Summary-

Course evaluations are open- Please Respond!

- www.courseevalum.umd.edu
- So far only **3** have responded (14%) !!
- Why?
  - For the benefit of your peers
  - Because your comments count and we use it to improve our teaching and/or redesign the course
  - Because your opinion is used to evaluate our performance
- ***Friday*** **is the last day!** The most common reason respondents gave for not participating was that they were too busy and/or ran out of time

Lots of Material!

- Going over the slides there were ~30 slides per lecture and 25 lectures- 800 slides!
- Wide variety of topics:

  stellar physics

  dynamics

  gas physics

  dust

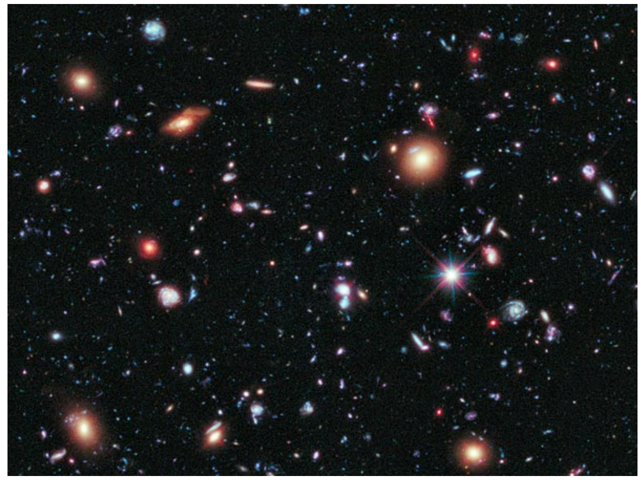
  star formation

  galaxy properties

  active galaxies .....

stuff not covered in text and the professors insistence on NOT covering stuff the text covers ...argh

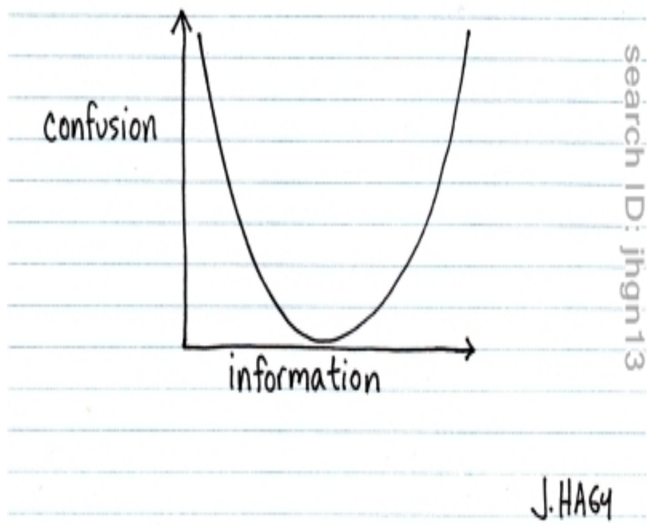
Congratulations for hanging in!



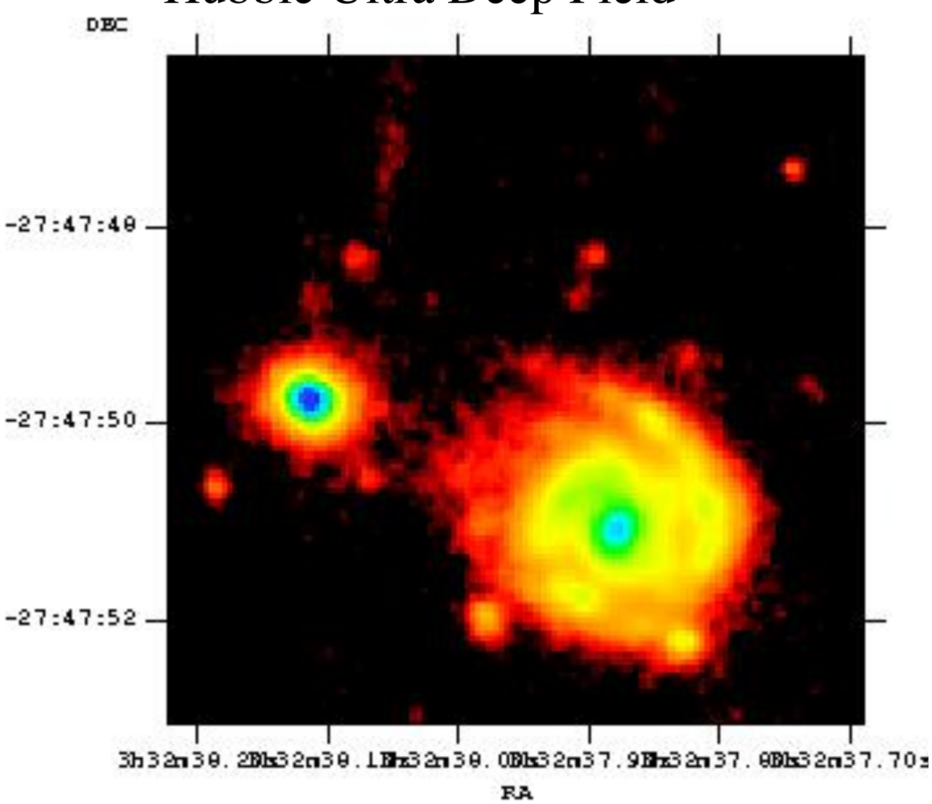
FINAL EXAM

- *<u>Friday May 19,</u> 10:30-12:30*
- Exam is in this room
- Cumulative, but with emphasis on material after the midterm
- No notes or books allowed
- **<u>Bring calculator</u>**

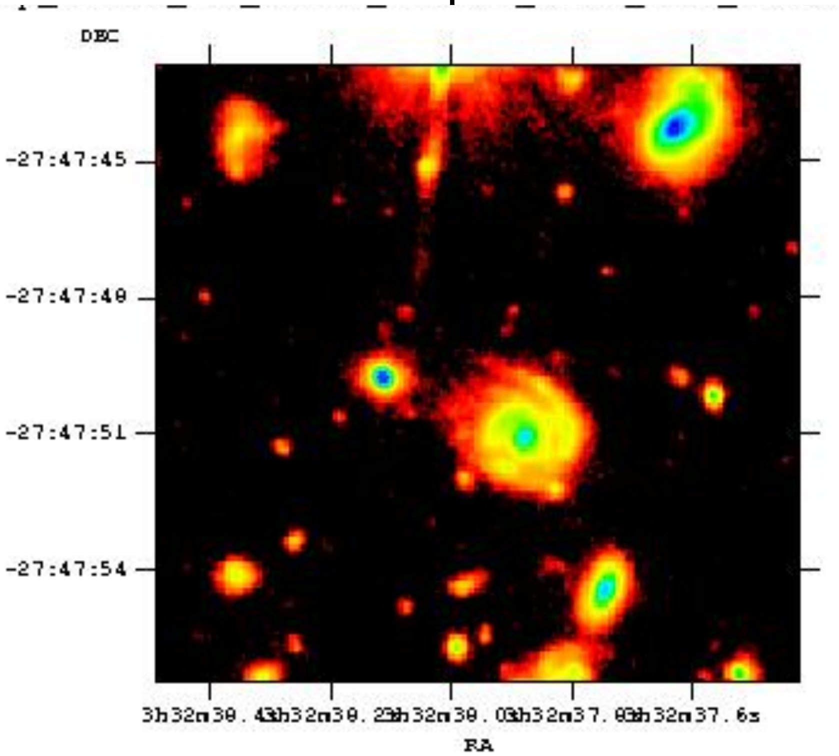
Maybe We Had a Bit of This



Hubble Ultra Deep Field



Hubble Ultra Deep Field



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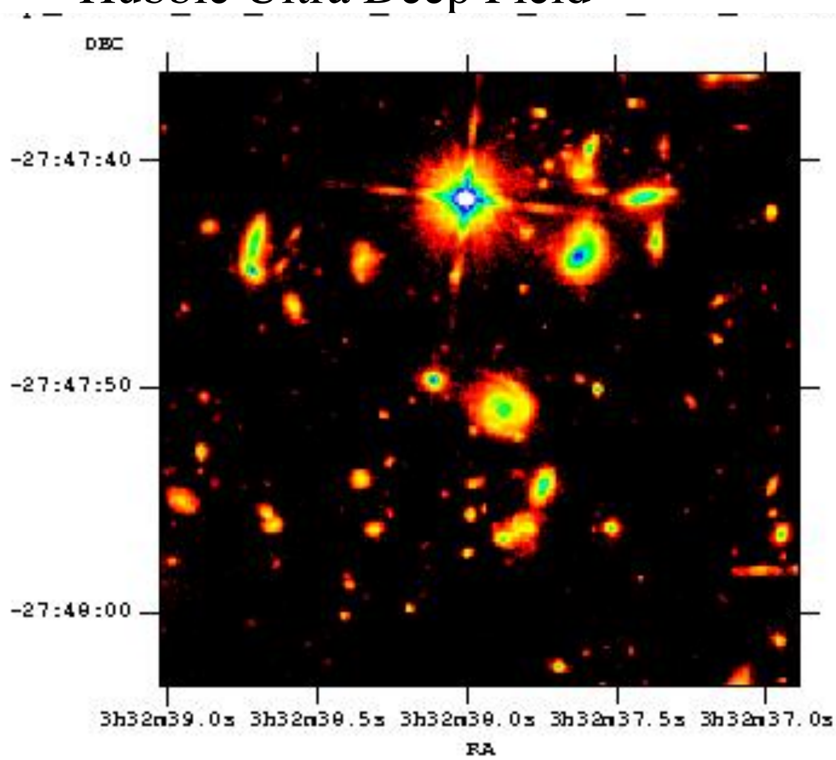
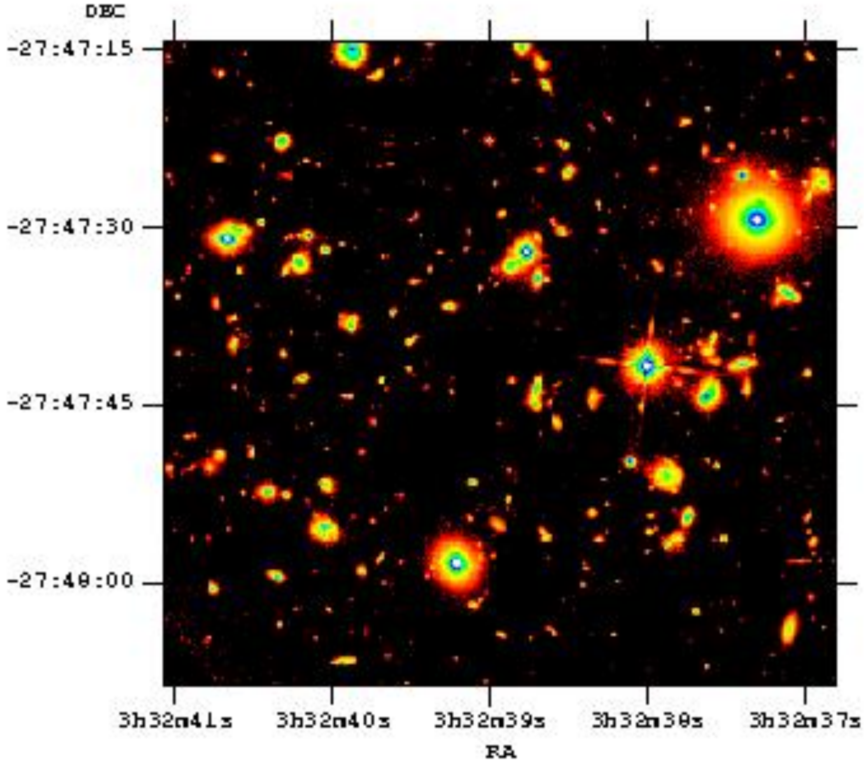
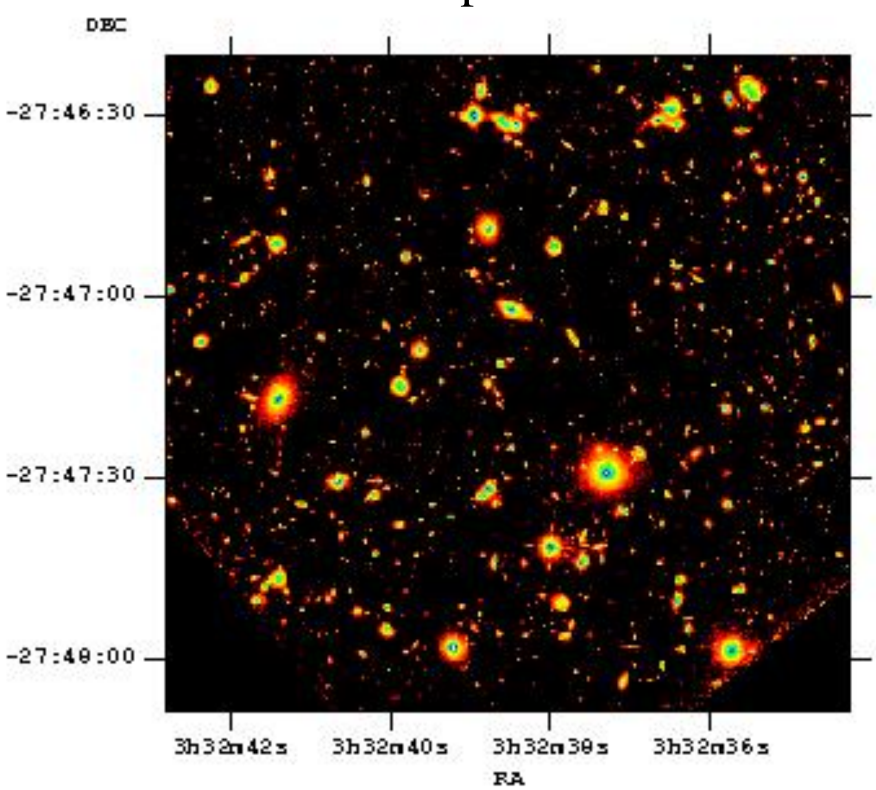


Hubble Ultra Deep Field

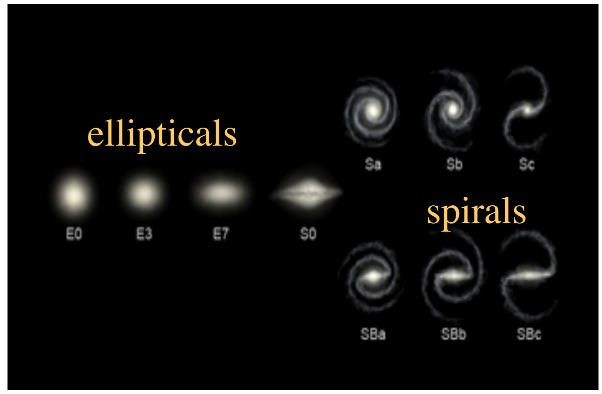


Hubble Ultra Deep Field



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.**



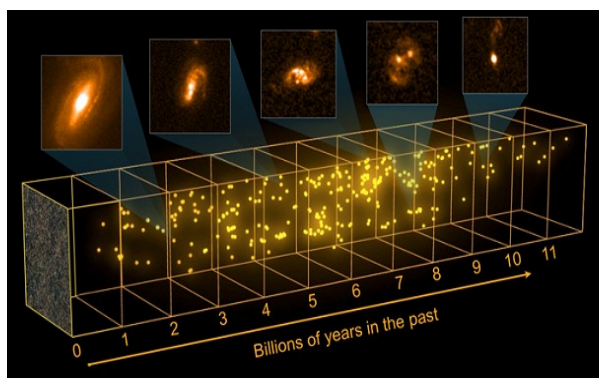
Galaxies come in a huge range of shapes and sizes

