# Galaxy Evolution

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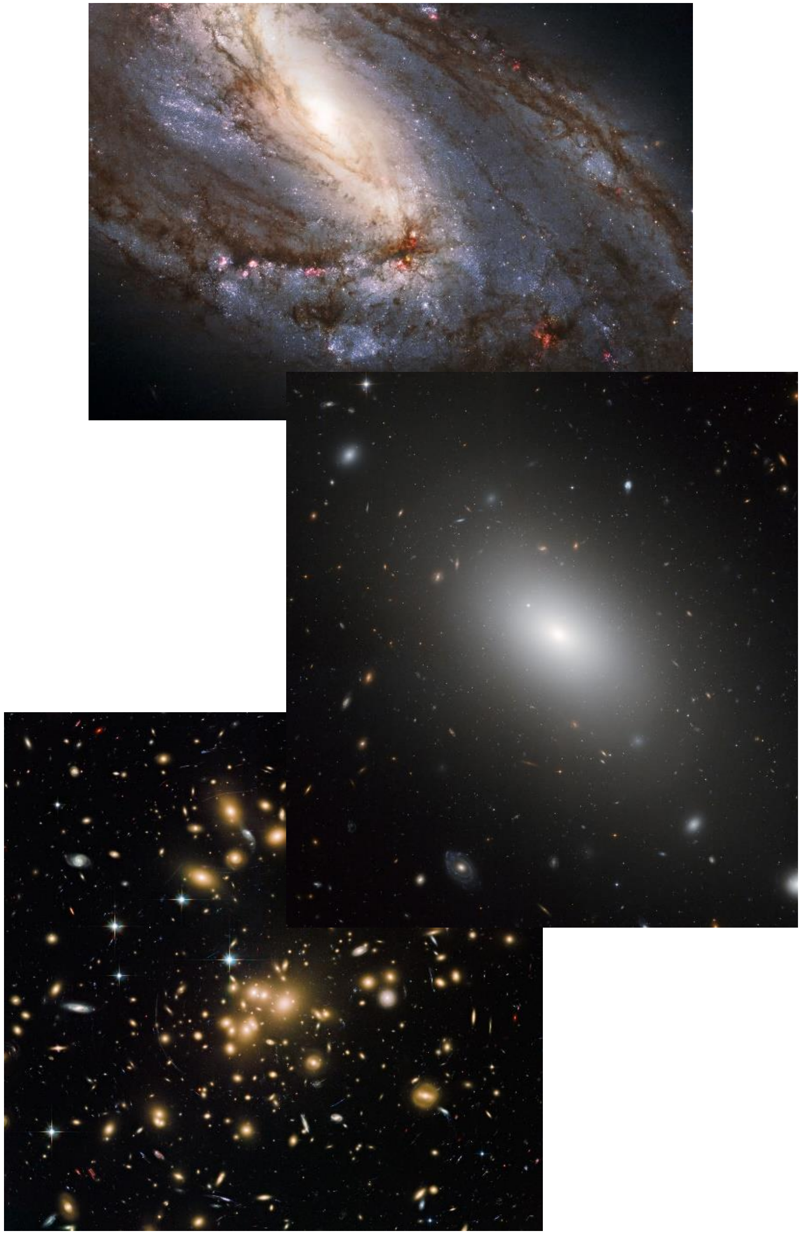
# Contents



# 1. Introduction

- A galaxy is a gravitationally bound system of millions to billions of stars of ~kpc size (← Not a precise definition!)
- A galaxy’s size is a few 100 times smaller than the mean separation between galaxies
- The density of stars inside a galaxy is ~$10^7$ larger than the global average density
- ➢ In this sense, galaxies are well-defined entities

# 1. Introduction

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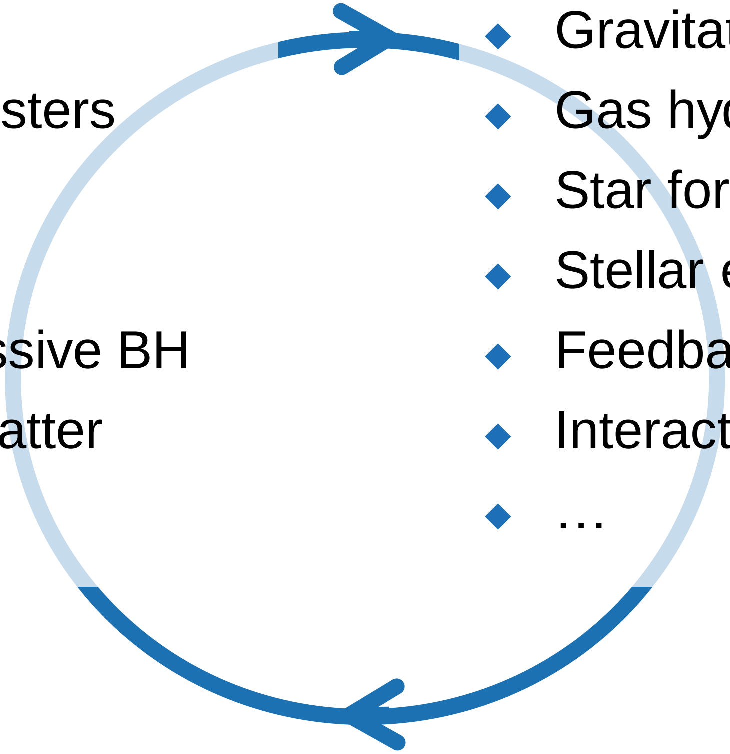


Galaxy constituents

- Dark matter
- Stars and star clusters
- Gas
- Dust
- Central supermassive BH
- Circumgalactic matter

Physical processes

- Gravitational collapse
- Gas hydrodynamics
- Star formation
- Stellar evolution
- Feedback
- Interaction with the environment
- …

➢ Complexity both in terms of description and modeling!

# 1. Introduction

- In addition, galaxy formation and evolution is not well localised in the parameter space of physical quantities
- The physical processes involved cover many orders of magnitude in size, time, mass, etc.
- Huge complexity and very rich phenomenology
- "Applied" science, requiring the synthesis of many branches of astrophysics, no fundamental theory
- Requires a multi-layered approach and a multitude of methods

# 1. Introduction

## Observations

Imaging and spectroscopy at all wavelengths

Statistical investigations of large samples (surveys)

Level of detail →

← Statistical power, completeness

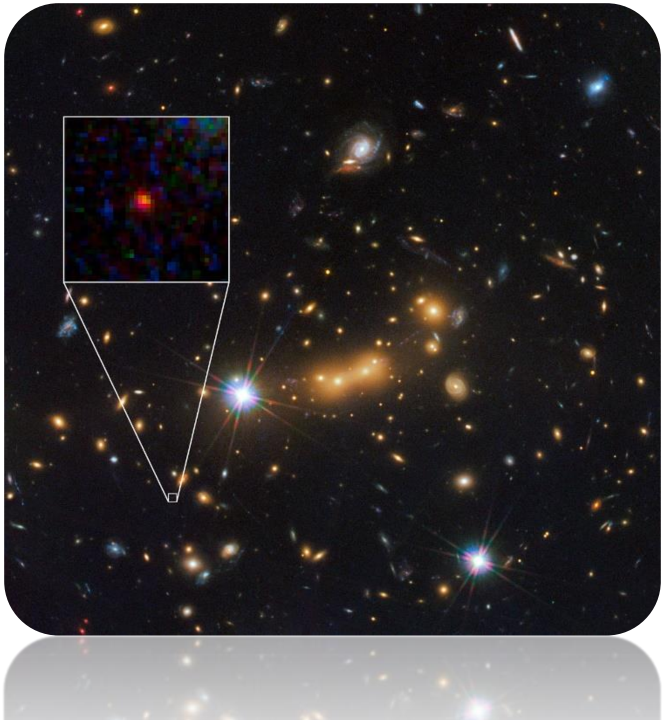
Detailed studies of small samples

## Theory

Analytical, semi-analytical, numerical

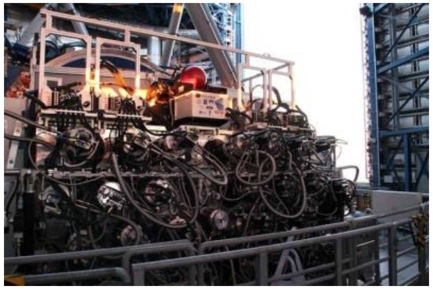
# 1. Introduction

- Timescales involved are too long to be able to directly observe galaxy evolution
- Forced to rely on the “lookback effect”: we can infer evolution only in a statistical sense by comparing samples of galaxies at different epochs (i.e. distances)
- Adds yet another layer of complexity (selection effects)



# 1. Introduction

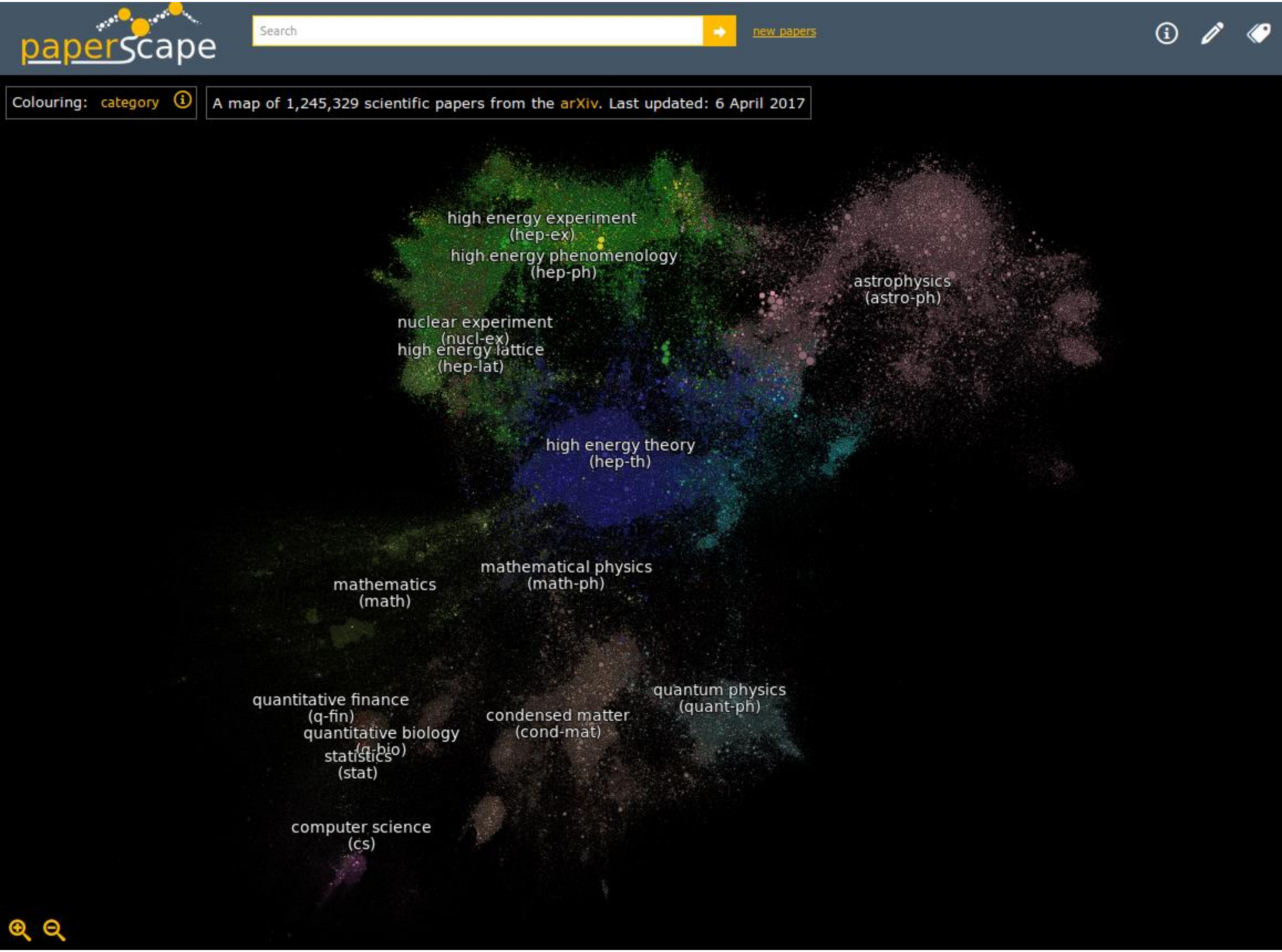
- Technologically challenging on all fronts!
- We require:
  - Large telescopes, both earth-bound and space-based, employing very different technologies at different wavelengths
  - Different types of telescopes
  - Diverse, complex instrumentation
  - Massive computing power



# 1. Introduction

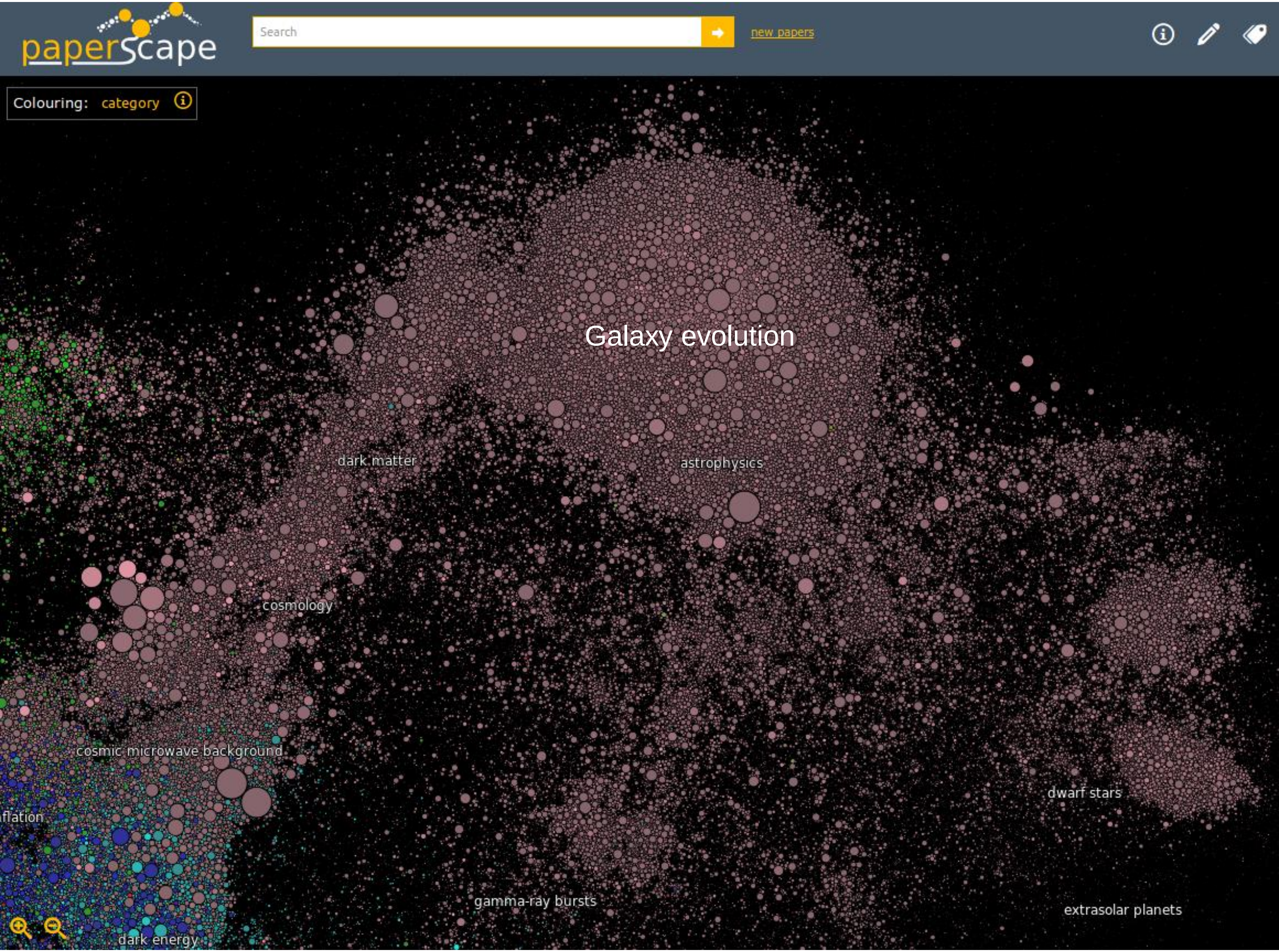
- Finally, in the face of all of this complexity, we have to make do with “observations” (as opposed to “experiments”)

- The problem of how galaxies form and evolve is by no means “solved”
- We do not even have a complete picture of the phenomenology yet! Things are still being discovered!
- Galaxy formation and evolution is a rapidly evolving research field
- Huge literature



Colouring: category

A map of 1,245,329 scientific papers from the arXiv. Last updated: 6 April 2017



Galaxy evolution

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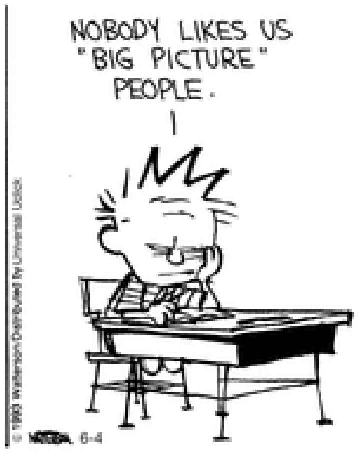
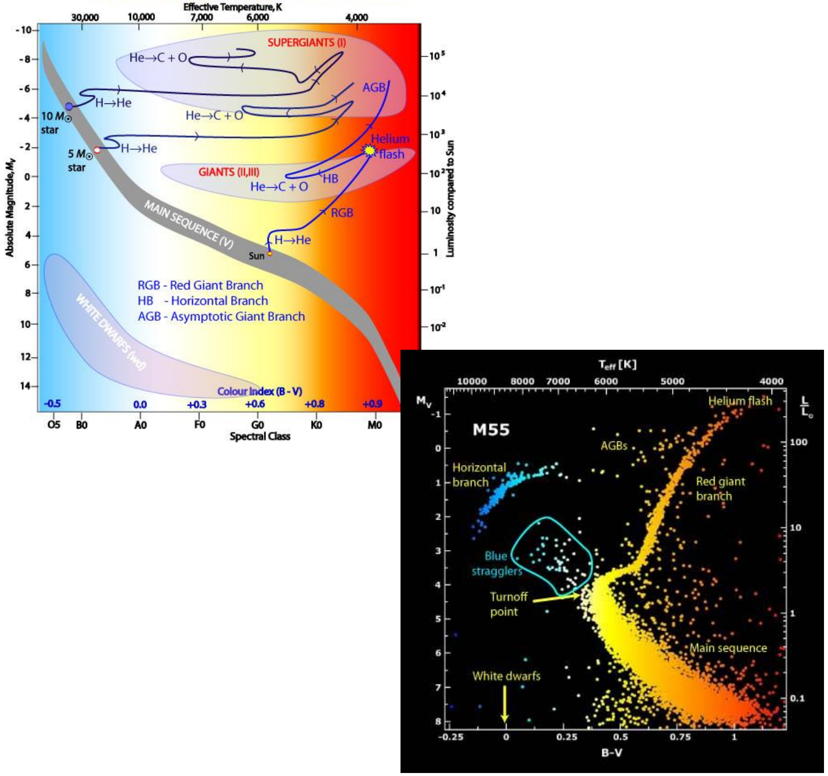
- Here: only a very broad-brush overview



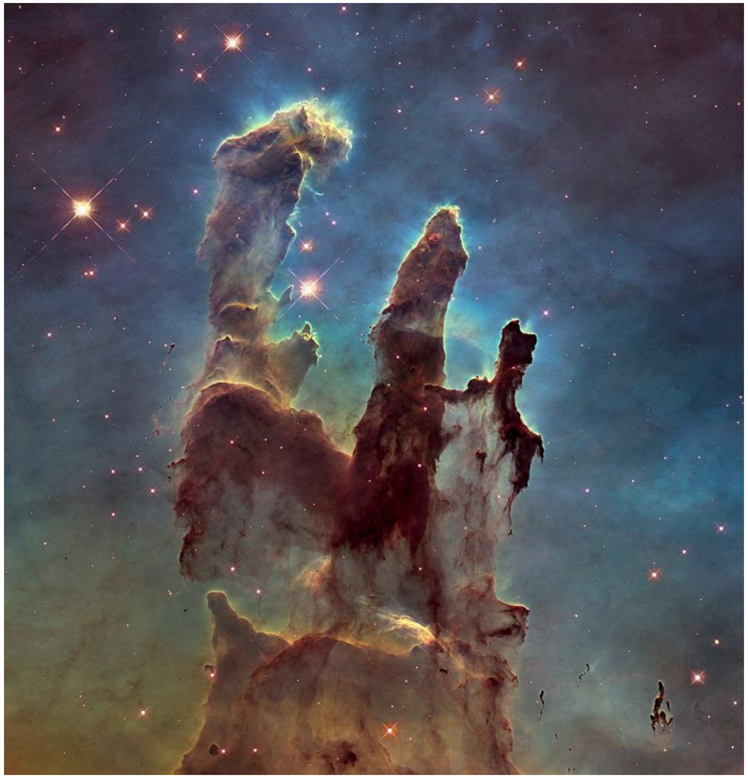
# 2.1 Galaxy constituents

- Stars
  - Dominate the optical appearance of galaxies
  - Dominant baryonic mass component for large galaxies
  - Different types of stars based on their luminosity, effective temperature and evolutionary stage
  - Usually cannot resolve individual stars
  - ➢ Only observe combined light of total stellar population
  - Usually dominated by the youngest, most massive stars ($L \propto M^{3.5-4}$)



# 2.1 Galaxy constituents

- Gas
  - Between 0 and ~50% of the baryonic mass, depending on galaxy type
  - Composition:
    - ~90% H (~70% by mass)
    - ~10% He (~30% by mass)
    - < 1% metals
  - Usually in different phases (n, p, T)
    - Atomic (neutral & ionised)
    - Molecular

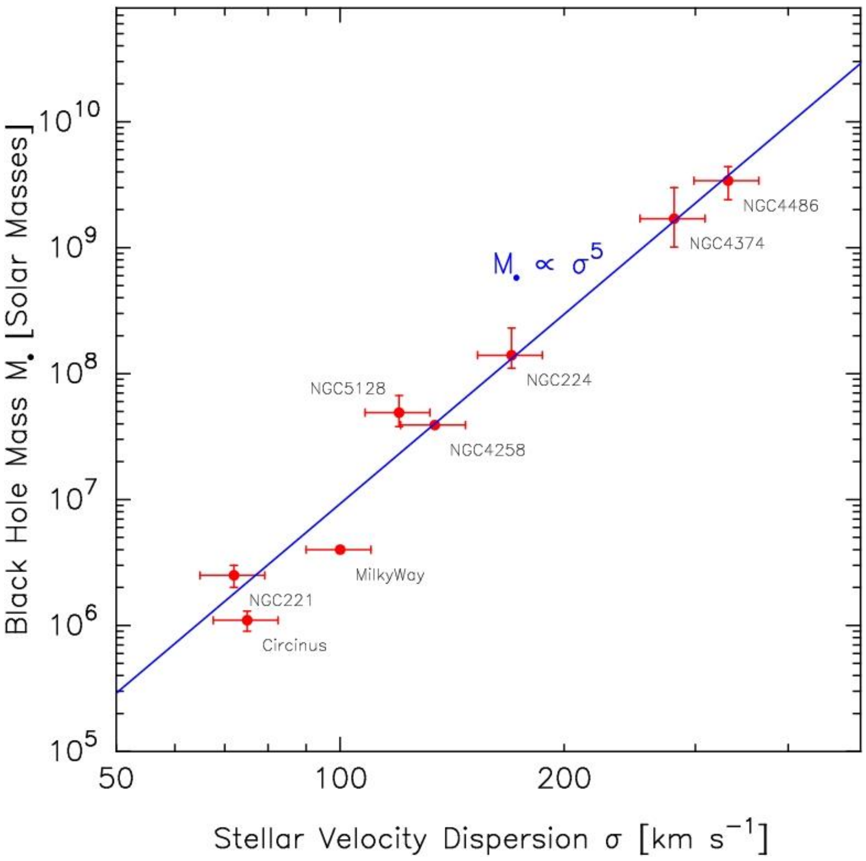


# 2.1 Galaxy constituents

- Dust
  - Abundance strong function of galaxy type
  - Always irrelevant in terms of mass
  - But: absorbs, scatters and reddens stellar light
  - ➢ Strong impact on optical appearance of galaxy
  - Reddening by dust usually degenerate with stellar population properties (age and metallicity)
  - Re-radiates absorbed energy in IR

# 2.1 Galaxy constituents

- Central supermassive black hole (SMBH)
  - Present in most bright galaxies
  - Completely irrelevant in terms of mass
  - Relevance of central SMBH for galaxy evolution established by observational correlations of SMBH mass with host galaxy properties
  - Unclear how central SMBH influences its host galaxy



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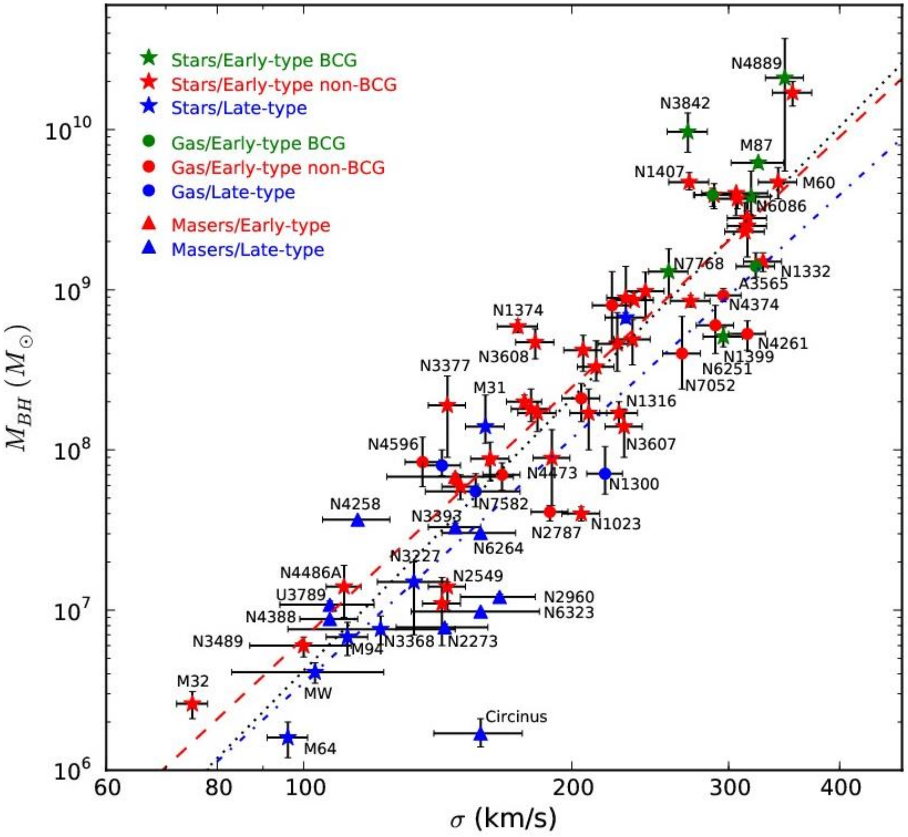
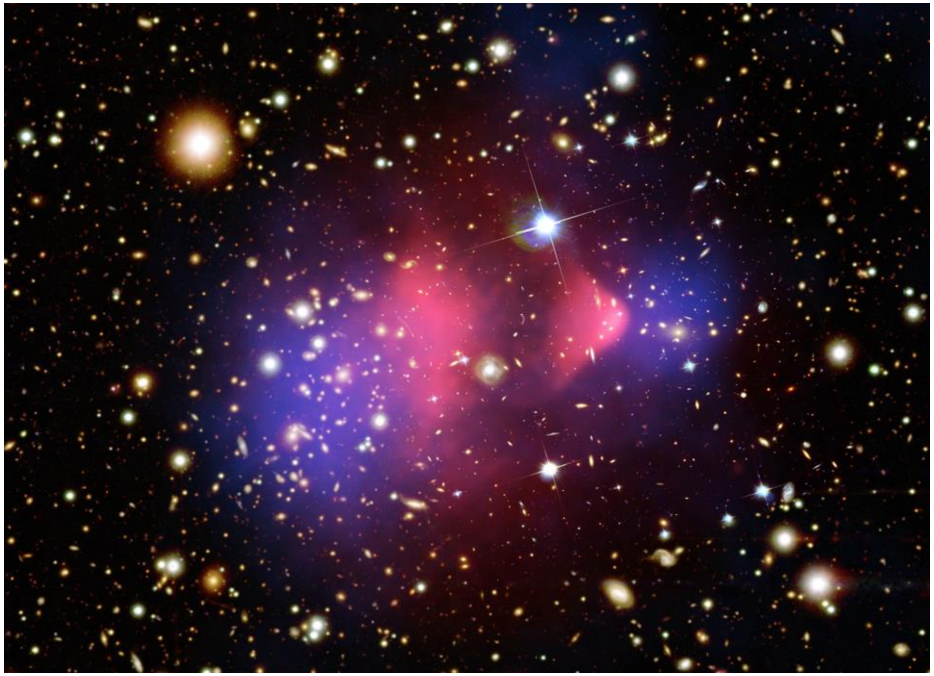


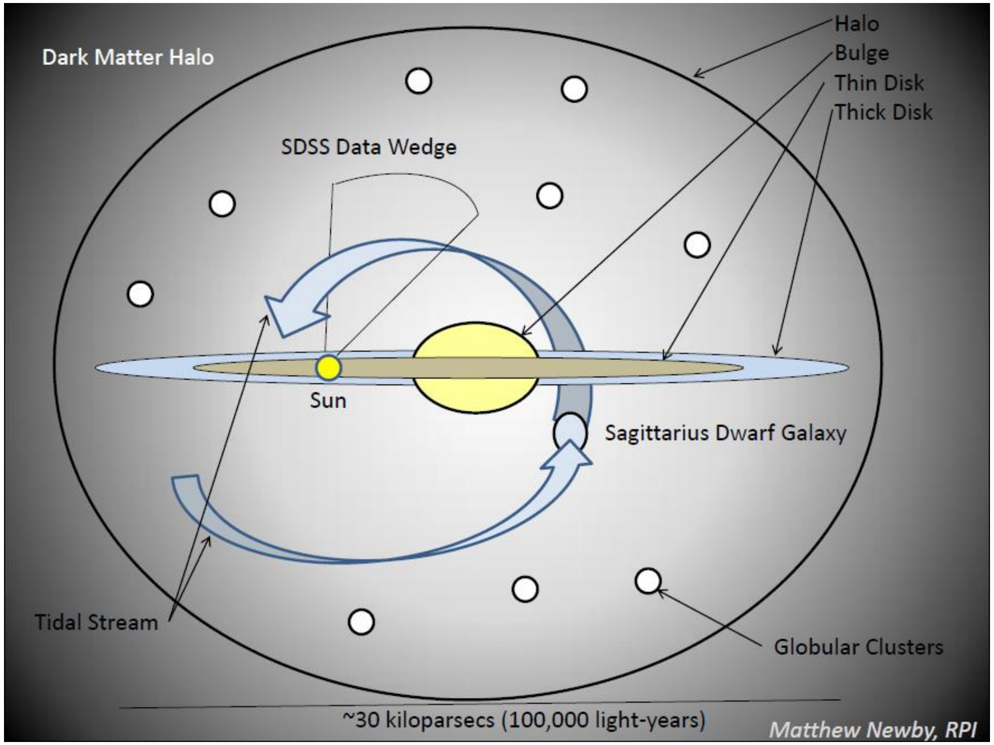
# 2.1 Galaxy constituents

- Dark matter
  - Dominates (~90%) the total mass of a galaxy
  - Interacts at most weakly with itself and baryonic matter
  - Presence inferred from rotation curves and stellar velocity dispersions
  - Collisionless
  - Mostly "cold" → CDM
  - No direct or indirect detection
  - ➢ Physical nature unclear



# 2.2 Galaxy structure

- Major structural components (of bright galaxies)
  - Disk
    - Rotationally supported
    - Bar
    - Spiral arms
  - Bulge (spheroid)
    - Supported by random motions
  - Stellar halo
  - DM halo
- No bulge → pure disk galaxy
- No disk → elliptical or spheroidal galaxy



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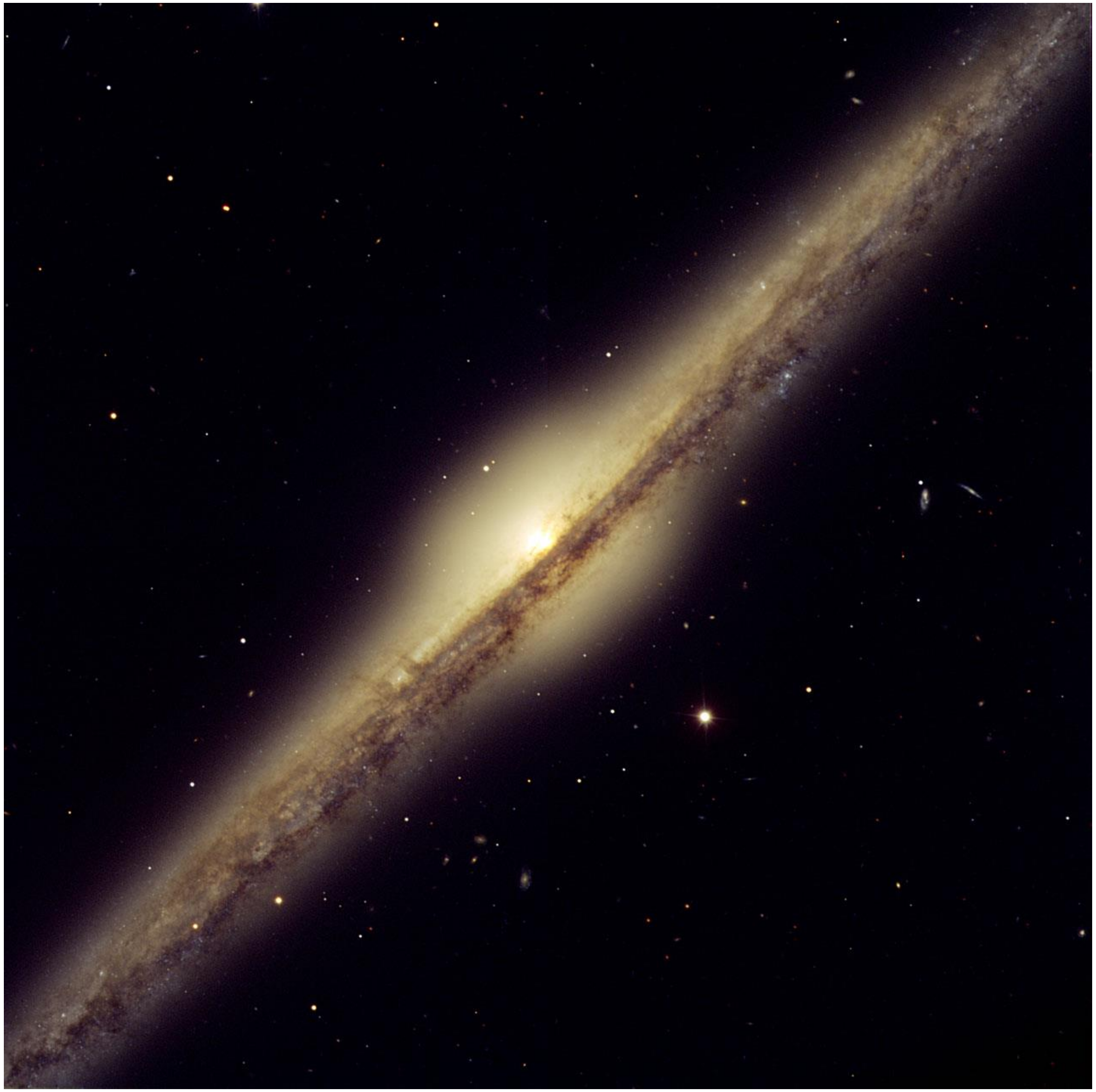

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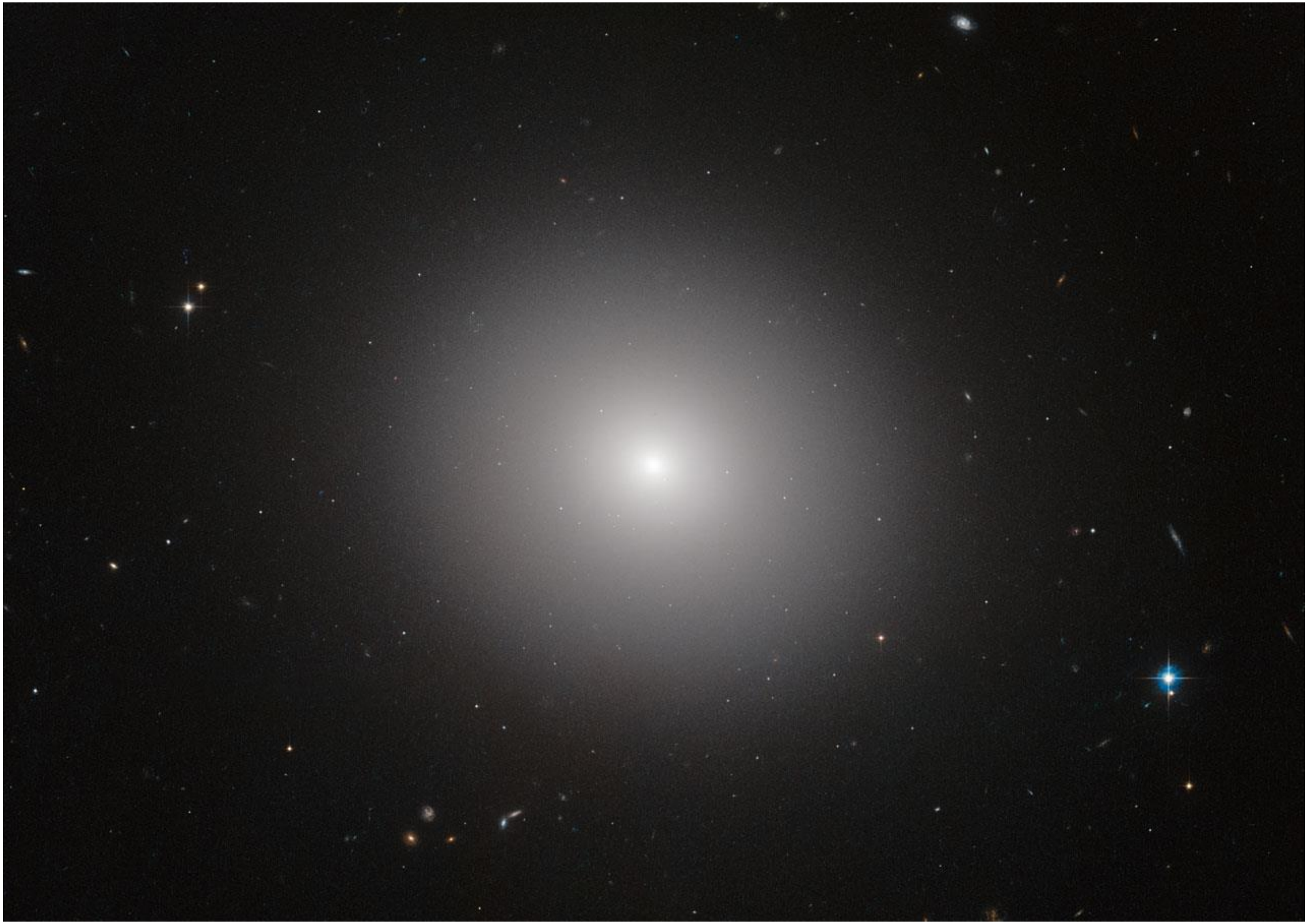

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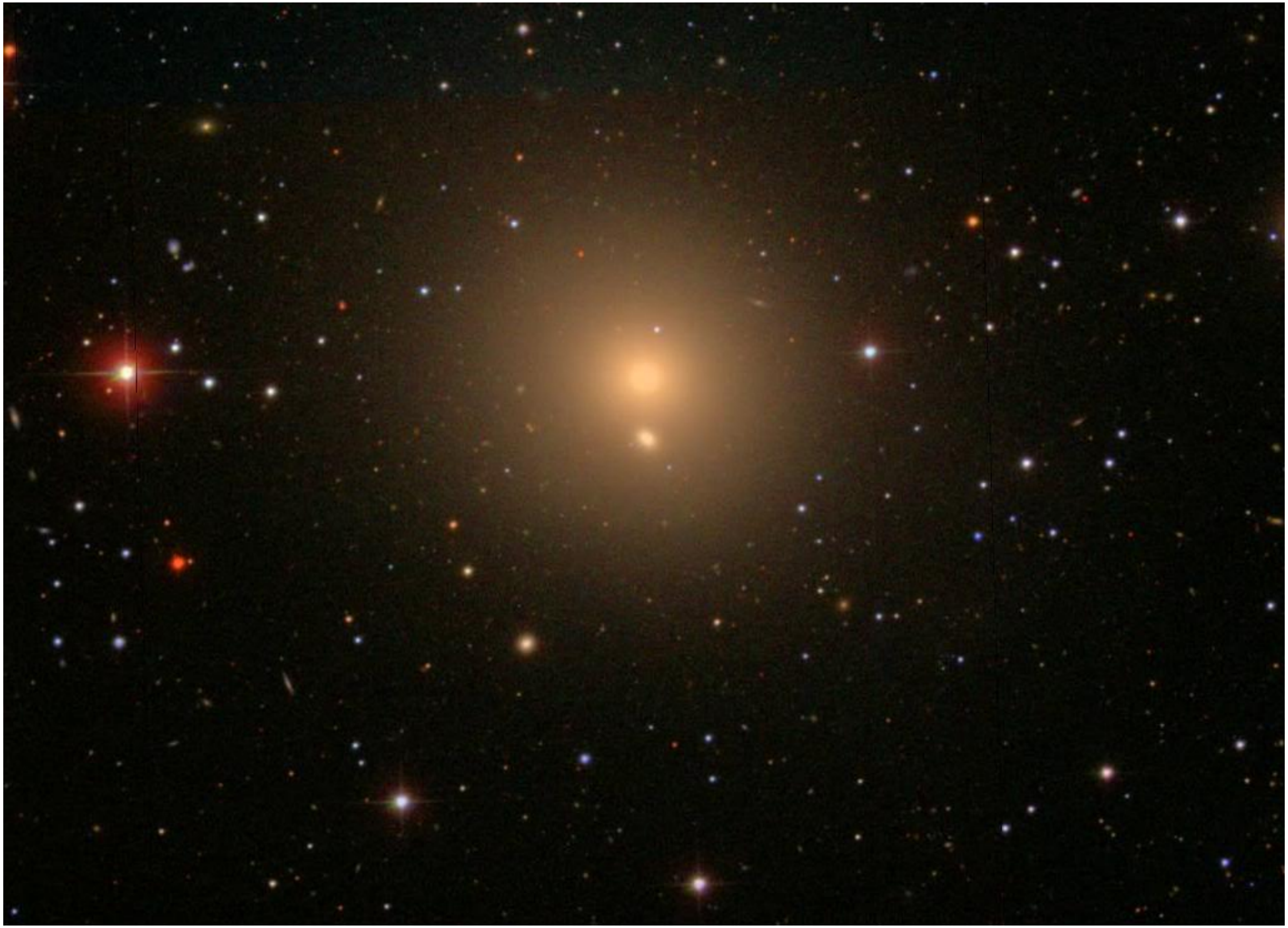

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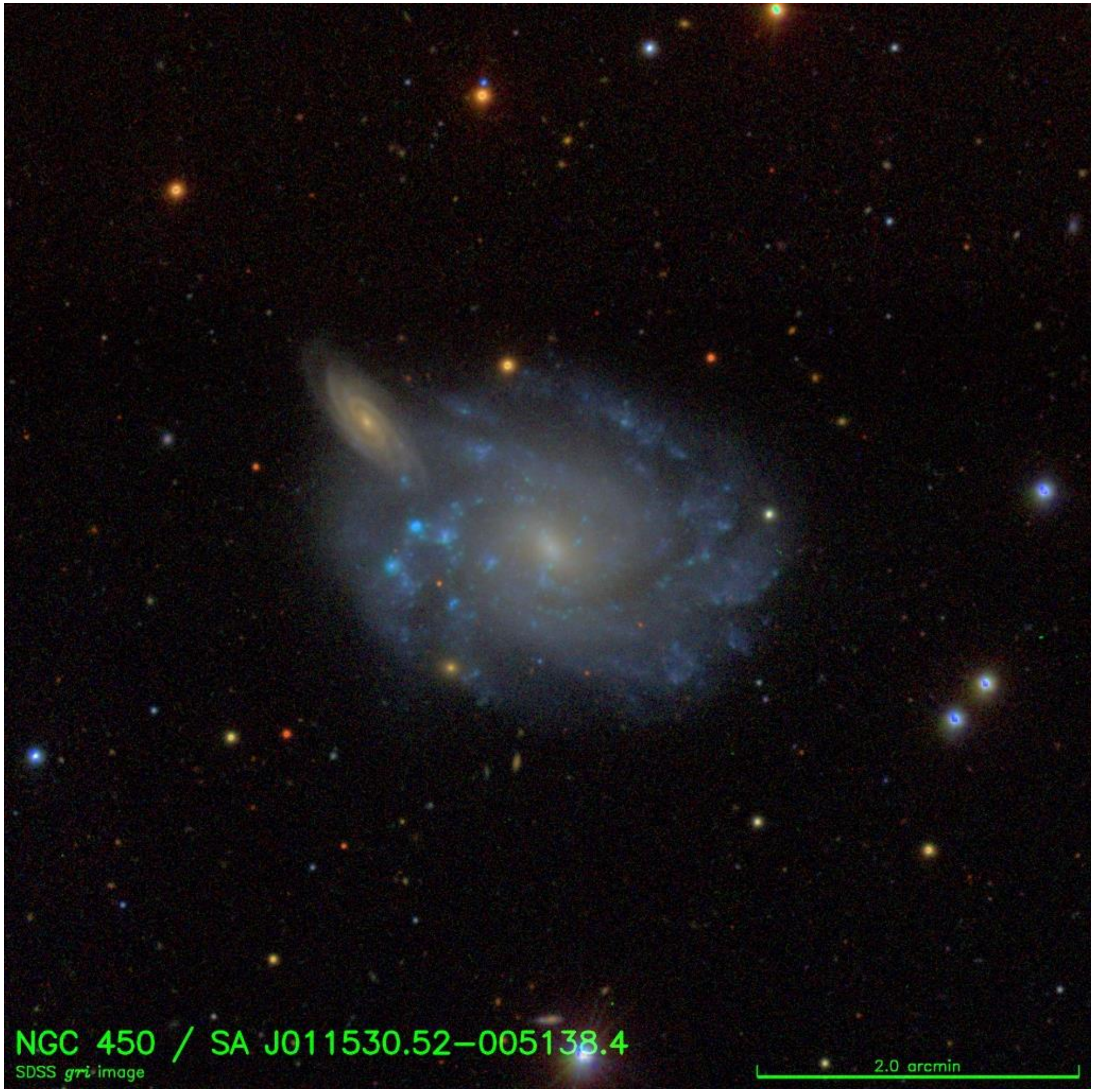


# 2.3 Main parameters

- The diversity of galaxies means that a number of parameters are required to describe a given galaxy adequately (unlike, e.g., main sequence stars). The most important are:
  - Morphology, structure
  - Luminosity, stellar mass
    Most basic, integral property of stellar population
  - Colour, additional characteristics of stellar population
    “Age” or better: star formation history, metallicity, initial mass function
  - Size, surface brightness
  - Cold gas mass, distribution
  - Dust mass, extinction curve, distribution
  - Nuclear activity
  - Environment
  - Distance, epoch

# 3. Interlude

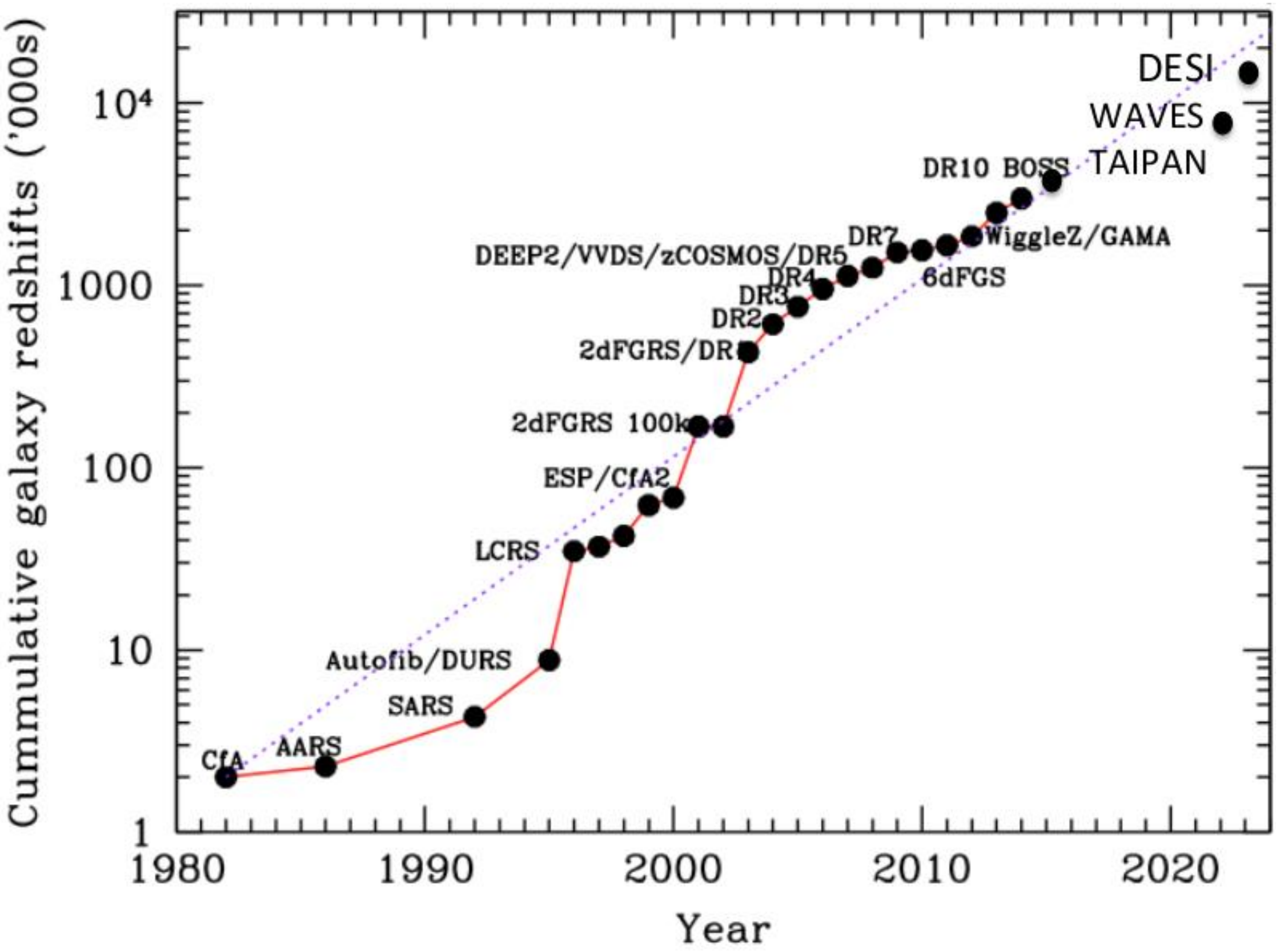
## So what are we trying to do?

