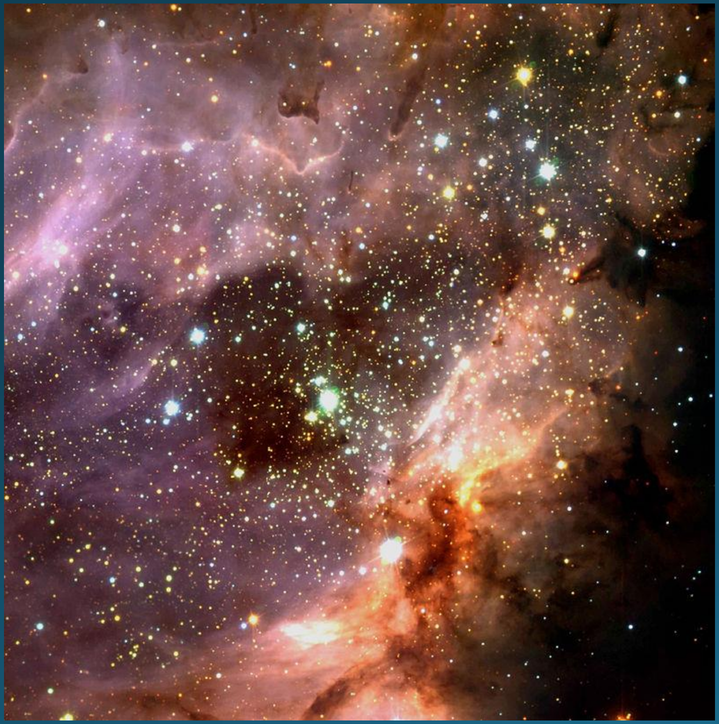
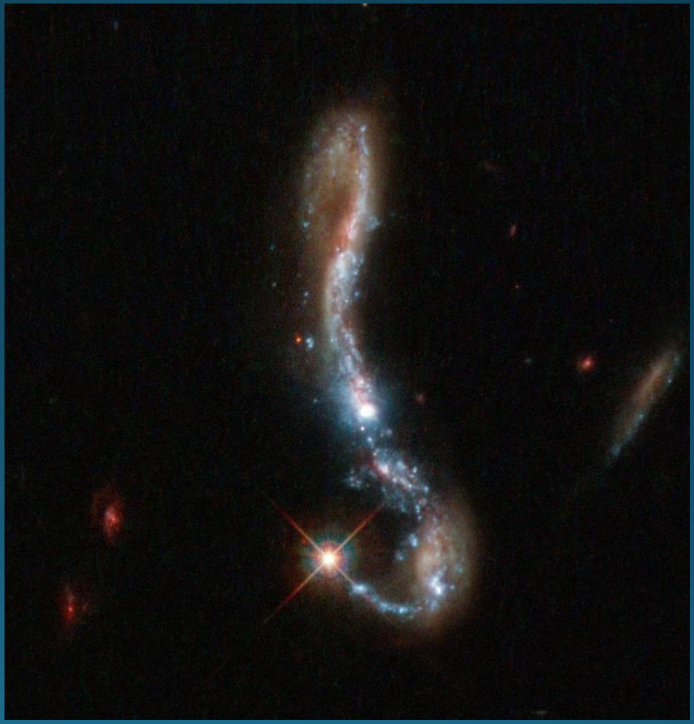
Physics of Galaxies 2018
Lecture 5: Star formation & Galaxy spectra

Outline

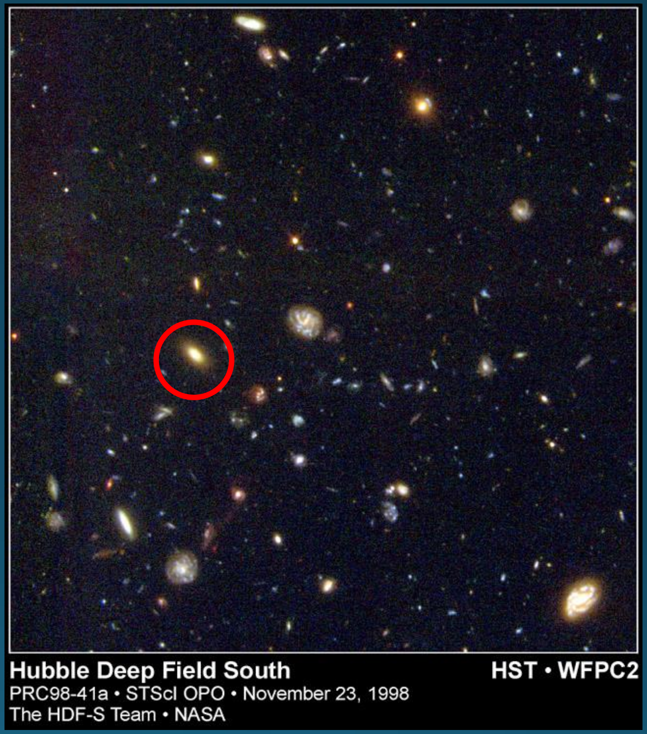
- Understanding galaxy spectra
- Star formation
- Cosmic star formation history
- The interstellar medium
- Dwarf galaxies
- Chemical evolution

Stellar Populations: Resolved vs. unresolved

Resolved

- Individual stars can be analyzed
- Applicable for Milky Way star clusters and the most nearby galaxies

Unresolved



- Integrated spectroscopy / photometry only
- The most common case in extragalactic astronomy

Stellar Evolution

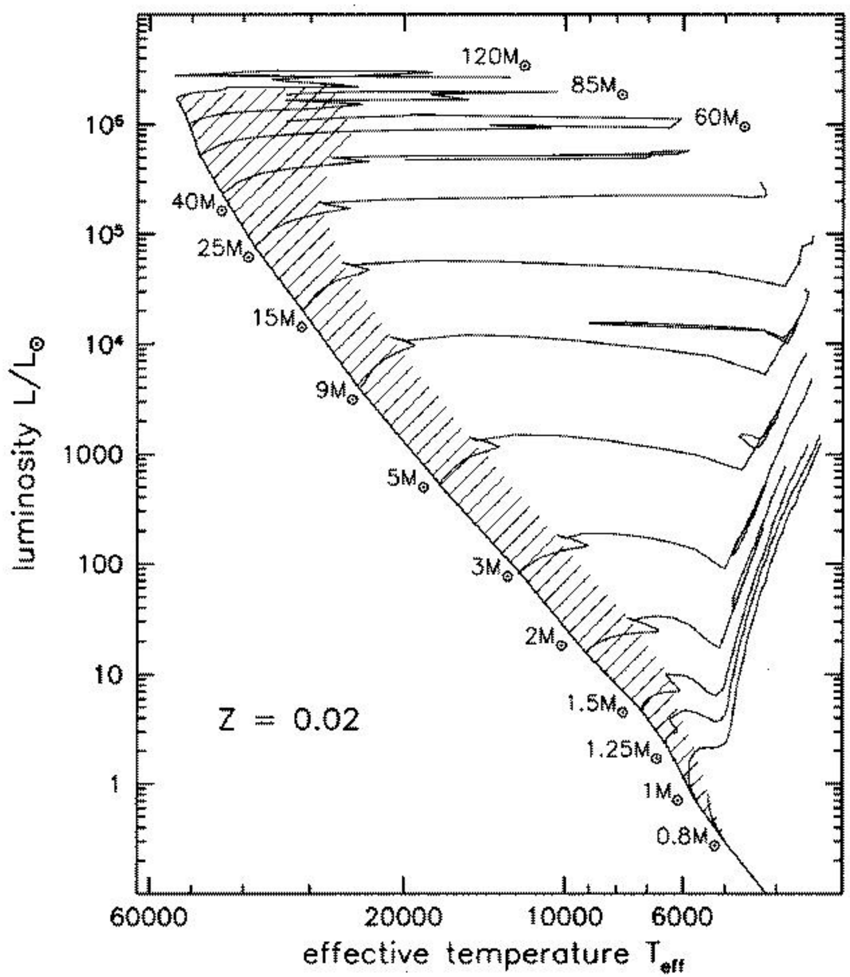
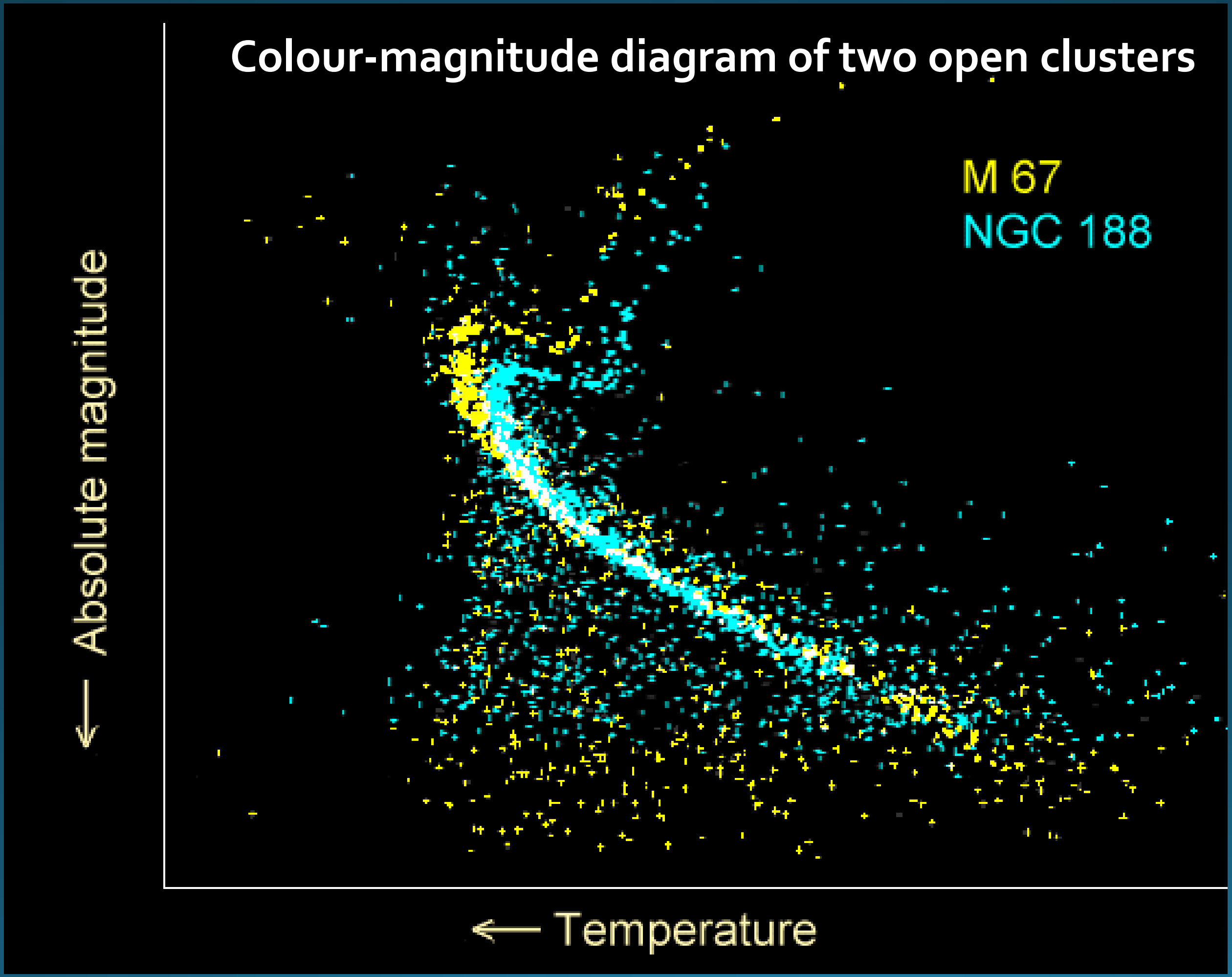
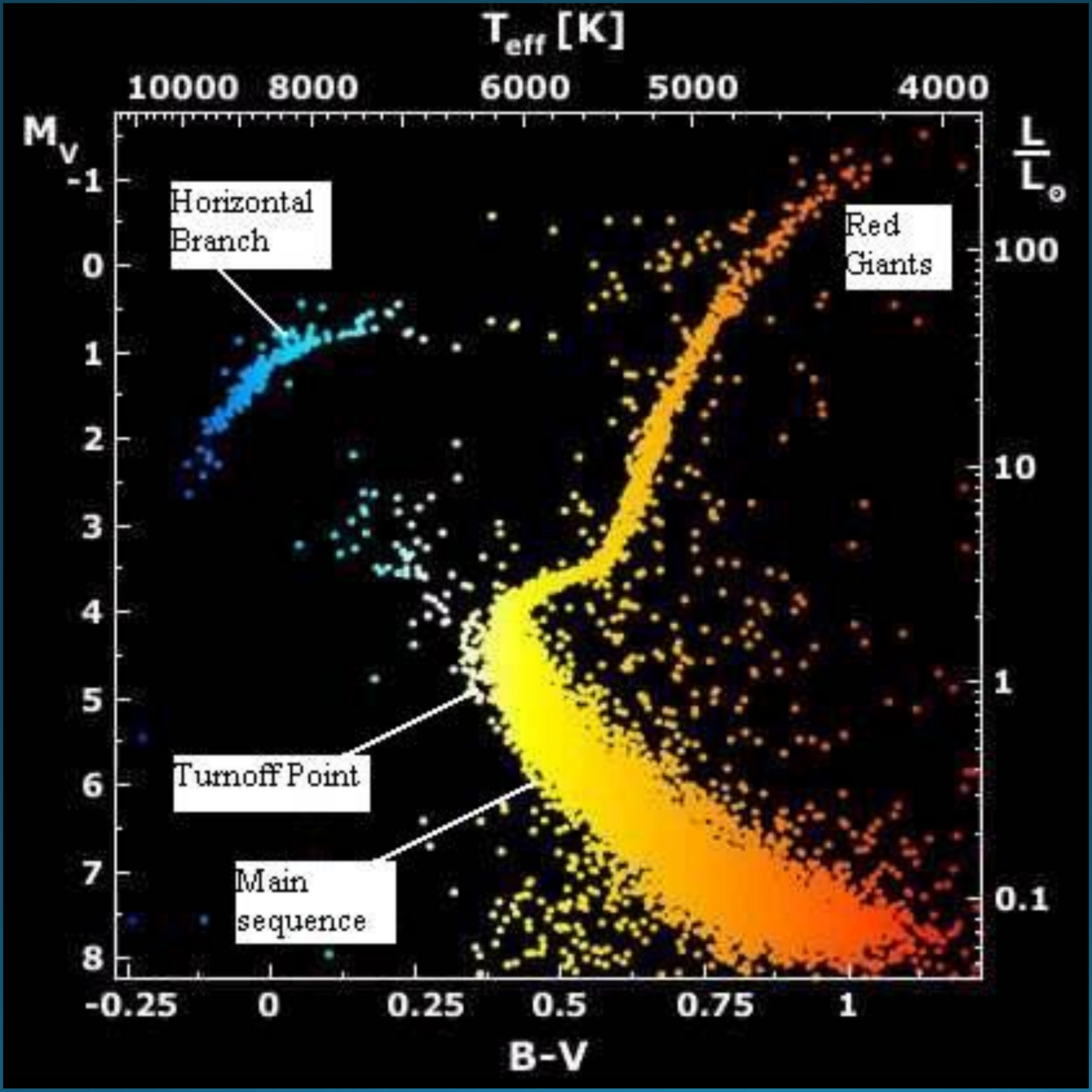


Figure 1.4 Luminosity and effective temperature during the main-sequence and later lives of stars with solar composition: hatched region shows where the star burns hydrogen in its core. Only the main-sequence track is shown for the $0.8\mathcal{M}_\odot$ star – Geneva Observatory tracks.

