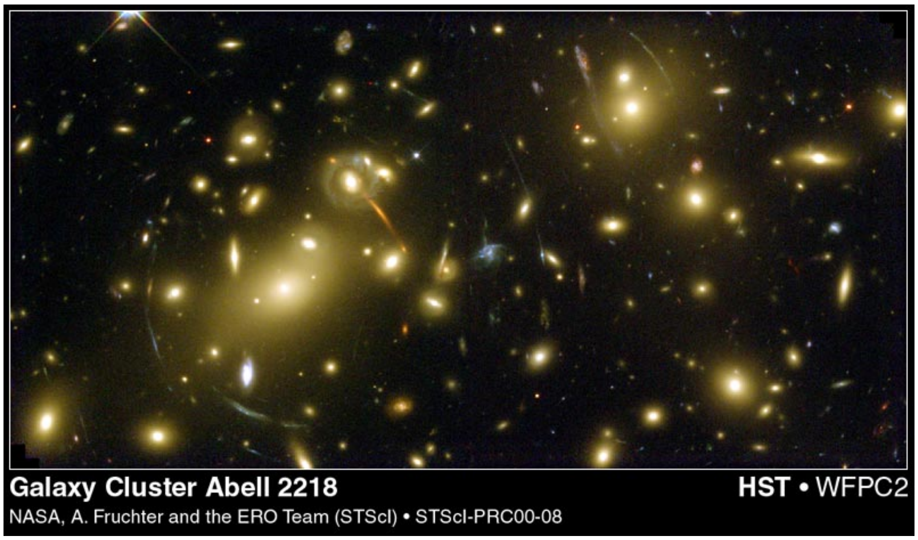
Gravitational lensing…Sec 7.4 of S&G

- In some cases, can also measure galaxy mass using gravitational lensing.
- Get good agreement with dynamical measurements



Lensing

- Angle of change
  $\alpha \sim 4GM/bc^2 = 2R_s/b$
- where R_s is the Schwarzschild radius* and b is the impact parameter
- Background images are distorted and amplified.
- Einstein radius for an isothermal sphere is

$\theta_E = \theta_e = 4\pi(\sigma_{sis}/c)^2 D_{ls}/D_s \sim (D_{ls}/D_s)(\sigma^2/186\text{km/sec})$ arc sec

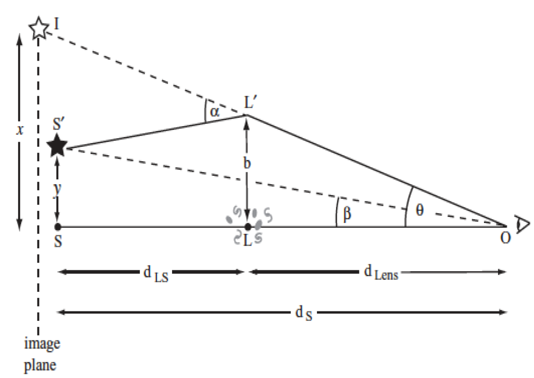
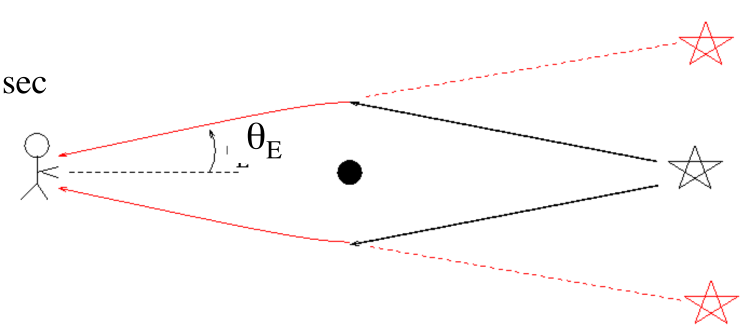


Fig. 7.14. The gravity of the mass $\mathcal{M}$ at L bends light from a distant source at S′ toward the observer at O; the source appears instead at position I.

