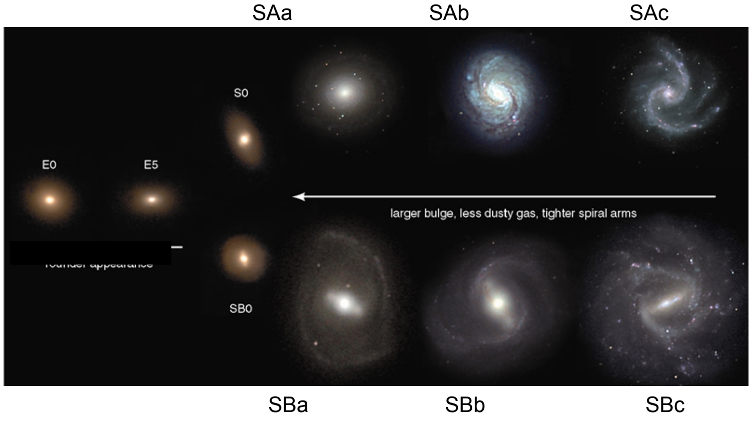
Astro 358

Galaxies and the Universe

Lecture 1 (Tu Jan 17): Course Overview

Present –Day Galaxies

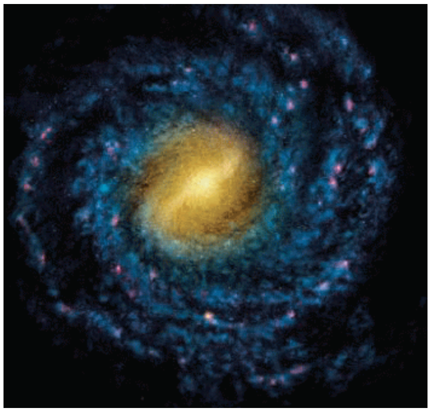
- Present-day galaxies : most have regular (relaxed , virialized) structures
  - High mass Ellipticals, Spirals
  - Low mass Dwarf Galaxies
- Small fraction of interacting/merging galaxies



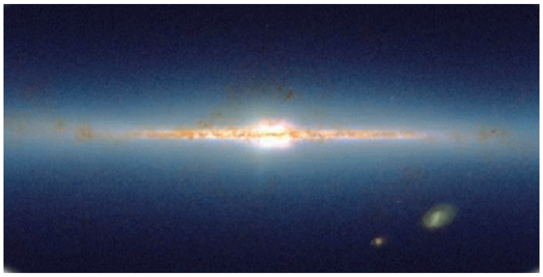
Our Galaxy, the Milky Way is a barred spiral galaxy.

The Sun is a star located 28,000 light years from the center of the galaxy.

The radius of the stellar disk is 50,000 light years.



Face-on view
(Artist's conception)



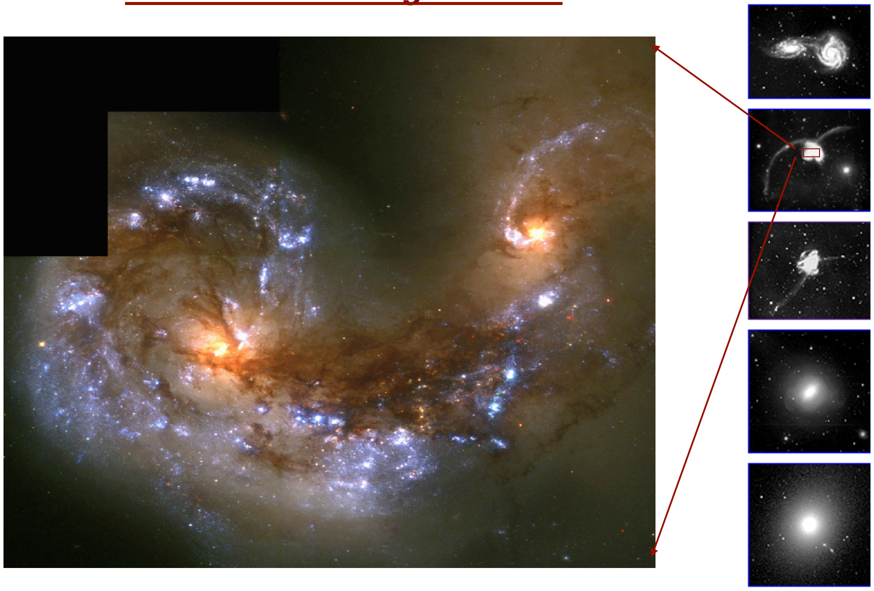
Edge-on view :
Actual infrared image
from COBE satellite

Nearby Major Merger

(Credit: NASA & ACS Science team)

HST image shows details of a collision between 2 spiral galaxies 30 kpc apart
(NASA/STScI/Hubble Heriitage)

Peculiar/Interacting Galaxies



The Antennae system: The HST image shows 2 disks with gas stripped out.

