# Galaxy Evolution

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*NCTS-TCA Summer Student Program 2023*

*Slides from George Djorgovski*

# Outline

1. **Background Universe**
   history, cosmology, cosmic inventory
2. **The many kinds of Galaxies**
   morphology, scaling relation, observational probes
3. **Galaxy evolution & first galaxies**
   star-formation and assembly history, JWST and EoR

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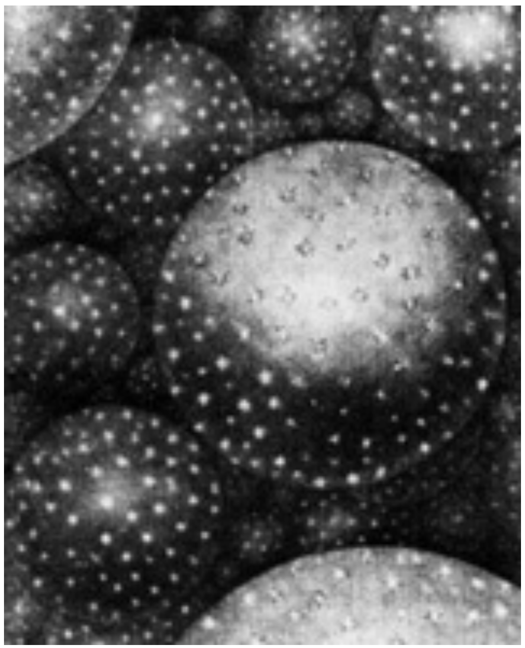
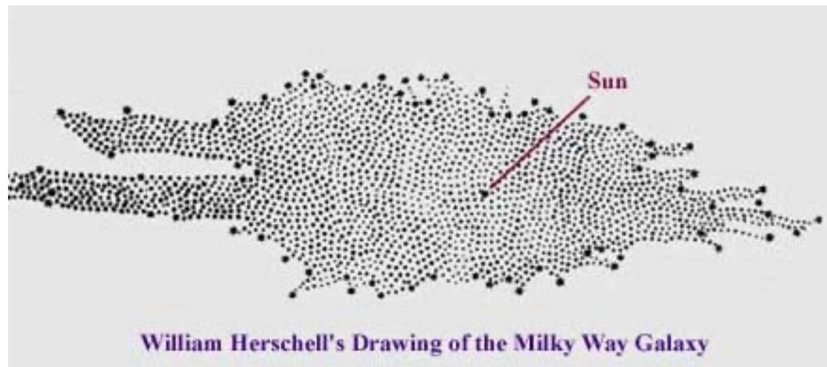
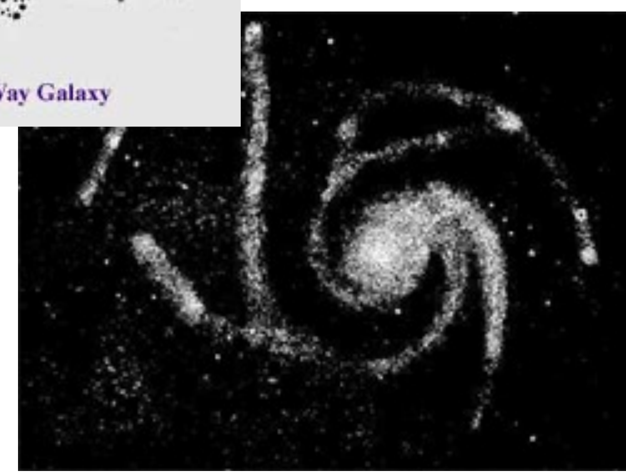
# The Discovery of Galaxies

**18th Century:**

- The first catalogs of "nebulae": Charles Messier, William Herschel
- The pioneers of "island universes": Thomas Wright, Immanuel Kant





**19th and Early 20th Centuries:**

- More catalogs, first spectra, but no physical understanding

# The Shapley-Curtis Debate
## on the nature of faint nebulae (= galaxies)

At the meeting of the National Academy of Sciences in Washington on 26 April 1920, Harlow Shapley of Mount Wilson and Heber D. Curtis of Lick Observatory gave talks under the title "The Scale of the Universe"

☚ Shapley argued that the nebulae are parts of our own Galaxy, the only one

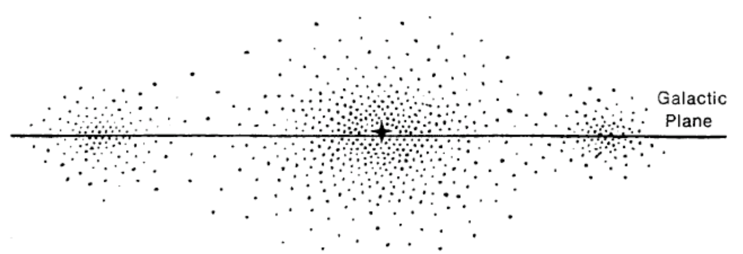


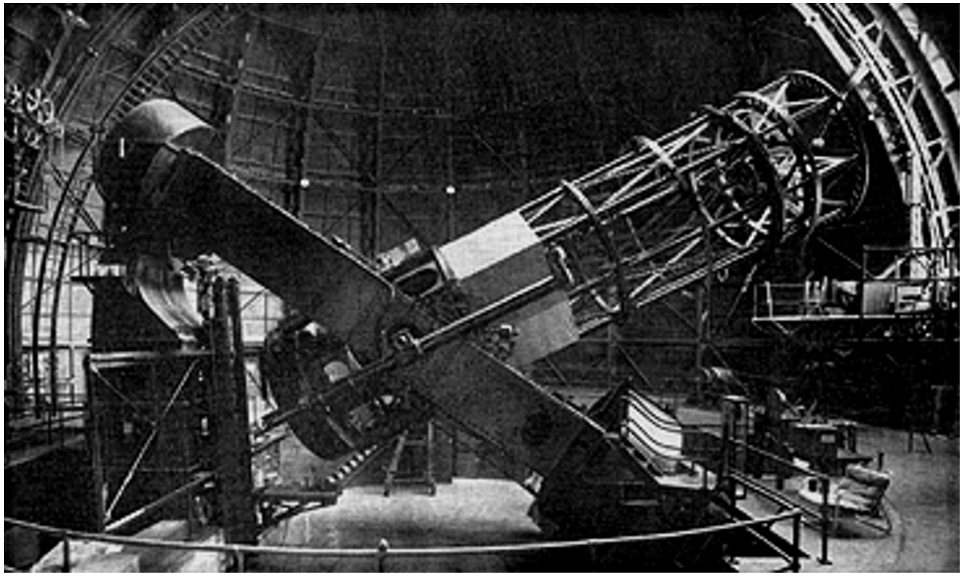

FIG. 3—Arthur Eddington's (1912) galaxy placed the Sun's position 60 LY above the center of the galactic plane.

Curtis ☛
thought that these are other galaxies, just like ours

# The Resolution: Nebulae are Extragalactic

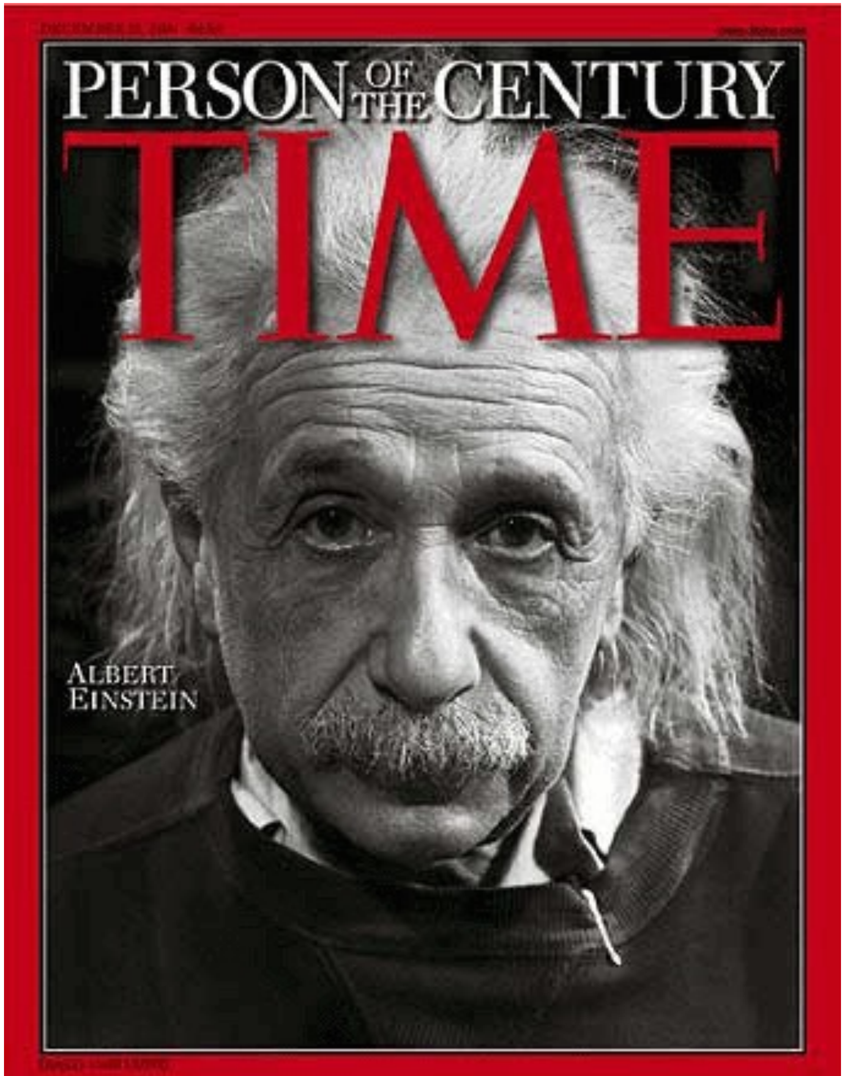
- In 1923 Hubble resolved Cepheids in M31 (Andromeda)
- A profound shift in the understanding of the scale of the universe

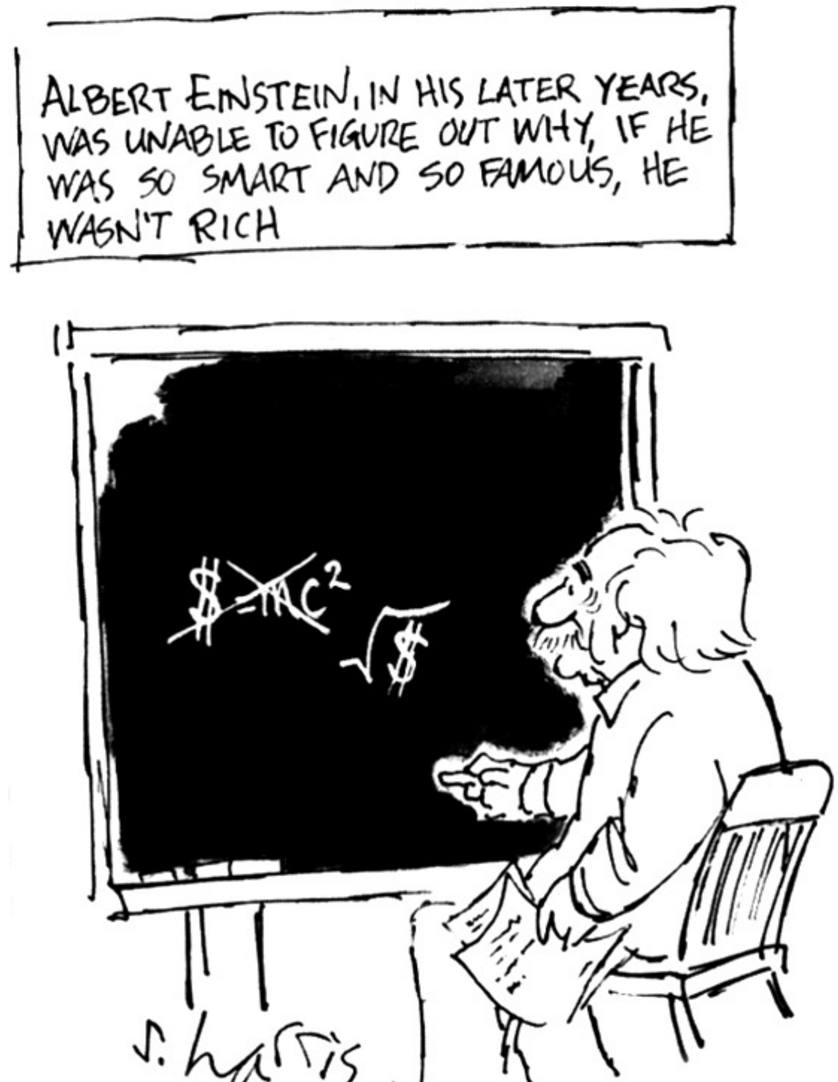

Edwin Hubble



The Mt. Wilson 100-inch

# Theoretical Basis of Modern Cosmology: The General Theory of Relativity (1915)

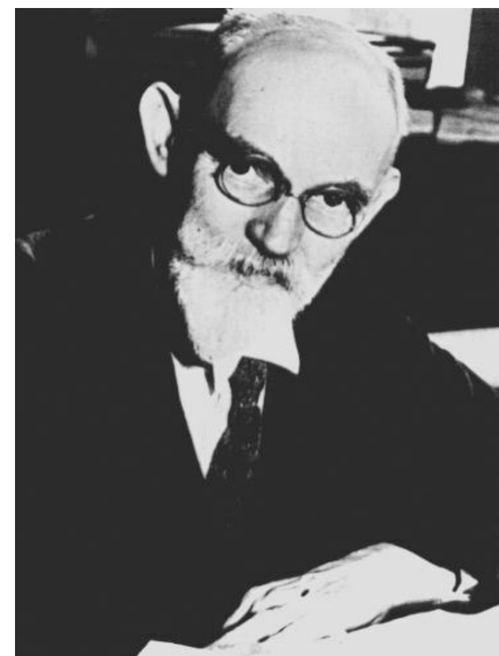


# The Early Cosmological Models

**Einstein** in 1917 constructed the first relativistic cosmological models. Thinking that the universe is static, he introduced the cosmological constant term to balance the force of gravity. This model was unstable, and he failed to predict the expansion of the universe, later calling this the biggest mistake of his career.

**Willem De Sitter** in 1917 also developed a similar model, but also obtained solutions of Einstein equations for a nearly empty, ***expanding*** universe.



In 1932, Einstein & De Sitter jointly developed another, simple cosmological model which bears their names.

# Discovery of the Expanding Universe

Vesto Melvin Slipher (1917)

Knut Lundmark (1924)

And also Carl Wirtz (1923)

TABLE I.

RADIAL VELOCITIES OF TWENTY-FIVE SPIRAL NEBULÆ.

| Nebula. | Vel. | Nebula. | Vel. |
|---|---|---|---|
| N.G.C. 221 | − 300 km. | N.G.C. 4526 | + 580 km. |
| 224 | − 300 | 4565 | +1100 |
| 598 | − 260 | 4594 | +1100 |
| 1023 | + 300 | 4649 | +1090 |
| 1068 | +1100 | 4736 | + 290 |
| 2683 | + 400 | 4826 | + 150 |
| 3031 | − 30 | 5005 | + 900 |
| 3115 | + 600 | 5055 | + 450 |
| 3379 | + 780 | 5194 | + 270 |
| 3521 | + 730 | 5236 | + 500 |
| 3623 | + 800 | 5866 | + 650 |
| 3627 | + 650 | 7331 | + 500 |
| 4258 | + 500 | | |

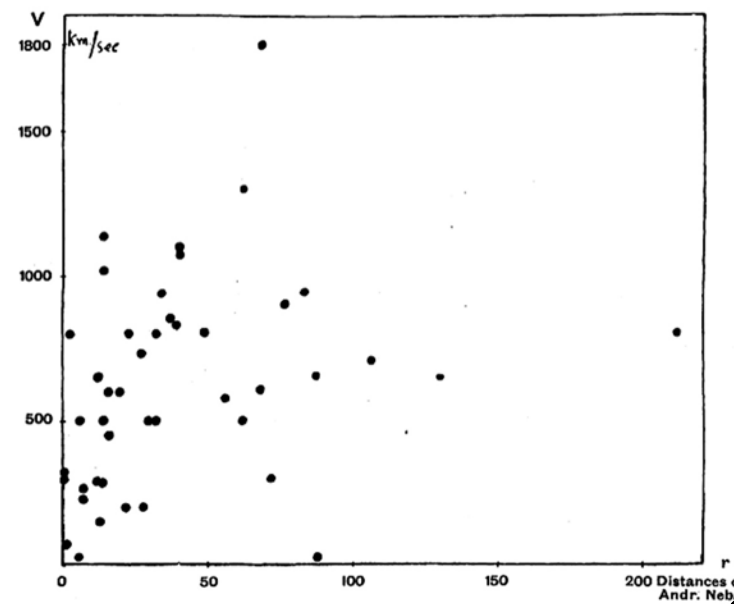



FIG. 5.—Relation between the relative distances (the unit is the distance of the Andromeda nebula) and the measured radial velocities of spiral nebulæ.

# Redshift as Doppler Shift

We define **doppler redshift** to be the shift in spectral lines due to motion:

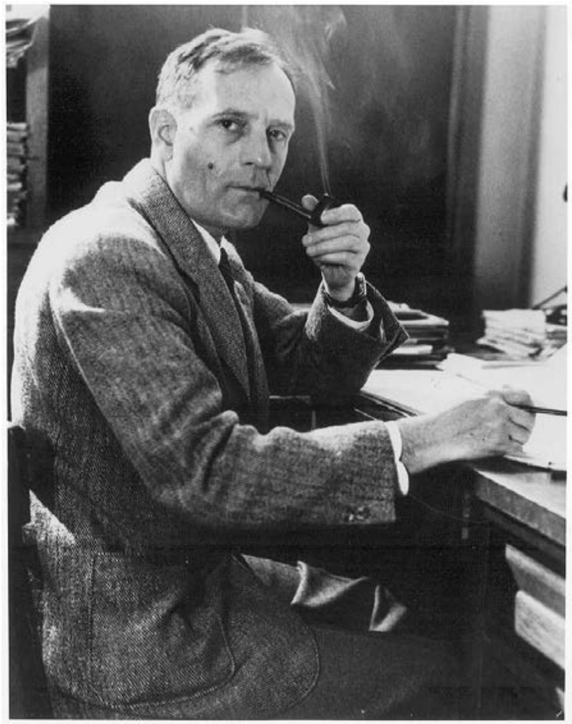
$$z = \frac{\Delta\lambda}{\lambda} = \sqrt{\frac{1 + v/c}{1 - v/c}} - 1$$

which, in the case of **v<<c** reduces to the familiar

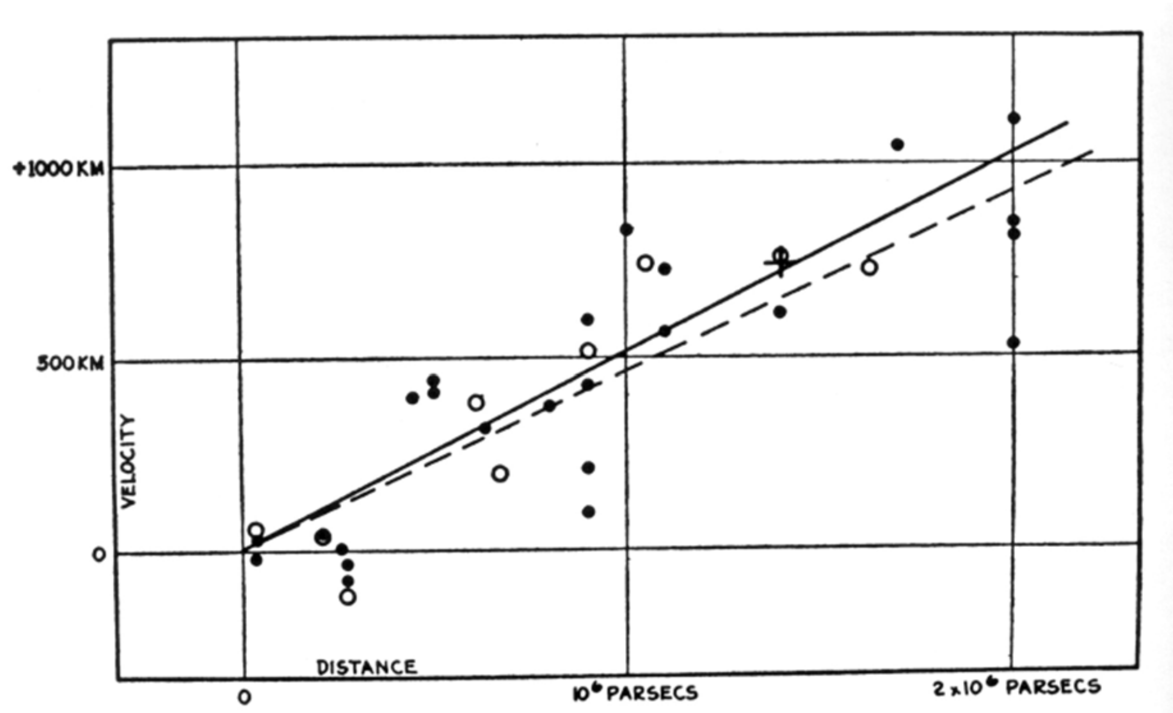
$$z = \frac{v}{c}$$

The **cosmological redshift** is something different, although we are often sloppy and refer to it in the same terms of the doppler redshift. The cosmological redshift is actually due to the **expansion of space** itself.

# Discovery of the Expanding Universe



Edwin Hubble (1929)

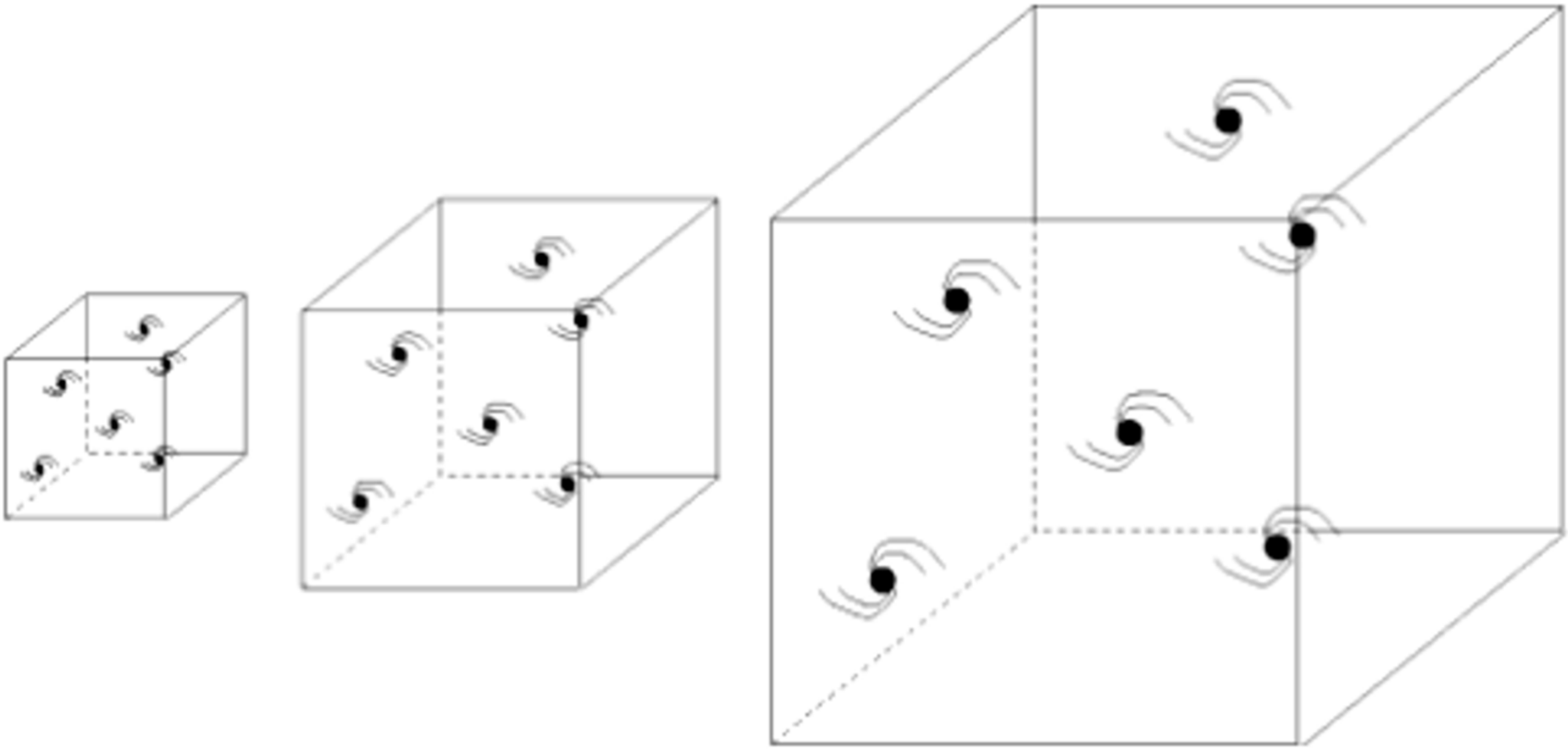



The Hubble diagram (1936)

However, Georges Lemaître came up with the same conclusion around the same time, probably independently.

The expansion of the universe was then called “the De Sitter effect”

# Expansion of the Universe

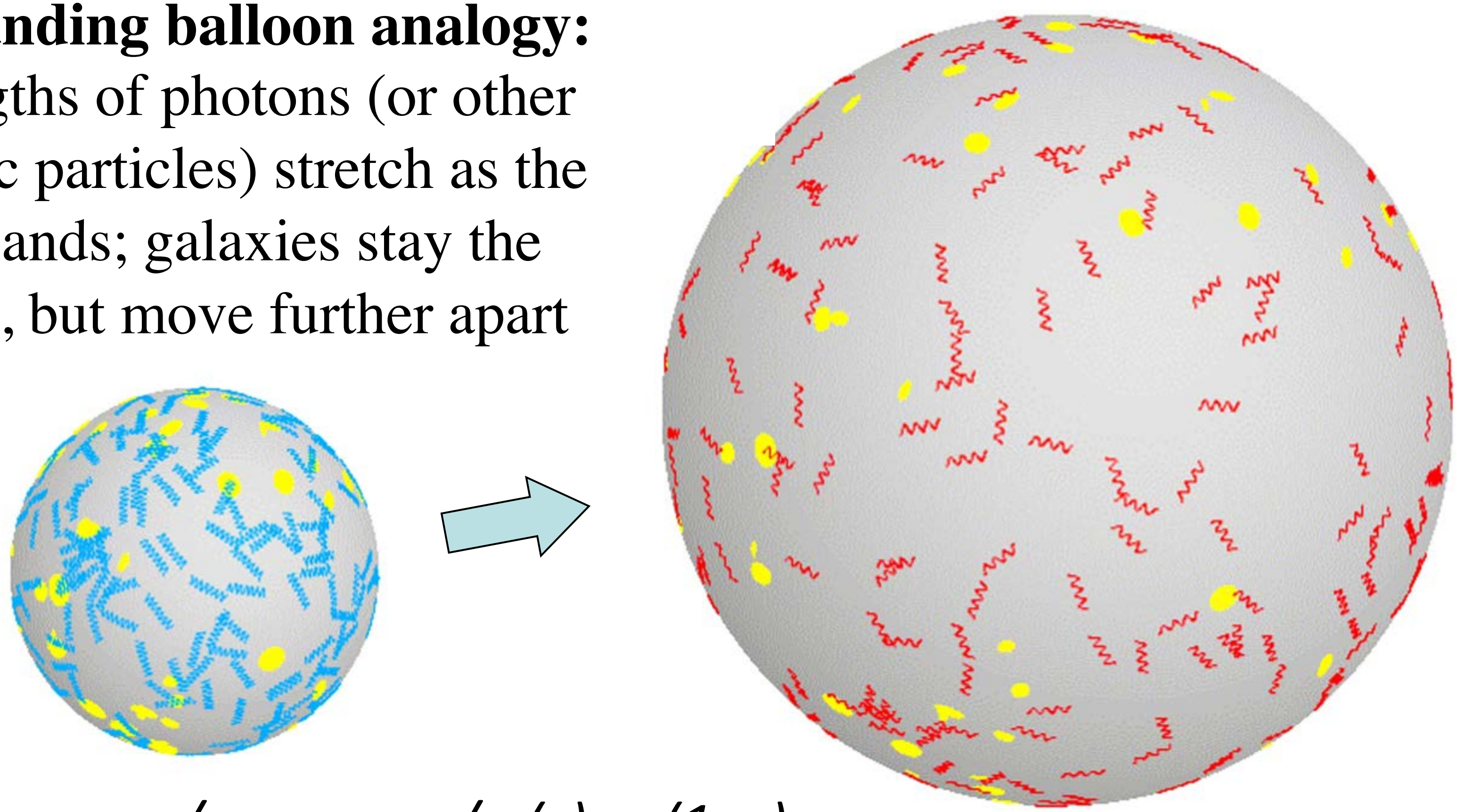


**The space itself expands**, and carries galaxies apart

In a homogeneous, isotropic universe, there is no preferred center

# The Cosmological Redshift

**The expanding balloon analogy:** Wavelengths of photons (or other relativistic particles) stretch as the space expands; galaxies stay the same size, but move further apart



$\lambda_{obs} / \lambda_{em} = a_{now} / a_{then} = a_0 / a(z) = (1+z)$

*Expansion factor* $a(z) = 1 / (1+z)$

But thanks to the Hubble law, the cosmological redshift turns out to be equivalent to the Doppler shift

# Discovery of the Dark Matter

- Fritz Zwicky (1933): from application of the virial theorem to Coma Cluster, deduced that it contains ~ 400 times the amount of mass in visible stars
- Similar results obtained for Virgo Cluster by Sinclair Smith in 1936

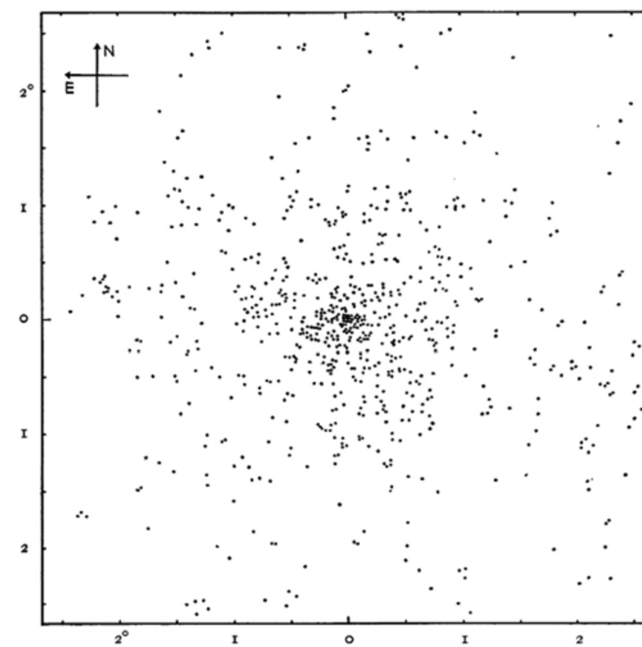
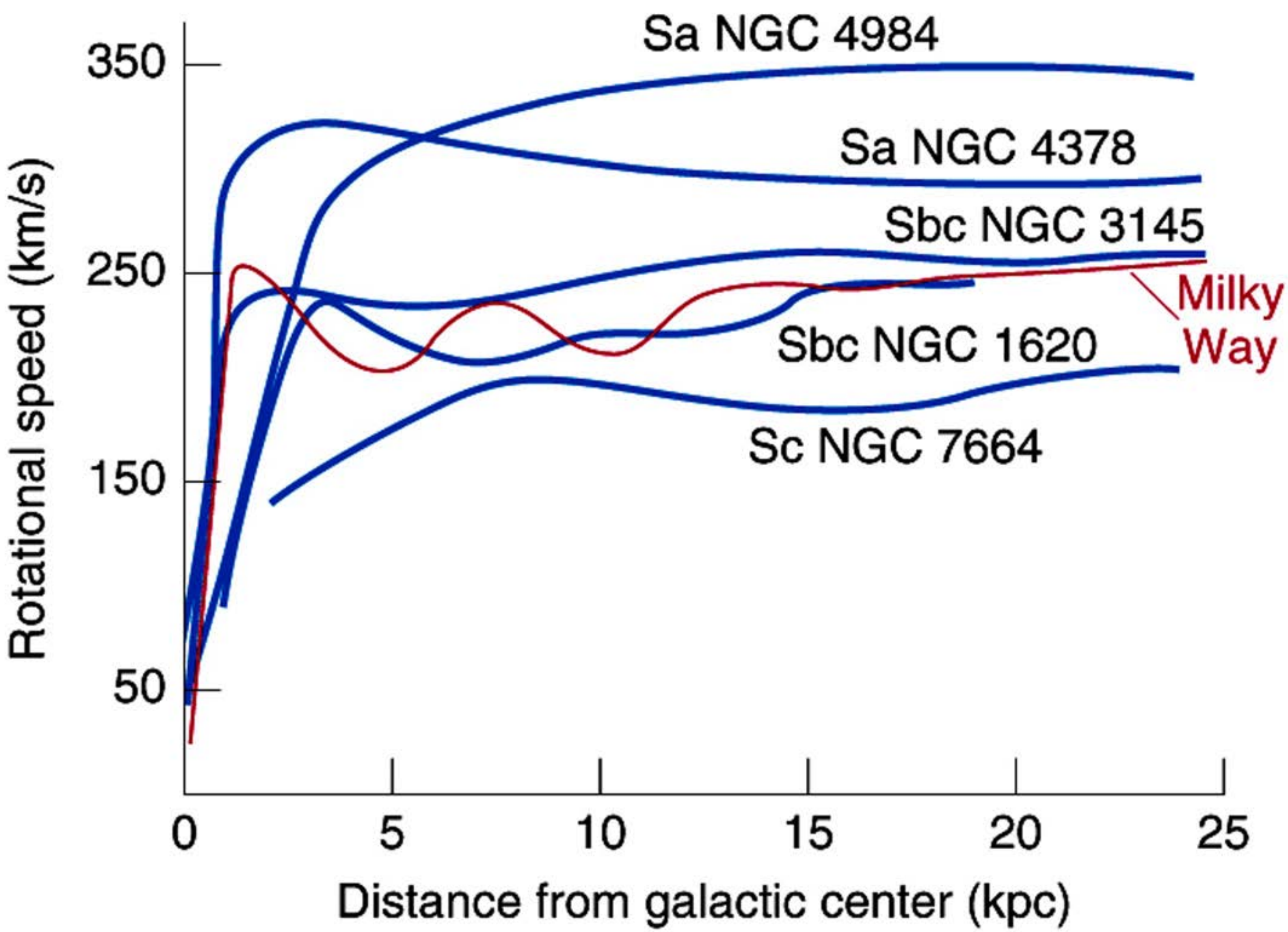