For resolved stellar populations: Colour-magnitude diagram





T_eff [K]
10000
8000
6000
5000
4000
M_V
-1
0
1
2
3
4
5
6
7
8
L/L☉
100
10
1
0.1
Horizontal Branch
Red Giants
Turnoff Point
Main sequence
-0.25
0
0.25
0.5
0.75
1
B-V

Intermission:
What do the colour indicies mean?

Typical optical to near-IR filter sequence:

U B V R I (Y) J H K

Are these colours 'red' or 'blue'?

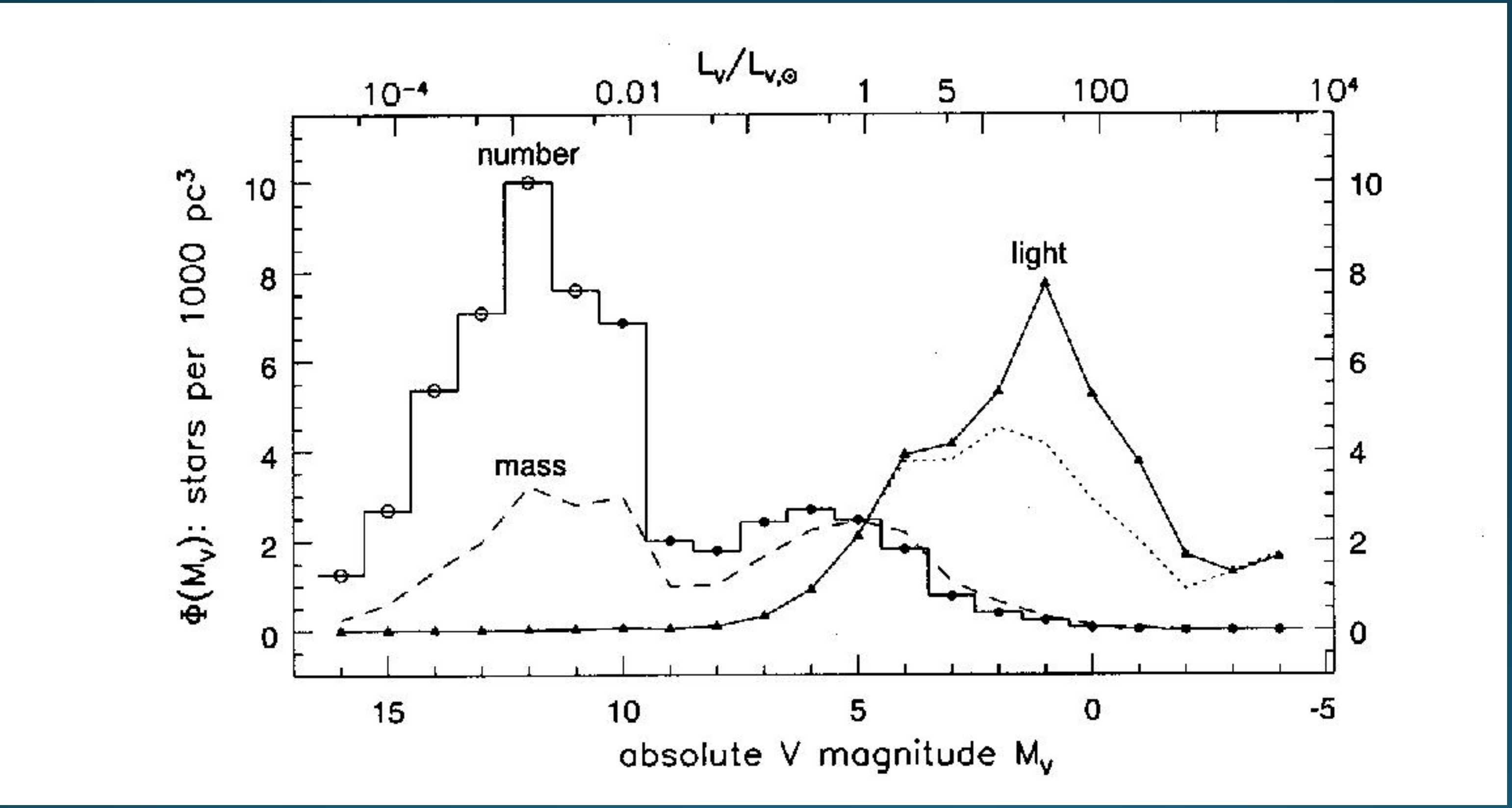
a) B-V = 2.0

b) V-K = -1.0

c) V-U = 3.0

d) R-I = 0.0

The Stellar Luminosity Function



Quantifies the luminosity distribution of stars in a stellar population – i.e. stars per luminosity bin within. a star cluster, a galaxy or a subcomponent of a galaxy (e.g. the disk)

The Stellar Initial Mass Function (IMF)

If you know the lifetimes of stars of different masses, you can use the the observed stellar luminosity function to say something about the IMF. The IMF is often expressed in power-law form:

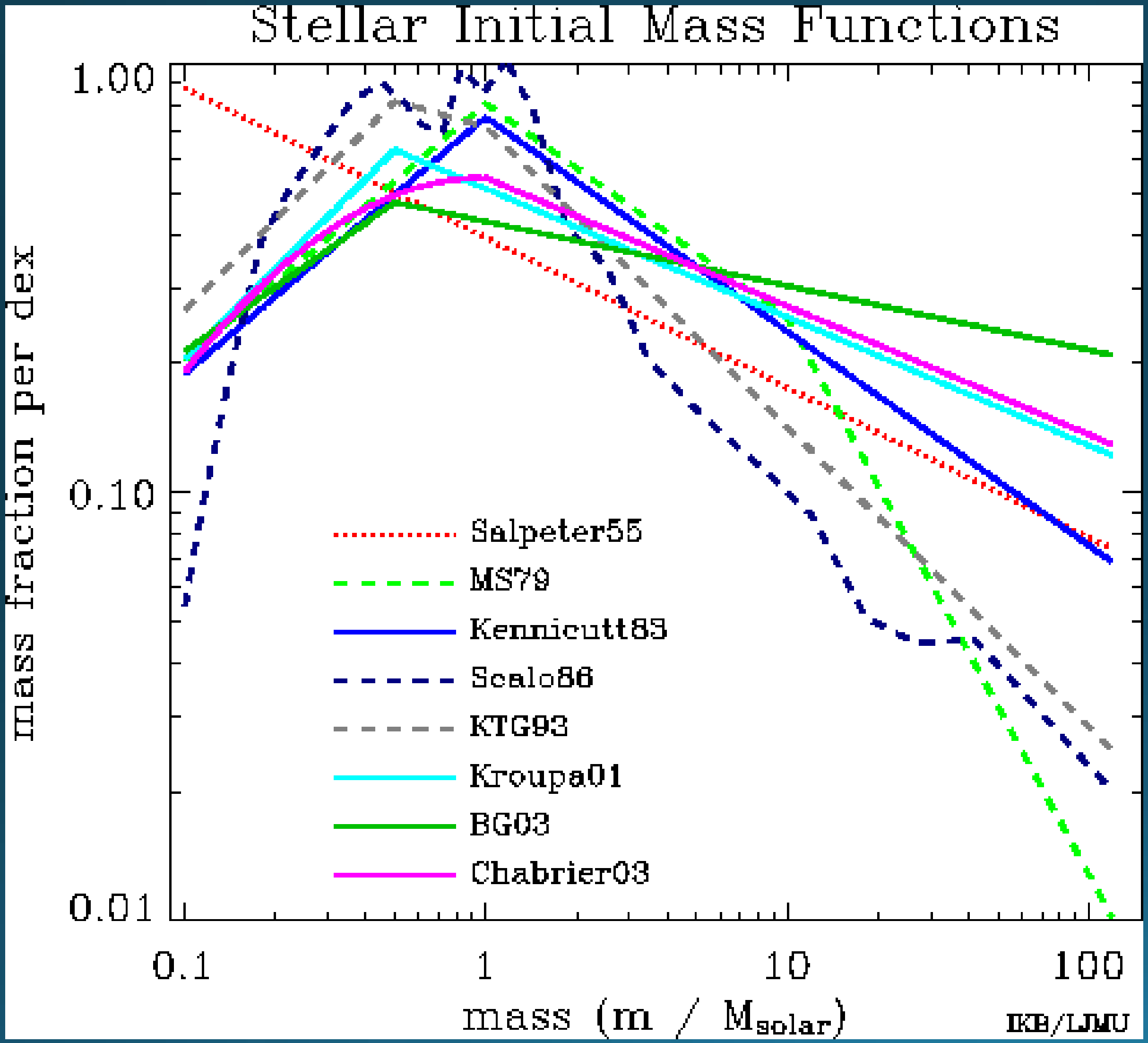
$$dN \propto M^{-\alpha} dM$$

d*N* is the number of stars per mass interval d*M*.

$\alpha = 2.35$ represents the slope of the Salpeter (1955) IMF.

This "classical" IMF is usually assumed to be a reasonable fit to stars of mass M>0.5-1.0 $M_{\odot}$ in the local Universe.

The Stellar Initial Mass Function (IMF) II

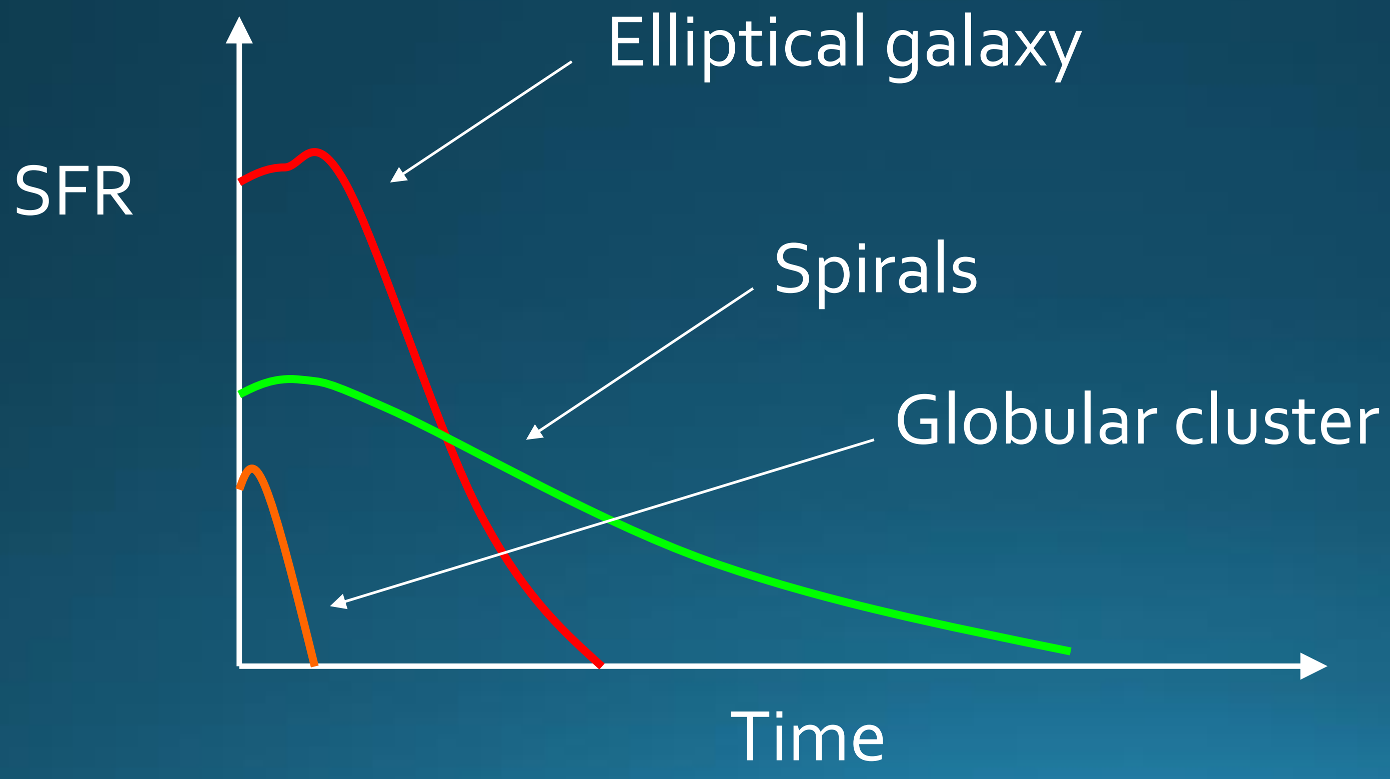


Mass range of stars:
≈ 0.08-120 $M_\odot$

Popular choices for the local IMF: Kroupa (2001) and Chabrier (2003) – both predict far fewer $M<1\ M_\odot$ stars than the Salpeter IMF

Star Formation Rate (SFR)

