Evolution of Galaxies

Observatoire astronomique
de Strasbourg

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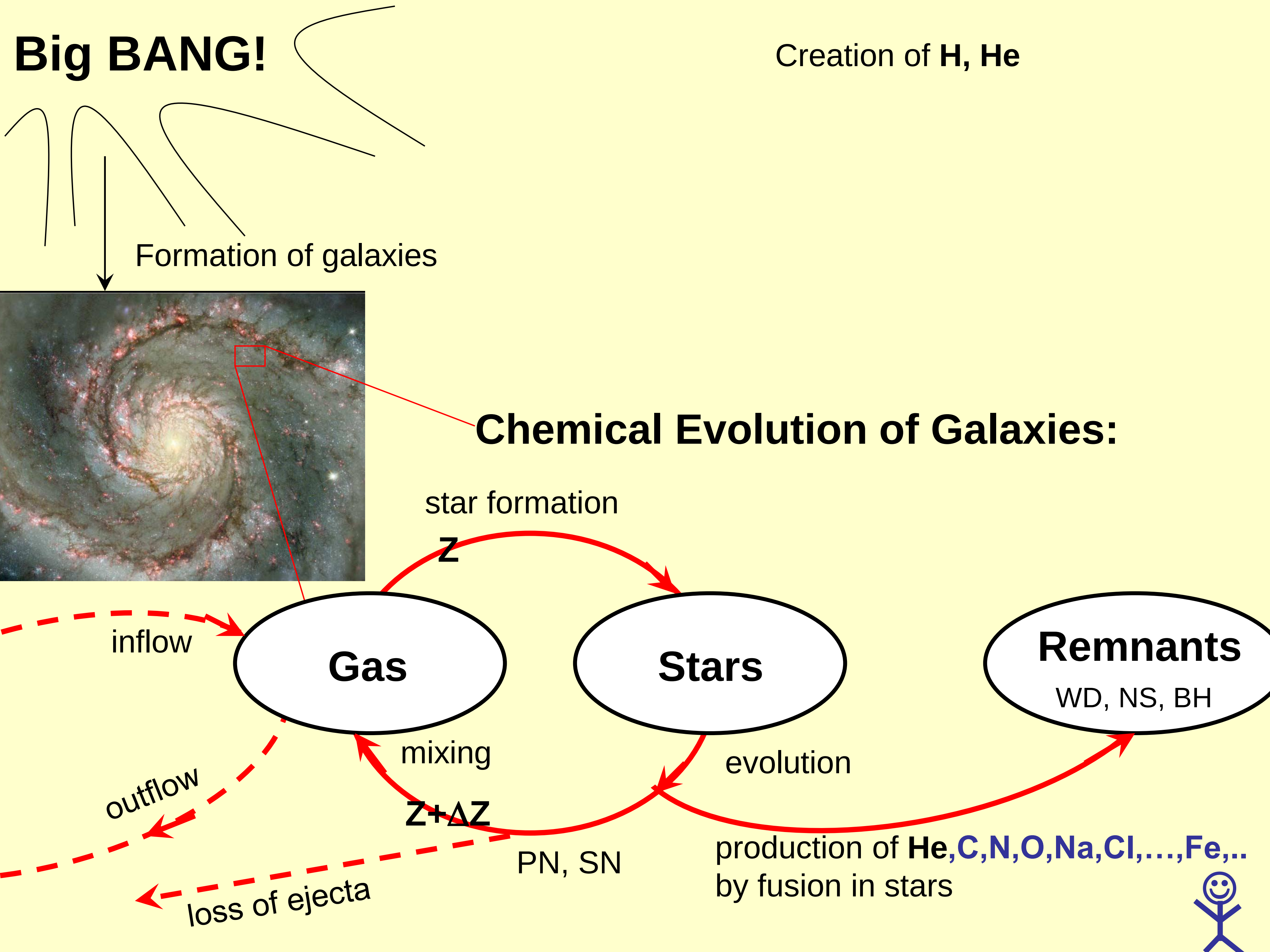
http://astro.u-strasbg.fr/~koppen/JKHome.html


Big BANG!
Creation of H, He
Formation of galaxies
Chemical Evolution of Galaxies:
star formation
Z
Gas
Stars
Remnants
WD, NS, BH
inflow
mixing
evolution
outflow
Z+ΔZ
PN, SN
loss of ejecta
production of He,C,N,O,Na,Cl,…,Fe,..
by fusion in stars

Overview

- Observed properties: Milky Way and galaxies
- Determination of abundances from gas
- Determination of abundances from stars
- Review of stellar evolution
- Nucleosynthesis in stars and the Big Bang
- IMF, SFR, SFH
- Chemical evolution: solar neighbourhood
- Abundance gradients, Mass-metallicity relation
- Galaxy formation, monolithic collapse
- The chemodynamical approach

Literature

- B.E.J.Pagel: Nucleosynthesis and chemical Evolution of Galaxies, Cambridge U.P. 1997, and 2nd ed. 2009
- J.Binney, D.Mihalas: Galactic Astronomy
- J.Binney, S.Tremaine: Galactic Dynamics

- R.Kippenhahn, A.Weigert: Stellar Structure and Evolution, Springer, 1990
- H.H.Voigt: Abriss Astronomie, Springer, 2012
- B.Baschek, A.Unsöld: New Cosmos, Springer
- G.Gilmore, I.King, P.van der Kruit: Milky Way as a Galaxy, Saas Fee 1989

Website for our course

- pdfs of lectures
- links to simulations
- infos

http://astro.u-strasbg.fr/~koppen/ue7b/

Evolution of Galaxies:

Observed Properties of Galaxies

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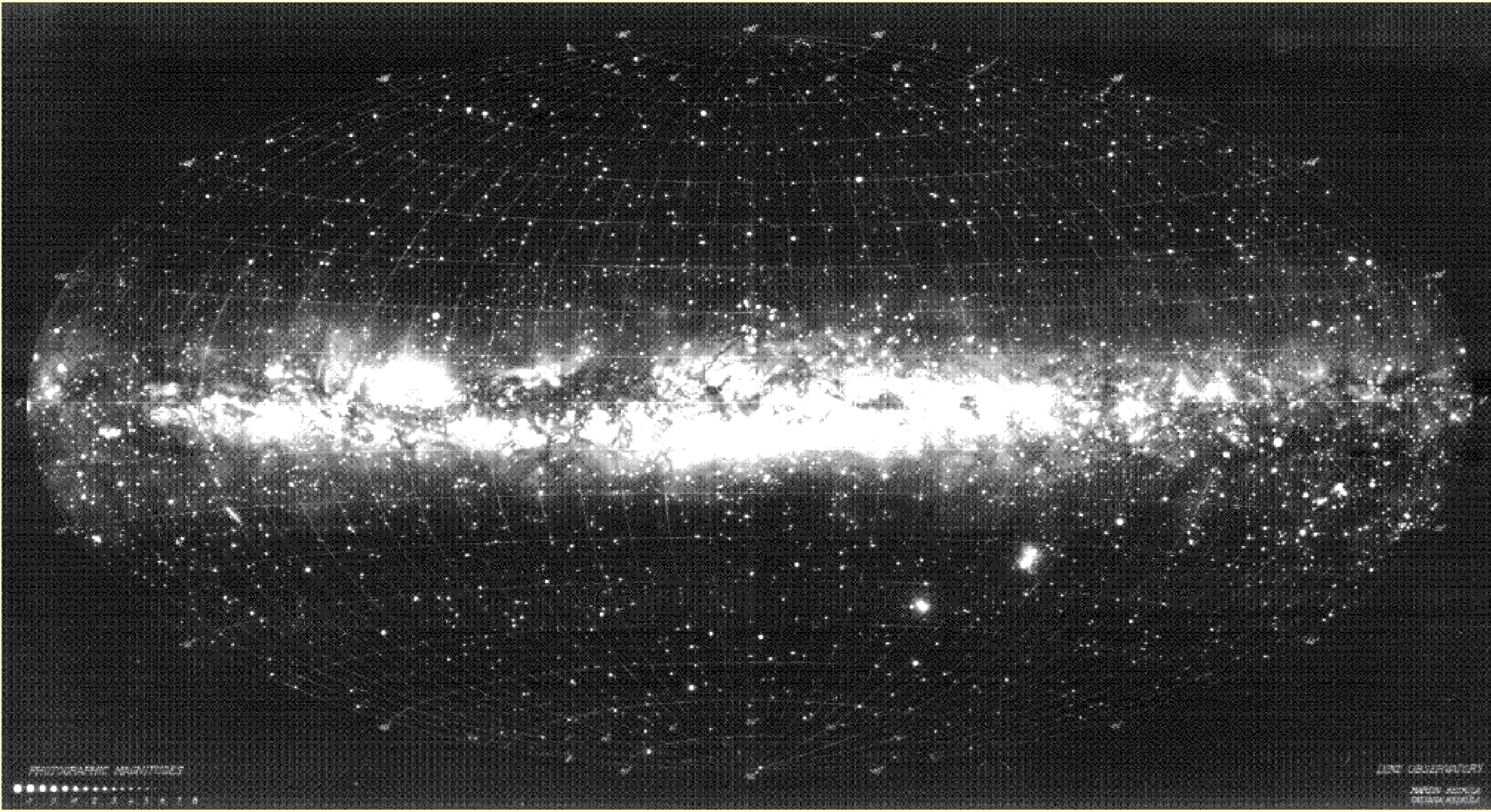
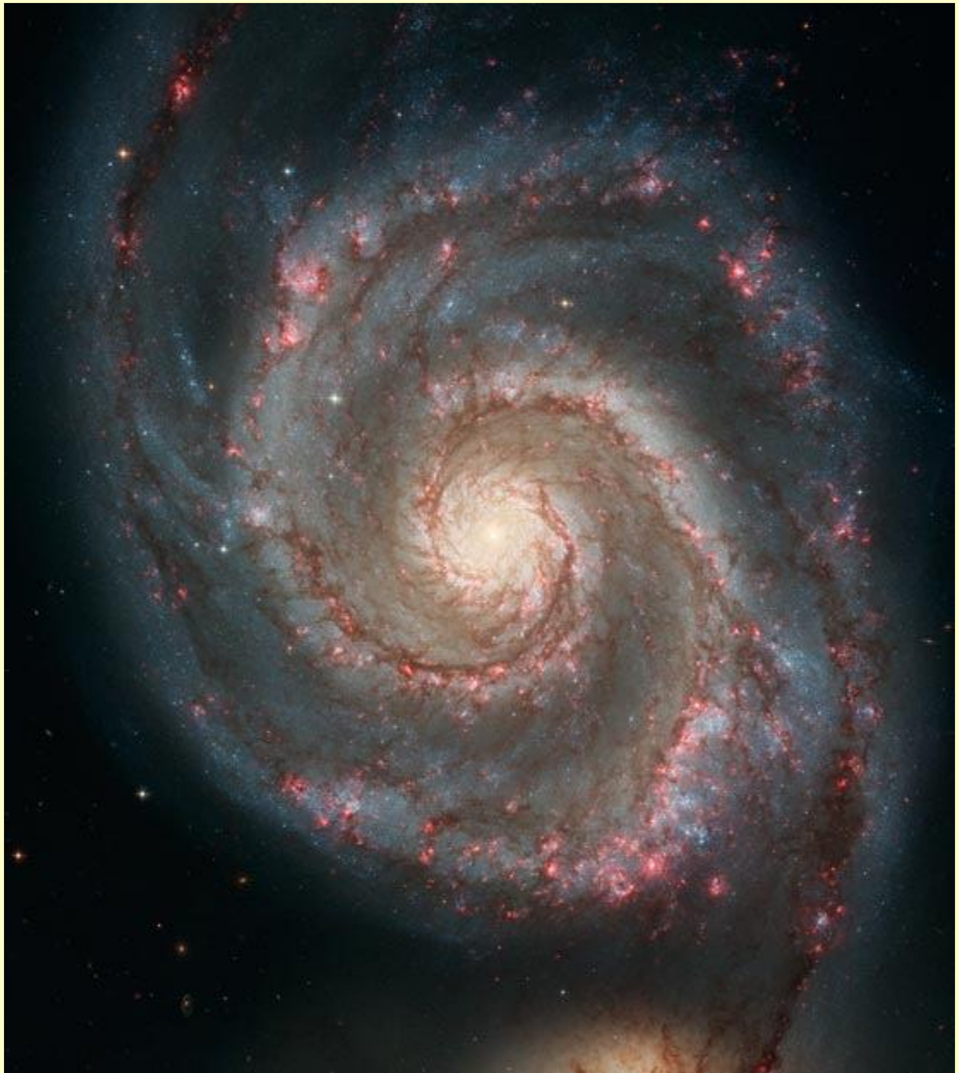
The Milky Way

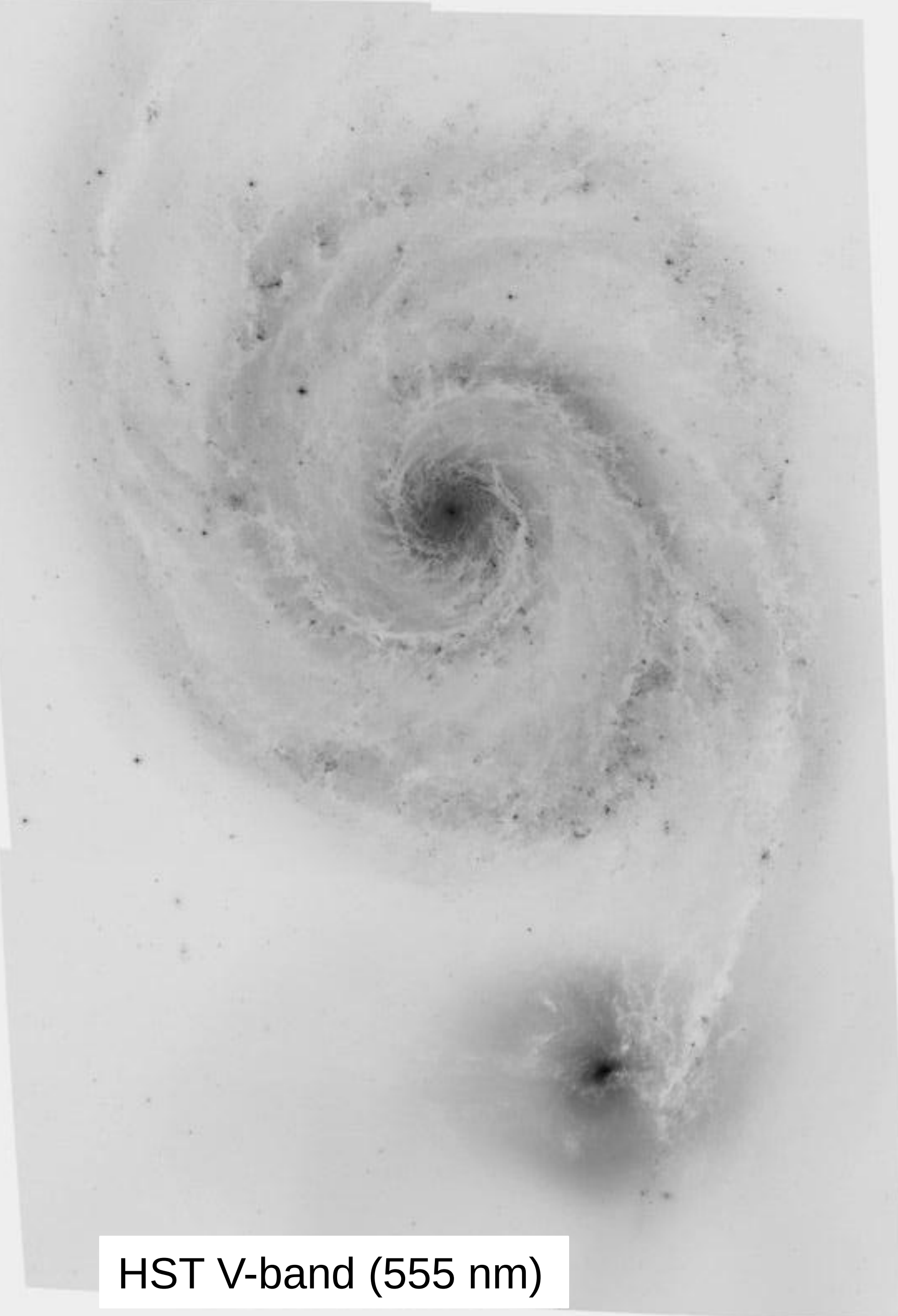


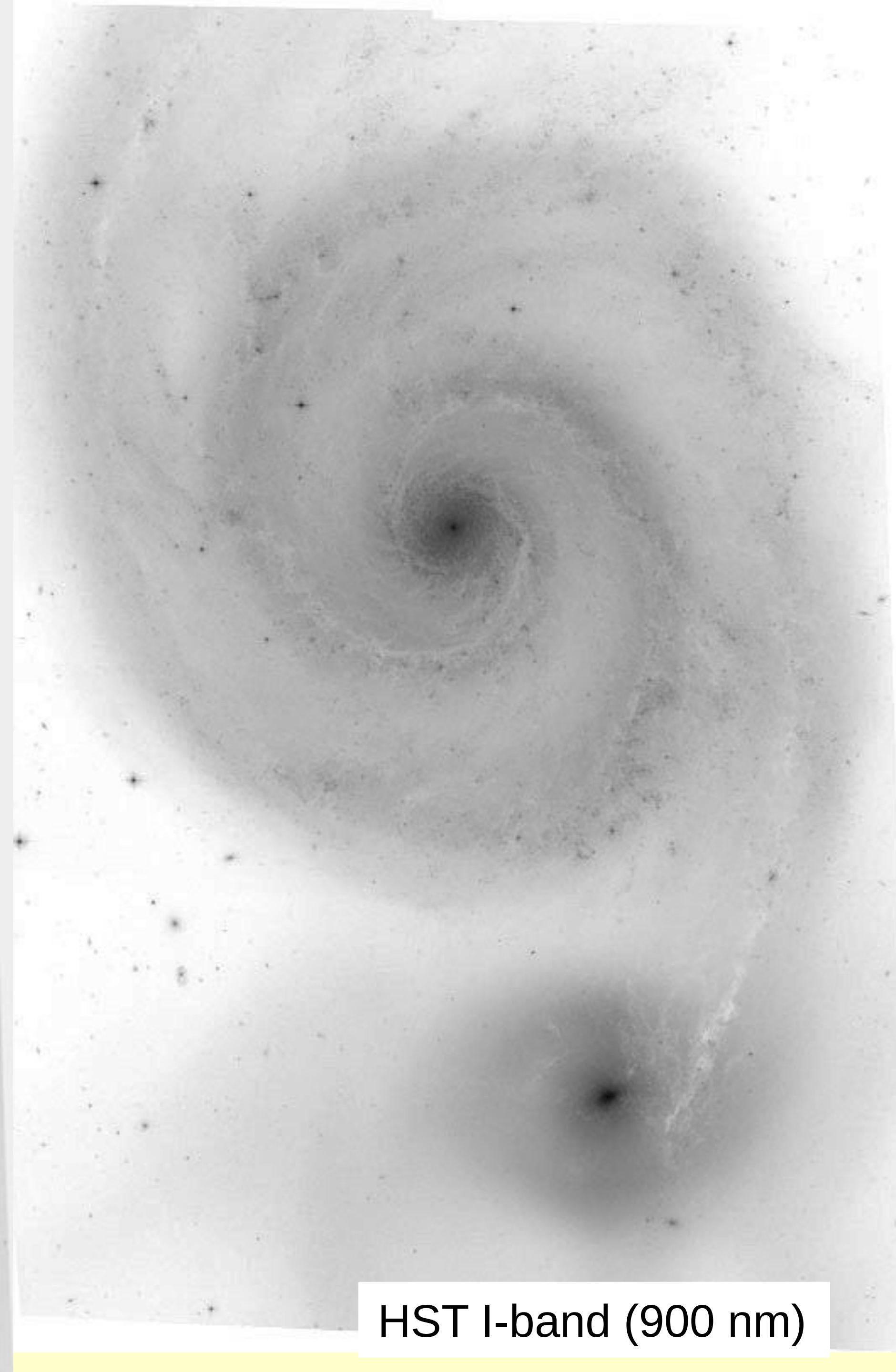
In galactic coordinates: l b

M51 or: if we could see the Milky Way from « above »

