Formation of Disk Galaxies (Part 1)

February 9

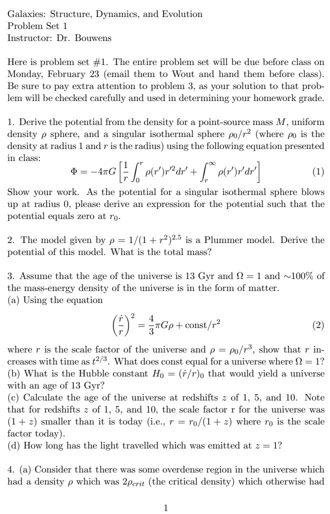
Layout of the Course

Lectures

Feb 2: Course Introduction, Overview, and Galaxy Formation Basics
$\boxed{\text{Feb 9: Disk Galaxies (I)}}$
Feb 12: Disk Galaxies (II)
Feb 16: Disk Galaxies (III) / Collisionless Stellar Dynamics
Feb 23: Collisionless Stellar Dynamics + Vlasov/Jeans Equations
Feb 26: Vlasov/Jeans Equations / Elliptical Galaxies (I)
Mar 9: Elliptical Galaxies (II)
Mar 23: Elliptical Galaxies (III)
Mar 30: Dark Matter Halos
Apr 13: Large Scale Structure
Apr 20: Galaxy Stellar Populations
Apr 23: Lessons from Large Galaxy Samples at z<0.2
May 4: Evolution of Galaxies with Redshift
May 11: Galaxy Evolution at z>1.5 / Review for Final Exam

Problem Set 1

(Distributed last week, due on Feb 23)



Galaxies: Structure, Dynamics, and Evolution
Problem Set 1
Instructor: Dr. Bouwens

Here is problem set #1. The entire problem set will be due before class on Monday, February 23 (email them to Wout and hand them before class). Be sure to pay extra attention to problem 3, as your solution to that problem will be checked carefully and used in determining your homework grade.

1. Derive the potential from the density for a point-source mass M, uniform density ρ sphere, and a singular isothermal sphere ρ_0/r^2 (where ρ_0 is the density at radius 1 and r is the radius) using the following equation presented in class:

$$\Phi = -4\pi G \left[\frac{1}{r} \int_0^r \rho(r') r'^2 dr' + \int_r^\infty \rho(r') r' dr' \right] \quad (1)$$

Show your work. As the potential for a singular isothermal sphere blows up at radius 0, please derive an expression for the potential such that the potential equals zero at r_0.

2. The model given by $\rho = 1/(1+r^2)^{2.5}$ is a Plummer model. Derive the potential of this model. What is the total mass?

3. Assume that the age of the universe is 13 Gyr and $\Omega = 1$ and ~100% of the mass-energy density of the universe is in the form of matter.
(a) Using the equation

$$\left(\frac{\dot{r}}{r}\right)^2 = \frac{4}{3}\pi G\rho + \text{const}/r^2 \quad (2)$$

where r is the scale factor of the universe and $\rho = \rho_0/r^3$, show that r increases with time as $t^{2/3}$. What does const equal for a universe where $\Omega = 1$?
(b) What is the Hubble constant $H_0 = (\dot{r}/r)_0$ that would yield a universe with an age of 13 Gyr?
(c) Calculate the age of the universe at redshifts z of 1, 5, and 10. Note that for redshifts z of 1, 5, and 10, the scale factor r for the universe was $(1+z)$ smaller than it is today (i.e., $r = r_0/(1+z)$ where r_0 is the scale factor today).
(d) How long has the light travelled which was emitted at $z = 1$?

4. (a) Consider that there was some overdense region in the universe which had a density ρ which was $2\rho_{crit}$ (the critical density) which otherwise had

1

Problem Set 1

(Distributed last week, due on Feb 23)

Practical Sessions

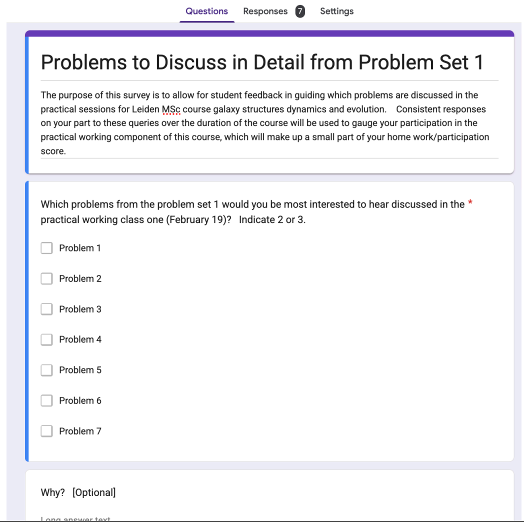
Opportunity to discuss hardest problems in working session on February 19

Feb 19: Board Work + Problem Set 1
Mar 12: Board Work + Problem Set 2
Mar 26: Problem Set 3 / Paper Presentations (4 slots)
Apr 2: Paper Presentations (7 slots)
Apr 16: Problem Set 4 / Paper Presentations (4 slots)
Apr 30: Problem Set 5 / Paper Presentations (4 slots)
May 7: Problem Set 6 / Paper Presentations (4 slots)

Problem Set 1

(Distributed last week, due on Feb 23)

Requested Feedback on Problems to Discuss in Class Here:



Homework Grade — What goes into It?

50% —> Graded Problem Sets (~6)
(Only One Problem from Each Set Graded)

30% —> Oral Presentation of a Solution During Practical Class

20% —> Attendance / Participation in Practical Classes
100% Score, if attend 71% of Classes
80% Score, if attend 57% of Classes
60% Score, if attend 43% of Classes
30% Score, if attend 29% of Classes

If you provide consistent feedback on problems to discuss in class, credit for 1 additional class attended.

Problem Set 1

(Distributed last week, due on Feb 23)

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Will be asking two groups of 3-4 people to present solutions to two problems from problem set 1 on February 19

I will contact 3-4 of you by tomorrow. Are there people who want to volunteer? If not, I will randomly pick names.

Don't worry, if you have questions you can contact Wout or myself to help in solving the problems.

Teaching Assistant

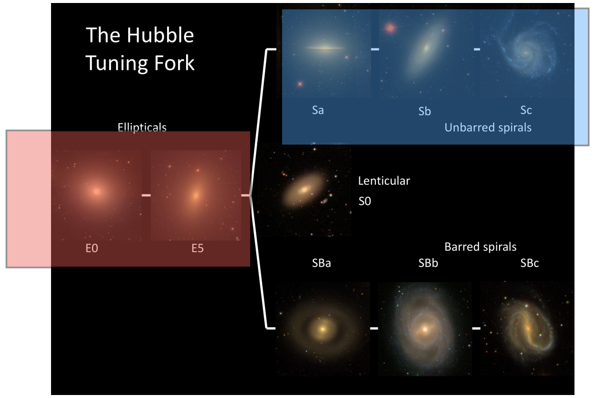
Wout Goesart
BW.3.21
goesaert@strw.leidenuniv.nl

Wout will be holding office hours on
Tuesday: 11:00-12:00
Friday: 10:30-11:30

Wout will also be available by appointment to answer your questions.

Review of Material from Last Week

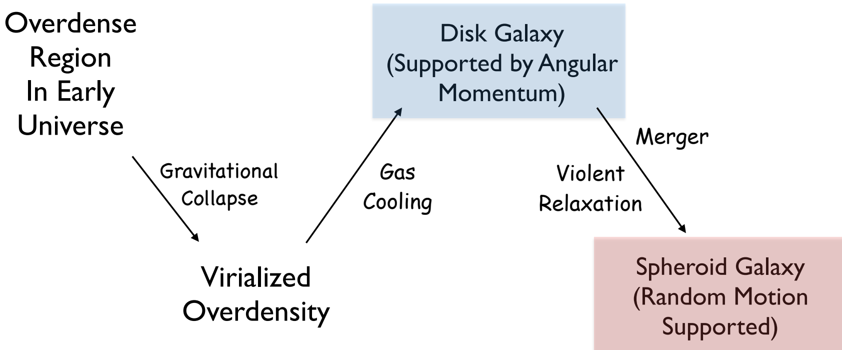
Galaxies have many different morphologies



Not surprisingly, these different morphologies reflect different formation mechanisms.

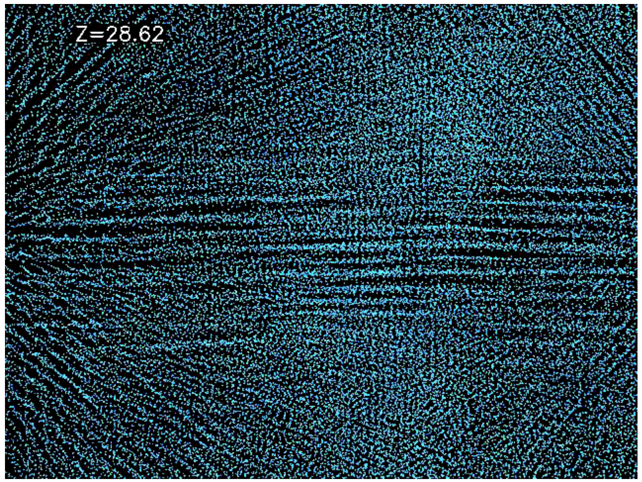
In this course, we will focus on many of these mechanisms, as we aim to understand galaxy formation and evolution.

Galaxy Formation: Major Steps



FIRST STEP: Gravitational Collapse

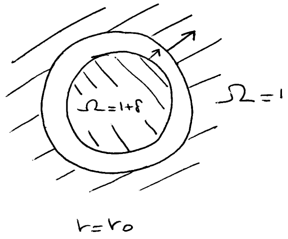
Galaxy formation is driven by the impact of gravity in forming collapsed, virtualized halos, consistently primarily of dark matter.



REVIEW: How do disk galaxies form?

FIRST STEP: Gravitational Collapse

Assume you have a spherically symmetric region of the universe where has an average density which is higher than the critical density.



$\delta = \rho/\rho_c - 1$

δ = Overdensity relative to critical...

$\rho_c = 3((dR/dt)/R)^2 / (8\pi G)$

The acceleration the outer shell of this spherical region will feel can be described by the following equation:

$$\ddot{r} = -\frac{GM(<r)}{r^2}$$

where M is the mass and r is the radius of the sphere

REVIEW: How do disk galaxies form?

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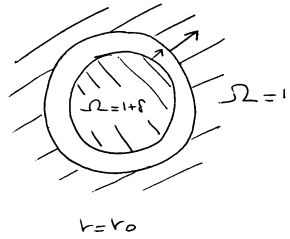


$\delta = \rho/\rho_c - 1$

δ = Overdensity relative to critical...

$\rho_c = 3((dR/dt)/R)^2 / (8\pi G)$

When used for cosmology

$\rho_c = 3H^2 / (8\pi G)$

$R/R(t=0) = 1/(1+z)$

H = Hubble constant

z = Redshift

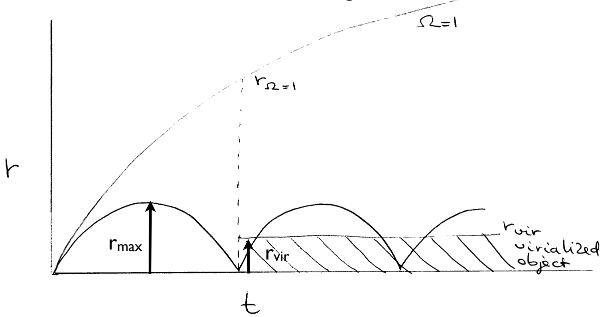
The acceleration the outer shell of this spherical region will feel can be described by the following equation:

$$\ddot{r} = -\frac{GM(<r)}{r^2}$$

where M is the mass and r is the radius of the sphere

If you trace the evolution of the radius of this spherically symmetric region, it will initially continue expansion, stop, and then turn around.

The radius of the spherically symmetric region will evolve as shown in the diagram to the lower left:



By solving the differential equation presented in last class, it can be shown that r_{max} and r_{vir} are as given below

$$r_{max} = \frac{1}{\frac{1}{4}(12\pi)^{2/3}} r_{\Omega=1}(t_{collapse}) \quad (\approx 0.36 r_{\Omega=1}(t_{collapse}))$$

$$r_{vir} = \frac{1}{\frac{1}{2}(12\pi)^{2/3}} r_{\Omega=1}$$

$$\frac{\rho_{vir}}{\rho(universe)(z = z_{vir})} = (r_{\Omega=1}/r_{vir})^3$$

$$= (1/2(12\pi)^{2/3})^3 = 18\pi^2 = 178$$

SECOND STEP: Gas cooling

The second essential step in the formation of galaxies is the need for baryons to be able to cool to the center of the collapsed halo.

During the initial gravitational collapse of an overdensity, we would expect the baryons to be distributed in a very similar way to the dark matter.

Both matter distributions are supported by the random motions of the particles.

However, in favorable conditions, baryons sink to the center of the gravitational potential, but dark matter remains where it is.

Baryonic gas particles can lose energy through radiative processes, but dark matter cannot.

The cooling rate can be expressed as

$$\text{cooling rate} = n^2\Lambda(T)$$

where n is the gas volume density and Λ(T) is the temperature dependent cooling rate.