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

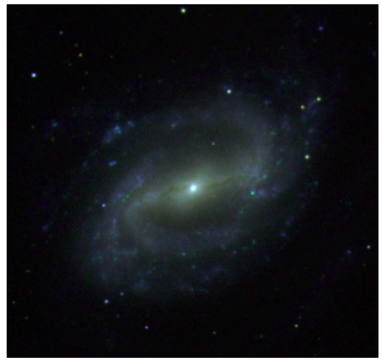
$M_{halo} > 10^{11} M_\odot$

V~350km/s

Highly Clustered

Old stars

little star formation now



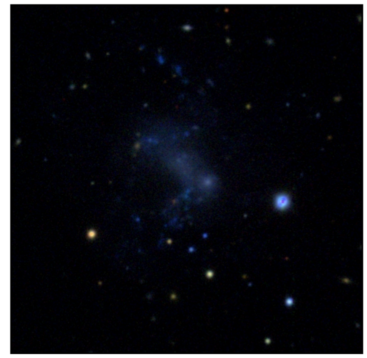
Spirals

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

V~200km/s

wide range of stellar ages

star forming



Dwarfs

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

V~30km/s

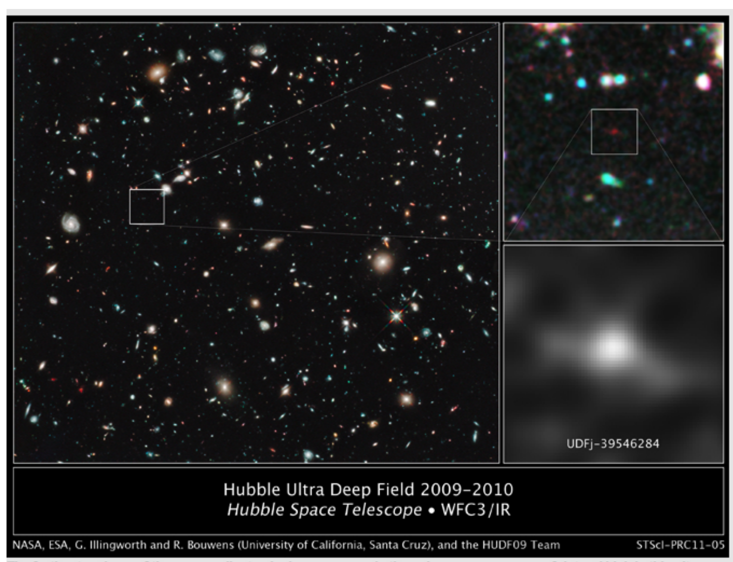
Weakly Clustered

Young stars

Numerous

Galaxies Over Cosmic Time

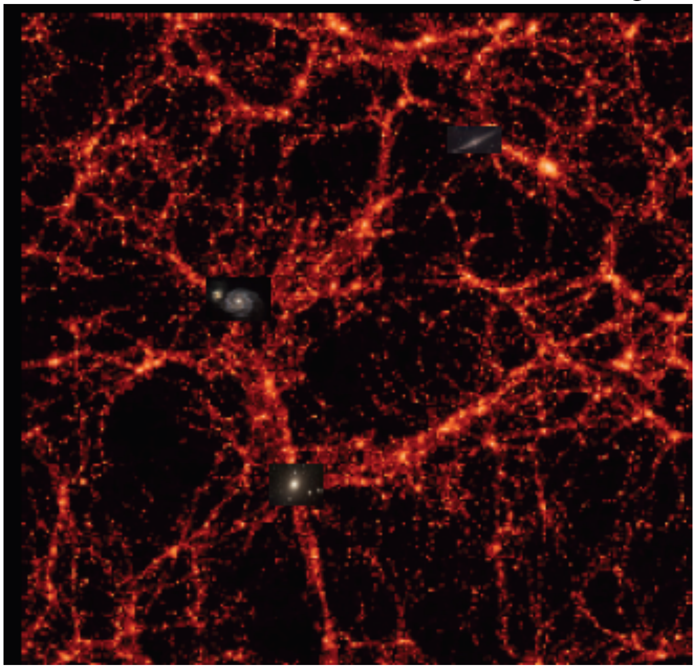
- Direct imaging has shown the existence of galaxies at z~8 (13Gyrs age, for an age of the universe model of 13.7Gyrs)
- Stellar ages: in the MW oldest stars are ~13.2Gyrs old (error of +/-2 Gyrs)
- Galaxies have changed enormously over cosmic time
- The present day pattern of galaxies emerged at z~1



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



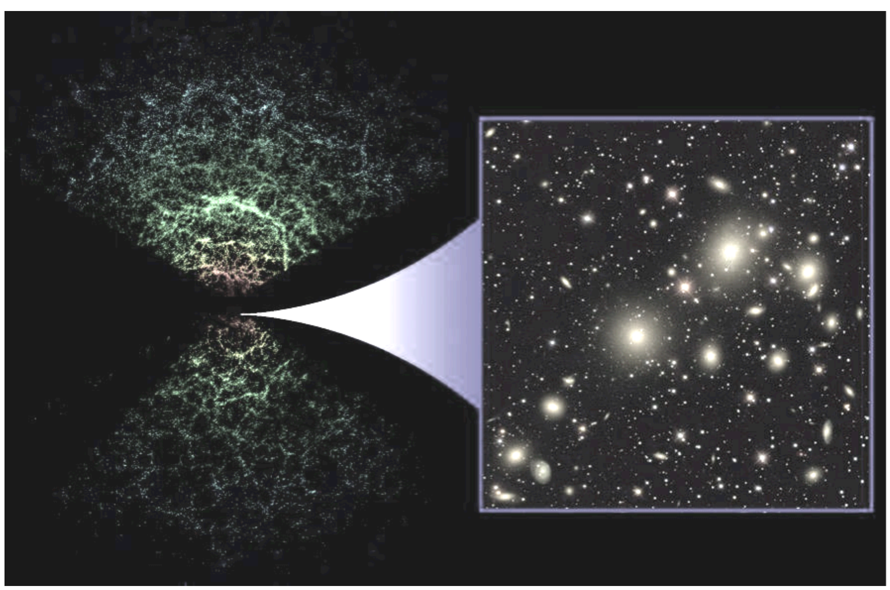
The cosmic web has structure at all scales but eventually becomes homogenous at R>70Mpc

Clusters are at the intersection of the filements of the web

Eric Bell

Large Scale distribution of normal galaxies

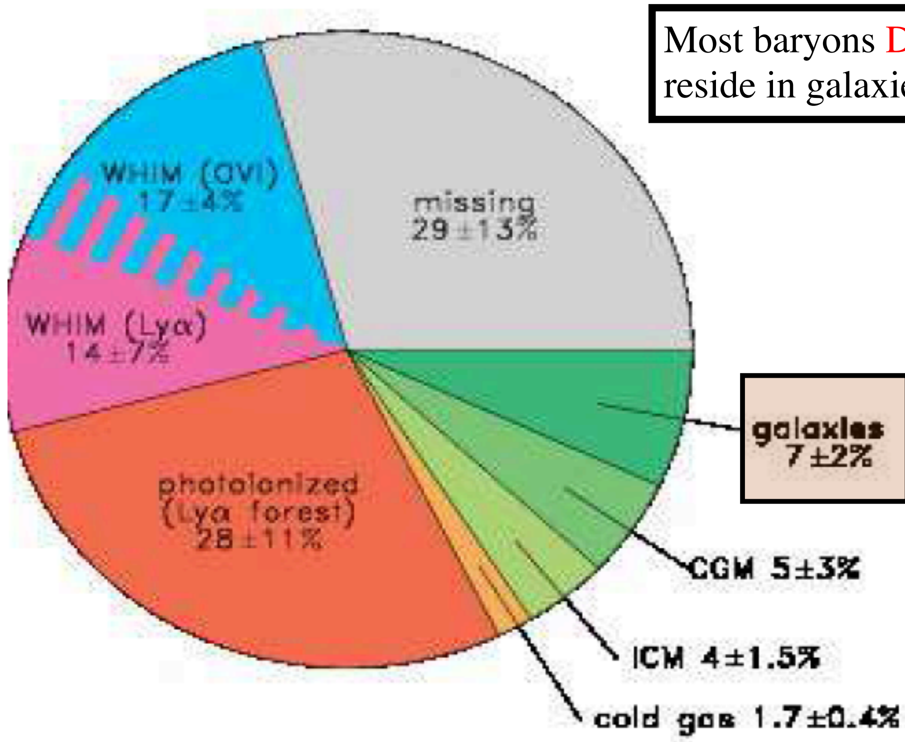
- On scales $<10^8$pc the universe is 'lumpy'- e.g. non-homogenous
- On larger scales it is homogenous- and isotropic



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

Where are the Baryons

Shull Danforth 2012



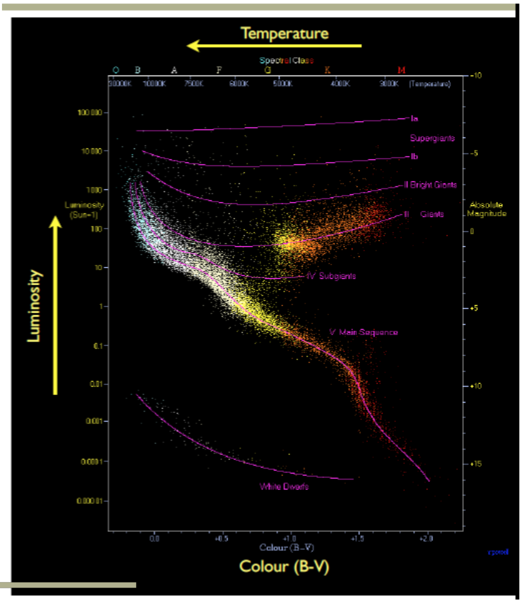
Most baryons DO NOT reside in galaxies

Stellar Populations of Galaxies- **2** Lectures

see MBW10.3- (sec 10.1-10.2 for stellar structure theory- will not cover this) parts of sec 2.2 and 6.3 in S&G

Top level summary

- stars with $M<0.9M_\odot$ have MS lifetimes $>t_{Hubble}$
- $M>10M_\odot$ are short-lived:$<10^8$years $\sim 1t_{orbit}$
- Only massive stars are hot enough to produce HI–ionizing radiation
- massive stars dominate the luminosity of a young SSP (simple stellar population)



HERTZSPRUNG-RUSSELL DIAGRAM

Plots luminosity of stars, versus their temperature.

Stars populate distinct regions of this plane, corresponding to particular evolutionary phases.

H-R(CMD) diagram of region near sun

H-R is theoretical

CMD is in observed units (e.g. colors)

Why Did **We** Study Stars???

- The UV-near IR band is one of the prime regions for studying galaxies since most of the light in that band comes from stars.
- The stellar populations of galaxies hold vital clues to their formation histories
- Stellar spectra contain information about
  - age
  - metallicity and abundance patterns (origin of elements)
  - star formation rate history (conversion of gas into stars)
  - dynamics of the system (ability to measure formation processes and dark matter)
- Understanding stellar spectra allows measurement of dust and dust distribution
- One needs to understand stellar spectrum to obtain information about the Initial Mass Function of stars.

Simplest Physics of Stellar Spectra

- "hot" opaque bodies emits a continuous spectra- quasi-black body.
- "hot" low density gas emits a sequence of emission lines. - a neon sign.

- "cold" low density gas, placed in front of a hot opaque body, produces a continuous spectrum with dark lines on top (absorption lines). - light from the sun.
- Every element (Hydrogen, Oxygen, Nitrogen etc.) produces
  - a unique set of (mostly) absorption lines
    - which contains information on the ionization state of the element, its velocity and elemental abundance

Luminosity Mass Relation (MBW *10.1.4-10.1.5)*

- On the main sequence (MS) stars of the same age and metallicity have simple scaling relations (first order) **between mass, temperature, luminosity and size**
  - Basic physics of stellar structure eqs (MBW sec 10.1.4 eq 10.61) stars on the main sequence:

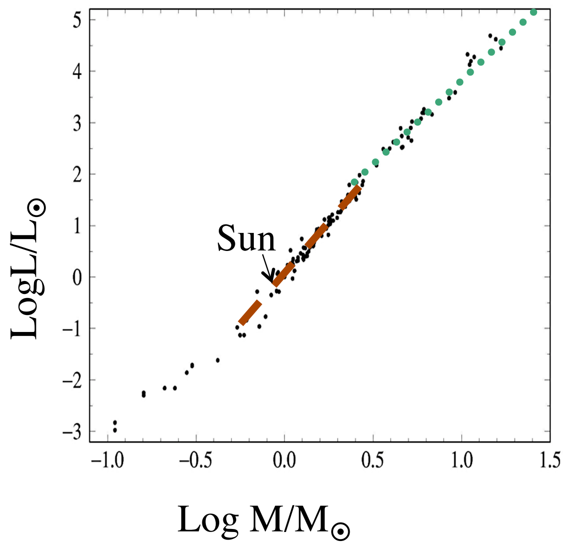
    Luminosity temperature **$L \sim T^b$** with $b \sim 4.1$ at low and 8.6 at high mass

    Notice the very strong dependences

    Lifetime on MS $\sim M/L \sim M^{-3}$

    Best global fit is $L \sim M^5$

    $R \sim M^{0.7}$



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Why are Stars Interesting

- Stellar data allow
  - high precision abundances for multiple elements in stars across the Galaxy, and the distributions of these chemical properties
  - kinematical data constrain dynamical models for the disk, bulge, bar and halo (where and how much matter is there)
  - explore the history of Galaxies by inferring the properties of stars as a function of age
  - From "The Apache Point Observatory Galactic Evolution Experiment (Apogee):Majewski et al 2015

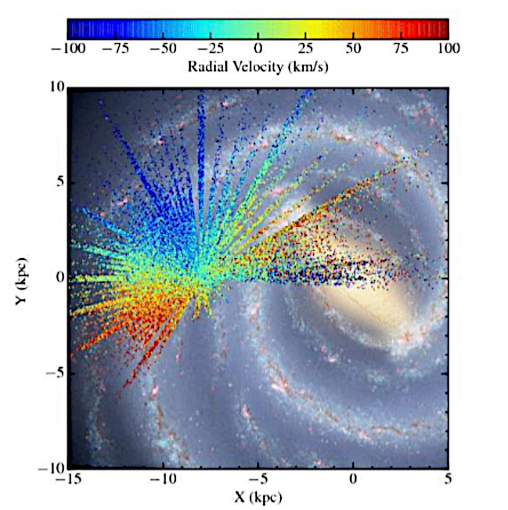
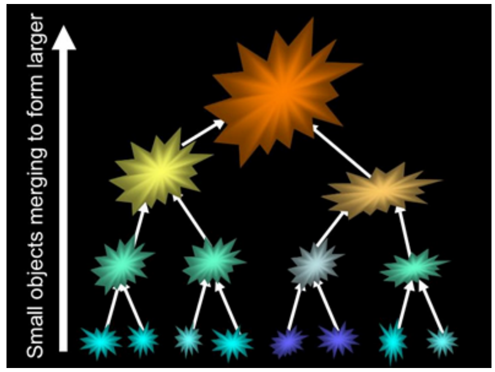


FIG. 24.— Star-by-star APOGEE heliocentric velocities as a function of Galactic X-Y position and projected on an artist's conception image of the Milky Way. The points represent main APOGEE

Velocity field of stars in MW

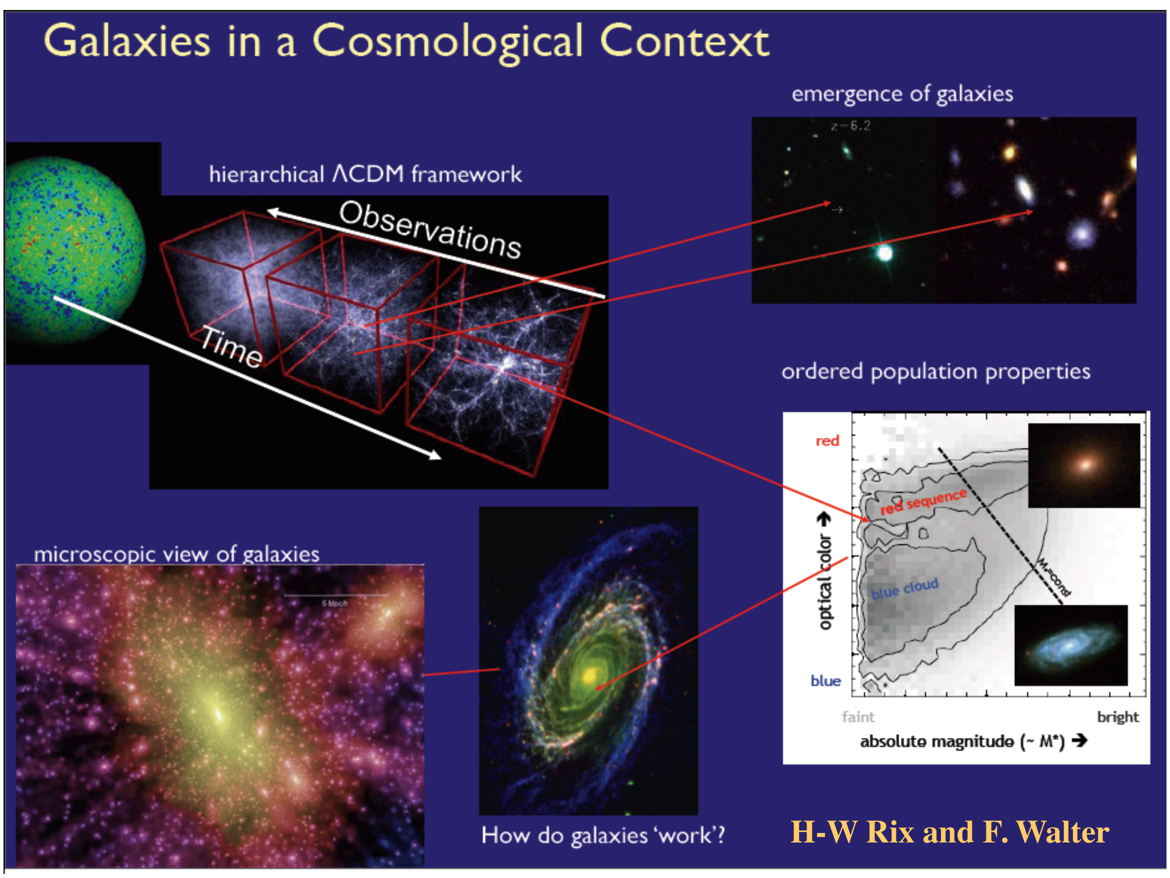
How Things Form

- 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



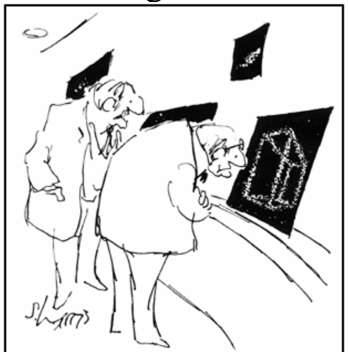
•Hierarchical clustering (or hierarchical merging) is the process by which larger structures are formed through the continuous merging of smaller structures.

•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).