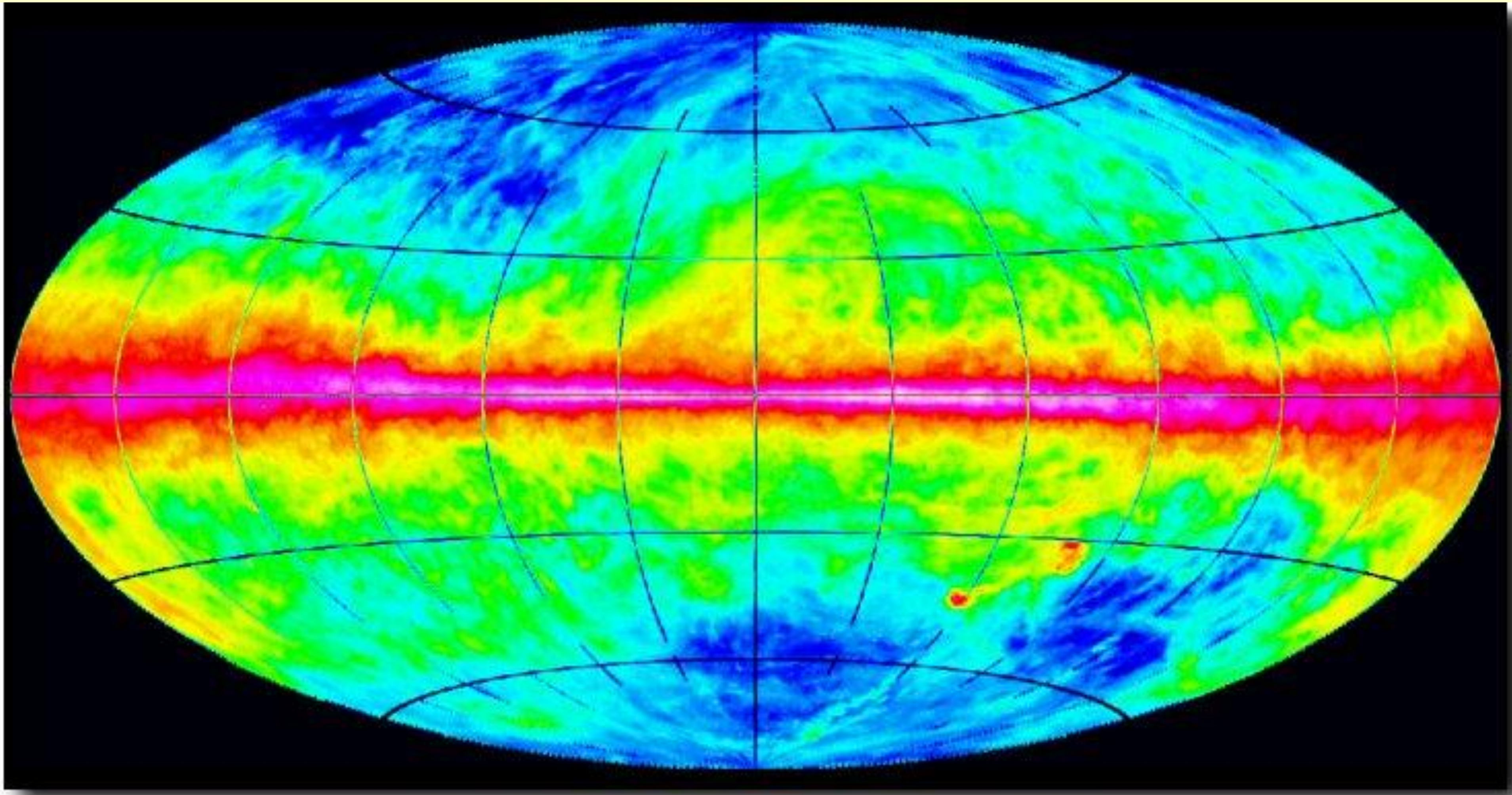


HST composite

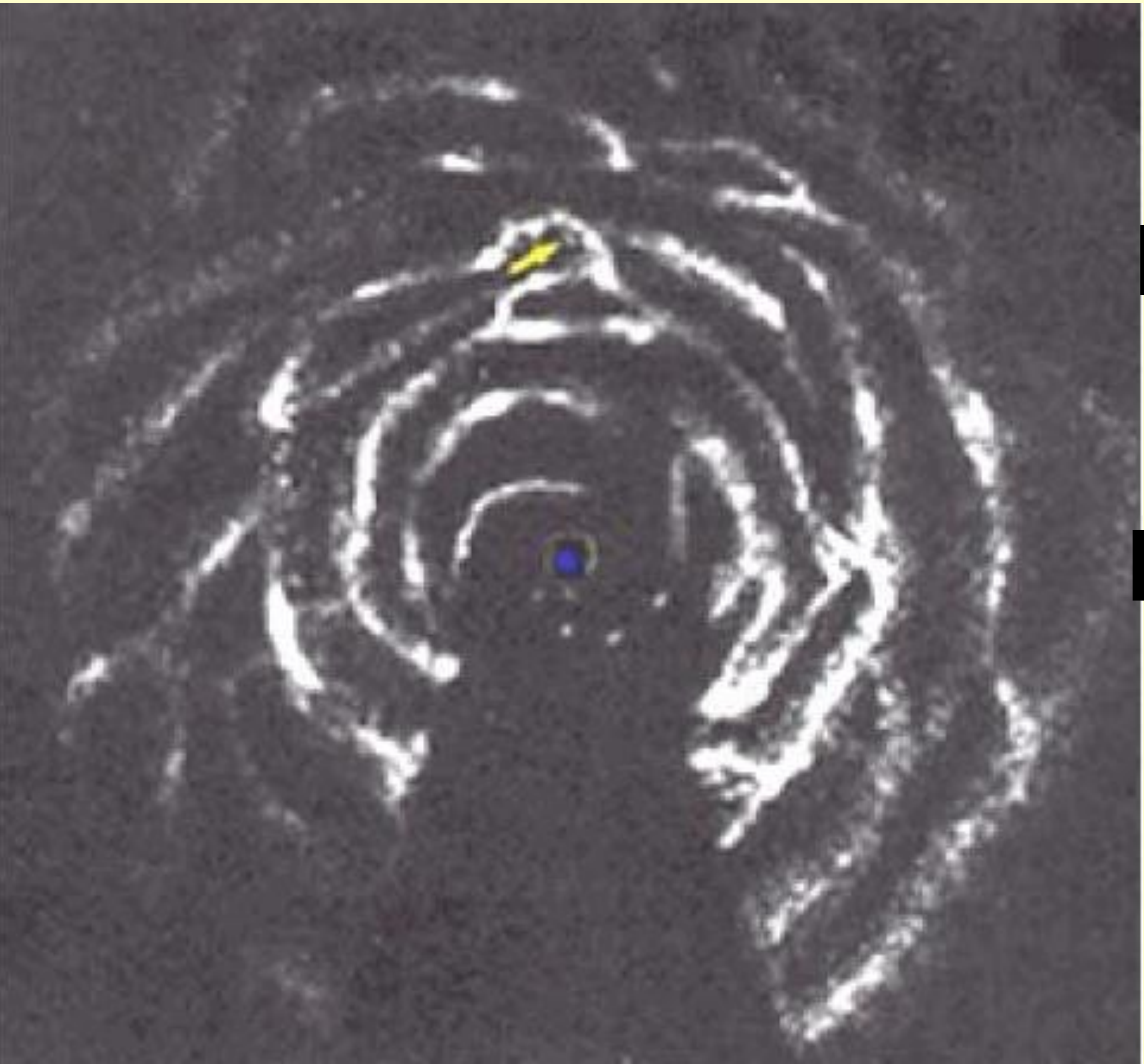

HST V-band (555 nm)


HST I-band (900 nm)

Our Milky Way at the 21 cm radio line from atomic hydrogen



HI is concentrated in spiral arms



Sun

Galactic Centre (Sgr A)

(Thin) Disk

- Stars: all types, but OB* in arms
- Gas: dust, molecular, neutral (enhanced in arms 3..5x); ionized (diffuse, HII regions in arms)
- Exponential density profile

  $\rho(r,z) \sim \exp(-r/R - |z|/H)$

  – Radial scale R

    3.5 kpc (stars, mol.gas) … 10 kpc (HI gas)

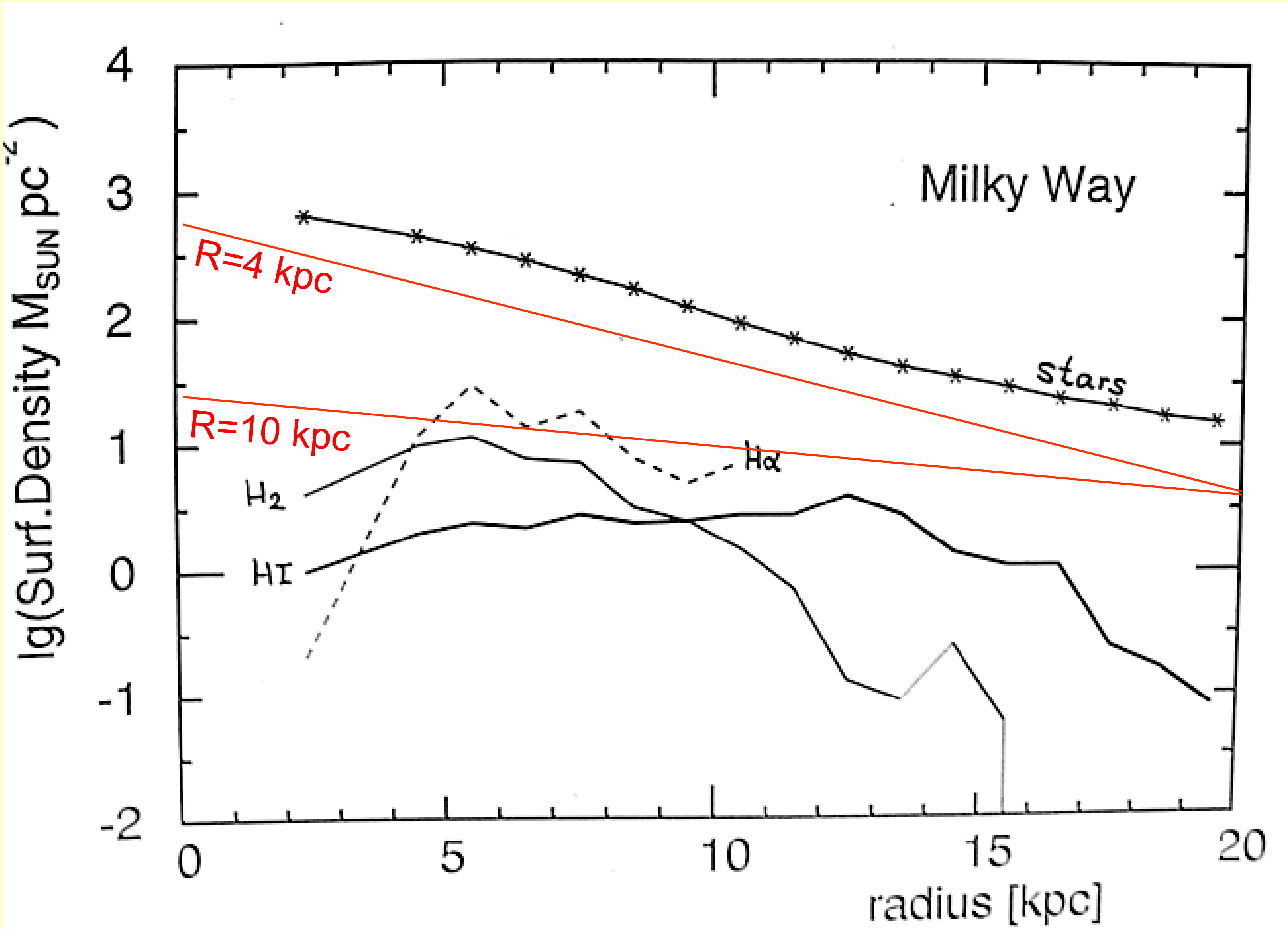
  – Scale height H

    140 pc (gas, HII, OB*, open clusters) …

    300 pc (KM*, PN) …

    500...1000 pc (ionized gas: Reynolds layer)

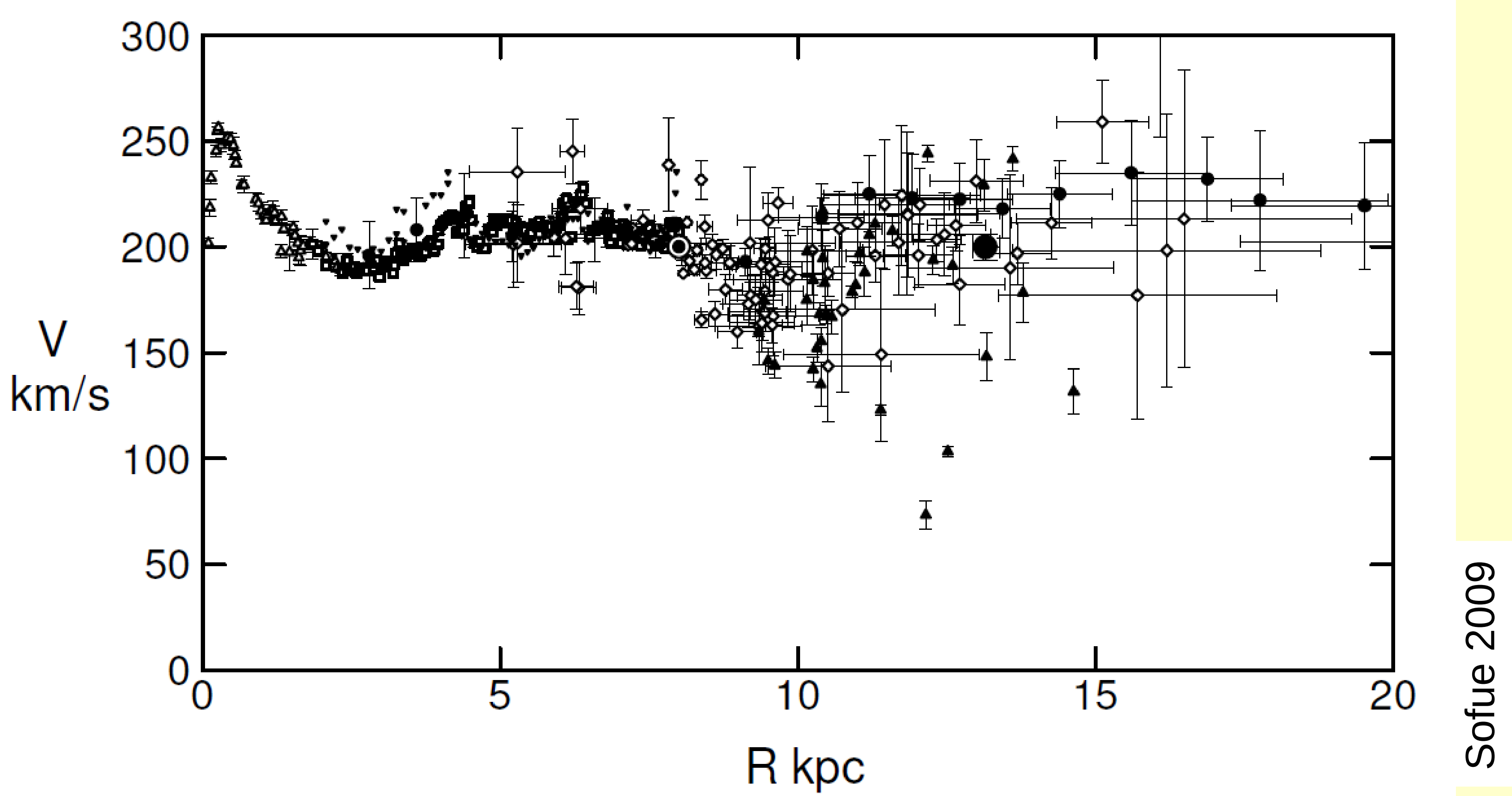
(Thin) Disk



Milky Way
stars
R=4 kpc
R=10 kpc
Hα
H2
HI
lg(Surf.Density MSUN pc-2)
radius [kpc]
4
3
2
1
0
-1
-2
0
5
10
15
20

(Thin) Disk

- Rotation: from 21cm HI line (1970ff)
  - ‘flat’ (differential) rotation 200 km/s



(Thin) Disk

- Rotation:
  - period 200 Myr near Sun
  - Keplerian circular orbits:

$$\mathrm{v} = \sqrt{\frac{GM}{r}} \propto r^{-1/2}$$

  - Solid body rotation (constant angular speed):

$$\mathrm{v} = r\omega \propto r$$

(only in the innermost 1 kpc)