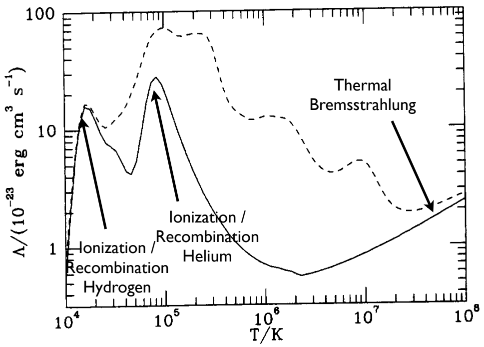


Figure 24.19 The cooling function $\Lambda(T)$. The solid line corresponds to a gas mixture of 90% hydrogen and 10% helium, by number. The dashed line is for solar abundances. (Figure from Binney and Tremaine, *Galactic Dynamics*, Princeton University Press, Princeton, NJ, 1987.)

SECOND STEP: Gas cooling

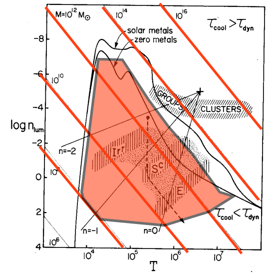
There are two time scales of interest in thinking about galaxy formation:

(1) dynamical time scale t_{dyn} ($\propto n^{-1/2}$)

(2) cooling time scale t_{cool}

For cooling to have any impact, $t_{cool} << t_{dyn}$

How do these time scales compare for various mass halos?



constant mass lines

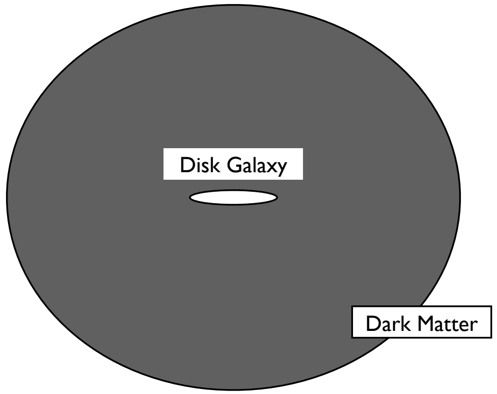
FIG. 1. Ostriker-Rees cooling diagram showing the actual locations of present-day galaxies and clusters. Data on galaxies came from the following sources - E's: σ's from Terlevich *et al.* (1981), M_{lum}/L from Faber and Gallagher (1979); Sc's: v_{rot}'s and radii from Burstein *et al.* (1981), M_{lum}/L_B assumed to be 1.6; Irr's: Thuan and Seitzer (1979). Data on groups and clusters from Rood and Dickel (1978). Cross is mean mass turning around today (White and Rees 1978). Heavy straight lines are clustering loci for various values of *n*. Light lines are the mass of a self-gravitating body composed purely of ordinary matter. Dashed line is

For sources with galaxy-sized masses (10^{10} M_{sol}), cooling is efficient...

However for cluster-scale masses (10^{14} M_{sol}), cooling is not efficient... and have lots of hot gas.

New Material

Let's consider a collapsed object with both dark matter (does not cool) + Baryons (can cool)

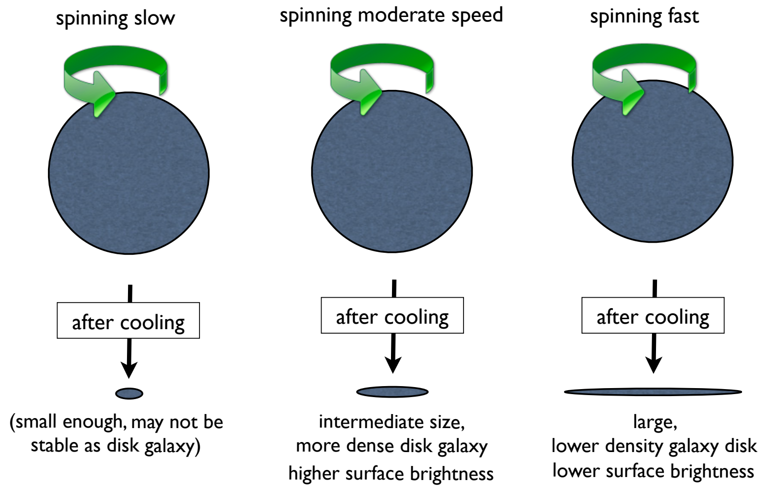


How extended is the baryonic mass at the center of collapsed sources?

What sets the physical size of disk galaxies?

What determines the Size of Disk Galaxies?

Likely the angular momentum of the halo



How far can the baryonic matter collapse into the center of the dark matter halo?

What stops it from collapsing to the center?

Angular momentum of the Baryonic Material

While radiative processes can remove energy from the gas, these processes preserve its angular momentum.

Gas can only collapse so far while preserving its angular momentum:

$$j = \frac{J}{m} = r_{start} < v > = r_{end} < v_{end} > = j_{end}$$

By comparing $<v_{end}>$ with $<v>$, we can determine $<r_{end}>/<r_{start}>$

This results in the formation of a gas disk (for a disk galaxy), since a disk is the minimum energy configuration that still conserves angular momentum.

What determines their Size?

The disk size r_d is a function of the radius of the collapsed halo R_{200} and the dimensionless angular momentum λ

$$r_{disk} = \lambda R_{200} / 2^{1/2}$$

where the dimensionless angular momentum is defined as follows:

$$\lambda = J\ E^{1/2} / (GM^{5/2})$$

The dimensionless angular momentum λ typically falls in the range: ~0.03 - 0.10 (from tidal torque theory)

Together, these two variables (mass + angular momentum) of the matter in a collapsed halo should determine most of the physical properties of a spiral galaxy.

What type of scaling relations might we expect to hold?

If we assume that there is a fixed circular velocity at large radii (as is the case for many disk galaxies):

the mass enclosed in some radius is

$$M = Rv_c^2/G$$

Assuming that galaxies form at a fixed redshift, we would expect

$$M \propto < \rho > R^3$$

Manipulating the second expression to derive an equation for R and substituting it in the first equation, we find

$$M \propto v_c^3$$

If the galaxy luminosity is proportional to mass, then

$$L \propto v_c^3$$

which isn't quite true, but is close to the observed scaling.

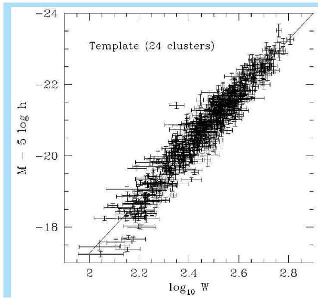
How do their structural parameters correlate?

The global properties of spiral galaxies are observed to correlate with each other:

Tully Fisher Relationship

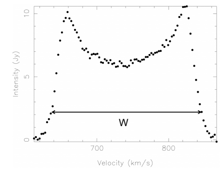
Luminosity $\propto v_c^4$

luminosity



~2 x circular velocity

measure this W parameter by looking at the total velocity spread for galaxy at single time (based on observations of 21 cm spectral line)



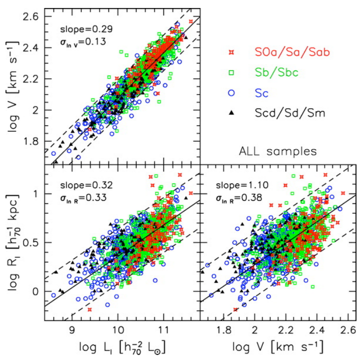
HI line profile for NGC 1744

Slope of Tully-Fisher Relationship depends on which wavelength one measures the luminosity

How do their structural parameters correlate?

also a correlation between luminosity and size

size



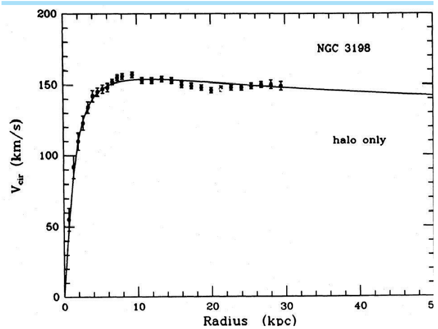
Courteau+2007

luminosity

it is clear that the size-luminosity relation is less tight!

What about the radial structure of disk galaxies?

From the Kinematic Information, we can derive a mean velocity along the line of sight vs. position (like for ellipticals)

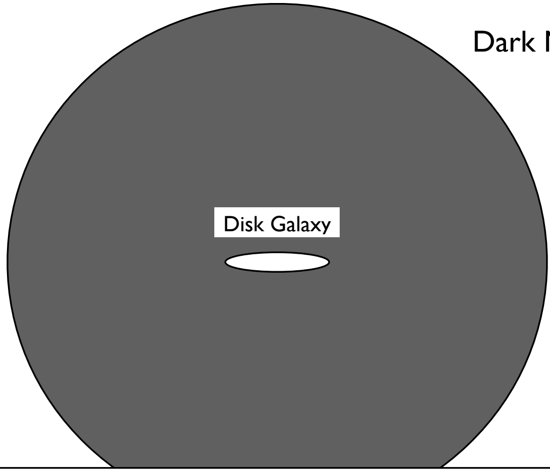


As we showed previously, from the line of sight "circular" velocity information we immediately have information on the enclosed mass.

$$\frac{d\Phi}{dr} = \frac{GM(<r)}{r^2} = \frac{v_c^2}{r}$$

Final Picture of Galaxy

Dark Matter Halo



Presence of Dark Matter Has Huge Impact on This

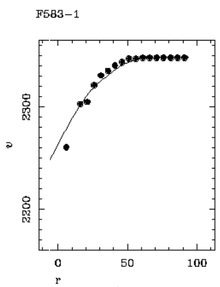
What is the evidence for significant mass in galaxies from dark matter?

(Mostly REVIEW from bachelor course)

Mass of Galaxies: Inferences from the Rotation Curve

Rotation Velocity

Line of Sight Velocity



Radius on Sky

Mass of Galaxies: Inferences from the Rotation Curve

What data are used for this?

Hα (optical spectroscopy) -- star-forming/ionized regions

CO (mm arrays) -- molecular hydrogen

HI (radio 21 cm) -- atomic hydrogen

Mass of Galaxies:
Inferences from the Rotation Curve

How do we derive masses?

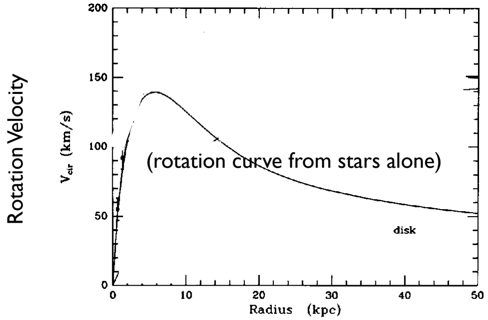
assume circular orbits:

$$\frac{v_c^2(r)}{r} = \frac{GM(<r)}{r^2}$$

The enclosed mass is directly given by

$$M(<r) = r v_c^2(r)/G$$

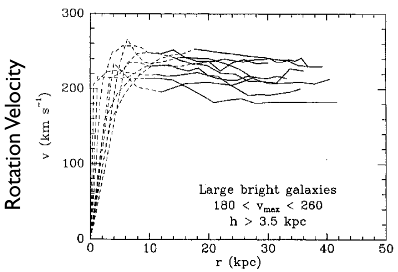
If the only matter in spiral galaxies was from the observed stars, then the rotation curve would look as follows:



V_c^2 (implied from stars) = $GM_{stars}(R)/R$ $\Rightarrow$ $v_c \propto 1/\sqrt{r}$

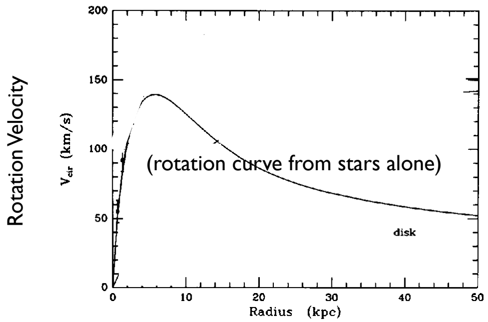
In such a case, the rotation curve would have an approximately Keplerian shape (i.e., $v_c \propto 1/r^{1/2}$) at large radii

Observations of the rotation curve always rapidly rise from center



Velocity of the rotation Curve is nearly always flat at the largest radii

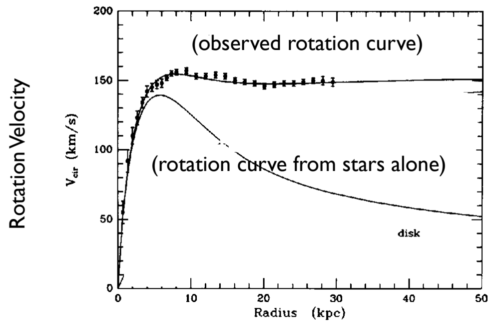
If the only matter in spiral galaxies was from the observed stars, then the rotation curve would look as follows:



V_c^2 (implied from stars) = $GM_{stars}(R)/R$ $\Rightarrow$ $v_c \propto 1/\sqrt{r}$

In such a case, the rotation curve would have an approximately Keplerian shape (i.e., $v_c \propto 1/r^{1/2}$) at large radii

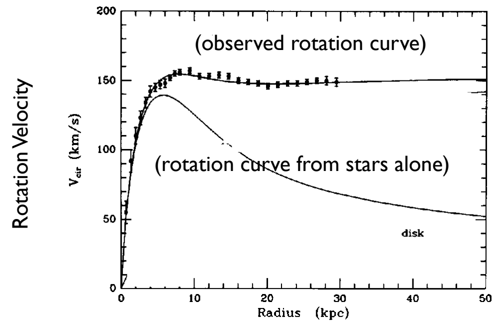
However, the observed rotation curve looks flat, even at large radii, and is very different from expectations if only stars contribute



V_c^2 (observed) > V_c^2 (implied from stars) = $GM_{stars}(R)/R$

This implies there must be another component...

