Elliptical Galaxies: Kinematics
• **Midterm exam** next Wednesday Feb 28

• **Next HW** (#6, on E’s) will be due Wed, Mar 7

• **Galaxy talks** – find & look over journal papers. Talk to me for further guidance on topic and references.
Key points on Elliptical galaxies

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

• 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
  kinematics of stars sometimes reveal surprises
spectrum of elliptical
Spectra of main sequence stars

- Cool + red
  low mass star – long-lived

- Warm + yellow

- Hot + blue
  high mass star – short-lived
spectra of main sequence stars

Cool + red

Warm + yellow

Hot + blue

spectrum of elliptical
model spectra of “galaxies” (stellar populations) at different times after burst of star formation

**simple stellar population:** bunch of stars of different masses (with particular IMF), all with same age during burst – lots of gas emission lines (like extreme Spiral)

long after burst – absorption lines from stars, no gas emission lines (like Elliptical)

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time in Gyr after start of burst
Compare the spectra of K giant star & S0 galaxy

2 differences:
1. galaxy spectrum is redshifted wrt MW star (expansion of universe)
2. lines broader in galaxy due to velocity smearing.
The observed profile of a stellar absorption line from a galaxy is generally complex because:

1. The distribution of stellar velocities at any point in a stellar system may be complex. (Stars in galaxies form a collisionless system, so the stars which pass through any point in a galaxy can have very different orbits.) (This is not true for gas, which is collisional, and generally has simpler kinematics)
The observed profile of a stellar absorption line from a galaxy is generally complex because:

2. The observed lines are a *weighted sum* of stars within a cylindrical 3D volume: **all stars along the line-of-sight (z direction) and within the spatial resolution element (x+y directions)**
Within each resolution element extended in x & y directions and at each depth z there are stars on various orbits. Only the LOS (z) component of velocity is observed via doppler shift. 

\[ z \text{ direction} = \text{Line of sight (LOS)} \]
Introduction to kinematics for Ellipticals

Ordered motions:

\[ v: \text{mean velocity } v = v_{\text{rot}} + v_{\text{noncirc}} \]

Disordered motions:

\[ \sigma: \text{velocity dispersion}, \text{measured by linewidth} \]

The ratio \( v/\sigma \) is used to compare the relative importance of ordered and random motions
Introduction to kinematics for Ellipticals

Ideally would like to measure $v$, $\sigma$ at every point in 3D space

$v/\sigma \sim \text{ordered/disordered}$

Observationally $v_{\text{los}}$ and $\sigma_{\text{los}}$ are luminosity-weighted averages over finite volumes and along line-of-sight

$v_{\text{los}}/\sigma_{\text{los}} \sim \text{ordered/disordered+ordered}$

(since averaging over large volume includes some ordered component which varies within volume)
Line-of-sight Velocity Distribution (LOSVD)

Observed spectrum = Spectrum of 1 star

\[ G(\lambda) = S(\lambda) \]

\[ F(\nu_{los}) \]

Velocity dispersion \( \sigma \) -- fit LOSVD with gaussian (even if distribution is not gaussian!)

\[ \mathcal{F}(\nu_{los}) S(\ln \lambda - \nu_{los}/c) \, d\nu_{los}. \]
Line of sight velocity distribution (LOSVD) for spiral disk

-200 km/s  0 km/s  +200 km/s

\[ V_{\text{los}} \]

**Small area of outer spiral disk**

**Simple case**

Fast rotation motion \( V_{\text{los}} = 200 \text{ km/s} \)

Small random motions \( \sigma_{\text{los}} = 20 \text{ km/s} \)

\( V_{\text{los}}/\sigma_{\text{los}} >> 1 \)

\[ \bar{V}_{\text{los}} = \text{mean los velocity} \]

\[ \sigma_{\text{los}} = \text{los velocity dispersion} = \text{FWHM}/2.35 \text{ (if gaussian)} \]
Stellar velocity dispersion in general is *anisotropic* (different in different directions)

\[ \sigma_R, \sigma_\phi, \sigma_z \] for stars need not be equal

this can happens for stars since they are *collisionless*

particles that experience many collisions end up with equal random motions in all directions
random motions of stars in disk of Milky Way is different in different directions!! more random motion in radial direction than azimuthal and vertical directions!