(Thin) Disk

- Rotation:
  - Spherically symmetric mass distribution:

$$\mathrm{v} = \sqrt{\frac{GM(r)}{r}}$$

M(r) = mass inside sphere of radius r

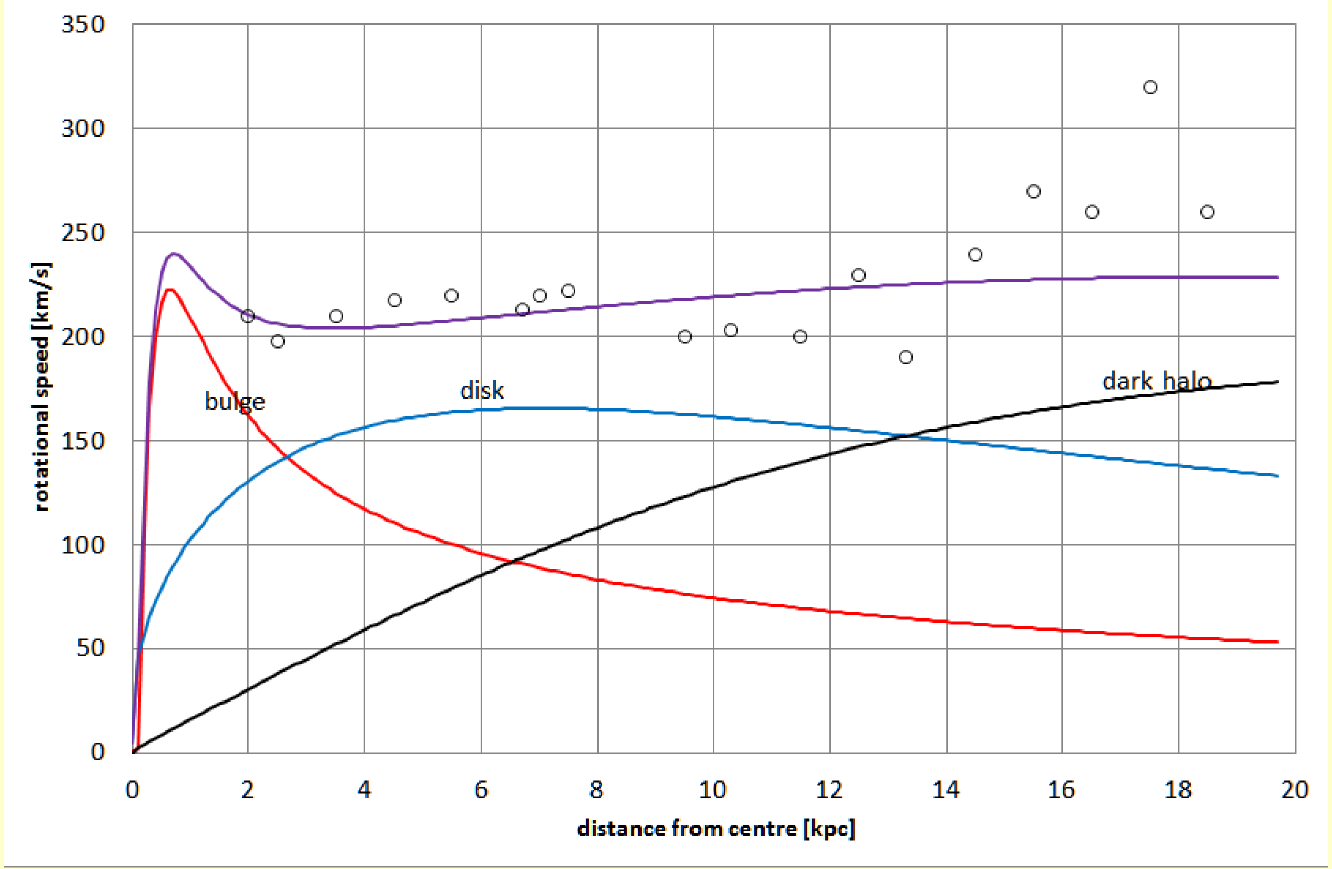
  - To get flat rotation curve, we would need

$M(r) \propto r$ or $\rho(r) \propto r^{-2}$

  - M31: v(16 kpc)=230 km/s ➔ M(16) = $2\ 10^{11}$ Msun

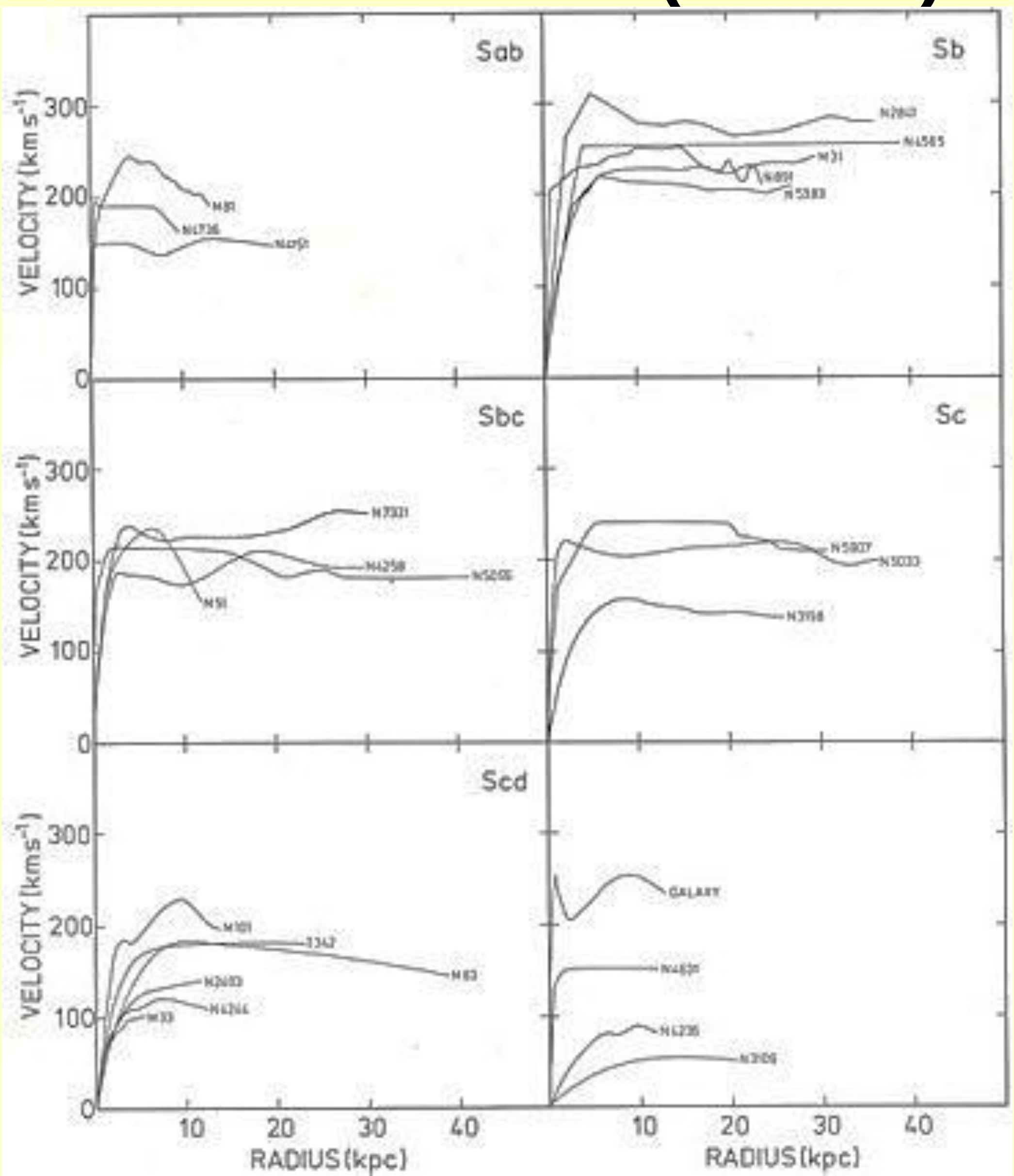
(Thin) Disk

- Rotation:
  - More elaborate modeling (Bahcall&Soneira,Robin et al.) with disk(s), spherical bulge&halo ➔ invisible (‘Dark matter’) spherical halo M(100 kpc) > 10^{12} Msun



Example of simple decomposition

(Thin) Disk



- Rotation: 'flat' rotation curves are found in all normal spiral galaxies – the Galaxy is not special!

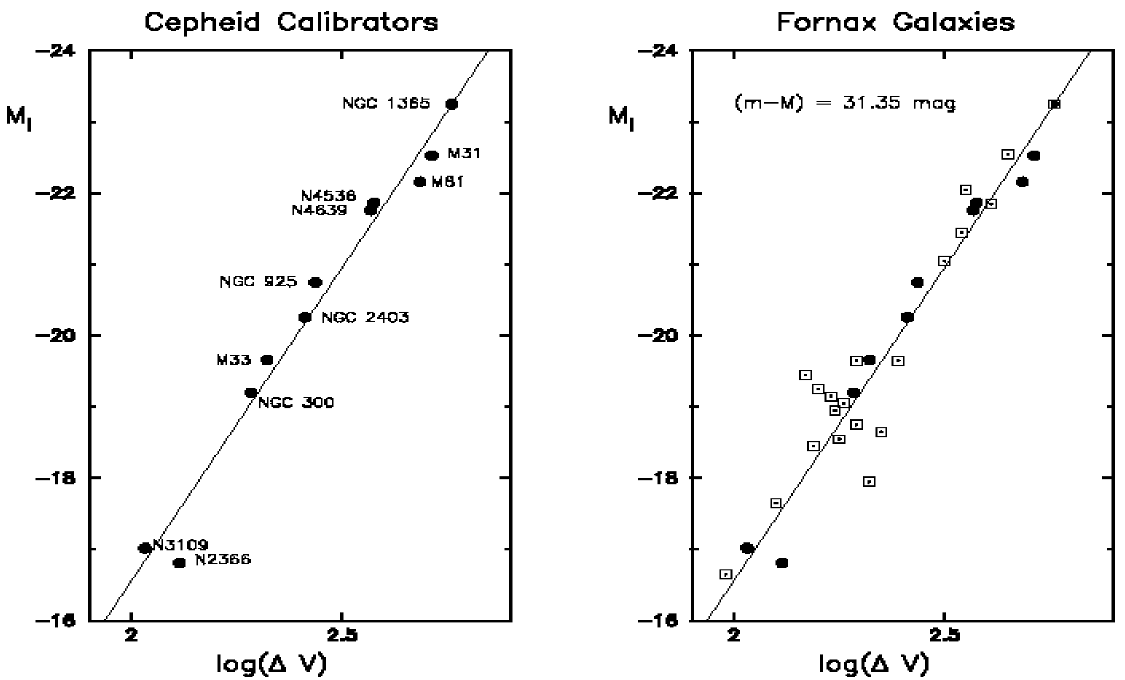
A.Bosma 1979

(Thin) Disk

- Rotation:
  - Tully-Fisher relation (1977)

$$(\Delta\lambda)^2 \propto v^2 \propto \frac{M}{R} \propto \frac{L_B}{R} \propto \frac{\textbf{distance}^2 * \text{Flux (= appar.brightness)}}{\text{(size/distance)} * \textbf{distance}}$$

(size/distance) = angular size



IPAC

(Thin) Disk

- Vertical velocity dispersion
  - << rotation speed ('rotationally supported')
  - σ_W = 1 ... 5 ... 10 ... 20 ... 40 ... km/s

    gas OB* A* $_{\text{weakline}}$F…M*

    $_{\text{strongline}}$F…K*

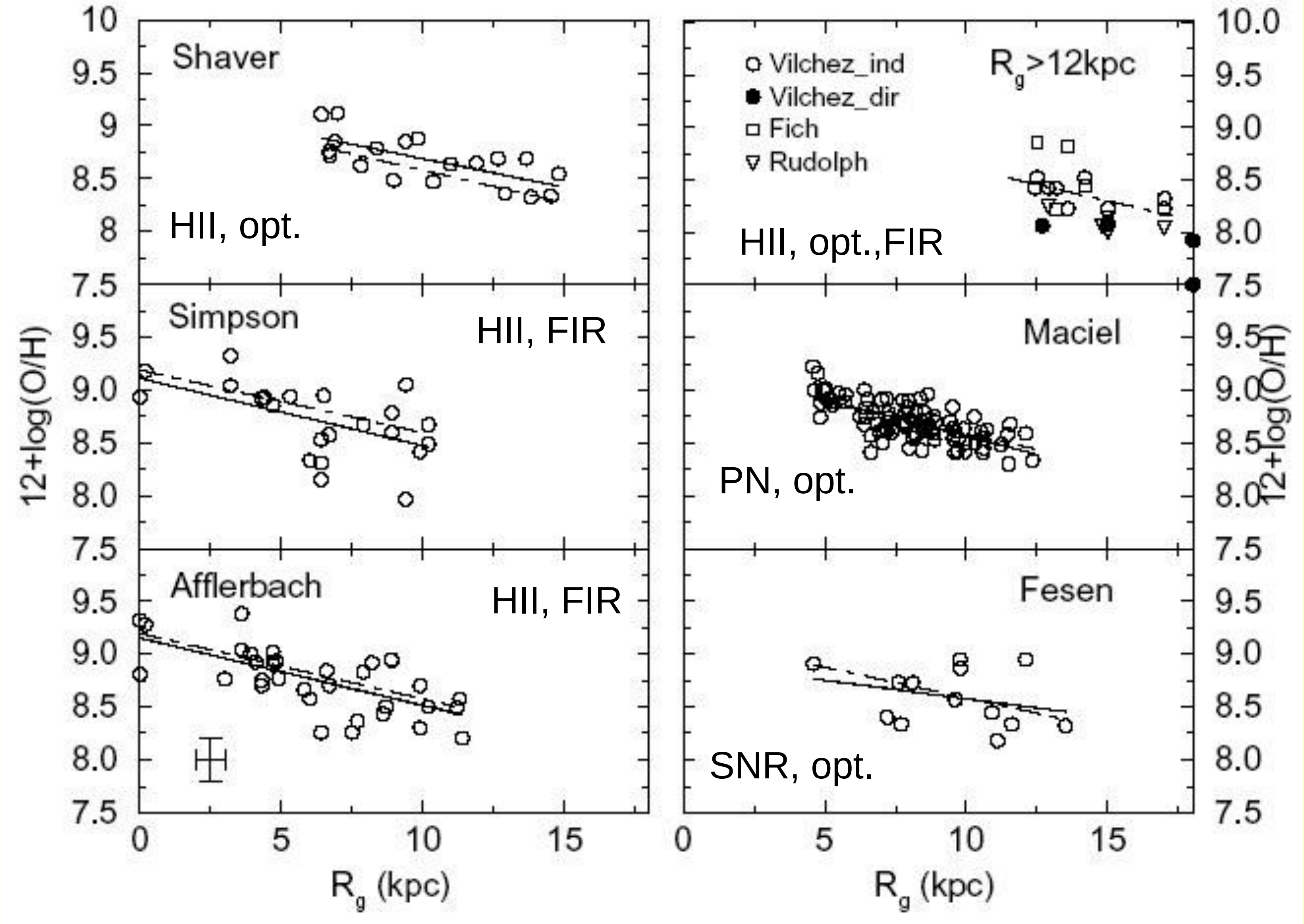
    open clusters

(Thin) Disk

- Metallicity
  - measured as O/H from gas (HII regions) and as [Fe/H] from stars
  - gas, B*: ½ solar,

    radial gradient -0.07 dex/kpc in O/H
  - stars: 1/10 … 1 solar

O/H abundance gradient



Thick Disk

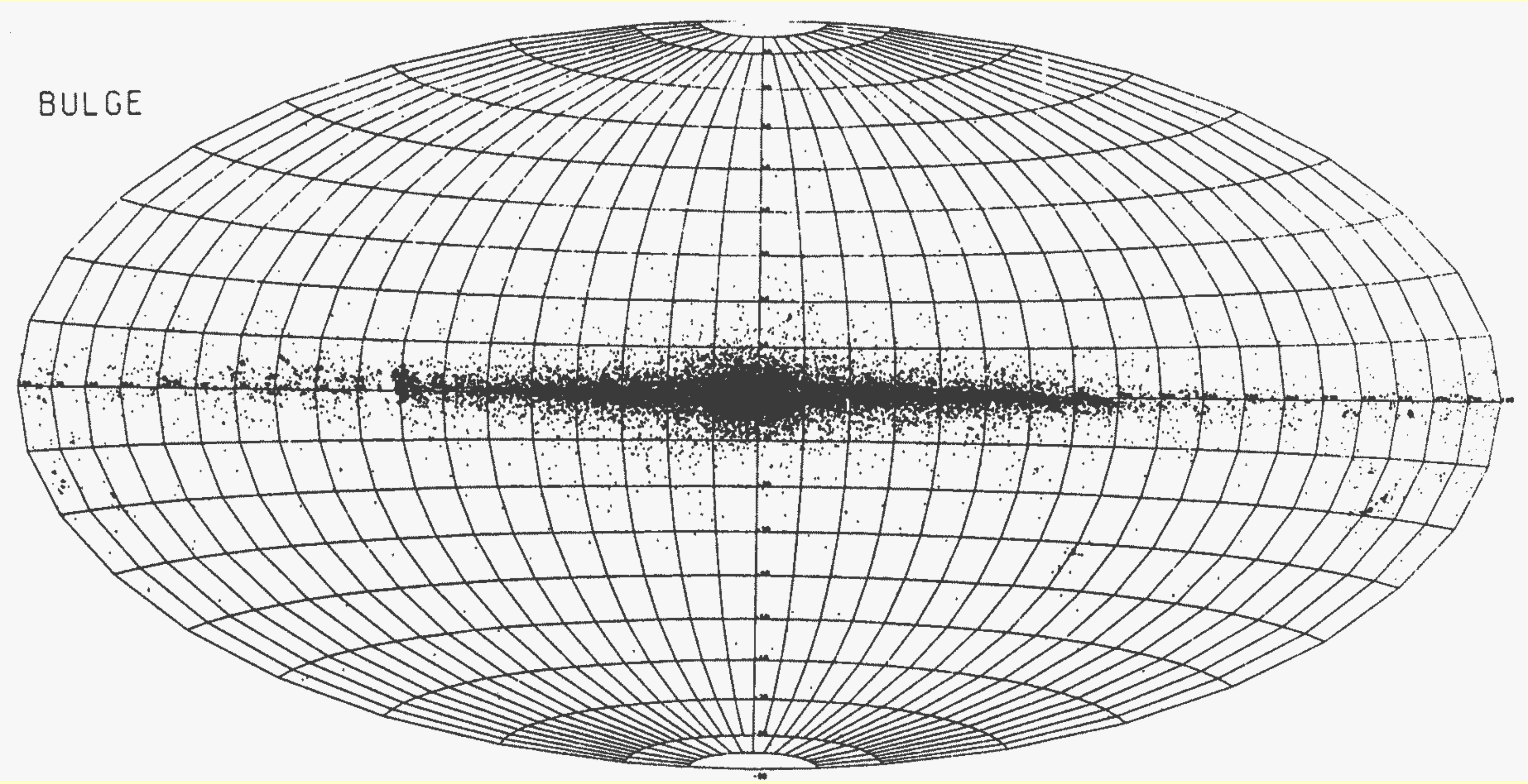
Mass: about 10% of thin disk

- Stars: 10..12 Gyr old
- Radial scale: like thin disk?
- Scale height: ~1 kpc
- Rotation: 30..50 km/s slower than thin disk
- Velocity dispersion: 30..50 km/s
- Metallicity: [Fe/H] ~ -1.2 .. -0.6
  - No strong radial gradient (but Si/Fe and Ca/Fe have +0.03 dex/kpc (???))

