Ay1 – Lectures 13 and 14 summary

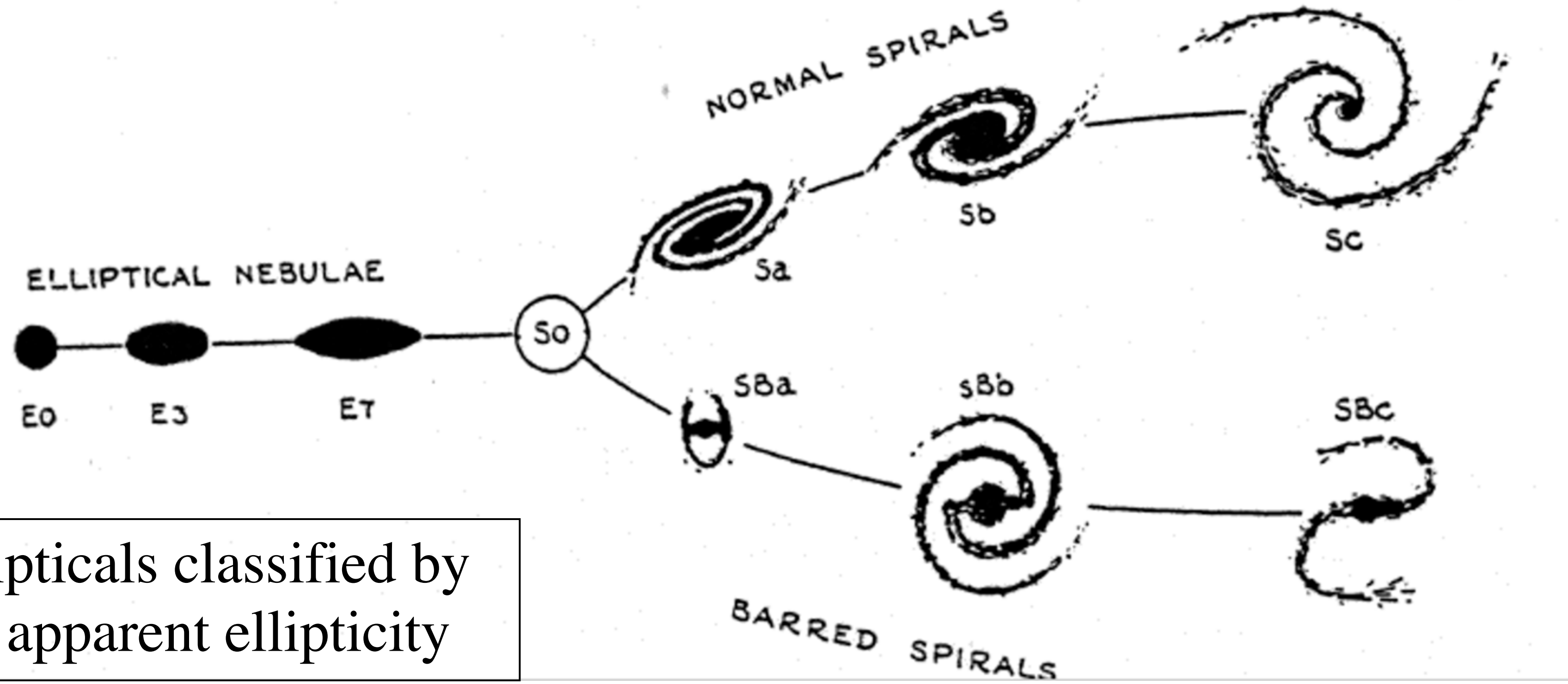
Galaxies and Their Properties

Galaxy Formation and Evolution

Galaxies

- The basic constituents of the universe at large scales, and the building blocks of the large-scale structure
- Have ***a broad range of physical properties***, which presumably reflects their evolutionary and formative histories, and gives rise to various morphological classification schemes (e.g., the Hubble type)
- Understanding of galaxy formation and evolution is one of the main goals of modern cosmology
- There are ~ 10^{11} galaxies within the observable universe
- Typical total masses ~ 10^8 - 10^{12} $M_\odot$
- Typically contain ~ 10^7 - 10^{11} stars

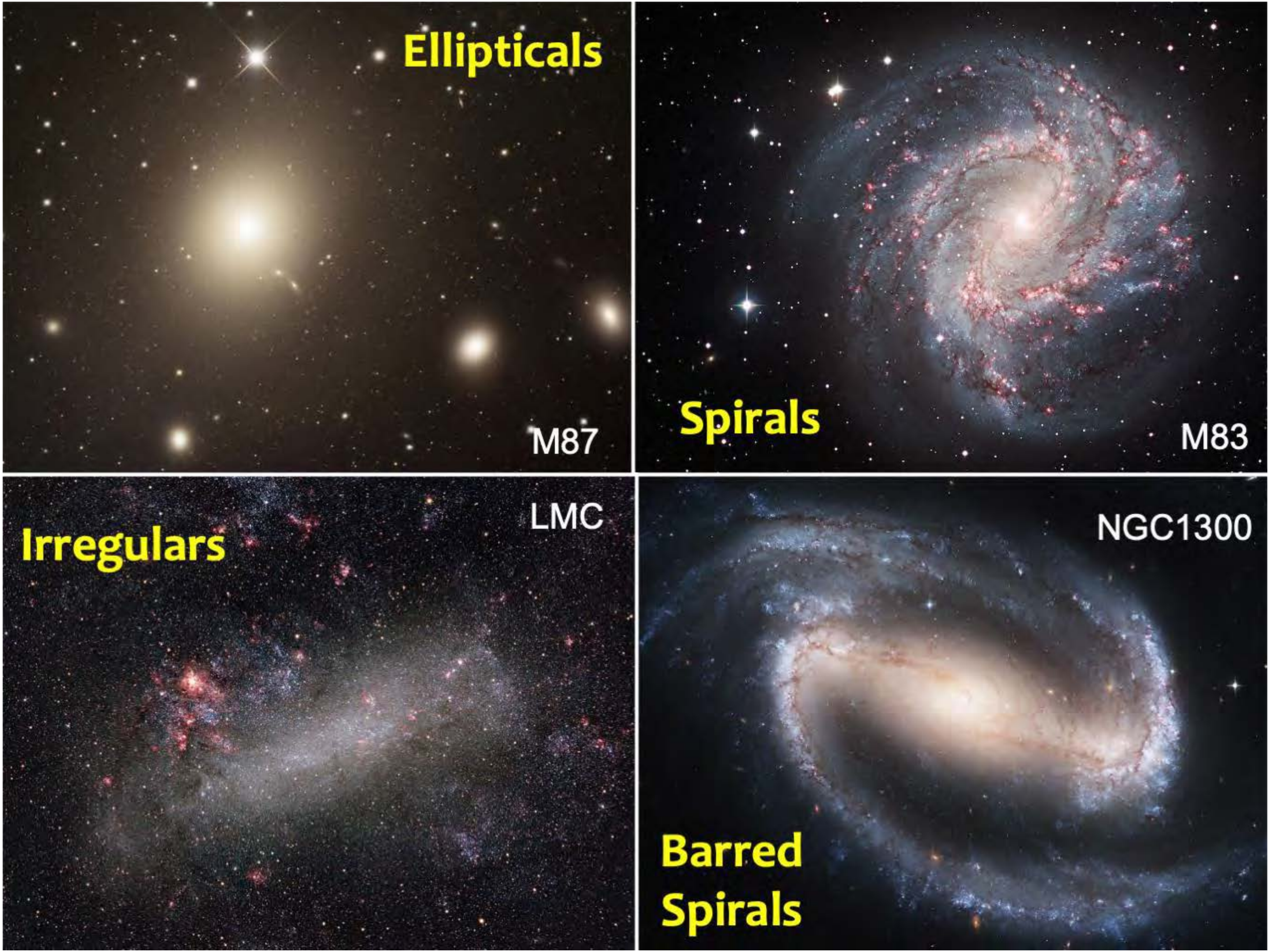
Hubble's Classification Scheme



Ellipticals classified by the apparent ellipticity

Spirals classified by the prominence of the spiral arms, and the presence of bars

Hubble thought (incorrectly) this was an evolutionary sequence, so ellipticals are called "early-type" and spirals "late-type" galaxies


Ellipticals
M87
Spirals
M83
LMC
Irregulars
NGC1300
Barred
Spirals

The Meaning of Galaxy Classification

- **Galaxy morphologies and other properties reflect different formative and evolutionary histories**
- Much can be explained by considering galaxies as composites made of *two dominant visible components*:
  1. Old, pressure supported bulges, where most of the star formation occurred early on
  2. Young(er), rotationally supported disks, where star formation happened gradually and is still going on
- Note that we do not involve in this the dominant mass component - the dark matter
- Nevertheless, there are some important and meaningful trends along the Hubble sequence

Galaxy Properties and the Hubble Sequence

Hubble sequence turned out to be surprisingly robust: many, but not all, physical properties of galaxies correlate with the classification morphology:

E S0 Sa Sb Sc Sdm/Irr →

- Pressure support ➔ Rotational support
- Passive ➔ Actively star forming
- Red colors ➔ Blue colors
- Hot gas ➔ Cold gas and dust
- Old ➔ Still forming
- High luminosity density ➔ Low lum. dens.

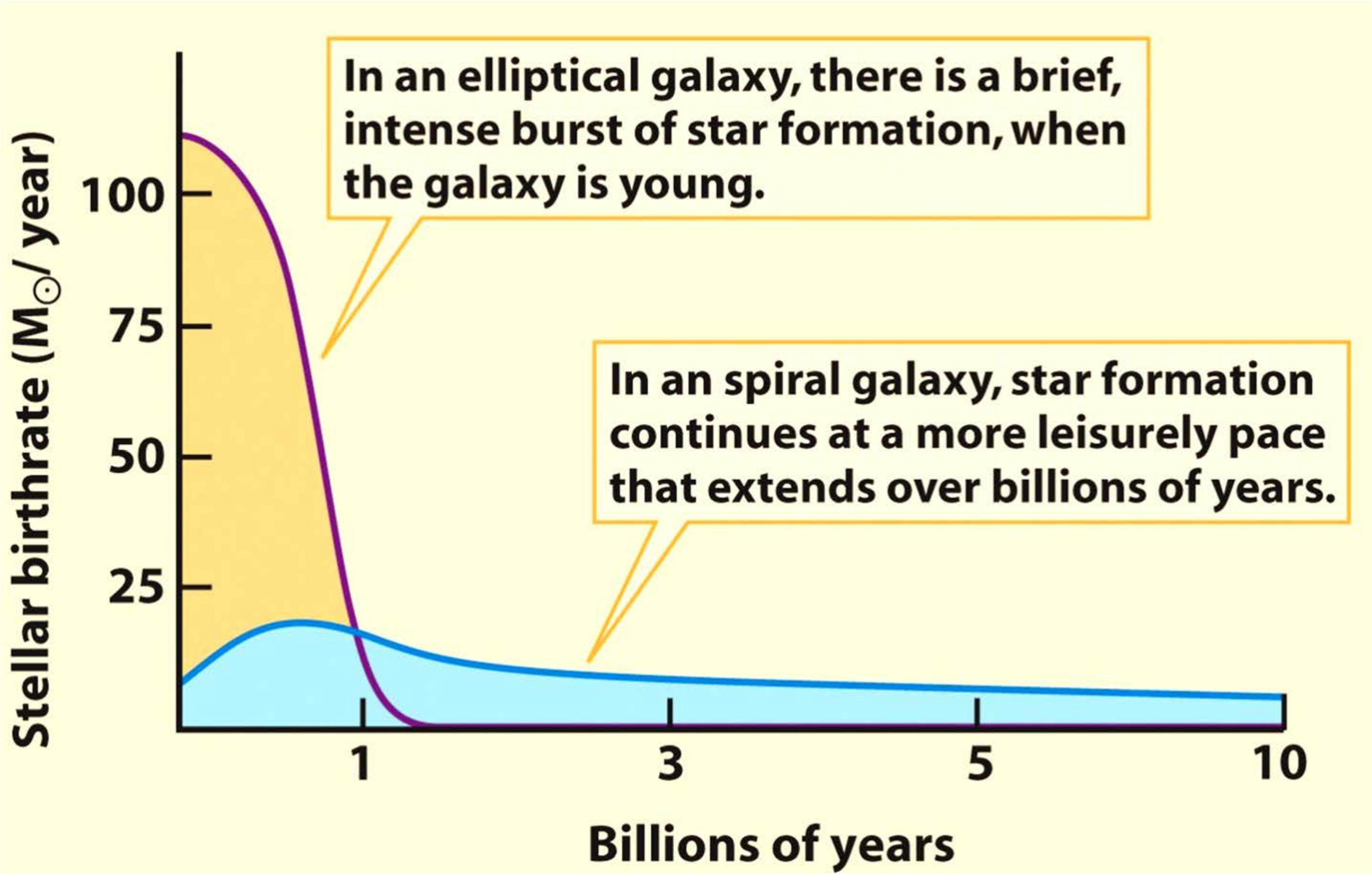
… etc.

But, for example, masses, luminosities, sizes, etc., do not correlate well with the Hubble type: at every type there is a large spread in these fundamental properties.

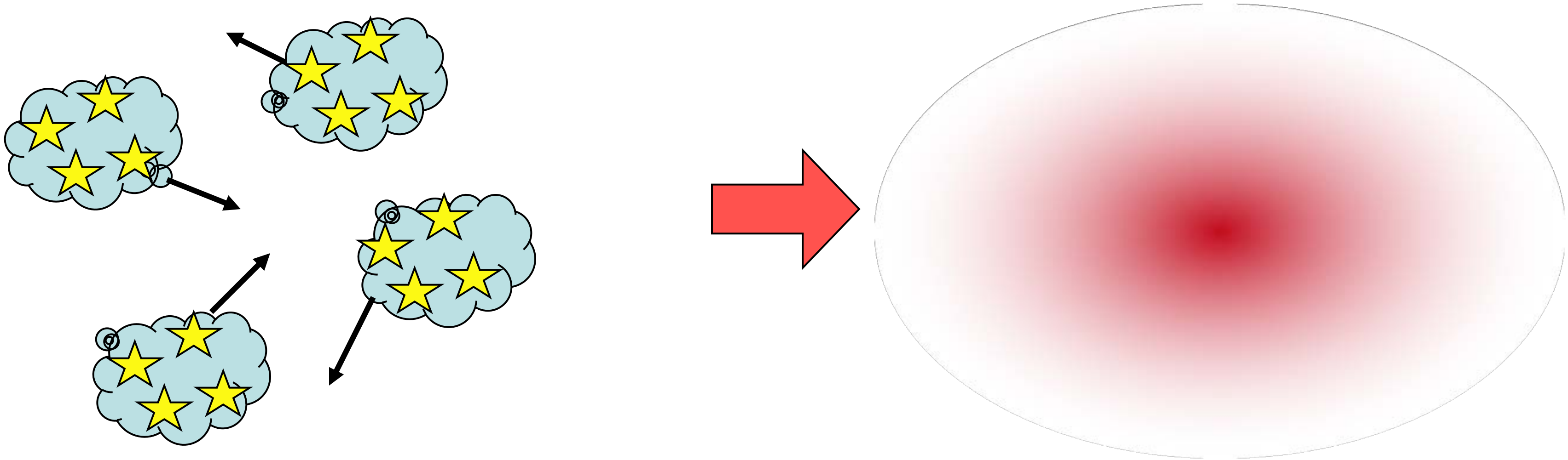
Interpreting the Trends Along the Hubble Sequence

- Probably the best interpretation of many of these is ***a trend in star formation histories:***
  - Ellipticals and early type spirals formed most of their stars early on (used up their gas, have older/redder stars)
  - Late type spirals have substantial on-going star-formation, didn't form as many stars early-on (and thus lots of gas left)
  - Spirals are forming stars at a few $M_{\odot}$ per year, and we know that there is ~ a few $\times$ $10^9 M_{\odot}$ of HI mass in a typical spiral
    - ✧ How long can spirals keep forming stars? It seems that some gas infall/resupply is needed
- These photometric/morphological properties also correlate with the dynamical properties