<table>
<thead>
<tr>
<th>Galactic component</th>
<th>$h_z$ or shape</th>
<th>$\sigma_x = \sigma_R$ (km s$^{-1}$)</th>
<th>$\sigma_y = \sigma_\phi$ (km s$^{-1}$)</th>
<th>$\sigma_z$ (km s$^{-1}$)</th>
<th>$\langle v_y \rangle$ (km s$^{-1}$)</th>
<th>Fraction of local stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hi gas near the Sun</td>
<td>130 pc</td>
<td>\approx 5</td>
<td>\approx 7</td>
<td></td>
<td>Tiny</td>
<td>Tiny</td>
</tr>
<tr>
<td>Local CO, H$_2$ gas</td>
<td>65 pc</td>
<td></td>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thin disk: $Z &gt; Z_\odot/4$</td>
<td>(Figure 2.9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>$\tau &lt; 3$ Gyr</td>
<td>\approx 280 pc</td>
<td>27</td>
<td>17</td>
<td>13</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>$3 &lt; \tau &lt; 6$ Gyr</td>
<td>\approx 300 pc</td>
<td>32</td>
<td>23</td>
<td>19</td>
<td>-12</td>
<td></td>
</tr>
<tr>
<td>$6 &lt; \tau &lt; 10$ Gyr</td>
<td>\approx 350 pc</td>
<td>42</td>
<td>24</td>
<td>21</td>
<td>-19</td>
<td></td>
</tr>
<tr>
<td>$\tau &gt; 10$ Gyr</td>
<td></td>
<td>45</td>
<td>28</td>
<td>23</td>
<td>-30</td>
<td></td>
</tr>
<tr>
<td>Thick disk</td>
<td>0.75–1 kpc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5%–15%</td>
</tr>
<tr>
<td>$\tau &gt; 7$ Gyr, $Z &lt; Z_\odot/4$</td>
<td>(Figure 2.9)</td>
<td>68</td>
<td>40</td>
<td>32</td>
<td>-32</td>
<td></td>
</tr>
<tr>
<td>$0.2 \lesssim Z/Z_\odot \lesssim 0.6$</td>
<td></td>
<td>63</td>
<td>39</td>
<td>39</td>
<td>-51</td>
<td></td>
</tr>
<tr>
<td>Halo stars near Sun</td>
<td>$b/a \approx 0.5$–0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>\sim 0.1%</td>
</tr>
<tr>
<td>$Z \lesssim Z_\odot/50$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halo at $R \sim 25$ kpc</td>
<td>Round</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>-215</td>
<td></td>
</tr>
</tbody>
</table>
Stellar velocity dispersion in general is anisotropic

\( \sigma_R, \sigma_\phi, \sigma_z \) need not be equal

\( \sigma_{\text{los}} \) depends on \( \sigma_R : \sigma_\phi : \sigma_z \) (ratios) and which components happen to be along l-o-s

Simplest case: isotropic velocity dispersion

\( \sigma_R = \sigma_\phi = \sigma_z = \sigma_{\text{los}} \)

(\( \sigma_{\text{los}} \) doesn’t depend on viewing angle)
LOSVD for elliptical

Small area of elliptical
Simple case
slow rotation motion $V_{\text{los}} \sim 20 \text{ km/s}$
large random motions $\sigma_{\text{los}} \sim 100 \text{ km/s}$
$V_{\text{los}} / \sigma_{\text{los}} << 1$

$V_{\text{los}} = $ mean los velocity
$\sigma_{\text{los}} = $ los velocity dispersion = FWHM/2.35 (if gaussian)
Complex case of LOSVD

-200 km/s

0 km/s

+200 km/s

$V_{\text{los}}$

Few stars with large counter-rotational motions and small random motions (accreted small galaxy?)

0 km/s

FWHM

Main component of line profile not symmetric not gaussian but $V_{\text{los}} < \sigma_{\text{los}}$

For most stars random motions dominate

Few stars with large rotational motions and small random motions (disk component?)
Are Ellipticals Oblate Spheroids whose shape is governed by rotation?
Are Ellipticals Oblate Spheroids whose shape is governed by rotation?

Open circles: mid-sized E’s (lower luminosity, $M_B > 19.5$

Filled circles: luminous ($M_B < 19.5$) E’s

Dotted line: oblate spheroid flattened by rotation (O.S.F.B.R.)