Thick Disk: possible origins

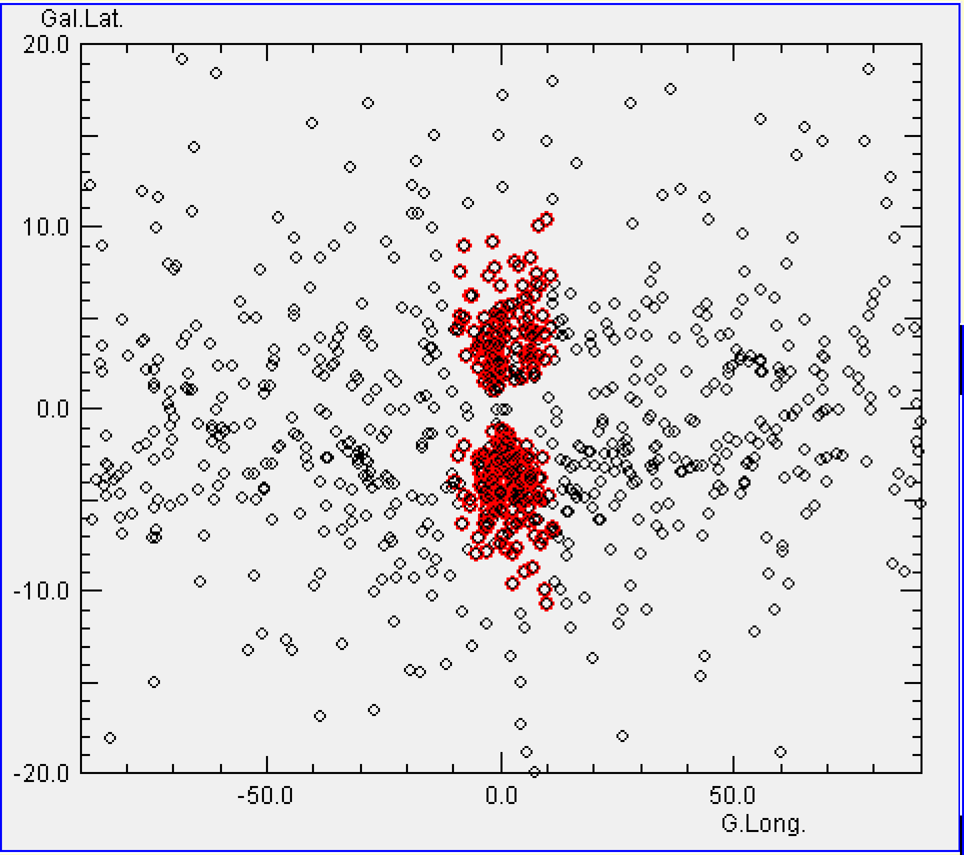
- Single event (merger, interaction) heats up thin disk
- Continuous heating of thin disk
- Deposition of low-Z stars from torn-up satellite galaxies
- Radial migration of stars

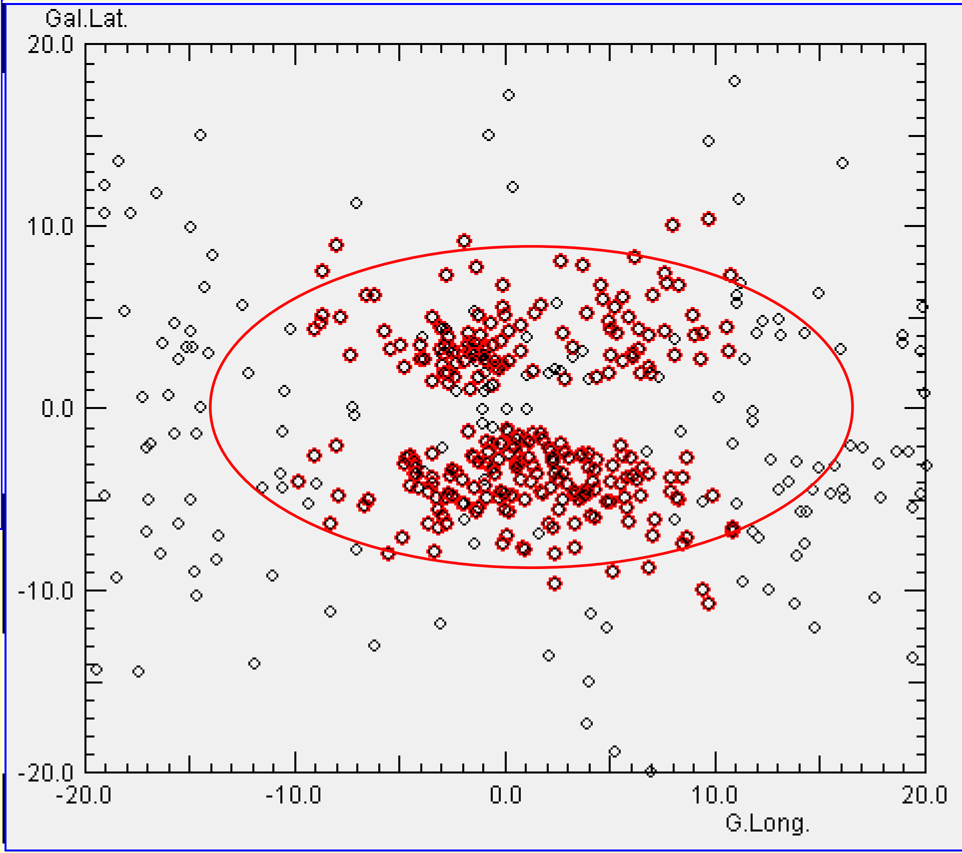
Bulge (and disk) stars



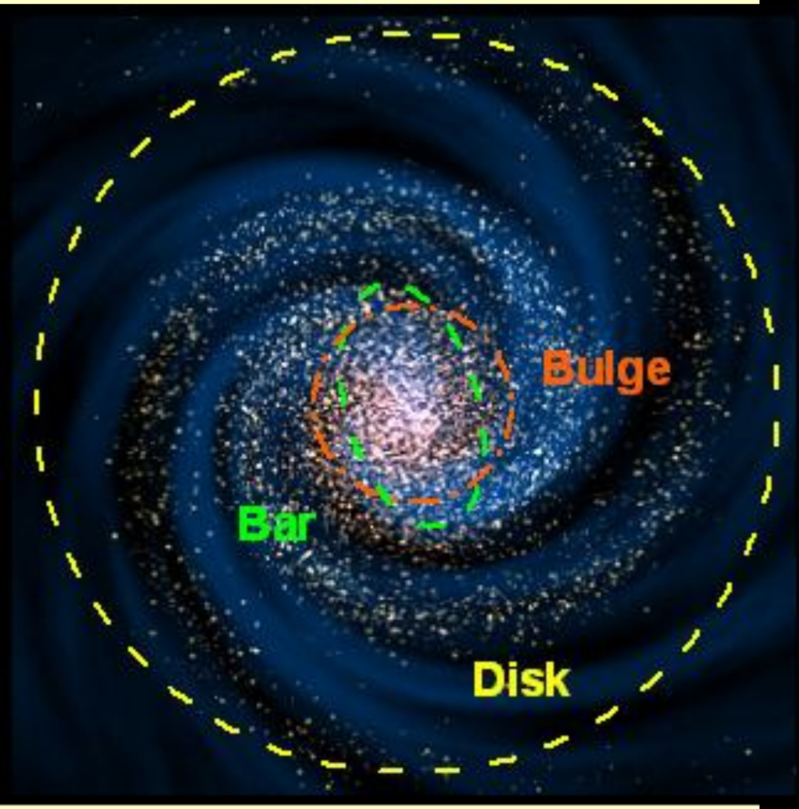
Stars detected at 12 and 25 µm (Habing 1985)

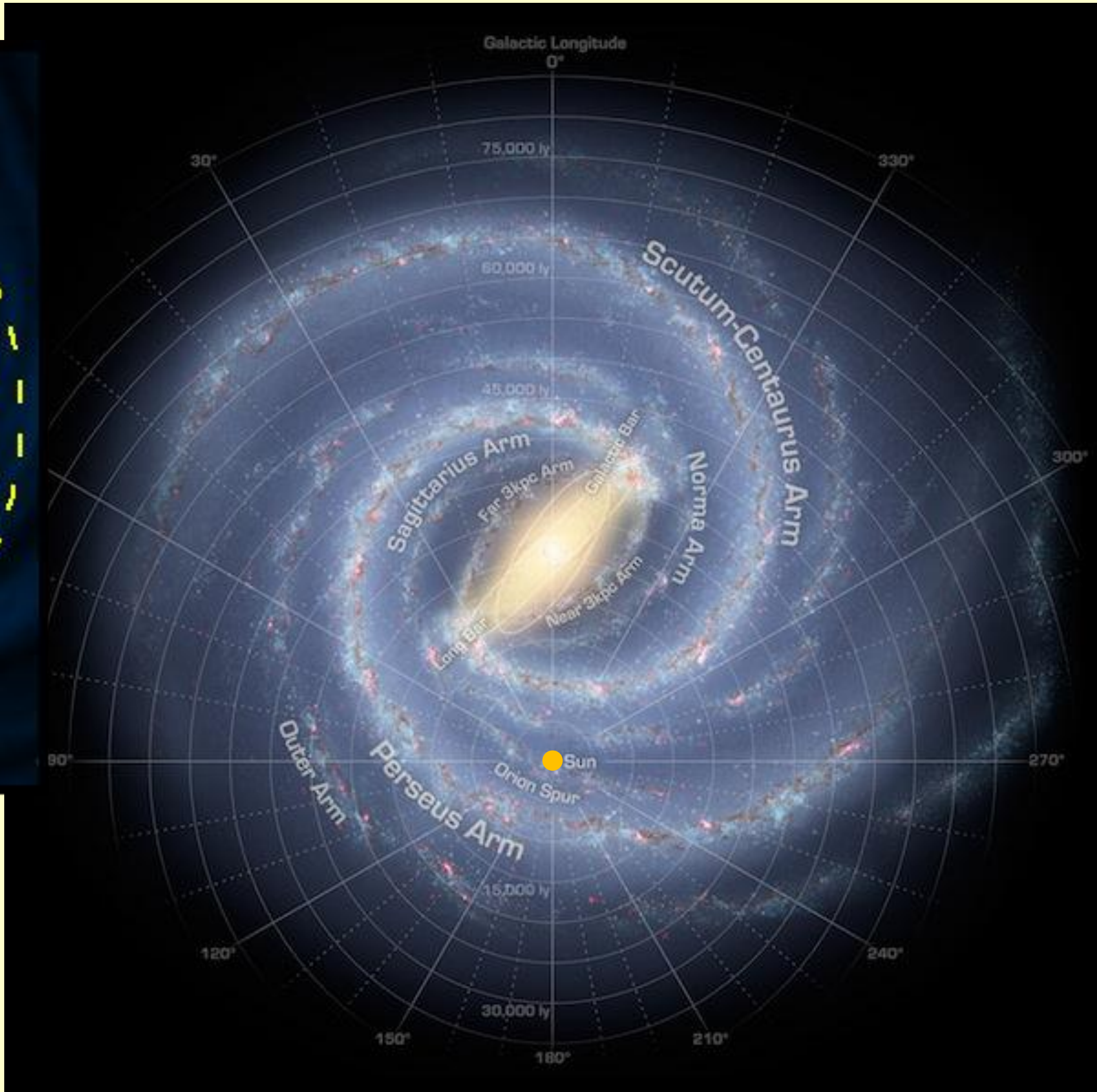
PN: Bulge and Disk



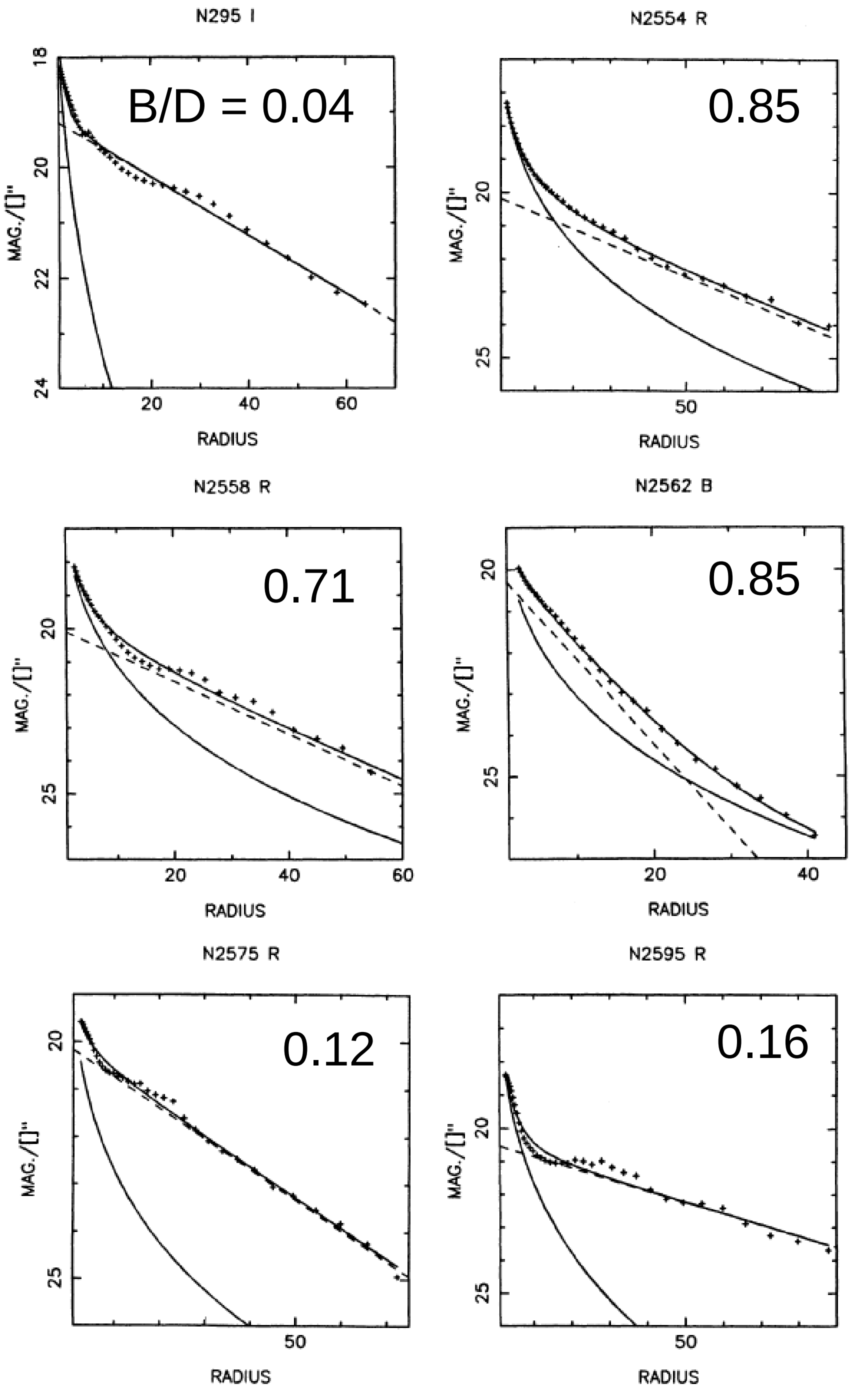


Artists' conceptions:





Disk/Bulge separation in external galaxies

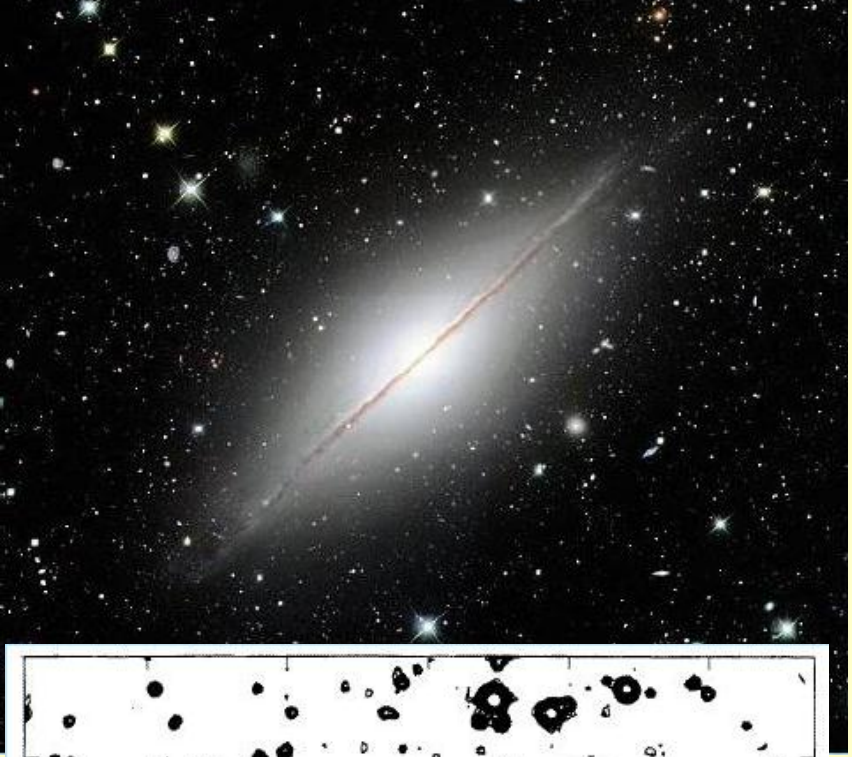


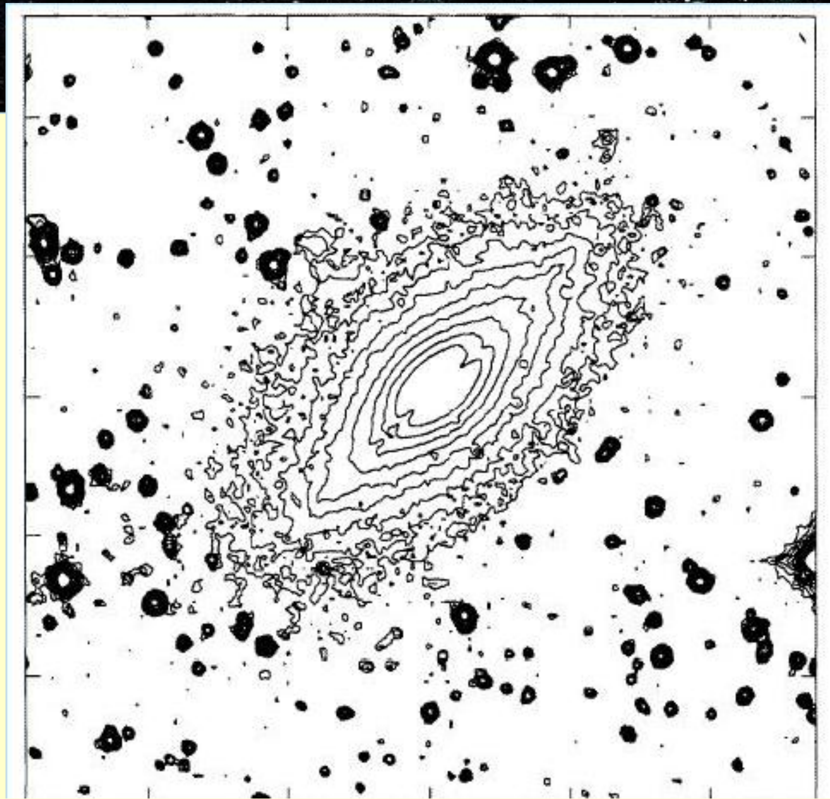
Assume:

- exponential profile for the disk
- r^(-1/4) profile for bulge

Try to get best fit

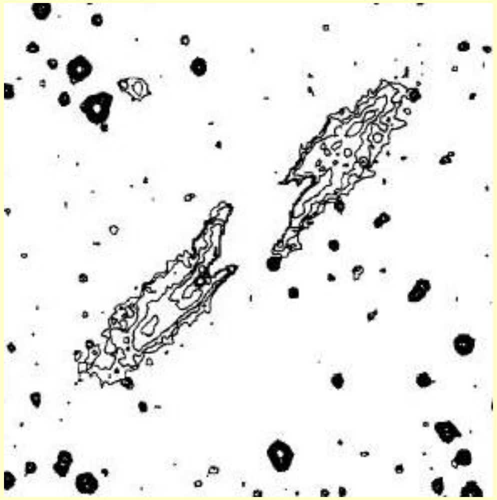
Schombert & Bothun 1987





Disk/Bulge separation in external galaxies

… also in 2D: subtract bulge model to get the disk



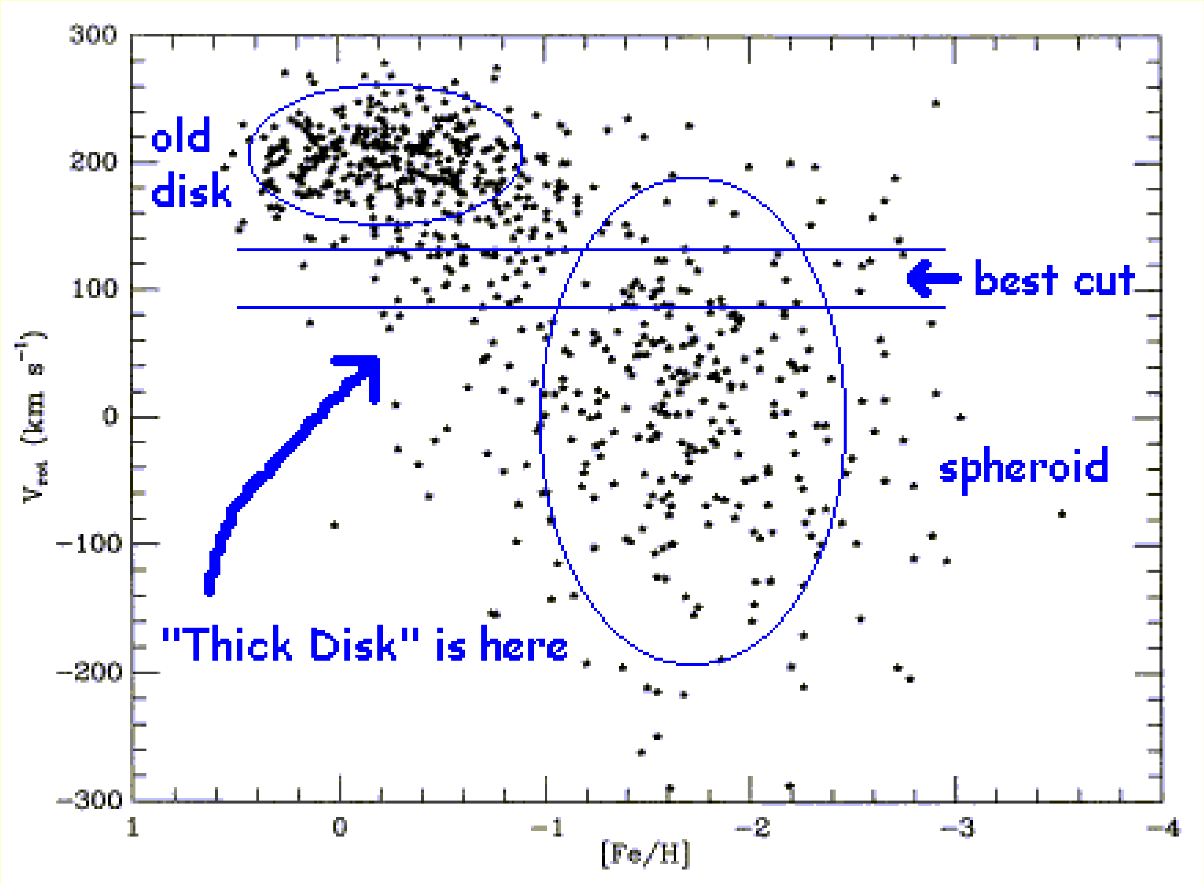
Van der Kruit 1987

Bulge

- Stars: red = evolved, metal-rich
- Spheroidal shape (1:0.7 axis ratio) < 1kpc
  - Prolate ellipsoid (20° towards Sun)
- Rotation: none
- Velocity dispersion: ~250 km/s (PN)
- Metallicity:
  - K-giants [Fe/H] = -0.7 … +0.7
  - PN: <[O/H]> ~= <[O/H]>$_{disk}$ ~= -0.3

Halo

- Stars: weak metal lines, high radial velocity, no gal.rotation, vel.disp. 100 km/s; globular clusters (age > 10 Gyr)



Carney 1990

Halo

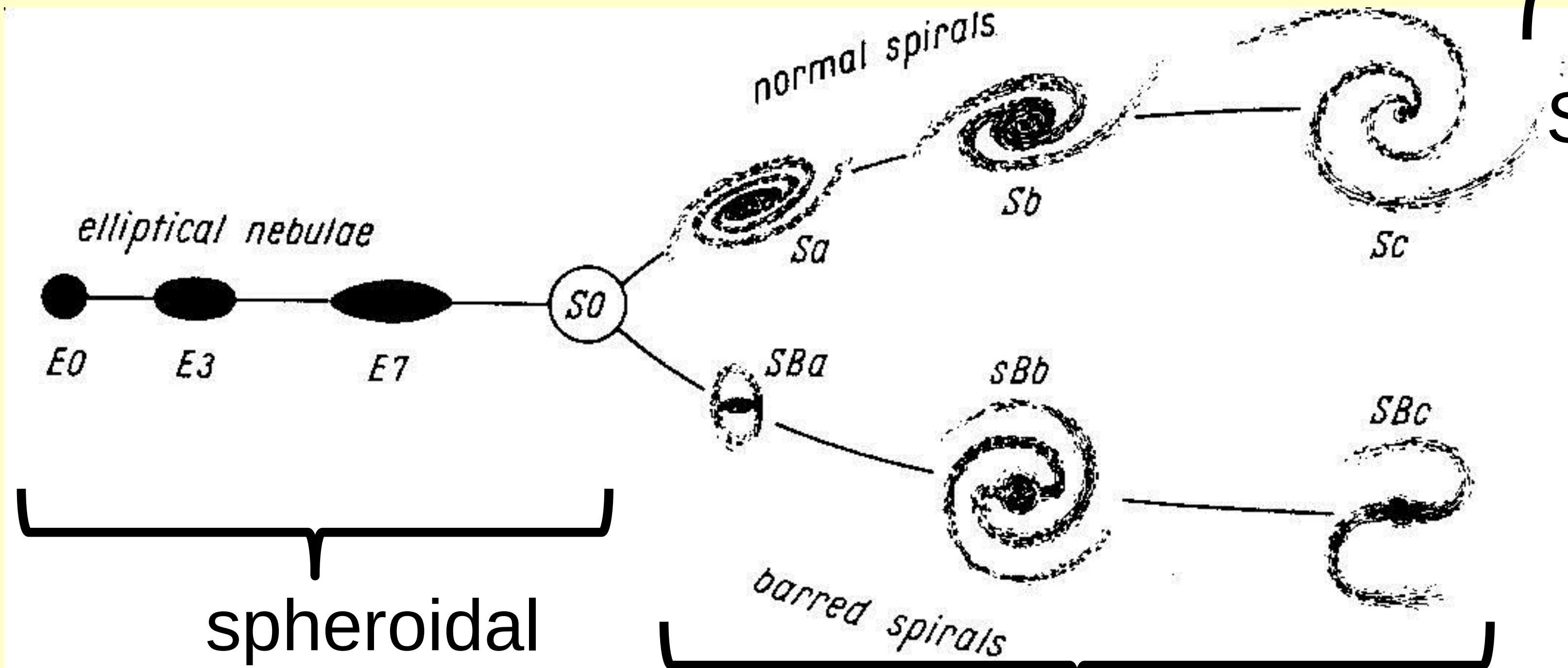
- Gas:
  - Ionized, metal-rich: expelled from disk ('galactic fountain')
  - HVC: high velocity HI clouds (distances? relation to LMC?)
- Spherical shape:
  - strong concentration to Gal. Centre $\rho(r) \sim r^{-3}$
  - 2 kpc mean height above Gal.plane
- (stellar) Metallicity: [Fe/H] < -1 … -1.5

Populations (Baade 1944)

objects	**Glob.clusters, halo stars**	**F..M stars, PN**	**OB stars, open clusters,T Tau**
<z> [pc]	2000	300	100
Concentr.to centre	strong	middle	none
Galactic rotation	no	yes	Yes
Vert.vel.disp.[km/s]	100	30	<10
[Fe/H]	-2 … -1	-1.5 … -0.5	0.0
Age [Gyr]	10	2 … 10	< 0.5
	Population II		**Population I**

Morphological Classification

Hubble's Tuning Fork (1926, 1936):



deVaucouleurs

Sd Sm Im

IBm

spheroidal

disk + bulge

tightness of spirals

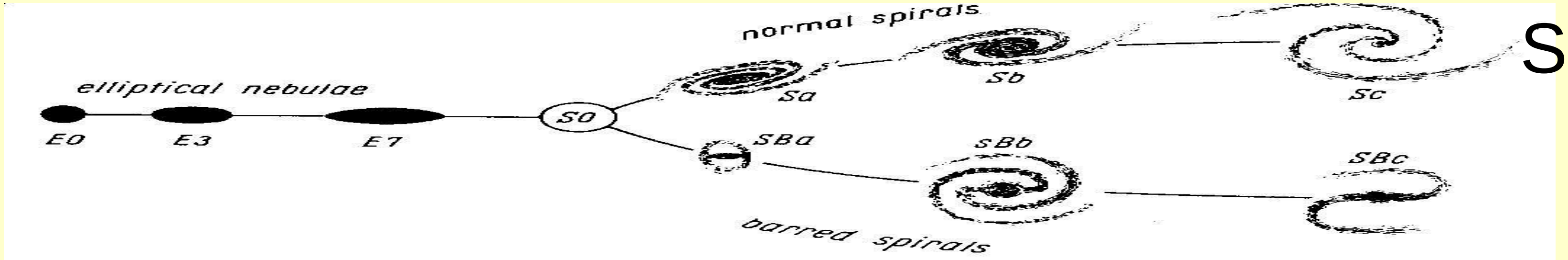
bulge/disk ratio

Systematic behaviour

'Early Type Galaxies' 'Late Type Galaxies'

deVaucouleurs' T-class

T = -5 ………………….. -2 ……1 ………… 3 ……………….. 6 ……………… 10



Sd Sm Im

IBm

Integrated colour:

red ----------------------------------monotonic------------------------------------- blue

Integrated spectral type:

late (K) ………………………………………………………………….. Early (<A)

HI gas:

no no no lowish high

Metallicity:

high low

Star formation:

no no no weak strong

useful other terms

- Morgan’s cD galaxies: big, rotationally symmetric, featureless, near centre of rich clusters (environment determines evolution)
- Elmegreen’s classification of spiral arms
  - Grand design = long, symmetric, sharply defined arms
  - Flocculent = ragged, patchy, chaotic
- Lenticulars (=S0, SB0): prominent disk (exp.profile!); no gas, OB*, dust, spiral arms;
  in the field: 10% but in clusters: 50% (environment!)

Elliptical Galaxies

- Smooth appearance, isophotes are concentric ellipses $\varepsilon = (a-b)/a = 0 \ldots 0.7$
- Radial profiles: surface brightness I(r) =
  - $(R_H/(R_H+r))^2$ Hubble
  - $\exp(-(r/r_0)^{-1/4})$ deVaucouleurs
  - $((1+\frac{r}{r_c})^{-1/2} + (1+\frac{r_t}{r_c})^{-1/2})^2$ King model

(= truncated model of hot gas in its own potential)

- Large range of luminosities (15 mag = 6 dex) M_B = -23 (giant) … -8 (dwarf)

Elliptical Galaxies

- Optical light dominated by evolved, metal-rich stars
- Colour-magnitude relation: brighter galaxies are redder = more metal-rich (➔mass-metallicity relation)
- Gas:
  - Hot corona ($10^6 \ldots 10^7$ K, <100 kpc, mass= 1..10% Mgal)
  - Cool gas+dust: very little (except. NGC1052)

Elliptical Galaxies: kinematics

- Velocity+dispersion from stellar absorption lines (intrinsic width ~20 km/s)
- Brighter galaxies (MB < -21): no rotation (<50…100 km/s); randomly oriented ‘thermal’ stellar motions: σ ~200 km/s (’pressure supported’)
- Fainter galaxies: some rotation $v \sim \sigma$

Elliptical Galaxies: masses

- Virial theorem $E_{kin} = -E_{pot}/2$ gives:

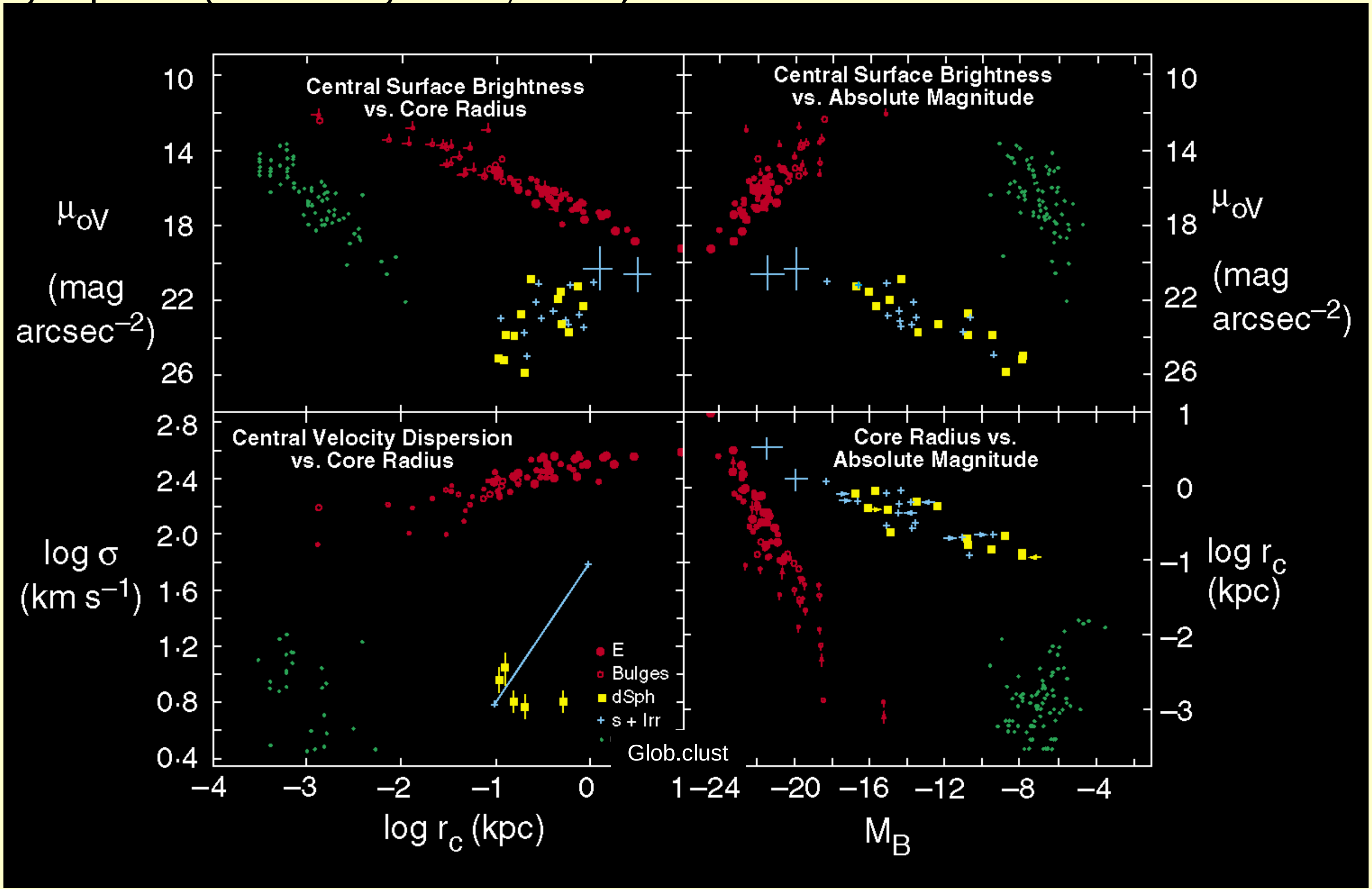
$$M \sigma^2 = GM^2/R$$

- M87 $M(r<4.4\ \mathrm{kpc}) = 2\ 10^{11}\ M_{sun}$

but also: presence of X-ray gas corona with $T < 3\ 10^7$ K, radius 440 kpc … this needs a mass of $3\ 10^{13} \ldots 10^{14}$ Msun (Dark Halo?!)

Ellipticals: fundamental plane

E and S0 populate in the space (radius, surface brightness, velocity dispersion) only a plane (Kormendy 1985, 1987):



Ellipticals: Metallicity

- Integrated stellar colours and spectra
- However: age-metallicity degeneracy of colours
- [Fe/H] = 0 … +0.4 in the centers of large E
- Elemental mixture is NOT scaled-solar: higher Mg/Fe
- Larger Es have higher metallicity (Mg2 index)
- Radial abundance gradient -0.02 dex/kpc

Two classes of Ellipticals

Disky-distorted isophotes

normal+low luminosity

rapid rotators

nearly isotropic v

oblate spheriodal

no cores

Boxy-distorted isophotes

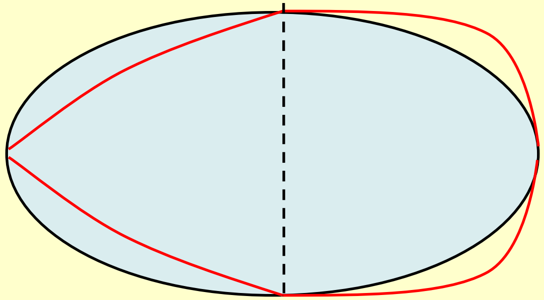
giant E

no rotation

anisotropic v

moderately triaxial

cuspy cores



Exaggerated!!!

