Evolution of Galaxies:
IMF – SFR - SFH

Observatoire astronomique
de Strasbourg

J.Köppen joachim.koppen@astro.unistra.fr

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

Galactic (Chemical) Evolution

is driven by stars which burn hydrogen on the Main Sequence → unique relation

mass-temperature-lifetime-yield

All we need to know: how many stars of each mass are born anywhere and at any time …

Stellar birth function

number of stars with mass $(m, m+\Delta m)$ on the main sequence born between $(t, t+\Delta t)$ in a region (x,y,z) in a galaxy out of a volume (mass) element

$$= SBF(m,t,x,y,z) * \Delta m * \Delta t * \rho \Delta V$$

There could be many other physically important parameters (gas density, gas temperature, shock frequency,magn.Field …), but the SBF is already too general to be useful!!!

More useful approach

SBF … = $IMF(m) * \Delta m \; * \; SFR(t,r) * \Delta t * \rho \Delta V$

- **Initial Mass Function** φ = spectrum of stellar masses at beginning of main sequence: various definitions dn/dm, dm/dm=m*dn/dm, dn/dlogm=m*dn/dm, dm/dlogm=m^2*dn/dm …

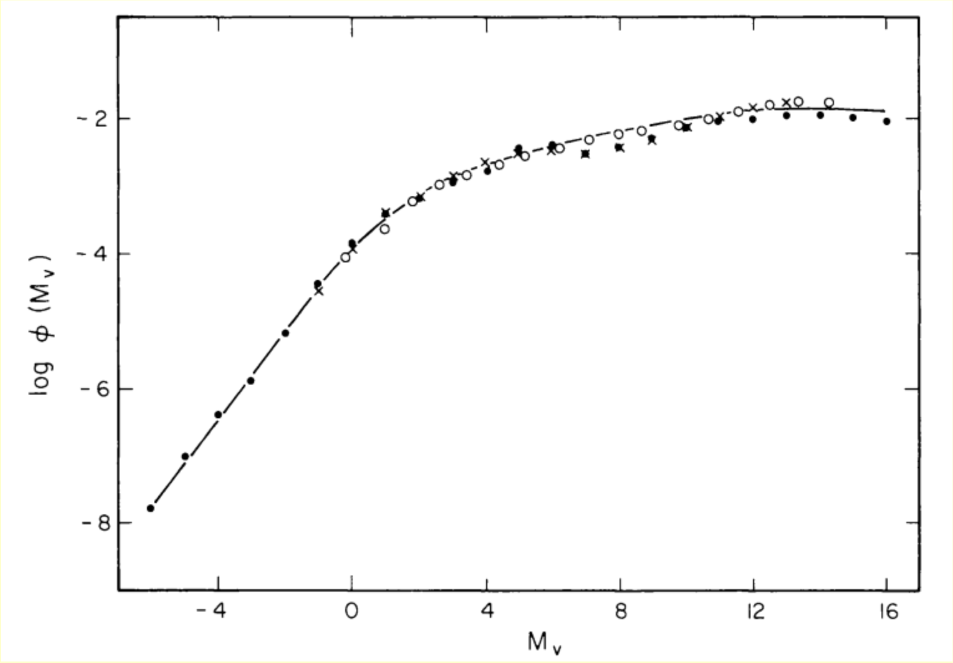
  $\int \varphi(m) dm = 1$, $\int \varphi(m) d\log m = 1$ ….

  [dn/dm] = 1/Msun ….
- **Star Formation Rate** ψ = how much gas mass is turned into how much stellar mass per unit of time [SFR] = Msun/Gyr/Msun

