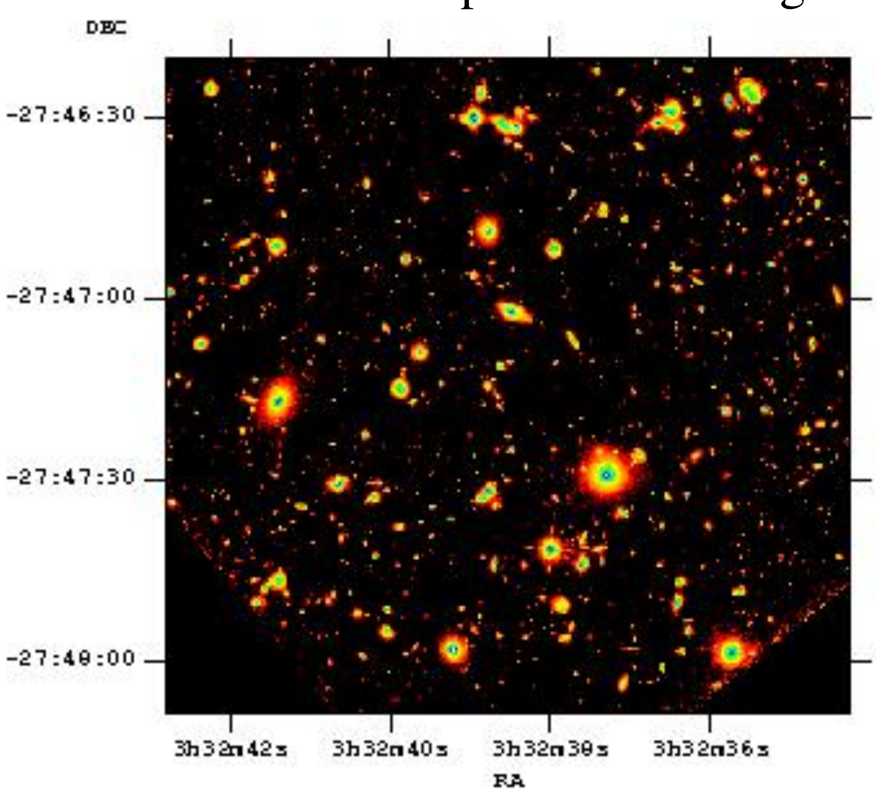
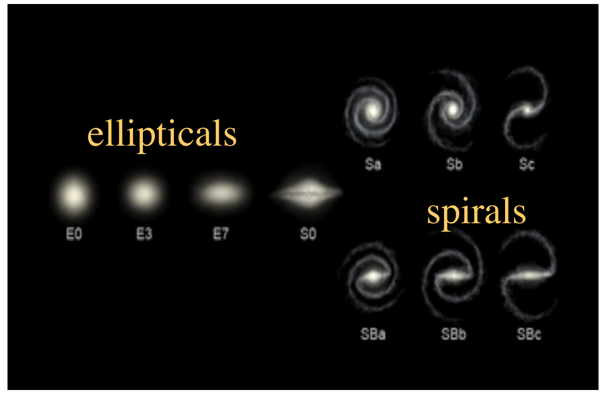
Summary-

Hubble Ultra Deep Field- ~3000 galaxies



Galaxies

- What is a galaxy?
  - Observationally
  - Theoretically
- Observationally
  - A lot of matter in 'one' place
    - historically matter was traced by optical light (due mostly to stars)
    - Now can find and study galaxies by radio and mm emission from ionized gas and by emission in x-rays from their ISM+ black holes
- Theoretically
  - A bound system with a mass between that of a globular cluster (~10^6 $M_\odot$ and a group of galaxies ~10^{13} $M_\odot$)
  - Most of the mass (>65%) is dark matter (>20x more DM than stars)
    - **e,g compact condensation of baryons near the center of dark matter halos.**



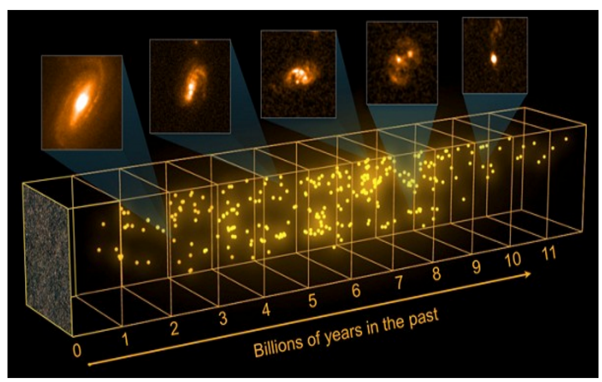
Galaxies come in a huge range of shapes and sizes

Generically divided into two generalized morphologies
spirals
ellipticals

Topics we covered

- Broad description of galaxies
- Stellar populations/star formation
- Gas and Dust in galaxies
- Milky Way as a detailed example of a galaxy
- Local group as extension of detailed example
- Galactic dynamics/need for dark matter
- Spiral galaxies
- Elliptical galaxies
- Galactic evolution/formation and cosmological implications
- Active Galactic nuclei -relation to host galaxy

- This is an **enormous** range of material; the level of detail varied greatly from section to section



The BIG Picture

- Essentially, all research on galaxies aims at answering how galaxies form and evolve
- Steps include understanding the role of the different galactic structural components in this history, and how they relate with each other..
- We linked structural analysis, kinematics and dynamics, stellar population properties and evolution, multi-wavelength observations, redshift evolution, and theory.
- From a theoretical point of view Galaxies reside in dark matter halos, but, are biased tracers of the underlying matter distribution: that is the observable galaxy properties such as luminosity are not *simple* tracers of dark matter.
  - we discussed how dynamical measurements as well as other observations can determine baryonic and dark matter distributions
- Galaxies change over cosmic time
  - at present most star formation occurs in spirals
  - ellipticals are old systems and formed most of their stars in the distant past.

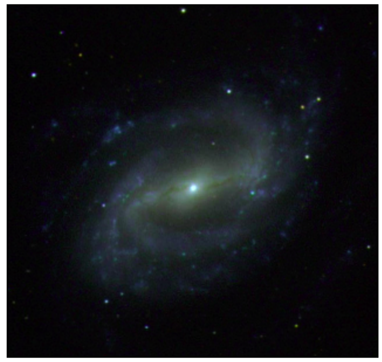
Modern galaxy research

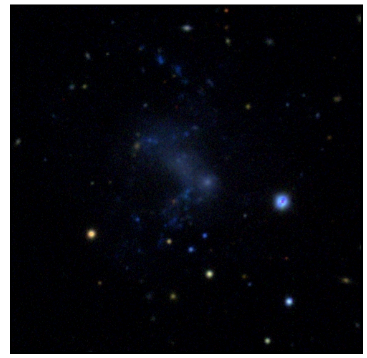
- Explain the observed galaxy population and its changes over cosmic time
- **Understand why galaxies show the extreme regularity of various parameters**
- Cosmic laboratories for all the details of astrophysics
  - star formation
  - interaction of baryons with dark matter
  - formation of the chemical elements
  - the relationship of black holes to their host galaxies (AGN)

What is galaxy research about?

- Explain galaxy population as consequence of initial conditions (+ stability arguments + feedback)
- Understand astonishing regularity of galaxy population
- Understand galaxies well enough to make them (even better) cosmological diagnostics
- Test of galaxy formation
- Have fun!

Galaxies:The Short of It





Ellipticals

$M_{halo} > 10^{11} M_{\odot}$

V~350km/s

Highly Clustered

Old stars

little star formation now

Spirals

$M_{halo} > 10^{10} M_{\odot}$

V~200km/s

wide range of stellar ages

star forming

Dwarfs

$M_{halo} > 10^{8} M_{\odot}$

V~30km/s

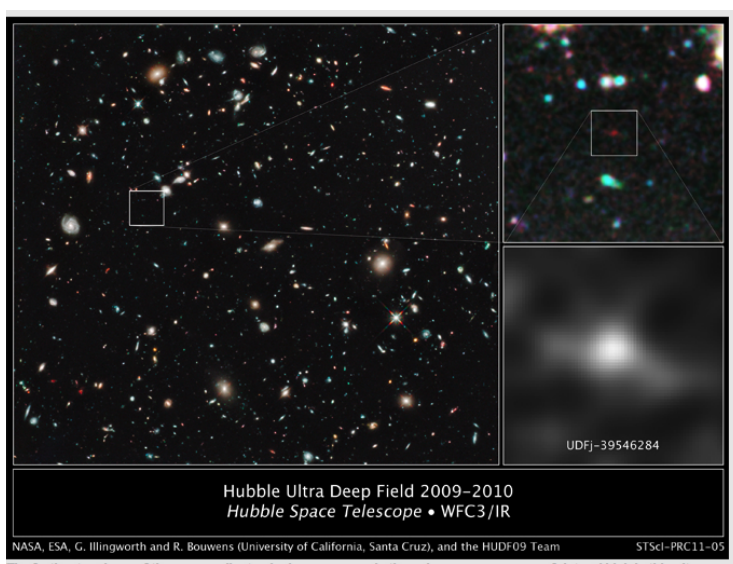
Weakly Clustered

Young stars

Numerous

Galaxies Over Cosmic Time

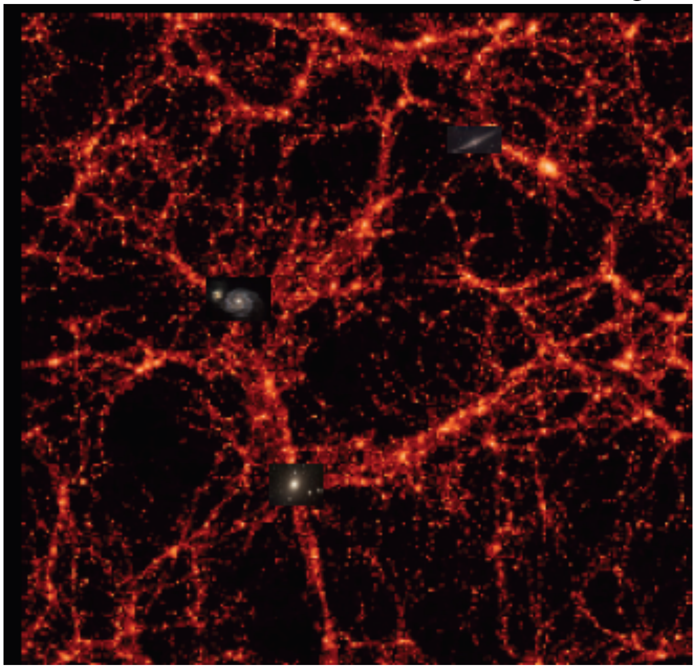
- Direct imaging by HST has shown the existence of galaxies at z~8 (13Gyrs age, for an age of the universe model of 13.7Gyrs)
- Stellar ages: in the MW oldest stars are ~13.2Gyrs old (error of +/-2 Gyrs)
- Galaxies have changed enormously over cosmic time
- The present day pattern of galaxies emerged at z~1



The farthest and one of the very earliest galaxies ever seen in the universe appears as a faint red blob in this ultra-deep–field exposure taken with NASA's Hubble Space Telescope. This is the deepest infrared image taken of the universe. Based on the object's color, astronomers believe it is 13.2 billion light-years away. (Credit: NASA, ESA, G. Illingworth (University of California, Santa Cruz), R. Bouwens (University of California, Santa Cruz, and Leiden University), and the HUDF09 Team)

Galaxies Do Not Live Alone

- Galaxies are part of the 'cosmic web'- representing overdense regions of both baryons and dark matter
- The effective size of the dark matter is much larger than the apparent stellar size



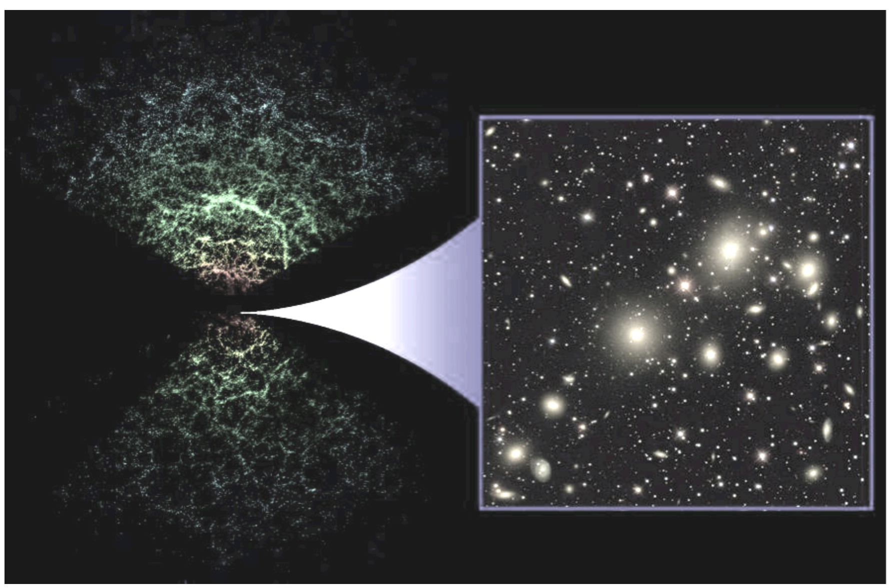
The cosmic web has structure at all scales but eventually becomes homogenous at R>70Mpc

Clusters are at the intersection of the filements of the web

Eric Bell

Large Scale distribution of normal galaxies

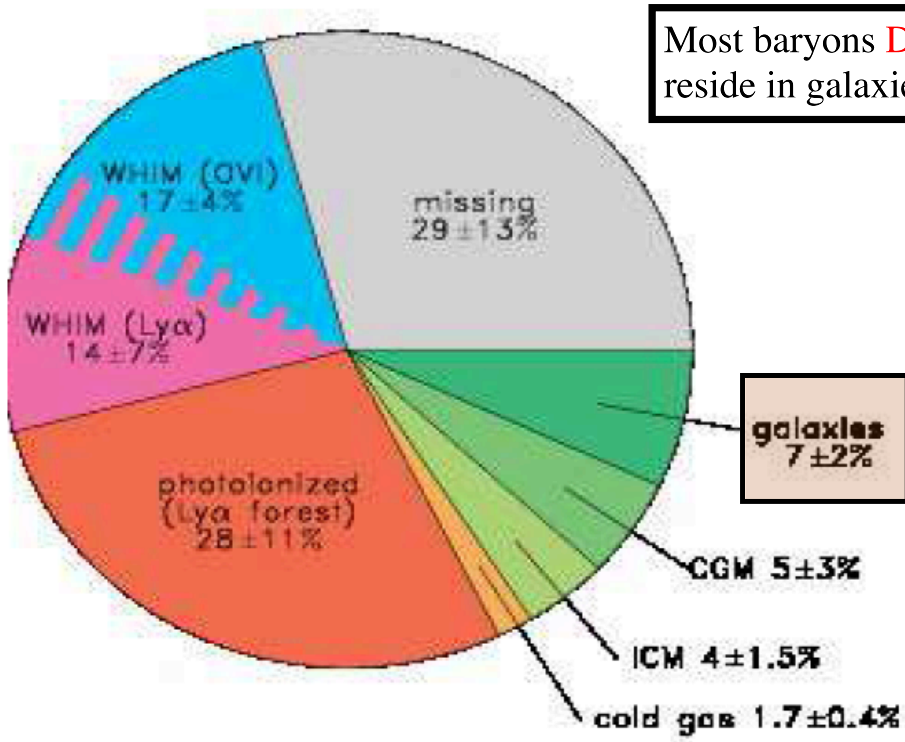
- On scales $<10^8$pc the universe is 'lumpy'- e.g. non-homogenous
- On larger scales it is homogenous- and isotropic



Sloan Digital Sky Survey- http://skyserver.sdss3.org/dr8/en/

Where are the Baryons

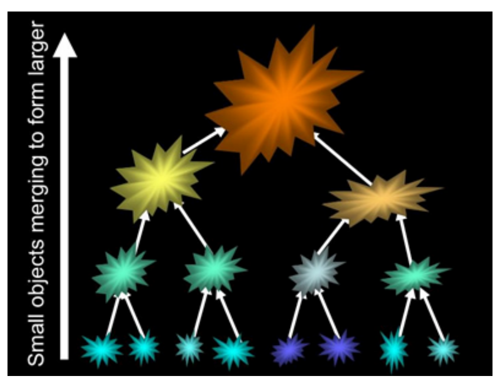
Shull Danforth 2012



Most baryons DO NOT reside in galaxies

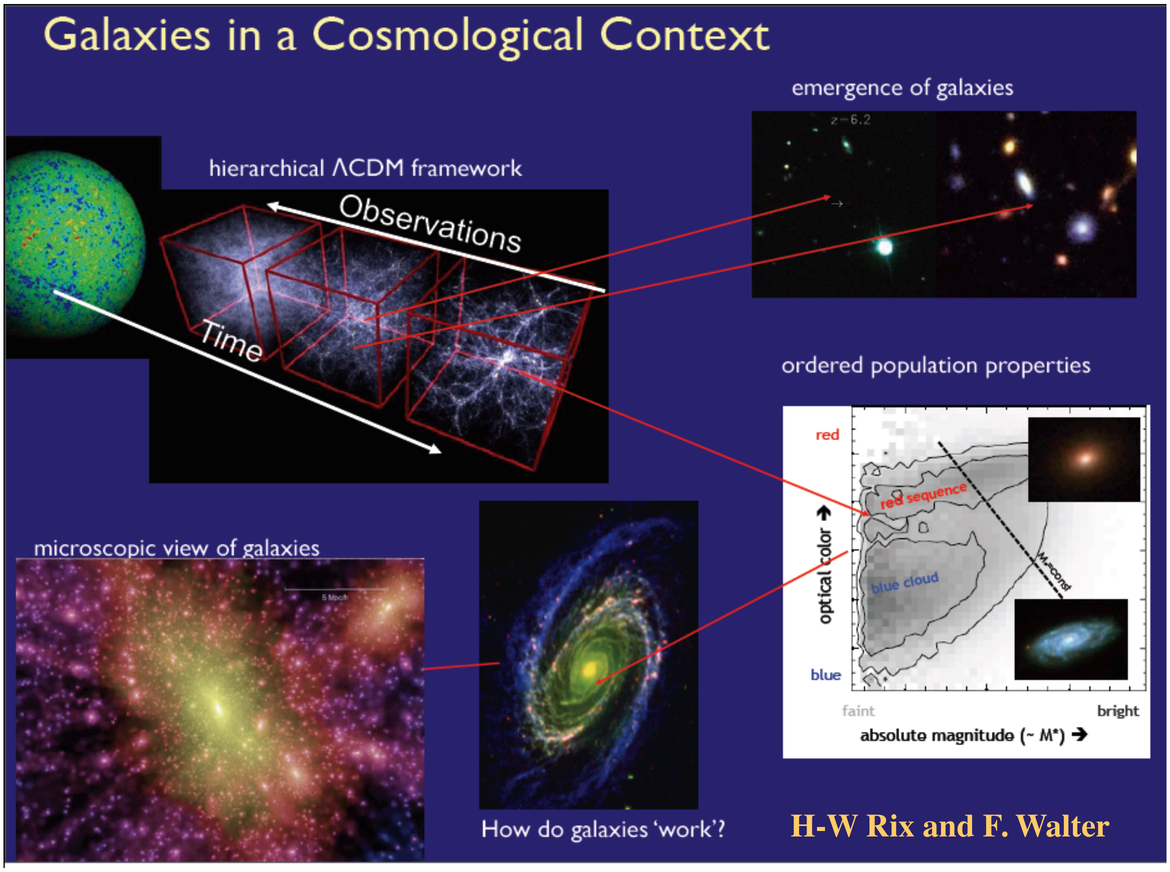
How Things Form

- Gravity acts on overdensities in the early universe making them collapse.
- As time goes on these collapsed regions grow and merge with others to make bigger things



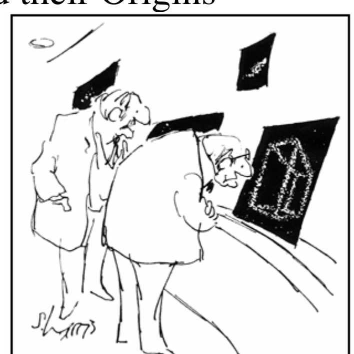
•Hierarchical clustering (or hierarchical merging) is the process by which larger structures are formed through the continuous merging of smaller structures.