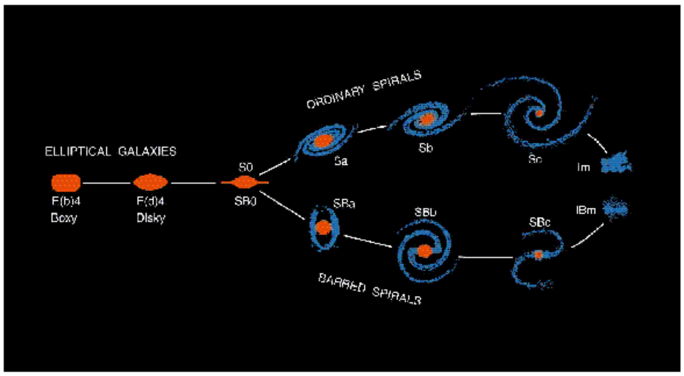


The Two Big Types of Galaxies and their Origins

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



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



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

Panchromatic MilkyWay

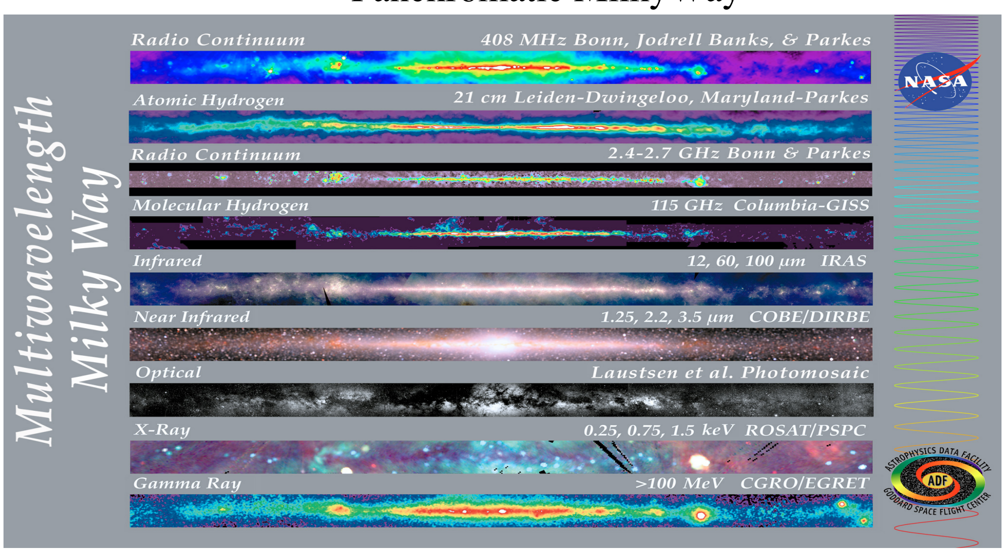
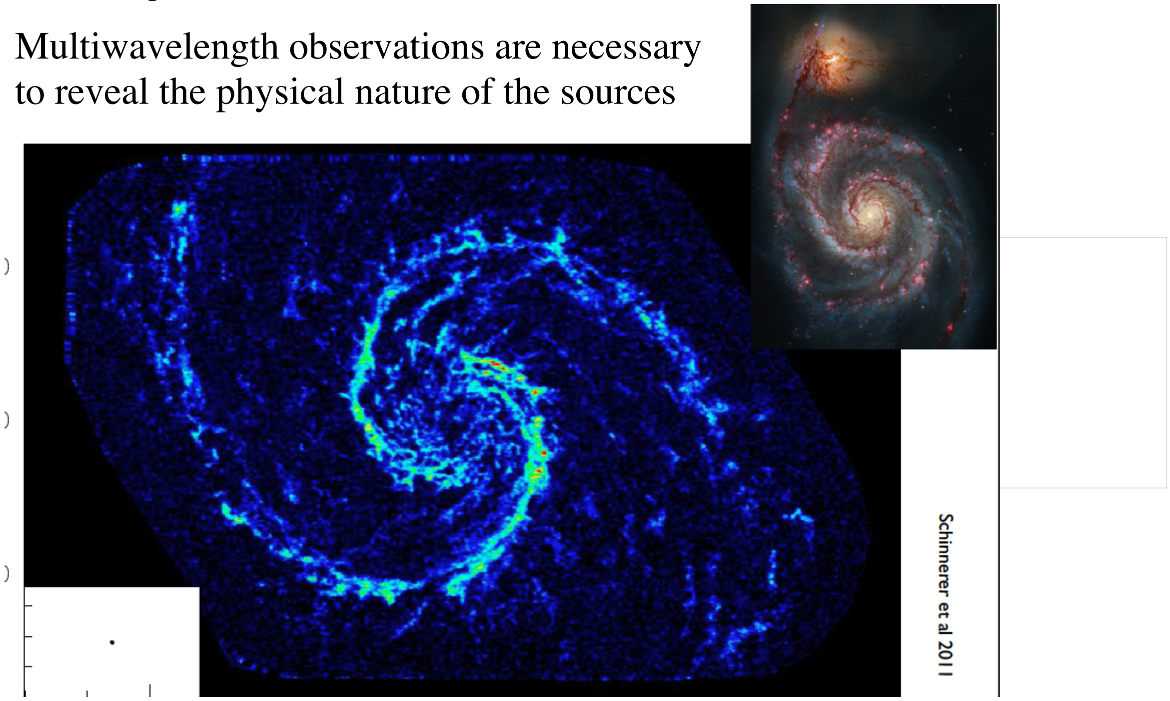


Image of MW galactic plane from radio through γ-rays-

appearance of galaxies can look very different in different wave bands due to the different physical origin of the emission (e.g. stars vs gas) and the different physical process (black body, synchrotron etc)

'Cool gas' (HI-hydrogen) and color coded
red is emission from warmer hydrogen, blue is young star,s reddish color due to is dust absorption)

Multiwavelength observations are necessary to reveal the physical nature of the sources



Dust

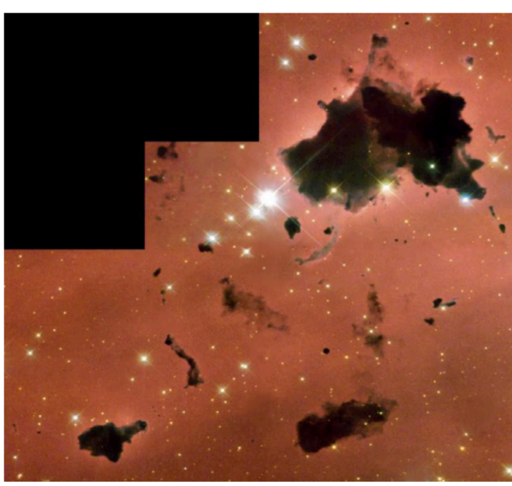
Controls the Optical,UV, IR properties of spirals

Not important in ellipticals at low redshift

Not effect radio or x-rays much

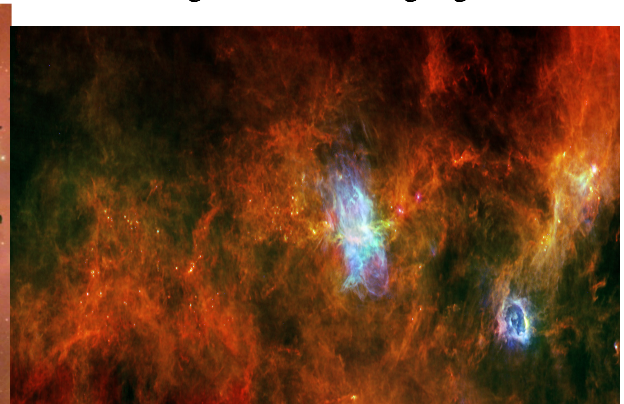
Optical image of star forming region

Interstellar extinction



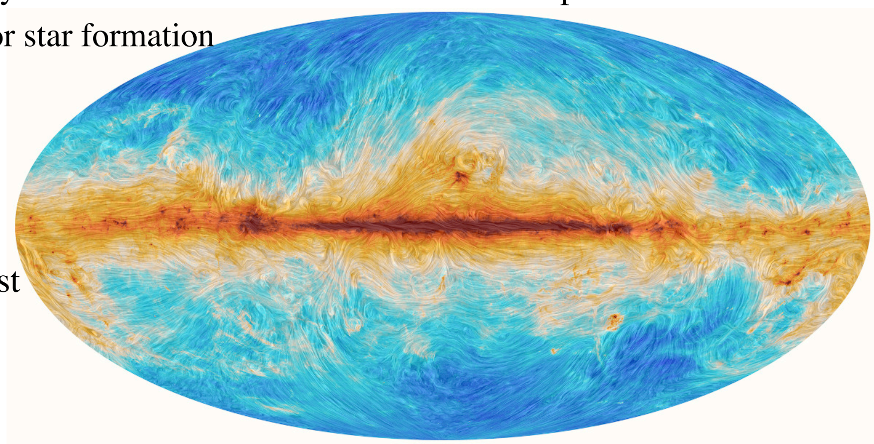
Interstellar Emission-

IR image of star forming region



Why Study Dust?? (Draine 2003)

- Dust grains play a central role in the astrophysics of the interstellar medium, from the thermodynamics and chemistry of the gas to the dynamics of star formation.
- Dust shapes the spectra of galaxies Radiation at short wavelengths is attenuated, and absorbed energy is re-radiated in the infrared.
  - Half of the energy emitted by stars in the MW is absorbed by dust and re-radiated in the IR
- Most of the heavy elements in the interstellar medium in spirals are in dust
- Dust is crucial for star formation



Planck map of dust emission and polarization in MW

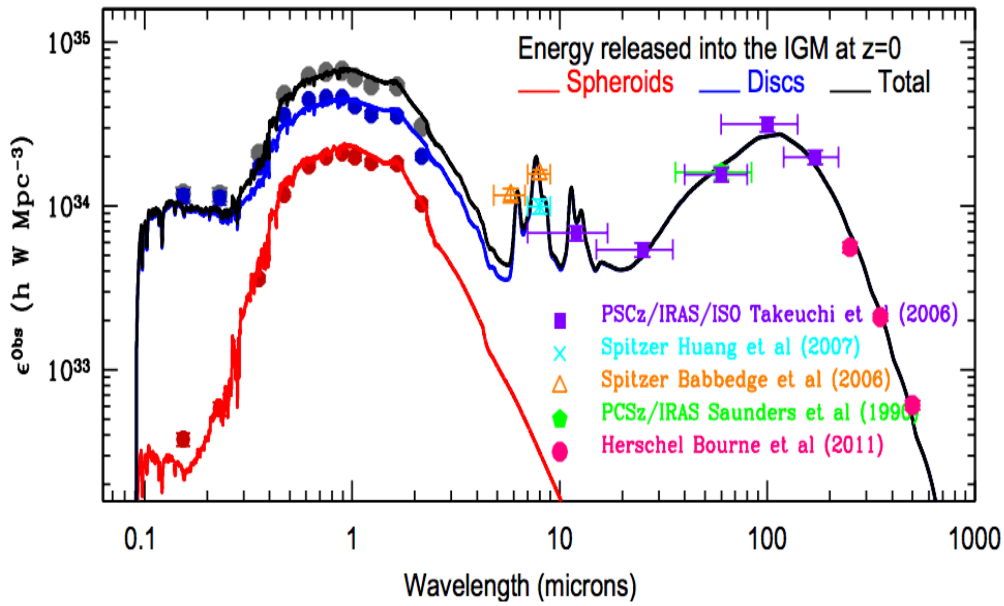
Summary of Dust

- Strong influence on
  - observational properties of galaxies (extinction, reddening, reprocessing)
  - physics of galaxies:
    - star formation
    - ISM
- Observed via
  - emission in IR
  - absorption in UV/optical
- Observational properties depend on
  - geometry
  - heating

- 'Backwards' evolution of IR spectrum with redshift allows 'easy' observation of high redshift universe

Energy Released By Galaxies

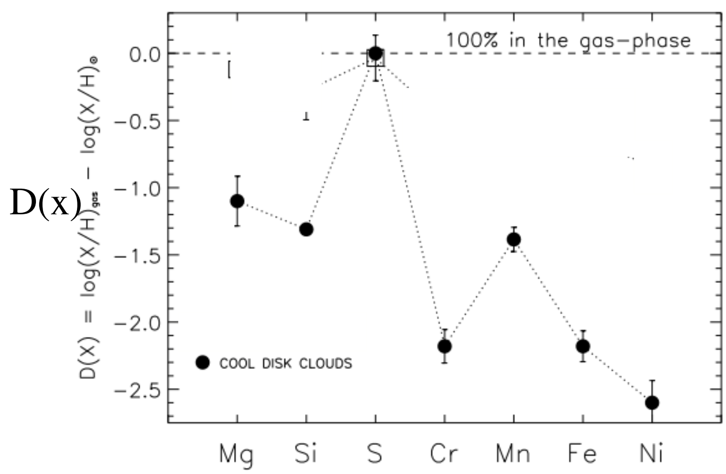
- Galaxy surveys have measured the total energy released by all low z galaxies across the UV-far IR (Driver 2012);
- **~40% of energy generated by stars is absorbed by dust and re-radiated in IR- this occurs predominately in spirals, ellipticals are relatively *dust poor***



Effects of Dust on Chemical Composition of ISM

- Dust 'depletes' the ISM of 'refractory' elements
  - Mg, Si, Al, Ca, Ti, Fe (75%), Ni are concentrated in interstellar dust grains.

dust formation involves condensation/adsorption, & not all elements condense efficiently to dust.



D(x)= 'depletion'- the reduction in the metallicity compared to solar

$D(X) = \log_{10}[N(X)/N(H)]_{obs} - \log_{10}[N(X)/N(H)]_{ISM}$

For example, D(C) = -0.7 means C/H is 20% of its expected value 80% in dust.

Reddening and Extinction

Extinction and reddening are linked

$A_V = R*E(B-V)$;

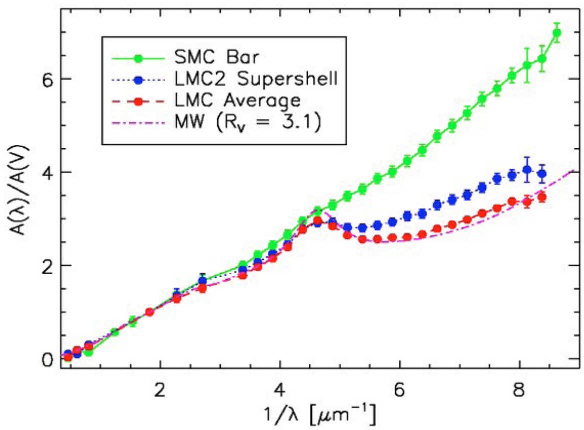
A_v is extinction

E(B-V) is reddening

R~3.1 for MW, 2.7 for SMC

- $k(\lambda)=A_\lambda/(E(B-V))=R_V A_\lambda/A_V$ and $A_\lambda = (2.5\ln\tau(\lambda))$ *-change in magnitude at wavelength λ due to extinction*

- $R_V=A_V/E(B-V)$
- $m_v-M_v=5\log d-5+A_v$

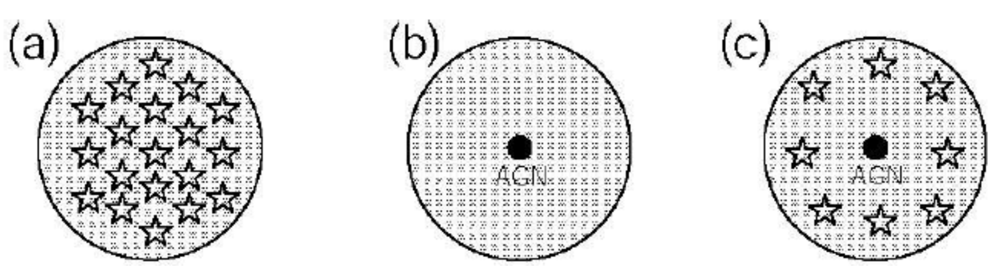


A_λ-A_v is a function of wavelength and can differ from place to place

Dust and Geometry

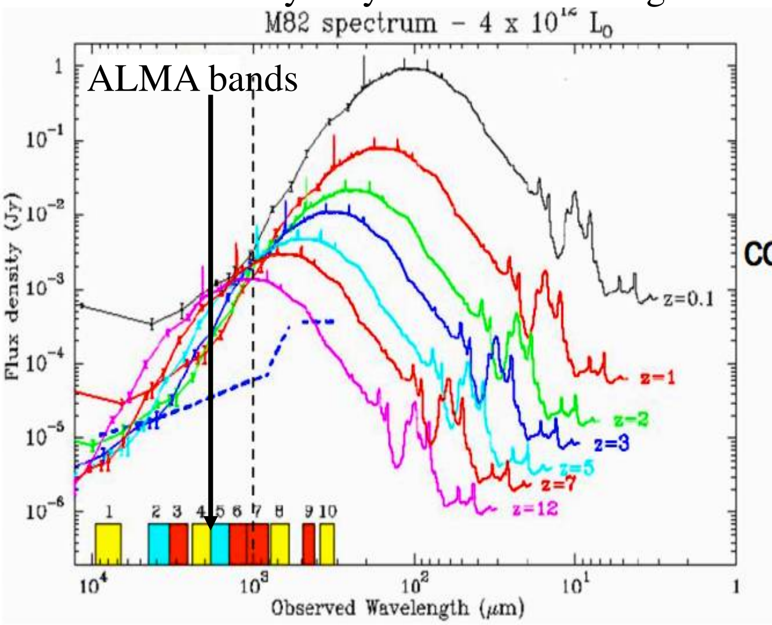
- The effect of dust depends on the relative geometry of the sources and the dust.
- in (a) the stars near the surface of the dust cloud have much less extinction and thus dominate the UV light
  - stars near the center are more absorbed and thus dominate the IR light
- In case (B) we have the classic case of a simple absorber and one light source (AGN)
- in case (C) we have one very luminous object (AGN) and stars

So it ain't simple



In the High Z Universe *Dust is Our Friend*

- FIR emission from dust has a negative 'K' correction (the observed flux is only weakly dependent on distance)
- It is thus relatively easy to detect distant galaxies in the FIR