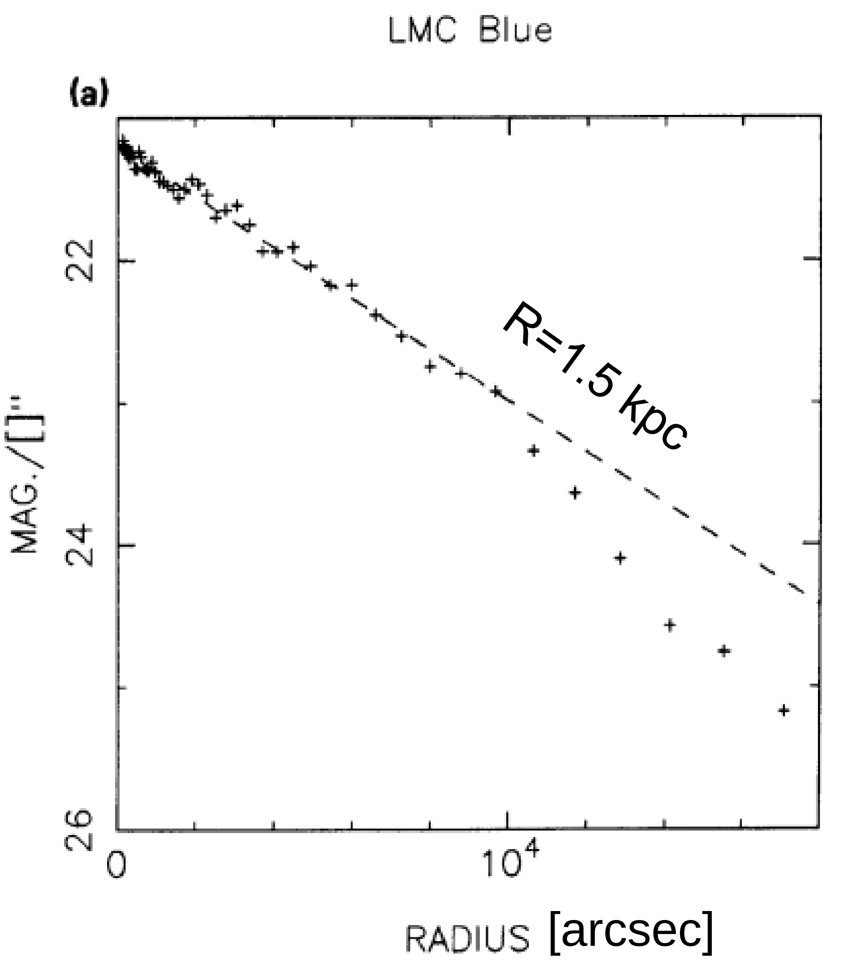
Irregular Galaxies

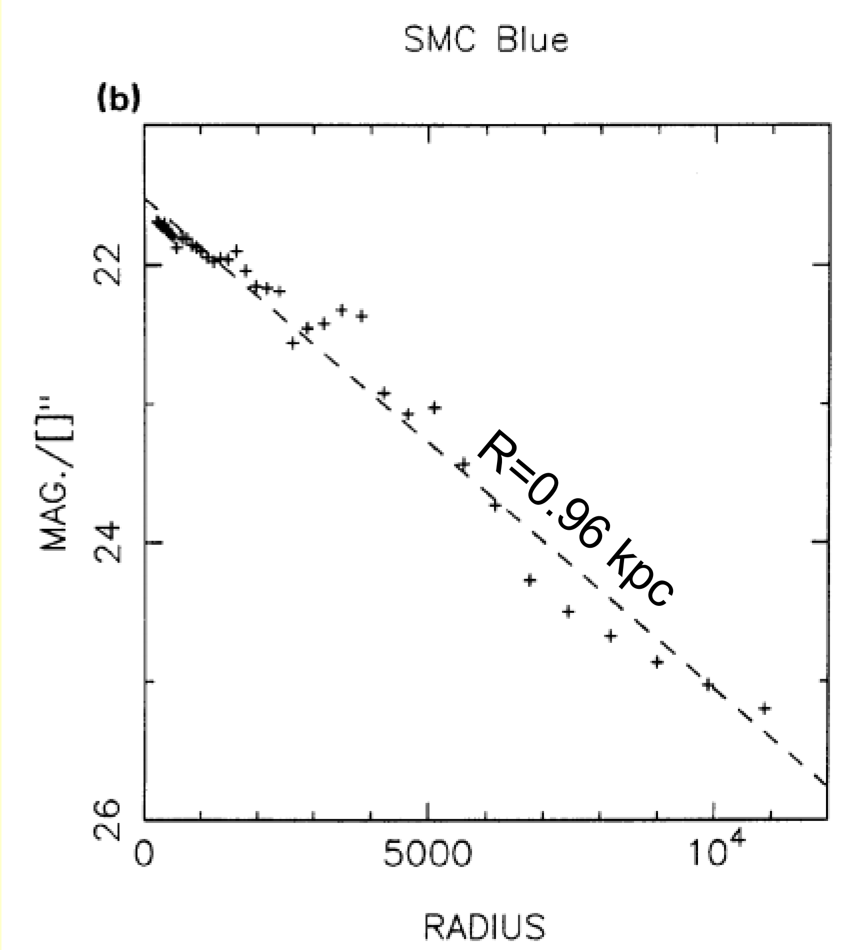
- Irregular shape, blue, gas-rich, HII regions: active star formation
- Classes:
  - Im = magellanic types (LMC, SMC)
  - I0 = {amorphous, intergalactic HII regions, blue gals with smooth profile, clumpy luminous gals}
- Tend to be fainter than normal E,S0,S
- Low surface brightness 10 … L_{sun}/pc^2
- But quite common: 1/3 to ½ of all gals.

LMC

Irregular Galaxies

- Mean radial profile: exponential (1..3 kpc)



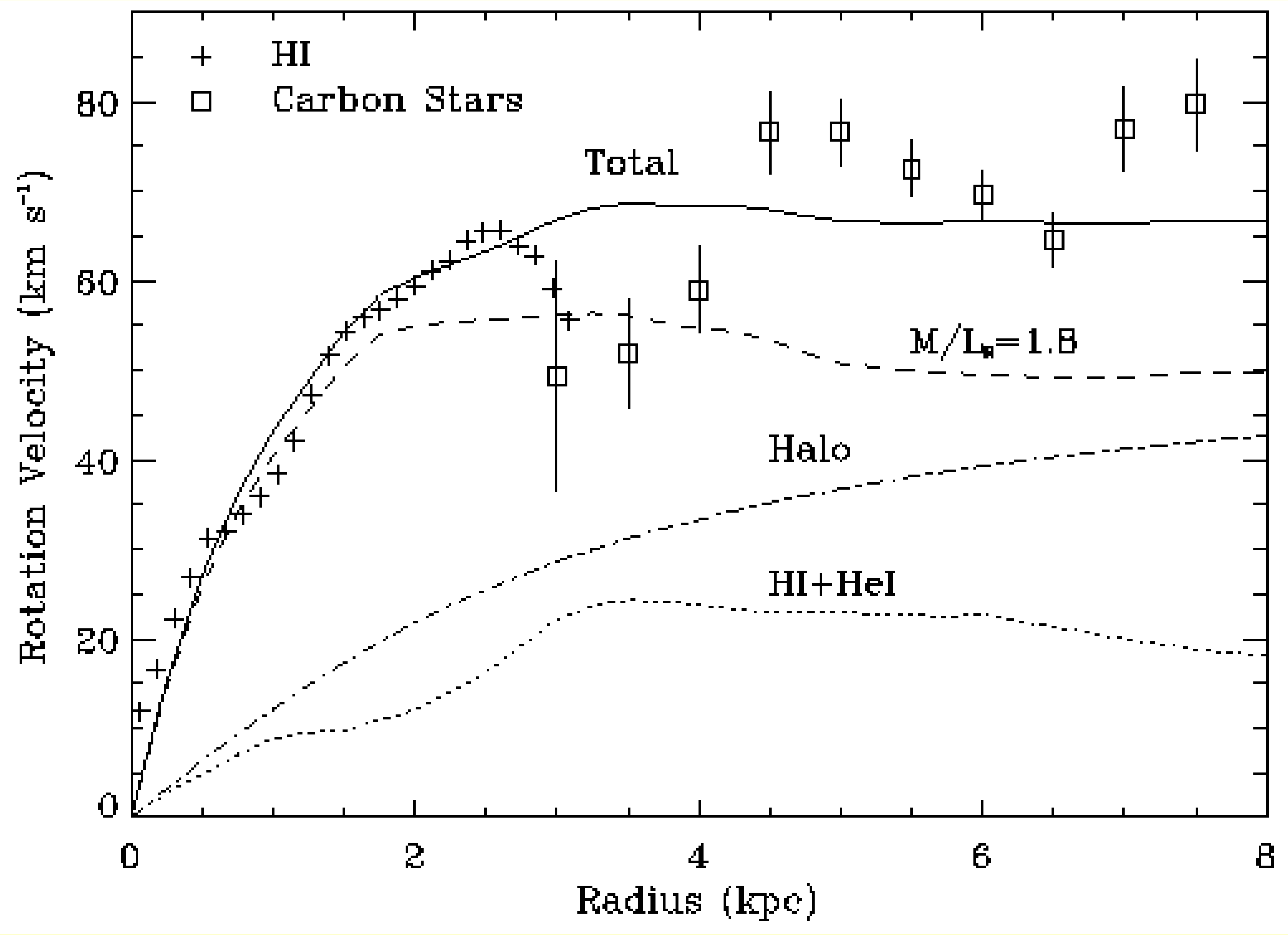


Bothun & Thompson 1988

Irregular Galaxies

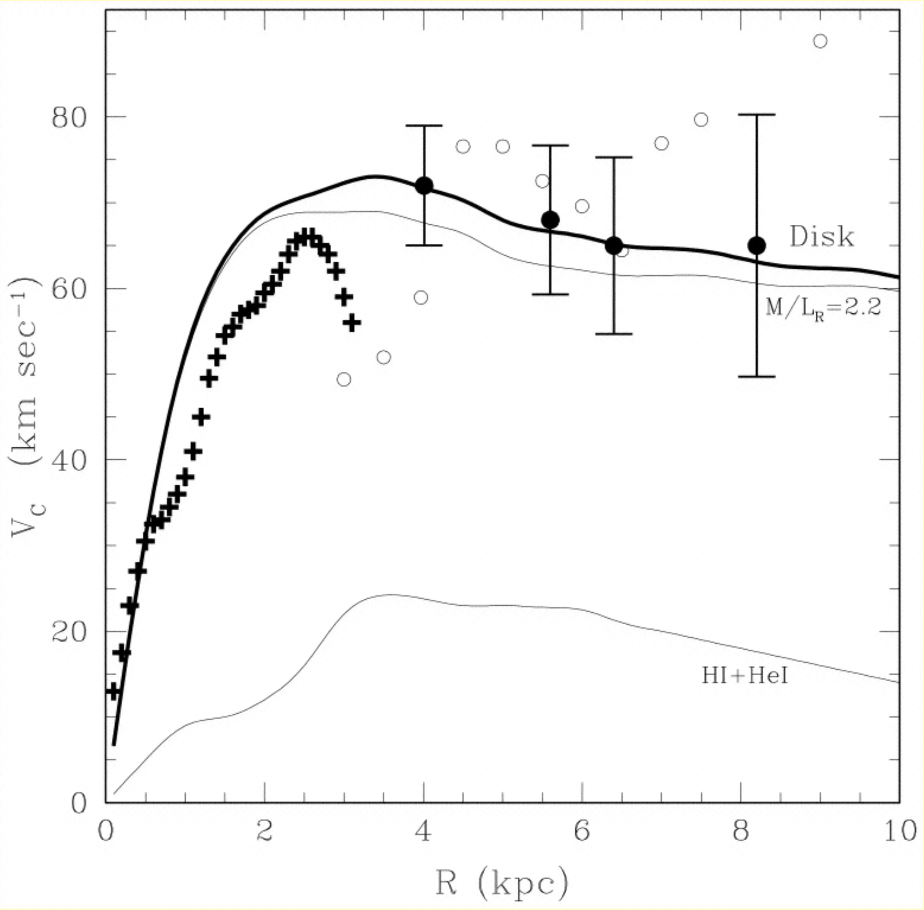
- Very blue colours: U-B ~-0.3 B-V~0.4
- Kinematics:
  - Slow rotators: 100 … km/s (HI)
  - Masses 10^8… 10^9 Msun LMC: 5±1 10^9 Msun
  - M/L_B ~ 2 … 10 1.6±0.2
  - Rotation curve: near rigid-body
  - Often no need for massive core or spherical halo …

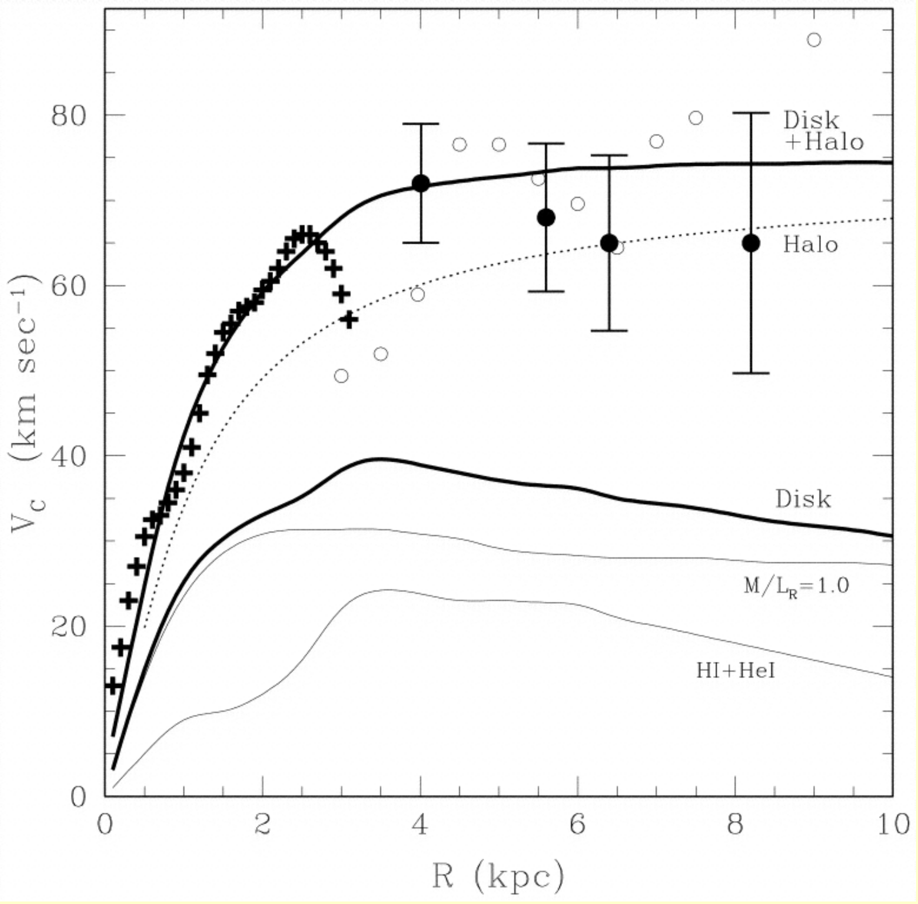
LMC rotation curve



Kim et al. 1998

max.disk vs. min.disk





Alves & Nelson 2000

Irregular Galaxies

- Metallicity+Abundances
  - Between SMC (-0.6) and LMC (-0.2)
  - I Zw 18 has [O/H] = -1.6
  - No radial gradient

Dwarfs and Giants

- Van den Bergh's luminosity classes: supergiants I … dwarfs V

- Luminosity function (Schechter 1976):

$$\frac{dn}{dL} = \left(\frac{L}{L*}\right)^{\alpha} \ \exp(-\frac{L}{L*})$$

field gals: α = 1.25±0.25   L*: M_B=-20.8

compact groups: $\alpha \approx 0$

Gas-poor dwarfs

- Dwarf Ellipticals (dE)
  - King or exponential profile
  - <1% gas
  - Old stellar population
  - Z ~0.3 … 1 Zsun
  - Slow rotation
  - M/L_B ~16
- Compact Ellipticals (cE): only satellites

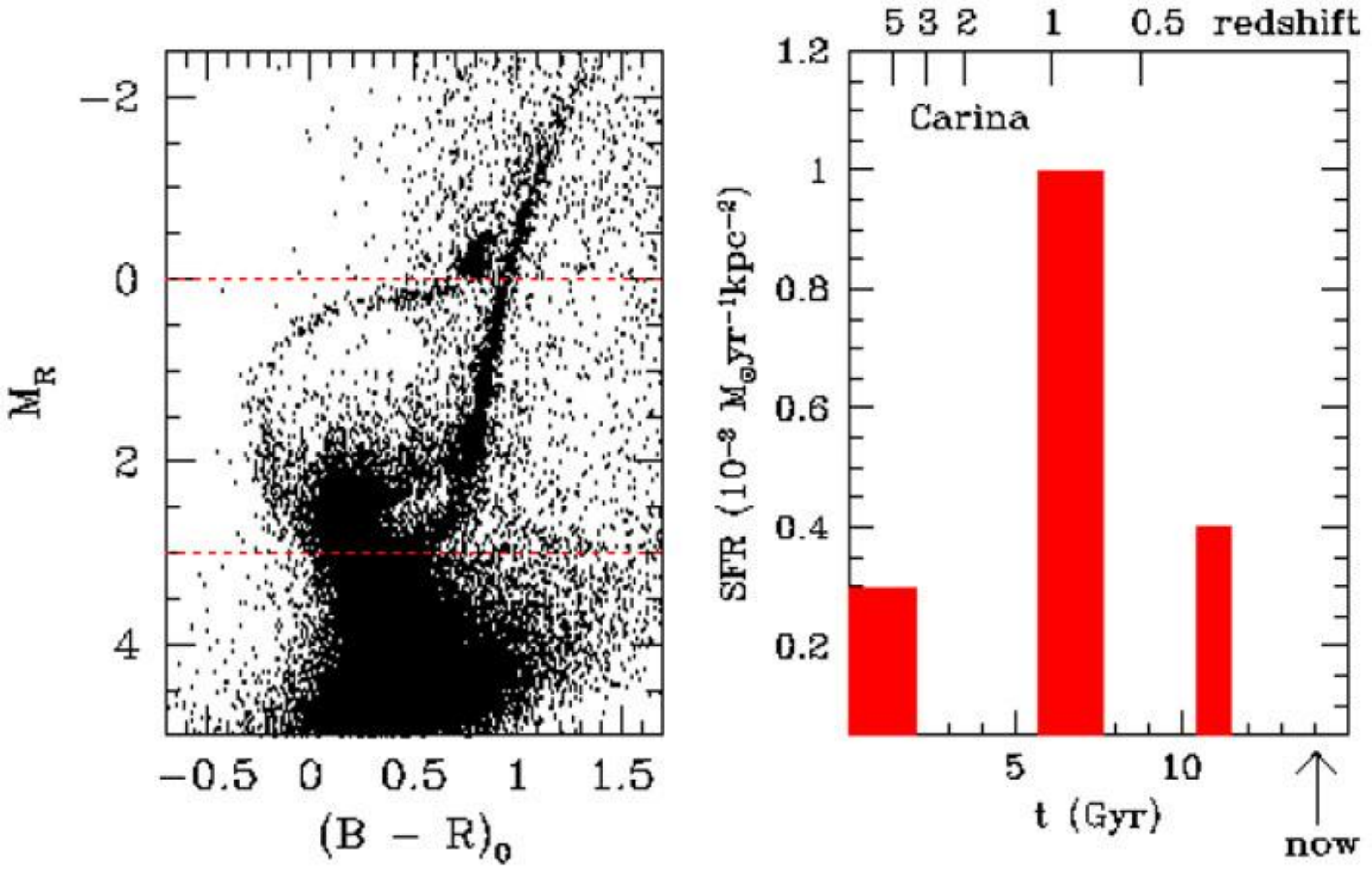
Gas-poor dwarfs

- Dwarf Spheroidals (dSph)
  - Satellites of MWG, M31
  - Most common type of galaxies in universe
  - M/L_B ~10 … 50
  - Metallicity increases with mass
  - CMDs: stellar population often with several distinct ages: SF events!