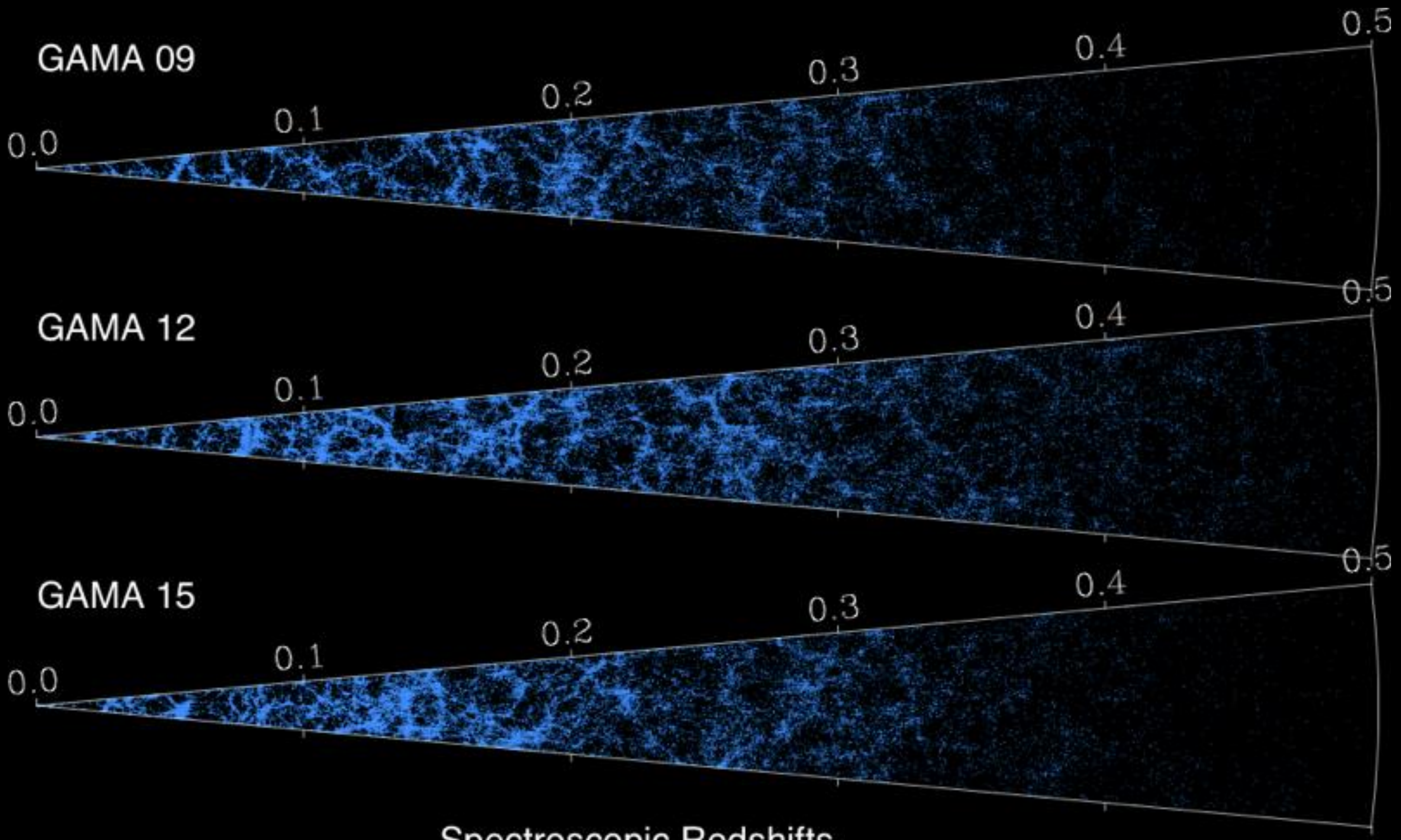
- Identify and understand the initial conditions and physical processes that lead to the formation of a galaxy with a specific set of intrinsic properties
- Determine and explain the statistical properties of the galaxy population as a whole, i.e. the distribution of galaxies with respect to their intrinsic properties (and in space), and its evolution:

  $$\mathrm{d}n = \phi(G_1, G_2, .., \mathbf{z})\,\mathrm{d}G_1\,\mathrm{d}G_2 \cdots$$

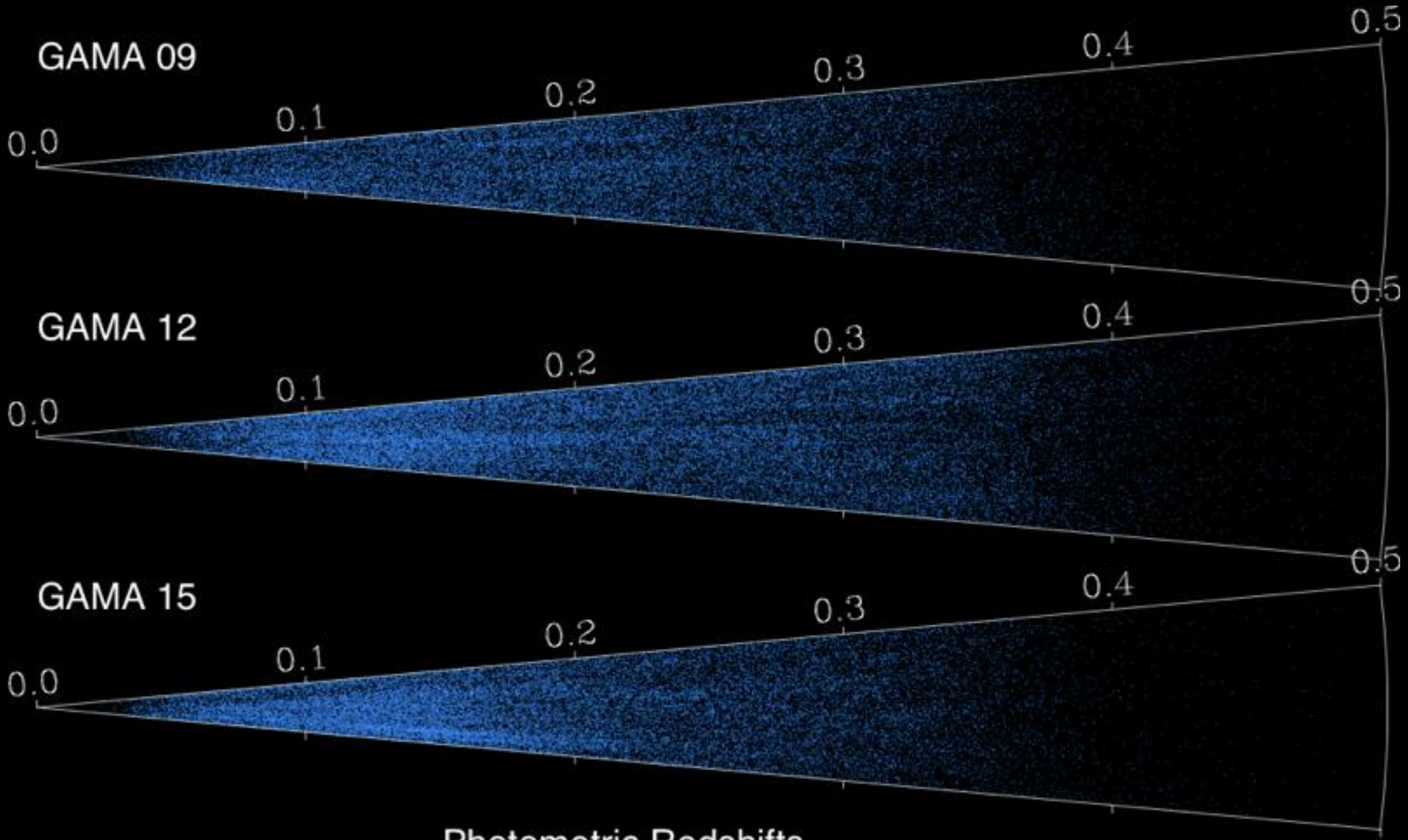
  where the $G_i$ each stand for some specific property of galaxies, such as luminosity, size, etc.
- Although it is both an observational and theoretical goal to determine the full joint distribution function, observational data are usually sufficient only to characterize the marginal distribution function w.r.t. a few quantities

# The rise of redshift surveys



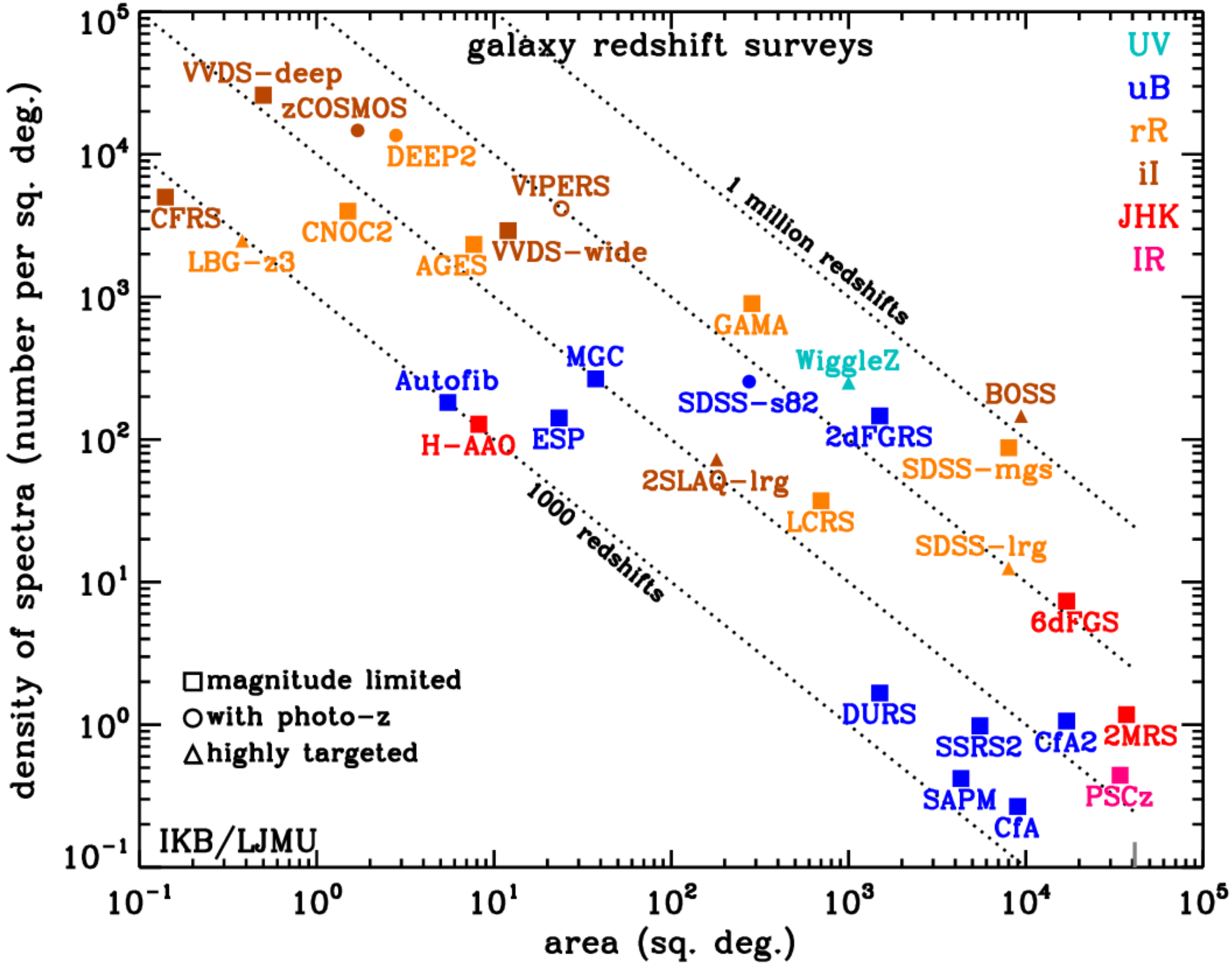


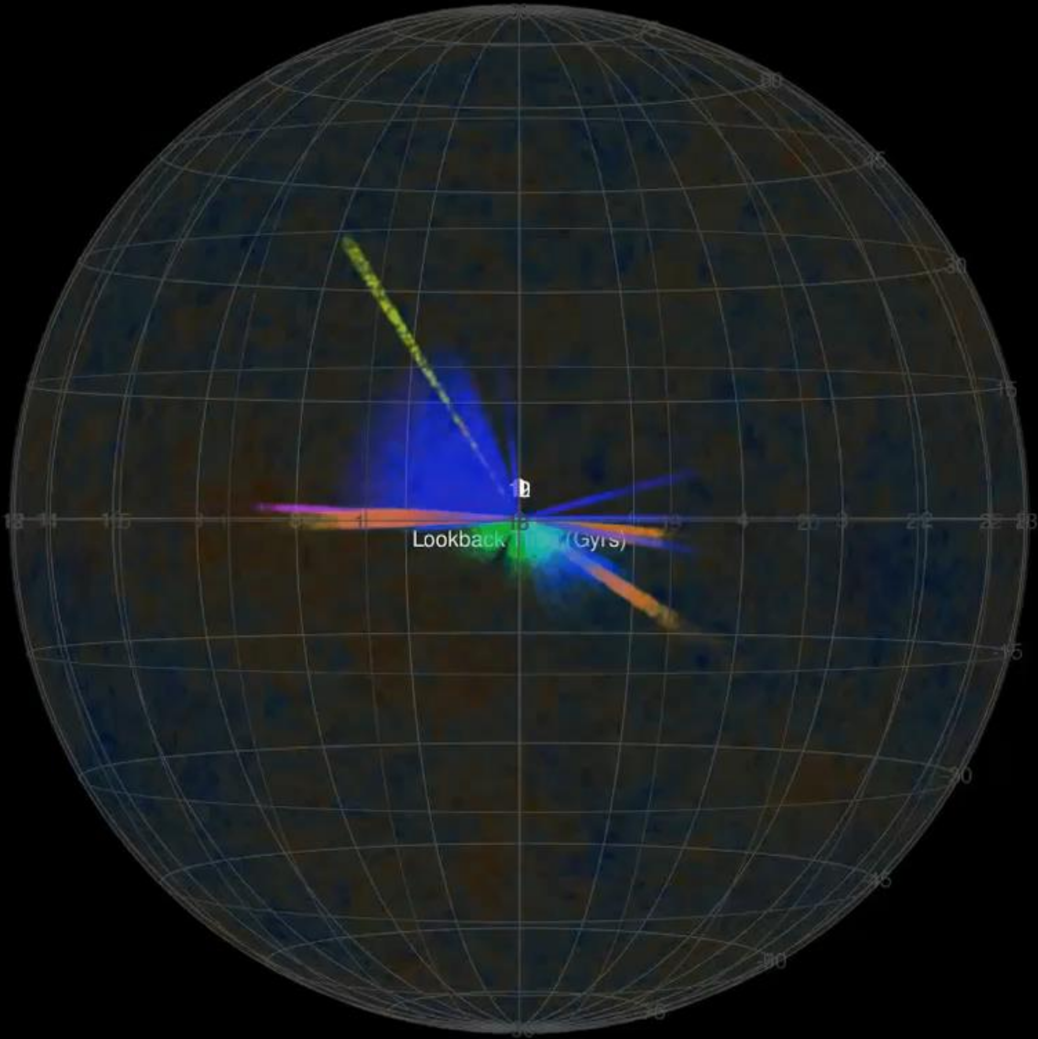
Spectroscopic Redshifts



Photometric Redshifts

# The rise of redshift surveys

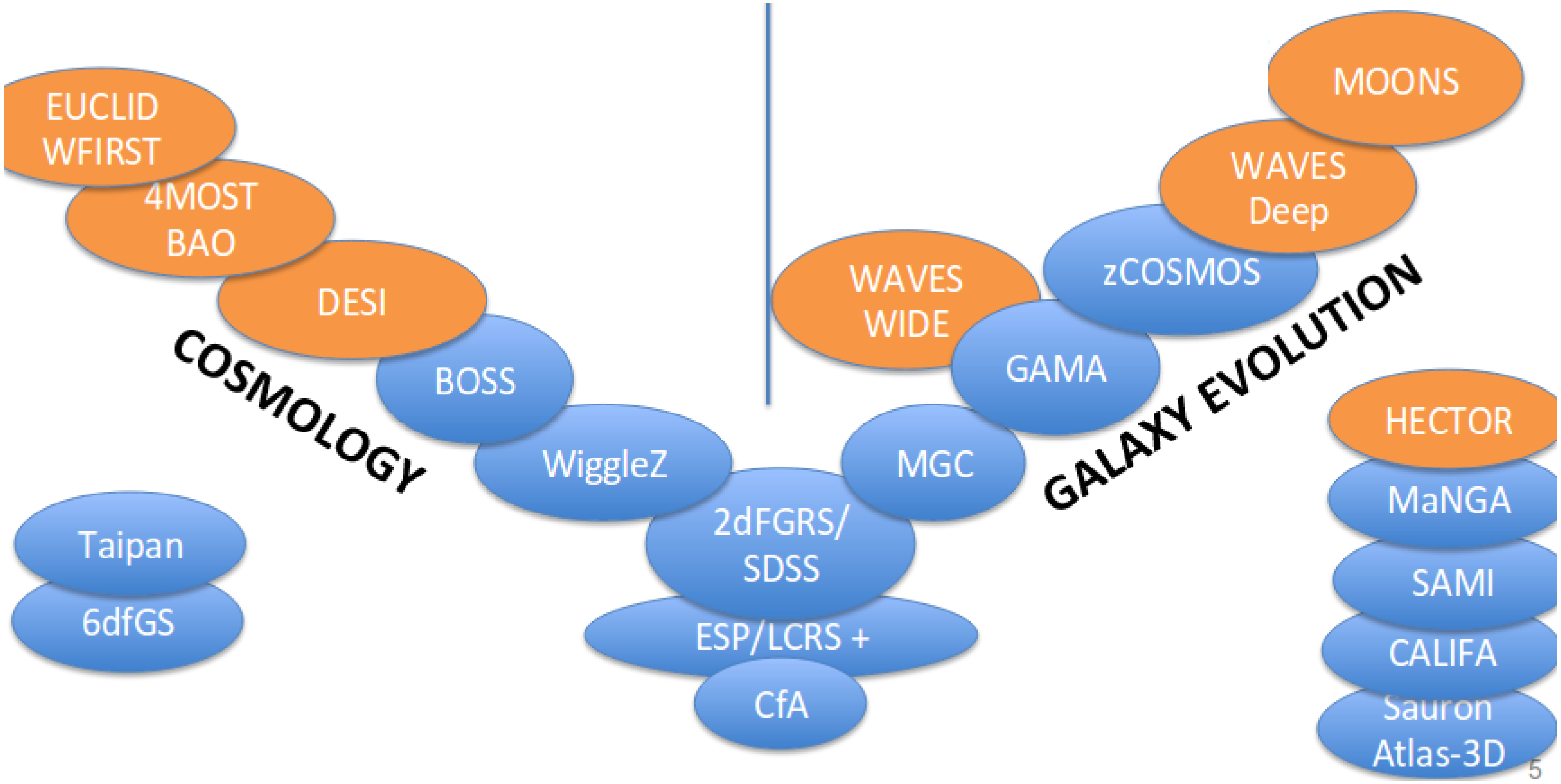



Lookback Time (Gyrs)

# Cosmology vs Galaxy Evolution surveys

- Galaxies as tracers of the mass distribution
- Volume!
- Stand-alone

- High fidelity
- Smaller regions
- Completeness!
- Multi-λ overlap



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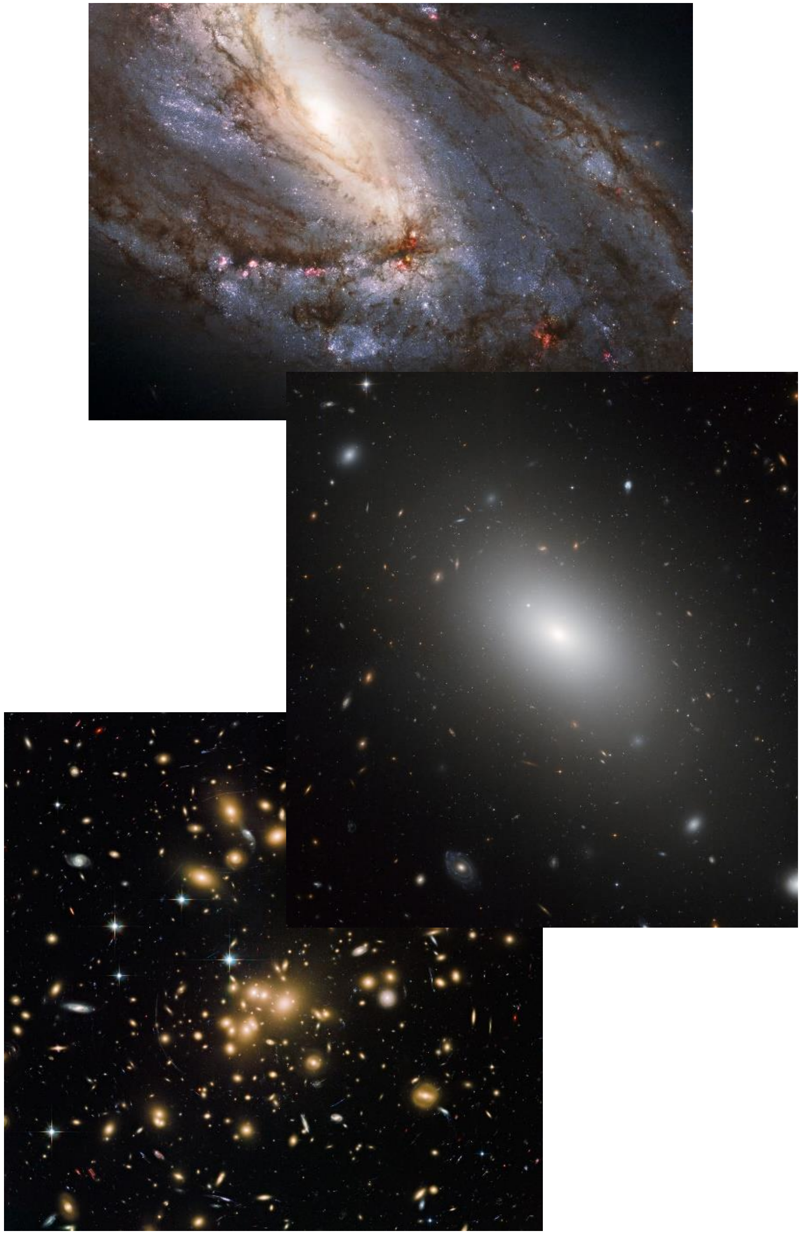
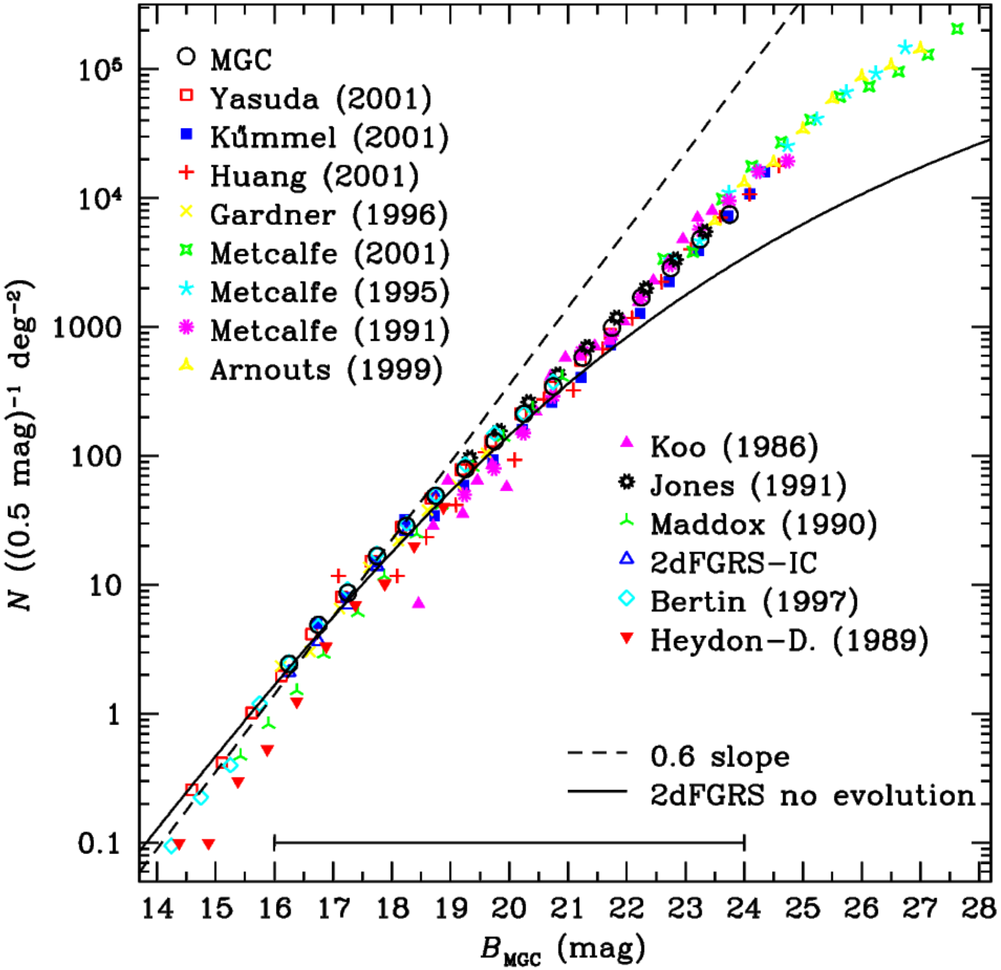
3. Interlude
4. **Properties of galaxies**
5. Basic elements of galaxy formation and evolution
6. Outstanding issues



# 4.1 Properties of galaxies: number counts

- Average number of galaxies per unit flux and unit area on the sky
- Galaxies are readily observable in huge numbers
- Depends on wavelength
- Despite its simplicity, this plot provides two important insights:
  - The Universe is not Euclidean
  - The galaxy population evolves



# 4.2 Properties of galaxies: luminosity

- Galaxy luminosities cover a huge range – many orders of magnitude

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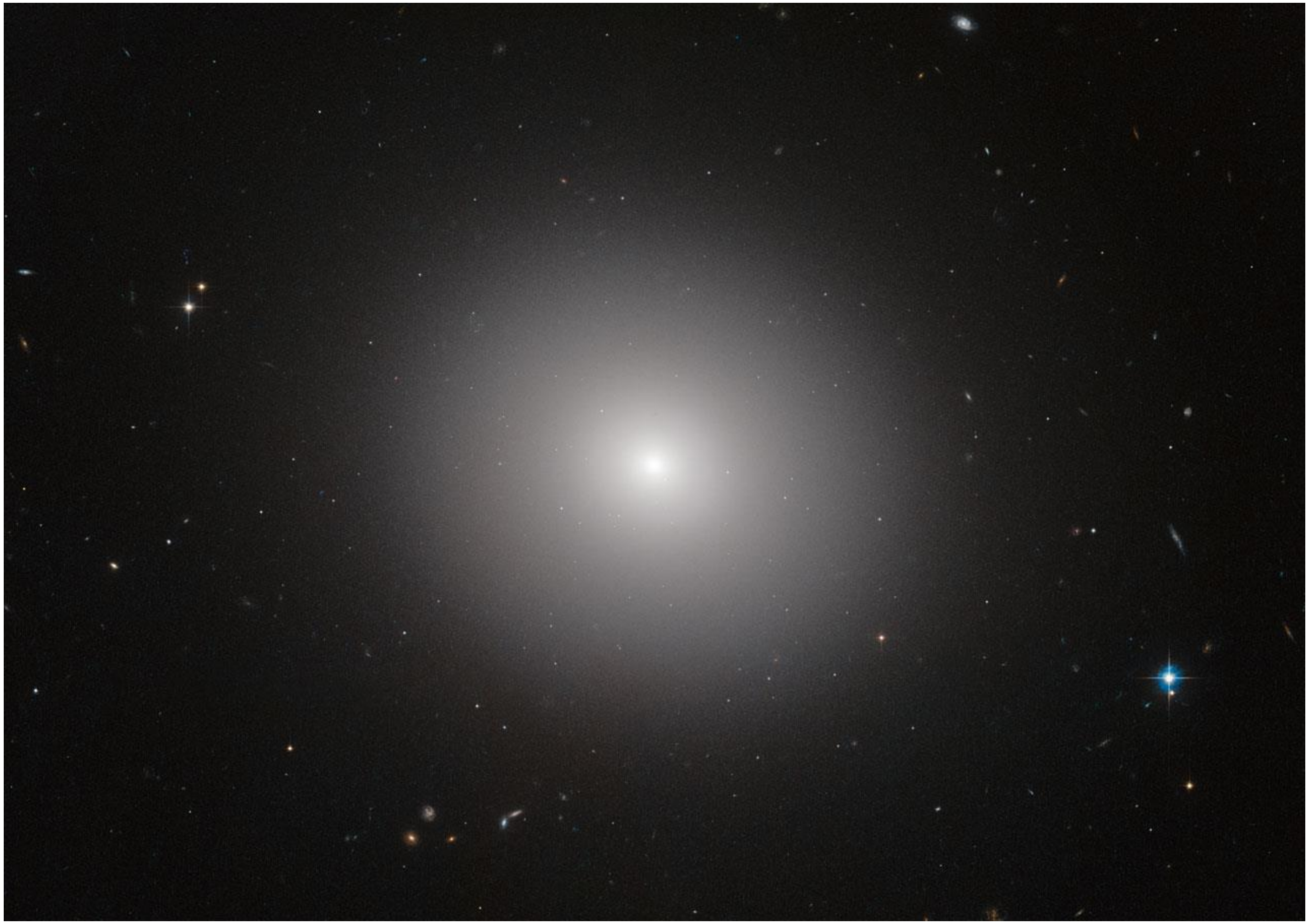

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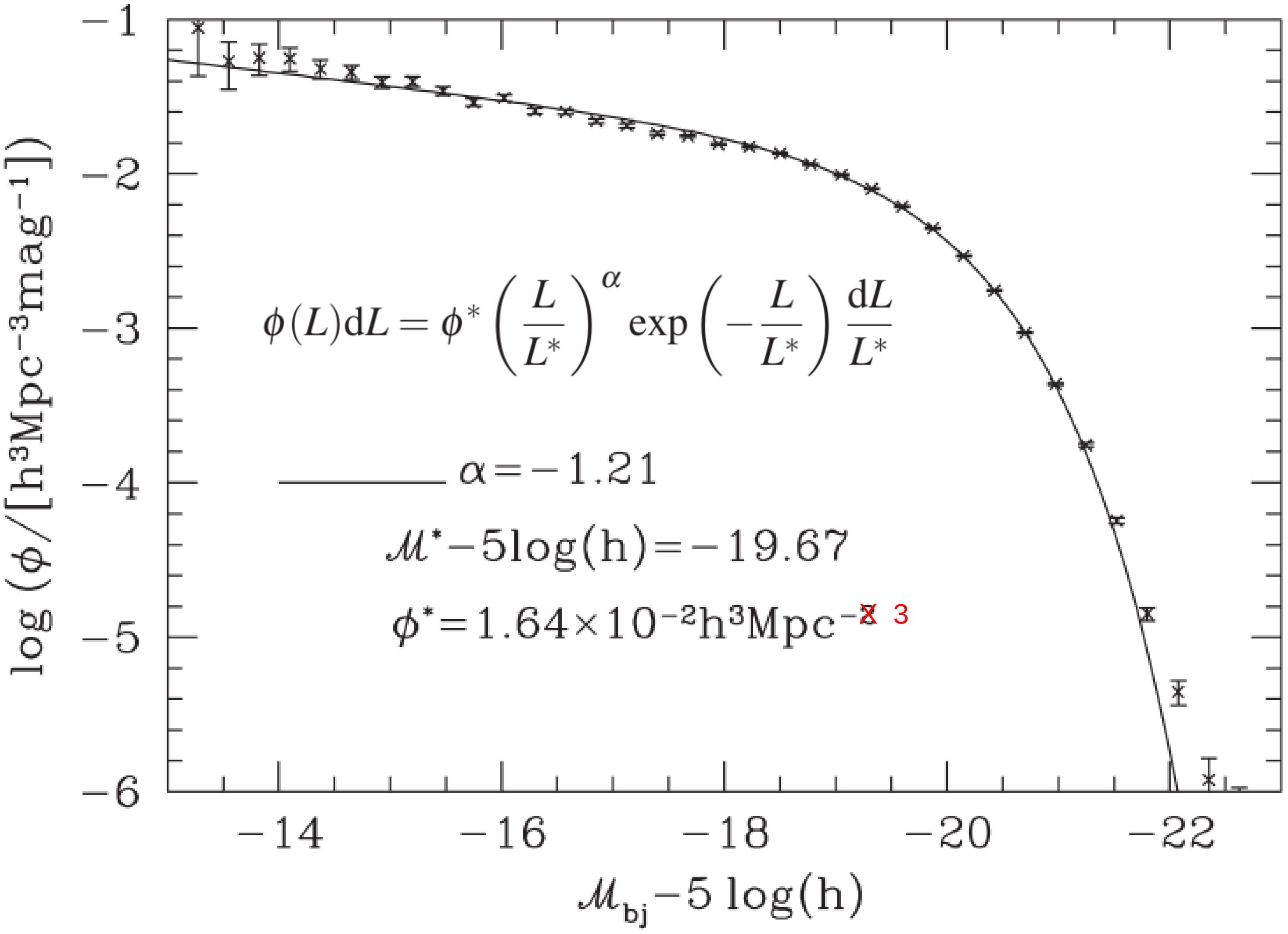
- Galaxy luminosities cover a huge range – many orders of magnitude
- Distribution in luminosity:
  Luminosity function (LF) = number of galaxies per unit volume per unit luminosity
- Empirically, the LF is well represented by a Schechter function (power-law + exponential cut-off):

$$\phi(L)\mathrm{d}L = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-\frac{L}{L^*}\right) \frac{\mathrm{d}L}{L^*}$$

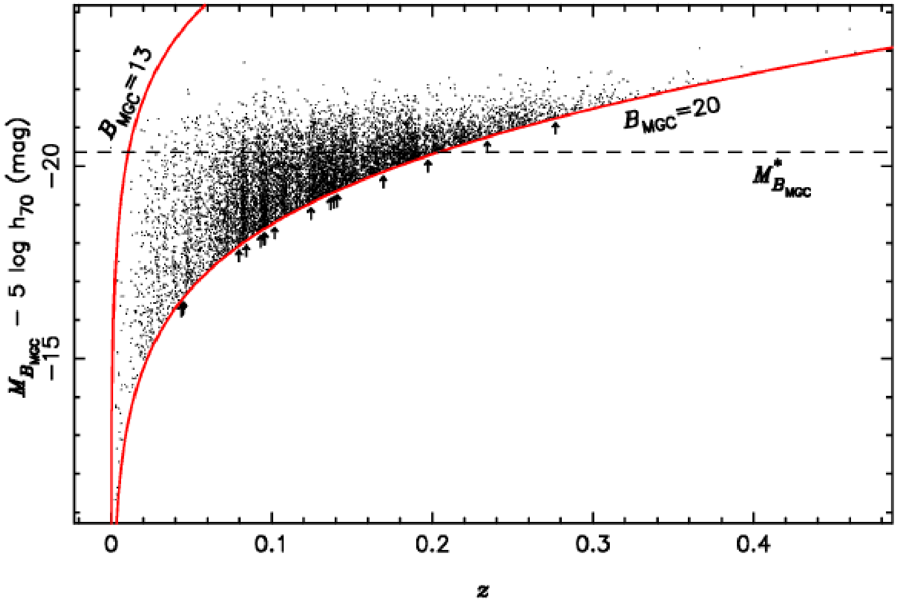
  - $\phi^*$ = normalisation
  - $L^*$ = characteristic luminosity (turnover point)
  - $\alpha$ = faint-end power-law slope

# 4.2 Properties of galaxies: luminosity



# 4.2 Properties of galaxies: luminosity

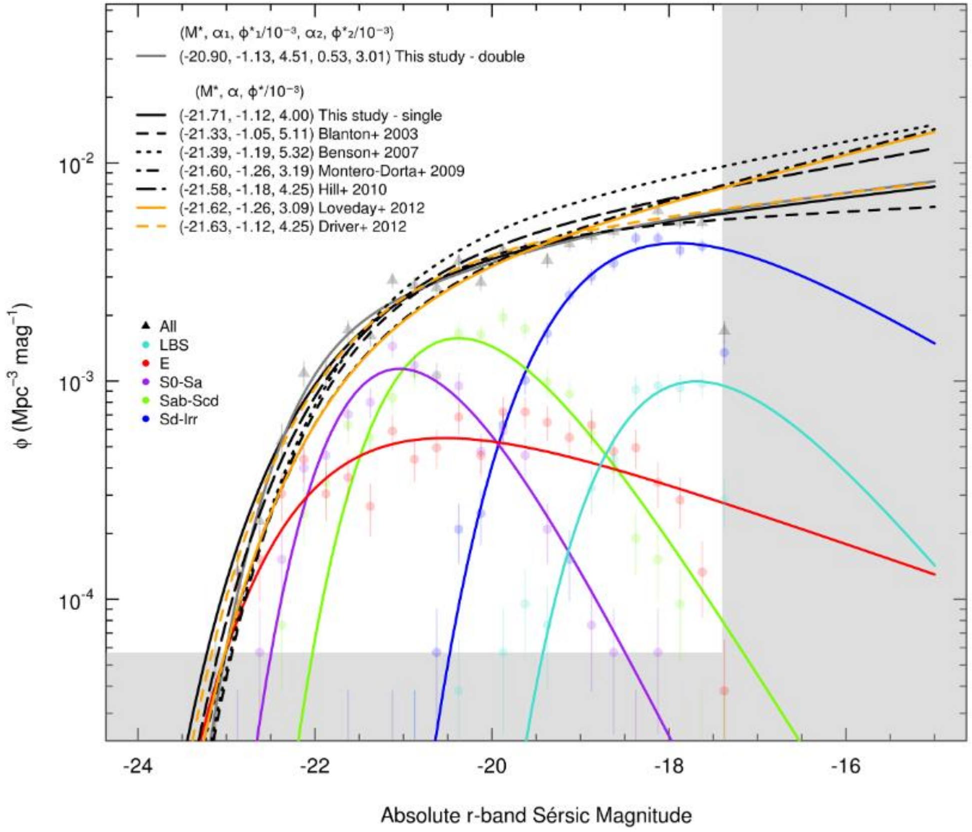
- Volume effects for a flux-limited sample (flux limits are usually imposed by available spectroscopic capability):



- Few galaxies have L >> L* because they are rare
- Few galaxies have L << L* because the volume over which they can be seen is small
- Most galaxies have L ≈ L*
- Selection effects are ubiquitous in extragalactic astronomy!

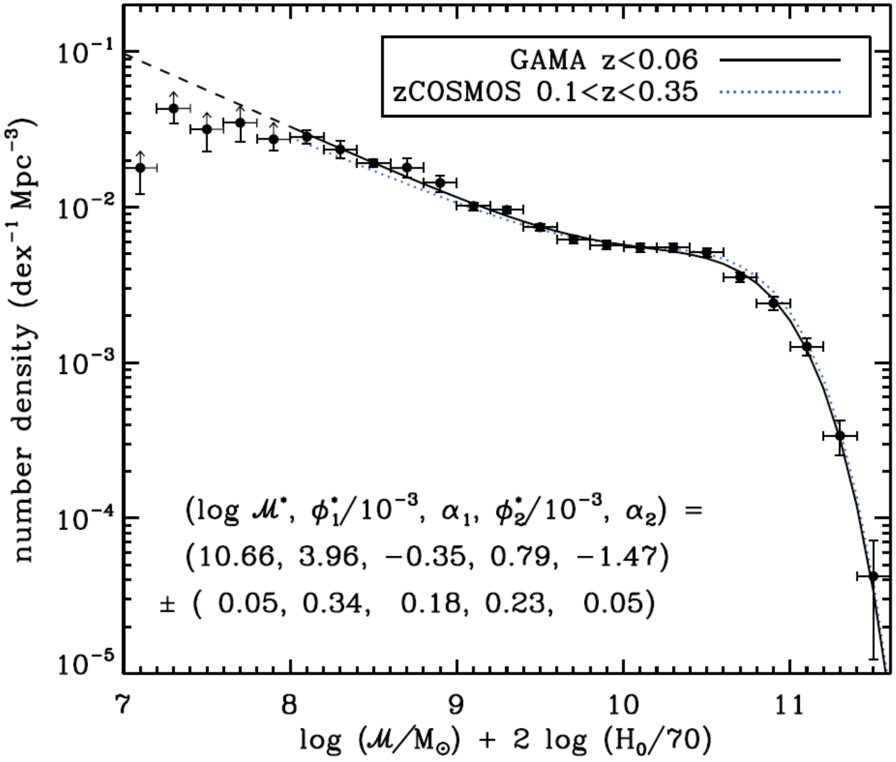
# 4.2 Properties of galaxies: luminosity

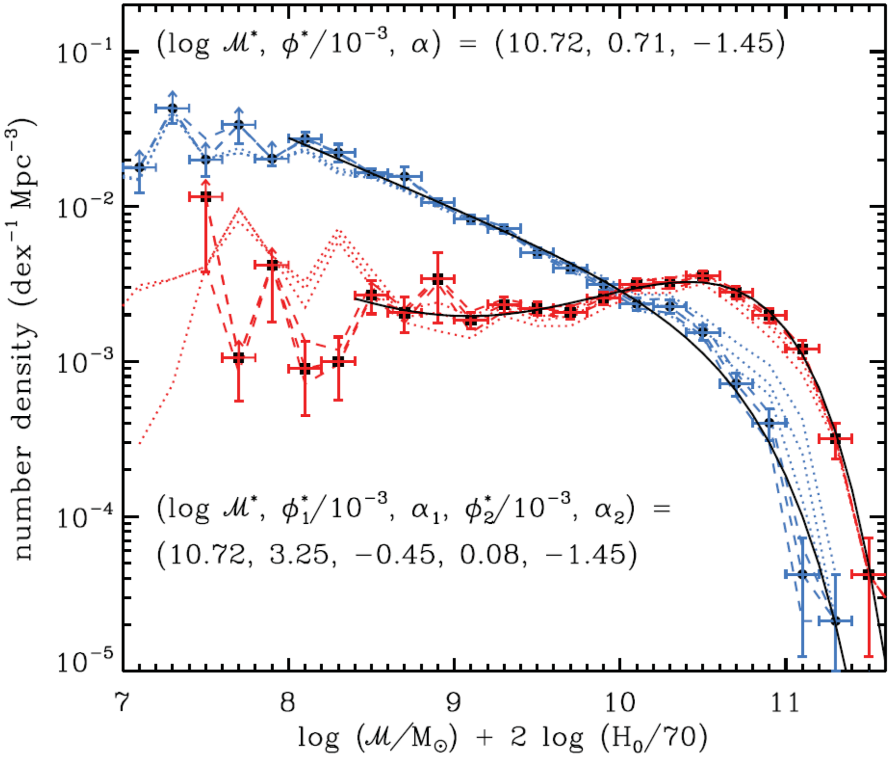
- The luminosity function varies as a function of:
  - Wavelength
  - Environment (cluster vs. field)
  - Redshift (evolution of the galaxy population)
  - Colour
  - Galaxy type
  - …



# 4.2.1 Properties of galaxies: stellar mass

- The stellar mass function is well represented by a double Schechter function:





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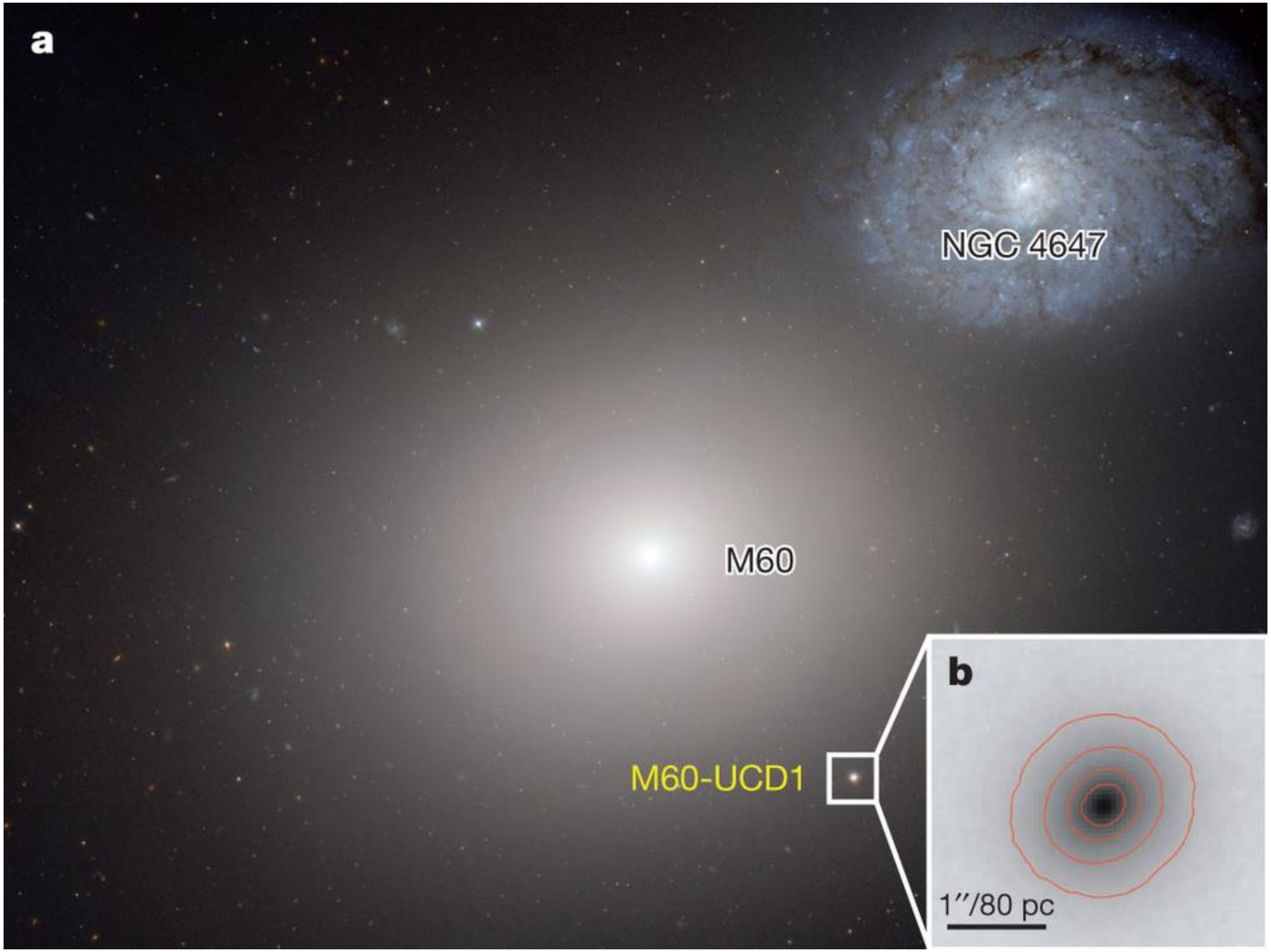
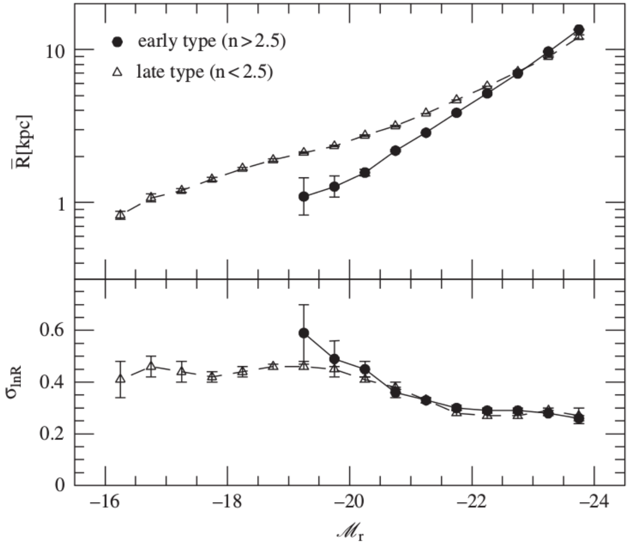


# 4.3 Properties of galaxies: size

- Galaxy sizes cover a huge range – many orders of magnitude
- Distribution in size = number of galaxies per unit volume per unit size
- Empirically, size is strongly correlated with luminosity, hence one usually considers the joint size-luminosity distribution
- At fixed L, the size distribution is roughly log-normal:

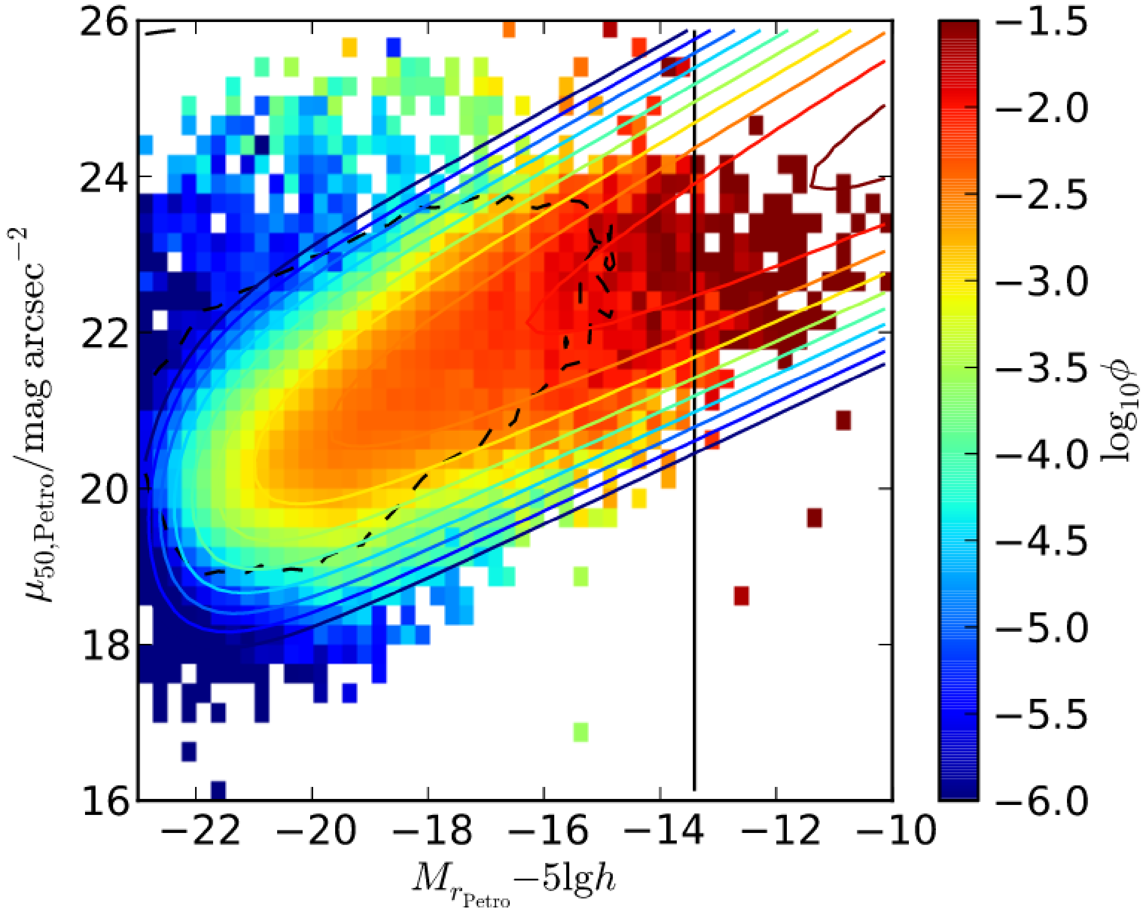
$$P(R|L)\,\mathrm{d}R = \frac{1}{\sqrt{2\pi}\sigma_{\ln R}} \exp\left[-\frac{\ln^2(R/\bar{R})}{2\sigma^2_{\ln R}}\right]\frac{\mathrm{d}R}{R}$$

- where both <R> and $\sigma_{\ln R}$ are functions of L:



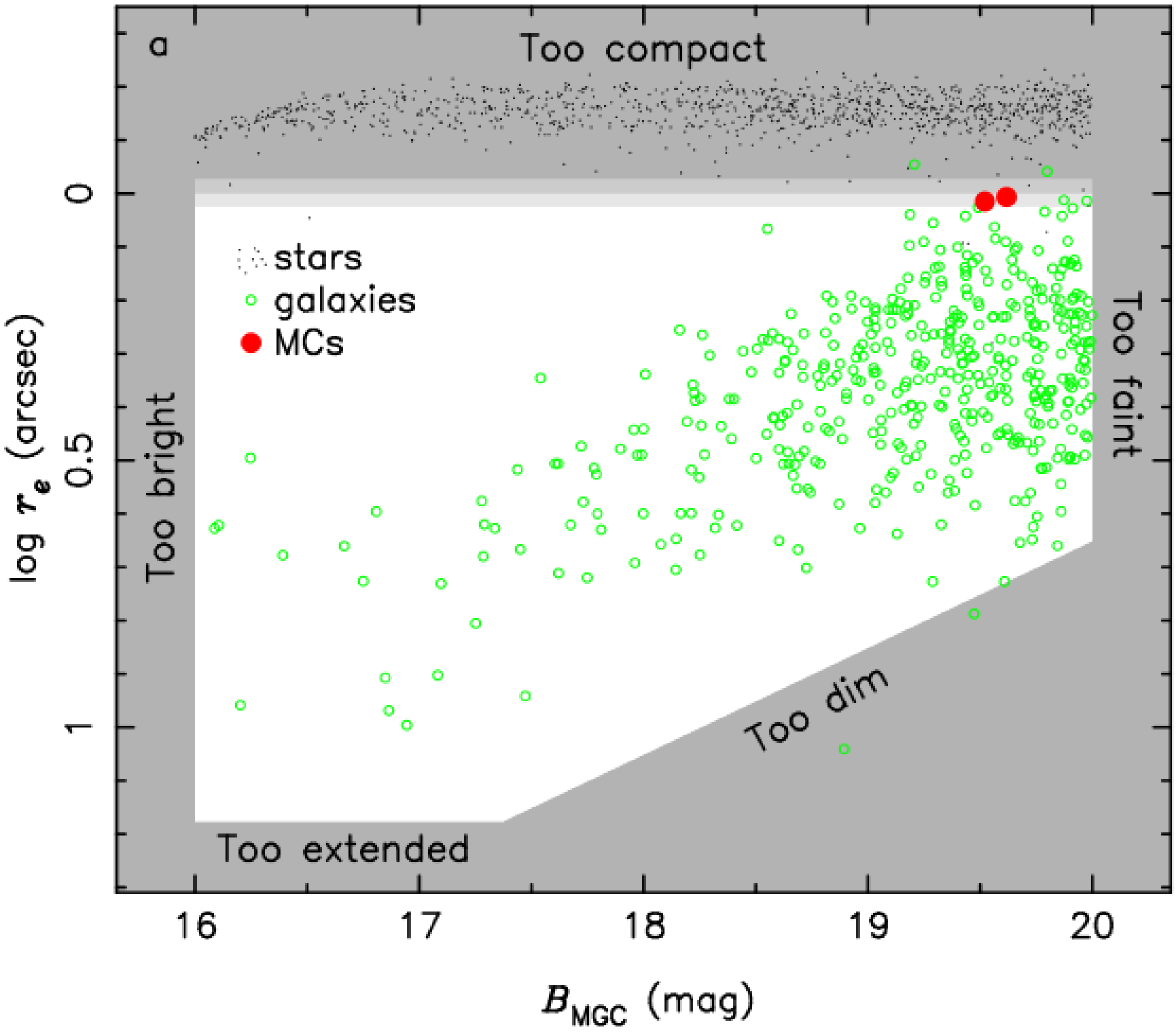
# 4.3 Properties of galaxies: size

- Instead of luminosity and size one can equivalently consider luminosity and surface brightness
- Bivariate brightness distribution:



# 4.3 Properties of galaxies: size

- Size and surface brightness are also subject to selection effects:



# 4.4 Properties of galaxies: morphology

- The term “morphology” refers to the visual appearance of galaxies in astronomical images
- Many galaxies display such striking morphologies that it seems self-evident that morphology encodes important information about the formation and evolution of galaxies

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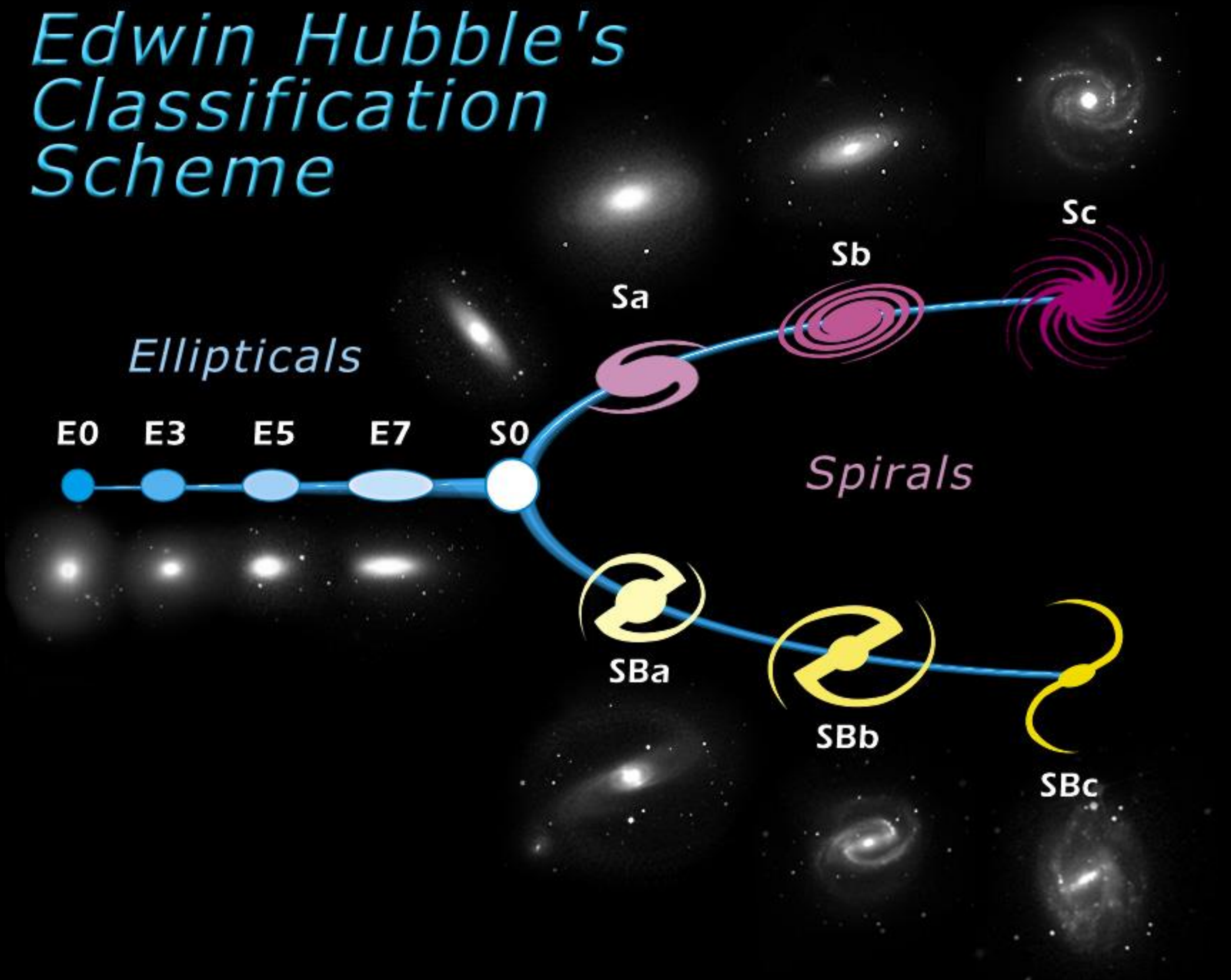
- The term “morphology” refers to the visual appearance of galaxies in astronomical images
- Many galaxies display such striking morphologies that it seems self-evident that morphology encodes important information about the formation and evolution of galaxies
- Question: what aspects of morphology, exactly, contain relevant information and how is this best extracted?
- Different approaches:
    - Morphological classification
    - Surface brightness profiles
    - Non-parametric classification

# 4.4 Properties of galaxies: morphology

- In the present-day Universe most bright galaxies display only a restricted set of morphologies
- In other words, these galaxies can be assigned to a finite set of (more or less) well-defined morphological classes
- Several such morphological classification systems have been devised, most prominently:
  - Hubble system (Hubble’s tuning fork)
  - de Vaucouleurs system

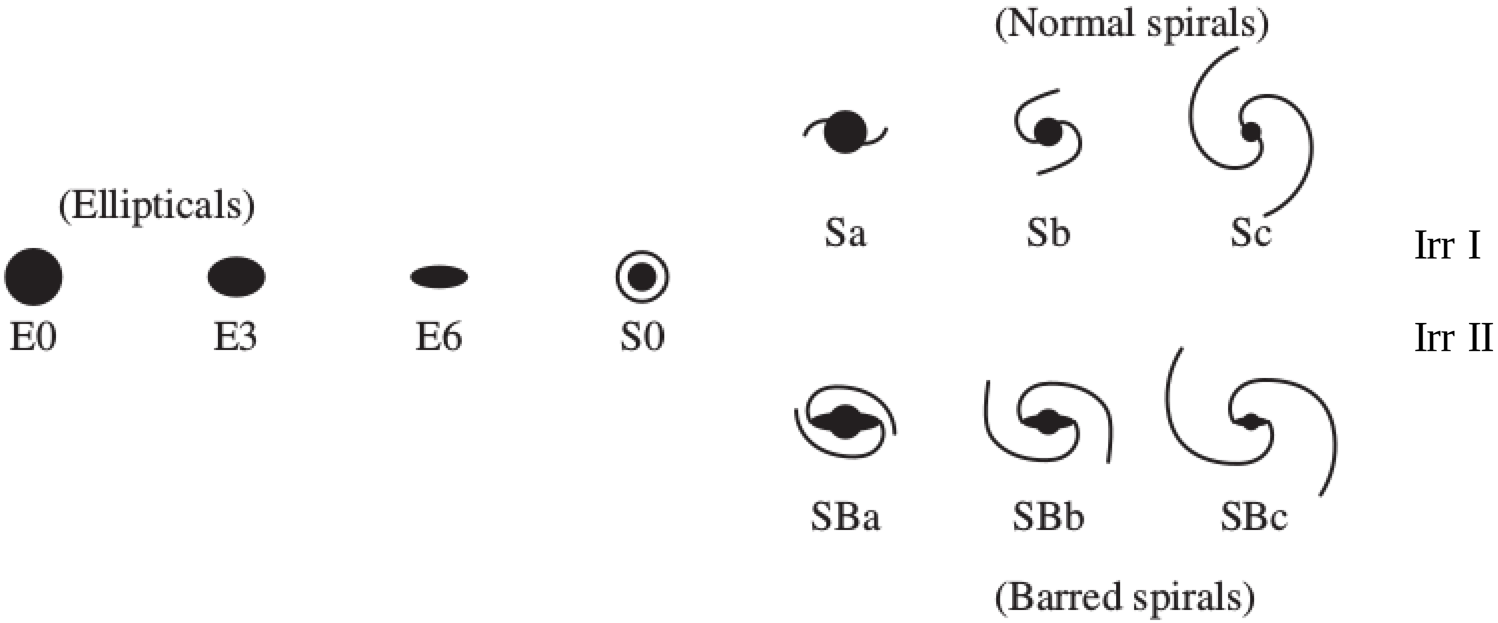
# Edwin Hubble's Classification Scheme



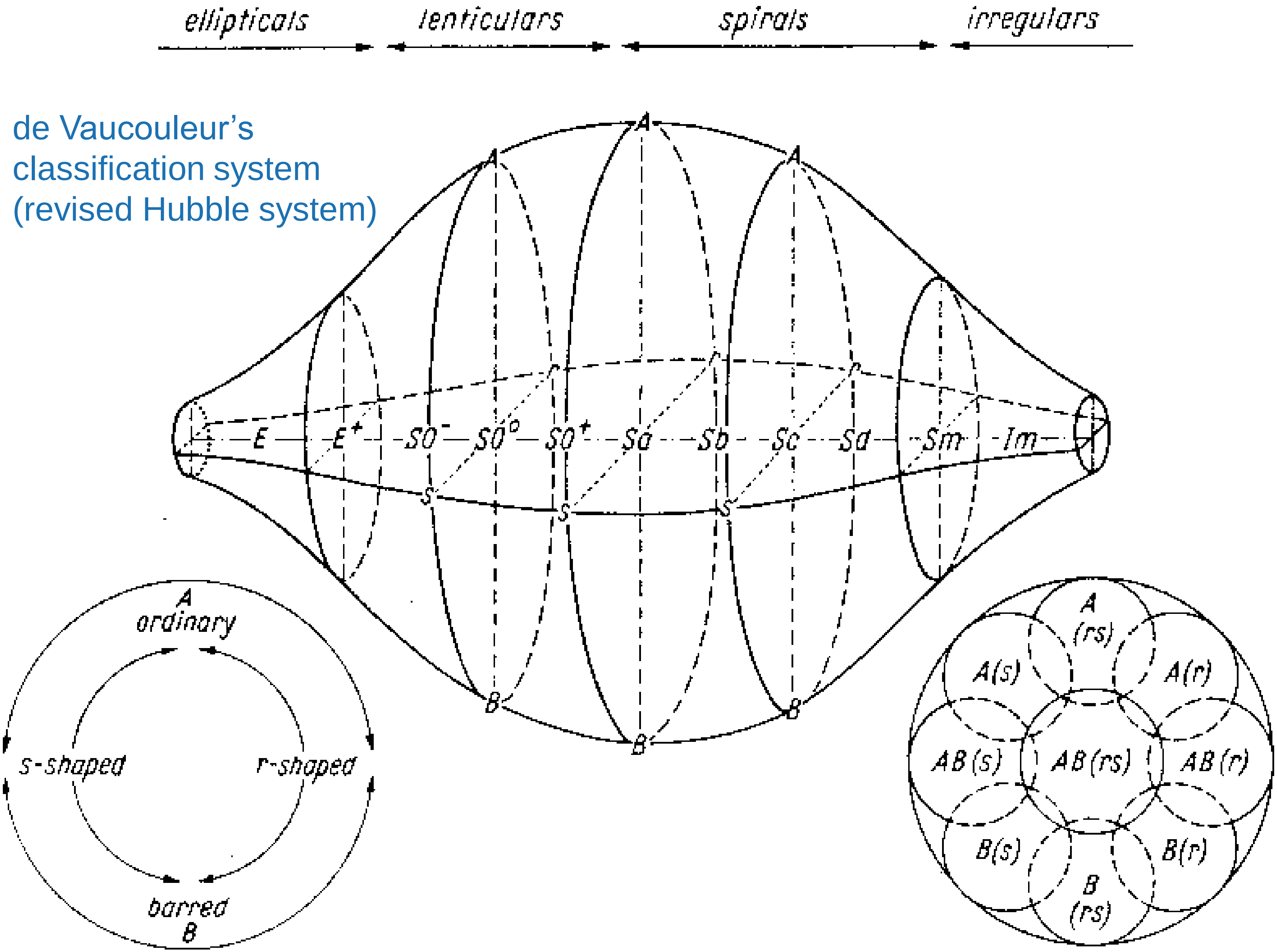
# 4.4 Properties of galaxies: morphology

## Hubble's classification system

- E and S0 often referred to as "early types", S(B) as "late types"
- Also: early and late-type spirals: S(B)a, S(B)c
- Not meant to indicate an evolutionary sequence



# de Vaucouleur’s classification system (revised Hubble system)



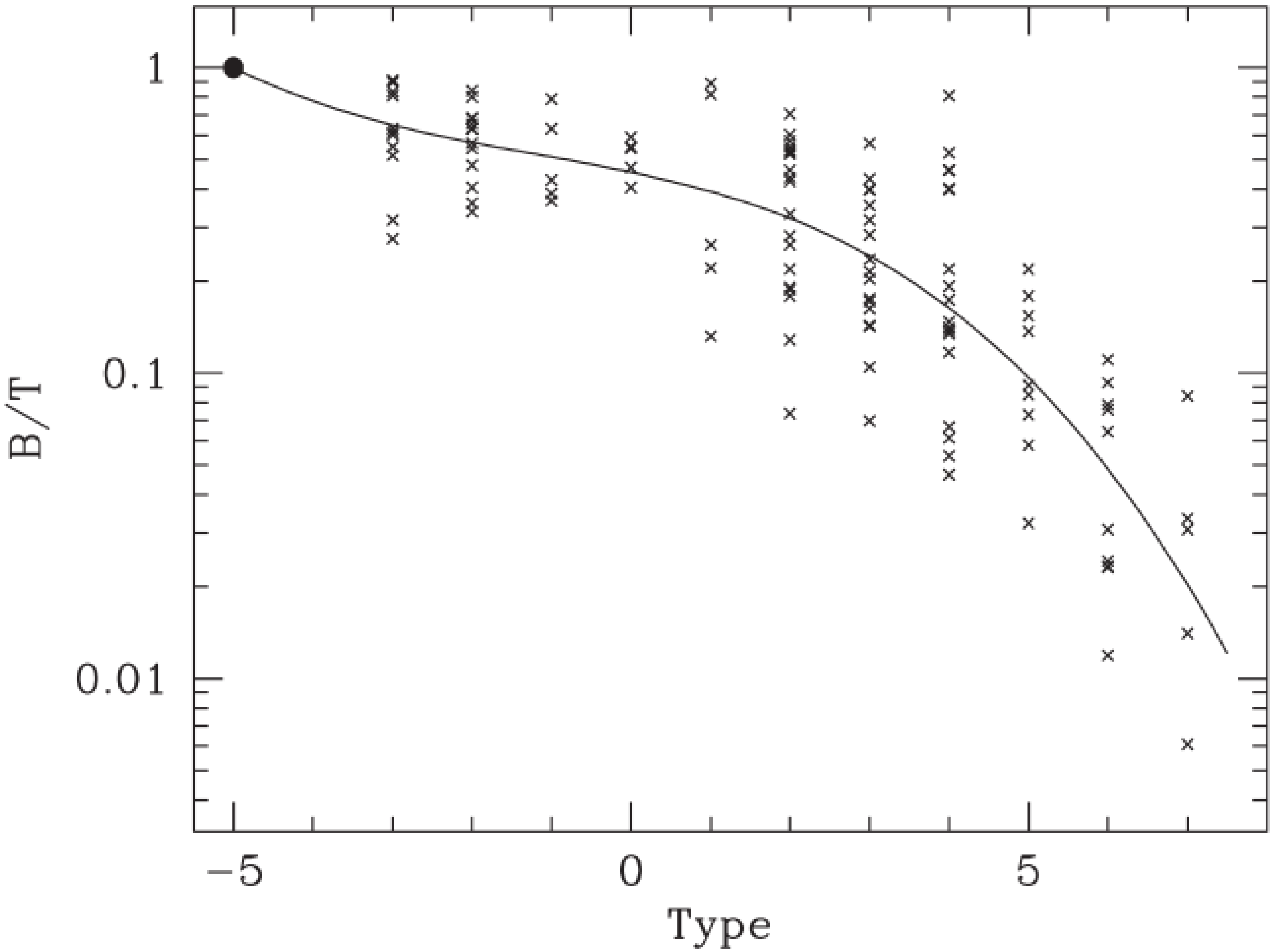
# 4.4 Properties of galaxies: morphology

## de Vaucouleur’s classification system

- Revision and extension of Hubble’s system
- Refinement of Hubble’s stage (E-S0-S), and extension to Sd, Sm, Im
- Change in nomenclature: S, SB → SA, SB
- Introduction of a third axis (in addition to stage and “barredness”): normal or ring-like: (s) or (r)
- Recognition that the boundaries between the “classes” along each of the three axes are fuzzy → explicit allowance for intermediate types
- Examples:
    - SAB(r)c
    - SA(rs)ab
    - IBm
- Caution: many workers in this field adopted the refinements and extensions to the Hubble stage but ignored the rest

# Example

# 4.4 Properties of galaxies: morphology



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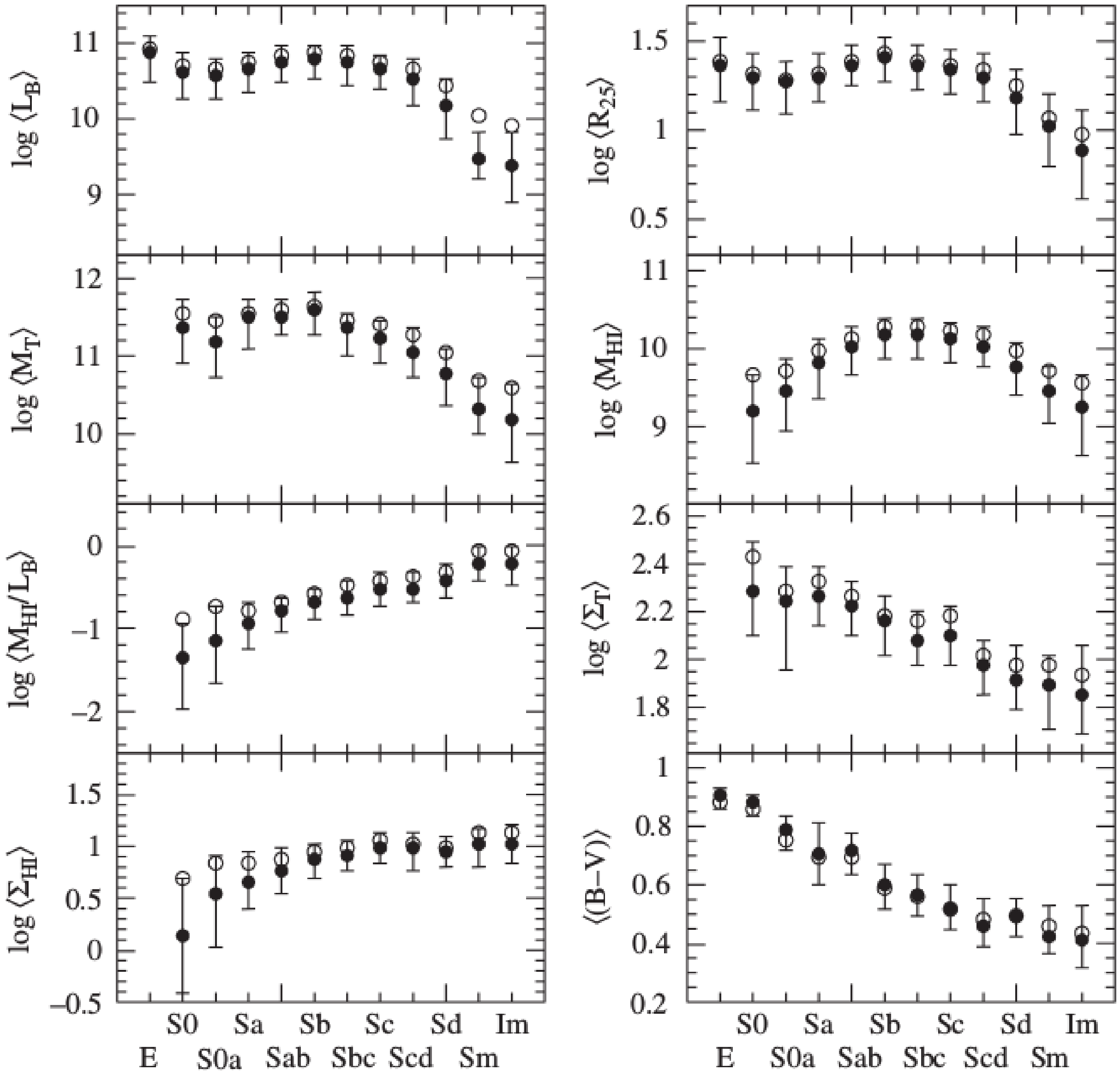


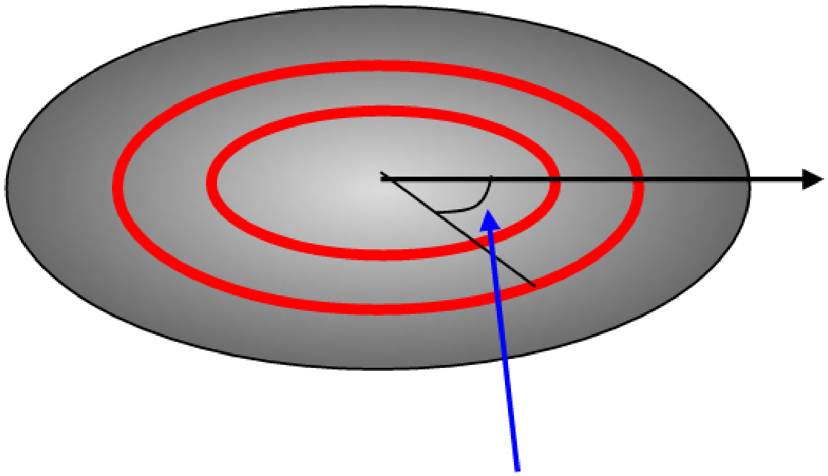
# 4.4 Properties of galaxies: morphology

- Apart from their physical characteristics, the visual appearance of galaxies depends on a number of additional, observational parameters:
  - Size relative to the size of a spatial resolution element of the image
  - Brightness relative to the background
  - Noise level of the image
  - Projection effects
  - Wavelength
- Furthermore, visual perception is subjective, i.e. it depends on the observer, although experienced classifiers usually agree with each other to within < ~1 Hubble type
- ➢ Development of more quantitative measures of morphology

- Also: breakdown of Hubble sequence at $z \approx 1 - 2$

# 4.5 Properties of galaxies: SB profile

- The 2D surface brightness distributions of both spheroids and disks are highly symmetric (although spiral arms and dust tend to reduce the symmetry)
- The 2D distribution can be reduced to a 1D surface brightness “profile” by averaging the 2D distribution along elliptical isophotes



azimuthal angle φ

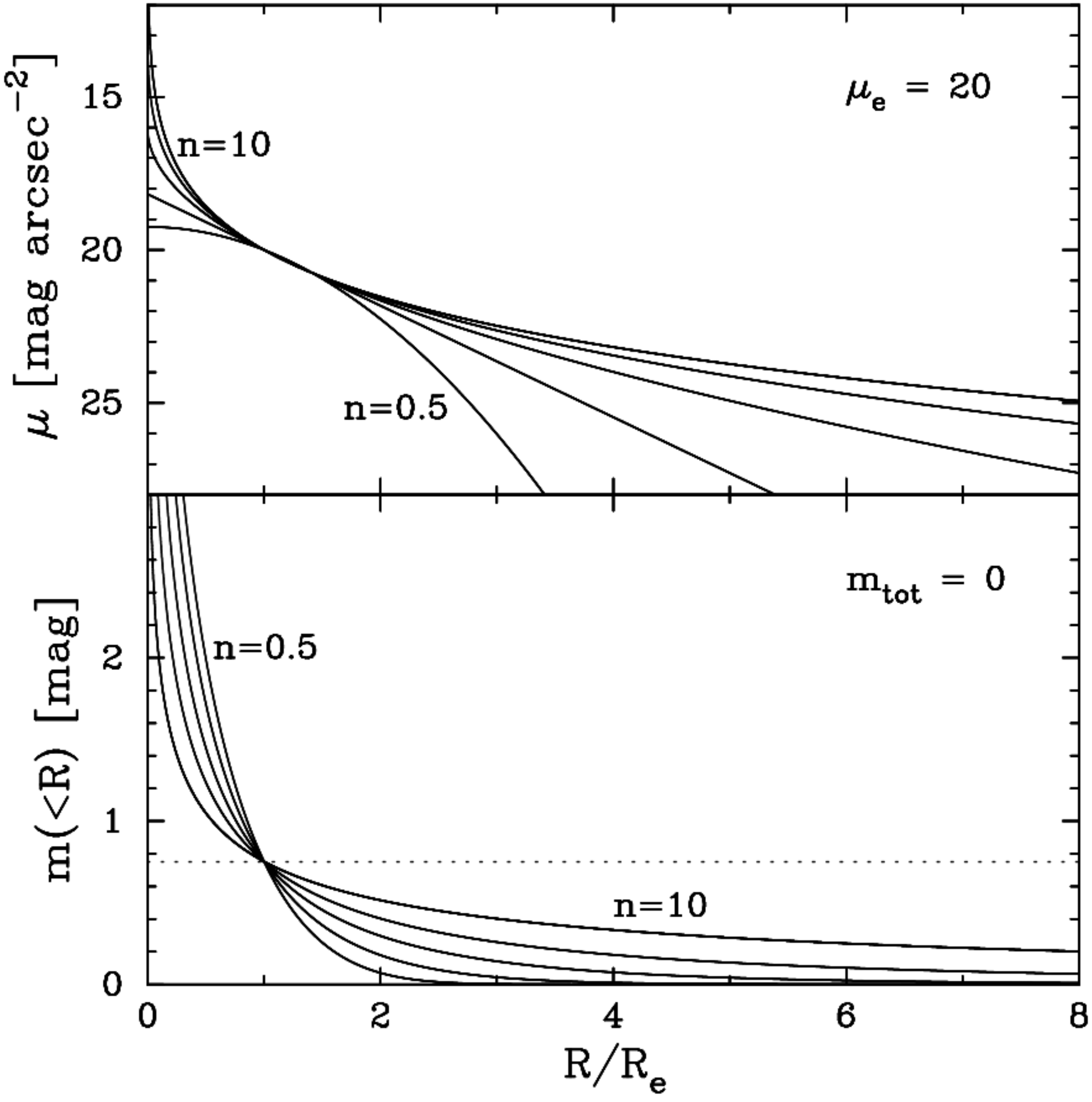
# 4.5 Properties of galaxies: SB profile

- The 2D surface brightness distributions of both spheroids and disks are highly symmetric (although spiral arms and dust tend to reduce the symmetry)
- The 2D distribution can be reduced to a 1D surface brightness “profile” by averaging the 2D distribution along elliptical isophotes
- The SB profiles of most spheroids and disks are well fit by the Sérsic function:

$$I(R) = I_0 \exp\left[-\beta_n \left(\frac{R}{R_e}\right)^{1/n}\right] = I_e \exp\left[-\beta_n \left\{\left(\frac{R}{R_e}\right)^{1/n} - 1\right\}\right]$$

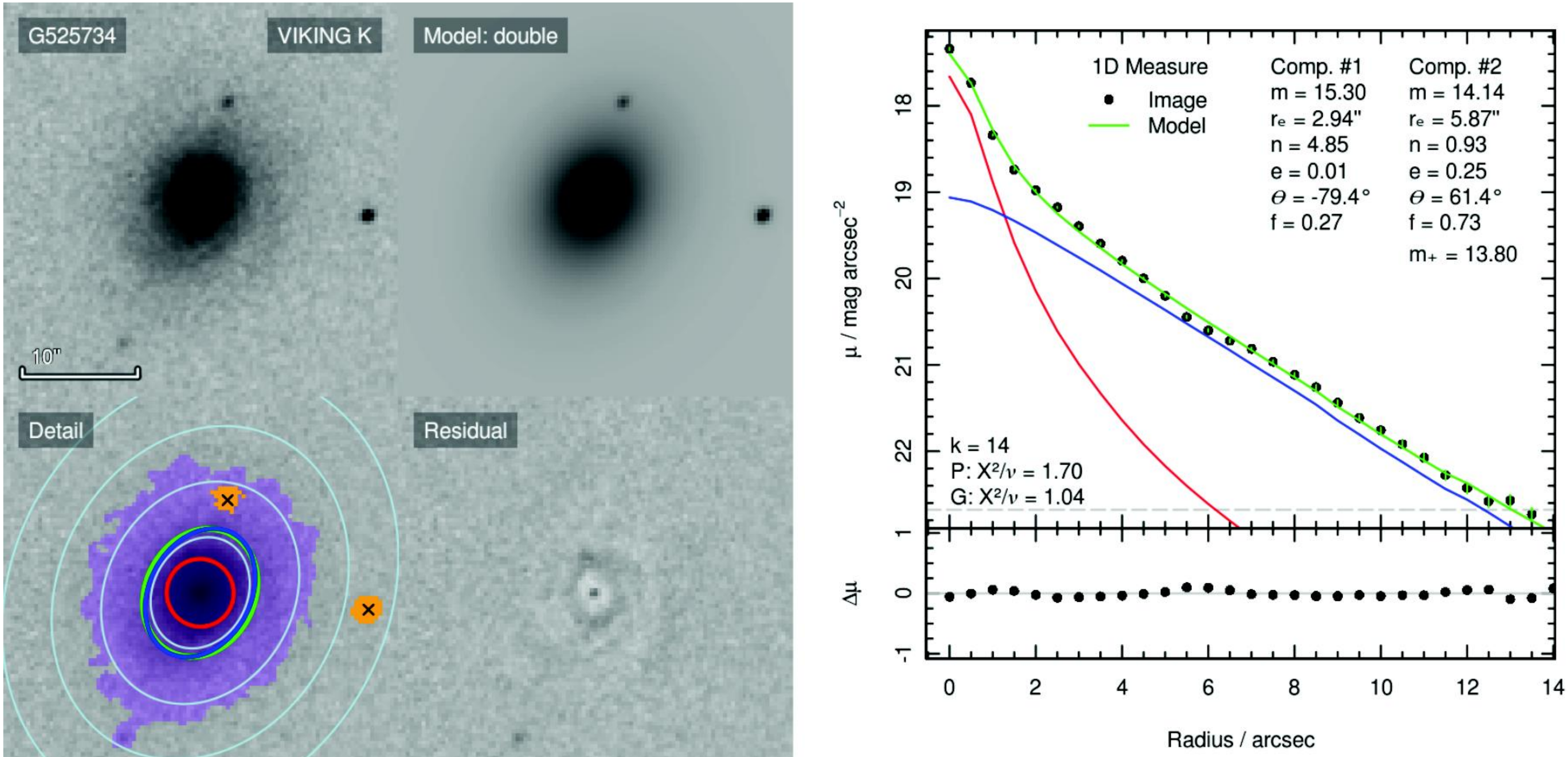
- $I$ = surface brightness, $[I]$ = flux / arcsec$^2$
- $R$ = distance from galaxy centre along major axis, $[R]$ = arcsec
- $R_e$ = radius that enclose half of the total flux, size
- $I_0$ = central SB, $I_e = I(R_e)$
- $n$ = Sérsic index, sets the concentration of the profile
  - $n = 1$: exponential profile
  - $n = 0.5$: Gaussian
  - $n = 4$: de Vaucouleurs profile
- $\beta_n = b_n$ = parameter that only depends on $n$

# 4.5 Properties of galaxies: SB profile

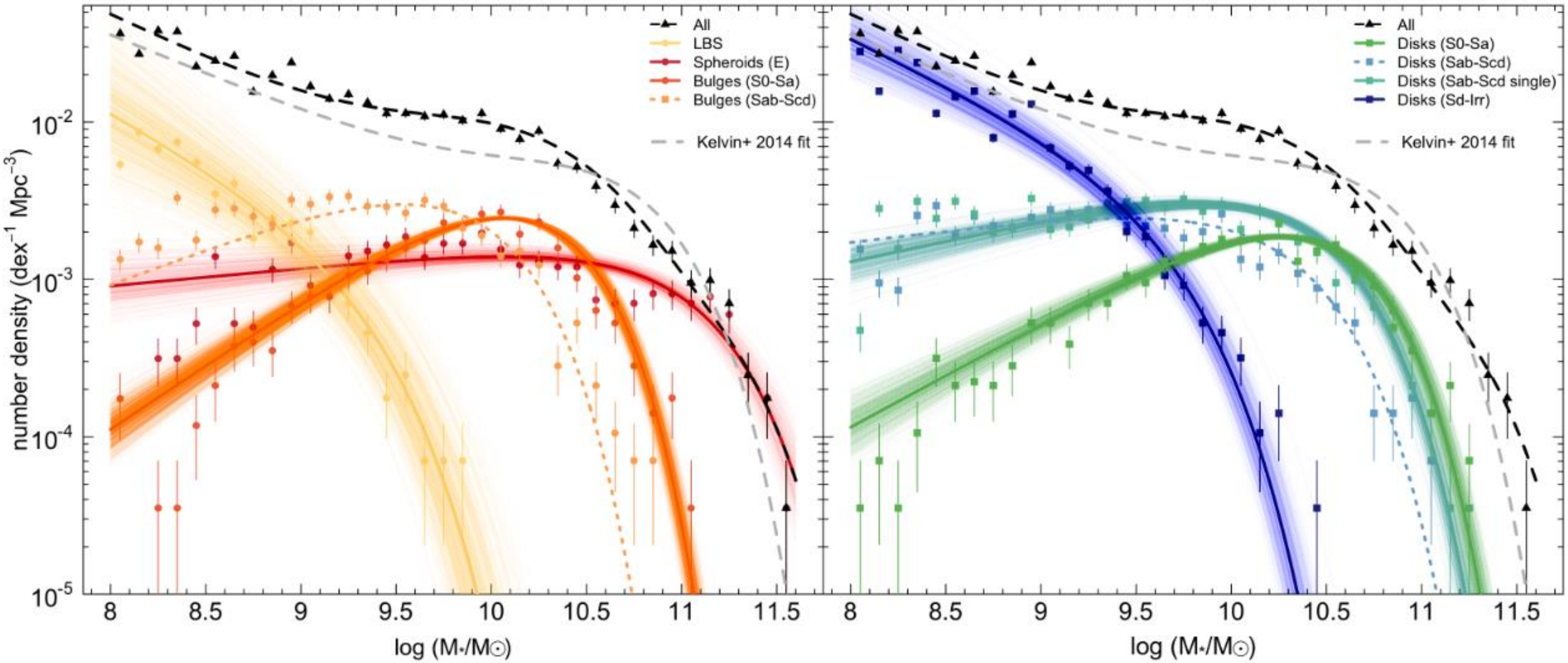


# 4.5 Properties of galaxies: SB profile

Example of a two-component galaxy. The model is fit to the 2D SB distribution. Note that the model SB profile needs to be convolved with the local PSF.

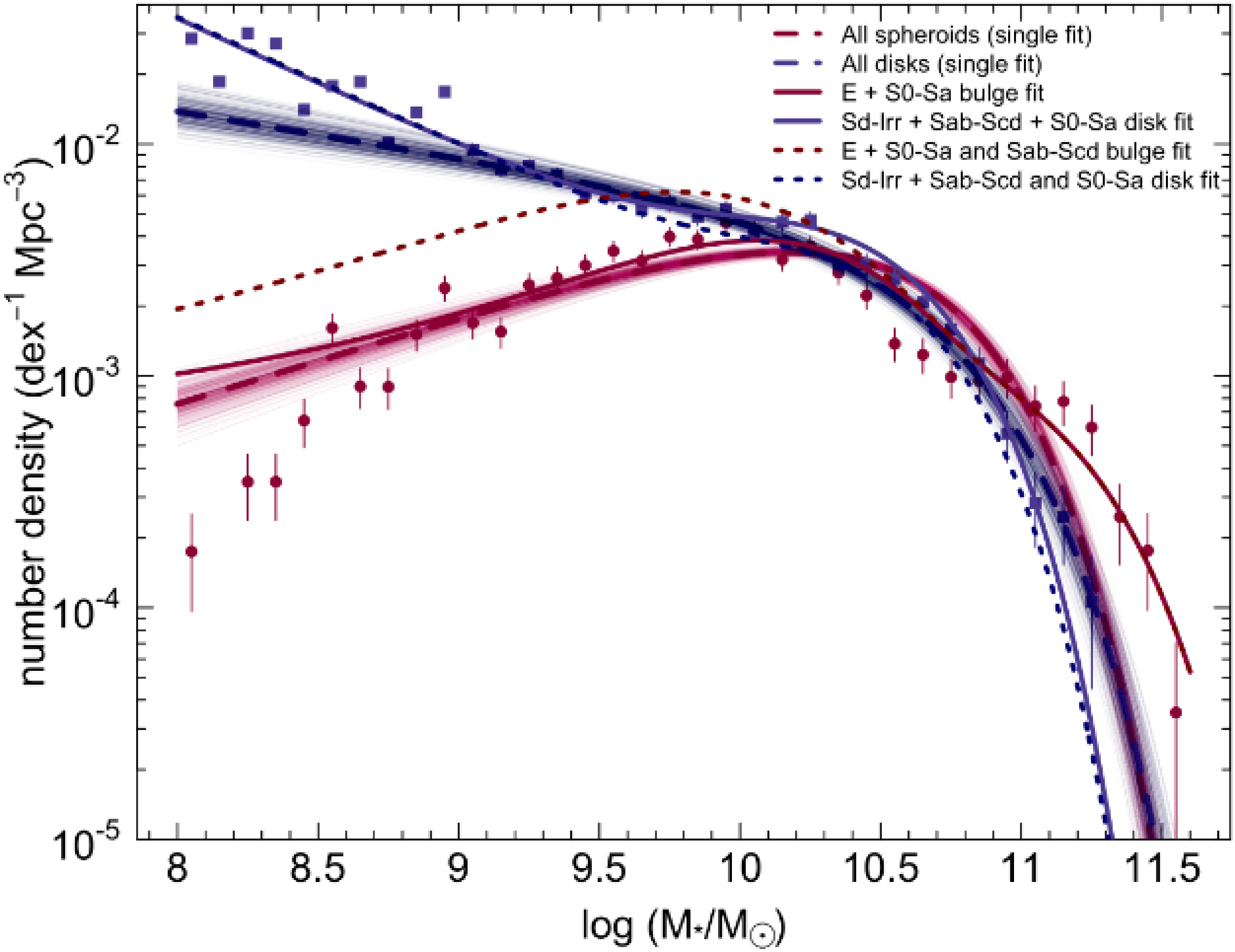


# Photometric decomposition → component properties



Stellar mass in spheroids ≈ stellar mass in disks

# Photometric decomposition → component properties



Spheroids dominate at the very high-mass end, disks at the low-mass end

# 4.5 Properties of galaxies: SB profile

- SB profile fiiting assumes highly symmetric and smooth profiles
- However, many features of galaxies do not fit this description:
  - Spiral arms
  - Dust lanes
  - (Dwarf) irregulars
  - Tidal features
  - Merging galaxies
- Other features may invalidate the assumed (double) Sérsic model:
  - Nuclear components
  - Bars
  - Disk truncation or flaring
  - Isophotal twisting
- When fitting a model with many degrees of freedom to data that are not in fact represented by the model → "unphysical" results (e.g. bulge larger than disk)

# 4.6 Properties of galaxies: non-parametric methods

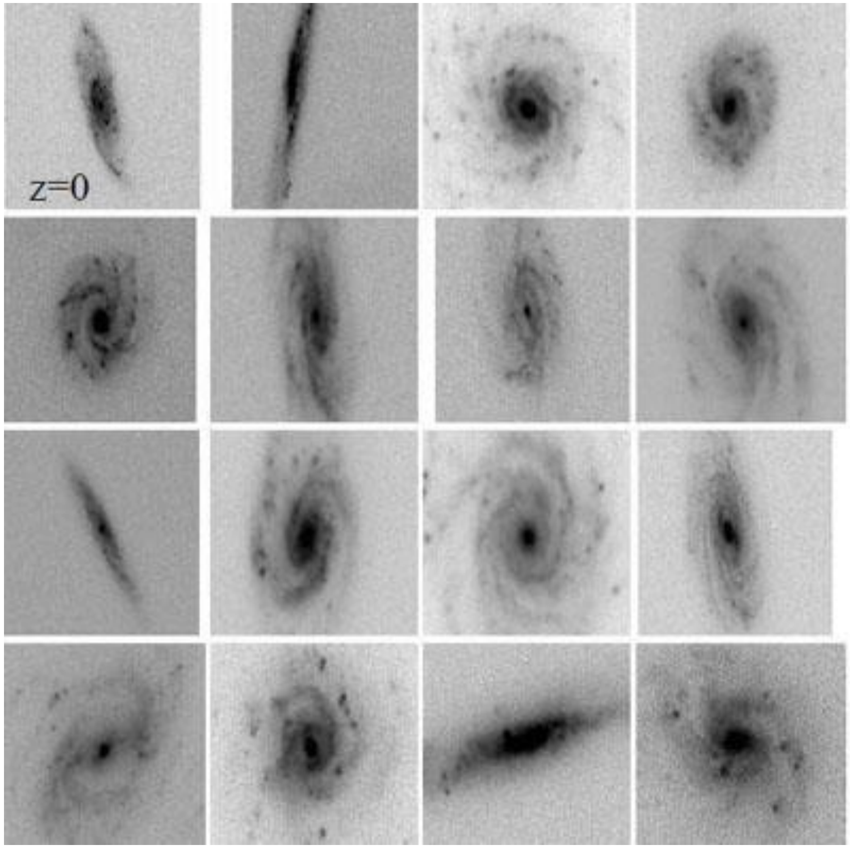
- These are methods of quantifying morphological characteristics in a model-independent way directly from the pixel data
- Examples:
  - Concentration, Asymmetry, clumpinesS (CAS)
  - Gini coefficient and $M_{20}$
  - Multi-mode, Intensity, Distance (MID)
  - Decomposition using a set of eigenfunctions (e.g. shaplets)
  - Machine Learning Algorithms (e.g. Artificial Neural Networks, Random Forests, Naïve Bayes, Support Vector Machines, …)
  - Possibly combined with Principal Component Analysis (PCA)
- Sounds simple in some cases, but details matter

- Particularly suited to high redshift galaxies which are largely irregular

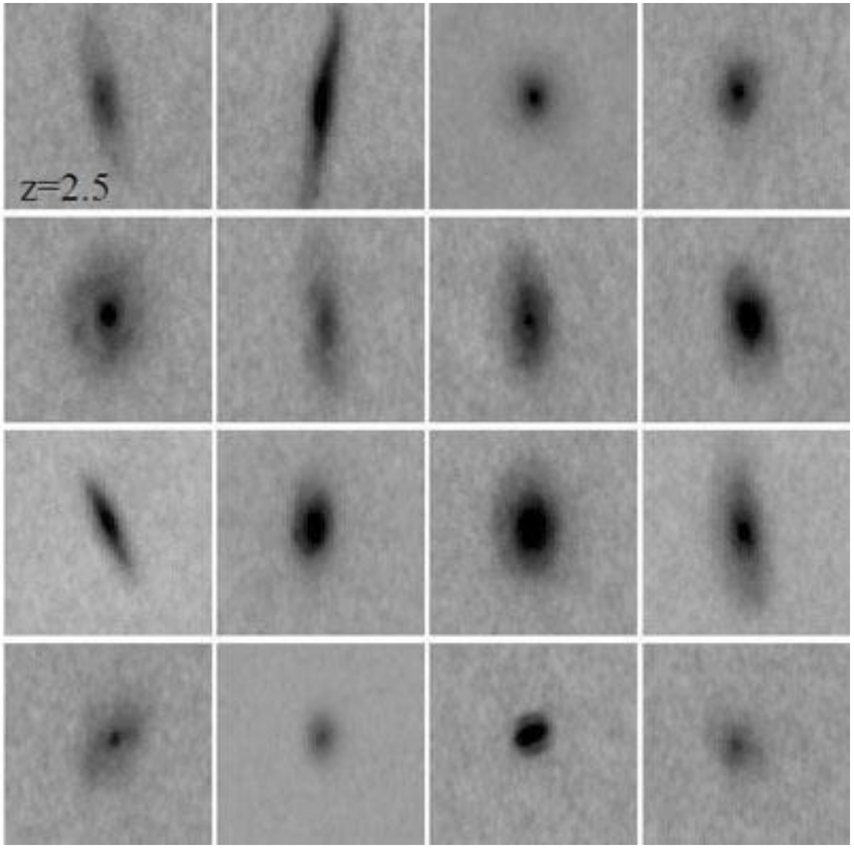
# 4.4 – 6 Properties of galaxies: morphology