- SFR: M_{solar}/yr
- Star formation history: SFR(t)

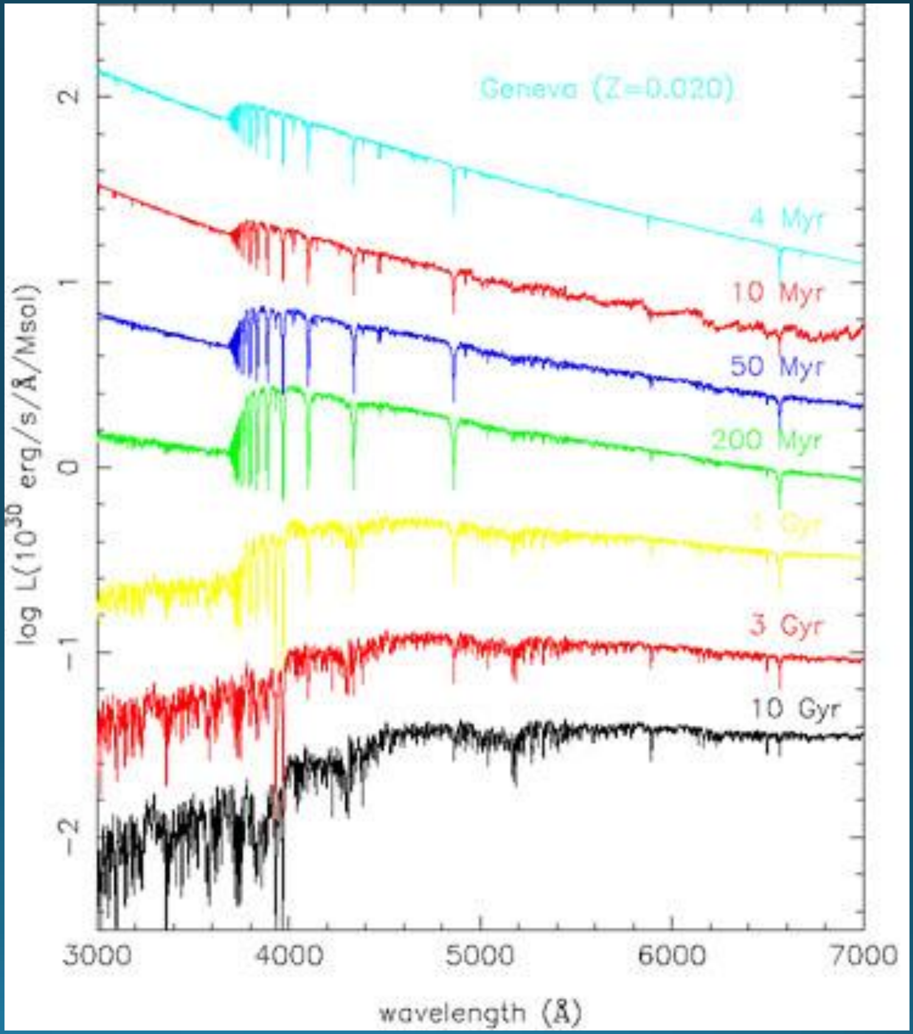


Spectral synthesis: Putting it all together

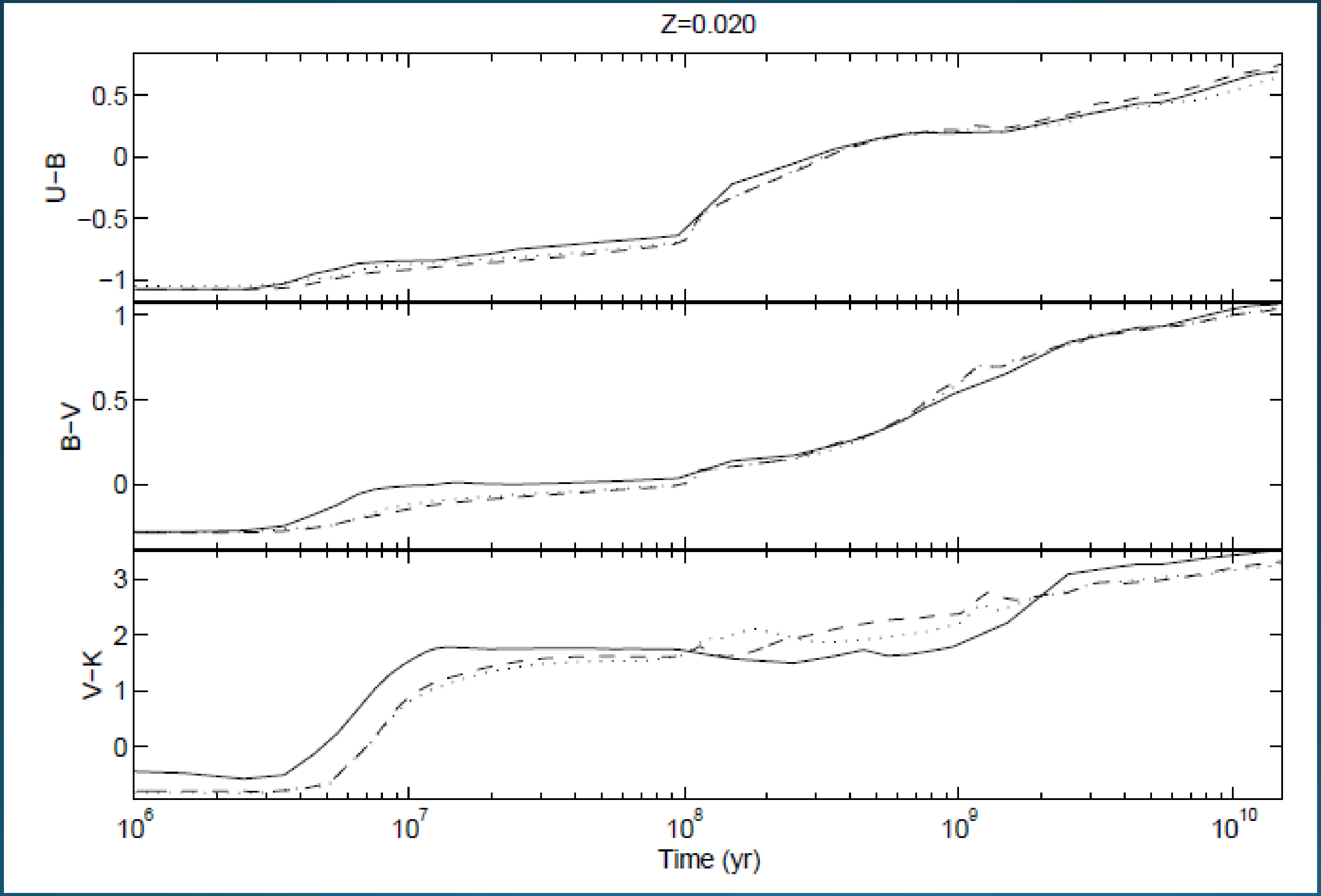
- Models for stellar evolution as a function of mass
- Assumption on IMF
- Assumption on star formation history

⇒Stellar population spectra as function of age and metallicity

There are many models of this type - some also predict nebular emission and dust effects

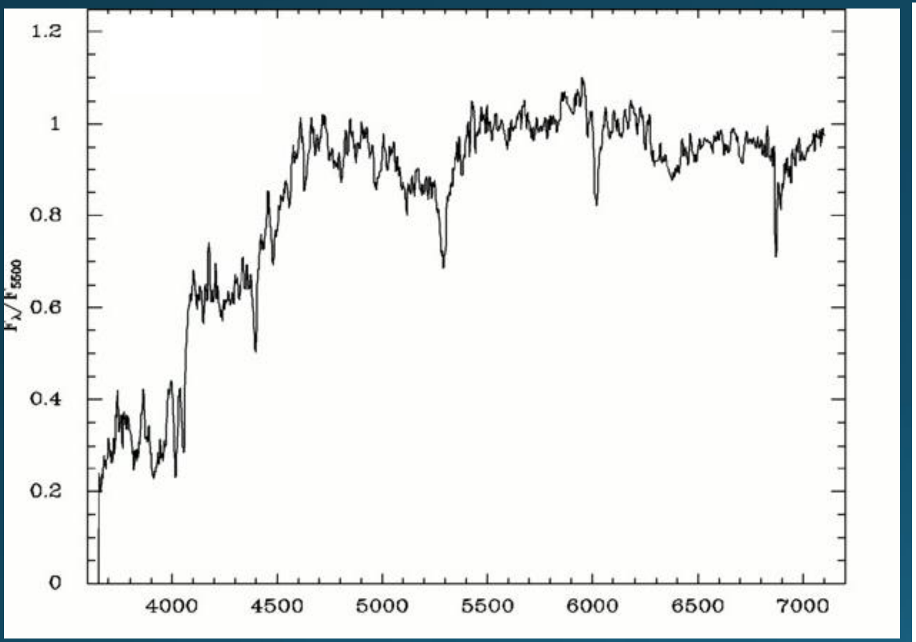


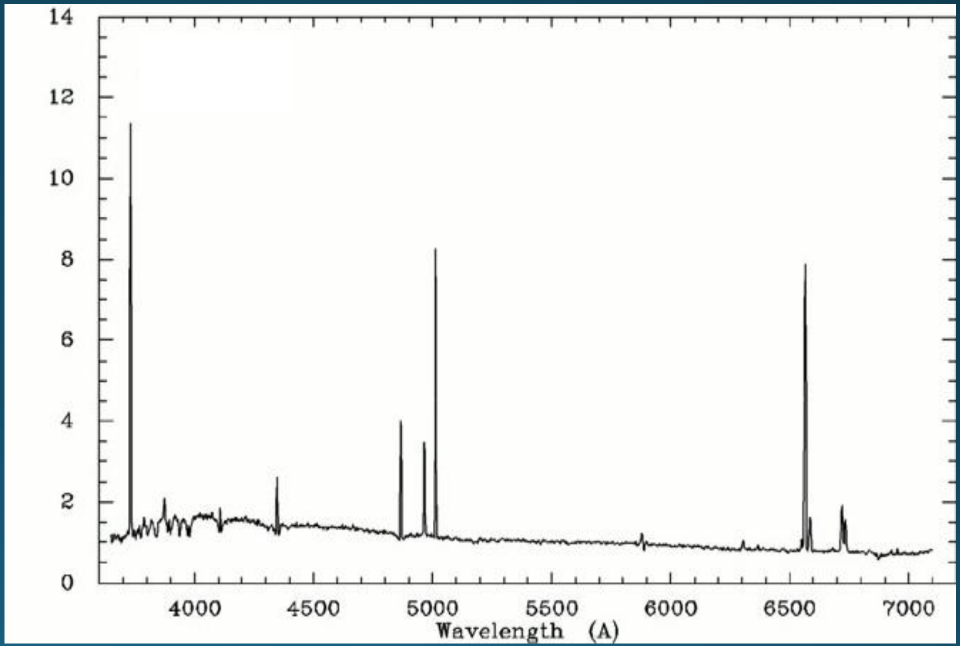
Spectral synthesis II



Example of model prediction: Colours as a function of age

Intermission: What do these galaxy spectra tell you?