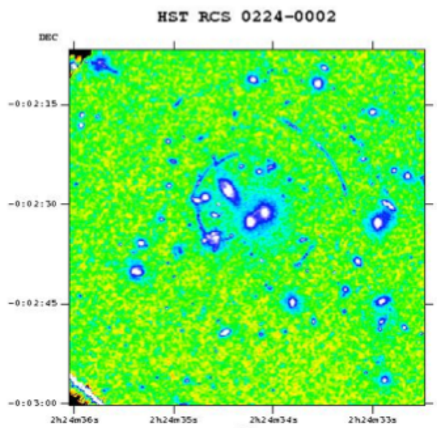
S&G 7.4.1,7.4.2

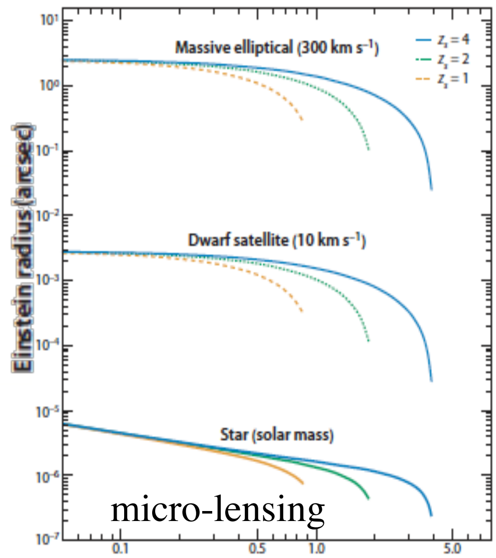


Schwarzschild radius= $2GM/c^2$

Why Giant Ellipticals as Lenses

- To 1st order strong lensing is only sensitive to the mass enclosed by the *Einstein radius*
- Ellipticals Einstein radii are ~2" over a wide range of redshifts - but only 1/1000 galaxies are strong lenses
- cross section (Einstein radius^2) goes as σ^4. Ellipticals tend to have higher σ



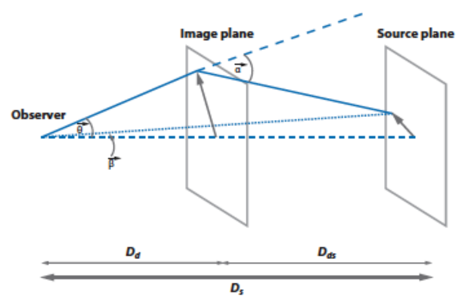


Deflector redshift

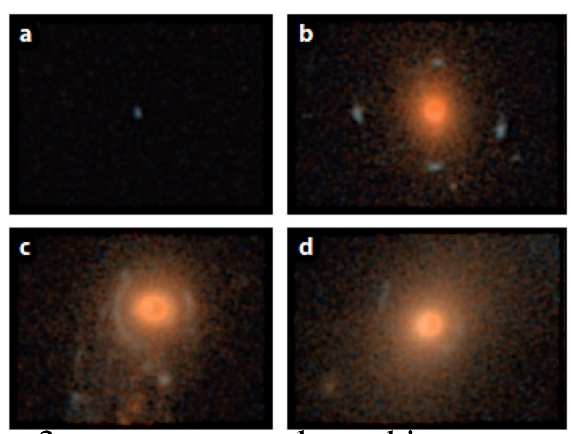
Treu 2010

Lensing- S&G 7.4.1,7.4.2

- Strong lensing observables—such as relative positions, flux ratios, and time delays between multiple images—depend on the gravitational potential of the foreground galaxy (lens or deflector) and its derivatives



- dynamical models provide masses enclosed within a *spherical* radius, while strong lensing measures the mass inside a *cylinder* with axis parallel to the line-of-sight
- **Einstein radius** $\theta_e = 4\pi(\sigma_{sis}/c)^2 D_{ls}/D_s$
  $= (\sigma_{sis}/186 \text{ km s})^2 D_{ls}/D_s$ arcsec
- where, σ_{sis} is the velocity dispersion of a simple isothermal potential D_{ls} is the distance from lens to source and D_s is the distance from observer to source