•The structures we see in the Universe today (galaxies, clusters, filaments, sheets and voids) are predicted to have formed by the **combination** of collapse and mergers according to Cold Dark Matter cosmology (the current concordance model).

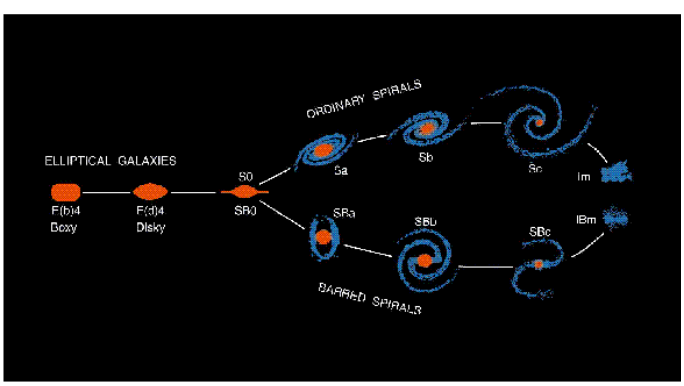


The Two Big Types of Galaxies and their Origins

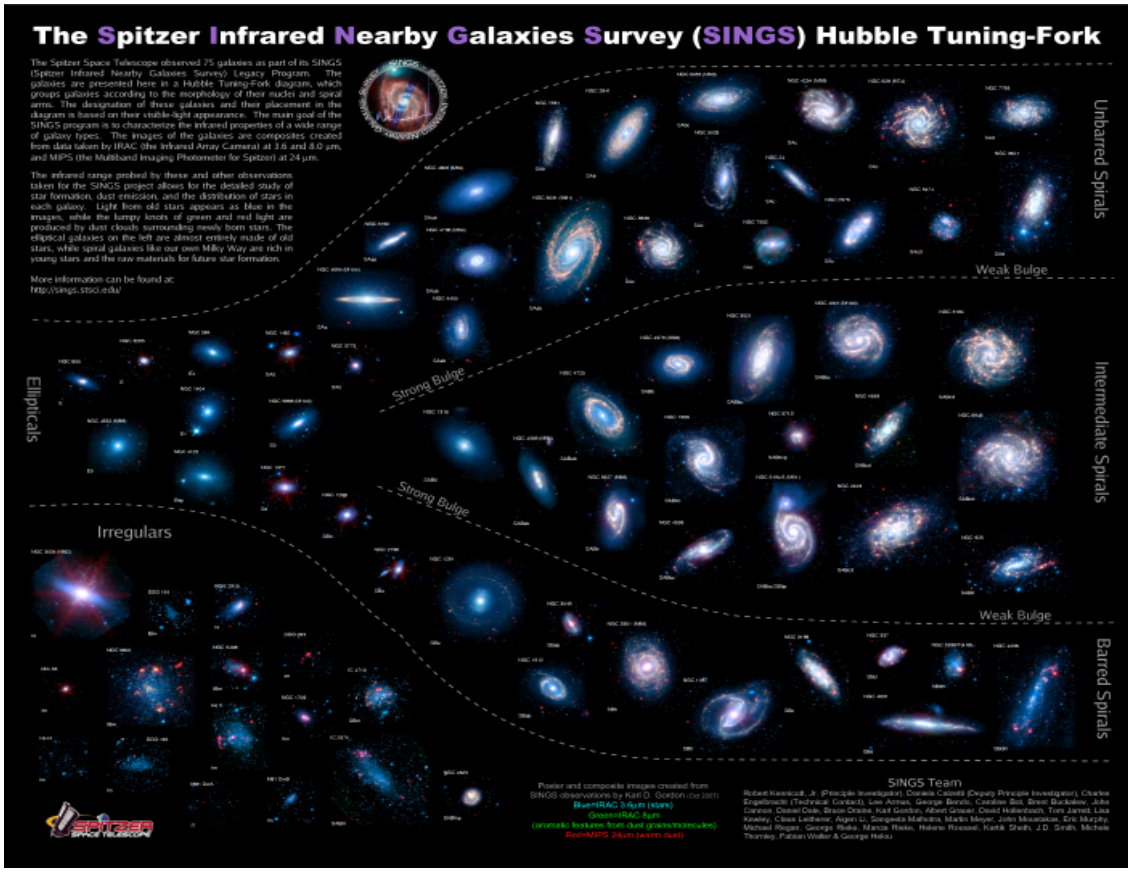
- The properties of galaxies form a distinct pattern:
- Ellipticals tend to be massive, red and old
- Spirals less massive blue and 'younger'
  - Colors are related to the amount of star formation at present



"You've seen spiral galaxies, you've seen elliptical galaxies..."



see: Kormendy J., Bender R. (1996) *ApJ*, **464**, L119



Panchromatic MilkyWay

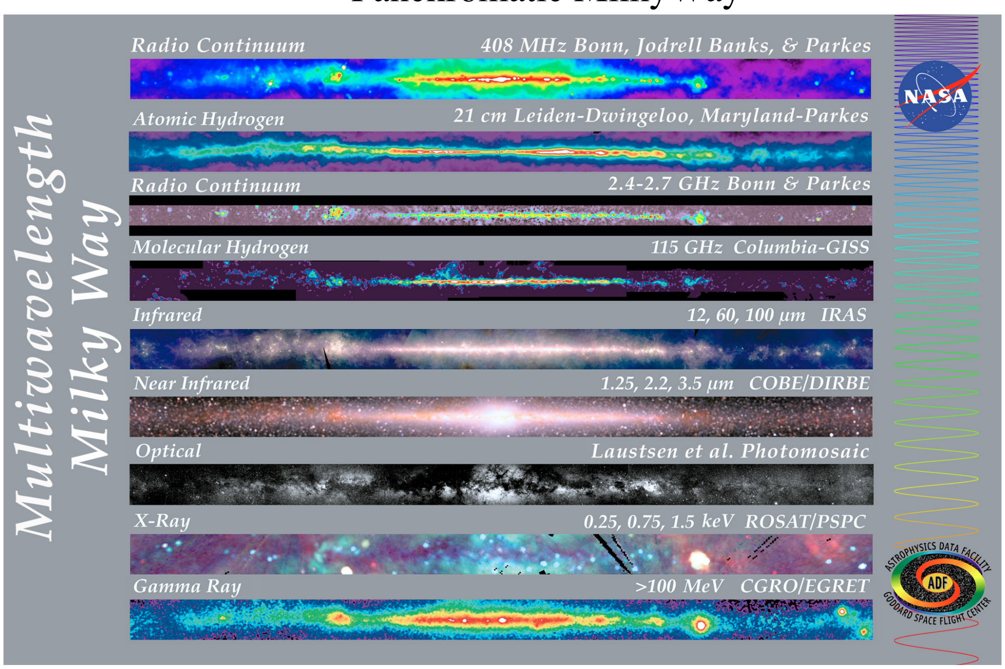
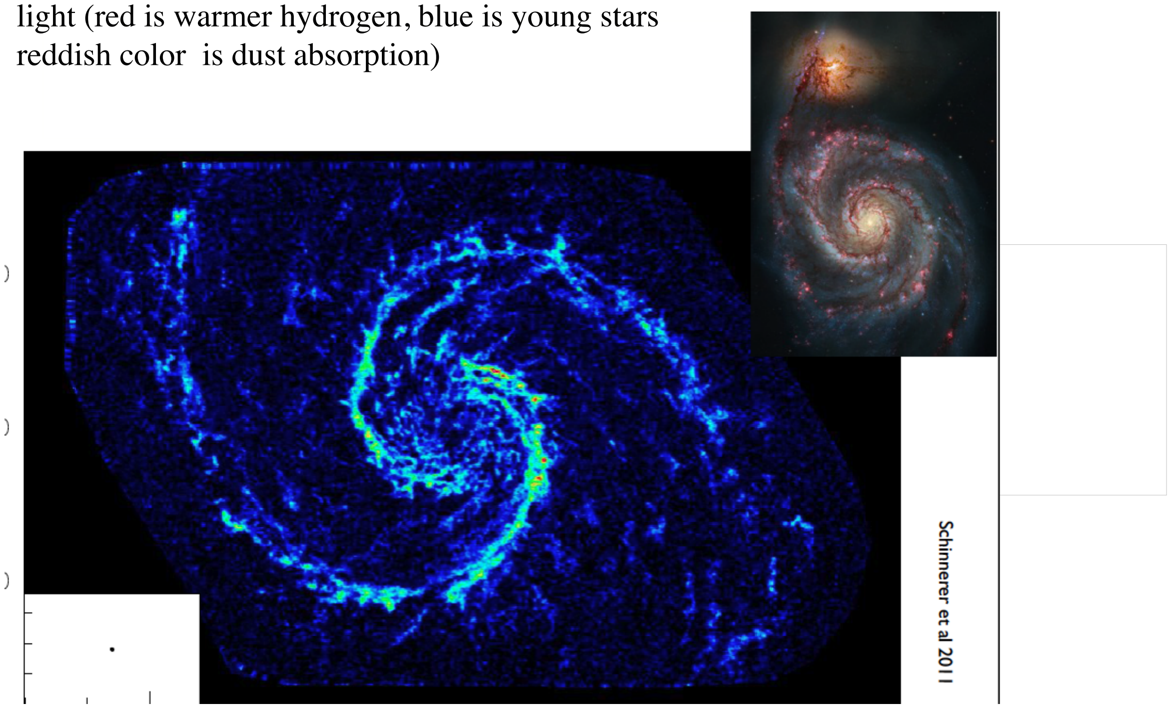


Image of MW galactic plane from radio through γ-rays- appearance of galaxies can look very different in different wave bands

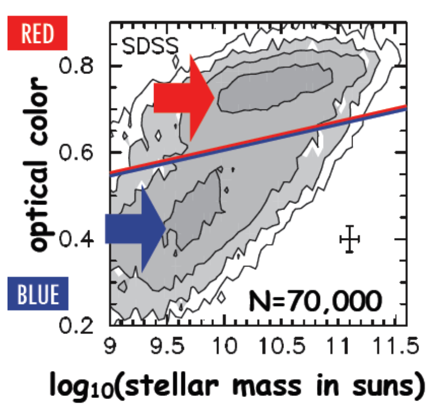
'Cool gas' (HI-hydrogen) and color coded
light (red is warmer hydrogen, blue is young stars
reddish color is dust absorption)



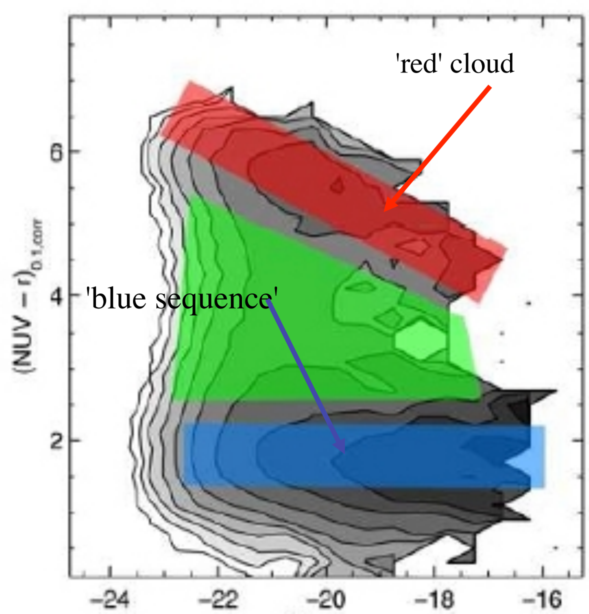
Galaxy Relations
Strong Connection of morphology

and physical properties

- Density of galaxies vs color and luminosity
- Galaxies fall into 2 broad classes
  - 'red' cloud-mostly ellipticals
  - **'blue sequence'** mostly spirals
  - Few galaxies between- 'green valley'



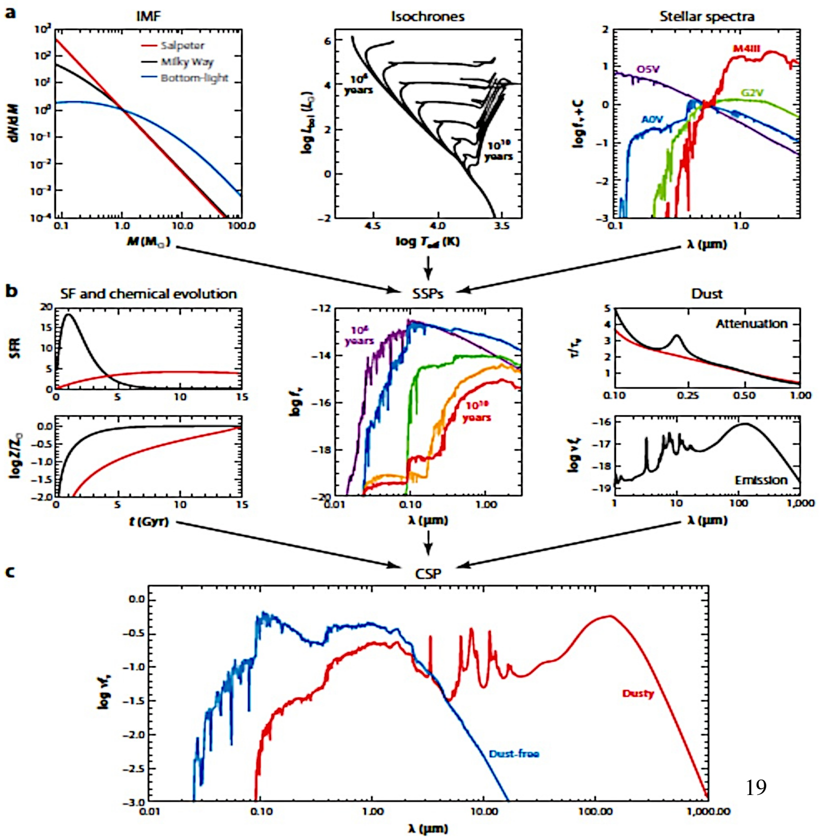
Isopleths- lines of constant galaxy density



Absolute magnitude
Baldry et al 2004

What is the Process – Conroy 2013

MBW sec 10.3



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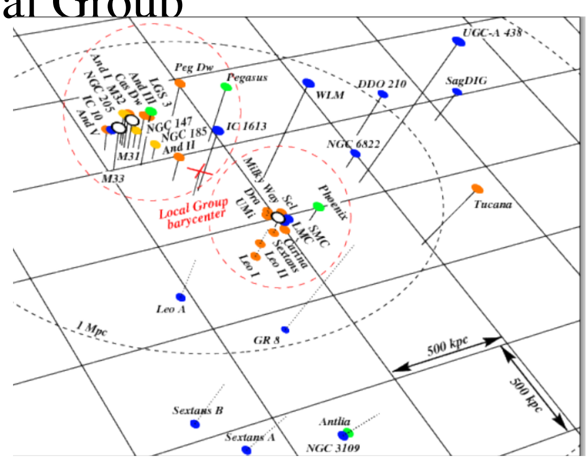
Local Group



- Our galactic neighborhood consists of one more 'giant' spiral (M31, Andromeda), a smaller spiral M33 and lots of (>35 galaxies), most of which are dwarf ellipticals and irregulars with low mass; **most are satellites of MW, M31 or M33**
- The gravitational interaction between these systems is complex but the local group is apparently bound.
- Major advantages
  - close and bright- all nearby enough that individual stars can be well measured as well as HI, H_2, IR, x-ray sources and even γ-rays
  - wider sample of universe than MW (e.g. range of metallicities, star formation rate etc etc) to be studied in detail

