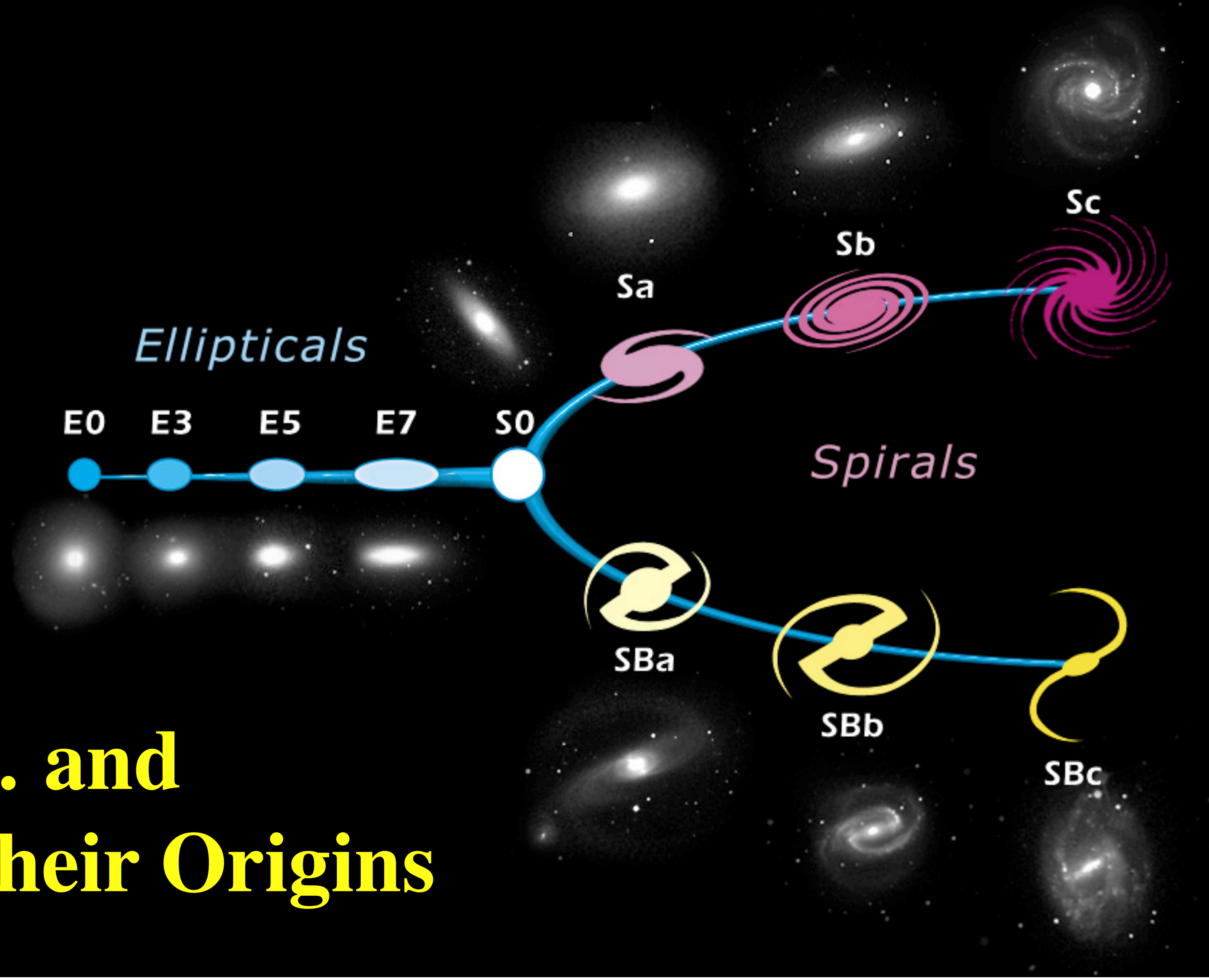
Trends Along the Hubble Sequence…

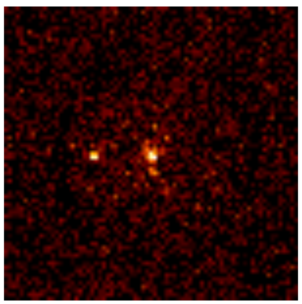


… and Their Origins

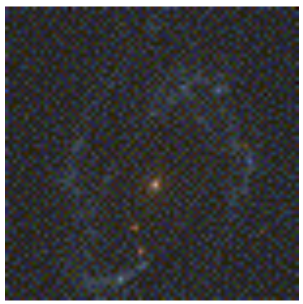
Problems With Traditional Galaxy Classification