- Always difficult to compare different morphological datasets
- Difficult to quantify evolution of morphology

Nearby galaxies



Same galaxies artificially redshifted

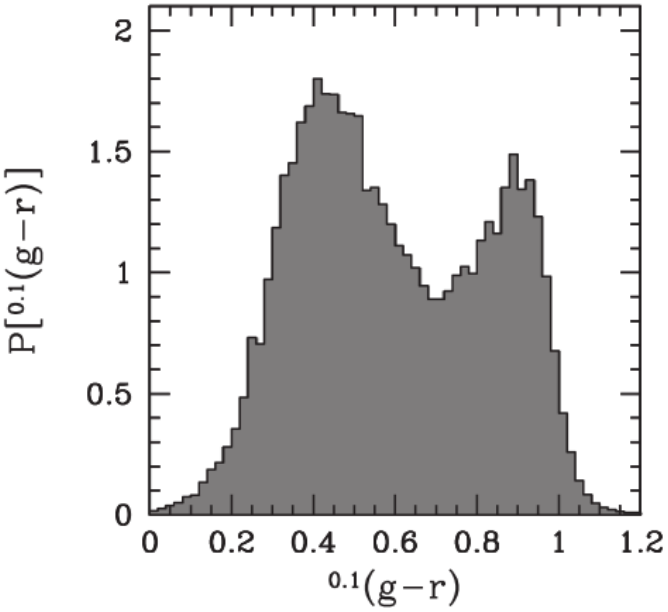


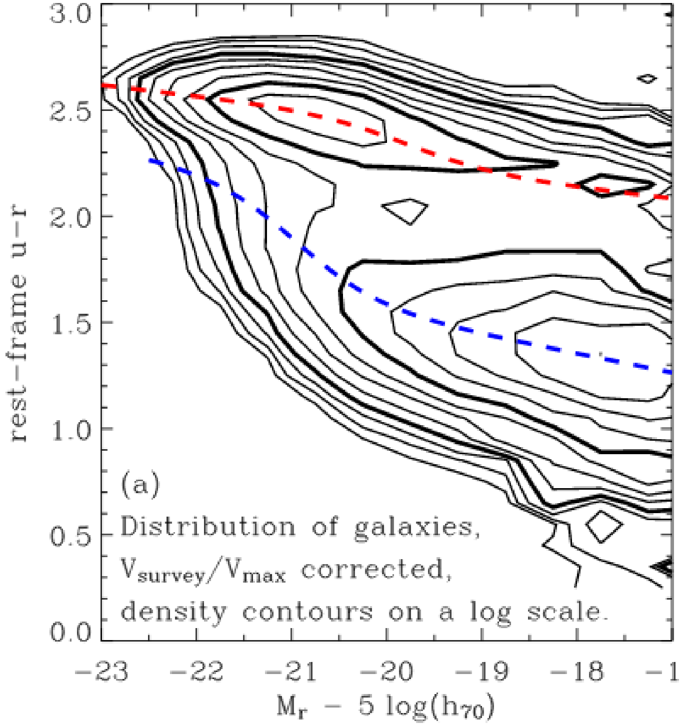
# 4.7 Properties of galaxies: colour

- More massive stars emit a larger fraction of their light at shorter wavelengths than lower mass stars ($T_{eff} \propto M^{3/8}$)
- More massive stars live shorter than lower mass stars ($t \propto M^{-2}$)
- The colour of a galaxy (i.e. of the integrated light of its stellar population) carries information about its star-formation history
- Colour = relative luminosity in two bands = crudest but easiest-to-obtain additional information about stellar population beyond its total luminosity in one band
- But: colour also depends on metallicity and dust

# 4.7 Properties of galaxies: colour

- The colour distribution of galaxies is bimodal
  - At lowest order, this reflects the distinction between spheroidals and disks
  - But this distinction is not "clean": disks can be red (dust) and spheroids can be blue
- The colour-magnitude distribution shows overlapping red and blue sequences





# 4.7 Properties of galaxies: colour

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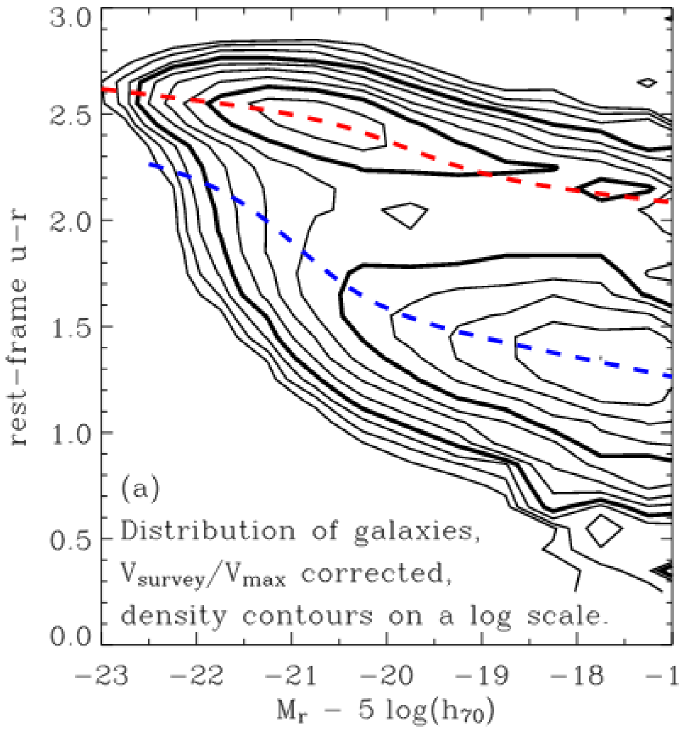
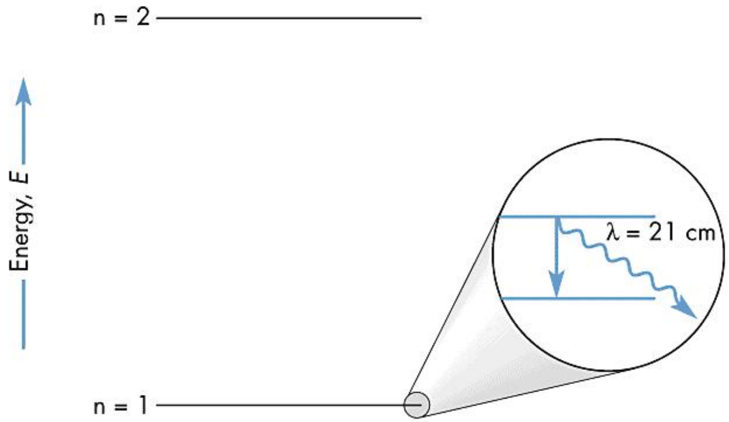
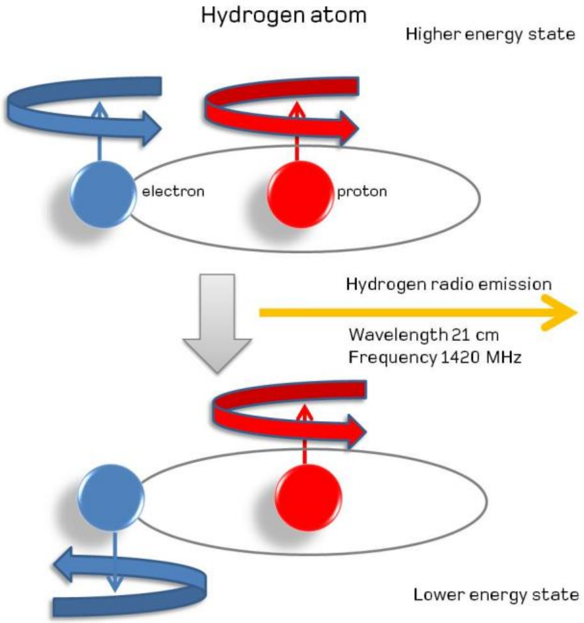
    - At lowest order, this reflects the distinction between spheroidals and disks
    - But this distinction is not “clean”: disks can be red (dust) and spheroids can be blue
- The colour-magnitude distribution shows overlapping red and blue sequences
- Within each sequence, brighter galaxies are redder
- Age, metallicity or dust effects with luminosity (mass)?



# 4.8 Properties of galaxies: cold gas (HI) mass

- At typical temperatures in the interstellar medium (ISM), HI is mostly in ground state (unless it‘s excited)
- No emission in the optical
- However, HI can be observed in the radio regime:
  21 cm line = transition between hyperfine structure levels of HI ground state

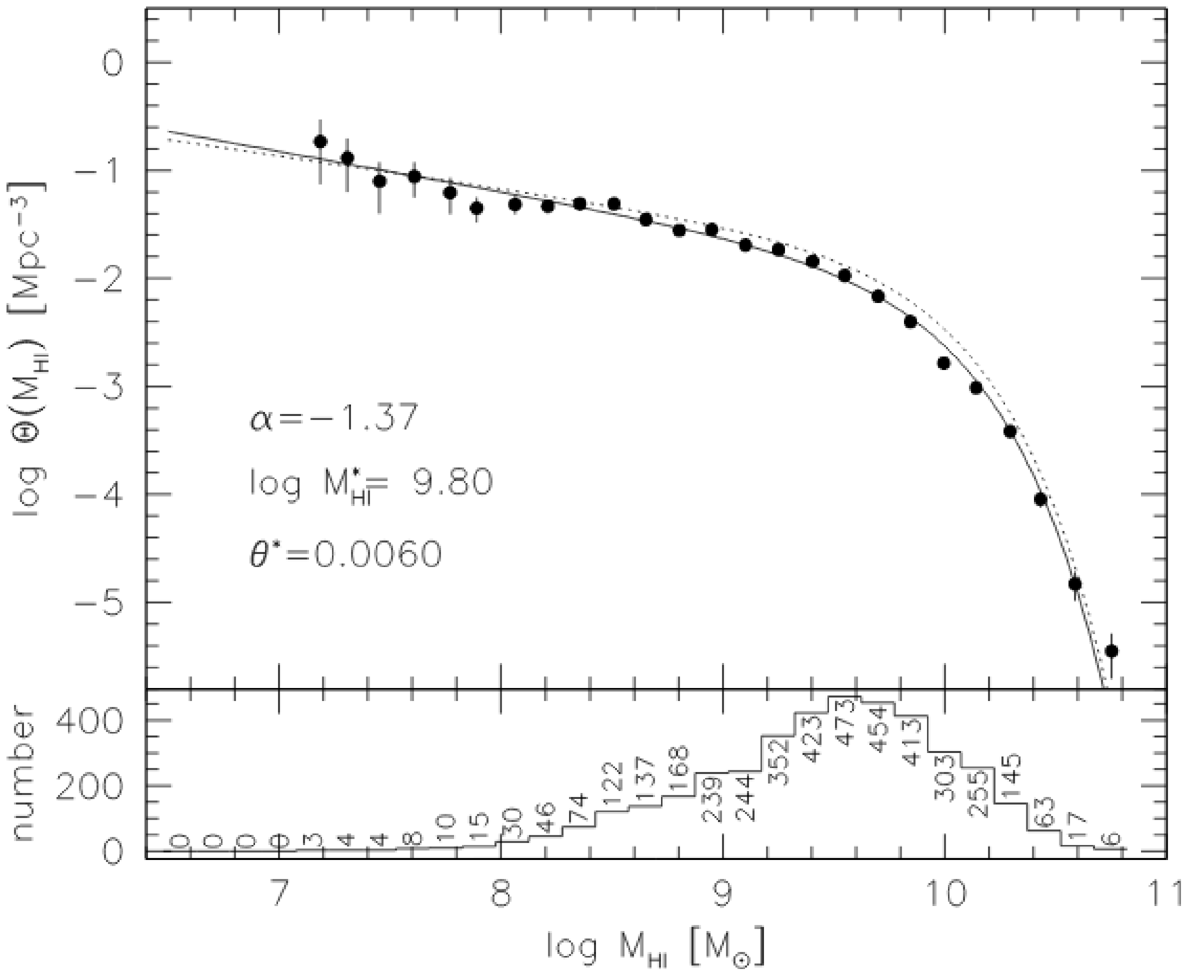




- $\Delta E \approx 6 \times 10^{-6}$ eV → $\nu = 1420$ MHz, $\lambda = 21.106$ cm

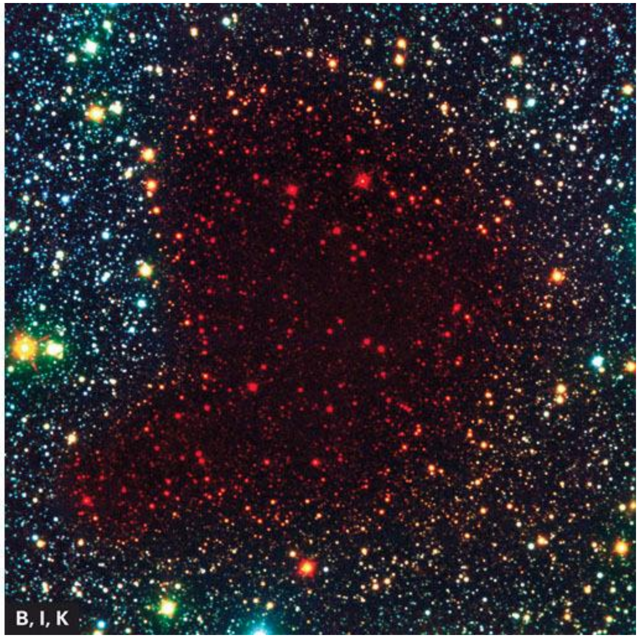
# 4.8 Properties of galaxies: cold gas (HI) mass

- "Blind" 21 cm surveys can be used to measure HI masses for large numbers of galaxies → HI mass function:



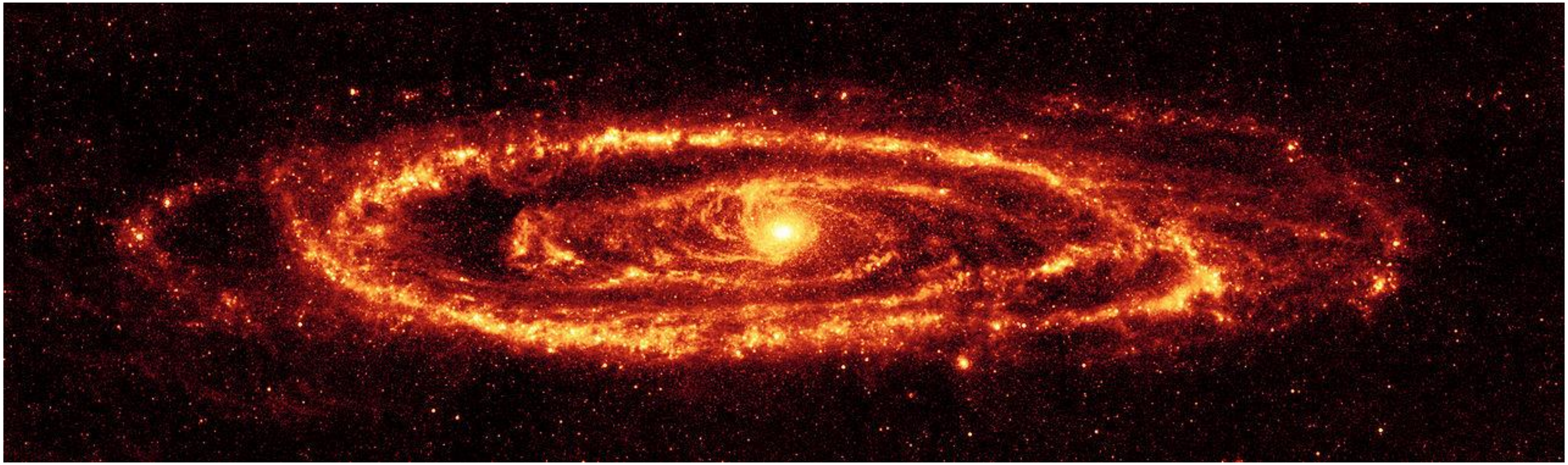
# 4.9 Properties of galaxies: dust

- Irrelevant in terms of mass
- Strong influence on optical appearance of galaxies through
  - Extinction
  - Reddening



# 4.9 Properties of galaxies: dust

- Irrelevant in terms of mass
- Strong influence on optical appearance of galaxies through
  - Extinction
  - Reddening
- No simple spectral lines
- But: each dust particle is a small solid body → black body radiation
- Continuum emission in IR



# 4.9 Properties of galaxies: dust

- Size of dust particles
  - $a \approx 0.05 - 0.35\ \mu m$
  - Size distribution: $dn/da \propto a^{-3.5}$
- Chemical composition
  - Graphite
  - Silicates
  - Carbon
  - CO
  - PAH
  - …
- Formation?
  - Requires high densities and temperatures → not in typical ISM
  - Stellar atmospheres
  - Stellar winds
  - Red giants

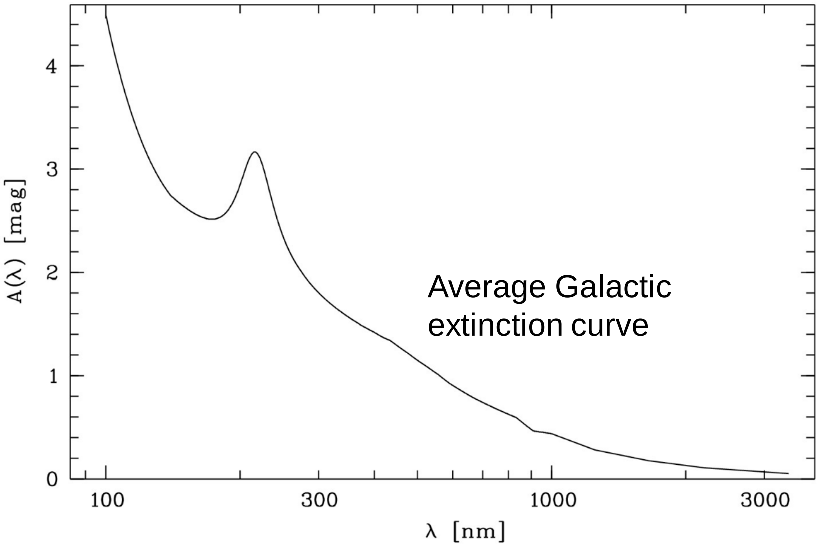
# 4.9 Properties of galaxies: dust

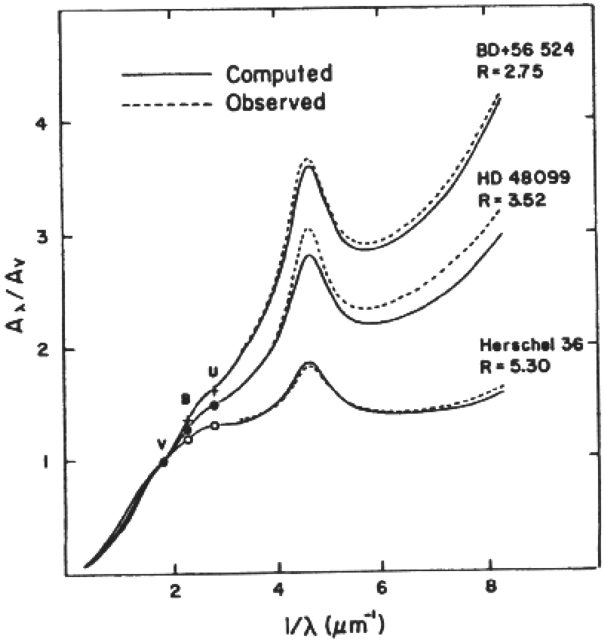
- Extinction depends on wavelength due to scattering
- Described by Mie scattering
- Assumption: dust = spherical particle with radius a:
- Geometric cross-section: $\sigma_g = \pi a^2$
- Scattering cross-section $\sigma_\lambda$ depends on wavelength:
  - $\lambda \approx a$ → $\sigma_\lambda \propto \lambda^{-1}$
  - $\lambda >> a$ → $\sigma_\lambda \rightarrow 0$
  - $\lambda << a$ → $\sigma_\lambda \rightarrow \text{const}$

- Reddening

# 4.9 Properties of galaxies: dust

- Observationally, many different extinction curves are found
- Great diversity even within Milky Way
- Features (e.g. “bump” at 220 nm)





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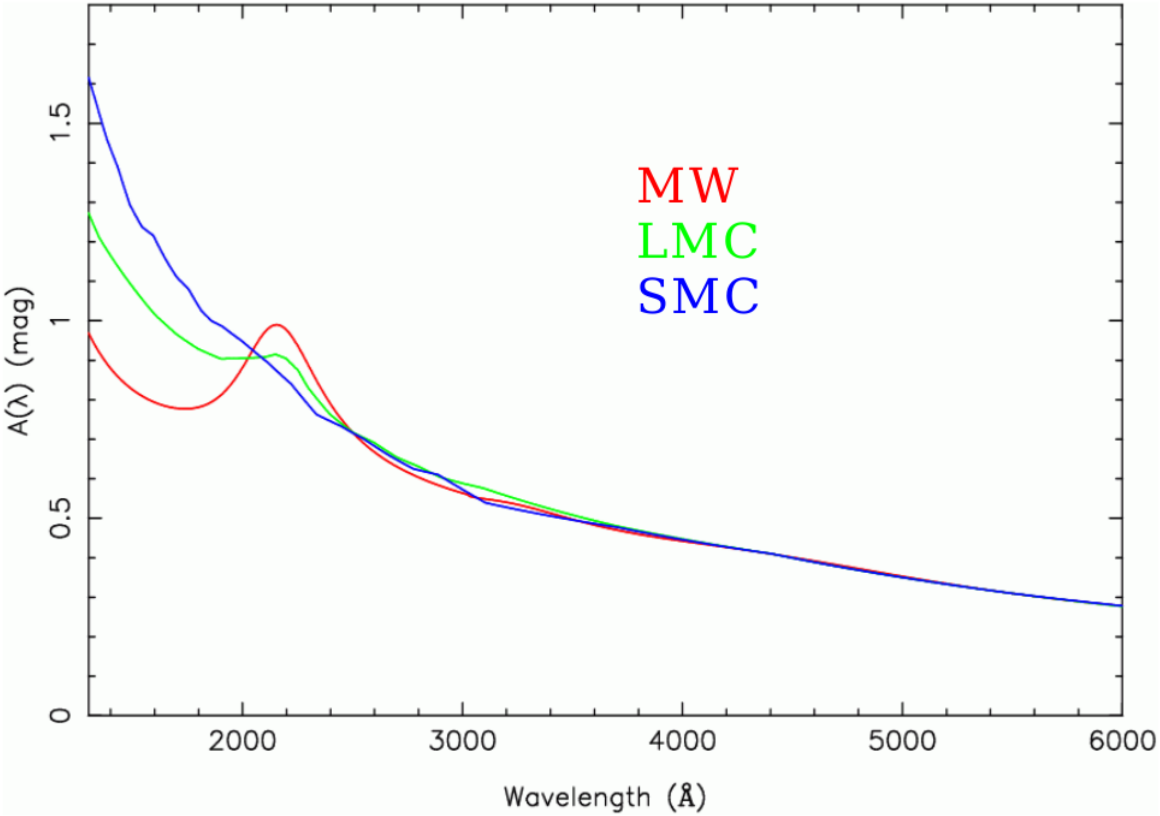
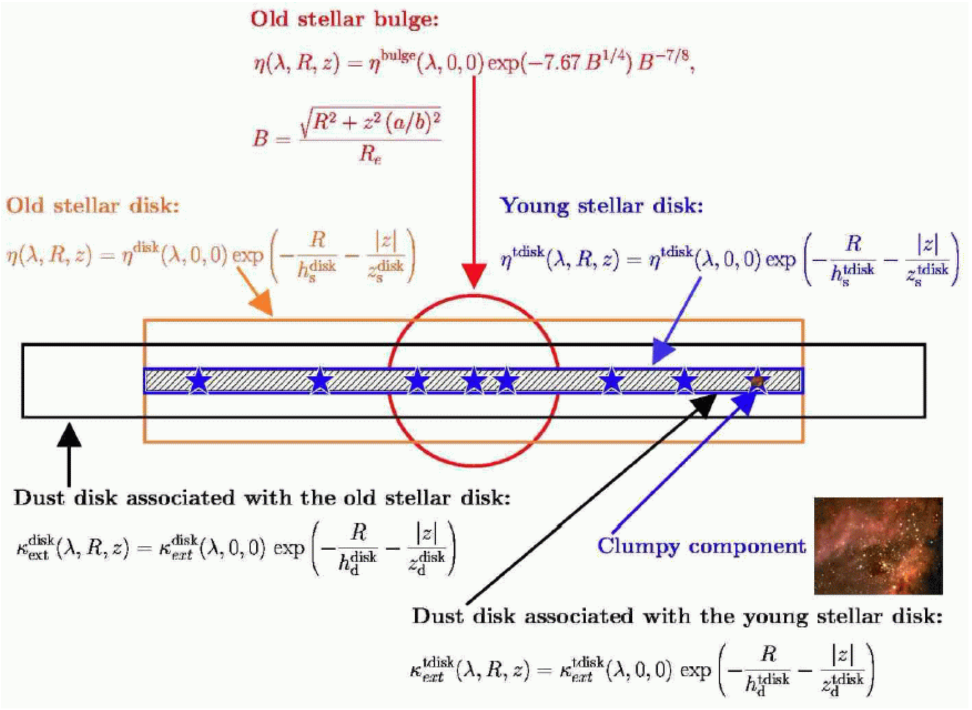


# 4.9 Properties of galaxies: dust

- Effect of dust on optical appearance of a galaxy depends not only on extinction curve but also on relative distribution of stars and dust
  - Attenuation($\lambda$) = starlight escaping from a galaxy / starlight produced
  - Attenuation also depends on viewing angle



**Old stellar bulge:**

$$\eta(\lambda, R, z) = \eta^{\rm bulge}(\lambda, 0, 0) \exp(-7.67\, B^{1/4})\, B^{-7/8},$$

$$B = \frac{\sqrt{R^2 + z^2\,(a/b)^2}}{R_e}$$

**Old stellar disk:**

$$\eta(\lambda, R, z) = \eta^{\rm disk}(\lambda, 0, 0) \exp\left(-\frac{R}{h_{\rm s}^{\rm disk}} - \frac{|z|}{z_{\rm s}^{\rm disk}}\right)$$

**Young stellar disk:**

$$\eta^{\rm tdisk}(\lambda, R, z) = \eta^{\rm tdisk}(\lambda, 0, 0) \exp\left(-\frac{R}{h_{\rm s}^{\rm tdisk}} - \frac{|z|}{z_{\rm s}^{\rm tdisk}}\right)$$

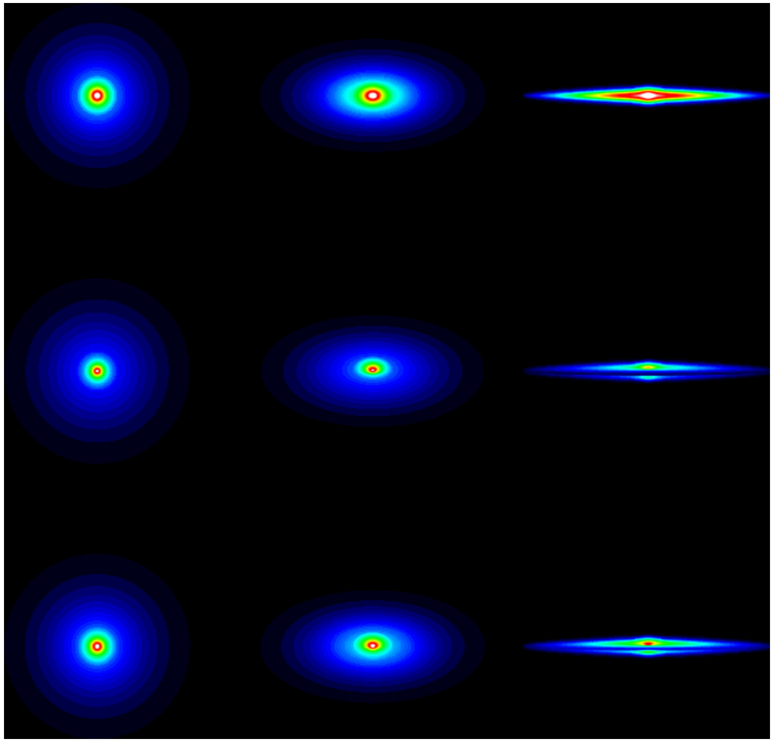
**Dust disk associated with the old stellar disk:**

$$\kappa_{\rm ext}^{\rm disk}(\lambda, R, z) = \kappa_{ext}^{\rm disk}(\lambda, 0, 0)\ \exp\left(-\frac{R}{h_{\rm d}^{\rm disk}} - \frac{|z|}{z_{\rm d}^{\rm disk}}\right)$$

**Clumpy component**

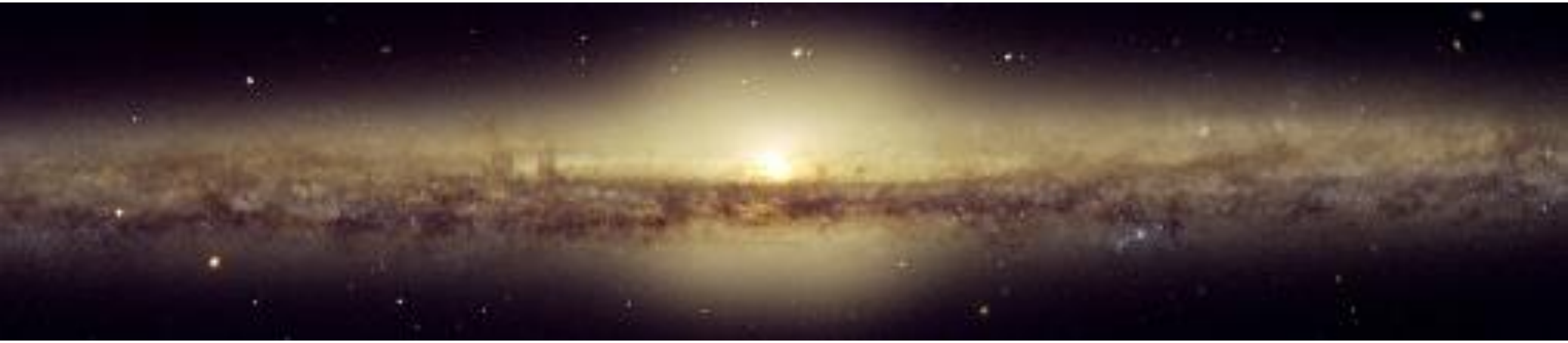
**Dust disk associated with the young stellar disk:**

$$\kappa_{ext}^{\rm tdisk}(\lambda, R, z) = \kappa_{ext}^{\rm tdisk}(\lambda, 0, 0)\ \exp\left(-\frac{R}{h_{\rm d}^{\rm tdisk}} - \frac{|z|}{z_{\rm d}^{\rm tdisk}}\right)$$



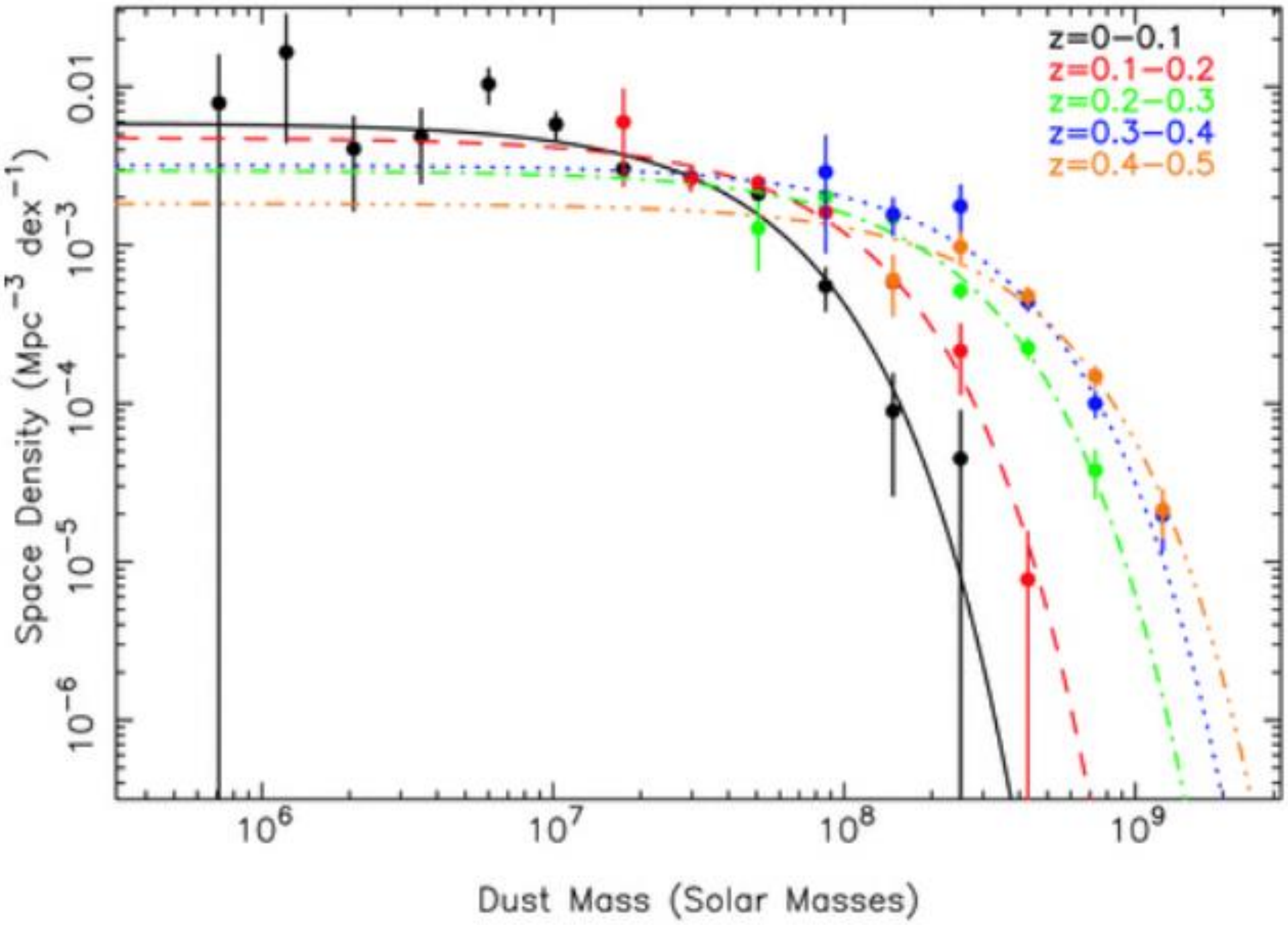
# 4.9 Properties of galaxies: dust

- Effect of dust on optical appearance of a galaxy depends not only on extinction curve but also on relative distribution of stars and dust
  - Attenuation($\lambda$) = starlight escaping from a galaxy / starlight produced
  - Attenuation also depends on viewing angle
- Viewing angle influences how much of both the disk and the bulge we see



# 4.9 Properties of galaxies: dust

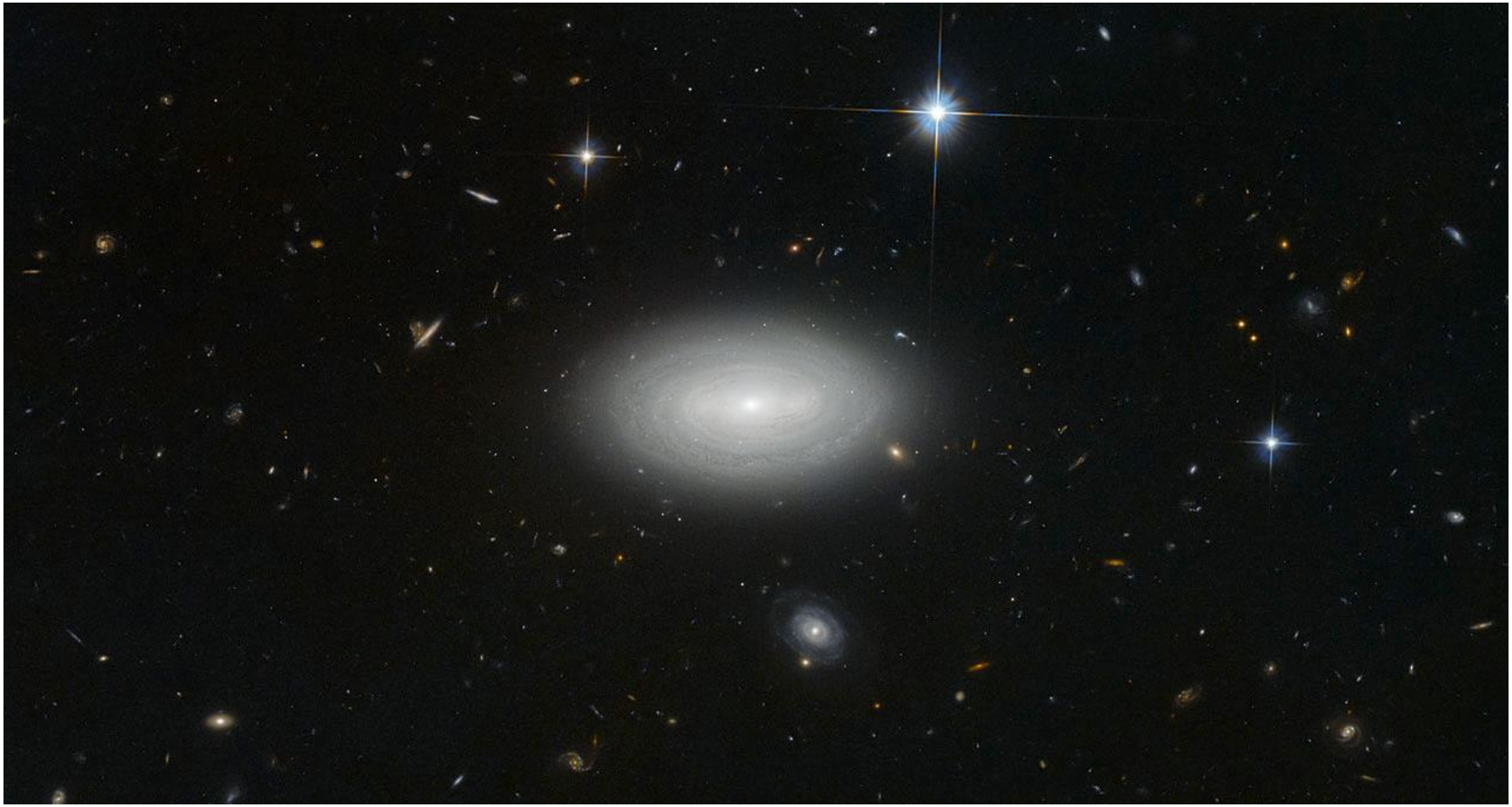
- Survey at 250 μm (Herschel) → dust mass function of galaxies:



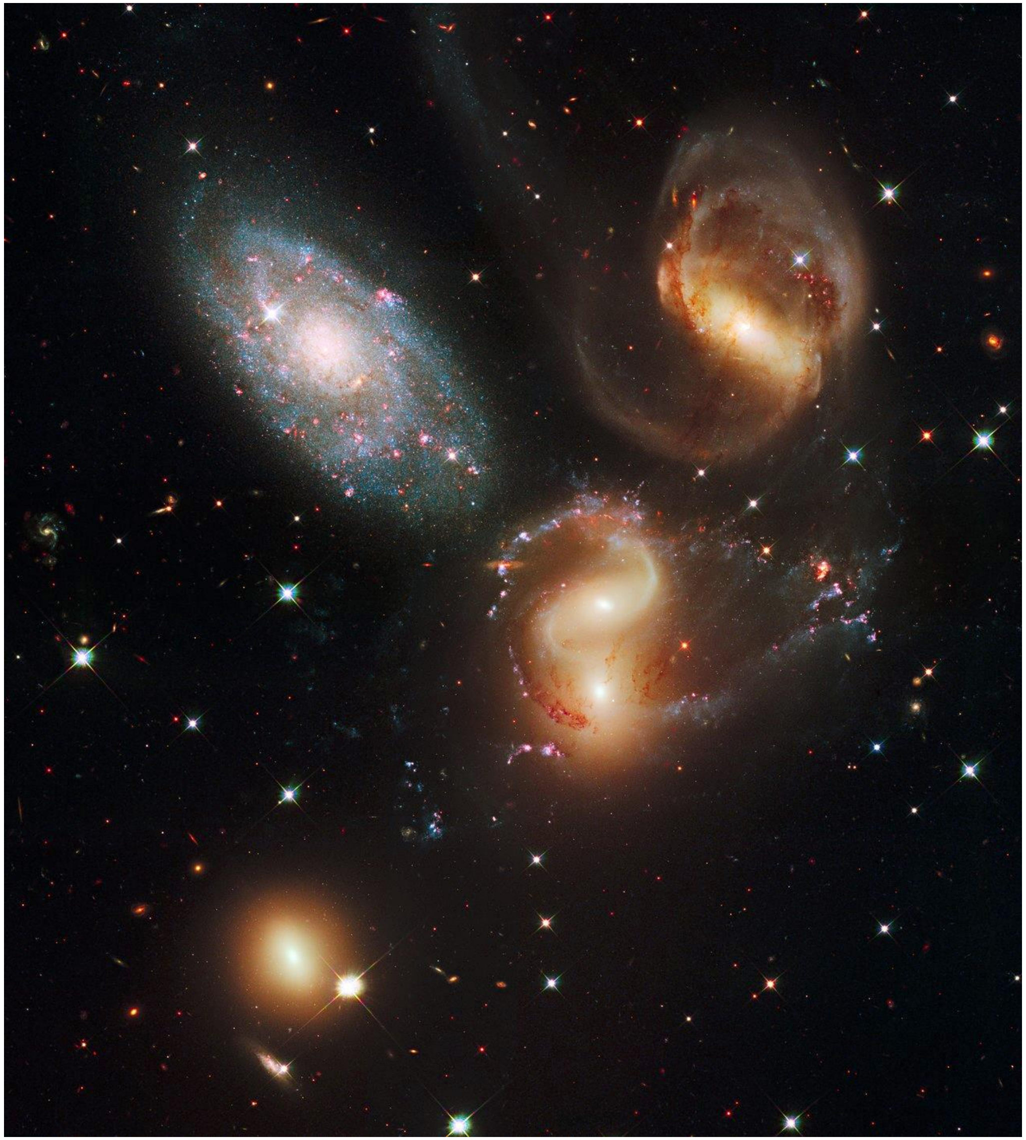
# 4.10 Properties of galaxies: environment

- Why does environment matter to galaxies?
- What is “environment”? How can one quantify “environment”?

# 4.10 Properties of galaxies: environment



# 4.10 Properties of galaxies: environment



# 4.10 Properties of galaxies: environment

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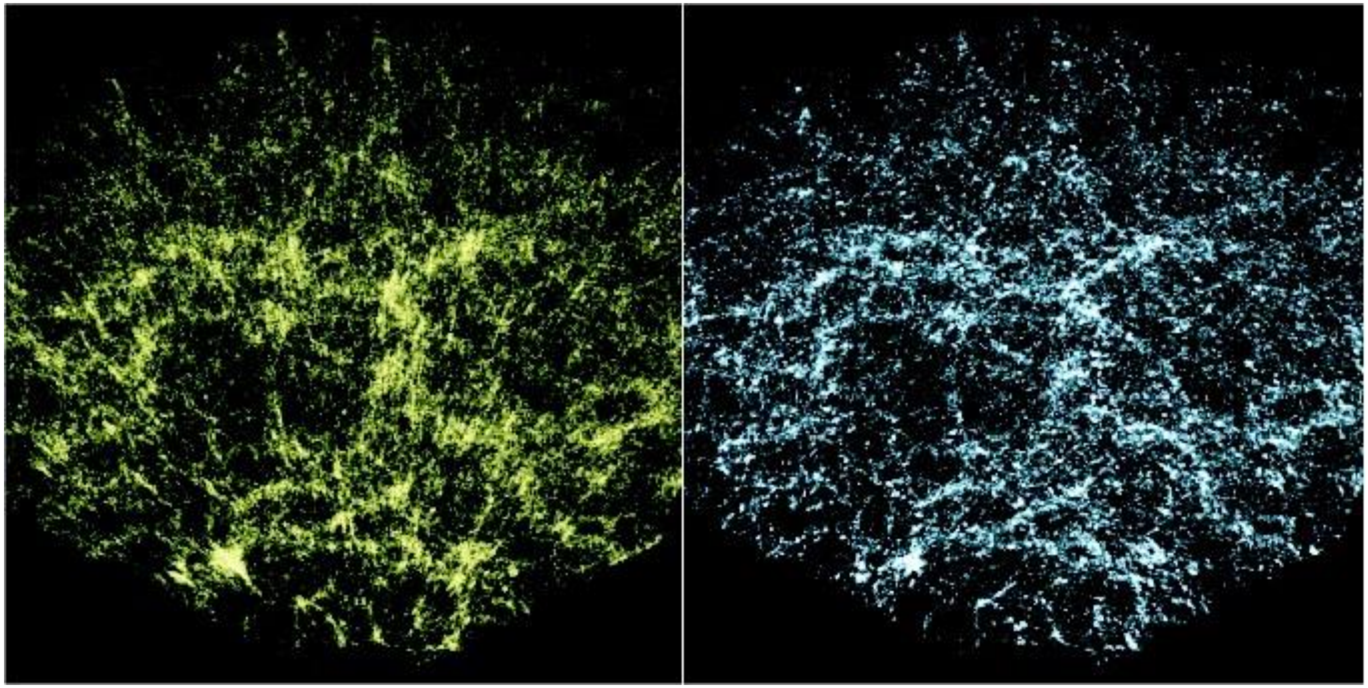
Why does environment matter?

- Frequency of interactions / mergers (rate of encounters with other galaxies $\propto$ density in 6D phase space)
- Gravitational environment → tidal effects
- Gaseous environment
  - Availability of cold gas for star formation
  - Ram-pressure stripping
- Radiative environment
- Densest regions collapsed first

# 4.10 Properties of galaxies: environment

What is “environment”? How can one quantify “environment”?

- In 2D? Projection effects!
- Or 3D? But redshift is not exactly the same thing as distance because of peculiar velocities



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- Over which scales? Which are relevant?

# 4.10 Properties of galaxies: environment

What is “environment”? How can one quantify “environment”?

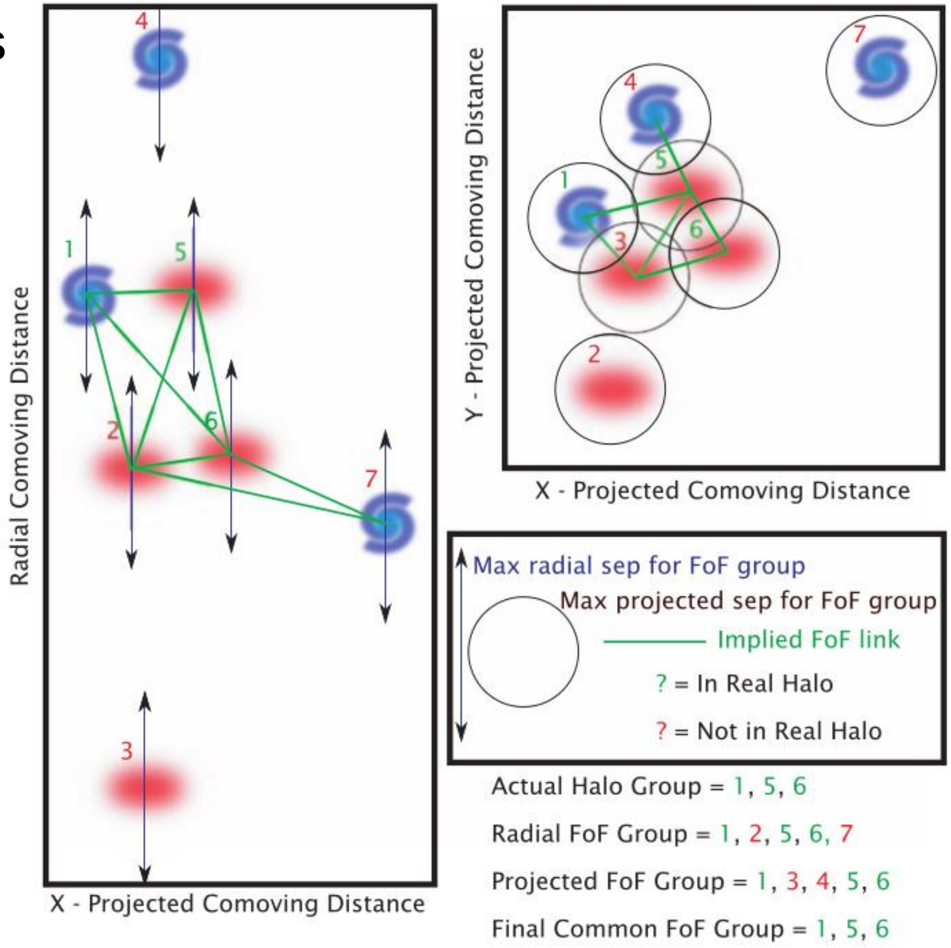
- In 2D? Projection effects!
- Or 3D? But redshift is not exactly the same thing as distance because of peculiar velocities
- Over which scales? Which are relevant?