Peculiar/Interacting Galaxies

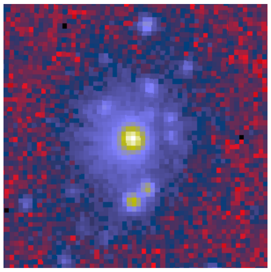
Polar ring galaxy NGC 4650

Cartwheel galaxy
Head-on collision

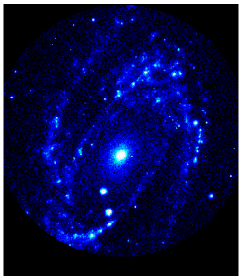
Ring galaxy AM 0644-741 50,000 ly across

Tracing the Contents of Galaxies

Need multi-λ observations to trace baryons (gas, dust, stars of different ages, mass)



X-ray/ROSAT

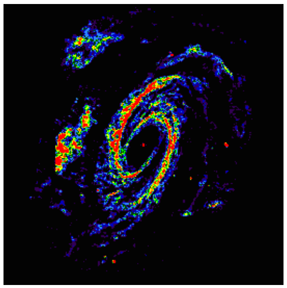


Ultraviolet/ASTR0-1

Visible light: HST

Near infrared/Spitzer

Far-infrared/Spitzer



Radio 21cm/VLA

Most of mass in a galaxy is in the form of dark matter rather than baryons (gas+ stars)

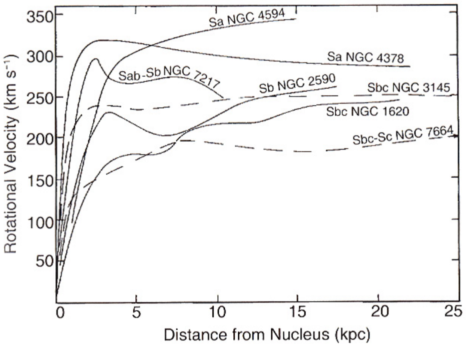


Fig. 3.15. Examples of rotation curves of spiral galaxies. They are all flat in the outer region and do not behave as expected from Kepler's law if the galaxy consisted only of luminous matter. Also striking is the fact that the amplitude of the rotation curve is higher for early types than for late types.

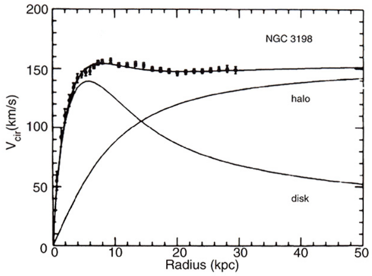
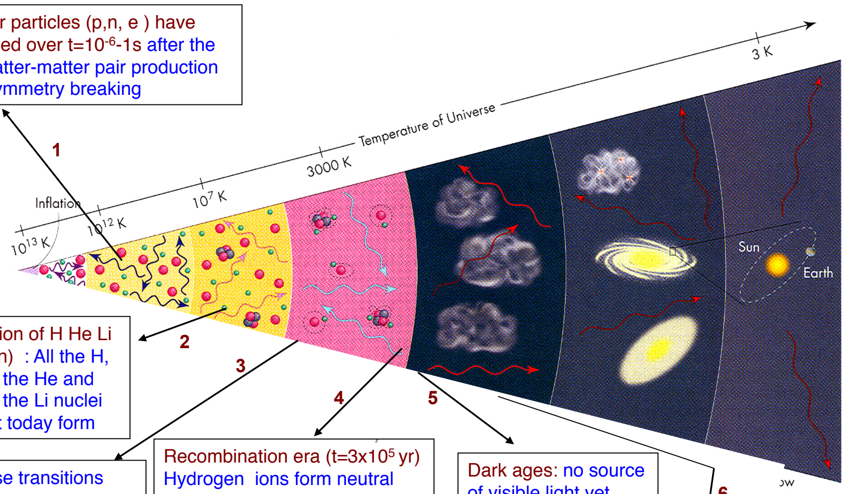


Fig. 3.16. The flat rotation curves of spiral galaxies cannot be explained by visible matter alone. The example of NGC 3198 demonstrates the rotation curve which would be expected from the visible matter alone (curve labeled "disk"). To explain the observed rotation curve, a dark matter component has to be present (curve labeled "halo"). However, the decomposition into disk and halo mass is not unambiguous because for it to be so it would be necessary to know the mass-to-light ratio of the disk. In the case considered here, a "maximum disk" was assumed, i.e., it was assumed that the innermost part of the rotation curve is produced solely by the visible matter in the disk

(EAC)

Galaxy Formation in a Cosmological Context

From the Big Bang to the emergence of the first proto-galaxies



Matter particles (p,n, e) have emerged over t=10^{-6}-1s after the antimatter-matter pair production and symmetry breaking

Formation of H He Li (t=3 min) : All the H, 90% of the He and 10% of the Li nuclei present today form

Universe transitions from radiation-dominated to matter-dominated (t=3x10^4 yr)

Recombination era (t=3x10^5 yr) Hydrogen ions form neutral atoms, and Universe changes from opaque to transparent. The photons released are the oldest ones we see and get redshifted to form the CMB at mm wavelengths and T=2.7 K

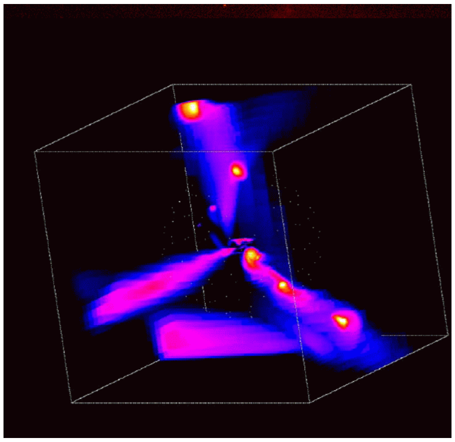
Dark ages: no source of visible light yet.

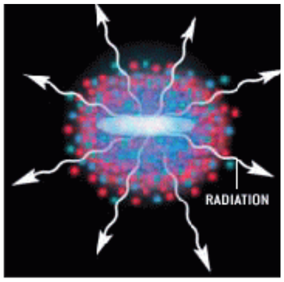
First luminous objects form: stars at t=1-2 x10^8 yr), then proto-galaxies (t=3-7x10^8yr) These end the dark ages and their UV light also reionized neutral H back to protons and electrons (reionization era) .