3 most common lensed images quad, Einstein ring, a double

Gravitational Lensing Elliptical Galaxies- see Strong Lensing by Galaxies ARAA 2010 T. Treu and sec 6.6 in MBW

For a **point mass** the Einstein radius is
$\theta_E=[(4GM/c^2)\ D_{LS}/D_L D_S]^{1/2}$

- Gravitational lensing, can measure the mass profiles of early-type galaxies, both in the nearby universe and at cosmological distances (Treu & Koopmans 2002a,b)
  - Model the total (dark matter + stars) mass profile as a spherical power law $\rho(r) \sim \rho(0)\ r^{-\gamma}$
  - $\gamma=2$ is SIS
- Need:
  - the Einstein radius of the lens,
  - the redshift of both the deflector galaxy and the lensed source,
  - and the velocity dispersion of the lens.

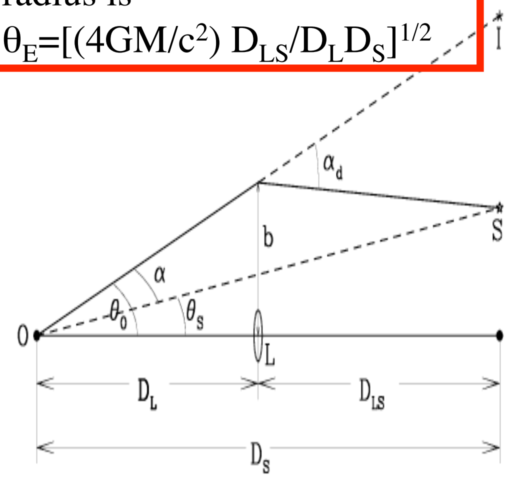
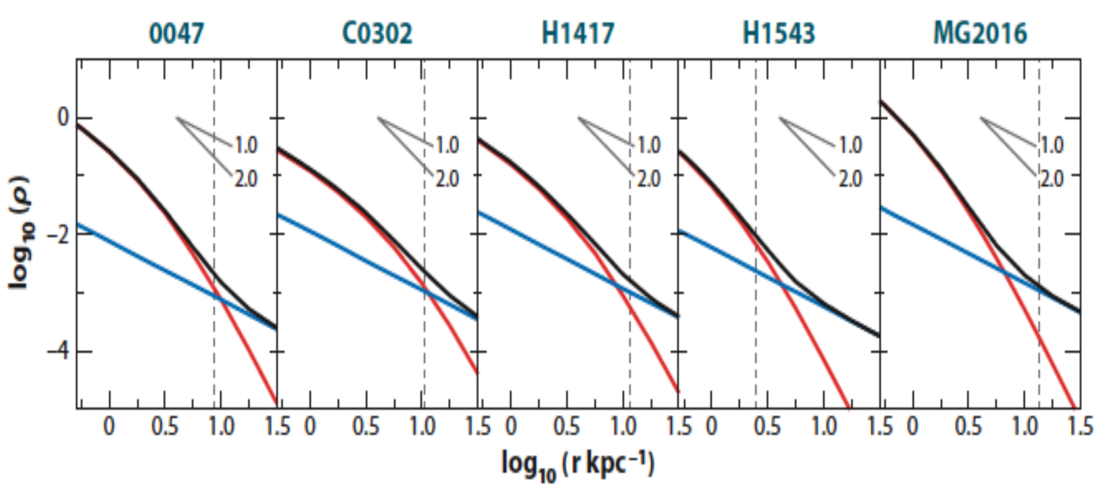