If the only matter in spiral galaxies was from the observed stars, then the rotation curve would look as follows:



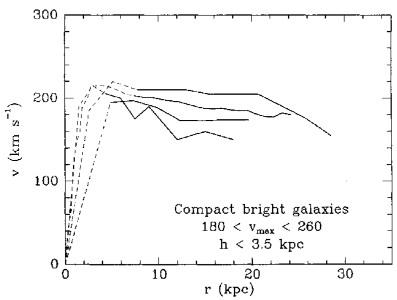
V_c^2 (observed) = $GM_{all}(R)/R$

V_c^2 (observed) = $G(M_{stars}(R)+M_{halo}(R))/R = GM_{stars}(R)/R + GM_{halo}(R)/R$

In principle, this allows us to measure the dark matter in galaxies very precisely. The challenge is that there is some uncertainty in measuring the mass in stars.

Observations of the rotation curve always rapidly rise from center

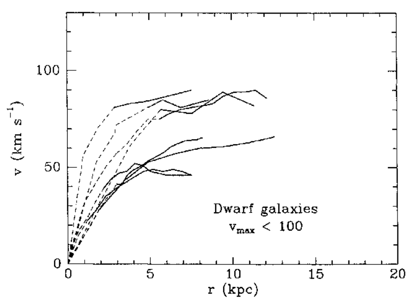
Rotation Velocity



For large luminous galaxies, the rotation curve falls slightly at largest radii (v_c independent of radius)

Observations of the rotation curve always rapidly rise from center

Rotation Velocity



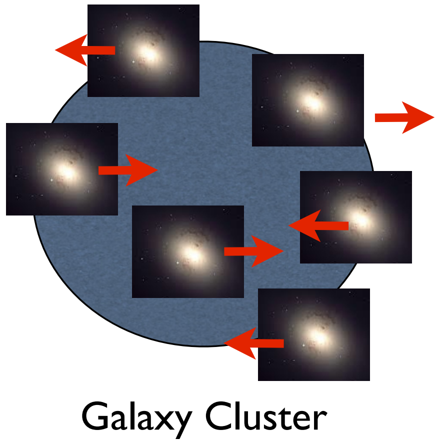
Nevertheless, for dwarf galaxies, the rotation curve is still slightly rising at largest radii.

Different dependencies of the circular velocities on radius for different galaxies tell us about mass profiles of dark matter and stars in these sources.

What other evidence is there for significant mass from dark matter?

(Mostly REVIEW from bachelor course)

Mass of Galaxy Clusters: Inferences From Velocity Dispersion



In clusters of galaxies, galaxies are observed to show a huge dispersion in their observed velocities along the line of sight:

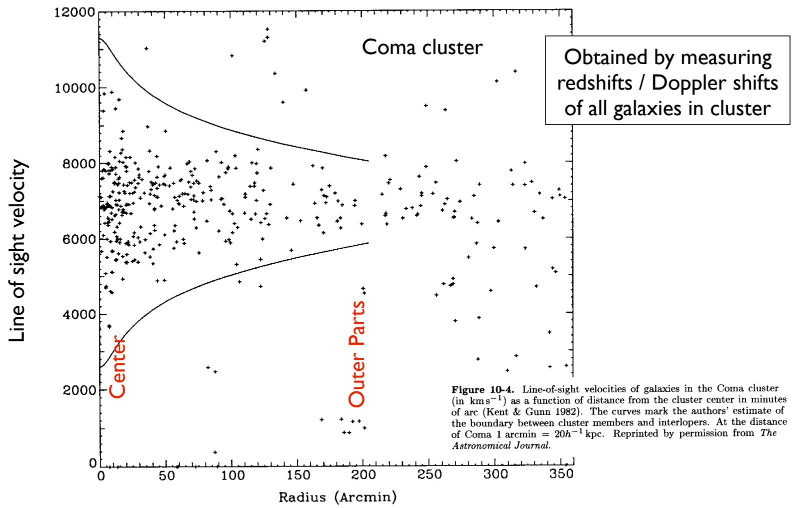


Figure 10-4. Line-of-sight velocities of galaxies in the Coma cluster (in km s^{-1}) as a function of distance from the cluster center in minutes of arc (Kent & Gunn 1982). The curves mark the authors' estimate of the boundary between cluster members and interlopers. At the distance of Coma 1 arcmin = 20h^{-1} kpc. Reprinted by permission from *The Astronomical Journal*.

Assuming virial equilibrium, we can derive the mass for a galaxy cluster from the observed spread in velocities:

$GM / R \sim v^2 \longrightarrow M \sim v^2 R / G$

Mass of Galaxy Clusters: Inferences from the x-ray emission

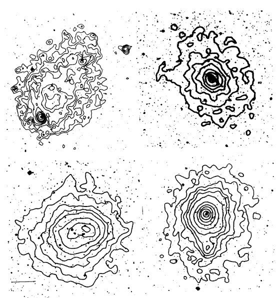


Figure 10-5. X-ray surface-brightness contours superimposed on photographs of several clusters of galaxies. Clockwise from top left, the clusters are A1367, A262, A85, and A2256 (see Jones & Forman 1984).

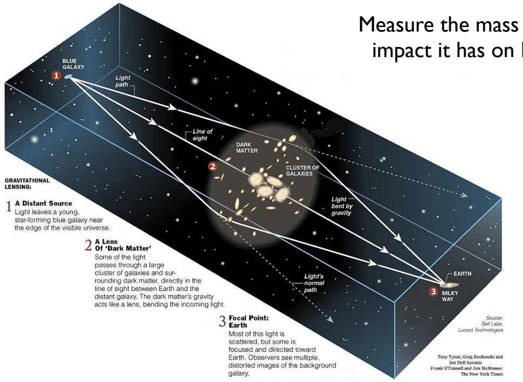
Derive total mass assuming hydrostatic equilibrium

$$\underbrace{\frac{dp}{dr}}_{\text{Pressure Gradient}} = \underbrace{-\rho \frac{GM(r)}{r^2}}_{\text{Gravitational Force}}$$

Can determine the density of the gas and pressure gradient from the x-ray light profile and the measured gas temperature.

This allows the total mass to be derived.

Mass of Galaxy Clusters: Inferences from Gravitational Lensing



Measure the mass of a galaxy cluster from the impact it has on light passing by the cluster

Diagram here shows such a measurement using multiple images of same sources, but often measurement made using distortion of galaxy shapes

From analyses of the x-ray light and the gravitational lensing of background galaxies around galaxy clusters, we find very similar masses for galaxy clusters.

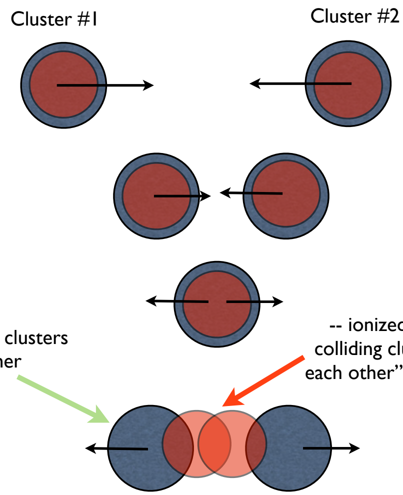
Bottom Line:

What is composition of galaxy clusters by mass?

Mass budget:
• Star mass fraction < 10 % of mass
• Gas mass fraction 20-30 % of total mass
• Remaining: dark matter 60-70 % !

Evidence from the Observations of Colliding Clusters

Reason it is useful can be seen from the following "simulation":



-- dark matter from the colliding clusters pass right through each other

-- ionized gas from the colliding clusters "run into each other" forming a shock

this presents us with a situation where the light (from baryons) and mass (from dark matter) are in different places

Evidence from the Observations of Colliding Clusters

-- how can we use the observations to see that baryons do not provide most of the mass

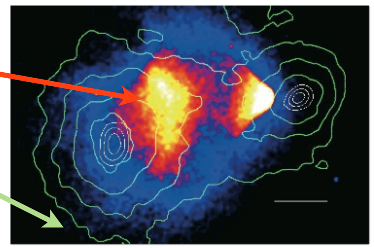
-- x-ray light shows us where the ionized gas (i.e., baryons) is

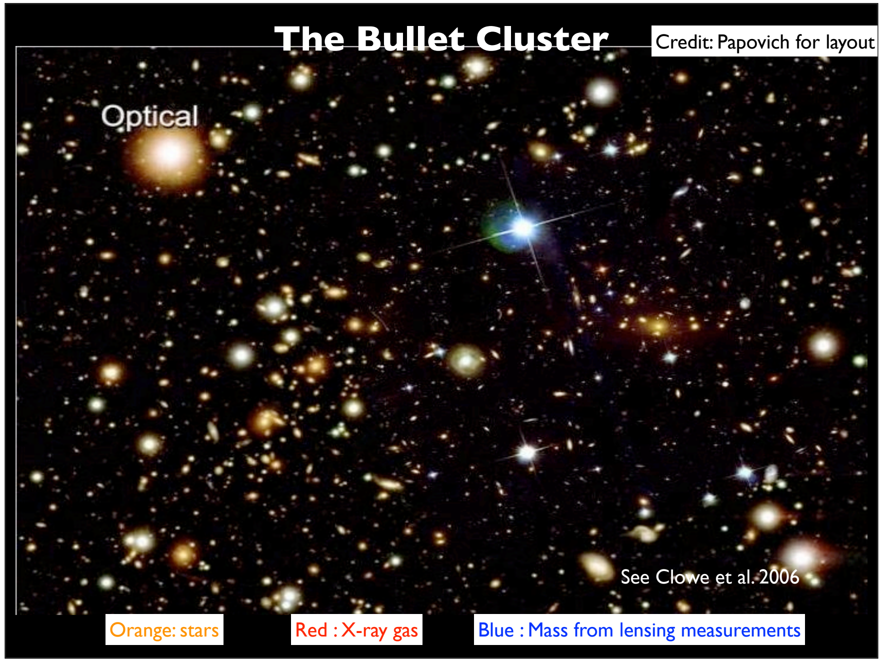
-- gravitational lensing shows us where the mass is (mostly dark matter)

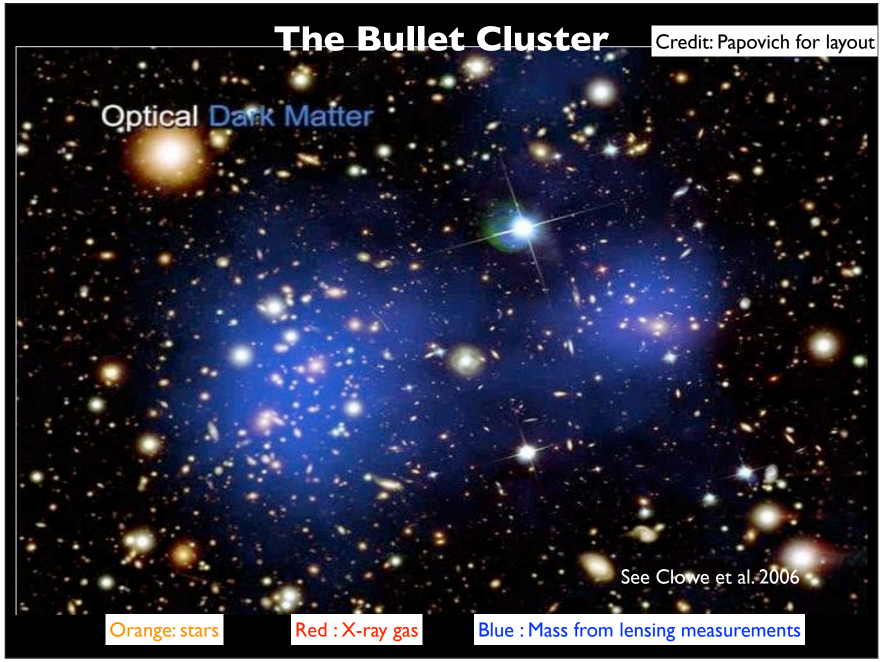
"Bullet Cluster" Clowe et al. 2006

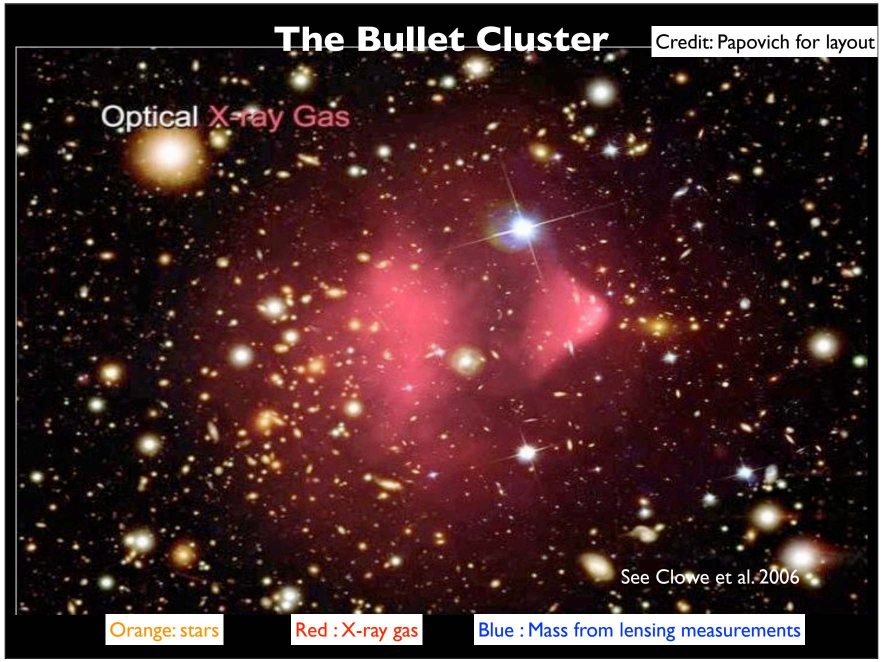
-- ionized gas from the colliding clusters "run into each other" forming a shock

