Rotation Curve



Klypin et al 2002

Building Blocks - Dark Matter

- Data is degenerate in different ratios of disk to dark matter
- **“Maximum-disk” hypothesis:**
  - Assume inner rotation curve driven by luminous mass alone
  - Calculate inner M/L, assume constant with radius
  - Derive full mass profiles for the luminous and dark matter
  - but maximum disk may not be correct!

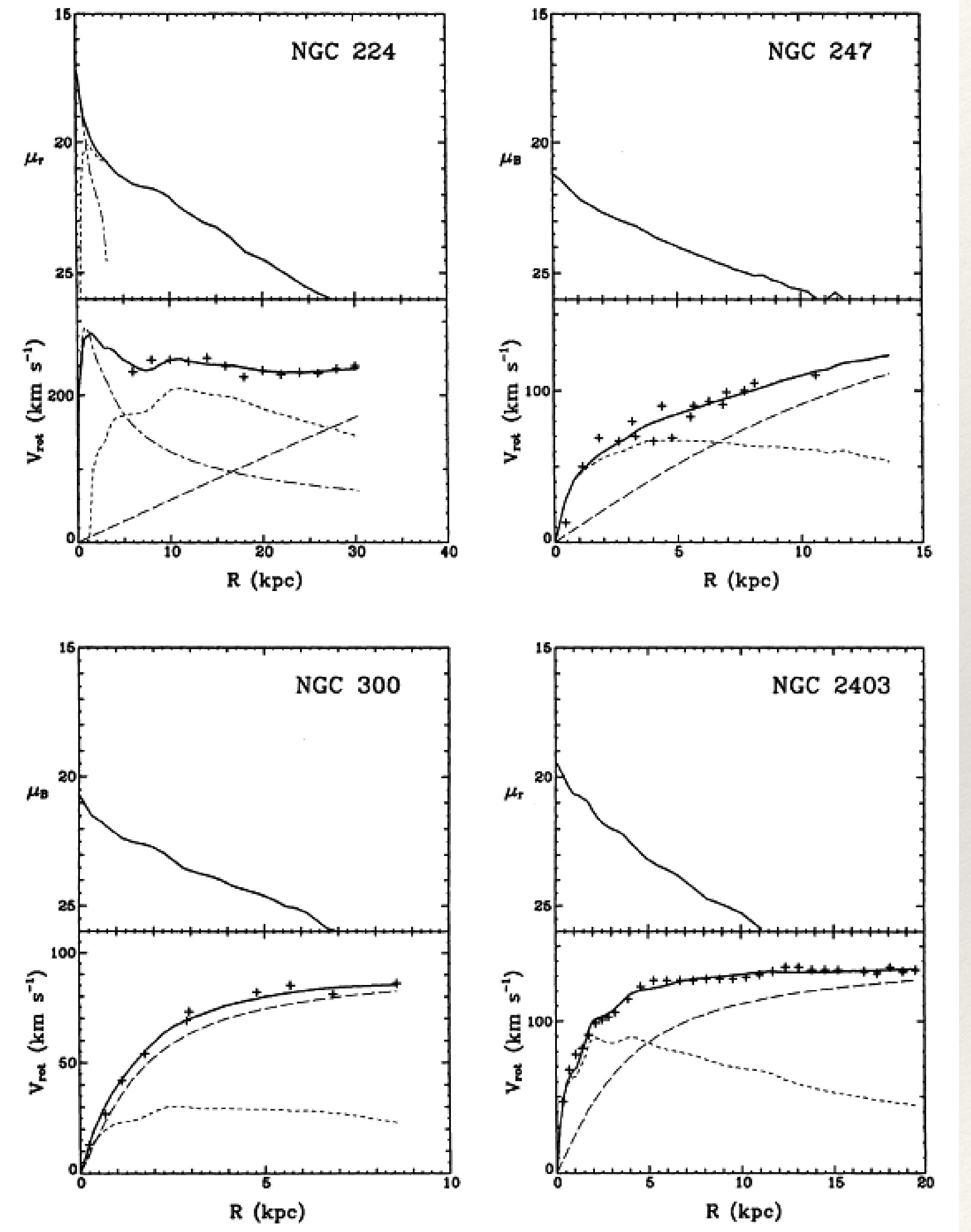


FIG. 1. Top panels: major-axis luminosity profiles for 16 spiral galaxies. The profile is decomposed into bulge (short- and long-dashed) and disk (short-dashed) components. Lower panels: observed rotation curves (pluses) and the best-fitting full solution (solid line). The separate contributions of the bulge, disk, and halo are also drawn.

Low surface brightness galaxies can help!

Building Blocks - Dark Matter

- Low surface brightness (LSB) galaxies:
    - larger contribution of dark matter
    - may provide more direct probes of dark matter distribution

