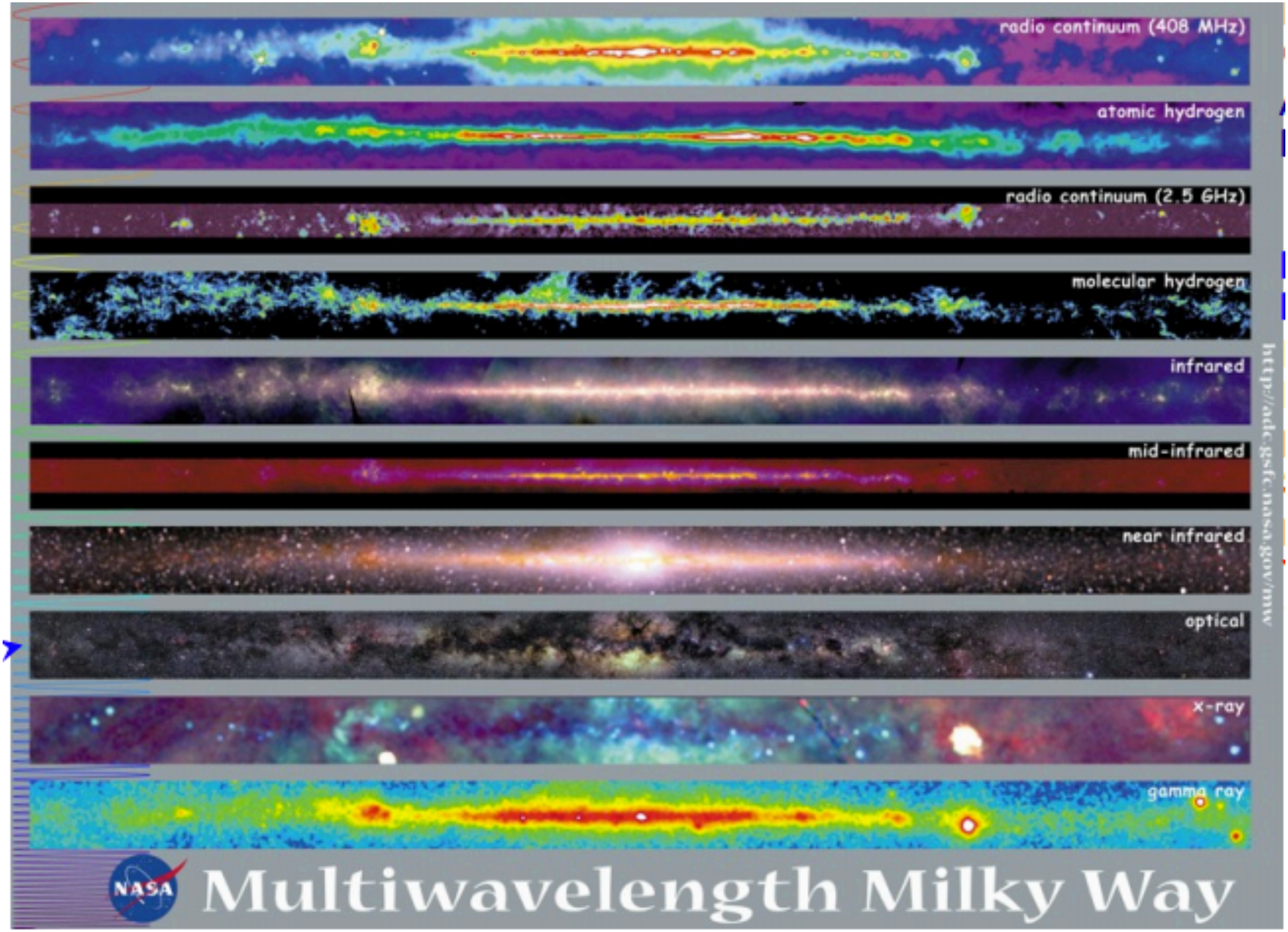
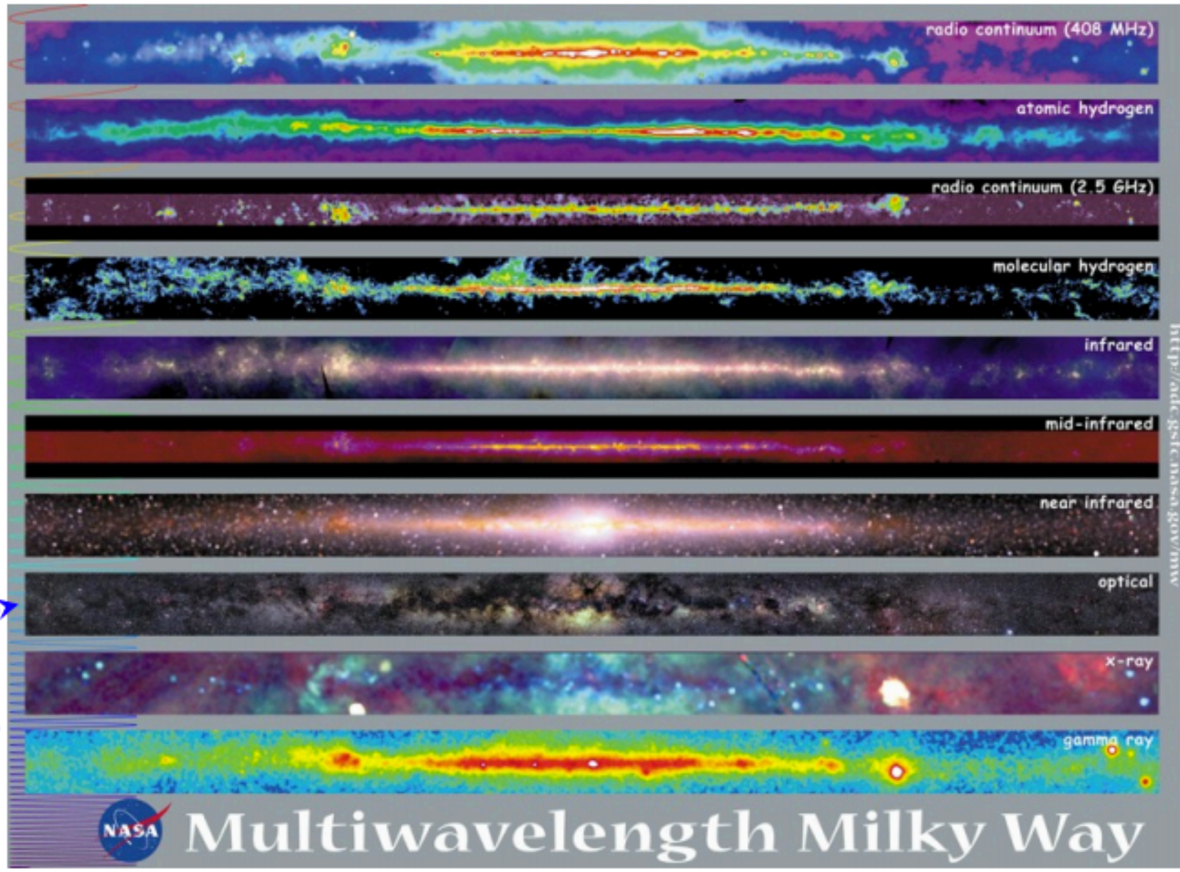