FIG. 3.—The Coma cluster of nebulae

- Largely ignored until 1970's, when flat galaxy rotation curves made the existence of DM unambiguous
- DM plays a key role in the models of structure formation
- The nature of the DM is now one of the outstanding problems of physics

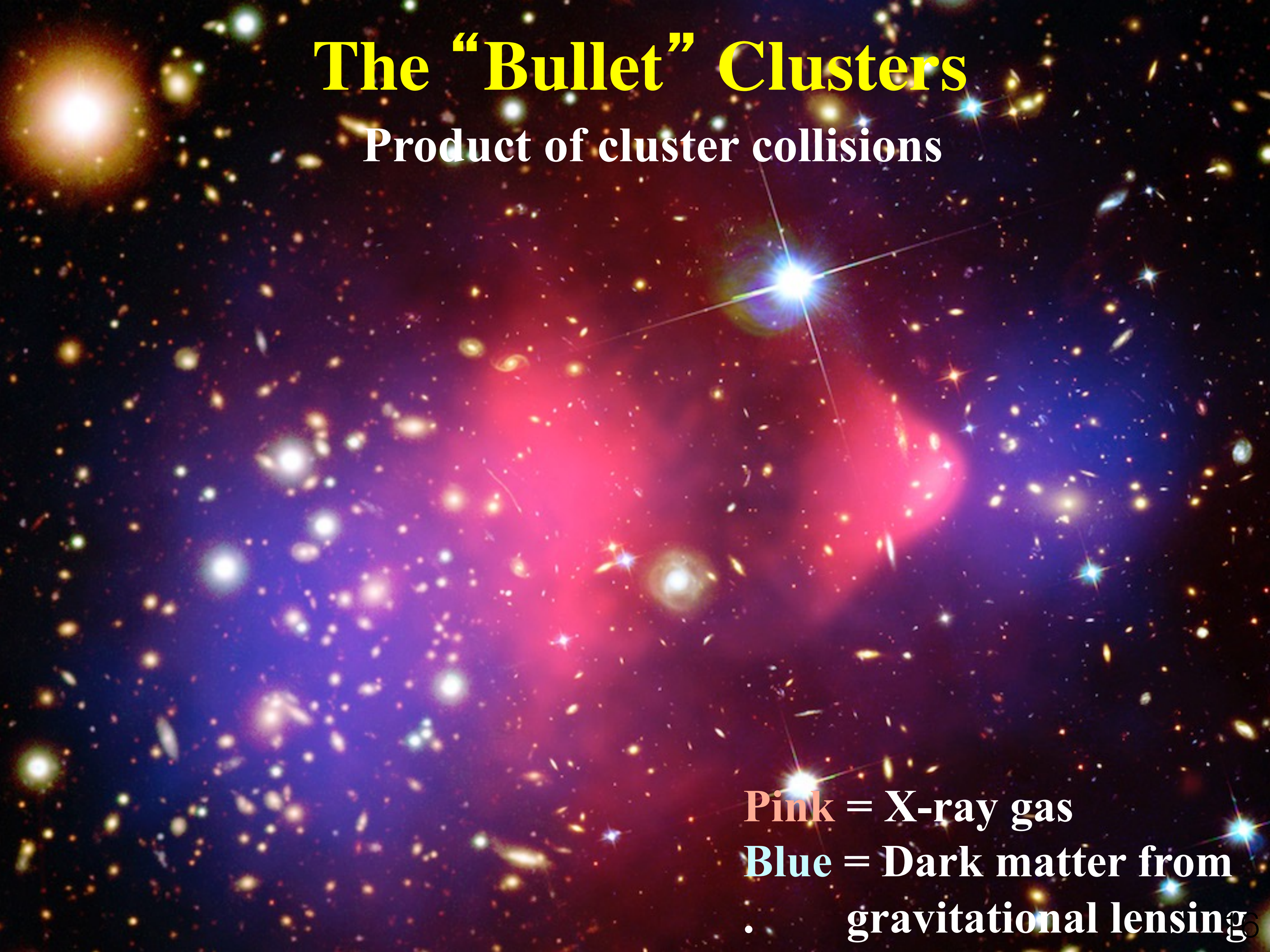
# Flat Rotation Curves of Disk Galaxies:
## The Other Key Piece of Evidence for the Existence of Dark Matter




Noted early by Jan Oort and others, but really got attention in the 1970's, due to the work by Vera Rubin, Kenneth Ford, Ken Freeman, Mort Roberts, and others

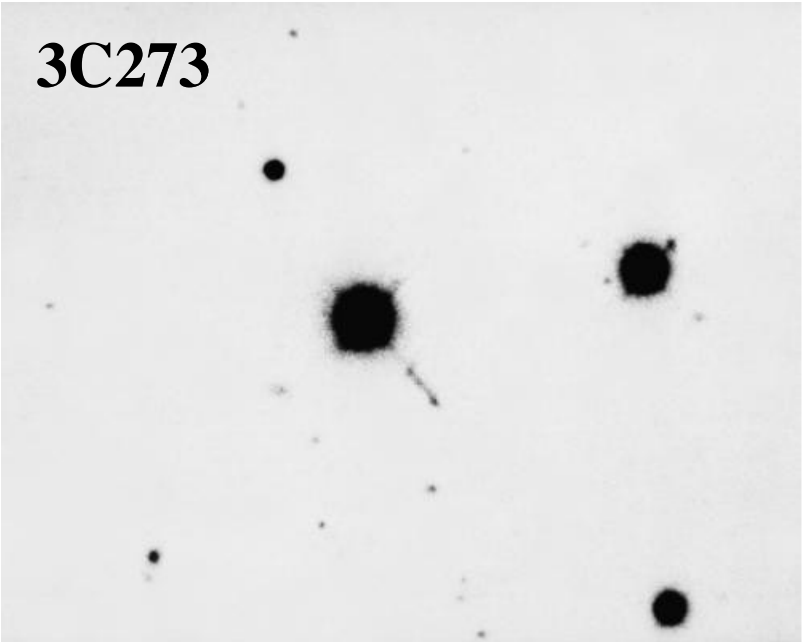
# The “Bullet” Clusters

## Product of cluster collisions

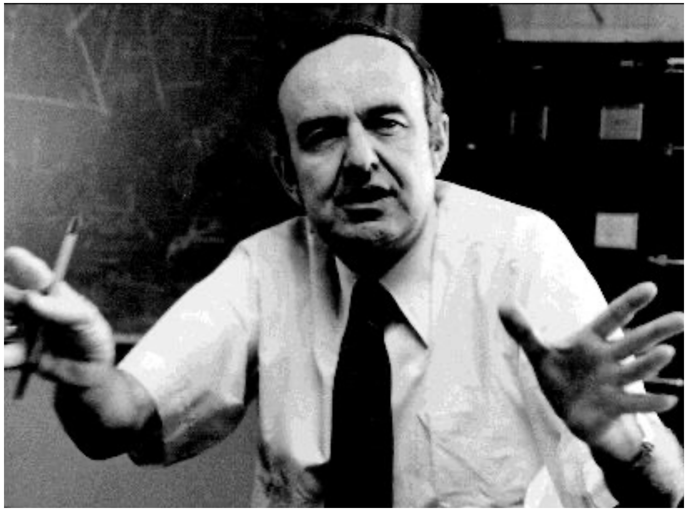


Pink = X-ray gas
Blue = Dark matter from
gravitational lensing

# Discovery of Quasars (1963)

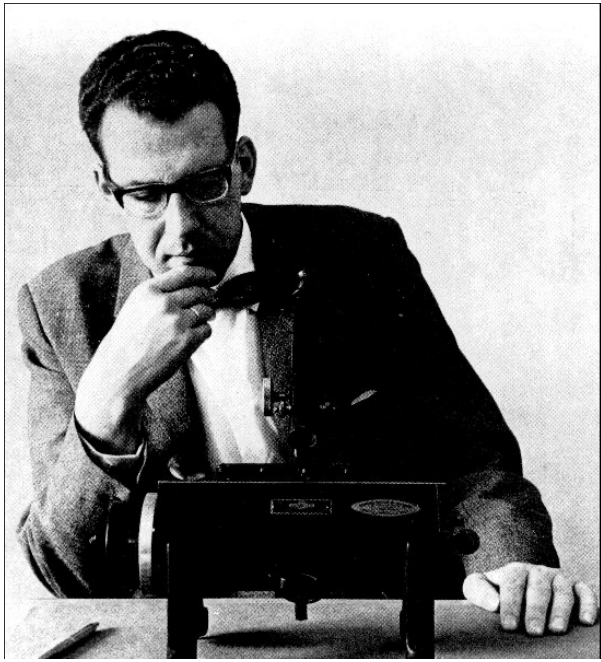



Cyril Hazard ➡ got the precise radio position

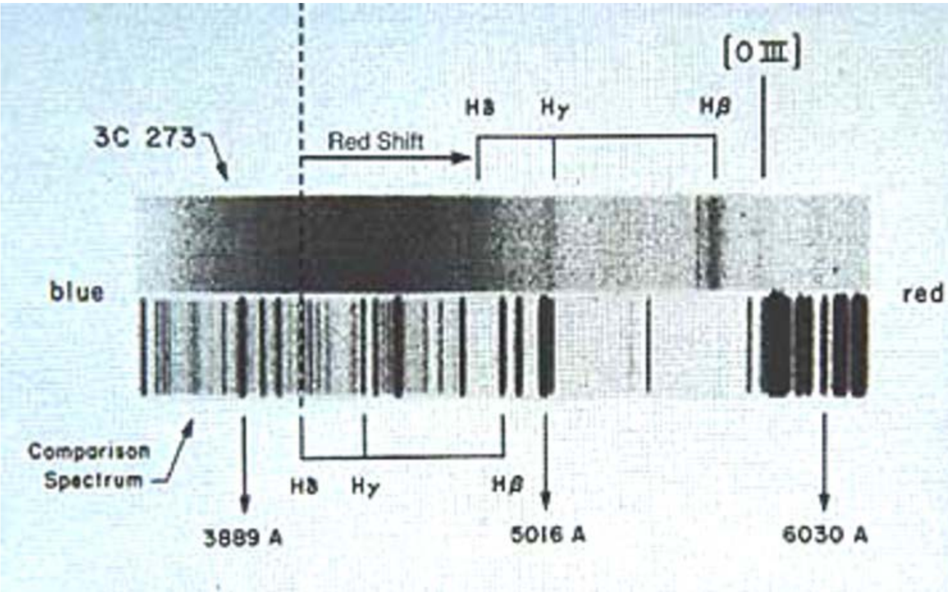


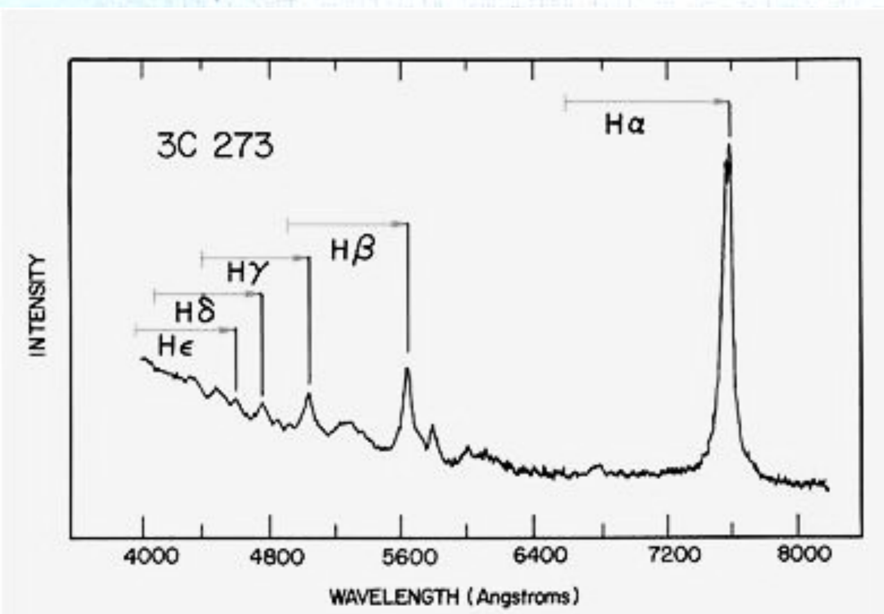
⬅ Allan Sandage got the optical ID

Maarten Schmidt ➡ figured out the spectrum and the redshift

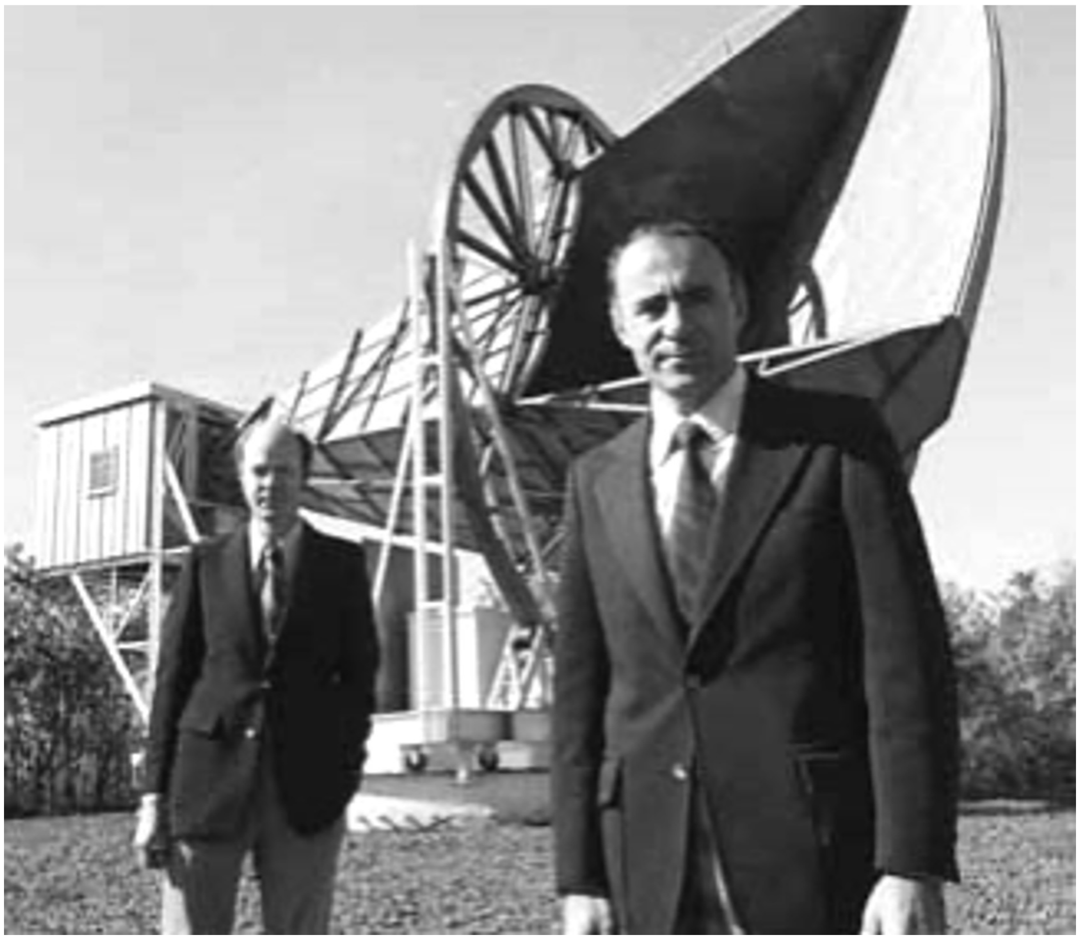


# Discovery of Quasars (1963)



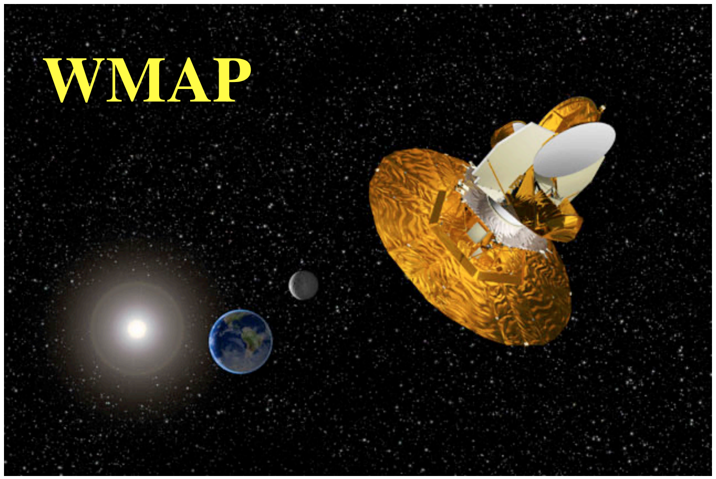

# Discovery of the Cosmic Microwave Background (CMBR): A Direct Evidence for the Big Bang

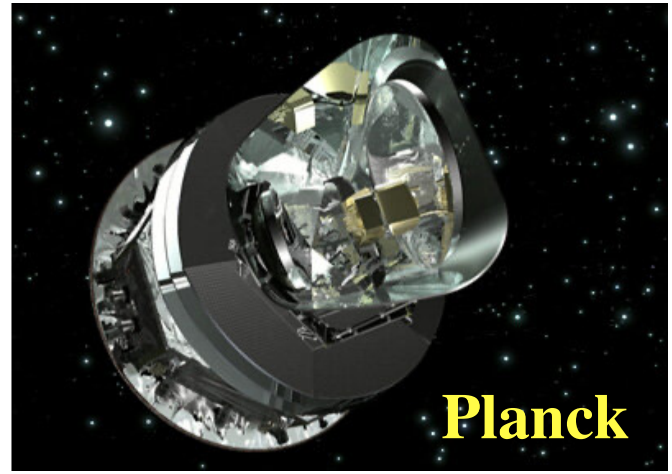


Arno Penzias &
Robert Wilson (1965)

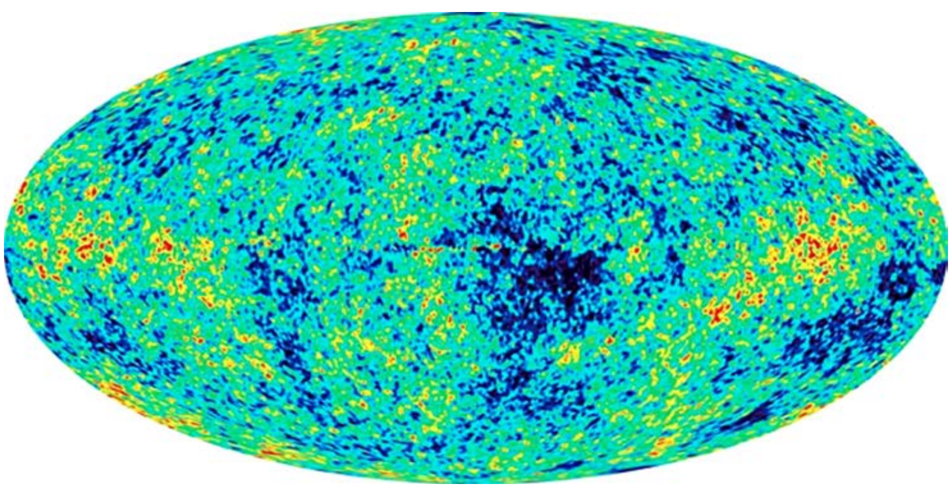
Nobel Prize, 1978

# Precision Cosmology From CMB (~1998 – Present)

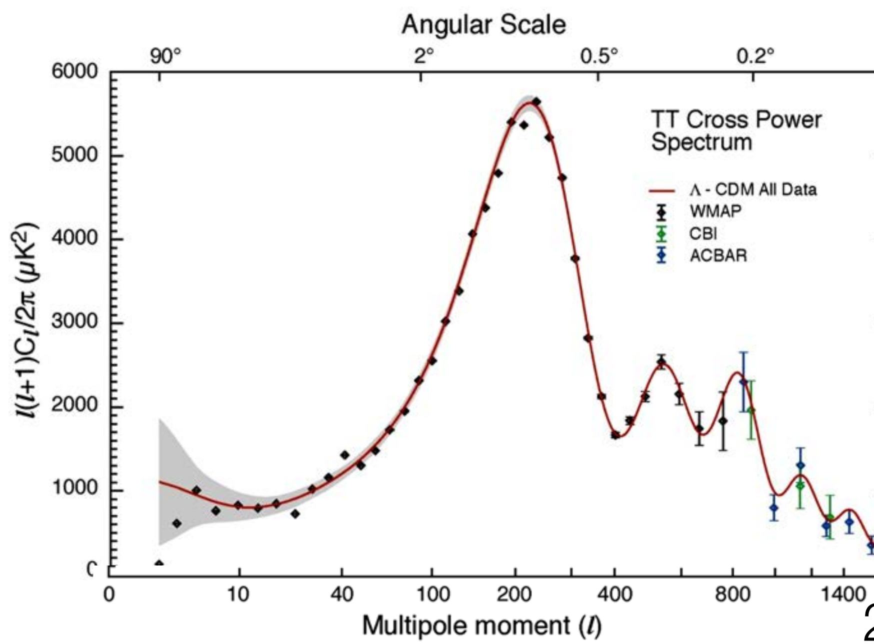



Temperature Fluctuations

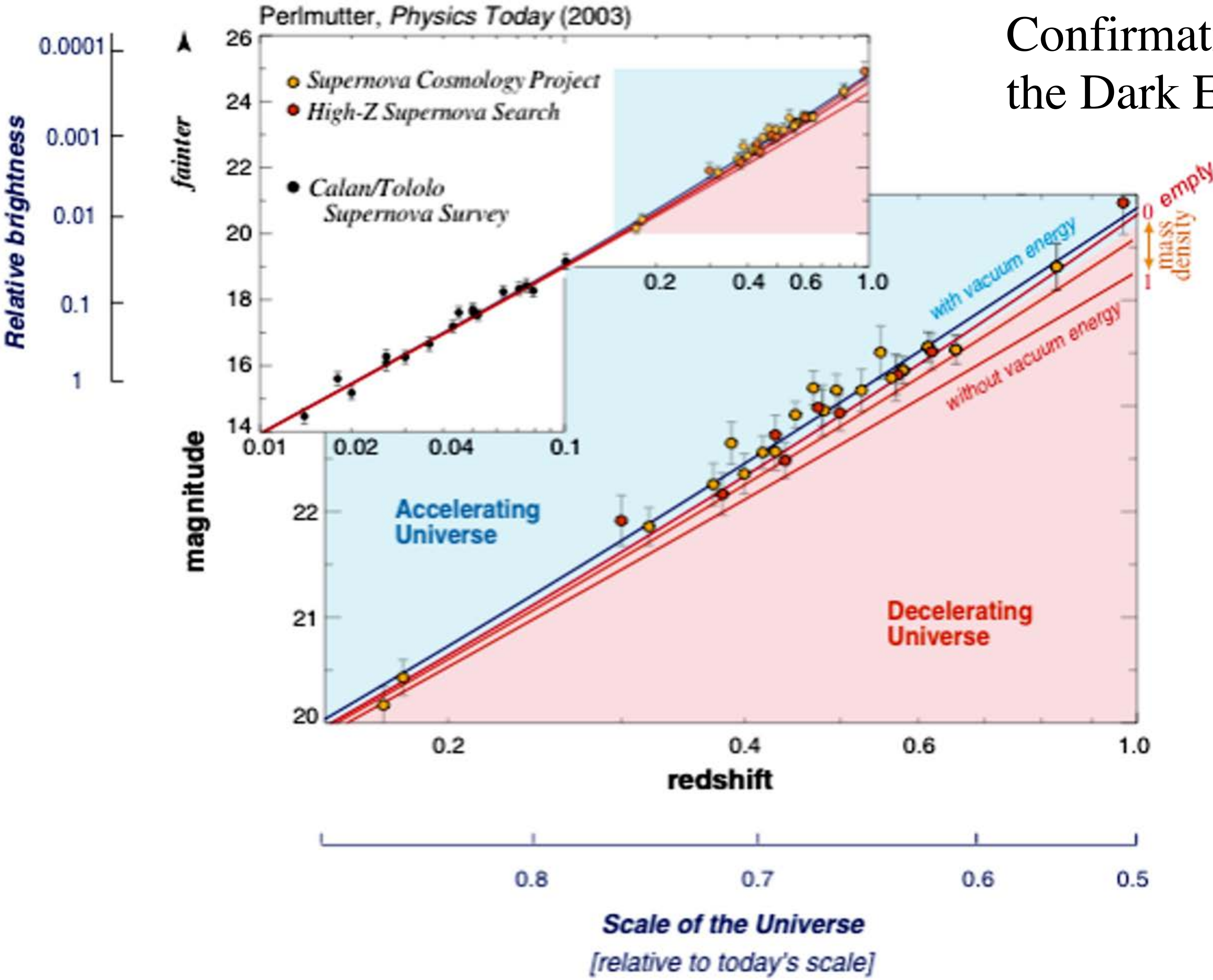


Angular Power Spectrum



# Supernova Hubble Diagram

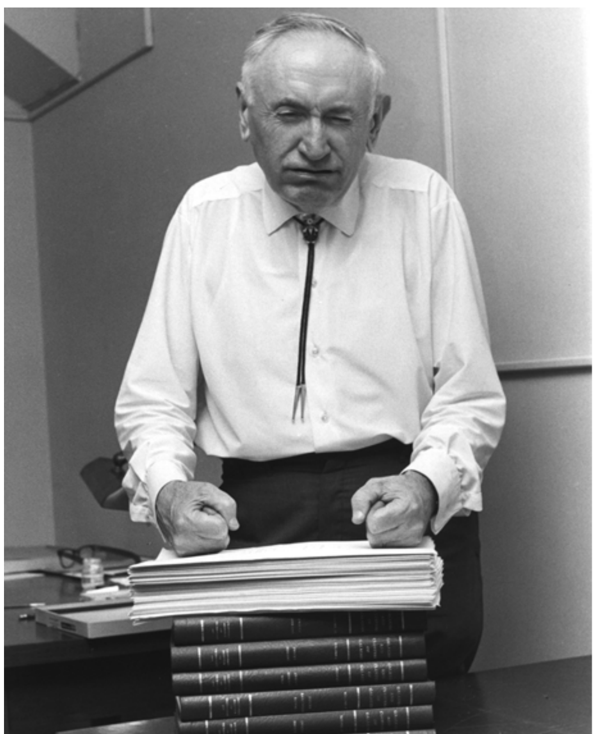
Confirmation of the Dark Energy



# Discovery of the Large Scale Structure

Universe was assumed to be homogeneous on scales larger than galaxies, until …

**1930's**: H. Shapley, F. Zwicky, and collab.
**1950's**: Donald Shane, Carl Wirtanen, others
**1950's - 1970's**: Gerard de Vaucouleurs, first redshift surveys
**1970's - 1980's**: CfA, Arecibo, and other redshift surveys



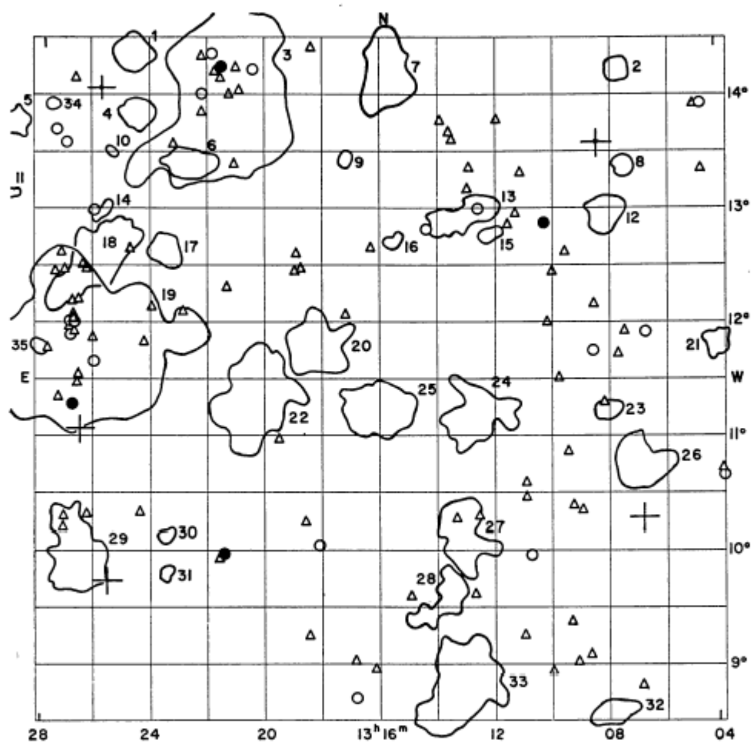
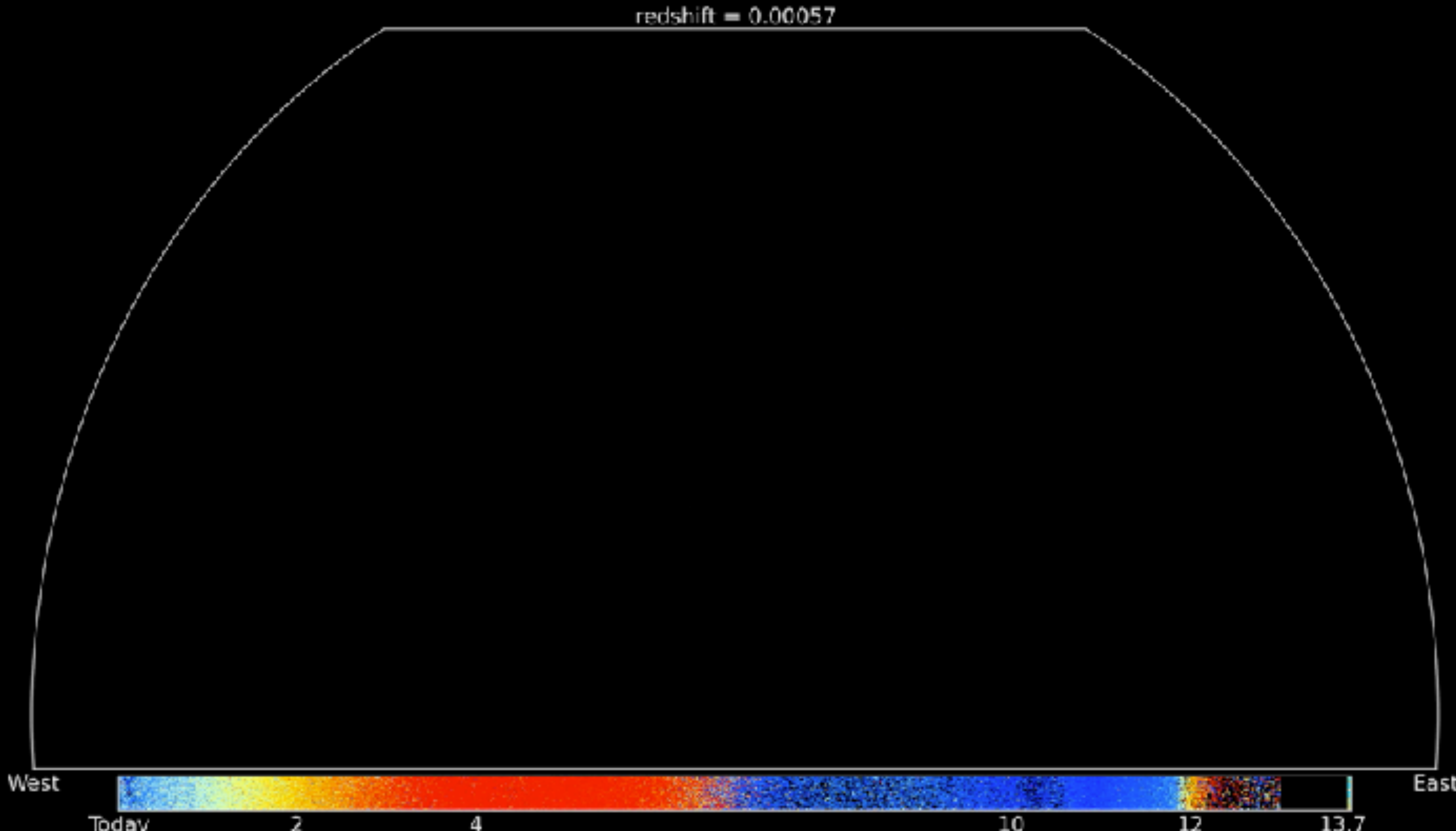


FIGURE 4

Zwicky's map of the overdensities in galaxy counts

# Today, with the Sloan Digital Sky Survey



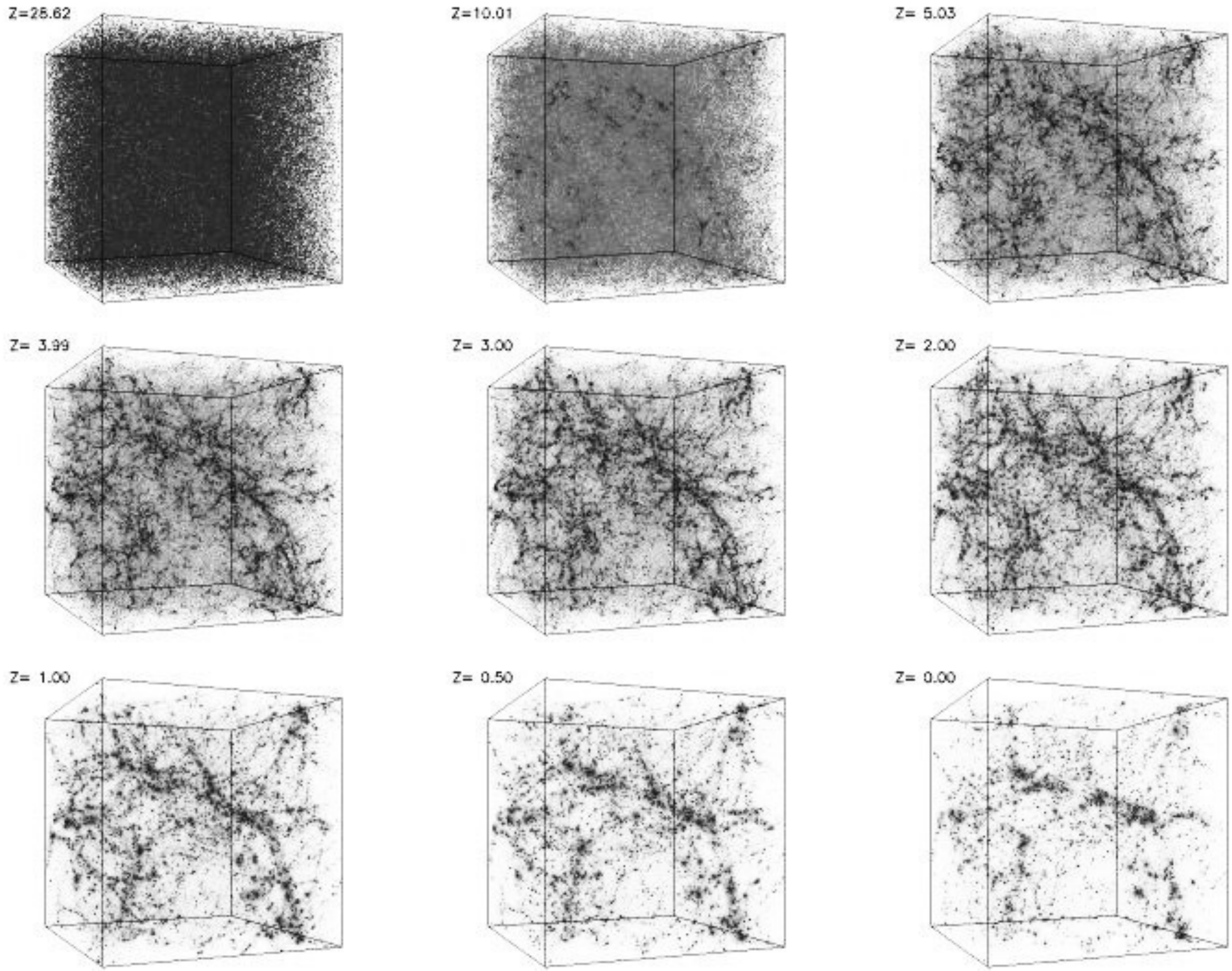

lookback time [Billions of years]