44 W.J.G de Blok & S.S McGough

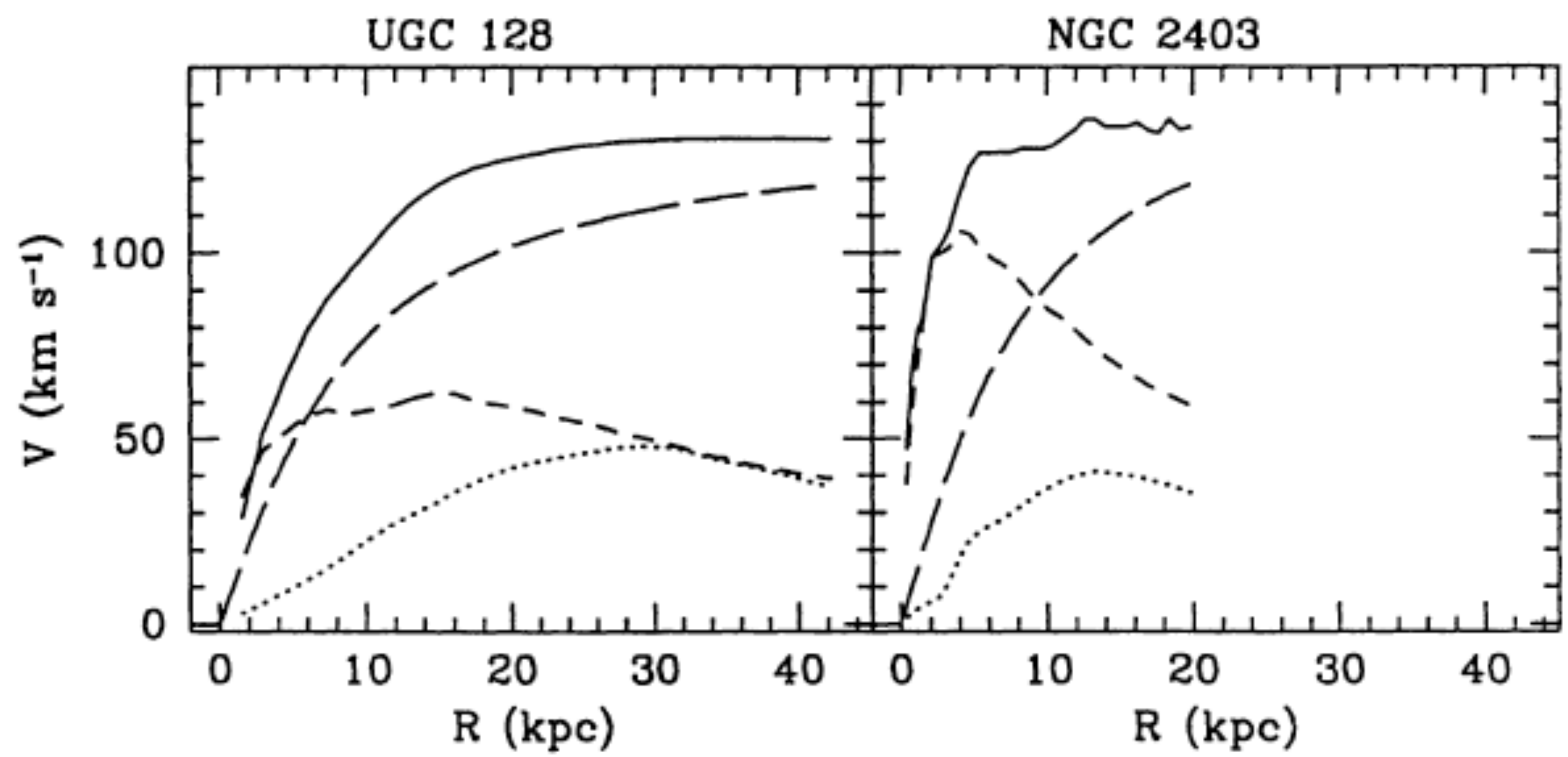


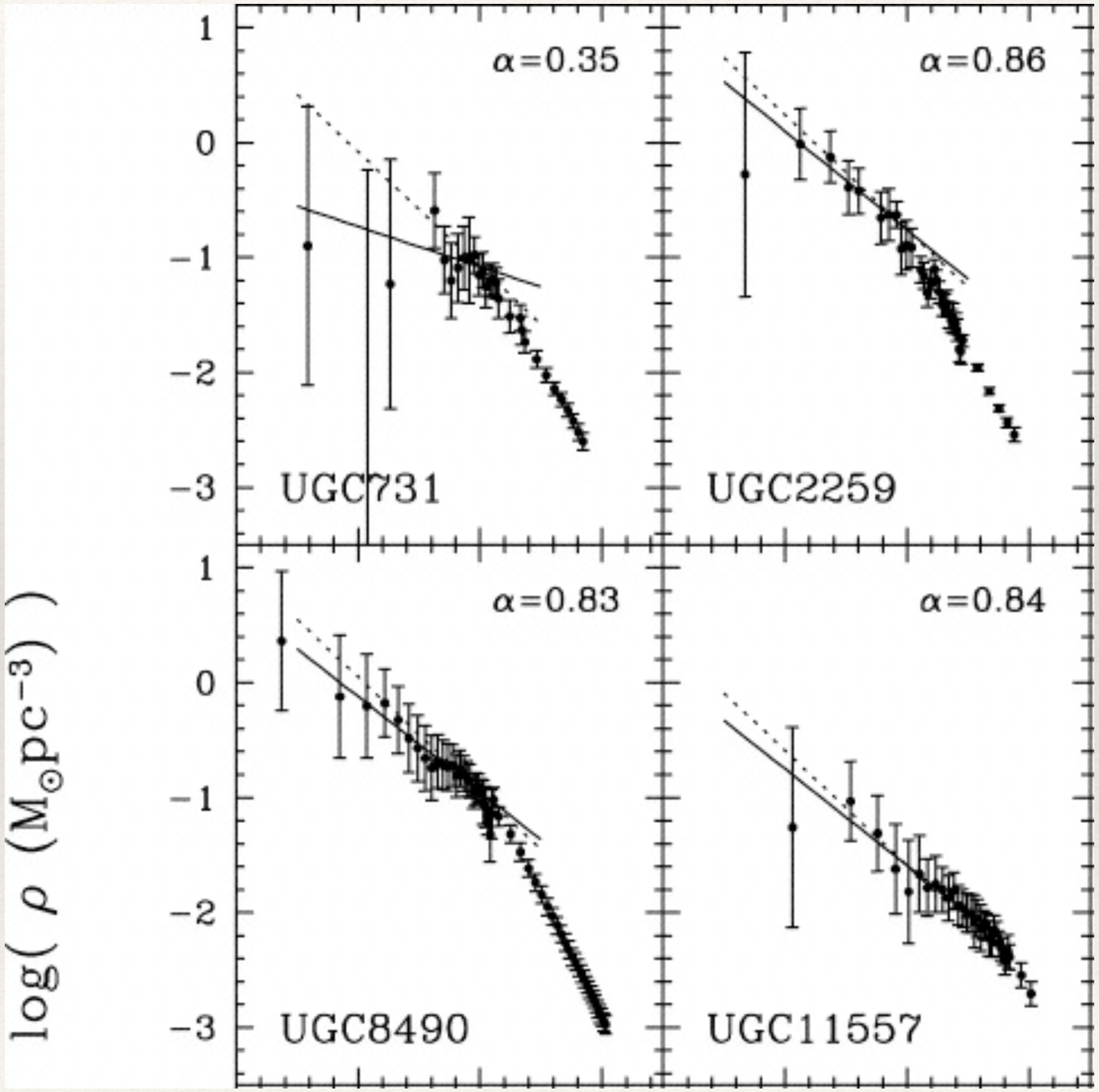
Figure 3. Comparison of the rotation curves of LSB galaxy UGC 128 and HSB galaxy NGC 2403. The full line is the observed rotation curve, the dotted curve that of the HI (scaled by 1.33 to take helium into account), the short-dashed line is the rotation curve of the maximum disc; the long-dashed line is the rotation curve of the halo.