Determination of the IMF

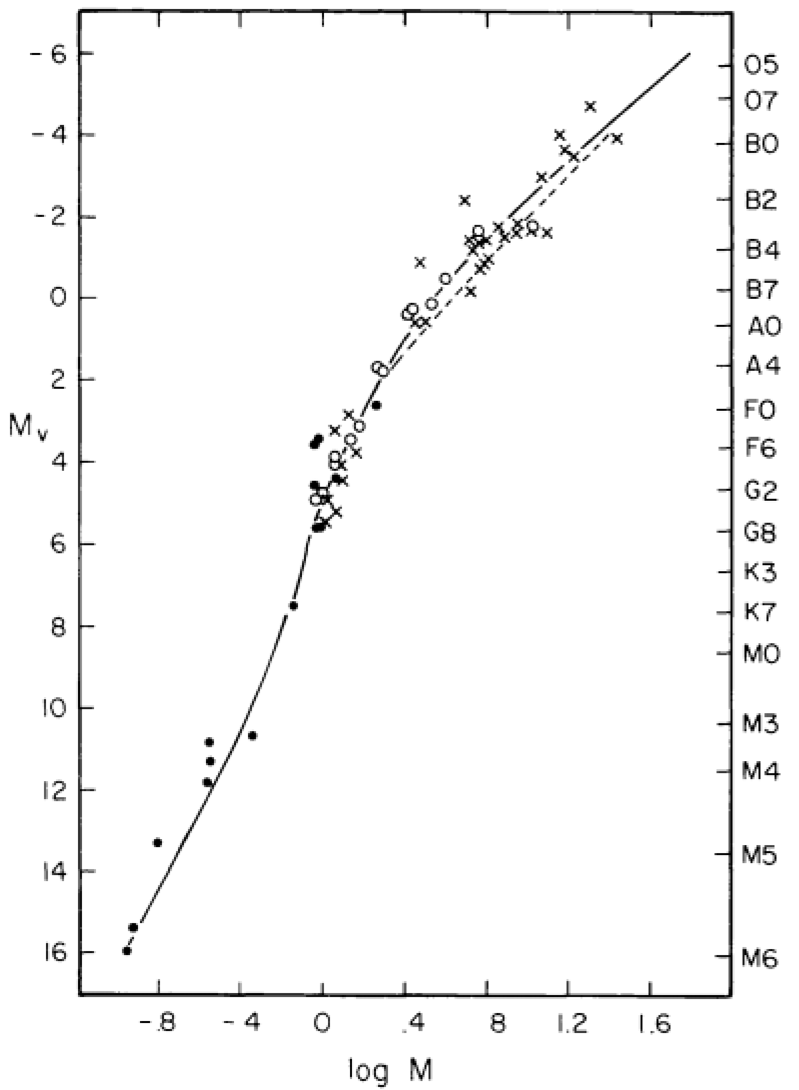
- Principle: count all main sequence stars …
- The local IMF (solar nh'd, < 1kpc)

(1) Apparent magnitude + distance → absolute brightness ➔ Luminosity function dn/dM



Miller+Scalo 1979

Determination of the IMF



(2) Eliminate giants, white dwarfs, binaries (HRD)

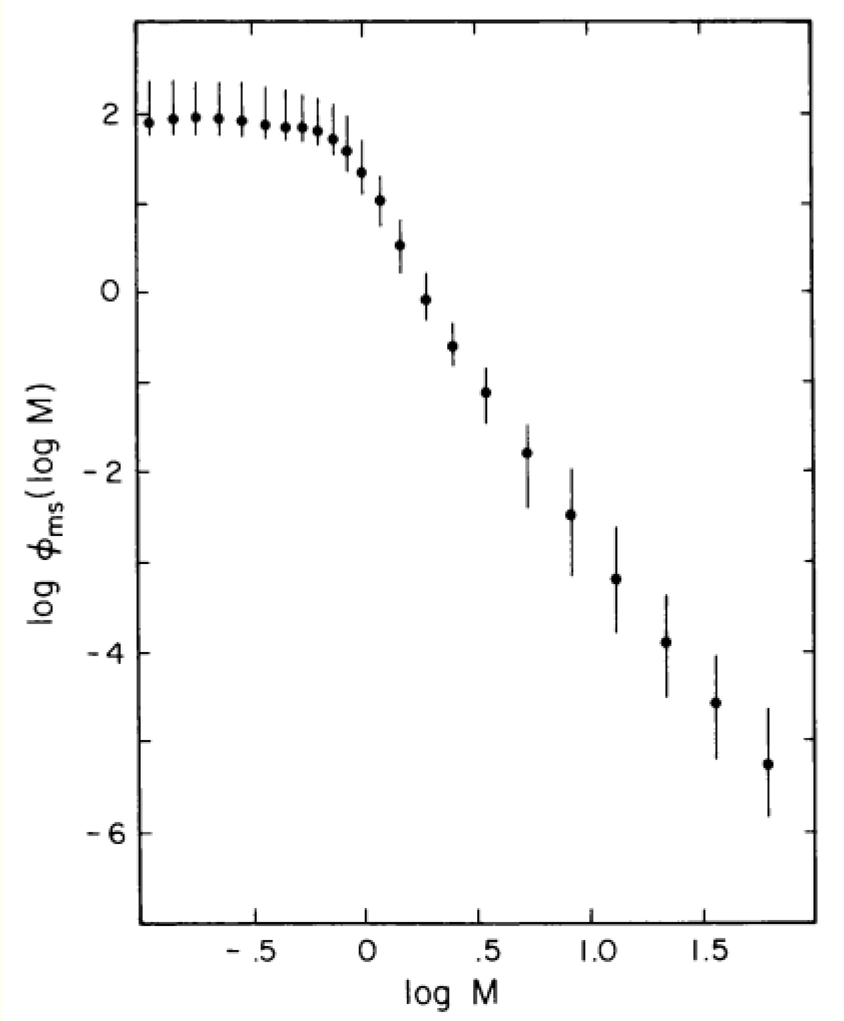
(3) Use magnitude-mass relation:

empirical: binary stars

theoretical: stellar structure+atmosphere (hence depends on composition)

Miller+Scalo 1979

Determination of the IMF



This gives the PresentDayMassFunction

PDMF = dn/dmass

Miller+Scalo 1979

Determination of the IMF

(4) Interpretation:

- Long-lived stars accumulate in time

$$\frac{dn}{dm} = \int_0^{t_1} \varphi(m) \quad (t)dt$$ for all stars with $\tau_{MS} > t_1$

disk evolution from t=0 to t_1

since we assumed time-independent IMF ….:

dn/dm = IMF(m) * <SFR> * t_1

O.K. for solar vicinity: m = 0.1 … 1 Msun,

i.e. later than G0, M_V > 5 mag

Miller+Scalo 1979

Determination of the IMF

(4) Interpretation:

- short-lived stars are the last generation only

$$\frac{dn}{dm} = \int_{t_1-\tau_{MS}(m)}^{t_1} \varphi(m) \quad (t)dt \qquad \text{for } \tau_{MS} < t_1$$

very short-lived stars: SFR=const   for $\tau_{MS} \ll t_1$

dn/dm = IMF(m) * SFR(t_1) * $\tau_{MS}(m)$

m > 2 Msun ➔ $\tau_{MS} < 1$ Gyr,

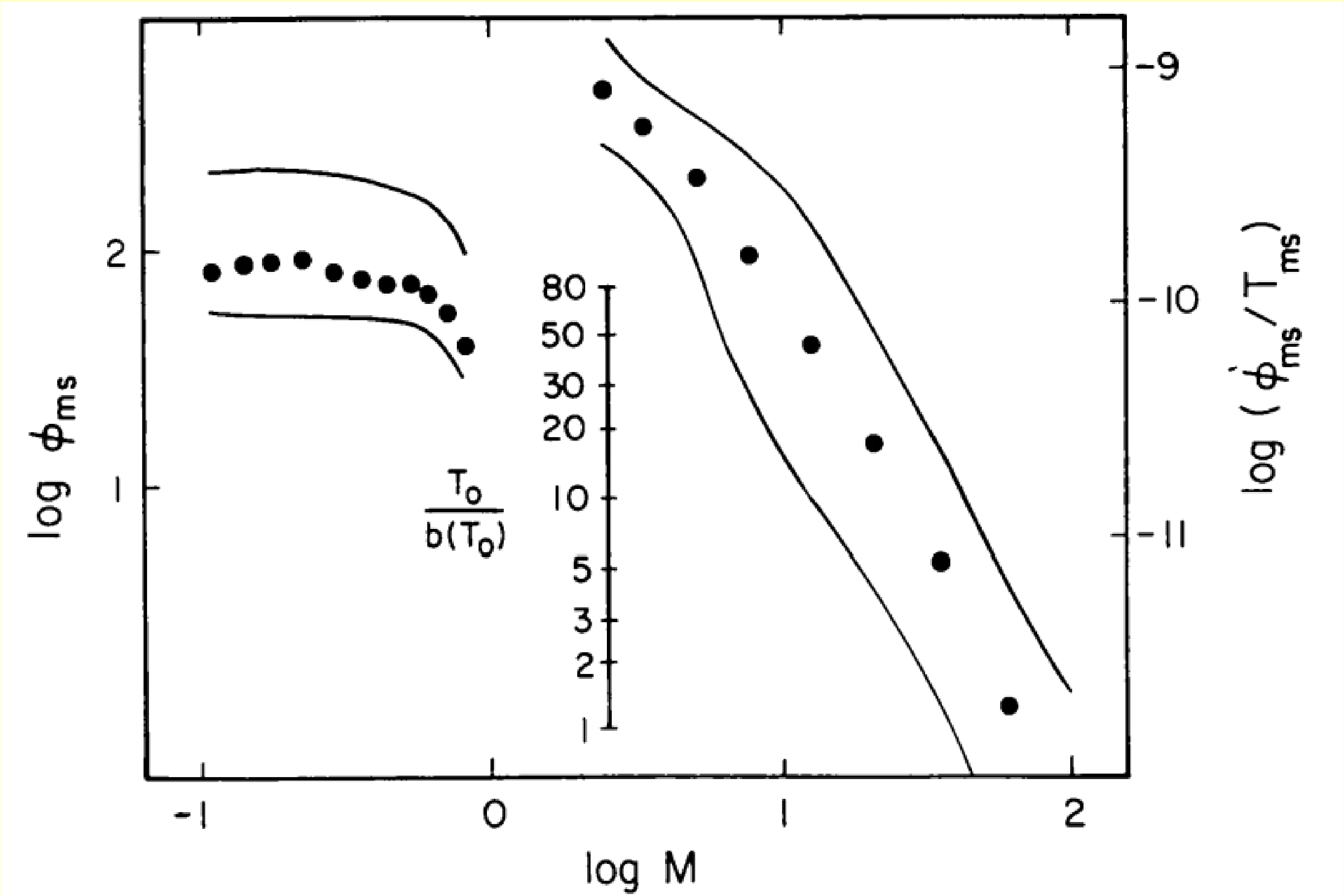
i.e. earlier than A0,M_V < 1 mag

Miller+Scalo 1979

Match the two cases

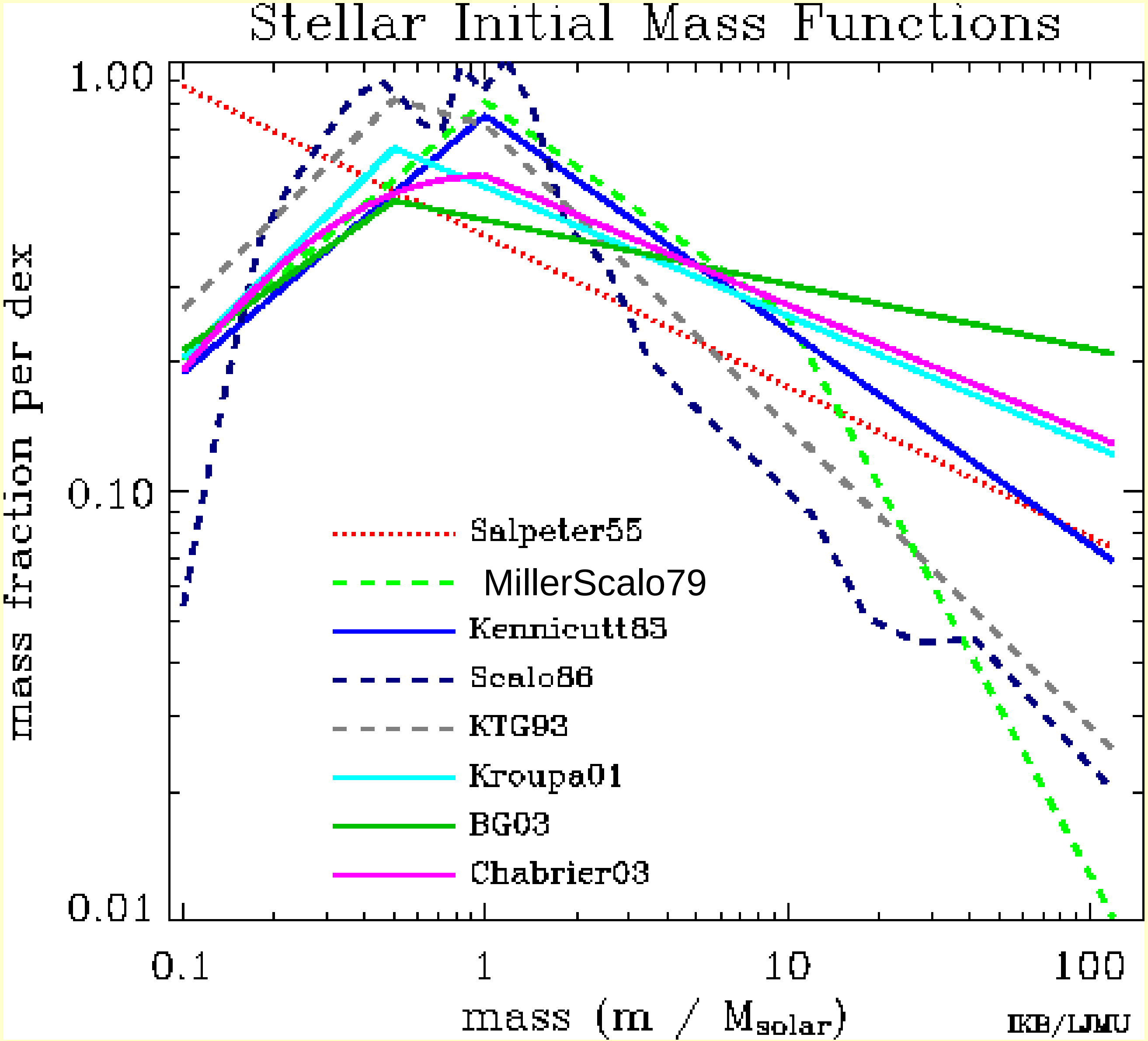
by demanding that IMF should be a continuous curve