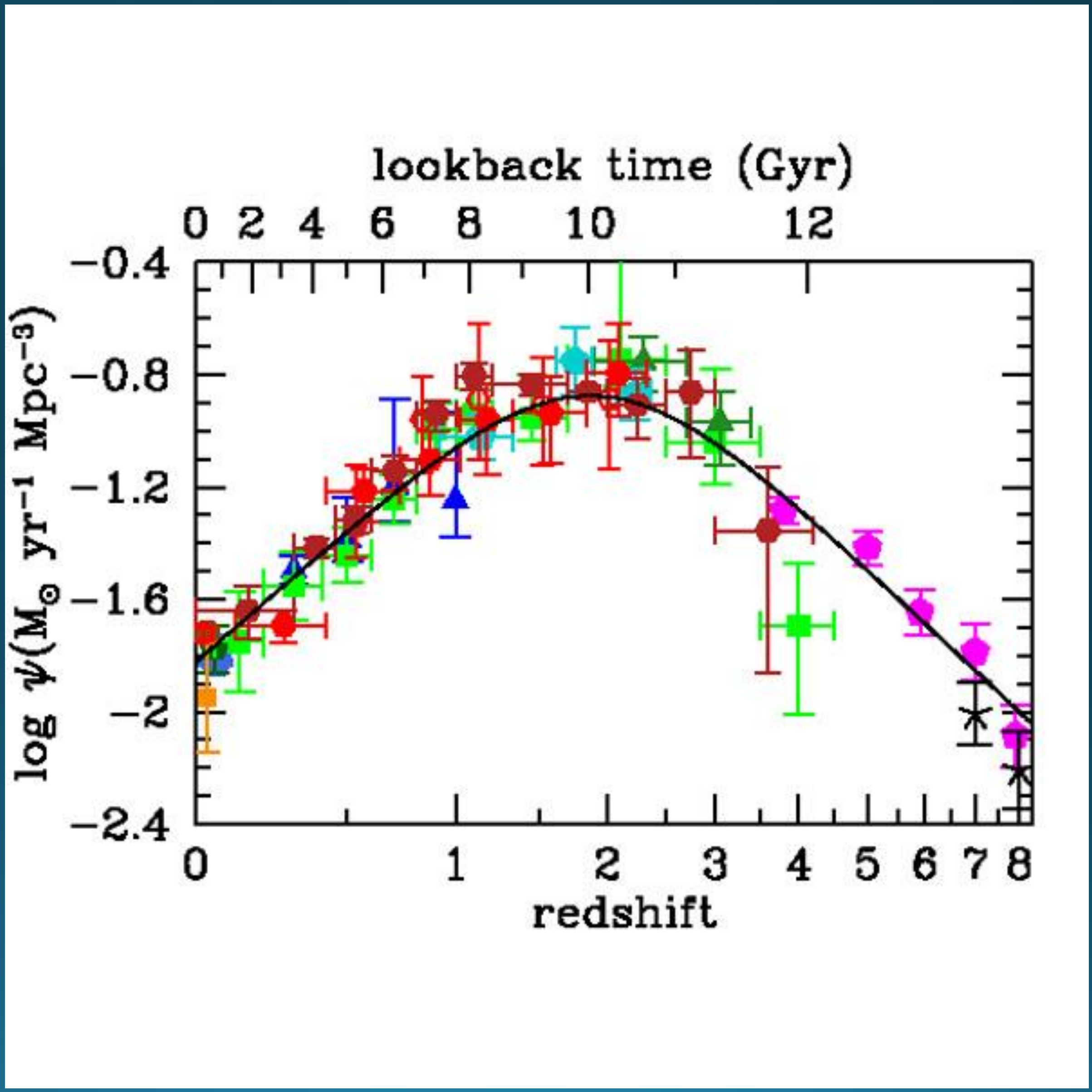




Star formation

Cosmic star formation history

Star formation rate (SFR) per comoving volume



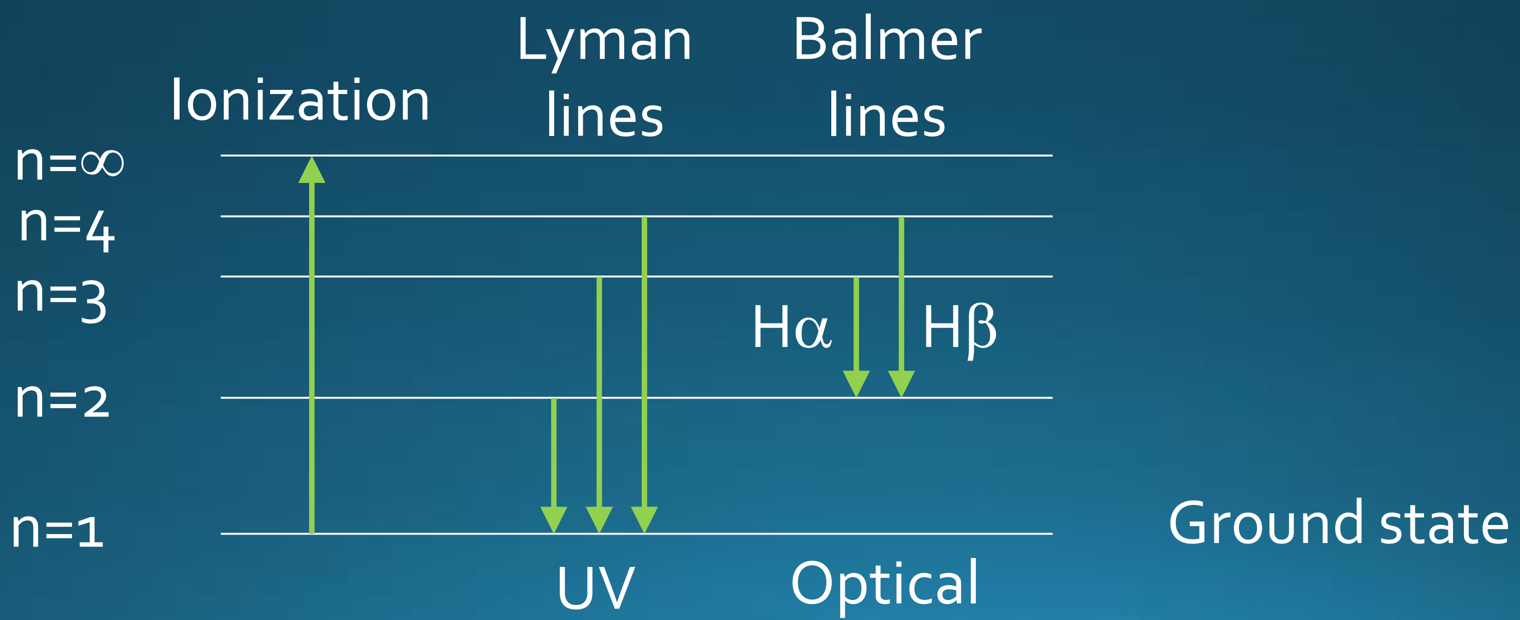
The cosmic SFR has dropped since z≈2, i.e. for about 10 Gyr

Indications of star formation I

- Recombination emission lines
- UV continuum
- IR thermal emission
- Radio continuum emission
- CO from molecular clouds

Recombination emission lines

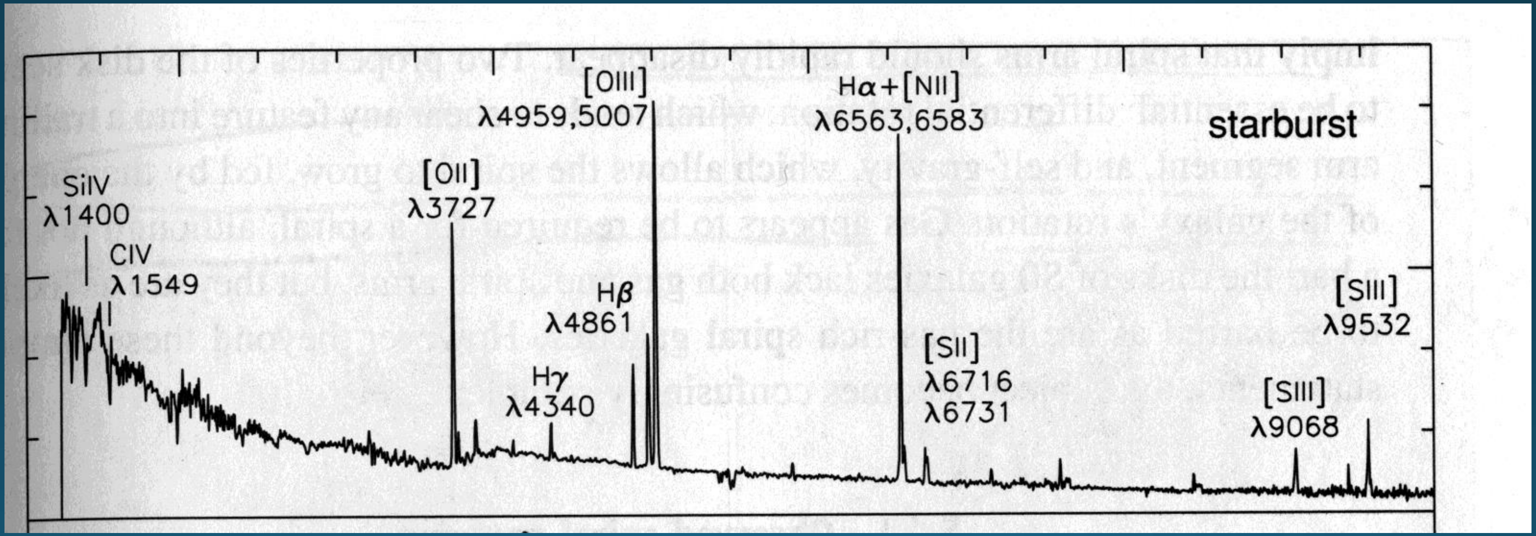
- Radiation with λ< 912 Å (Lyman continuum) from hot stars ionize hydrogen
- When proton and electron recombine → cascade towards ground state → Recombination emission lines



Recombination emission lines

- In star-forming regions, Hα & Hβ are very prominent in the optical region
  - Hα: 6563 Å
  - Hβ: 4861 Å

Flux

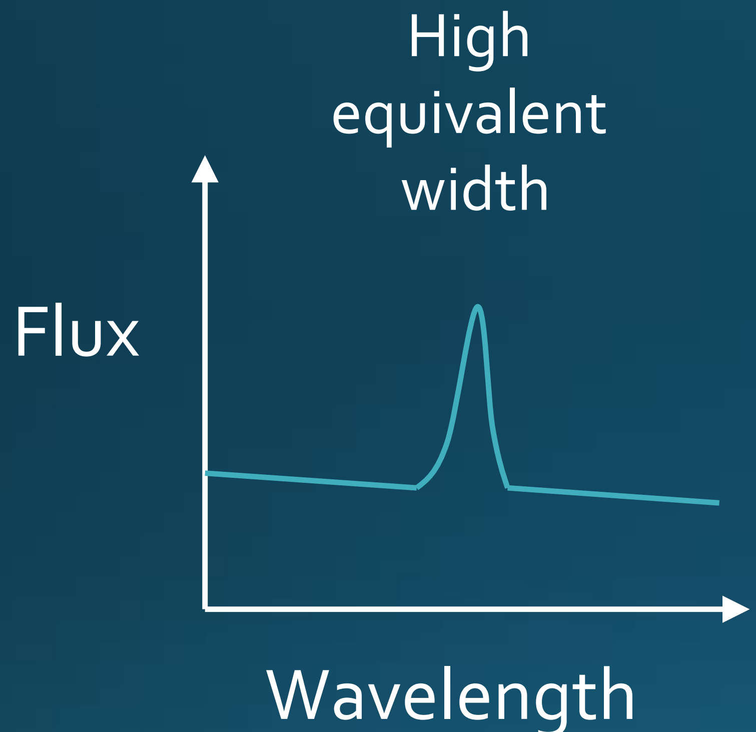


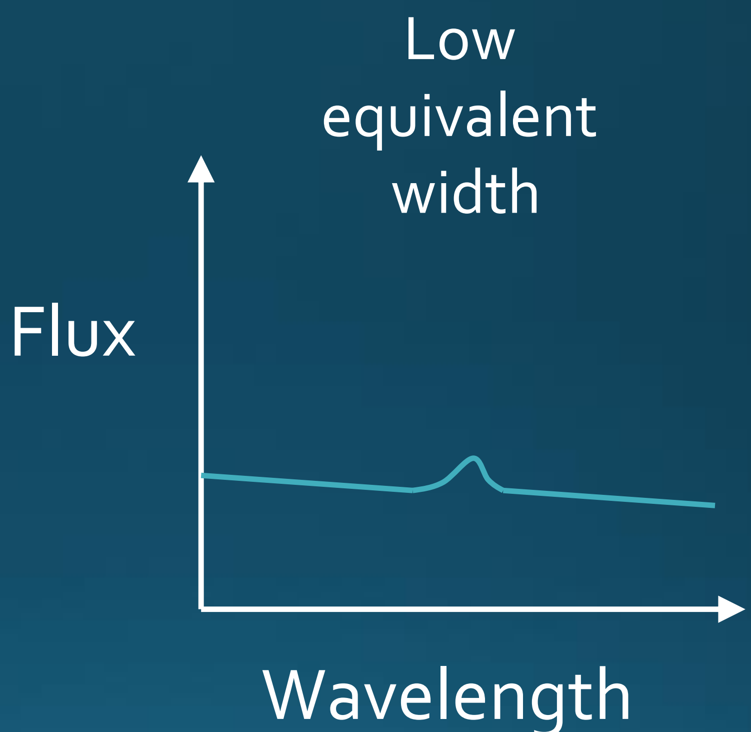
Wavelength

But beware: Other processes (shocks, black hole accretion etc.) can also contribute to emission line fluxes

Emission-line equivalent width

How strong are the lines relative to the continuum?





High equivalent width (EW) in hydrogen recombination lines indicates presence of high-mass stars ($M>10\text{-}20\ M_{\odot}$) with lifetimes < 20 Myr

For instance, high EW(Hα) $\rightarrow$ young or actively star-forming system

Recombination emission lines

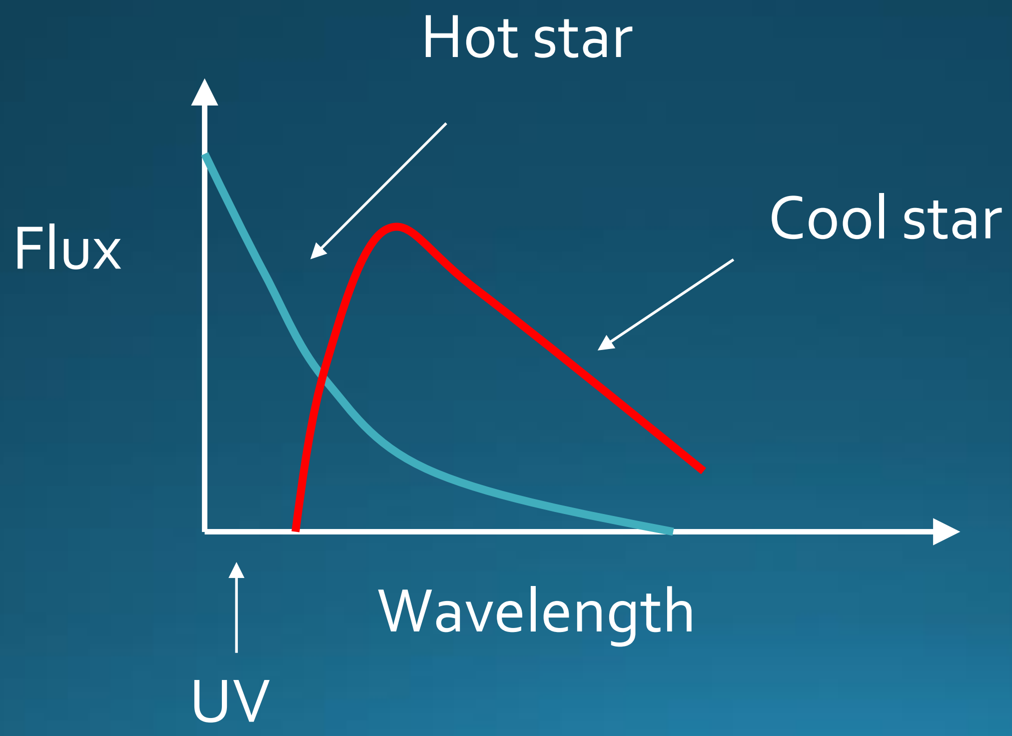
- Hα luminosity can be used to estimate the SFR:

$$SFR(M_{\mathrm{solar}}/\mathrm{yr}) = 7.9 \times 10^{-42} L_{\mathrm{H\alpha}}(\mathrm{erg/s})$$