Appearance of galaxies is strongly dependent on **which wavelength** the observations are made in.

e.g., the nearby galaxy M81:



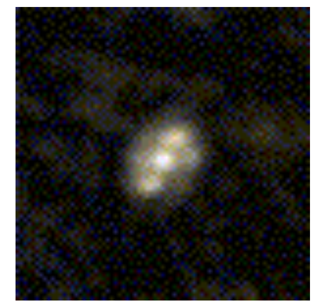
X-ray



UV

Visible

Near-IR



Far-IR

Note: large change in appearance between the UV and the near infrared images.

Galaxies look "clumpier" in the UV, and increasingly smooth as we go to the visible and longer wavelengths.

Problems With Traditional Galaxy Classification

Subjective - *especially for spiral galaxies*

However, there are automated, objective schemes to classify galaxies, using measured image parameters.

Superficial - *based on appearance, not physical properties*

Galaxy types or families can be defined in a parameter space of various measured/physical quantities. Different galaxy families follow different correlations.

Incomplete - *misses the major dichotomy of dwarfs and giants*
(not separated in the traditional Hubble sequence)

Dwarfs also exist in gas rich / gas poor, star forming or not, and perhaps other varieties

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

  … and that spiral arms may be mainly ornamental …
- Nevertheless, there are some important and meaningful trends along the Hubble sequence

Variation of Galaxy Properties Along the Hubble Sequence

	E	S0	Sa	Sb	Sc	Sd	Irr
Color	Red	→					Blue
Stellar Pop.	Old	Old + Intermediate		Old + Intermediate + Young		Intermediate + Young	
SFR	zero	low →		higher →			high
HI (gas)	Zero/ low	low →		modest →		high	highest
dust	Zero/ low	Higher		highest			Lower (less metals)
Dyn.	Bulge/halo dom.		Disk dominated, so rotation				

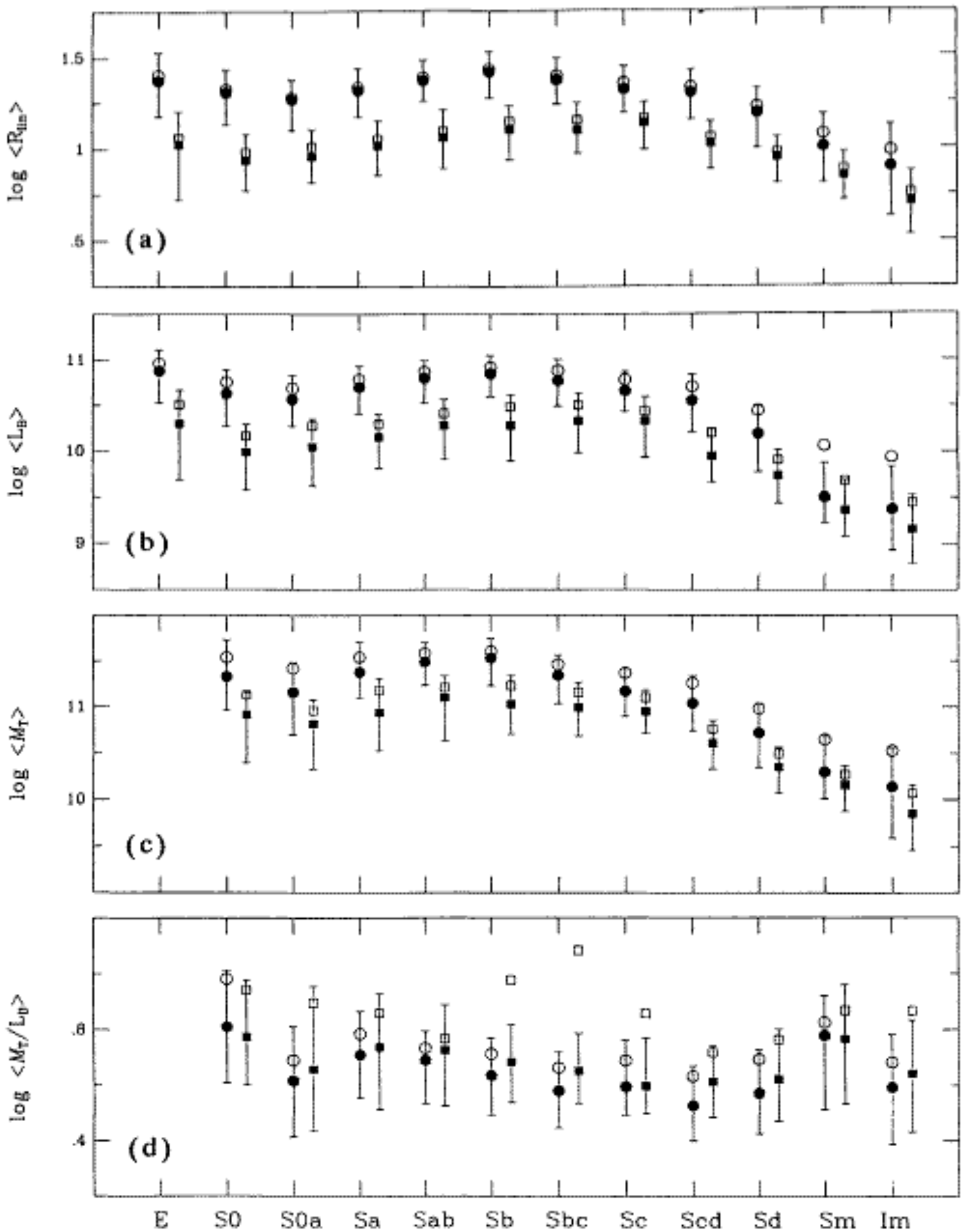
Galaxy Properties and the Hubble Sequence