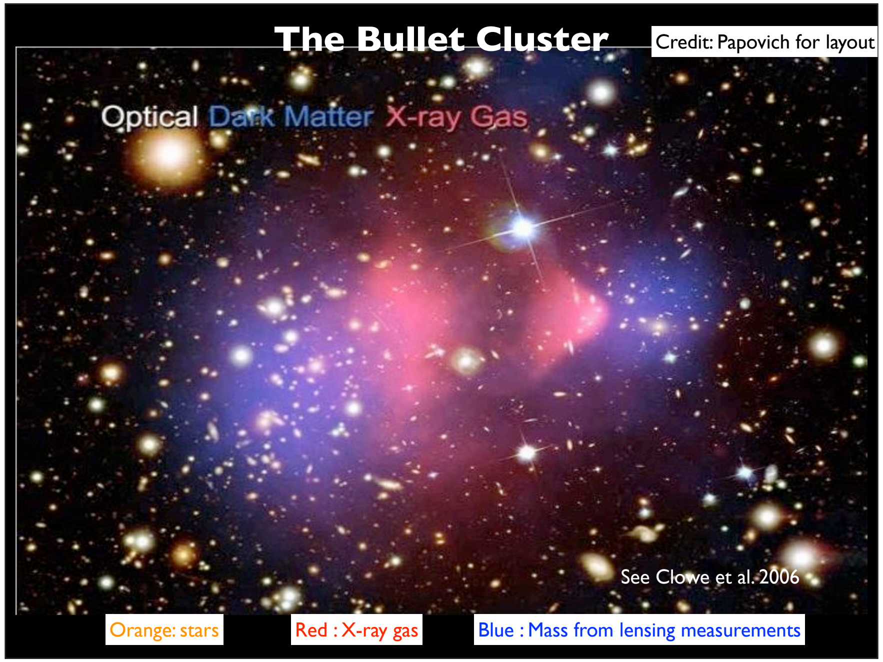
-- dark matter from the colliding clusters pass right through each other




The Bullet Cluster
Credit: Papovich for layout
Optical
See Clowe et al. 2006
Orange: stars
Red : X-ray gas
Blue : Mass from lensing measurements


The Bullet Cluster
Credit: Papovich for layout
Optical Dark Matter
See Clowe et al. 2006
Orange: stars
Red : X-ray gas
Blue : Mass from lensing measurements


The Bullet Cluster
Credit: Papovich for layout
Optical X-ray Gas
See Clowe et al. 2006
Orange: stars
Red : X-ray gas
Blue : Mass from lensing measurements


The Bullet Cluster
Credit: Papovich for layout
Optical Dark Matter X-ray Gas
See Clowe et al. 2006
Orange: stars
Red : X-ray gas
Blue : Mass from lensing measurements

What does this imply about the matter density of the universe?

(Mostly REVIEW from bachelor course)

In assessing the amount of matter in the universe, usually this is done relative to the density of matter in the universe necessary to stop the expansion of the universe.

The critical density of the universe (needed to stop expansion at time infinity) is

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

We then compare the observed density of matter in the universe ρ_0 with the critical density ρ_c using the parameter Ω_0. We define it as follows:

$$\Omega_0 = \rho_0/\rho_c$$

What does this imply about the matter density of the universe?

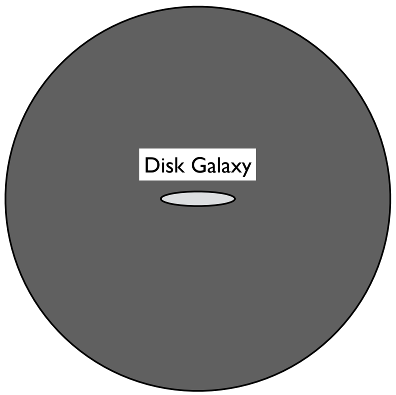
Table 10-2. Estimates of the density parameter

Method	$\Upsilon_V/\Upsilon_\odot$	Ω_0
Solar neighborhood	5	$0.003h^{-1}$
Elliptical galaxy cores	$12h$	0.007
Local escape speed	30	$0.018h^{-1}$
Satellite galaxies	30	$0.018h^{-1}$
Magellanic Stream	> 80	$> 0.05h^{-1}$
Rotation curve of NGC 3198	$> 28h$	> 0.017
X-ray halo of M87	> 750	$> 0.46h^{-1}$
Local Group timing	100	$0.06h^{-1}$
Groups of galaxies	$260h$	0.16
Clusters of galaxies	$400h$	0.25
Virgocentric flow	–	0.25
Nucleosynthesis	–	$(0.01 - 0.05)h^{-2}$
Inflation	–	1

NOTES: All lines except the last three are based on the luminosity density (10-24). Nucleosynthesis estimate omits density in non-baryonic matter. Several methods, such as Local Group timing and X-ray halo of M87, depend on h in complicated ways, and this dependence has been suppressed. See text for further detail.

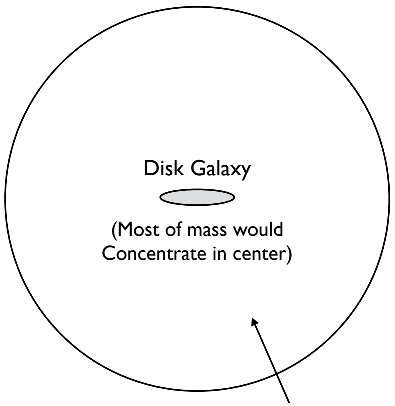
As we probe larger physical scales outside galaxies, we find a lot of matter!

Disk Galaxy with Dark Matter



Dark Matter Halo

Disk Galaxy (if no Dark Matter)

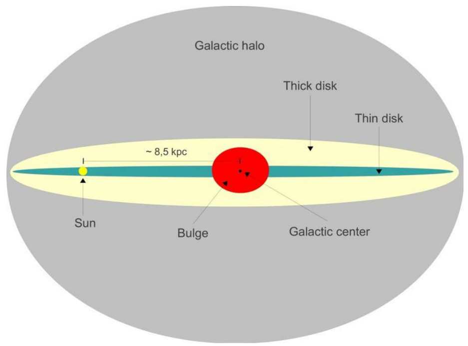


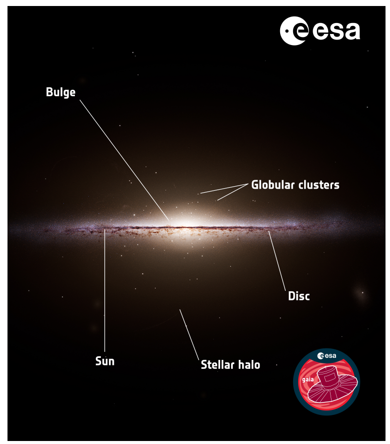
The halo out here would likely contain much less mass

Brief Context: Structure of Disk Galaxy

Four Basic Components:

1. Thin Disk
2. Thick Disk
3. Halo
4. Bulge





Brief Context: Structure of Disk Galaxy

Four Basic Components:

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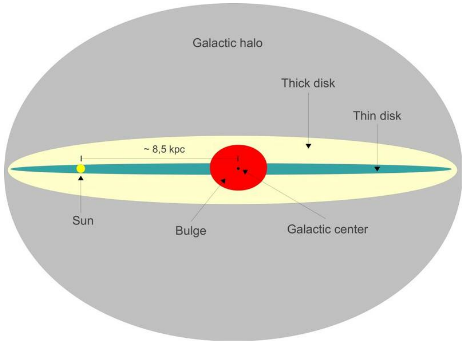
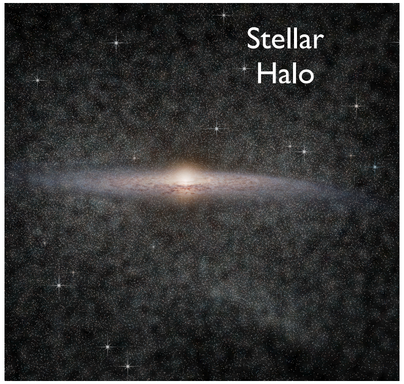




Existence of Both Thin and Thick Disk

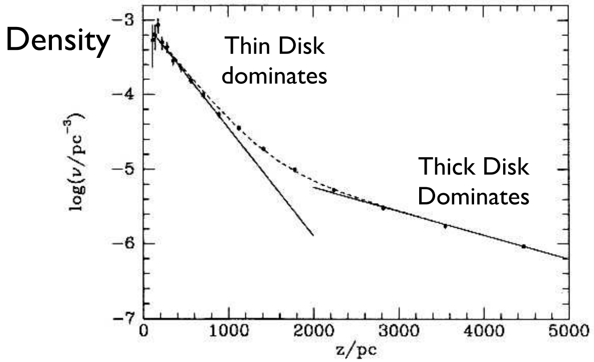
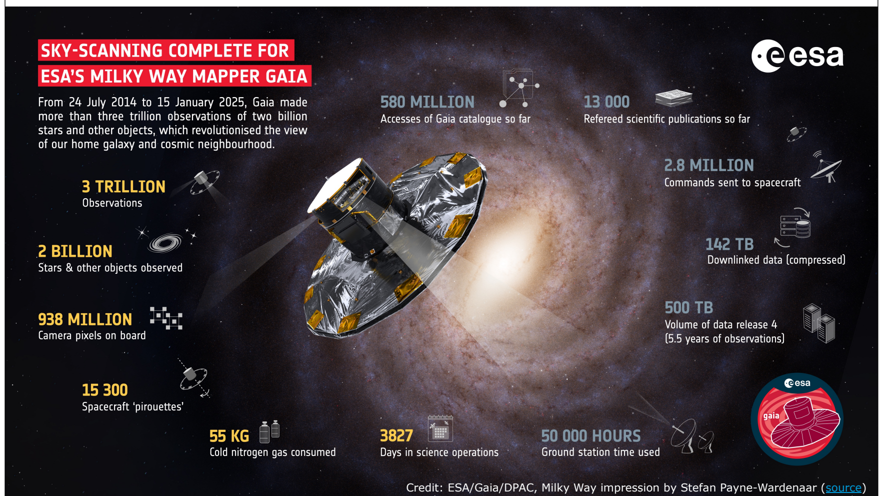


Figure 10.25 The space density as a function of distance z from the plane of MS stars with absolute magnitudes $4 \leq M_V \leq 5$. The full lines are exponentials with scale heights $z_0 = 300\,\mathrm{pc}$ (at left) and $z_0 = 1350\,\mathrm{pc}$ (at right). The dashed curve shows the sum of these two exponentials. [From data published in Gilmore & Reid (1983)]

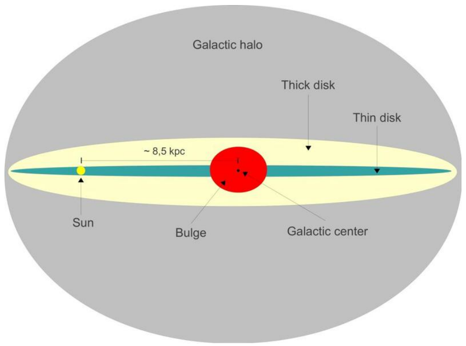
Of course, with recent Gaia data, it is clear that even these distinctions are too simple.

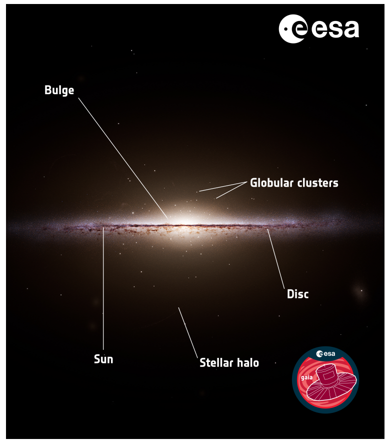


Brief Context: Structure of Disk Galaxy

Four Basic Components:

1. Thin Disk
2. Thick Disk
3. Halo
4. Bulge





Ages & Metal Abundances of Different Components

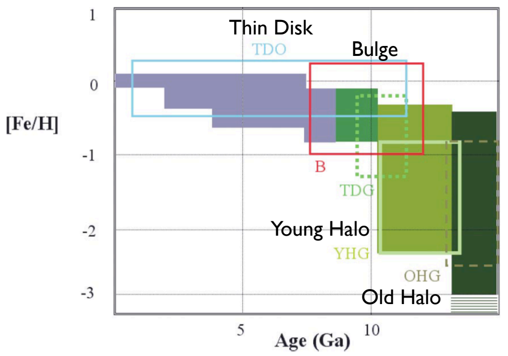
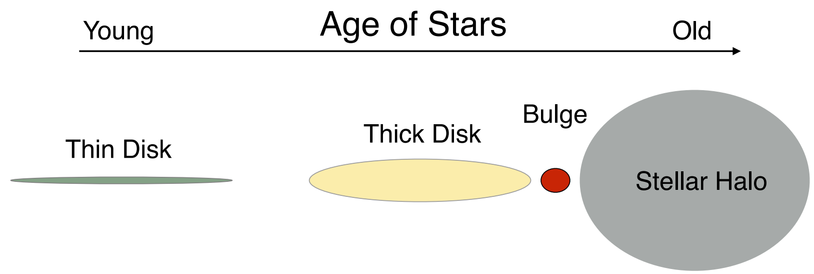


Fig. 1.16 The age-metallicity relation of the Galaxy for the different components (see text): TDS – thin disk stars; TDO – thin disk open clusters; ThDS – thick disk stars; ThDG – thick disk globulars; B – bulge; YHG – young halo globulars; OHG – old halo globulars.