Growth of galaxies

In current paradigms of galaxy evolution,

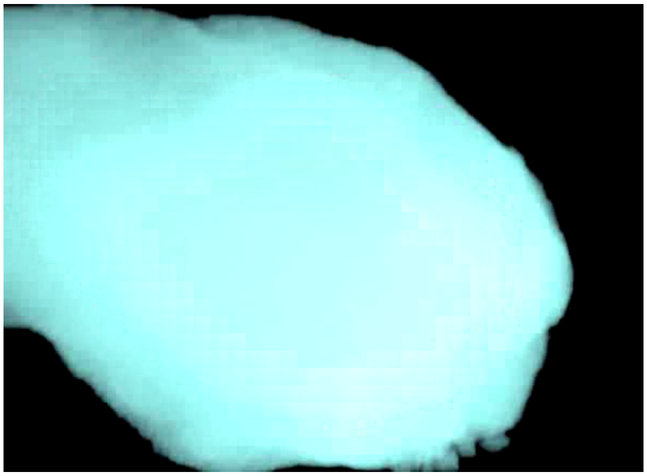
- Buildling blocks made of dark matter (DM) and baryons are embedded within cosmological large-scale filaments
- Each building block is a proto-galaxy, made of a DM halo + a disk of baryons (gas+stars) .





DM = red
Baryons (gas) =blue/white.

Schematic: Forming a Milky Way Type Galaxy in LCDM models



Courtesy: Frank Governato

Galaxy grows via smooth accretion, minor mergers and major mergers

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Growth mode of galaxies

Inflow of mass into galaxies via
- smooth accretion of gas from cosmological filaments
- satellite accretion from cosmological filaments
- major and minor mergers

Redistribution of mass + angular momentum WITHIN galaxies via
- non-axisymmetric structures such as stellar bars
- major and minor mergers

Mass outflow and feedback processes
- winds driven by starbursts and AGN

Galaxy Evolution: Role of Feedback from Star Formation

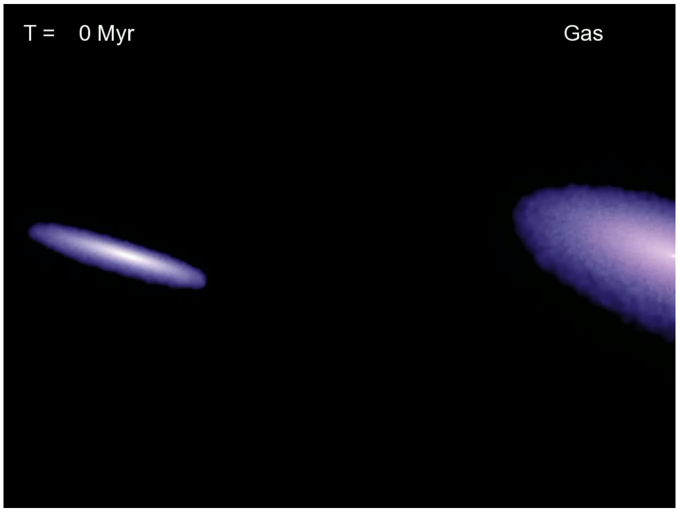
Credit: M. Westmoquette (University College London), J. Gallagher (Univ. of Wisconsin-Madison), L. Smith (Un. College London), WIYN//NSF, NASA/ESA

Role of Feedback from Star Formation

Gas inflow into central regions of galaxues can lead to powerful episodes of star formation called starbursts

The energy released by the starbursts can in turn eject gas in a starburst-wind. The wind is shown in purple in the Halpha image of the galaxy M82.

Qualitative picture: Role of Feedback from BHs



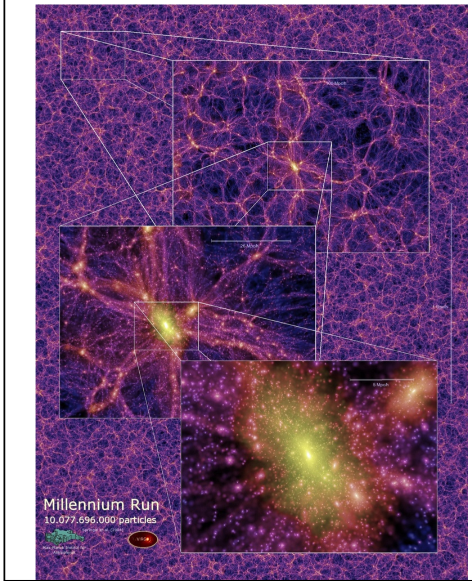
Credit: V. Springel

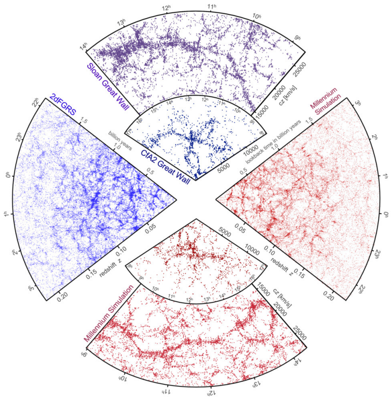
Gas inflows feed central star formation and BH until energy generated by mass accretion onto BH heat/expel gas, quenching both star formation and BH growth

Theoretical ΛCDM models of Galaxy Evolution

Theoretical ΛCDM models of structure evolution

ΛCDM models = good paradigm for how dark matter and structure evolves on large scales .The evolution of dark matter is controlled primarily by gravity



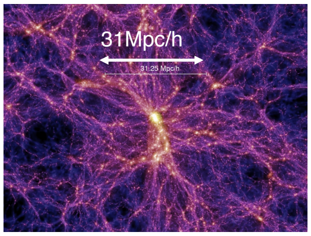


(Springel et al. 2005)

Millenium Run : 10^{10} particles
Follows DM in region D=15 Mpc/h
Resolution = 5 kpc/h

Challenges for theoretical models of galaxy evolution

There are no unique/robust prediction for the evolution of galaxies due to the uncertainties in modeling the baryons (gas)



→ how to translate merger history of dark matter halos into merger history of galaxies?