Building Blocks - Dark Matter

- Results
- Numerical dark matter simulations predict "**cuspy**" profiles:
  - **Navarro-Frenk-White (NFW) profile:**

$$\rho = \frac{\rho_0}{\frac{r}{r_s}\left(1+\frac{r}{r_s}\right)^2}$$

Swaters et al 2003

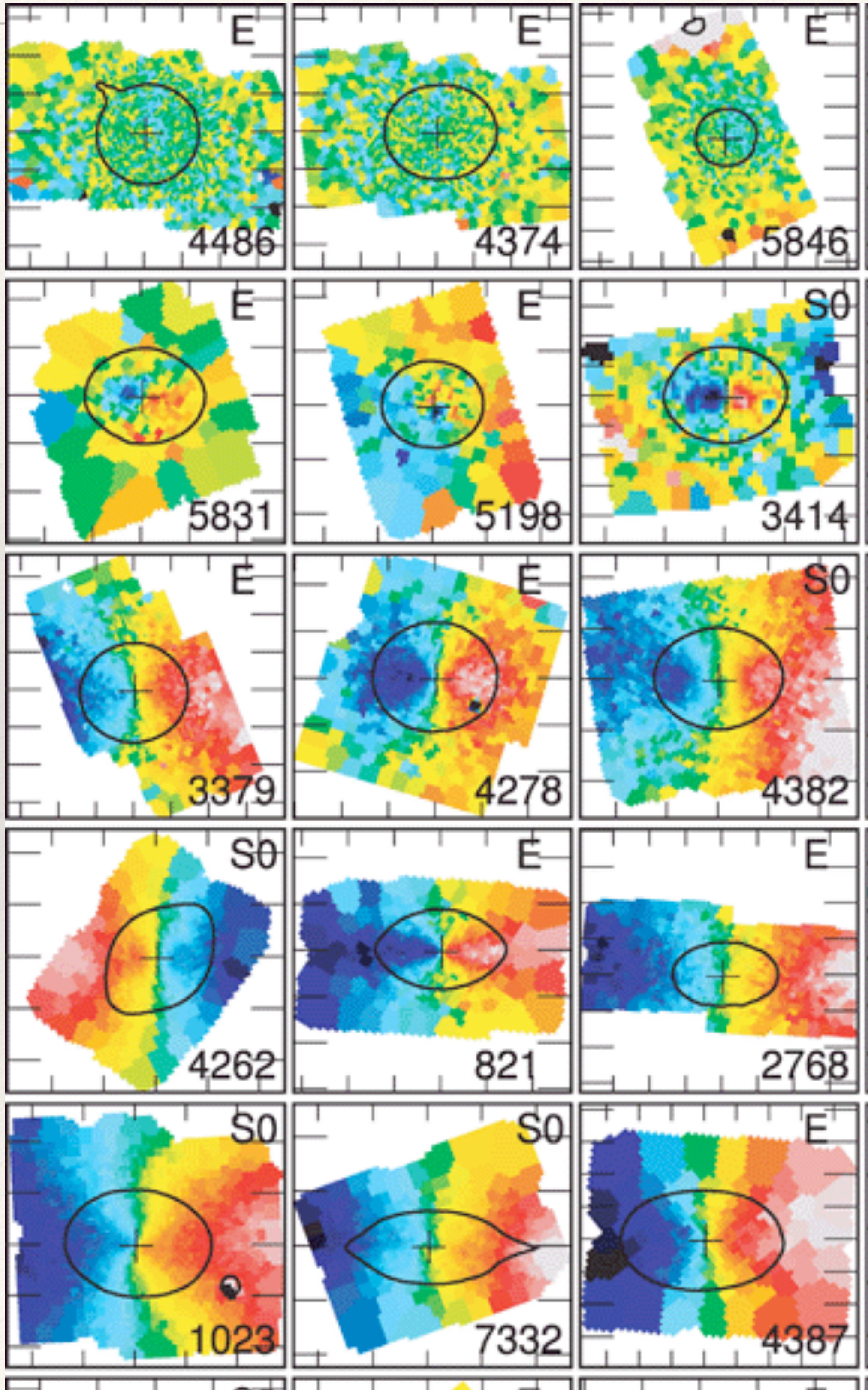


Log(r) [kpc]

- ome observations suggest more of a **core:**
  - Observational uncertainties?
  - Baryons affecting dark matter profile?
  - Nature of dark matter?

Building Blocks - Dark Matter

Emsellem et al. 2007



- Dark matter in elliptical galaxies
  - More challenging to observe directly than in spirals
  - Some progress made using:
    - Stellar kinematics (IFU data)
    - Kinematics of planetary nebulae, globular clusters, rare gas disks
    - Density / temperature profiles of X-ray halos (assuming hydrostatic equilibrium)
  - **Bottom line — Es have dark matter!**
- Note that DM mass often described by circular velocity, even if tracer is not rotating:

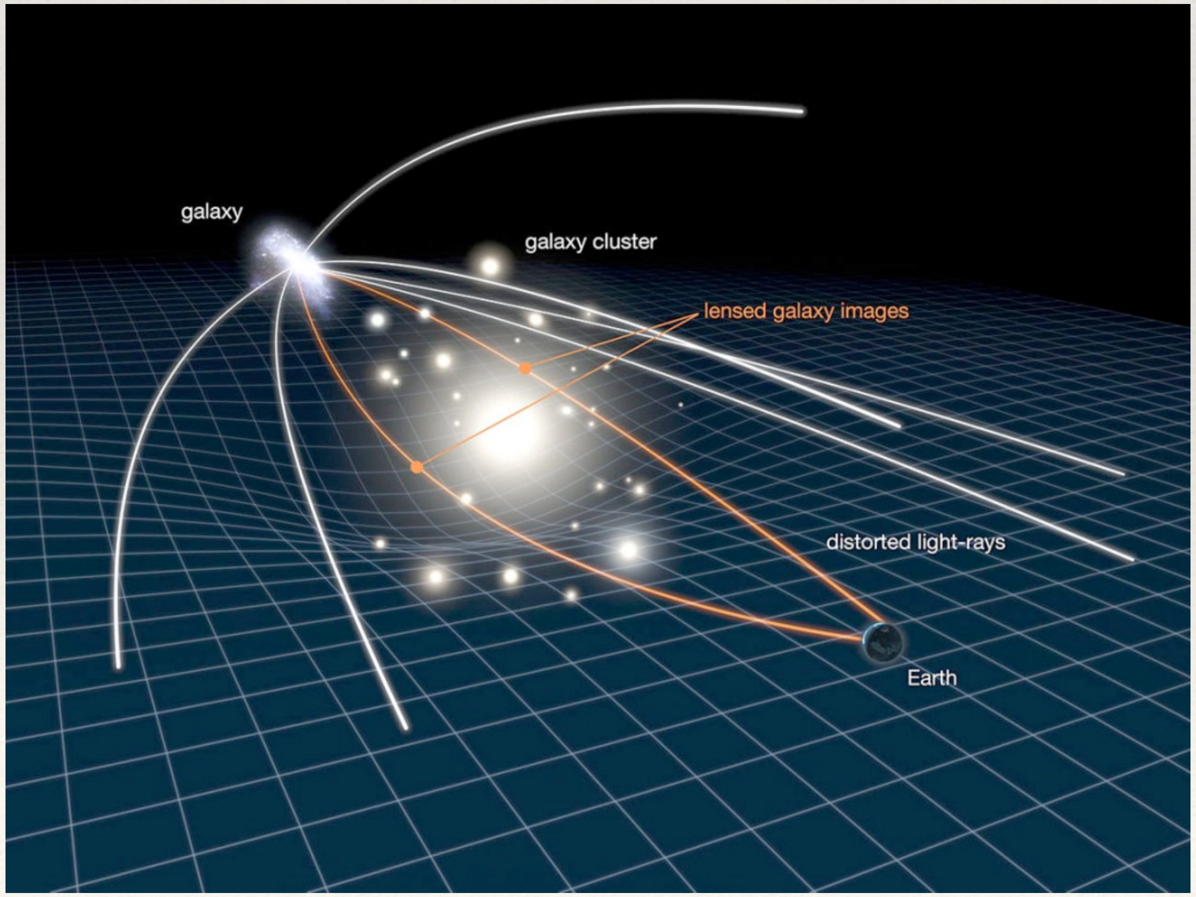
$$v_{circ} \equiv \sqrt{\frac{GM(r<R)}{R}}$$