dSph of the Local Group

Name	Type	M_V	Distance [kpc]
NGC 185	dSph/dE3p	-15.3	620
NGC 147	dSph/dE5	-15.1	660
Fornax	dSph	-13.7	131
Sagittarius	dSph	-13::	18
And I	dSph	-11.8	725
And II	dSph	-11.8	725
Leo I (Regulus)	dSph	-11.7	273
Scupltor	dSph	-10.7	78
And III	dSph	-10.3	725
Psc = LGS3	dIrr/dSph	-10.2	760
Sextans	dSph	-10.0	79
Phoenix	dIrr/dSph	-9.9	390
Leo II	dSph	-9.9	215
Tucana	dSph	-9.5	870
Ursa Major	dSph	-8.9	63
Carina	dSph	-8.9	87
Draco	dSph	-8.6	76

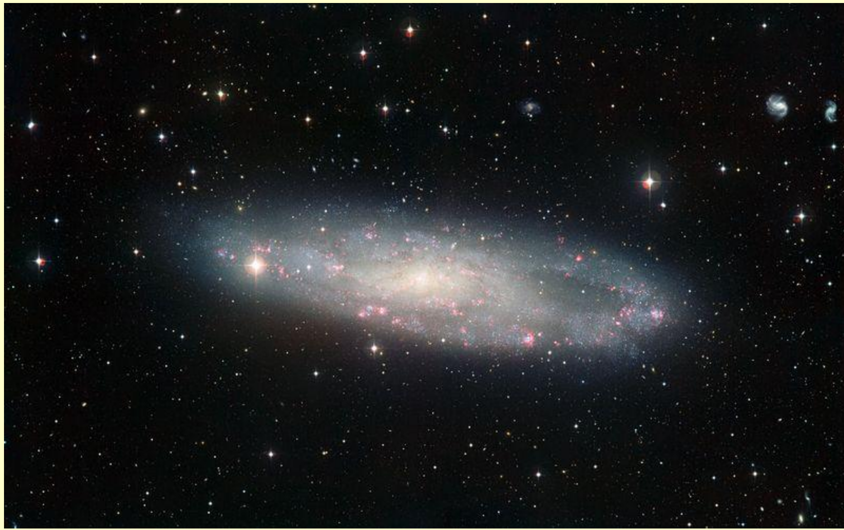
Carina dSph



Mateo 1998

Gas-rich dwarfs

- Dwarf irregular (dIrr)
  - 20% of dwarfs
  - Exponential density profile
  - High gas fraction, blue stars, HII regions
  - 1/30 … ½ Zsun
  - M/L_B = 2 … 10
- Dwarf spirals (dS)
  - S0, Sa … Sd
  - avoid dense regions



NGC 247 ESO

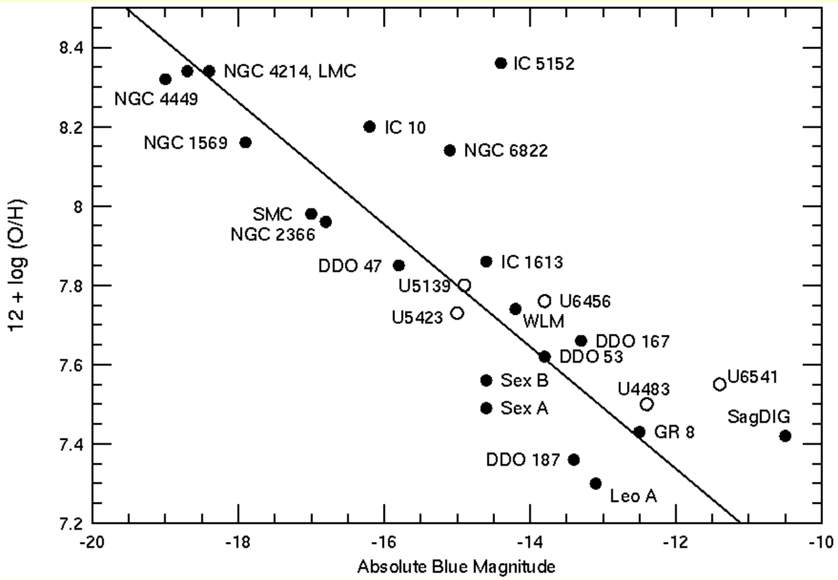
Gas-rich dwarfs

- Blue Compact Dwarf {Galaxies} (BCD{G})
  - 5% of dwarfs
  - Blue continuum, HII regions
  - < 1 kpc radius
  - < 5 10^9 Msun; HI: 10^8… 10^9 Msun
  - 1/30 … **1/10** … ½ Zsun
  - $M/L_B \sim 1$
  - Extended, diffuse old KM* population (IR)
  - High <u>current</u> SFR, still gas-rich ➔ starbursts

Evolution of dwarfs

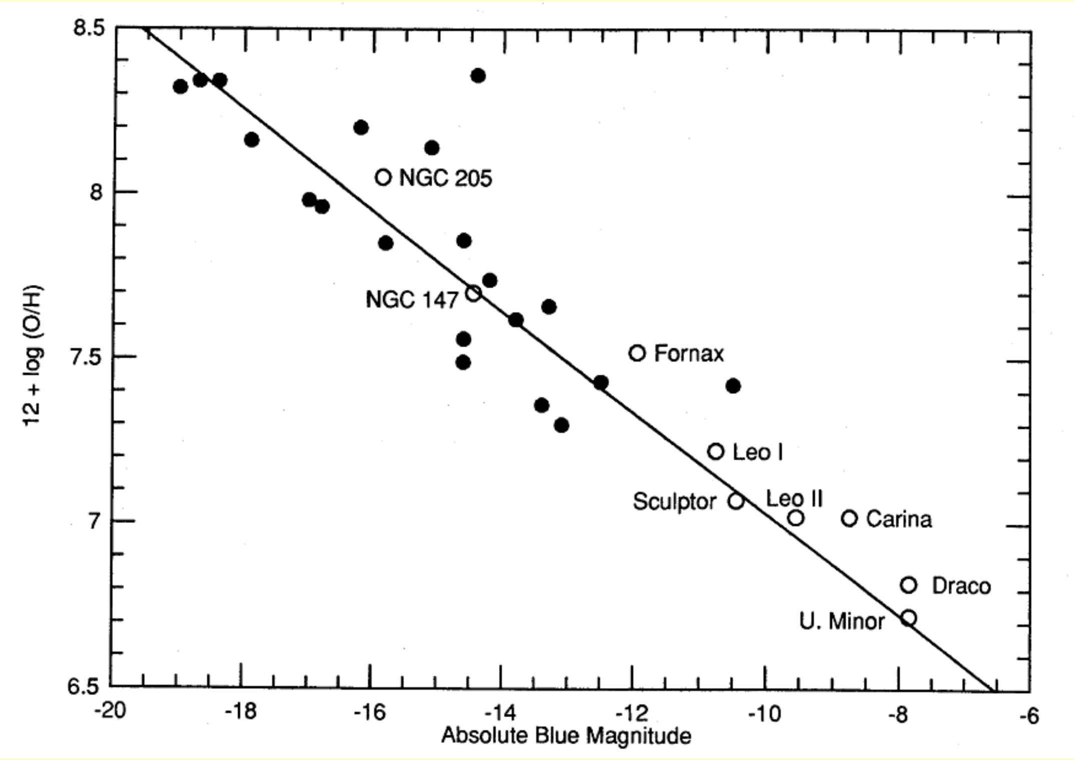
- dE and dIrr from different initial conditions(density, dark matter …)
- dIrr → dE by gas removal (interaction, stripping)
- dIrr → BCD → → dE

Mass-Metallicity Relation

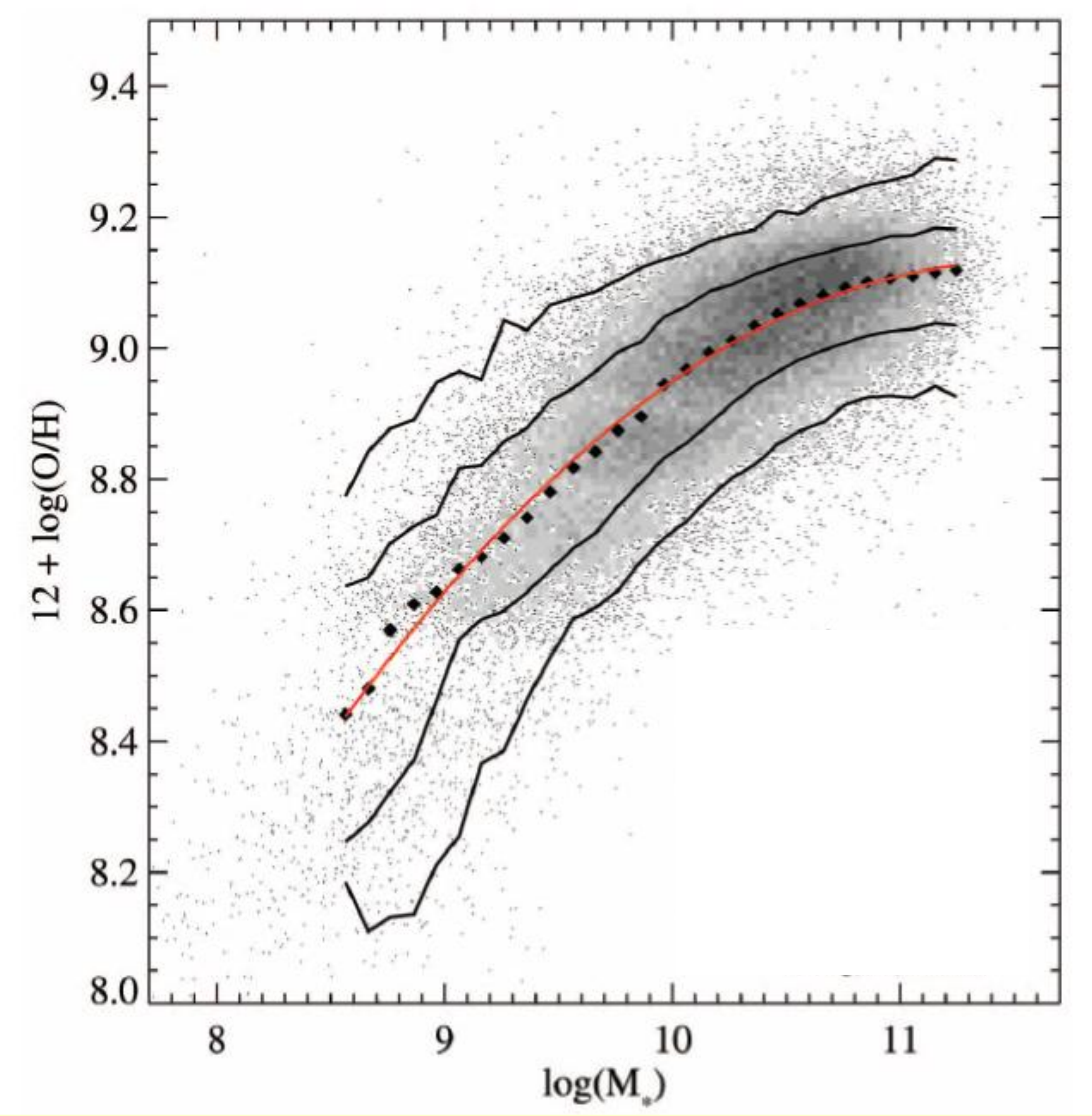


← Gas-rich galaxies (Skillman 1989)

o = gas-poor galaxies (scaled via [Fe/O]=0)



Mass-Metallicity Relation



53000 galaxies
at z~0.1
from SDSS

Tremonti 2004

Other types of galaxies

- LSB (low surface brightness)
  - 22 ... 24 mag/arcsec^2 < 21.65 (Freeman)
  - low SB with normal luminosities
  - NGC 4411 A/B near M87
  - Malin 1, 2 (big, very red, old pop., low HI)
  - Dwarfs: dIrr, dS, dSph

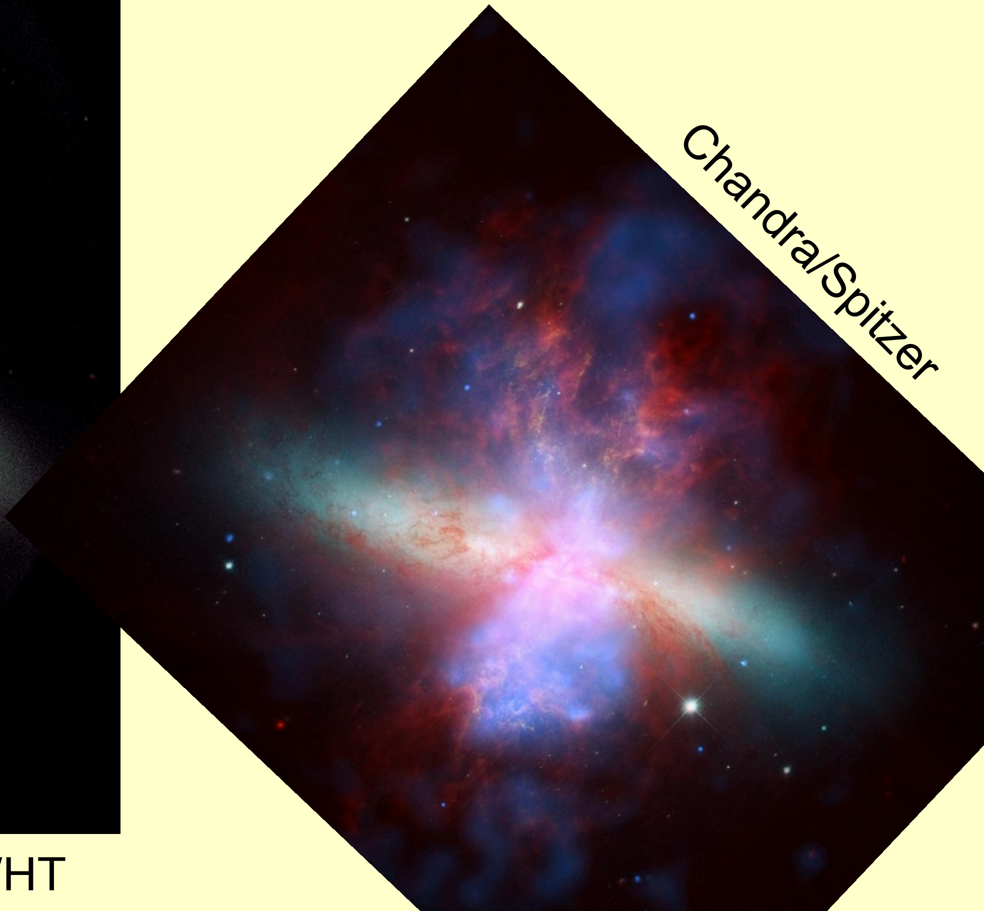
Other types of galaxies

- Active galaxies: high current star formation
  - IRAS starburst gals: NGC 6240, 4553 with L_{IR}/L_B ~100 while =4 (M82), 0.5 (MWG), 0.03 (M31)
  - Markarian Gal. (cf. Seyferts)
  - Amorphous Gal. (M82)
  - Haro Gal.
  - Intergalactic HII regions (heterogenous class..)

M82 ‘exploding galaxy’

Rodrigues-Gil, WHT

Optical image: Spiral galaxy with $H\alpha$ emitting filaments ejected from central region undergoing strong star formation (visible in Xrays and IR)

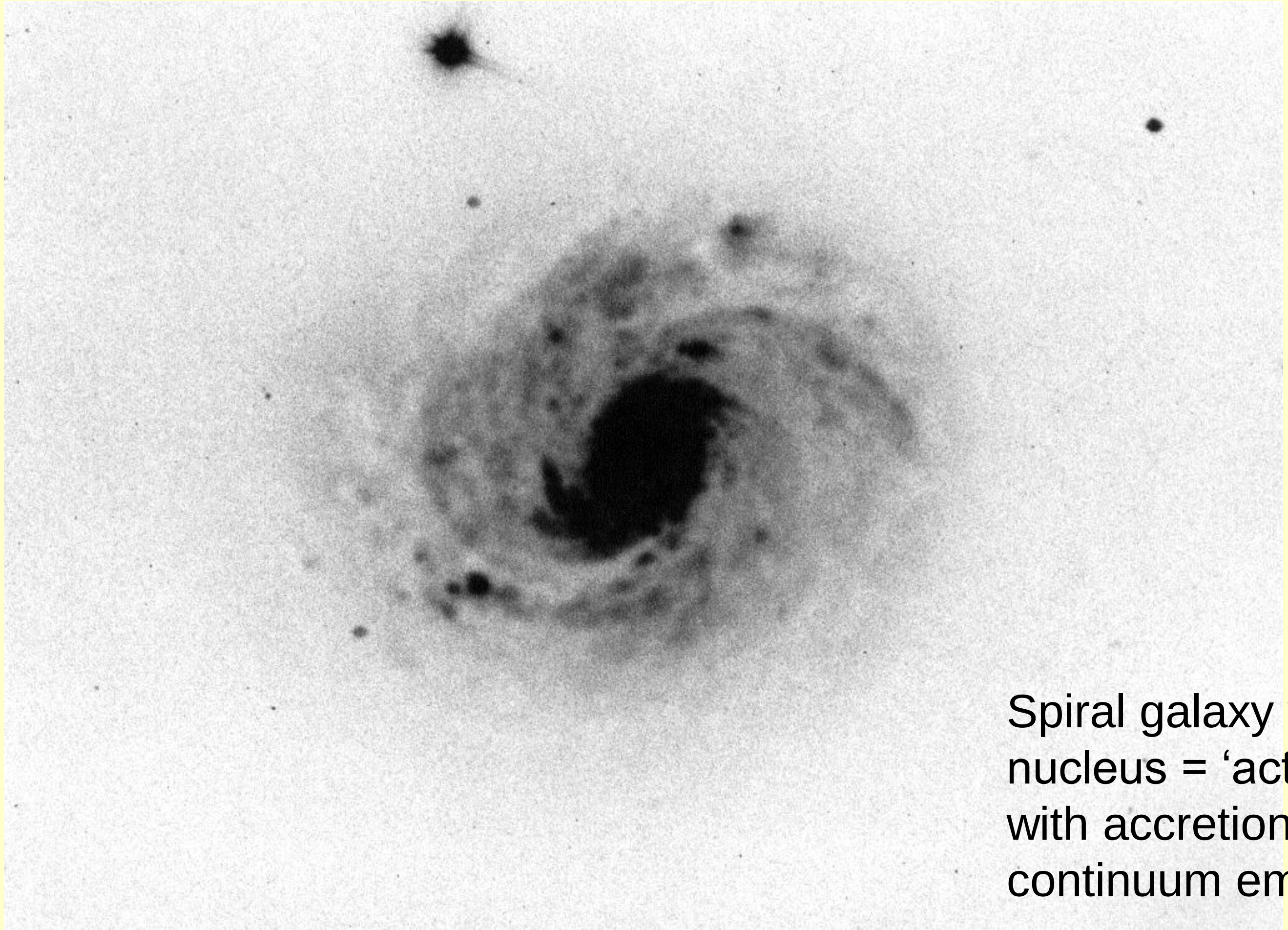


Chandra/Spitzer

Other types of galaxies

- Objects with active nucleus
  - Quasars
  - Blazars = BL Lac objects
  - Seyfert 1 and 2 galaxies
  - LINER = low Ionization Nuclear Emissionline Regions