Properties of Components



Correlation between Age and Metallicity of Stars

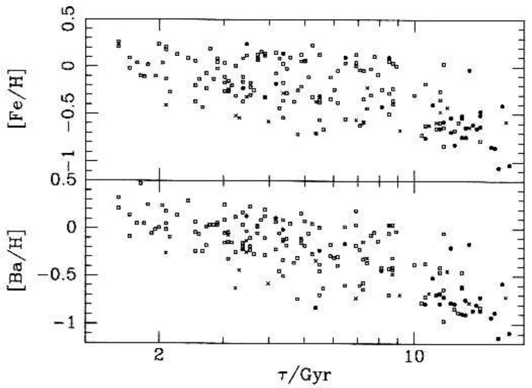
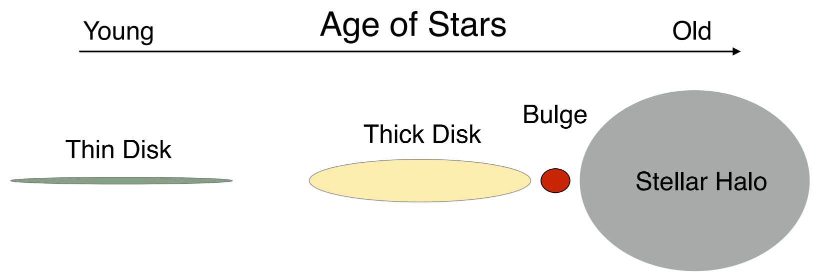


Figure 10.18 The dependence upon age of the abundances of iron and barium. The characteristic Galactocentric radius of each star, R_m, is indicated by different symbols: • ⇒ $R_m < 7$ kpc; □ ⇒ $7\,\mathrm{kpc} < R_m < 9\,\mathrm{kpc}$; × ⇒ $R_m > 9$ kpc. [After Edvardsson *et al.* (1993) from data kindly supplied by B. Edvardsson]

Old stars have a lower metallicity than your stars. This suggests that the metallicity of the gas (from which the stars formed) increased gradually with time.

This is expected to happen, due to metals being injected into the gas by stellar winds and supernovae.

Properties of Components



Higher Metallicity

Lower Metallicity

Lower Metallicity Stars also Show a [α/Fe] enhancement

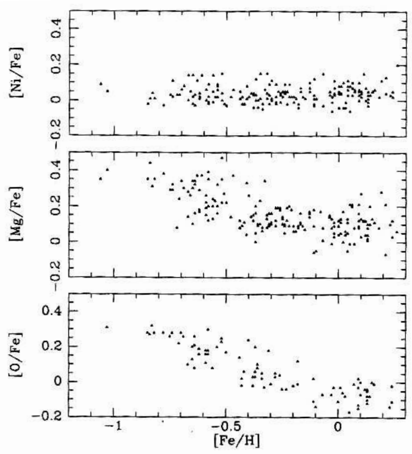
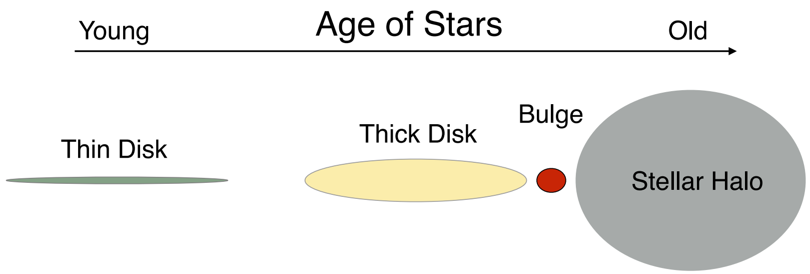


Figure 10.17 The dependence upon the abundance of Fe of the ratios of Ni, O and Mg to Fe. The ratio of Ni to Fe is flat because these elements are produced alongside one another. The ratios of O and Mg to Fe decline with increasing Fe abundance because O and Mg, which are produced by short-lived stars, were formed before the disk became heavily polluted by iron from type Ia supernovae, which have long-lived progenitors. [After Edvardsson *et al.* (1993) from data kindly supplied by B. Edvardsson]

This is thought to be the case because SNe II produce metals earlier in the star formation history of galaxies than SNe Ia and produce a higher [α/Fe] abundance

Properties of Components



Higher Metallicity

Lower Metallicity

Higher Rotation Speed

Low Rotation Speed

Stars in the Stellar Halo Move Very Differently from Stars in the Disk

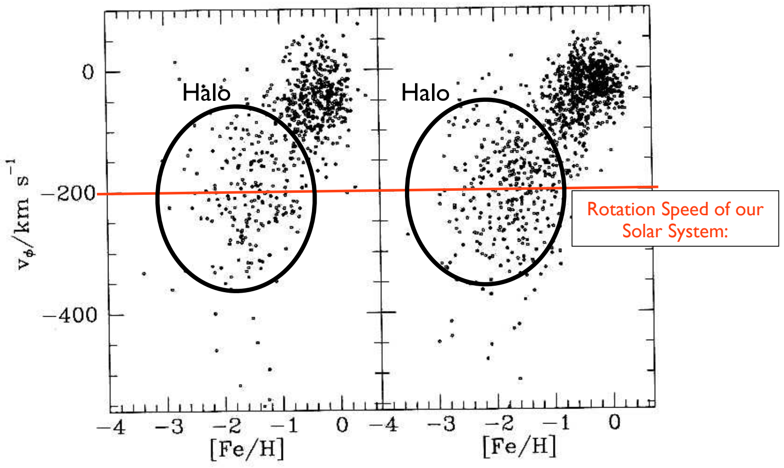
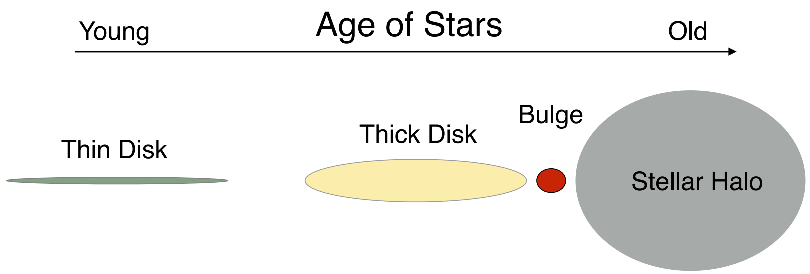


Figure 10.36 [Fe/H] versus v_ϕ from Nissen & Schuster (1989) (left panel, 611 stars) and Carney *et al.* (1996) (right panel 1022 stars). [From data kindly supplied by B. Carney and P. Nissen]

Properties of Components



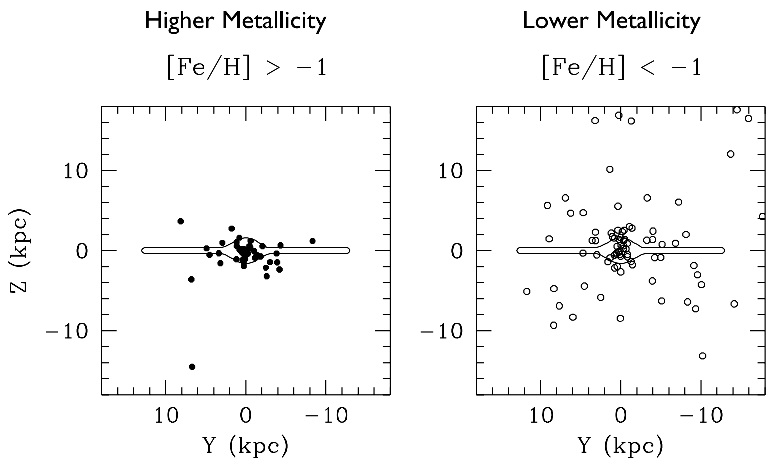
Higher Metallicity

Lower Metallicity

Higher Rotation Speed

Low Rotation Speed

Segregation in Metallicity between Disk and Halos even seen in star clusters



How Did the Stellar Halo of the Milky Way and Other Disk Galaxies Form?

Stellar Halo	Thin Disk
Low Metallicity	High Metallicity
Old Ages	Young Ages
Little Rotation	High Rotation
Older, lower metallicity star clusters	Younger, higher metallicity star clusters

ELS Monolithic Collapse Model

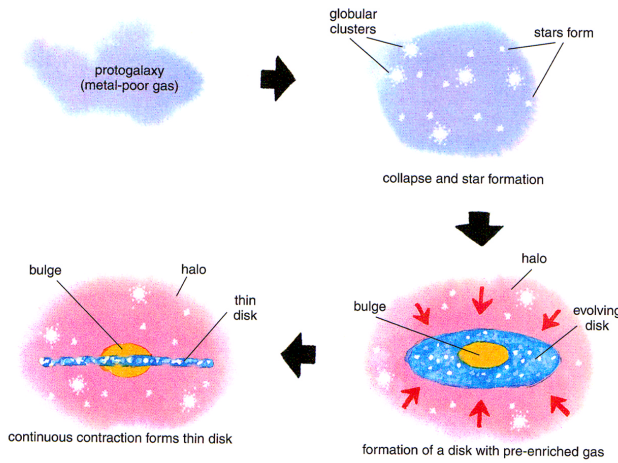


Figure 6. The "ELS" model holds that the Milky Way formed from the rapid collapse of a single cloud of gas. Stars formed early in the collapse maintained the dynamics of the metal-poor gas and so now travel around the Galaxy in elliptical orbits within the halo. As the cloud collapsed *(red arrows)* preferentially along its rotational axis, it formed a disk that had been enriched with the metals produced by the early generations of halo stars.

ELS Monolithic Collapse Model

The ELS model (Eggen, Lynden-Bell, and Sandage 1962): the Milky Way formed from the rapid collapse of a large proto-galactic nebula: top-down approach

The oldest halo stars formed early, while still on nearly radial trajectories and with low metallicity

Then the disk formed because of angular momentum conservation, and disk stars are thus younger and more metal rich

The ongoing star formation is confined to distances ~100 pc from the mid-lane at a typical rate of a few solar masses per year

Zinn & Searle (1978) Hierarchical Model

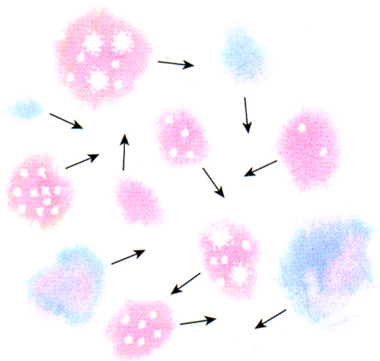


Figure 7. The Searle and Zinn model proposes that the Milky Way formed from an aggregation of several cloud fragments. This model helps to explain the observed differences in the metallicity of globular clusters in the galactic halo. Since each of the cloud fragments had independent histories, some may have evolved more than others, and so have produced objects of greater metallicity.

Searle & Zinn (1978) Hierarchical Model

A bottom-up scenario: galaxies are build from merging smaller fragments (similar to but not the same hypothesis that giant ellipticals formed from merging spiral galaxies).

By observing galaxies at higher redshifts, we are probing the epoch of galaxy formation - indeed at large redshift have very different morphologies, and the fraction of spirals in galaxy clusters is higher than today.

Two Competing Models for Formation of Stellar Halo in Milky Way

ELS Monolithic Collapse

Halo formed in first Gyr

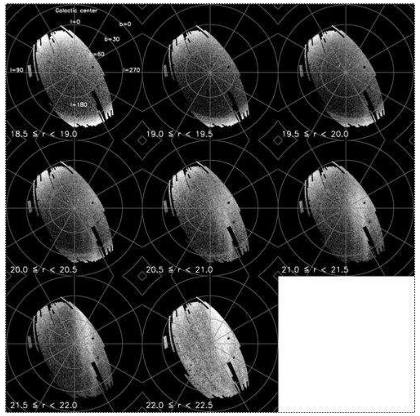
Zinn & Searle Hierarchical Model

Halo built up from mergers

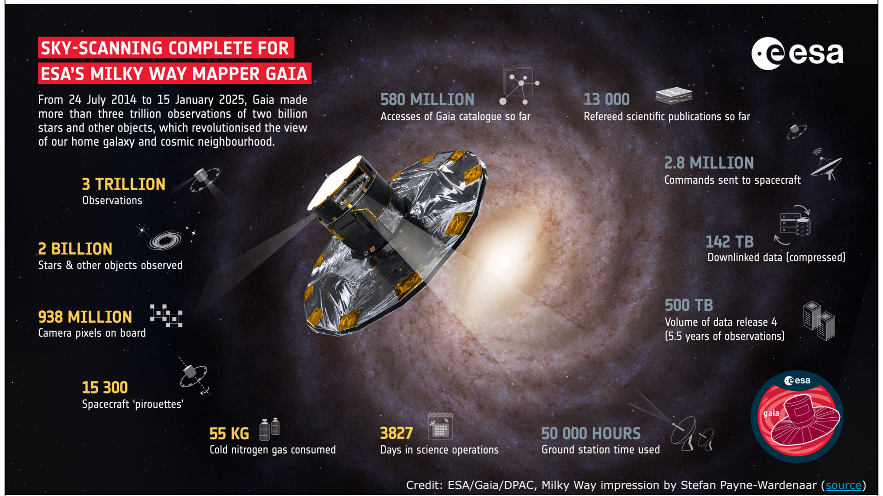
Which was correct?