Star Formation History in Galaxies

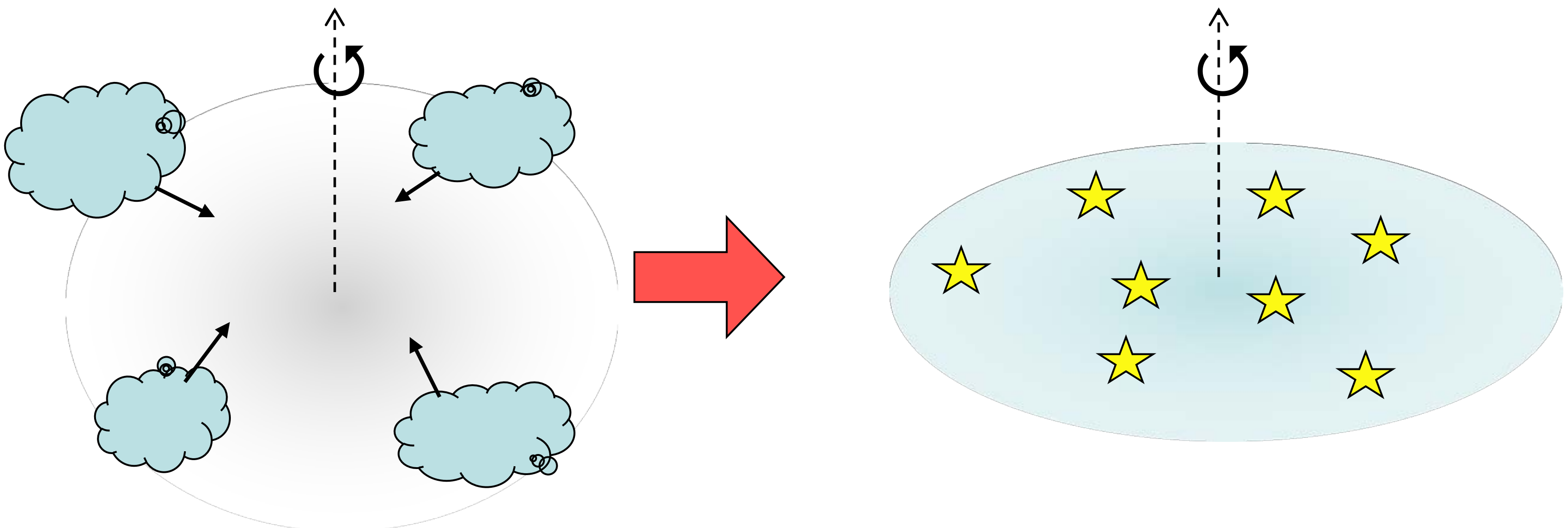


Formation of Galaxy Spheroids and Dynamics of Stellar Populations



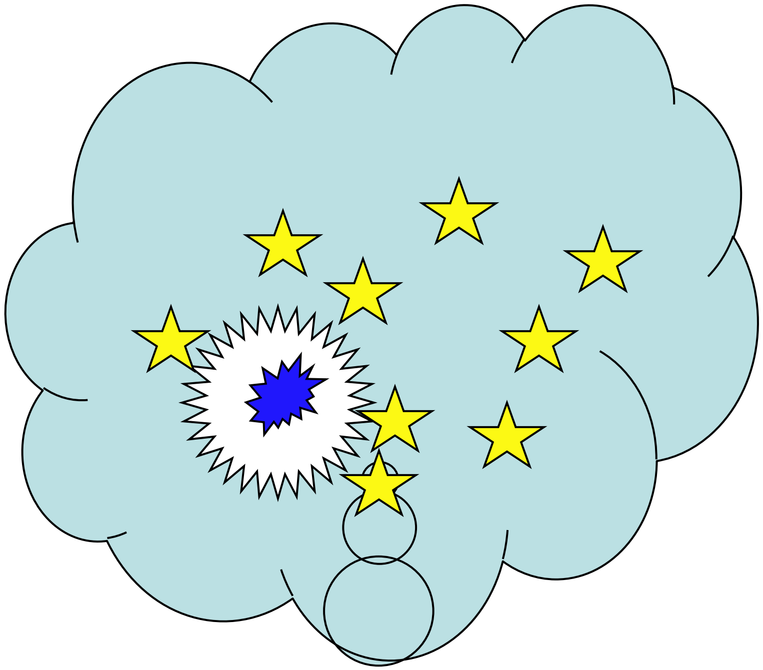
Stars "remember" the dynamics of their orbits at the time of formation, since dynamics of stellar systems is dissipationless. If stars form in dwarf protogalactic fragments which then merge, this will result in a pressure-supported system, *i.e.*, a spheroid (bulge or halo, or an elliptical galaxy). Their metallicities will reflect the abundances in their parent systems.

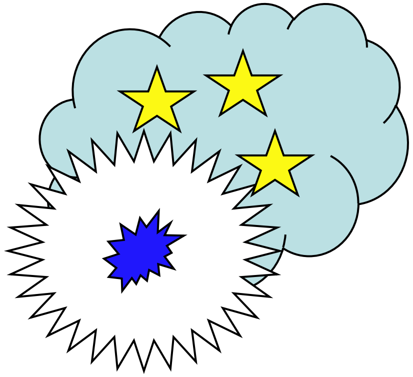
Formation of Galaxy Disks and Dynamics of Stellar Populations



If protogalactic clouds merge dissipatively in a potential well of a dark halo, they will settle in a thin, rotating disk = the minimum energy configuration for a given angular momentum. If gas settles into a (dynamically cold) disk before stars form, then stars formed in that disk will inherit the motions of the gas (mainly an ordered rotation).

Chemical Self-Enrichment in Young Stellar Systems





In a massive system, supernova ejecta are retained, and reused for subsequent generations of stars, which achieve ever higher metallicities.

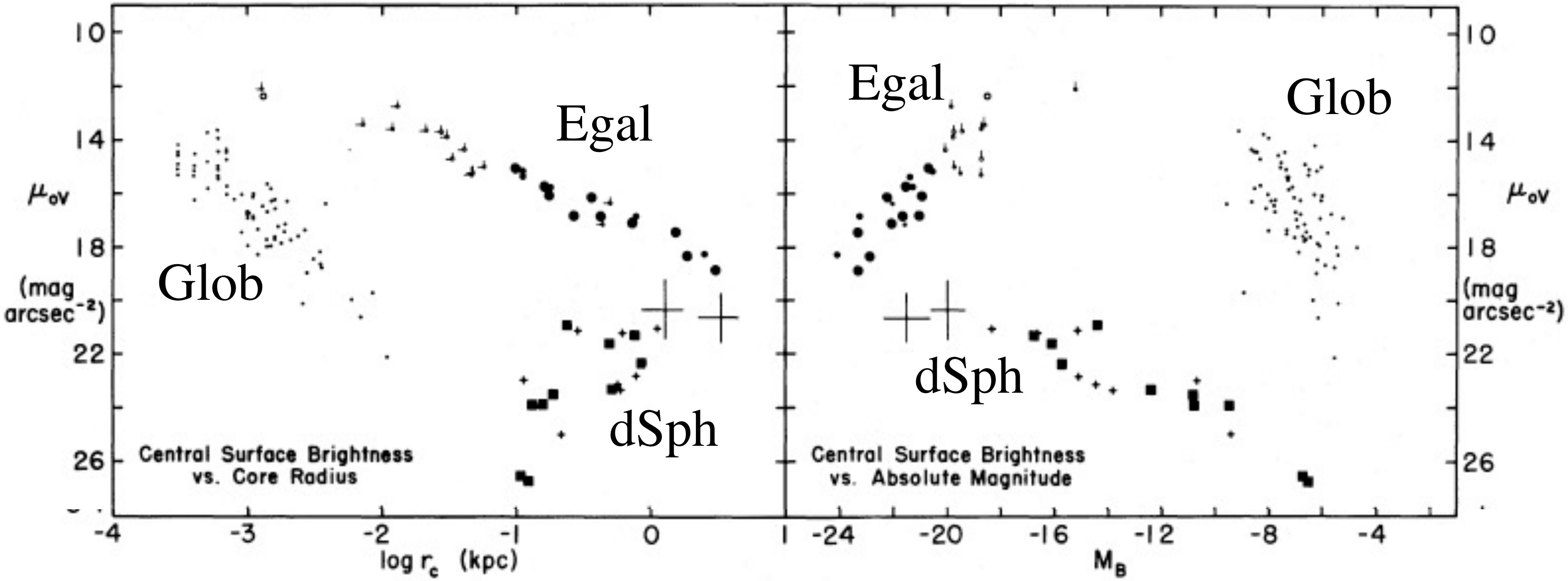
In a low-mass system, supernova shocks and star winds from massive young stars expell the enriched gas and may supress any subsequent star formation. The system retains its initial (low) metallicity.

Dwarf Galaxies

- Low-luminosity: $10^6 - 10^{10}\ L_\odot$, low-mass: $10^7 - 10^{10}\ M_\odot$, small in size, ~ few kpc
- Often low surface brightness, so they are hard to find!
- More than one family of objects:
  - Gas-poor, passive (dE and dSph)
  - Gas-rich, star forming
- Why are dwarf galaxies important?
  - Majority of galaxies are dwarfs!
  - Dwarf galaxies may be remnants of galaxy formation process: relatively simple systems, not merger products
  - Dwarf galaxies are currently being cannibalized by larger galaxies

Dwarf Galaxies

- Dwarf ellipticals (dE) and dwarf spheroidals (dSph) are a completely different family of objects from normal ellipticals
- They follow completely different correlations from giant galaxies, suggestive of different formative mechanisms
- They are generally dark matter (DM) dominated, especially at the faint end of the sequence



Merging / Interacting Systems

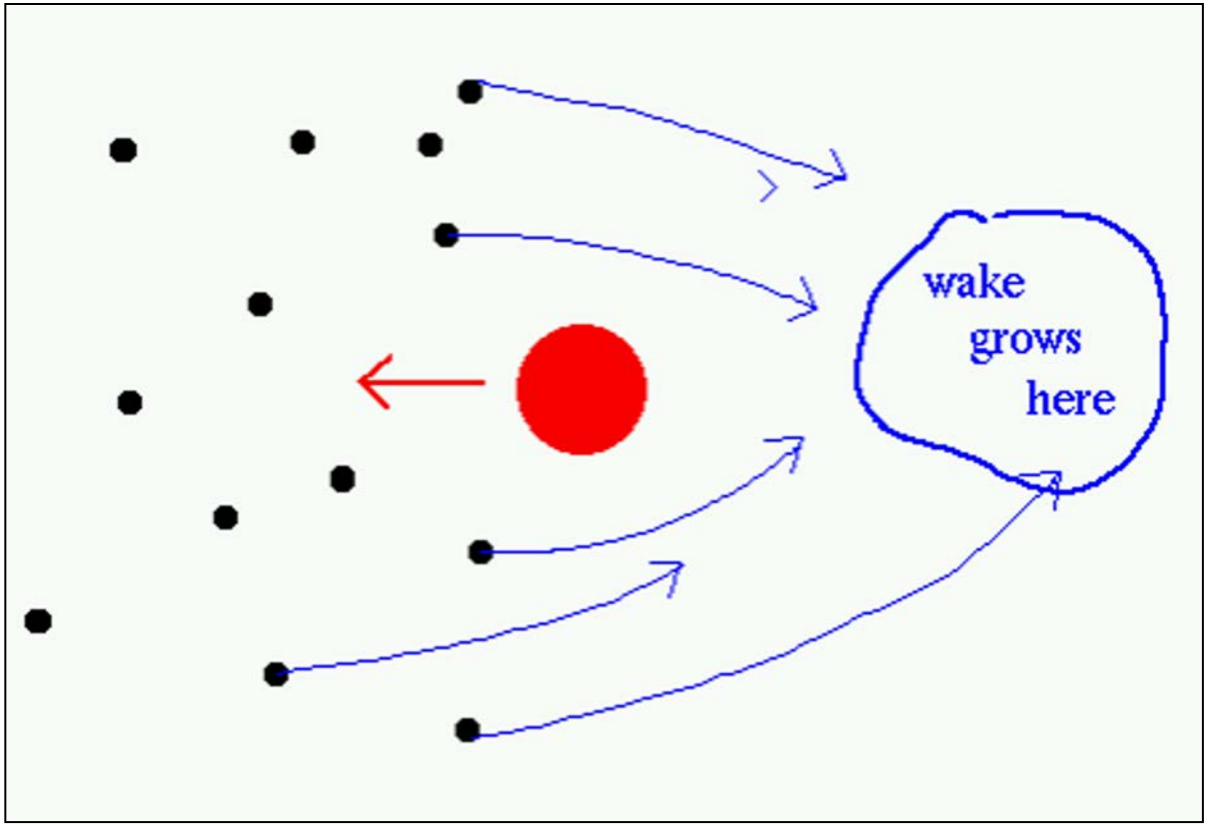
Galaxies in the process of a transformation, generally from disks to ellipticals

In late stages of a merger, the two galaxies are indistinguishable, and the product does not look like any standard galaxy type

Antennae Merger

Dynamical Friction

- As a massive galaxy moves through a "sea" of stars (and the dark halo), it causes a wake behind it increasing the mass density behind it; the same effect applies to galaxy pass-bys
- This increase in density causes the galaxy to slow and lose its orbital kinetic energy
- The galaxy will eventually fall in and merge with its companion
- Local example: the Magellanic Clouds

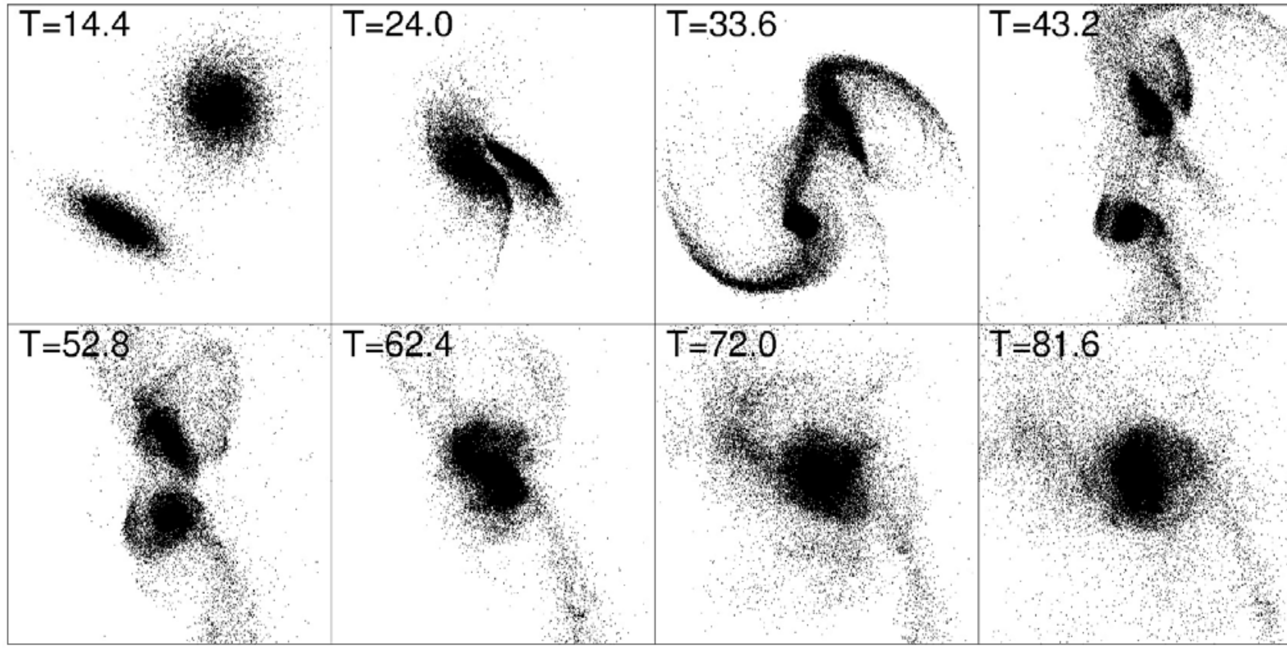


Numerical Simulations of Galaxy Mergers

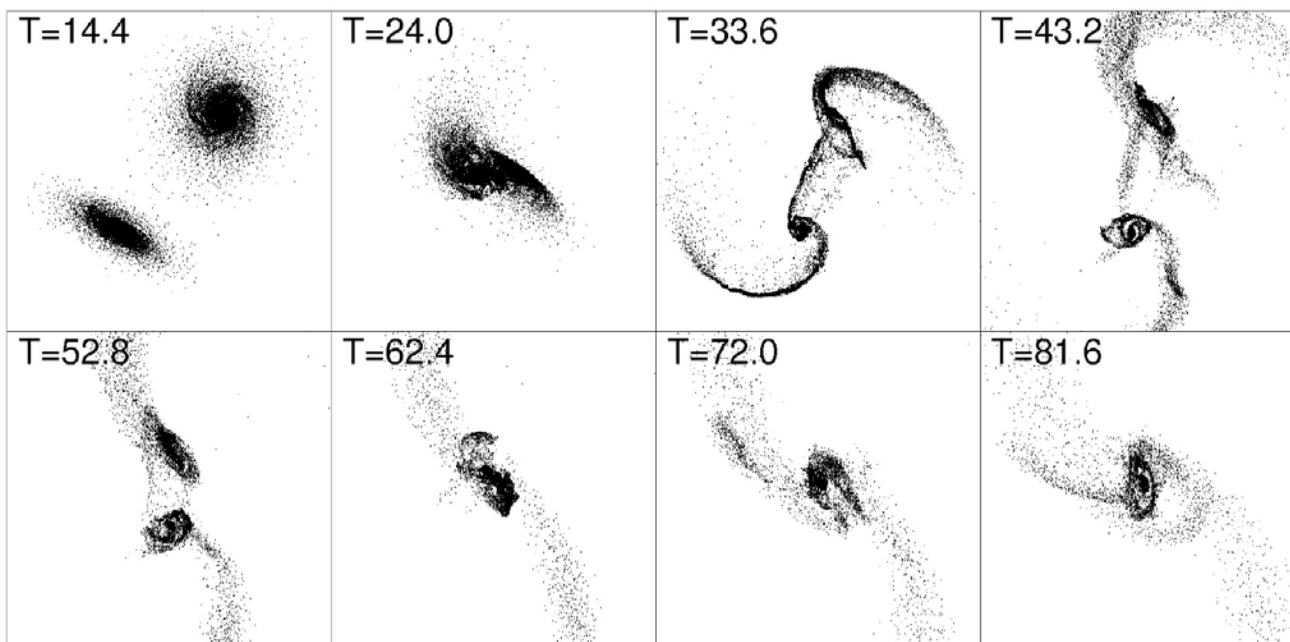
Merge 2 disk galaxies: the remnant looks just like an elliptical galaxy

Orbital kinetic energy converts to the internal kinetic energy

Gas quickly looses energy (since it is dissipative), and sinks towards the center of the remnant, where it can fuel a starburst, or an AGN if a massive black hole is present



Stars ↑ (non-dissipative) Gas ↓ (dissipative)



Quantifying Properties of Galaxies

For galaxies of different types, we would like to quantify:

- The distribution of light - need photometric measurements
- The distribution of mass - need kinematical measurements
- Relative distributions and interplay of various components, e.g., stars, gas, dark matter - need multiwavelength measurements, as different components tend to emit most energy in different wavebands, e.g., stars $\rightarrow$ visible/near-IR, cold gas $\rightarrow$ radio, dust $\rightarrow$ far-IR, hot gas $\rightarrow$ x-rays, etc.
- Chemical composition, star formation rates - need spectroscopy

All these measurements can then be analyzed using:

- Dynamical models
- Stellar population synthesis models
- Galaxy evolution models

Note: we tend to measure different observables for different galaxy types!