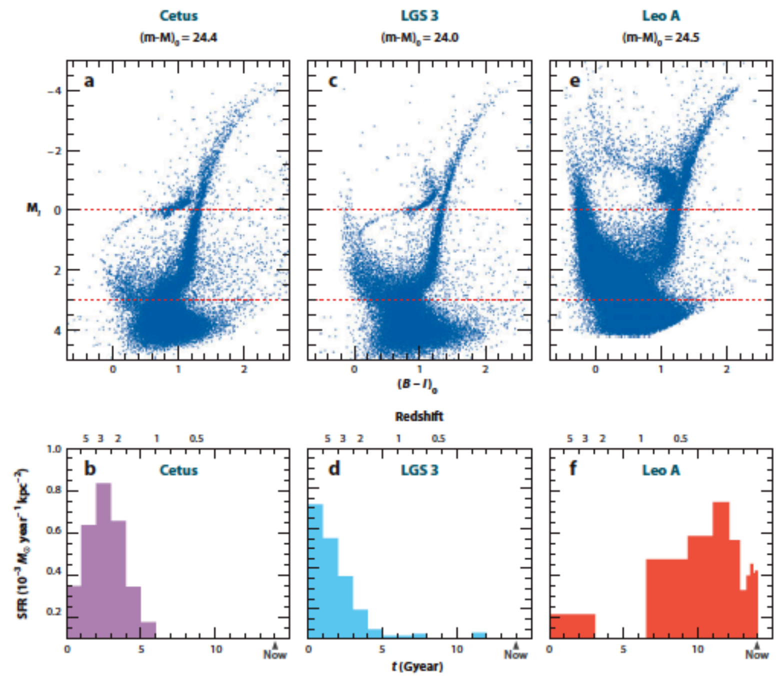
–allows study of dark matter on larger scales and first glimpse at galaxy formation

–calibration of Cepheid distance scale

MBW fig 2.31

Star Formation Histories Local Group Dwarfs

- With HST can observe color magnitude diagram for individual stars in local group galaxies
- Using the techniques discussed under the stars lectures can invert this to get the star formation history
- Note 2 extremes: very old systems (Cetus, wide range of SF histories (Leo A)



0 10 now

t (Gyr)

Local Group Summary-

- What is important
  - local group enables detailed studies of objects which might be representative of the rest of the universe (e.g CMDs of individual stars to get SF history, spectra of stars to get metallicity, origin of cosmic rays etc)
  - wide variety of objects -2 giant spirals, lots of dwarfs
  - chemical composition of other galaxies in local group (focused on dwarfs and satellites of the MW) similar in gross terms, different in detail; indications of non-gravitational effects (winds); went thru 'closed box' approximation allowed analytic estimate of chemical abundance
  - dynamics of satellites of MW (Magellanic clouds) clues to their formation, history and amount of dark matter
  - dwarfs are the most dark matter dominated galaxies we know of- closeness allows detailed analysis.
  - dwarf galaxy 'problem' are there enough low mass dwarfs around MW??- lead to discussion later in class about galaxy formation and Cold dark matter models

Spirals-The Components

Disks:

Rotationally supported, lots of gas, dust, star formation occurs in disks, spiral arms

Origin in CDM models: disk galaxies form in halos with high angular momentum and quiet recent assembly history, ellipticals are the slowly-rotating remnants of repeated merging events. Disks, form out of gas that flows in with similar angular momentum to that of earlier-accreted material

Bulges:

- somewhat spheroidal featureless (no spiral arms, bars, rings etc) that stick out of the disk plane,
- mostly old stars (not much dust or star-forming regions),
- kinematically hot, i.e. dynamically supported by the velocity dispersion of their stars- but they do rotate more significantly than ellipticals

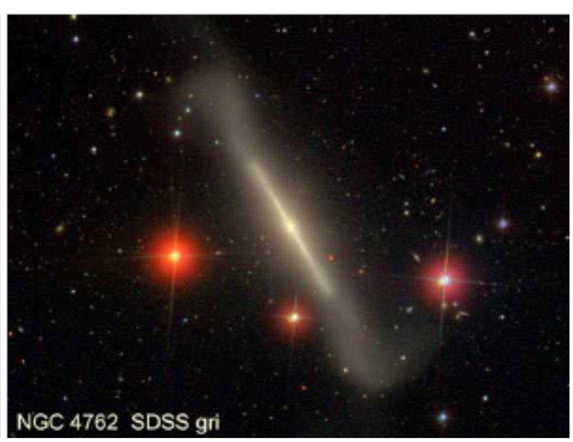
Origin

- thought to form via mergers (i.e. accretion of usually smaller external units)- disks reform later after merger by accretion of gas.

Spirals

- have cold gas and dust
- present day star formation
- many have internal structure (spiral arms and bars)
- a bulge and disk (large range in relative importance)
- host **radio quiet AGN**
- are more frequent in lower density environments
- appearance of galaxy can change radically depending on the 'stretch'
- x-ray luminosity is dominated by binaries
- ISM is highly structured

NGC 4594- Hubble Heritage



NGC 4762 SDSS gri

Dust

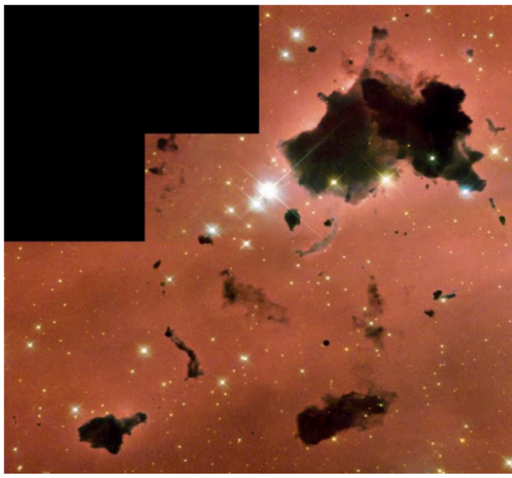
Controls the Optical,UV, IR properties of spirals

Not important in ellipticals at low redshift

Not effect radio or x-rays much

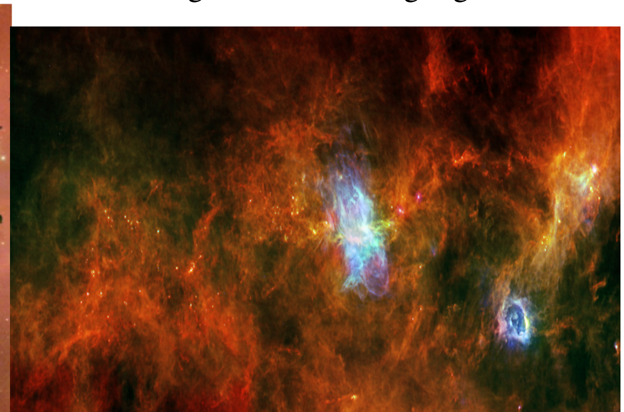
Optical image of star forming region

Interstellar extinction

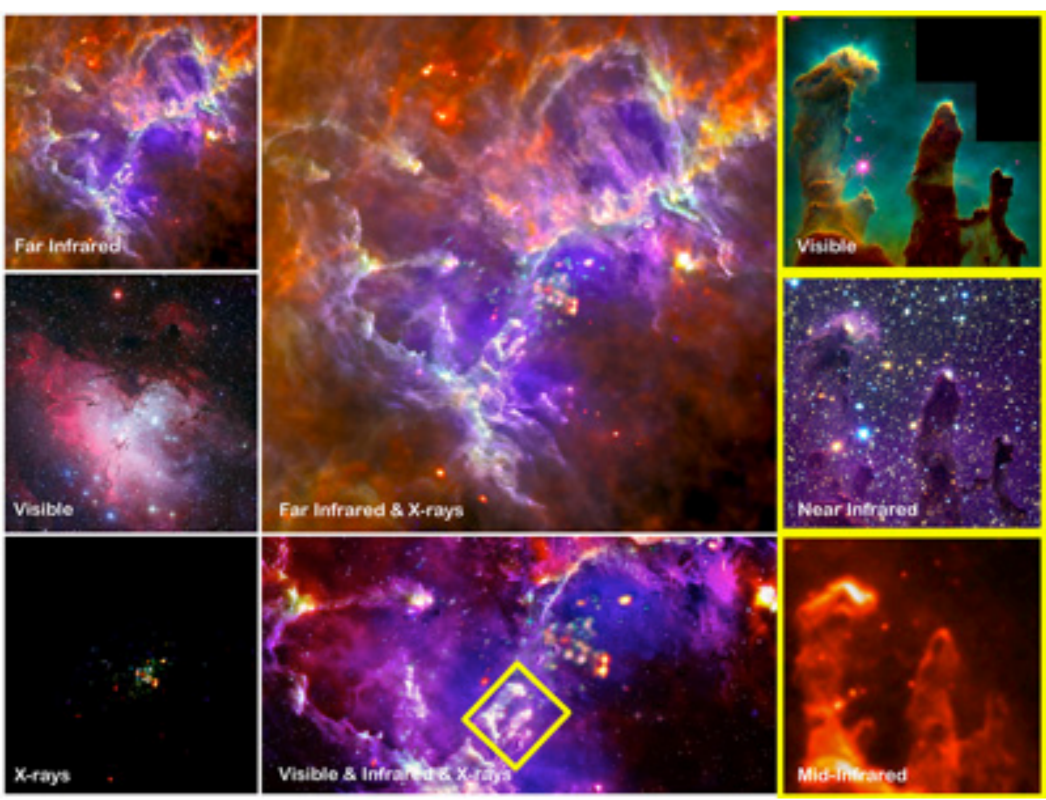


Interstellar Emission-

IR image of star forming region



Emission and Absorption in MultipleWave Bands



Star Formation

The physics of star formation (what processes produce stars) and the astrophysics (where and when were the stars produced) are two of the dominant issues in astrophysics at present- unfortunately they are not covered by the text.

- Stars form from dense, cold gas either in disks or in gas that is violently shock compressed (in mergers)

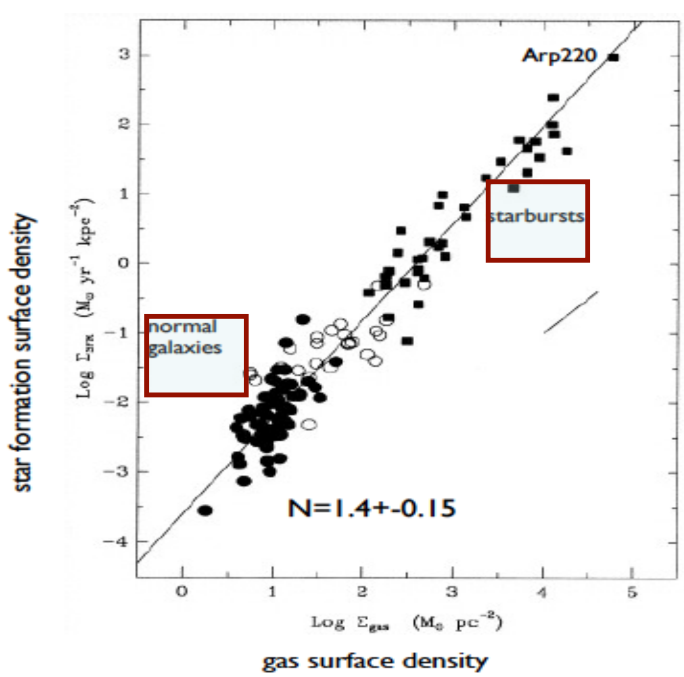
Current SF can be estimated from a variety of techniques

- Hα observations, which gives the number of ionizing photons if one assumes that all ionizing photons are used and eventually re-emitted - ionizing photons are almost exclusively emitted by massive (hot) stars which have short lifetimes; slo the effects of dust can be large
- far-IR flux - this assumes that a constant fraction of the emitted stellar energy is absorbed by dust
- radio continuum emission - this statistically correlated very well with the IR radiation- physics is complex since radio emission comes from synchrotron radiation from relativistic electrons+ thermal bremmstrahlung from hot gas
- far-UV flux (- which is primarily emitted by young (hot) stars- but older /less massive than those responsible for Hα
- X-ray emission- produced by 'high mass' x-ray binaries (a Neutron star or black hole with a massive companion)

Kennicutt Schmidt Law

- **Relation of star formation rate per unit area to gas surface density (an observable)**
- $\Sigma_{SFR}=A\sigma^{n}_{gas}$; n~1.4

gas consumption efficiency is low ~1.5×10^{9}yrs to convert all the gas into stars



Gravity and Dynamics-Spherical Systems

- Newtons 1st theorm : a body inside a a spherical shell has no net force from that shell $\nabla\phi = 0$
- Newtons 2nd theorm ; a body outside the shell experiences forces as if they all came from a point at the center of the shell-Gravitational force at a point outside a closed **sphere** is the same as if all the mass were at the center
  - This does not work for a thin disk- cannot ignore what is outside of a given radius
- One of the prime observables (especially for spirals) is the circular velocity; in general it is $V^2(R)/R=G(M<R)/R^2$ more accurate estimates need to know shape of potential
- so one can derive the mass of a flattened system from the rotation curve

----

- point source has a potential $\phi=-GM/r$
- A body in orbit around this point mass has a circular speed $v_c^2=r\ \phi d/dr=GM/r$
- v_c=sqrt(GM/r); Keplerian
- Escape speed from this potential v_{escape}=sqrt(2ϕ)=sqrt(2GM/r) (conservation of energy KE=1/2mv^2_{escape})

Full Up Equations of Motion- Stars as an Ideal Fluid(S+G pgs140-144, MBW pg 163)

Continuity equation (particles not created or destroyed)

$d\rho/dt+\rho\nabla.v=0$; $d\rho/dt+d(\rho v)/dr=0$

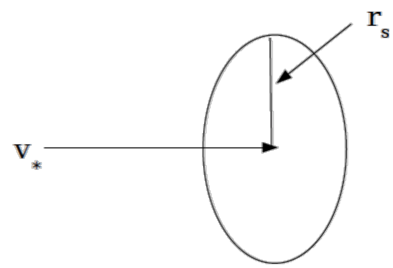
Eq's of motion (Eulers eq)
$dv/dr=\nabla P/\rho-\nabla\Phi$

Poissons eq $\nabla^2\Phi(r)=-4\pi G\rho(r)$
example

•Point mass $\phi(r)=-GM/r$; $F(R)=-\nabla\phi=d\phi/dr=-GM/r^2$

How Often Do Stars Encounter Each Other

For a 'strong' encounter $GmM/r>1/2mv^2$ e.g. potential energy exceeds KE
So a critical radius is $r<r_s=2GM/v^2$



Putting in some typical numbers $m\sim 1/2M_\odot$
$v=30$km/sec $r_s=1$AU
So how often do stars get that close?

consider a cylinder $Vol=\pi r^2_s vt$; if have n stars per unit volume than on average the encounter occurs when
$n\pi r^2_s vt=1$, $t_s=v^3/4\pi nG^2m^3$

Putting in typical numbers $\sim 4x10^{12}(v/10km/sec)^3(m/M_\odot)^{-2}(n/pc^3)^{-1}$ yr
a very long time (universe is only 10^{10}yrs old- galaxies are essentially collisionless

Virial Theorem

(2KE)+Potential energy (W) =0

after a few dynamical times, if unperturbed a system will come into Virial equilibrium-time averaged inertia will not change so $2<T>+W=0$

For self gravitating systems $W=-GM^2/2R_H$; R_H is the harmonic radius- the sum of the distribution of particles appropriately weighted
$1/R_H=1/N\,\Sigma_i\,1/r_i$
The virial mass estimator is $M=2\sigma^2R_H/G$; for many mass distributions $R_H\sim 1.25\,R_{eff}$
where sR_{eff} is the half light radius σ is the 3-d velocity dispersion

Jeans Eq

- $n\partial(\langle v_j\rangle/\partial t) + n\langle v_i\rangle \partial\langle v_j\rangle/\partial x_i = -n\partial\phi/\partial x_j - \partial(n\sigma^2_{ij})/\partial x_i$
- So what are these terms??
- Gas analogy: Euler's eq of motion

  $\rho\, \partial\mathbf{v}/\partial t + \rho\, (\mathbf{v}\ .\ \nabla)v = -\nabla P - \rho\nabla\Phi$
- $n\partial\phi/\partial x_j$: gravitational pressure gradient
- $n\sigma^2_{ij}$ "stress tensor" is like a pressure, but may be anisotropic, allowing for different pressures in different directions - important in elliptical galaxies and bulges 'pressure supported' systems (with a bit of coordinate transform one can make this symmetric e.g. $\sigma^2_{ij}=\sigma^2_{ji}$)

Characteristic Velocities

$v^2_{circular}$=r dΦ(r)/dt=GM/r; v=sqrt(GM/r) Keplerian

velocity dispersion **$\sigma^2=(1/\rho)\int\rho\,(\partial\Phi(r,z)/\partial z)dz$**

or alternatively $\sigma^2(R)=(4\pi G/3M(R)\int r\rho(r)\, M(R)\, dr$

escape speed =v_{esc}=sqrt(2Φ(r)) or $\Phi(r)=1/2v^2_{esc}$
so choosing r is crucial

Jeans Equations MBW sec 5.4.3

- Since f is a function of 7 variables, obtaining a solution is challenging
- Take moments (e.g. integrate over all **v**)
- let n be the space density of 'stars'

$\partial n/\partial t + \partial(n\langle v_i\rangle)/\partial x_i = 0$; continuity eq. zeroth moment

first moment (multiply by v and integrate over all velocities)

$\partial(n\langle v_j\rangle/\partial t) + \partial(n\langle v_i v_j\rangle)/\partial x_i + n\partial\phi/\partial x_j = 0$

equivalently

$n\partial(\langle v_j\rangle/\partial t) + n\langle v_i\rangle\,\partial\langle v_j\rangle/\partial x_i = -n\partial\phi/\partial x_j - \partial(n\sigma^2_{ij})/\partial x_i$

where

n is the integral over velocity of f; $n=\int f\, d^3v$

$\langle v_i\rangle$ is the mean velocity in the i^{th} direction $= (1/n)\int f\, v_i\, d^3v$

$\sigma^2_{ij} = \langle (v_i - \langle v_i\rangle)(v_j - \langle v_j\rangle)\rangle$ "stress tensor"

$= \langle v_i v_j\rangle - \langle v_i\rangle\langle v_j\rangle$

Spherical systems- Elliptical Galaxies and Globular Clusters

- For a steady-state non-rotating spherical system, the Jeans equations simplify to

$$(1/n)d/dr\,(n\langle v^2_r\rangle) + 2\beta\langle v^2_r\rangle/r = -GM(R)/r^2$$

- where $GM(R)/r^2$ is the potential and $n(r)$, $\langle v^2_r\rangle$ and $\beta(r)$ describe the 3-dimensional density, radial velocity dispersion and orbital anisotropy of the tracer component (stars)

$\beta(r) = 1-\langle v^2_\theta\rangle/\langle v^2_r\rangle$; $\beta = 0$ is isotropic, $\beta=1$ is radial

- We can then present the mass profile as
- $GM(r) = -r\langle v^2_r\rangle\,[(d\ln n/d\ln r) + (d\ln\langle v^2_r\rangle/d\ln r) + 2\beta]$
- while apparently simple we have 3 sets of unknowns $\langle v^2_r\rangle$, $\beta(r)$, $n(r)$
- and 2 sets of observables I(r)- surface brightness of radiation (in some wavelength band) and the lines of sight projected velocity field (first moment is velocity dispersion)
- It turns out that one has to 'forward fit'- e.g. propose a particular form for the unknowns and fit for them.