SDSS

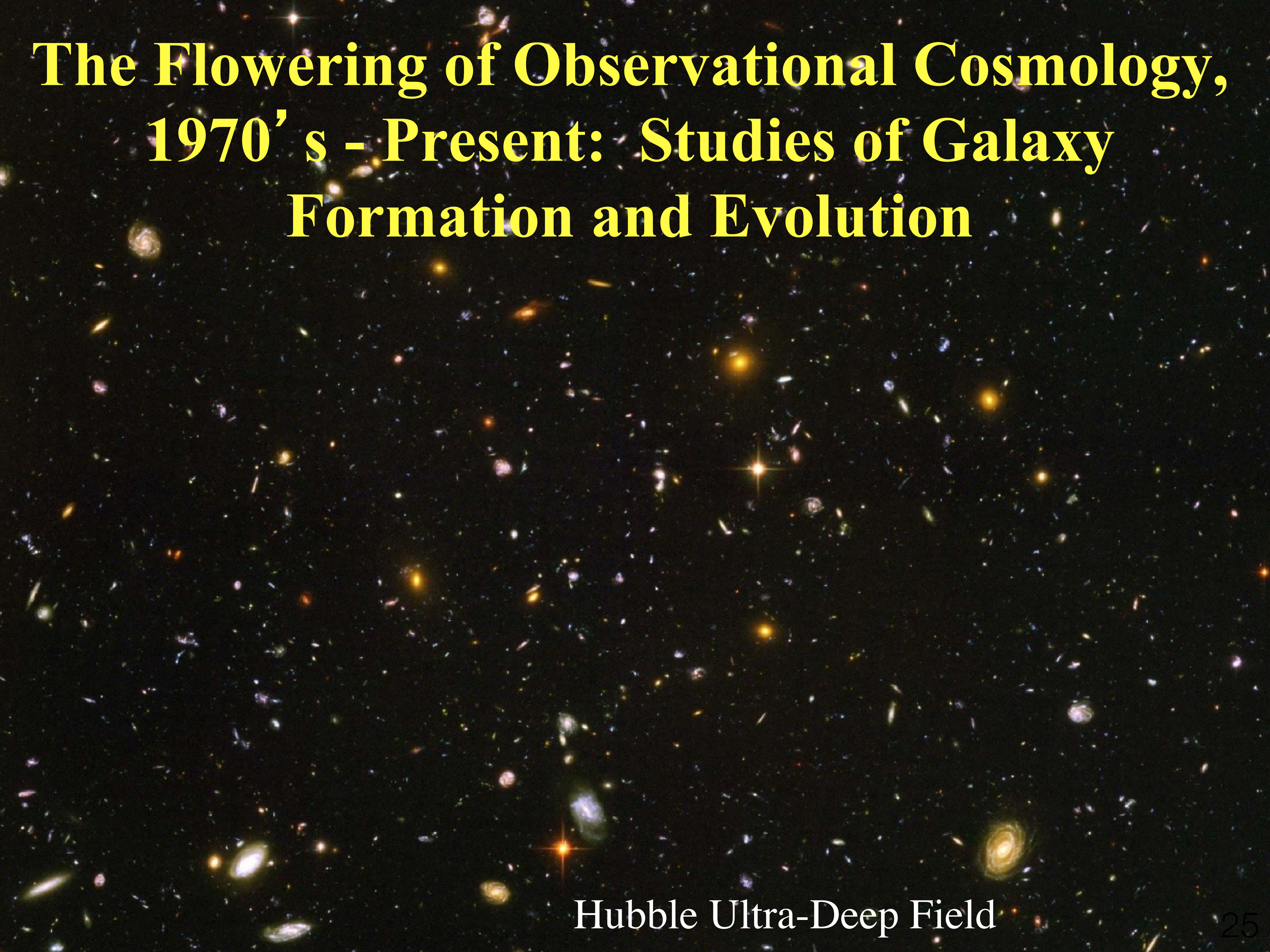
Mendez & Ménard

# Numerical Simulations of Structure and Galaxy Formation: 1970's - Present

A "cosmic cube" simulation by A. Kravtsov

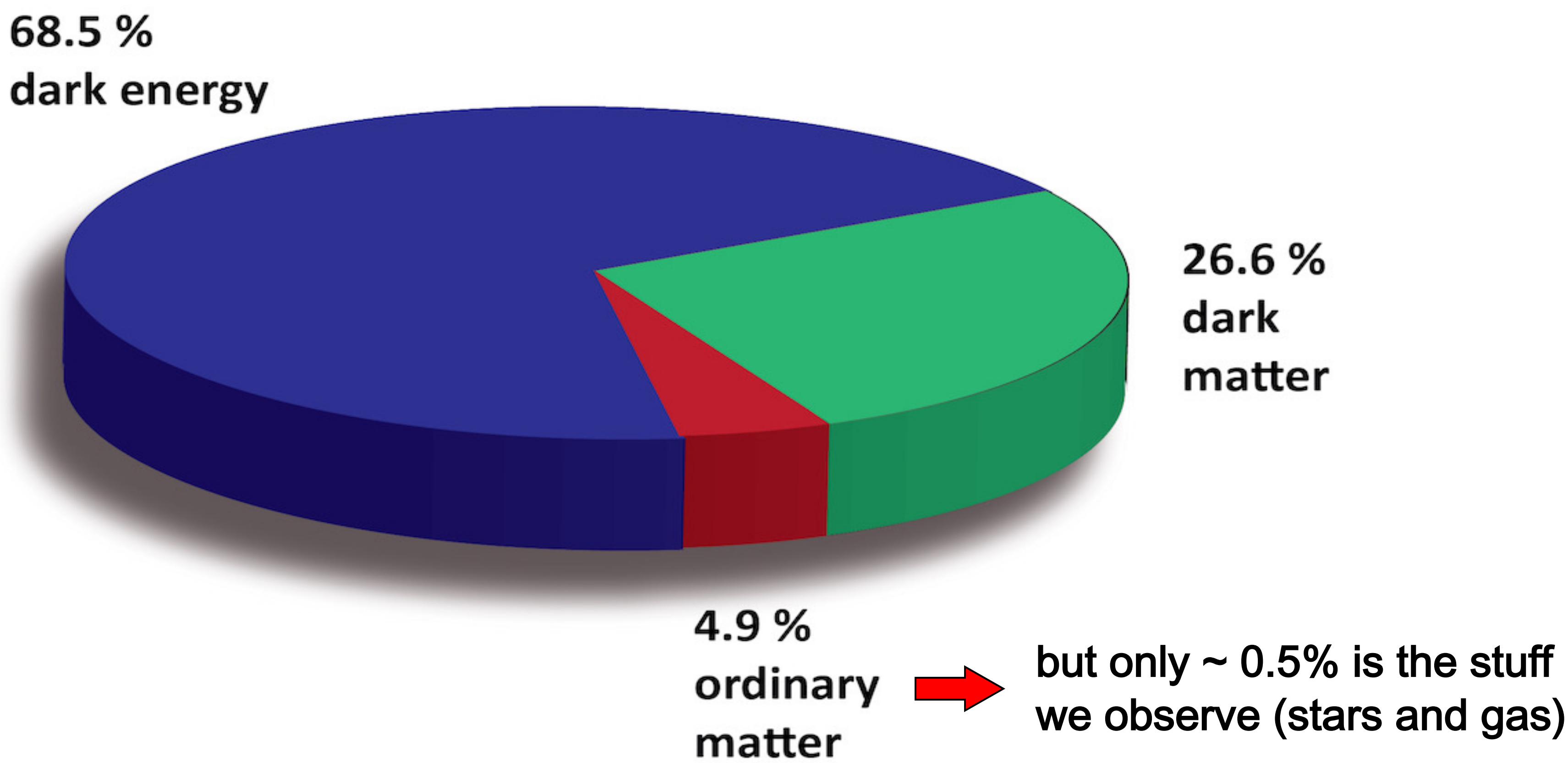


# The Flowering of Observational Cosmology, 1970’s - Present: Studies of Galaxy Formation and Evolution



Hubble Ultra-Deep Field

# The Composition of the Universe



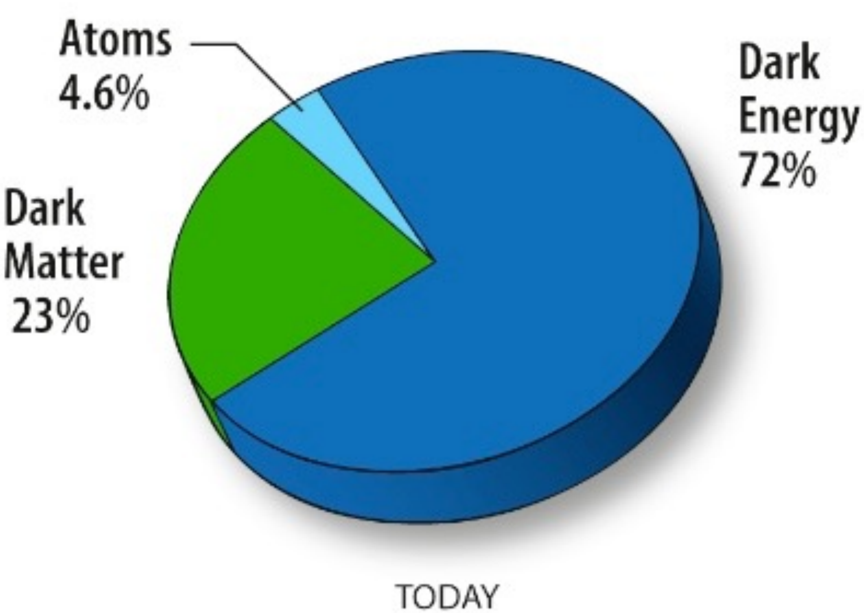

- A picture consistent with many different observations, in a Concordance Cosmology
- The nature of the Dark Matter and Dark Energy are among the most outstanding problems of science today

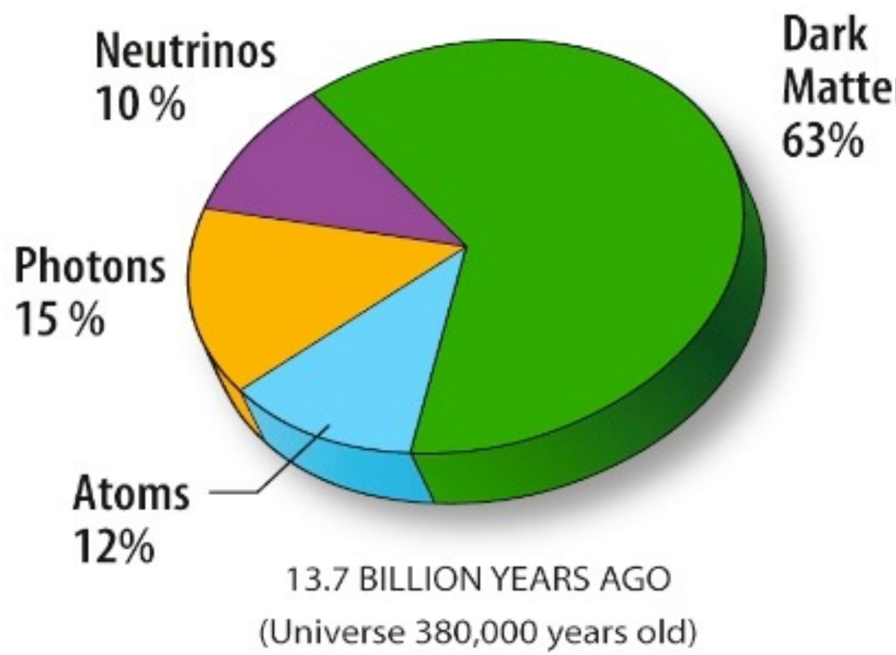
# The Contents of the Universe Evolve

The relative abundances of different components change in time, due to their different EOS behavior:

Now

Recombination era




Baryons also move gas <—> stars, DM particles may decay, DE may be in the form of a quintessence

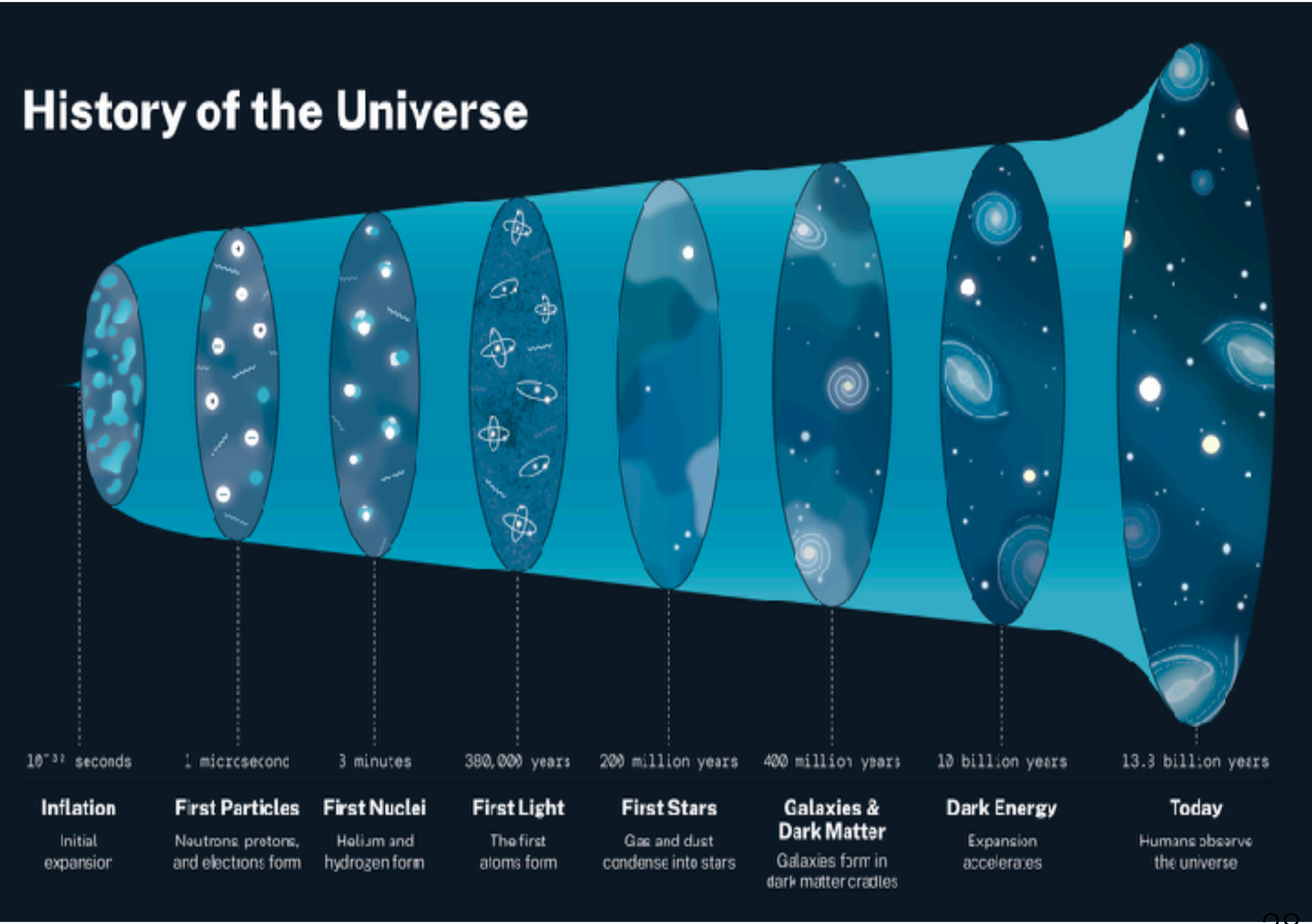
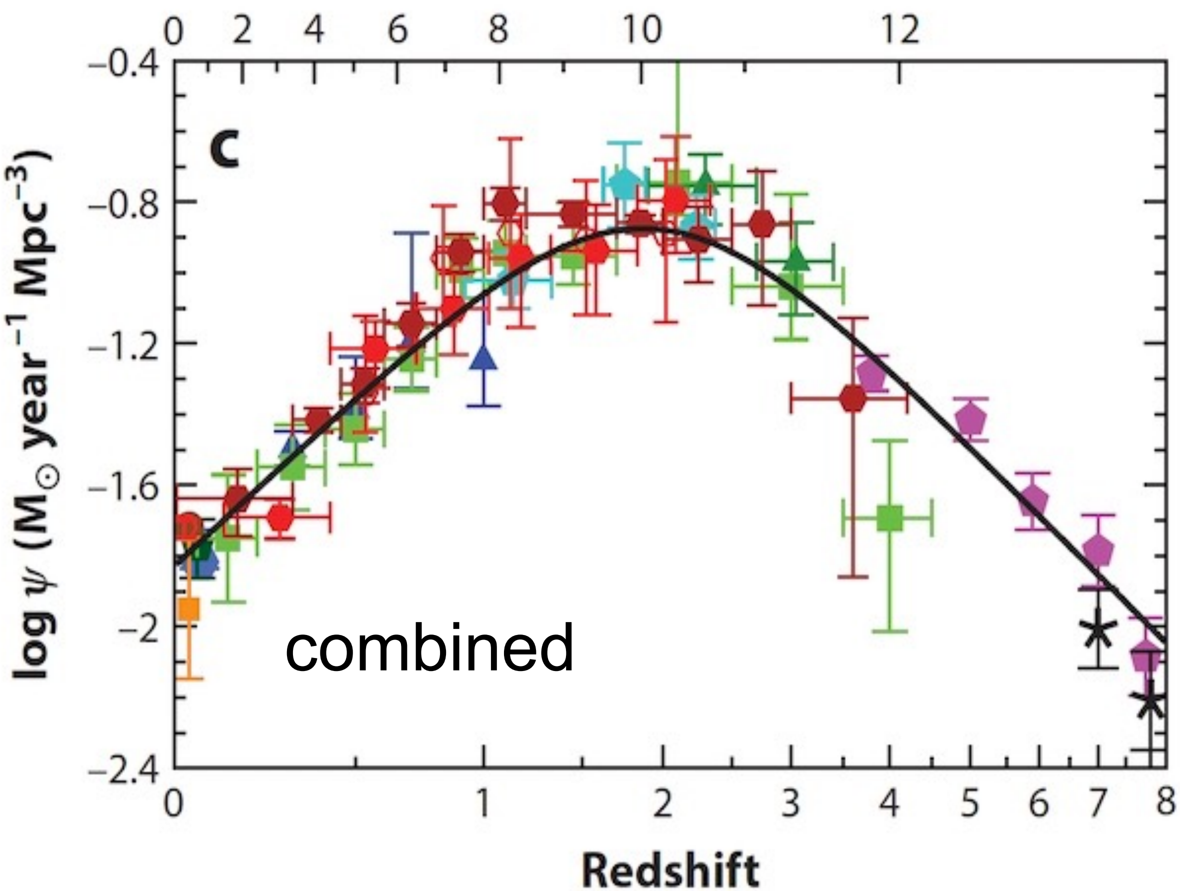



Image credit: NASA

# Cosmic Star Formation History

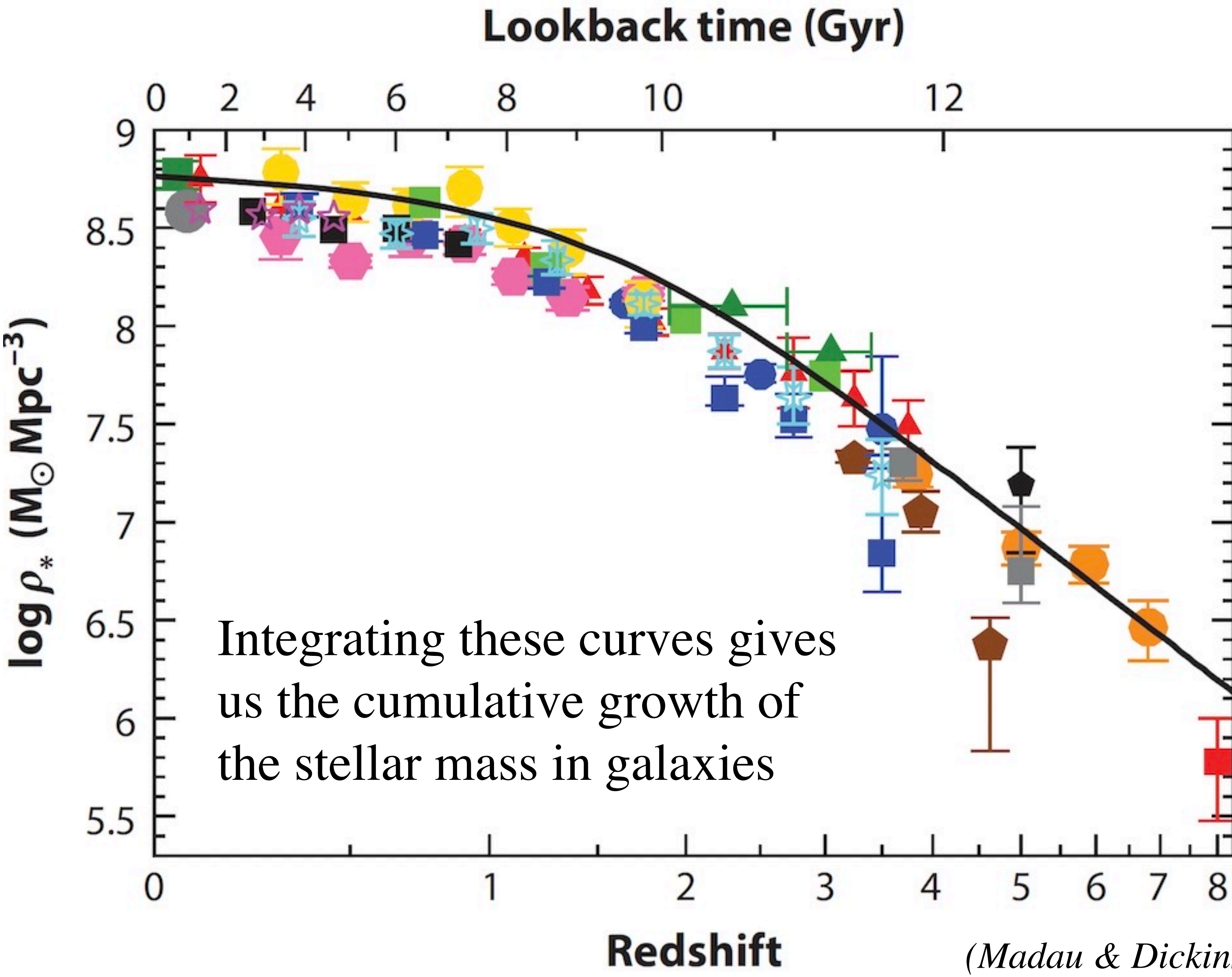
Observations in UV/optical give us the unobscured star formation rate, and in Far-IR/sub-mm the obscured component




The average star formation peaks around z ~ 2 (the "cosmic noon")

*(Madau & Dickinson 2014)*

# Build-up of the Stellar Mass Density




Integrating these curves gives us the cumulative growth of the stellar mass in galaxies

*(Madau & Dickinson 2014)*

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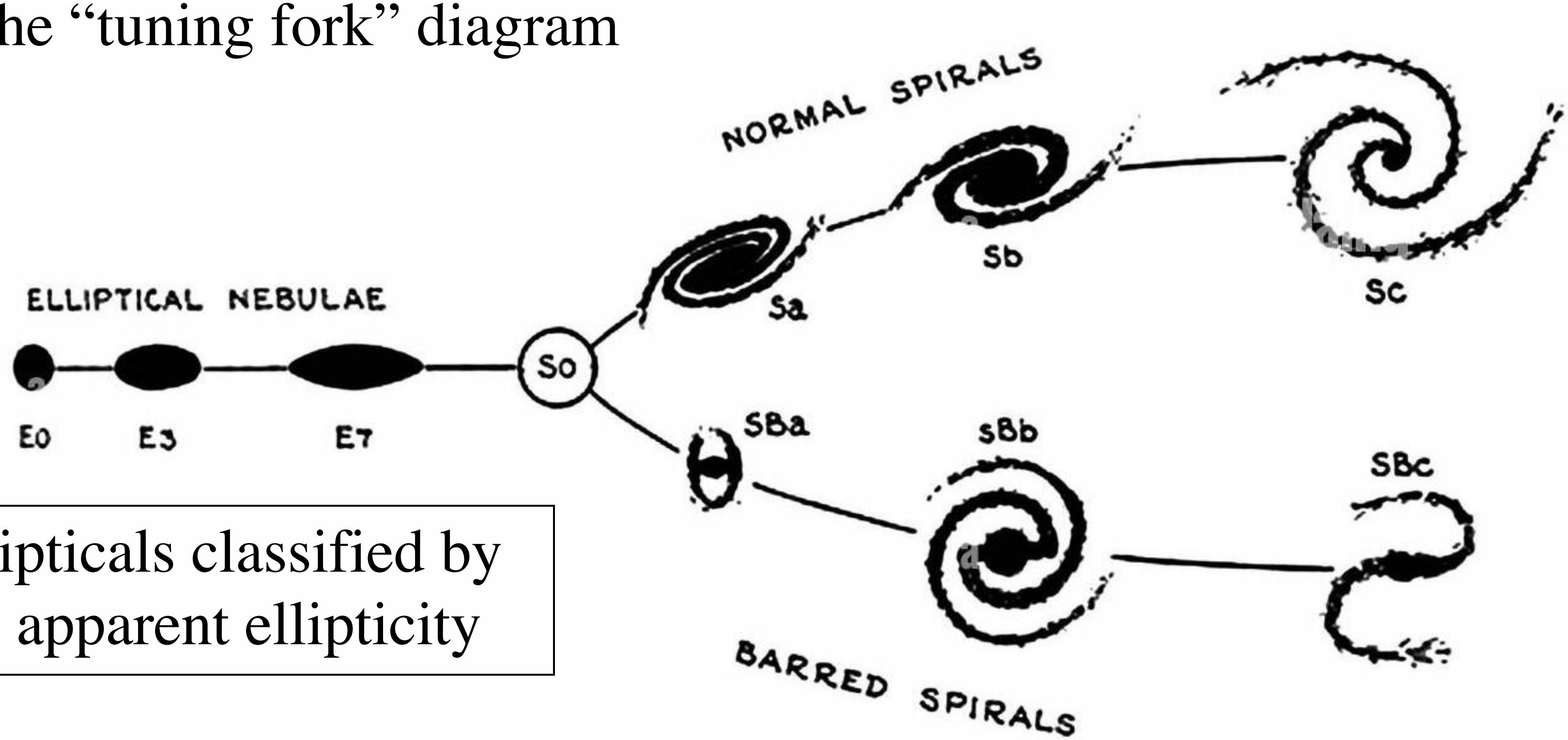
# Galaxies

- The basic constituents of the universe at large scales
  - Distinct from the LSS as being too dense by a factor of $\sim 10^3$, indicative of an "extra collapse", and a dissipative formation
- 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 $\sim 10^{11}$ galaxies within the observable universe
- Typical total masses $\sim 10^8$ - $10^{12}\ M_\odot$
- Typically contain $\sim 10^7$ - $10^{11}$ stars

# Hubble's Classification Scheme

The "tuning fork" diagram




Ellipticals classified by the apparent ellipticity

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

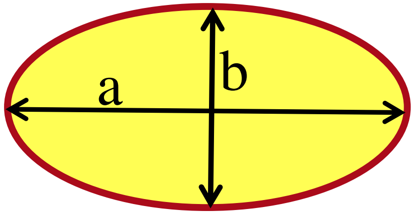
Hubble thought (incorrectly) this was an evolutionary sequence, so ellipticals are called "early-type" and spirals "late-type" galaxies

# Elliptical Galaxies

- About 20% of field galaxies are E's, but most E's are in clusters
- There are subtypes:
  - E's (normal ellipticals)
  - cD's (massive bright ellipticals at the centers of galaxy clusters)
  - dE's (dwarf ellipticals)
  - dSph's (dwarf spheroidals)

  } Not really ellipticals, a different class of objects
- Smooth and almost featureless: no spiral arms or dust lanes. Generally lacking in cool gas, and hence few young blue stars
- Classified by the apparent ellipticity:

$$\varepsilon = 1 - \frac{b}{a}$$




Elliptical galaxies are denoted E$n$, where: $\frac{b}{a} = 1 - \frac{n}{10}$

A round elliptical is E0, the most elongated ellipticals are E7

# Lenticular (S0) Galaxies

- Transition class between ellipticals and spirals are the S0 galaxies, also called **lenticulars**
- S0 galaxies have a rotating disk in addition to a central elliptical bulge, but the disk lacks spiral arms or prominent dust lanes, i.e., no active star formation
- Lenticulars can also have a central bar, in which case they are labeled SB0
- May originate from spirals that have exhausted their gas, or that were stripped


Sombrero galaxy

# Spiral Galaxies

Named for their bright spiral arms, which are prominent due either to bright O and B stars (evidence for recent star formation), and dust lanes.

Define two parallel sequences of spirals:

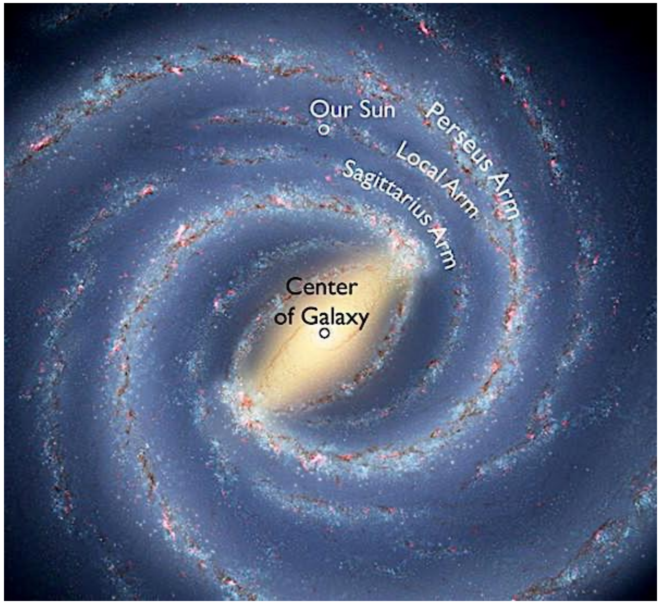
**Sa Sb Sc Sd**

Central bulge becomes less important
Disk becomes more important
Spiral arms become more open and ragged

**SBa SBb SBc SBd**

As above, except that these galaxies also have a central, linear **bar**, while the Sa, Sb… are unbarred

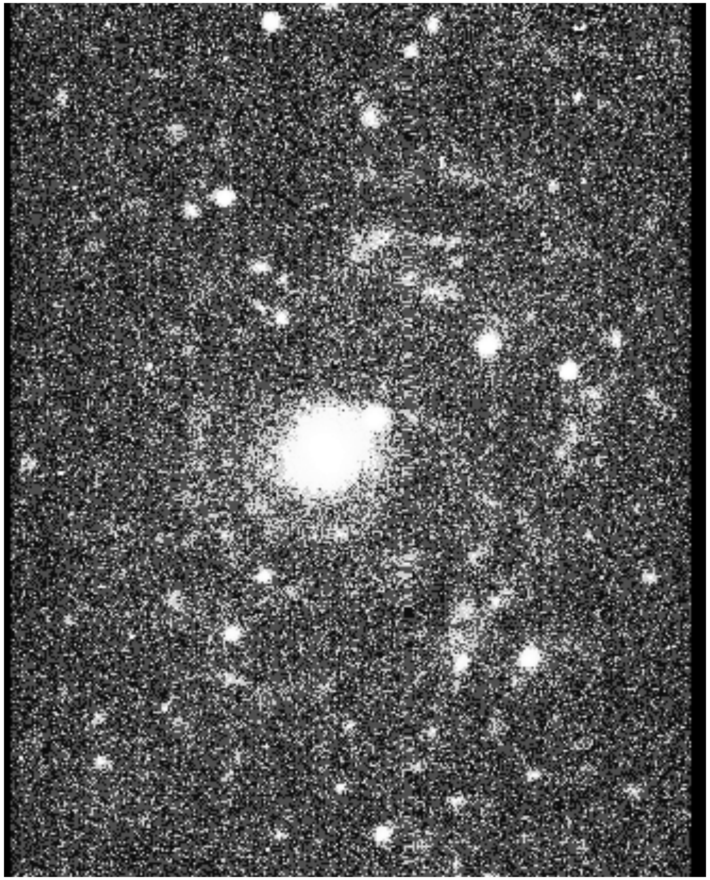
# Barred Galaxies




- Half of all disk galaxies - Milky Way included - show a central bar which contains up to 1/3 of the total light
- Bars are a form of dynamical instability in differentially rotating stellar disks
- Bar patterns are not static, they rotate with a pattern speed, but unlike spiral arms they are not density waves. Stars in the bar stay in the bar
- The asymmetric gravitational forces of a disk allow gas to lose angular momentum (via shocks) compressing the gas along the edge of the bar. The gas loses energy (dissipation) and moves closer to the center of the galaxy, where it can fuel an active nucleus (if present)

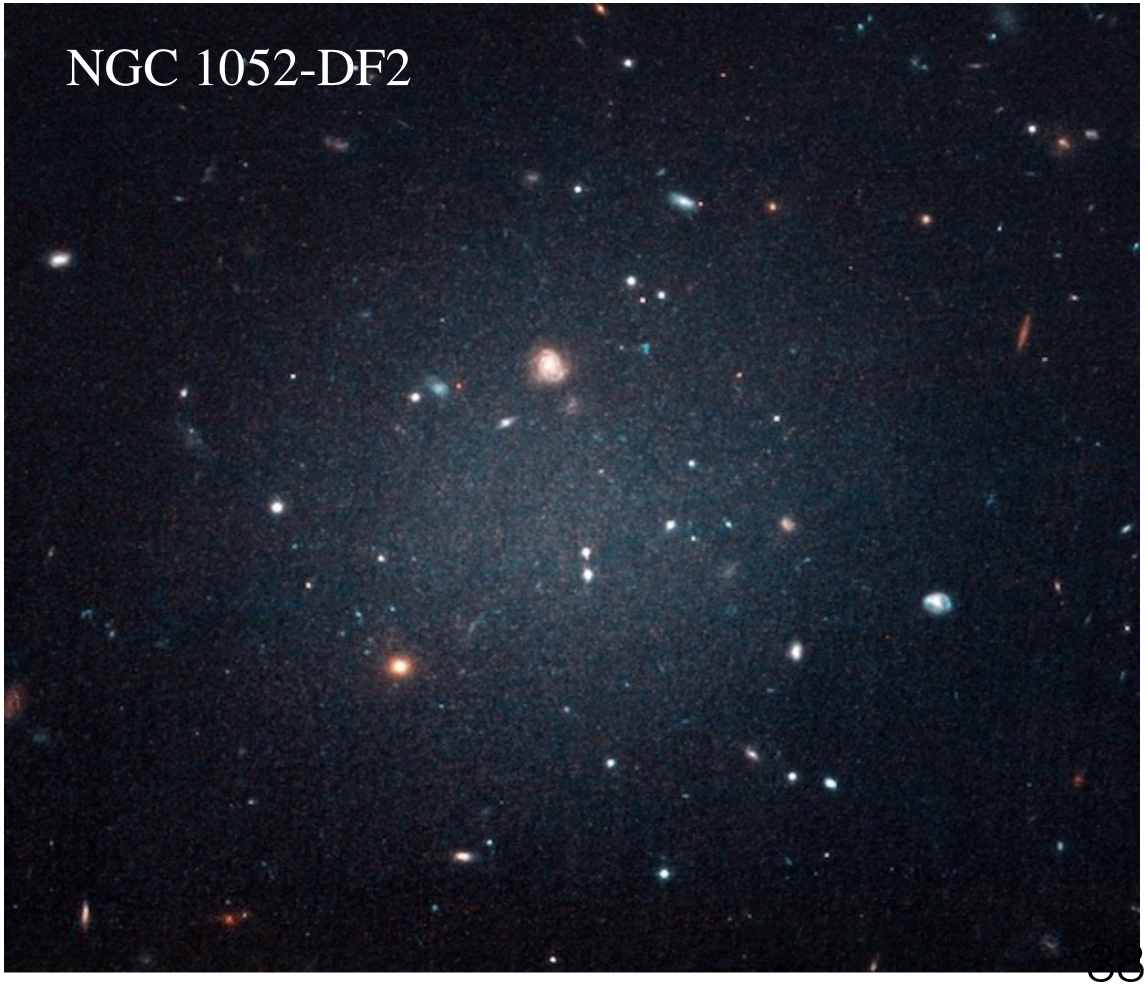
# Low Surface Brightness Disks

**Malin 1 - a prototype**



Normal size, gas, but many fewer stars

Very hard to find - surveys are biased against low surface brightness objects




Some may be dark matter deficient (?)