Galaxy Scaling Laws

- When correlated, global properties of galaxies tend to do so as power-laws; thus "scaling laws"
- They provide a *quantitative means of examining physical properties of galaxies* and their systematics
- They *reflect the internal physics* of galaxies, and are a product of the *formative and evolutionary histories*
  - They are different for different galaxy families
  - A "fossil evidence" of galaxy formation
- Correlations between distance-dependent and distance-independent quantities can be used to measure relative distances of galaxies

The Tully-Fisher Relation

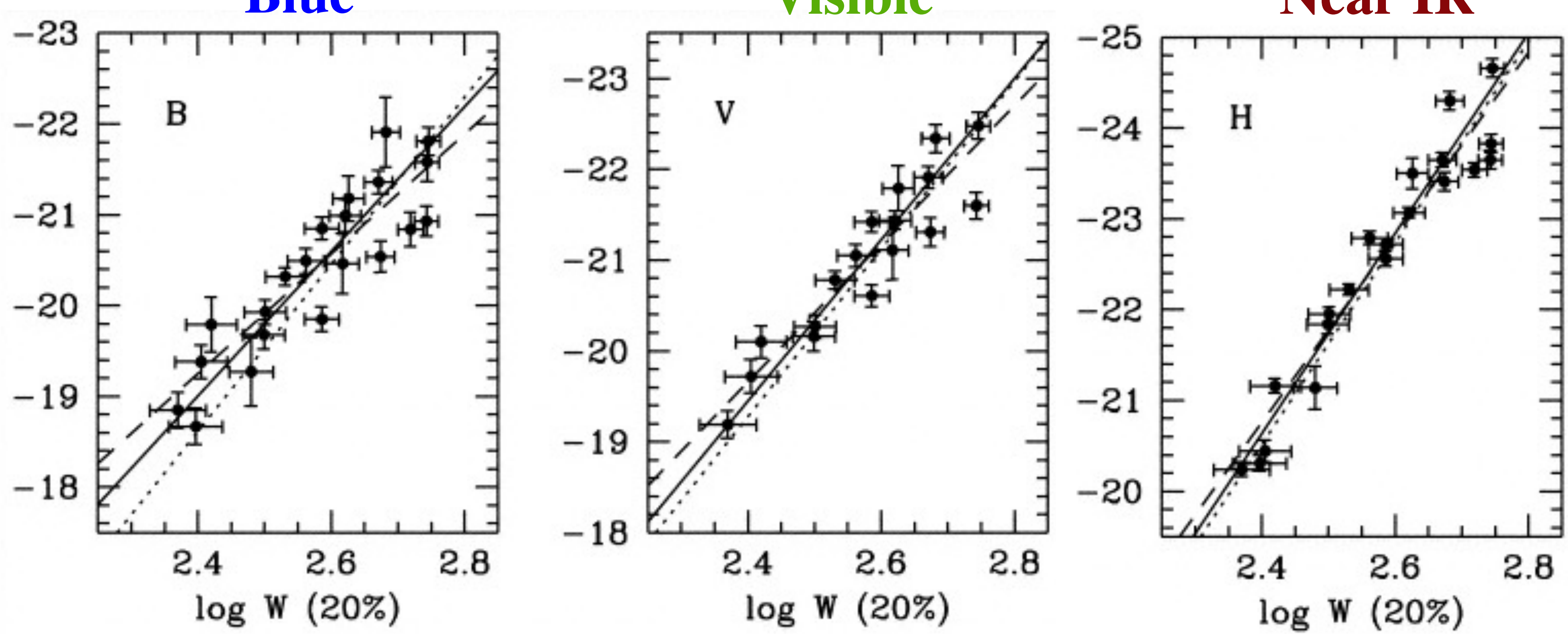
- A correlation of luminosity vs. rotational speed (often measured as a H I 21 cm line width) relation for spirals:

$$L \sim V_{rot}^{\gamma}, \gamma \approx 4, \text{ varies with wavelength}$$

- Scatter is ~ 10% at best, better in the redder bands

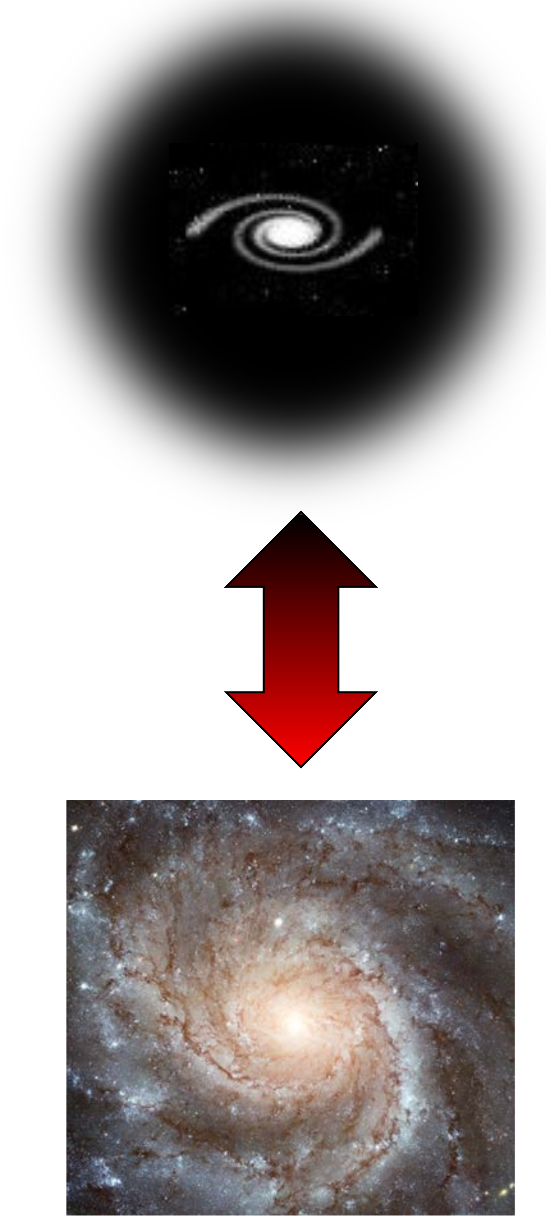
Blue Visible Near IR

Absolute Magnitude



log H I velocity width

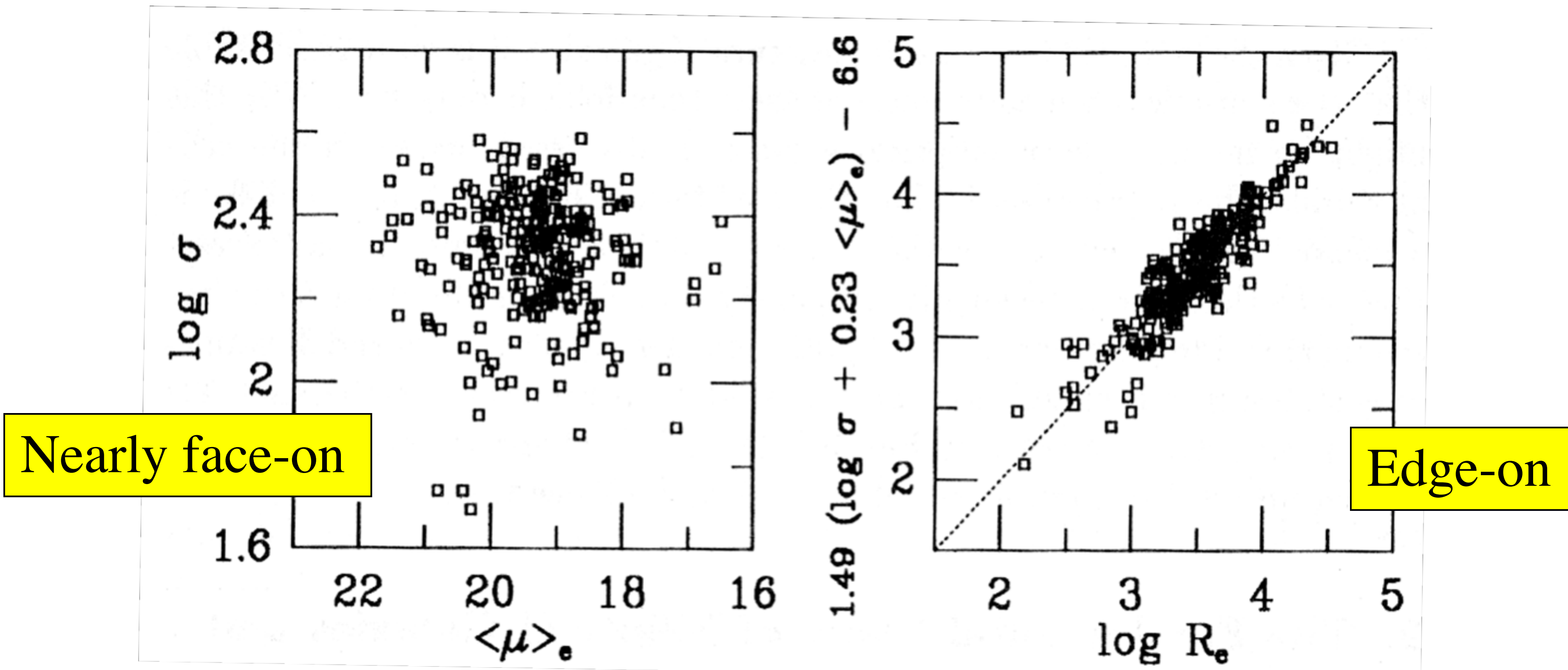
Why is the TFR So Remarkable?



- Because it connects a property of the dark halo - the maximum circular speed - with the product of the net integrated star formation history, i.e., the luminosity of the disk
- Halo-regulated galaxy formation/evolution?
- The scatter is remarkably low - even though the conditions for this to happen are known not to be satisfied
- Thus, the TFR offers some important insights into the physics of disk galaxy formation
- And we use it to measure relative distances to spiral galaxies

Scaling Relations for Ellipticals

Many fundamental properties of ellipticals are connected through ***bivariate scaling relations*** (derive one from 2 others), called the **Fundamental Plane**, commonly expressed as a bivariate scaling relation $\boldsymbol{R \sim \sigma^{1.4} I^{-0.8}}$, where $\boldsymbol{R}$ is the radius, $\boldsymbol{I}$ the mean surface brightness, $\boldsymbol{\sigma}$ the velocity dispersion



Deriving the Scaling Relations

Start with the Virial Theorem: $$\frac{GM}{\langle R\rangle} = k_E \frac{\langle V^2\rangle}{2}$$

Now relate the observable values of ***R*, *V*** (or ***σ***), ***L***, etc., to their "true" mean 3-dim. values by simple scalings:

$$R = k_R \langle R\rangle \qquad V^2 = k_V \langle V^2\rangle \qquad L = k_L I R^2$$

One can then derive the "virial" versions of the FP and the TFR:

$$R = K_{SR} V^2 I^{-1} (M/L)^{-1}$$

$$L = K_{SL} V^4 I^{-1} (M/L)^{-2}$$

Where the "structure" coefficients are:

$$K_{SR} = \frac{k_E}{2G k_R k_L k_V}$$

$$K_{SL} = \frac{k_E^2}{4G^2 k_R^2 k_L k_V^2}$$

Deviations of the observed relations from these scalings must indicate that either some ***k***'s and/or the ***(M/L)*** are changing

Galaxies Must Evolve

- Stars evolve: they are born from ISM, evolve, shed envelopes or explode, enriching the ISM, more stars are born…
- Structure evolves: density fluctuations collapse and merge in a hierarchical fashion

Galaxy Evolution

Assembly of the mass → **Conversion of gas into stars and v.v., feedback processes**

DM dominated
Cannot be observed directly, but may be inferred
Easy to model, mainly dissipationless

This is what is observed, and where energy is generated
Dissipative, and very hard to model

Evolution Timescales and Evidence

Timescales for galactic evolution span wide range:

~ 100 Myr - galaxy free-fall and cooling time scales

10 -100 Myr - lifetimes of massive stars

10 -100 Myr - lifetime of the bright phase of a luminous Active Galactic Nucleus (?)

Few × 100 Myr - rotation period of spiral galaxy

~ Gyr - time required for two galaxies to merge

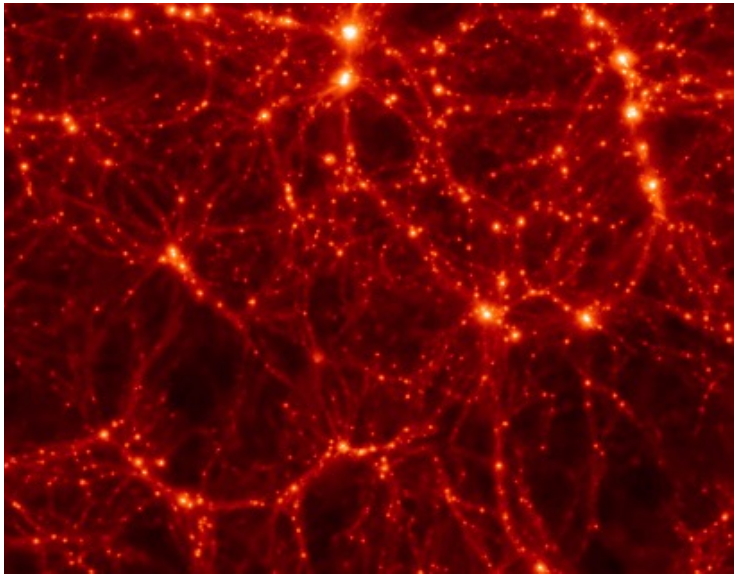
~ 10 Gyr - age of the Universe

Observational evidence for evolution is found in:

- Stellar populations in the Milky Way (e.g., metallicity as a function of stellar age, etc.)
- Systematics of nearby galaxy properties
- **Properties of distant galaxies seen at earlier epoch**

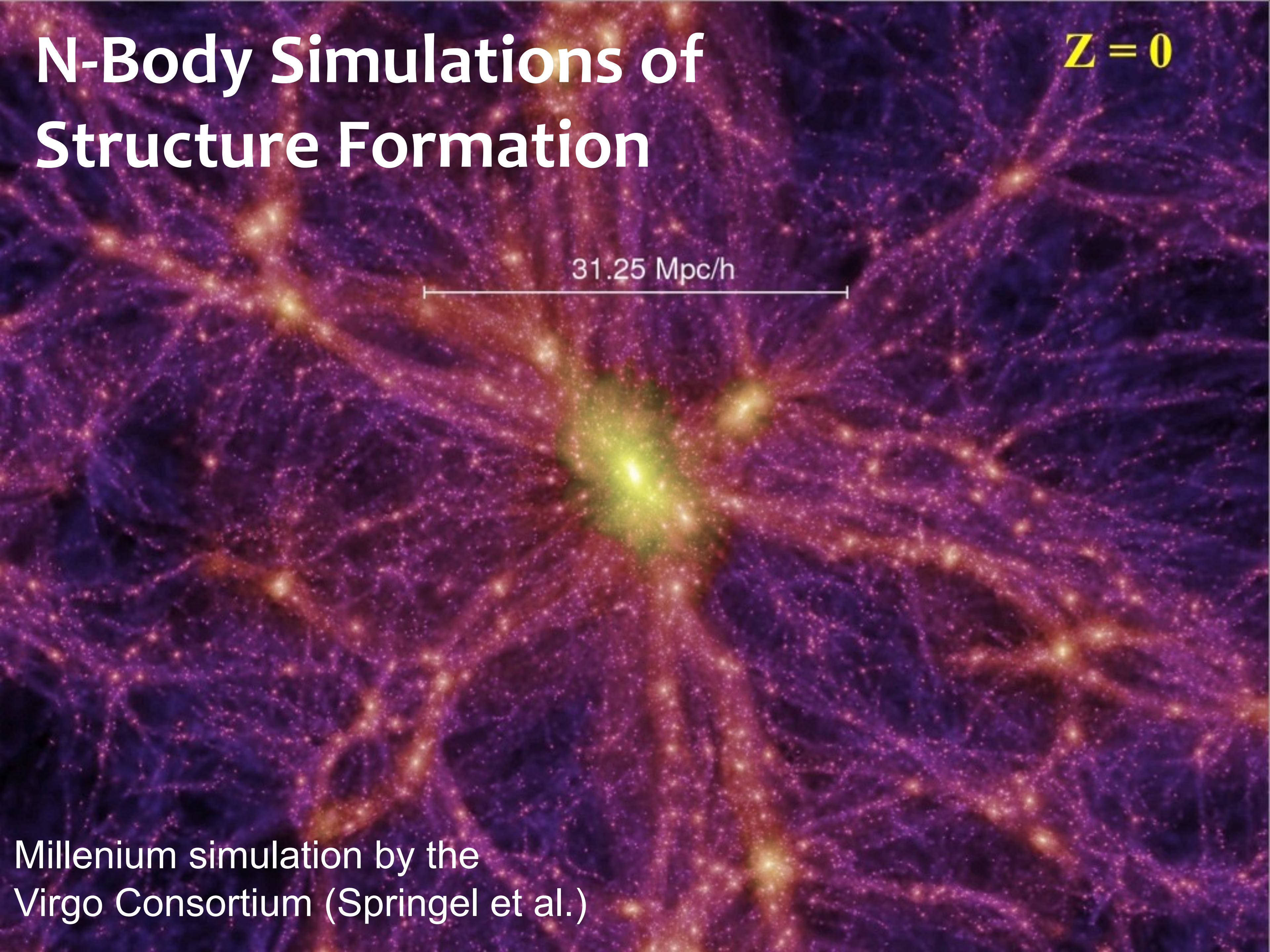
Theoretical Tools and Approaches

1. **Assembly of the mass:** numerical modeling of structure formation. Fairly well advanced, but it is hard to treat any dissipative processes very accurately. Well constrained from large-scale structure formation



2. **Evolution of stellar populations:** based on stellar evolution models, and fairly well understood. Lots of parameters: the stellar initial mass function, star formation history, stellar evolutionary tracks and spectra as functions of metallicity. Poorly constrained

N-Body Simulations of Structure Formation



Millenium simulation by the
Virgo Consortium (Springel et al.)