Building Blocks - Dark Matter

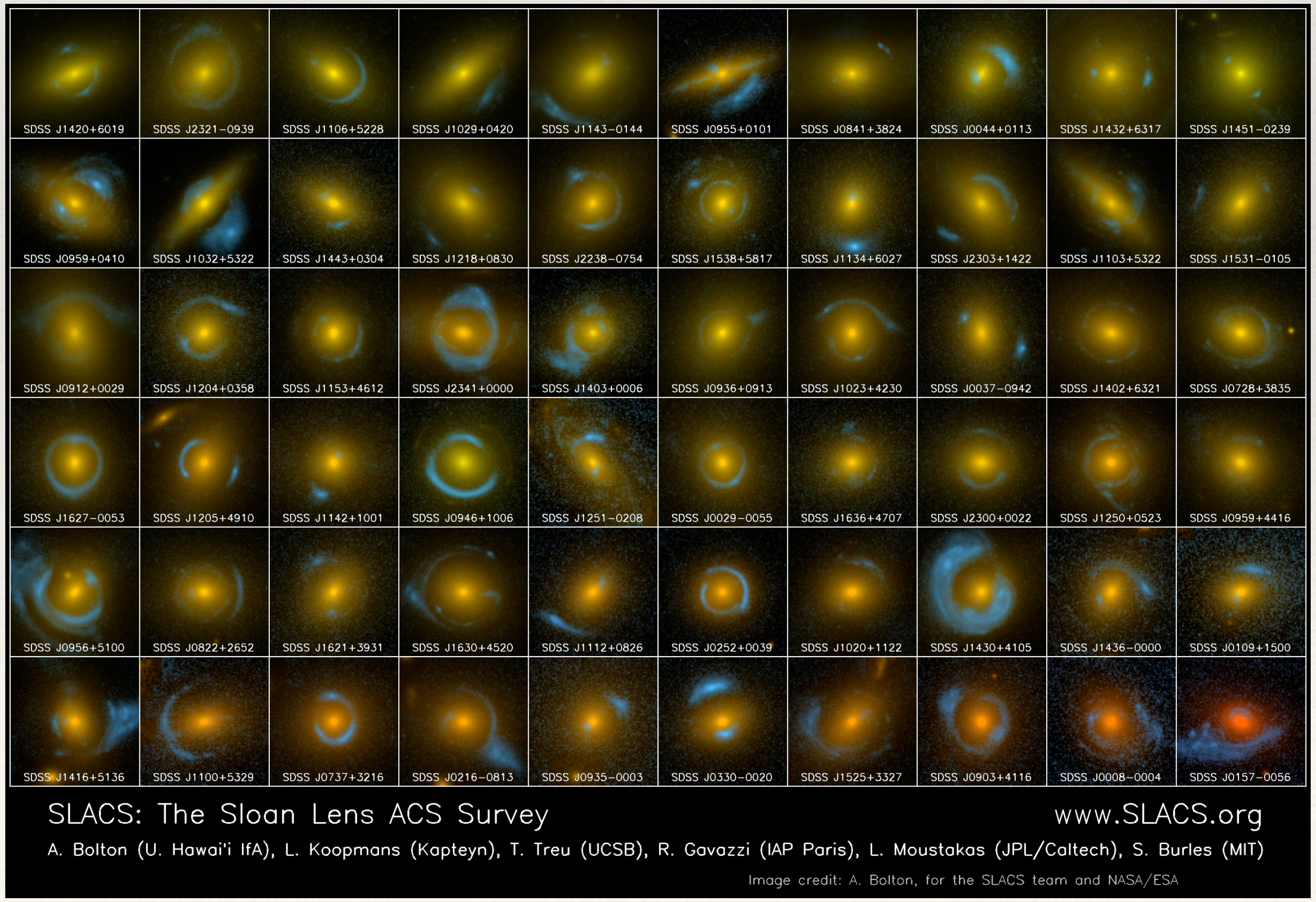
- Based on simulations, dark matter halos expected to extend far beyond tracers used for rotation curves in spirals and for typical estimators in ellipticals
  - simulations suggest virial radii of galaxies few hundred kpc
- to determine total masses of galaxies, need to probe mass distribution farther out

Building Blocks - Dark Matter

- **Gravitational lensing by individual galaxies:**
  - strong lensing — massive lens close to background source on sky
    - multiple images, strong distortion (arcs, rings)
    - model individual images to derive mass profile

