Key points on Elliptical galaxies

• Largest (most massive) galaxies in universe are E’s

• Among the Oldest galaxies in universe
  most of their stars formed early in universe;
  the galaxy may have grown or changed since early universe

• Appear simple but are complex
an Elliptical Galaxy
Properties characterizing E’s

- Little or no star formation
- Little or no dust or cold gas
- Little or no stellar substructure within galaxy
- Isophote shapes nearly elliptical

BUT! Great diversity and complexity in E’s!
Elliptical galaxies
Properties characterizing E’s

- Little or no star formation
- Little or no dust or cold gas
- Little or no substructure within galaxy
- Isophote shapes nearly elliptical

*is this enough to specify that a galaxy is an elliptical?*
Elliptical M32

Dwarf “elliptical” NGC 205
Elliptical M32
Compact, high central stellar density of stars
Little or no gas & star formation

Dwarf “elliptical” NGC 205
Not compact, low central surface density of stars
Little or no gas & star formation
Surface brightness vs. luminosity for various stellar systems

NGC 205 (dwarf elliptical) and M32 (elliptical) are different types of galaxies, even though they have similar mass & no ongoing star formation. E’s are much more compact than dE’s.
Radial light profiles of disks vs. E’s + bulges

Compared to an exponential (n=1) distribution, an n=4 distribution has more stars at small & large radii, and fewer at intermediate radii.
Functions fit to Galaxy Radial light profiles

**Exponential disk:** \( I(r) = I(0) \exp\left(\frac{-r}{r_d}\right) \)

**deVaucouleurs \( r^{1/4} \) bulge law:** \( I(r) = I(r_{\text{eff}}) \exp\left\{ -7.67\left[ \left( \frac{r}{r_{\text{eff}}} \right)^{1/4} - 1 \right] \right\} \)

**Sersic law:** \( I(r) = I(r_{\text{eff}}) \exp\left\{ -b_n\left[ \left( \frac{r}{r_{\text{eff}}} \right)^{1/n} - 1 \right] \right\} \)

- \( n = \) Sersic index
- \( b_n = 1.999n - 0.327 \) for \( n > 1 \)
- \( n = 1-4 \) typically

If \( n=1 \) exponential (all disk) \textit{disks of spirals, S0s, dwarf Es}

If \( n=4 \) deVaucouleurs \( r/4 \) law (all bulge) \textit{giant E’s, globular clusters}

1<\( n<4 \) \textit{bulges of spirals and S0s} (higher \( n \) for large L bulges)

If \( n<2 \) for entire spiral or S0: small bulge-disk ratio

If \( n>2 \) for entire spiral or S0: large bulge-disk ratio

**Advantage of Sersic law:** \textit{can describe entire profile shape with just 1 number \( n \)}
Dwarf irregular (SMC)

Dwarf “elliptical” NGC 205
Dwarf irregular (SMC)
Not compact, low central surface density of stars
Lots of gas & star formation

Dwarf “elliptical” NGC 205
Not compact, low central surface density of stars
Little or no gas & star formation
NGC 205 (dwarf elliptical) and SMC (dwarf irregular) have similar stellar masses and similar stellar distributions, but differ in their gas content and amount of ongoing star formation (dIs have them, dEs have none).
Properties characterizing E’s

• Little or no star formation
• Little or no dust or cold gas
• Little or no substructure within galaxy
• Isophote shapes nearly elliptical

If you use just these properties, you include both “real ellipticals” as well as dwarf galaxies that are not true ellipticals
Properties characterizing (real) E’s

• Little or no star formation
• Little or no dust or cold gas
• Little or no substructure within galaxy
• Isophote shapes nearly elliptical
• Radial light distribution: \( n \approx 4 \)
Elliptical galaxies

• **Real ellipticals:**
  Giant E or E cD \( L >> L^* \) (\( L \sim 2-10L^* \))
  luminous \( L \sim L^* \) (\( L \sim 0.5-2L^* \))
  midsized \( L < L^* \) (\( L \sim 0.1-0.5L^* \))

  Luminous and mid-sized E’s have different properties on average but there is overlap and no clear division between them.