Pre-GAIA, there was strong evidence for a lack of uniformity in the distribution of halo stars on the sky

Fig. 3
Stellar halo of the Milky Way as seen by SDSS. The gray scale denotes the logarithm of the number density of $0.2 \leq g - r \leq 0.4$ stars per square degree in eight different magnitude (therefore mean distance) slices; a Lambert azimuthal equal-area polar projection is used. The black areas are not covered by the SDSS DR5, and reflect the great circle scanning adopted by the SDSS when collecting its imaging data. Apparent "hot pixels" are stellar overdensities from globular clusters and dwarf galaxies.

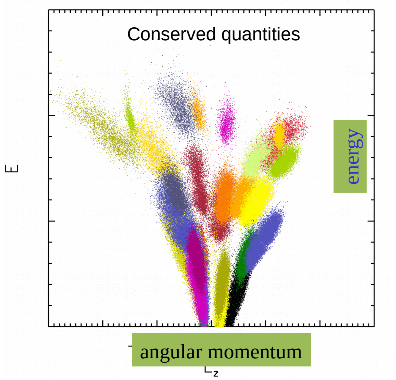


Favored Zinn & Searle (1978) Model



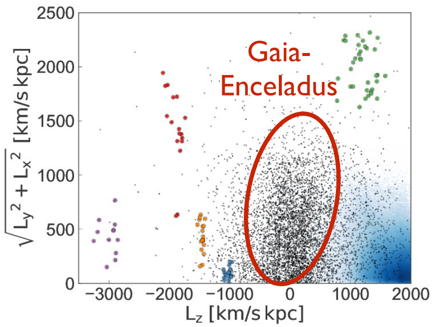
Assessment of the Dynamical Information using GAIA

Simulation



Helmi & de Zeeuw (2000)

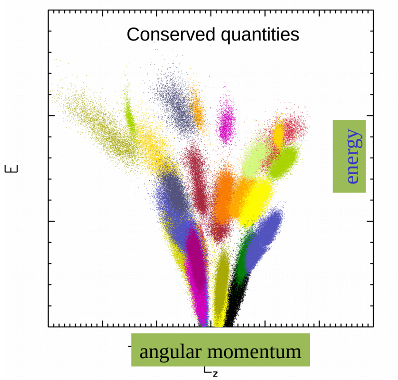
GAIA Observations



Koppelman+2018

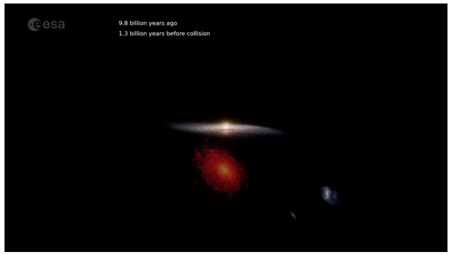
Assessment of the Dynamical Information using GAIA

Simulation



Helmi & de Zeeuw (2000)

Simulation of Gaia-Enceladus Merger



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Two Competing Models for Formation of Stellar Halo in Milky Way

ELS Monolithic Collapse

Halo formed in first Gyr

Zinn & Searle Hierarchical Model

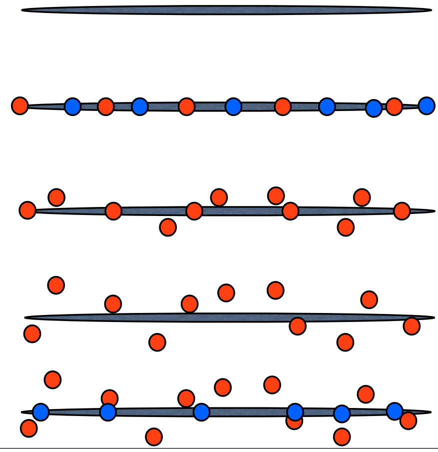
Halo built up from mergers

GAIA Results Show this Model is Largely Correct

What about the Thick Disk?

How might the thick disk form?

=> Disk Heating (from spiral arms, molecular clouds, minor mergers)



cooling causes gas to settle in a very thin disk (i.e., the minimum energy configuration that preserves angular momentum)

stars form from the cool gas and begin their lives in the plane of the disk

as time goes on, due to some heating mechanism (e.g., mergers with small galaxies), stars are given small kicks out of the plane (and oscillate in and out of plane)

the scale height of the stars increases as time goes on (due to more collisions)

while old stars have large scale heights, newly formed stars have small scale heights (formed in the gas disk)

Is there evidence for disk heating?

Yes, the velocity dispersion of a population of stars depends on the age. The older the population of stars, the higher the velocity dispersion.

Interestingly, the velocity dispersion in the 3 directions change in very characteristic ways -- with, for example, $\sigma_\Phi \sim \sigma_r$

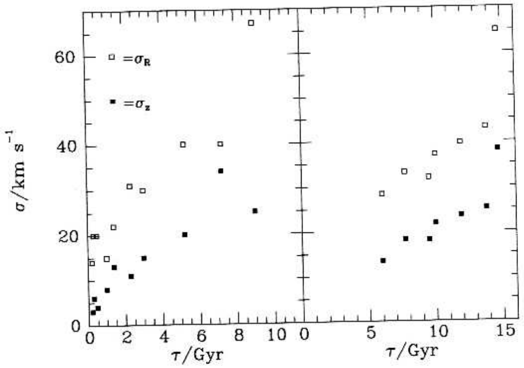


Figure 10.20 Velocity dispersion versus age as determined by Jahreiss & Wielen (1983) (left panel) and by the Danish group (right panel). Aside from a difference in the age scales used in these studies, the two determinations are broadly consistent with one another. [From data published in Jahreiss & Wielen (1983) and in Strömgren (1987)]

How might the thick disk form?

=> Debris from Past Merging onto the Milky Way

What about the Gas Distribution?

Obviously, spiral galaxies have gas (neutral hydrogen, molecular hydrogen, ionized hydrogen). Most of the gas resides in the disk. Some gas disks are warped in the outer parts.

Typical gas masses are around 3-6 x 10^9 solar masses. In galaxies like our own, the amount of neutral gas and molecular gas are similar. The molecular gas is concentrated mostly towards the center of the gas.

Neutral gas content in a strongly warped galaxy:

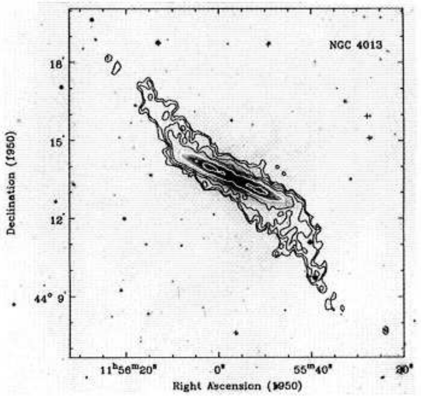


Fig. 1. Total H I map of NGC 4013 superposed on the optical image. Contours are at levels of 1.02 10^{20}, 2.03 10^{20}, 4.06 10^{20}, 8.13 10^{20}, 20.32 10^{20}, and 46.82 10^{20} H-atoms cm^{-2}. The resolution is indicated by the beam in the lower right corner

What about the Gas Distribution?

Molecular and neutral gas in NGC 6946. The neutral gas is traced best by CO emission. Here the CO emission is shown, super imposed on the SDSS imge of the galaxy. The CO is strongly peaked at the center.

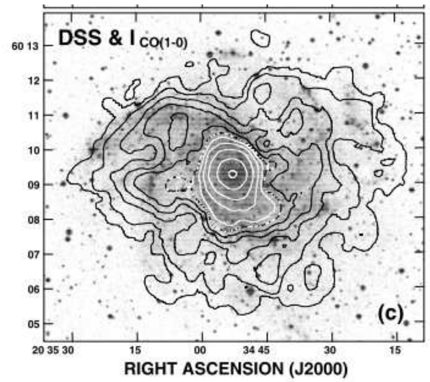
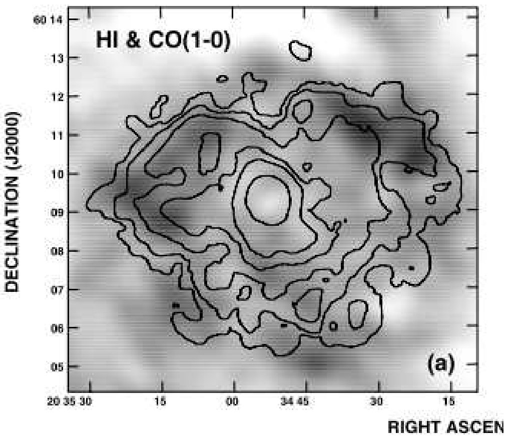


FIG. 2.—CO(1–0) integrated and peak intensity maps for NGC 6946. (*a*) CO(1–0) integrated intensity map. The gray scale ranges from 0 to 50 K km s^{-1}. The contour levels are 1, 2.5, 5, 7.5, 10, 12.5, 15, 20, 30, 50, and 70 K km s^{-1}. The 55″ (FWHM) circular beam is displayed at the lower left. (*b*) CO(1–0) peak intensity map. The gray scale ranges from 0 to 0.52 K. The contour levels are 0.10, 0.17, 0.23, 0.30, 0.37, and 0.43 K. (*c*) DSS uncalibrated optical image with the same I_{10} contours shown in (*a*).

What about the Gas Distribution?

Here is the H I 21-cm emission line map:



What about the Gas Distribution?

And here is shown the amount of gas in molecular and neutral form (assuming some conversion from CO emission to H_2 surface density)

The H_2 dominates at the center, the H I in the outer parts. Why? H_2 can only form if the gas is shielded from UV radiation. Hence, at high surface brightnesses and at high metallicity, more dust will be present and more shielding is possible.

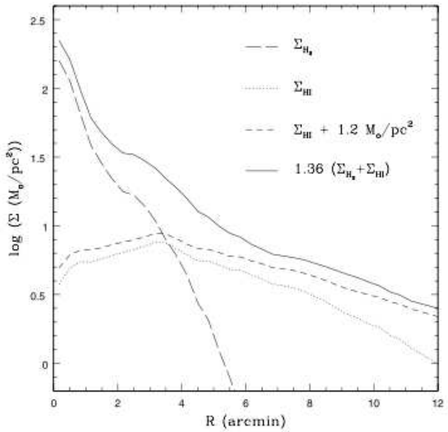
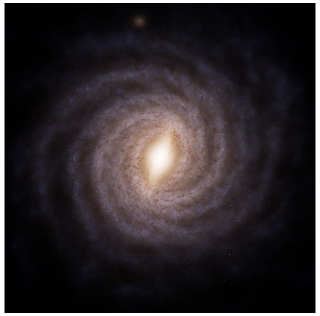


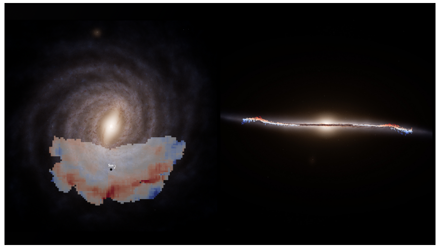
FIG. 8.—Gas surface density vs. radius in NGC 6946. Plotted are Σ_{H_2} derived using the standard conversion factor; $\Sigma_{H\,I}$ from the observed emission; $\Sigma_{H\,I}$ increased for the VLA missing flux estimate; and the total gas surface density increased by a factor of 1.36 to include the He and heavier element content. All have been corrected for inclination (cos *i*). At our assumed distance of 6 Mpc, 1′ = 1.75 kpc.

What else has been learned about the Milky Way from GAIA?

Milky Way is a Barred Spiral



The Disk of the Milky Way is Significantly Warped



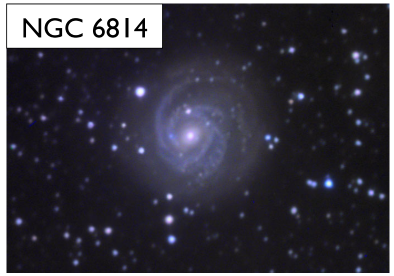
What else has been learned about the Milky Way from GAIA?

How can we understand spiral structure in disk galaxies?

Well-defined spiral structure is present in many galaxies.

Whirlpool Galaxy
Messier 51

NGC 6814



In many cases, the spiral structure is so well organized that the galaxies are called "grand-design" spirals

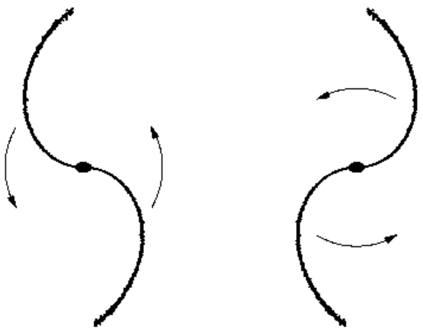
Other times the spiral structure is less well organized

Flocculent Spiral Galaxy: NGC 2841

How is such spiral structure put in place?

How does it evolve?

As disk galaxies rotate, do spiral arms lead or trail the rotation?

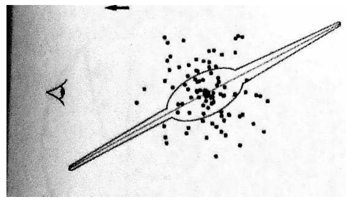


As disk galaxies rotate, do spiral arms lead or trail the rotation?

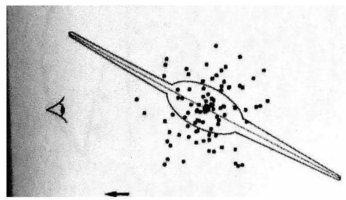
How can we settle this observationally?