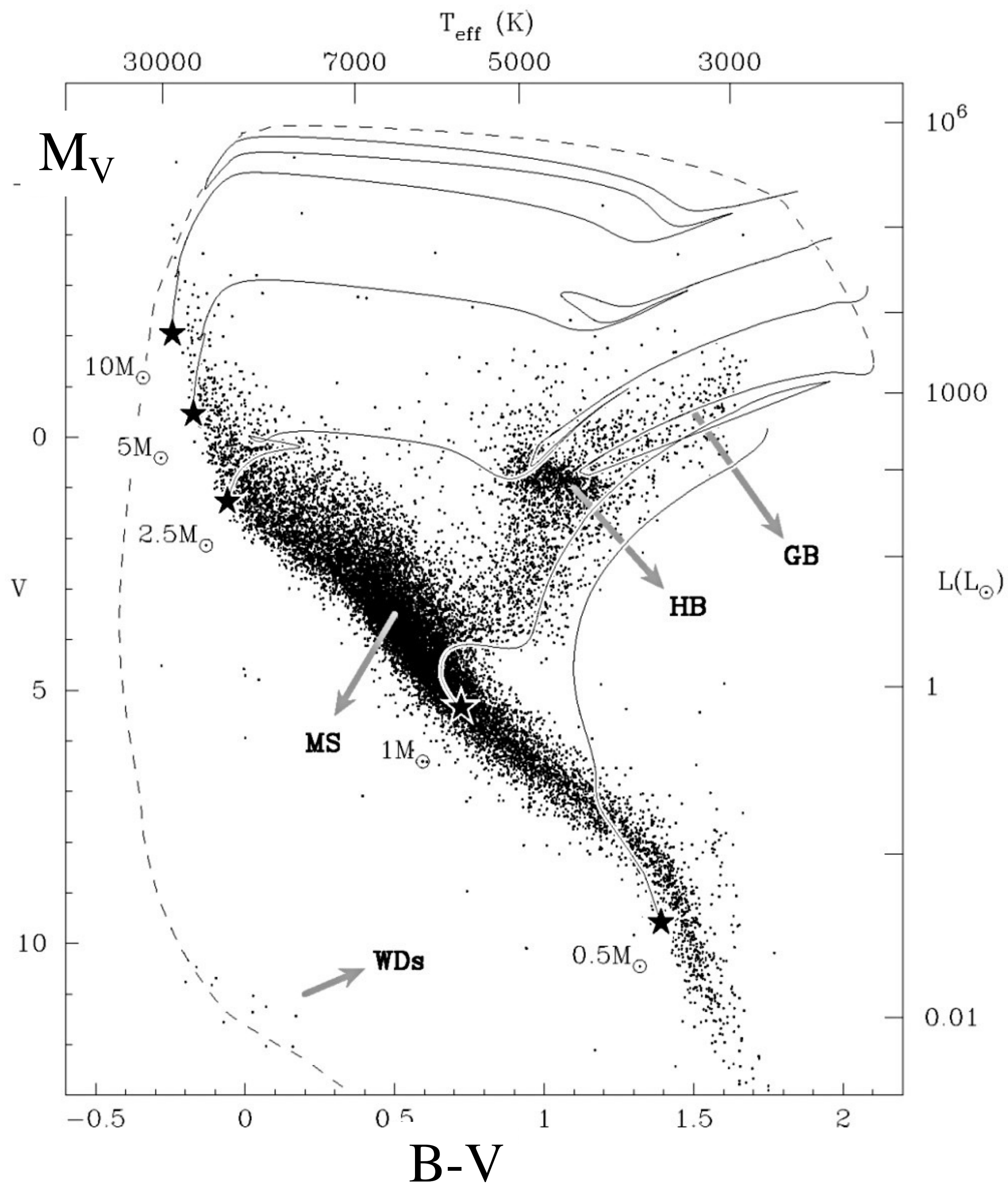
Modeling Evolution of Stellar Pop's

- Stellar evolution is relatively well understood both observationally and theoretically; the key points:
  - Massive stars are very hot, blue, very luminous, and have very short lives; they dominate the restframe UV light
  - Thus we expect largest effects in the bluer parts of the spectrum
- Star formation histories are a key assumption:
  - Ellipticals are best fit by a burst of early star formation followed by a relatively "passive evolution" where they fade and get redder quickly
  - Spirals are best fit by a slowly declining or nearly constant star formation – they stay bluer and don't fade as much

Stellar Population Synthesis Models

We can synthesize predicted galaxy spectra as a function of time by assuming the following:

- Star formation rate as a function of time
- Initial mass function of stars
- Libraries of stellar spectra for stars of different masses, metallicities and ages, etc.
- Stellar evolutionary tracks (isochrones)

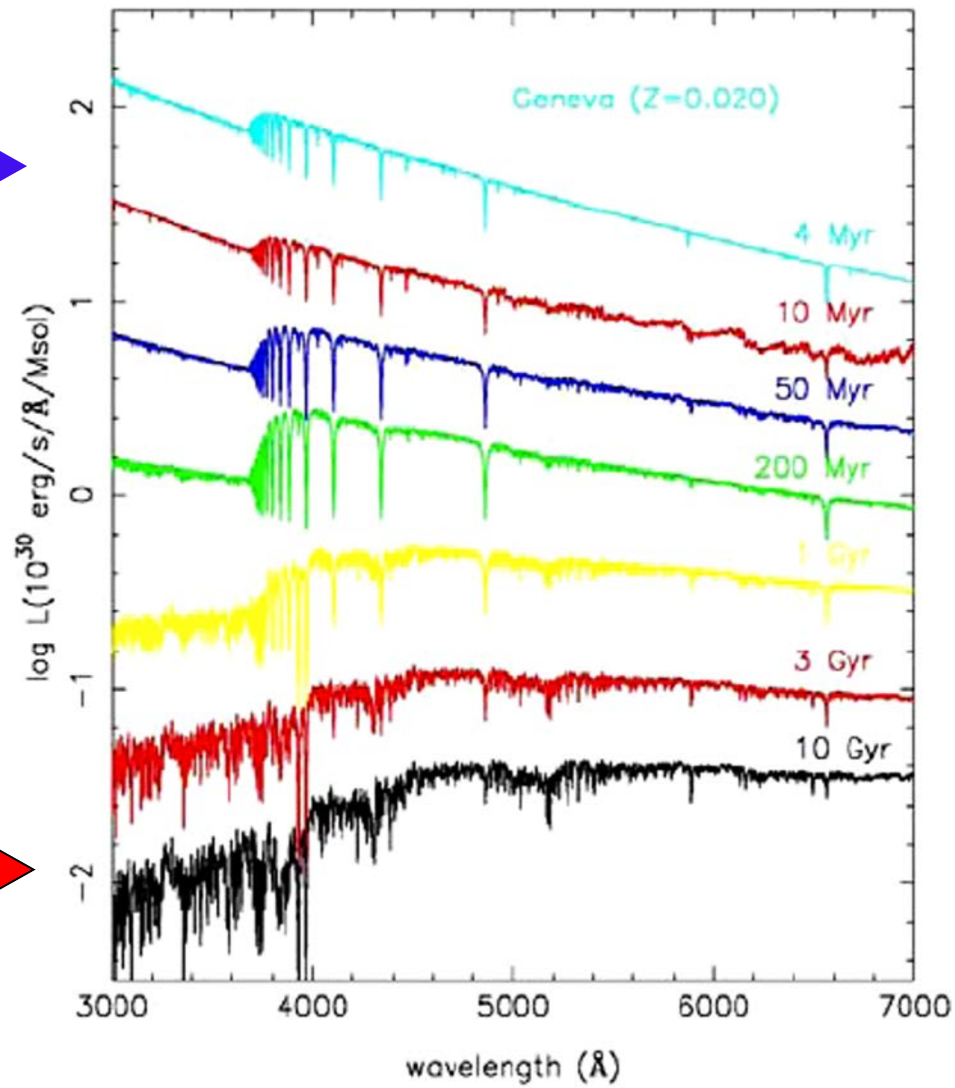


Predicted Spectral Evolution

Young stellar population: light dominated by the luminous, hot, massive stars

But they do not live very long, so the spectra gradually become dimmer and redder

Billions of years after the initial burst of star formation, the light is dominated by the old, longer lived red giants, and the change slows down



Generally, models fade in time, and faster in the UV than in the IR

Observational Tools and Approaches

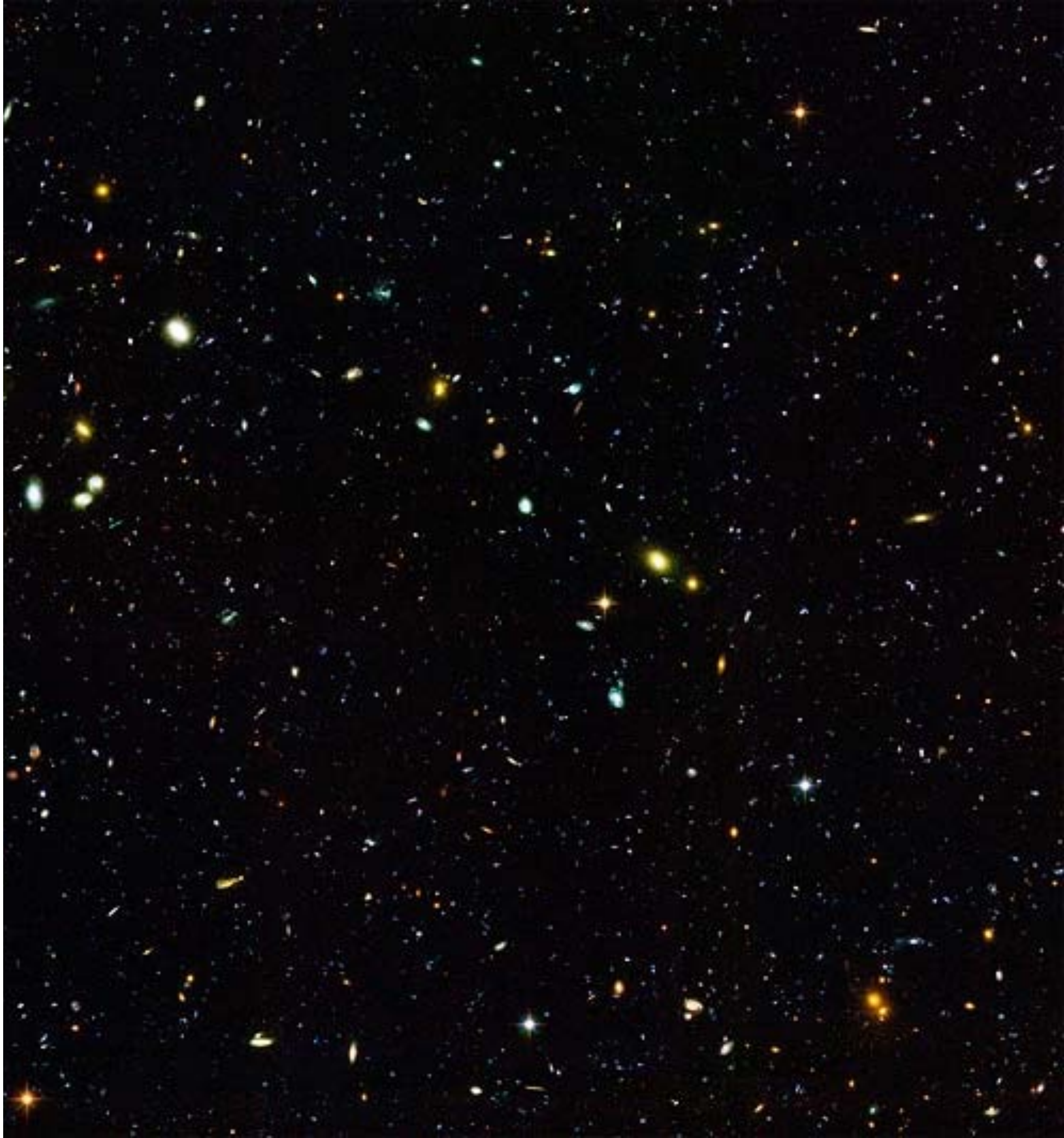
- **Deep imaging surveys** and source counts, at wavelengths from UV to FIR
  - Sources are always selected in emission, and any given band has its own selection effects and other peculiarities
  - With enough bandpasses, one can estimate "photometric redshifts", essentially very low resolution spectroscopy; may be unreliable
  - Measurements of galaxy clustering provide additional information
- **Deep spectroscopic redshift surveys**: redshifts are usually obtained in the visible, regardless of how the sources are selected
  - As a bonus, one can also estimate current star formation rates and rough chemical abundances from the spectra
- **Diffuse extragalactic backgrounds:** an integrated emission from all sources, regardless of the flux or surface brightness limits
  - Extremely hard to do
  - No redshift information

Observing Galaxy Evolution

- If redshifts are not available, we can do source counts as a function of limiting flux or magnitude; and colors as a function of magnitude (acting as a proxy for distance - not a great approximation)
- But you really do need redshifts, to get a true evolution in time, and disentangle the various evolution effects
- The field is split observationally:
  - **Unobscured star formation** evolution: most of the energy emerging in the restframe UV, observed in the visible/NIR
  - **Obscured star formation**: energy from young stars reprocessed by dust to emerge in FIR/sub-mm
  - They have different limitations and selection effects

A proven powerful combination is to use deep HST imaging (e.g., HDF N and S, HUDF, GOODS field, etc.) and Keck or other 6 to 10-m class telescope for spectroscopy.

Various deep fields also have multi-wavelength data from Chandra, VLA, Spitzer …

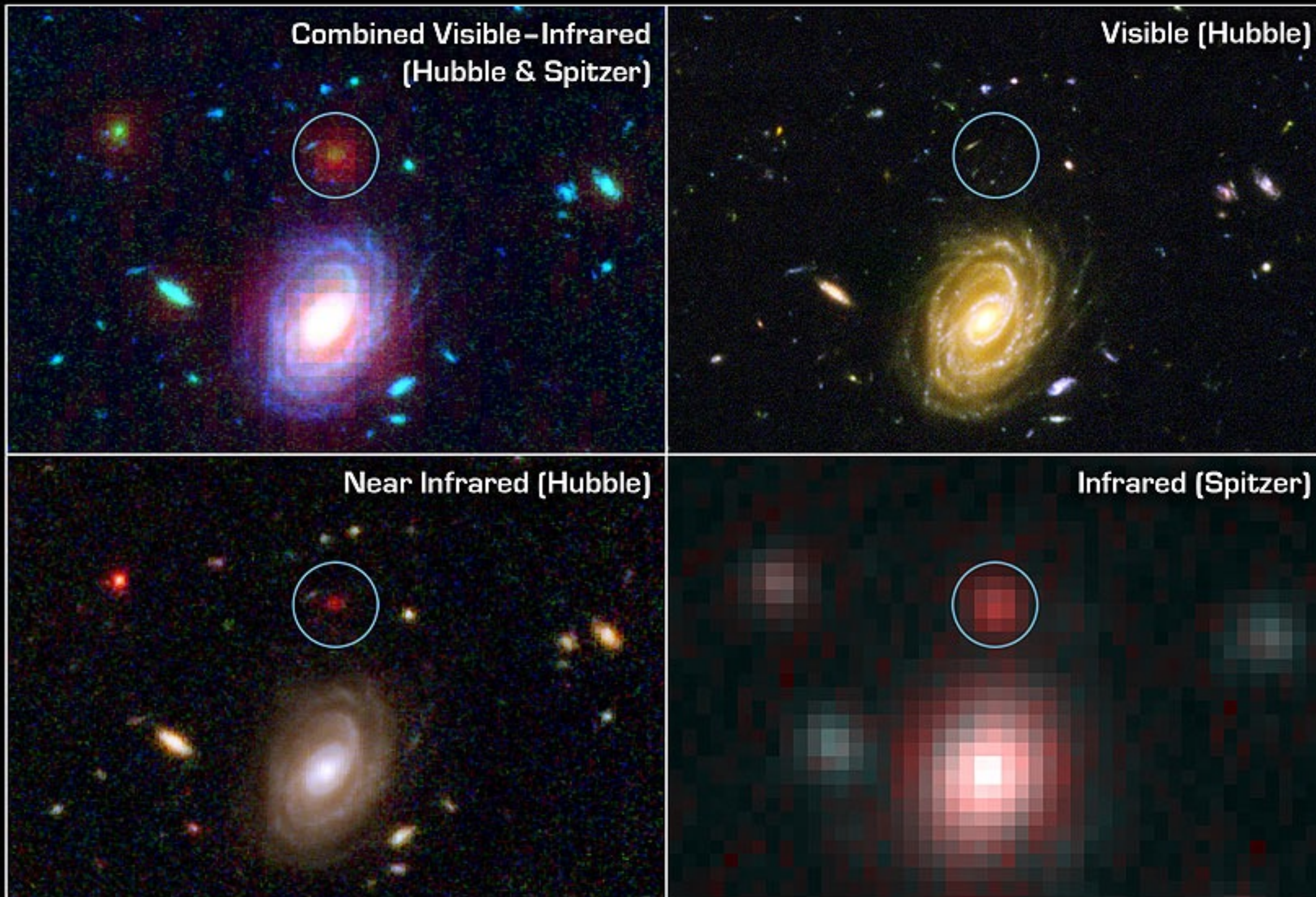


Galaxies in the past were…

- Bluer
- Brighter at a given mass

but

- Smaller mass on the average
- Smaller in size
- More numerous



Distant Galaxy in the Hubble Ultra Deep Field

Spitzer Space Telescope • IRAC
Hubble Space Telescope • ACS • NICMOS

NASA, ESA / JPL-Caltech / B. Mobasher (STScI/ESA)