• **Not real ellipticals:**
  “Dwarf E” \( dE \) \( L < 0.1L^* \)
  \( dSph \) \( L < 0.001L^* \)

  Dwarf E’s are clearly distinct from giant E’s.
  *Their stellar distributions resemble disk galaxies, and they are not true ellipticals.* Better name: early type dwarfs.

\[ L^* = 2 \times 10^{10} \, L_{\odot} \approx L_{\text{MW}} = \text{“knee” (break) in galaxy luminosity function} \]
The cD-type is a classification in the Yerkes galaxy classification scheme, one of two Yerkes classifications still in common use, along with D-type. The "c" in "cD" refers to the fact that the galaxies are very large, hence the adjective supergiant, while the "D" refers to the fact that the galaxies appear diffuse. A backformation of "cD" is frequently used to indicate "central Dominant galaxy". cDs are also frequently considered the largest galaxies.
Functions fit to Galaxy Radial light profiles

**Exponential disk:** \[ I(r) = I(0) \exp \left( -\frac{r}{r_d} \right) \]

**devVaucouleurs r^{1/4} bulge law:** \[ I(r) = I(r_{\text{eff}}) \exp \left\{ -7.67 \left( \frac{r}{r_{\text{eff}}} \right)^{1/4} - 1 \right\} \]

**Sersic law:** \[ I(r) = I(r_{\text{eff}}) \exp \left\{ -b_n \left( \frac{r}{r_{\text{eff}}} \right)^{1/n} - 1 \right\} \]

\( n = \text{Sersic index} \)
\( b_n \) chosen to make \( r_{\text{eff}} \) the effective radius (encloses \( \frac{1}{2} \) the light)

\( b_n = 1.999n - 0.327 \) for \( n > 1 \)

\( n = 1-4 \) typically

**If** \( n = 1 \) **exponential (all disk)** disks of spirals, S0s, dwarf Es

**If** \( n = 4 \) **devVaucouleurs r/4 law (all bulge)** giant E’s, globular clusters

\( 1 < n < 4 \) **bulges of spirals and S0s** (higher \( n \) for large L bulges)

**If** \( n < 2 \) for entire spiral or S0: small bulge-disk ratio

**If** \( n > 2 \) for entire spiral or S0: large bulge-disk ratio

**Advantage of Sersic law:** *can describe entire profile shape with just 1 number* \( n \)
How is a n=4 distribution made?
Both Elliptical galaxies and star clusters have n=4 distributions

• Merger rearranges the stars in a n=1 disk
• Energy range of stars increased in merger:
  * some lose energy, fall toward center
  * some gain energy, driven outwards
Merger simulation of Equal-mass spirals

elapsed time ~ 1 Billion years

Steinmetz
Merger remnant NGC 7252

(ESO La Silla)
Merger remnant NGC 7252 (Schweizer 1981)

Merger simulation -- 2 equal mass disks (Hernquist 1992)

Images of NGC 7252 at different depths (Schweizer 1981)

Radial light profile resembles $r^{1/4}$ law in both merger remnant and simulations

Hernquist 1992
how orbital energies of stars change during merger

before merger, stars in disk galaxy have narrow range of orbital energies

after merger, stars have much broader range of energies – some have lost energy & some have gained energy

Figure 4-20. The evolution of the differential energy distribution of the model shown in Figure 4-19. The corresponding times are: \( t = 0 \) (dashed and then dash-dot curve); after one initial free-fall time (dotted and then dash-dot curve); after violent relaxation has ceased (full curve). Energy is measured in units of \( GM/R_e \), where \( M \) is the system’s mass and \( R_e \) is the effective radius of the \( R^{1/4} \) model that best fits the final configuration (see Figure 4-22). (After van Albada 1982.)