NGC 1068 prototype Seyfert



Spiral galaxy with a bright nucleus = ‘active’ black hole with accretion disk (line and continuum emission)

Observations at high redshift

- Butcher+Oemler (1978): distant clusters contain more blue galaxies (higher past SFR)
- Galaxy counts: at fainter magnitudes more redshifted galaxis ➔ need correction of colours due to redshift (‘K-correction’)
- MediumDeepSurvey (HST, Abraham 1996): $z \sim 0.5$: similar to today

Observations at high redshift

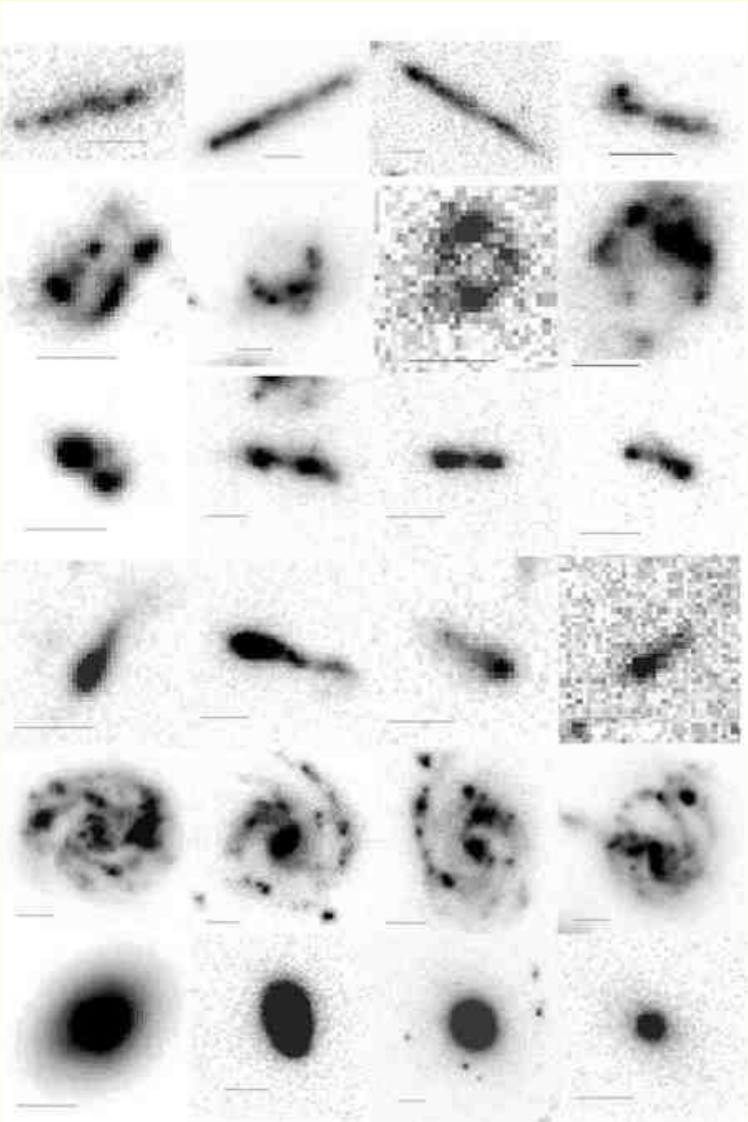
- Hubble Deep Field (Williams 1996): 10 d, 150 orbits, dec.95, 4 colours in 2.6’x2.6’ field towards UMa ➔ 25 (z>2), 130 (z=), 300 with JHK, 3000 with UBVI
  - More asymmetric and distorted gals
  - No grand-design spirals
  - No barred spirals
  - ‘tadpoles’ etc. not seen today

Observations at high redshift

	Shapley-Ames (B)	MDS (I, z~0.5)	HDF (I)
E + S0	24%	20	30
S + Irr	69	63	31
SB	20	4	0.5
???	7	17	39

- No change between today and z=0.5
- Fewer spirals in HDF
- No barred spirals in HDF
- More strange types in HDF

UHDF (2004)



Chains,

Clump clusters,

Doubles,

Tadpoles,

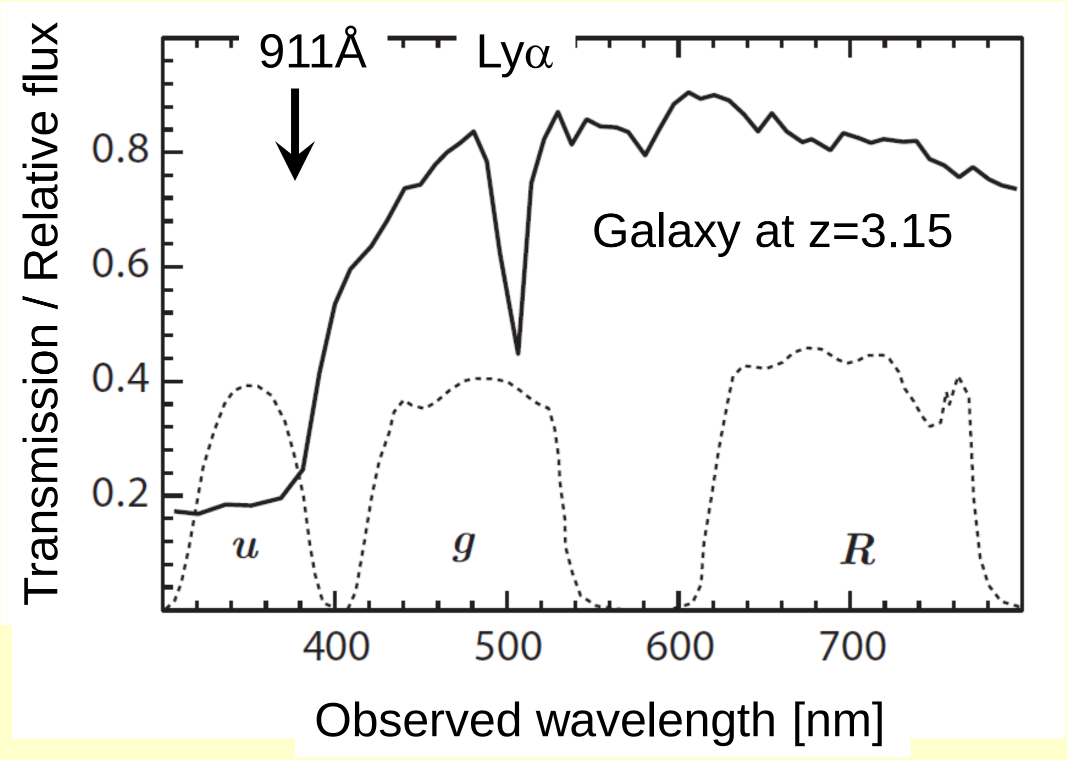
Spirals,

Ellipticals

Elmegreen 2005

Photometry at high redshift

- Lyman Break Galaxies: spectrum is redshifted so much that u-filter receives no signal:

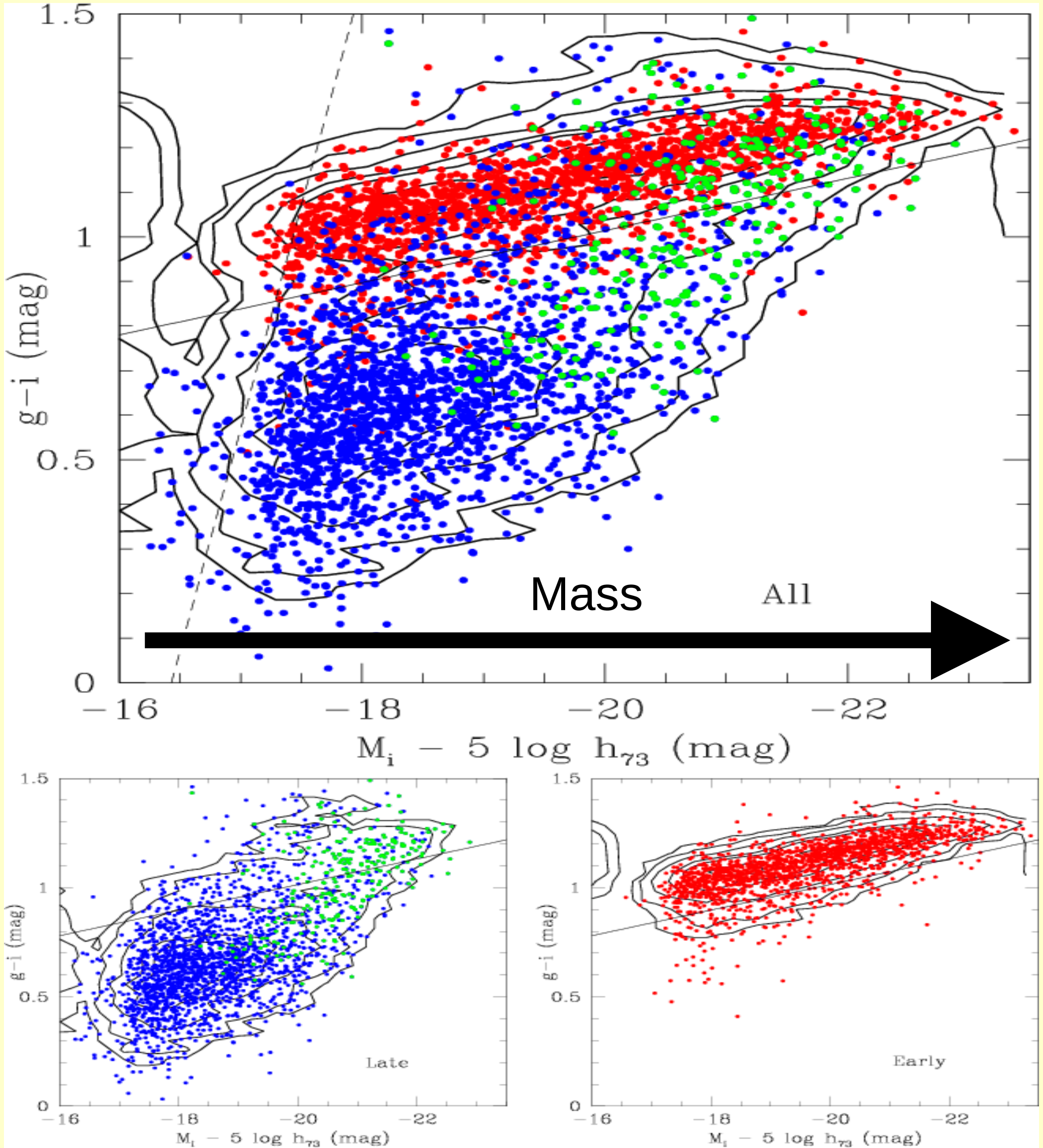


Review: M.Giavalisco 2002

Large photometric surveys

- 2dF, SDSS, Combo17 …
- Red sequence = E+S0 (galaxies with no current star formation)
- Blue cloud = spirals = galaxies with current satr formation

Large photometric surveys



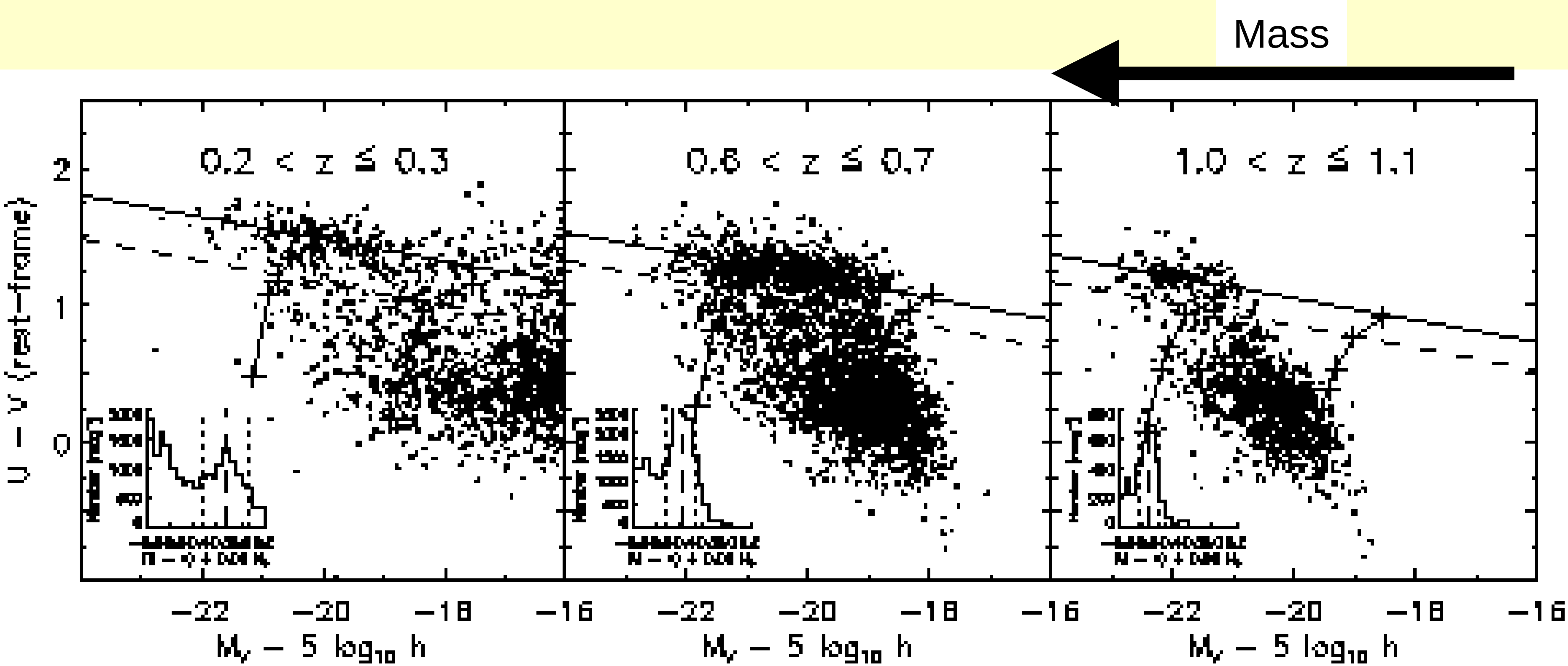
Red = dE,E,S0,S0a

Green = Sa, Sb

Blue = Sbc, Im, BCD

from SDSS data
z=0   Gavazzi 2010

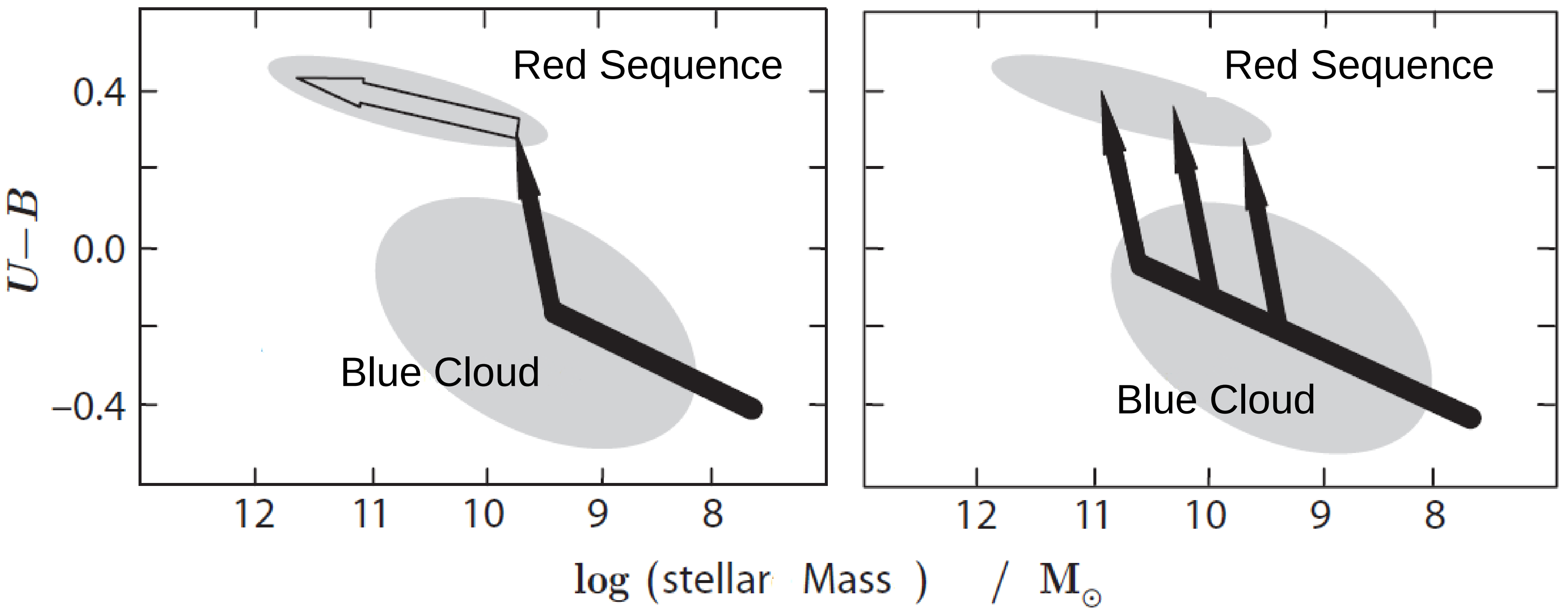
Evolution with redshift
z = 0.2 … 1.1



- COMBO17: 24000 galaxies in 17 colour bands
- red/blue ratio doubled since z=1
- number of blue gals has dropped

Bell et al. 2004

Scenarios



Dry mergers: spirals lose gas loss and stop SF, ellipticals grow by merging

Wet mergers: spirals stop SF due to loss or consumption of gas