This will become very important for elliptical galaxies

Mass Determination

- for a perfectly spherical system one can write the **Jeans equation** as
- **$(1/\rho)d(\rho\langle v_r\rangle^2)/dr+2\beta/r\langle v_r\rangle^2=-d\phi/dr$**
- where ϕ is the potential and β is the anisotropy factor $\beta=1-\langle v_\theta\rangle^2/\langle v_r\rangle^2$
- since $d\phi/dr=GM_{tot}(r)/r^2$
- one can write the mass as
- $M_{tot}(r)=r/G\langle v_r\rangle^2\ [\{(\mathrm{dln}\ \rho/\mathrm{dln}r)+(\mathrm{dln}/\langle v_r\rangle^2)/\mathrm{dln}r\}+2\beta]$
- expressed in another way

$$M(r) = \frac{V^2 r}{G} + \frac{\sigma_r^2 r}{G}\left[-\frac{d\ln\nu}{d\ln r} - \frac{d\ln\sigma_r^2}{d\ln r} - \left(1-\frac{\sigma_\theta^2}{\sigma_r^2}\right) - \left(1-\frac{\sigma_\phi^2}{\sigma_r^2}\right)\right]$$

- Notice the nasty terms
- V_r is the rotation velocity σ_r $\sigma_{\theta,}$ σ_ϕ are the 3-D components of the velocity dispersion ν is the density of stars
- All of these variables are 3-D; we observe projected quantities !
- The analysis is done by generating a set of stellar orbits and then minimizing
- Rotation and random motions (dispersion) are both important.

Summary of Dynamical Equations

- **gravitational pot'l $\Phi(r)=-G\int\rho\ (r)/|r-r'|\ d^3r$**
- **Gravitational force $F(r)= -\nabla\Phi(r)$**
- **Poissons Eq $\nabla^2\Phi(r)= 4\pi G\rho$; if there are no sources**

  Laplace Eq $\nabla^2\Phi(r)= 0$
- **Gauss's theorem** : **$\int\nabla\Phi(r)\bullet ds^2=4\pi GM$**
- **Potential energy $W=1/2\int r\rho(r)\nabla\Phi d^3r$**

- In words Gauss's theorem says that the integral of the normal component of $\nabla\Phi$ over and closed surface equals $4\pi G$ times the mass enclosed

Spherical Systems: Homogenous sphere of radius a

Summary

- $M(r)=4/3\pi r^3\rho$ (r<a); r>a $M(r)=4/3\pi r^3 a$
- Inside body (r<a); $\phi(r)=-2\pi G\rho(a^2-1/3\ r^2)$ (from eq. 2.38 in B&T)

Outside (r>a);)$\phi(r)= -4\pi G\rho(a^3/3)$

Solid body rotation $v_c^2 = -4\pi G\rho(r^2/3)$

Orbital period $T=2\pi r/v_c=\mathrm{sqrt}(3\pi/G\rho)$;

a crossing time (dynamical time) $=T/4=\mathrm{sqrt}(3\pi/16G\rho)$

potential energy $W=-3/5GM^2/a$

The motion of a test particle inside this sphere is that of a simple harmonic oscillator $d^2r/dt^2= -G(M(r)/\ r^2=4\pi G\rho r/3$ with angular freq $2\pi/T$

no matter the intial value of r, a particle will reach r=0 in ~the dynamical time

In general the dynamical time t_{dyn}~1/sqrt(G<ρ>)

and the 'gravitational radius' $r_g= GM^2/W$

Variety of "Simple" Potentials

- Point mass $\phi(r)=-GM/r$
- Plummer sphere : simple model for spherical systems
  - $\phi(r)=-GM/\mathrm{sqrt}(r^2+a^2)$
- Singular isothermal sphere $\phi(r)=4\pi Gr^2_0\rho(r_0)\ \ln(r/r_0)$

  some interesting properties- circular speed is constant at

  $\mathrm{sqrt}(4\pi Gr^2_0\rho(r_0))$
- A disk $\phi(R, z) = -GM/sqrt(R^2 + (a_K + |z|)^2$
- The *Navarro–Frenk–White* (NFW) potential

  $\phi(R)=4\pi Ga^2_0\rho(r_0)\ [\ln(1+r/a_0)/(r/a_0)$

  – this form fits numerical simulations of structure growth

Not so Simple - Plummer Potential sec 2.2 in B&T

- Many astrophysical systems have a 'core'; e.g. the surface brightness flattens in the center (globular clusters, elliptical galaxies, clusters of galaxies, bulges of spirals) so they have a characteristic length
- so imagine a potential of the form $-\phi(r)=-GM/\mathrm{sqrt}(r^2+b^2)$; where b is the Plummer scale length

$\nabla^2\Phi(r)=(1/r^2)\, d/dr(r^2 d\phi/dr)=3GMb^2/(r^2+b^2)^{5/2}=4\pi G\rho(r)$ Poissons eq

and thus

$\rho(r) =(3GM/4\pi b^3)[1+(r/b)^2]^{-5/2}$

Now take limits $r<<b$ $\rho(r) =(3GM/4\pi b^3)$ constant

$r>>b$ $\rho(r) =(3GM/4\pi b^3)r^{-5}$ finite

Plummer potential was 'first' guess at modeling 'real' spherical systems; it is one of a more general form of 'polytropes' B&T (pg 300)

Potential energy $W=3\pi GM^2/32b$

Virial Theorem S&G pg 120, MBW pg 234

- S+G pg 120-121, MBW 5.4.4, B&T pg 360
- **$\frac{1}{2}d^2I/dt^2$ =2KE+W** (no ext' forces) I = moment of inertia = $\Sigma m_i r_i^2$ (sum over i=1,N particles)
- A rather different derivation (H Rix)
- Consider (for simplicity) the 1-D Jeans eq in steady state (more later)
- $\partial/\partial x[\rho v^2]+\rho\partial\phi/\partial x=0$
- Integrate over velocities and then over positions...
- $-2E_{kin}=E_{pot}$ (static)
- or restating in terms of forces
- if T= total KE of system of N particles < >= time average

call the 'virial 'Q

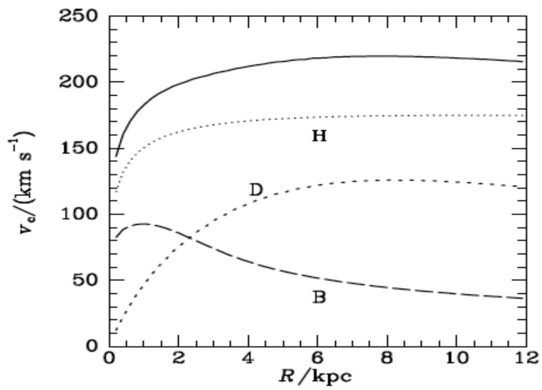
$$Q=\frac{1}{2}\frac{dI}{dt}=m\sum r.\frac{dr}{dt}=\sum p.r$$

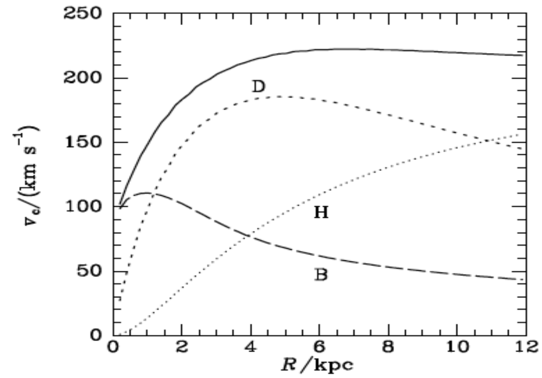
$$dQ/dt=\sum F.r+2T$$

$2\langle T\rangle=-\Sigma(F_k \bullet r_k)$; summation over all particles k=1,N

Modeling Spirals

- As indicated earlier to fit the observed density and velocity distributions in the MW one needs a 3 component mass distribution
- Traditionally this is parameterized as the sum of
  – disk $\Sigma(R) = \Sigma_0[\exp(-R/a)]$
  – spheroid (bulge) using $I(R) = I_0 R_s^2/[R+Rs]^2$ or similar forms
  – dark matter halo $\rho(r)=\rho(0)/[1+(r/a)^2]$
- See B&T sec 2.7 for more complex forms- 2 solutions in B&T- notice extreme difference in importance of halo (H) (table 2.3)





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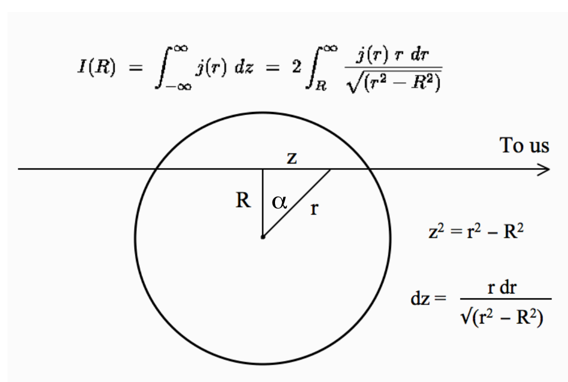
Projection Effects

from M. Whittle

http://www.astro.virginia.edu/class/whittle/astr553/Topic07/t7_projection.ht

- Observed luminosity density I(R)=integral over true density distribution j(r) (in some wavelength band)
- Same sort of projection for velocity field but weighted by the density distribution of tracers
- $I(R)\sigma(r)^2 = 2\int[(v_r \cos\alpha - v_\theta \sin\alpha)^2 nr]/\mathrm{sqrt}(r^2-R^2)$
- Density distribution solution is an Abel integral (see appendix B.2 in B&T) with solution of the form
- while the velocity solution is also an Abel integral
- There are a few useful I(R) & j(r) pairs that can both be expressed algebraically



$$j(r) = \frac{-1}{\pi}\int_r^{\infty} \frac{dI}{dR}\frac{dR}{\sqrt{(R^2-r^2)}}$$

Relaxation...continued (MBW pg

- The net vectoral velocity due to these encounters is zero, but the mean square change is not

  $\delta v^2 = (2Gm/bv)^2 (2N/r^2) b\delta b$ (see B&T pg 34 eq. 1.3.2) - now integrating this over all impact parameters from b_{min} to b_{max}
- one gets $\delta v^2 \sim 8N(Gm/rv)^2 \ln \Lambda$; where r is the galaxy radius

  $\ln \Lambda$ is the Coulomb logarithm = $\ln(b_{max}/b_{min})$
- For gravitationally bound systems the typical speed of a star is roughly $v^2 \sim GNm/r$ (from KE=PE) and thus $\delta v^2/v^2 \sim 8 \ln \Lambda/N$
- For each 'crossing' of a galaxy one gets the same δv so the number of crossing for a star to change its velocity by order of its own velocity is $n_{relax} \sim N/8 \ln \Lambda$
- So how long is this?? well $t_{cross} \sim r/v$; $v^2 \sim GNm/r$, $b_{max} \sim r$, $b_{min} \sim Gm/v^2$, so $\Lambda \sim rv^2/(Gm) \sim N$ and thus
- $t_{relax} \sim (0.1N/\ln N) t_{cross}$; if we use $N \sim 10^{11}$; t_{relax} is much much longer than t_{cross}
- In all of these systems the dynamics over timescales $t < t_{relax}$ is that of a collisionless system in which the constituent particles move under the influence of the gravitational field generated by a smooth mass distribution, rather than a collection of mass points

Why a Detailed analysis of the MilkyWay

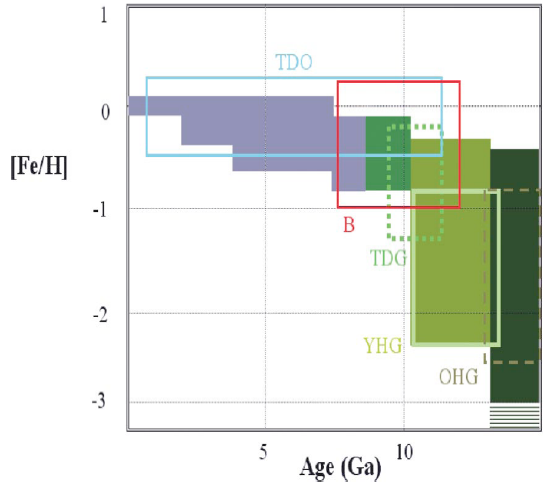
- What processes might determine galaxy disk structure?

  what sets the exponential radial and vertical profiles of stars
- Were all or most stars born from a well-settled gas disk near the disk plane Or was some fraction of disk stars formed from very turbulent gas early on
- Are there discernible signatures of the stellar energy feedback to the interstellar medium a crucial 'ingredient' of (disk) galaxy formation models
- What was the role of mergers –an integral part of ΛCDM cosmogony?
  - How much stellar debris did they deposit ?
- All of these questions are not only relevant for the Milky Way in particular, but to spirals as a whole. (Adapted from Rix and Bovy 2013) and for formation models-the question of how to test for the importance of galaxy formation *ingredients* through comparison with observational data is actively under way.

Components of MW Disk

- The positions, velocities, chemical abundances, and ages of MW stars are very strongly and systematically correlated
- In the disk:
  - younger and/or more metal-rich stars are "statistically" older.
- Subcomponents of the Disk can be defined on the basis of the spatial distribution, kinematics, or chemical abundances.
- Most common has been to describe the Disk in terms of a dominant thin disk and a thick disk, with thin–thick disk samples of stars defined spatially, kinematically, or chemically

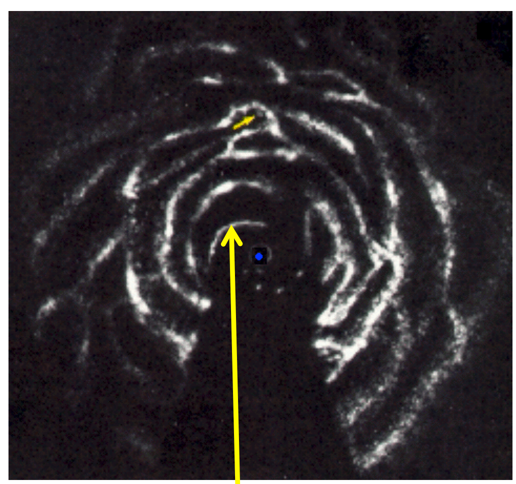
Freeman and Bland-Hawthorn

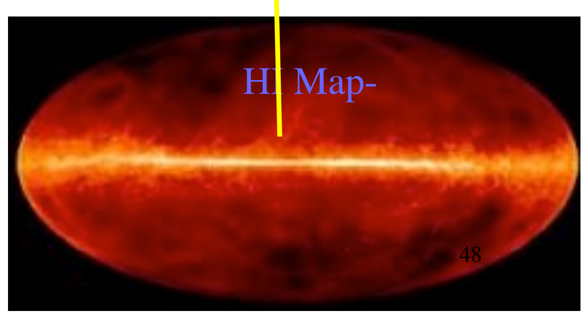


blue= thin disk stars
green =thick disk stars
B= bulge stars
black= halo stars

HI Maps- Major Way to Trace MW Velocity Field

- HI lies primarily in the plane- maps have velocity data associated with them- allows dynamics to be determined
  - deproject HI velocity and intensity map to show total structure of the galaxy
- Not affected by dust- shows detailed structures.
- see review article by Kalbela and J. Kerp on the web page
- Neutral atomic hydrogen (HI) traces the interstellar medium (ISM) over a broad range of physical conditions.
- 21-cm emission line is a key probe of the structure and dynamics of the Milky Way Galaxy.