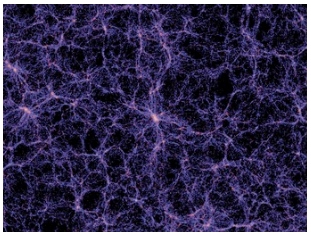
→ which star formation laws describe the conversion of gas into stars?

→ How to model fededback from stars and BHs?

→How to treat the interstellar medium: the cold, hot and warm gas between stars?

→ Limited dynamic range and spatial resolution: cannot simultaneously simulate large scale environment and resolve galaxy components (bulge, bar, disk)

[N=$10^{10,}$ D=500Mpc/h, Resolution~5kpc/h]



Understanding physics of galaxy evolution

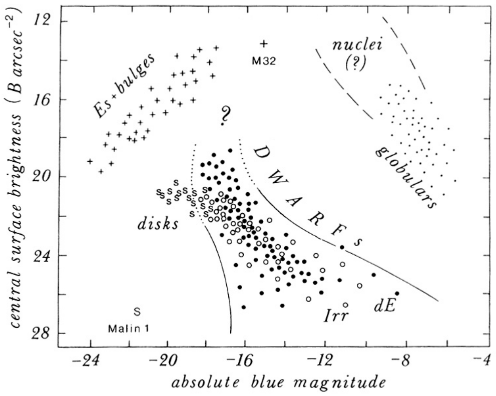
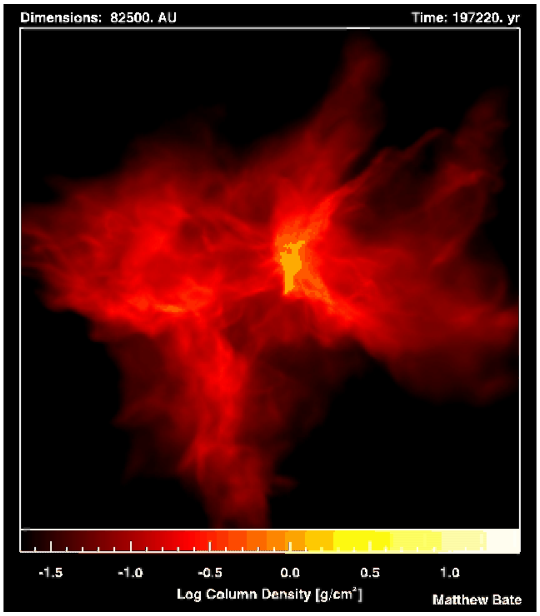


Figure 4.18 Dwarf and giant galaxies occupy different regions in a plot of absolute V-magnitude and measured central surface brightness; because of 'seeing', the true peak brightness may be higher. At left, luminous elliptical galaxies and the bulges of disk systems have very high surface brightness at their centers. The rightmost of the 'dE' points (filled circles) represent what this text calls dwarf spheroidals; open circles mark irregular and dwarf irregular galaxies. Disks of spiral galaxies are marked 'S'. Malin 1 is a low-surface-brightness galaxy; see Section 5.1 – B. Binggeli.

SCALING RELATIONS: E+ bulges follow a different Luminosity-SB relation from Spirals, dIrr dE

Physics and laws of star formation

Collapse of a cloud to form star



The simulation shows a molecular cloud of mass 50 Mo, with initial diameter of 0.37 pc , temperature of 10 K.

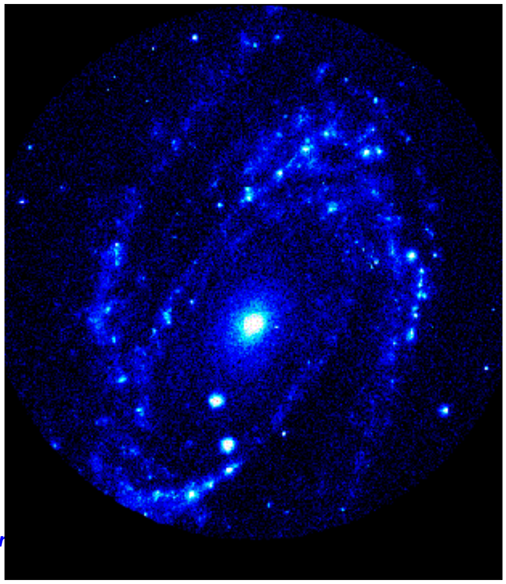
Jean mass M_J = 1 Mo
for T=10 K, n=10^5 atoms cm-3

High density regions within the cloud gravitationally collapse and fragment to form stars

Surrounding some of these stars are swirling discs of gas which may go on later to form planetary systems like our own Solar System.