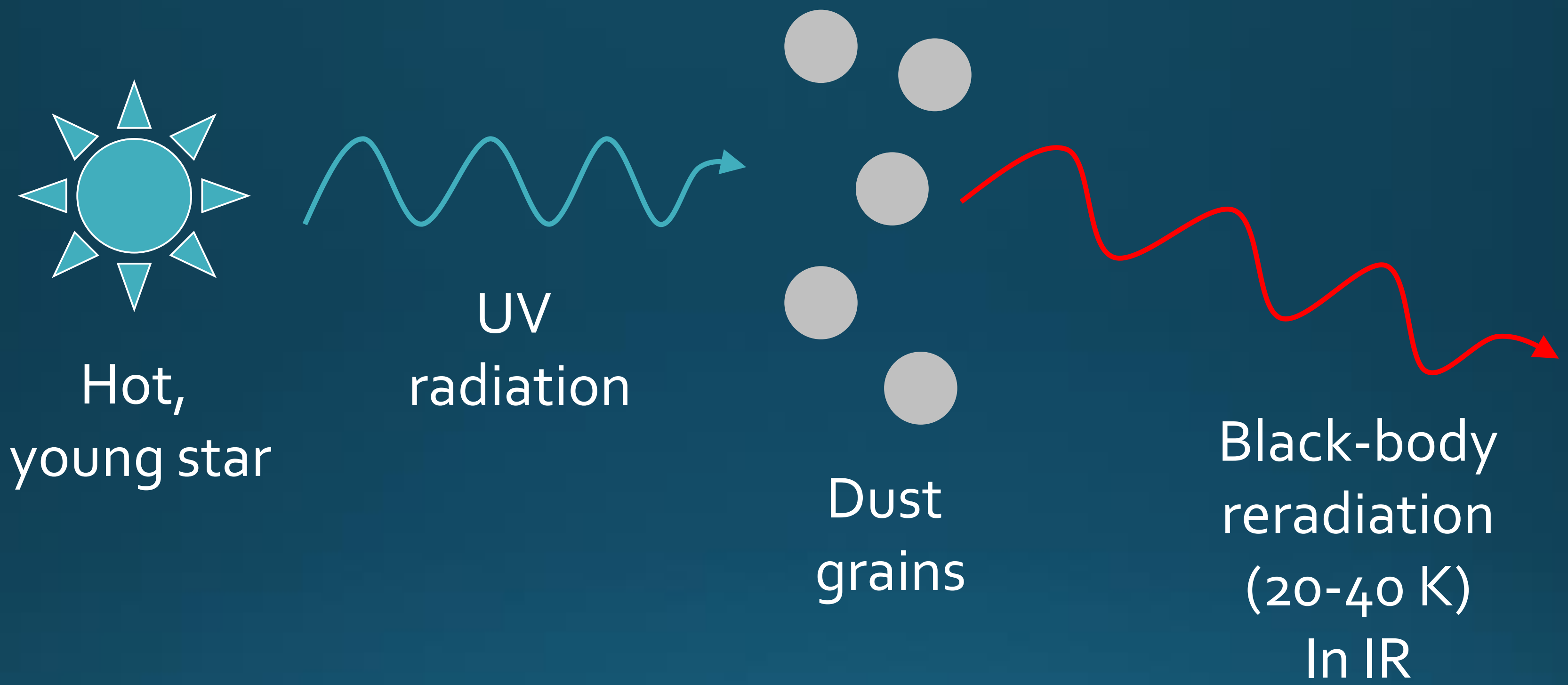
- Measurements of Hα & Hβ luminosities can constrain the amount of dust reddening

UV continuum

- Young, massive stars are hot $\rightarrow$ High UV-luminosity
- L_{UV} can (in analogy with $L_{H\alpha}$) be related to SFR



IR Thermal Continuum



High L_{IR}/L_B indicates high star formation

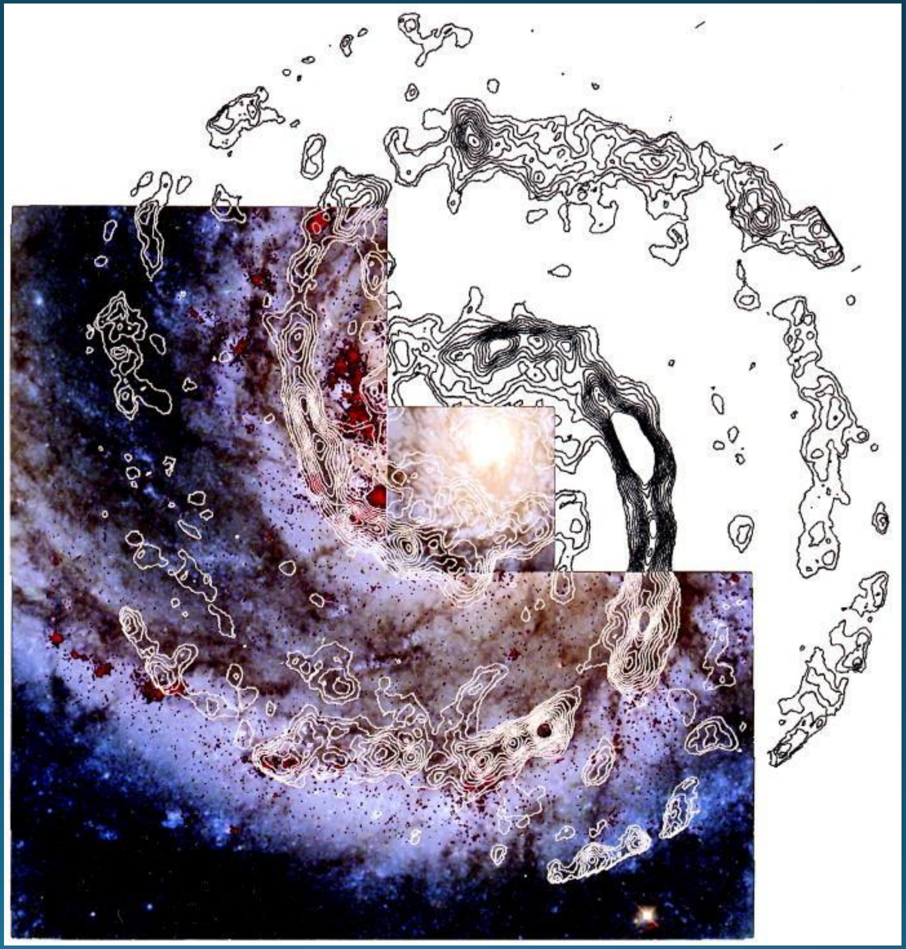
Radio continuum emission

- Star-forming galaxies emit a lot of cm-wavelength radio emission
- Posssible origin: synchrotron radiation from particles accelerated in supernova remnants
- Supernovas trace SFR $\rightarrow$
  cm-wavelength radiation trace SFR

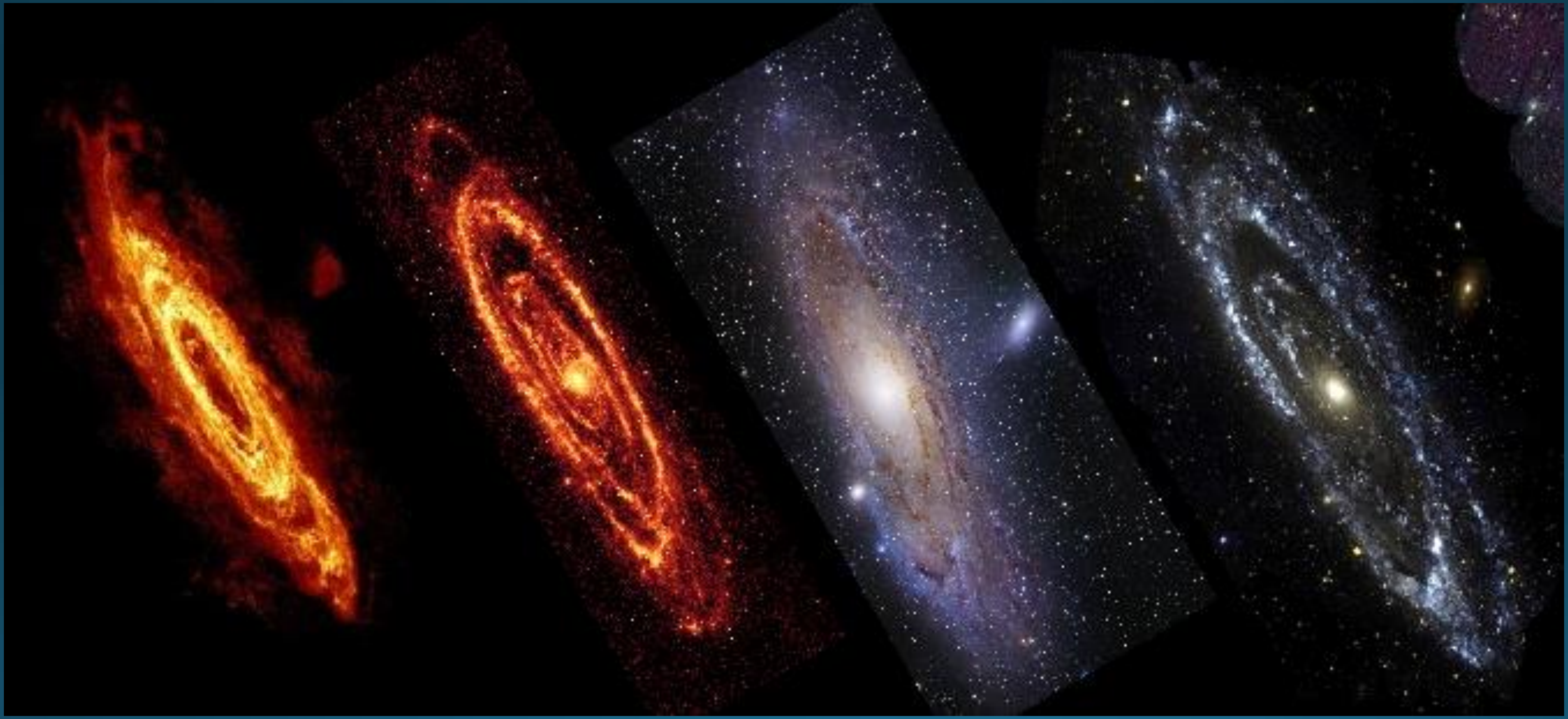
Recall: Dust extinction is not an issue for radio observations

CO from Molecular Clouds

- Star formation starts in giant molecular clouds → Molecules (like CO) trace star formation

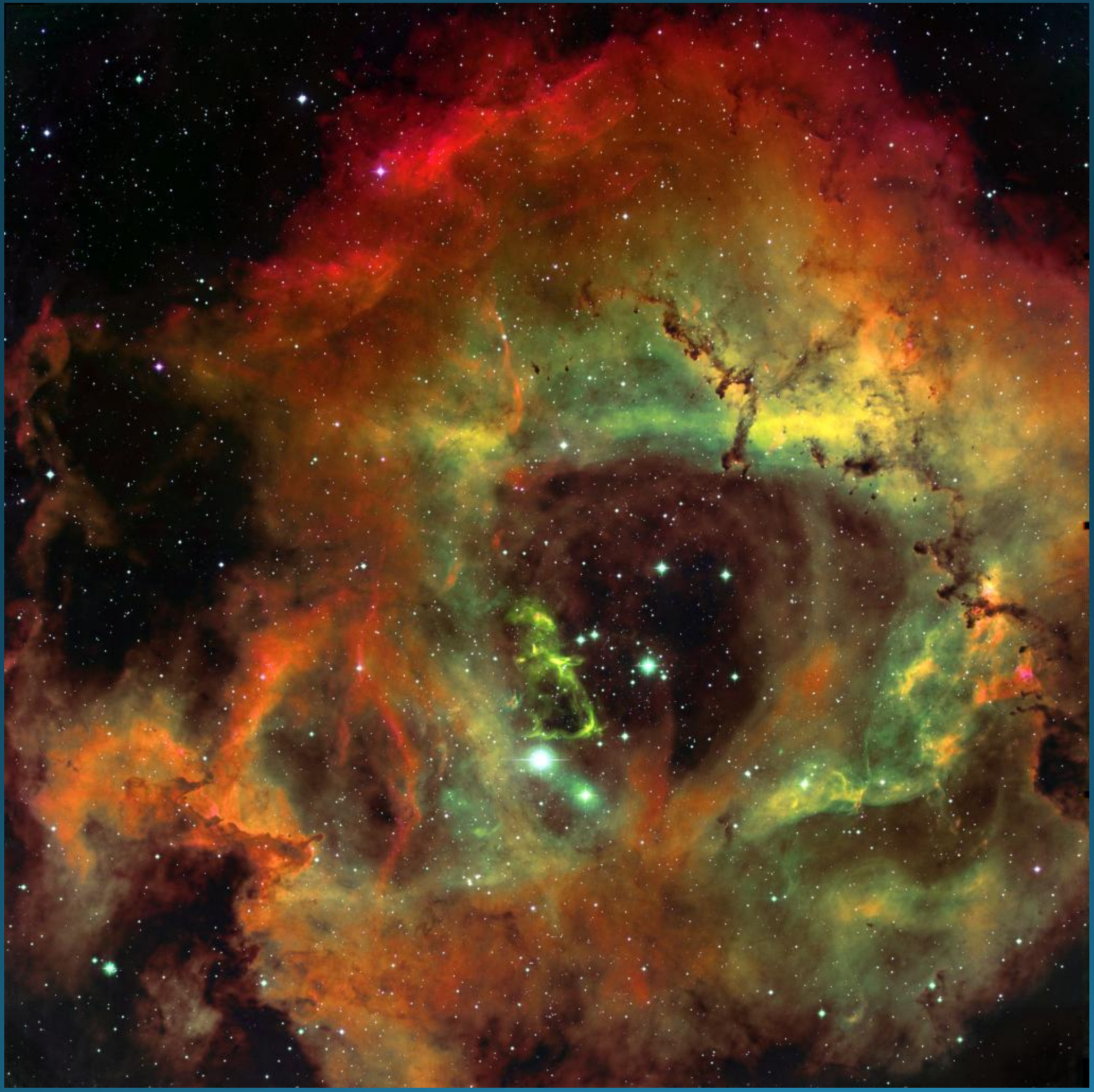


Intermission: What wavelength range?