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way

Fuel from which stars can form

Reprocessed star light

UV: direct probe of High-mass SF



Radio: molecular clouds, GMCs

Atomic Hydrogen: Low-density or hot gas

Molecular Hydrogen: Dense, cold gas

Far-Infrared: Hot cores & clouds, SF

Mid-Infrared: Star-forming cores

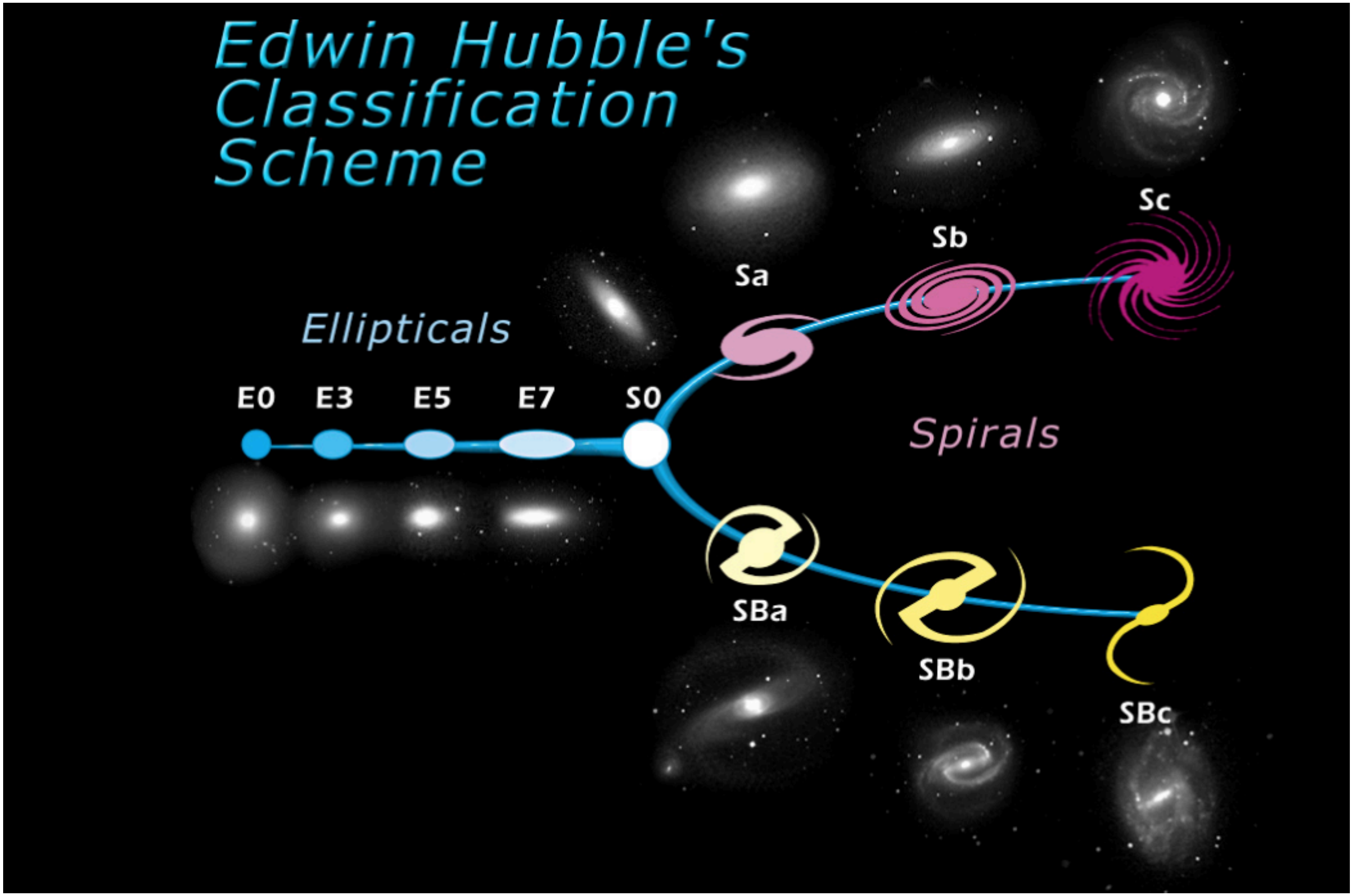
Near-Infrared: Young, embedded stars

Visual: Dark clouds, sites of SF

UV-Visual spectra: HII, ionised regions

HI gas

Hubble Sequence



Star formation History

- Position of a galaxy within the Hubble Sequence reflects only the detail of its origin:
  - E.g. amount of mass and velocity distribution (and DM) that led to the formation of that given galaxy

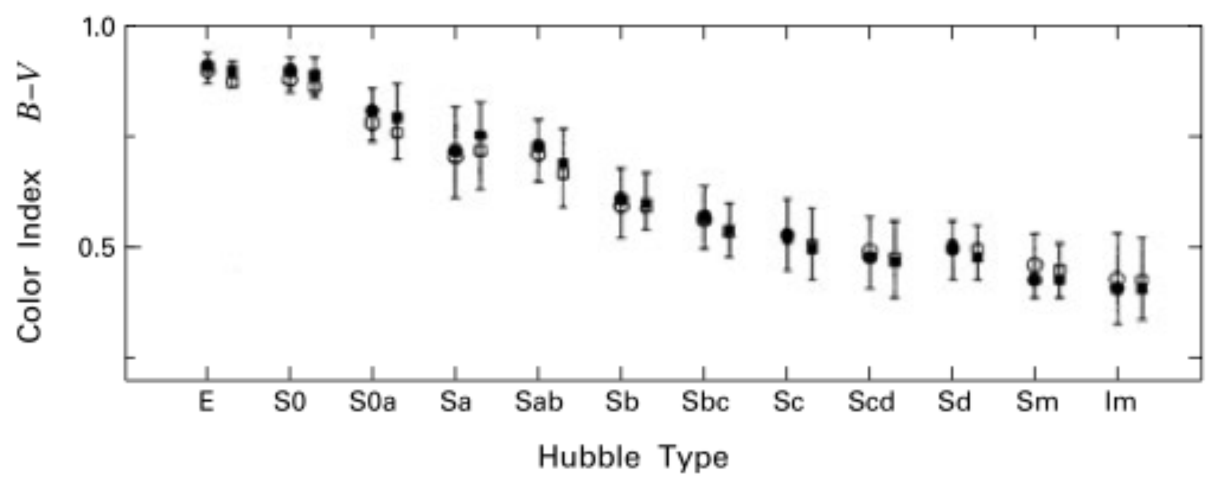


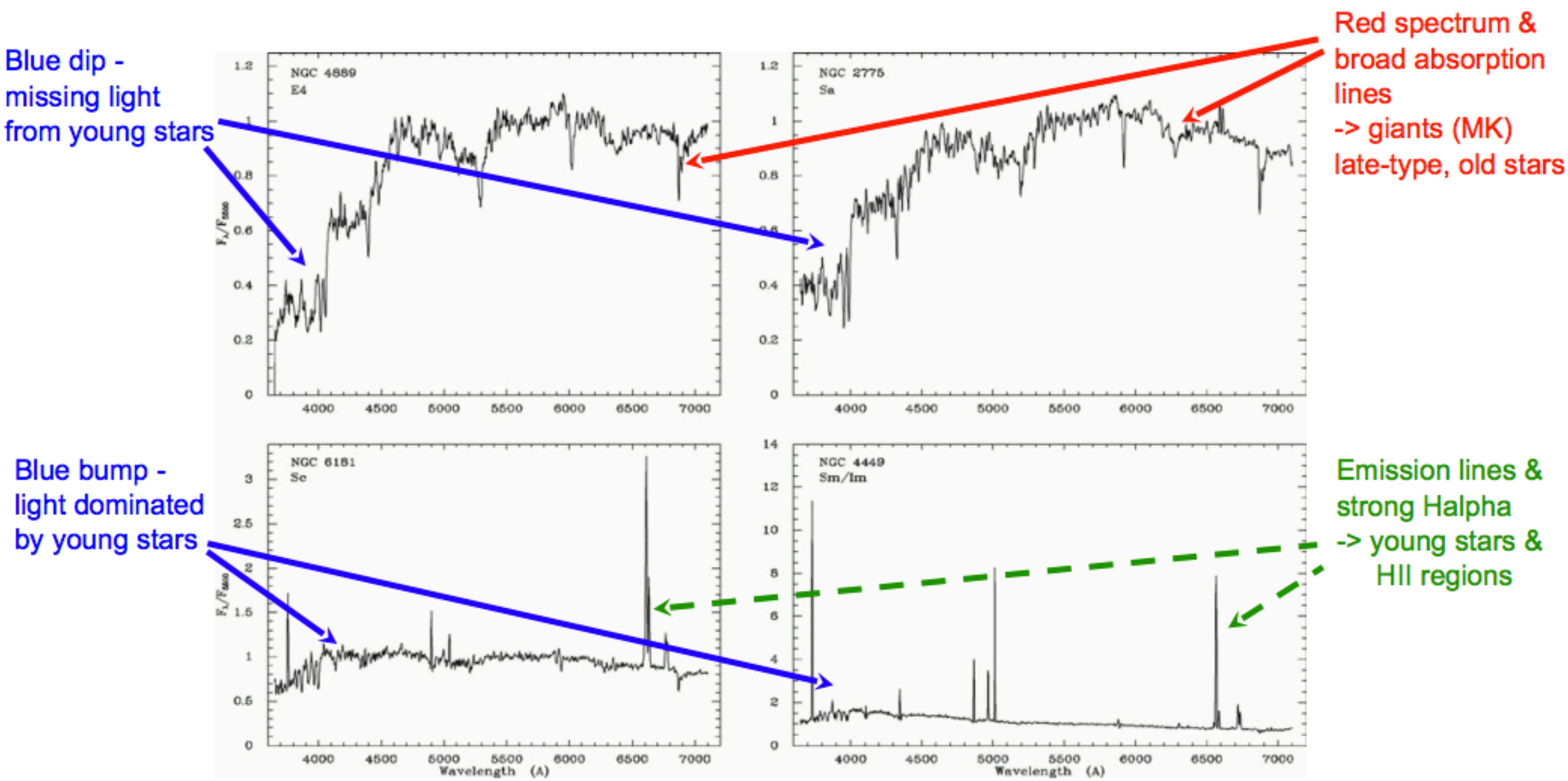
Figure 19.4 The color index $B - V$ of galaxies as a function of their Hubble type. Note that the latter contains intermediate spiral types (such as Sbc), as well as the Magellanic irregulars Sm and Im (see text). The two sets of data points were produced by averaging from two different galaxy catalogs. Error bars represent counting statistics.