# Dwarf Galaxies

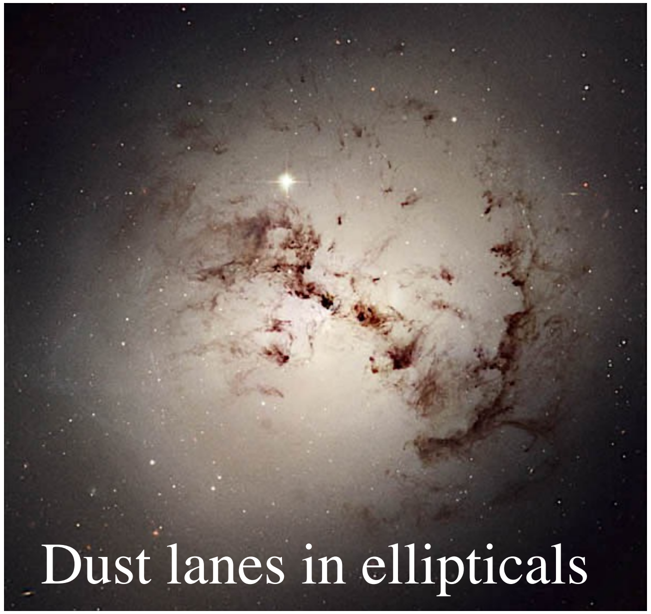
- Low-luminosity: $10^6 - 10^{10}\ L_\odot$, low-mass: $10^7 - 10^{10}\ M_\odot$, small in size, ~ few kpc
- Often low surface brightness, so they are hard to find!
- More than one family of objects:
  - Gas-poor, passive (dE and dSph)
  - Gas-rich, star forming
- Why are dwarf galaxies important?
 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


# Galaxy Morphology Can Change

But generally just in one direction: disks → ellipticals

We see this process in galaxy mergers

Stellar “shells”



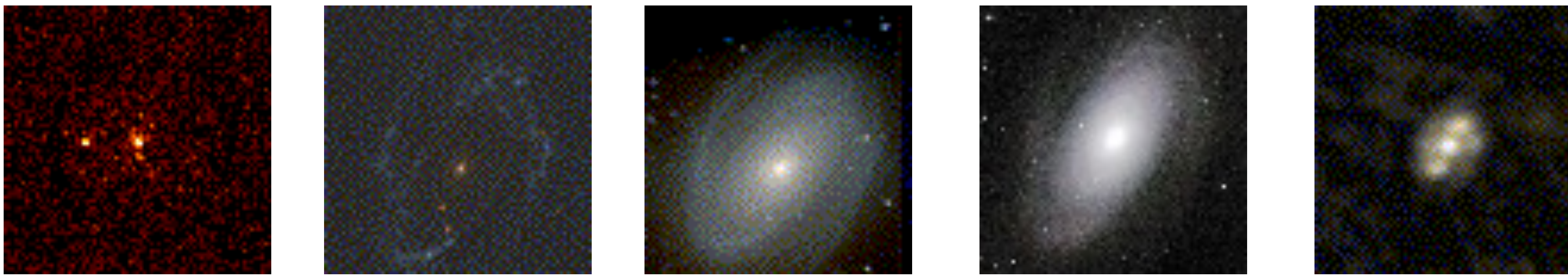
Dust lanes in ellipticals

These are remnants of “partially digested” galaxy disks

# 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.

# 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

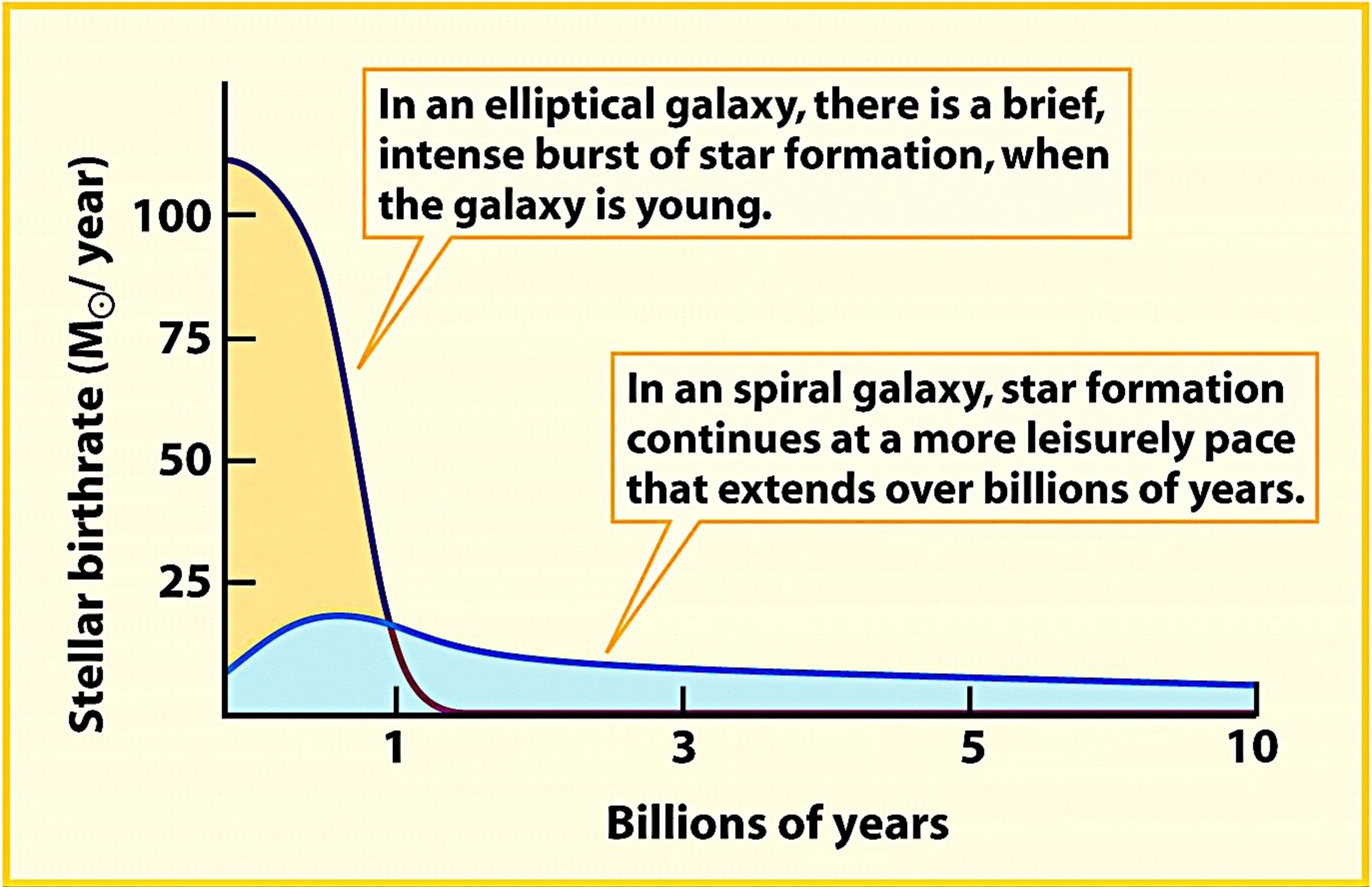
Pressure support ➞ Rotational support
Passive ➞ Actively star forming
Red colors ➞ Blue colors
Hot gas ➞ Cold gas and dust
Old ➞ Still forming
High luminosity density ➞ Low lum. dens.
… etc.

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 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

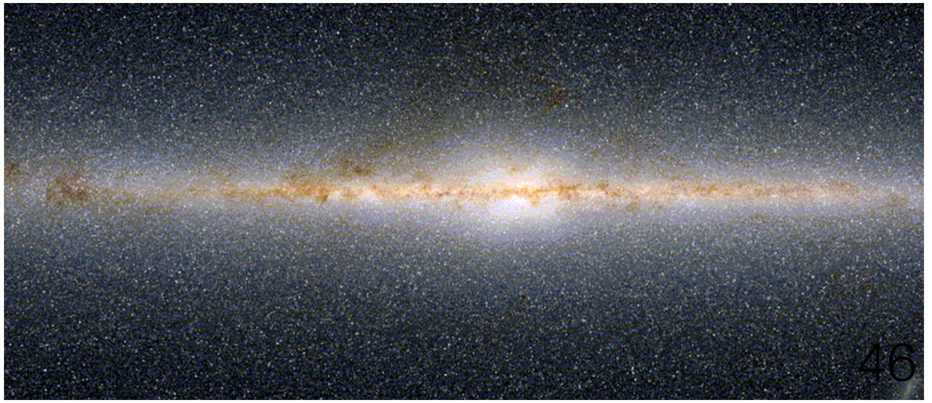
# Stellar Populations

- 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

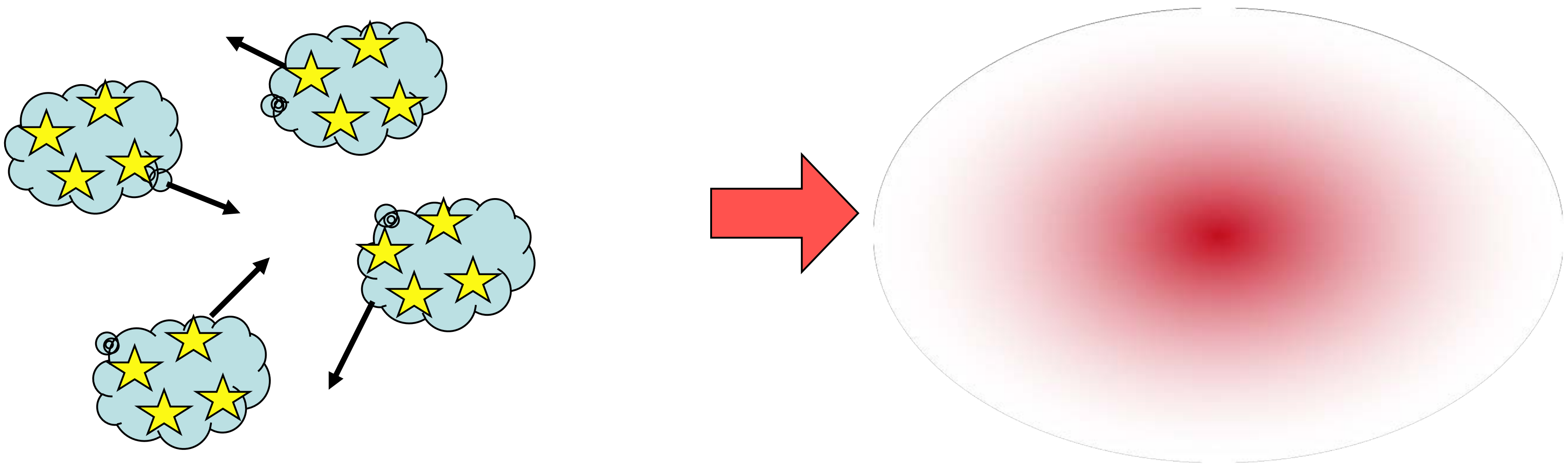
# Stellar Populations and Dynamical Subsystems in Galaxies

- 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

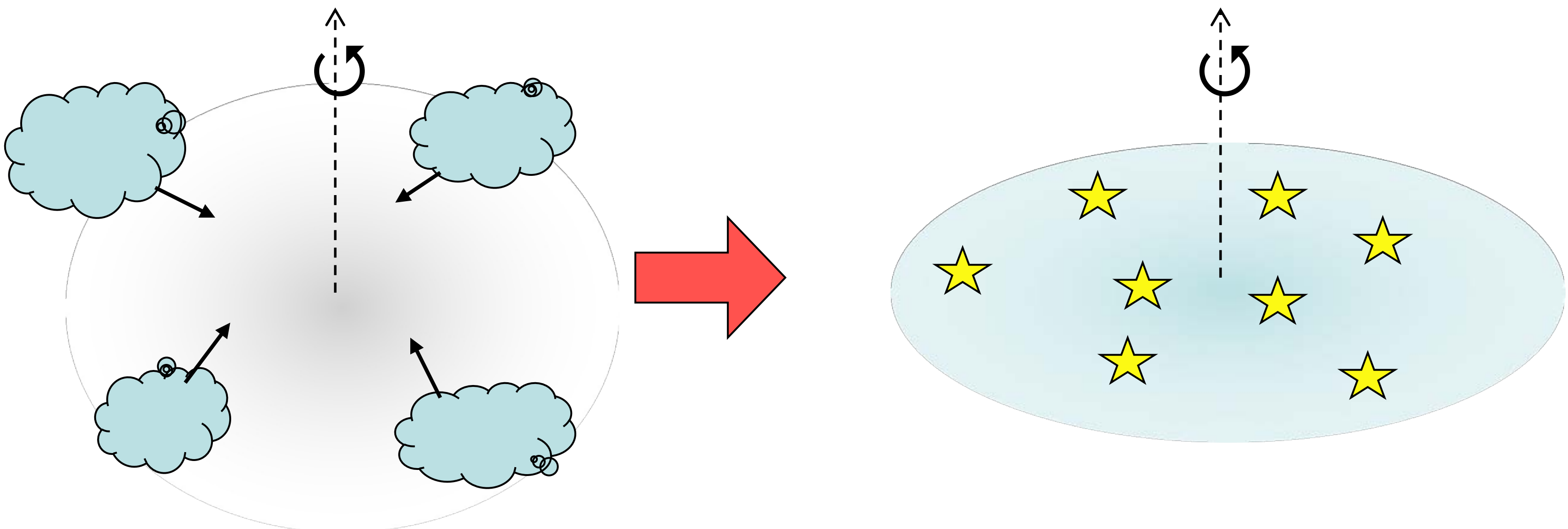


# Formation of Galaxy Spheroids and Dynamics of Stellar Populations



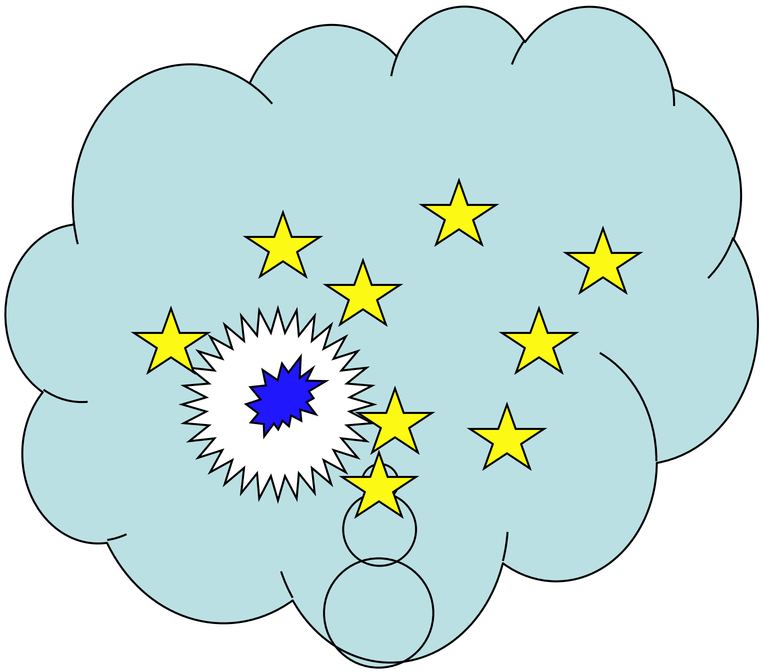
Stars "remember" the dynamics of their orbits at the time of formation, since dynamics of stellar systems is dissipationless. If stars form in dwarf protogalactic fragments which then merge, this will result in a pressure-supported system, *i.e.*, a spheroid (bulge or halo, or an elliptical galaxy).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

# Formation of Galaxy Disks and Dynamics of Stellar Populations

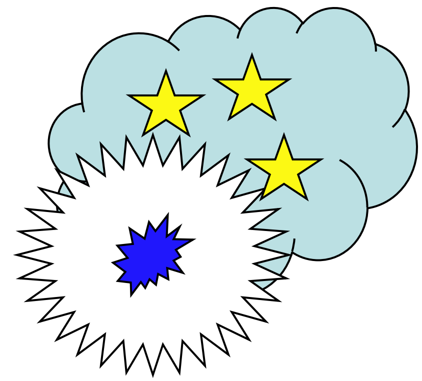


If protogalactic clouds merge dissipatively in a potential well of a dark halo, they will settle in a thin, rotating disk = the minimum energy configuration for a given angular momentum. If gas settles into a (dynamically cold) disk before stars form, then stars formed in that disk will inherit the motions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

# Spiral Galaxies: Basic Components

- **Disks:** generally metal rich stars and ISM, nearly circular orbits with little random motion, spiral patterns
  - Thin disks: younger, star forming, dynamically very cold
  - Thick disks: older, passive, slower rotation and more random motions
- **Bulge:** metal poor to super-metal-rich stars, high stellar densities, mostly random motion – similar to ellipticals
- **Bar:** present in ~ 50 % of disk galaxies, mostly older stars, some random motions and a ~ solid body rotation?
- **Nucleus:** central (<10pc) region of very high mass density, massive black hole or starburst or nuclear star cluster
- **Stellar halo:** very low density (few % of the total light), metal poor stars, globular clusters, low density hot gas, little or no rotation
- **Dark halo:** dominates mass (and gravitational potential) outside a few kpc, probably triaxial ellipsoids, radial profile ~ singular isothermal sphere, DM nature unknown

# Multi-Phase ISM

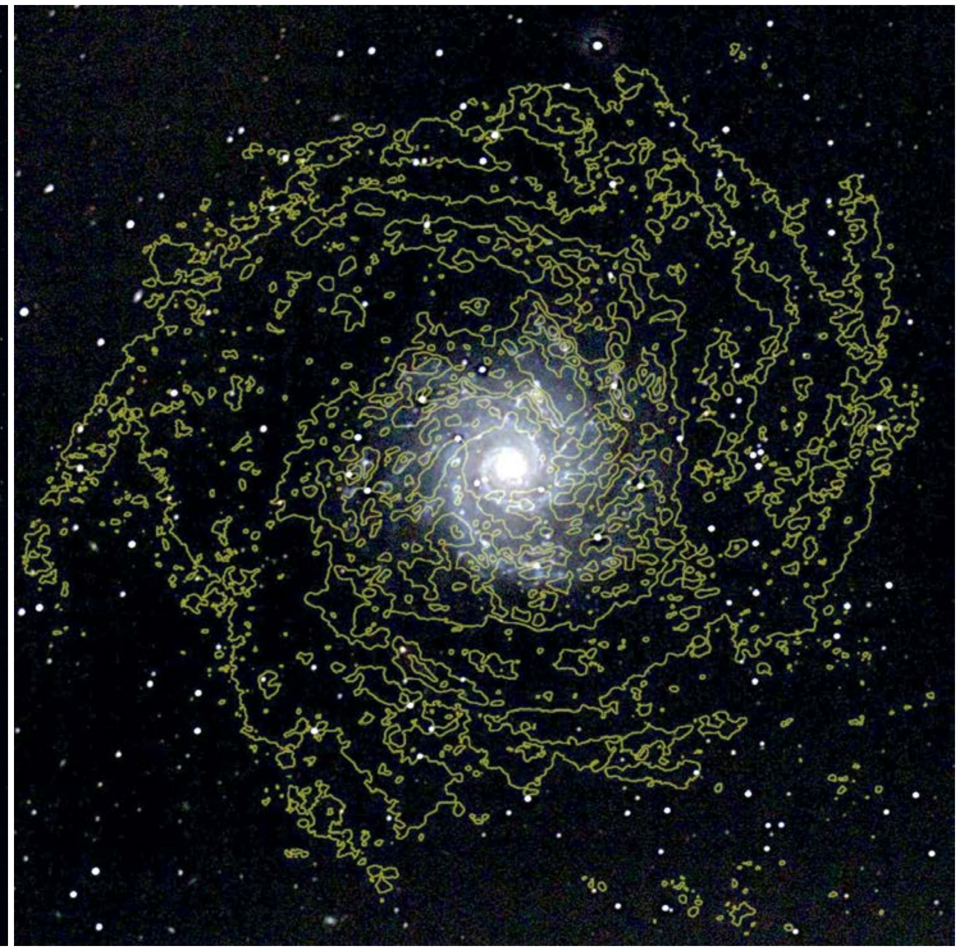
The ISM has a complex structure with 3 major components:

1. **Cold** (T ~ 30 - 100 K), dense ($n_{H\,I} > 10\ cm^{-3}$) atomic (H I) and molecular ($H_2$, CO, …) gas and dust clouds
   - ☆ Only ~ 1 - 5 % of the total volume, but most of the mass
   - ☆ Confined to the thin disk
   - ☆ Low ionization fraction ($x_{H\,II} < 10^{-3}$)
   - ☆ Stars are born in cold, dense clouds
2. **Warm** ($T \sim 10^3 - 10^4$ K) neutral & ionized gas, $n \sim 1\ cm^{-3}$
   - ☆ Energized mainly by UV starlight
   - ☆ Most of the total ISM volume in the disk
3. **Hot** ($T \sim 10^5 - 10^6$ K), low density ($n \sim 10^{-3}\ cm^{-3}$) gas
   - ☆ Galactic corona
   - ☆ Almost fully ionized, energized mainly by SN shocks

# Neutral Hydrogen vs. Starlight

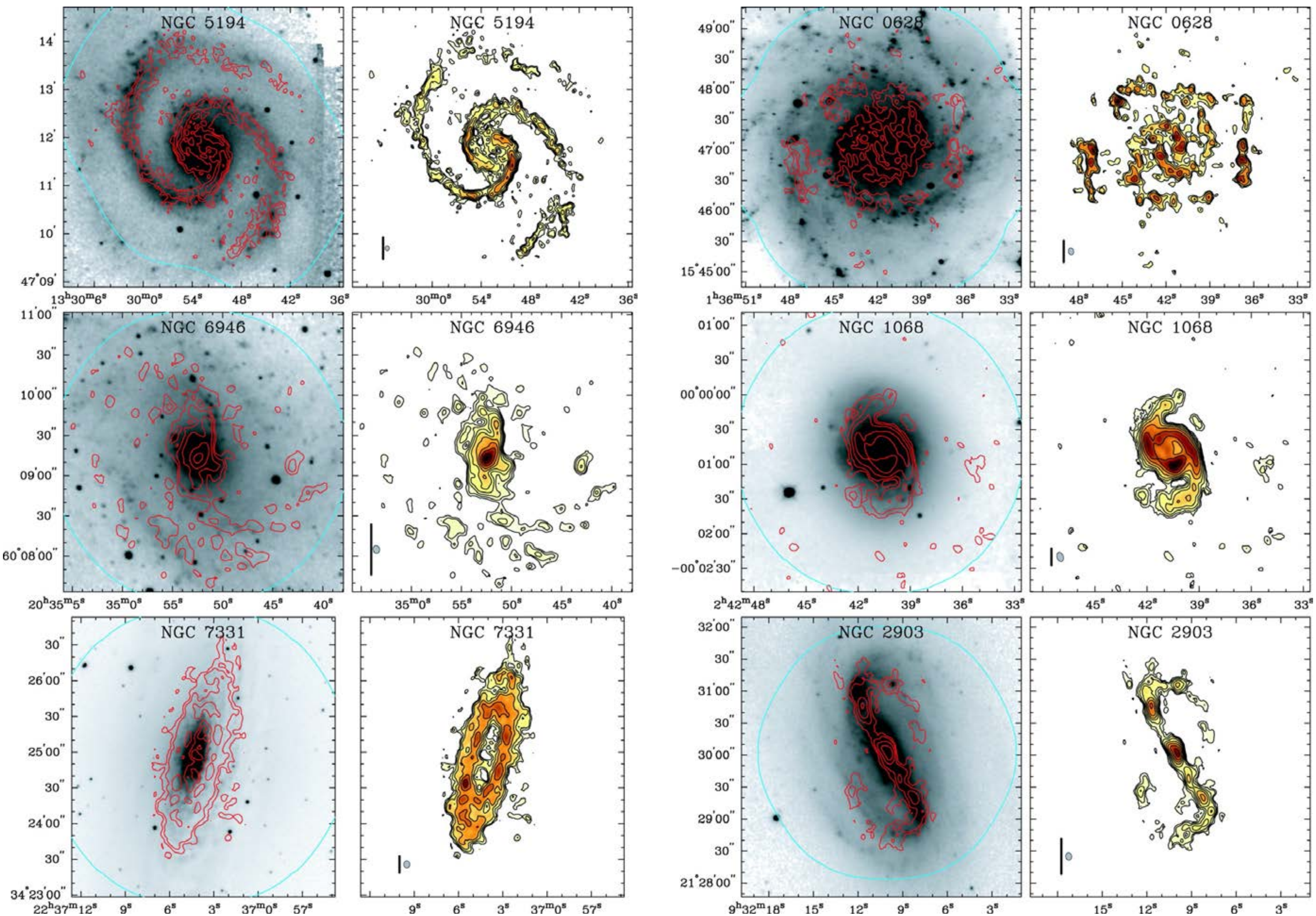
H I (contours) generally follows the spiral arms …

… but it also extends well past the visible light of the disk



This suggests that the stellar disks form from the inside out

# Visible Light and Molecular Gas (CO)



# Elliptical Galaxies

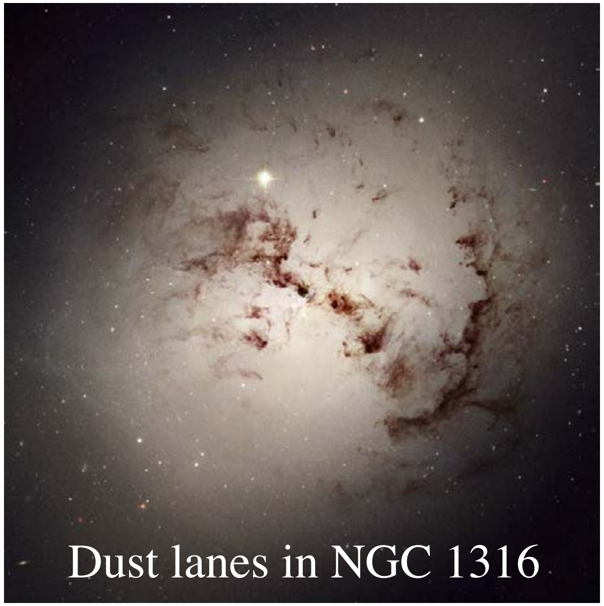
**Old view:** ellipticals are boring, simple systems

- Ellipticals contain no gas & dust
- Ellipticals are composed of old stars
- Ellipticals formed in a monolithic collapse, which induced violent relaxation of the stars, stars are in an equilibrium state

**Modern view:**

- Most/all ellipticals have hot x-ray gas, some have dust, even cold gas
- Ellipticals do rotate, but most of the kinetic energy support (and galaxy shapes) come from an anisotropic velocity dispersion
- Some contain decoupled (counter-rotating) cores, or other complex kinematics
- Some have weak stellar disks
- Ellipticals formed by mergers of two spirals, or hierarchical clustering of smaller galaxies

M87



Dust lanes in NGC 1316

# Elliptical Galaxies: Surface Photometry

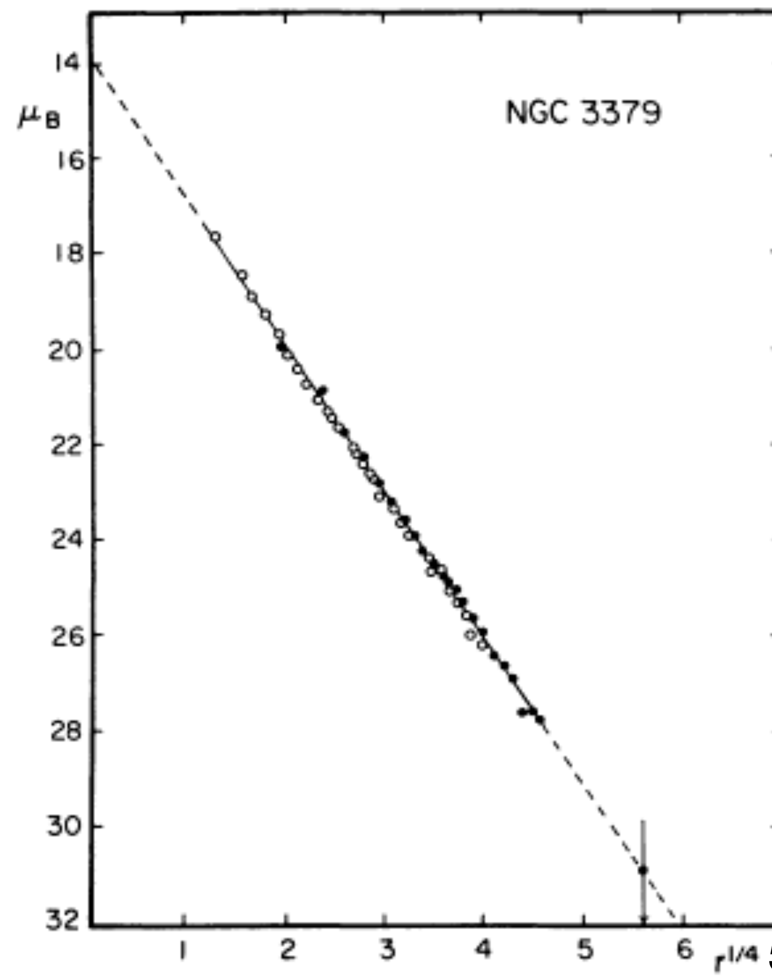
Surface brightness = projected luminosity density of elliptical galaxies falls off smoothly with radius. Measured (for example) along the major axis of the galaxy, the profile is normally well represented by the *$R^{1/4}$ or de Vaucouleurs law*:

$$I(R) = I(0)\, e^{-kR^{1/4}}$$

where k is a constant. This can be rewritten as:

$$I(R) = I_e\, e^{\left\{-7.67\left[(R/R_e)^{0.25}-1\right]\right\}}$$

where $R_e$ is the ***effective radius*** - the radius of the isophote containing half of the total luminosity, typically a few kpc. $\boldsymbol{I_e}$ is the surface brightness at the effective radius.