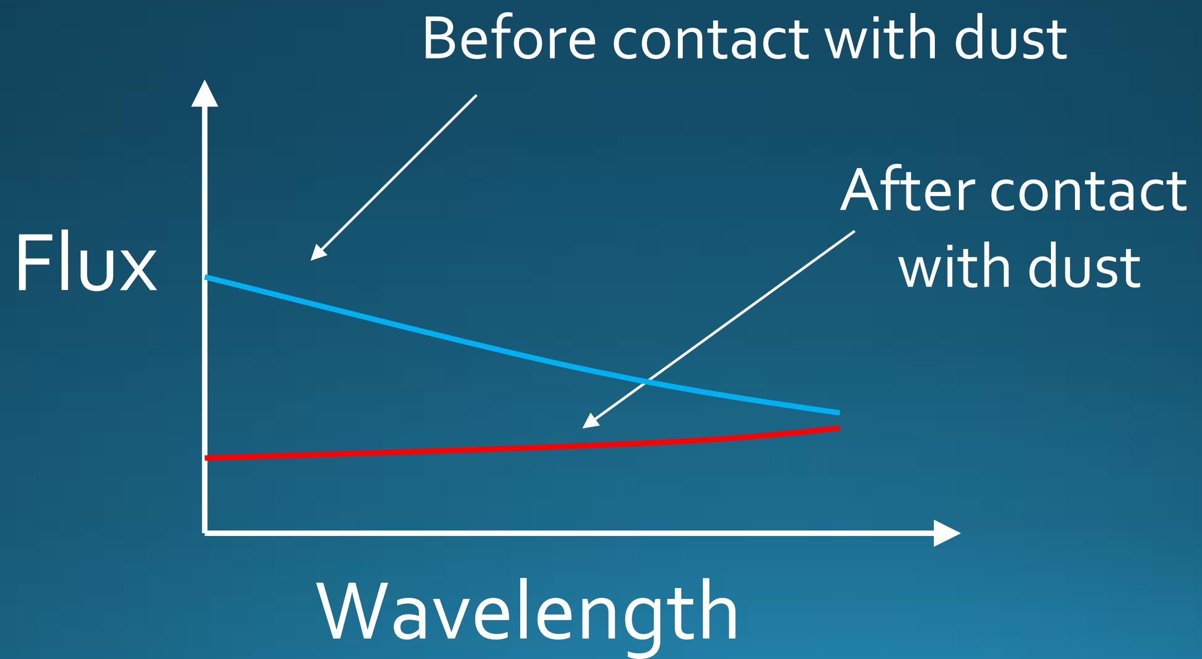
Andromeda at four different wavelengths

The Interstellar medium



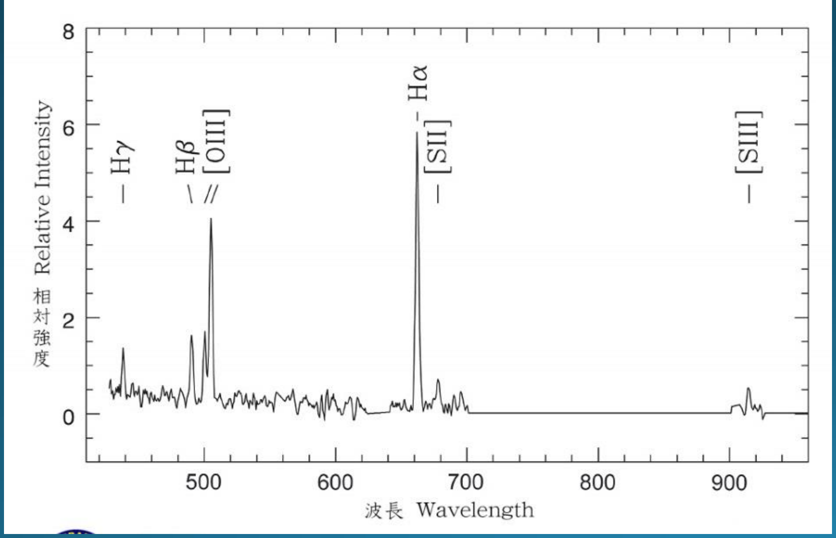
Dust extinction

- Dust absorbs light in UV/optical
- Dust opacitiy is wavelength-dependent: Blue light is absorbed more efficiently than red light → **Reddening of the spectrum**

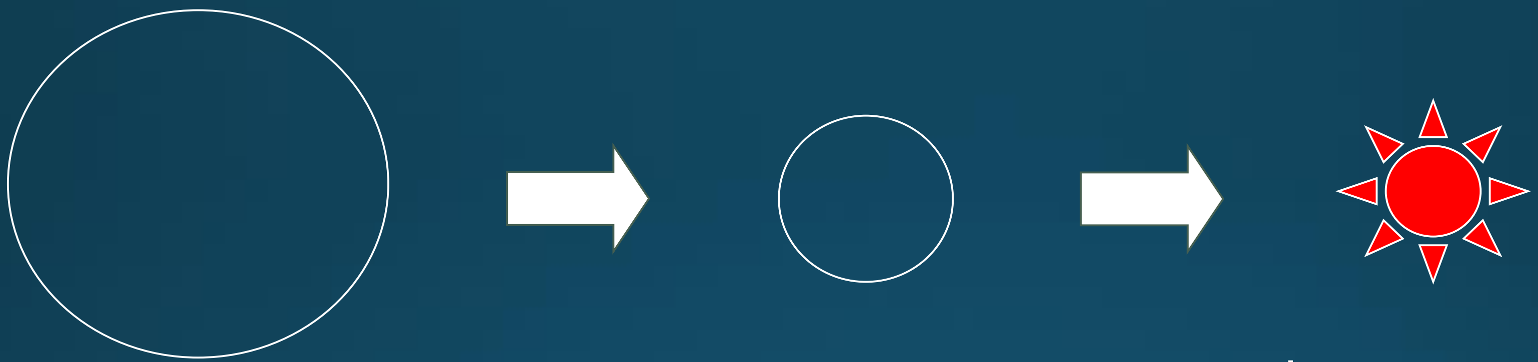


Dust extinction II

- The Balmer decrement $H\alpha/H\beta$, can be estimate the amount of dust reddening in galaxies with emission lines
- Theory predicts $L_{H\alpha}/L_{H\beta}\approx 2.87$ from gas ionized by stars (Note: $L_{H\alpha}/L_{H\beta}$ is often written $H\alpha/H\beta$)
- Dust reddening $\rightarrow$ $L_{H\alpha}/L_{H\beta}>2.87$
- Knowing $L_{H\alpha}/L_{H\beta}$ and using an extinction curve (extinction as function of wavelength), dust reddening can be corrected for



Star Formation Made Simple

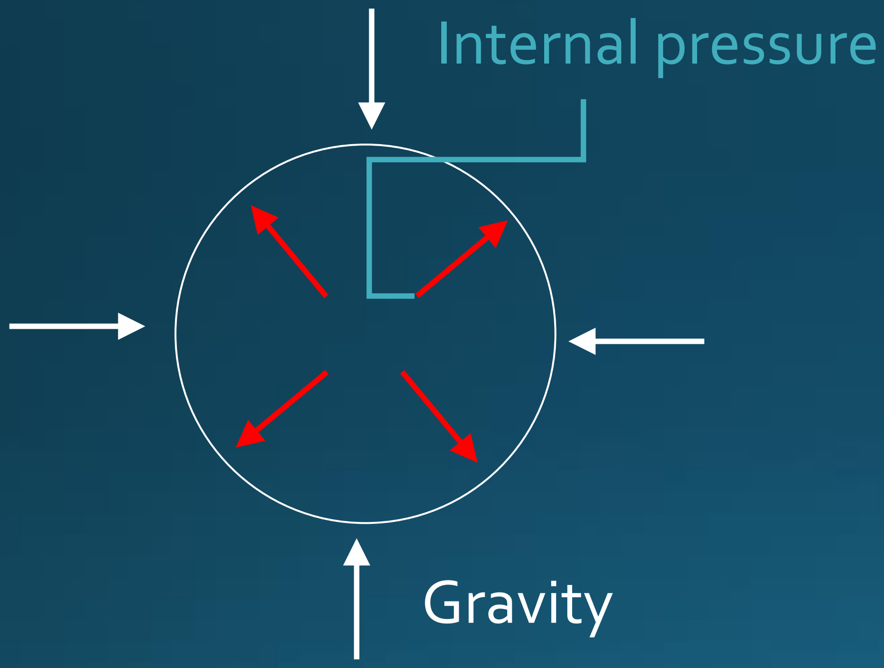


Gas cloud

Collapse due to self-gravity→ Temperature rises

Thermonuclear reactions kick in → A star is born

When Does Star Formation Occur?



Gas cloud

Gravity wins when
Length > Jeans length, λ_J:

$$\lambda > \lambda_J = \frac{\sigma_v}{\sqrt{G\rho}}$$

Or equivalently, when
mass > Jeans mass, M_J:

$$M > M_J = \frac{\pi}{6}\lambda_j^3\rho_m$$

When Does Star Formation Occur?

$M<M_J$ ensures stability on small scales

On larger scales, regions of size D
are prevented from collapse by disk rotation if:

$$D > D_{\text{critical}} = \frac{2G\Sigma}{3\Omega^2}$$

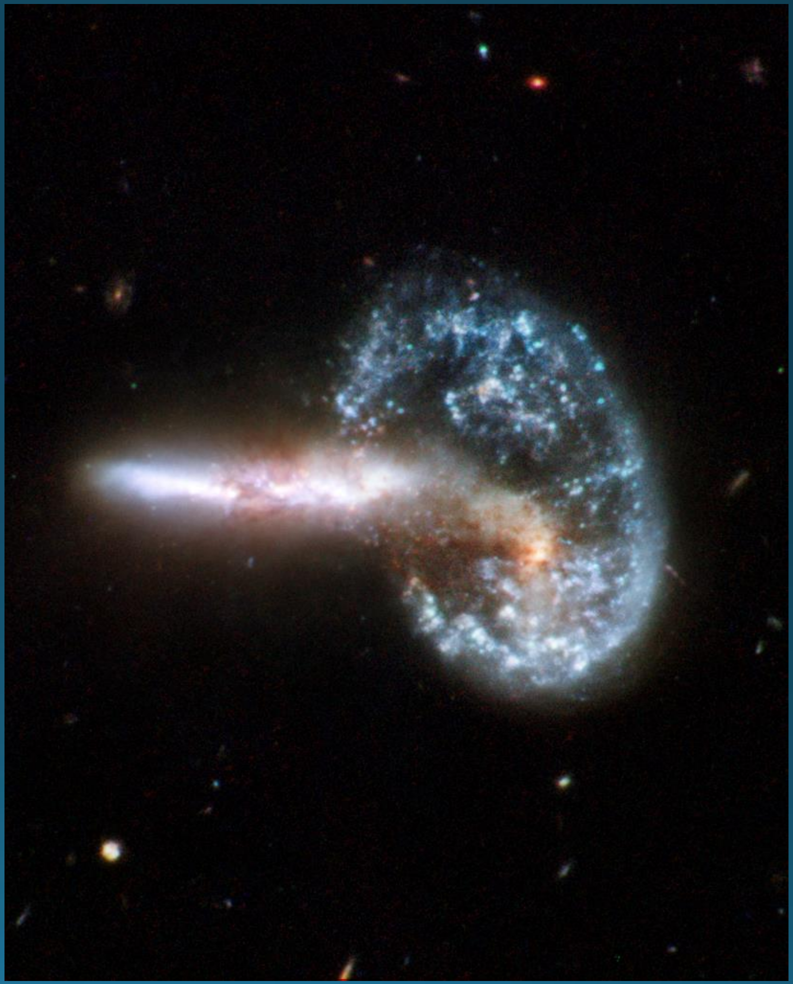
Surface Density

Angular velocity

Low-surface brightness disks fulfil this criterion!

Star formation triggers

- Gravitational instabilities
  - $M>M_J$
  - $D<D_{critical}$
- Density waves
  - Compression in spiral arms
- Direct collisions



Negative Feedback from Star Formation

- Gas ionized by massive stars
  - Gas must be cool to collapse
- Winds from Supernovae
  - Loosen up compressed regions
  - Removes gas from low-mass galaxies (blow-out)

A Wolf-Rayet star (high-mass star with huge ionizing flux and mass loss due to winds)

Star Formation Efficiency

Typically less than 10% of the available gas is converted into stars before feedback prevents further star formation

Star formation rate (assumed constant during star formation episode)

Duration of star formation episode

Star formation efficiency

$$\varepsilon = \frac{\mathrm{SFR}\,\tau}{M_{\mathrm{H}_2}} \leq 0.1$$

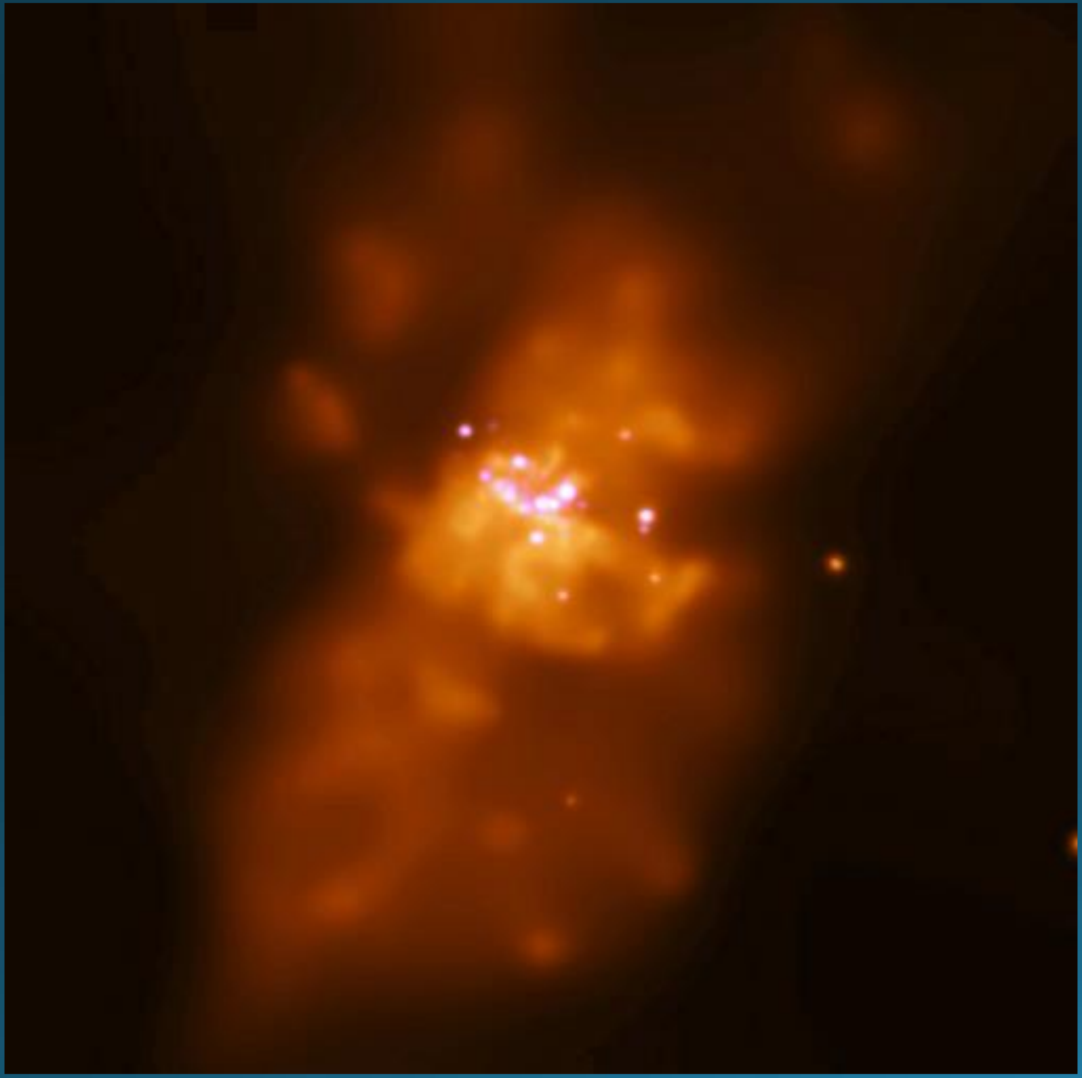
Starburst Galaxies

M81 & M82

Starburst Galaxy M82

Intermission: What are you witnessing here?