Projection effects: both $V_{\text{los}}$ and $\epsilon$ vary by appx $\sin(i)$ for inclined system

**observed** (apparent) ellipticity

**observed** $v_{\text{los}}(\text{max})/\sigma_{\text{los}}$
E galaxy rotation vs. dispersion $v << \sigma$

$V_{rot} \sim 30 \text{ km/s}$ $\sigma \sim 250 \text{ km/s} \rightarrow v/\sigma \sim 0.1$ is low!! Most motion in random directions!

$v$ and $\sigma \sim$ constant over much of galaxy, although is $\sim 50\%$ higher in center

$->$ often reasonable to characterize E galaxy with single value of $v$ and $\sigma$
Are Ellipticals Oblate Spheroids whose shape is governed by rotation?

2 oblate spheroids with same $\sigma$:

- **Small** $v_{rot}$
  - Slightly elliptical, only a bit flattened by small $v_{rot}$

- **Large** $v_{rot}$
  - Highly elliptical, flattened by large $v_{rot}$
Are Ellipticals Oblate Spheroids whose shape is governed by rotation?

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Projection effects: both $V_{\text{los}}$ and $\epsilon$ vary by appx $\sin(i)$ for inclined system

Most mid-sized E’s (& bulges) roughly consistent with O.S.F.B.R.
Many luminous E’s NOT O.S.F.B.R. but must instead be triaxial bodies flattened by anisotropic distribution of random velocities.
Triaxial galaxies: flattened by anisotropic velocity distribution

Random motions dominate ordered motions (e.g. rotation). But random motions can have different amplitudes in different directions (x,y,z).
80% of E’s show deviations from purely elliptical isophotes

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

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

$\cos(4\phi)$ term generally dominates

- $a_0$ term – size of ellipse
- $a_1$ term – offset center
- $a_2$ term – ellipse of different shape
- $a_3$ term – egg-shaped distortion, generally small

**Equation of ellipse:**

$x = a \cos \phi$

$y = b \sin \phi$

$r = [x^2 + y^2]^{1/2}$
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 $(a(4)/a \sim -0.01)$. 
stellar kinematics ($V/\sigma$) vs. Disky-Boxy isophote shapes

Open circles: lower lum E’s ($M_B>19.5$)

Filled circles: luminous E’s ($M_B<19.5$)

$$\frac{V}{\sigma_*} = \frac{v_{\text{max}}/\sigma}{v/\sigma_{\text{iso}}}$$

measured expected for oblate spheroid

Disky E’s have high $V/\sigma$ (more ordered motion)

These galaxies contain significant disks (o.s.f.b.r.) in addition to dynamically hotter component

Most boxy E’s have low $V/\sigma$ (more random motion)

dynamically hot – formed (at least partly) by mergers
\( V/\sigma \) vs. Luminosity (\( \sim \)stellar mass)

Open circles: mid-sized E’s (lower lum., \( M_B > 19.5 \))

Filled circles: luminous (\( M_B < 19.5 \)) E’s

\[
(\frac{v}{\sigma_*}) = \frac{v_{\text{max}}/\sigma}{(v/\sigma_{\text{iso}})}
\]

In low mass E’s rotation important
In many high mass E’s random motions most important
Many high luminosity E’s are triaxial bodies with low $v/\sigma$ and boxy isophotes
- Could form through mergers of gas-poor galaxies (less dissipation during formation) or low angular momentum mergers(?)
Many low luminosity E’s are oblate spheroids with high $v/\sigma$ and disky isophotes
→ Could form through mergers of gas-rich galaxies (since gas settles to a rotating disk before it forms many stars)(more dissipation during formation) or high angular momentum mergers(?)
Disky E’s contain embedded stellar disks, may be part of continuous sequence with SO’s.
Stellar velocity fields of slow & fast rotator ETGs

full velocity fields (from IFUs) give clearer picture of kinematics than single pixel or slit

ETG = “Early Type Galaxies” = E + S0

Maps show central ~40” (SAURON FOV 33”x41”)
Emsellem etal 2011 ATLAS3D
kinematics work better than isophote shapes to separate 2 classes of E’s (depends less on viewing angle)

“fast rotators”
kinematics and shape consistent with oblate spheroids (~86% of nearby ETGs)
ture ellipticities 0.35-0.85

“slow rotators”
kinematics and shape inconsistent with oblate spheroids – so triaxial
(~14% of nearby ETGs)
most massive Es

\[ \lambda_R \equiv \frac{\langle R | V | \rangle}{\langle R \sqrt{V^2 + \sigma^2} \rangle}, \]
Elliptical galaxies