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.



Radius

Luminosity

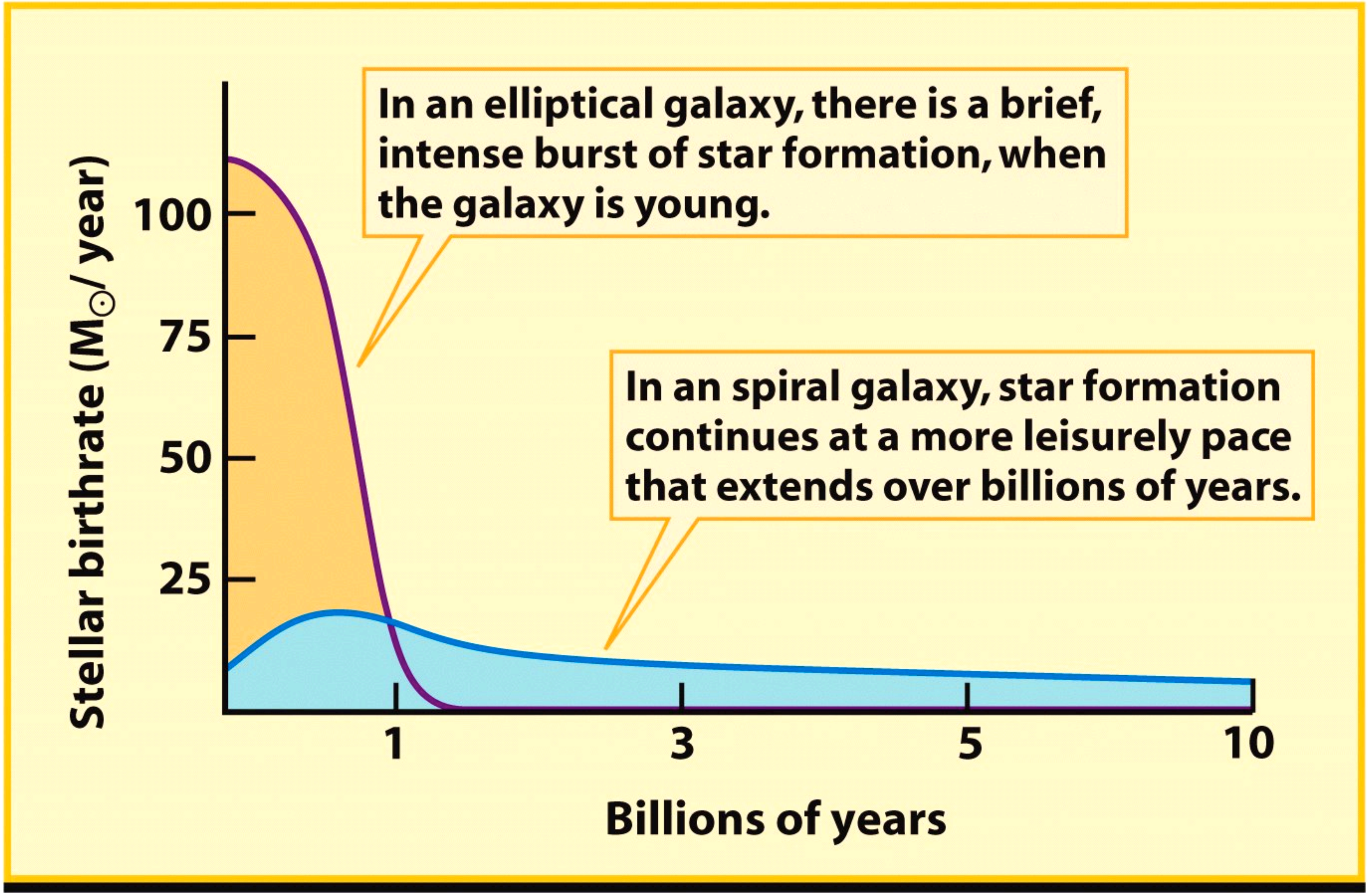
Mass

(M/L)

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 x $10^9 M_\odot$ of HI mass in a typical spiral
    - How long can spirals keep forming stars?? It seems that some gas infall/resupply is needed

Star Formation History in Galaxies



The stellar birthrate in galaxies

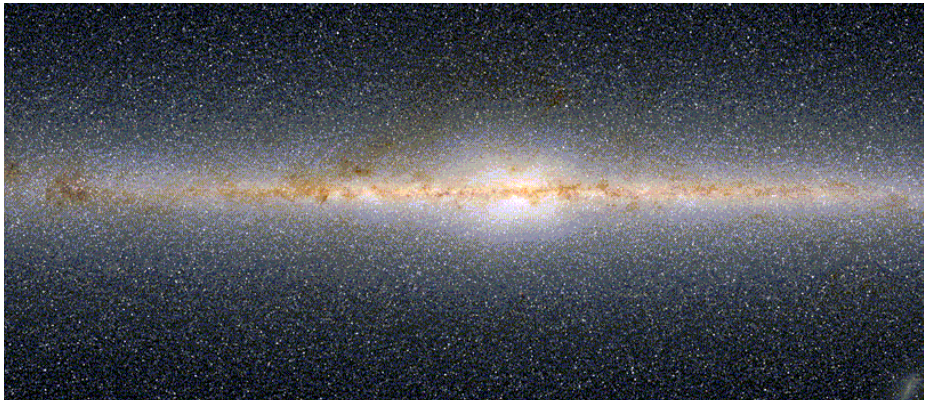
Stellar Populations

- A key concept in our understanding of galaxies
- In 1944, Walter Baade used the 100-inch Mt. Wilson telescope to resolve the stars in several nearby galaxies: M31, its companions M32 and NGC 205, as well as the elliptical galaxies NGC 147 and NGC 145
- Realized the stellar populations of spiral and elliptical galaxies were distinct:
  - **Population I:** objects closely associated with spiral arms – luminous, young hot stars (O and B), Cepheid variables, dust lanes, HII regions, open clusters, metal-rich
  - **Population II:** objects found in spheroidal components of galaxies (bulge of spiral galaxies, ellipticals) – older, redder stars (red giants), metal-poor