Starburst Galaxies



M82 in X-rays

Recommended Definitions of Starbursts

- Global starburst:
  - SFR high enough to consume the gas in less than one Hubble time over a size larger than a single HII-region
- Local starburst:
  - SFR increases by factor of 10 or more across an HII-region

Starbursts are transient phenomena unless new gas is added!

Starburst galaxies

Lots of research in Uppsala in past 30 years on these

- Gas-consumption timescale:

$$t_{\mathrm{gas}} = \frac{M_{\mathrm{gas}}}{SFR}$$

- Typical galaxy: SFR~0.1 M_{solar}/yr

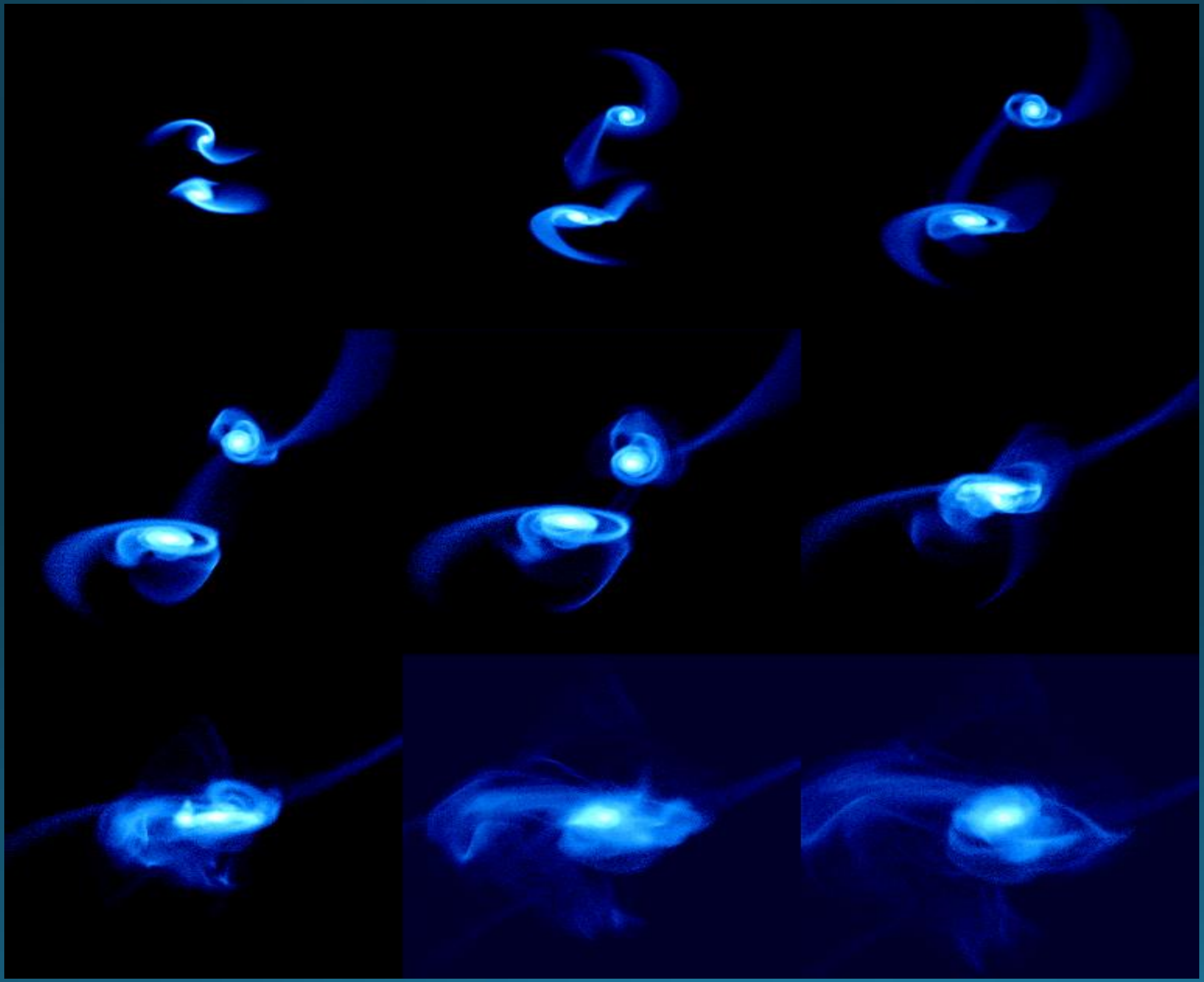
- Common, but dangerous starburst definition:

  SFR > 50 M_{solar}/yr

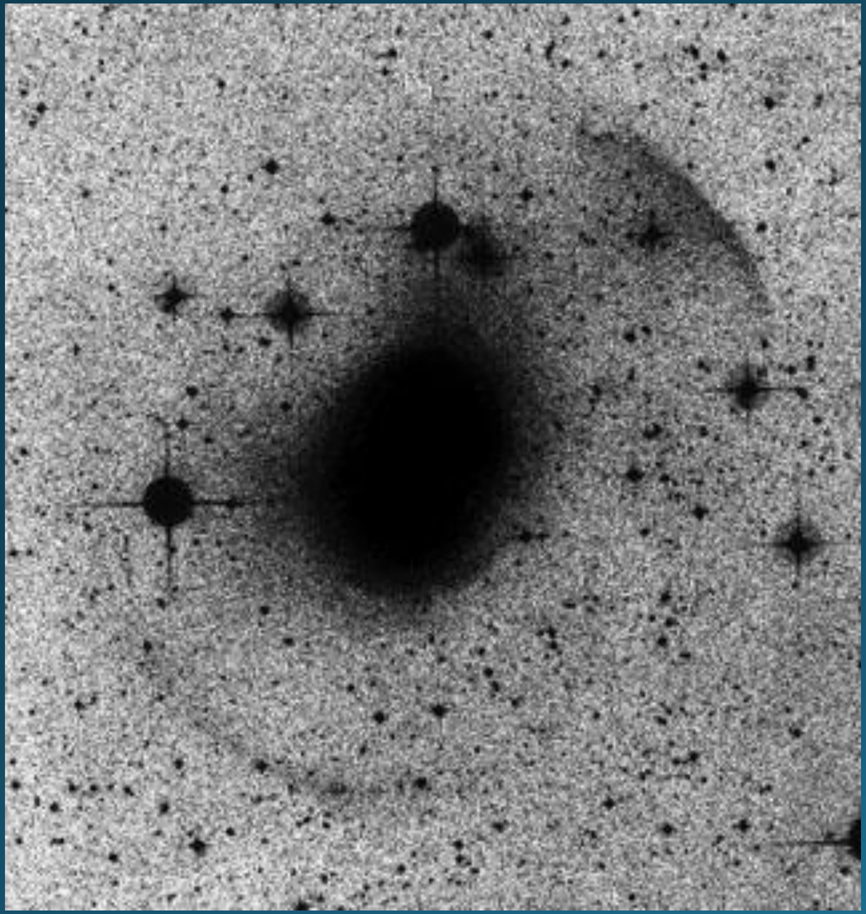
Starburst Galaxies

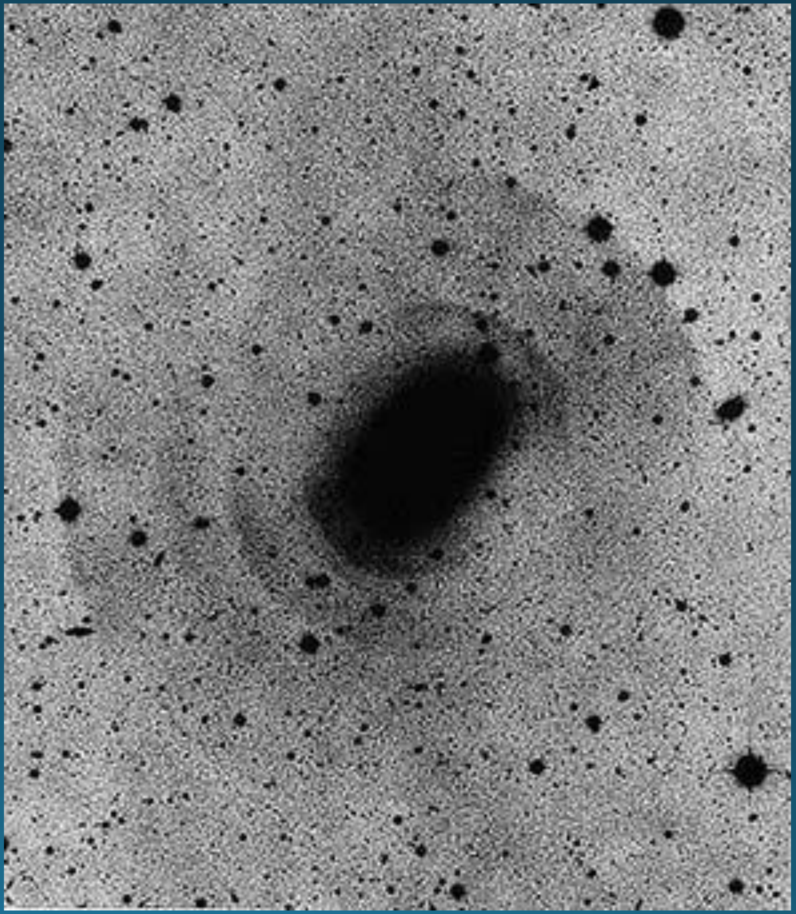
- Possible triggers:
  - Mergers/collisions
  - Interactions (controversial)
  - Large intergalactic gas clouds falling into a galaxy

Galaxy Interactions & Mergers

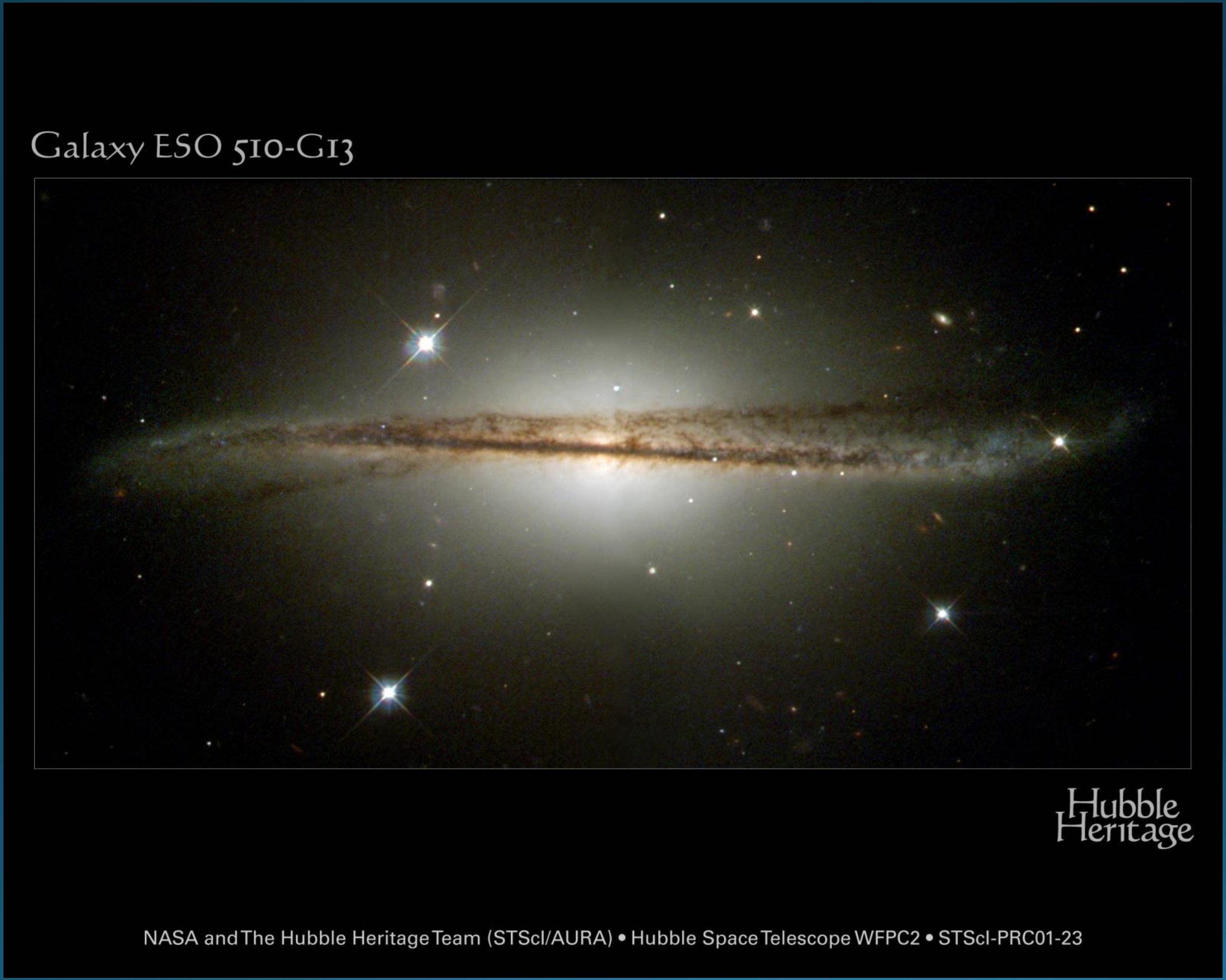


Signs of interaction: Shells





Signs of Interactions: Warps



Signs of interaction: Tidal Tails

Intermission: What do you think is happening here?