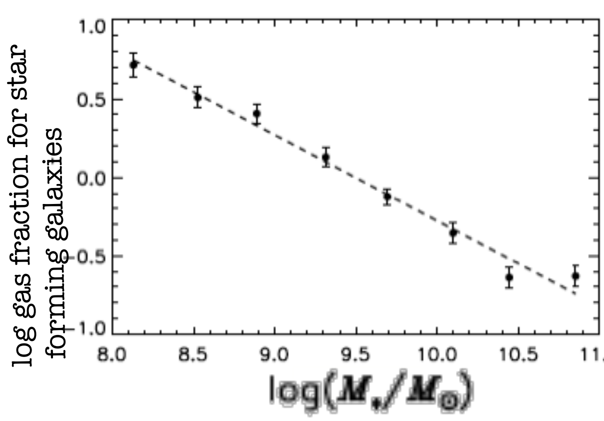
The steep submm SED counteracts the $1/D^2$ cosmological dimming

R. Maiolino

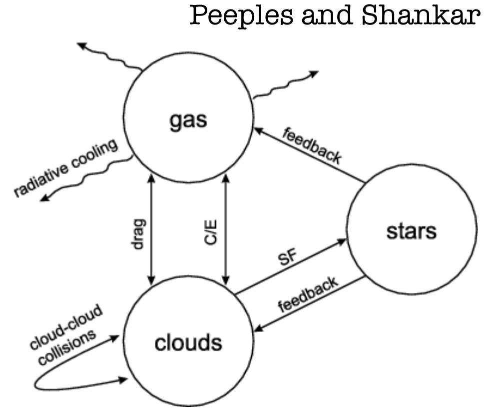
37

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(s)
  - dynamics



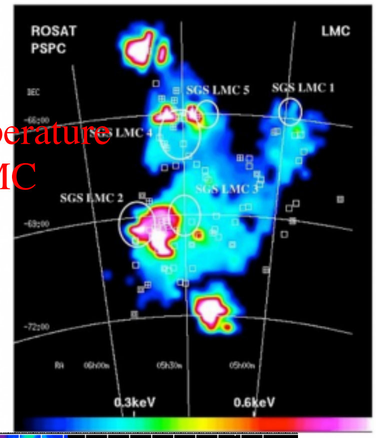
Peeples and Shankar 2011

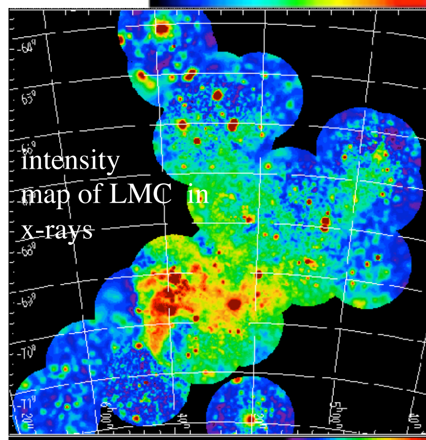


Big Questions

- What is the volume filling factor of the hot ISM?
- What is the distribution of the temperature, density, and velocity
- What are typical scales in the ISM and why?
- What is the effect of turbulence , magnetic fields and cosmic rays?
- How is the ISM related to star formation?
- Why is the ISM in spirals and ellipticals so different in density and temperature?

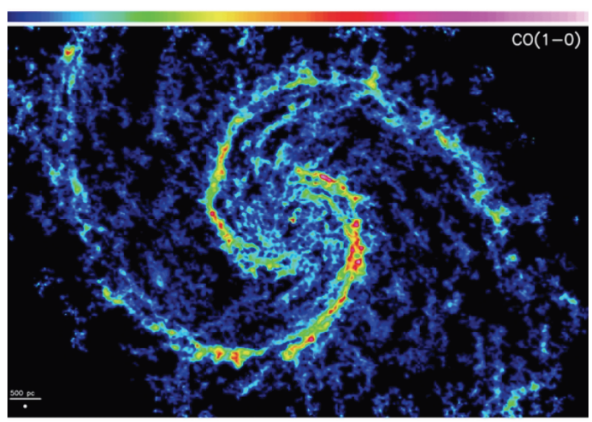
x-ray temperature map of LMC





- 'Cold' gas: dominates in **Spirals-***many phases*
  - neutral hydrogen
  - molecular gas-Dense molecular clouds, have most of the total mass of the interstellar gas
    - of key importance for star formation, occupy a negligible fraction of the total volume
  - warm ionized gas-has persistent transient states out of thermal pressure balance

GAS-ISM



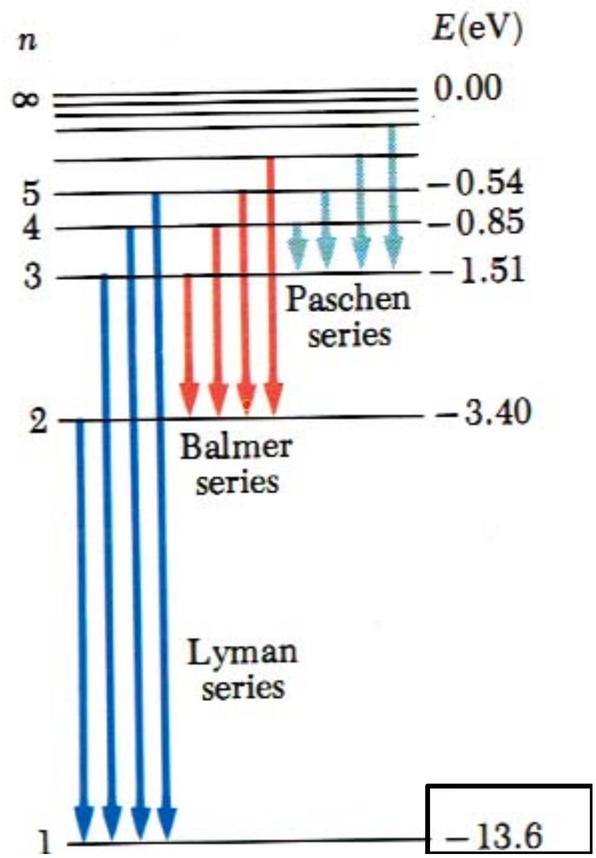
CO Image of M51

Milky-Way-like galaxies cold gas mass~10% of the stars

CO is major tracer of molecular gas but ~ one CO molecule for every 10^4 of H_2.

Atomic Lines

- The energy levels and transitions for **hydrogen**
  - **e.g Lyman is n → 1**
  - Balmer is **n → 2**
- Each element and ionization set has a similar (but more complex) set of lines
- The probability of emitting a given line depends on the temperature and density of the gas



Physics of Emission from Gas-MWB sec 10.3.7

- Gas is heated/excited/ionized by photons (stars, AGN), shocks (supernova) and gravity
- Atomic transitions reveal the ionization state, temperature, density, velocity structure and chemical composition of the gas.
- Three 'main modes of excitation
  - Photoionization: photon from source eject electron from ion- to do this photon needs to have energy greater than ionization potential (e.g. 13.6 eV for Hydrogen; O,B stars, AGN)
  - Collisional ionization: gas is excited by collisions with 'hot' electrons (again electron energy has to be above threshold). Electrons have Maxwell-Boltzman energy distribution in equilibrium (S&G eq. 3.58)
  - Shocks due to supernova

A Bit of Physics-TimeScales

For a sphere of gas, if thermal pressure is balanced by self-gravity the timescale to collapse (the **Jeans time**)

- $\tau_J \sim 1/\mathrm{sqrt}(4\pi G\rho)$ which is similar to the free falltime (S&G eq 3.23)-The *free-fall time* t_{ff} is roughly the time that a gas cloud of density ϱ would take to collapse under its own gravity (Also see MWB pg 14)

  $\tau_{ff}=(3\pi/32G\rho)^{1/2} = 4.4 \times 10^4$ yr $/\mathrm{sqrt}\{n_H/10^6\}$ if gas is hydrogen
- *Jeans length* $\lambda_J = c_s\,\mathrm{Sqrt}(\pi/G\varrho)$ *S&G 2.24*

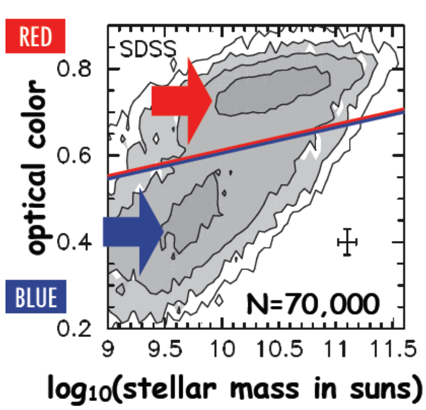
n_H is the particle density

ρ is the mass density

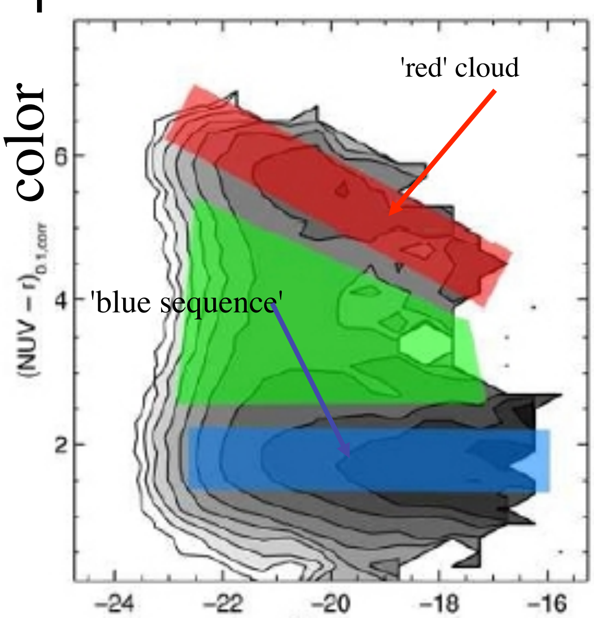
https://en.wikipedia.org/wiki/Jeans_instability;

Galaxy Relations
Strong Connection of morphology and physical properties

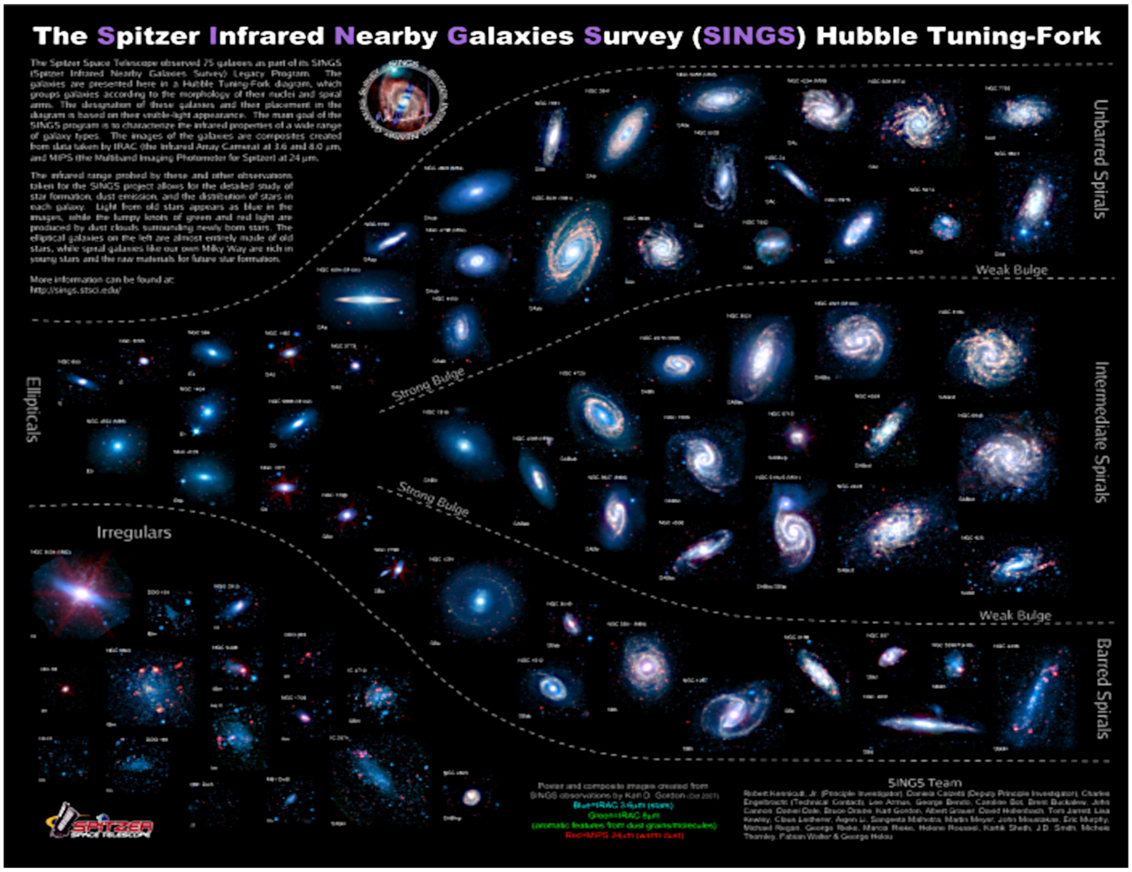
- Density of galaxies vs color and luminosity
- Galaxies fall into 2 broad classes
  - 'red' cloud-mostly ellipticals
  - **'blue sequence'** mostly spirals
  - Few galaxies between- 'green valley'



Isopleths- lines of constant galaxy density

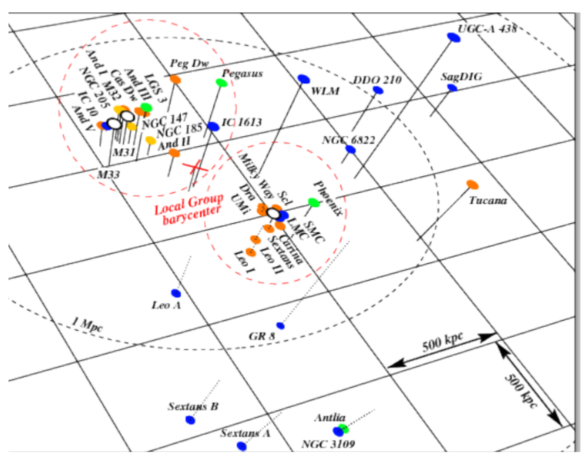


Baldry et al 2004



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) which be can studied in detail



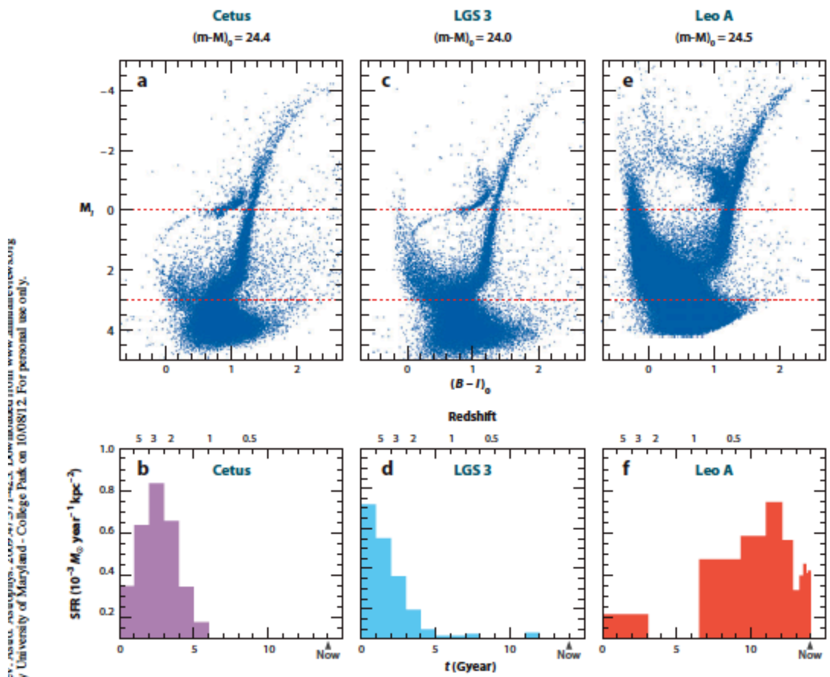
–allows study of dark matter on larger scales and first glimpse at galaxy formation

–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??- constraint on 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

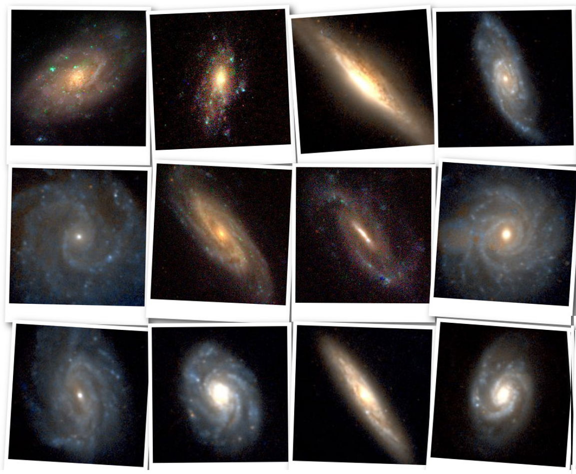
- thought to form via mergers (i.e. accretion of usually smaller external units)- disks reform later after merger by accretion of gas.