Star formation in the disk of spiral galaxies

Σ_{cr}



Star formation in the disk of spiral galaxies

Using the gravitational instability model to account for the threshold gas density for SF disk of spirals

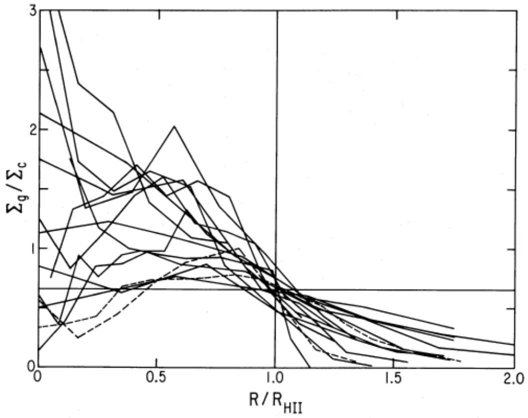


FIG. 11.—Radial dependence of the ratio of gas surface density to the critical density for gravitational stability (eq. [4]), for the galaxies with active star-forming disks. The radial coordinate is normalized to the radius of the H II region disk. The horizontal line indicates the value for the stability parameter ($\alpha = 0.67$) which best fits the observed star formation thresholds. Dashed lines denote M33 and NGC 2403.

$$\Sigma_{crit} = \alpha\ (\kappa\ \sigma/3.36\ G\Sigma) = \alpha\ \Sigma_c$$

$\alpha \sim 0.7$ *for all galaxies !*

Kennicutt 1989

Black Holes

Central BH in Galaxies

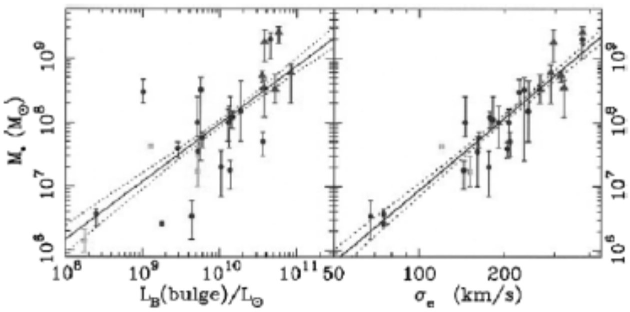


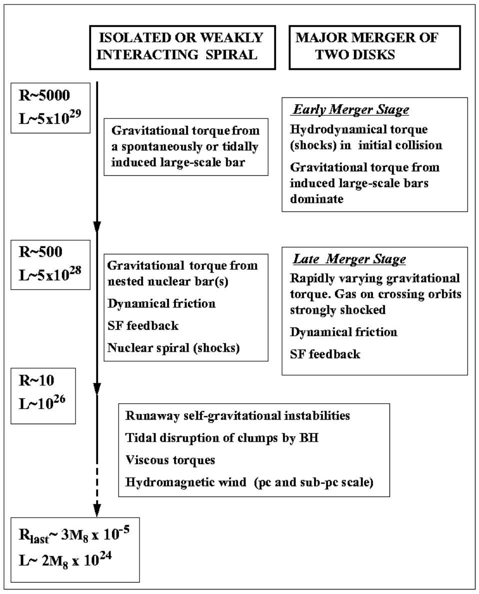
Fig. 1. Correlation between central BH mass and circumnuclear velocity dispersion – Black hole mass versus bulge luminosity (*left*) and the luminosity-weighted aperture dispersion within the effective radius (*right*). Green squares denote galaxies with maser detections, red triangles are from gas kinematics, and blue circles are from stellar kinematics. Solid and dotted lines are the best-fit correlations and their 68% confidence bands. (From Gebhardt et al. 2000)

(Fig from Gehbardt et al 2000)

Fueling the Central BH :The Angular Momentum Problem

Before gas in the outer disk at a radius R of ~5 kpc can can feed a black hole , its specific angular momentum L must be lowered by a factor of 10^5.

Stellar bars, interactions or mergers can help partially



ISOLATED OR WEAKLY INTERACTING SPIRAL

MAJOR MERGER OF TWO DISKS

R~5000
L~5x10^{29}

Gravitational torque from a spontaneously or tidally induced large-scale bar

Early Merger Stage
Hydrodynamical torque (shocks) in initial collision
Gravitational torque from induced large-scale bars dominate

R~500
L~5x10^{28}

Gravitational torque from nested nuclear bar(s)
Dynamical friction
SF feedback
Nuclear spiral (shocks)

Late Merger Stage
Rapidly varying gravitational torque. Gas on crossing orbits strongly shocked
Dynamical friction
SF feedback

R~10
L~10^{26}

Runaway self-gravitational instabilities
Tidal disruption of clumps by BH
Viscous torques
Hydromagnetic wind (pc and sub-pc scale)

R_{last}~ $3M_8 \times 10^{-5}$
L~ $2M_8 \times 10^{24}$

$\mathrm{cm}^2\,\mathrm{s}^{-1}$

(Jogee 2006, Ch6, AGN Physics on All Scales; astro-ph/0408383)

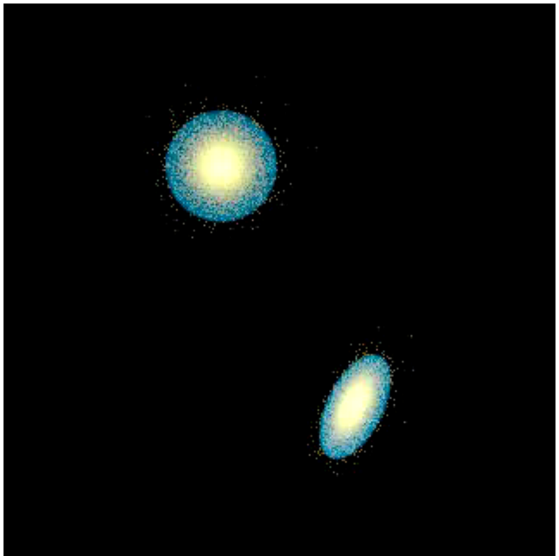
Stellar Bars : Redistributing mass in galaxies

A stellar bar shocks gas and funnels it into the central parts of a disk galaxy where