- Number of galaxies within some aperture or volume → density
- Distance to nth nearest neighbour
- Halo mass
- By dimensionality of surrounding large-scale structure
  - Void, sheet, filament, cluster/group
  - Density field

# 4.10 Properties of galaxies: environment

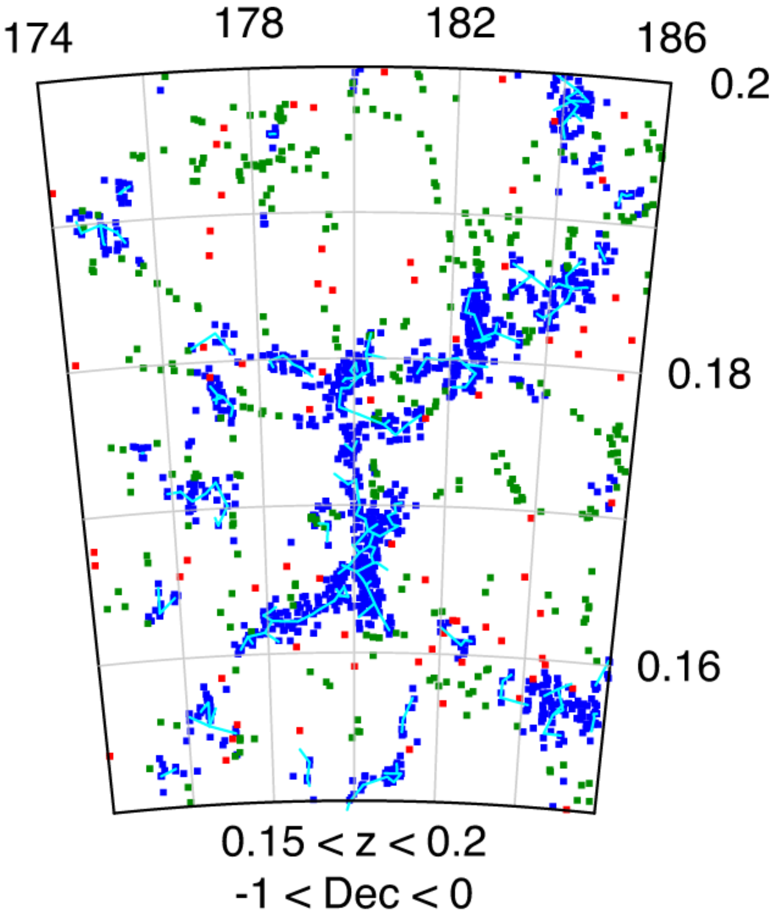
- Grouping of galaxies by friends-of-friends method:

- Assembly of large samples of groups and clusters
- Derivation of halo mass by
  - Galaxy kinematics
  - Weak lensing



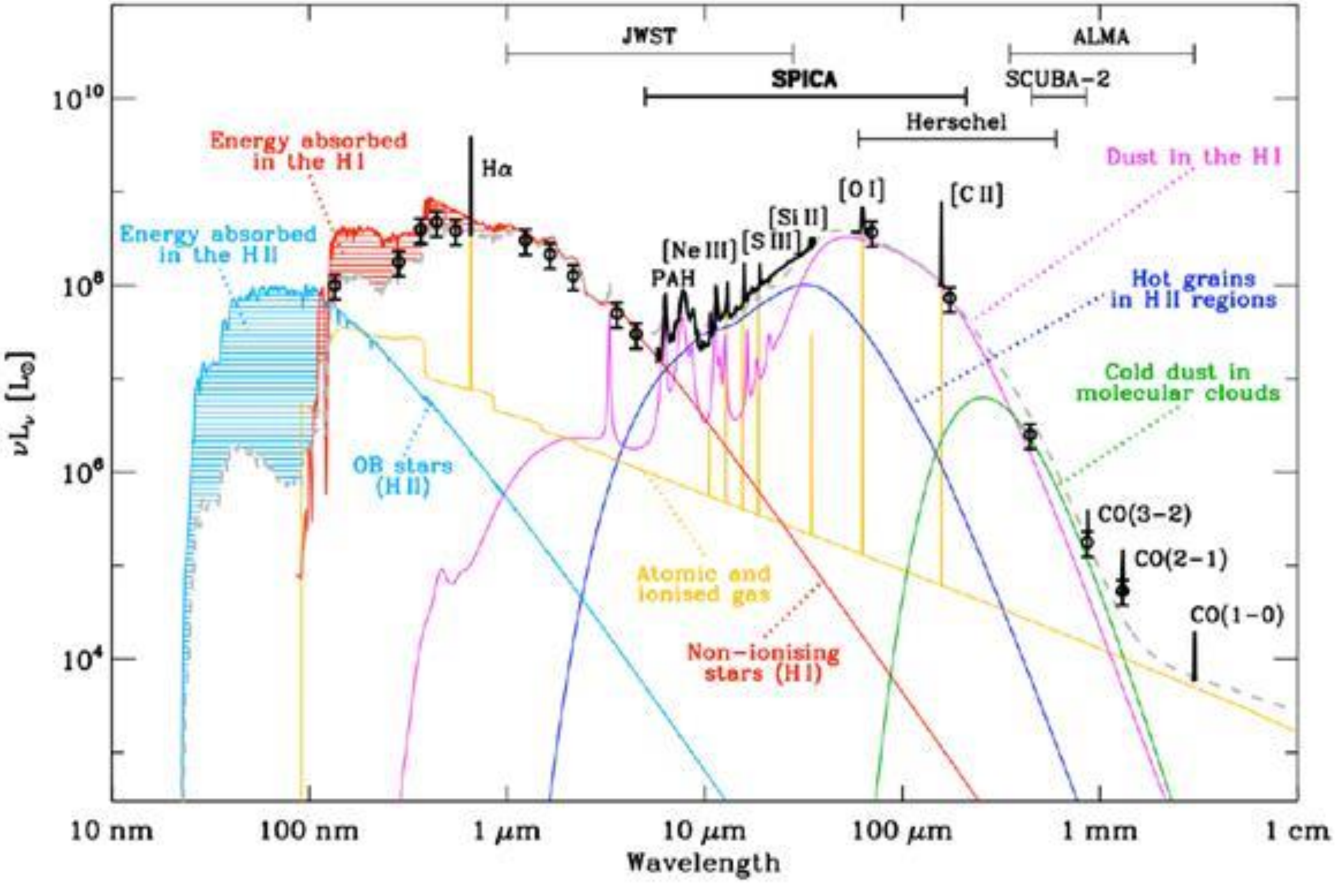
# 4.10 Properties of galaxies: environment

- Application of a minimal spanning tree (MST) to both groups and galaxies:
- Environmental classification by group, filament, tendril, void



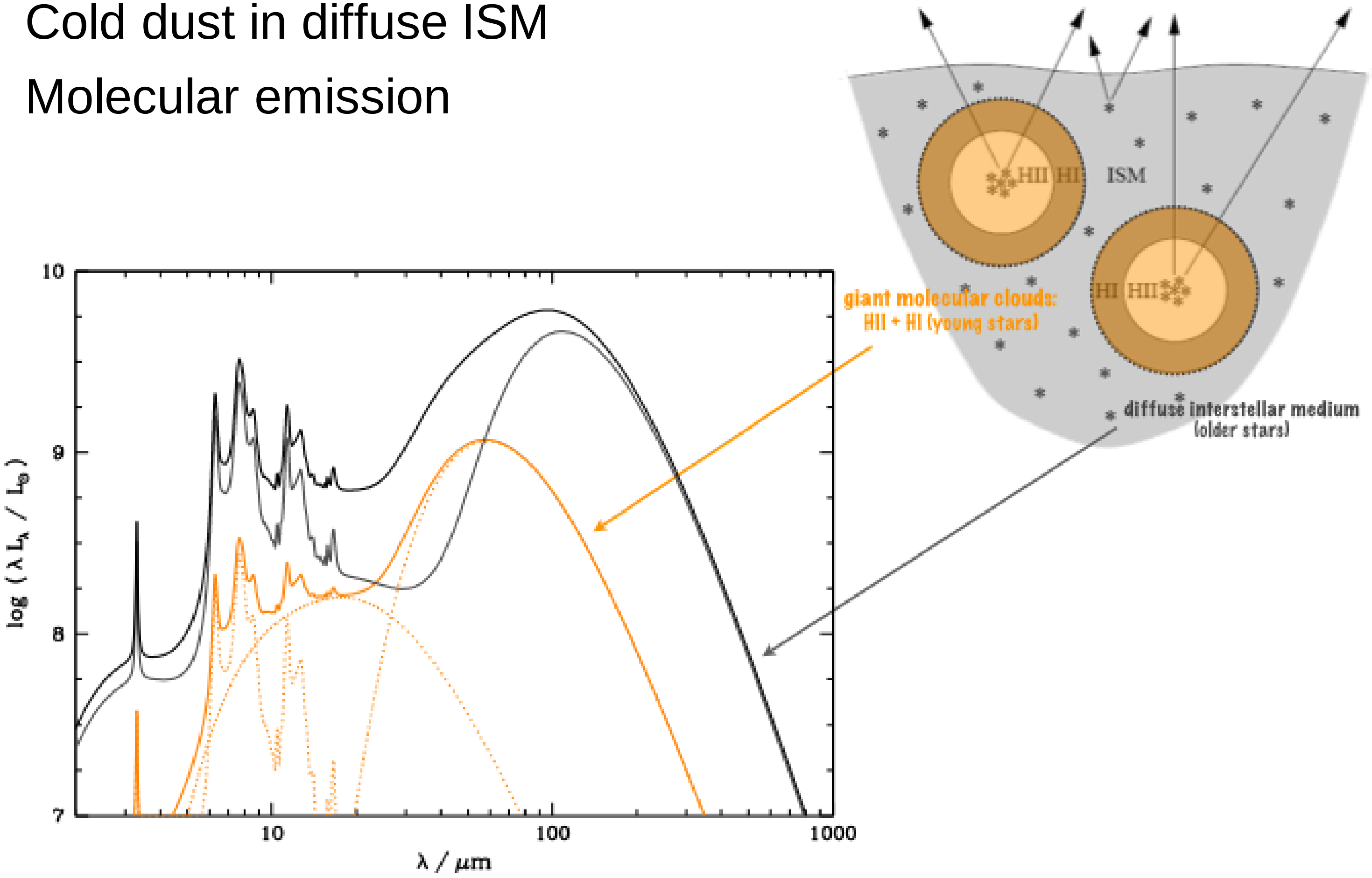
# 4.11 Spectral properties of galaxies

- The spectral energy distribution (SED) of galaxies can be understood as the combined emission from multiple star, dust and gas components:

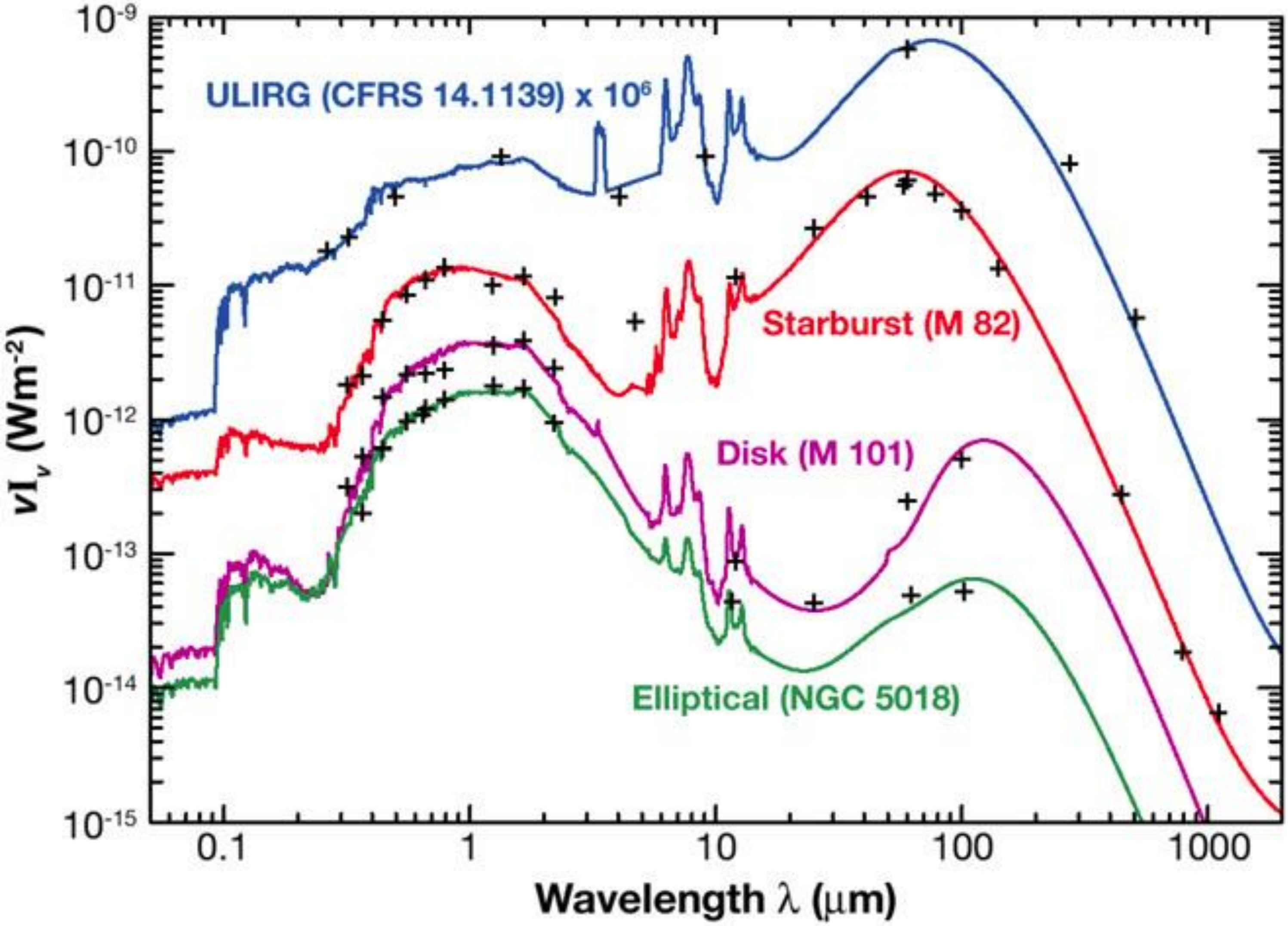


# 4.11 Spectral properties of galaxies

- Multiple dust components:
  - Warm dust in HII regions (heated by young stars)
  - Cold dust in diffuse ISM
  - Molecular emission



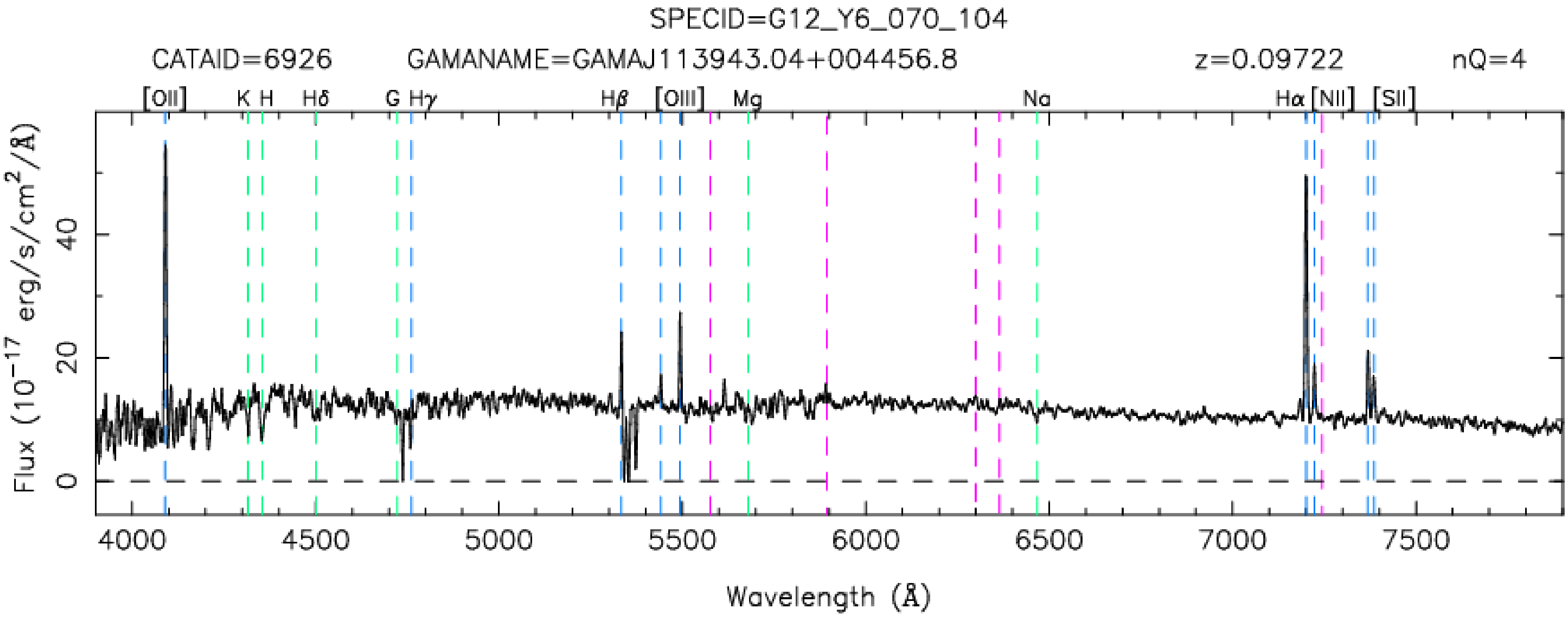
# 4.11 Spectral properties of galaxies



# 4.11 Spectral properties of galaxies

## Elements of restframe optical spectra of galaxies

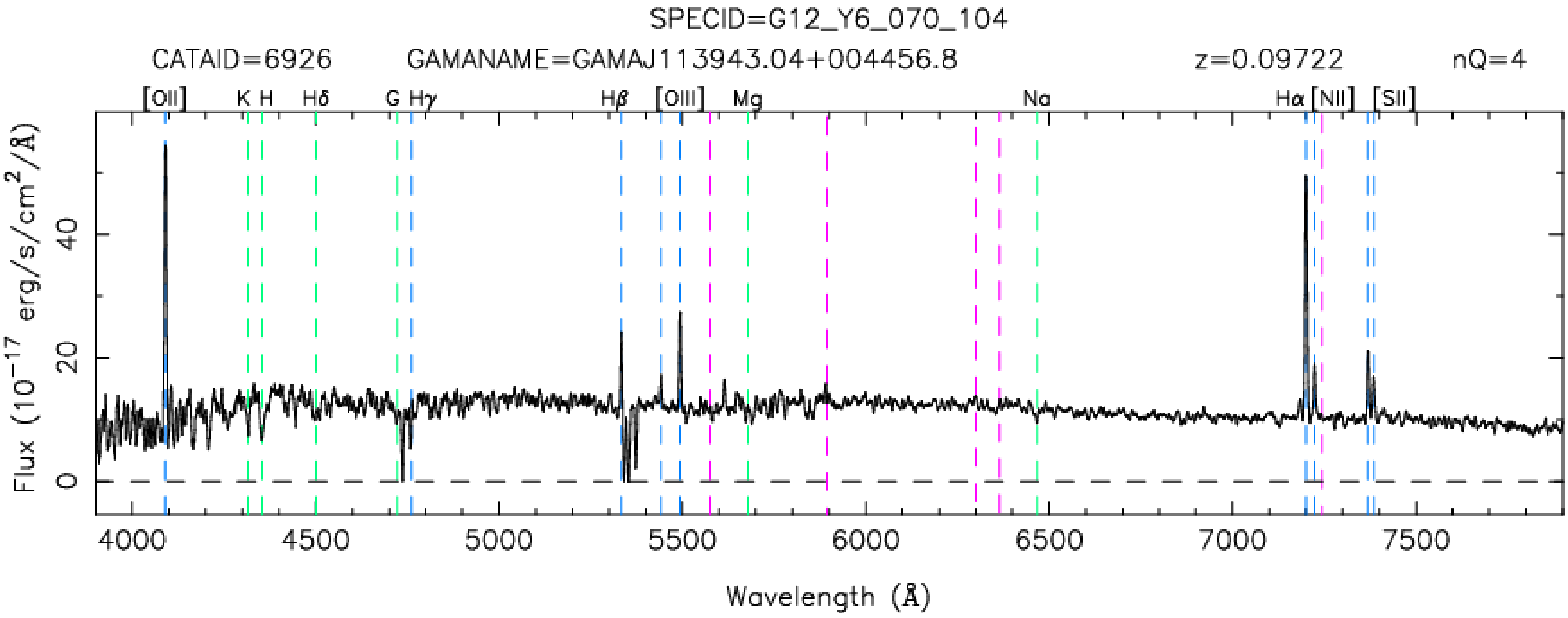
- Continuum
- Absorption lines
- Emission lines



# 4.11 Spectral properties of galaxies

## Elements of restframe optical spectra of galaxies

- Continuum
  - Combined photospheric continua of stellar population (≈ sum of many black body spectra at different temperatures)
  - ➢ Shape provides information on stellar population



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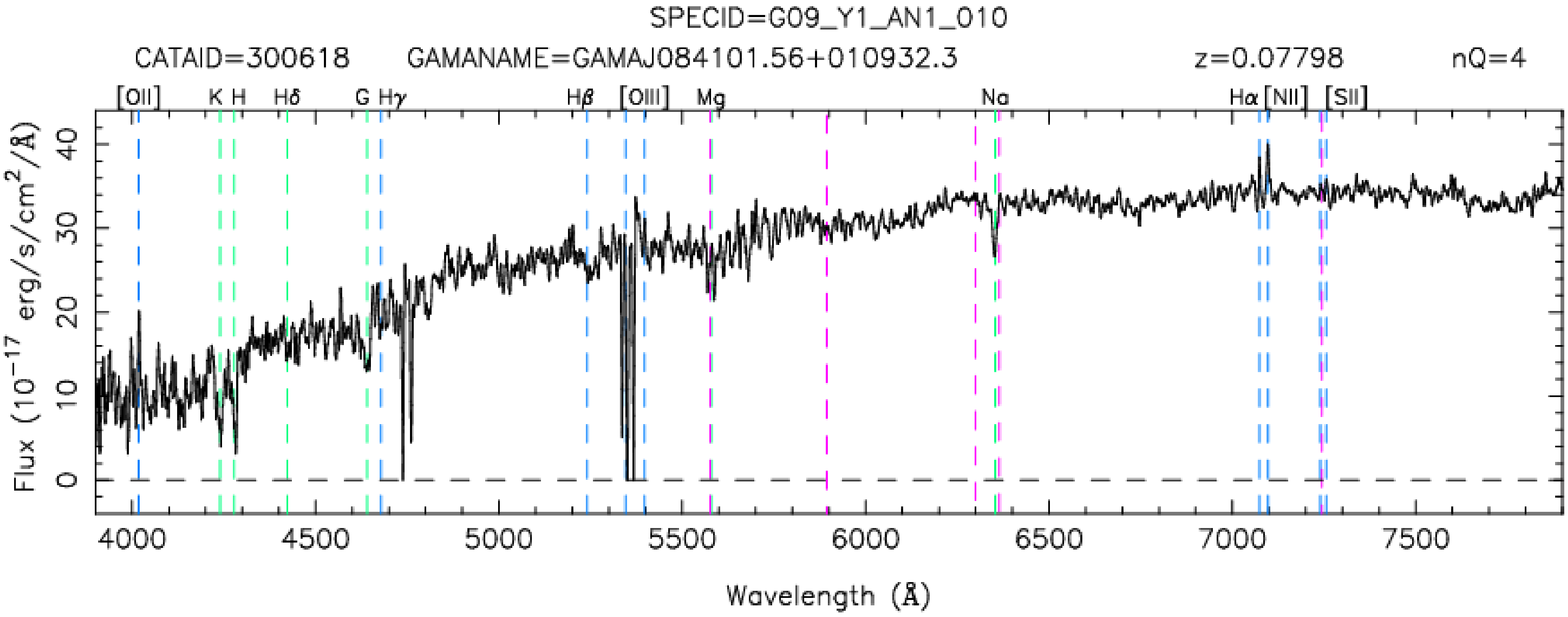
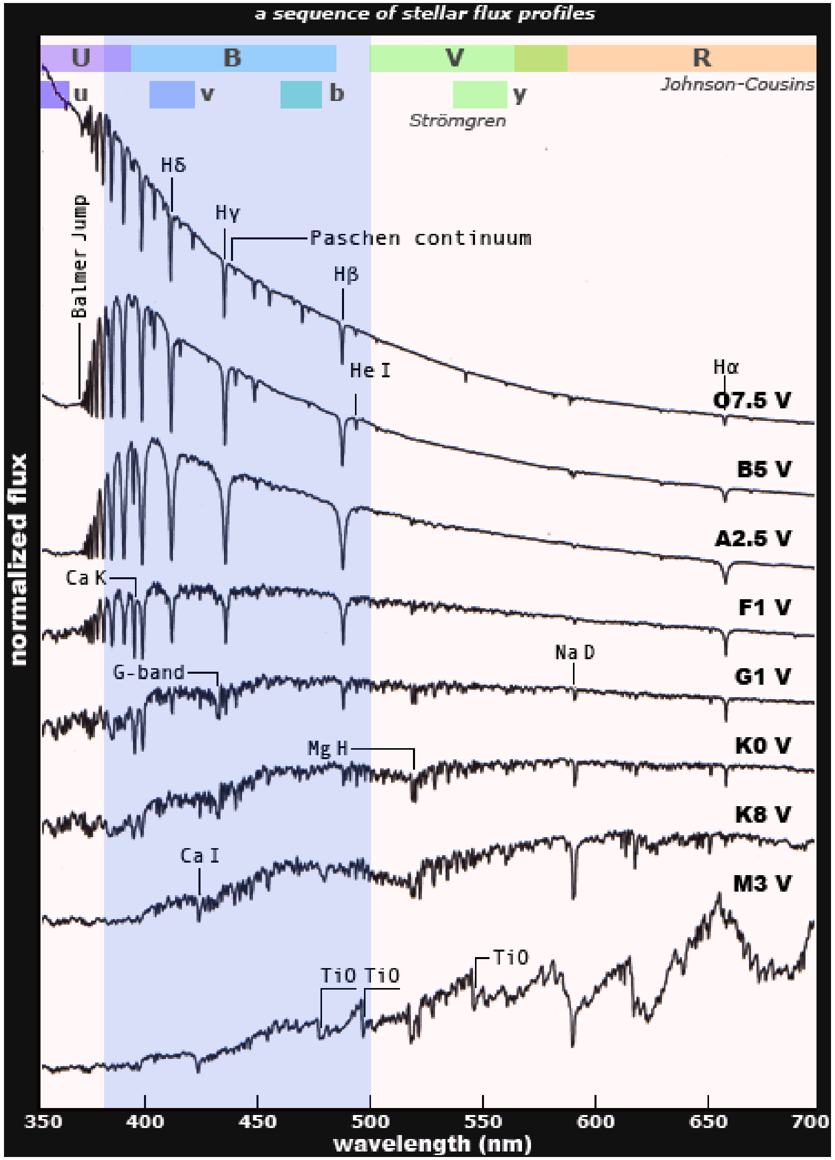


# 4.11 Spectral properties of galaxies

Stellar spectra:



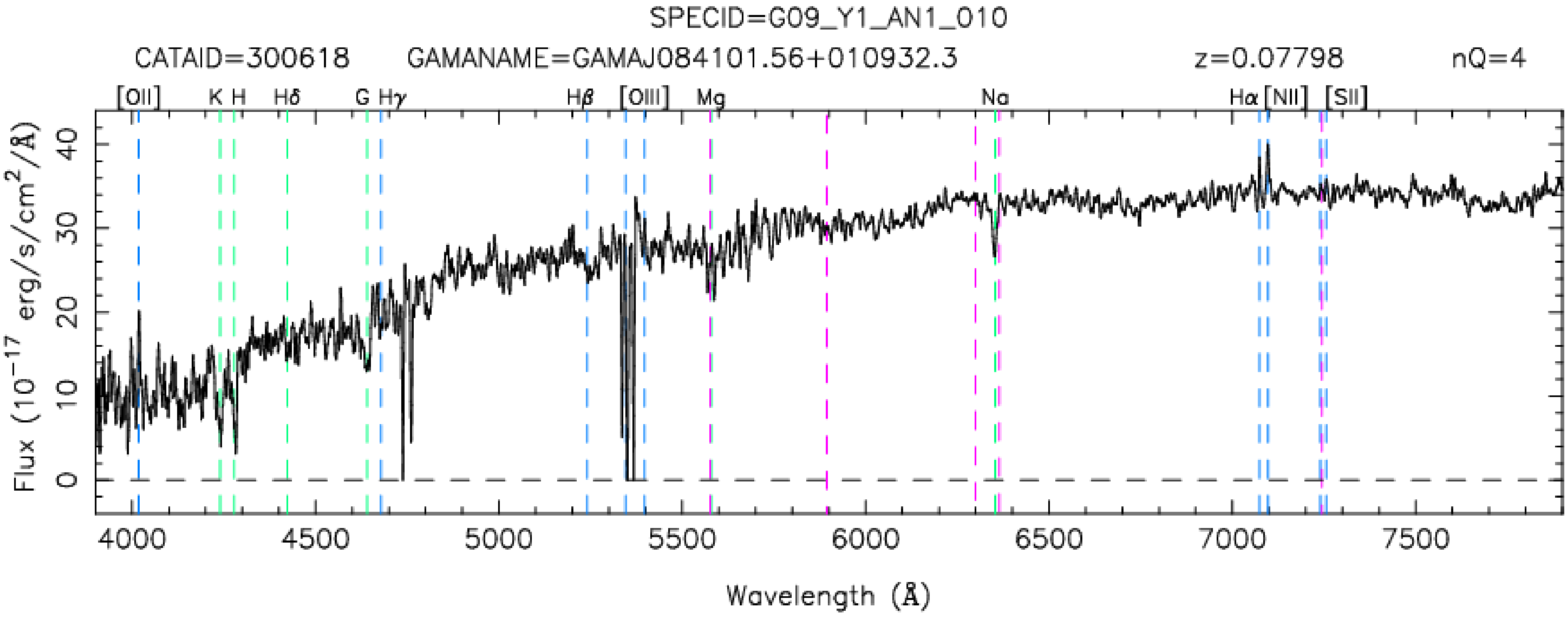
Massive, hot, young

Low-mass, cool, old

# 4.11 Spectral properties of galaxies

## Elements of restframe optical spectra of galaxies

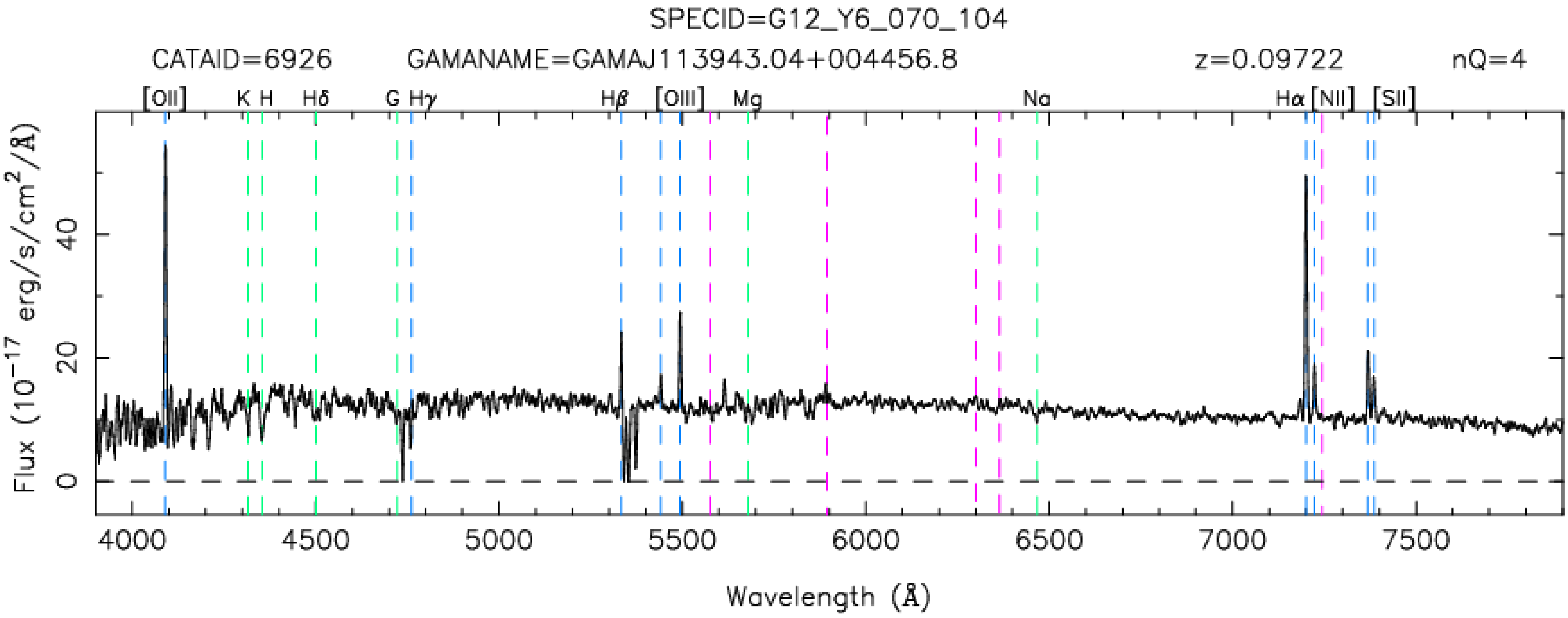
- Absorption lines
  - Mostly from H and metals in stellar photospheres
  - ➢ Stellar age and metallicity indicators
  - ➢ Stellar kinematics



# 4.11 Spectral properties of galaxies

## Elements of restframe optical spectra of galaxies

- Emission lines
  - Mostly recombination radiation from photoionised gas
  - Information on ionising radiation field → star formation, AGN
  - Gas kinematics



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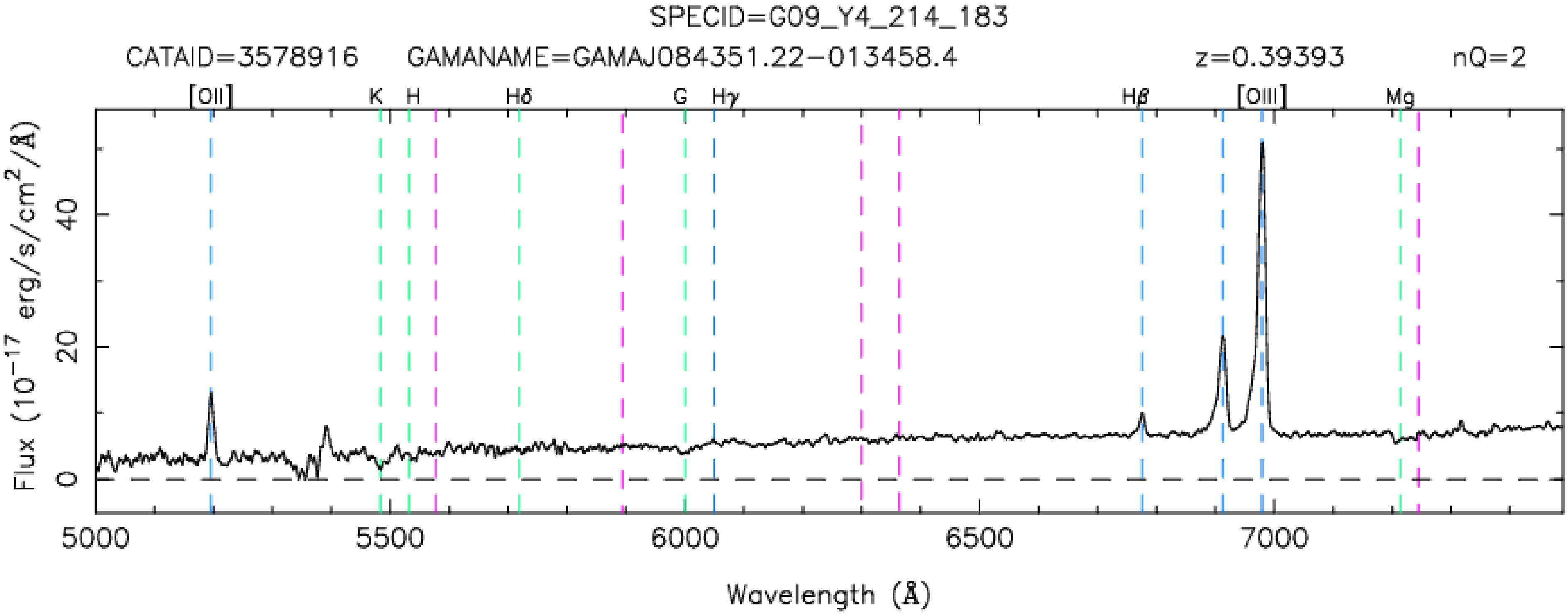
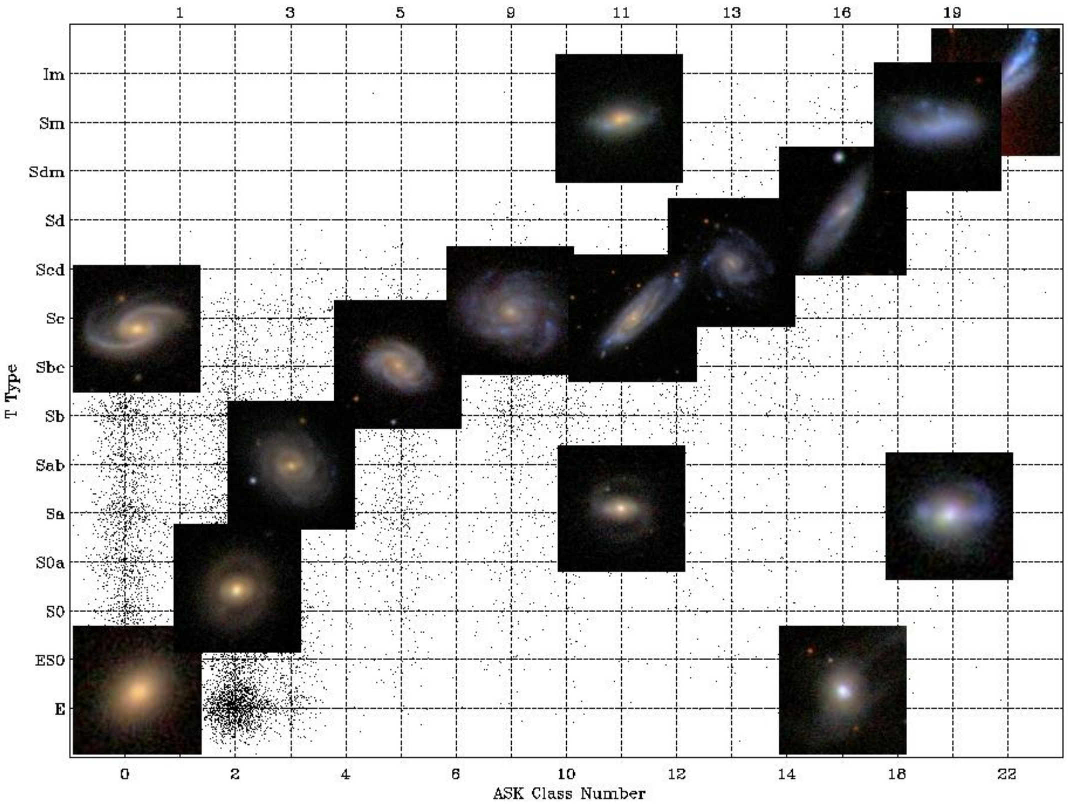


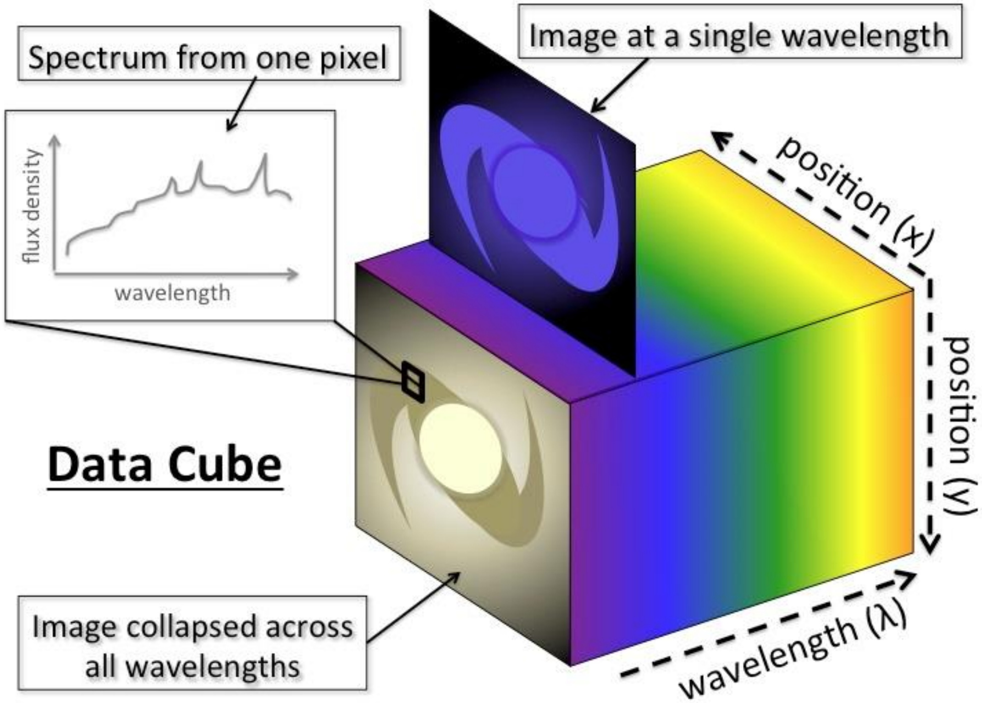
# 4.11 Spectral properties of galaxies

- The presence of strong aborption lines requires significant amounts of metals in stellar photospheres and hence implies an older stellar population
- The presence of emission lines requires hot and therefore massive and therefore young stars
- Correspondence between spectral and morphological types

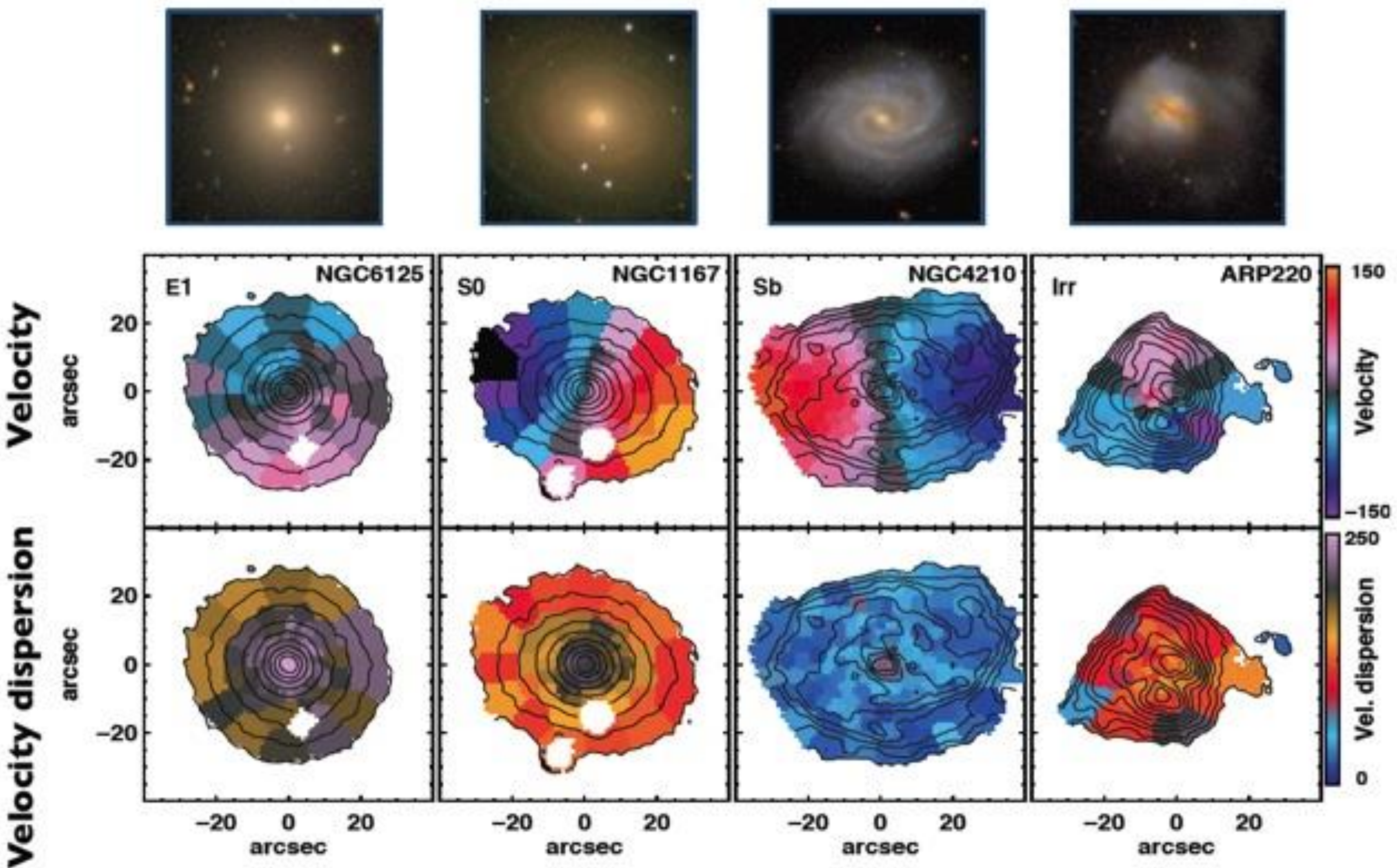


# 4.11 Spectral properties of galaxies

- So far we have only considered integrated-light spectroscopy, i.e. spectroscopy without any spatial information (e.g. fibre spectroscopy)
- We can obtain spatially resolved spectroscopy by using
  - Slits (1D spatial information)
  - Integral field spectroscopy (2D spatial information)



# 4.11 Spectral properties of galaxies



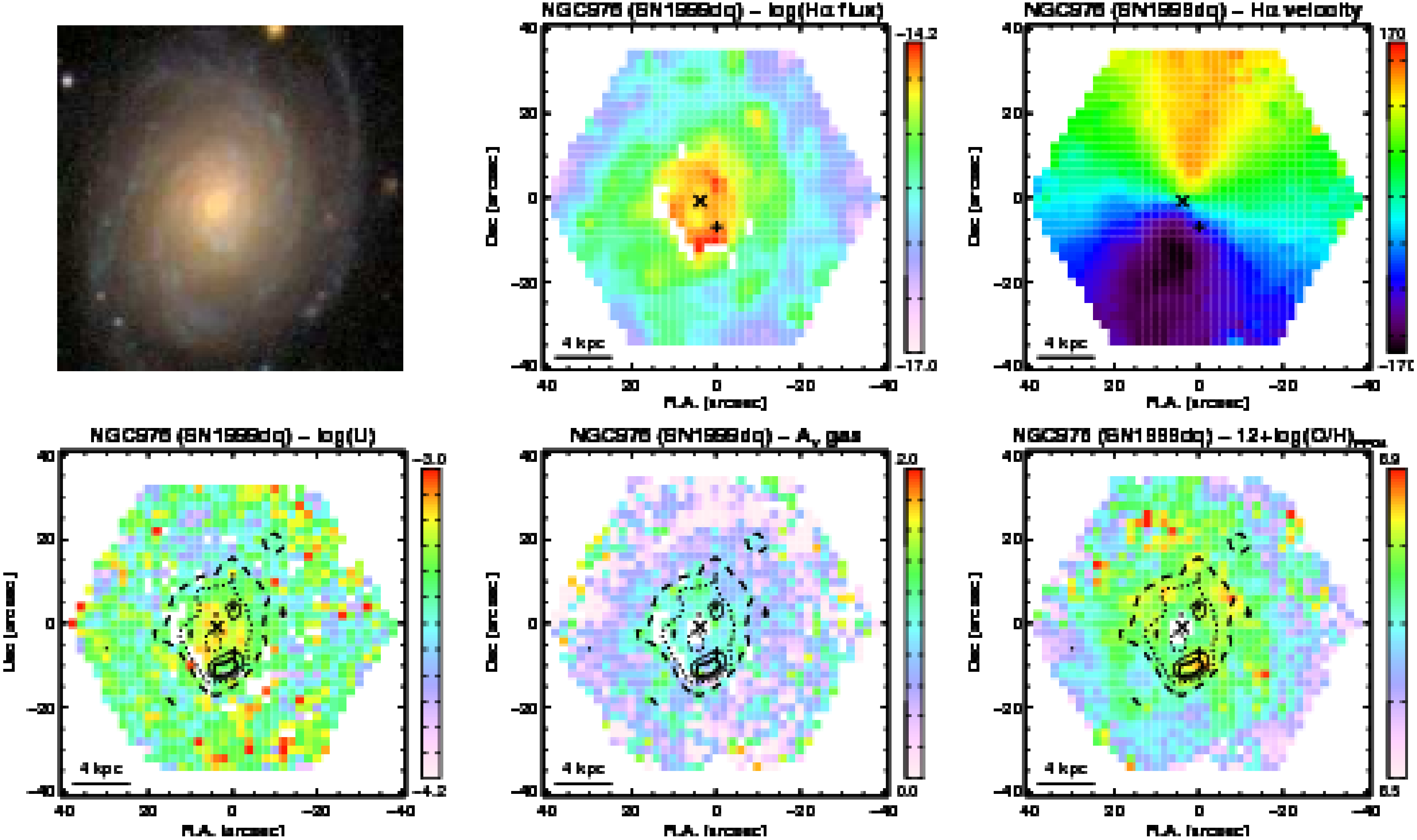
Slow Rotator
low V, high σ

Bulge+Disk
high V, high σ

Pure Disk
high V, low σ

Interacting

# 4.11 Spectral properties of galaxies



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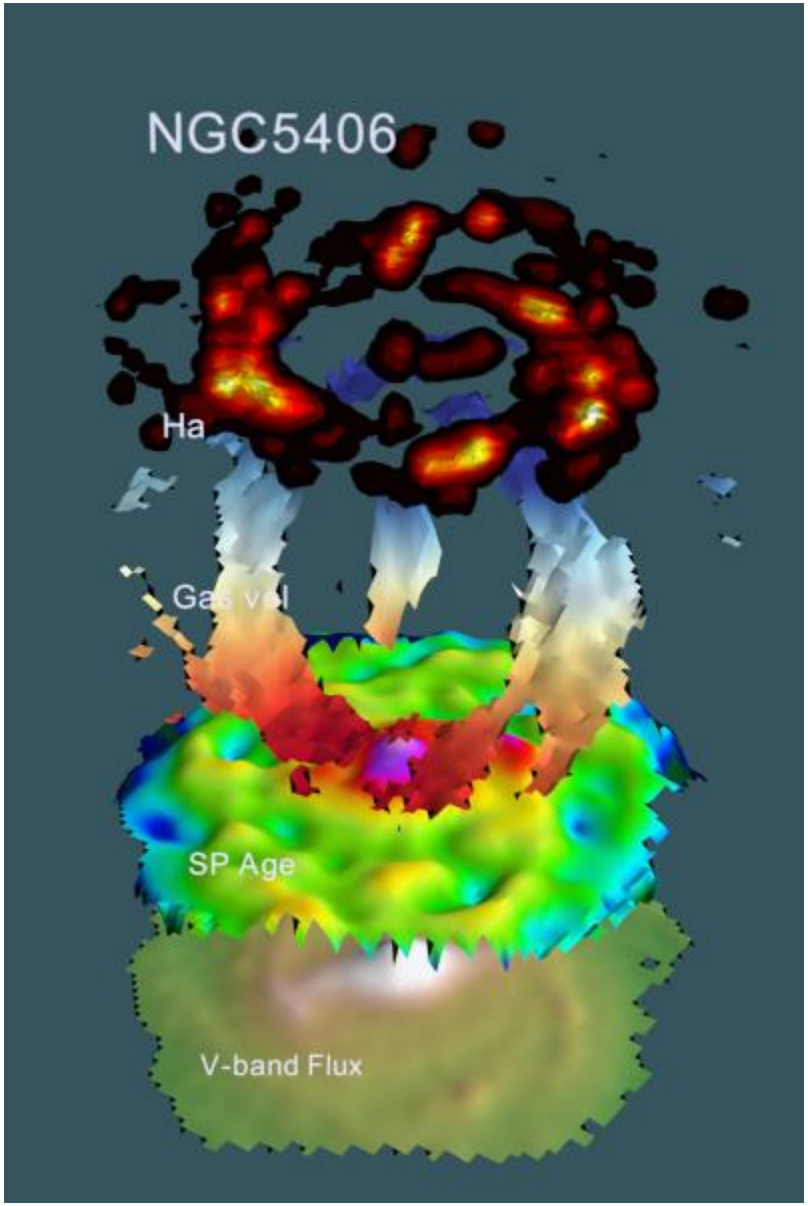