Galactic Rotation- S+G sec 2.3, B&T sec 3.2

- Consider a star in the midplane of the Galactic disk with Galactic longitude, l, at a distance d, from the Sun. Assume circular orbits radii of R and R_0 from the galactic center and rotational velocities of V and , V_0

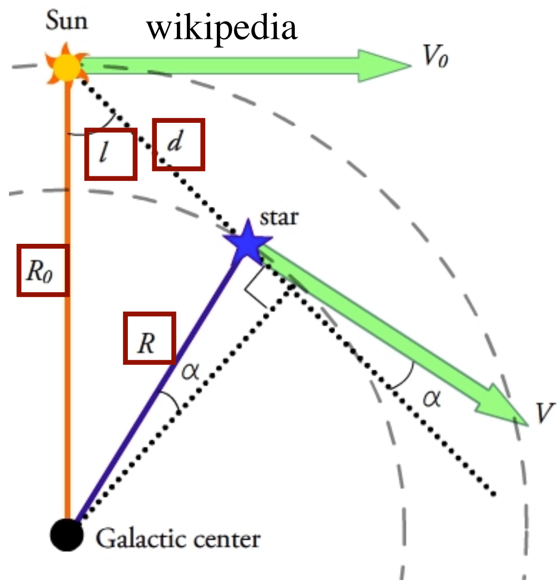
- The 2 components of velocity- radial and transverse are then for circular motion
- $V_{observered, radial}$=V(cos α)-V_0sin(l)
- $V_{observered ,tang}$=V(sin α)-V_0 cos(l)
- using the law of sines

sinl/R~ cosα/R_0

which gives

$V_{observered, radial}$=R_0sin(l)[(V/R)-(V_0/R_0)] S&G 2.11

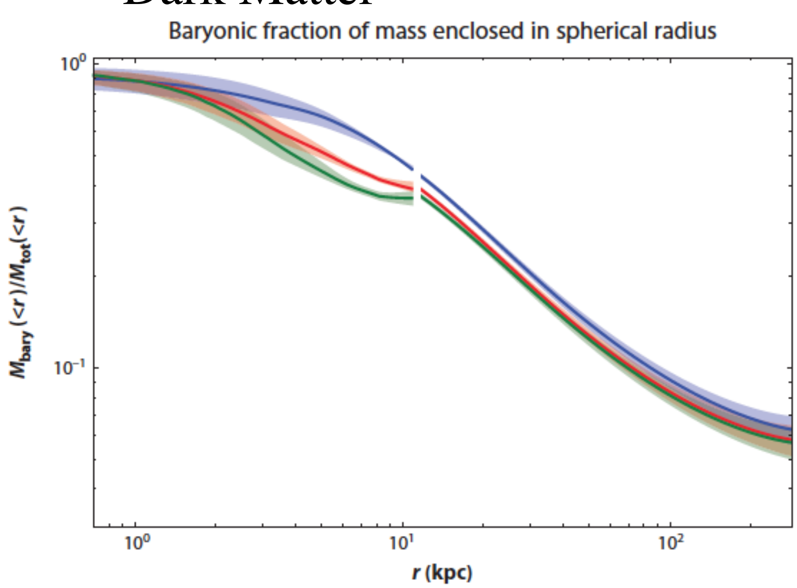
Much more later



Since we have 'poor' idea of distance rely on tangent point
at 0<l<90 radial velocity is highest at the tangent point where los passes closest to galactic center

Dark Matter

- Using best estimates of all the baryons
- the fraction of the gravitational mass that is baryonic varies from ~95 % near the galactic center, ~50% near the sun down to ~7% at the virial radius compared to 16% for the universe as a whole



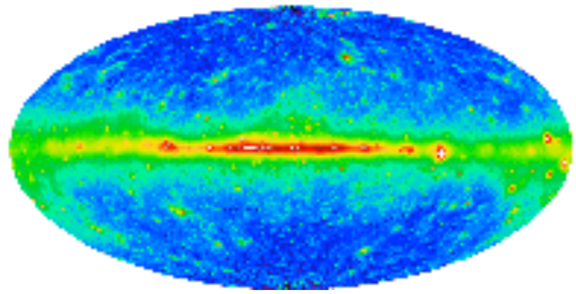
Bland-Hawthorn and Gerhard 2016

Cosmic Rays-100th Anniversary of their Discovery in 2012

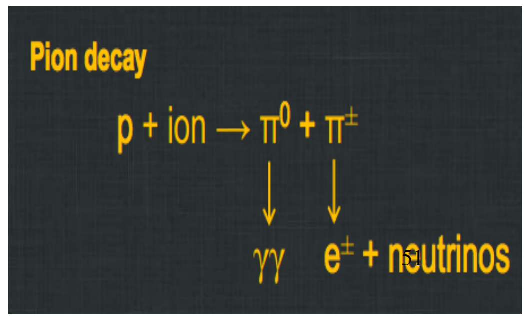
http://www.aps.org/publications/apsnews/201004/physicshistory.cfm

- These are very hard to study in other galaxies
  - they are visible by the synchrotron emission emitted by electrons spiraling in the magnetic field
  - γ-rays emitted by relativistic particles hitting gas
  - Direct measurements at earth
- MW
  - direct measures of CRs e.g. in situ
  - detailed γ-ray maps of MW
    - convolution of cosmic ray energy spectrum and intensity with target (gas) density
  - Very detailed radio maps

Origin: acceleration of particles in supernova shocks via first order Fermi process - total power ~10^{41} ergs/sec~10% of SN shock energy



Fermi map of MW



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Distribution of Light in Disk (S+G eq 2.8)

the thin disk and the thick disk has a similar form but different scale height and density of stars

Radial scale length of a spiral disk

$\Sigma(r)=\Sigma_0 \exp(-R/R_d)$**;** integrate over r to get total mass $M_d=2\pi\Sigma_0 R^2_d$

$\Sigma(r)$ is surface density

Vertical density distribution is also an exponential $\exp(-z/z_0)$ **so total distribution is product of the two**

$\rho(R,z)=\rho_0 \exp(-R/R_d)\exp(-z/z_0)$

while we may know the scale length of the stars, that of the dark matter is not known.

Also the nature of the dark matter halo is not known:- disk/halo degeneracy

Somewhat more precisely the 3-D luminosity distribution is $L(R,z)=L_0\exp(-R/h)/\mathrm{sech}^2(z/2z_0)$ with luminosity density $L_0=0.05L_\odot/pc^3$

Even more detail

Each spectral type can be characterized by a scale height, a possible indicator of age. The older the star, the more dynamical interactions it has had (Spitzer and Schwarzschild 1951).
The result is an increase in the spatial velocity of older stars (particularly along the vertical axis of the disk).
M dwarfs have relatively large scale heights, ~ 300 pc, in contrast to the younger A-type stars with ~ 100 pc (see table 2.1 in S+G)

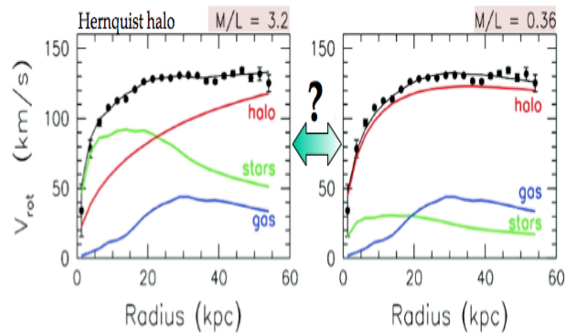
Spirals and Dark Matter

- Rotation-curve decomposition - primary tool for measuring the distribution of dark matter in spiral galaxy halos, **but** uncertainties in the mass-to-light ratio of the luminous disk and bulge make accurate estimates difficult (IMF-mass degeneracy)
- Disk-halo conspiracy- there is no 'feature' in the rotation curve indicating where dark matter starts to dominate- smooth transition!

- Disks in equilibrium

  Rotation provides total mass within a given radius.

  Vertical oscillations of disk stars provides disk mass within given height inside a cylinder:



Dark matter dominates mass (and potential) outside ~a few scale lengths

At the radius where the velocity curve flattens ~15-30% of the mass is in baryons

Halo

- Totally dominated by dark matter but does have gas (HI) ,some field stars and globular clusters

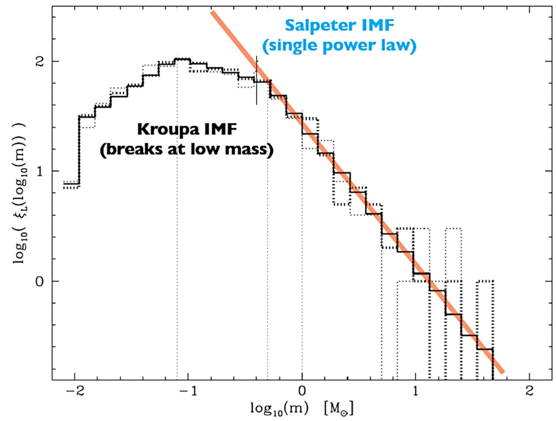
TABLE 23.1 Overall Properties of the Galactic Disk, Halo, and Bulge

GALACTIC DISK	GALACTIC HALO	GALACTIC BULGE
Highly flattened	Roughly spherical—mildly flattened	Somewhat flattened and elongated in the plane of the disk ("football shaped")
Contains both young and old stars	Contains old stars only	Contains both young and old stars; more old stars at greater distances from the center
Contains gas and dust	Contains no gas and dust	Contains gas and dust, especially in the inner regions
Site of ongoing star formation	No star formation during the last 10 billion years	Ongoing star formation in the inner regions
Gas and stars move in circular orbits in the Galactic plane	Stars have random orbits in three dimensions	Stars have largely random orbits but with some net rotation about the Galactic center
Spiral arms	No obvious substructure	Ring of gas and dust near center; Galactic nucleus

From Chaisson

Initial Mass Function-IMF MBW 9.6

- The distribution of stellar masses at t=0 (birth)
- The origin of the form of the IMF is not well understood
- There are several forms proposed
  - Saltpeter- $\Phi(m)=N(M)\sim M^{-2.35}dM$ for $M>M_\odot$ (Salpeter 1953)
    - much of integrated stellar mass near $1M_\odot$
  - Kroupa/Scalo/Chabrier IMFs- flatten at low masses
- At present it is controversial if the IMF is universal or a function of age, metallicity, density etc



Kroupa IMF

$\Phi(M)=dN/dM = A\, M^{-1.3}$ $(0.1 \le M_\odot \le 0.5)$

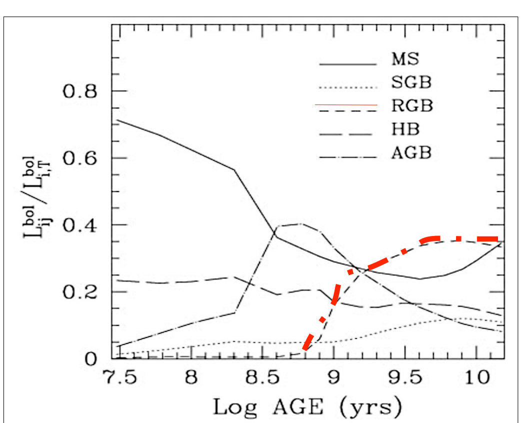
$0.5\, A\, M^{-2.3}$ $(0.5 \le M_\odot \le 100)$

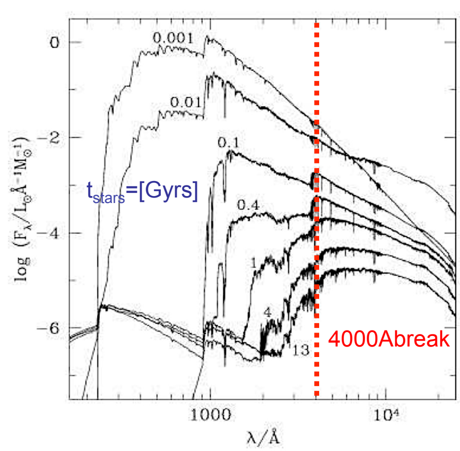
piece-wise continuous

Kroupa IMF has 1.6x less total mass than the Saltpeter IMF for the same normalization but ~ same amount of light $\langle M\rangle=0.6M_\odot$

Luminosity and Colors Changes of a SSP

- As SSP ages the relative luminosity due to different parts of the H-R diagram changes
  - young systems MS dominated by massive stars
  - Older systems(>2Gyrs)-dominated by red giant branch
  - If star formation is a continuous process which stars produce most of the luminosity and where most of the stellar mass lies can be quite different





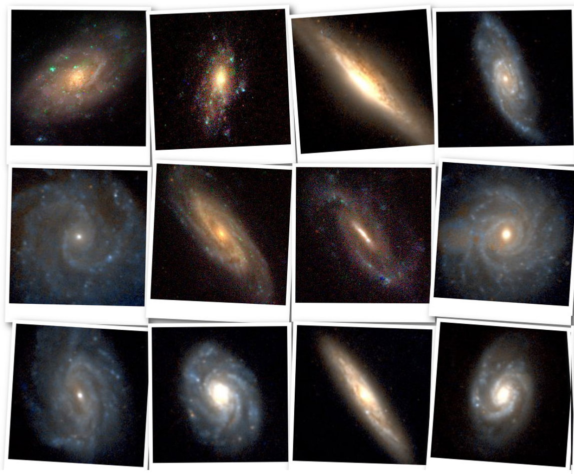
Spectral energy distribution UV-IR of a SSP as it ages

Notice the enormous changes in the UV and blue

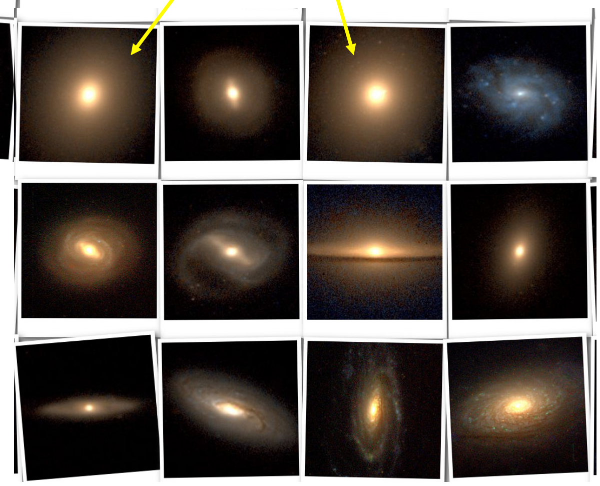
A slow fading in the IR

A Bit of the Galaxy Zoo

Mostly disk…

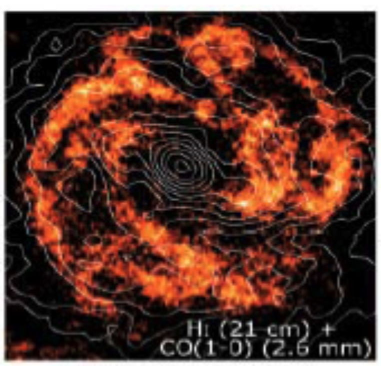


Mostly spheroid…

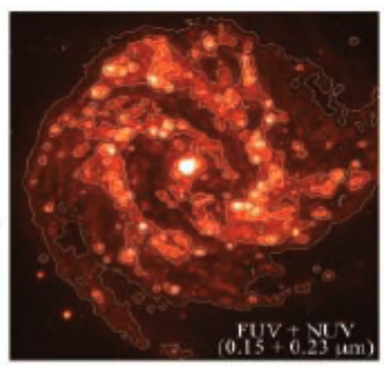


- Disk-bulge separation is tricky and influenced by inclination angle and dust and wavelength observed (disks standout in the blue, bulges in the red)

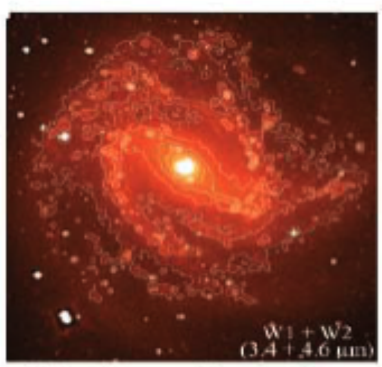
M 83: from Gas to Stars



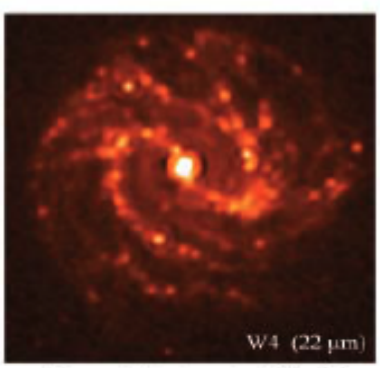
Neutral gas is the *reservoir*, molecular gas fuels the star formation



Young hot stars represent the current epoch of star formation



Evolved star population constitutes the *Stellar Backbone*



Very small dust grains efficiently reprocess energy from star formation

Spiral galaxies are panchromatic objects different physical process are best shown in different wavebands

Neutral gas (HI and CO)
dust (IR emission)
old stars (red optical light)
young stars (UV light)

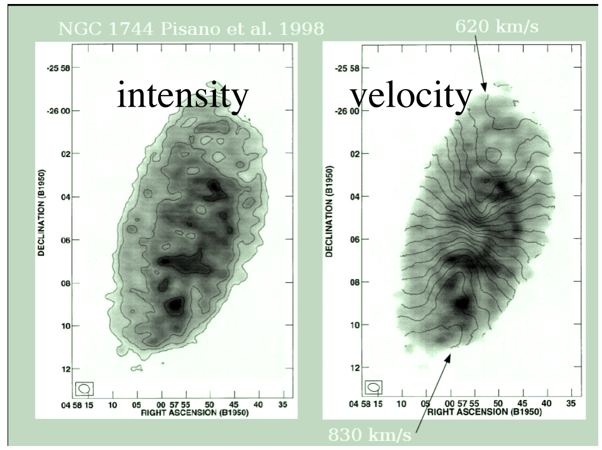
HI

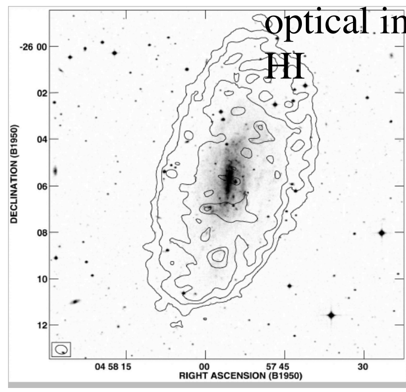
- Spirals have large HI disks

– This gas is optically thin

This means that we see all the gas and can measure the amount directly from the line intensity

- HI gas is much more extended than the optical light, $r_{HI} > 2.5\ R_{25}$
- – Gives a unique tracer for the velocity in spiral galaxies
- Spider diagram orientation and velocity field

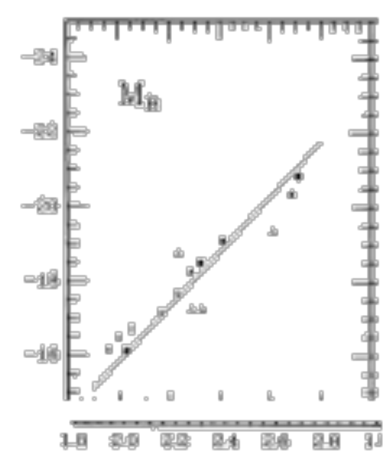




Tully-Fisher for Spiral Galaxies

- relationship between the speed at which a galaxy rotates,v, and its optical luminosity L_{opt}: (the normalization depends on the band in which one measures the luminosity and the radius at which the velocity is measures
- $L_{opt} \sim Av^4$
- Since luminosity depends on distance^2

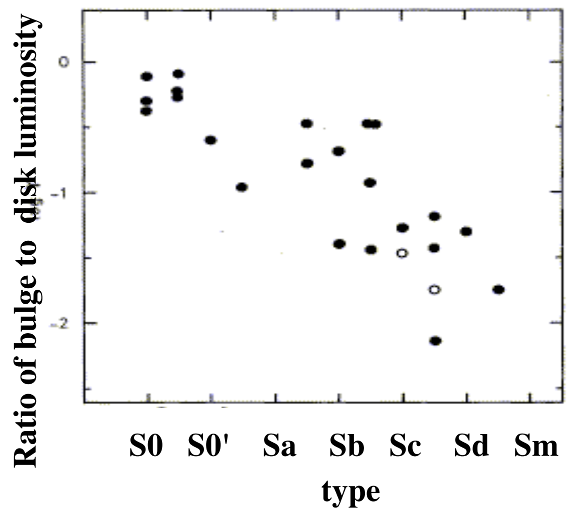
while rotational velocity does not, this is a way of inferring distances.