Spirals

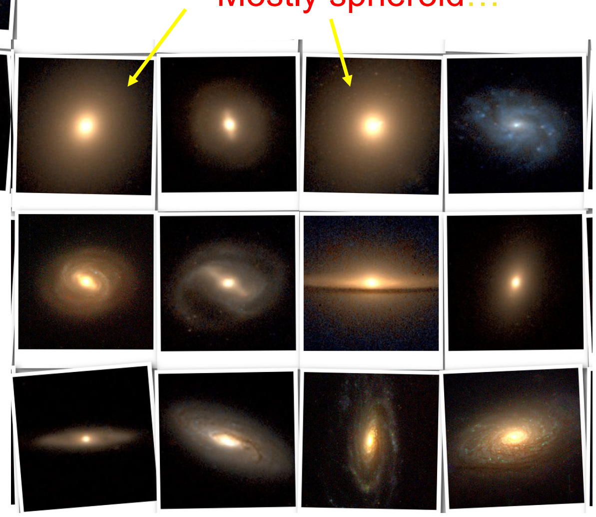
- have cold gas and dust
- present day star formation
- many have internal structure (spiral arms and bars)
- a bulge and disk (large range in relative importance)
- host **radio quiet AGN**
- are more frequent in lower density environments
- appearance of galaxy can change radically depending on the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

A Bit of the Galaxy Zoo

Mostly disk…

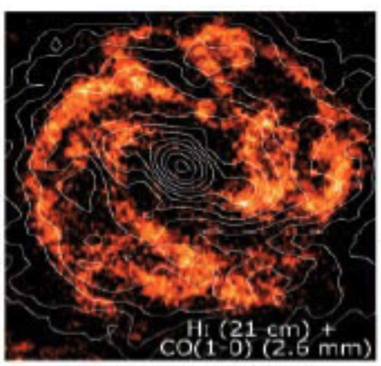


Mostly spheroid…

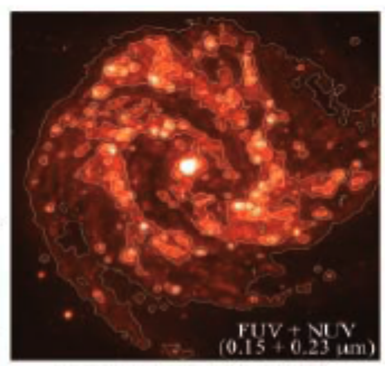


- Disk-bulge separation is tricky and influenced by inclination angle and dust and wavelength observed (disks standout in the blue, bulges in the red)

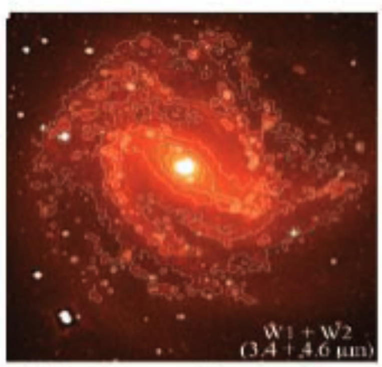
M 83: from Gas to Stars



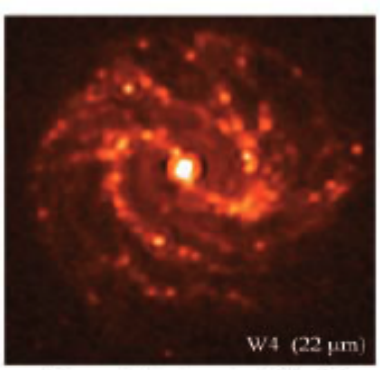
Neutral gas is the *reservoir*, molecular gas fuels the star formation



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)

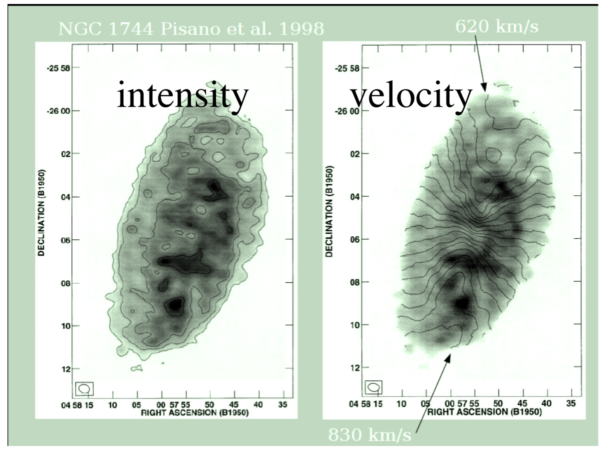
HI

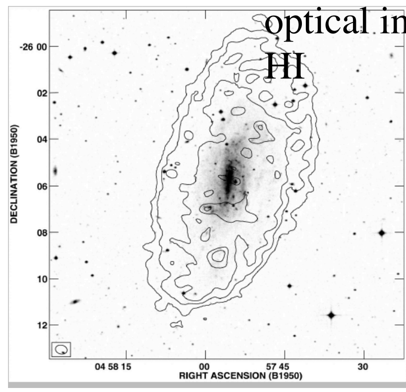
- Spirals have large HI disks

– 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





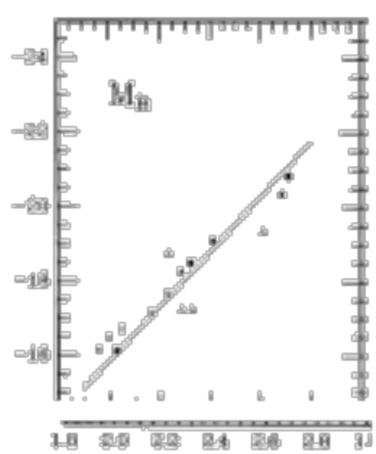
optical image and HI

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.

Absolute luminosity measured in magnitudes

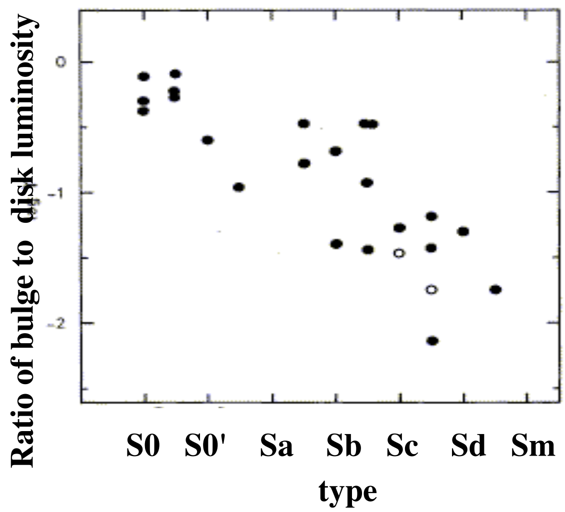


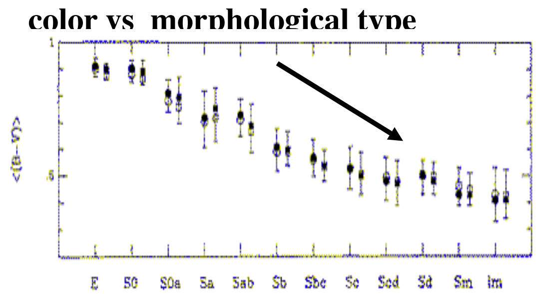
log rotational velocity

Spirals

The Hubble type of a spiral correlates with

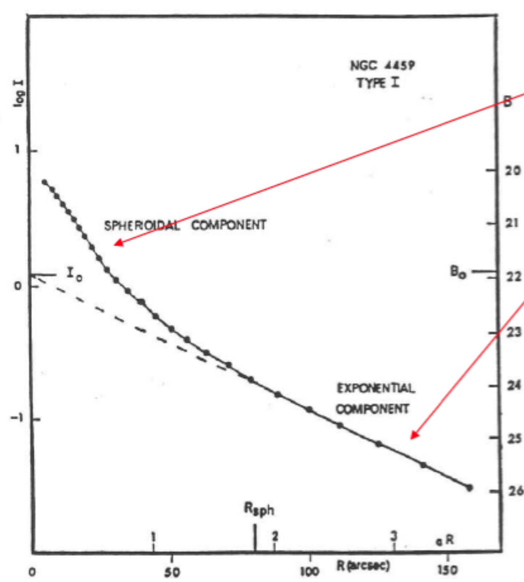
- bulge/disk luminosity ratio
- relative content of cool gas (H I)
- mass concentration
- stellar population (how many young/ old stars)
- nuclear properties
- chemical abundances in the ISM
- star formation history and integrated stellar spectrum
- bulges of spirals tend to have old stars, disks younger 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)*





Azimuthally Averaged Light Profiles

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



$$logI \propto R^{1/4} \quad \text{(inner)};$$

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

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

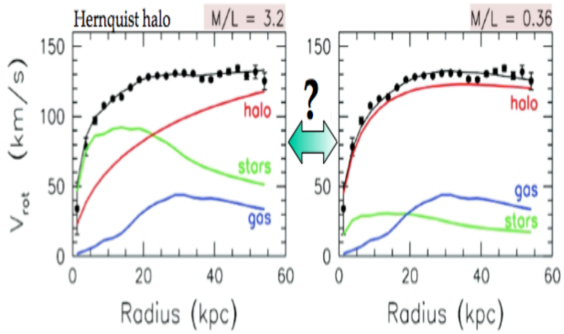
Spirals and Dark Matter

- 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:



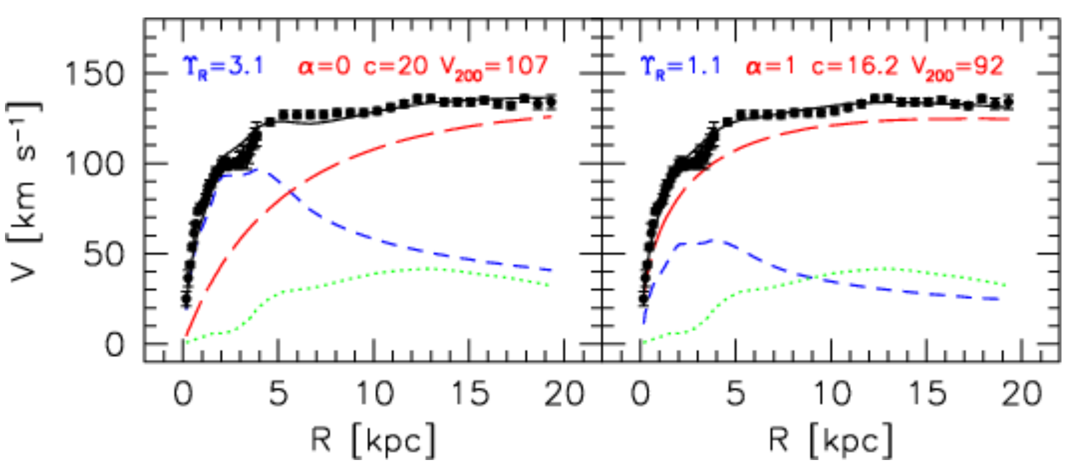
Dark matter dominates mass (and potential) outside ~a few scale lengths

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

Disk Halo Degeneracy

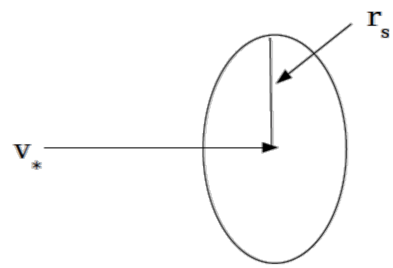
- MBW fig 11.1: two solutions to rotation curve of NGC2403: stellar disk (blue lines), dark matter halo - red lines.

- Left panel is a 'maximal' disk, using the highest reasonable mass to light ratio for the stars, the right panel a lower value of M/L



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 $m \sim 1/2 M_\odot$
$v = 30$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
$n\pi r^2_s vt = 1$, $t_s = v^3 / 4\pi n G^2 m^3$

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

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

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 $2\langle T\rangle + W = 0$

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 $M=2\sigma^2 R_H/G$; 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

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

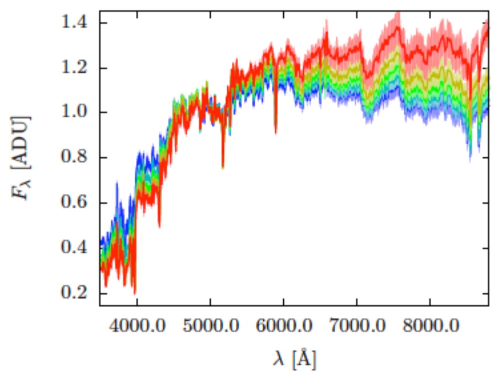
GALACTIC DISK	GALACTIC HALO	GALACTIC BULGE
Highly flattened	Roughly spherical—mildly flattened	Somewhat flattened and elongated in the plane of the disk ("football shaped")
Contains both young and old stars	Contains old stars only	Contains both young and old stars; more old stars at greater distances 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

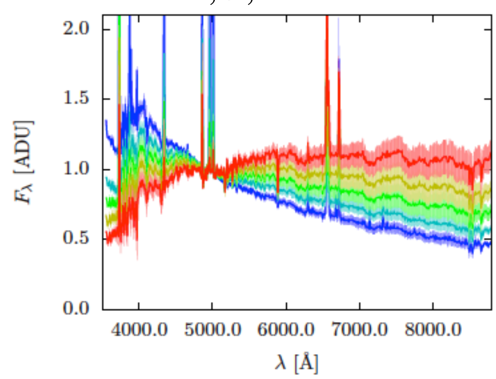
From Chaisson

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)

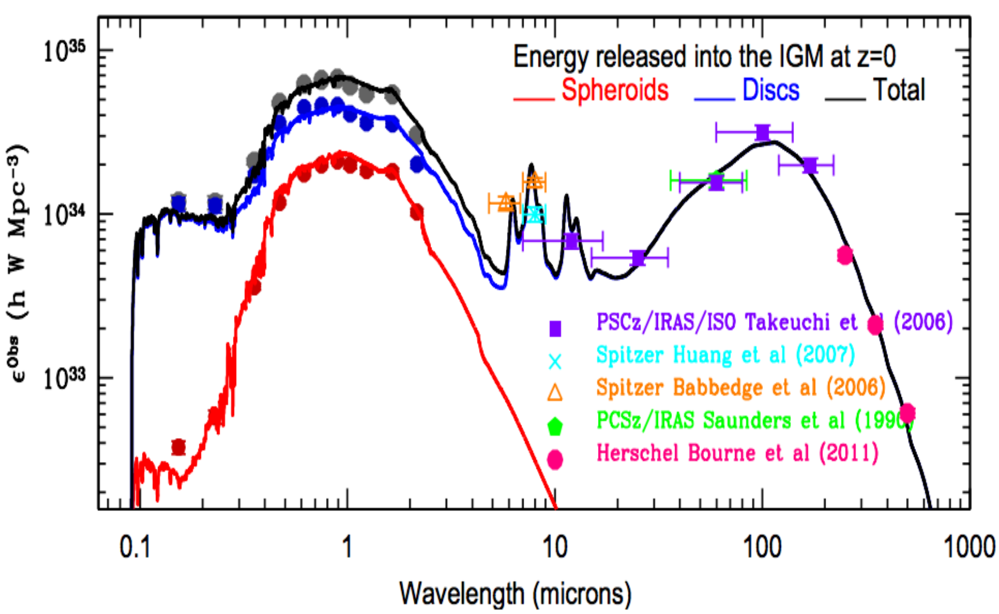
emission lines due to H,O,Ne etc





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 1.3×10^{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



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-

- 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

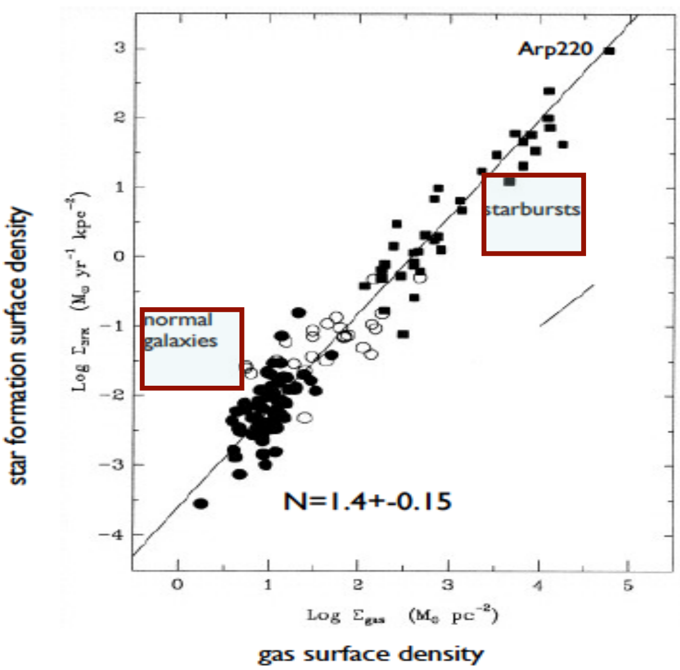
- Hα observations, which gives the number of ionizing photons if one assumes that all ionizing photons are used and eventually re-emitted - ionizing photons are almost exclusively emitted by massive (hot) stars which have short lifetimes; slo the effects of dust can be large
- far-IR flux - this assumes 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 σ (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

this σ is NOT the velocity dispesion



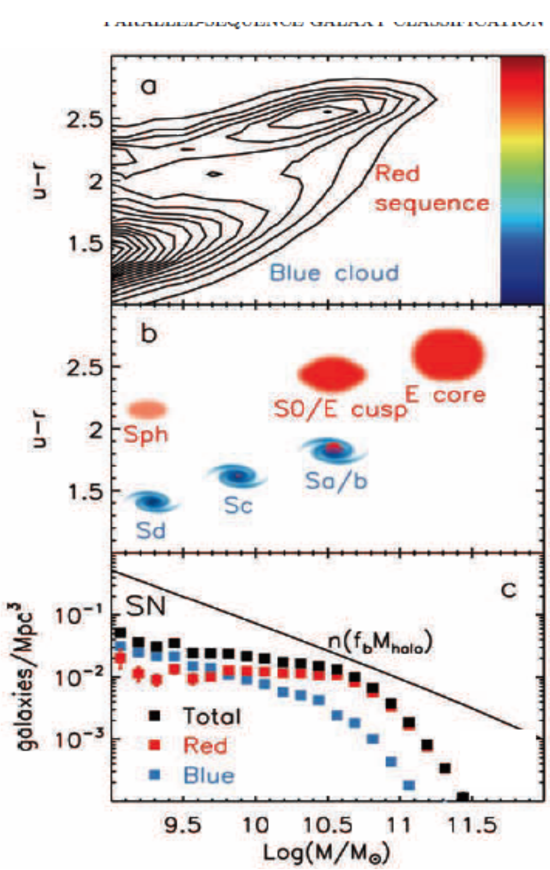
The Big Picture- Two Populations

- 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

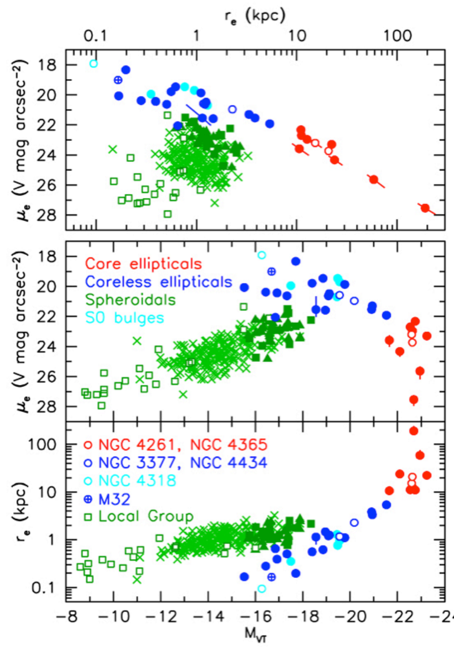
bottom panel shows the galaxy mass function divided by color (Cattaneo et al 2009)-