# 4.12 Relations among properties

- So far, we have considered a number of galaxy properties (luminosity, size, morphology, etc)…
- … and their distributions (at least for some properties: luminosity function, size function)
- Any viable galaxy formation and evolution model must be able to explain and reproduce these distributions
- However, additional information about the processes of galaxy formation and evolution is encoded in the relations between these properties
- Relations between galaxy properties provide extremely strong constraints for models

# 4.12 Relations among properties

- Note: most of the time the relation between two (or more) parameters consists of a correlation with some scatter
- Thus the relation between properties x and y usually consist of
  - $\langle y \rangle = f(\langle x \rangle)$
    - Usually: $\langle y \rangle = A \langle x \rangle^{\alpha}$ , i.e. $\log(\langle y \rangle) = \alpha \log(\langle x \rangle) + \text{const}$
  - Scatter: $\sigma_y(x)$
- Need to understand all of this: intercept, slope and scatter

# 4.12 Relations among properties

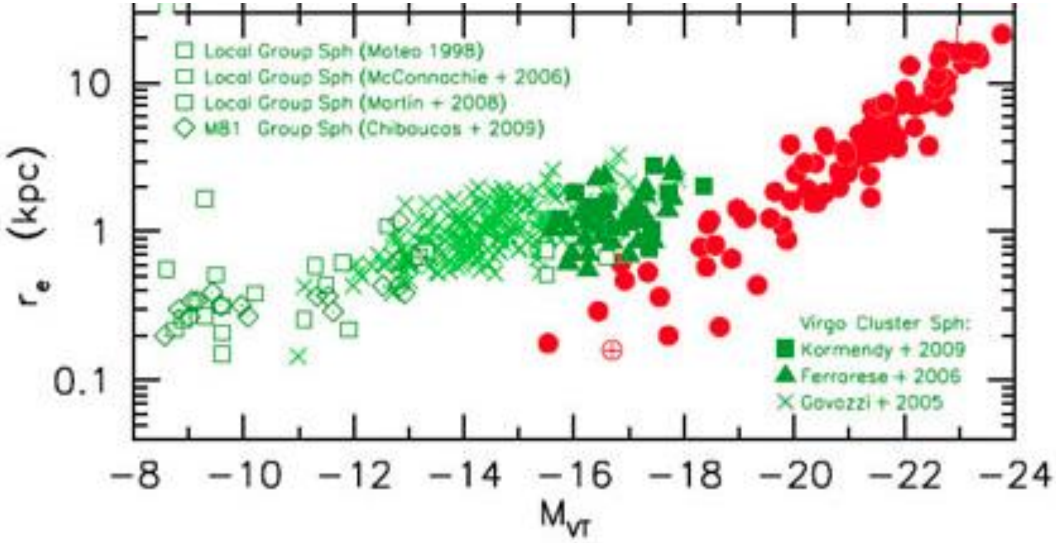
- We have already encountered some relations. In particular, the correlation between morphology and kinematics / characteristics of the stellar population / cold gas content:

- Pressure supported
- Red colours / old stars / no ongoing SF
- Low gas fraction

- Rotational support
- Blue colours / young stars / active SF
- High gas fraction

# 4.12 Relations among properties

- Since the relations between the properties of galaxies should reflect the evolutionary physics, different evolutionary channels should produce different relations:



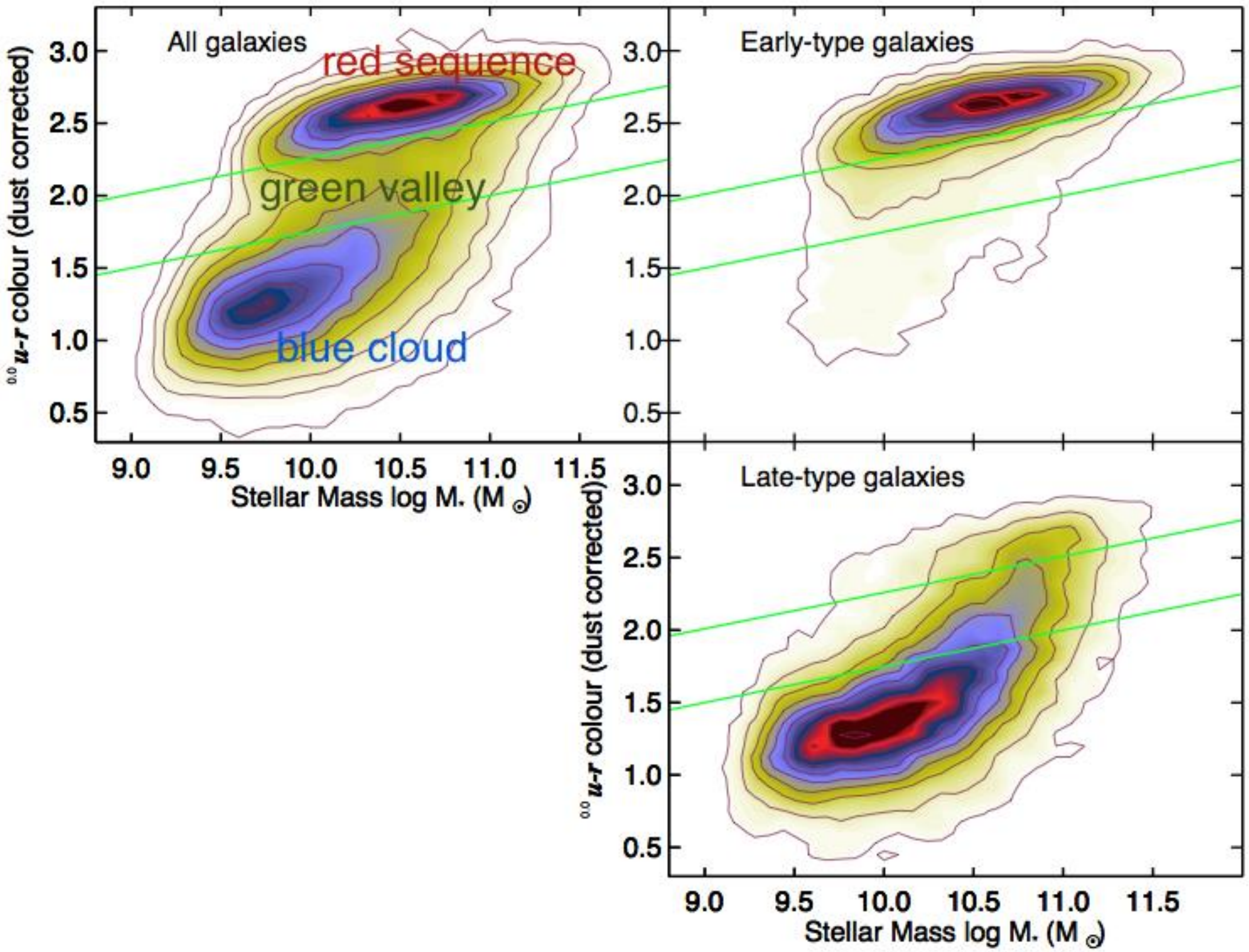
- We can use relations between properties as a quantitative means of classifying galaxies into different families on the basis of physical properties: a galaxy "class" is defined by the relation(s) its members obey

# 4.12 Relations among properties

- There are many, many relations between properties
- Multi-dimensional relations
- Can be difficult to identify “fundamental” properties
- May need to control for z when investigating x vs. y
- Correlation $\neq$ causation
- “True” relations between properties x and y may be obscured by transformation to observable proxies of x and y
- What is noise, what is intrinsic scatter?
- Unaccounted-for selection effects may create, destroy or alter relations
- Disentanglement of all of these effects require large samples

# 4.12 Relations among properties

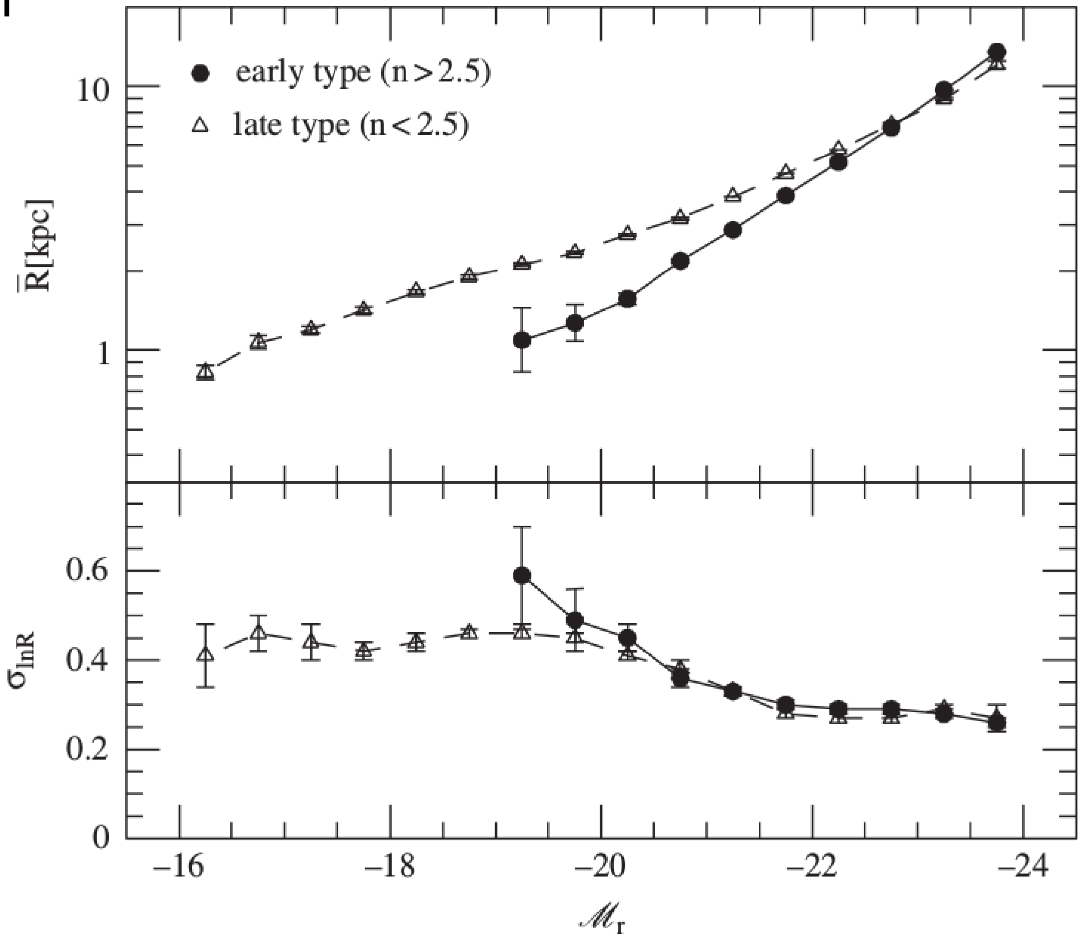
## Colour-magnitude relation



# 4.12 Relations among properties

## Size-luminosity relation

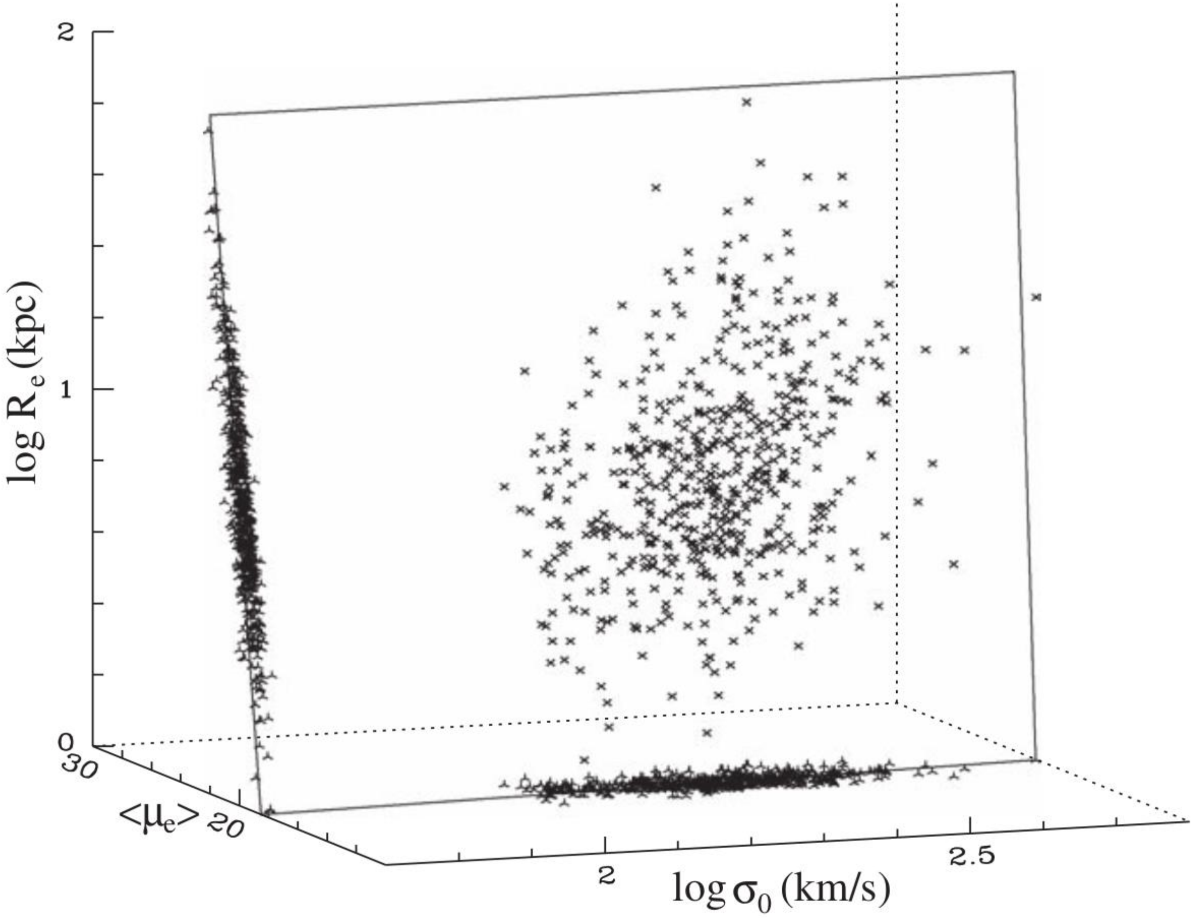
- At fixed L, size distribution is log-normal
- Disks: size distribution linked to distribution of angular momentum
- Spheroids: size distribution linked to merger history



# 4.12 Relations among properties

## Ellipticals: fundamental plane

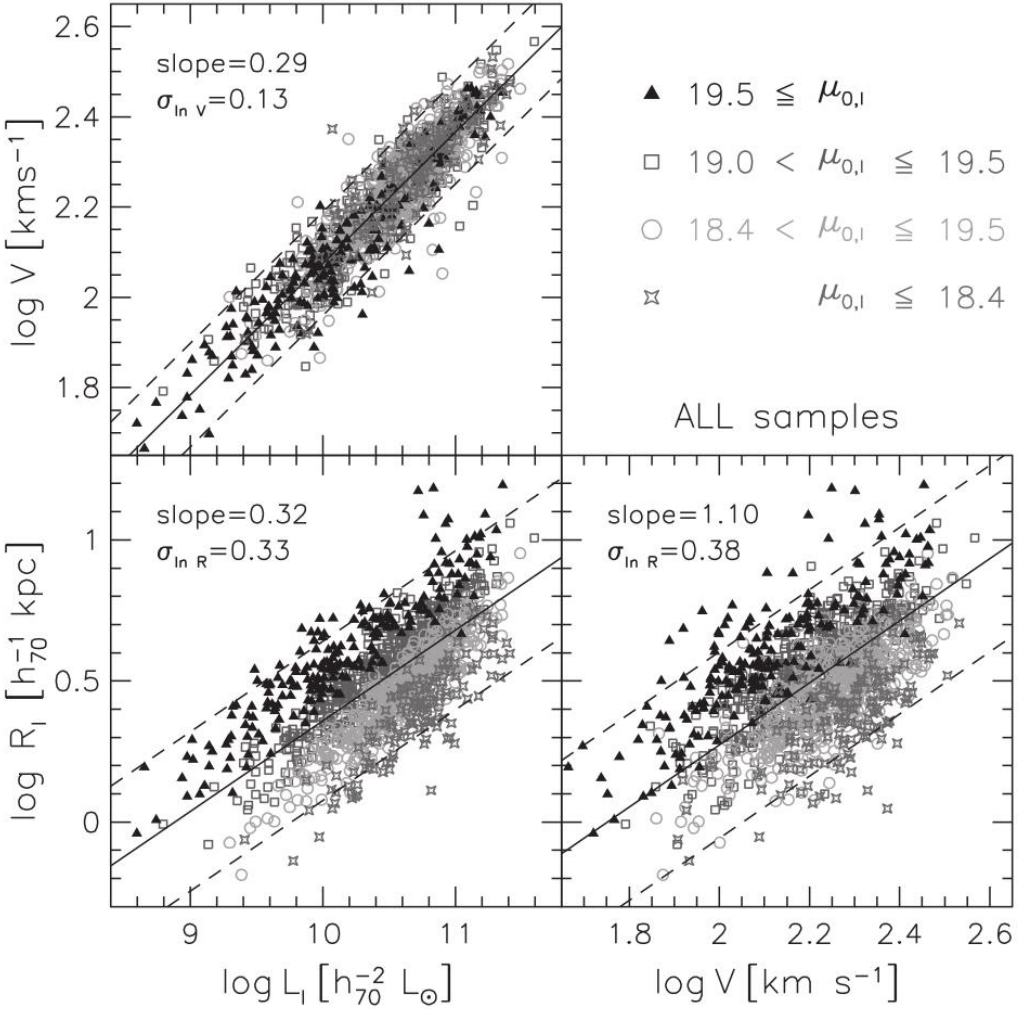
- $\log(R_e / \mathrm{kpc}) = 1.5 \log(\sigma / (\mathrm{km/s})) - 0.75 \log(\langle I \rangle_e) + \mathrm{const}$
- Relates size, mass and luminosity



# 4.12 Relations among properties

## Disks: Tully-Fisher relation

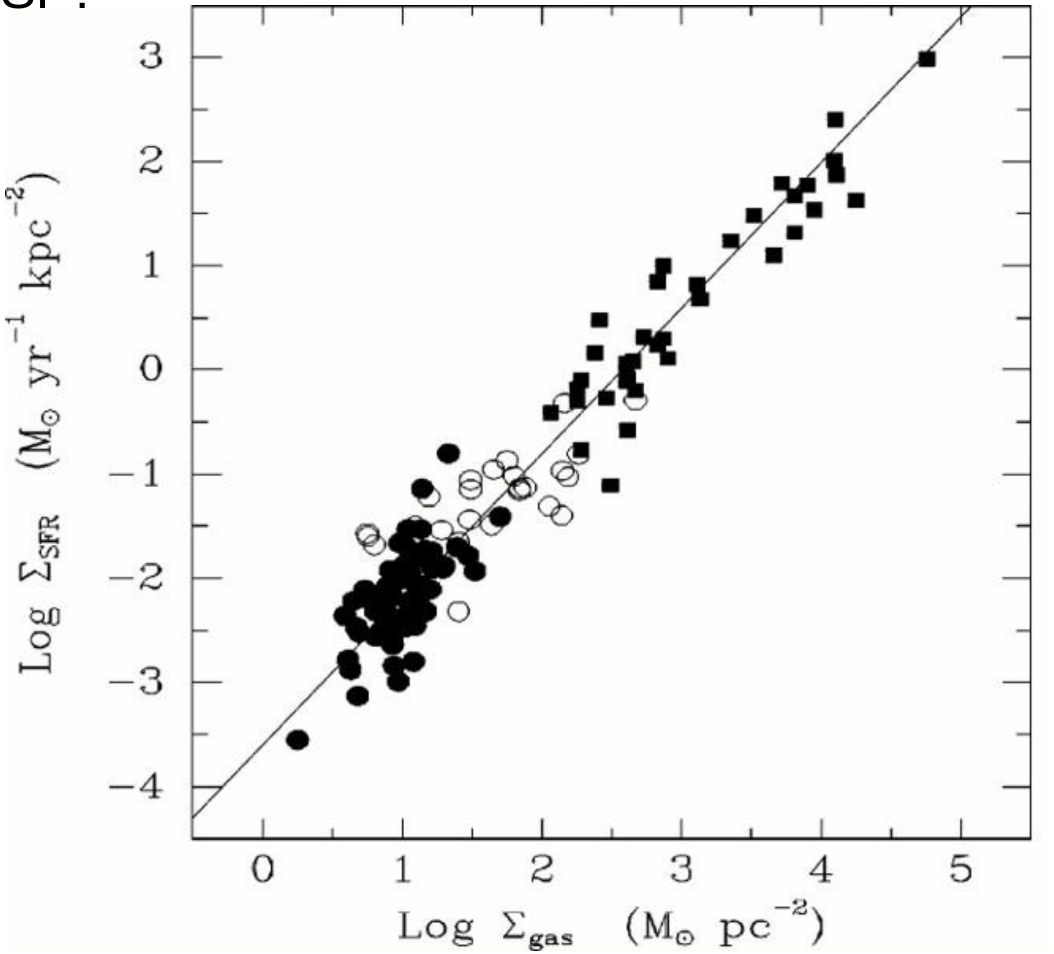
- $L = 2.9 \times 10^{10} \, (v \, / \, (200 \text{ km/s}))^{3.4} \, L_\odot$



# 4.12 Relations among properties

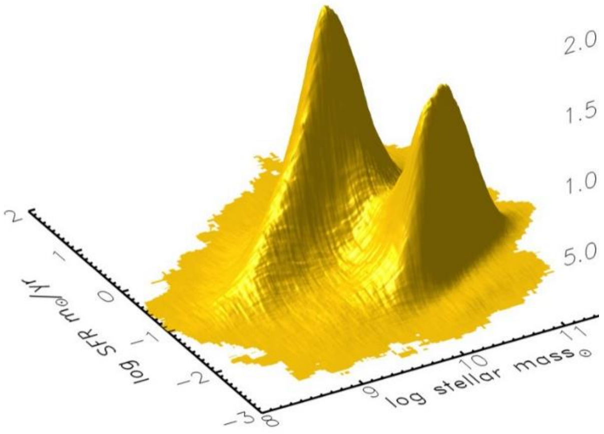
## Kennicutt-Schmidt law

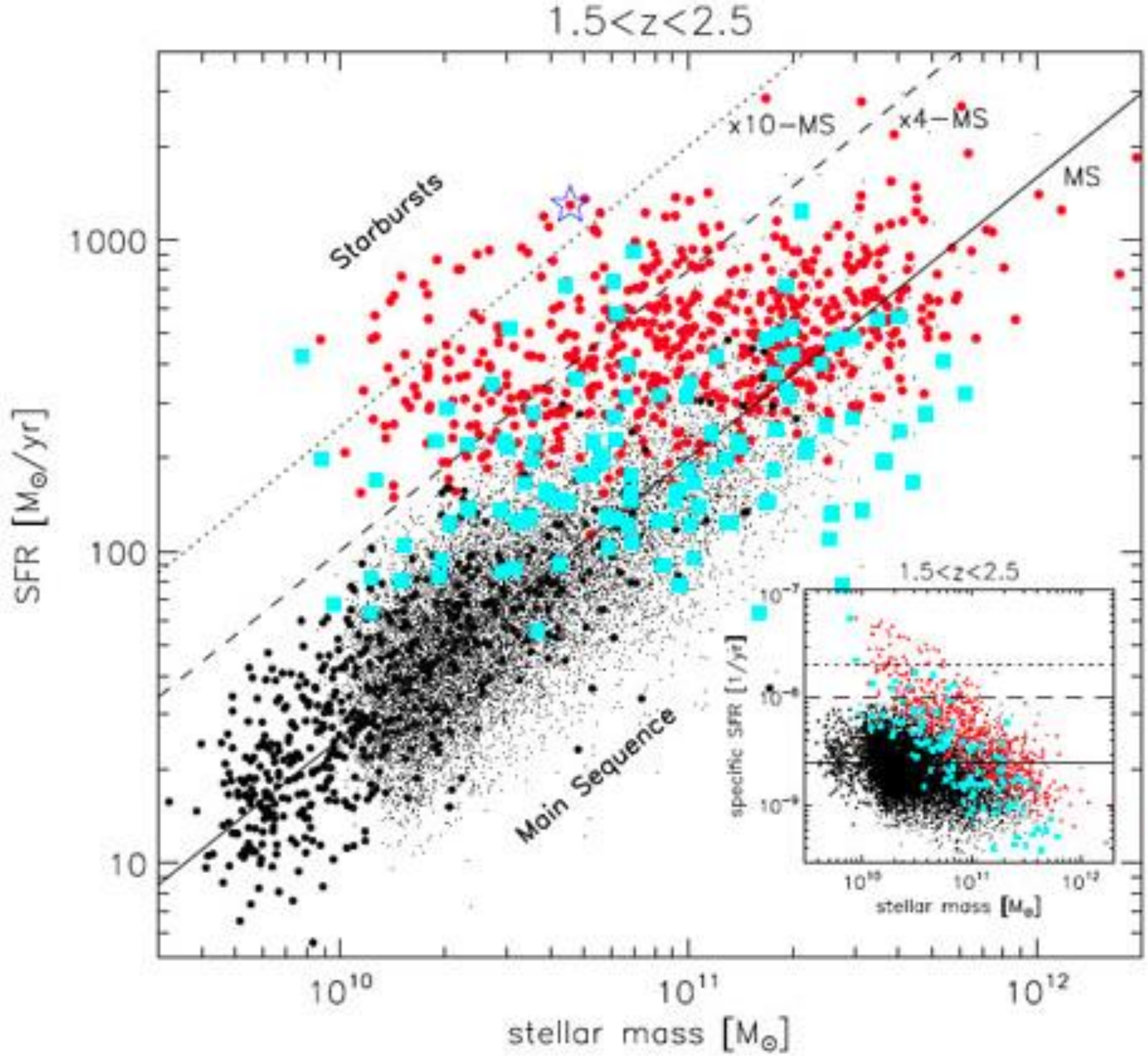
- $\Sigma_{SFR} = 2.4 \times 10^{-4} (\Sigma_{gas} / (M_\odot/pc^2))^{1.4} M_\odot yr^{-1} kpc^{-2}$
- What regulates SF?



# 4.12 Relations among properties

## SFR-M* relation

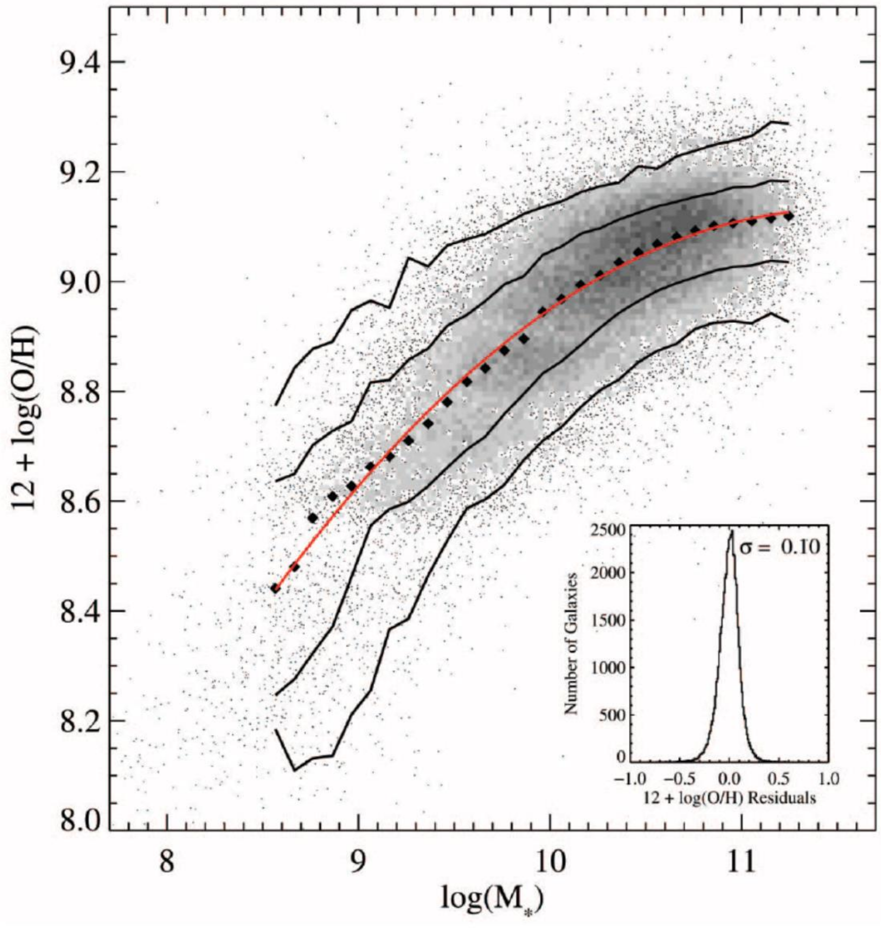




# 4.12 Relations among properties

## Mass-metallicity relation

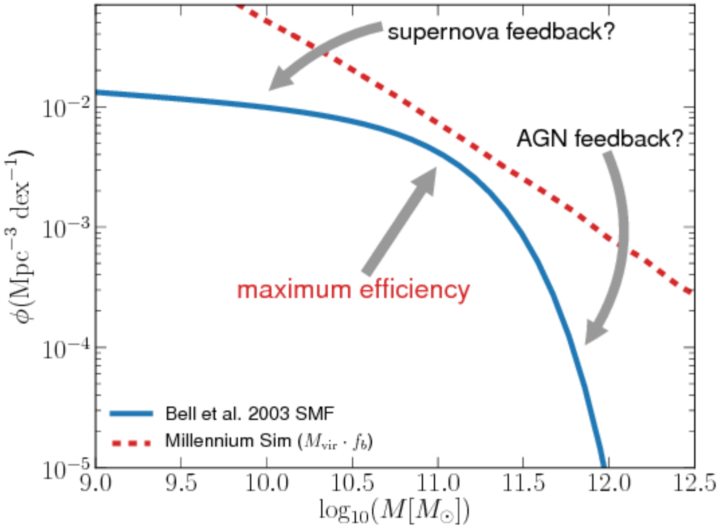
- Here: gas-phase metallicity as measured by O abundance
- Important constraint for models of chemical evolution

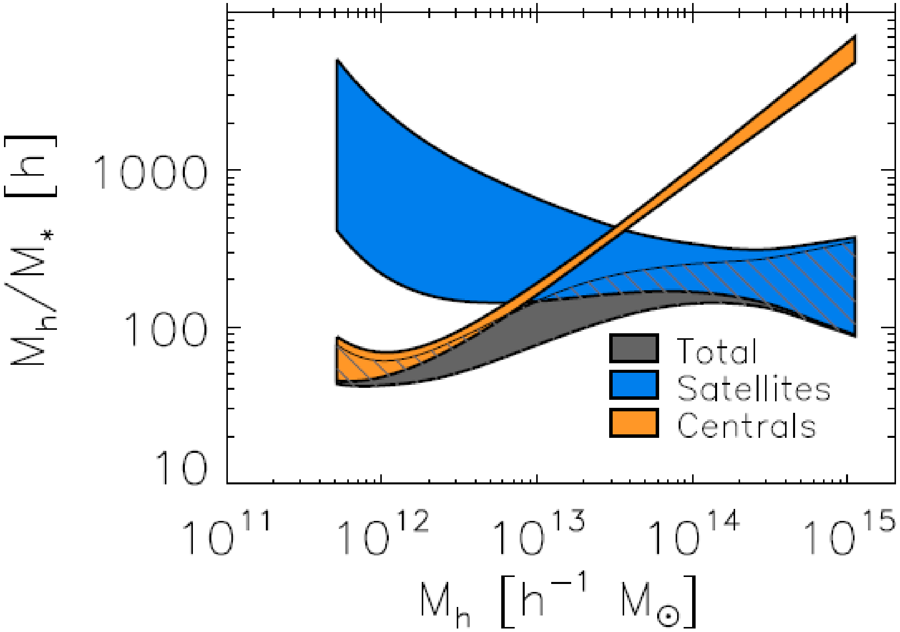


# 4.12 Relations among properties

## $M_{halo}$-$M_*$ relation

- Expect to see a peak in $M_*/M_{halo}$

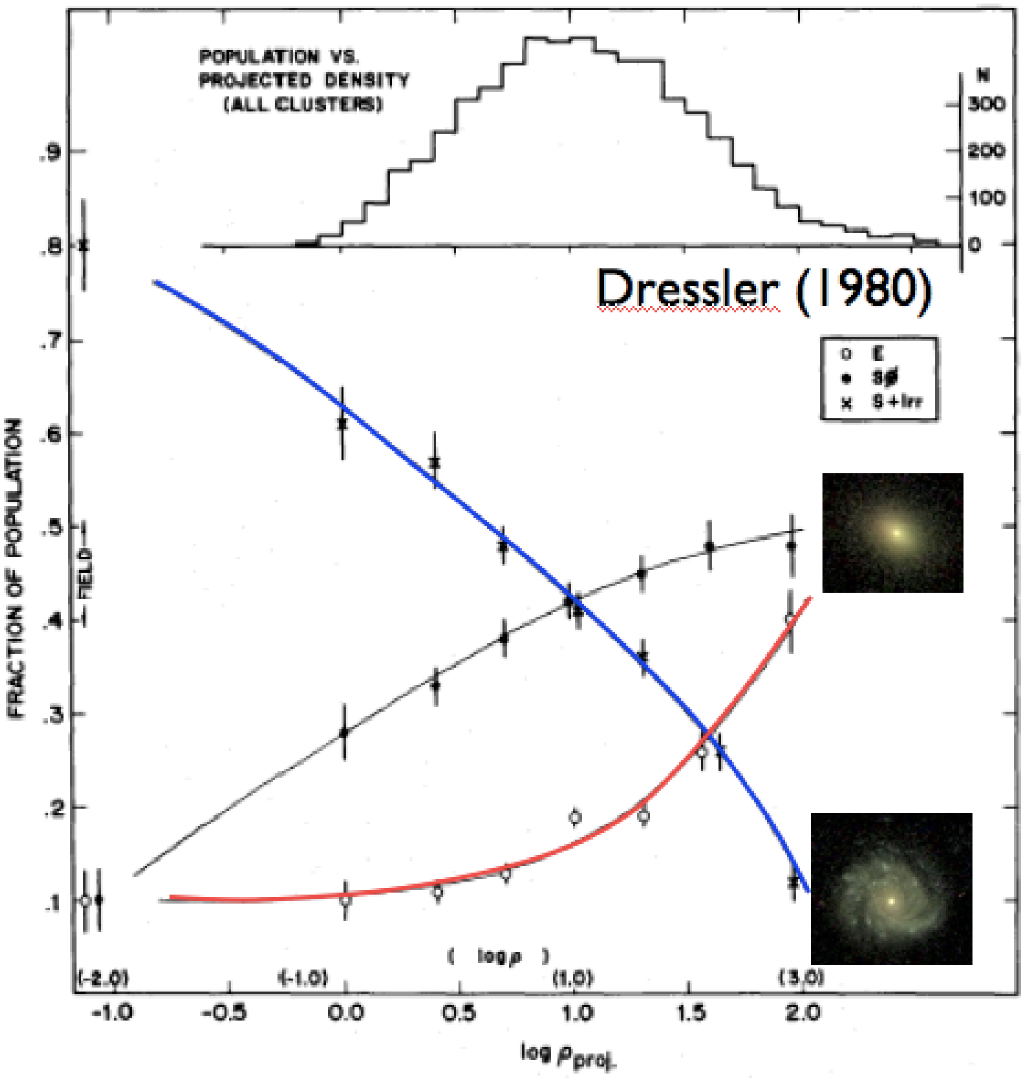




# 4.12 Relations among properties

## Morphology-density relation

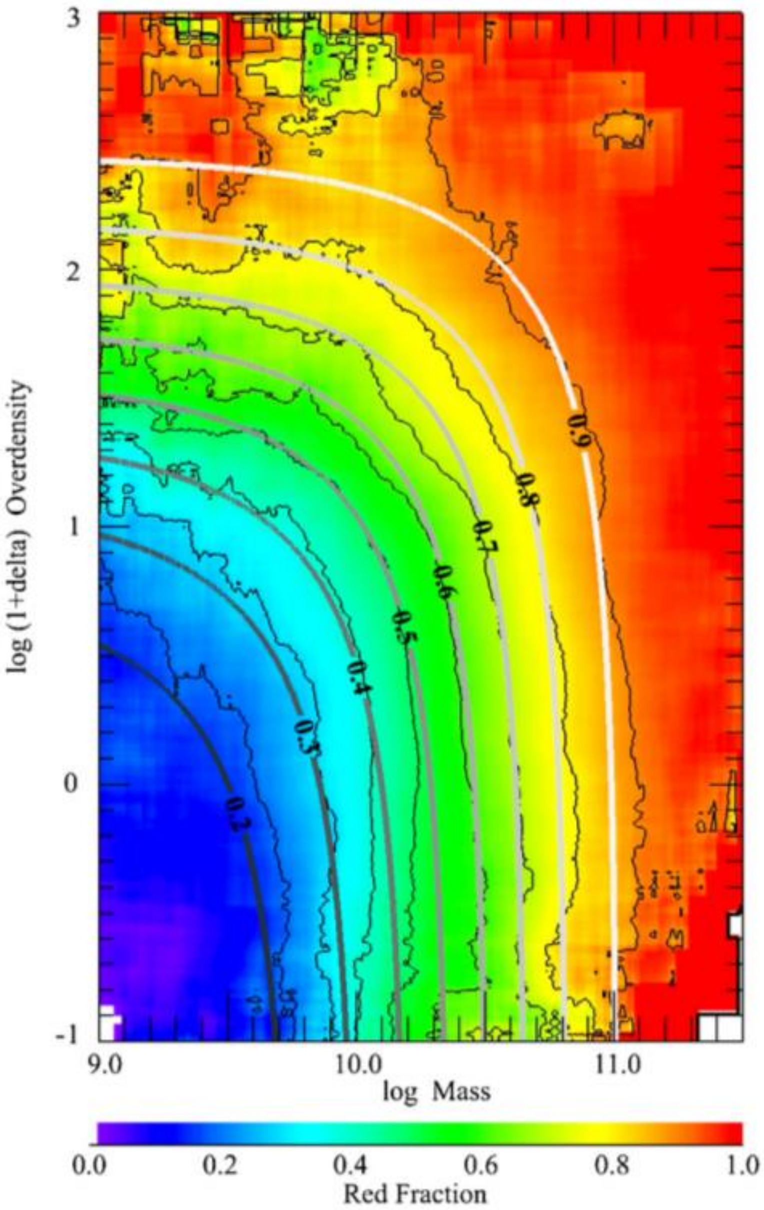
- Dependence of morphological mix on local galaxy density
- Just one of many correlations with environment



# 4.12 Relations among properties

## Morphology-density relation

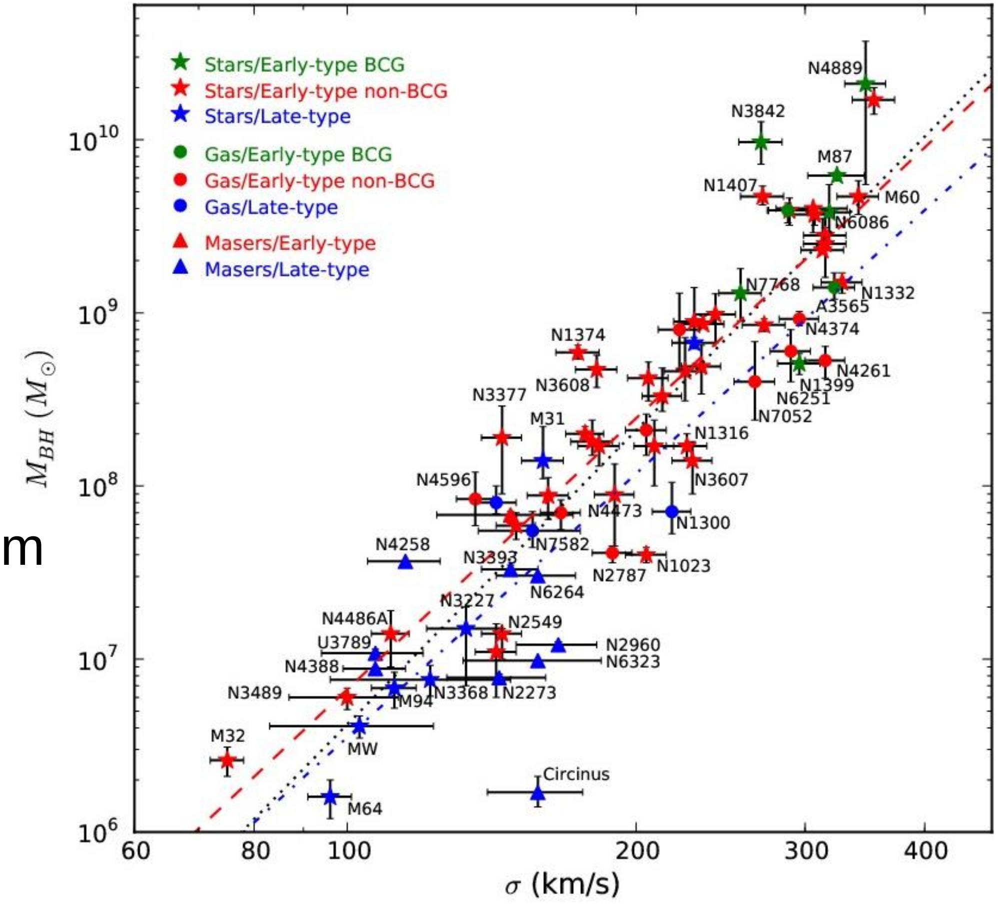
- Dependence of morphological mix on local galaxy density
- Just one of many correlations with environment
- Morphological mix also depends on stellar mass



# 4.12 Relations among properties

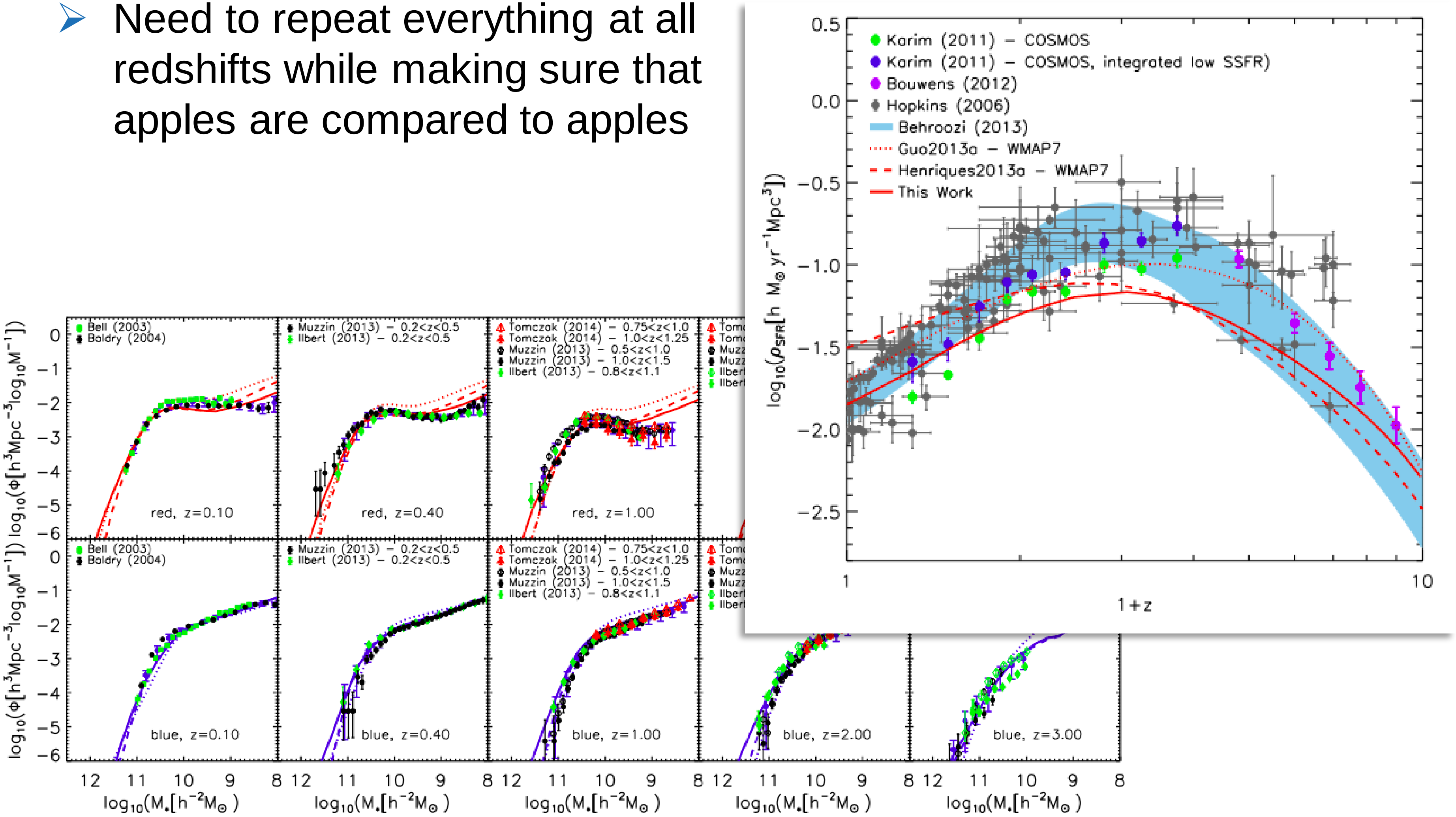
## $M_{BH}$-$\sigma$ relation

- $M_{BH} = 1.3 \times 10^8 \, (\sigma / (200 \text{ km/s}))^{3.7-5} \, M_\odot$
- Connects BH mass with properties of host galaxy
- Evidence of co-evolution?
- How is the tightness of the relation maintained during mergers?
- Alternatively: do mergers produce a tight correlation from an arbitrary $M_{BH}/M_{bulge}$ distribution?