Ellipticals are redder: emission dominated by old, low-mass, stars

Irregulars are bluer: emission dominated by main sequence stars

Measuring the star-formation rate in other galaxies

Integrated light and spectrum vs. Hubble type:



Kennicutt 1998

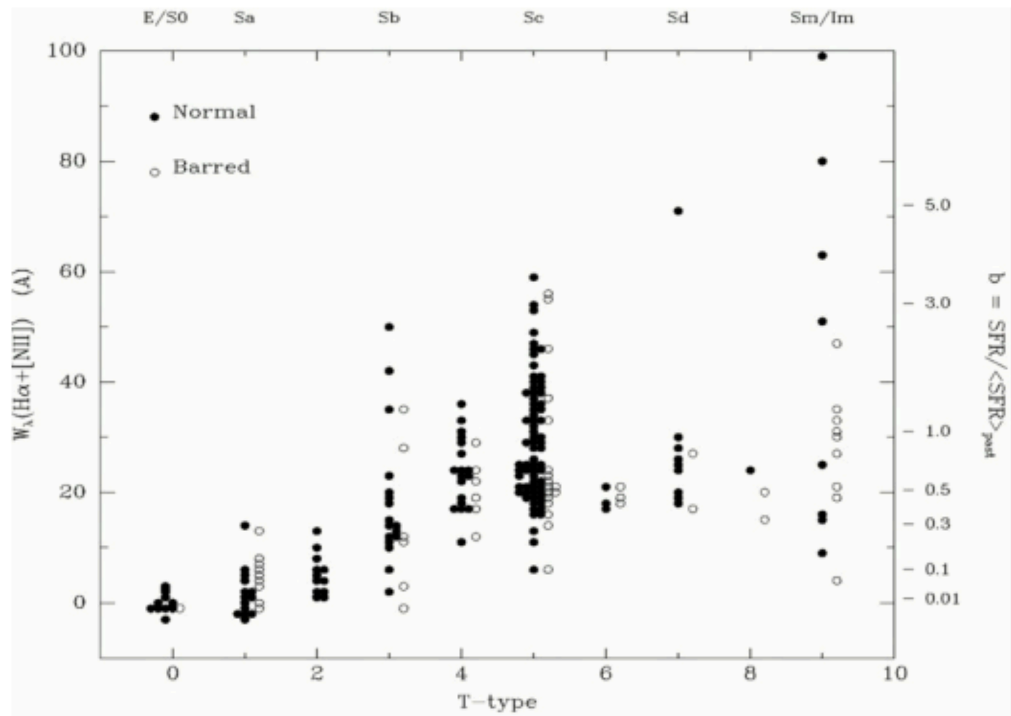
H_α luminosity if a very good tracer of star formation

Variations in the SFR across the Hubble sequence

Halpha as the most direct probe of recent star formation:

SFR < 0.01 --> 20 Msun / year

Galaxy type	SFR [Msun / year]
gas-poor Ellipticals, S0	< 0.01
gas-rich spirals	< 20
starburst galaxies	< 100
Ultraluminous IR galaxies	< 1000

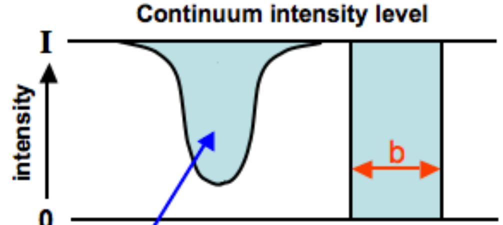


- the highest SFRs are always associated with tidal interactions and mergers.

- spiral galaxies always show some level of high-mass star formation.

- the SFRs between spiral galaxies vary by factors of ~10 in dependence on

  * gas content
  * interactions & re-fuelling
  * short-term variations in the SFR (a non-continuous SF history)