FIG 6.6 IN MBW

Mass Profiles From Lensing + Photometry

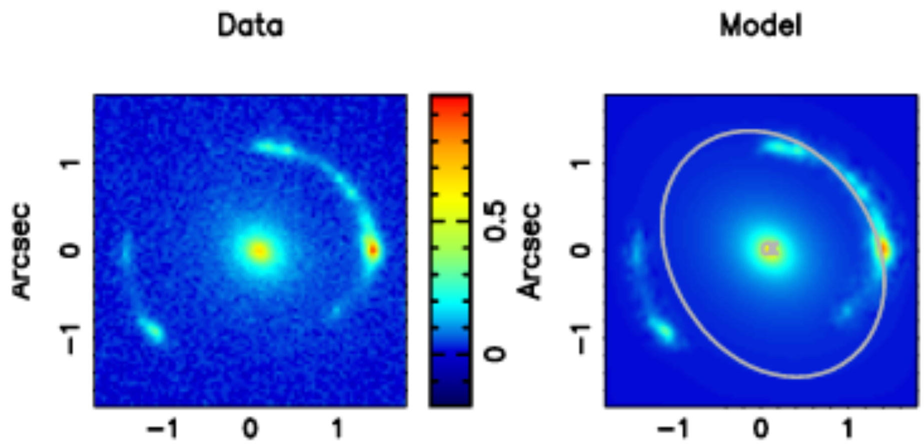
- Blue is <u>mass density</u> of dark matter, red that of stars for 4 galaxies (Treu 2010) as a function of radius (vertical line is Einstein radius)
- **Dark dominates in all of these at large radii**
- But *inner regions are dominated by stellar mass*
- *The average slope is 2, consistent with SIS*



blue is dark matter, **red** is stars, **black** is total

Modeling The Images

- Put in shape of the potential, offset of systems observed surface brightness distribution (Parameterized as an elliptical Sérsic profile)
- gravitational lensing conserves surface brightness



Mergers

- The surface brightness profiles are a hint to the formation process
- hierarchical clustering implies that different galaxies are the products of different merger histories in which different progenitor morphologies and encounter geometries produced a variety of results.
- It is remarkable that the remnants of such varied mergers shows so much regularity (Kormendy 2009)

There are several simple types of mergers

- wet (lots of cold gas)- e.g. spiral x spiral
- dry (little cold gas)- elliptical x elliptical
- wide range of mass (dwarf into normal)

Seems likely that both dissipational collapse and mergers are likely involved in the formation of elliptical galaxies

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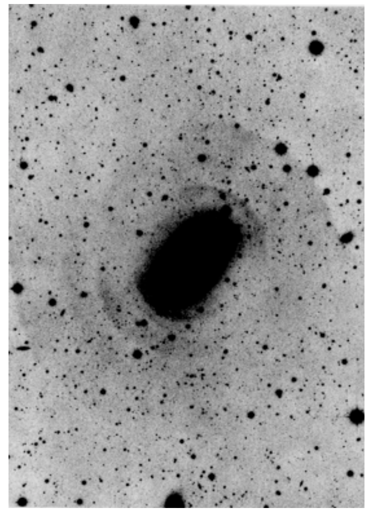
Deviations from Sersic

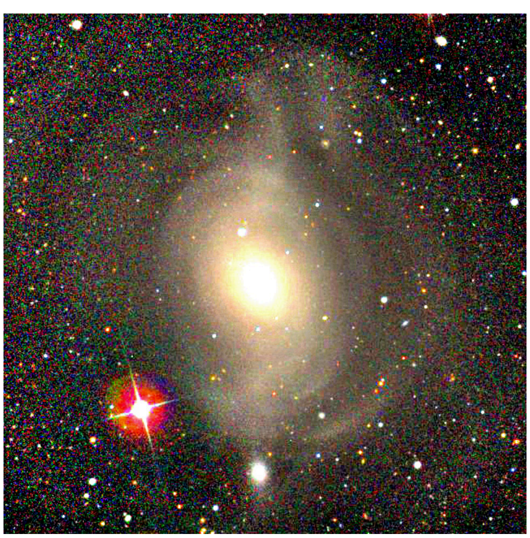
- ~10-20% of ellipticals show 'ripples'- indicative of a merger (MBW ***13.3.5 Merging Signatures)***



But such fine structures form only when the merger involves at least one dynamically cold progenitor (disk or dwarf galaxy);
mergers between two dynamically hot systems (i.e. between two ellipticals) do not produce shells and ripples, because the intrinsic velocity dispersion is too high