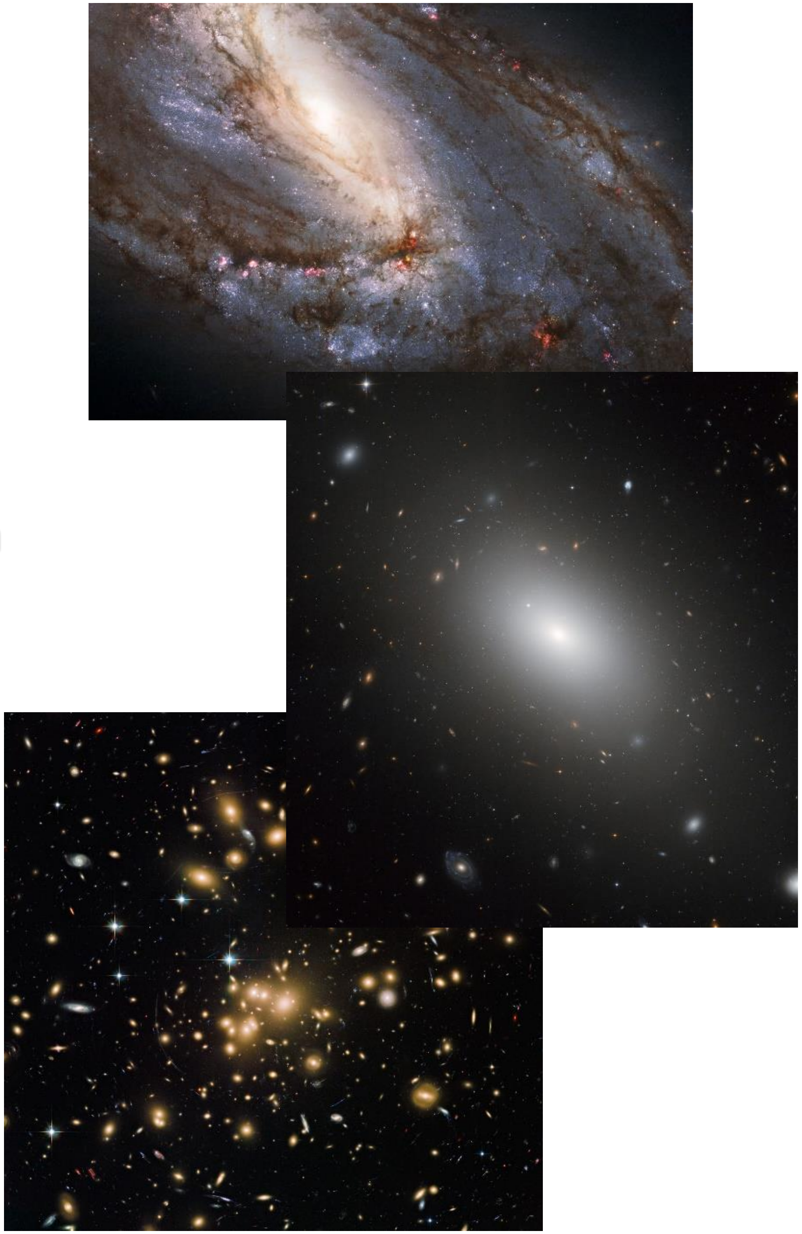


# 4.13 Evolution of properties

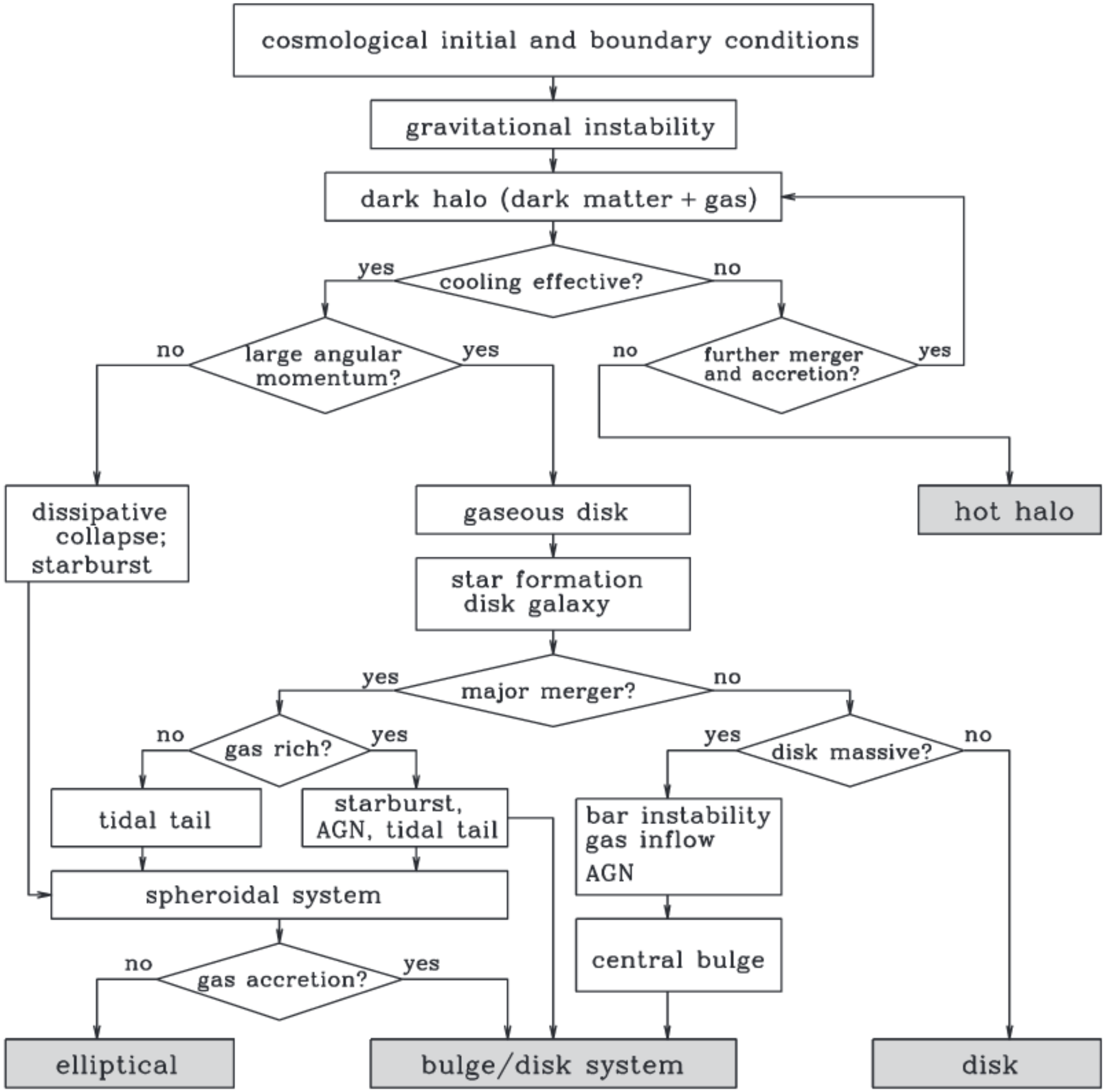
- All of the above properties, their distributions and relations, evolve with redshift
- Need to repeat everything at all redshifts while making sure that apples are compared to apples



# Contents

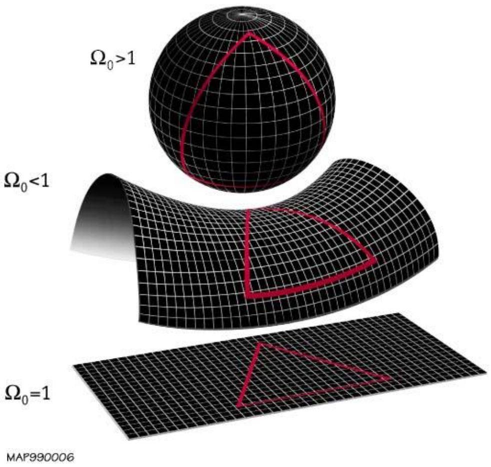


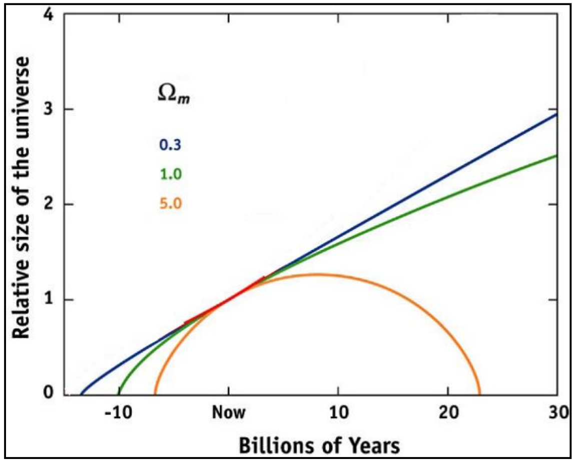
# 5. Basic elements of galaxy formation



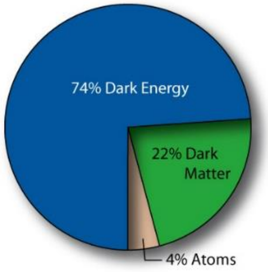
# 5.1 Cosmology

- General relativity
- Cosmological principle (homogeneity and isotropy)
- FLRW metric
- Uniquely determined by geometry (k) and expansion history (R(t))



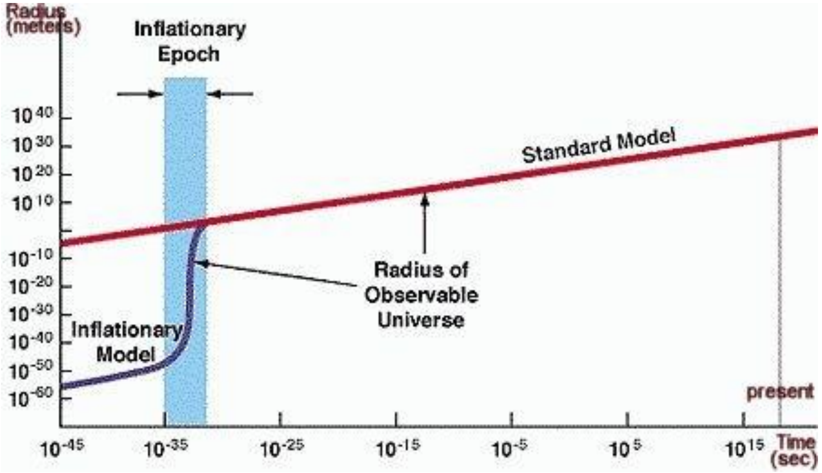


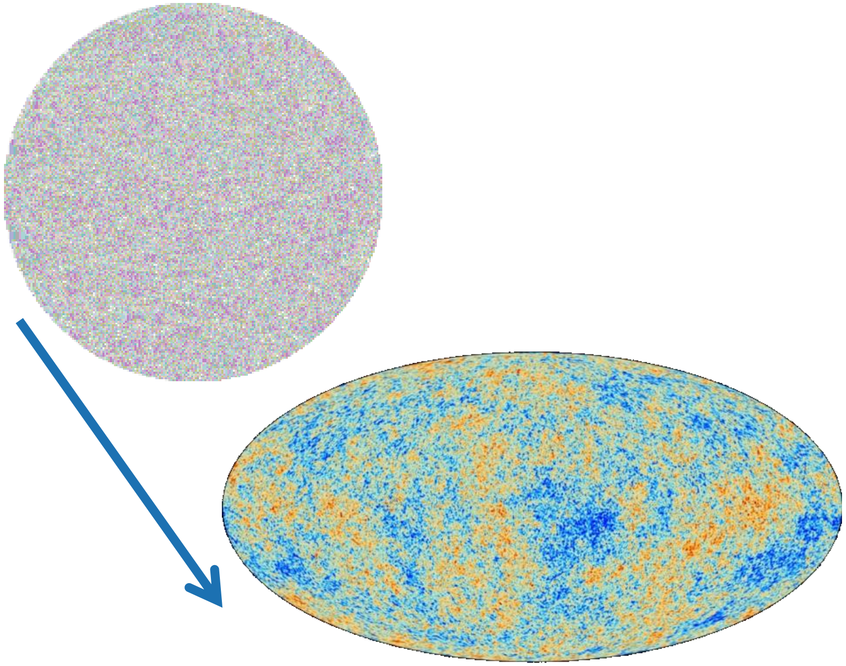
- These are in turn determined by the mass-energy budget of the Universe:



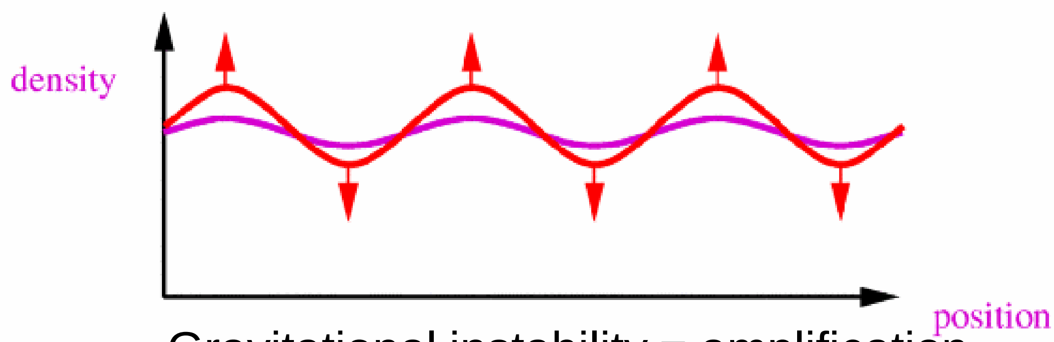
# 5.2 Initial conditions

- The “basic” cosmological model does not explain the emergence of structure in the Universe.
- Source of initial density perturbations from which galactic structures could develop is still not entirely clear.
- Best bet: a period of inflationary expansion in the very early Universe (at end of GUT era) that inflates quantum fluctuations to a macroscopic scale



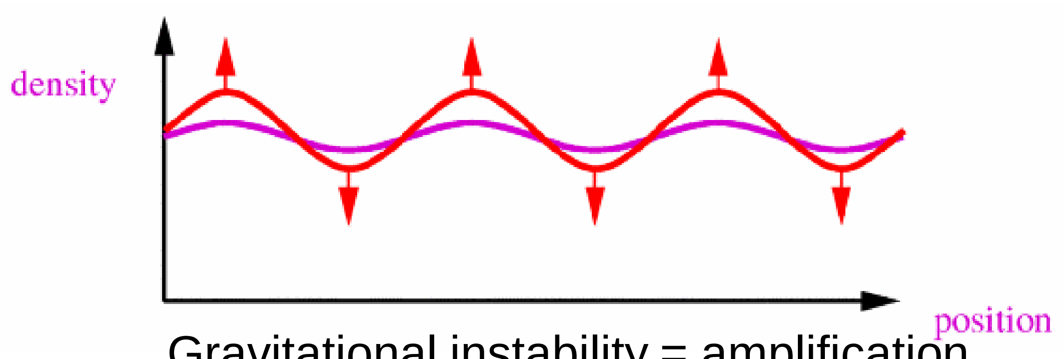


# 5.3 Structure formation



Gravitational instability = amplification of initial density perturbations

# 5.3 Structure formation

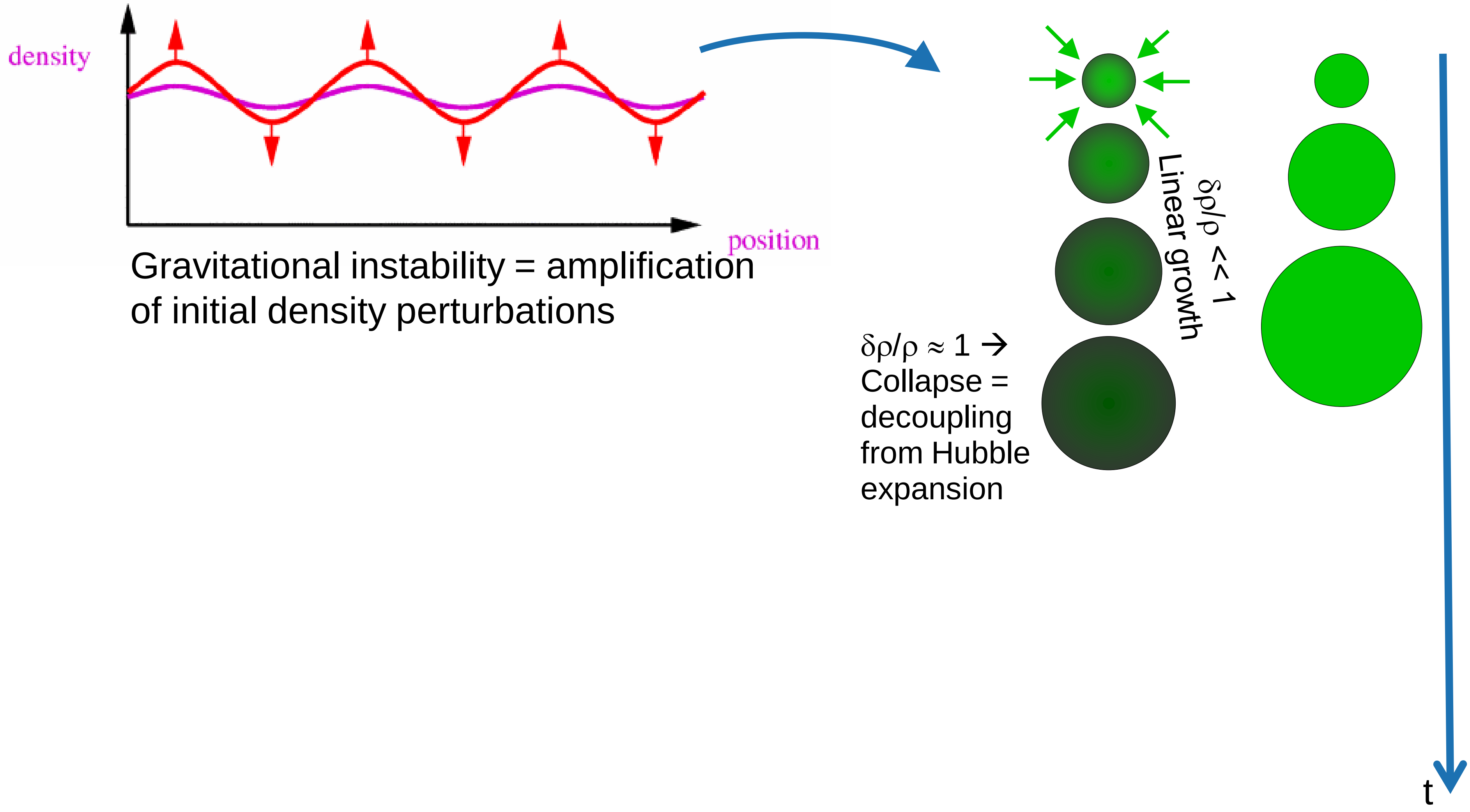


Gravitational instability = amplification
of initial density perturbations

Governed by 3 equations:

- Continuity $$\frac{\mathrm{D}\rho}{\mathrm{D}t} + \rho \nabla_{\mathbf{r}} \cdot \mathbf{u} = 0$$
- Euler $$\frac{\mathrm{D}\mathbf{u}}{\mathrm{D}t} = -\frac{\nabla_{\mathbf{r}} P}{\rho} - \nabla_{\mathbf{r}} \phi$$
- Poisson $$\nabla_{\mathbf{r}}^2 \phi = 4\pi G \rho$$

# 5.4 Halo formation



Gravitational instability = amplification of initial density perturbations

Increased density region

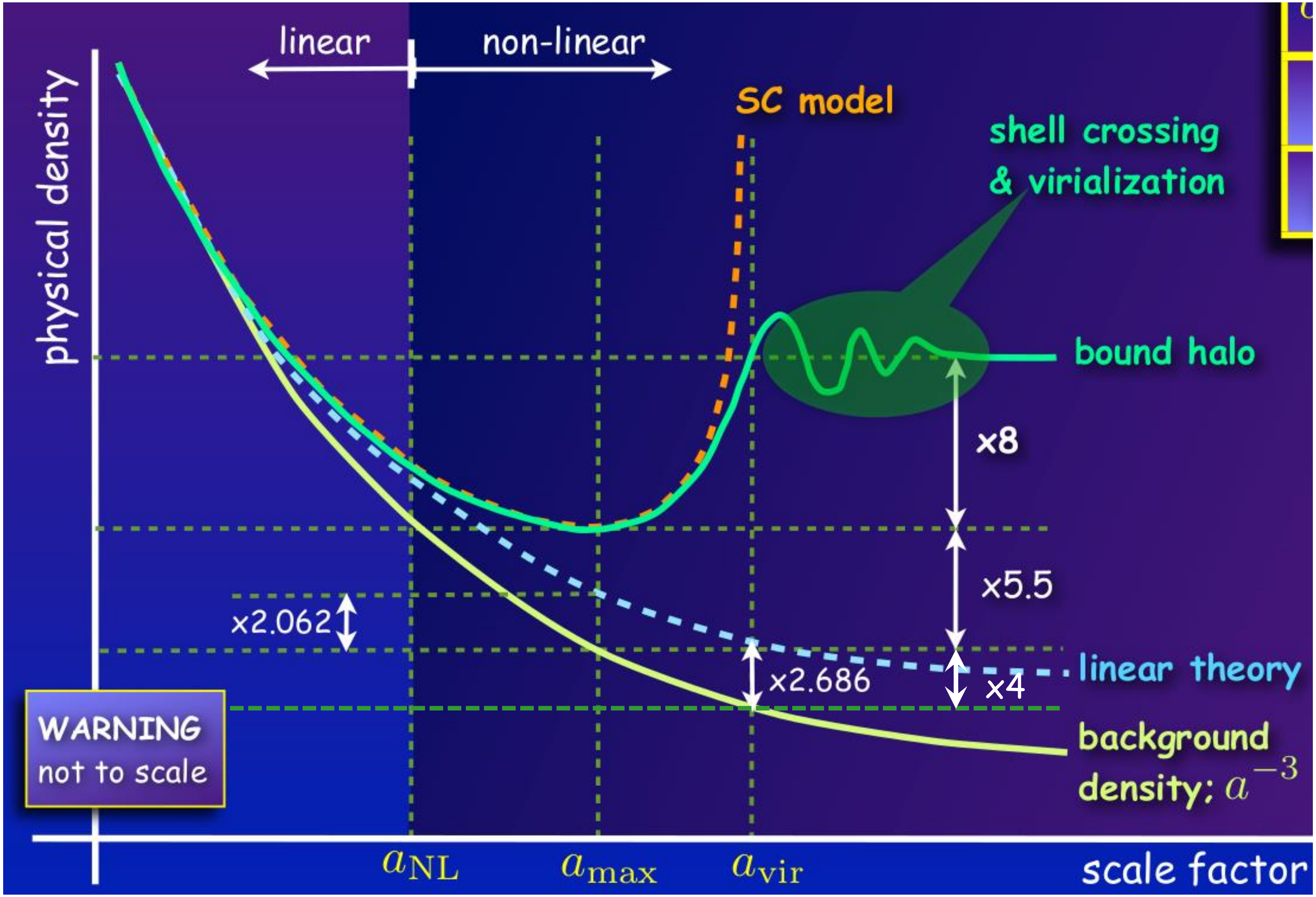
Average density region

Linear growth

$\delta\rho/\rho << 1$

$\delta\rho/\rho \approx 1$ → Collapse = decoupling from Hubble expansion

# 5.4 Halo formation



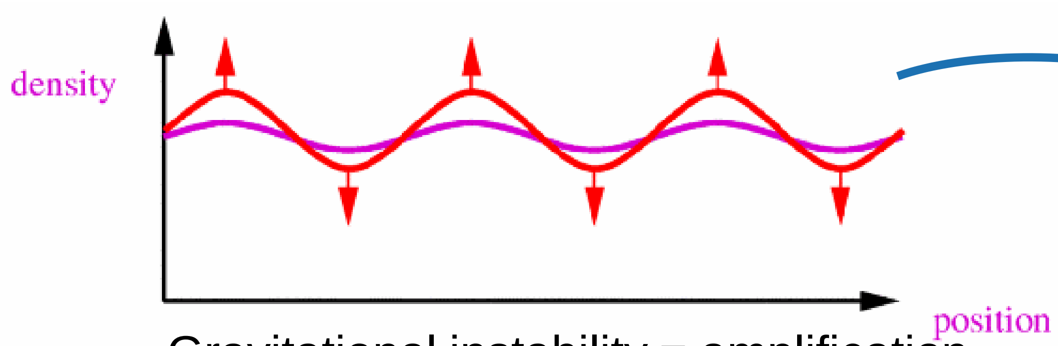
# 5.4 Halo formation

- Relaxation mechanisms available to collisionless systems:
  - Phase mixing
    Diffusion of initially close-by points in phase-space due to the difference in frequencies between neighboring orbits
  - Chaotic mixing
    Diffusion of initially close-by points in phase-space due to the chaotic nature of their orbits
  - Violent relaxation
    Change in energy of individual particles due to changes in the overall potential
  - Landau damping
    Damping and decay of perturbations due to decoherence between particles and waves

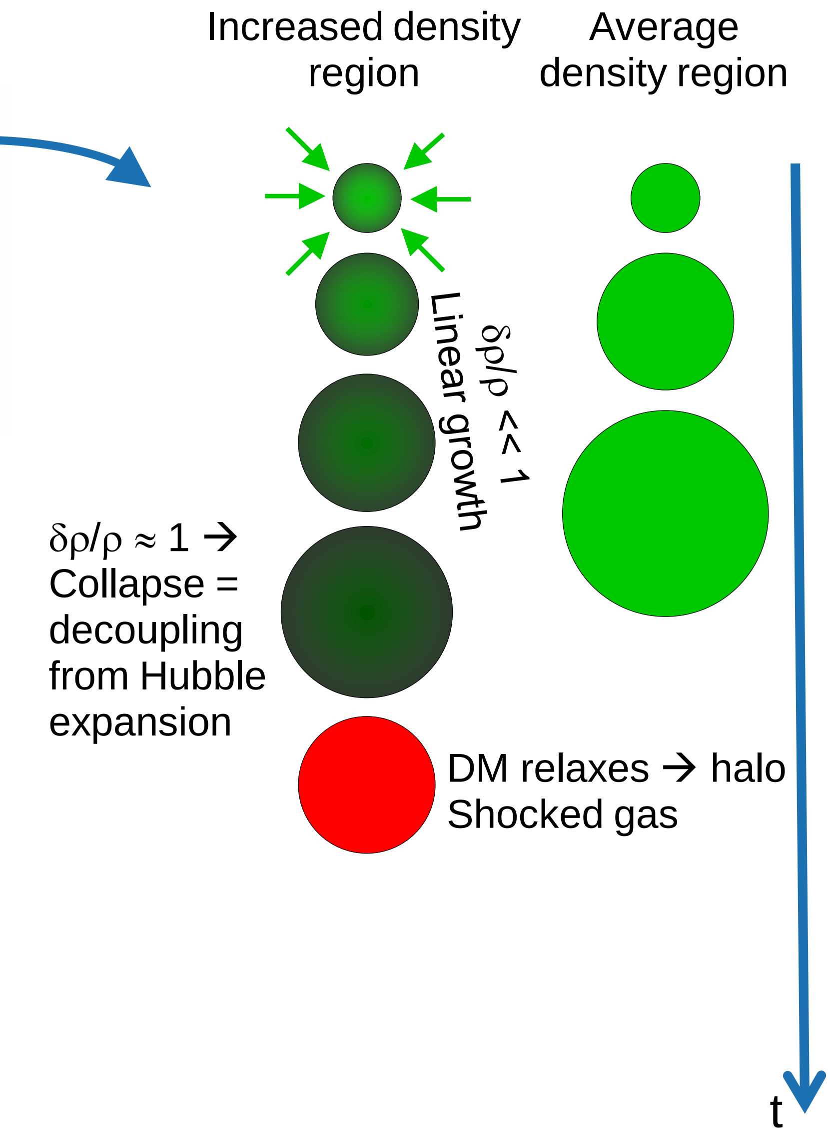
# 5.4 Halo formation

- End state is a system in equilibrium, governed by collisionless dynamics (collisionless Boltzmann equation)
- Obeys the virial theorem: $2K + W = 0 \rightarrow E = K + W = -K = W/2$
- No success in describing end state with statistical mechanics
- ➢ Need numerical simulations
  - End state depends on details of collapse…
  - … and on initial conditions
  - In particular: initial value of virial ratio = $|2T/W|$
  - CDM halos all expected to have formed from very low $|2T/W|$
  - Linked to universal density profile of CDM halos?

# 5.4 Halo formation



Gravitational instability = amplification of initial density perturbations



Increased density region

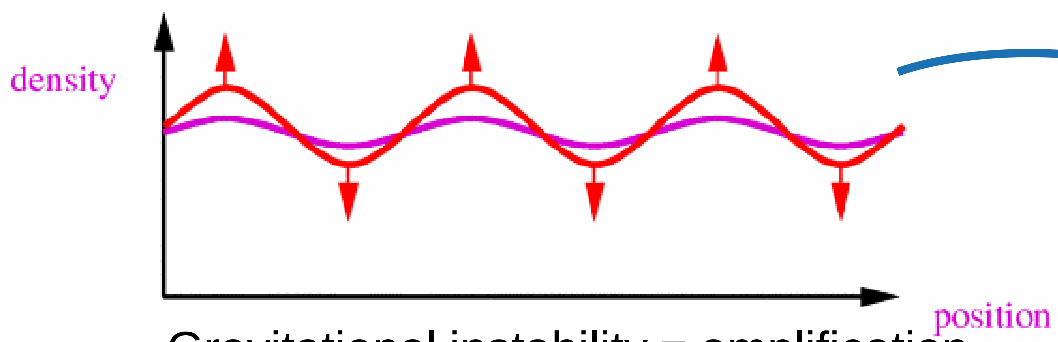
Average density region

$\delta\rho/\rho \ll 1$
Linear growth

$\delta\rho/\rho \approx 1 \rightarrow$ Collapse = decoupling from Hubble expansion

DM relaxes → halo
Shocked gas

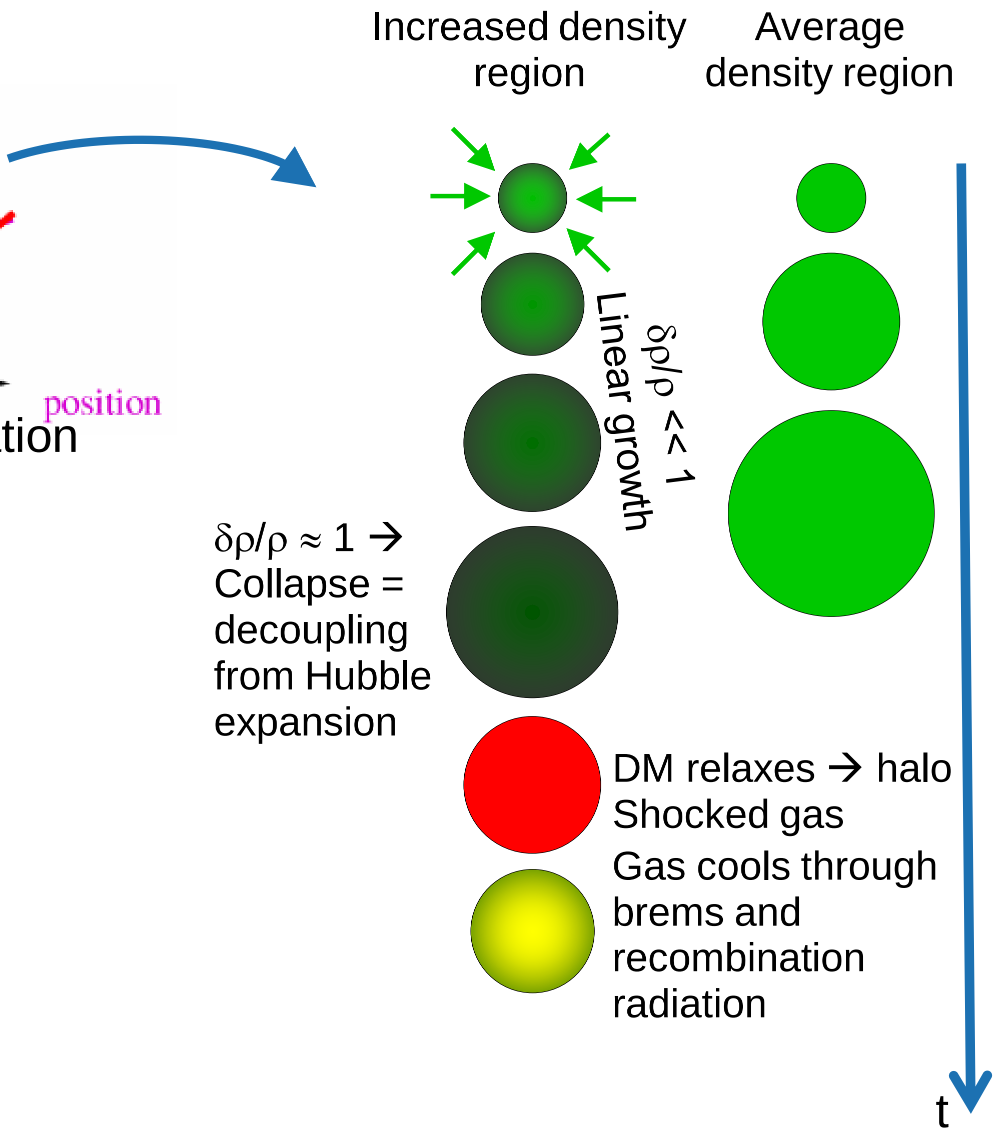
# 5.5 Gas cooling



Gravitational instability = amplification of initial density perturbations

Gas cooling depends strongly on:

- Temperature
- Density
- Chemical composition of gas



Increased density region

Average density region

Linear growth

$\delta\rho/\rho \ll 1$

$\delta\rho/\rho \approx 1$ → Collapse = decoupling from Hubble expansion

DM relaxes → halo
Shocked gas

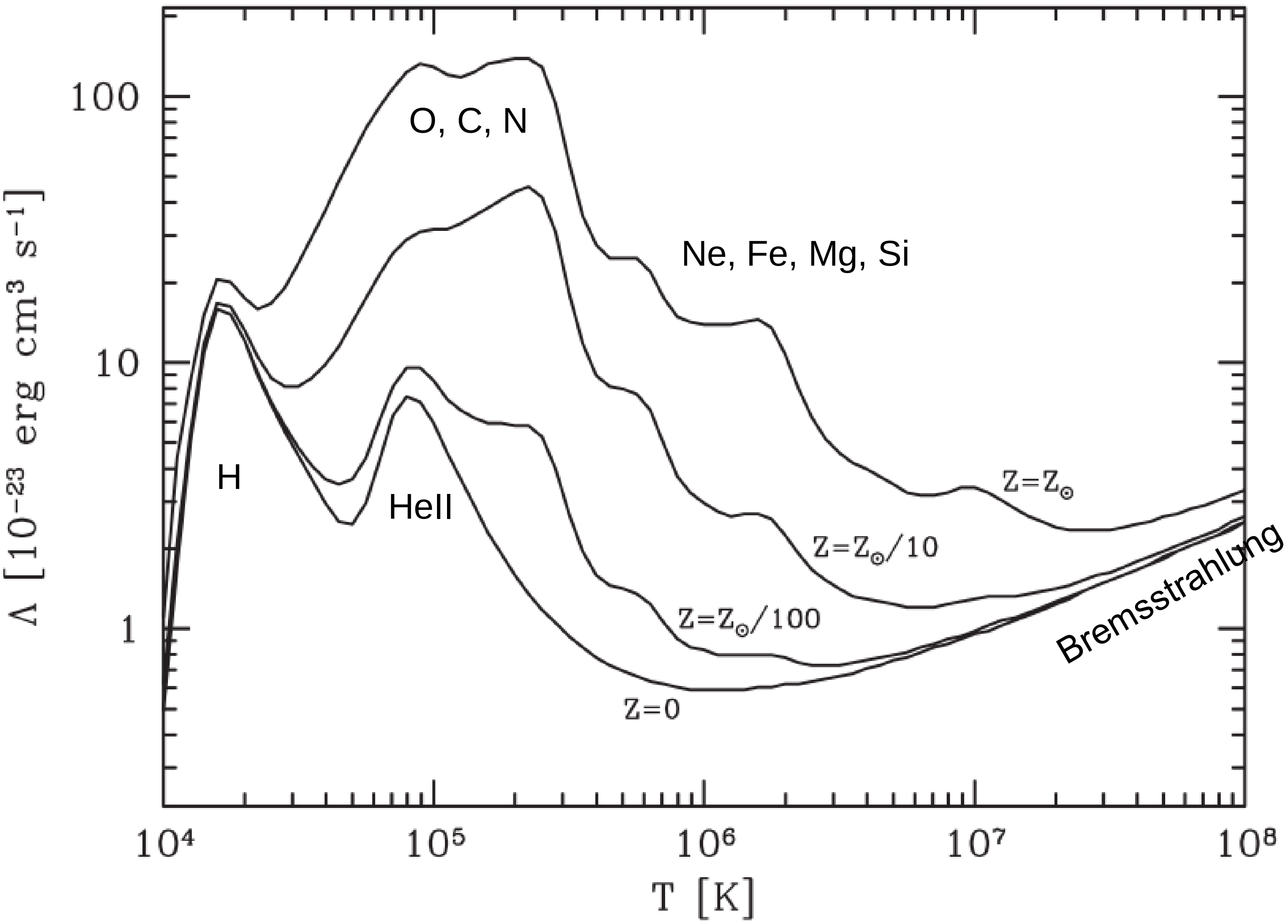
Gas cools through brems and recombination radiation

# 5.5 Gas cooling

## Cooling processes

- Compton cooling
  - $e^-$ lose energy to CMB, important at high z
- Radiative processes
  - Bremsstrahlung (free-free)
  - Recombination (free-bound)
  - Collisional ionisation (bound-free)
  - Collisional excitation (bound-bound)
  - All depend on T
  - Define cooling function: $\Lambda(T) \equiv \frac{\mathscr{C}}{n_{\rm H}^2}$ (independent of $n_H$)

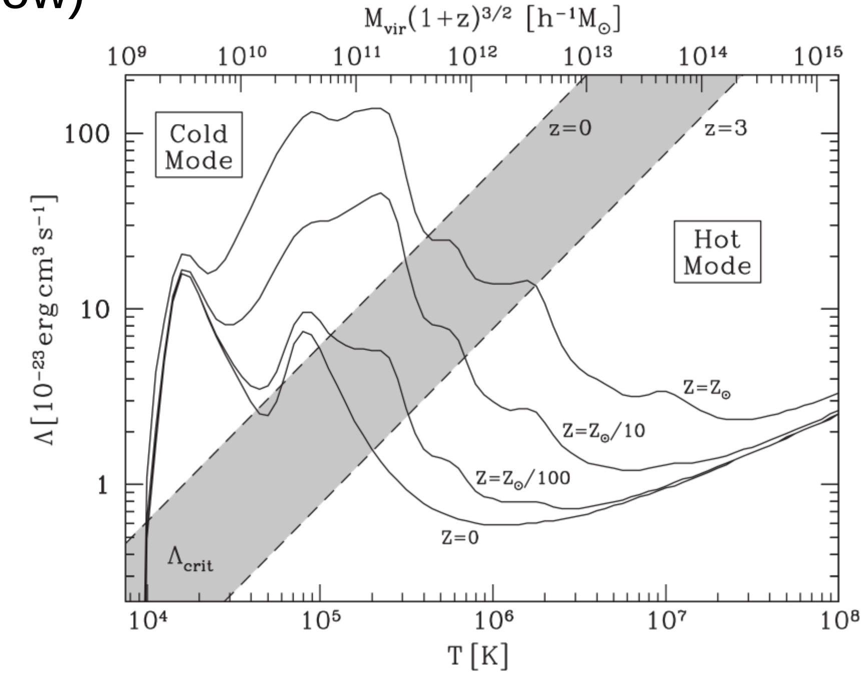
# 5.5 Gas cooling



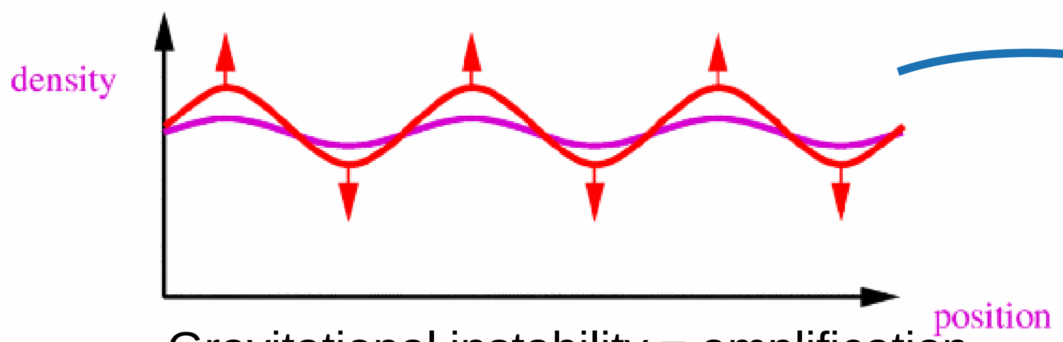
# 5.5 Gas cooling

- Cooling timescale: $t_{\rm cool}(r) = \dfrac{3n(r)k_{\rm B}T(r)}{2n_{\rm H}^2(r)\Lambda(T)}$ (faster near centre)

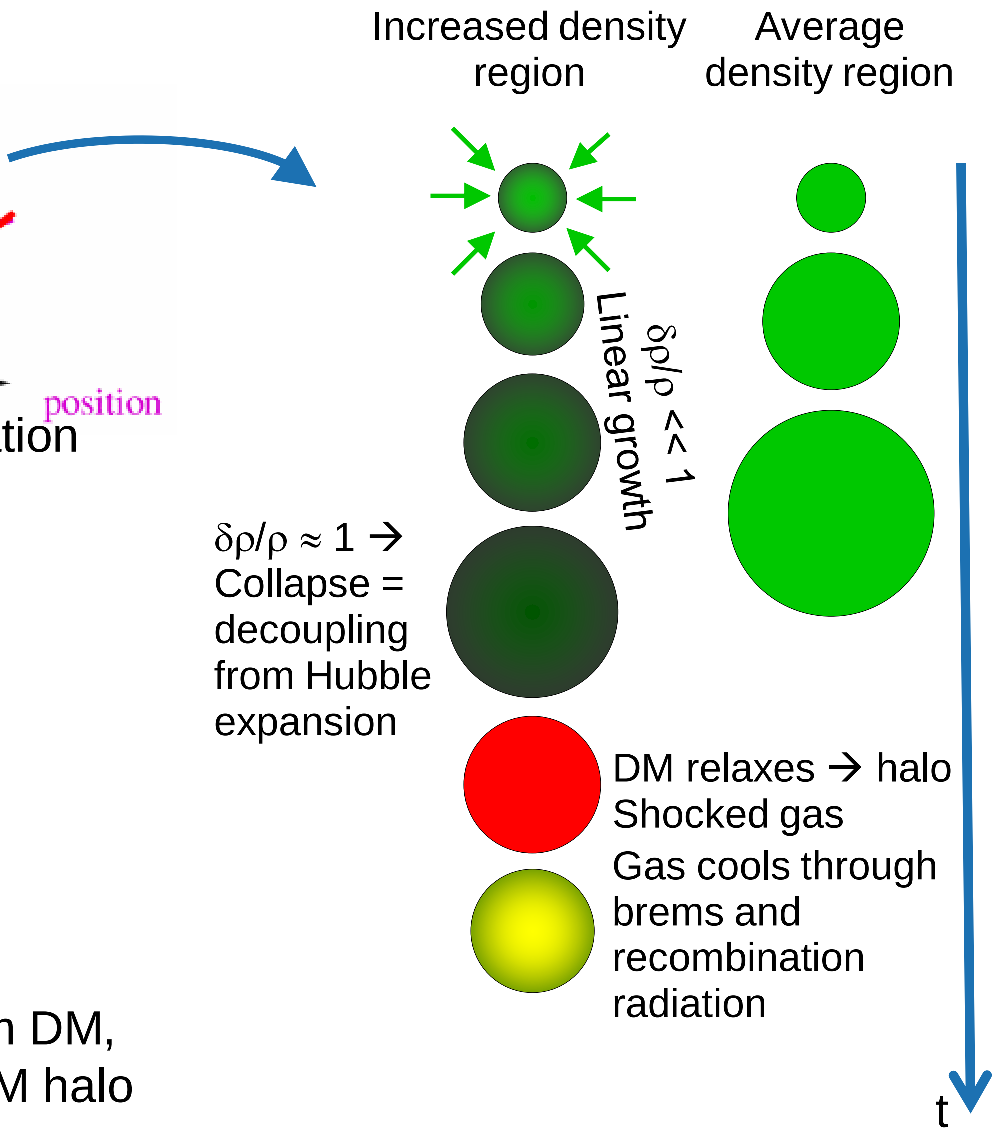
- $t_{\rm cool} > t_{\rm H}$: cooling unimportant → hydrostatic equilibrium
- $t_{\rm ff} < t_{\rm cool} < t_{\rm H}$: quasi-hydrostatic equilibrium, evolves on cooling timescale, system has time to react as gas cools
- $t_{\rm cool} < t_{\rm ff}$: catastrophic cooling → gas is never heated to $T_{\rm vir}$ (no shock, cold flow)



# 5.5 Gas cooling



Gravitational instability = amplification of initial density perturbations



Increased density region

Average density region

$\delta\rho/\rho \approx 1$ → Collapse = decoupling from Hubble expansion

DM relaxes → halo
Shocked gas

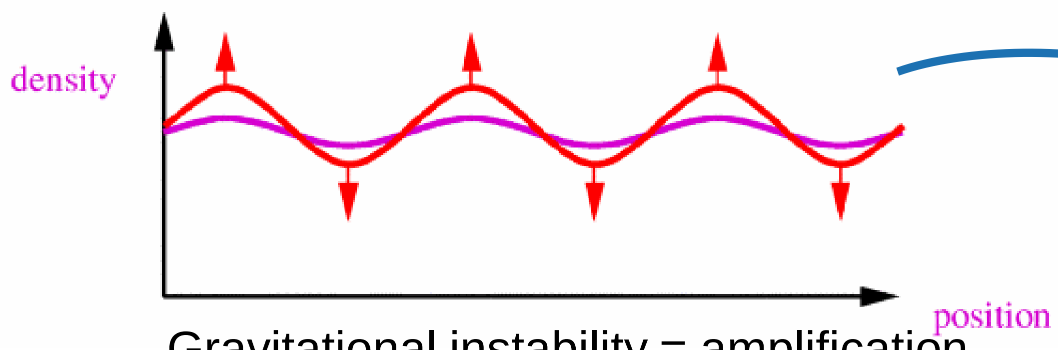
Gas cools through brems and recombination radiation

Gas cooling depends strongly on:

- Temperature
- Density
- Chemical composition of gas

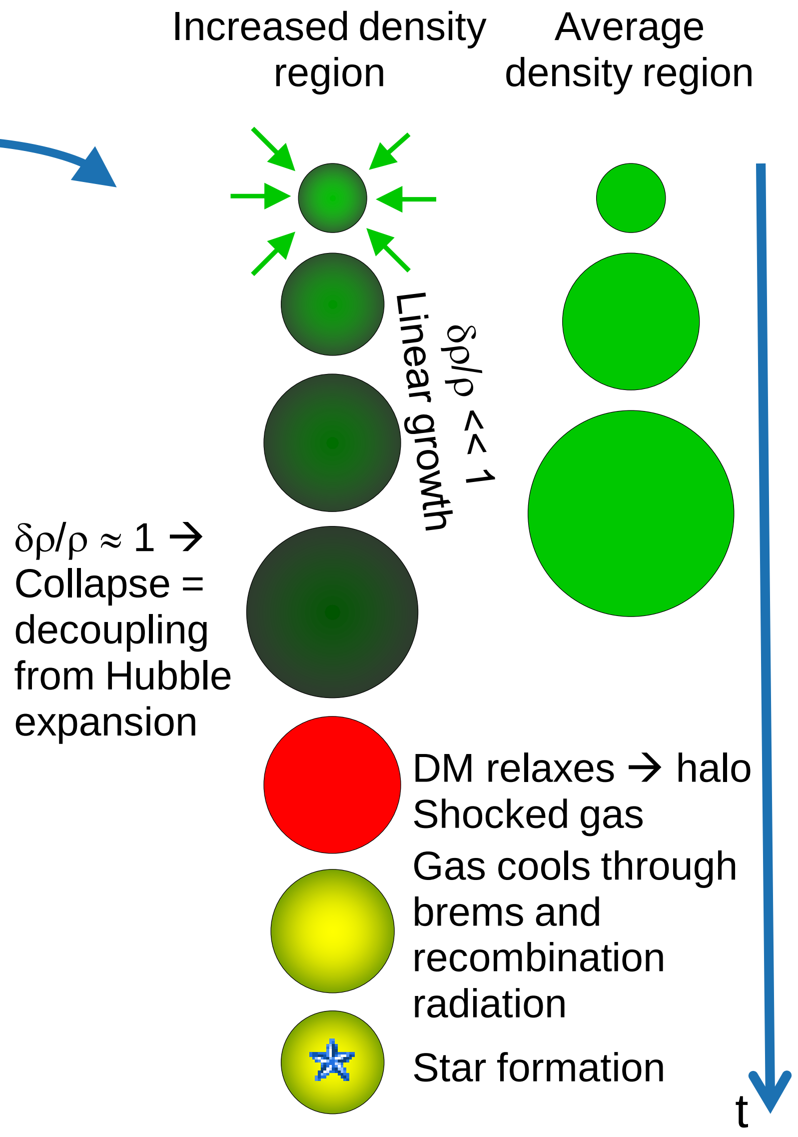
Cooling → segregation of gas from DM, collects as cold gas in centre of DM halo → proto-galaxy (disk)

# 5.6 Star formation



Gravitational instability = amplification of initial density perturbations

- Eventually: self-gravity of gas dominates → runaway collapse, fragmentation → star formation (SF)
- Details still poorly understood
  - Initial mass function (IMF)?
- Two SF modes:
  - Quiescent
  - Bursting



Increased density region

Average density region

Linear growth $\delta\rho/\rho << 1$

$\delta\rho/\rho \approx 1$ → Collapse = decoupling from Hubble expansion

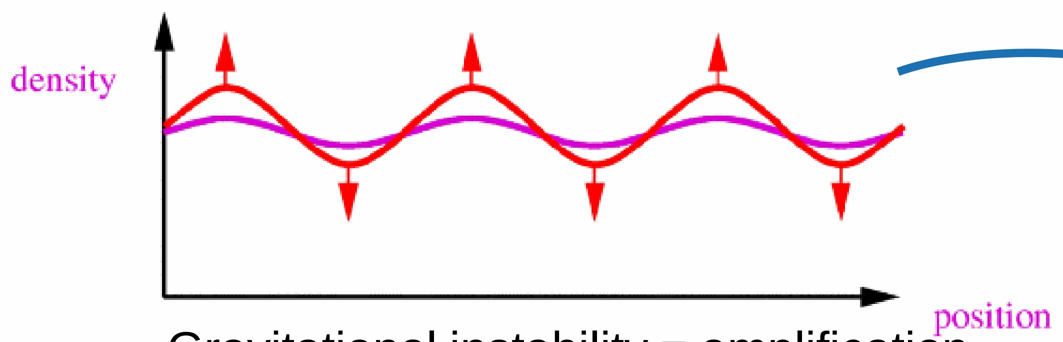
DM relaxes → halo

Shocked gas

Gas cools through brems and recombination radiation

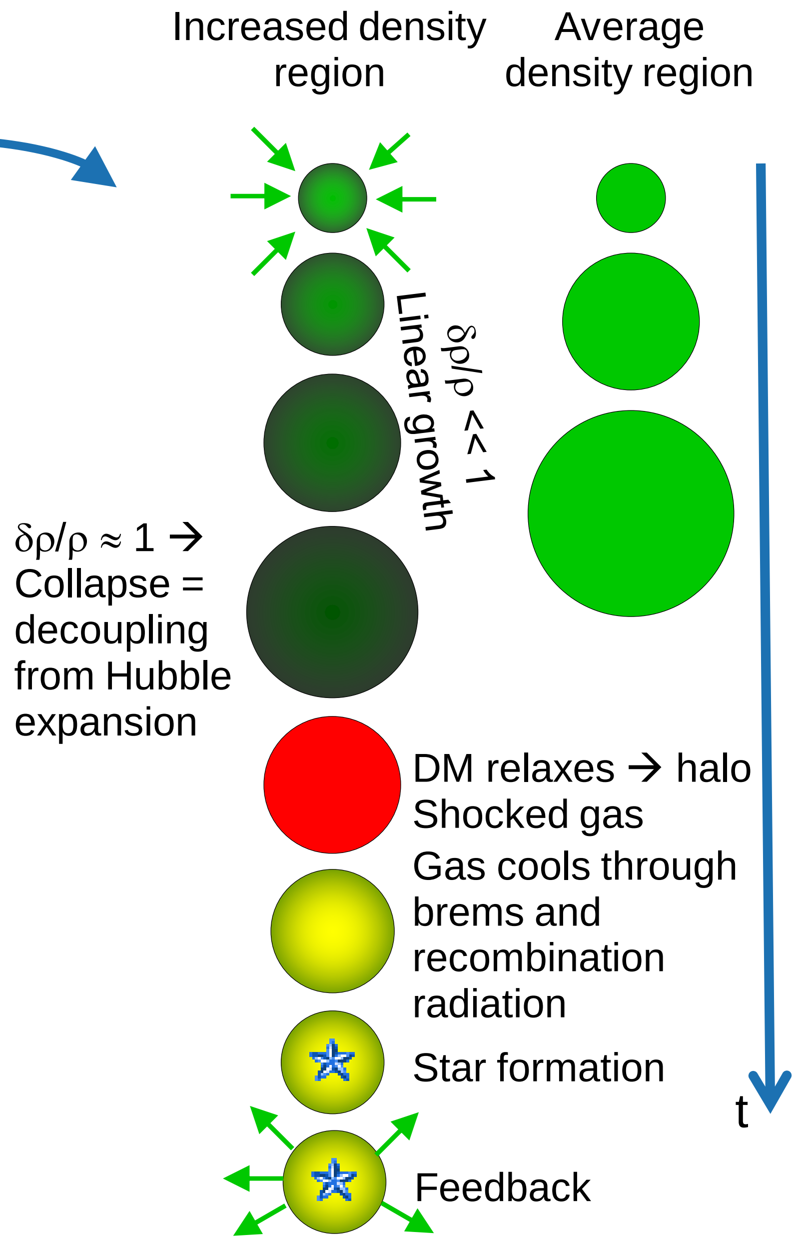
Star formation

# 5.7 Feedback



Gravitational instability = amplification of initial density perturbations

- To prevent all of the gas from forming stars, the gas needs to be stopped from cooling, reheated or expelled.
- Feedback from:
  - AGN (high-mass)
  - Supernovae (low-mass)