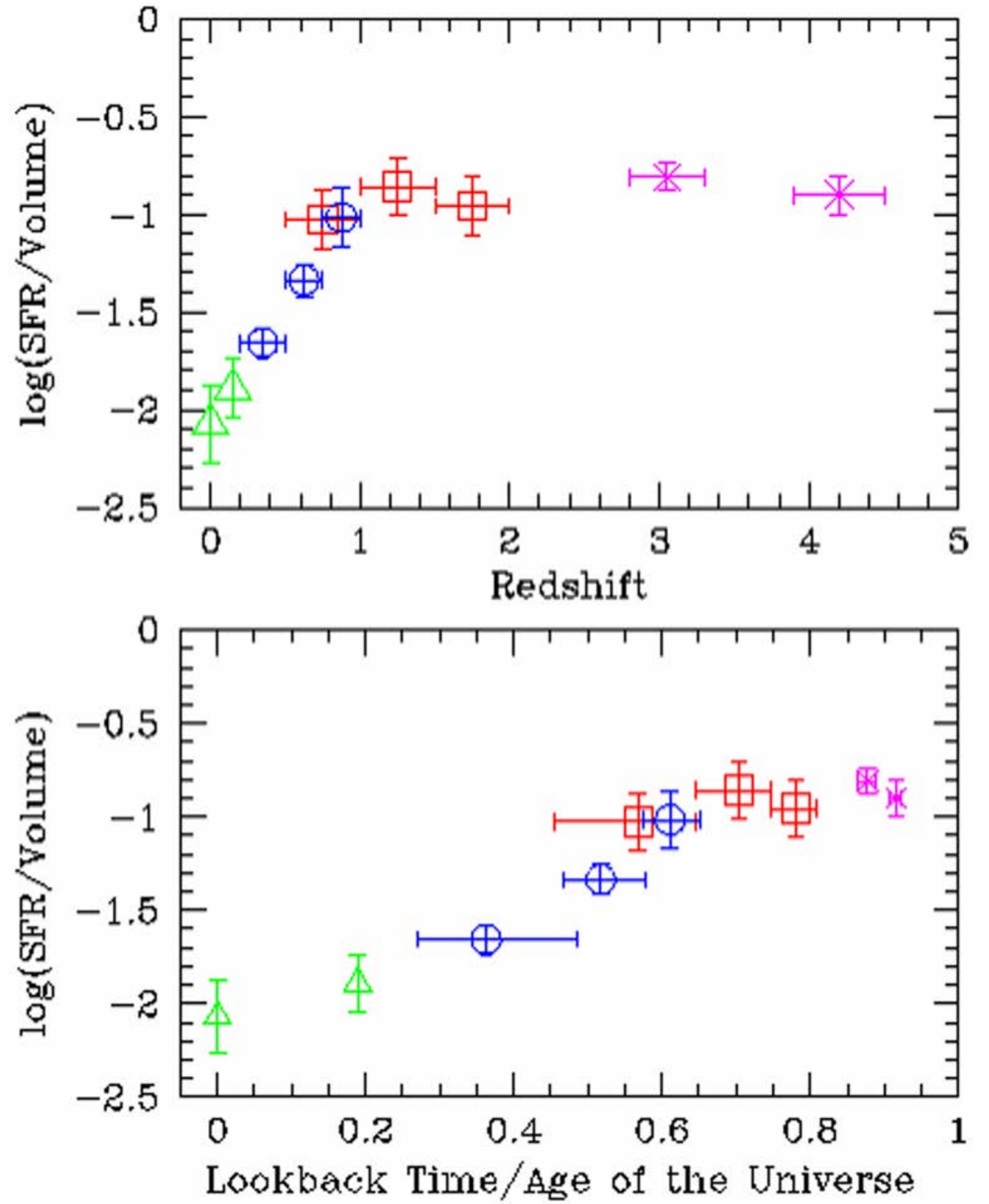
ssc2005-19a

Cosmic Star Formation History

From various luminosity densities converted to star formation rates, we can construct a possible history of the comoving SFR density

At face value it implies the universe was much more active in the past (z ~1 - 2) but what happens earlier is unclear

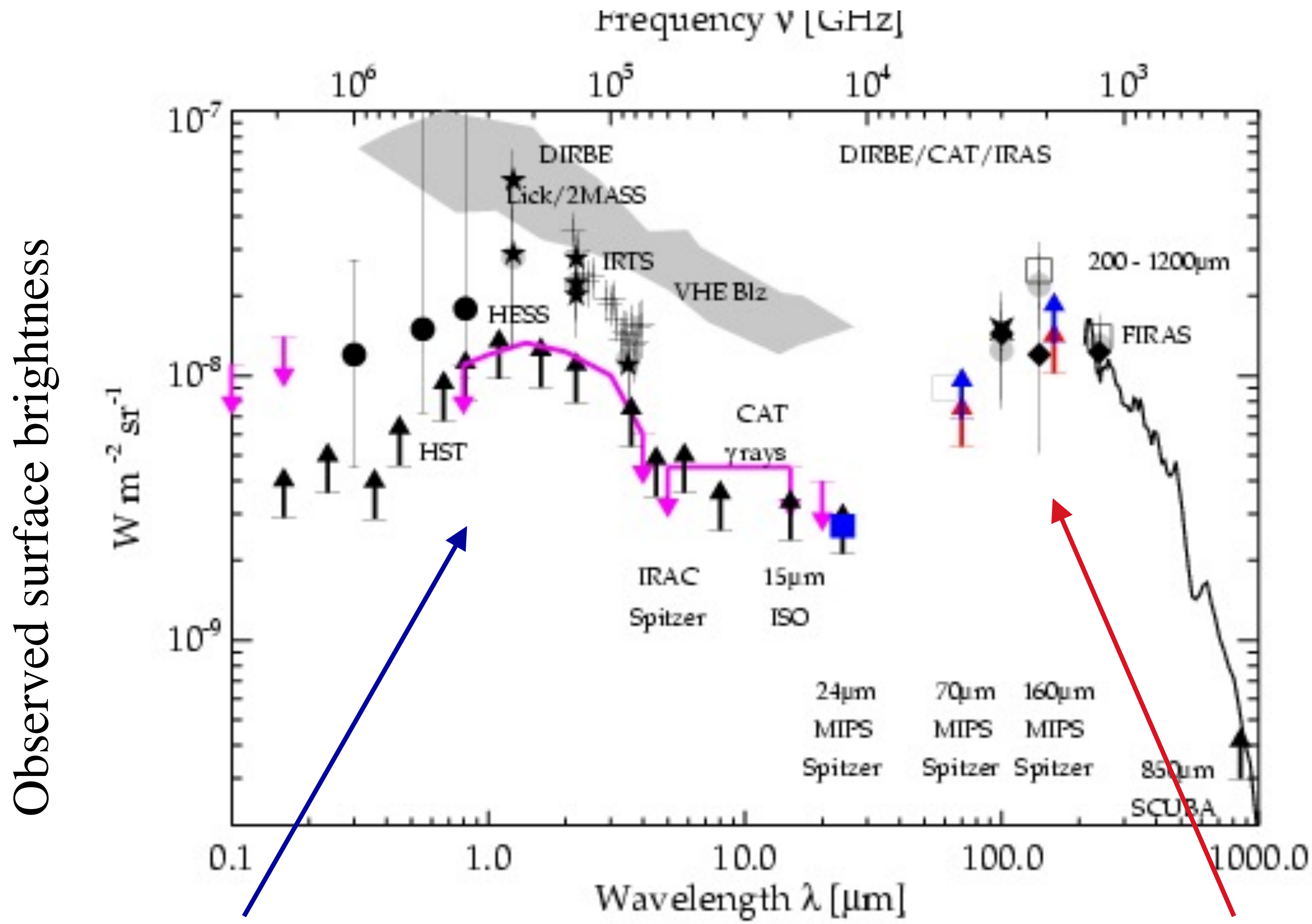
There are many complications of interpretation, including the reliability of each SFR diagnostic, dust extinction, incompleteness, etc.



All Starlight in the Universe

- Any deep survey is limited in flux and surface brightness: some fainter and/or more diffuse sources are likely missed; thus, our source counts give us only a lower limit to the total energy emitted by evolving galaxies
- An alternative approach is to measure ***integrated diffuse backgrounds, due to all sources***
  - This is really hard to do, for many reasons
  - Redshifts are lost, but at least the energy census is complete
- The total energy in the diffuse extragalactic backgrounds from UV to sub-mm is ~ 100 nW m^{-2} sr^{-1} (±50% or so)
  - This is distributed roughly equally between the UV/Opt (unobscured SF) and FIR/sub-mm (obscured SF)
  - A few percent of the total is contributed by AGN
  - This is only a few percent of the CMB

Diffuse Optical and IR Backgrounds



Unobscured component
(restframe UV, obs. Optical/NIR)

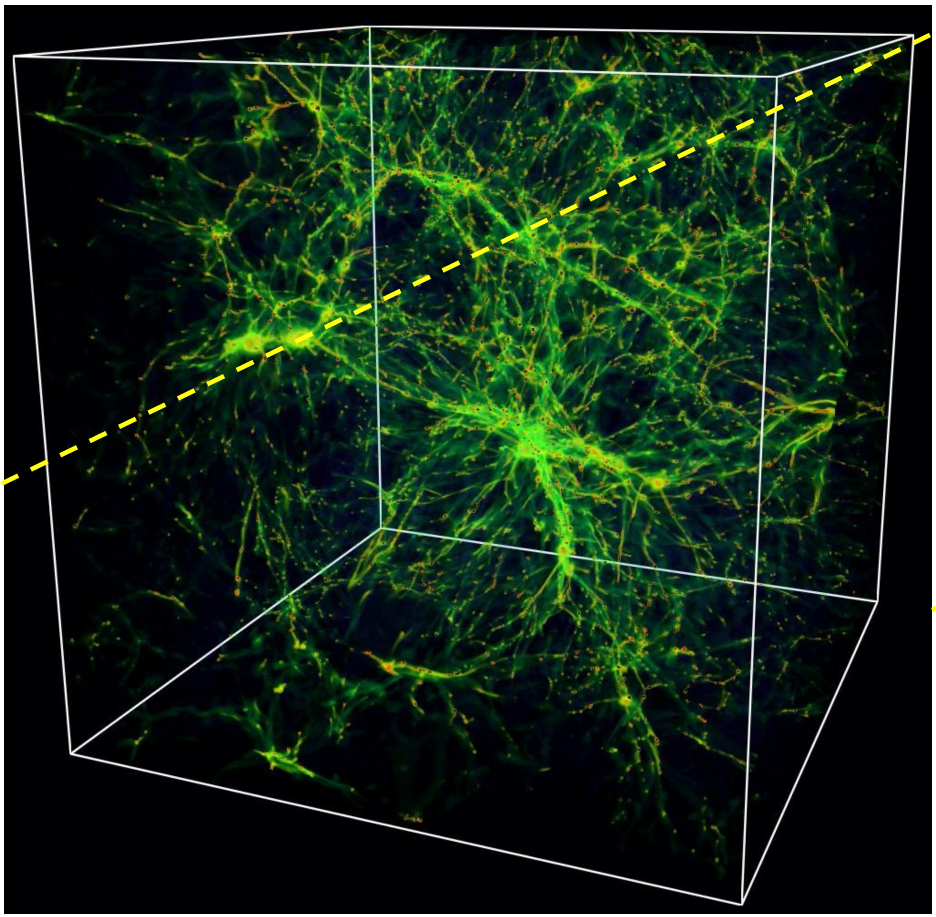
Obscured component
(restframe FIR, obs. FIR/sub-mm)

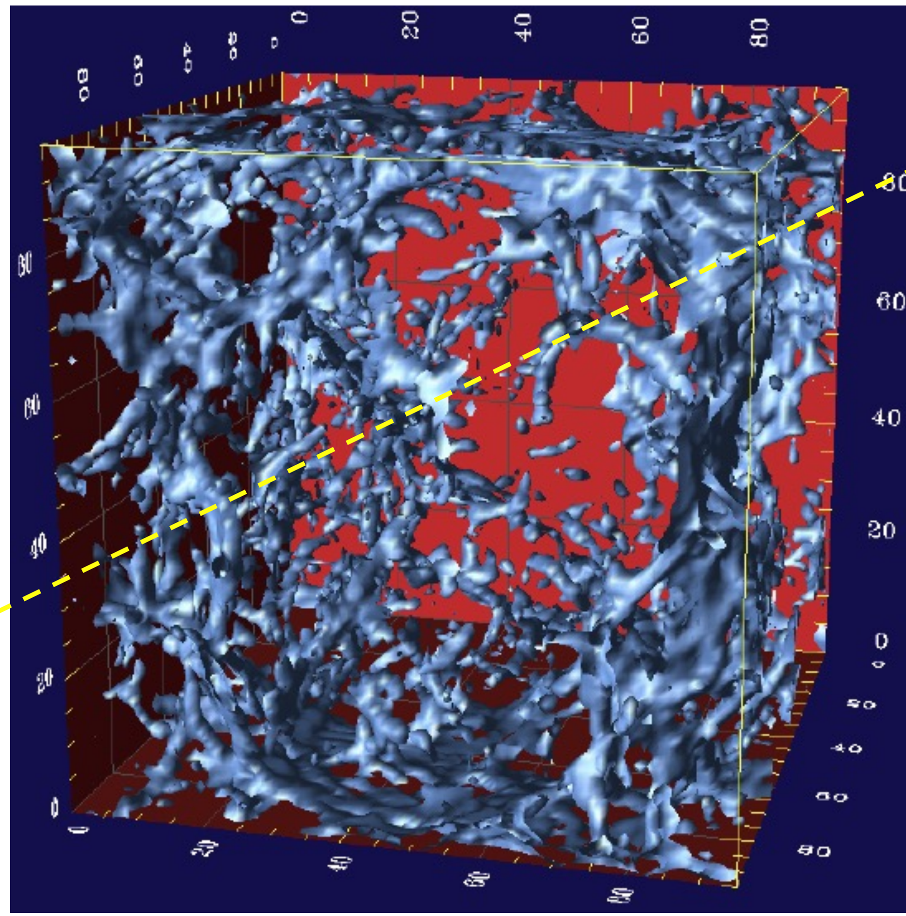
Intergalactic Medium (IGM)

- Essentially, baryons between galaxies
- Its density evolution follows the large scale structure formation, and the potential wells defined by the dark matter, forming a web of filaments, the co-called **"Cosmic Web"**
- Gas falls into galaxies, where it serves as a replenishment fuel for star formation
- Likewise, enriched gas is driven from galaxies through the radiatively and SN powered **galactic winds**, which chemically enriches the IGM
- Chemical evolution of galaxies and IGM thus track each other
- Star formation and active galactic buclei provide the **ionizing flux** for the IGM

Cosmic Web: Numerical Simulations

Our lines of sight towards some luminous background sources intersect a range of gas densities, condensed clouds, galaxies …

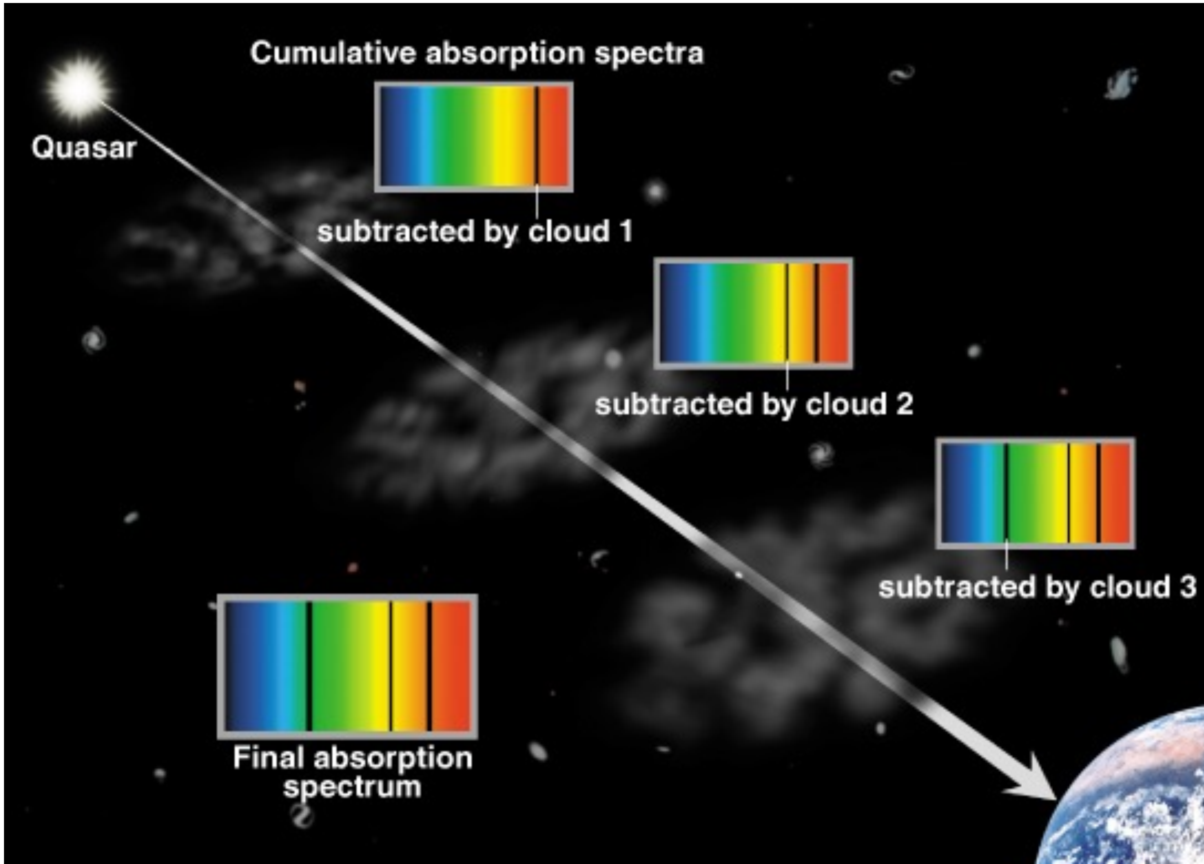




(from R. Cen)