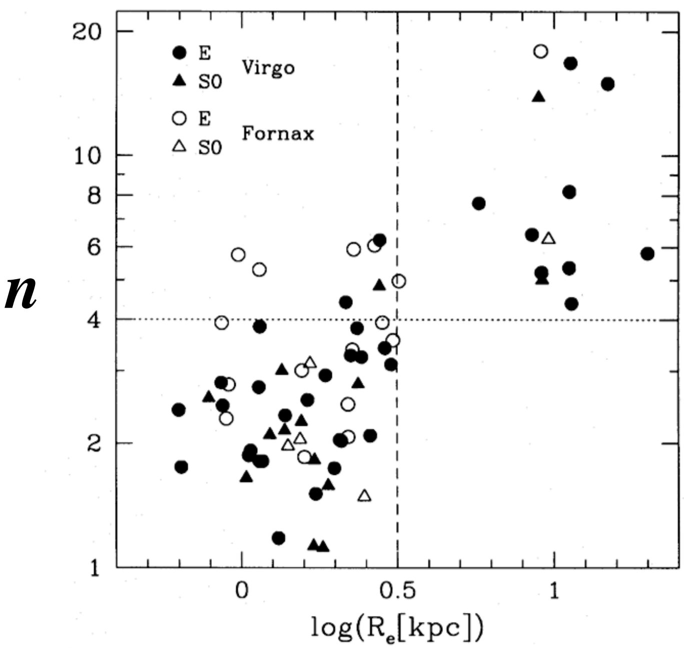
# Elliptical Galaxies:  Surface Photometry

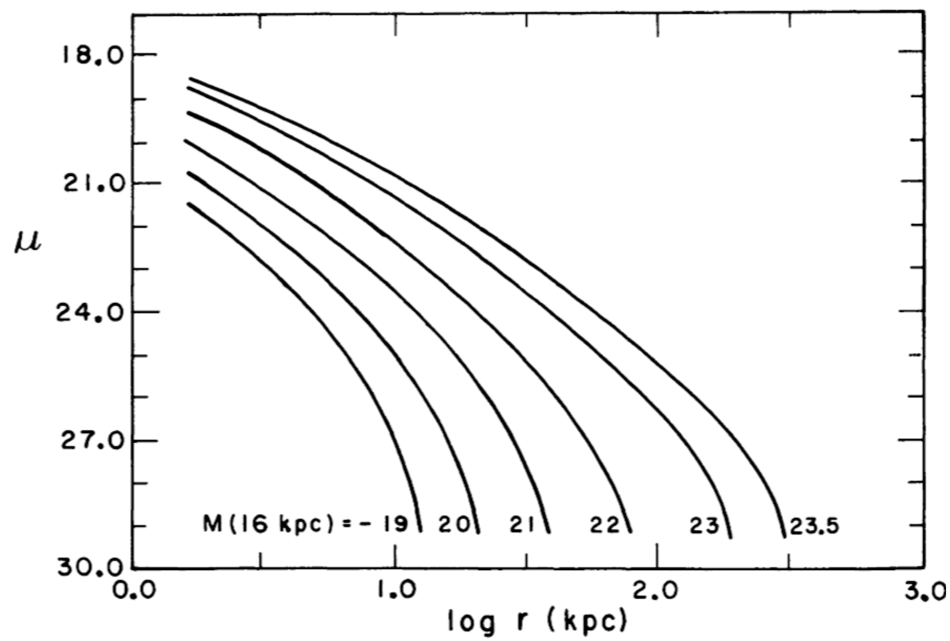
***More generally, it is the Sersic profile:***

$$\Sigma(r) = \Sigma_0 \exp\left\{-b_n\left[(r/r_e)^{1/n}\right]\right\}$$

where $\Sigma$ is the surface brightness in linear units (not magnitudes), $\mathbf{b_n}$ is chosen such that half the luminosity comes from $R < R_e$.  This law becomes de Vaucouleurs for $n = 4$, and exponential for $n = 1$.

There is a systematic trend that the $n$ is larger, i.e., the profiles are shallower with the increasing luminosity:



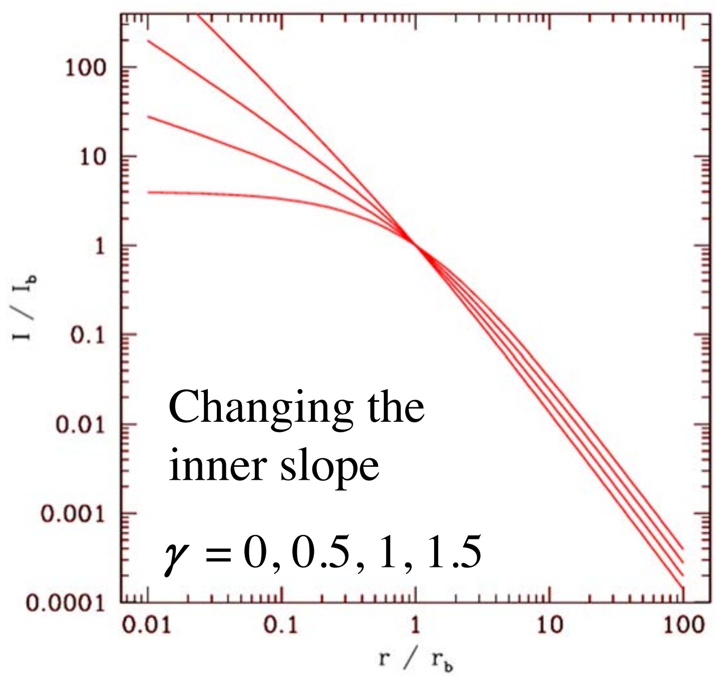
# The Cores and Nuclei of Ellipticals

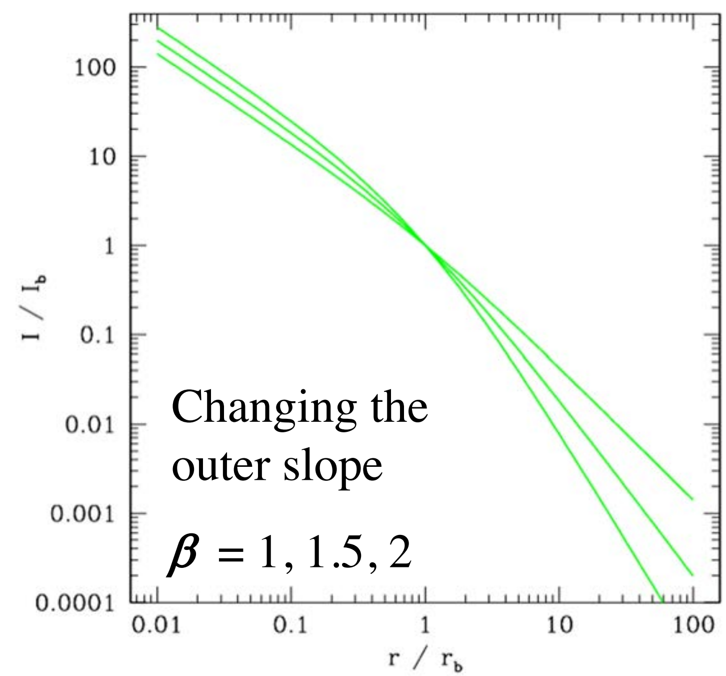
Close to the center profiles deviate from the $R^{1/4}$ law:

- More luminous ellipticals tend to have **cores** - region where the surface brightness flattens and is ~ constant
- Less luminous ellipticals tend to have power law **cusps** – surface brightness rises steeply towards the center

This is described by a more general "Nuker" profile:

$$I(R) = I_b 2^{(\beta-\gamma)/\alpha}\left(\frac{R}{R_b}\right)^{-\gamma}\left[1+\left(\frac{R}{R_b}\right)^{\alpha}\right]^{(\gamma-\beta)/\alpha}$$



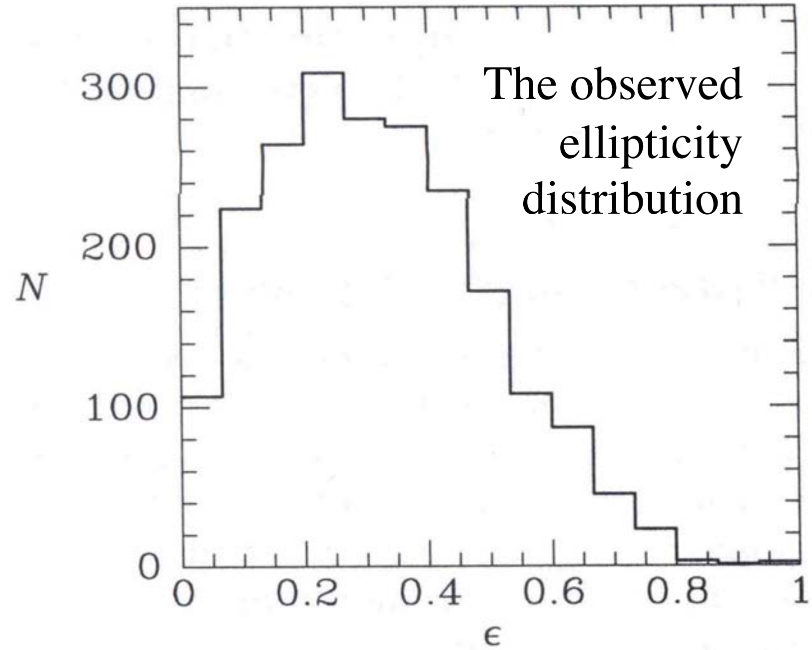



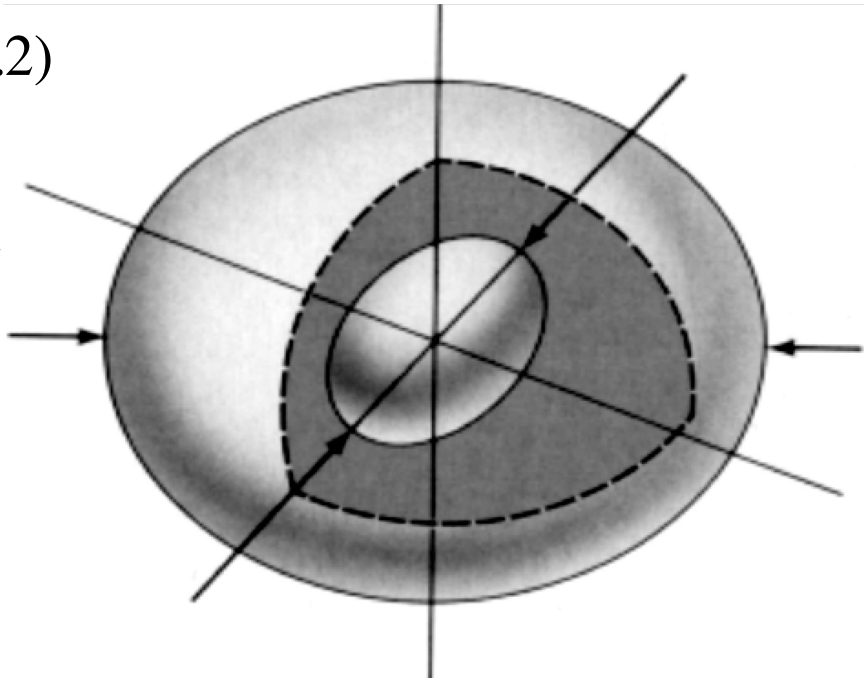
# Shapes of Ellipticals

- Ellipticals are defined by E*n*, where $n=10\varepsilon$, and $\varepsilon=1-b/a$ is the ellipticity, *as projected on the sky*
- More generally, we believe that they are mildly ***triaxial ellipsoids***, defined by three axes, *a*, *b*, and *c*, typically

  $a{:}b{:}c \sim 1 : 0.95 : 0.65$ (dispersion ~ 0.2)

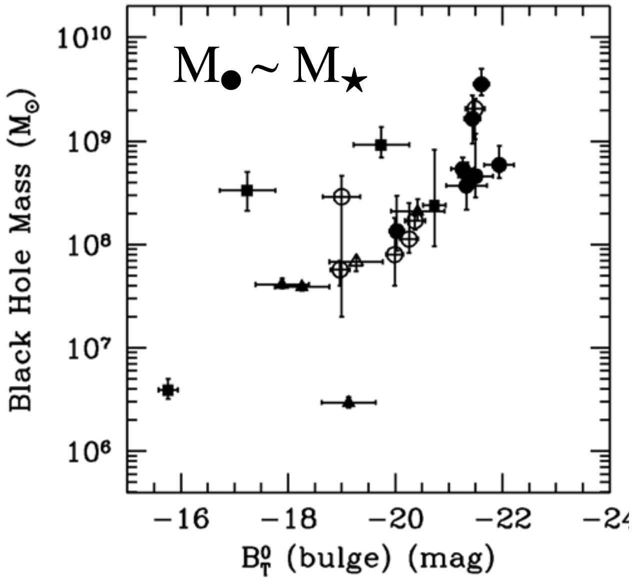
- Triaxiality produces *isophotal twists* (would not see these if galaxies were purely oblate or prolate)
- It is due to the ***anisotropic velocity dispersions***, which stretch the galaxies in proportion along their 3 principal axes

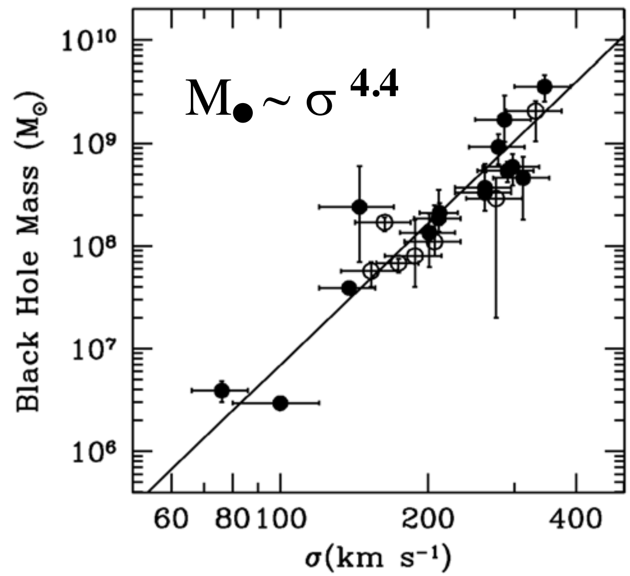


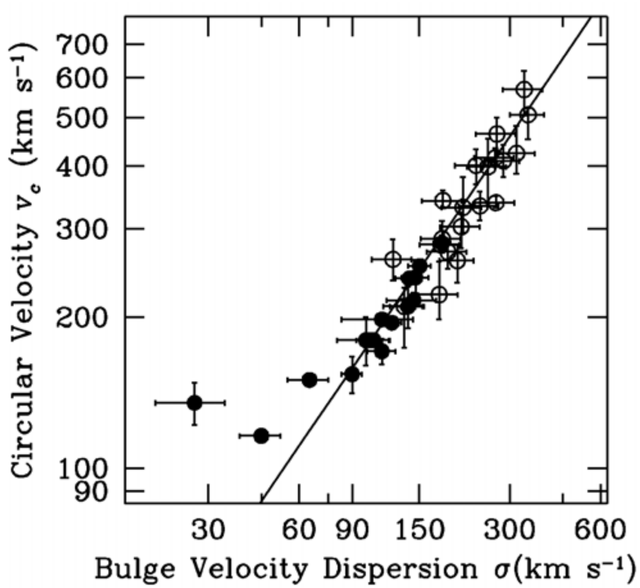



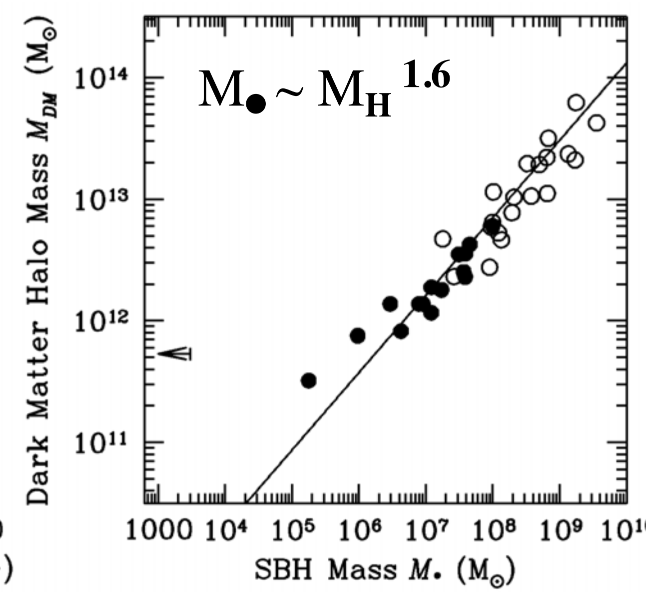
*(from Binney & Merrifield)*

# The SMBH - Host Galaxy Correlations



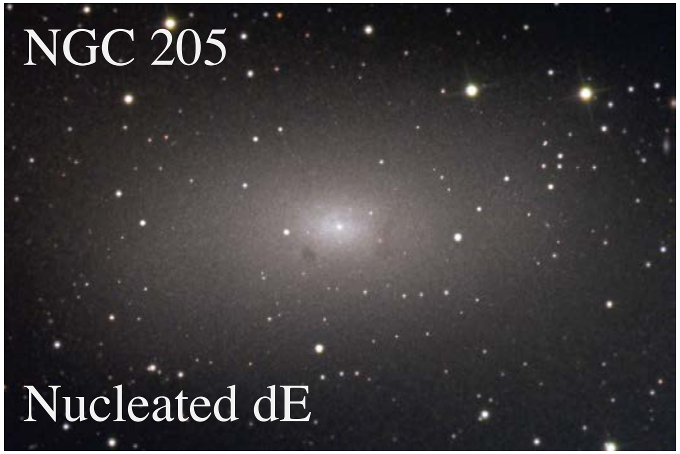

Formation and growth of the central supermassive black holes are closely coupled with those of their host galaxies

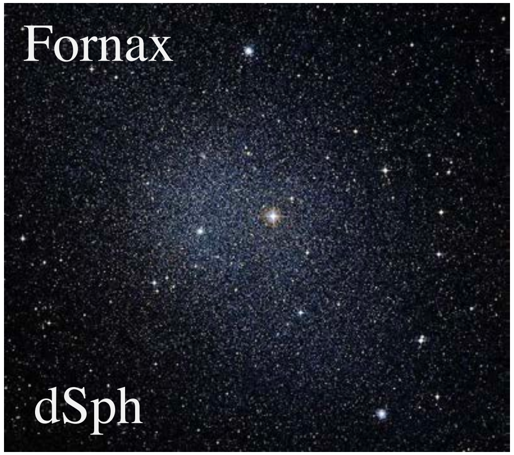
# Elliptical Galaxies: Key Points

- Elliptical galaxies and bulges contain *old, metal-rich stellar populations*, and some show signs of recent merging
- They are supported against their self gravity by *random motions of stars*, with little or no rotation, and their shapes are *triaxial ellipsoids due to the anisotropic velocity dispersion*
- There is some variety in their radial density profiles, with larger galaxies being less concentrated
- Their stellar populations are *redder and more metal-rich closer to their centers*, indicative of a chemical self-enrichment
- More massive ellipticals have larger mass-to-light ratios, which can have multiple physical causes
- *Most (all?) contain supermassive black holes* in their centers, whose masses are correlated with the host galaxy properties, indicating a *shared formation mechanism*

# Dwarf Galaxies

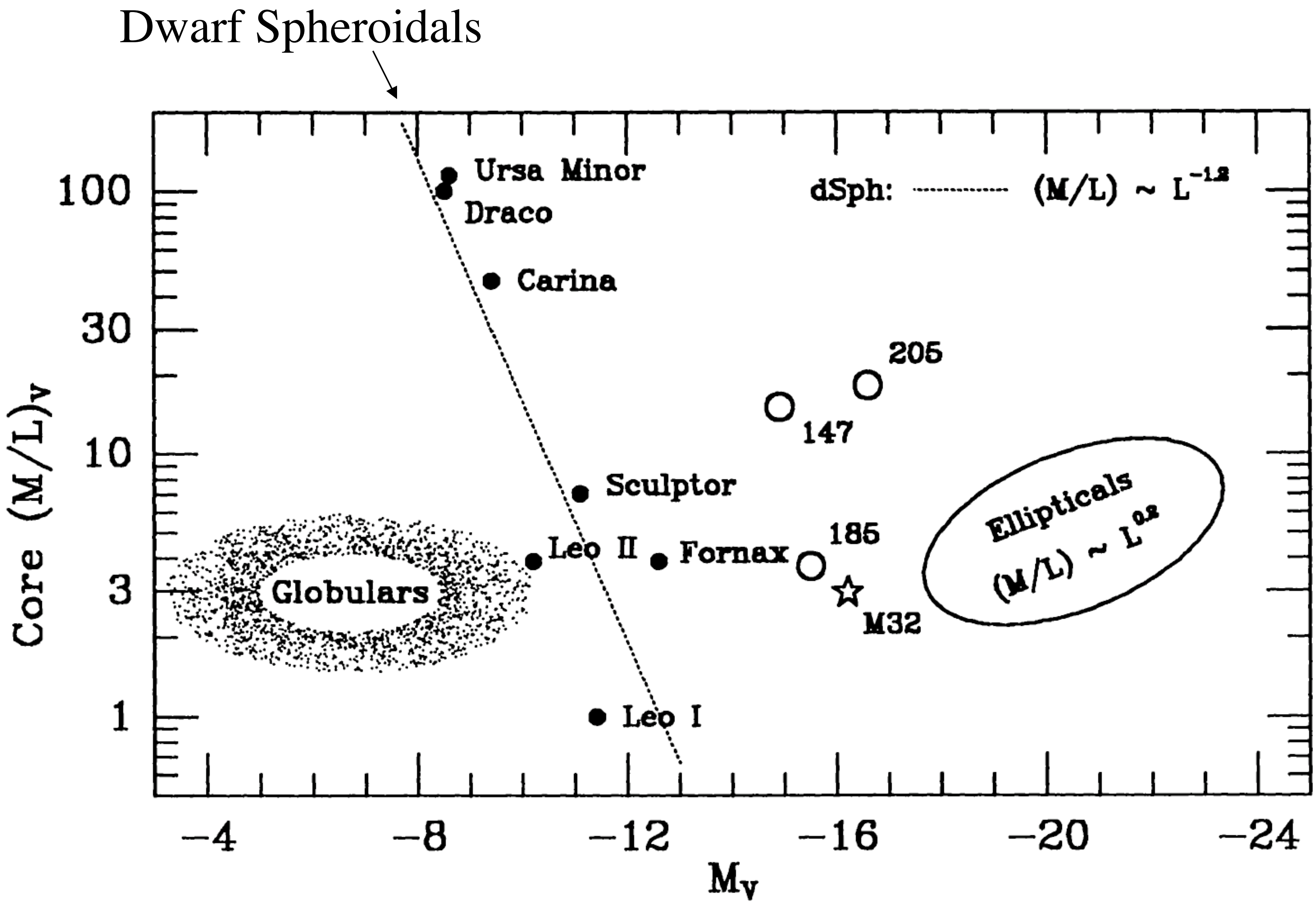
- Dwarf ellipticals (dE) and dwarf spheroidals (dSph) are different families of objects from normal ellipticals – they are not just small E's




- Dwarfs 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
- Supernova (SN) winds can remove baryons from these low-mass systems, while leaving the DM, while the more massive galaxies retain and recycle their SN ejecta

# Mass to Light Ratios



# Scaling relations

# Galaxy Scaling Laws

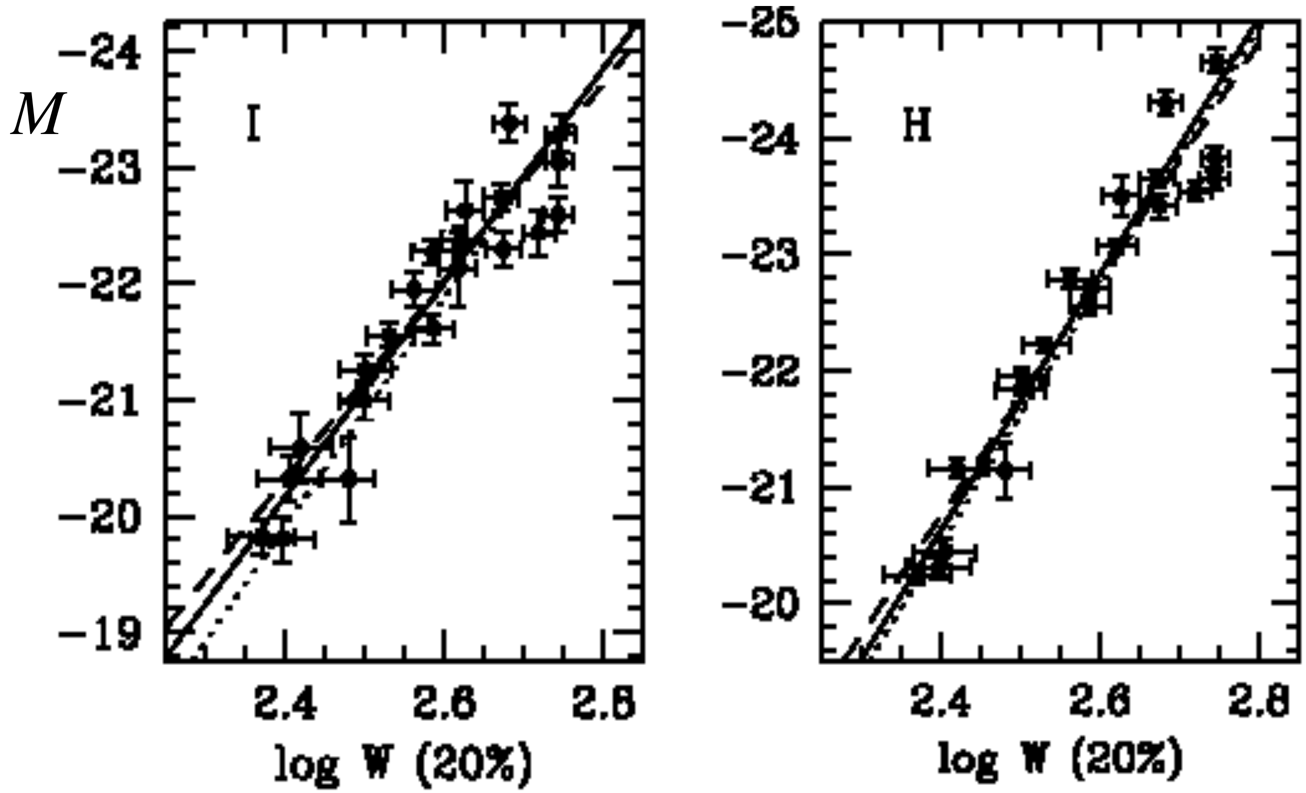
- When correlated, global properties of galaxies tend to do so as power-laws; thus "scaling laws"
- They provide a ***quantitative means of examining physical properties of galaxies and their systematics***
- They ***reflect the internal physics of galaxies, and are a product of the formative and evolutionary histories***
  - Thus, they could be (and are) different for different galaxy families
  - We can use them as a fossil evidence of galaxy formation
- When expressed as correlations between distance-dependent and distance-independent quantities, they can be used to measure relative distances of galaxies and peculiar velocities: thus, it is really important to understand their intrinsic limitations of accuracy, e.g., the possible environmental dependences

# The Tully-Fisher Relation

- A well-defined luminosity vs. maximum rotational speed relation for spirals:

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

The slope can be also measured from any set of galaxies with roughly the same distance - e.g., galaxies in a cluster - even if that distance is not known




- Scatter can be as low as ~ 10%, better in the redder bands

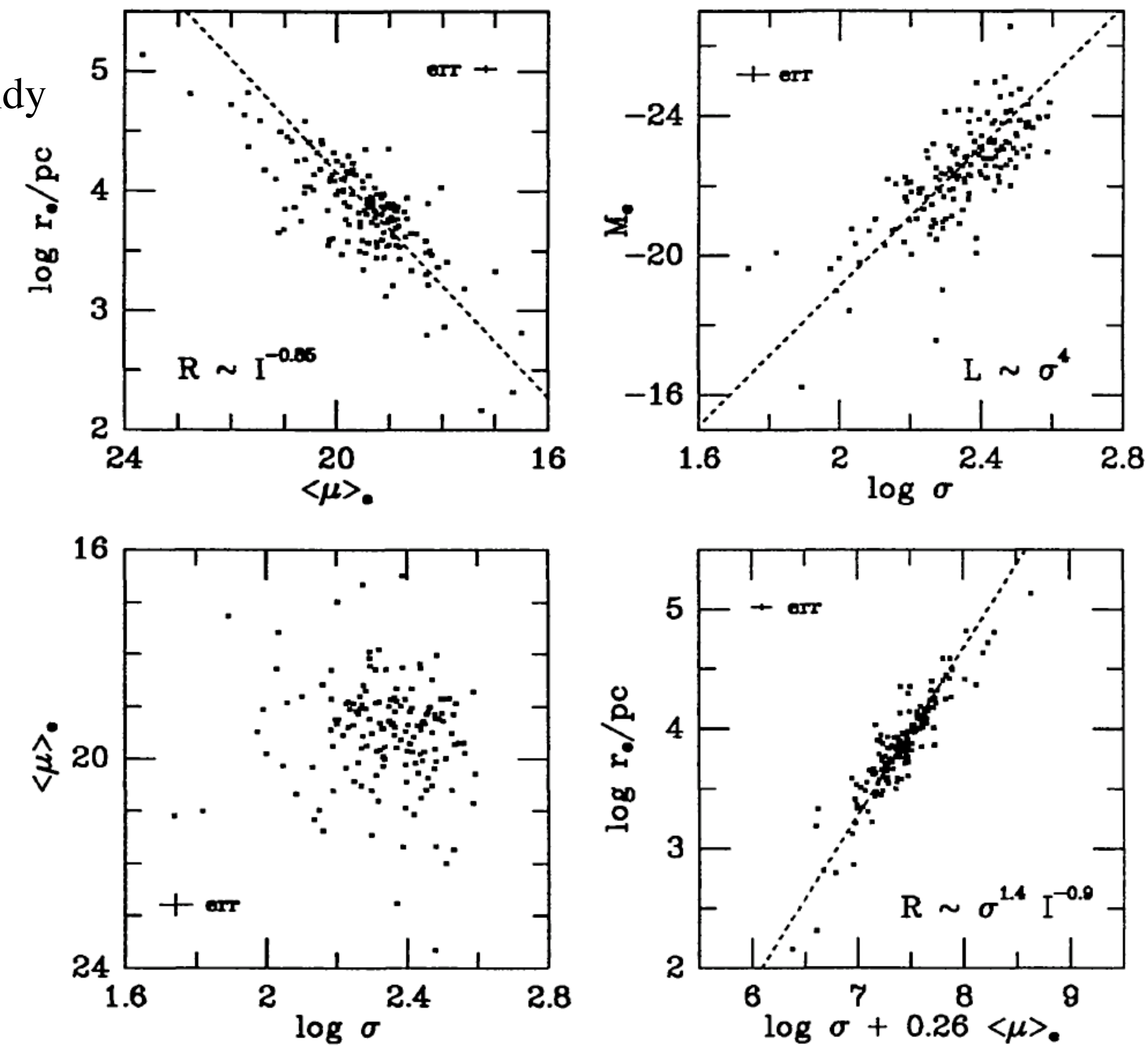
# Why is the TFR So Remarkable?