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

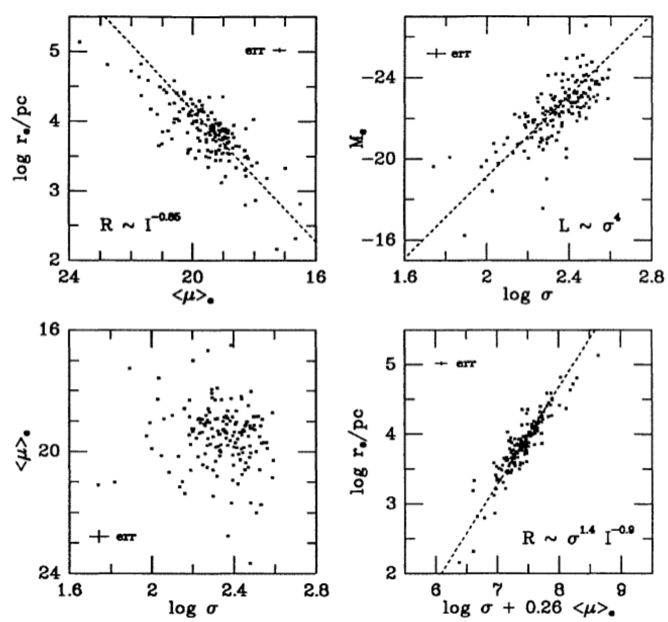
- Visual Impression: smooth, roundish- deceptively simple appearing- collisionless systems
- While visually 'similar' detailed analysis of spheroids groups them into 3 categories
  - Massive/luminous systems: little rotation or cool gas, flat central brightness distribution (cores), triaxial; lots of 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



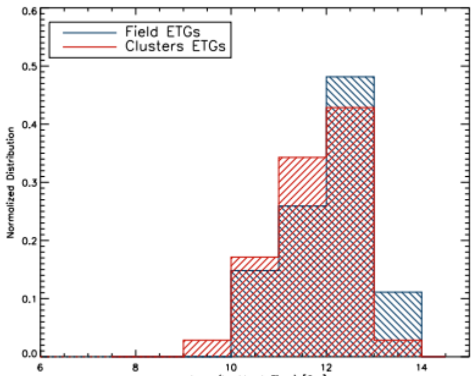
2 Projections of the fundamental parameter plane of elliptical galaxies. *Top*

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

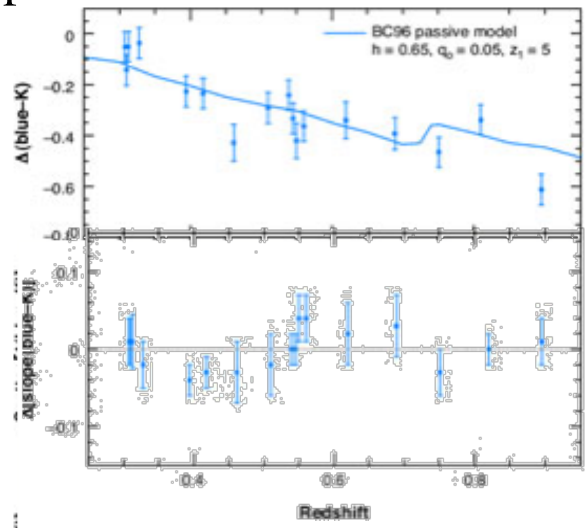
Higher z observations constraint on origin of Ellipticals

- 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



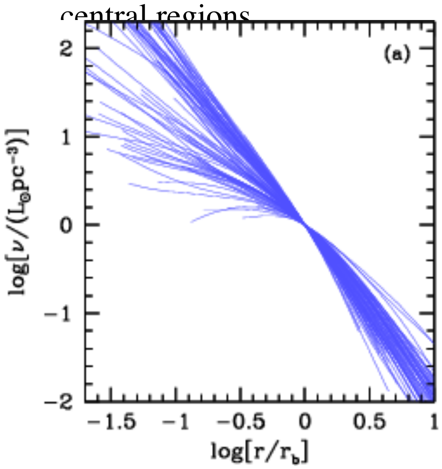
look back time of star formation

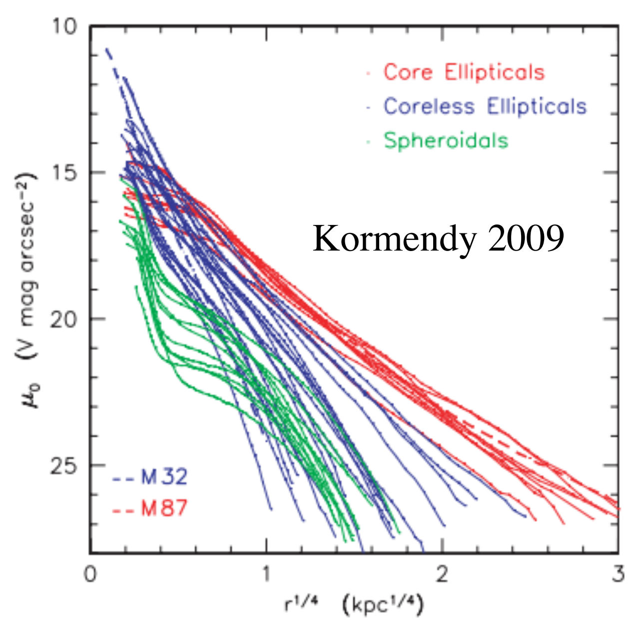


using the consistency of the colors of these galaxies with 'passive' evolution the ages of massive ellipticals in clusters is ~10-13Gyr (!)- Rettura et al 2012

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

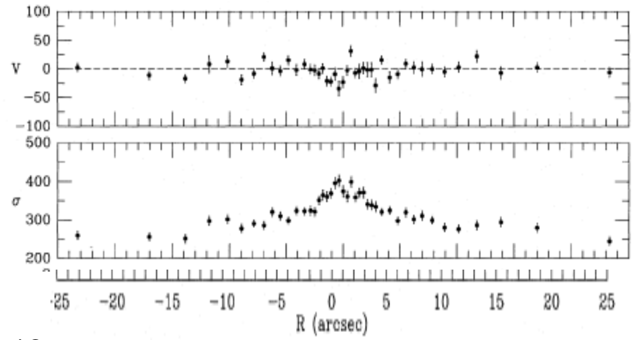




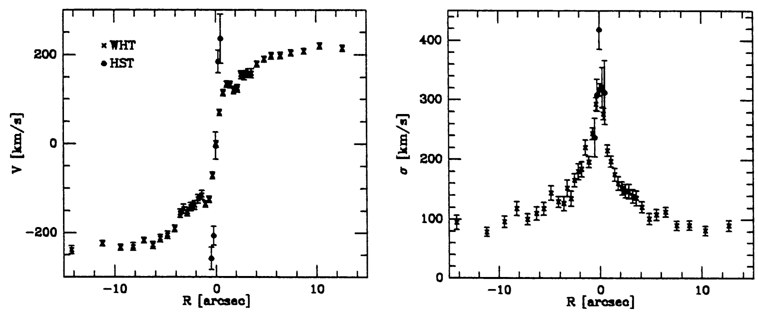
Kinematics

- 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



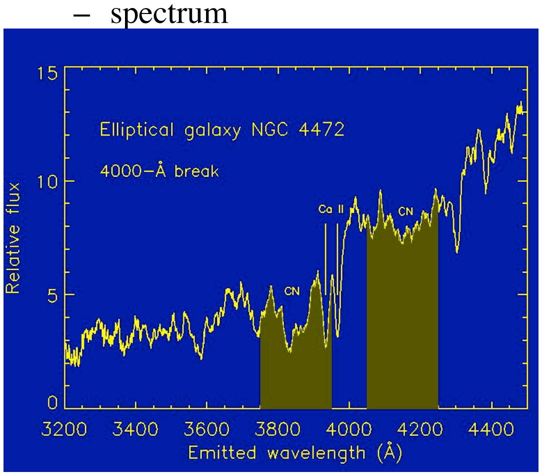
NGC4342
van den Bosch



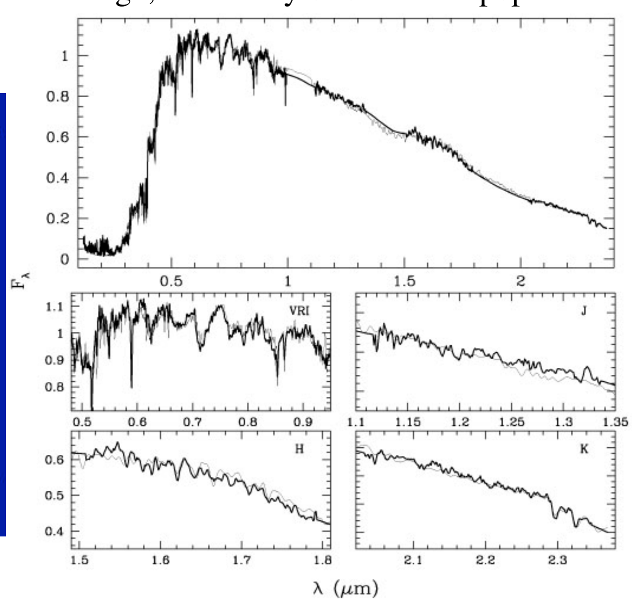
For NGC4342 its observed
flattening is consistent with rotation

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 Determination

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

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

•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

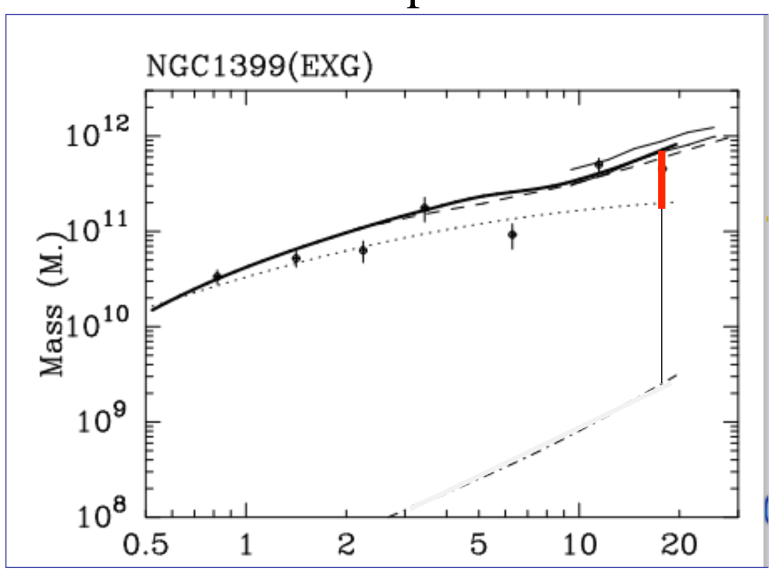
•All of these variables are 3-D; we observe projected quantities !

•The analysis is done by generating a set of stellar orbits and then minimizing

•Rotation and random motions (dispersion) are both important.

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

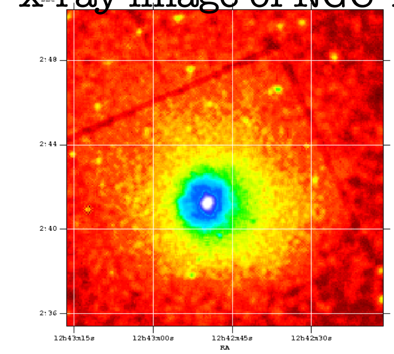


•Use hydrostatic equilibrium to determine mass $\nabla P=-\rho_g\nabla\phi(r)$ where $\phi(r)$ is the gravitational potential of the cluster (which is set by the distribution of matter) P is gas pressure and ρ_g is the gas density

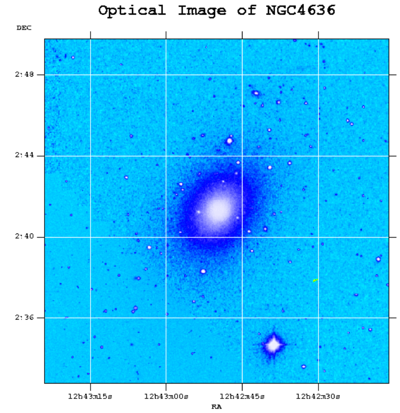
ISM In Ellipicals

- 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

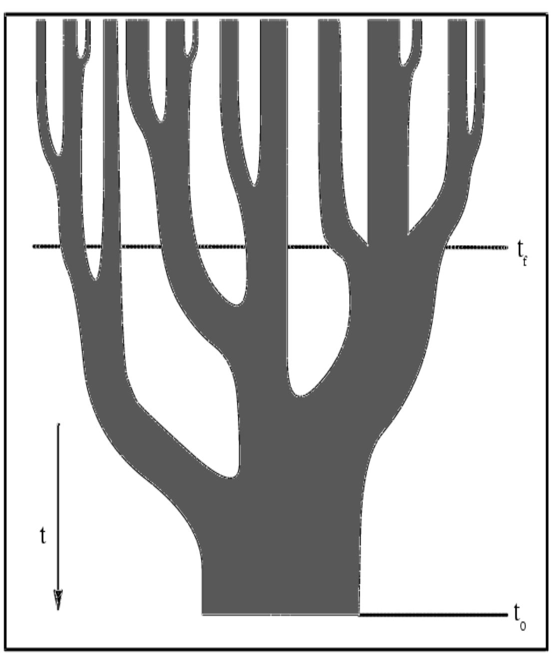
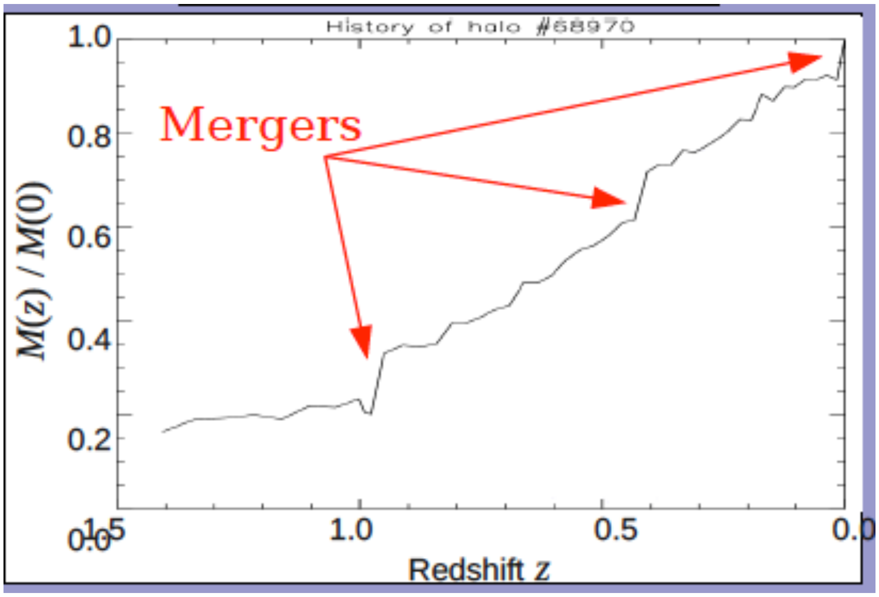


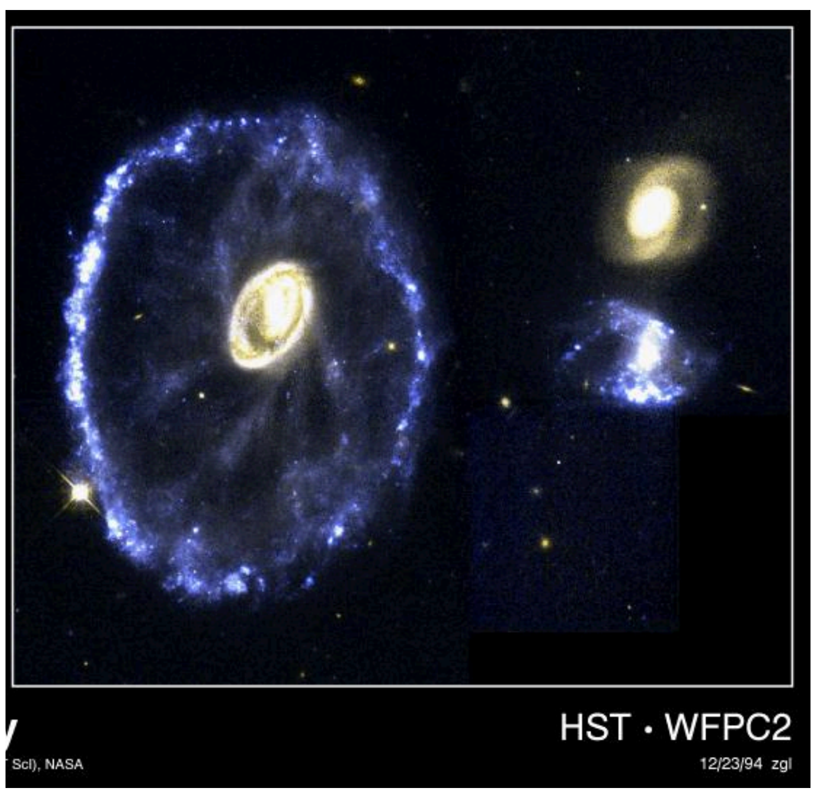
Figure 6. A schematic representation of a "merger tree" depicting the growth of a halo as the result of a series of mergers. Time increases from top to bottom in this figure and the widths of the branches of the tree represent the masses of the individual parent halos. Slicing through the tree horizontally 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.