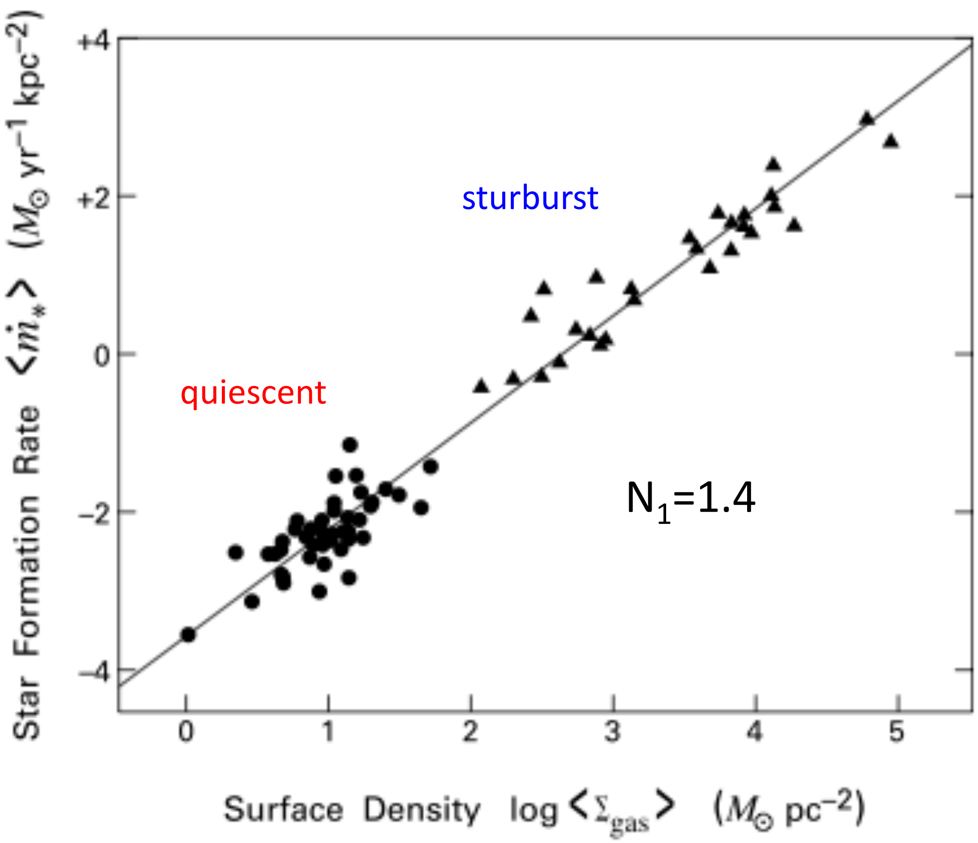
Kennicutt 1998

Schmidt Law

- Compare the activity of spirals with the supply of gas

$$\langle \dot{m}_* \rangle = A_1 \langle \Sigma_{gas} \rangle^{N_1}$$

Atomic + molecular gas divided by disk area



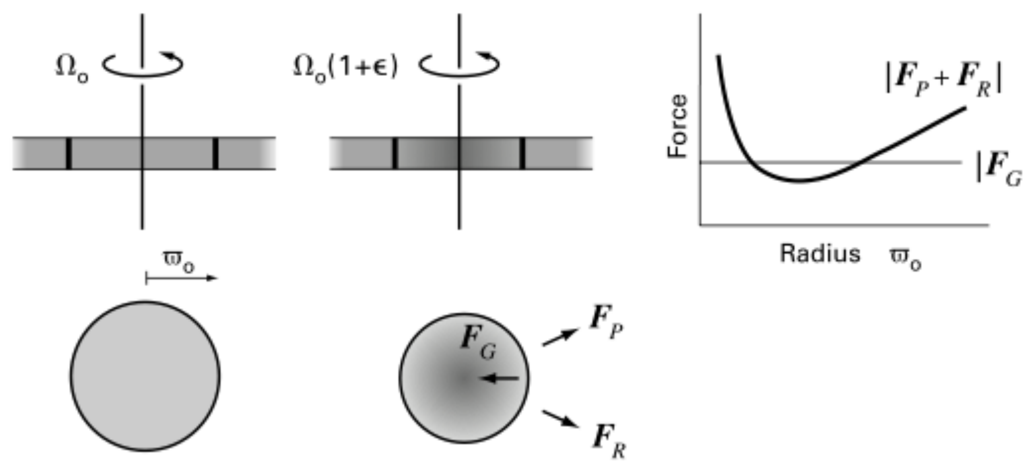
Density Threshold

- Is there a threshold below which one cannot sustain vigorous star formation ?
  - Motivated by spiral galaxies whose disk extends beyond the region where Hα is detected
  - Hα exhibits a sharp cut off ; HII regions are still found but with a lower surface density

- It depends on whether a disk satisfied the conditions for fragmentation/collapse
  - Well described by the Toomre Q-parameter

Centrifugal force and internal pressure balance gravity

$$Q \equiv \frac{\kappa\, a_s}{\pi\, G\, \Sigma} > 1 \qquad \textit{for stability}$$



Star Formation Threshold

- Toomre Parameter predicts the truncation fairly well
- The gravity is not given by gas but by the stars

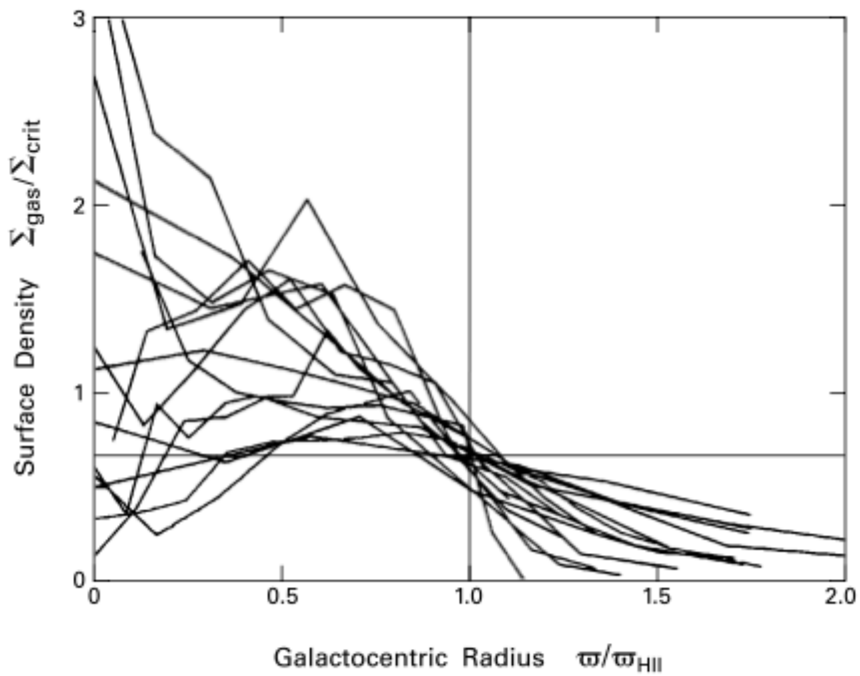
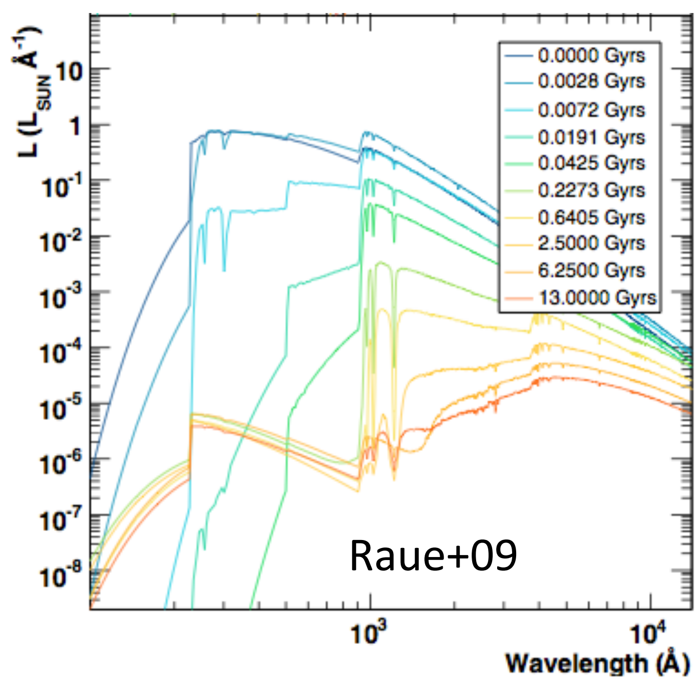


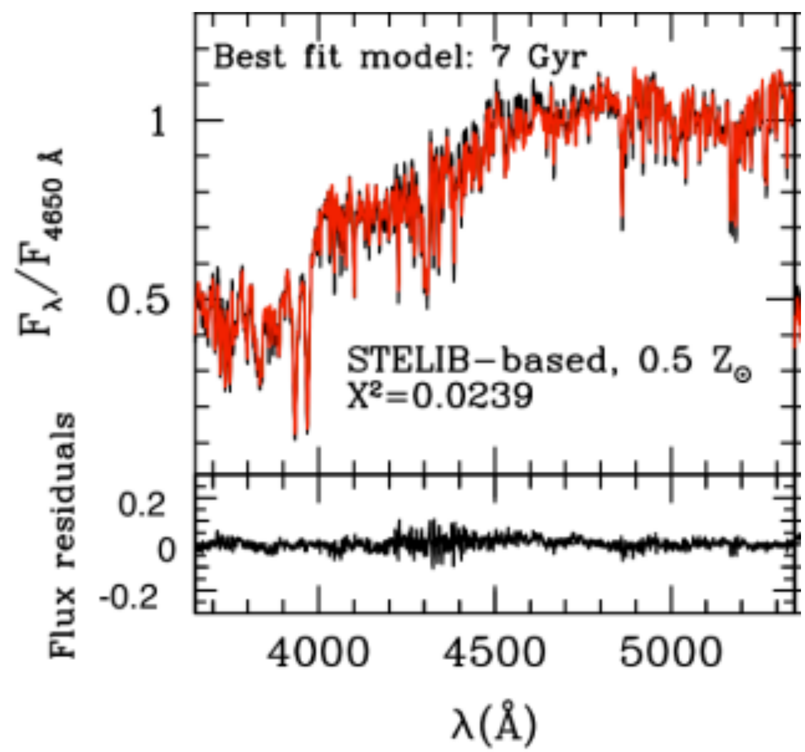
Figure 19.8 Total gas surface density as a function of radius in the disks of spiral galaxies. The surface density is normalized to the critical value, and the radius to the star formation threshold, as measured by Hα. The straight, horizontal line corresponds to a numerical coefficient of 0.67 on the lefthand side of equation (19.3).