- 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
- Suggests a halo-regulated galaxy formation/evolution?
- The scatter is remarkably low - even though the conditions for this to happen are known not to be satisfied (e.g., a large spread in surface brightness and M/L ratios at any given luminosity)
- There is some important feedback mechanism involved, which we do not understand yet
- Thus, the TFR offers some important insights into the physics of disk galaxy formation

# Scaling Relations for Ellipticals

Kormendy rel’n

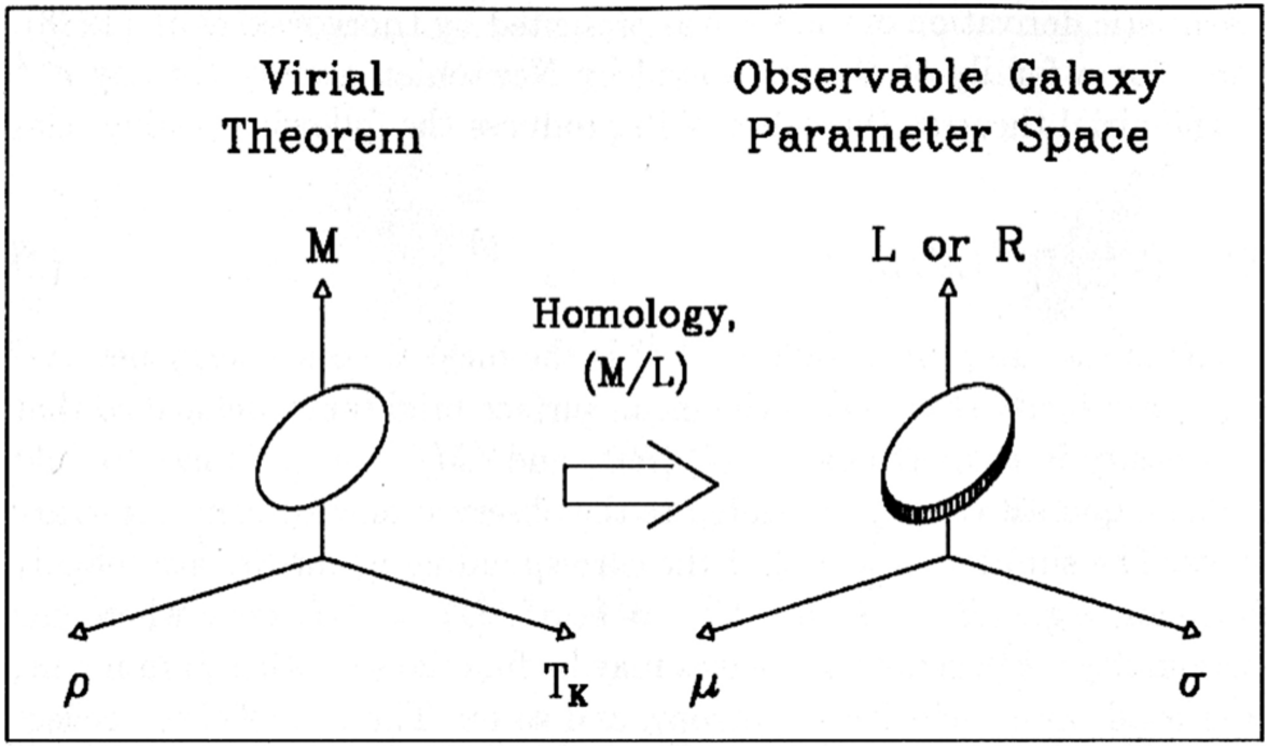
Faber-Jackson rel’n




Cooling diagram

Fundam. Plane

# From Virial Theorem to FP




Virial Theorem, $m\sigma^2 \sim GmM/R$

# Galaxy Scaling Laws: Key Points

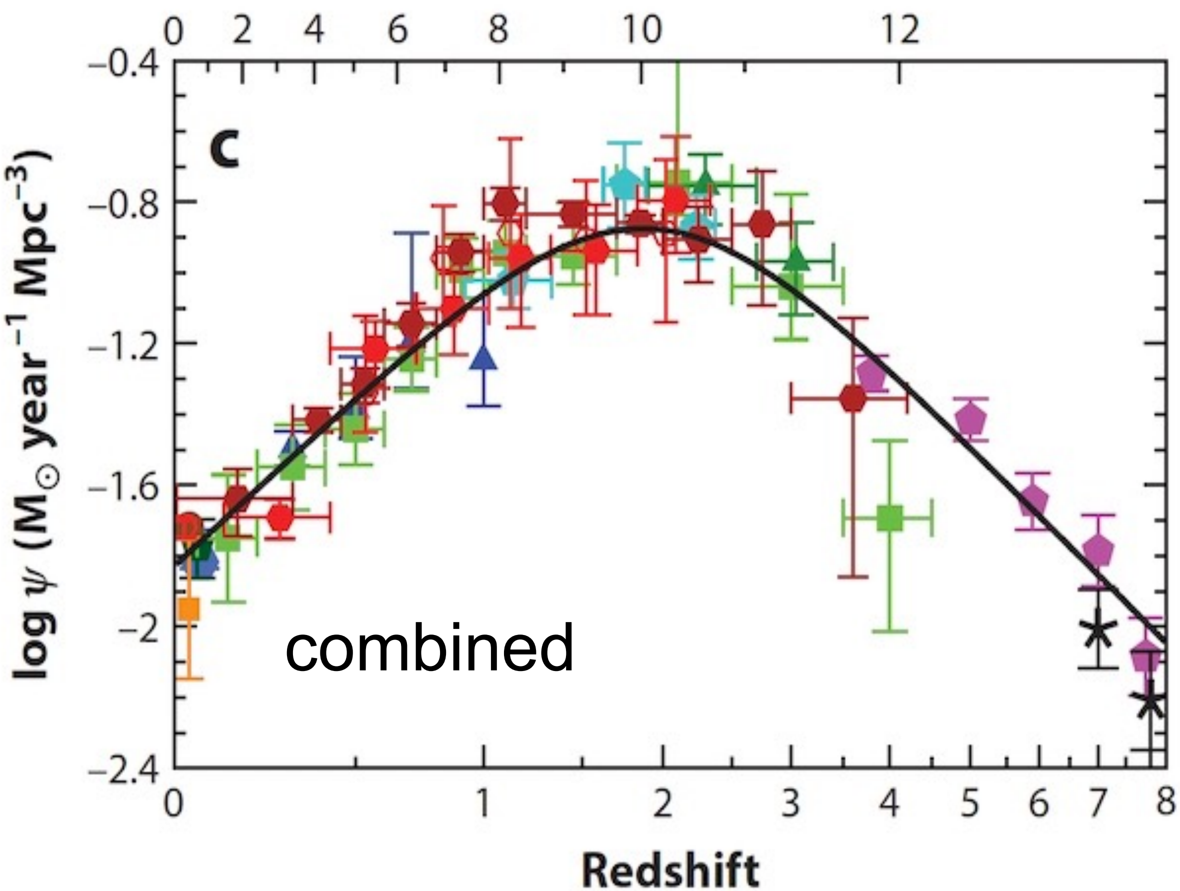
- Many *fundamental properties of galaxies are correlated*, typically as *power laws (scaling relations)*, e.g., the Tully-Fisher relation for spirals and the Fundamental Plane relations for ellipticals
- These relations contain ***information about their formative and evolutionary histories***, and can sometimes be used as ***distance indicator relations***
- Their basic forms reflect the virial theorem (i.e., galaxies are self-gravitating systems), but ***the details and the small scatter are still not fully understood***
- These relations indicate a strong coupling between the galaxy dynamics and structure and their star formation history
- ***Dwarf galaxies obey different scaling relations*** from the large galaxies, indicative of different formation mechanisms

# Outline

1. **Background Universe**
   history, cosmology, cosmic inventory
2. **The many kinds of Galaxies**
   morphology, scaling relation, observational probes
3. **Galaxy evolution & first galaxies**
   star-formation and assembly history, JWST and EoR

# Cosmic Star Formation History

Observations in UV/optical give us the unobscured star formation rate, and in Far-IR/sub-mm the obscured component




The average star formation peaks around z ~ 2 (the "cosmic noon")

*(Madau & Dickinson 2014)*

# 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 x 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

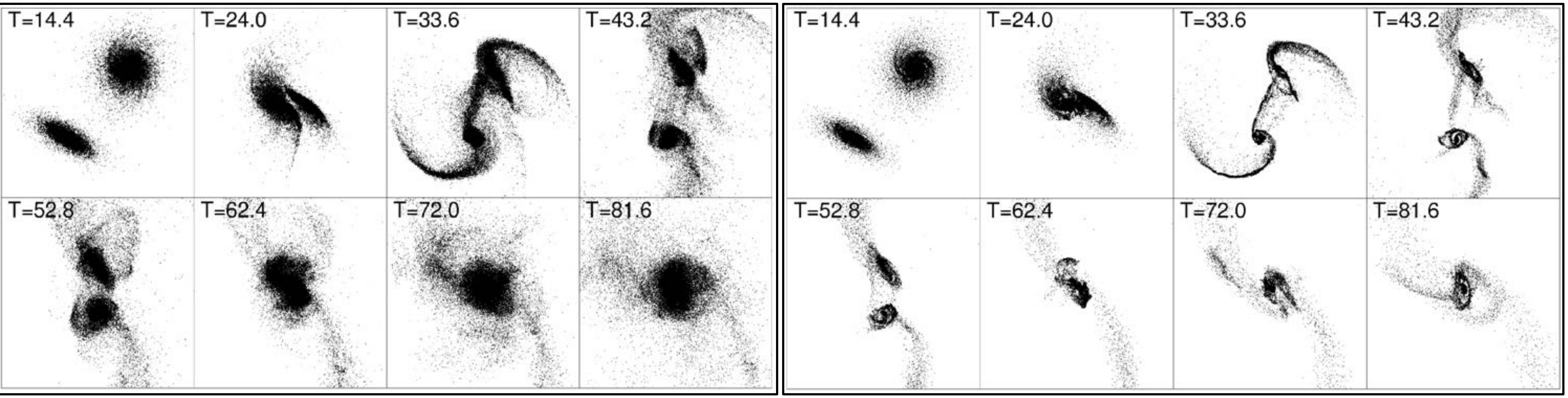
1. **Assembly of the mass:** numerical modeling of structure formation. Fairly well advanced, but it is hard to treat any dissipative processes very accurately. Well constrained from cosmology (LSS formation)
2. **Evolution of stellar populations:** based on stellar evolution models, and fairly well understood. Lots of parameters: the stellar initial mass function, star formation history, stellar evolutionary tracks and spectra as functions of metallicity. Poorly constrained a priori.
3. **Hybrid schemes,** e.g., "semi-analytical" models. Use both of the above to assemble comprehensive models, but not constrained very well

# 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 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

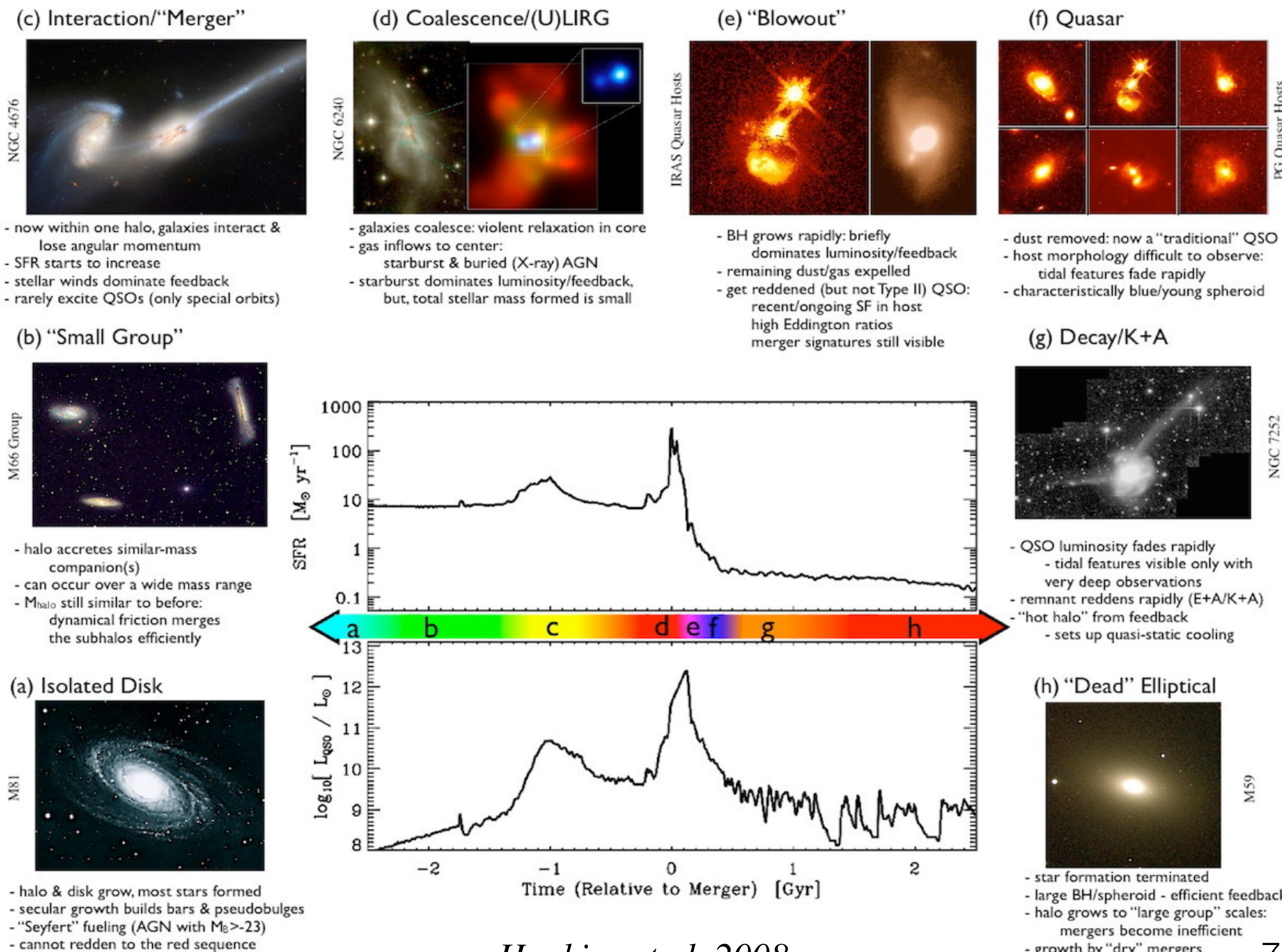
# Galaxy Merging / Dynamical Evolution

- Commonly observed today, and must have been more important in the past, a part of the overall hierarchical structure formation
- Mergers change the numbers and mass distribution function of galaxies, and their internal structure/morphology
- Dissipative merging can lead to starbursts and feeding of AGN




Stars and DM (Dissipationless)

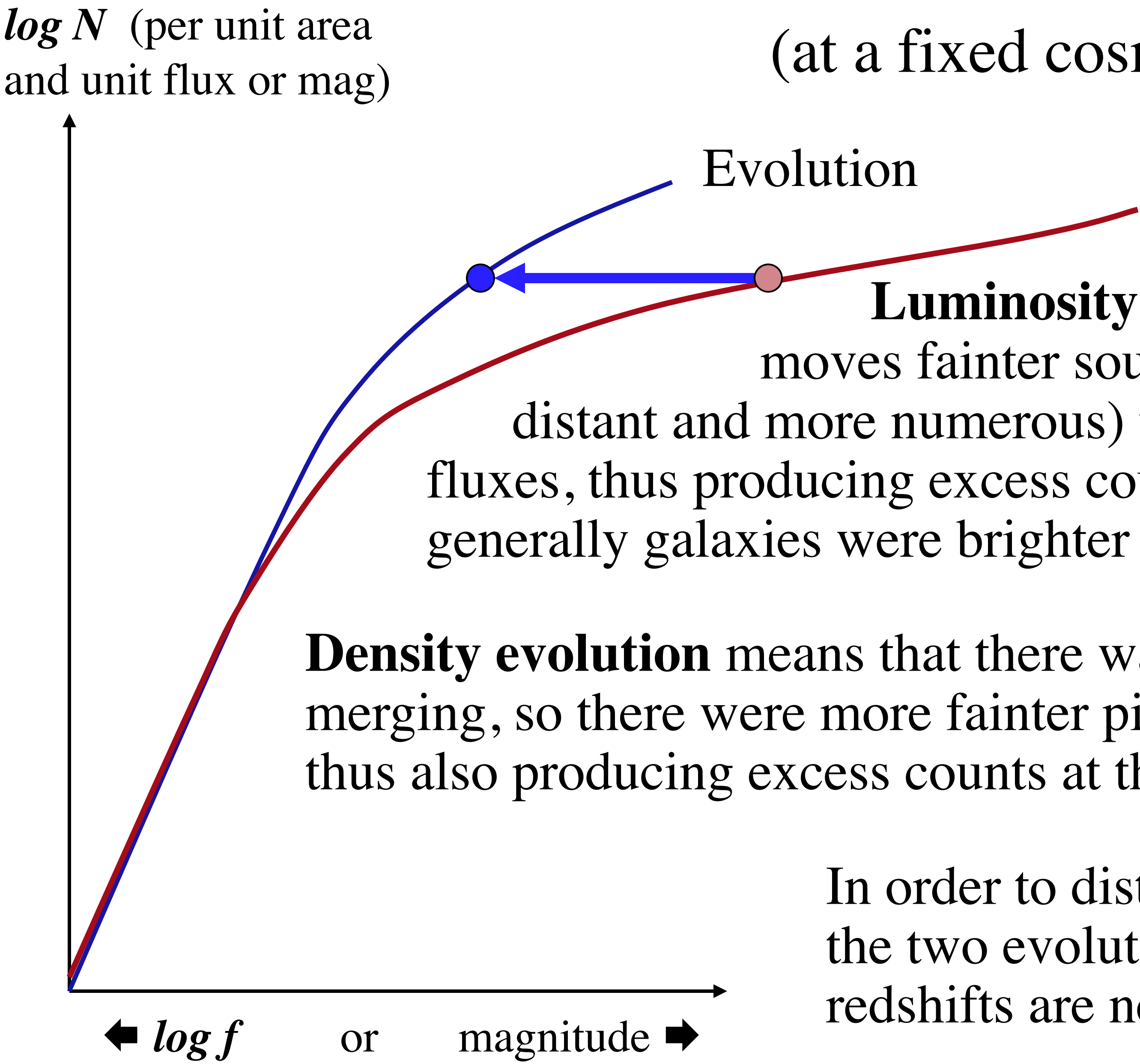
Gas (Dissipative)




*Hopkins et al. 2008*

# Source Counts: The Effect of Evolution

(at a fixed cosmology!)



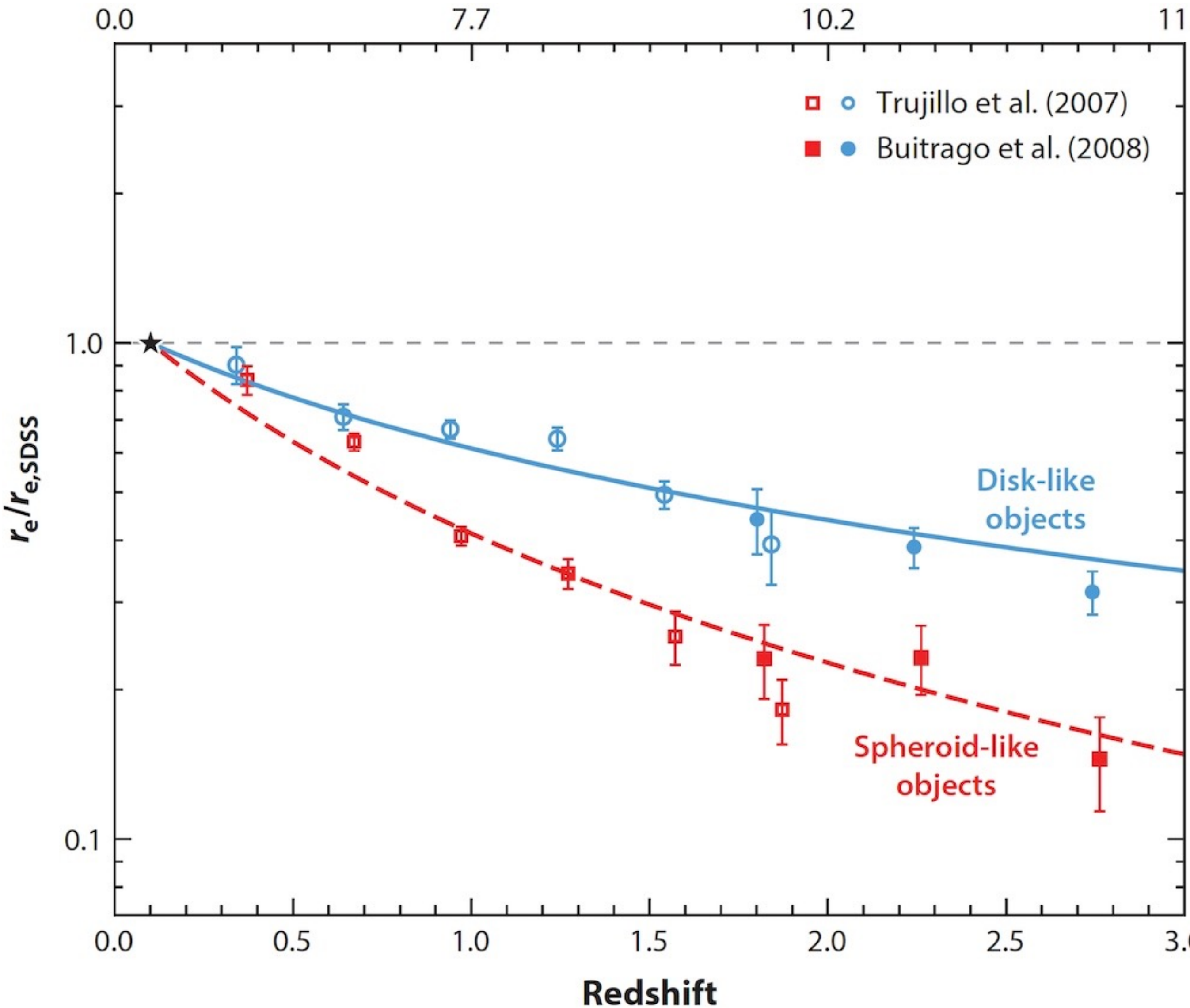

**Luminosity evolution** moves fainter sources(more distant and more numerous) to brighter fluxes, thus producing excess counts, since generally galaxies were brighter in the past

**Density evolution** means that there was some galaxy merging, so there were more fainter pieces in the past, thus also producing excess counts at the faint end

In order to distinguish between the two evolution mechanisms, redshifts are necessary

# Evolution of Galaxy Sizes

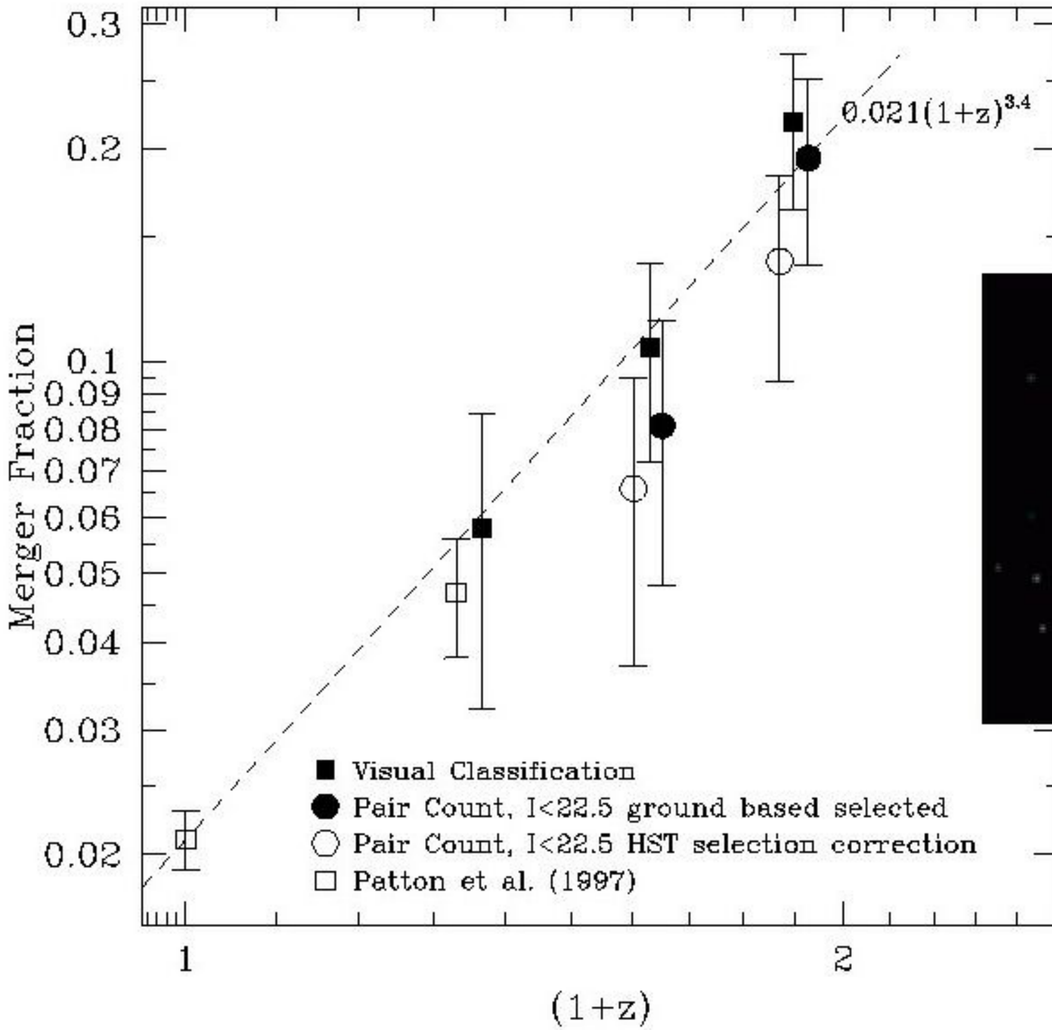
HST imaging suggests that *galaxies were smaller in the past*

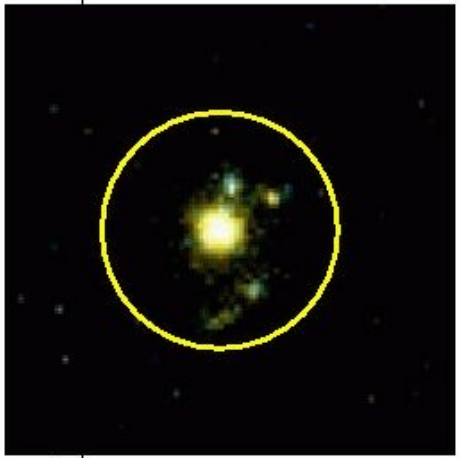


# Evolution of the Merger Rate

*Merger fraction*

*~ $(1 + z)^{3.4}$*



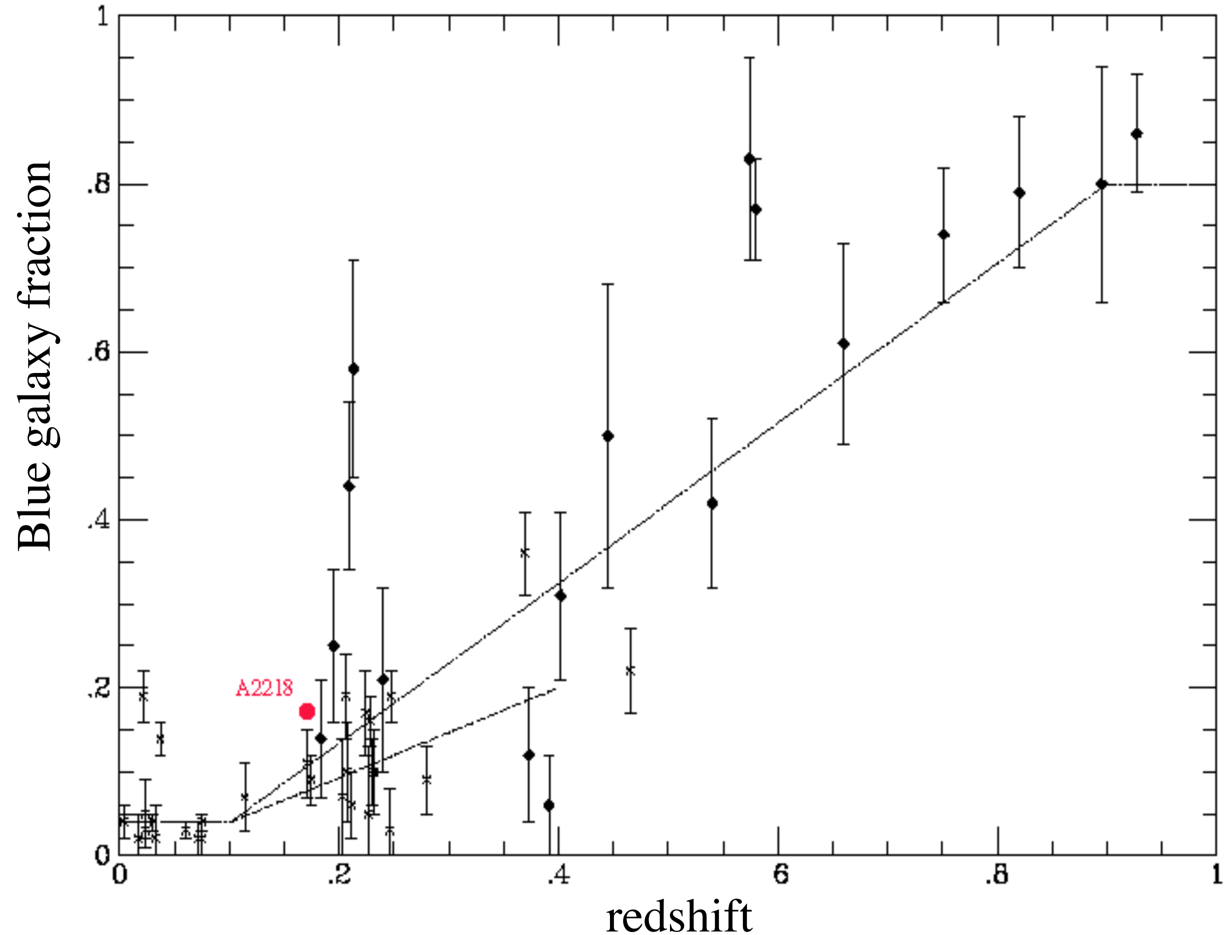



(LeFevre et al. 2000)

Good evidence for a rapid rise in merging fraction at higher z's, but conversion to mass assembly rate is not straightforward

# Galaxy Evolution in Clusters

Generally, we may expect a systematic difference in galaxy evolution processes in different large-scale environments, due to galaxy encounters, gas ram pressure stripping in clusters, etc.

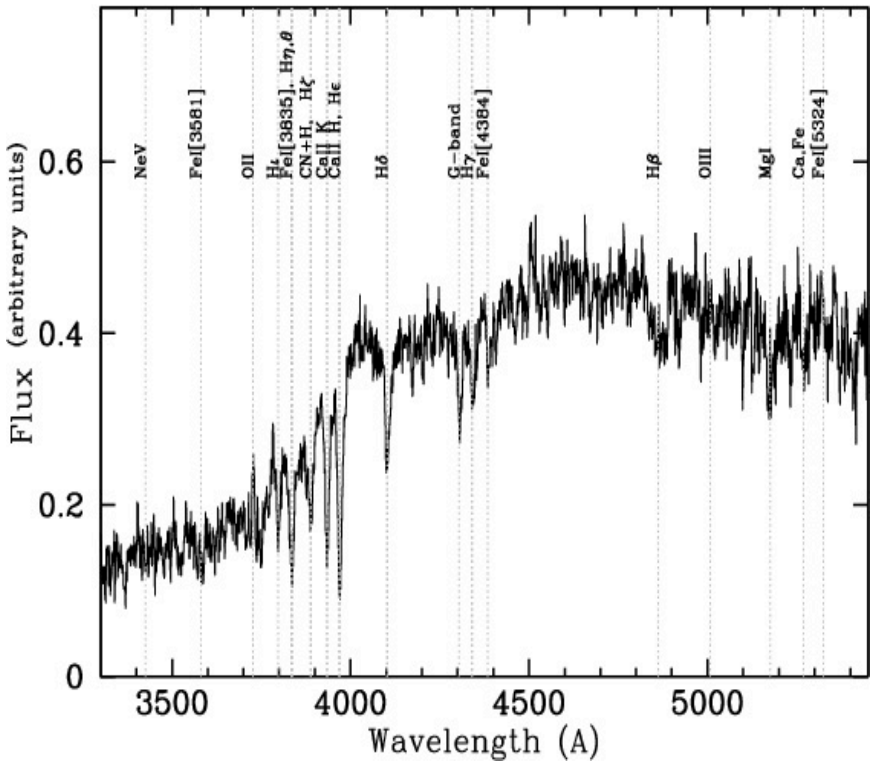



The first observational evidence was the **Butcher-Oemler effect:** the fraction of blue galaxies in clusters increases dramatically at higher redshifts

# Post-Starburst Galaxies

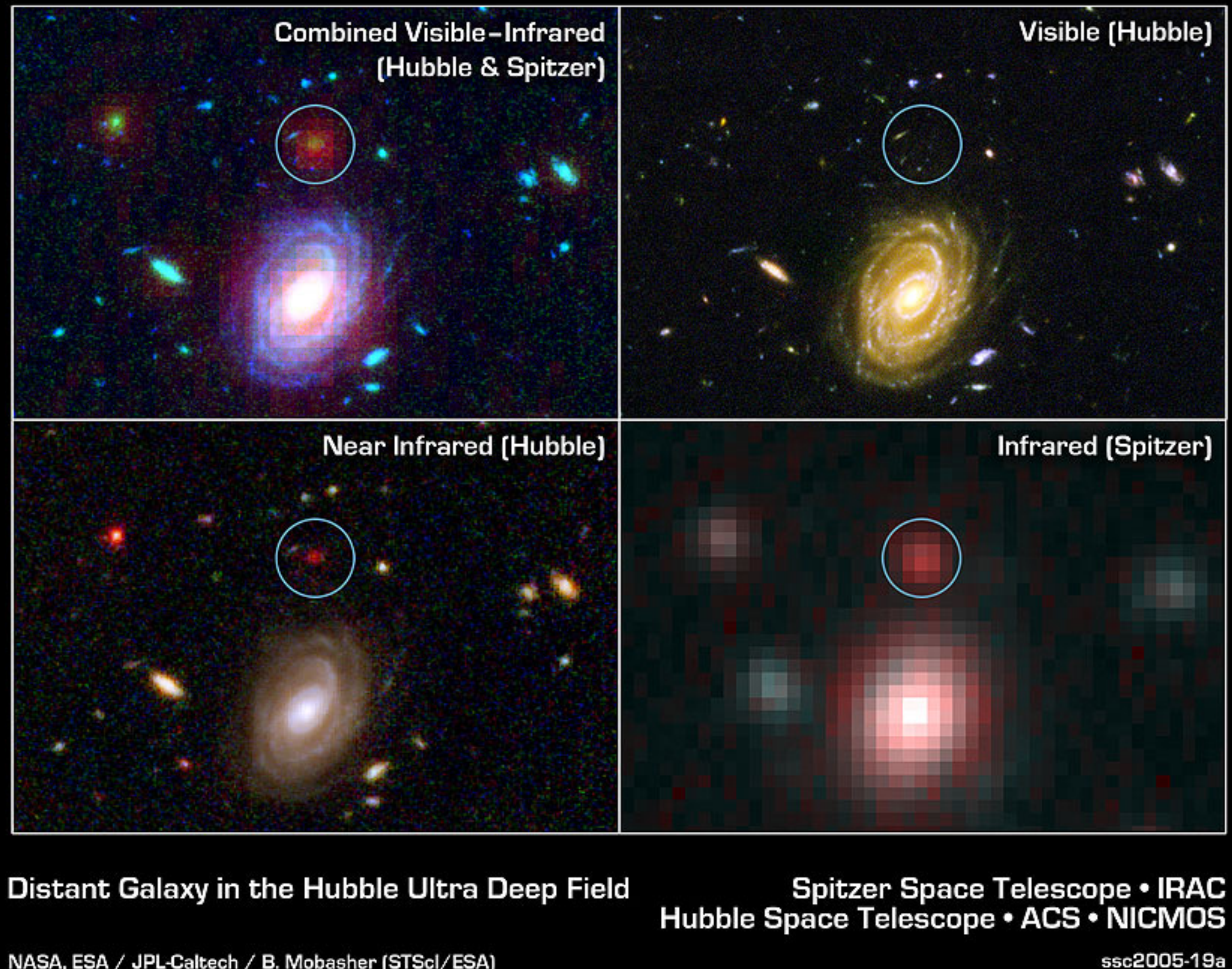
- These blue galaxies in distant clusters are a mix of regular star-forming spirals, some AGN, and a *new type:*

- There is a significant population of ***post-starburst galaxies*** in distant clusters (~20%), these have K+A (or E+A) spectrum, showing both the features of a K-star (typical E galaxy spectrum) plus the strong Balmer absorption lines of an A star (~ 1 Gyr old)

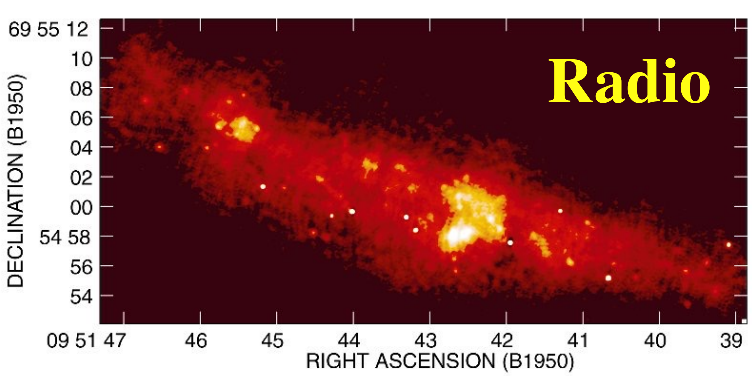



- This is probably related to the conversion of S0 to S galaxies (morphology density) and the Butcher-Oemler effect