Binney & Tremaine 2008
How is a n=4 distribution made?
Both Elliptical galaxies and star clusters have n≈4 distributions

• Merger rearranges the stars in a n=1 disk
• Energy range of stars increased in merger:
  *some lose energy, fall toward center*
  *some gain energy, driven outwards*
• Process which acts to redistribute energies of stellar orbits in galaxy mergers:
  *violent relaxation* – orbits changed by changing large-scale gravitational potential
How is a n=4 distribution made?

Both Elliptical galaxies and star clusters have n=4 distributions

- Merger rearranges the stars in a n=1 disk
- Energy range of stars increased in merger:
  
  *some lose energy, fall toward center*
  
  *some gain energy, driven outwards*

- Process which acts to redistribute energies of stellar orbits in galaxy mergers:
  
  *violent relaxation* – orbits changed by changing large-scale gravitational potential

- Process which acts to redistribute energies of stellar orbits in star clusters:
  
  *2-body relaxation* – orbits changed by star-star gravitational interactions
Ellipticals: exceptions to $r^{1/4}$ law

1. Outer galaxy ($r>\text{many kpc}$)
   - cDs: fit by $n\sim4$ over most of galaxy but extra light at large $r$ (remains of accreted galaxies?)
   - mid-sized/luminous Es – some have less light at large $r$ than $r^{1/4}$ – could be tidal truncation but not clear

2. Inner galaxy ($r<\sim100$ pc) “cores” and “cusps”

3. Nuclei ($r<\text{few pc}$) there are compact nuclear star clusters in some galaxies, and extra light component
some cD galaxies (giant ellipticals in cluster centers) have extra stellar halo at large radii

cDs: formed or modified by dynamical processes in clusters.
In a rich cluster, the outer envelopes of galaxies will be stripped by tidal effects during galaxy collisions. cDs are (partly) built from the debris of these collisions.
centers of ellipticals: cores & cusps

• For Es there is correlation between $L_{\text{tot}}$ and central light distribution

• Largest & brightest Es have lower central SBs and larger $R_{\text{core}}$ (this is unlike spirals where there is a weaker relation between disk CSB and $L$)

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**Core** – flattish SB profile in center, typical for luminous Es

**Cusp** – sharply peaked SB profile in center, typical for mid-sized Es

$R^{1/4}$ distribution at large $R$
Elliptical cores & cusps: reasons for difference

Not well understood, 2 possibilities:

1. Effects of central MBHs on orbits of stars
Gravitational interactions between stars and MBHs drive some stars to larger radii; bigger effect in more massive galaxies which have more massive MBHs

2. Different merger types for different galaxy masses
a. wet (gas-rich) merger leads to greater central concentration of gas which then undergoes star formation, making more cusplike stellar distribution; maybe gas-rich mergers more important in lower mass Es
b. dry (no gas) mergers have no gas which can become centrally concentrated due to dissipation; if only stars in merger, will not become so centrally concentrated since stars are collisionless and can’t so easily lose their orbital energy; maybe dry mergers more important for higher L galaxies
Properties characterizing (real) E’s

• Little or no star formation
• Little or no dust or cold gas
• Little or no substructure within galaxy
• Isophote shapes nearly elliptical
• Radial light distribution: $n \approx 4$
• None highly flattened: minimum $b/a \sim 1/3$
Possible 3D shapes (isodensity surfaces) of ellipticals

- **Prolate spheroid** $a=b<c$
  - Hard to make these?
  - Some E’s like this?