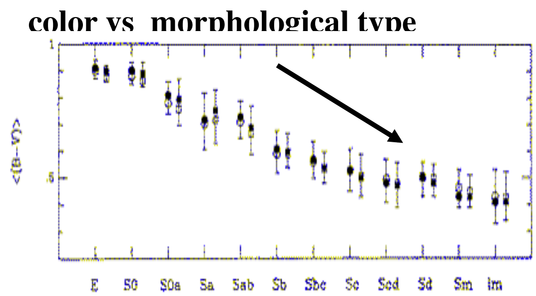


Spirals

The Hubble type of a spiral correlates with

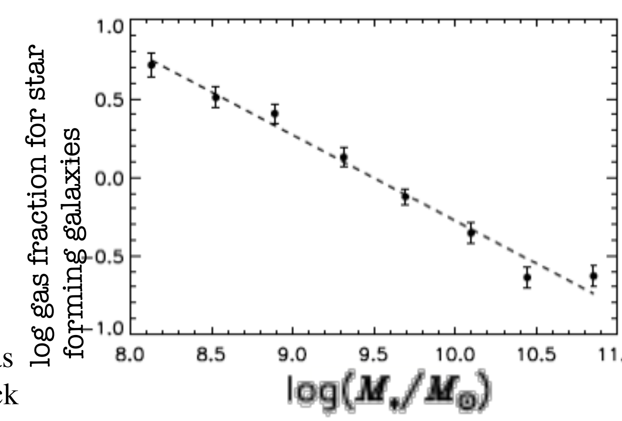
- bulge/disk luminosity ratio
- relative content of cool gas (H I)
- mass concentration
- stellar population (how many young/ old stars)
- nuclear properties
- chemical abundances in the ISM
- star formation history and integrated stellar spectrum
- bulges of spirals tend to have old stars, disks younger stars
- *A lot of the detail depends on what wavelength one observes in (e.g. the UV favors hot young stars, the IR dust, x-rays hot gas and binaries)*



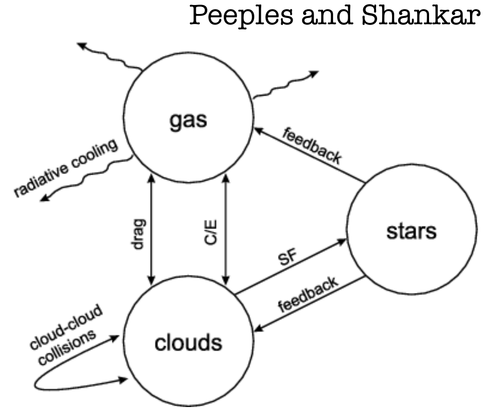


Gas

- Other than stars the baryons in galaxies lie in 3 forms
  - gas
  - rocks
  - dust (0.1% of mass)
- the % mass in rocks and dust is small
- There is an interplay between the stars and gas,with stars forming out of the gas and with enriched gas being ejected back into the interstellar medium from evolved stars.
- There exist a vast array of spectral diagnostics for the gas in both emission and absorption which can reveal
  - chemical composition
  - temperature
  - velocities
  - ionization mechanism

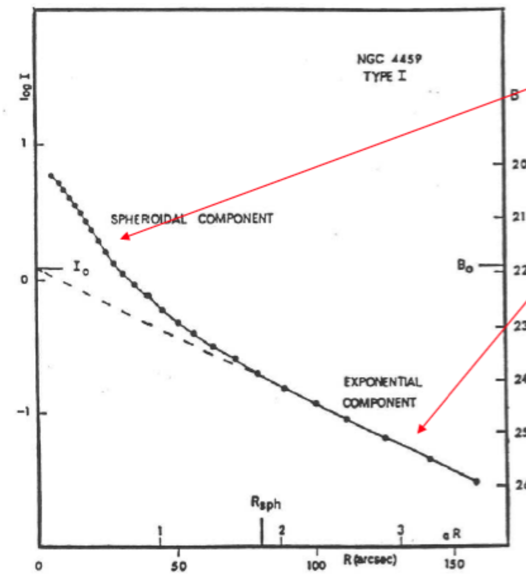


Peeples and Shankar 2011



Azimuthally Averaged Light Profiles

- Bulge is more concentrated than the disk: bulge is described by Sersic profile, disk by an exponential profile



$log I \propto R^{1/4}$ (inner);

$I(R) = I_0 e^{-\alpha r}$ (outer)

α is the inverse scale height

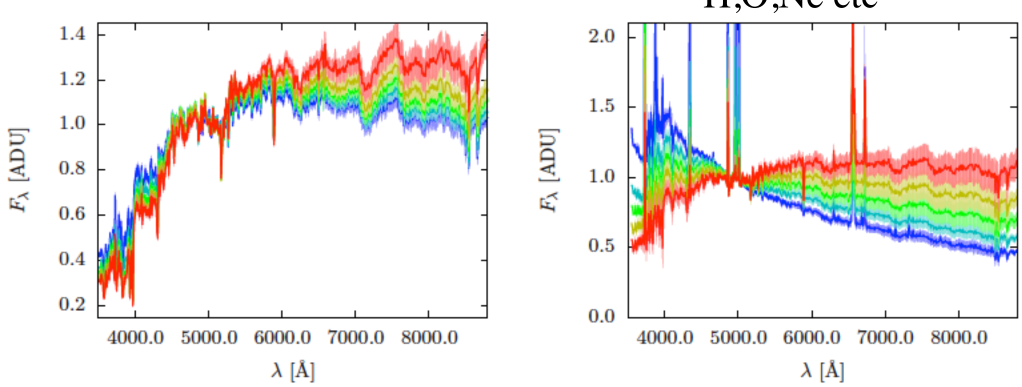
(Freeman 1970)

This is an approximation, galaxies with strong bars or other non-azimuthally symmetric features will clearly change this

Galaxy spectra- Please also refer to lectures on stars

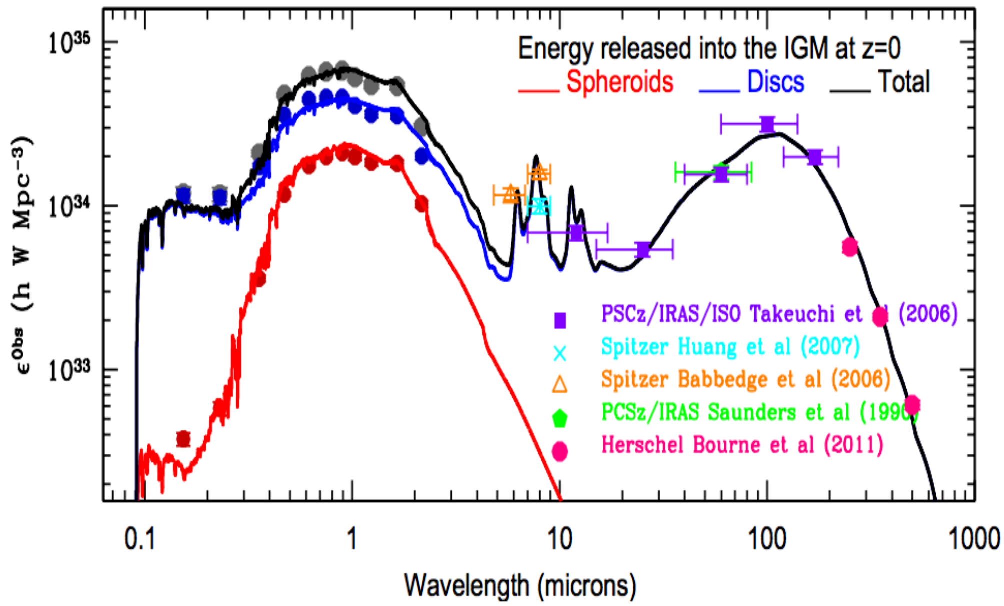
- Sequence of ages of a composite SSP population (star forming- spiral population)
- bulges are dominated by stellar absorption lines and have little 'blue' light
- The star forming galaxies- *almost all spirals at low redshift*, show emission lines (from ionized gas) and much more blue light (especially when they are young)

emission lines due to H,O,Ne etc



Energy Released By Galaxies

- Extensive galaxy surveys have allowed the measurement of the total energy released by all low z galaxies across the UV-far IR spectrum $1.3\text{x}10^{35}$ W/Mpc^3(Driver 20120; 35-45% of energy generated by stars is absorbed by dust and re-radiated in IR- this occurs predominately in spirals



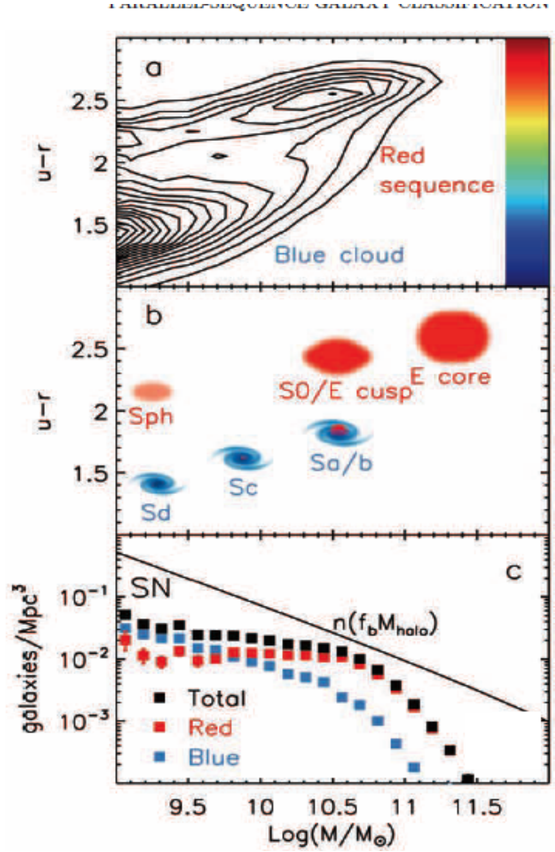
The Big Picture- Two Populations

- top panel color distribution vs mass of a large sample of local galaxies from the SDSS

Middle panel is the morphologies that dominate at each mass

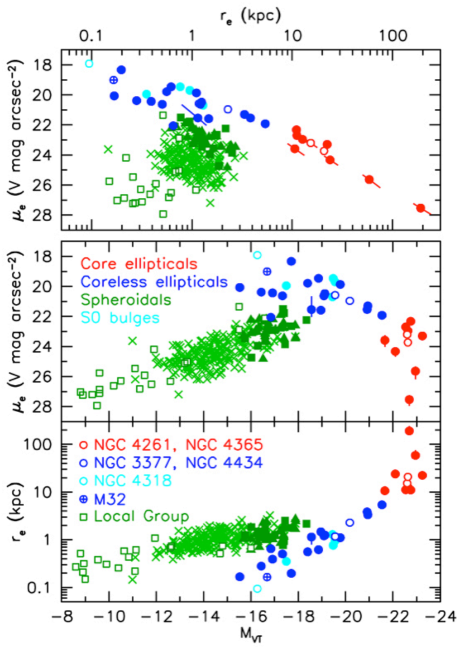
bottom panel shows the galaxy mass function divided by color (Cattaneo et al 2009)-

the black solid line is the prediction from cold dark matter theory of the number density of halos vs mass- <u>notice does not agree with the galaxy mass distribution</u>



Spheroidal (Elliptical) Galaxies MBW chap 13, S+G ch 6

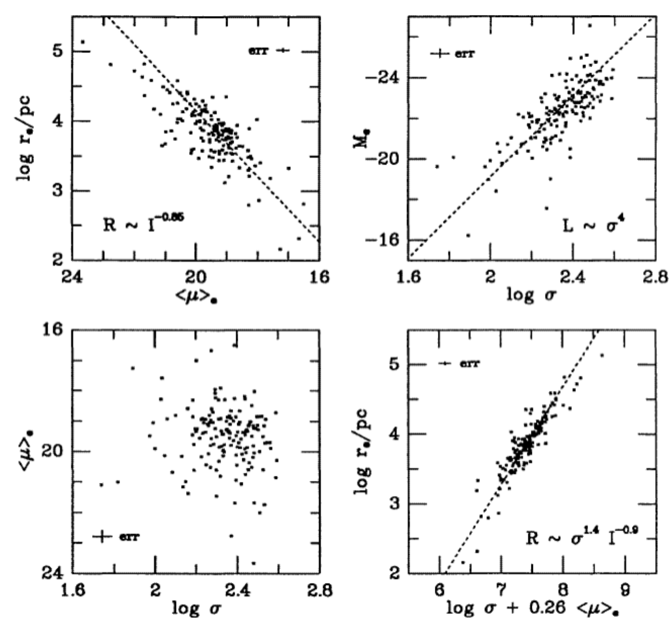
- Visual Impression: smooth, roundish- deceptively simple appearing- collisionless systems
- While visually 'similar' detailed analysis of spheroids groups them into 3 categories
  - Massive/luminous systems: little rotation or cool gas, flat central brightness distribution (cores), triaxial; lots of hot x-ray emitting gas, stars very old, lots of globular clusters. Low central surface brightness
  - Intermediate mass/luminosity systems: power law central brightness distribution, little cold gas; as mass drops effective rotation increases, oblate
  - Dwarf ellipticals: no rotation, exponential surface brightness
- At $M>10^9 M_\odot$ general properties **fall on the 'fundamental plane'** which includes metallicity, velocity dispersion, size , surface brightness (and some other properties)
- Spiral galaxies bulges, while visually similar are physically different in many ways from E galaxies



Absolute M

Fundamental Plane of Elliptical Galaxies

- There are a set of parameters which describes virtually all the properties of elliptical galaxies and are strongly connected



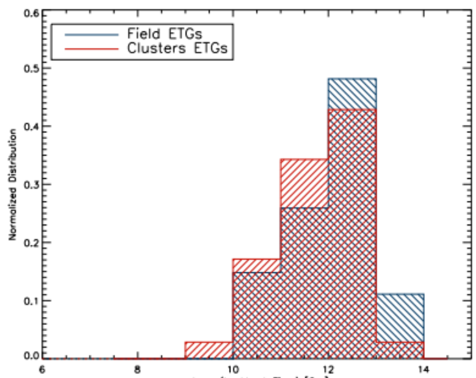
2 Projections of the fundamental parameter plane of elliptical galaxies. *Top*

r_e= scale length
μ= surface brightness
σ= velocity dispersion
M=absolute magnitude

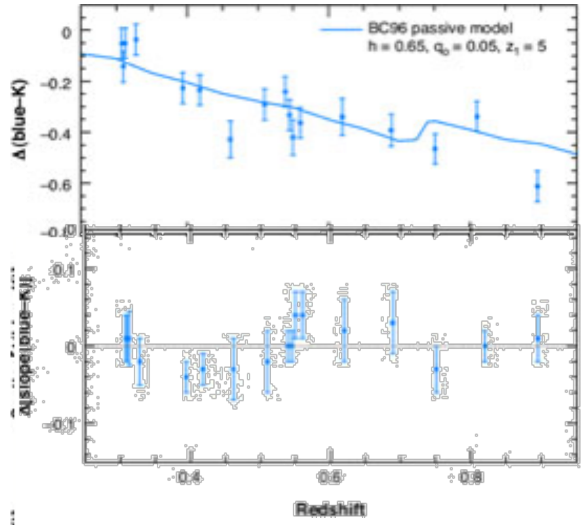
Higher z observations constraint on origin

- At higher z massive elliptical galaxies in clusters have colors and luminosities (at z<1.2) consistent with 'passive' evolution e.g. galaxy forms at higher z and does not change with time and stars 'just evolve'- a SSP (!)