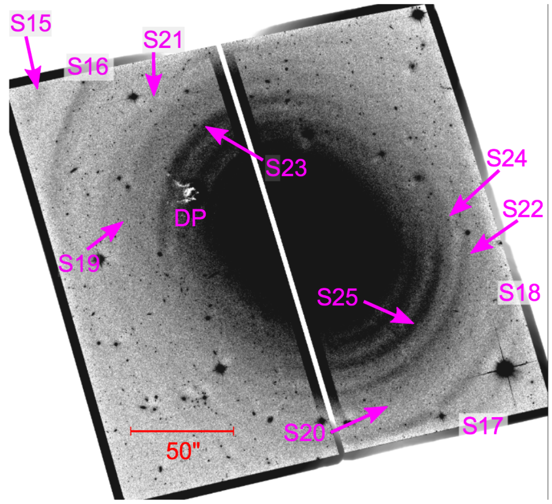
Shells

- The incidence of mergers inferred from shells- they come from the merger of a small with a big galaxy



Shell Formation

- Schweiver (1983) –small galaxy colliding with larger one
- Small galaxy completely tidally disassociated the stars from that galaxy oscillate independently in the potential well of the new system (dominated by the elliptical) on more or less radial orbits
- They spend most of their time at the apocenters- the shells
- The wrapping in phase space (stars with smaller periods have more oscillations) give the multiple shells (Quinn 1984)



NGC3923 Bilek et al 2015

The Big Picture of Elliptical Galaxy Formation

- Hierarchical clustering leads to galaxy mergers that scramble disks and make ellipticals
- Merger progenitors usually contain gas; gravitational torques drive it to the center and feed starbursts
- quasar energy feedback has a major effect on the formation of bright ellipticals
  - This helps to explain why supermassive BHs correlate with bulges but not disks
- bulges and ellipticals are made in mergers, but disks are not.
- spheroids are thought to be formed via gas-poor mergers that efficiently transfer angular momentum
- But correctly reproducing the structural scaling relations and their evolution for both disks and spheroids, as well as the correct overall evolution of the number densities of these two populations, remains an open challenge.

What are the Differences

i) Monolithic Dissipative Collapse

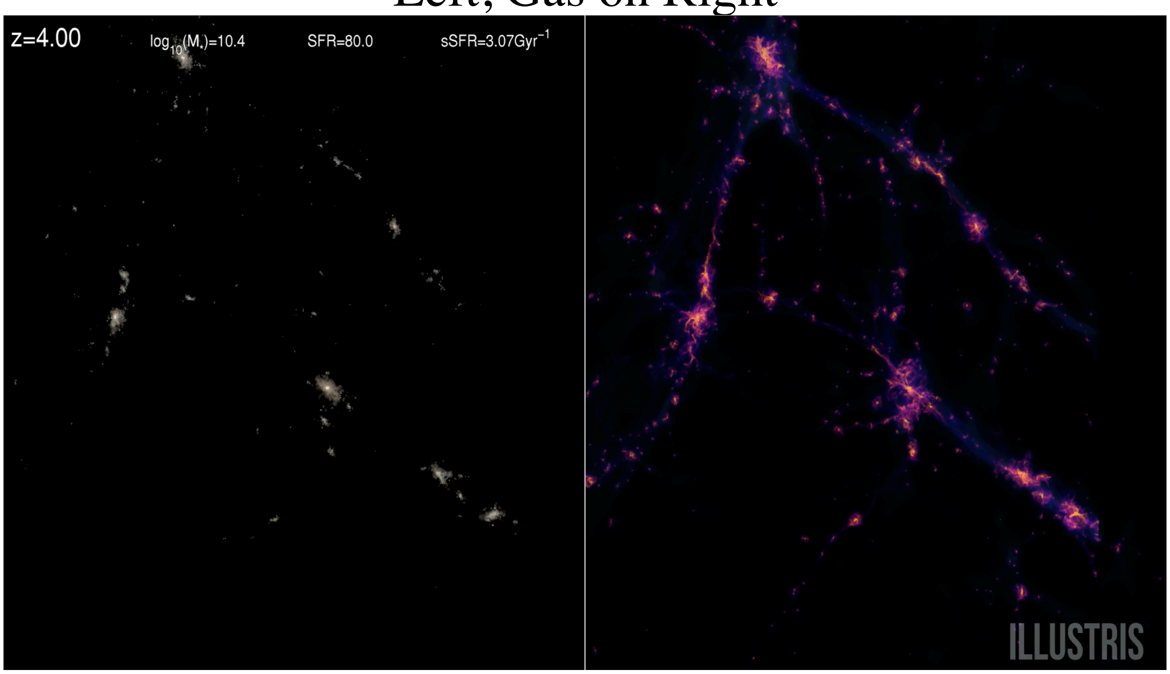
- Early massive gas cloud undergoes dissipative collapse
  - Huge starburst during collapse
    - Very luminous high redshift objects detected with high SFR.
  - Clumpiness during collapse
    - violent relaxation