Stellar Population Synthesis models

- One can interpret galaxy spectra as the integrated emission of stars currently residing in the galaxy
  - Aging stellar population: old stars are still present while the massive/young are instantaneous
  - Start from an IMF
  - Star formation rate as a function of time
  - Metallicity slowly increasing with time
  - Fit parameters to match optical spectrum

$$F_\lambda(t) = A \int_0^t \dot{M}_*(t-\tau)\, f_\lambda(\tau)\, d\tau \ .$$

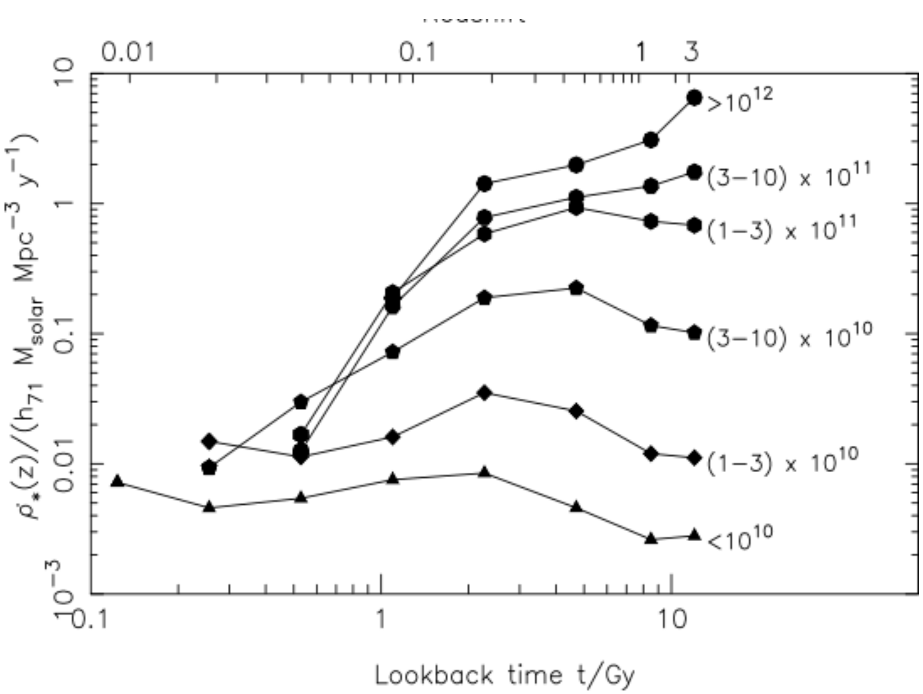


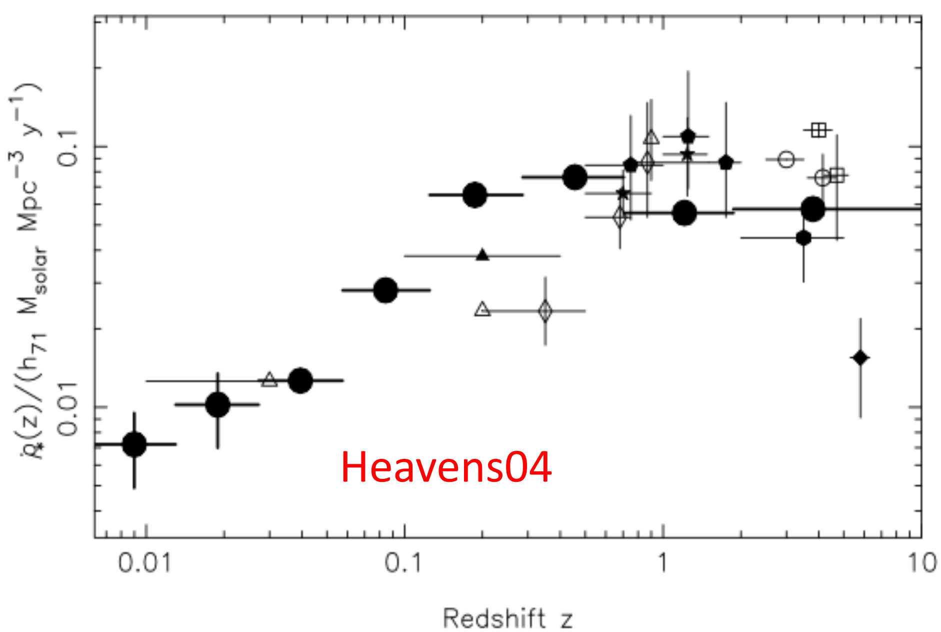


Star Formation History:

$$F_\lambda(t) = A \int_0^t \dot{M}_*(t-\tau)\, f_\lambda(\tau)\, d\tau$$

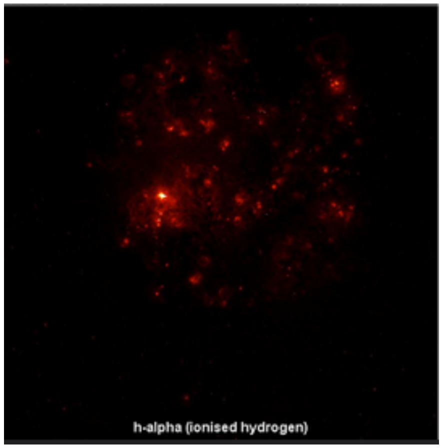
- For each galaxy one can measure/constrain the star formation history as a function of time
  - Not really well constrained for a single galaxy
- Use many (thousands, e.g. SDSS) galaxies and constrain the global star formation history of the Universe
  - Complementary to detecting high-z galaxies

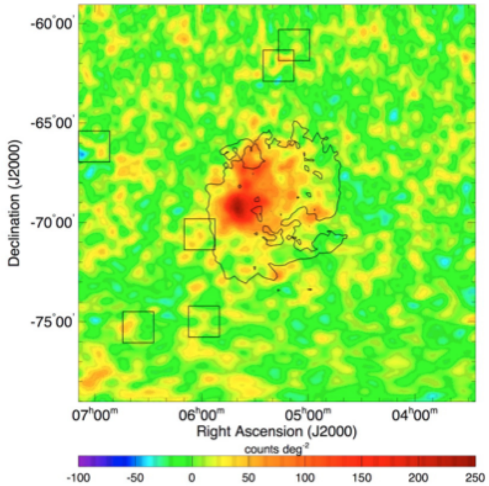




Activity in Irregulars

- The size of HII regions (and the number of O-B stars) within them increase along the Hubble sequence
- Irregulars have HII regions with hundreds of O-B stars
  - Their shape is due to the many HII regions disturbing the underlying disk-like geometry
- Prototypical example is the LMC (50 kpc from M.W.)
  - The region called 30 Doradus contains ~100 O-B stars in a cavity up to ~1 kpc across
  - Low mass objects (hundreds of T-Tauri objects are visible as well