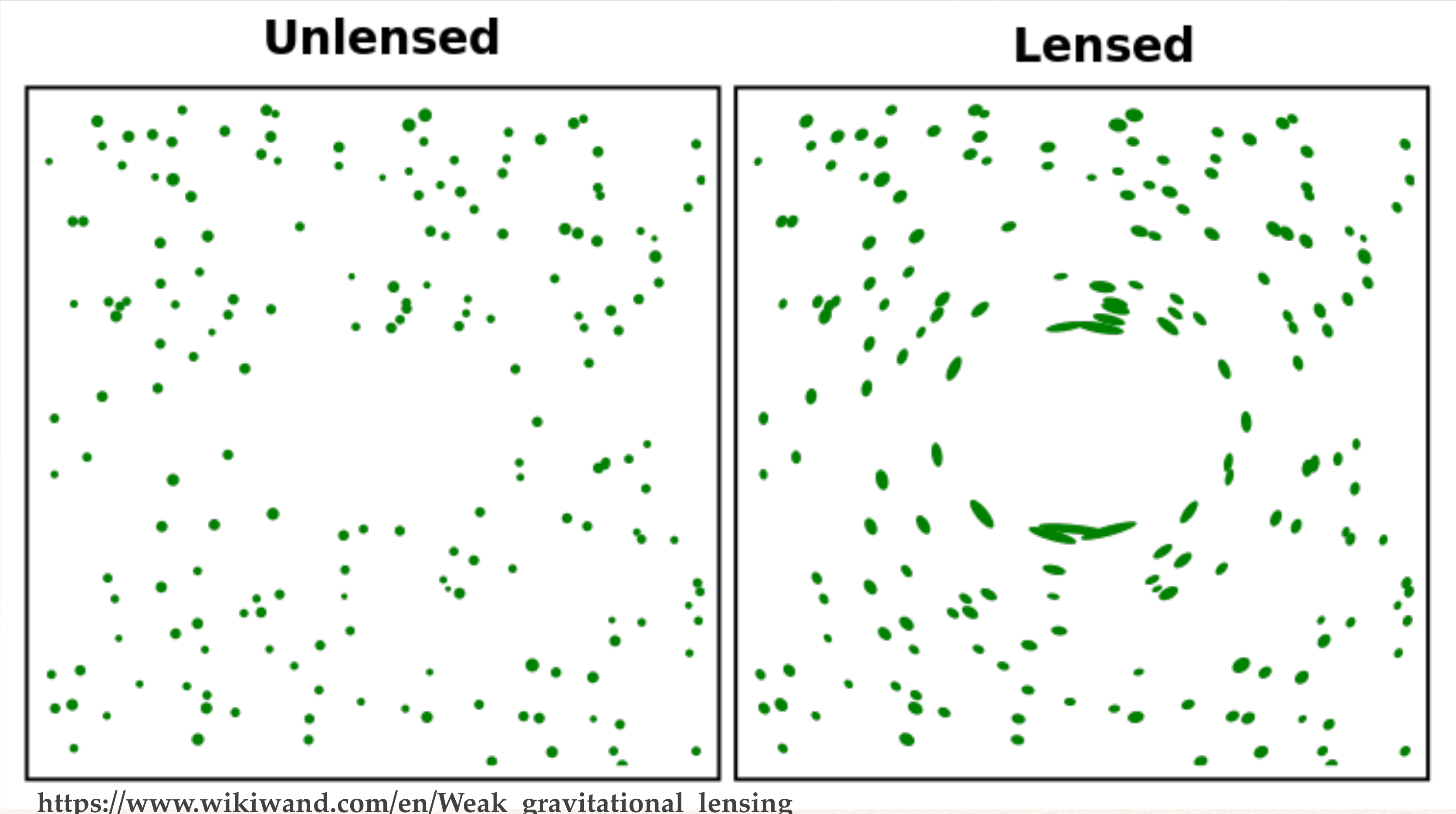


Credit: CFHTLenS

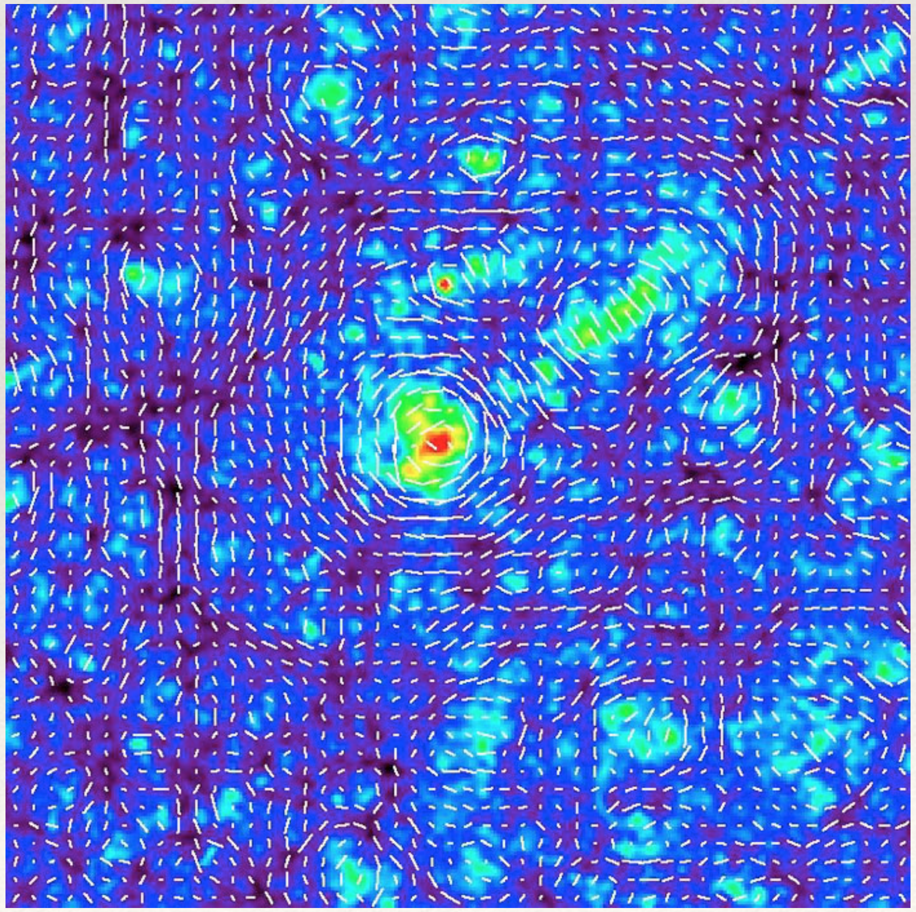


Building Blocks - Dark Matter

- **Gravitational lensing by individual galaxies:**
  - weak lensing — weaker lens / greater projected distance
    - slight stretching / magnification
    - measure statistically for many background galaxies