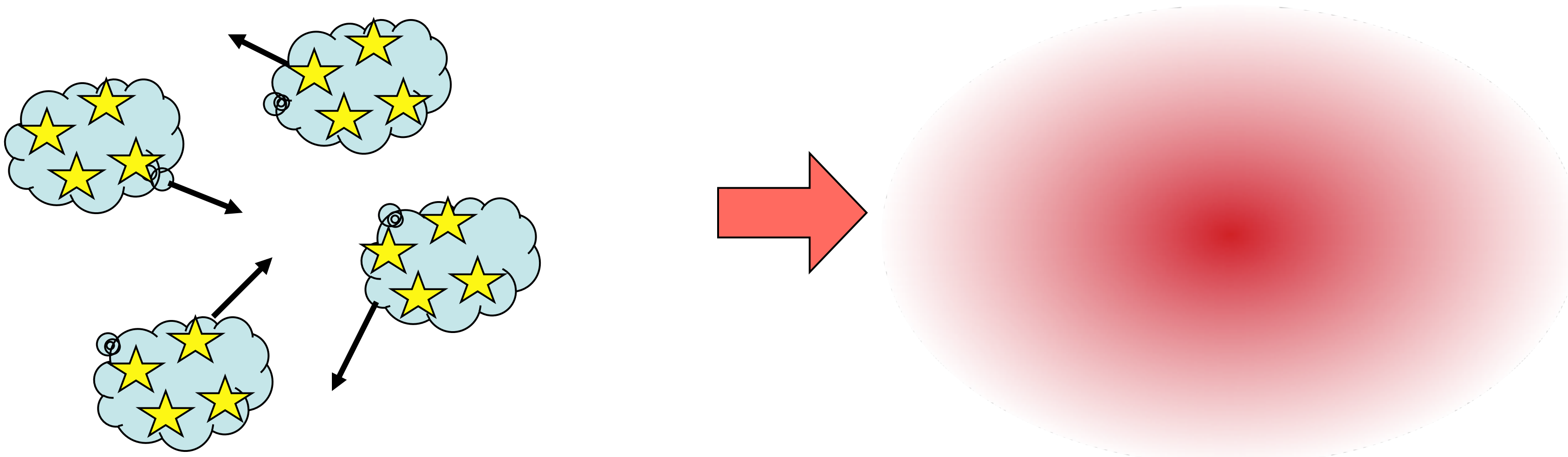
Stellar Populations and Dynamical Subsystems in Galaxies

- The picture today is more complex: it is useful to thing about generalized stellar populations as subsystems within galaxies, characterized by the:
  - Location and morphology, density distribution
  - Dynamics (rotation, random motions, their distribution)
  - Star formation rate and mean age
  - The presence and nature of its interstellar medium

  etc., etc.
- For example, in the Milky Way, we can distinguish:
  - Young thin disk
  - Old thick disk
  - Metal-rich bulge (and bar?)
  - Metal-poor stellar halo