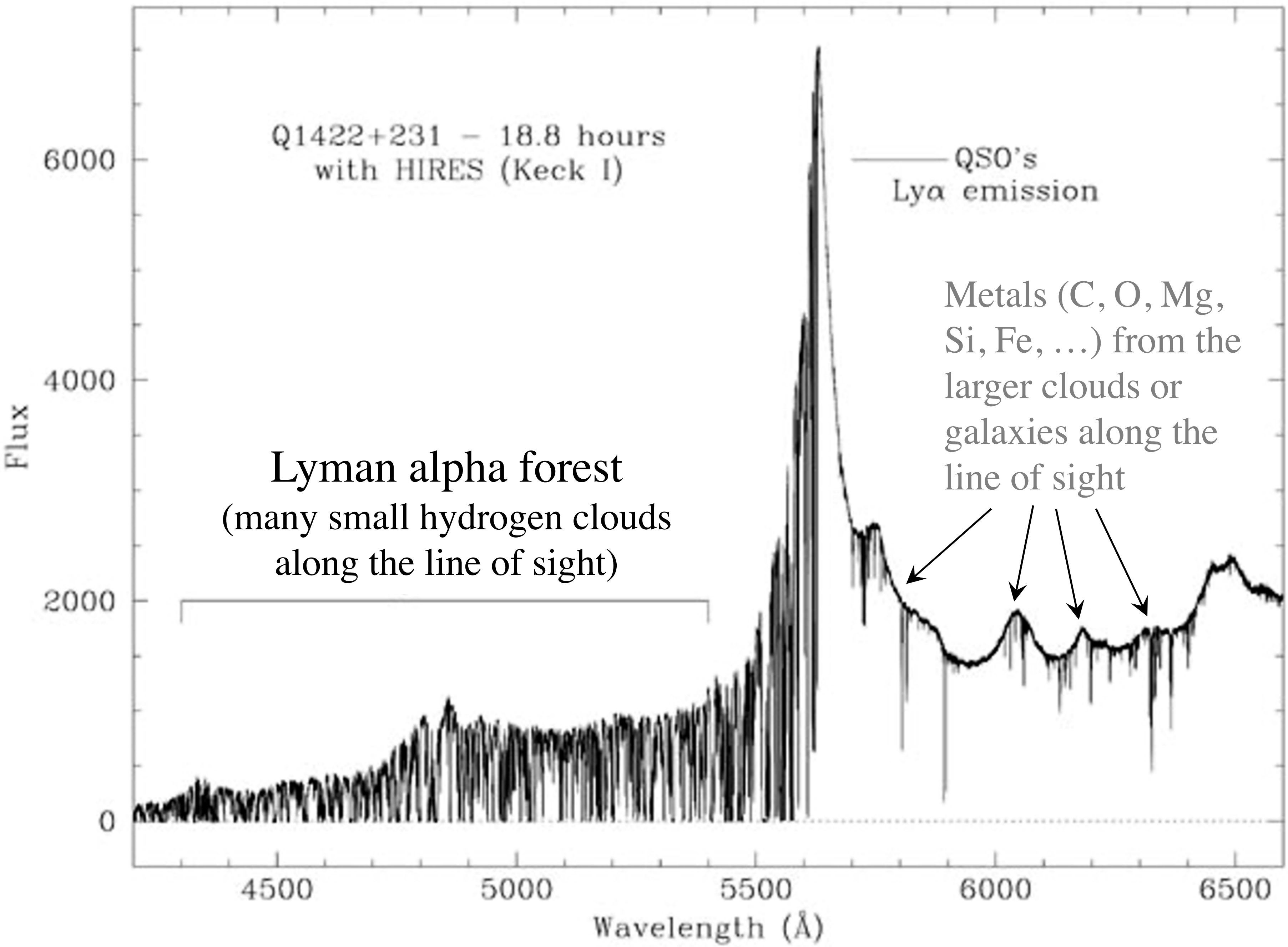
QSO Absorption Line Systems

- An alternative to searching for galaxies by their ***emission*** properties is to search for them by their ***absorption***
- Quasars are very luminous objects and have very blue colours which make them relatively easy to detect at high redshifts
- GRB are also used
- Note that this has ***different selection effects*** than the traditional imaging surveys: not by luminosity or surface brightness, but by the size and column density



Types of QSO Absorption Lines

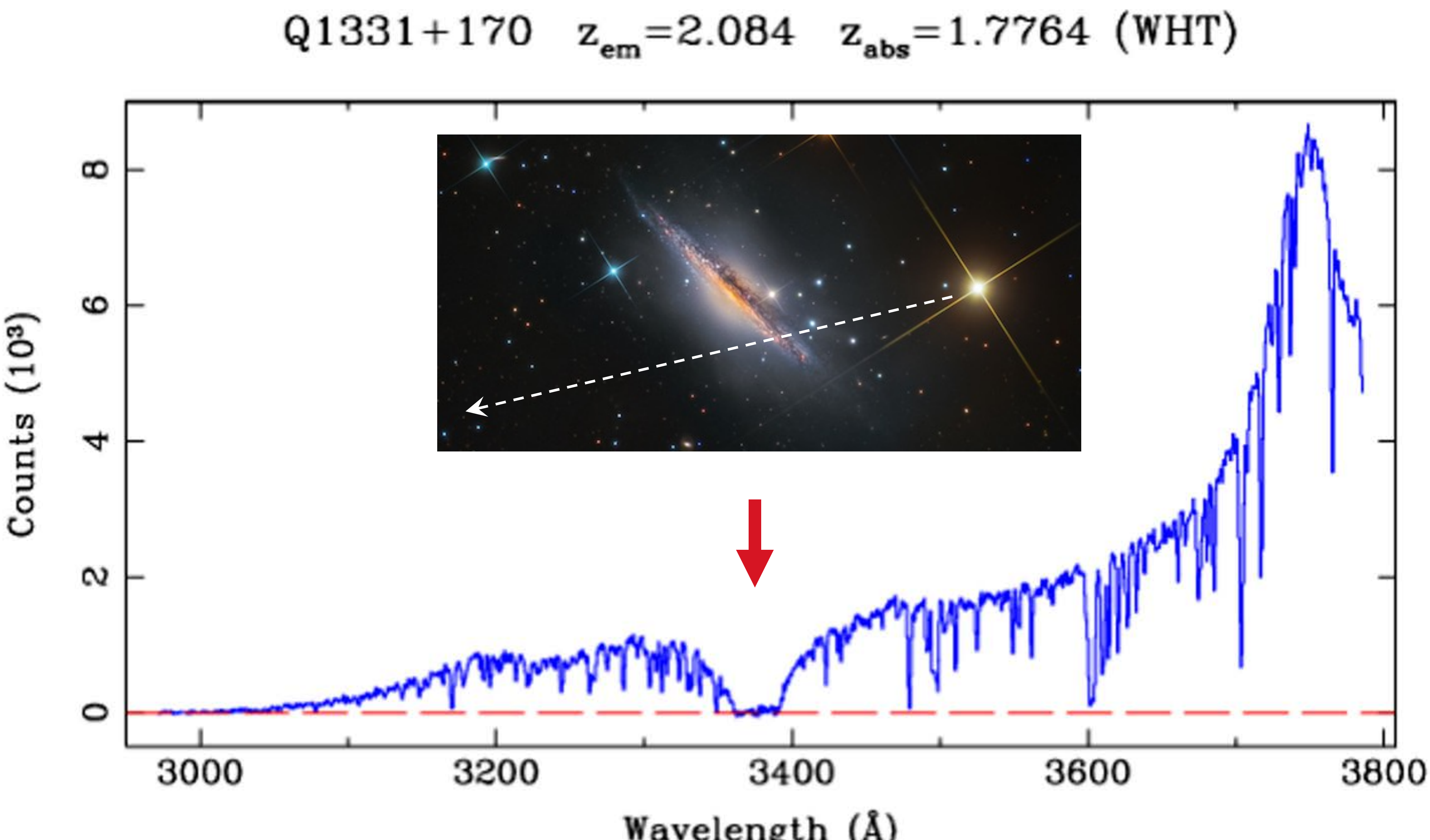
- **Lyman alpha forest:**
  - Numerous, weak lines from low-density hydrogen clouds
  - Proto-galactic clouds, with low density, they are not galaxies
- **Lyman Limit Systems** (LLS) **and "Damped" Lyman alpha** (DLA) absorption lines:
  - Rare, strong hydrogen absorption, high column densities
  - Coming from intervening galaxies
  - An intervening galaxies often produce both metal and damped Lyman alpha absorptions
- **Helium** equivalents are seen in the far UV part of the spectrum
- **"Metal" absorption lines**
  - Absorption lines from heavy elements, e.g., C, Si, Mg, Al, Fe
  - Most are from intervening galaxies



Q1422+231 – 18.8 hours
with HIRES (Keck I)
QSO's
Lyα emission
Metals (C, O, Mg, Si, Fe, …) from the larger clouds or galaxies along the line of sight
Lyman alpha forest
(many small hydrogen clouds along the line of sight)
Flux
6000
4000
2000
0
4500
5000
5500
6000
6500
Wavelength (Å)

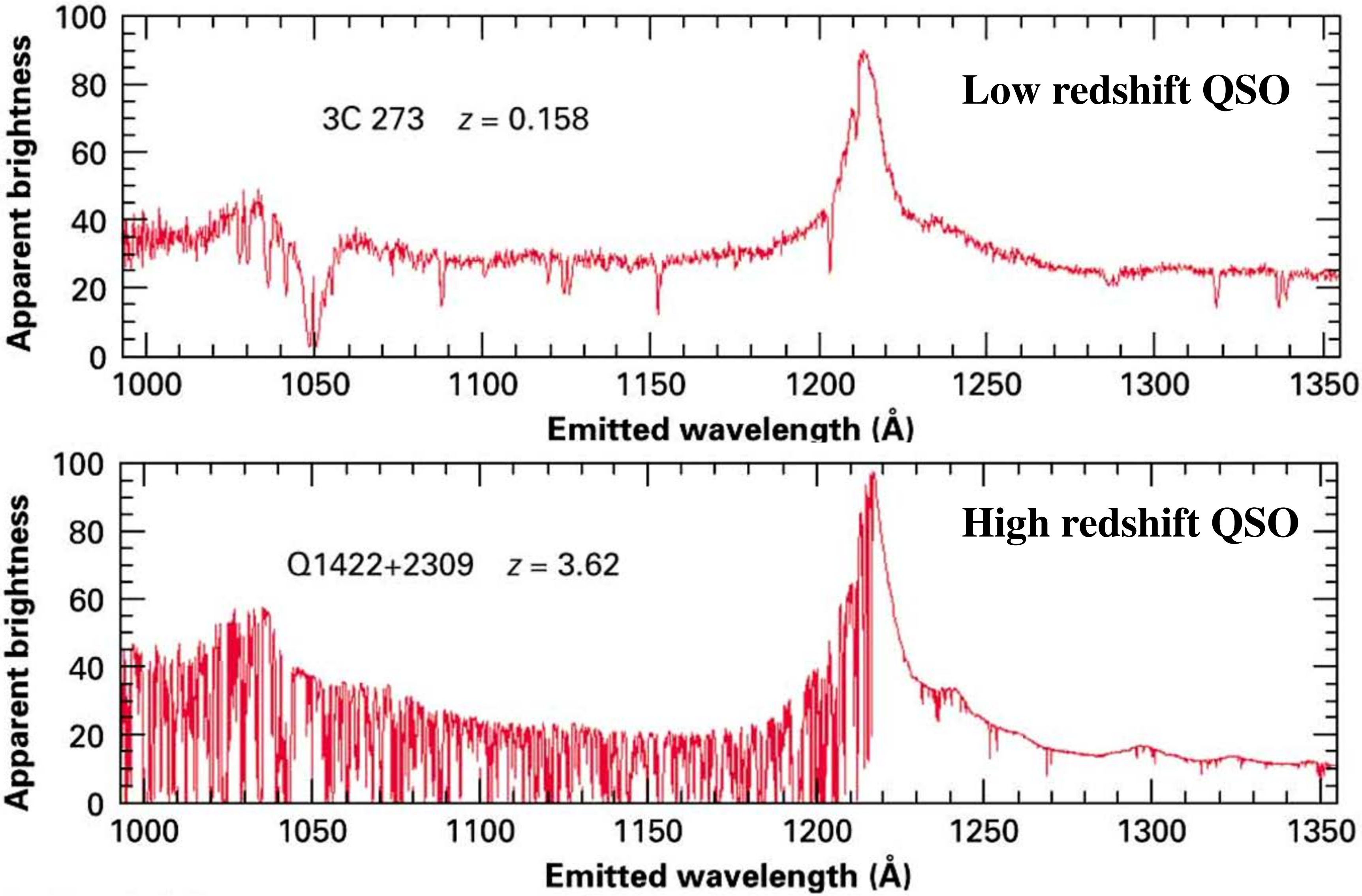
Damped Lyman α Systems

Saturated absorbers from distant galaxy disks



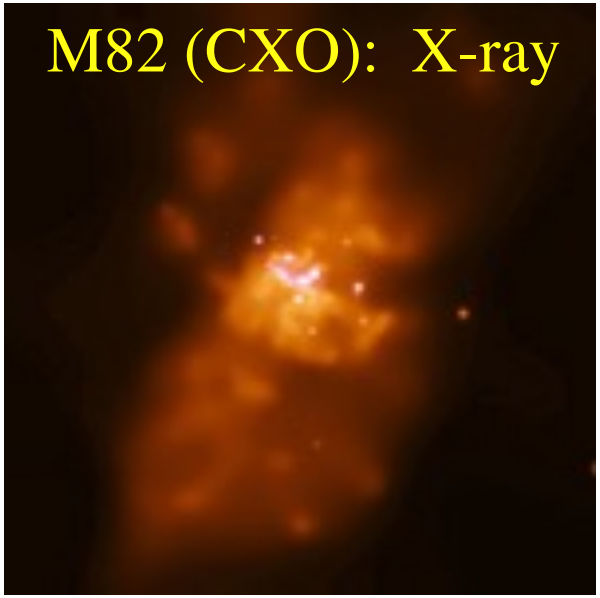
Evolution of the Hydrogen Absorbers

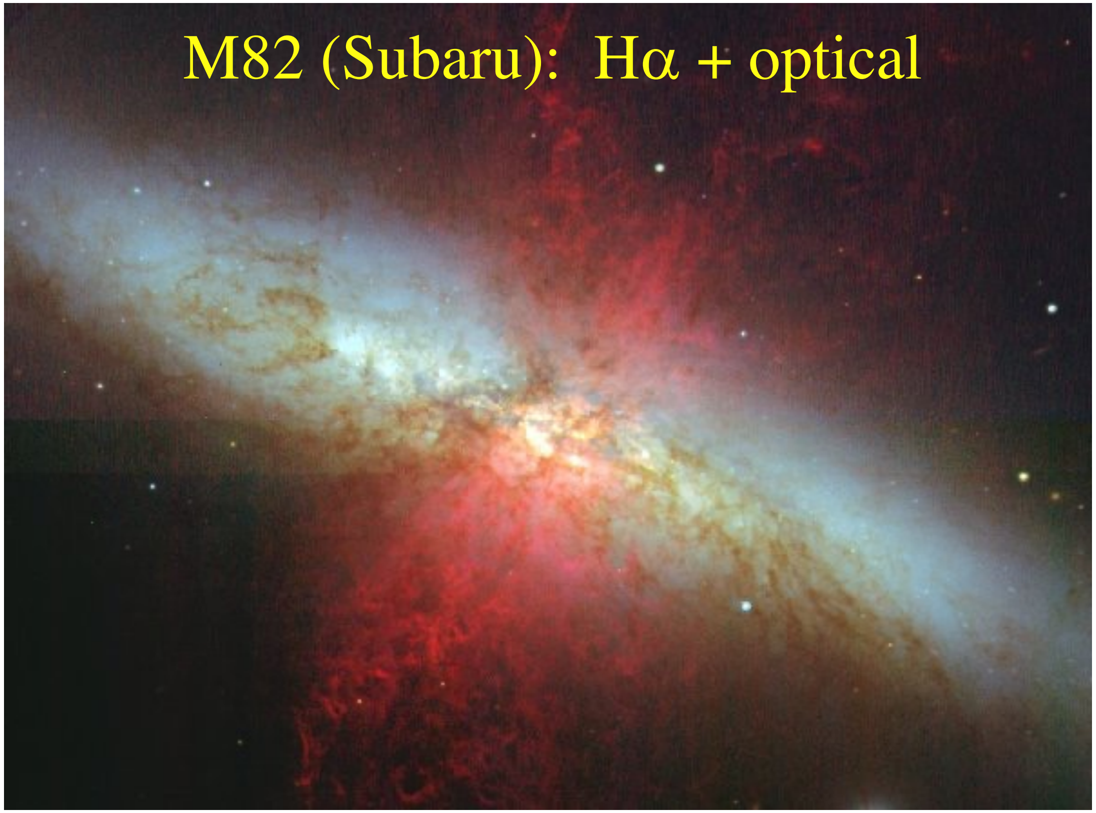
They were much more numerous far away (= early on)