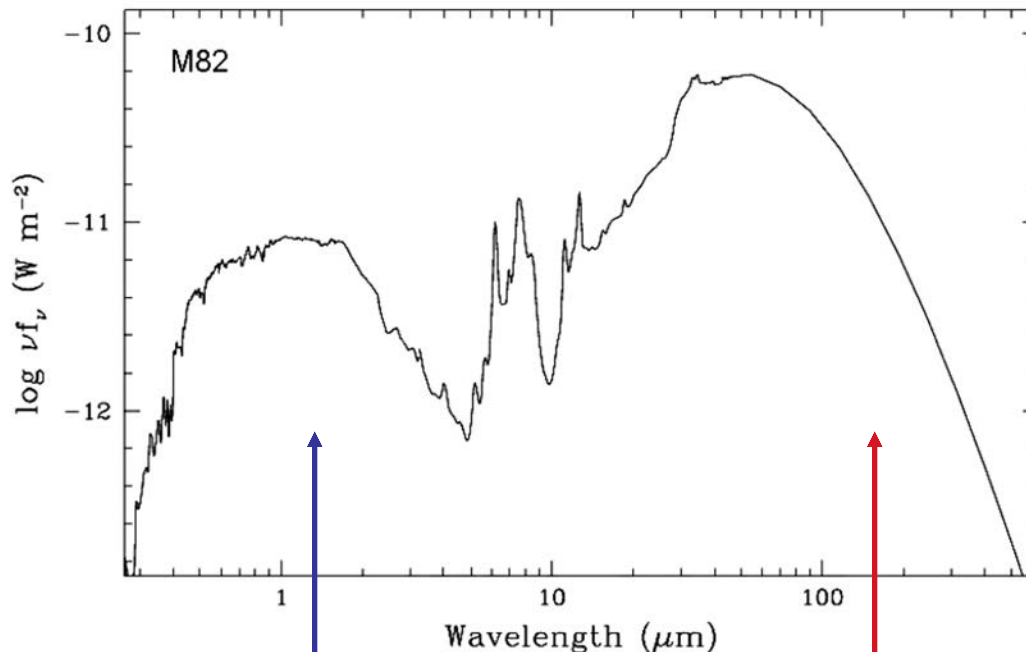
# Dust Obscured Galaxies



# M82, a Prototypical Starburst Galaxy

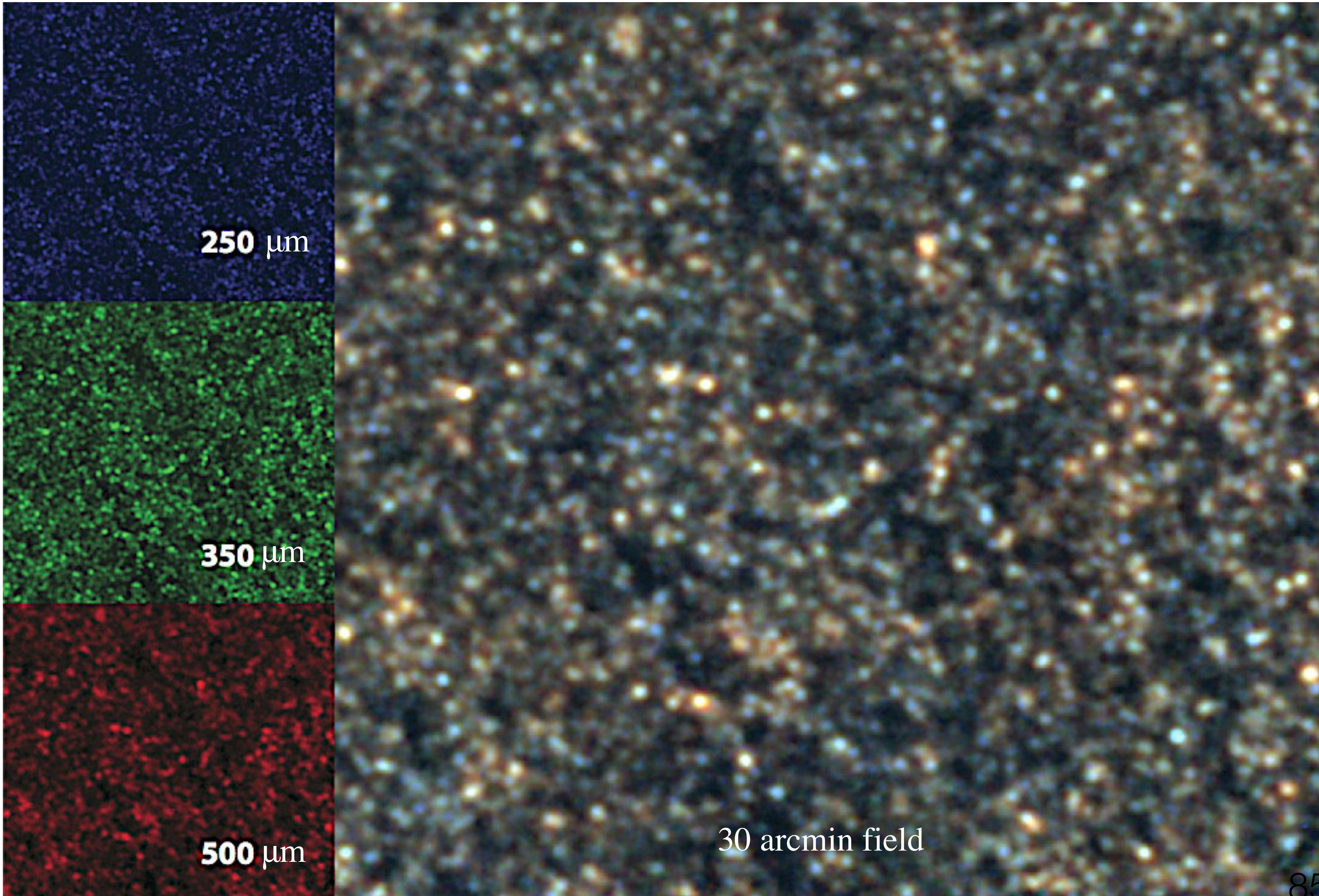

The spectrum of M82, UV to sub-mm



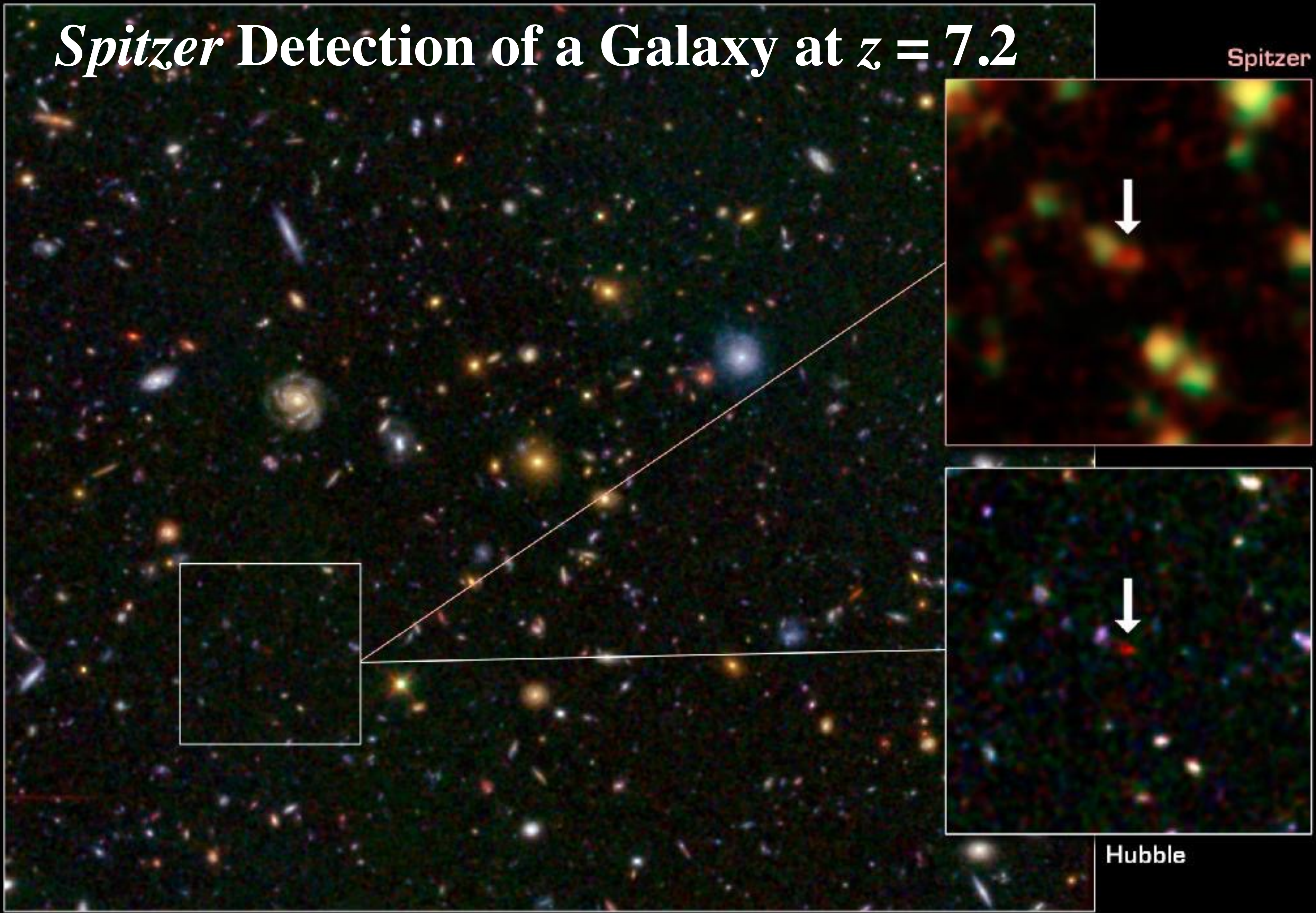

Unobscured starlight

Reprocessed radiation from dust

# *Herschel* FIR Image of the GOODS-N Deep Field



# *Spitzer* Detection of a Galaxy at $z = 7.2$

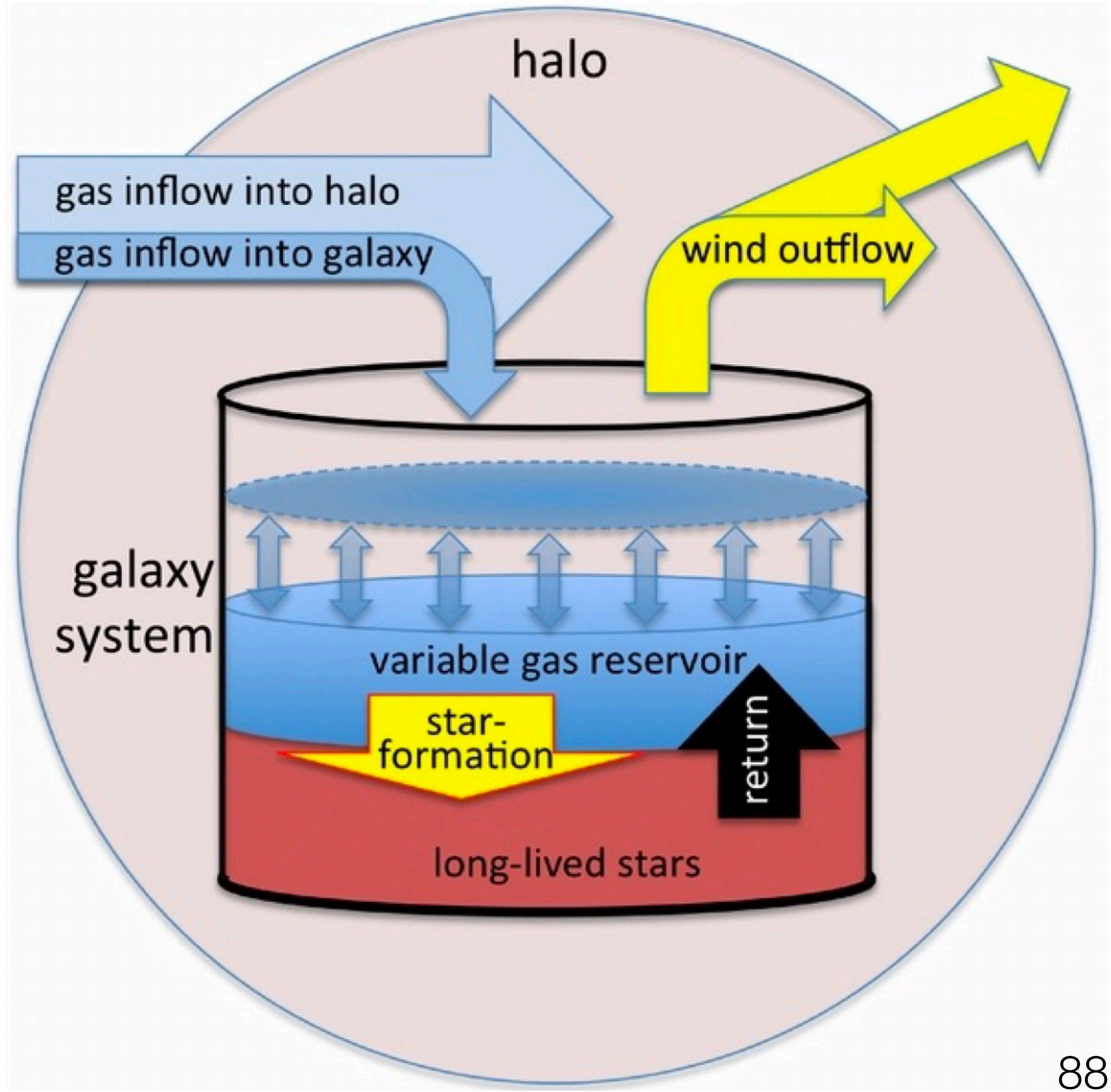


# And Now With the JWST

# The Cosmic Chemical Evolution

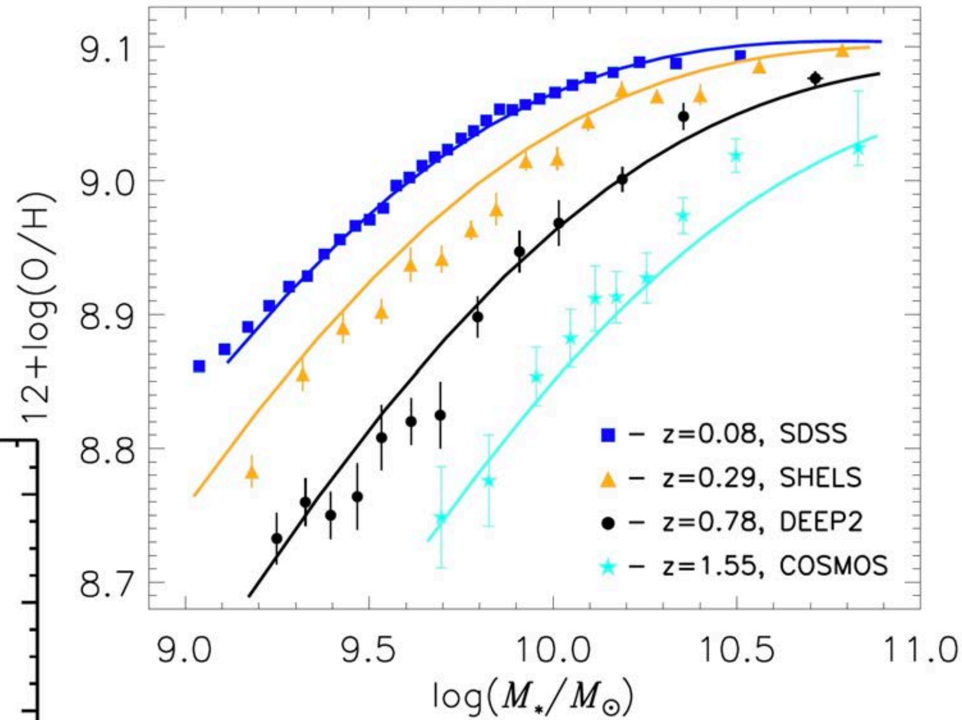
A schematic view:

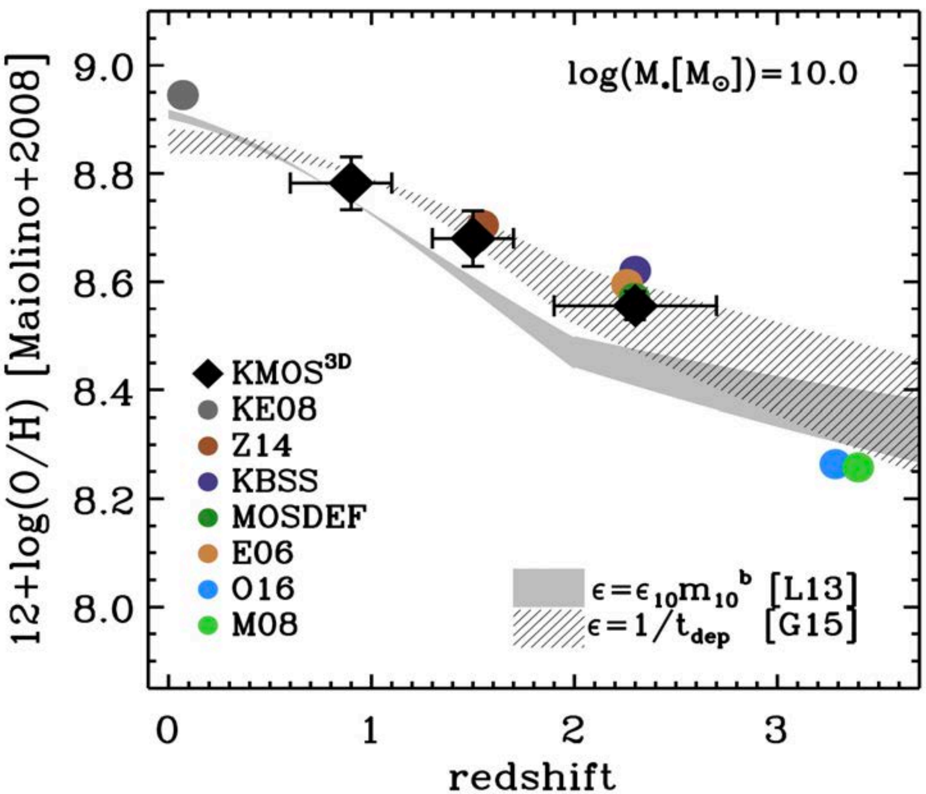
Details of these processes are very messy and hard to model or simulate. So, simplified (semi)analytical models and assumptions are often used, e.g., the "closed box" model, or the "instanteneous recycling" approximation



# Chemical Evolution in Redshift

Similar mass-metallicity trends exist at any given redshift →

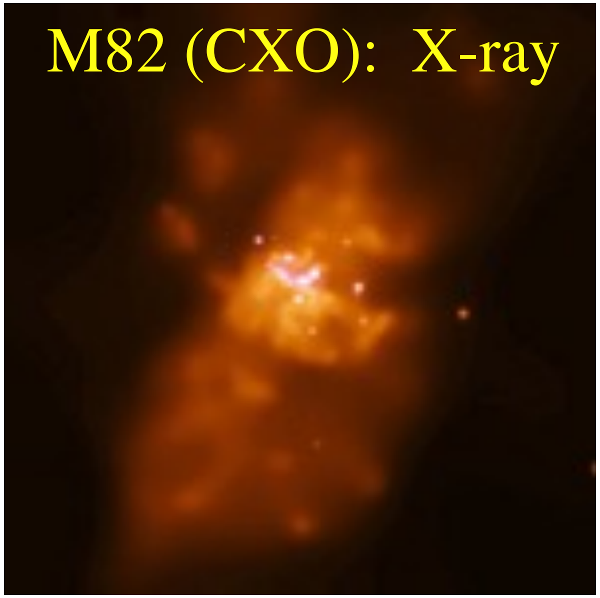


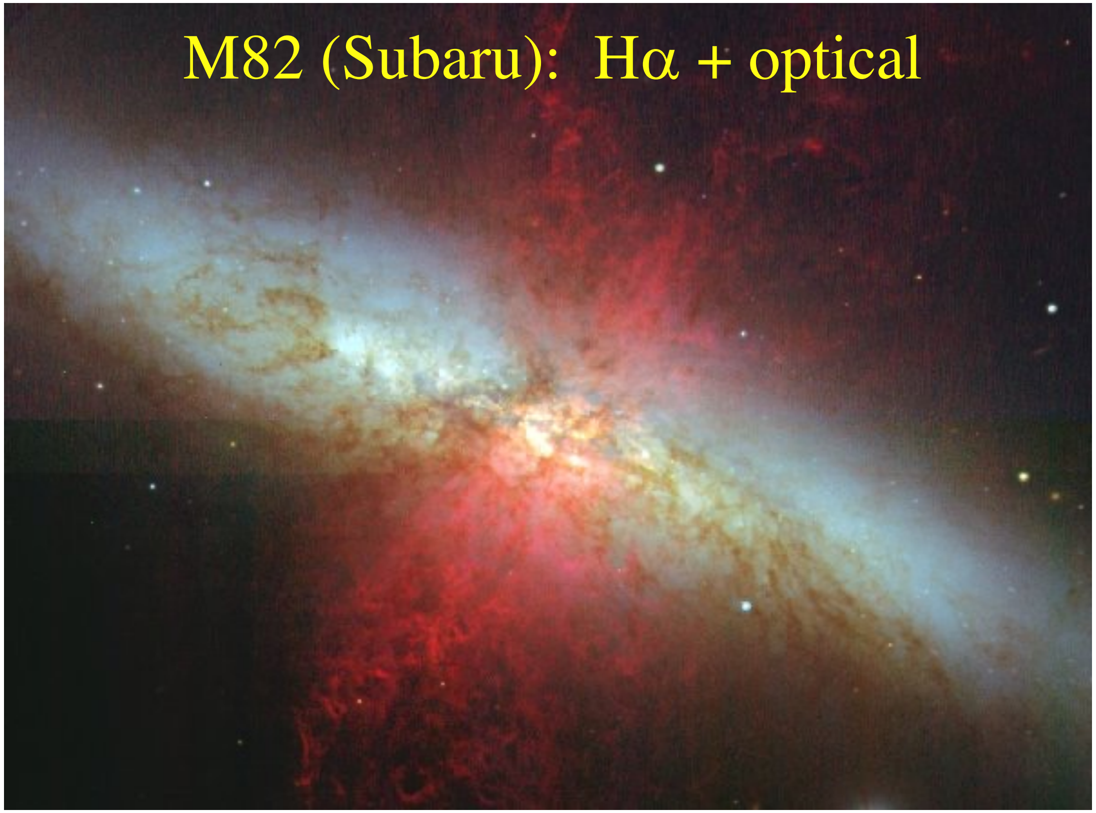



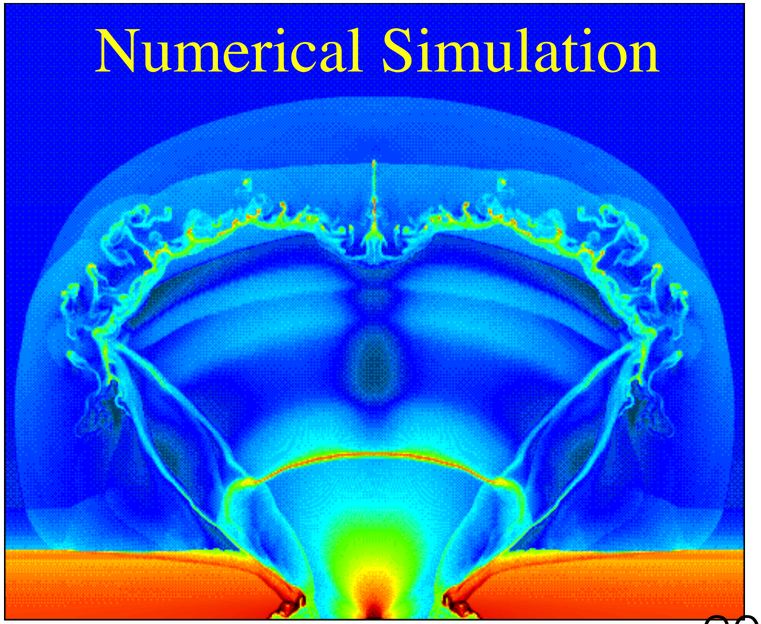

← But the overall metallicity of galaxies increases in time

# Galactic Winds

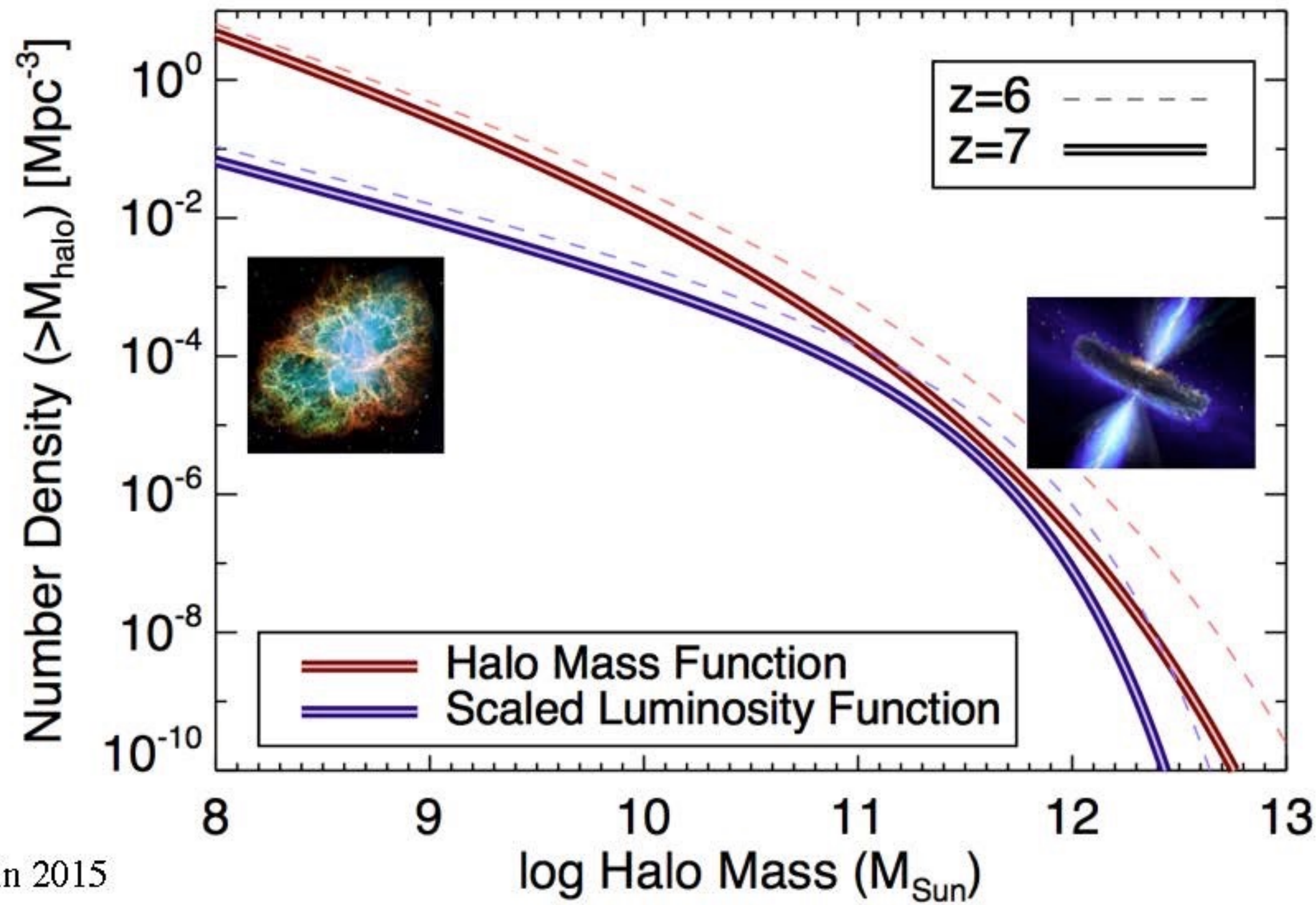
Starburst can drive winds of enriched gas (e.g., from supernova ejecta) out to the intergalactic medium. This gas can then be accreted again by galaxies. In a disk galaxy, the winds are generally bipolar outflows



# SN and AGN Feedback Modified the Halo Mass Function




Finkelstein 2015

# Physical Processes of Galaxy Formation

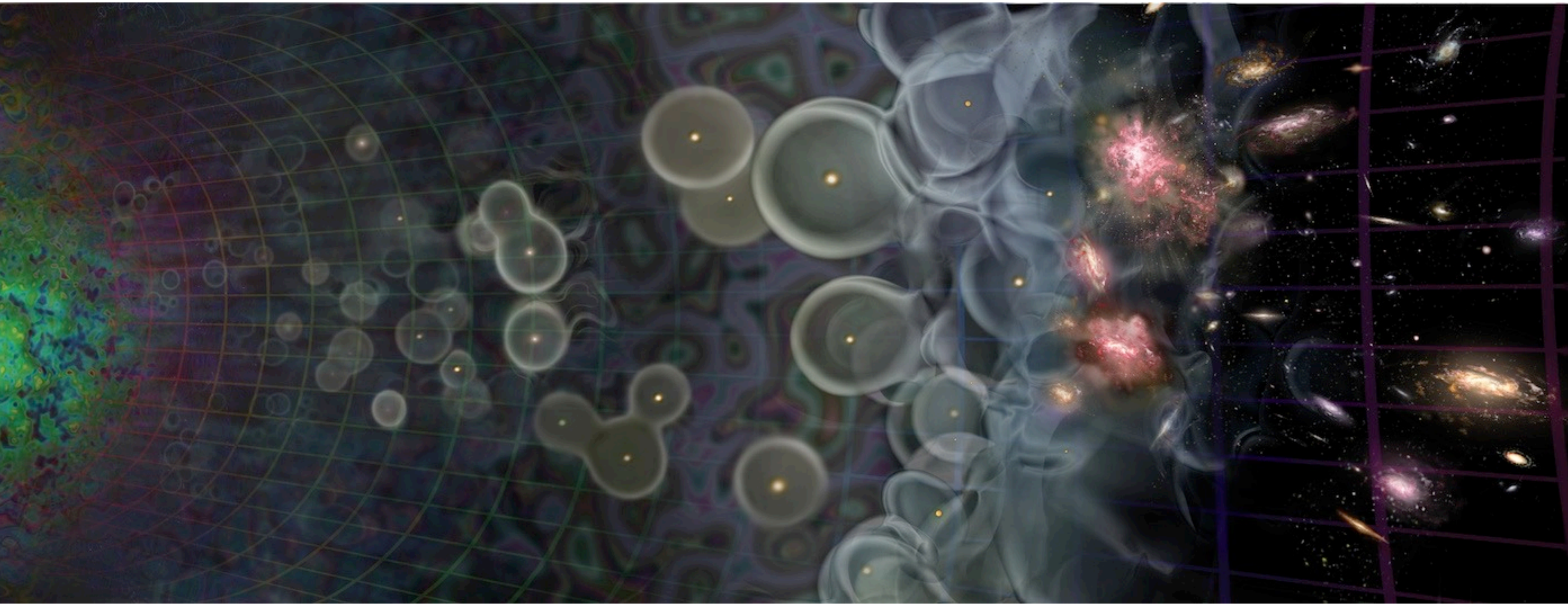
Galaxy formation is actually ***a much messier problem than structure formation.*** In addition to gravity and build-up of host dark halos (fairly well understood) we need to add:

- Shock heating of gas
- Cooling of gas into dark halos
- Formation of stars (also not a well understood process!) from the cold gas
- The evolution of the resulting stellar population
- Feedback processes generated by the ejection of mass and energy from evolving stars
- Production and mixing of heavy elements (chemical evolution)
- Effects of dust obscuration
- Formation of black holes at galaxy centers and effects of AGN emission, jets, etc.

… etc., etc., etc.