Impossible to tell for face-on spiral galaxies or edge on galaxies

Use galaxies that are mildly inclined



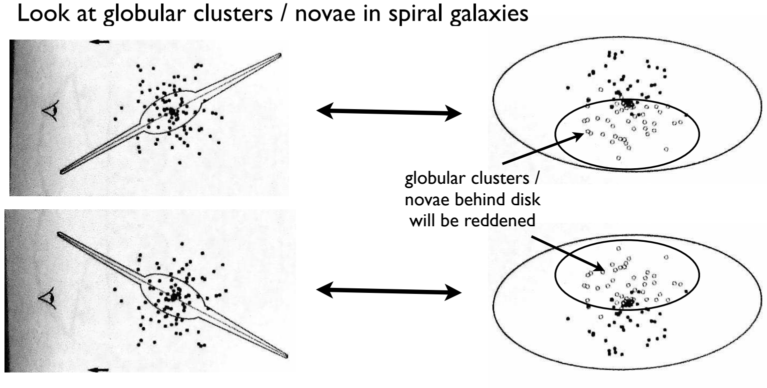
How can we distinguish the above from this?



As disk galaxies rotate, do spiral arms lead or trail the rotation?

How can we settle this observationally?

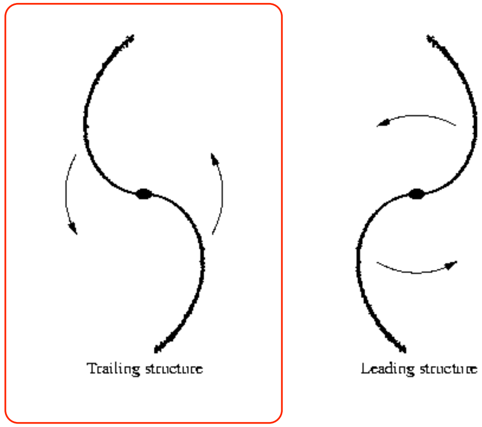
Look at globular clusters / novae in spiral galaxies



Globular clusters / novae behind disk will be highly reddened

As disk galaxies rotate, do spiral arms lead or trail the rotation?

Most spiral arms are found to be trailing.

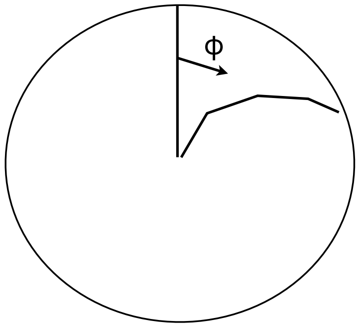


How do the arms in spiral galaxies evolve with time?

Now let us consider the time evolution of azimuthal position of each spiral arm:

$$\phi(R,t) = \phi_0 + \Omega(R)t.$$

which is also a function of radius R (because of differential rotation)



Ω(R) = angular rotation speed

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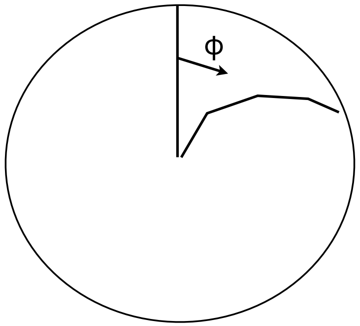


Ω(R) = angular rotation speed

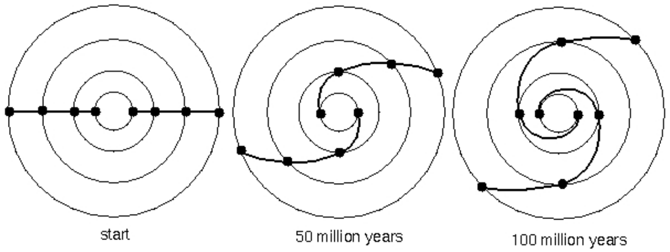
$\Omega(R) = v_{circular} / R$

~ constant

Implies angular rotation speed is smaller at large radii

Winding Problem

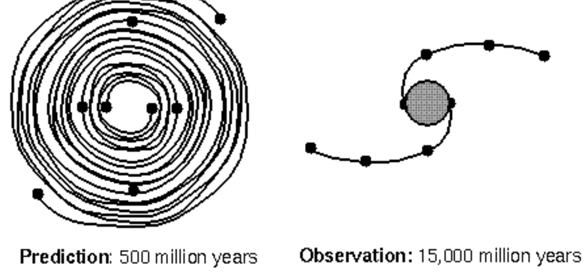
The revolution time for stars is smaller for stars on smaller radial orbits.



Differential rotation: stars near the center take less time to orbit the center than those farther from the center. Differential rotation can create a spiral pattern in the disk in a short time.

If the spiral arms rotate in the same way as the particles located in the spiral arms, differential rotation would cause the spiral arms to wind up.

Winding Problem



Assuming that the spiral arms rotate in the same way as the particles in these arms, one would predict that the spiral arms in a galaxy would wind up very quickly.

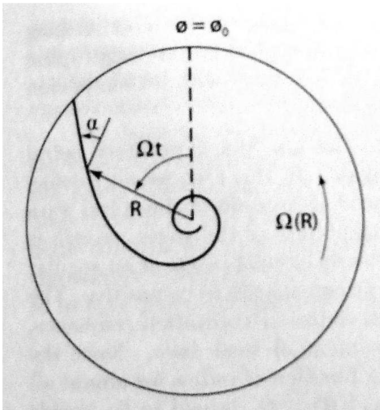
This is in contrast to what is observed!

Winding Problem: How big is the discrepancy?

Consider the pitch angle.

We define the pitch angle α for spiral arms as follows:

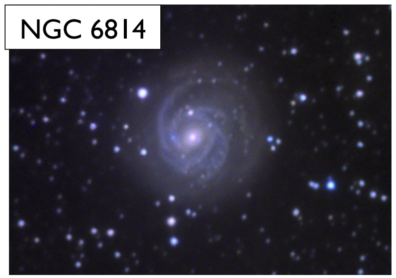
$$\cot \alpha = \left| R \frac{\partial \phi}{\partial R} \right| ,$$

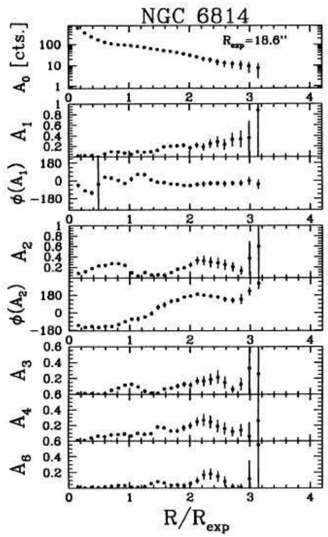


Fitting 2D light profiles of Spiral Galaxies

We can try to fit the two dimension surface brightness profile of spiral galaxies with the function:

$$\frac{I(R,\phi)}{\overline{I}(R)} = 1 + \sum_{m=1}^{\infty} A_m(R) \cos m[\phi - \phi_m(R)]$$





Fitting 2D light profiles of Spiral Galaxies

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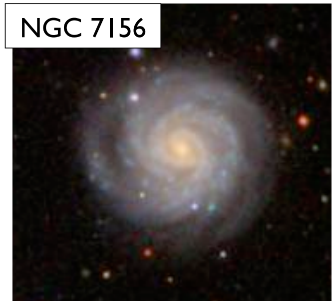
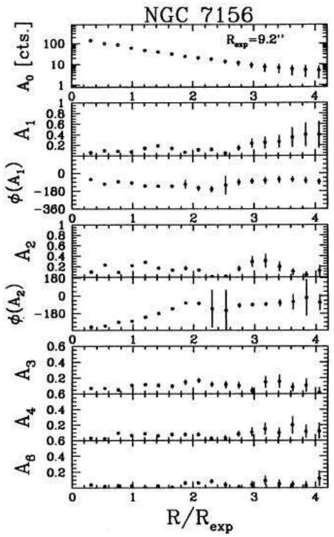
$$\frac{I(R,\phi)}{\overline{I}(R)} = 1 + \sum_{m=1}^{\infty} A_m(R)\cos m[\phi - \phi_m(R)]$$

NGC 7156





What range of pitch angles are observed?

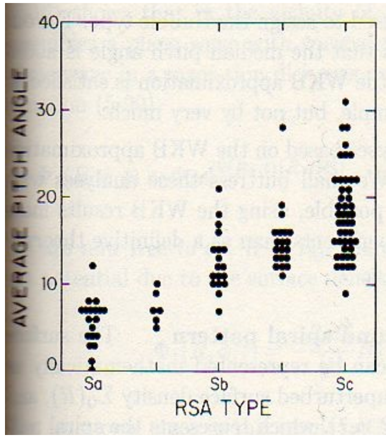


Figure 6-12. Measured pitch angle as a function of Hubble type for 113 galaxies (Kennicutt 1981). Reprinted by permission of *The Astronomical Journal.*

How do we predict the pitch angle will change?

$$\cot\alpha = \left|R\frac{\partial\phi}{\partial R}\right|, \longrightarrow \cot\alpha = Rt\left|\frac{d\Omega}{dR}\right|$$

$$\phi(R,t) = \phi_0 + \Omega(R)t.$$

$\longrightarrow$ cot α = Rt (v_c / R^2) = $v_c t$/R

For galaxies with a flat rotational curve v_c = RΩ = 200 km/s, R = 5 kpc, and t = 10 Gyr, then α ~ 0.15 degrees (much smaller than observed)

Observed pitch angles of ~10-20 degrees differs dramatically from expectation of 0.15 degrees from this simple baseline model.

How can we solve the winding problem?

Density Wave Theory

Lin & Shu (1964-1966)

The spiral arms in disk galaxies are not fixed structures that rotate around the center of disk galaxies, but rather density waves.

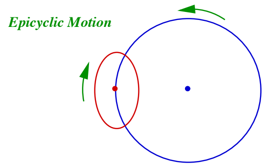
These density waves can move at a different speed than the stars within the galaxy itself.

The speed at which the spiral density waves propagate around the disk of a spiral galaxy is called the pattern speed Ω_p.

We will investigate this in more detail, but first let us look at epicyclic motion by stars in galaxies!

Epicyclic orbits

Stars that rotate around the center of disk galaxies are on epicyclic orbits:



This may not seem intuitive to you, but it is actually expected and you encountered this concept already in your study of the rotation of planets around the sun in the solar system.

Epicyclic orbits

Let us analyze the orbit of a star in some axisymmetric potential Φ(R)

Assume that the star has angular momentum L_z

The energy of a star in this potential is as follows:

$$E = \frac{1}{2}\left[\dot{R}^2 + (R\dot{\theta})^2 + \dot{z}^2\right] + \Phi = \frac{1}{2}\left(\dot{R}^2 + \dot{z}^2\right) + \Phi_{\rm eff}$$

where

$$\Phi_{\rm eff}(R,z) = \Phi(R,z) + \frac{L_z^2}{2R^2}$$

Gravitational Potential

Centrifugal barrier

Epicyclic orbits

How does Φ_{eff} (R) behave?

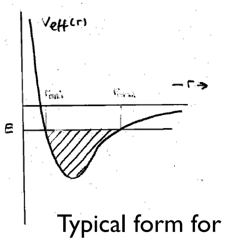
$$\Phi_{\rm eff}(R,z) = \Phi(R,z) + \frac{L_z^2}{2R^2}$$

Different Cases:

Point Mass: Φ (R) ~ 1/R

Isothermal Sphere: Φ (R) ~ log R

Homogeneous Density Φ (R) ~ R^2



Typical form for Φ_{eff} (R)

What happens to Φ_{eff}(R) at large and small radii?

As R → 0, $L_z^2/2R^2$ centrifugal term always dominates.

As R →∞, Φ(R) term dominates.

Φ_{eff} (R) has a minimum at some radius R_g. Stars orbiting around a galaxy at that radius will be on a circular orbit.

Epicyclic orbits

Expand the potential Φ_{eff} (R) about the radial position R_g and the vertical position z=0 as a Taylor series:

$$\Phi_{\rm eff} = \Phi_{\rm eff}(R_{\rm g},0) + \frac{1}{2}\left(\frac{\partial^2\Phi_{\rm eff}}{\partial R^2}\right)_{(R_{\rm g},0)} x^2 + \frac{1}{2}\left(\frac{\partial^2\Phi_{\rm eff}}{\partial z^2}\right)_{(R_{\rm g},0)} z^2 + \mathrm{O}(xz^2). \quad (3.76)$$

where x = R - R_g.

The first order terms in this expansion dΦ_{eff} (R)/dx, dΦ_{eff} (R)/dz and the second order term d$^2\Phi_{eff}$ (R)/dxdz are zero given that we are expanding the potential about a local minimum.