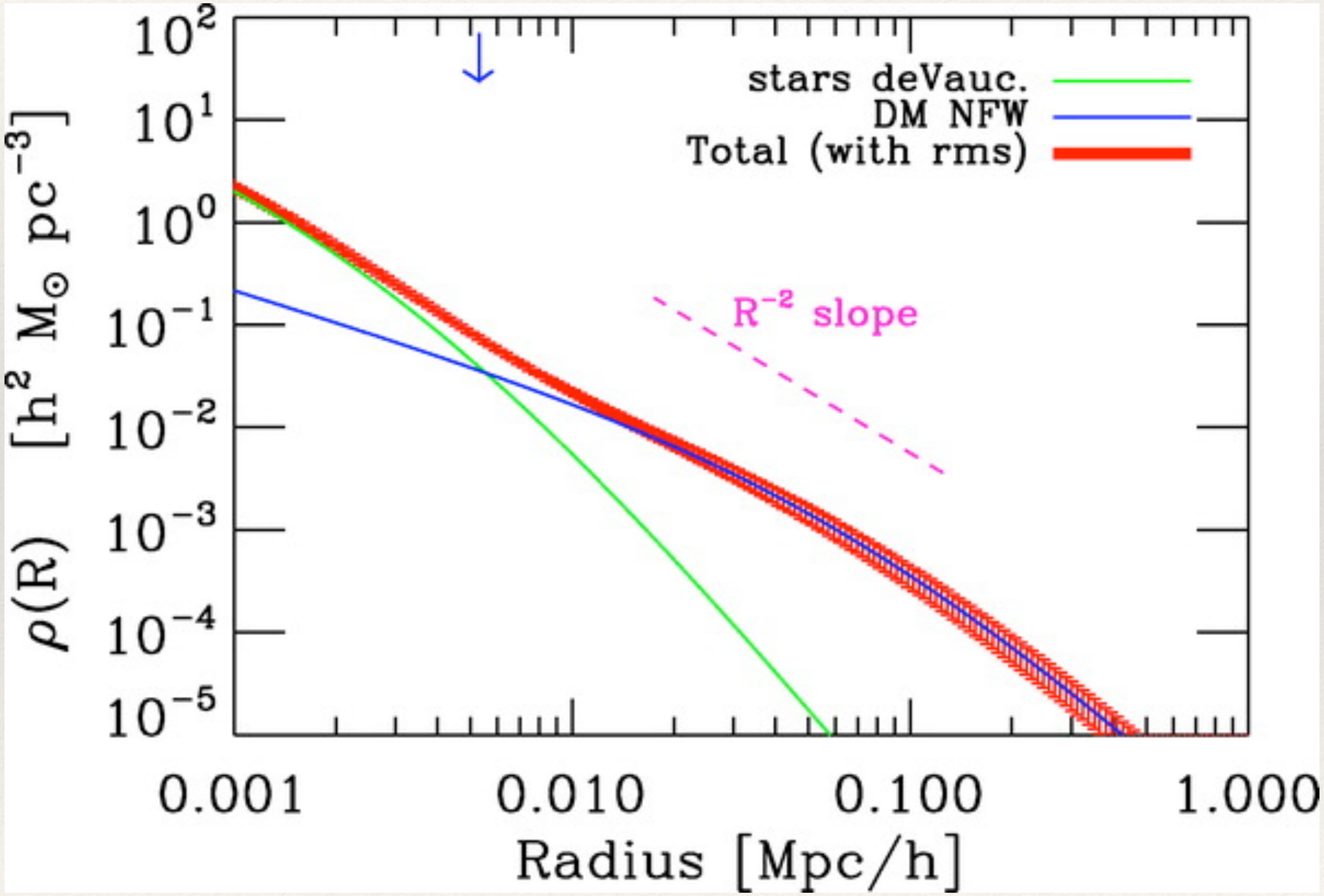
https://www.wikiwand.com/en/Weak_gravitational_lensing



Cosmic shear field within cosmological N-body simulation (Credit: T. Hamana)

Building Blocks - Dark Matter

- **Gravitational lensing by individual galaxies:**
  - Derive extended mass profiles of galaxies
  - M/L ratio ~ 10s-100s at very large radii



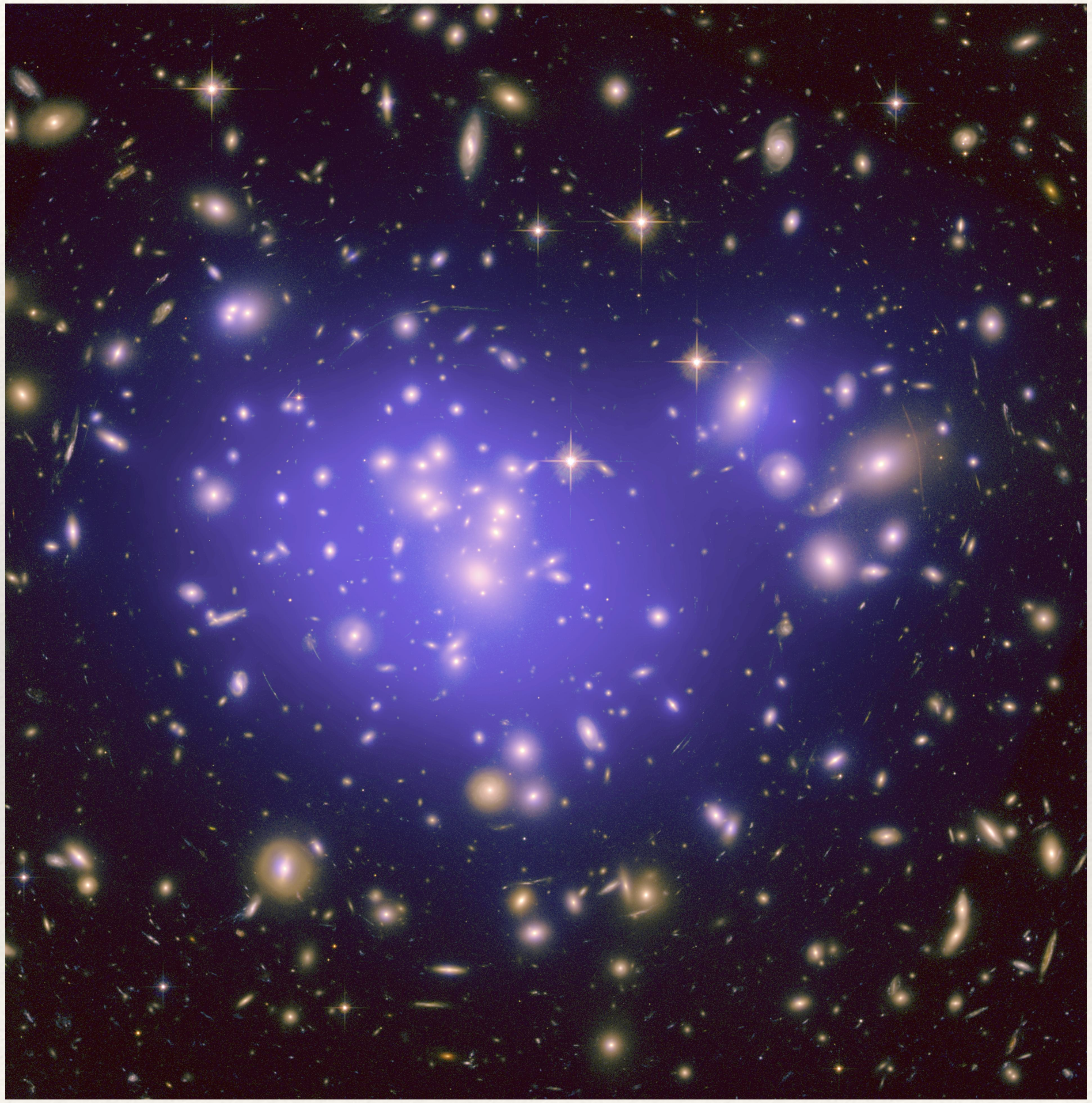
Gavazzi et al. 2007

Building Blocks - Dark Matter

- Other methods for getting total masses to larger radii:
  - motions of satellite galaxies
  - in conjunction with simulations, "halo abundance matching": sort observed galaxies by stellar mass and simulated galaxy by total mass and use this to associate total masses to observed galaxie