Metallicity

- Metallicity, Z: Mass fraction of elements other than H and He
  - $Z_{solar} \approx 0.013\text{-}0.016$ (depending on who you believe)
- Abundance ratio:

$$[A/B] = \log_{10}\left(\frac{(\text{number of A atoms / number of B atoms})_{\text{object}}}{(\text{number of A atoms / number of B atoms})_{\text{sun}}}\right)$$

- Often [Fe/H] or [O/H] is also referred to as "metallicity"

Metallicity

- The metallicity of the stars can be measured using absorption lines
- The metallicity of the gas can be measured using emission-line ratios
- E.g. a measurement of the following emission lines:
  - OII at 3727 Å
  - OIII at 4959 and 5007 Å
  - Hβ at 4861 Å

gives R_{23} , which can be converted into [O/H]

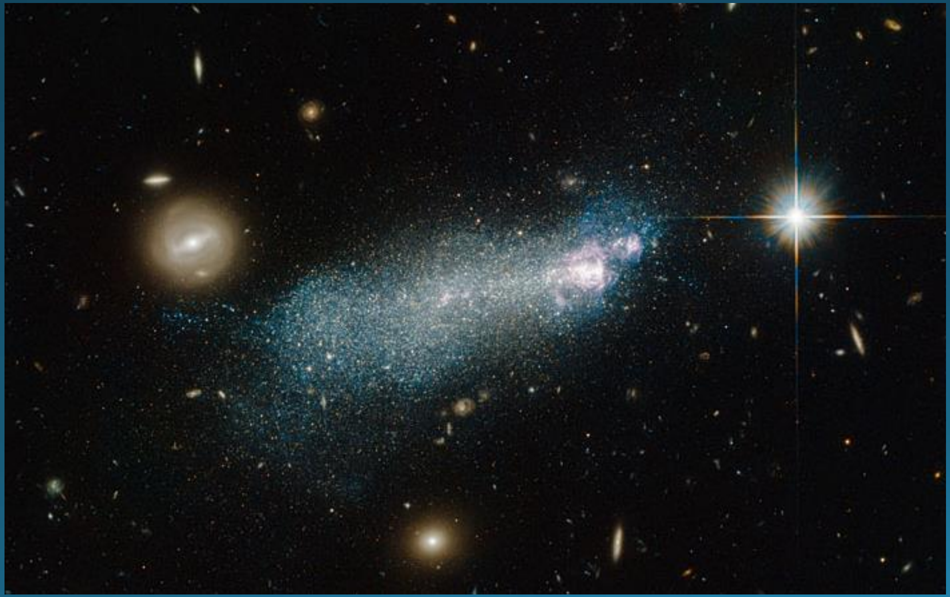
$$\log R_{23} = \log\left(\frac{L_{[\mathrm{OII}]\lambda 3727} + L_{[\mathrm{OIII}]\lambda\lambda 4959,5007}}{\mathrm{L}_{\mathrm{H}\beta}}\right)$$

Dwarf Galaxies

- "Dwarf" typically implies small size, small mass, low luminosity and low central surface brightness
- Common, but sloppy definition:

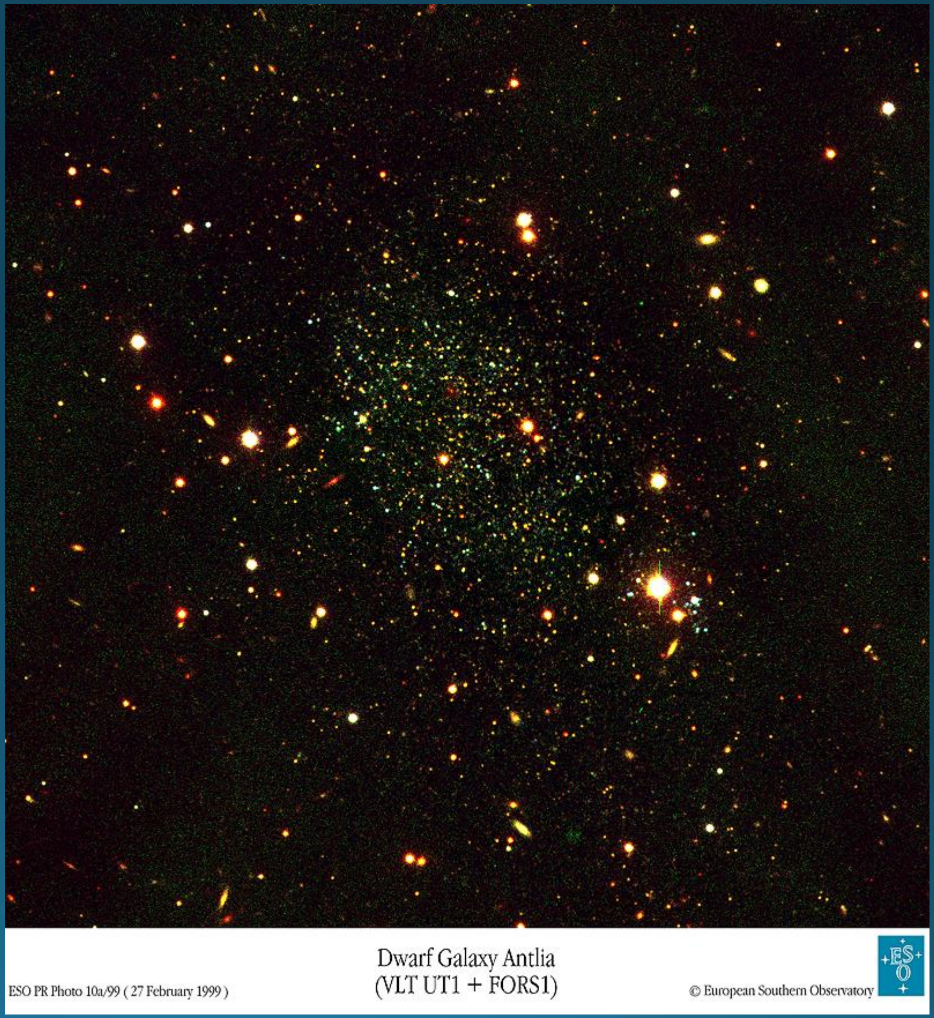
  $M_B > -18$ or -17

- In general: Higher total M/L than in normal galaxies $\rightarrow$ Extremely dark-matter dominated



Dwarf Galaxies

- Often difficult to distinguish from normal galaxies, without measuring luminosity
- Tell-tale sign: when you see right through them, it's either a dwarf galaxy or a star cluster



Dwarf Spheroidals (dSph)

- Almost no gas
- Very diffuse (can often see right through them)
- Old; no stars younger than 1—2 Gyr
- Metal-poor ($Z<10\% \ Z_{solar}$)
- Random motion dominates: $v_{rot}/\sigma_v<1$
- Probably triaxial
- May have luminosities as low as globular clusters, but are bigger and have globular clusters of their own

The Fornax Dwarf Spheroidal galaxy

Dwarf Ellipticals (dE) & Compact Ellipticals

- Dwarf Ellipticals:
  - Similar to dSph, but more luminous
  - Distinction somewhat unclear, many people write dE/dSph
- Compact Ellipticals:
  - Rare (example: M32 in Local Group)
  - High density
  - More rotationally supported than dE/dSph: $v_{rot}/\sigma_v \geq 1$

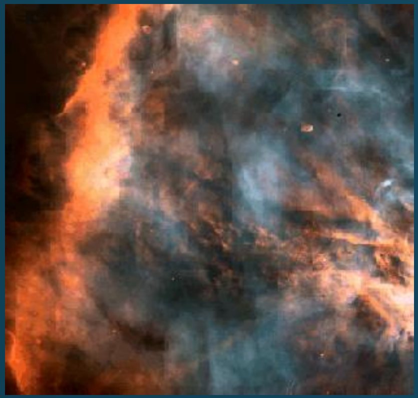
Dwarf Irregulars

Dwarf Irregulars

- Contain gas and young stars
- Metal-poor: ($Z<10\%\ Z_{solar}$)
- Some rotationally supported, some not:
  - Low L-systems: $v_{rot}/\sigma_v<1$
  - High L-systems: $v_{rot}/\sigma_v \approx 4$—$5$

Intermission:
What type of dwarf?

Chemical evolution



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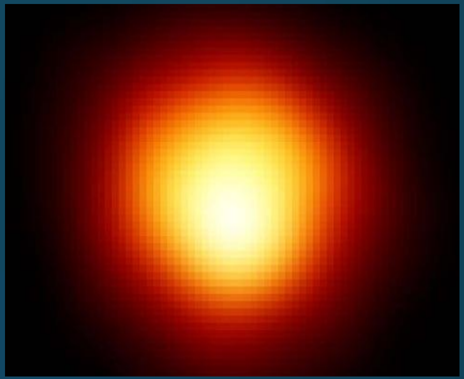

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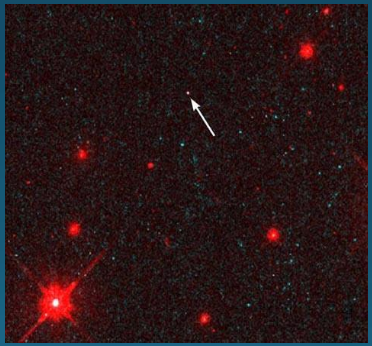
A star is born…

…consumes its fuel…

→



…possibly explodes…

…then fades away

Stellar evolution made simple

The Closed-Box Model

- No gas added or lost from the system
- Yield, p:
  - Determines return of heavy elements to interstellar medium
  - Often defined as mass fraction of heavy elements returned per mass locked up in stellar remnants (black holes, neutron star, white dwarfs) and long-lived, very low-mass stars

The Closed-Box Model

$$Z(t) = Z(0) + p\ln\left(\frac{M_{\rm gas}(0)}{M_{\rm gas}(t)}\right)$$

Prediction:

Gas-rich systems are metal-poor (e.g. dI)

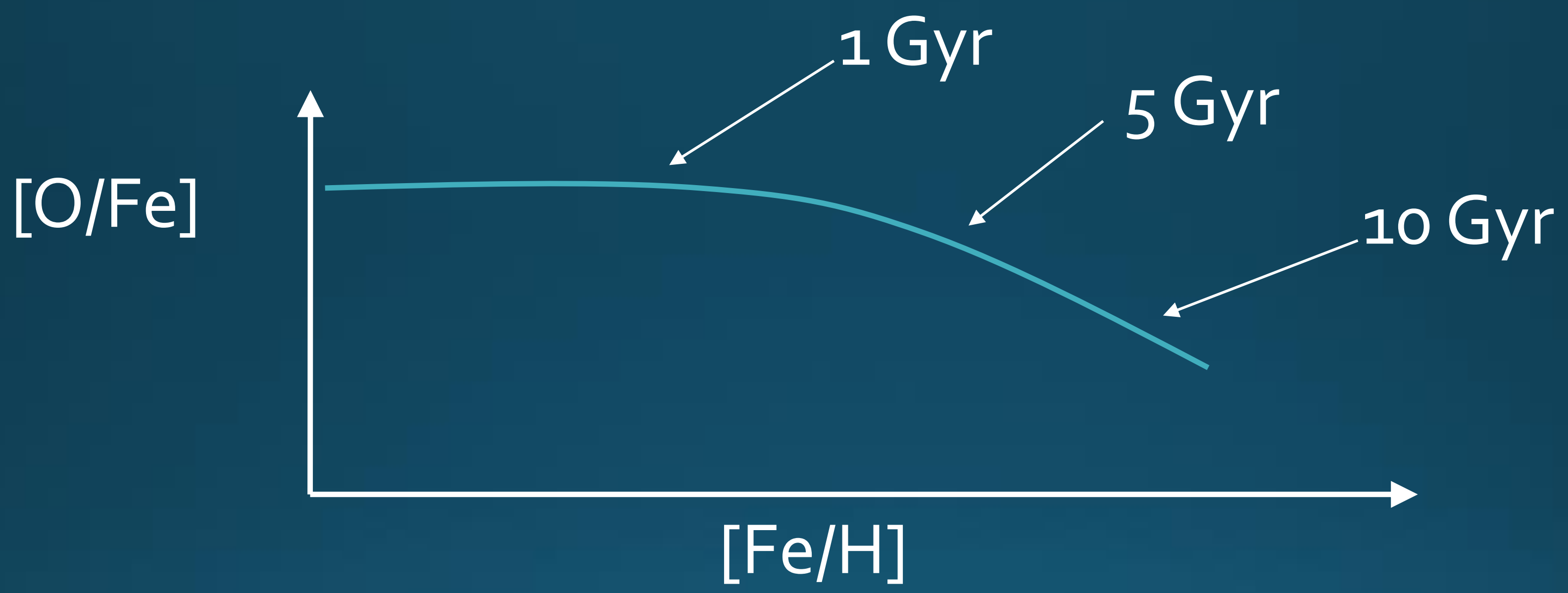
Gas-poor systems are metal-rich (e.g. E)

However, dSph are gas-poor and metal-poor...

Relaxation of the Closed-Box Assumption

- Blow-out of gas by stellar winds
  - Mainly in low-mass systems (dwarf galaxies, globular clusters, first galaxies)
- Infalling gas
  - Intergalactic gas clouds (primordial metallicity)
  - Merger with gas-rich galaxy

Chemical Evolution of Individual Elements



- Type II supernovae: O (quick)
- Type Ia supernovae: Fe (prolonged)