- → it ignites powerful central bursts of star formation….starbursts.. 10 billions L_{sun}!
- → It may help to feed the central monster (black hole)

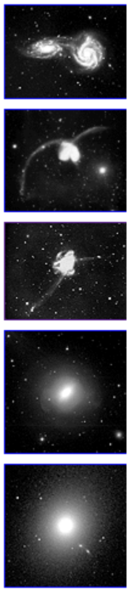
Galaxy Mergers

Major merger



(Mihos & Hernquist; DM halo + Stars =yellow, gas= blue, Duration = 1 Gyr)

Major mergers: gas inflows, conversion of gas to stars, violent relaxation of stars converting disk configuration into spheroidal distribution of stars



Data
The Toomre Sequence

Current and Future Interactions of Milky Way (SBbc spiral)

→It is presently 'digesting' the Spr I (dSp?) = accretion or **minor merger**

→ It is interacting w/ SMC (63 kpc)) and LMC (50 kpc) to give Magellanic stream of atomic H.

→ System of SMC and LMC may be sinking via dynamical friction into M Way: **minor merger**

→ It has a warp and thick disk → may be due to a past **minor mergers**

→ Milky Way is moving at 83 km/s toward M31 (SAb) at d=770 kpc: **future major merger**

The role of environment on galaxy evolution

Morphology-density relation

In core of Abell 1689 cluster E/S0 dominate over spirals

Spirals visible in outskirt of cluster and in field

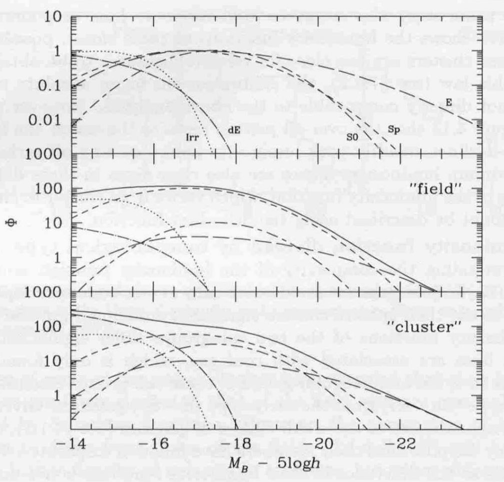


Figure 4.14 Luminosity functions for galaxies of various morphological types. The top panel shows The separate functions at arbitrary normalization, while the lower panels show approximately how these components combine to produce the total luminosity function in the field and in clusters.

Morphology-density relation

The relative frequency of early-type (E, S0, dE) galaxies compared to late-type galaxies (Sprials, dIrr) is higher in high density environments (clusters) than in low density environments (field)

Frequency of E+S0:Sp
= 40%+50% :10% in cluster
= 10%+10%: 80% in field

Frequency of dE wrt dIrr
= higher in cluster than in field

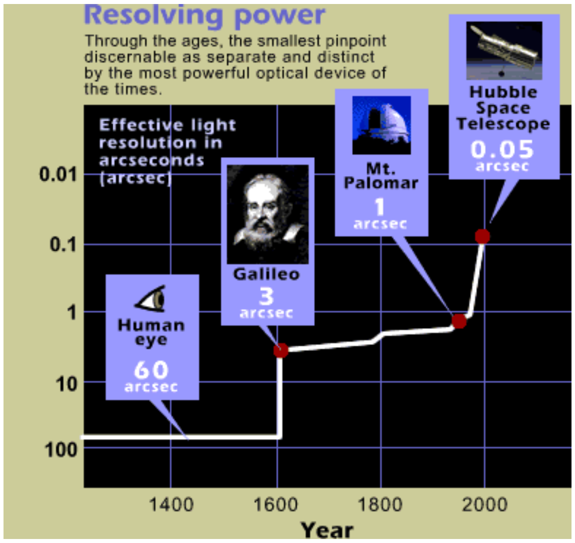
The MDR is reflected in the LF of the field and cluster, when the LF is 'decomposed' into the separate LFs of galaxies of different morphological types.

Galaxies have different properties in low vs high density environments : fields, groups, clusters

The Nature vs Nurture Debate : Is this difference due to
- assembly bias (earlier formation time and higher merger rates)
- physical processes in clusters (ram pressure stripping, harrasment, strangulation)

Galaxy Surveys with HST to map galaxies at early cosmic epochs

Optical Images from HST are sharper than ground image by a factor of over 30



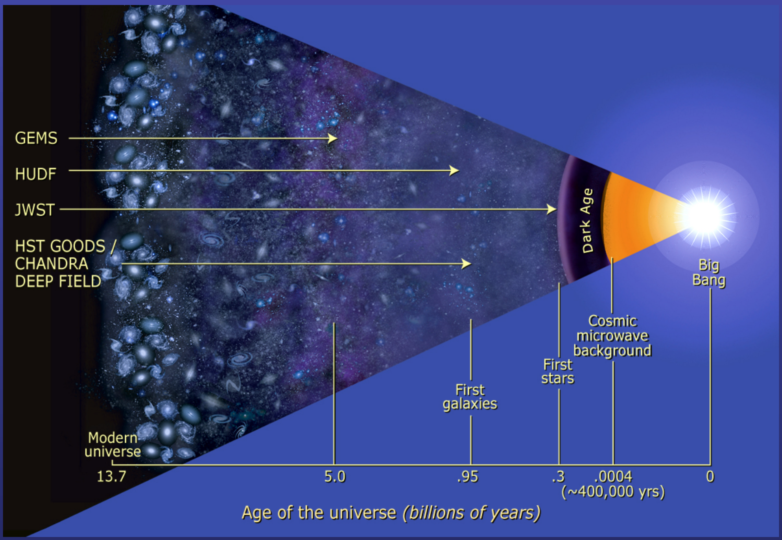
HST vs Ground-based data for very distant galaxies (redshift 0.2-1)