$cD \quad L >> L^* \quad (L \sim 2 - 10 L^*) \quad$ generally triaxial, boxy, slow rotators

luminous $L \sim L^* \quad (L \sim 0.5 - 2 L^*) \quad$ mix

midsized $L < L^* \quad (L \sim 0.1 - 0.5 L^*) \quad$ generally oblate, disky, fast rotators

No sharp cutoffs

$L^* = 2 \times 10^{10} L_{\text{sun}} \approx L_{MW} = \text{“knee” (break) in galaxy luminosity function}$

why? the most massive galaxies have (on average) experienced the most mergers – and mergers of big galaxies without much gas make boxy, triaxial galaxies
Disky (fast rotating) ellipticals are a natural extension of the sequence of galaxies with bulges & disks but little cold gas or star formation. Disky E’s have higher B/D than S0’s. Their “bulges” are rotating.

Boxy (slow rotating) ellipticals are different. No disks. Not much rotation.
Which Elliptical has odd core kinematics?

Franx, Illingworth & Heckman 1989
Which Elliptical has odd core kinematics?

Franx, Illingworth & Heckman 1989
Which Elliptical has odd core kinematics?

In NGC 4406 (M86), the inner and outer galaxy rotate about different axes! They differ by 90 deg.

-> Evidence of merger
Kinematically decoupled cores

- gas driven to center in merger
- settles to disk in plane different from outer galaxy
- undergoes star formation to form central stellar disk
Kinematically decoupled core in elliptical NGC 4365

- Inner 7” rotates orthogonally to main body of galaxy
- Inner 4” disky, outer part boxy
- Inner part $v/\sigma = 1.3$ (disklike)
- 2% of total mass in central decoupled disk
- Shallow central cusp
- Overall galaxy is triaxial
- No shells or other morphological peculiarities
- No sign of dust
- Age of stellar population is $\sim 14$ Gyr in both decoupled disk and main body
- Formed through old merger(s)

Davies et al. 2001

NGC 4365 SDSS image
Kinematically Decoupled Cores in ~30% of E’s

**Abrupt change >20 deg in kinematic PA**

- Exist in large fraction of slow rotator E’s (more luminous, boxy, triaxial), and in smaller fraction of fast rotator E’s (less luminous, disky, oblate)

- Most are in slow rotator E’s – their KDCs are the largest (kiloparsec-scale KDCs) and oldest (older than 8 Gyr)

- A few fast rotator E’s have KDCs which are more compact (less than a few hundred parsec), and younger (a range of stellar ages from 0.5 to 15 Gyr with 5/6 younger than 5 Gyr). Most are counter-rotating (McDermid+2006).

Krajnovic etal 2008
Rotating both ways at once!

the amazing galaxy NGC 4550

- Image looks featureless
  no dust and no ongoing star formation –
  an Elliptical E7
  (flattest known E)

- But ... the motions of the stars reveal bizarre behavior
Measuring Spectra in NGC 4550

- WIYN Sparsepak fiber array spectrograph
- Obtain a spectrum at each of 90 positions
- Measure motions of stars from the Doppler shifts of their spectral lines

Fiber positions on image of NGC 4550
Spectra showing motions of stars in NGC 4550

Each spectral line shows the motions of stars, via the doppler shift.

Lines show 2 peaks – one bunch of stars rotating toward us (blueshifted), the other bunch of stars rotating away from us (redshifted).
normal galaxy

![Graph showing velocity distribution for a normal galaxy.]

galaxy with counterrotating stars

![Graph showing velocity distribution for a galaxy with counterrotating stars.]

WIYN
How did NGC 4550 form?

**best guess:**

- Merger of very gas-rich galaxy with pre-existing stellar disk

- Counterrotating gas settles to plane of rotating stellar disk

- Gas undergoes star formation once it settles to disk plane, forming a counterrotating stellar disk!

*galaxies with very extended counterrotating stellar disks are rare*
Evidence for accretion & mergers in E’s

- Disturbed dust & gas
- Shells & ripples & outer tidal features in stellar distributions
- Kinematically distinct cores
- Major merger remnants resemble E’s

Large fraction (>50%) of E’s show evidence for merger/accretion more in boxy than disky, but also many disky
→ E’s continue to increase their mass with age