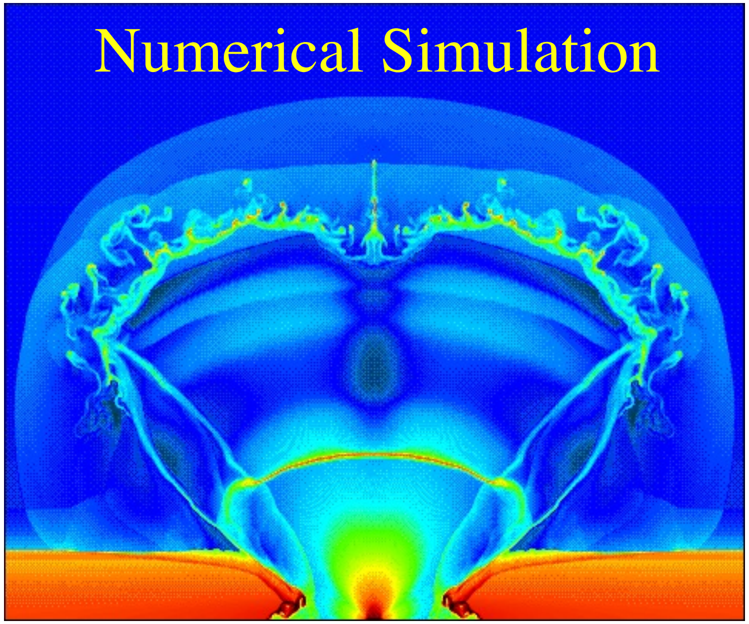


Galactic Winds

Starburst can drive winds of enriched gas (e.g., from supernova ejecta) out to the intergalactic medium. This gas can then be accreted again by galaxies. In a disk galaxy, the winds are generally bipolar outflows







Galaxy Formation

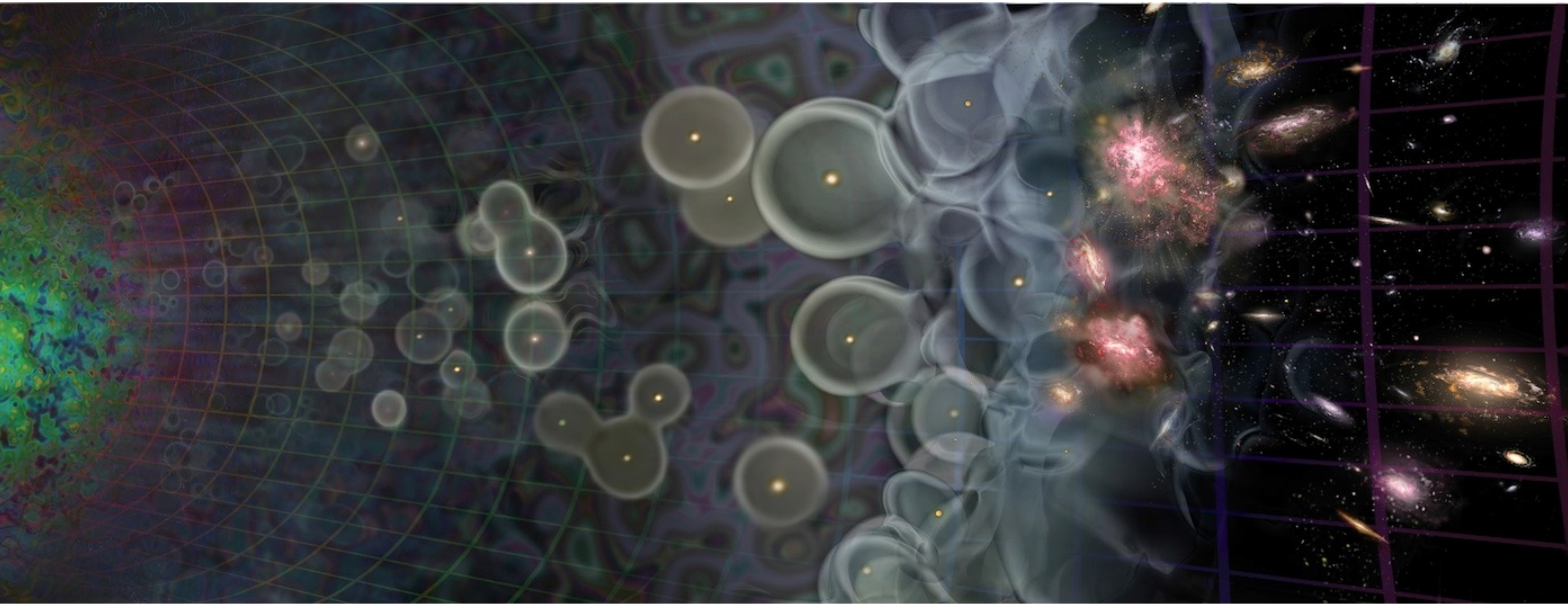
- The early stages of galaxy evolution - but there is no clear-cut boundary, and it also has two principal aspects: assembly of the mass, and conversion of gas into stars
- Must be related to large-scale (hierarchical) structure formation, plus the dissipative processes
- Probably closely related to the formation of the massive central black holes as well
- Generally, we think of massive galaxy formation at high redshifts ($z \sim 3 - 10$, say); dwarfs may be still forming now
- Observations have found populations of what must be young galaxies (ages < 1 Gyr), ostensibly progenitors of large galaxies today, at $z \sim 5 - 7$
- The frontier is now at $z \sim 7 - 20$, the so-called Reionization Era

A General Outline

- The smallest scale density fluctuations keep collapsing, with baryons falling into the potential wells dominated by the dark matter, achieving high densties through cooling
  - This process starts right after the recombination at $z \sim 1100$
- Once the gas densities are high enough, star formation ignites
  - This probably happens around $z \sim 20$ - 30
  - By $z \sim 6$, UV radiation from young galaxies reionizes the unverse
- These protogalactic fragments keep merging, forming larger objects in a hierarchical fashion ever since then
- Star formation enriches the gas, and some of it is expelled in the intergalactic medium, while more gas keeps falling in
- If a central massive black hole forms, the energy release from it can also create a considerable feedback on the young host galaxy

An Outline of the Early Cosmic History

(illustration from Avi Loeb)



Recombination: Release of the CMBR

Dark Ages: Collapse of Density Fluctuations

Reionization Era: The Cosmic Renaissance

Galaxy evolution begins

Energy Release From Forming Galaxies

- Release of the binding energy from a collapsing protogalaxy

  Typically ~ 10^{59} erg

- Thermonuclear burning in stars

  Typically ~ 10^{60} erg

- Release of the binding energy from the collapsing protostars

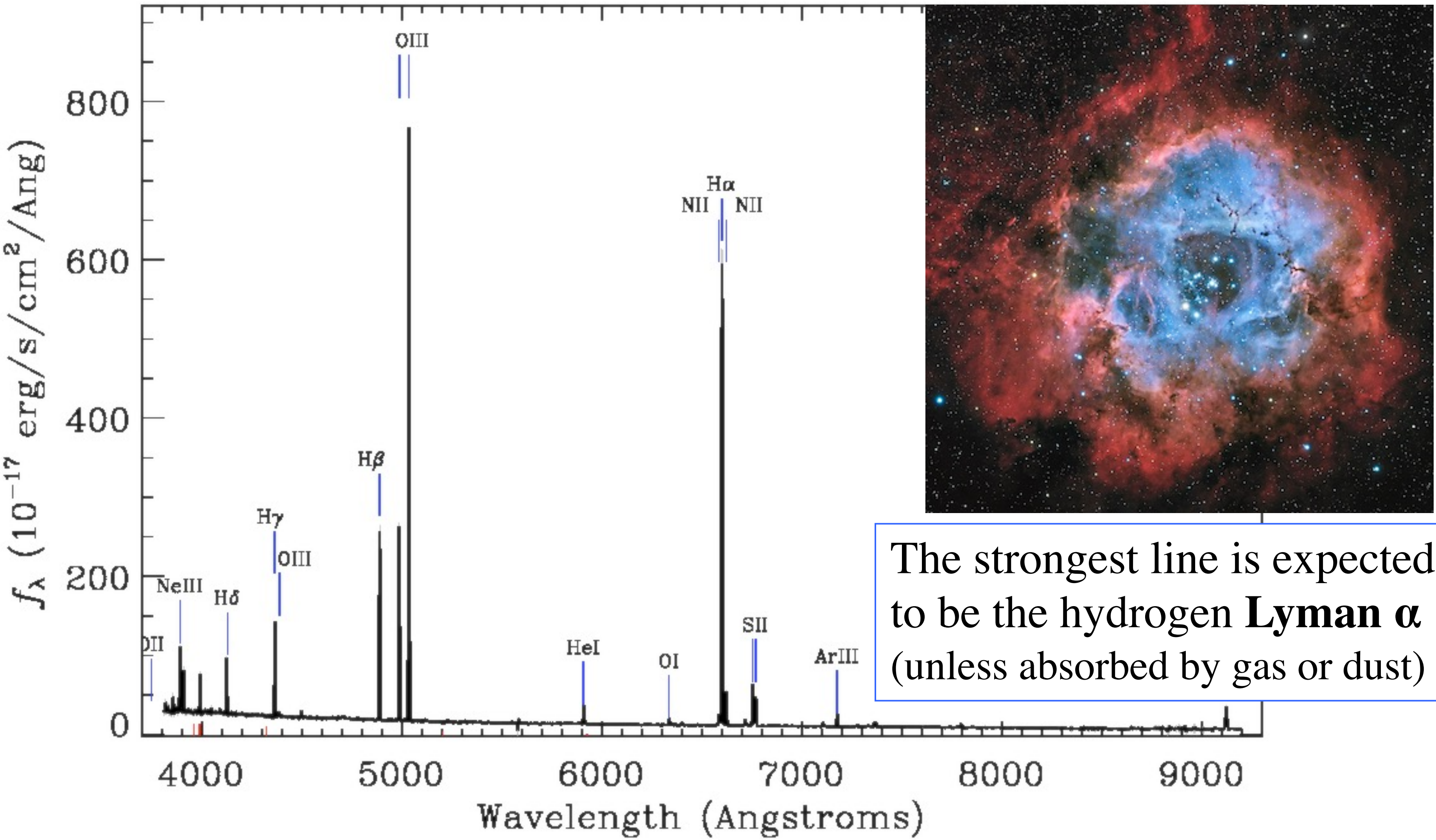
  Typically ~ 10^{59} erg

- Energy input from an active nucleus, if present

  Up to ~ 10^{60} erg

Emission Line Search for Young Galaxies

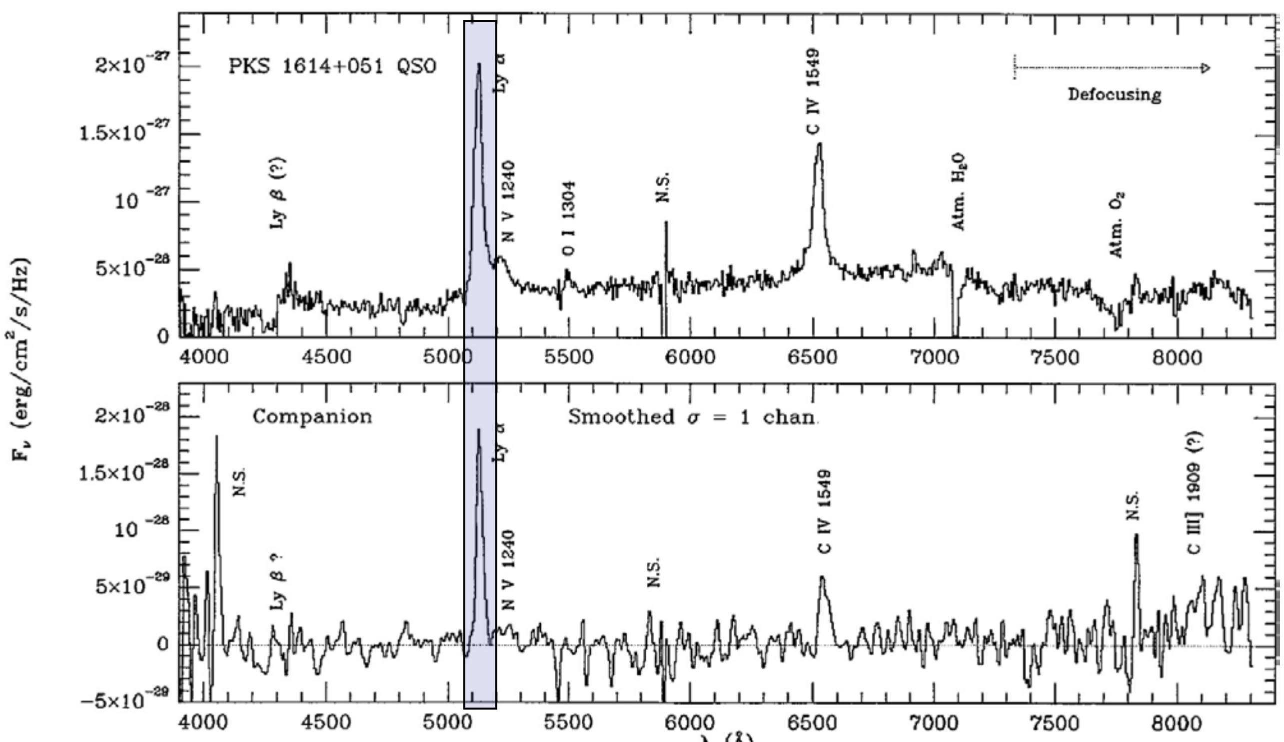
Spectra of star forming regions have strong recombination lines of hydrogen and various ions, e.g., Hα**,** [O III], etc.

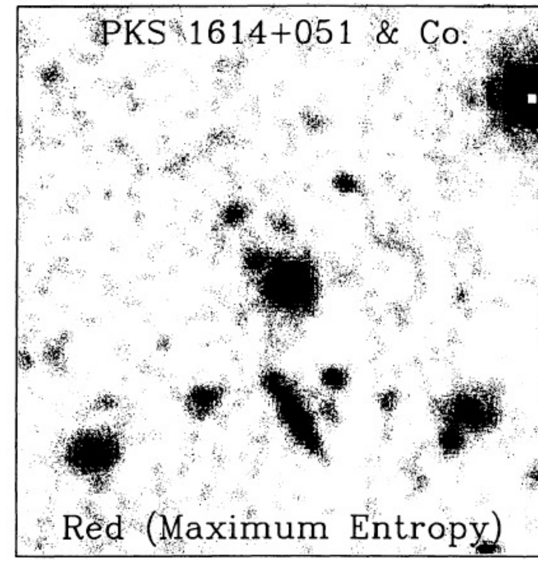


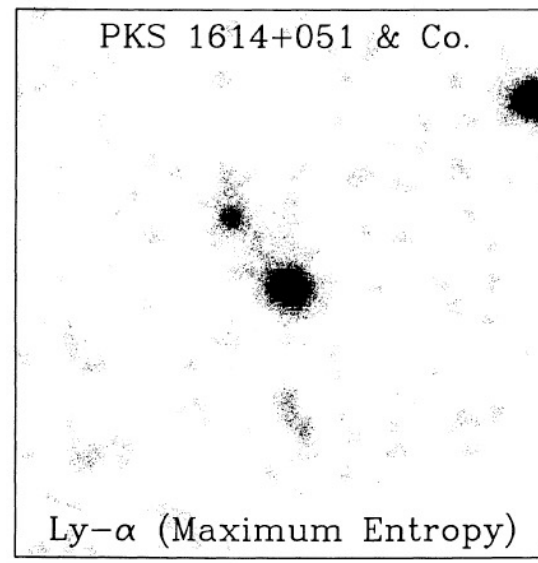
The strongest line is expected to be the hydrogen **Lyman α** (unless absorbed by gas or dust)