ETG-early type galaxies



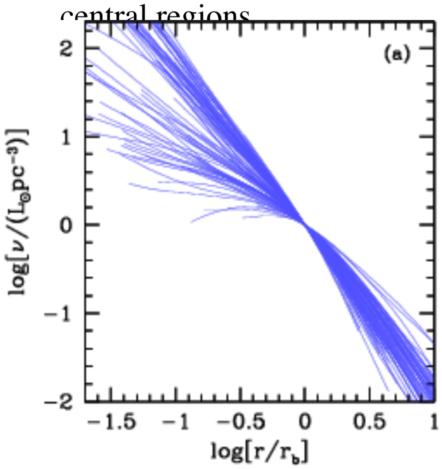
look back time of star formation

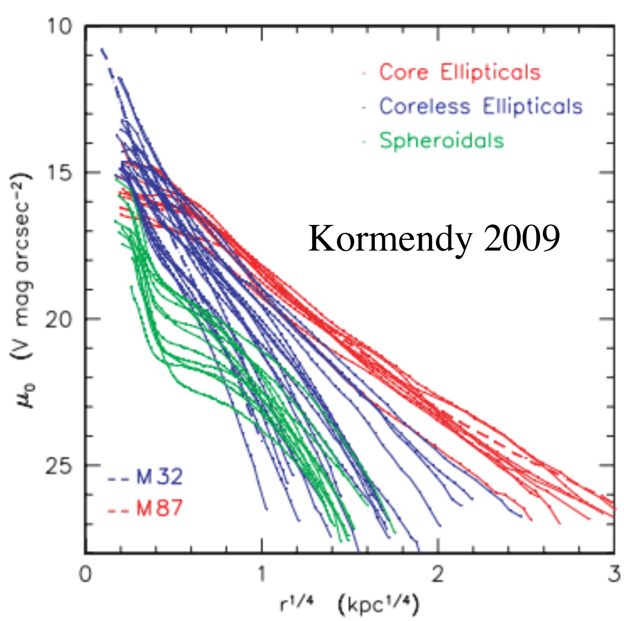


using the consistency of the colors of these galaxies with 'passive' evolution the ages of massive ellipticals in clusters is ~10-13Gyr (!)- Rettura et al 2012

Wide Range of Sizes- But Homologous

- the family of spheroids can usually be well fit by the Sersic model, but there are some deviations in the centers (cores and cusps)
- More luminous galaxies tend to have cores, less luminous roughly power law shape in central regions

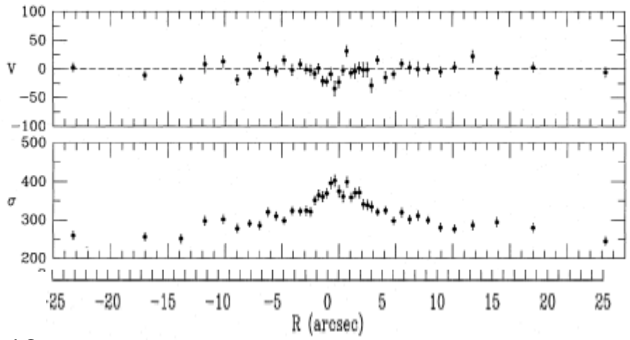




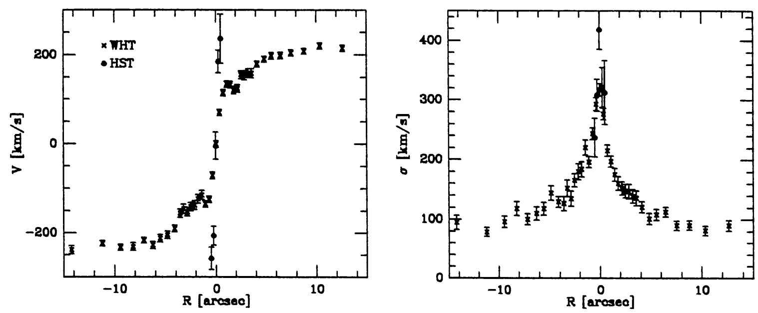
Kinematics

- Kinematics- the features used to measure the velocity field are due to stellar absorption lines: however these are 'blurred' by projection and the high velocity dispersion of the objects.
- Spatially resolved spectra help...
- Examples of 2 galaxies M87 and NGC 4342 showing one with no rotation and the other with lots of rotation
- The other parameter is velocity dispersion- the width of a gaussian fit to the velocity

M87van der Maerl



NGC4342
van den Bosch

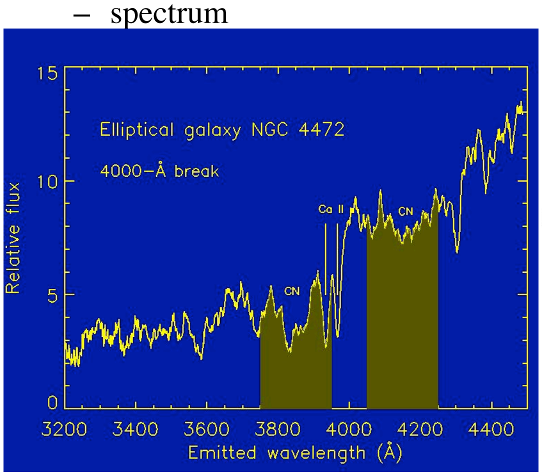


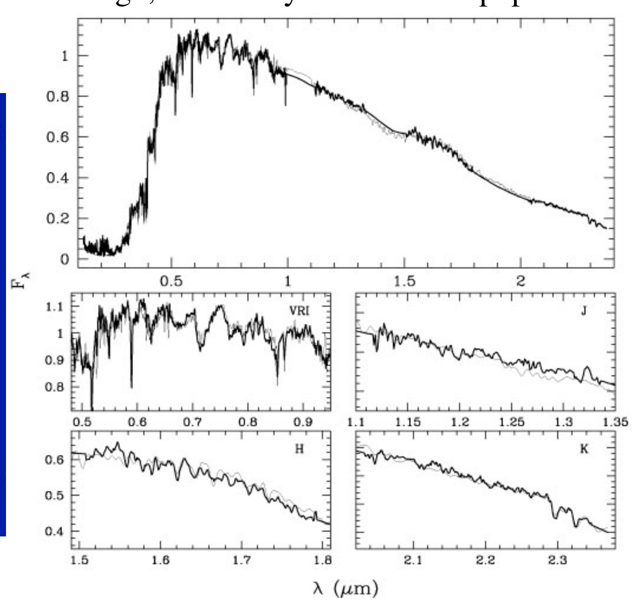
For NGC4342 its observed
flattening is consistent with rotation

Spectrum of Ellipticals

- Optical and near IR spectrum dominated by old stars-how do we know this?
  - colors
  - spectrum

'standard' optical colors
UBVRI are not very sensitive to age, metallicity of old stellar pops

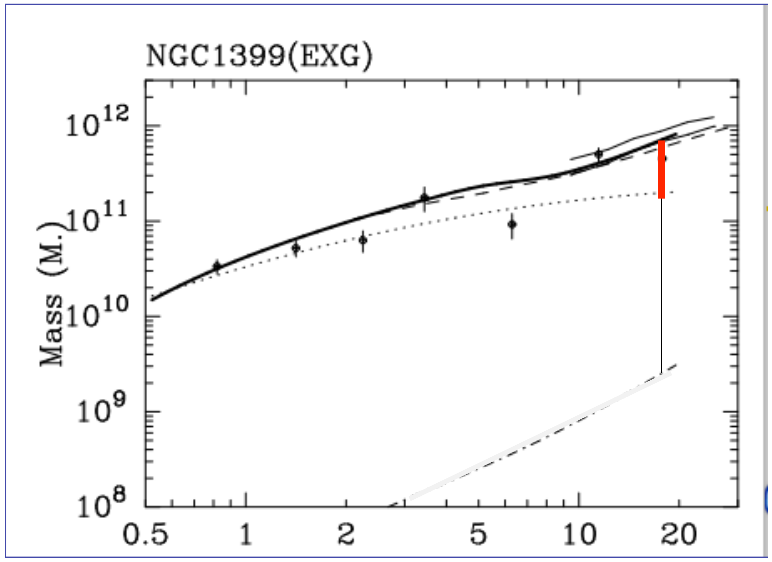




see GuyWorthy's web page http://astro.wsu.edu/worthey/dial/dial_a_model.html

Mass Profile of NGC1399- A Giant Elliptical

- Solid line is total mass
  - dotted is stellar mass
  - dash-gas mass is gas mass
- In central regions gas mass is ~1/500 of stellar mass but rises to 0.01 at larger radii
- **Dark matter dominates at larger radii** -factor of 5 greater than baryonic mass in this galaxy

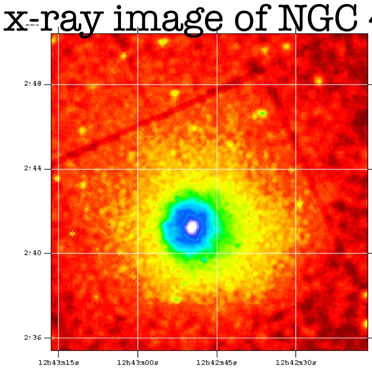


•Use hydrostatic equilibrium to determine mass $\nabla P = -\rho_g \nabla \phi(r)$ where $\phi(r)$ is the gravitational potential of the cluster (which is set by the distribution of matter) P is gas pressure and ρ_g is the gas density

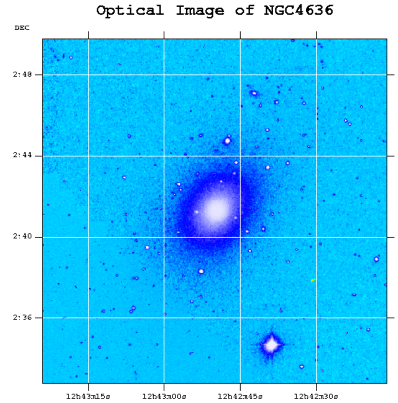
ISM In Ellipicals

- Predominately hot kT~10^6-10^7K and thus visible only in the x-ray
  - the temperature is set, predominantly by the depth of the potential well of the galaxy (if it were hotter it would escape, if colder fall)
  - The metallicity of the gas is roughly solar

x-ray image of NGC 4636



Optical Image of NGC4636



Hierarchical Formation of Structure

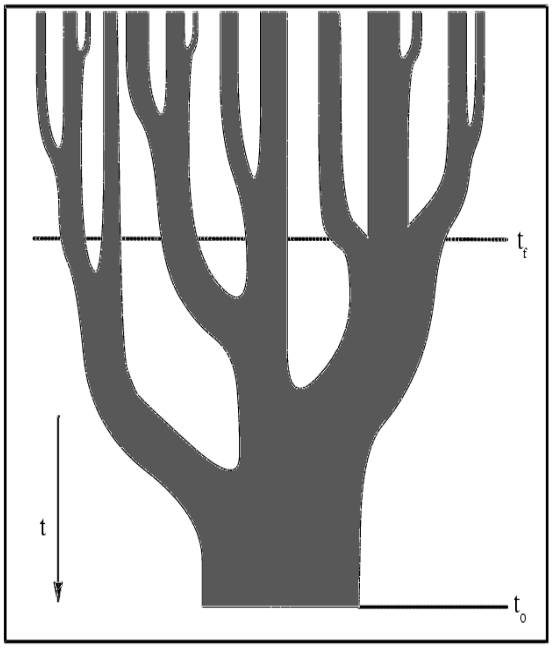
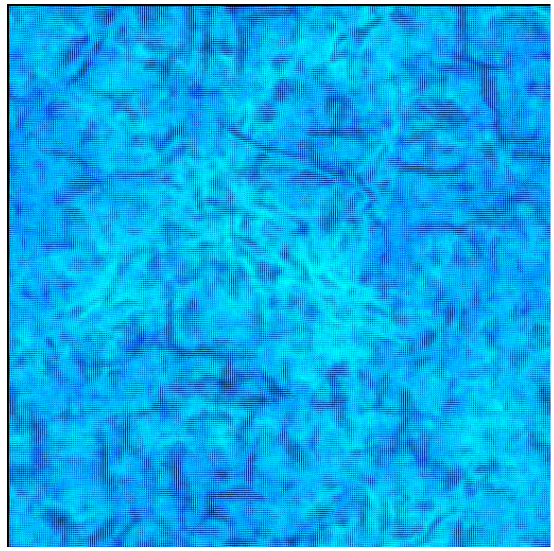
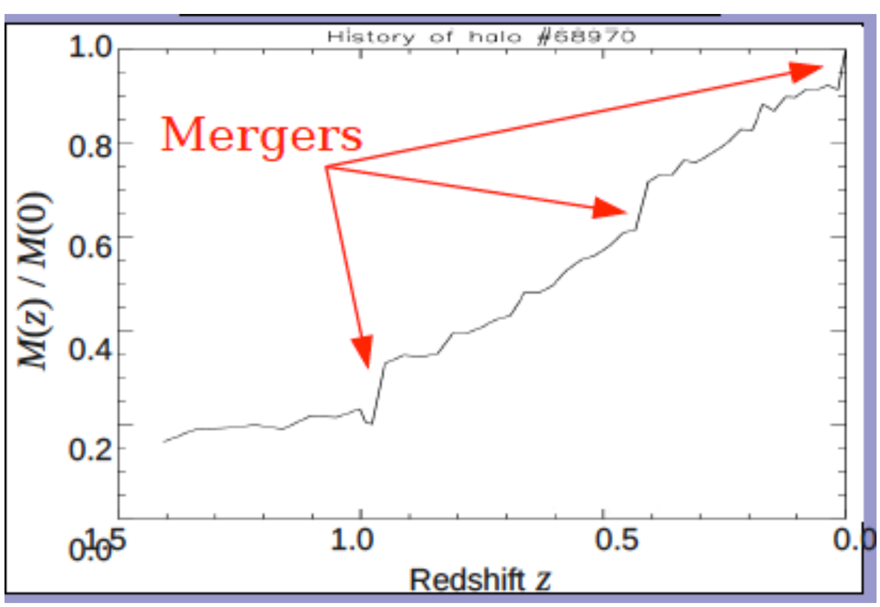


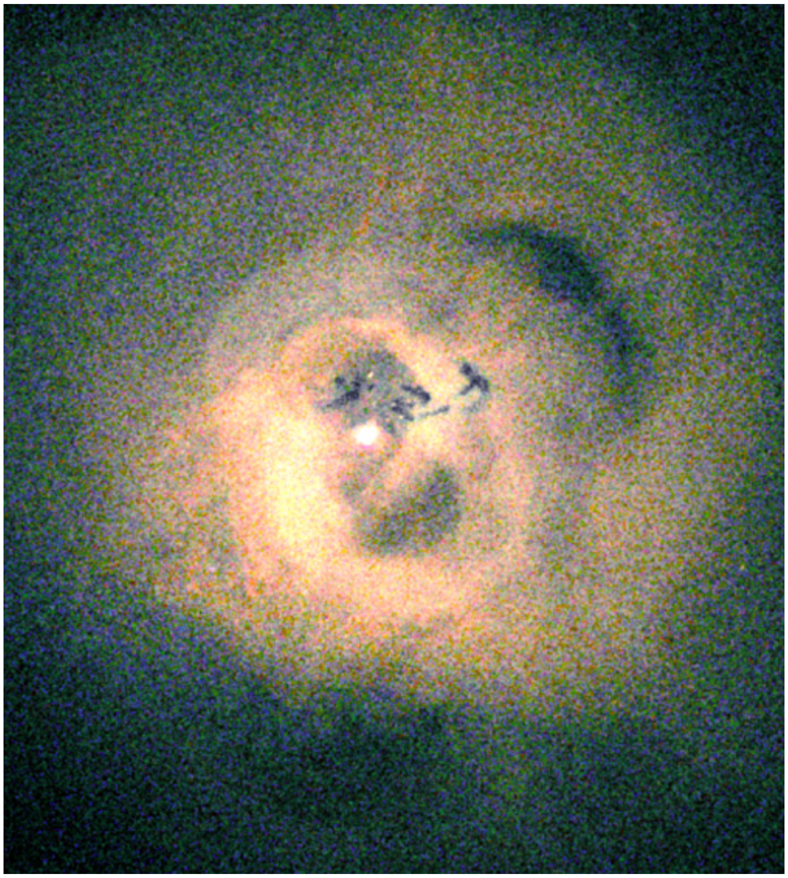
Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally gives the distribution of masses in the parent halos at a given time. The present time t_0 and the formation time t_f are marked by horizontal lines, where the formation time is defined as the time at which a parent halo containing in excess of half of the mass of the final halo was first created.



Bode

- Big mergers are rare, but increase the mass a lot - growth by both collapse and mergers

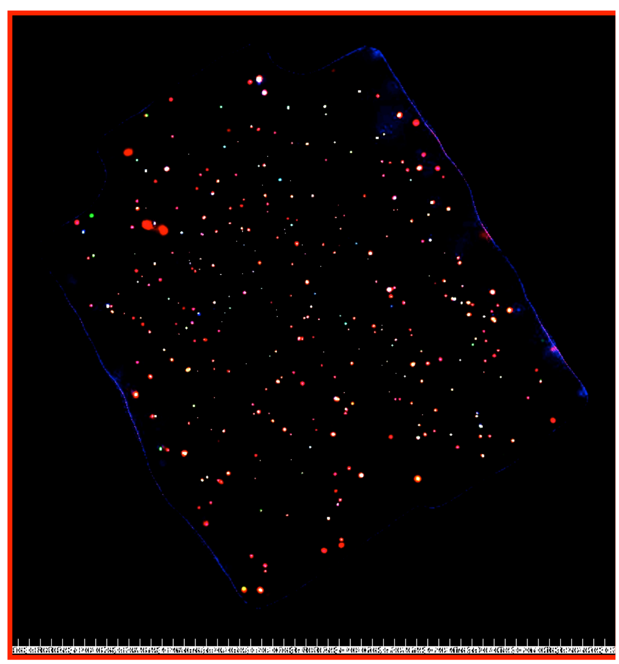




- In clusters can 'see' the effect of feedback from the AGN (x-ray image of the Perseus cluster showing the 'bubbles'

The History of Active Galaxies

- Active Galaxies (AKA quasars, Seyfert galaxies etc) are radiating massive black holes with $L \sim 10^7 - 10^{14} L_{sun}$
- The change in the luminosity and number of AGN with time are fundamental to understanding the origin and nature of massive black holes and the creation and evolution of galaxies
- ~20% of all energy radiated over the life of the universe comes from AGN- a strong influence on the formation of all structure.