Hubble ACS image from GEMS (tile 56)

Combo-17 Ground image (tile 56)

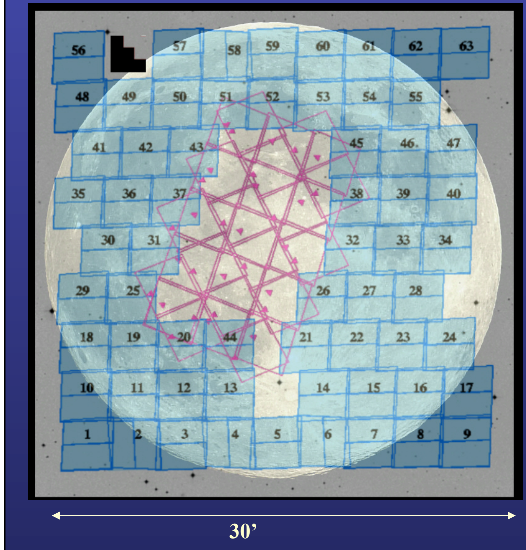
Note the huge improvement in spatial resolution in going from the ground-based Combo-17 image (1.5”) to space-based Hubble ACS image (0.1”).

Probing Early Cosmic Epochs with GEMS and HUDF



GEMS surveys galaxies out to lookback times of 8 Gyr, when Univ was 5.7 Gyr old
HUDF surveys galaxies out to lookback times of 13 Gyr , when Univ was 0.7 Gyr old

Constraints from the GEMS survey



GEMS is largest-area imaging survey conducted using 2 filters on the ACS camera aboard HST

GEMS survey area

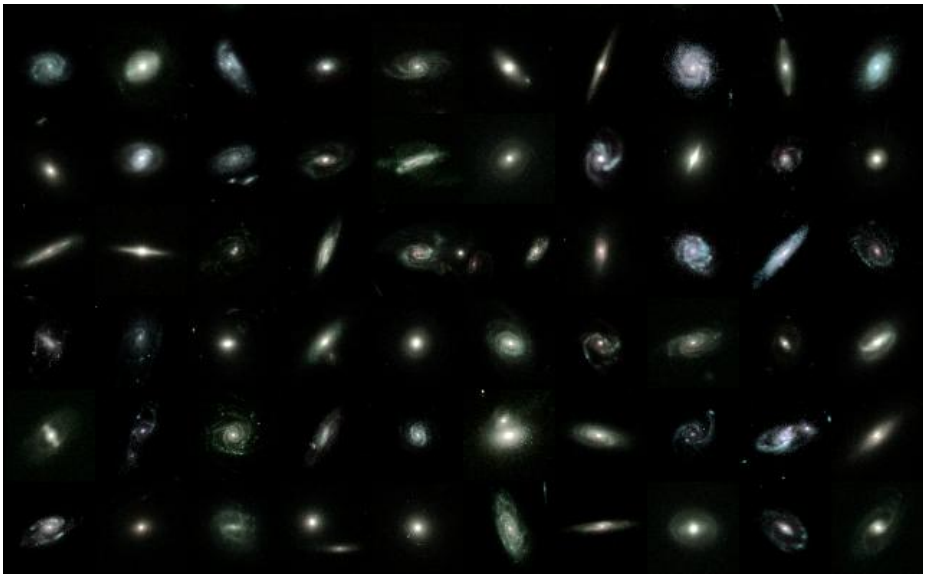
= 77 ACS pointings patched together

= 30’x30’= size of full moon on sky

= 120 x area of Hubble Deep Field (HDF) conducted with WFPC2 in 1995

= 72 x area of Hubble Ultra Deep Field (HUDF)

GEMS also has galaxy spectra which provide accurate redshifts for ~9000 galaxies.
The redshifts are used to derive the lookback times, which lie in the range 2 to 9 Gyr



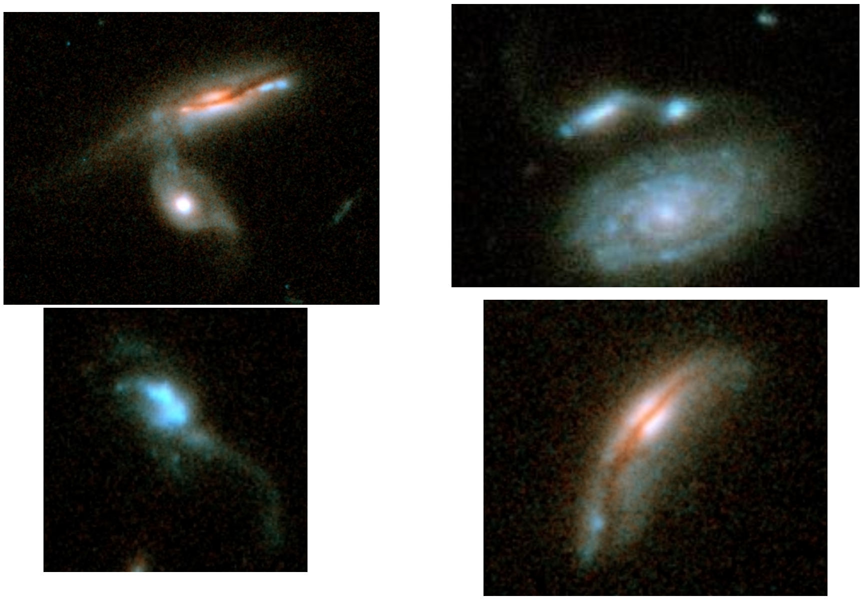
Example of galaxies over z=0.7-1.0 (T_{back}~ 6-8 Gyr)