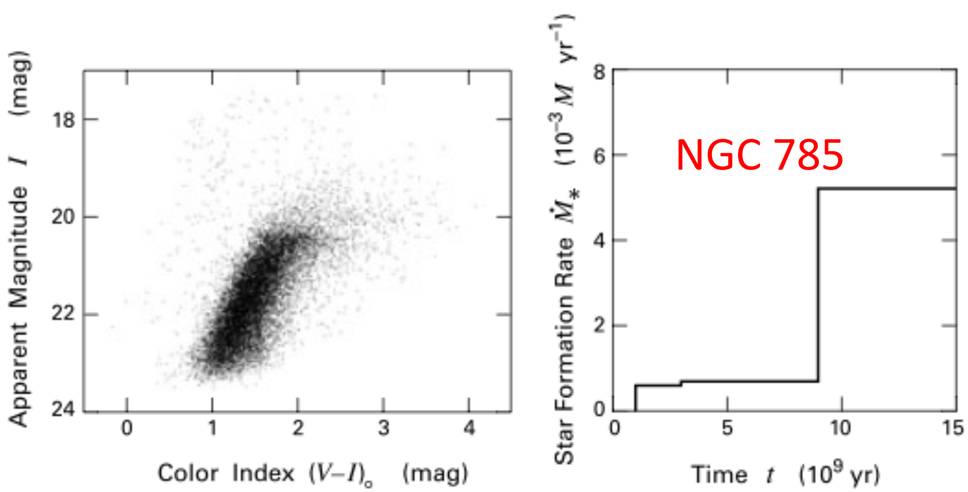


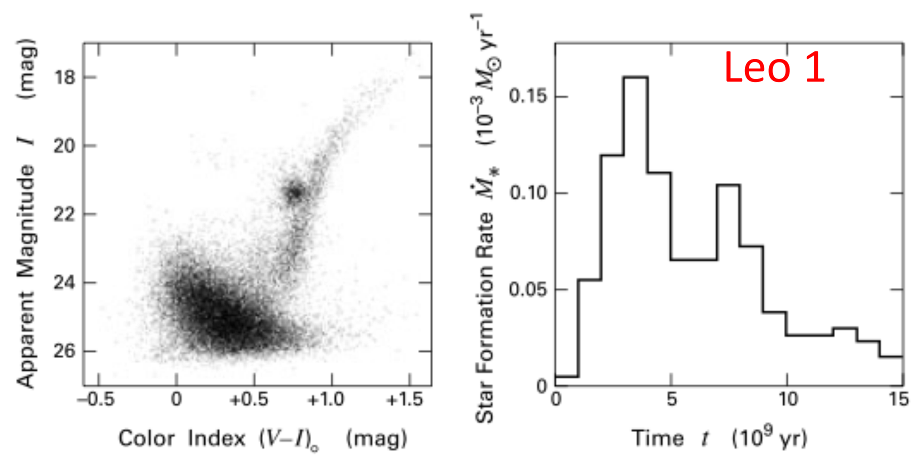
Star formation in The Local Group

Question: how many Spirals are there in the LG ?

- The LG comprises several galaxies gravitationally bound within 2MPc
  - Spirals: MW, M31, M33
  - Many irregular/dwarfs etc

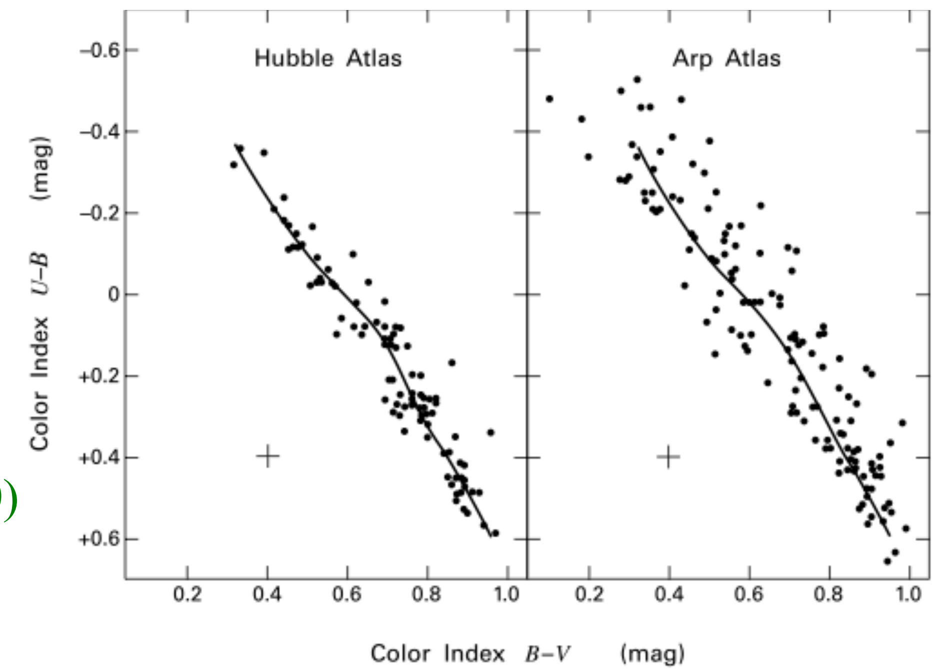
- Despite being so close, the star formation history of these galaxies can be quite different





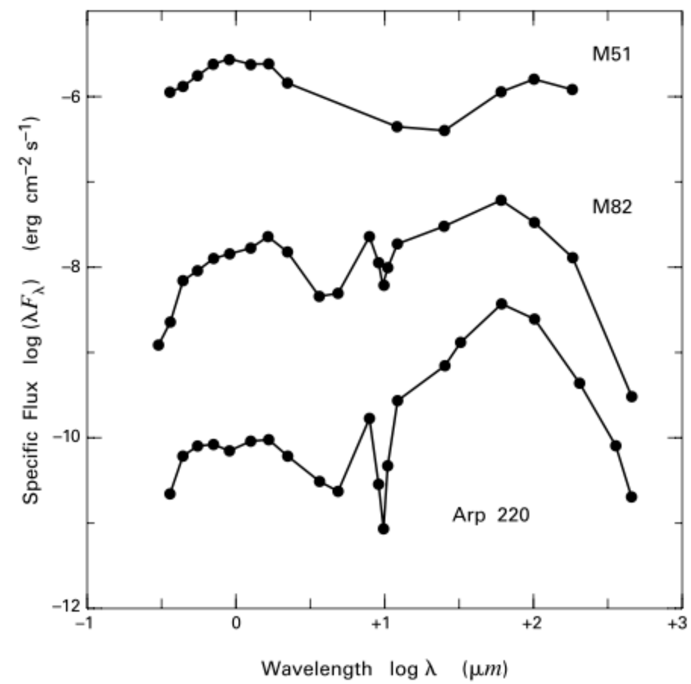
Starburst Galaxies

- Galaxies with large star formation
  - Often exceeding the M.W. one by ~100
  - Phenomenon is short lived
  - Typically occurs near galaxy center
  - SB. Gal. lie on the Schmidt law (slide 10)



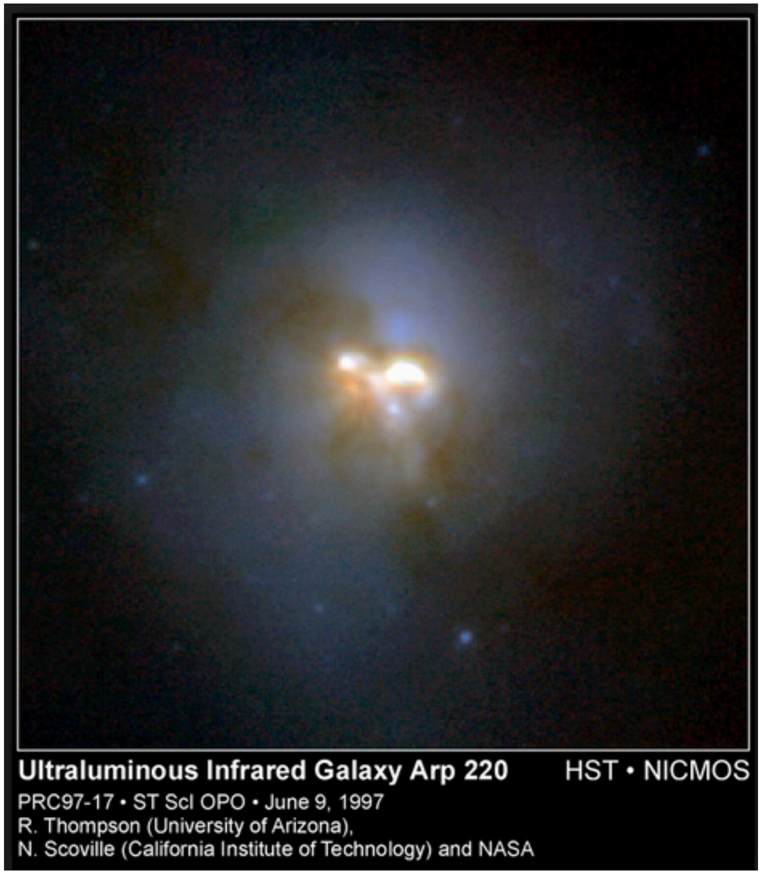
- Question:
  - How do SB. G. accumulate gas so quickly ??