X-ray Color Image (1deg)
of the Chandra Large Area X-ray Survey-
CLASXS

Galaxy formation and accretion on supermassive black holes appear to be closely related

Black holes play an important role in galaxy formation theories

Observational evidence suggests a link between BH growth and galaxy formation:

- M_B-σ relation
- Similarity between cosmic SFR history and quasar evolution

Theoretical models often assume that BH growth is self-regulated by **strong** feedback:

- Blow out of gas in the halo once a crtitical M_B is reached
  Silk & Rees (1998), Wyithe & Loeb (2003)

Feedback by AGN may:

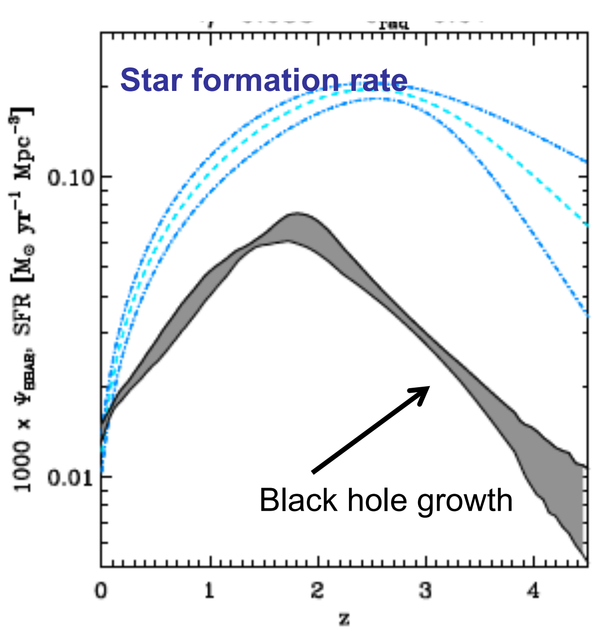
- Solve the cooling flow riddle in clusters of galaxies
- Explain the cluster-scaling relations, e.g. the tilt of the L_x-T relation
- Explain why ellipticals are so gas-poor
- Drive metals into the IGM by quasar-driven winds
- Help to reionize the universe and surpress star formation in small g

Springel 2004

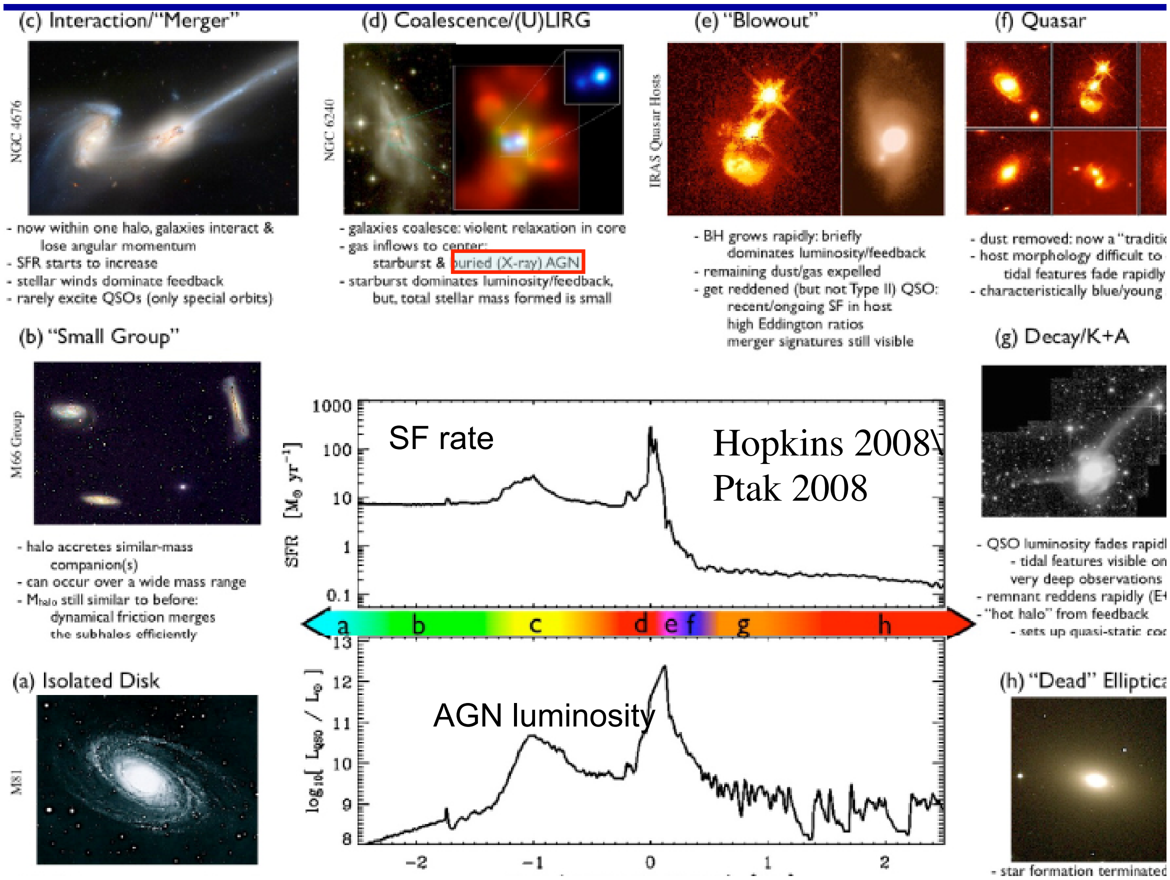
Galaxy formation models need to include the growth and feedback of black holes !

SFR Rate and AGN Growth

- To first order the growth of supermassive black holes (as traced by their luminosity converted to accretion rate) and the star formation rate are very similar
  - showing similar rises and falls
  - It this cause and effect?- e.g. feedback

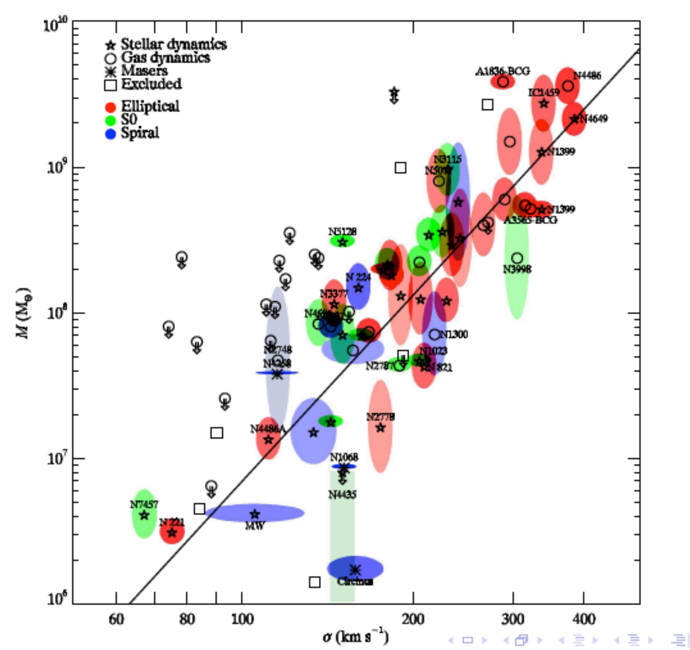


Merloni 2010



Mass of Black Hole Compared to Velocity Dispersion of Spheroid

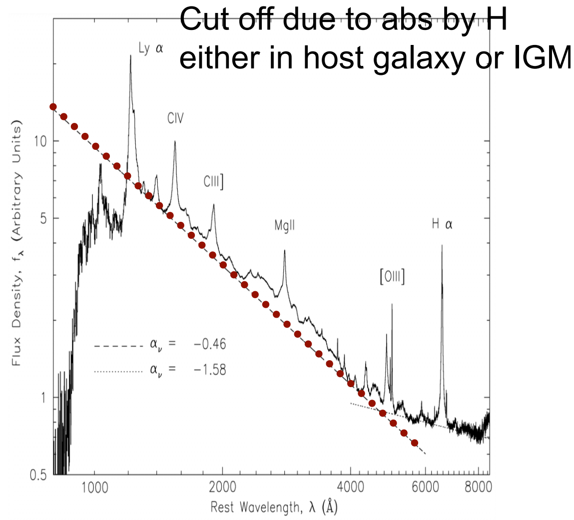
- Sample of non-active galaxies compare mass of black hole (derived later) with velocity dispersion of stars
- Very high detection rate of BHs in 'normal' galaxies- both spheroids and disks.

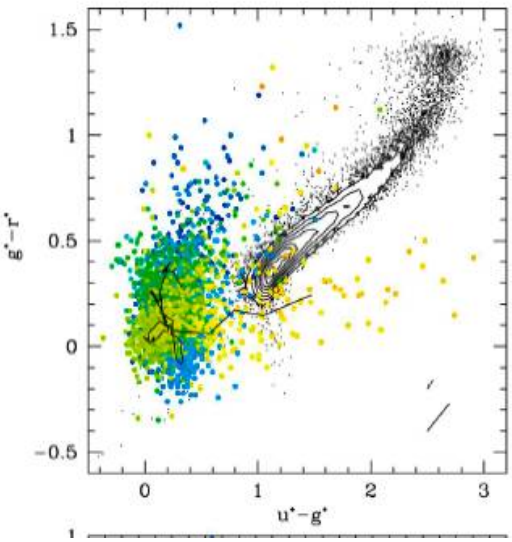


Gultekin 2009

Optical Properties of AGN

- **Strong lines** of hydrogen, carbon, oxygen, magnesium ….

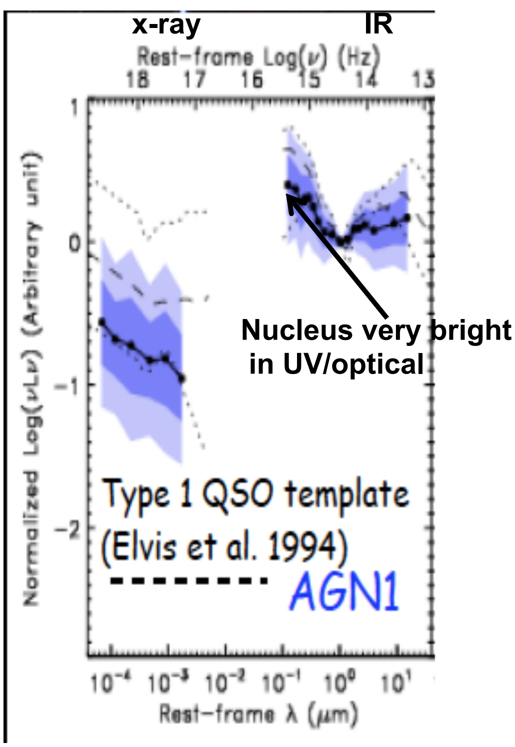


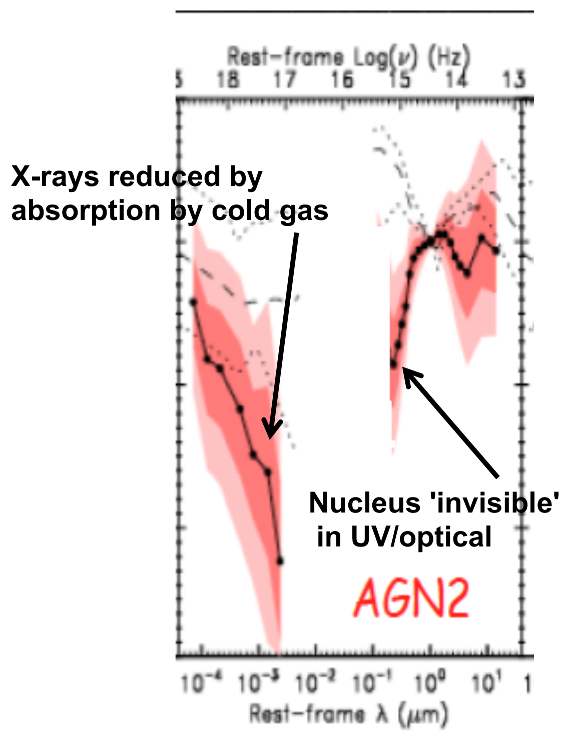


Unusual optical colors (Richards et al SDSS)- **quasars in color**, **stars are black**

UV-Optical Continuum is thought to arise via thermal emission in an accretion disk

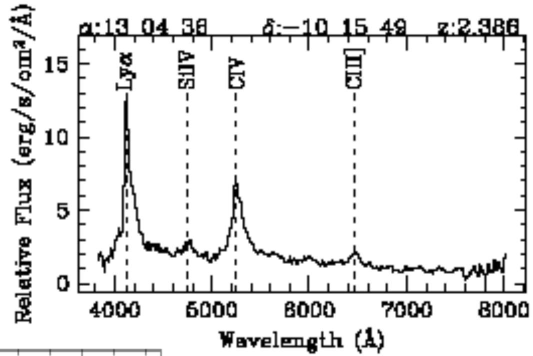
Broad Band Continuum (IR-Xray)

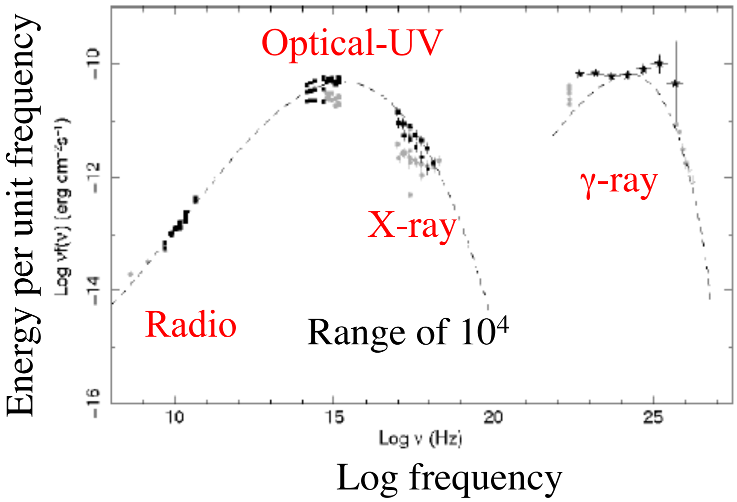




Broad Band Properties of AGN

- **Broad band continuum- very different from stars or galaxies**
- **Strong UV lines not seen in stars**
  ….
- Can be very variable
- 3 types Seyfert I, II and Blazars



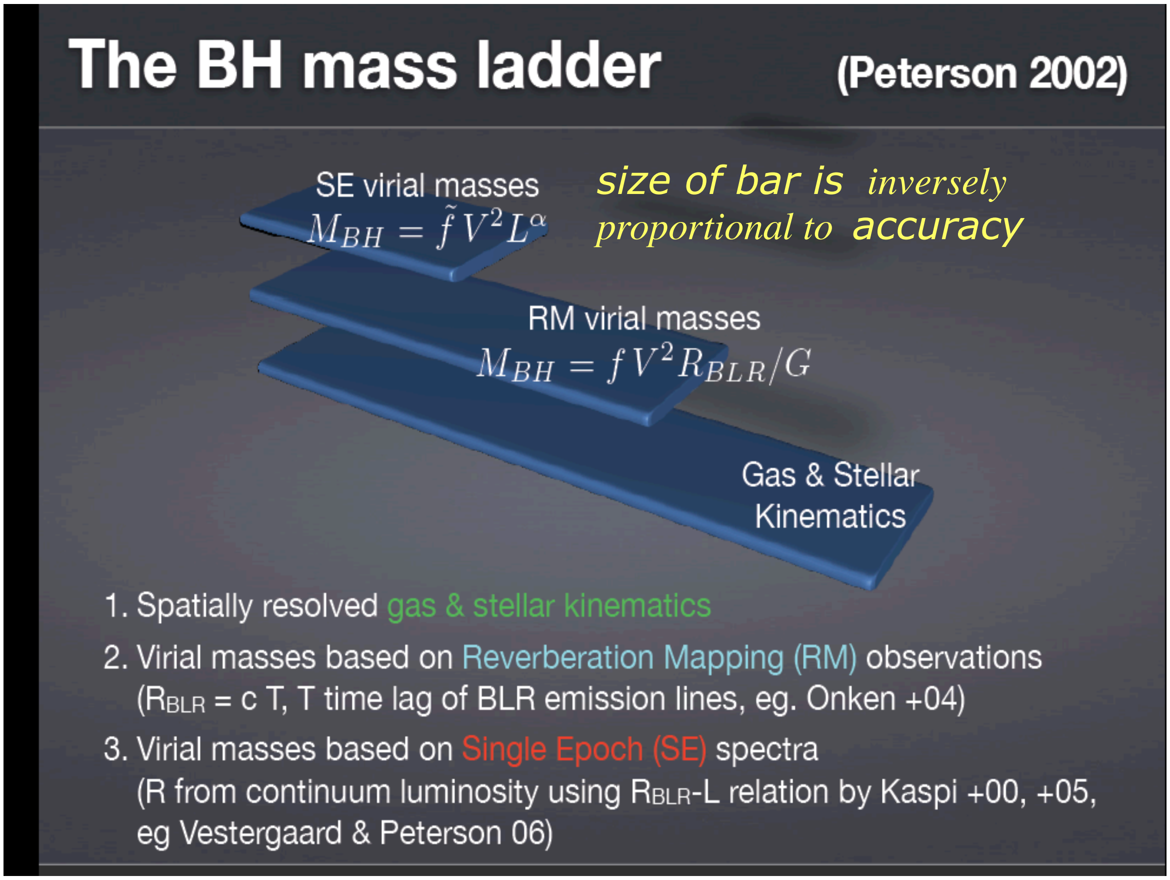


Broad band spectral energy distribution (SED) of a 'blazar' (an active galaxy whose observed radiation is dominated by a relativistic jet 'coming at' us

A large fraction of the total energy appears in the γ-ray band

Co-evolution of Galaxies and Black Holes-Summary

- Theoretical models for the coevolution of galaxies and supermassive black holes are based on combining analytic models and numerical simulation of structure formation in the dark matter with ideas about how star formation
  and black hole accretion operate in practice
- Over cosmic time, galaxies grow through two main mechanisms: accretion of gas and mergers
- In a merger, the disk component of each galaxy is scrambled and tidal forces between the two galaxies drain away angular momentum from the cold gas in the disk of the galaxy, allowing it to flow into the inner region, delivering gas to the supermassive black hole.
- The scrambled disk material settles into a newly created spheroid.
- If the each of the merging galaxies contained their own supermassive black holes, these too might merge to form a single larger one.
- The release of energy from the merger-induced AGN and starburst is so intense that it may blow away most or all of the remaining gas in a powerful outflow.
- The end result is a single galaxy with a larger bulge and a substantially more massive black hole (Heckman and Kauffmann 2012)


The BH mass ladder
(Peterson 2002)
SE virial masses
$M_{BH} = \tilde{f} V^2 L^{\alpha}$
size of bar is inversely proportional to accuracy
RM virial masses
$M_{BH} = f V^2 R_{BLR}/G$
Gas & Stellar Kinematics
1. Spatially resolved gas & stellar kinematics
2. Virial masses based on Reverberation Mapping (RM) observations
(R_{BLR} = c T, T time lag of BLR emission lines, eg. Onken +04)
3. Virial masses based on Single Epoch (SE) spectra
(R from continuum luminosity using R_{BLR}-L relation by Kaspi +00, +05, eg Vestergaard & Peterson 06)