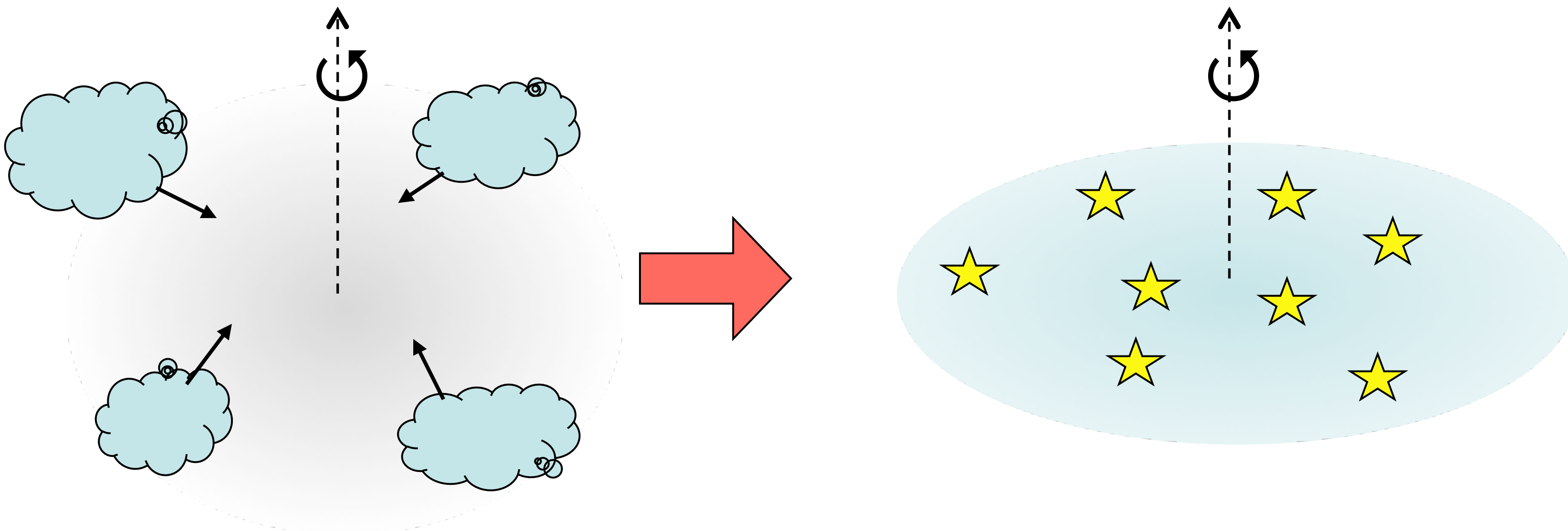


Formation of Galaxy Spheroids and Dynamics of Stellar Populations



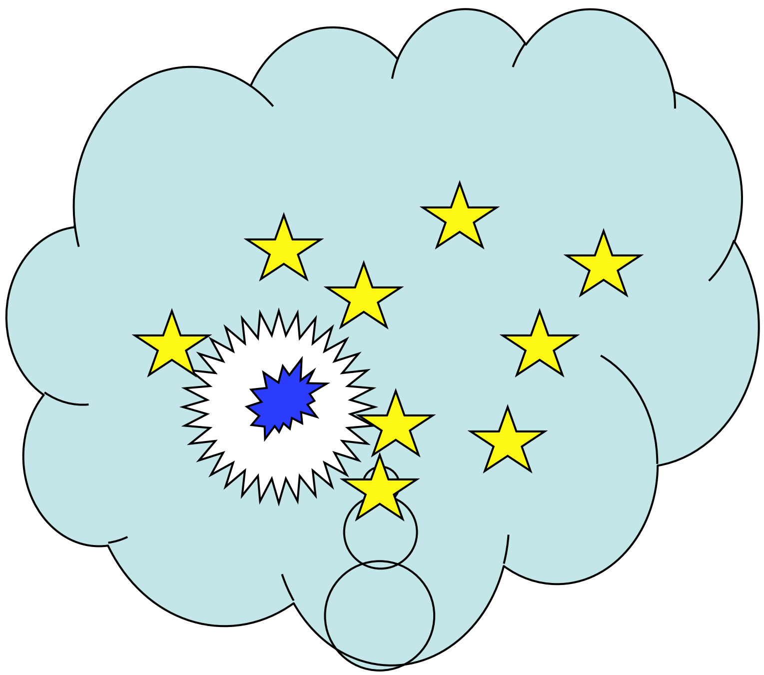
Stars "remember" the dynamics of their orbits at the time of formation, since dynamics of stellar systems is dissipationless. If stars form in dwarf protogalactic fragments which then merge, this will result in a pressure-supported system, *i.e.*, a spheroid (bulge or halo, or an elliptical galaxy).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

Formation of Galaxy Disks and Dynamics of Stellar Populations

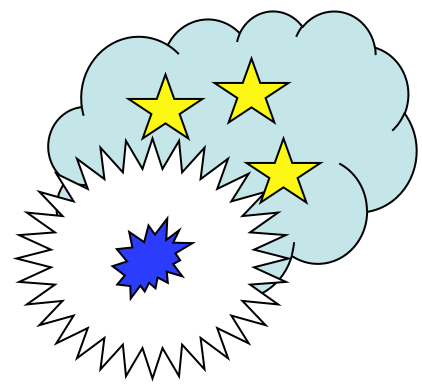


If protogalactic clouds merge dissipatively in a potential well of a dark halo, they will settle in a thin, rotating disk = the minimum energy configuration for a given angular momentum. If gas settles into a (dynamically cold) disk before stars form, then stars formed in that disk will inherit the motions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

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 → visible/near-IR, cold gas → radio, dust → far-IR, hot gas → 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!


Next:
Spiral Galaxies: Photometric Properties