- **Oblate spheroid** $a=b>c$
  - Can be flattened by rotation
  - Some E’s like this

- **Triaxial ellipsoid** $a<b<c$
  - No rotational symmetry
  - Some E’s like this
Triaxial ellipsoids

Triaxial ellipsoid \( a < b < c \)

No rotational symmetry \((\text{shape cannot be caused by rotation})\)

Projected 2D shape not circular from (almost) any angle
Shapes of Ellipticals

A 3D body can be described by set of nested isodensity (light or mass) surfaces. Need to know:

• What is shape of isodensity surface at each radius? Does shape vary with radius?
• Does orientation (principal axes) of shape change with radius?
Shapes of Ellipticals

A 3D body can be described by set of nested isodensity (light or mass) surfaces. Need to know:

• What is shape of isodensity surface at each radius? Does shape vary with radius?
• Does orientation (principal axes) of shape change with radius?

Very hard to know all this for individual galaxy from projected image, but can constrain shapes:

• Through kinematics of individual galaxy
• Through statistics of image shapes for large samples
3D shapes of ellipticals

• Some E’s are probably oblate spheroids (generally lower luminosity & “disky”)

• Many E’s are triaxial ellipsoids (generally higher luminosity & “boxy”)
Evidence for triaxial bodies in some Es

Photometry

A. very few of most luminous Es appear round on sky; inconsistent with them being oblate spheroids.

[but statistics of projected shapes consistent with many mid-sized Es being oblate spheroids]

B. isophotal twisting – a triaxial body with varying shape (a:b:c ratios) with radius will show twisted isophotes when viewed from most directions

[but isophote twisting does not prove triaxiality – can also get it from oblate spheroids whose principle axes change with radius]
using statistics to constrain true 3D shapes

projection effects make shapes look rounder

edge-on more common than face-on, so if galaxies are oblate spheroid, then true axial ratios not too different from apparent ratios
distribution suggests many E’s have intrinsic axial ratio ~0.7-0.8
very few luminous galaxies with q>0.95 suggests many of these galaxies are triaxial rather than oblate
L* galaxies are rounder on average; those more or less luminous are less round
A triaxial galaxy viewed at random angle (not along one of principal axes) will show isophote twists if the triaxial shape (a:b:c ratio) varies with radius, even if the principal axes are constant with radius.
Isophote twisting: in some cases due to tidal interactions?

NGC 205, companion of M31
van den Bergh images in Kormendy (1982)

Orientation of principal axes probably changes with radius. Isodensity surfaces need not be triaxial.

Gravitational torque by other galaxy affects outer galaxy more than inner galaxy.
Evidence for triaxial bodies in some Es

Kinematics

A. Random motions larger than rotational motions (not enough rotation for shapes to be caused by rotational flattening)

B. Kinematic properties of outer and inner parts of E’s often different (e.g., outer part rotates about different axis than inner part)
Do these galaxies have elliptical light distributions?
Properties characterizing (real) E’s

- Little or no star formation
- Little or no dust or cold gas
- Little or no substructure within galaxy
- Isophote shapes *nearly* elliptical

\( many \ have \ small \ but \ important \ deviations \ from \ elliptical \ shapes \)

- Radial light distribution: \( n \approx 4 \)
- None highly flattened: minimum \( b/a \sim 1/3 \)

**BUT!** Great diversity and complexity in E’s!
80% of E’s show deviations from purely elliptical isophotes

Deviations from ellipses can be described by a Fourier series expansion in azimuth

\[ \Delta r(\phi) = a_3 \cos(3\phi) + b_3 \sin(3\phi) + a_4 \cos(4\phi) + b_4 \sin(4\phi) + \ldots \]

\[ x = a \cos \phi \]
\[ y = b \sin \phi \]
\[ r = [x^2 + y^2]^{1/2} \]

- \( a_0 \) term – size of ellipse
- \( a_1 \) term – offset center
- \( a_2 \) term – ellipse of different shape
- \( a_3 \) term – egg-shaped distortion, generally small
- \( \cos(4\phi) \) term generally dominates
Disky & boxy isophotes in Ellipticals

Schematic diagrams of
disky isophotes with $a_4/a=0.1$
and boxy isophotes with $a_4/a=-0.1$

Disky
$a_4 > 0$

Boxy
$a_4 < 0$

Figure 5. — Schematic drawing illustrating isophotes with $a(4)/a = +0.1$ and $a(4)/a = -0.1$.