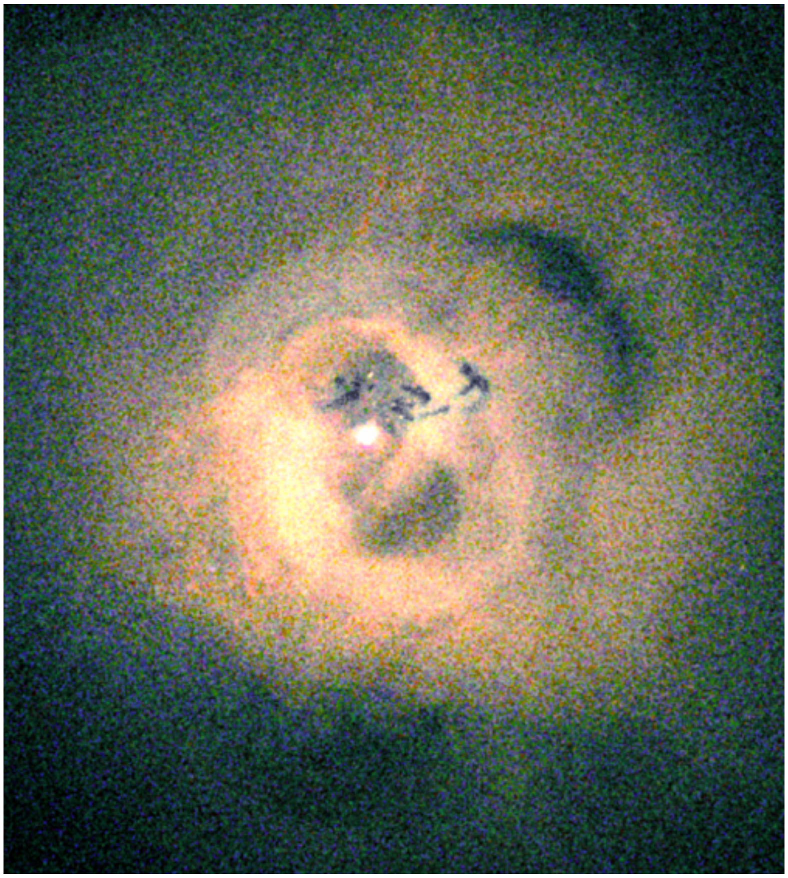
Bode

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



- A bulls-eye collision- the Cartwheel galaxy
- ring-like structure ~150,000 ly across (larger than the Milky Way)
- The ring is a wave of star formation traveling outwards at about ~10^2 km/sec
- As the wave passes outward it compresses and heats the matter that it passes through, triggering star formation.





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

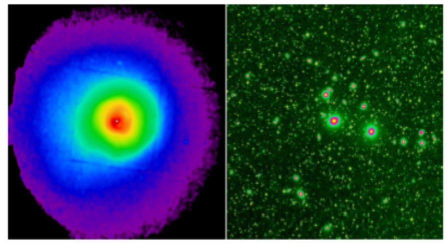
Clusters

Clusters of Galaxies Ch 7 S&G

- Clusters of galaxies are the largest gravitationally bound systems in the Universe.

In the optical band they appear as over-densities of galaxies with respect to the field average density: hundreds to thousands of galaxies moving in a common gravitational potential well (a smaller assembly is defined a galaxy group).

- The typical masses of clusters of galaxies are ~ 10^{13}- $10^{15} M_{\odot}$ (10^{46} - 10^{51} gm) and their virial radii (size) are of the order of 1 - 4 Mpc (10^{24}-10^{25} cm).
- The combination of size and mass leads to velocity dispersions/temperatures of 300-1200km/sec; 0.5-12 keV
- Dimensional analysis : M~kTR; σ^2~kT



X-ray optical

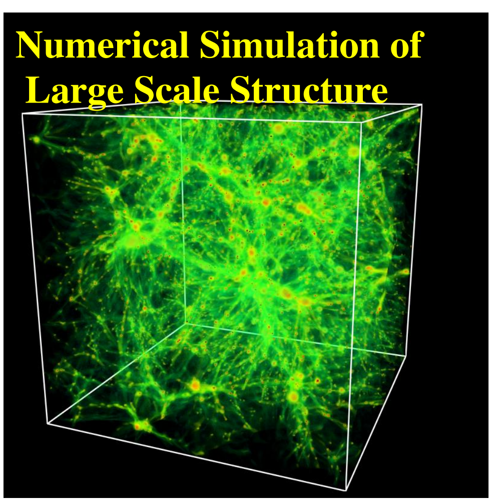
Perseus cluster d~73Mpc

Dark matter simulation

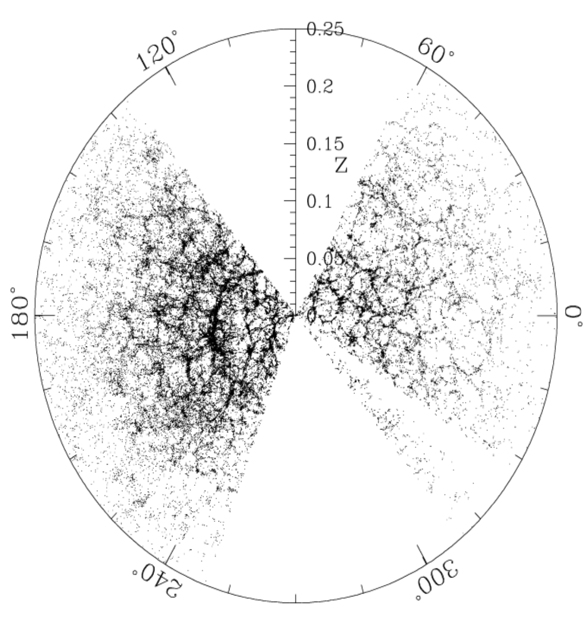
V.Springel

Cosmic Web (again)

- The large scale structures are 'seen' in both the all redshift surveys out to the largest redshifts



Blanton et al. (2003) (astro-ph/0210215)



Dark Matter

The existence of dark matter in clusters and groups of galaxies is indicated by

1) high mass-to-light ratio.

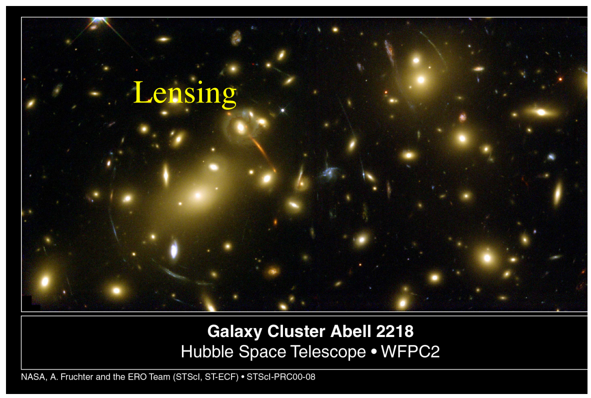
estimate the cluster total mass by assuming that the member galaxies have become dynamically relaxed and that they are in an equilibrium configuration-the virial theorem) to obtain the virial mass

2) lensing and x-ray measurements

The observed optical luminosity of the galaxies corresponds to a mass that is much lower than the total cluster mass

- **So a large quantity of matter not visible as stars**
  - X-ray emitting gas constitutes a portion- ~1/6th of this "missing mass".

In clusters ratio ratio of DM to baryonic matter is ~6:1

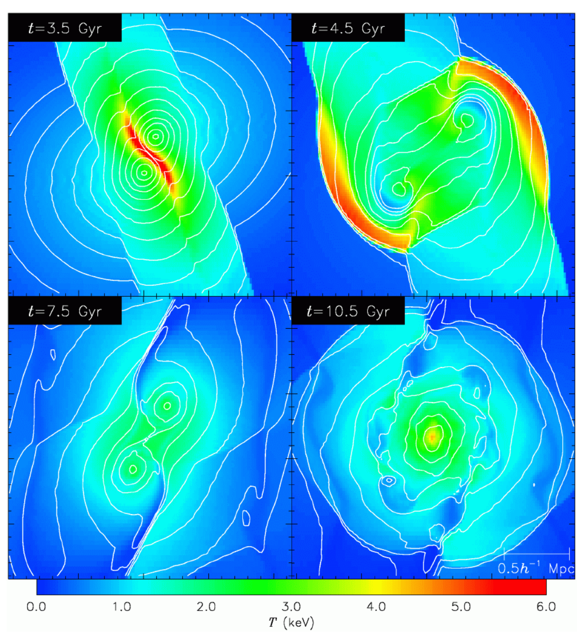


Merger Shocks

⇨ Main heating mechanism of intracluster gas

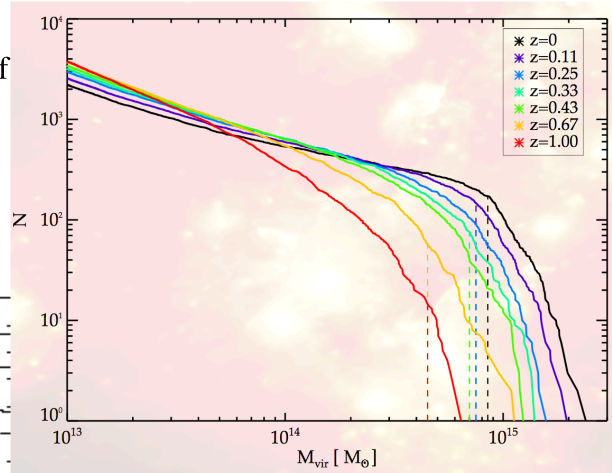
- Most of energy in large clusters due to gravity, conversion of potential energy into heat via merger shocks

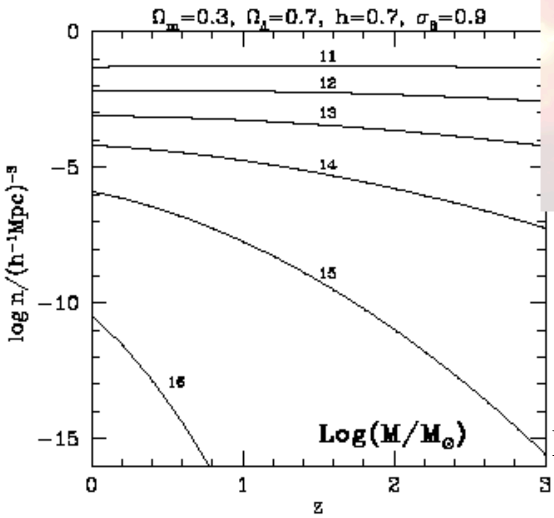
ICM/IGM records thermal history of Universe



Massive Clusters Grow at Late Times

- In standard cosmologies the number of massive clusters (log $M_{\odot}$~15) increases by ~ 30x from z~1 to the present





H. Mo

G. Yepes and the MUSIC Collaboration

X-ray Mass Estimates

- use the equation of hydrostatic equilibirum
-

$$\frac{dP_{gas}}{dr} = \frac{-G\mathfrak{M}_*(r)\rho_{gas}}{r^2} \qquad (3)$$

where P_{gas} is the gas pressure, ρ_{gas} is the density, G is the gravitational constant, and $\mathfrak{M}_*(r)$ is the mass of M87 interior to the radius r.

$$P_{gas} = \frac{\rho_{gas} K T_{gas}}{\mu \mathfrak{M}_H} \qquad (4)$$

where μ is the mean molecular weight (taken to be 0.6), and $\mathfrak{M}_H$ is the mass of hydrogen atom.

$$\frac{KT_{gas}}{\mu\mathfrak{M}_H}\left(\frac{d\rho_{gas}}{\rho_{gas}} + \frac{dT_{gas}}{T_{gas}}\right) = \frac{-G\mathfrak{M}_*(r)}{r^2}dr, \qquad (5)$$

which may be rewritten as:

$$-\frac{KT_{gas}}{G\mu\mathfrak{M}_H}\left(\frac{d\log\rho_{gas}}{d\log r} + \frac{d\log T_{gas}}{d\log r}\right)r = \mathfrak{M}_*(r) \qquad (6)$$

Putting numbers in gives

$$M(r) = -3.71\times10^{13}\,M_{\odot}\,T(r)\,r\left(\frac{d\log\rho_g}{d\log r} + \frac{d\log T}{d\log r}\right),$$

ere T is in units of keV and r is in units of Mpc. (

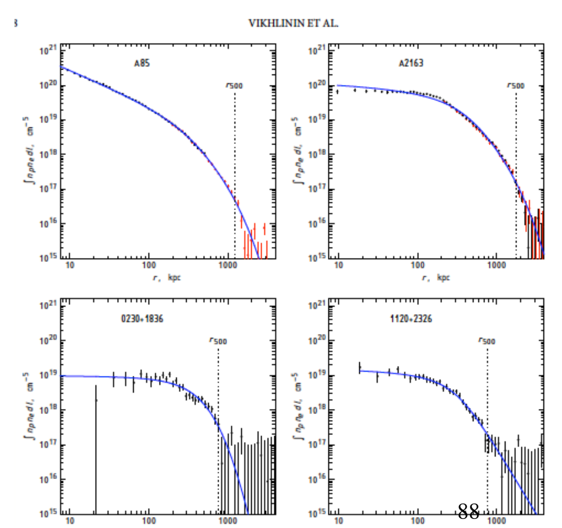


FIG. 5.— Examples of the surface brightness profile modeling for clusters shown in Fig. 3 and 4. The observed X-ray count rates are converted to the projected emission measure integral (see § 3.4 and V06). The black and red data points show the *Chandra* and *ROSAT* measurements, respectively. The best fit models (the projected emission measure integral for the three-dimensional distribution given by eq. 2) are shown by solid lines. The dashed lines indicate the estimated r_{500}

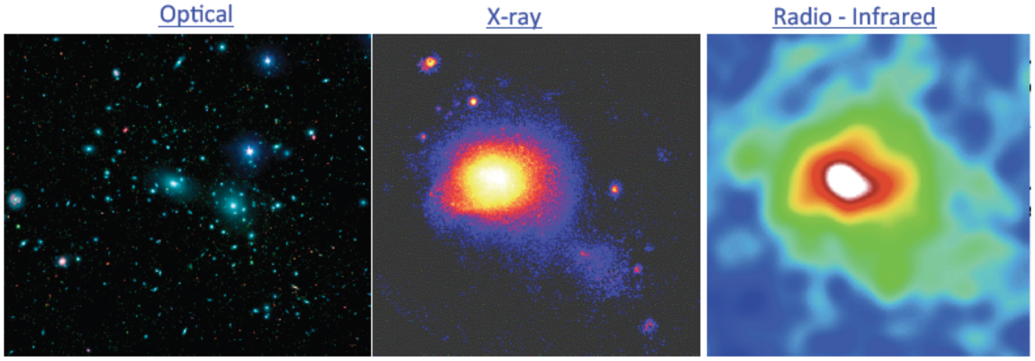
Intracluster Gas

- Majority (75%) of observable cluster mass (majority of baryons) is hot gas
- Temperature $T \sim 10^{7\text{-}8}$ K ~ 1-10 keV
- Electron number density $n_e \sim 10^{-3}$ cm^{-3}
- Mainly H, He, but with heavy elements (O, Fe, ..)
- Mainly emits X-rays
- $L_X \sim 10^{45}$ erg/s, most luminous extended X-ray sources in Universe
- Age ~ 2-10 Gyr

Sarazin

How are they found

Optical | X-ray | Radio - Infrared



Optical	X-ray	Radio - Infrared
Current Surveys:	Current Surveys:	Current Surveys:
SDSS	ROSAT	Planck
PanSTARRS	XMM	SPT
		ACT
Future Surveys:	Future Surveys:	Future Surveys:
LSST	EROSITA	CCAT
DES		SPTpol
Euclid		

Pierpaoli 2013

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

- Gravitational lensing, can measure the mass profiles of clusters and early-type galaxies, both in the nearby universe and at cosmological distances (Treu & Koopmans 2002a,b)

- Need:
  - the Einstein radius of the lens,
  - the redshift of both the deflector galaxy and the lensed source