- Because of the dust SB. G. are bright in IR
  - Ultra-luminous IR Gal (ULIRG) have $>10^{12} L_{sun}$
  - ULIRG have SFR of $> 10^3\ M_{\odot}/yr$



How do Starbursts get their fuel ?

- Arp 220 show a disturbed morphology with a two-plumes structure
  – It's a merging galaxy
- SFR increases with decreasing distance between 2 galaxies
- Tidal interactions pulls the gas
- The gravity is given by DM and stars
  – The gas follows like a fluid and gets shocked : e.g. it radiates
  – The energy losses allow the gas to spiral down towards the center and settle in the potential well
- We understand where circum-nuclear gas comes from, but how does it get to the center ?



Stellar Bars

- A perturbation is needed to torque gravitationally the gas allowing it to lose angular momentum
  - The instability has to be strong for a lot of gas to be funneled quickly
- SPH simulations show that the gas bar precedes the stellar one, which will then exert a braking torque on the gas

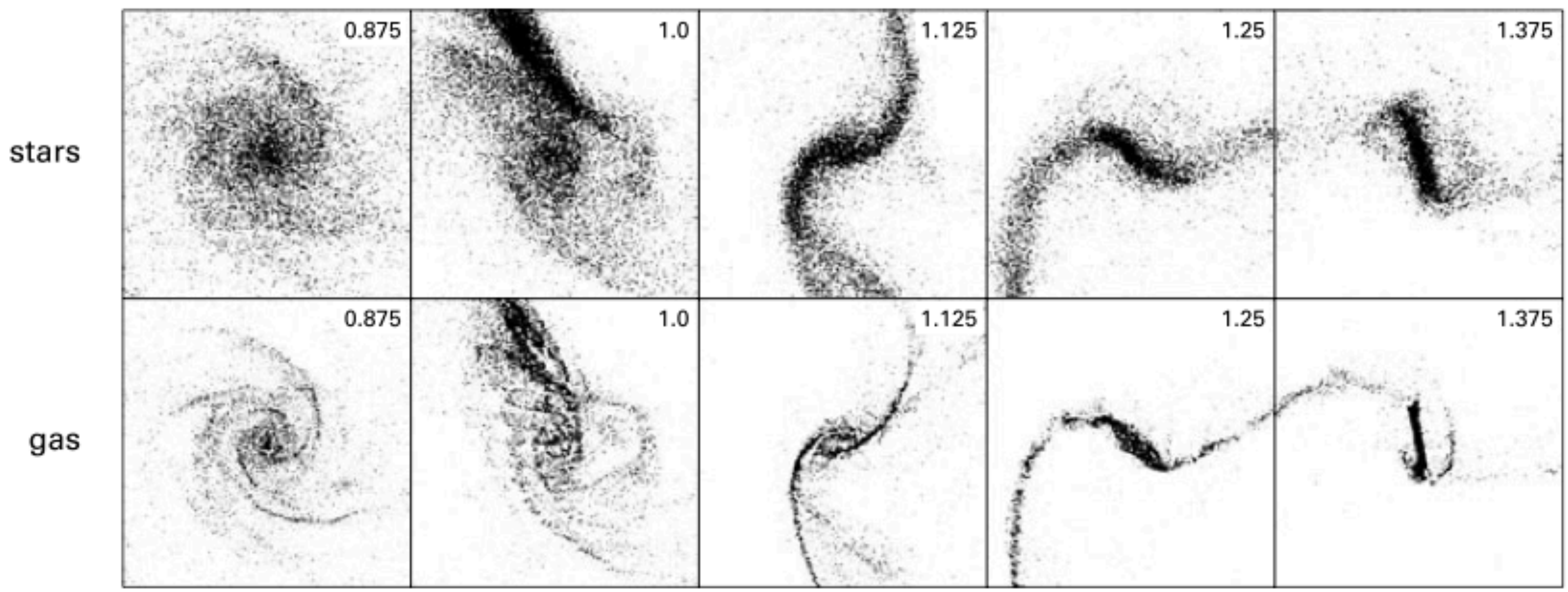
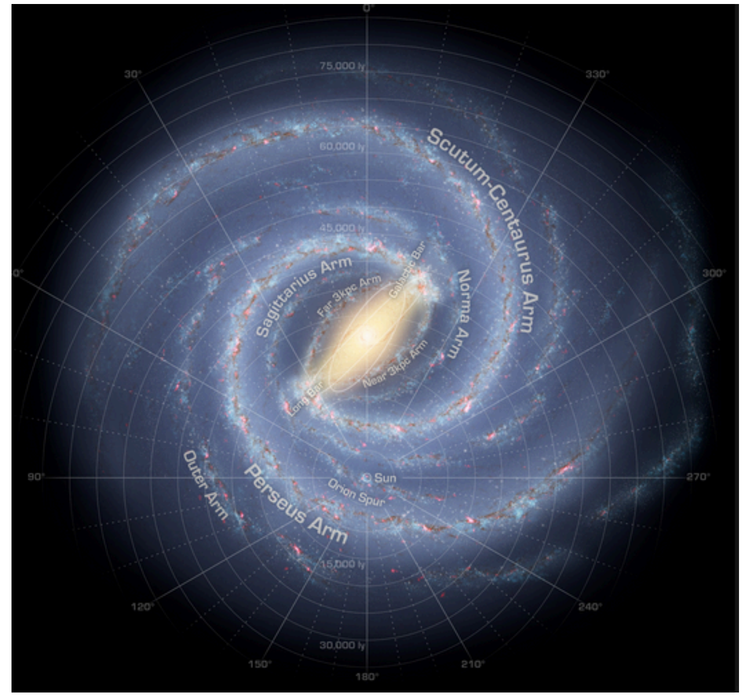
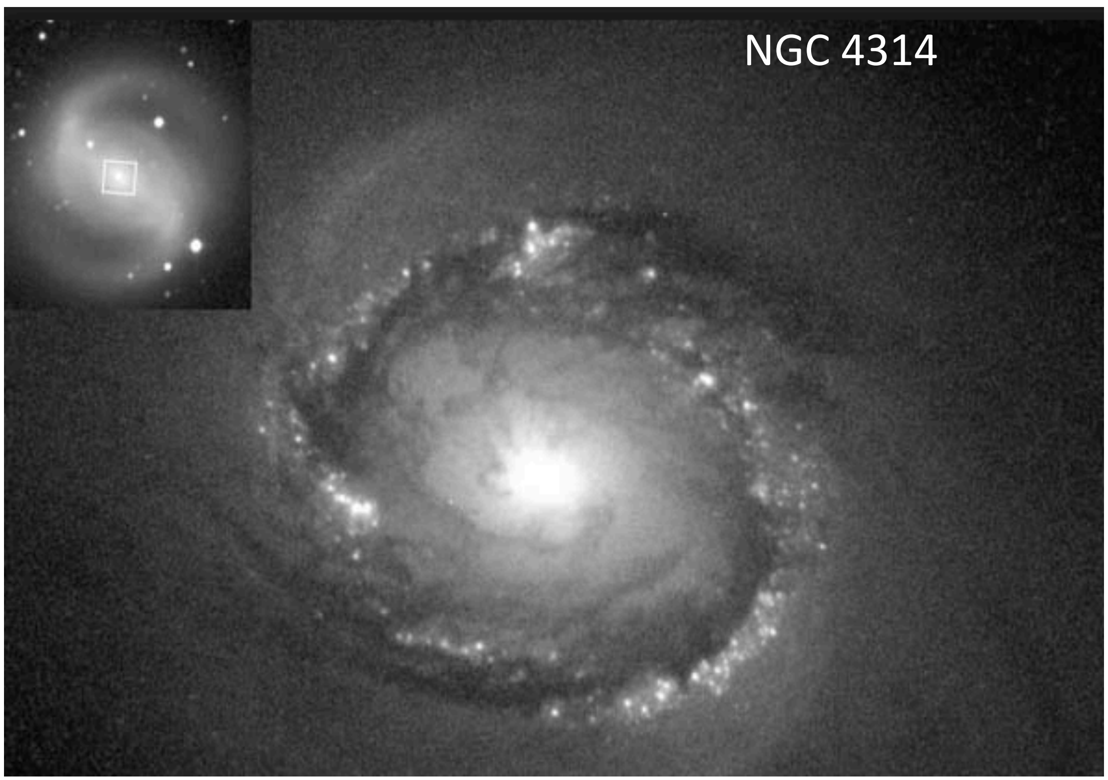