Increased density region

Average density region

$\delta\rho/\rho \ll 1$ Linear growth

$\delta\rho/\rho \approx 1$ → Collapse = decoupling from Hubble expansion

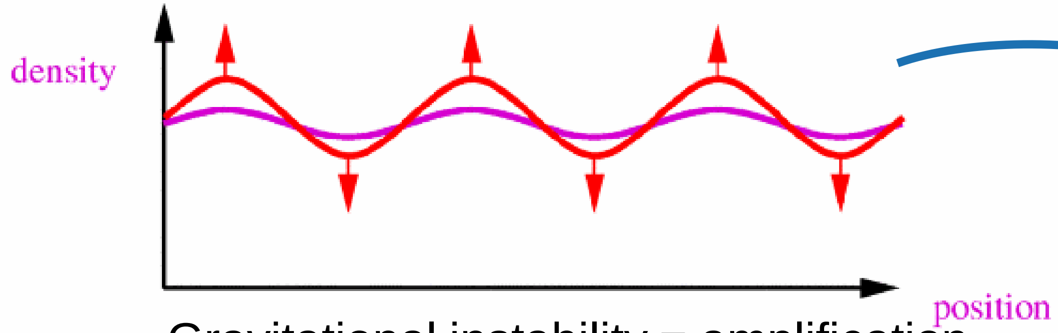
DM relaxes → halo
Shocked gas

Gas cools through brems and recombination radiation

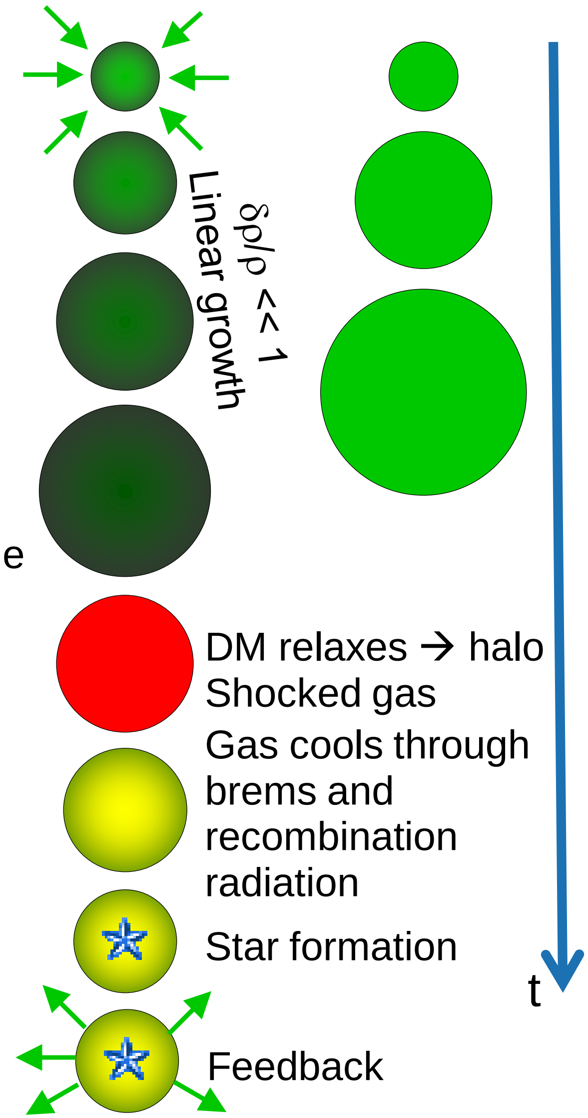
Star formation

Feedback

# 5.7 Feedback



Gravitational instability = amplification of initial density perturbations



Increased density region

Average density region

Linear growth

$\delta\rho/\rho << 1$

$\delta\rho/\rho \approx 1$ → Collapse = decoupling from Hubble expansion

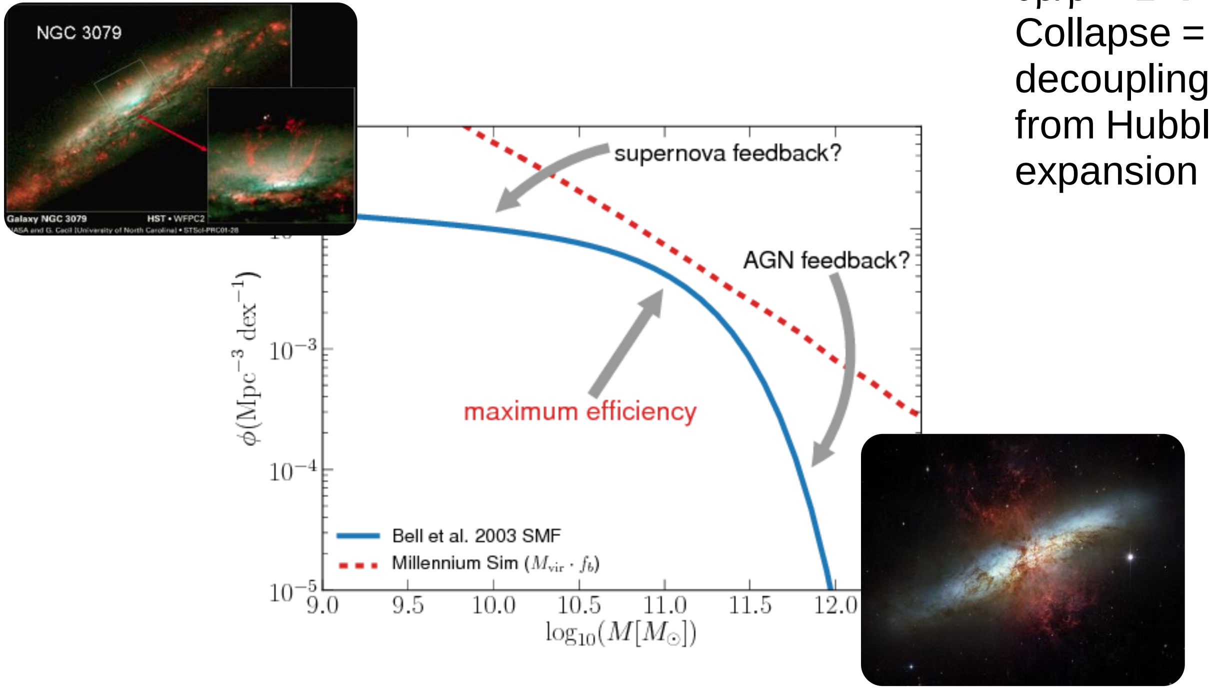
DM relaxes → halo
Shocked gas

Gas cools through brems and recombination radiation

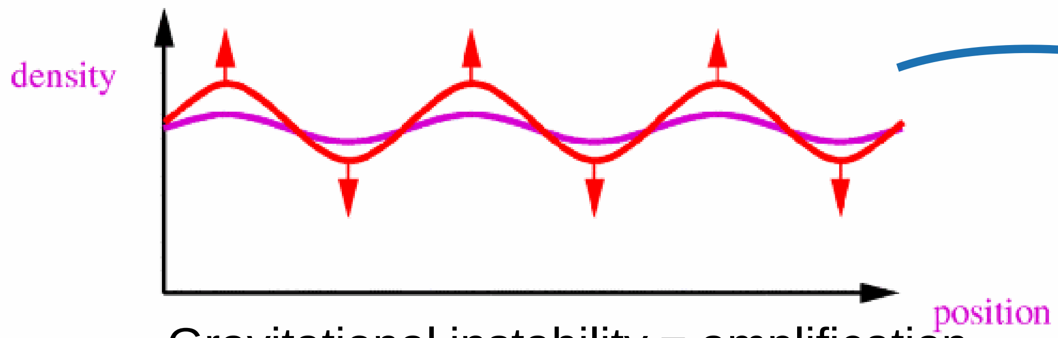
Star formation

Feedback

t

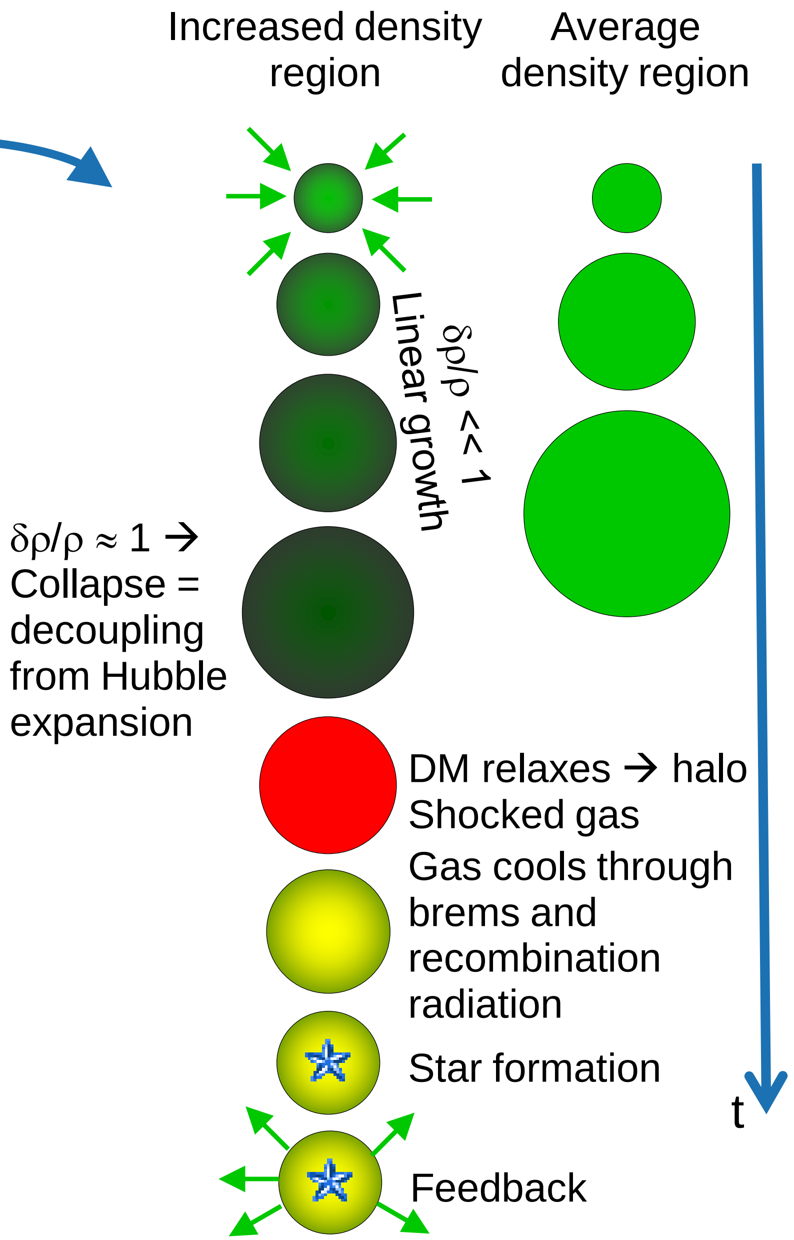


# 5.7 Feedback



Gravitational instability = amplification of initial density perturbations

- To prevent all of the gas from forming stars, the gas needs to be stopped from cooling, reheated or expelled.
- Feedback from:
  - AGN (high-mass)
  - Supernovae (low-mass)
- Details poorly understood



Increased density region

Average density region

Linear growth

$\delta\rho/\rho << 1$

$\delta\rho/\rho \approx 1$ →
Collapse =
decoupling
from Hubble
expansion

DM relaxes → halo
Shocked gas

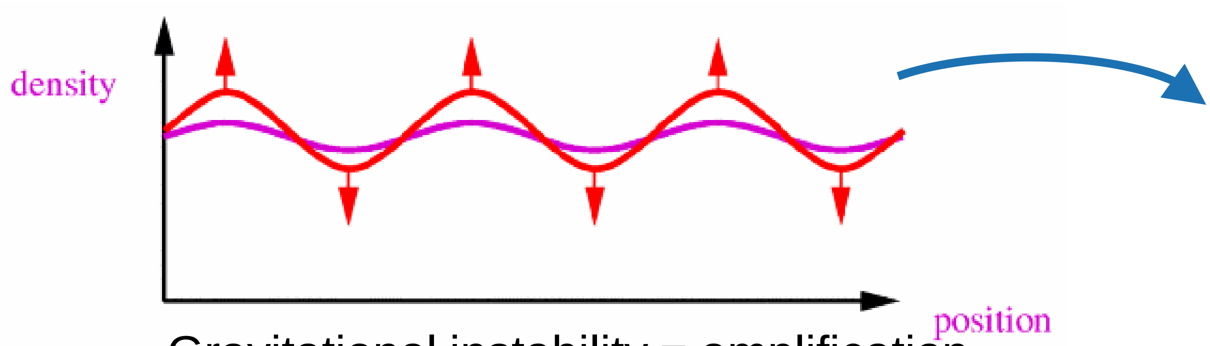
Gas cools through
brems and
recombination
radiation

Star formation

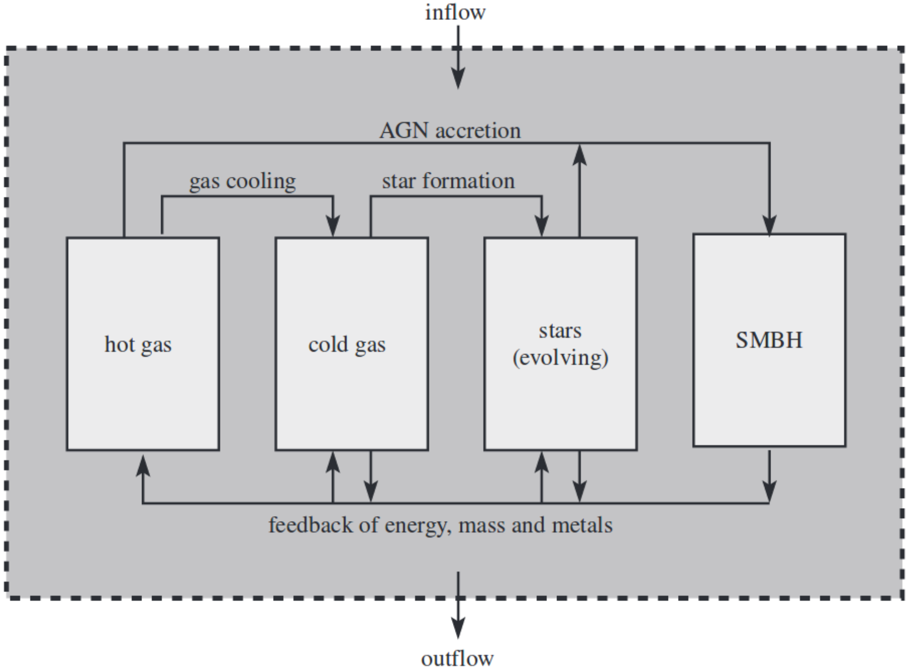
Feedback

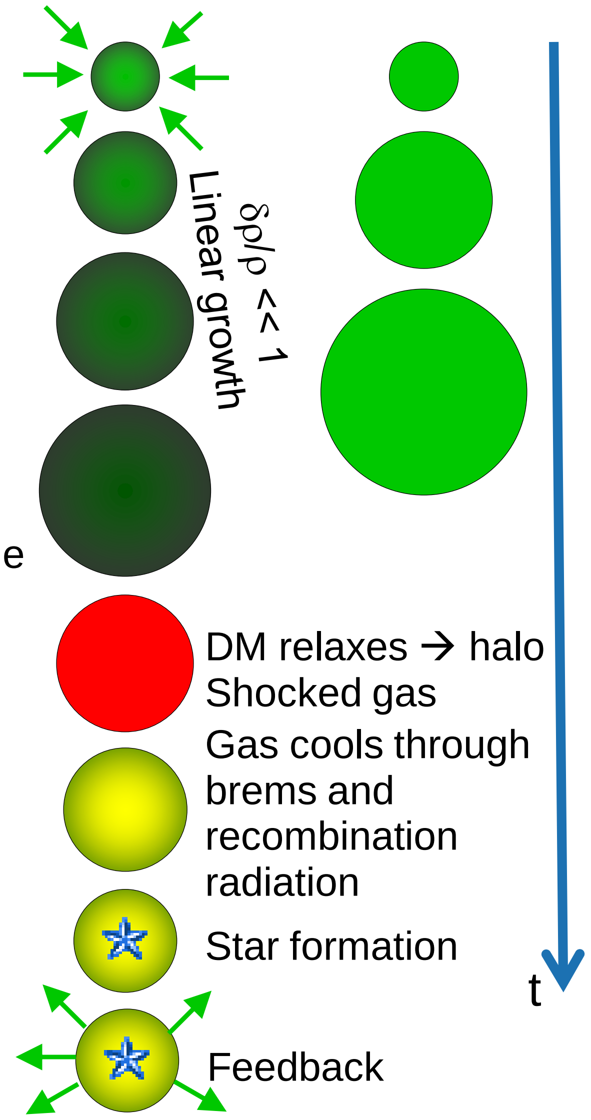
t

# 5.7 Feedback



Gravitational instability = amplification of initial density perturbations





Increased density region

Average density region

Linear growth

$\delta\rho/\rho \ll 1$

$\delta\rho/\rho \approx 1$ → Collapse = decoupling from Hubble expansion

DM relaxes → halo
Shocked gas

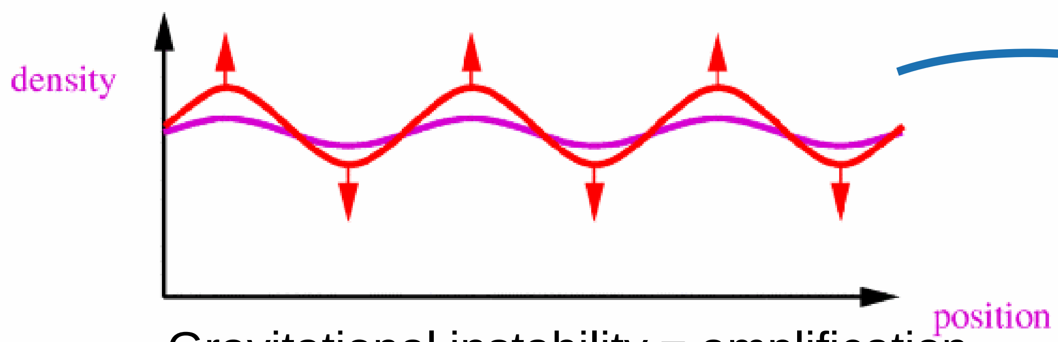
Gas cools through brems and recombination radiation

Star formation

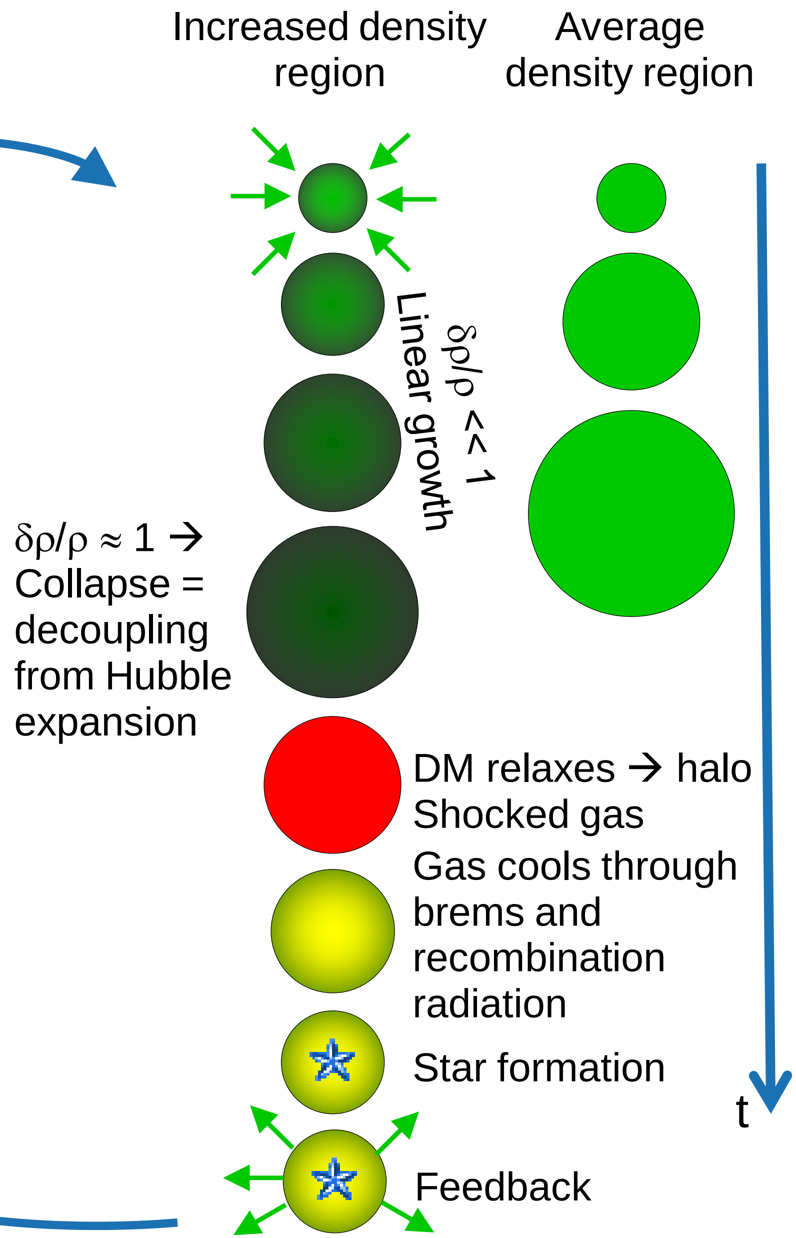
Feedback

t

# 5.8 Mergers



Gravitational instability = amplification of initial density perturbations



Increased density region

Average density region

$\delta\rho/\rho \ll 1$ Linear growth

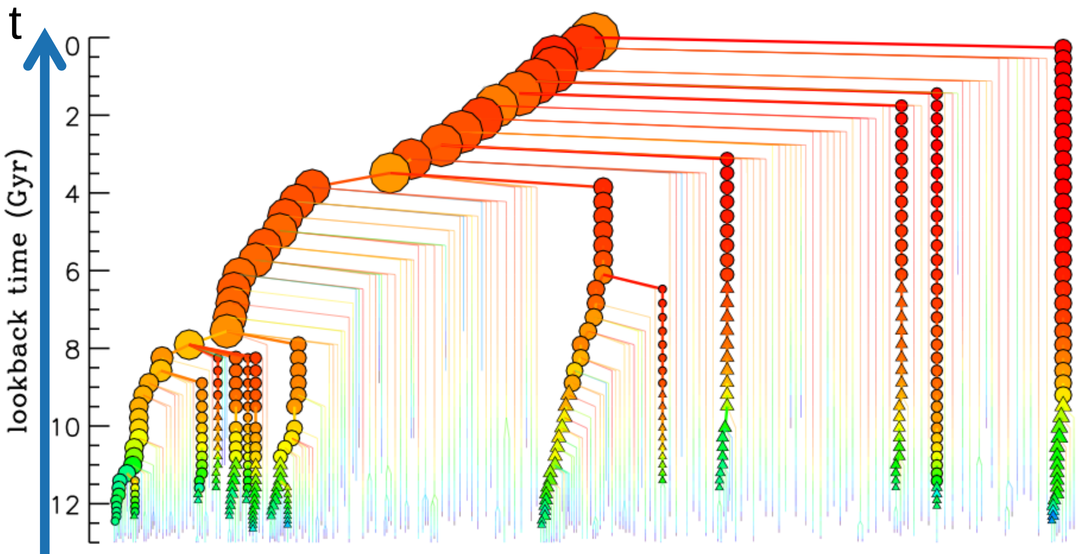
$\delta\rho/\rho \approx 1$ → Collapse = decoupling from Hubble expansion

DM relaxes → halo
Shocked gas

Gas cools through brems and recombination radiation

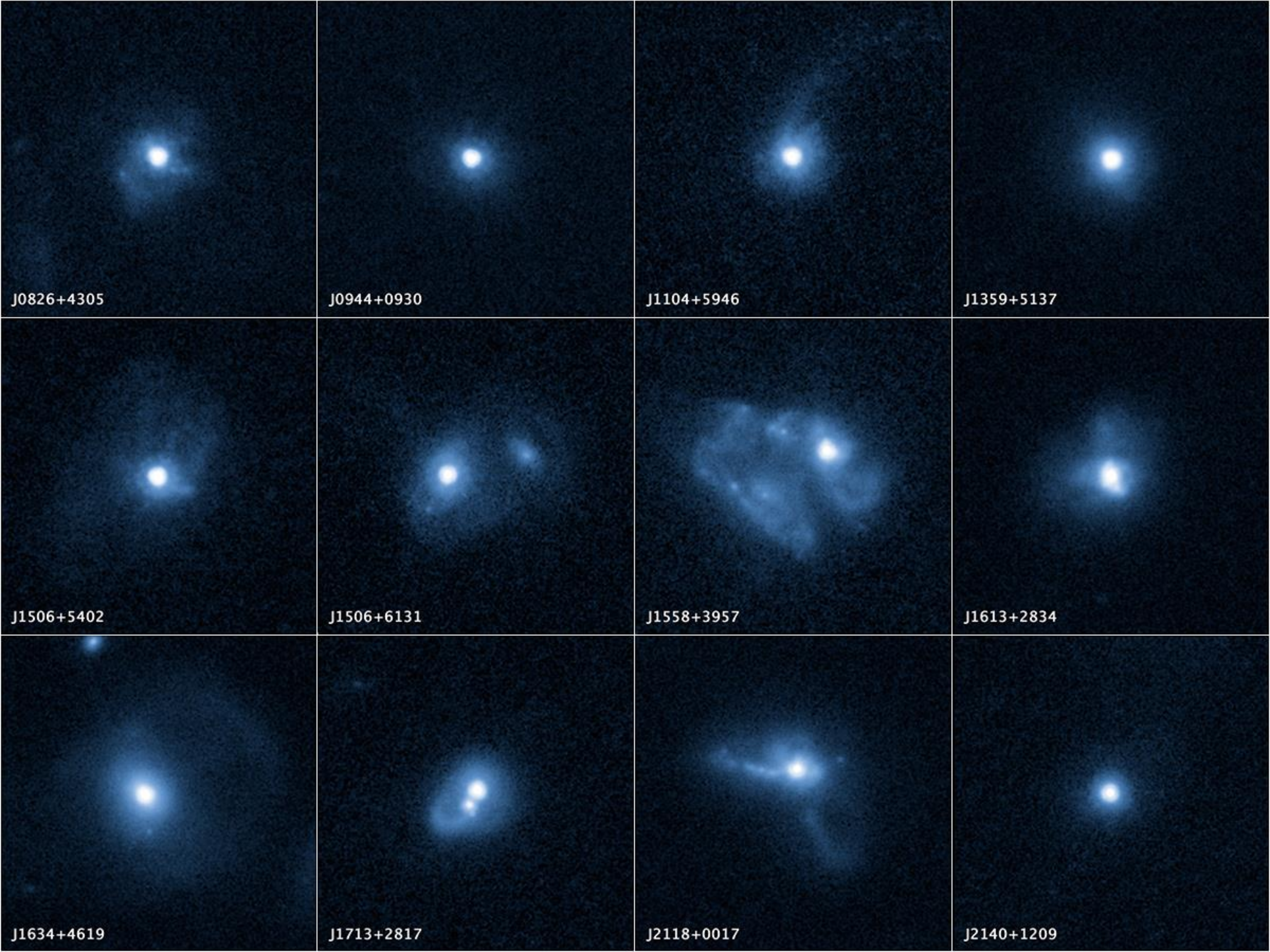
Star formation

Feedback



Hierarchical growth

# 5.8 Mergers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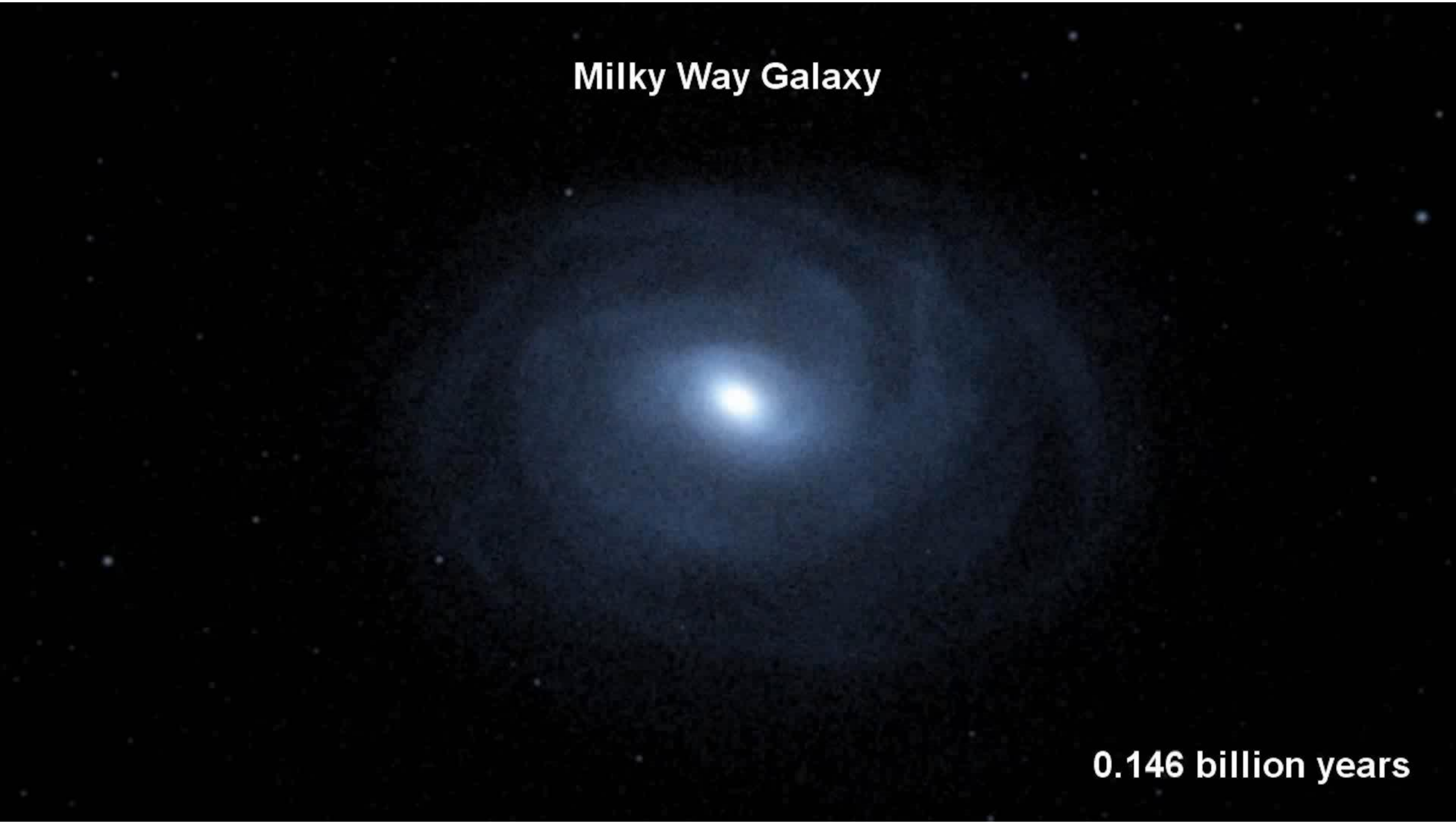
J2118+0017
J2140+1209

# 5.8 Mergers

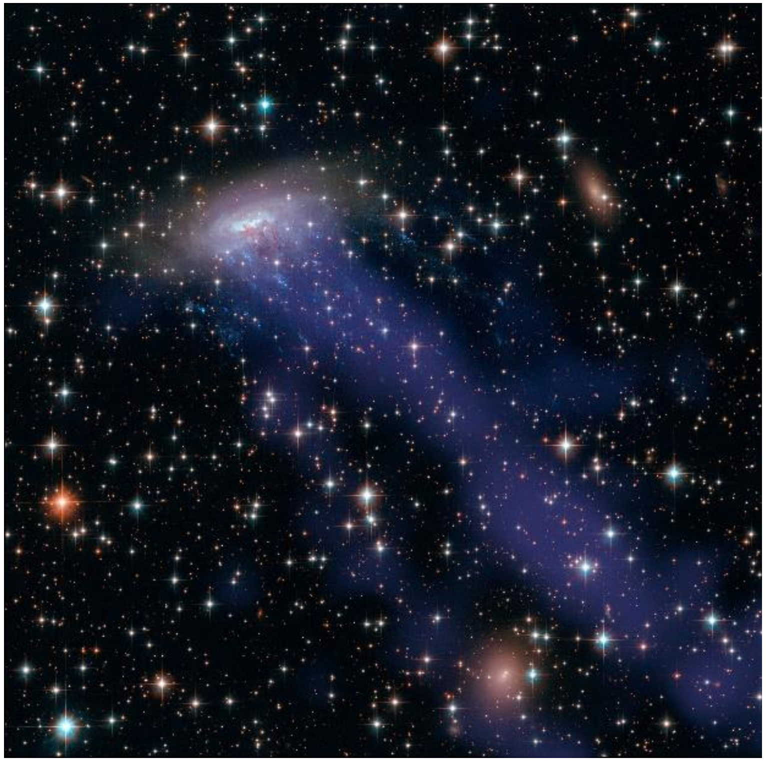


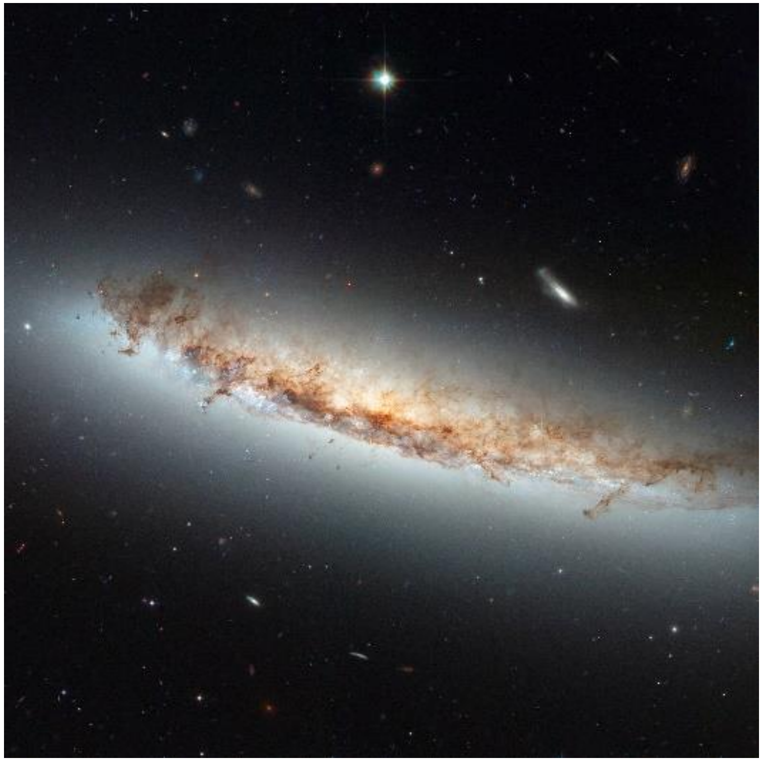
# 5.9 Dynamical evolution

- Tidal stripping
  Tidal interactions with other galaxies can remove stars, gas and DM, and perturb the structure:

# 5.9 Dynamical evolution

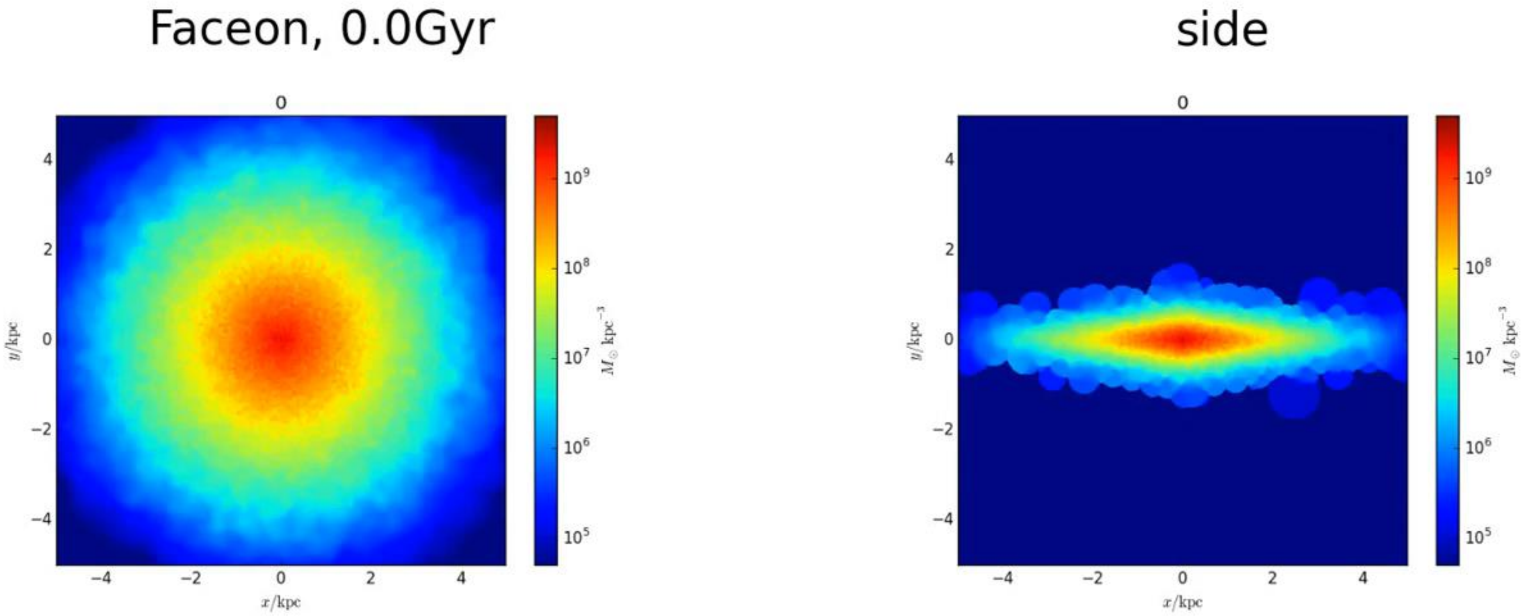
- Tidal stripping
- Ram-pressure stripping
  Movement of a satellite galaxy through the hot halo gas of another galaxy causes a drag to be exerted on the ISM of the satellite → ablation of gas and dust:





# 5.9 Dynamical evolution

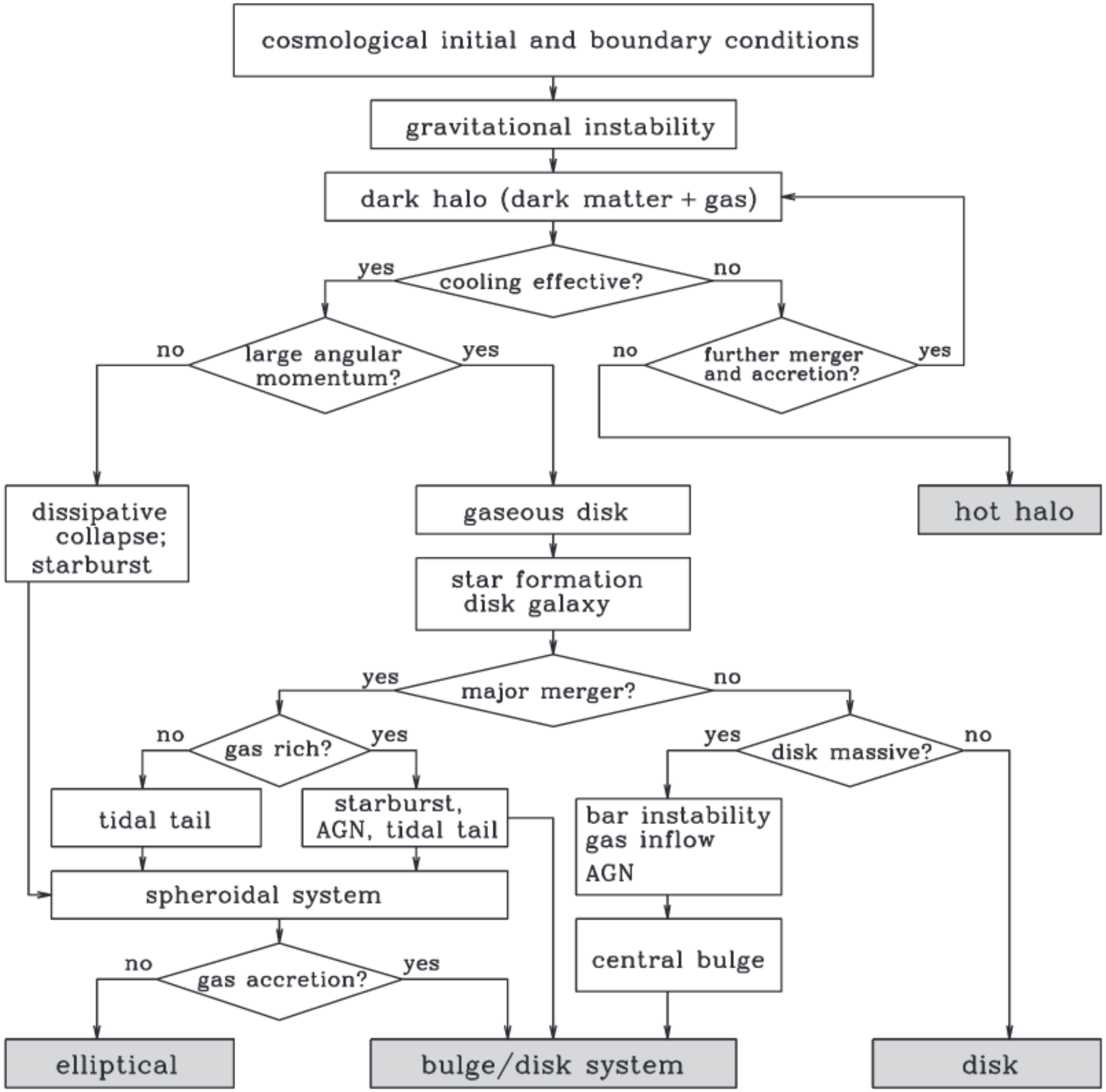
- Tidal stripping
- Ram-pressure stripping
- Internal dynamical effects ("secular evolution")
  - Changes of structure and morphology due to large-scale redistributions of mass and angular momentum
  - Especially in galaxy disks (disk instability)
  - Bars
  - Pseudo-bulges



# 5.10 Chemical evolution

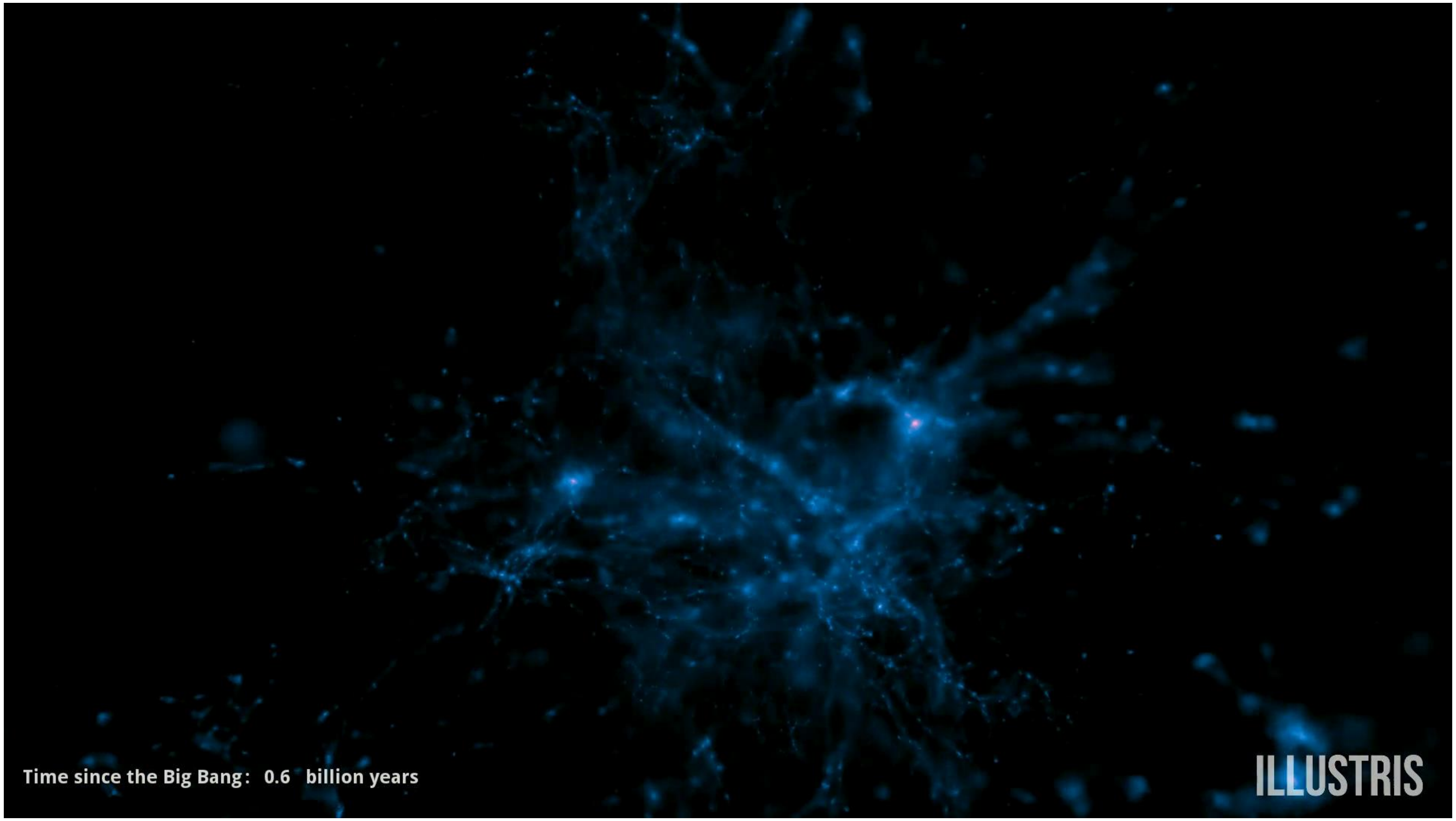
- Stars produce heavy elements through nuclear fusion
- These are returned to the ISM by stellar winds or supernovae
- The metallicity of the ISM and of newly formed stars changes over time
- Changes the luminosities and colours of newly formed stars
- Changes the cooling efficiency of the gas
- Changes the abundance of dust
- Evolution is made more complicated by:
    - Infall of “fresh” gas
    - Blow-out of gas by feedback processes
    - Mergers

# 5. Basic elements of galaxy formation



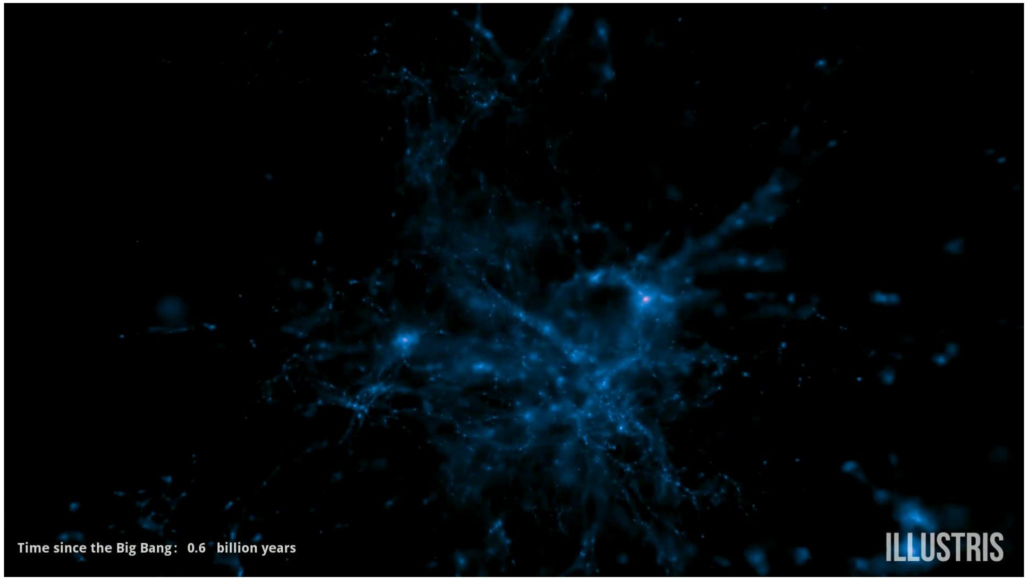
# Putting it all together: numerical models

- Simultaneous simulation of DM and gas hydrodynamics + “recipes” for “sub-grid physics”: cooling, photo-ionisation, star formation and evolution, feedback



# Putting it all together: numerical models

- Constrain sub-grid physics with selected set of observations
- “Predict” everything else
- Compare to observations
- Identify discrepancies
- Find and understand the reasons for the discrepancies
- Fix the model without breaking existing successes



# 6. Outstanding issues

This topic merits entire conferences and books…

My personal list:

- Star formation efficiency and the nature of feedback as a function of halo mass
- Fuelling and cessation of star formation
- Roles of galaxy interactions and mergers versus in-situ processes
- Relative prevalence of disks and spheroids
- Mass-size relations of disks and spheroids
- Downsizing
- Co-evolution of central SMBH and their host galaxies
- ...