Figure 6. — R-image of NGC 4660, an elliptical galaxy with a disk-component in the isophotes ($a(4)/a \sim +0.03$).

Figure 7. — R-image of NGC 5322, an elliptical galaxy with box-shaped isophotes ($a(4)/a \sim -0.01$).
Isophotal analysis for disky elliptical

Ellipticity varies with radius, Is largest at r>10” (disky region) Sharp change at r=10”

PA changes a bit especially at r>10” (modest isophote twisting)

Disky isophotes $a_4 > 0.01$ at r>10” Elliptical isophotes at r<10”

Bender et al 1988
Isophotatal analysis for disky elliptical

Ellipticity varies with radius,
Is largest at r>10” (disky region)
Sharp change at r=10”

PA changes a bit
especially at r>10”
(modest isophote twisting)

Disky isophotes $a_4>0.01$ at r>10”
Elliptical isophotes at r<10”

$a_3$ value small at all radii
-> Deviations from ellipses
well described by disky/boxy

Bender etal 1988
Isophotal analysis for boxy elliptical

Ellipticity varies slightly with radius

PA nearly constant with radius (almost no isophote twisting)

Boxy isophotes $a_4/a < -0.01$ at $r > 10''$
Slightly disky isophotes
$a_4/a \sim 0.01$ at $r < 5''$

Bender et al. 1988
Isophotal analysis for boxy elliptical

Ellipticity varies slightly with radius

PA nearly constant with radius (almost no isophote twisting)

Boxy isophotes $a_4/a < -0.01$ at $r > 10''$
Slightly disky isophotes $a_4/a \sim 0.01$ at $r < 5''$

$a_3/a$ value small at all radii
$\rightarrow$ Deviations from ellipses well described by $a_4/a$ (disky/boxy)

Bender et al. 1988
so what are “disky” and “boxy” Es?

• **Disky galaxies:** pointed isophotes indicate presence of weak, highly inclined stellar disks which lie within larger “bulge-like” component (mostly oblate spheroids)

• **Boxy galaxies:** triaxial galaxies have many stars on “box orbits” which have no fixed sense of rotation around center, and which fill a roughly boxed-shape region (mostly triaxial galaxies)
Disky ellipticals

Large bulge with embedded stellar disk. Similar to Sa galaxy M104, but without gas & dust & with less prominent stellar disk.
Boxy Ellipticals

• probably triaxial ellipsoids...
Orbits in triaxial potential (non-rotating)

a.) Loop orbit:
Rotates around center, angular momentum not constant, but falls within some narrow range

b.) Box orbit:
no fixed sense of rotation around center & angular momentum varies greatly, sometimes 0
Can pass through center!

c.) Chaotic orbit
Box orbits in elliptical galaxies

Box-like orbits in triaxial galaxies with figure rotation

Deibel+2011
Disky vs. Boxy Ellipticals

• **Disky galaxies:** pointed isophotes indicate presence of weak, highly inclined stellar disks which lie within larger “bulge-like” component (mostly oblate spheroids)

• **Boxy galaxies:** triaxial galaxies have many stars on “box orbits” which have no fixed sense of rotation around center, and which fill a roughly boxed-shape region (mostly triaxial galaxies)
Modified version of Hubble classification scheme showing disky & boxy ellipticals

disky E’s & S0’s are part of a continuum with varying B/D ratios.
if mass in disk is small compared to mass in bulge, it is hard to see the disk & galaxy will be classified as (disky) elliptical
if mass in disk is significant compared to mass in bulge, it is easy to see the disk & galaxy will be classified as lenticular
boxy E’s are different …