Figure 19.17 Numerical simulations of stars (*upper panels*) and gas (*lower panels*) in two interacting galaxies. One galaxy, tilted 71° to our line of sight, only appears in the second pair of panels. Each unit of the displayed, nondimensional time corresponds to 2.5×10^8 yr.

Some Examples

- Our own Milky Way has bars
- In some cases the fuel does not reach the center

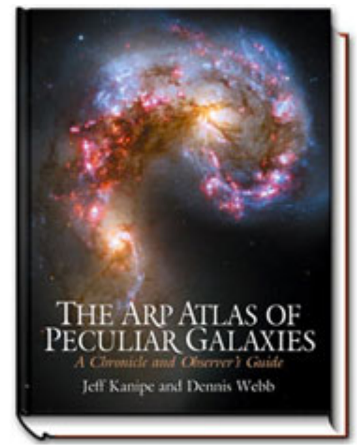


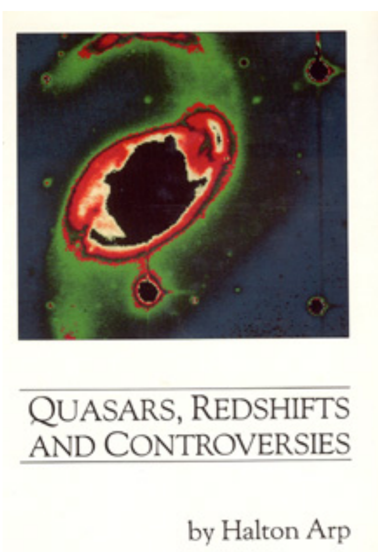


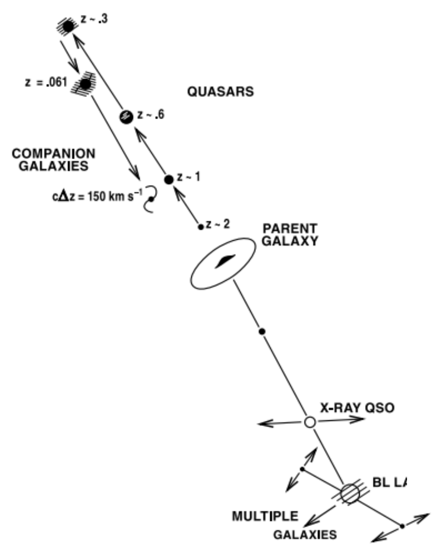
Arp Catalog

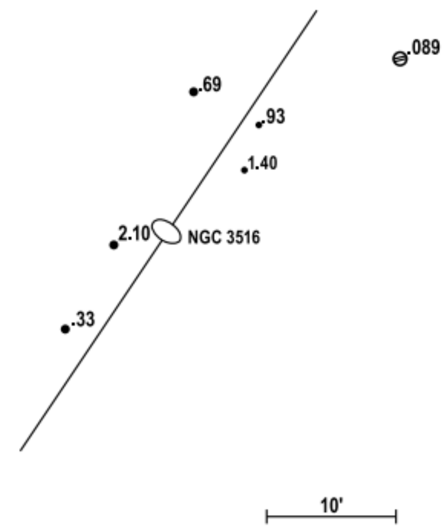
(…and Arp's second life)

- Halton Arp was the assistant of Hubble
- The atlas of peculiar galaxies
  - Arp 220, antenna, the mice, Stephan's Quintet, M82
- He also advocated that many quasars, supposed to be at high-z are actually associated to low-z galaxies
- *"…quasars are not the brightest, most distant and rapidly moving things in the observed universe - but they are among the youngest. "*









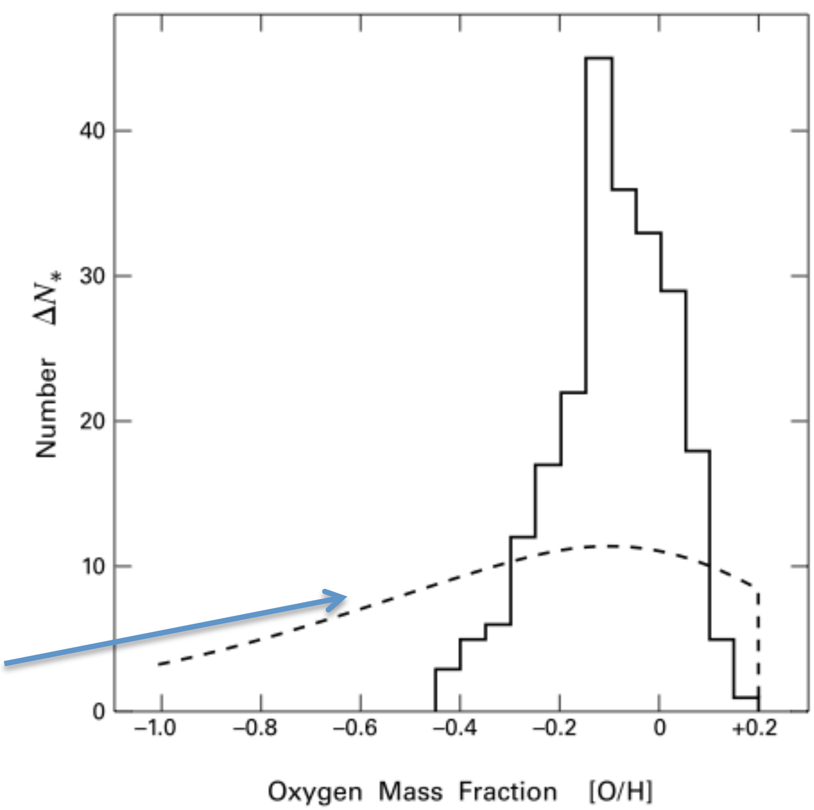
G-Dwarf Problem

- Star formation in our galaxy can be understood by looking at the metallicity of stars
  - Mass of heavy elements must slowly rises
  - G-type stars have life times of ~10^{10} yr
    - *There should be some very low metallicity stars around us*

- Conflict between theory and data
  - Not many low-Z stars

- Solutions ?
  - Early metal-poor stars were all massive and all exploded
  - Continue accretion of fresh gas

$$\frac{\Delta N_*}{\Delta[\mathrm{O/H}]} = \frac{\alpha_\odot\, x_O\, N_{\mathrm{tot}}}{\log e\,[1 - \exp(-\alpha_{\max})]} \exp(-\alpha_\odot\, x_O)$$



Readings

- Chapter 19 in `The Formation of Stars’
- Kennicut 1998