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

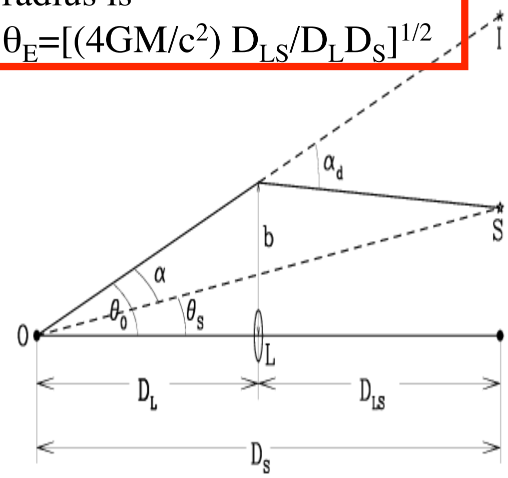
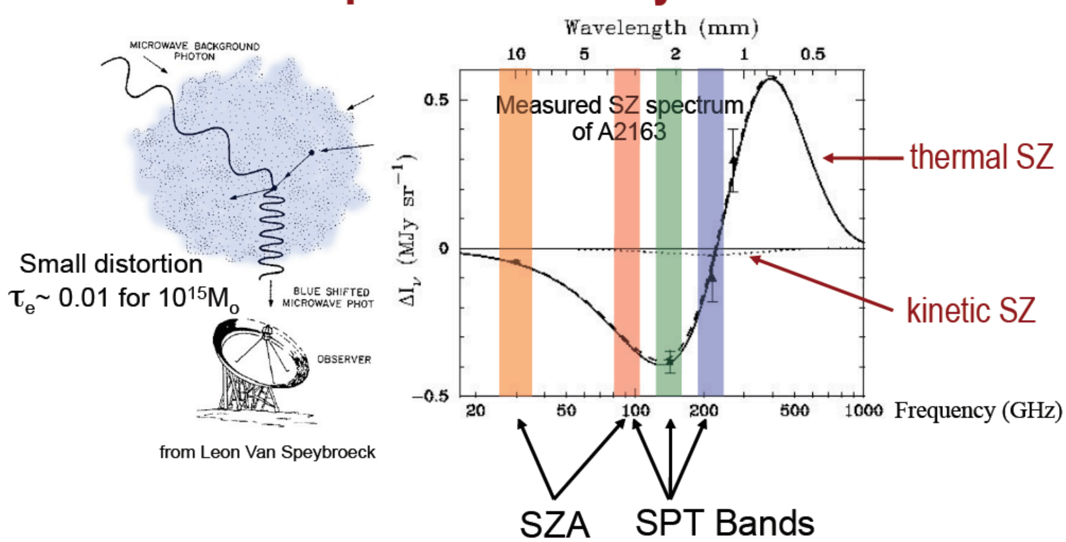


FIG 6.6 IN MBW

The Sunyaev-Zel'dovich Effect: probe of Galaxy clusters

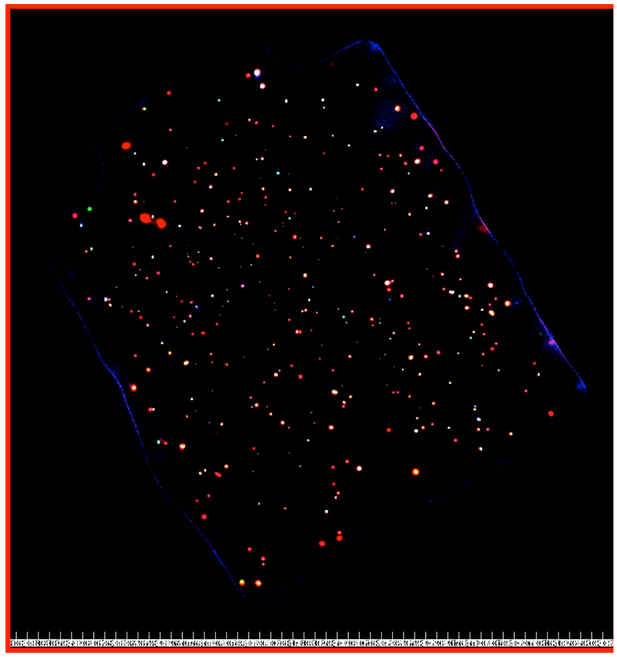


Carlstrom

Redshift independent: $\frac{\Delta T_{SZE}}{T_{CMB}} \propto \int n_e T_e \, dl$

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:

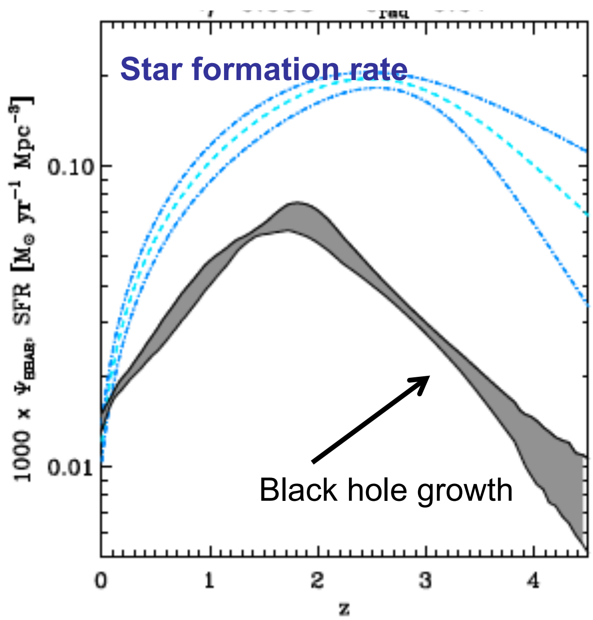
- Solve the cooling flow riddle in clusters of galaxies
- Explain the cluster-scaling relations, e.g. the tilt of the L_x-T relation
- Explain why ellipticals are so gas-poor
- Drive metals into the IGM by quasar-driven winds
- Help to reionize the universe and surpress star formation in small g

Springel 2004

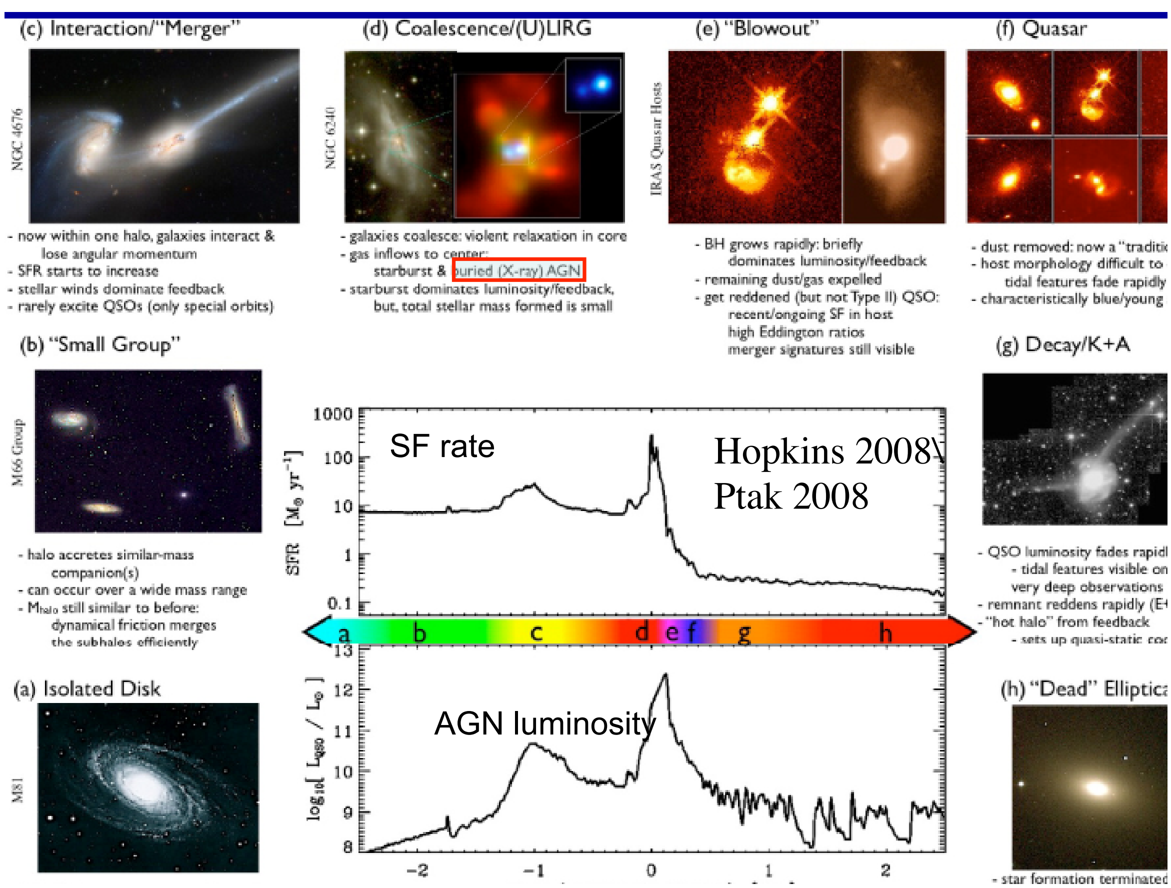
Galaxy formation models need to include the growth and feedback of black holes !

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

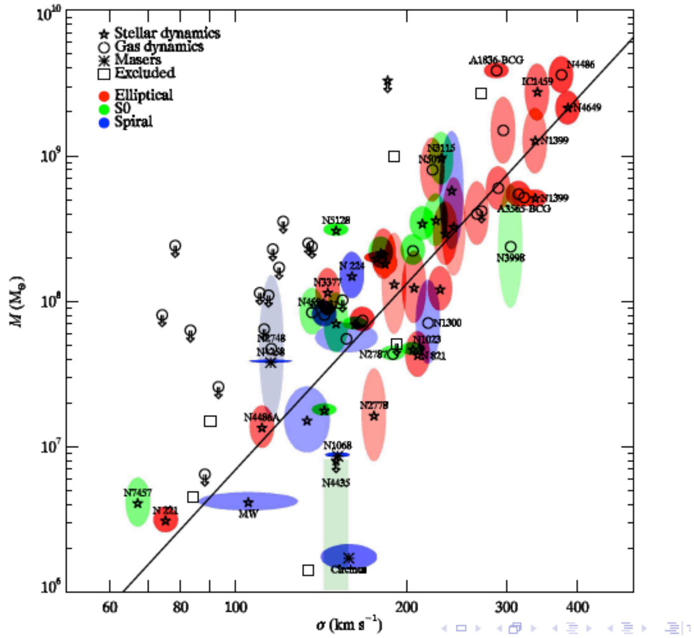


Merloni 2010



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.

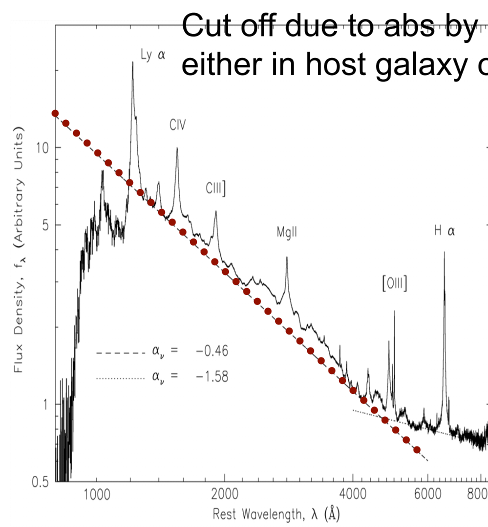


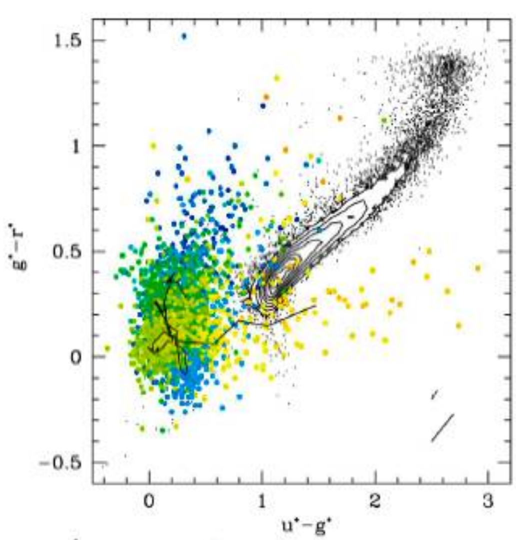
Gultekin 2009

Optical Properties of AGN

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

Cut off due to abs by H either in host galaxy or IGM

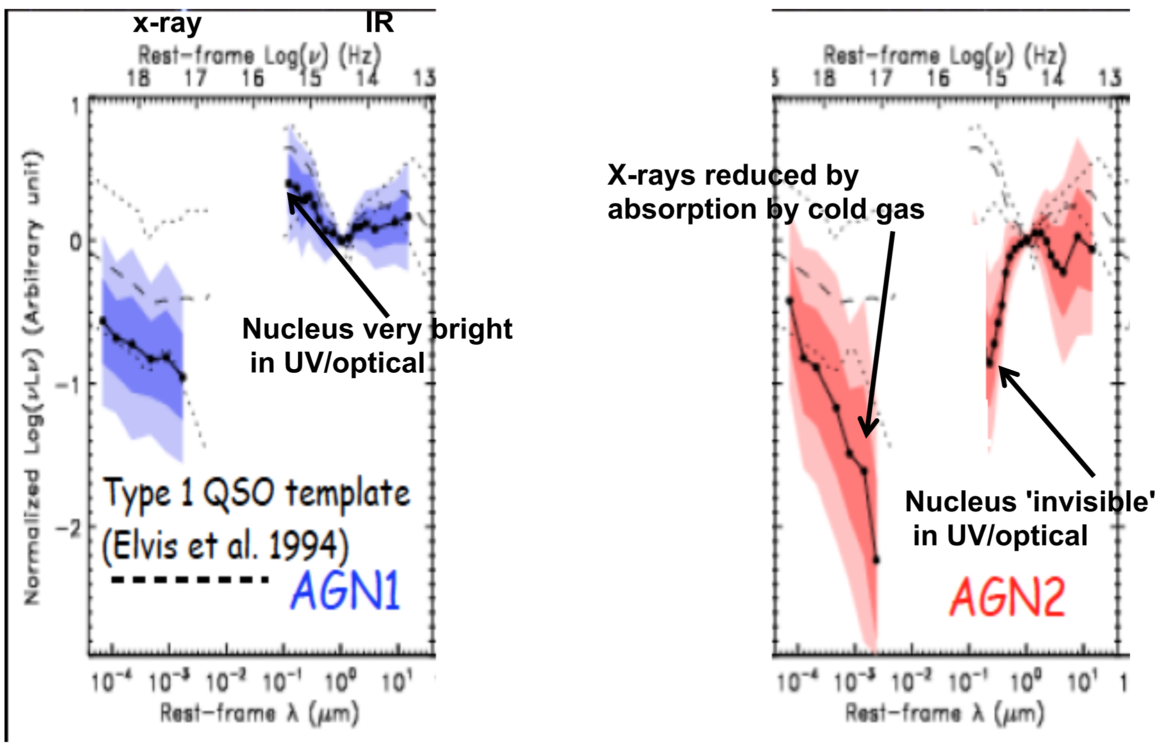




Unusual optical colors (Richards et al SDSS)- **quasars in color**, **stars are black**

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

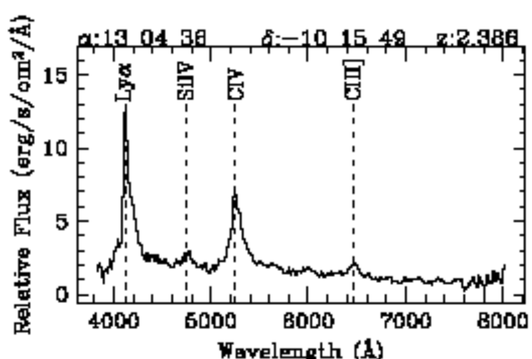
Broad Band Continuum (IR-Xray)

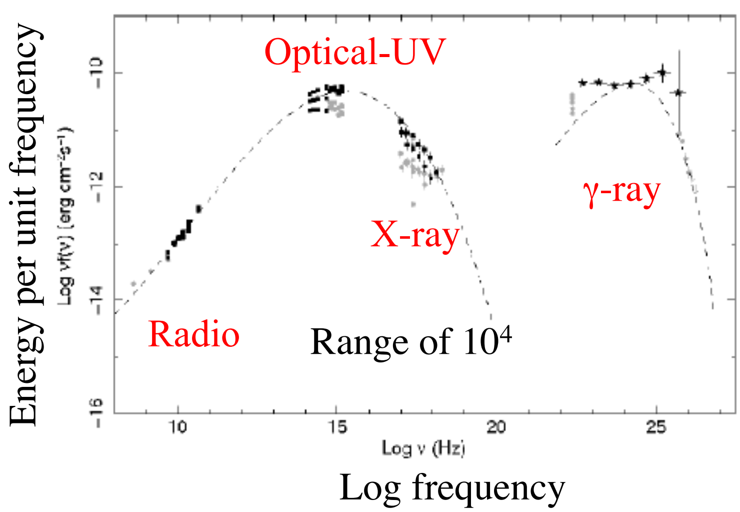


Broad Band Properties of AGN

- **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)

Its Turtles all the way down...

- Stephen Hawking's 1988 book "A Brief History of Time" begins with the following famous anecdote.

- A well-known scientist gave a public lecture on astronomy. He described how the earth orbits around the sun and how the sun, in turn, orbits around the center of a vast collection of stars called our galaxy. At the end of the lecture, a little old lady at the back of the room got up and said: "What you have told us is rubbish. The world is really a flat plate supported on the back of a giant tortoise." The scientist gave a superior smile before replying, "What is the tortoise standing on?" "You're very clever, young man, very clever," said the old lady. *"But it's turtles all the way down!"*