Narrow-Band Imaging

A greatly increased contrast for an object with a strong line emission

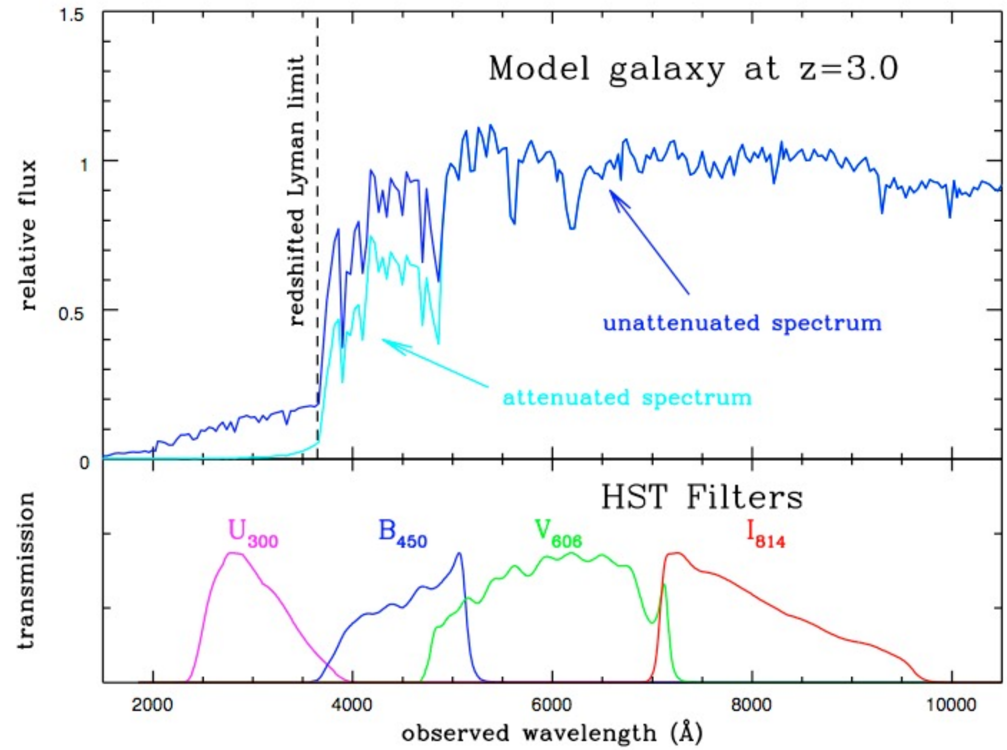


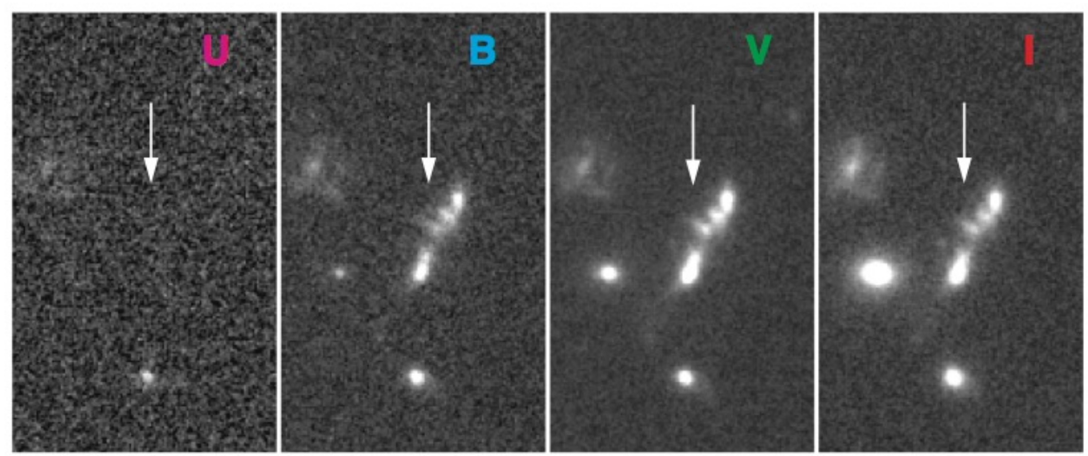




The Lyman-Break Method

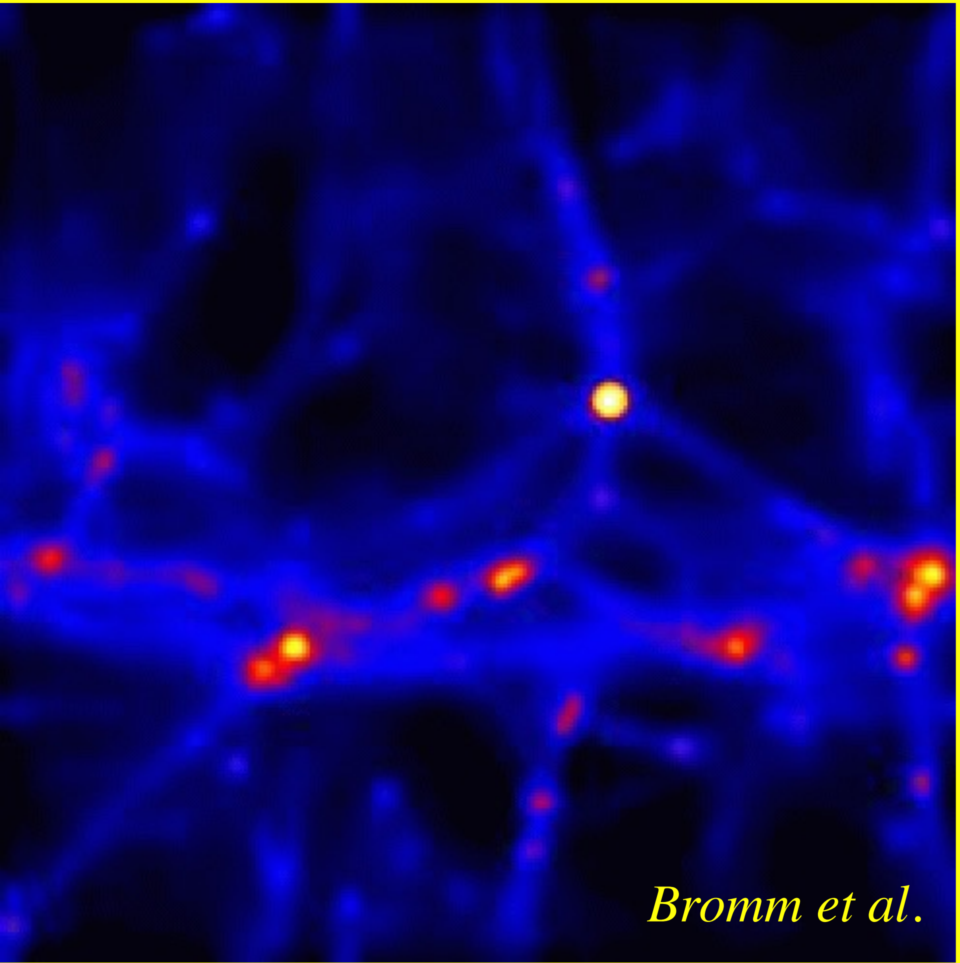
Absorption by the interstellar and intergalactic hydrogen of the UV flux blueward of the Ly alpha line, and especially the Lyman limit, creates a continuum break which is easily detectable by multicolor imaging

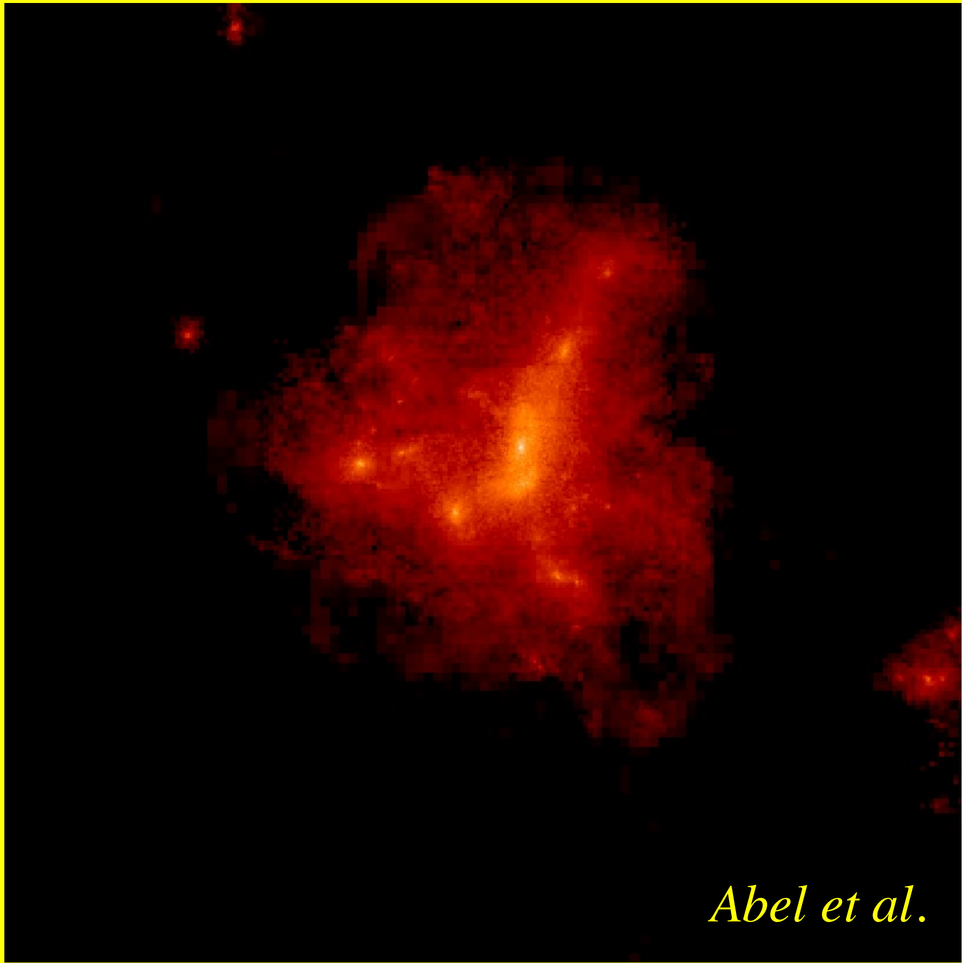




The First Stars

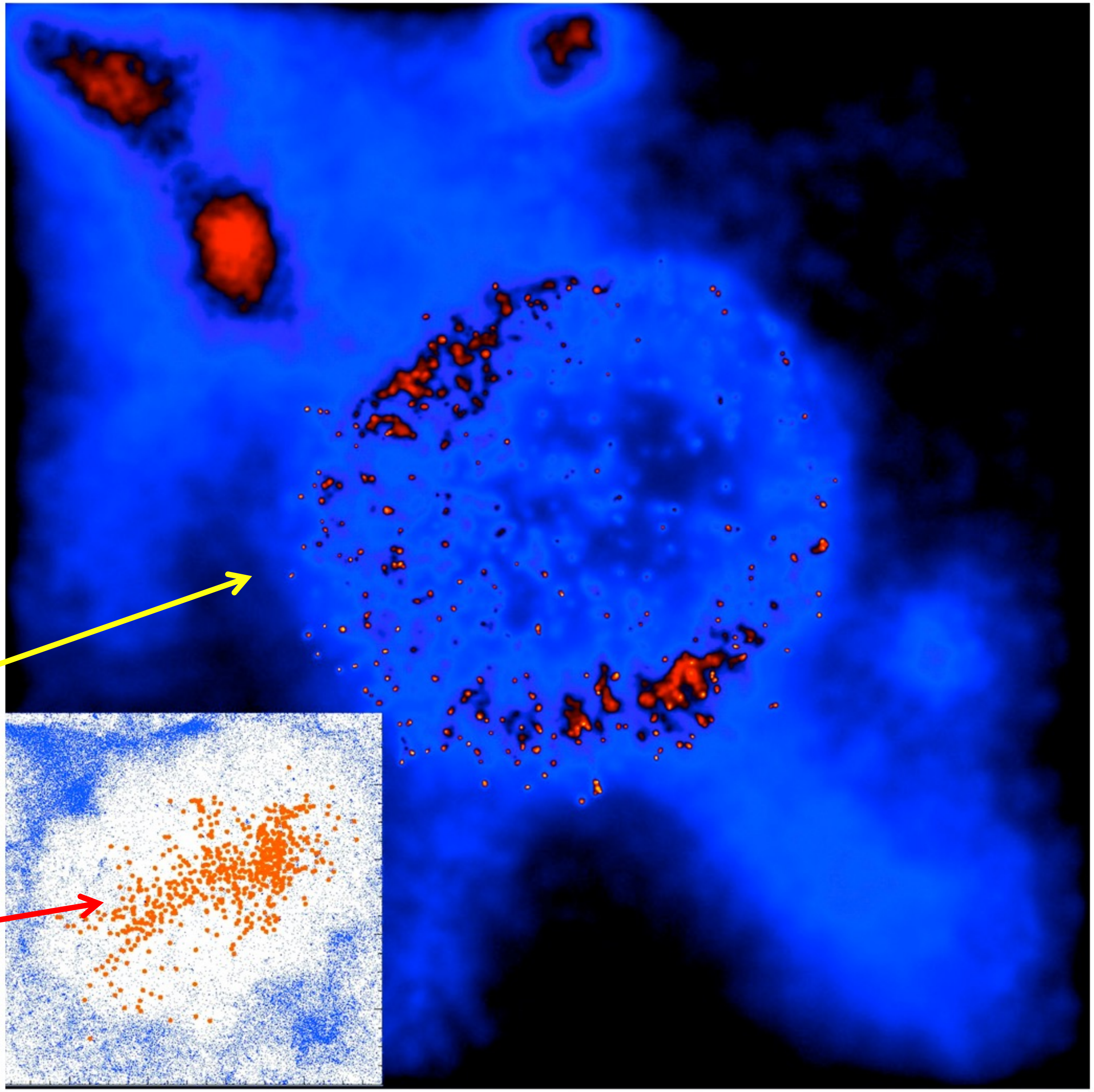
Gas infall into the potential wells of the dark matter fluctuations leads to increased density, formation of H_2, molecular line cooling, further condensation and cloud fragmentation, leading to the formation of the **first stars**





Population III Supernovae

- Early enrichment of the protogalactic gas
- Transition to the "normal" Pop II star formation and IMF when the metallicity reaches a critical value $Z_{crit} \sim 10^{-3.5} Z_{\odot}$



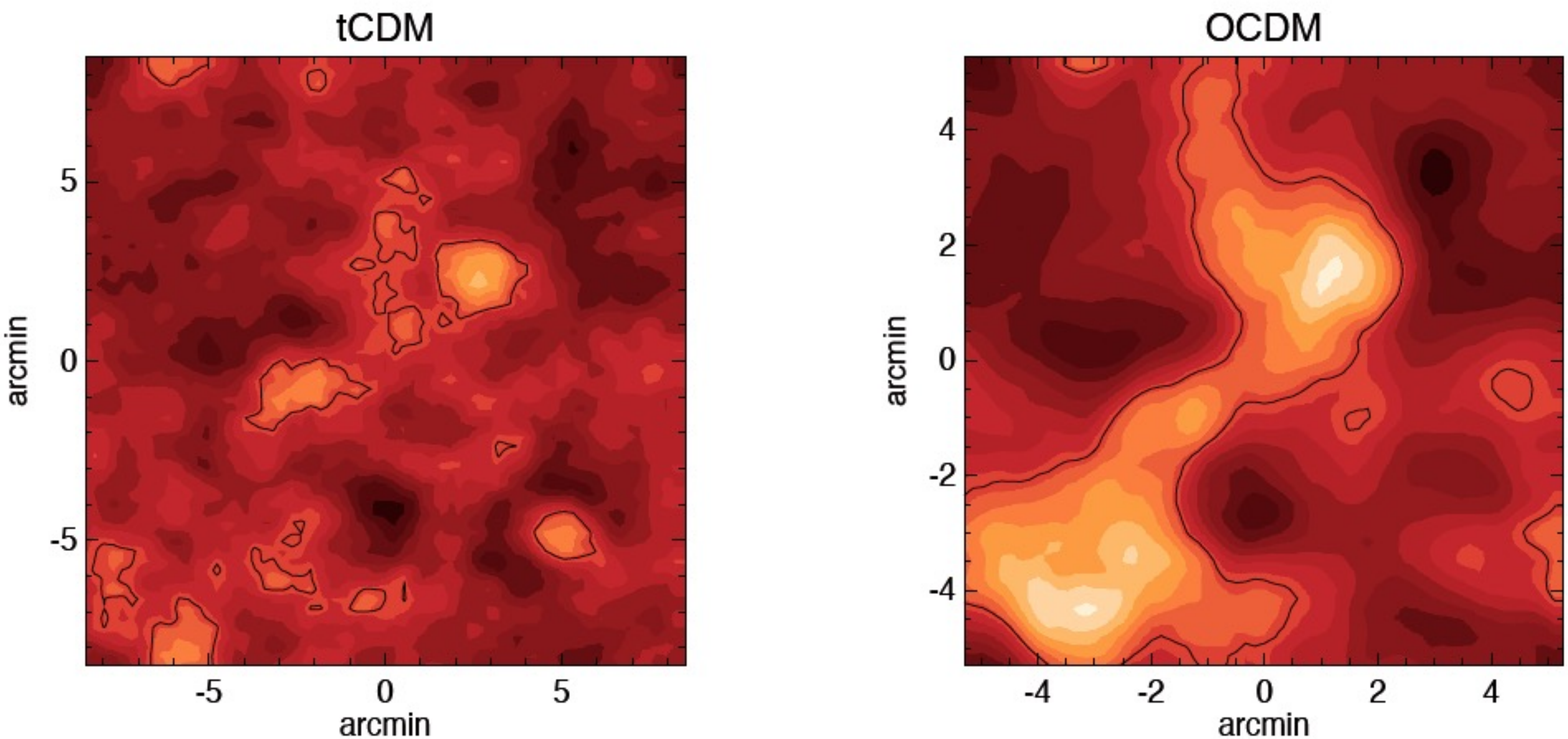
Simulated Pop III SN shell after $\sim 10^6$ yr

Distrib. of metals (red)

(from Bromm et al. 2003)

Looking Even Deeper: The 21cm Line

We can in principle image H I condensations in the still neutral, pre-reionization universe using the 21cm line. Several experiments are now being constructed or planned to do this, e.g., the Mileura Wide-Field Array in Australia, or the Square Kilometer Array (SKA)



(Simulations of z = 8.5 H I, from P. Madau)