Building Blocks - Dark Matter

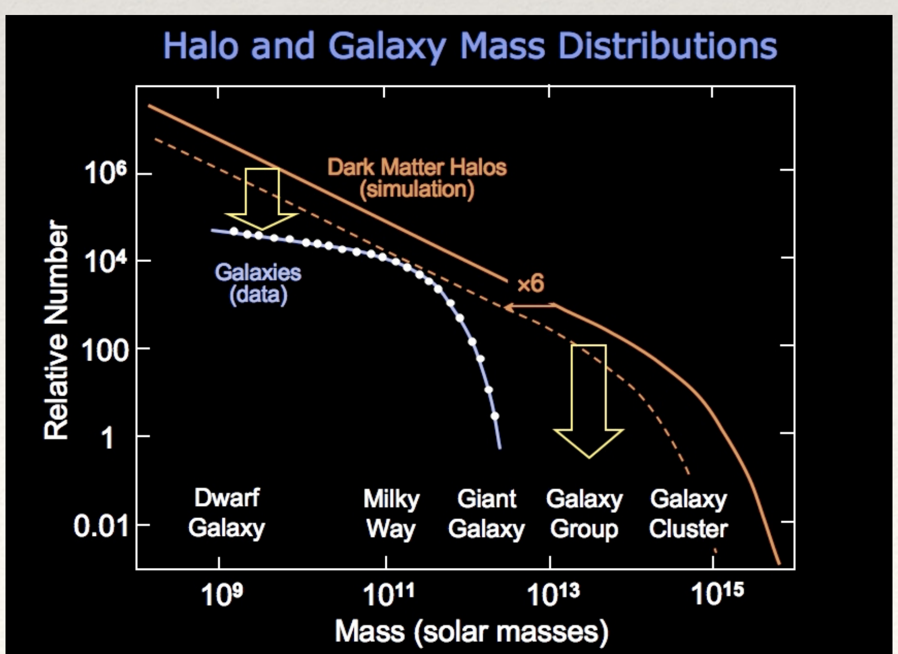
- On even larger scales, measure **dark matter in clusters**
  - cluster galaxy velocities
  - hot (X-ray) gas
  - gravitational lensing
  - M/L ratios of several 100s-1000s!



Abell 1689 (NASA)

Building Blocks - Dark Matter

- Results: Stellar mass vs total mass relation
- Mtot/Mstellar seems to show trend with stellar mass, increasing a lower and higher stellar masses
- Effects of increased feedback at lower and higher masses?
    - supernova feed back at lower masses
    - AGN feedback at higher masses