Example of interacting/merging galaxies at lookback =3 to 8 Gyr

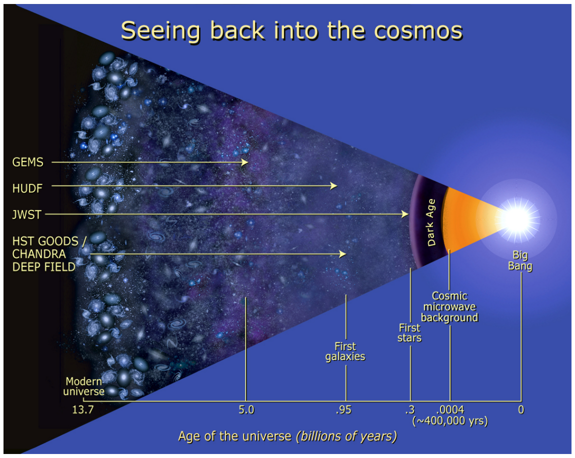
(Jogee, Miller, Penne et al. & GEMS collaboration 2009, ApJ)

Example of interacting/merging galaxies at lookback =3 to 8 Gyr

2



(Jogee, Miller, Penne, et al. & GEMS collaboratiion 2009, ApJ)



From the first billion years to 13.7 billion year

0.0	9	13.0	13.7	Lookback Time in Gyr
13.7 (100%)	4.7 (35%)	0.7 (5%)	0 (0%)	Age of Universe in Gyr and %

Today, mature galaxies on the Hubble sequence are in place

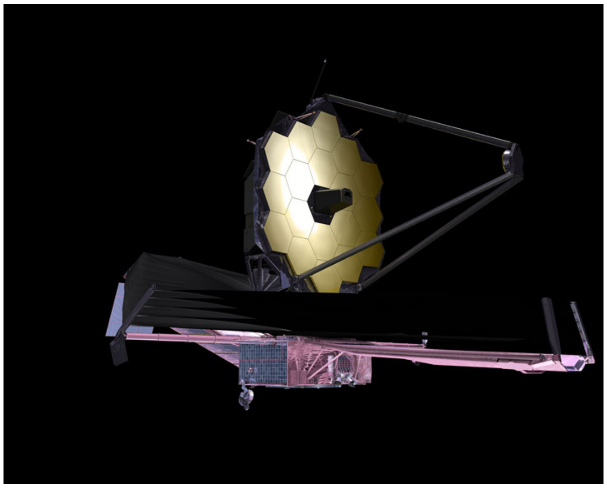
Over the last 12 billion years the mass + structures (disks, bars, bulges) of galaxies grow THROUGH PROCESSES THAT ARE NOT WELL UNDERSTOOD

Chaotic period ~ 13.0 Gyr ago where first proto-galactic disks structures form and merge. The Universe is dominated by violent major mergers at early times.

Looking Ahead

The Future: JWST

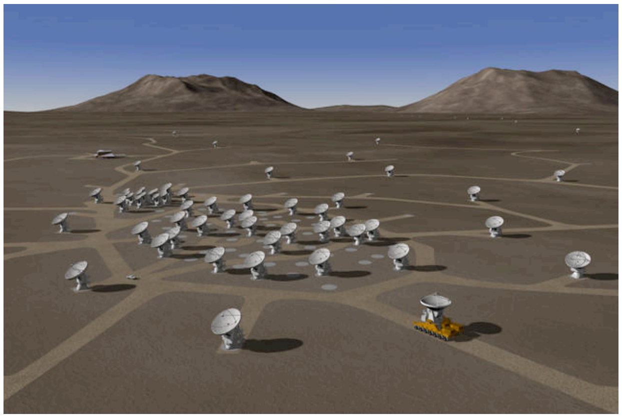
- JWST = James Webb Space Telescope, launch in 2014, successor to Hubble
  Cold Infrared telescope, 6.5 m mirror, L2 orbit to block light from Sun, Earth Moon
  Will probe the end of the dark ages: the formation of the first galaxies and stars



The Future: ALMA

ALMA: Atacama Large Millimeter Array : International radio observatory

Will probe the cold gas and dust from which stars, planets, galaxies form out to very early epochs when the Universe was only 0.1 Gyr old (1% of its present age)



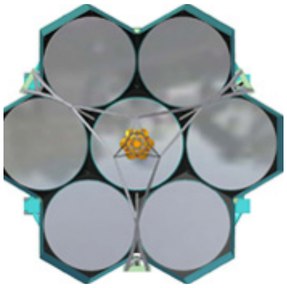
64 telescopes at 5000 m in Chajnantor plain in Chile (flat low water vapor site)

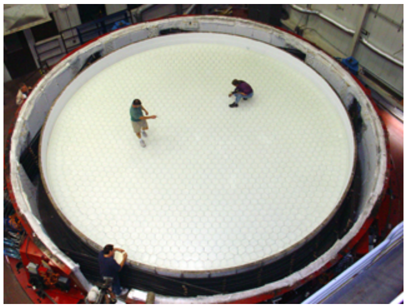
International project:
USA, Canada, Europe
East Asia, and Chile

The Future: ALMA

View from west side of Chilean Atacama Desert towards ALMA site

The Future: Giant Magellan Telescope (GMT)





22 m aperture (seven 8.4-m mirrors) First light in 2016

GMT partners include **UT Austin**, Harvard, Texas A&M, Univ. of Arizona, Carnegie Institution of Washington, Smithsonian Astrophysical Observatory, Australian National University