# An Outline of the Early Cosmic History

*(illustration from Avi Loeb)*



**Recombination:** Release of the CMBR

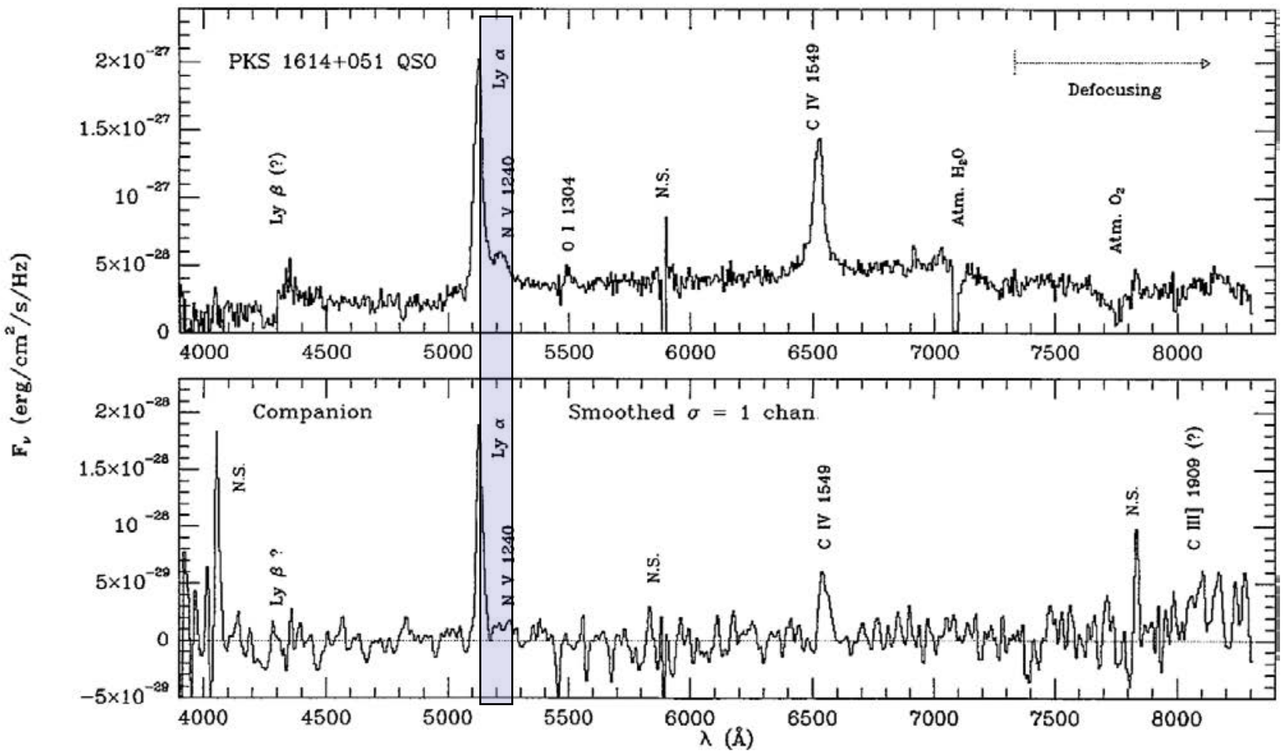
**Dark Ages:** Collapse of Density Fluctuations

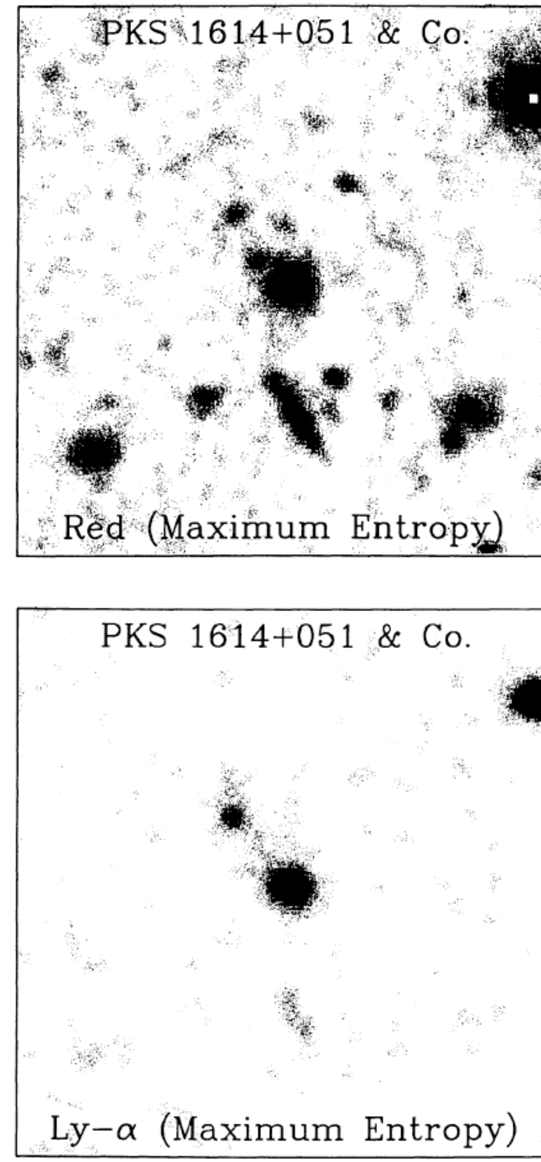
**Reionization Era:** The Cosmic Renaissance

Galaxy evolution begins

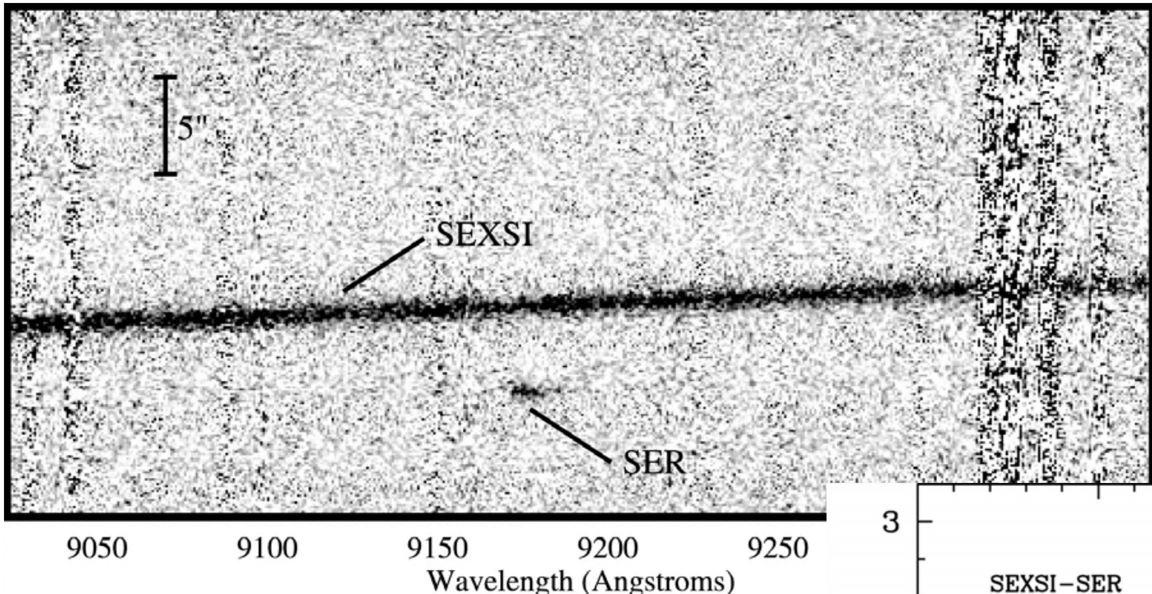
# Narrow-Band Imaging

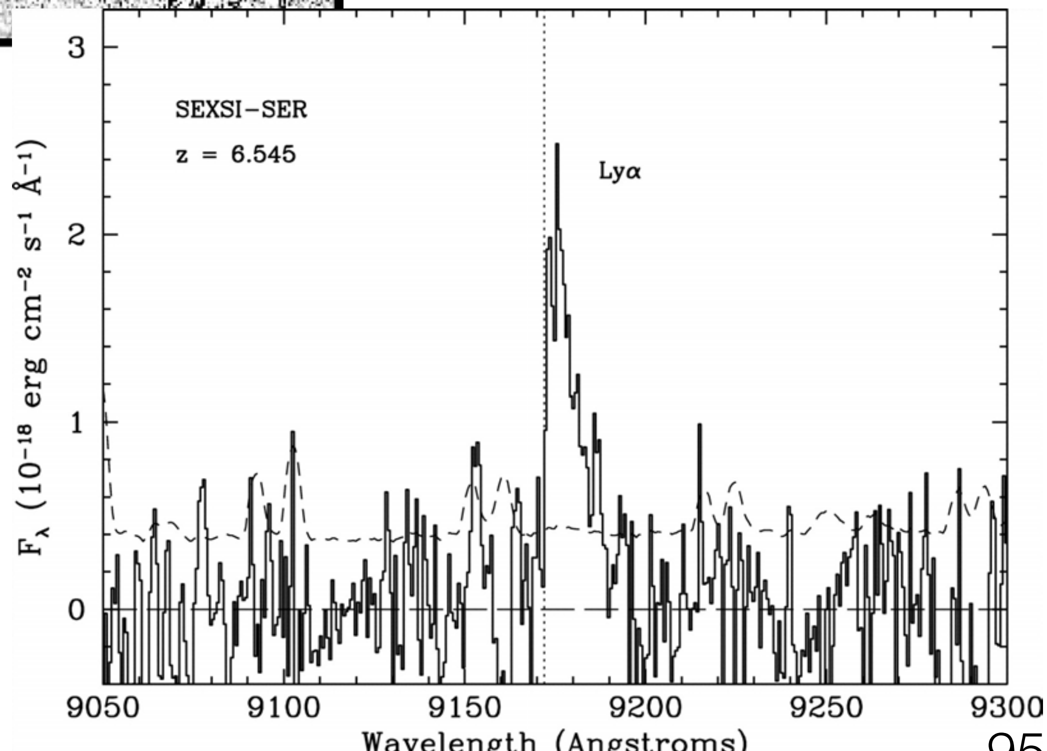
A greatly increased contrast for an object with a strong line emission



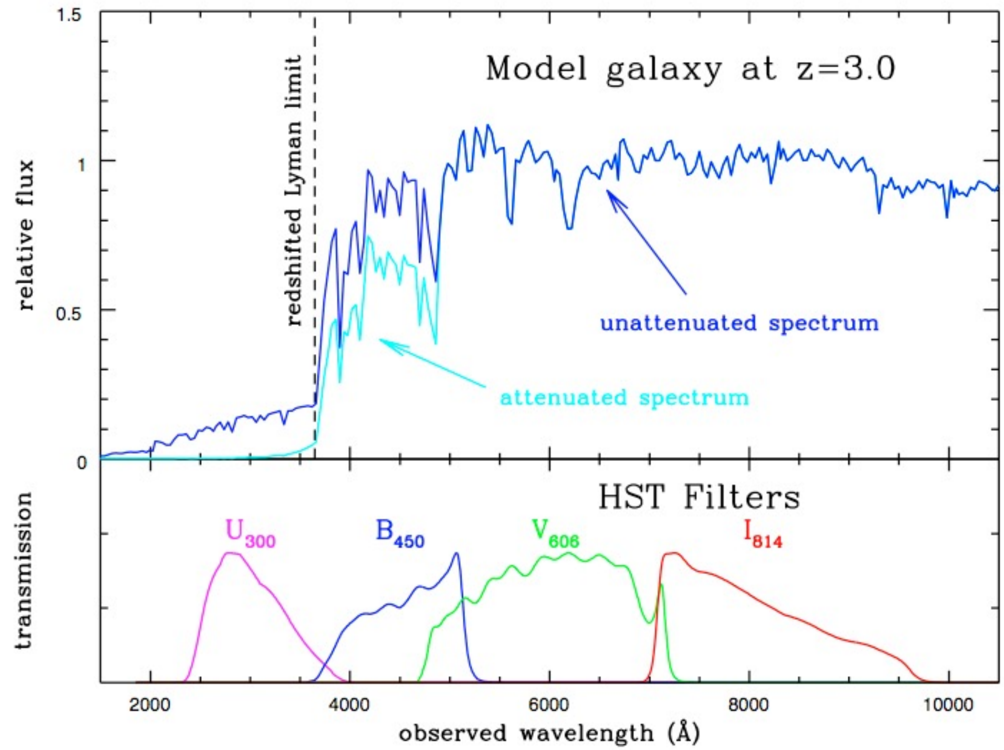
# Long-Slit Spectroscopy + Serendipity

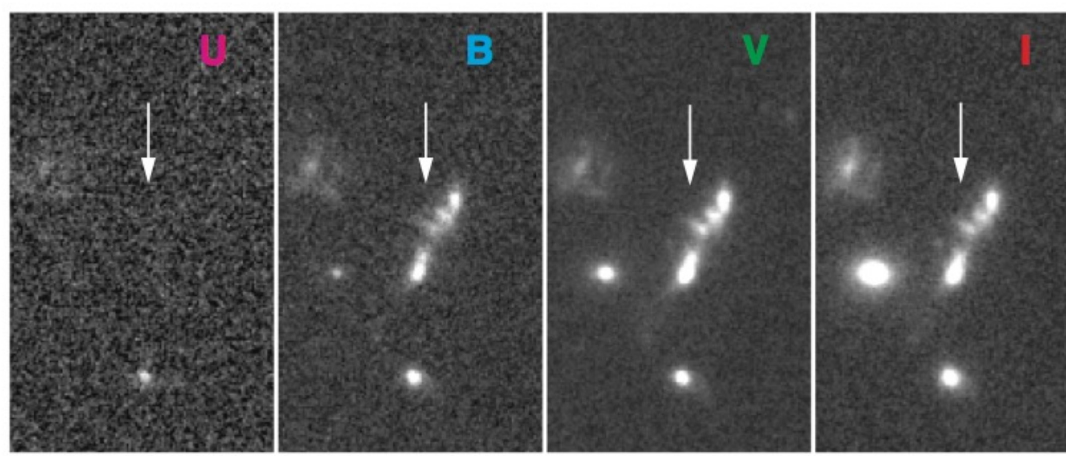


# The Lyman-Break Method

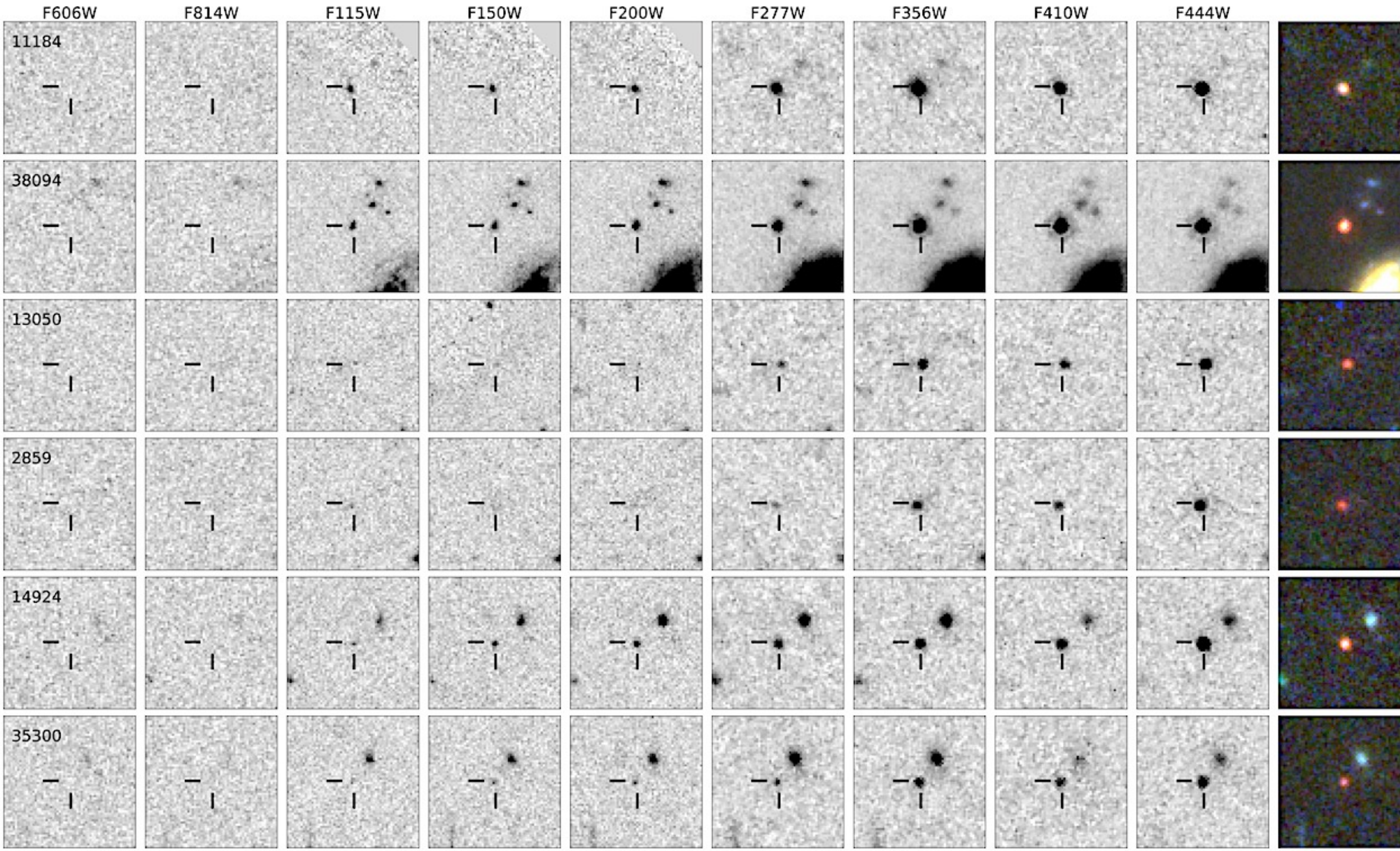
Absorption by the interstellar and intergalactic hydrogen of the UV flux blueward of the Ly alpha line, and especially the Lyman limit, creates a continuum break which is easily detectable by multicolor imaging



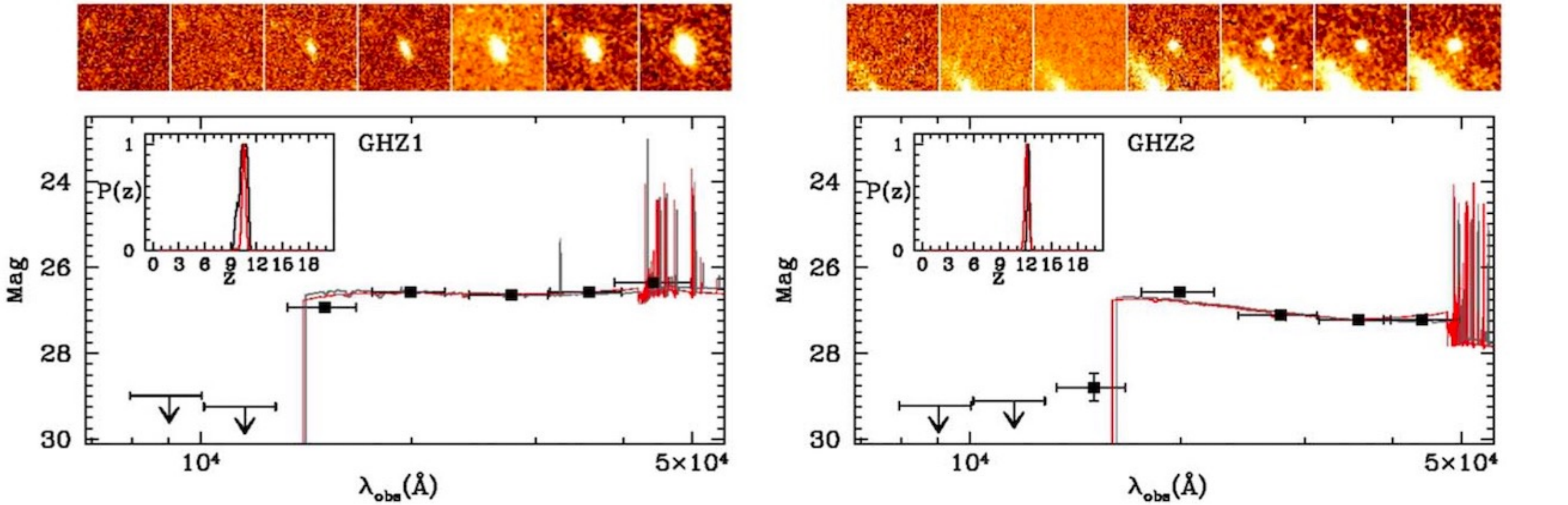
# Examples of JWST Color Selection

Images in different filters, from 0.6 μm to 4.44 μm

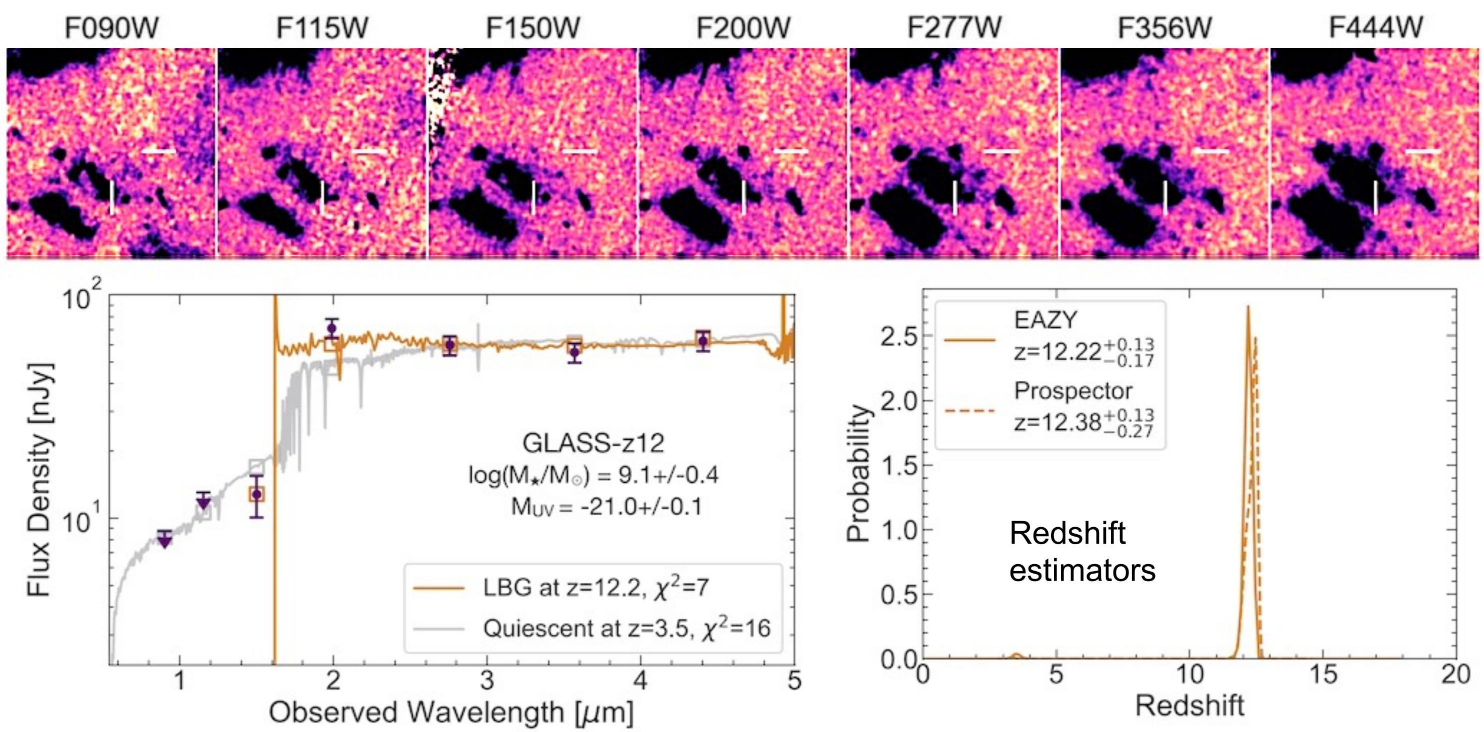



*Labbe et al. 2022*

# Photo-z Redshift Estimators

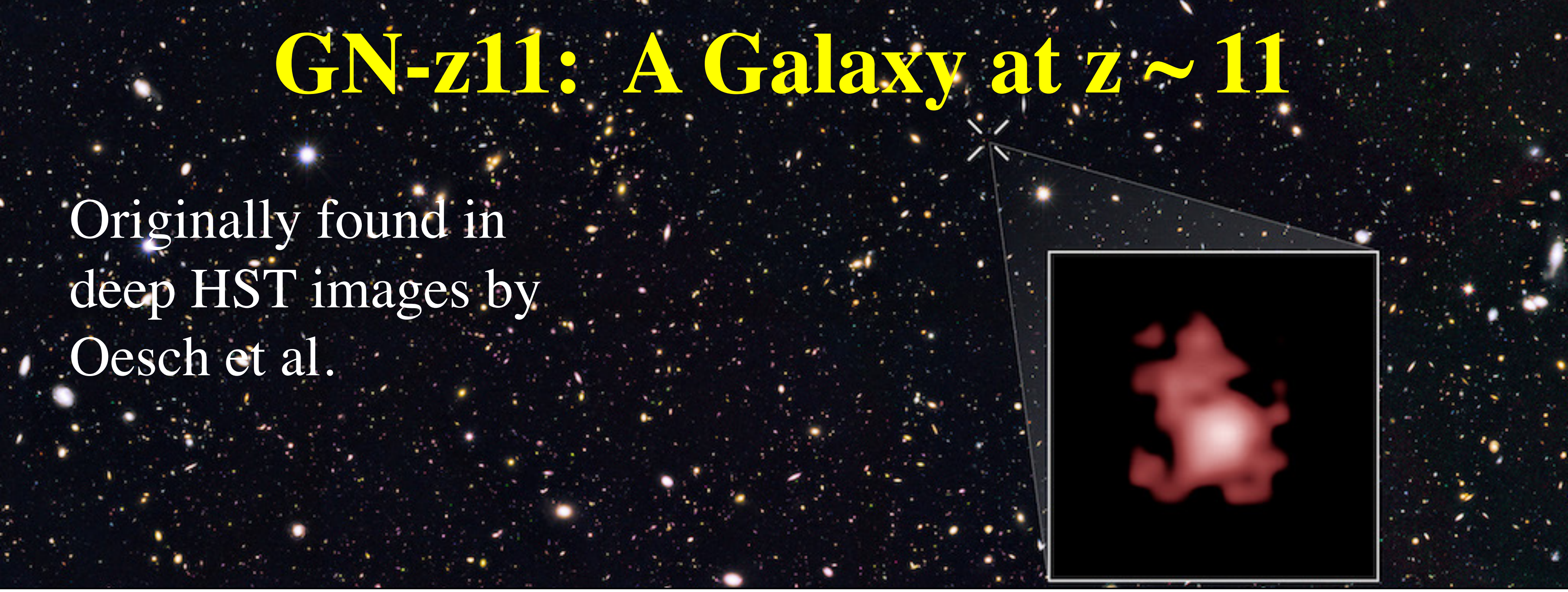



Castellano et al. 2022

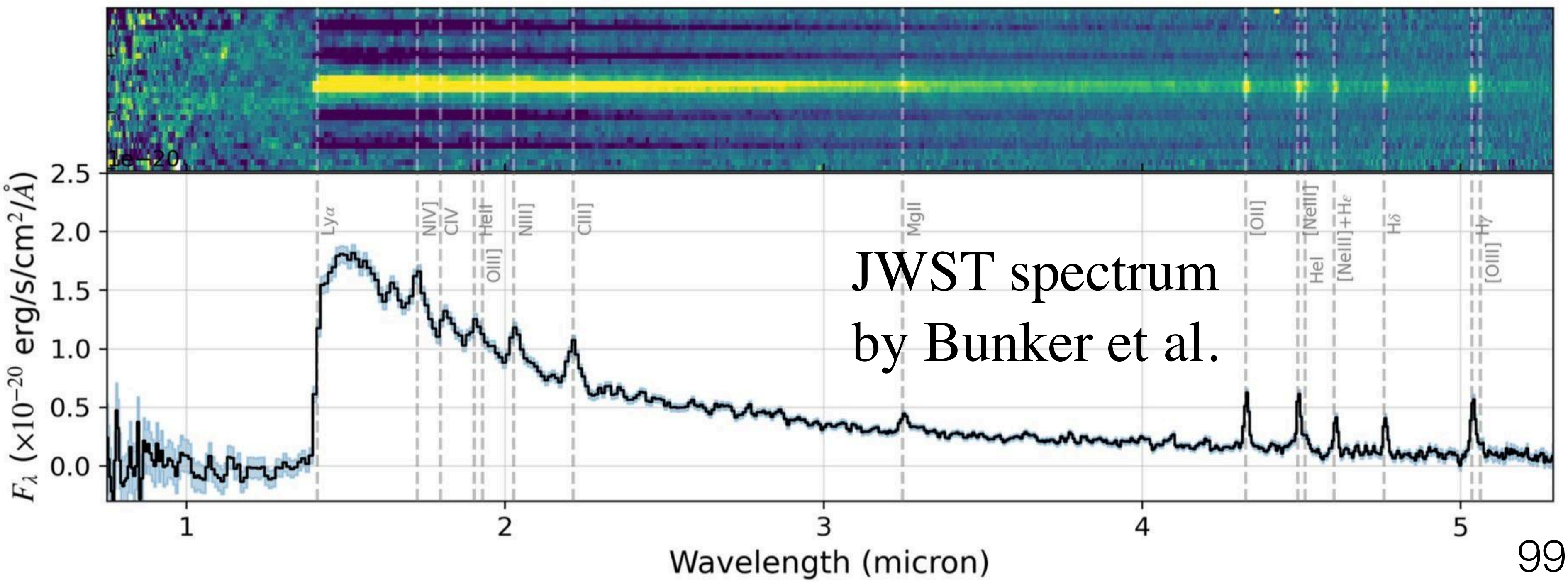



Naidu et al. 2022

# GN-z11: A Galaxy at z ~ 11



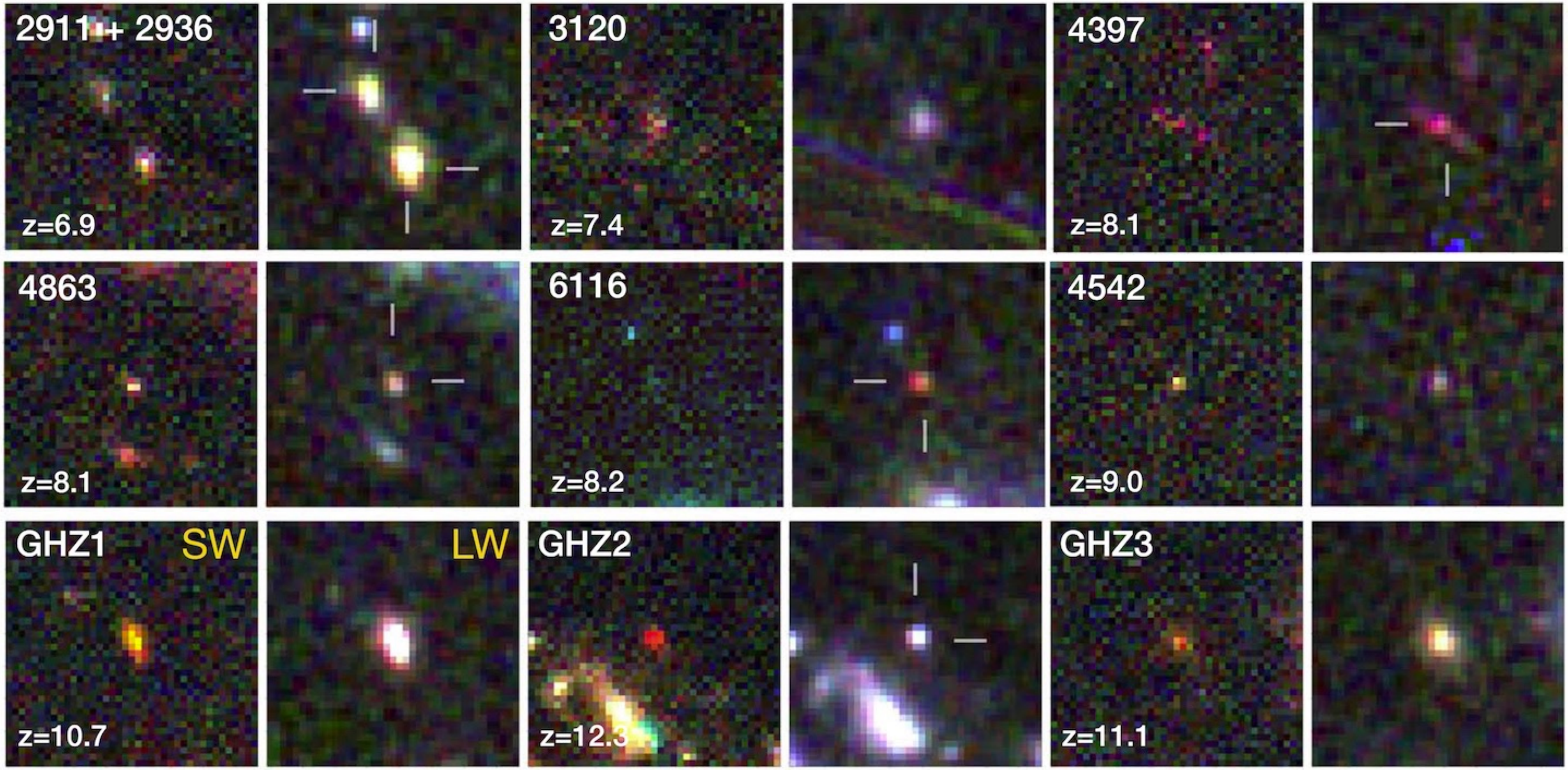
Originally found in deep HST images by Oesch et al.




JWST spectrum by Bunker et al.

# Examples of JWST Galaxies at z ~ 7 – 12

*(Treu et al. 2023)*

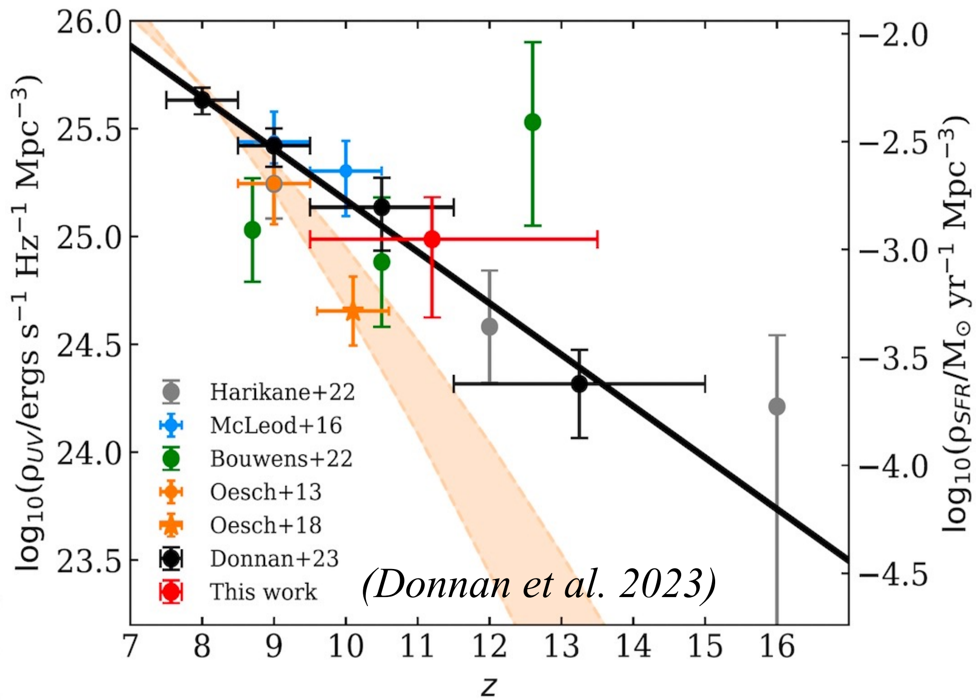


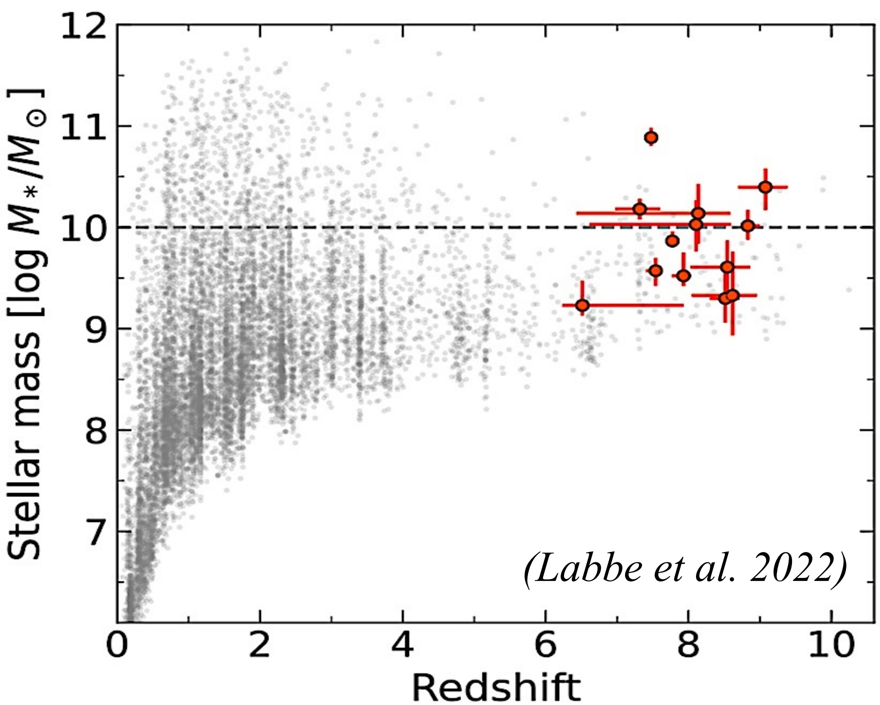

SW = 1.15, 1.45, 2.00 μm filters
LW = 2.77, 3.56, 4.44 μm filters
Images are 2.4 arcsec wide

Mostly compact, but sometimes extended morphologies

# Surprisingly Early Galaxy Formation?

Unexpectedly high UV luminosity density (~ SFR) at $z \geq 12$, when the universe was ~ 370 Myr old, and stellar masses M ~ $10^9$ $M_\odot$.




It would be hard to start forming stars before the universe age of ~ 100 Myr

# Key takeaways

Galaxy evolution is a multi-scale, complex subject that has many unsolved problems to be studied