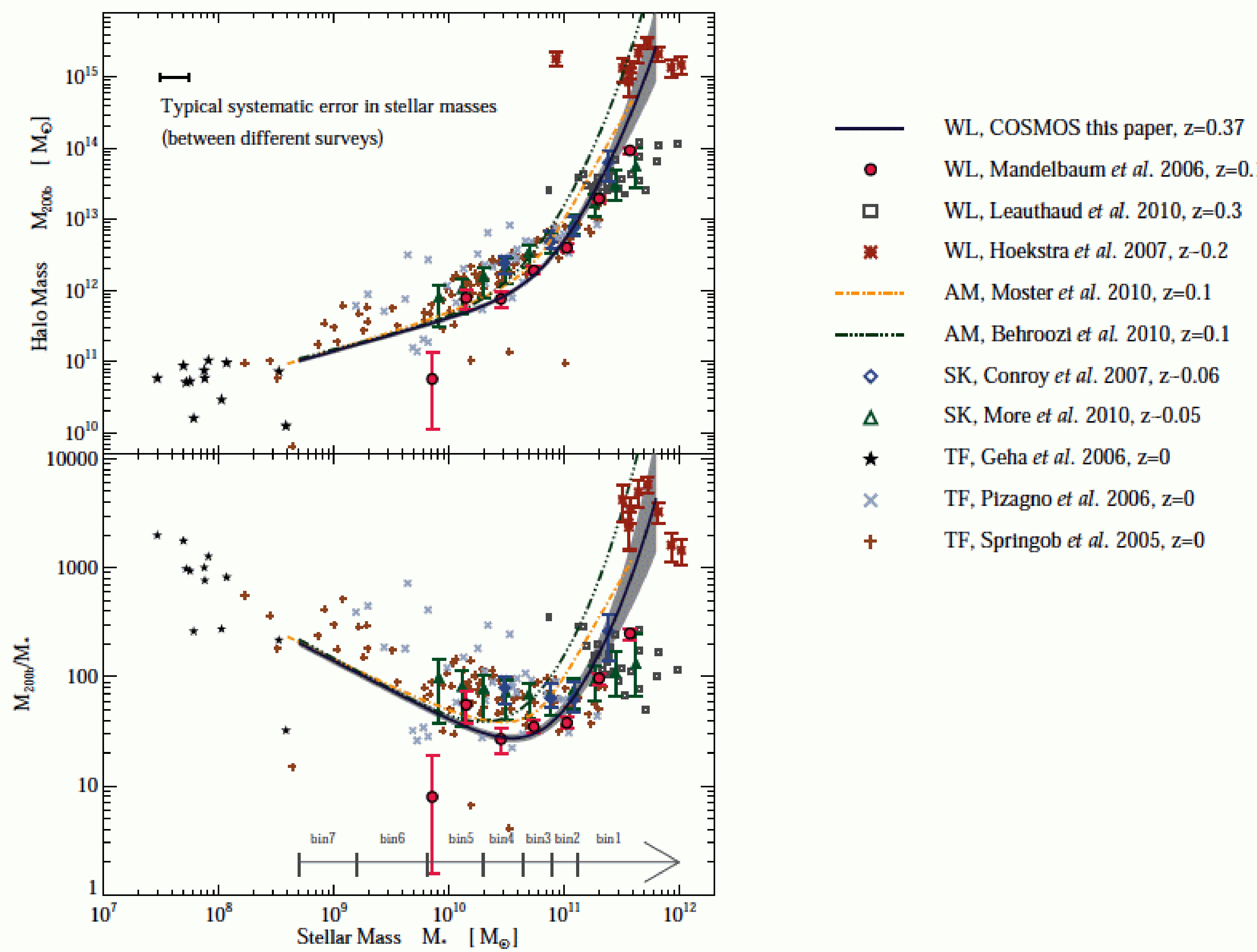
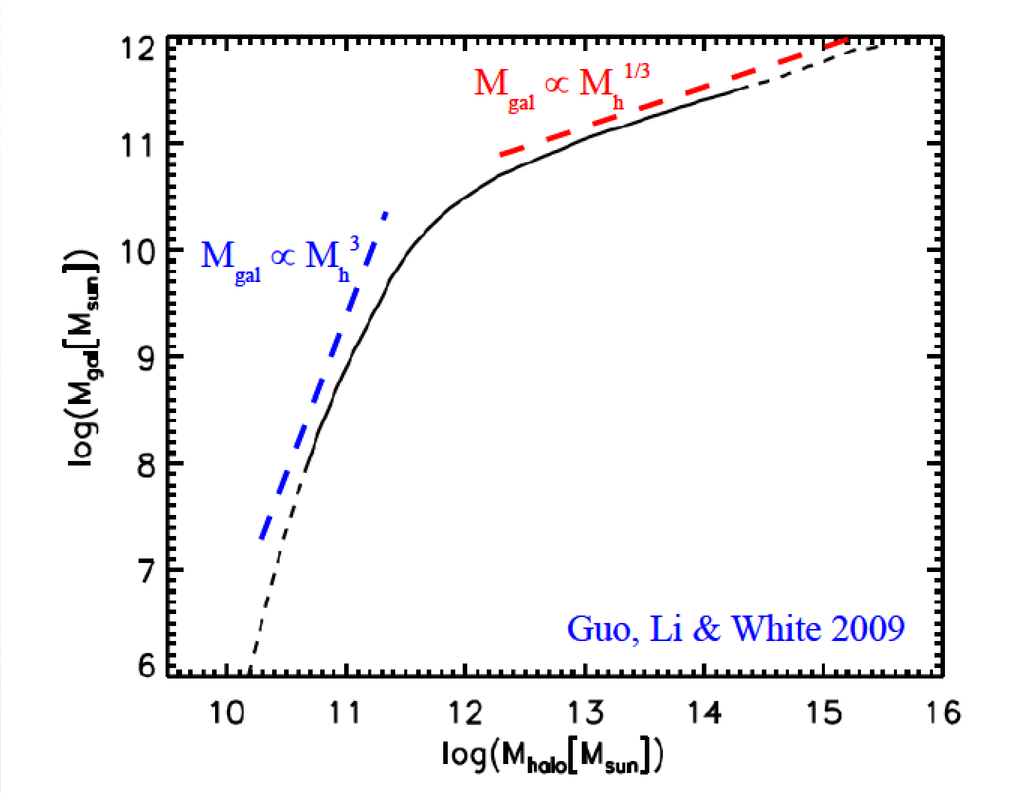
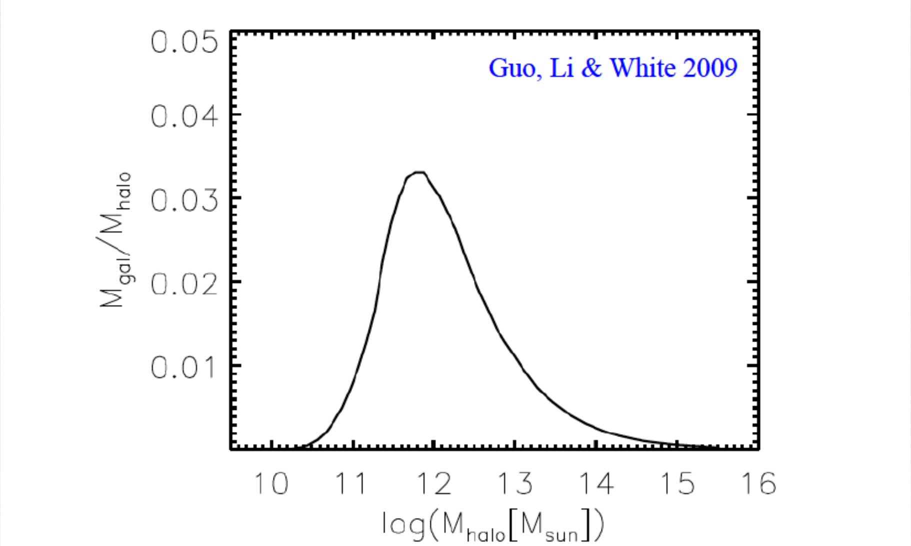


FIG. 10.— Top panel: inferred SHMR in the z_1 redshift bin compared to other low redshift measurements from weak lensing (WL), abundance matching (AM), satellite kinematics (SK), and the Tully Fisher relation (TF). The COSMOS z_1 results are shown by the solid dark blue line and the shaded grey region represents the one sigma error on the SHMR. This SHMR represents $\langle \log_{10}(M_*(M_h)) \rangle$. With the exception of Conroy et al. (2007), all data points either use or have been converted to this same averaging system . Overall, there is a broad agreement between various probes. Detailed comparisons between various data-sets however, are limited by systematic differences in stellar mass estimates due to varying assumptions (e.g., star formation histories, extinction laws, stellar population models). Bottom panel: dark-to-stellar mass ratio as a function of stellar mass. We observe a clear variation in M_{200b}/M_* with M_{200b}/M_* reaching a minimum of $M_h/M_* \sim 27$ at $M_* \sim 4.5 \times 10^{10}$ $M_\odot$ and $M_{200b} \sim 1.2 \times 10^{12}$ $M_\odot$. The dark-to-stellar mass ratio rises sharply at $M_* > 5 \times 10^{10}$ $M_\odot$ so that a cluster of halo mass $M_{200b} \sim 10^{15}$ $M_\odot$ will reach a ratio of $M_{200b}/M_* \sim 2000$. Note that this ratio only refers to the ratio between the halo mass and the stellar mass of the *central galaxy*. For example, in the case of clusters, we are comparing the ratio of the cluster halo mass to stellar mass of the central Brightest Cluster Galaxy (BCG).

Building Blocks - Dark Matter

- Relatively small fraction of mass is in stars!
- Galaxies like the MW may be most efficient at forming stars, but still relatively low efficiency





- The maximum halo mass fraction in central galaxy stars is 3.5%
- This is attained for halos similar in mass to the Milky Way's halo
- The fraction drops very rapidly to higher and lower masses