Represent the second derivatives of Φ_{eff} (R) with respect to R and z as κ and ν:

$$\kappa^2(R_{\rm g}) \equiv \left(\frac{\partial^2\Phi_{\rm eff}}{\partial R^2}\right)_{(R_{\rm g},0)} \quad ; \quad \nu^2(R_{\rm g}) \equiv \left(\frac{\partial^2\Phi_{\rm eff}}{\partial z^2}\right)_{(R_{\rm g},0)}$$

Epicyclic orbits

Then the time evolution of x and z are as follows:

$$\ddot{x} = -\kappa^2 x,$$
$$\ddot{z} = -\nu^2 z.$$

Since $d\Phi_{eff}/dR = 0$ at $R = R_g$

$$\frac{\partial \Phi_{\mathrm{eff}}}{\partial R} = \frac{\partial \Phi}{\partial R} - \frac{L_z^2}{R^3} = 0$$

and since $\Phi_{eff} = \Phi + L_z^2 / 2R^2$, we can also rewrite κ as

$$\kappa^2(R_g) = \left(\frac{\partial^2 \Phi_{\mathrm{eff}}}{\partial R^2}\right)_{(R_g,0)} + \frac{3L_z^2}{R_g^4} = \left(\frac{\partial^2 \Phi}{\partial R^2}\right)_{(R_g,0)} + \frac{3}{R_g}\left(\frac{\partial \Phi}{\partial R}\right)_{(R_g,0)},$$

Epicyclic orbits

Since we can write the orbital frequency Ω(R) as follows:

$$\Omega^2(R) = \frac{1}{R}\left(\frac{\partial \Phi}{\partial R}\right)_{(R,0)} = \frac{L_z^2}{R^4},$$

We then rewrite κ as follows:

$$\kappa^2(R_g) = \left(R\frac{\mathrm{d}\Omega^2}{\mathrm{d}R} + 4\Omega^2\right)_{R_g}$$

For a point mass ($\Omega \propto R^{-3/2}$), $\kappa = \Omega$

For an isothermal sphere ($\Omega \propto R^{-1}$), $\kappa = \Omega\,(2)^{1/2}$

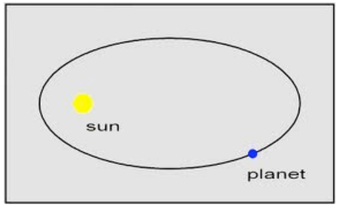
For solid body rotation (Ω = constant), $\kappa = 2\Omega$

In general, $\Omega < \kappa < 2\,\Omega$

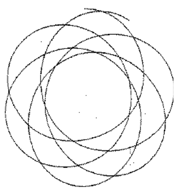
Therefore, a star can only undergo 2 revolutions in its epicyclic orbit in the time it finishes an entire orbit around the center of the galaxy.

Epicyclic orbits

For the case of a point mass ($\Omega \propto R^{-3/2}$), e.g., solar system, the epicyclical time perfectly matches the rotation time around the central body so that orbits close on each other.



In general, this is not true, however. Orbits regress and one finds a planar rosette.



Epicyclic orbits

Using the measured values for κ and Ω at the radial position of the sun in our galaxy is as follows:

$\kappa = 1.3\,\Omega$

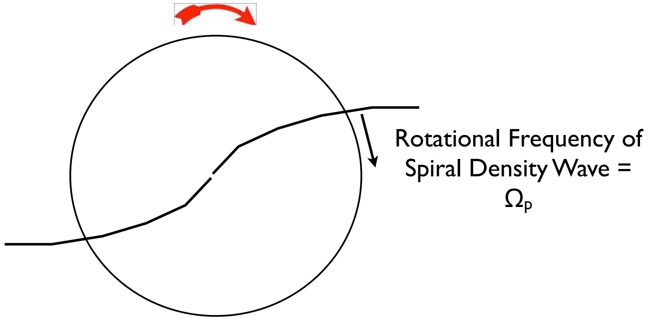
similar to the case for an isothermal sphere...

Period for orbit around galaxy = $2\pi/\Omega$

Period for epicyclic orbit = $2\pi/\kappa$

Which resonances drive spiral density wave growth?

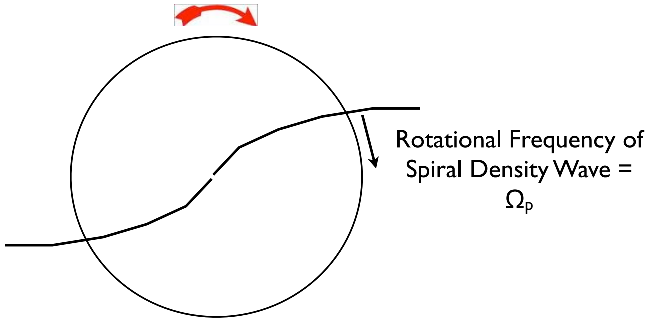
Now let us now consider a possible spiral density wave in the disk of a galaxy:



In these illustrations, let's adopt the most common type of "grand design" spiral galaxy where we just have 2 arms (rotational symmetry = 180 degrees)

Which resonances drive spiral density wave growth?

When might we expect growth of a spiral density wave?



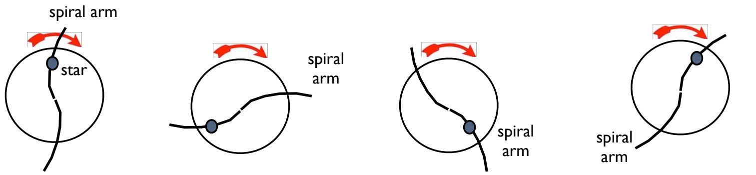
We might expect such if a star completes one period of epicyclic motion every time it encounters the spiral density wave in its orbit around the galaxy.

Which resonances drive spiral density wave growth?

Let us consider a few examples of the orbit of stars that would finish a complete epicyclic orbit in the spiral density wave itself:

Example #1: The star is moving at the same speed as the spiral density in orbiting around the center of a galaxy.

Let's consider snapshots in time where the star completes an entire epicyclic orbit. Typically a star must complete 70% of a revolution around a galaxy before this happens.



one epicyclic orbit
time = $2\pi/\kappa$
spiral pattern ~ 250 deg
star orbitted ~ 250 deg

two epicyclic orbits
time = $4\pi/\kappa$
spiral pattern ~ 500 deg
star orbitted ~ 500 deg

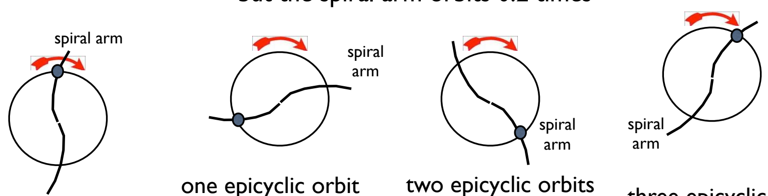
three epicyclic orbits
time = $6\pi/\kappa$
spiral pattern ~ 750 deg
star orbitted ~ 750 deg

Which resonances drive spiral density wave growth?

Let us consider a few examples of the orbit of stars that would finish a complete epicyclic orbit in the spiral density wave itself:

Example #2: The star is traveling much faster than the speed of the spiral density wave.

Let's consider snapshots in time where the star completes an entire epicyclic orbit. In this case, the star again completes 70% of an orbit, but the spiral arm orbits 0.2 times



time = 0

one epicyclic orbit
time = $2\pi/\kappa$
spiral pattern ~ 70 deg
star orbitted ~ 250 deg

two epicyclic orbits
time = $4\pi/\kappa$
spiral pattern ~ 140 deg
star orbitted ~ 500 deg

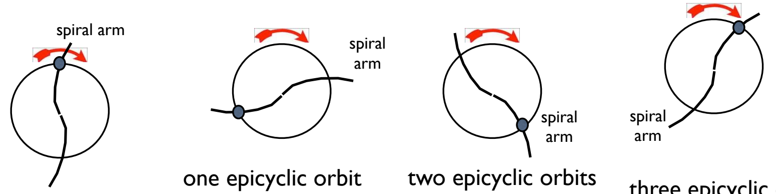
three epicyclic orbits
time = $6\pi/\kappa$
spiral pattern ~ 210 deg
star orbitted ~ 750 deg

Which resonances drive spiral density wave growth?

Let us consider a few examples of the orbit of stars that would finish a complete epicyclic orbit in the spiral density wave itself:

Example #3: The star is traveling much slower than the speed of the spiral density wave.

Let's consider snapshots in time where the star completes an entire epicyclic orbit. In this case, the star again completes 70% of an orbit, but the spiral arm orbits 1.2 times (instead of just 0.2 times)



time = 0

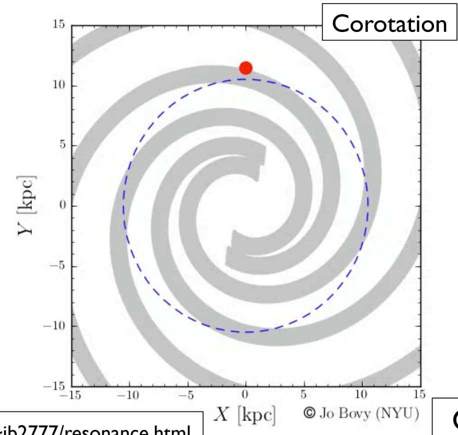
one epicyclic orbit
time = 2π/κ
spiral pattern ~ 430 deg
star orbitted ~ 250 deg

two epicyclic orbits
time = 4π/κ
spiral pattern ~ 860 deg
star orbitted ~ 500 deg

three epicyclic orbits
time = 6π/κ
spiral pattern ~ 1290 deg
star orbitted ~ 750 deg

Which resonances drive spiral density wave growth?

Let us look at a few movies that illustrate these concepts rather directly:

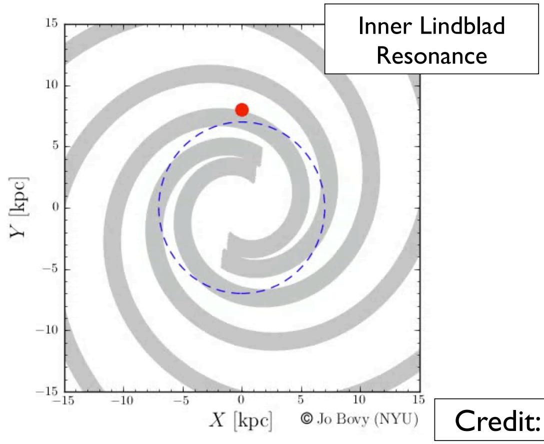


http://cosmo.nyu.edu/~jb2777/resonance.html

Credit: Jo Bovy

Which resonances drive spiral density wave growth?

Let us look at a few movies that illustrate these concepts rather directly:



Credit: Jo Bovy

Which resonances drive spiral density wave growth?

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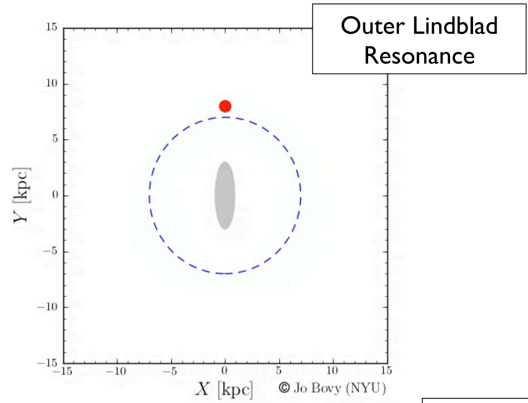


Credit: Jo Bovy

Which resonances drive spiral density wave growth?

To ensure that some arbitrary star can complete an epicyclic orbit in the same time it takes to move from one region in the spiral arm to another, the following condition must be satisfied:

some integer

$$m(\Omega_p - \Omega) = n\kappa$$

# of Spiral Arms

Orbital Frequency of Spiral Arms

Orbital (or Azimuthal) Frequency of Stars on Circular Orbits

Epicyclic (or radial) Frequency

The only integers n for this relation that are interesting are 0, +1, -1.

Which resonances drive spiral density wave growth?

This results in a number of well known resonances:

		Most relevant cases:
Inner Lindblad resonance:	$\Omega_p = \Omega - \kappa/m$	$\Omega_p = \Omega - \kappa/2$
Outer Lindblad resonance:	$\Omega_p = \Omega + \kappa/m$	$\Omega_p = \Omega + \kappa/2$
Corotational radius:	$\Omega_p = \Omega$	$\Omega_p = \Omega$

In most cases, the only relevant case is that of two spiral arms, i.e., m = 2

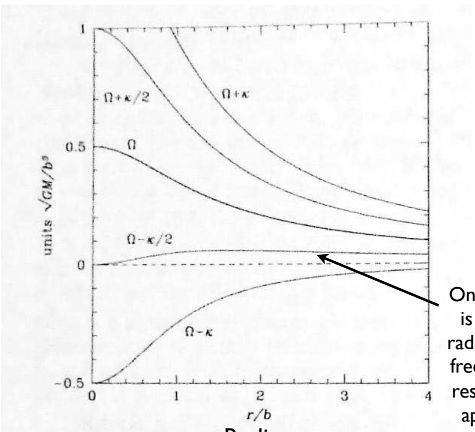
At what orbital frequencies for the spiral arms are these resonances relevant?

Compute $\Omega_p = \Omega - \kappa/2, \Omega, \Omega + \kappa/2$

How does the resonant frequencies vary by radius?

Ω_p

Orbital frequency for spiral arms at which these resonances become important



isochrone potential

One thing you should note is the extended range in radius where the rotational frequency for one of these resonances, i.e., $\Omega - \kappa/2$ is approximately constant.

Radius

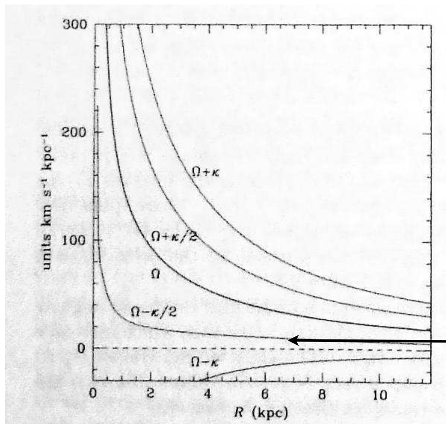
At what orbital frequencies for the spiral arms are these resonances relevant?

Compute $\Omega_p = \Omega - \kappa/2, \Omega, \Omega + \kappa/2$

How does the resonant frequencies vary by radius?

Ω_p

Rotational frequency for spiral arms at which these resonances become important



model 1 for our Galaxy from BT 2.7

Again $\Omega - \kappa/2$ is almost independent of radius!

Radius

What are the typical physical radii where these resonances apply?