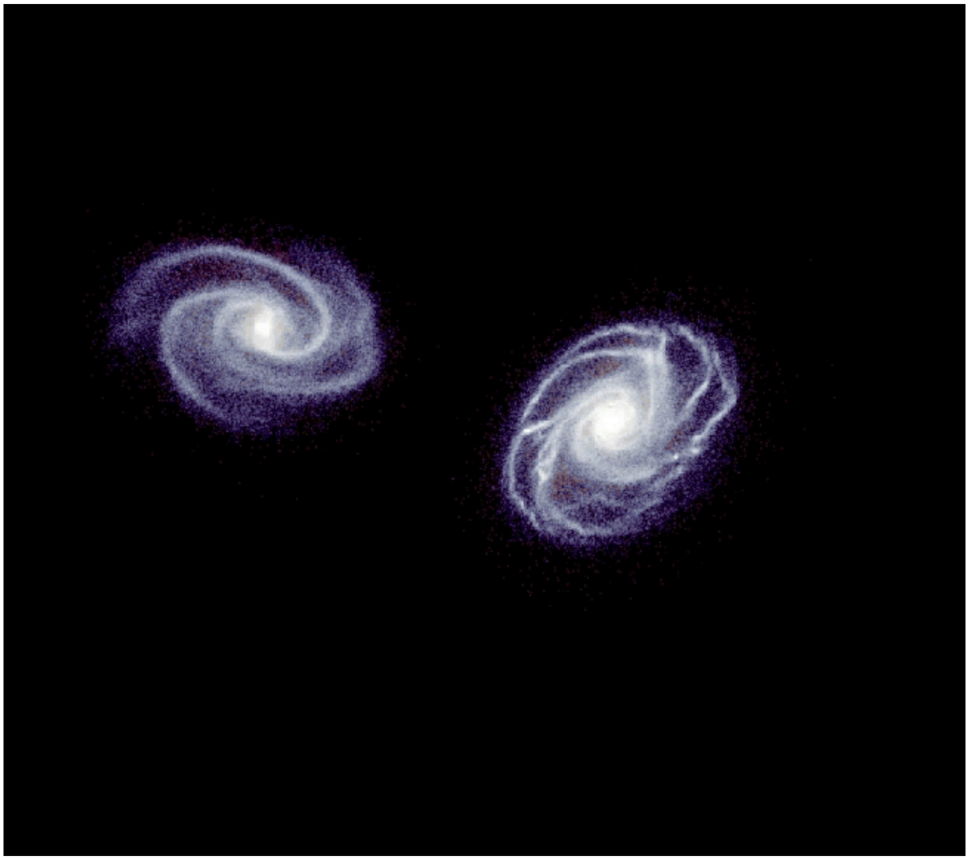
(ii) Hierarchical Mergers

- Early universe much denser: e.g. z ~ 2 density ~ 27 times higher than today.
- Mergers/interactions probably common.
- Sequence of galactic mergers, starting with pre-galactic substructures
- Galaxies continue to grow during z ~ 1-2
  - old ellipticals at z ~1 already exist
- Galaxies fall into clusters and merging ceases (encounter velocities too high)

- Both process seem to be necessary varying from object to object over cosmic time

Formation of an Elliptical- Stellar Light on Left, Gas on Right





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End of Ellipticals