$$\frac{IMF(low\,mass)}{IMF(high\,mass)} = \frac{<SFR>}{SFR(t_1)}\frac{t_1}{\tau_{MS}(m)} \approx 0.18\ \ldots 2.5$$



Miller+Scalo 1979

The local IMF



Shown here as dmass/ dlog(stellar mass) = m² * dn/dm

NB. In first attempt to get the IMF **Salpeter in 1955 used a power law**

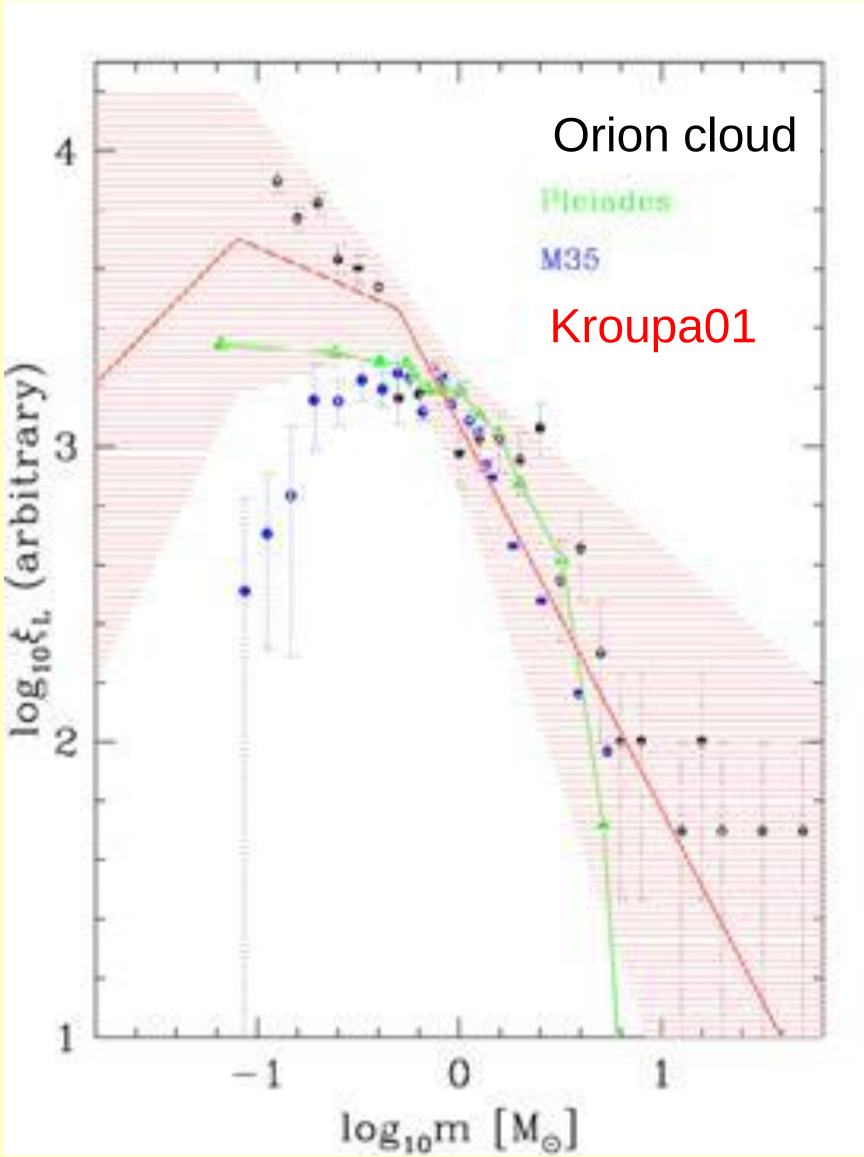
$dn/dm \propto m^{-2.35}$

still useful for

-- reference

-- if nothing is known!

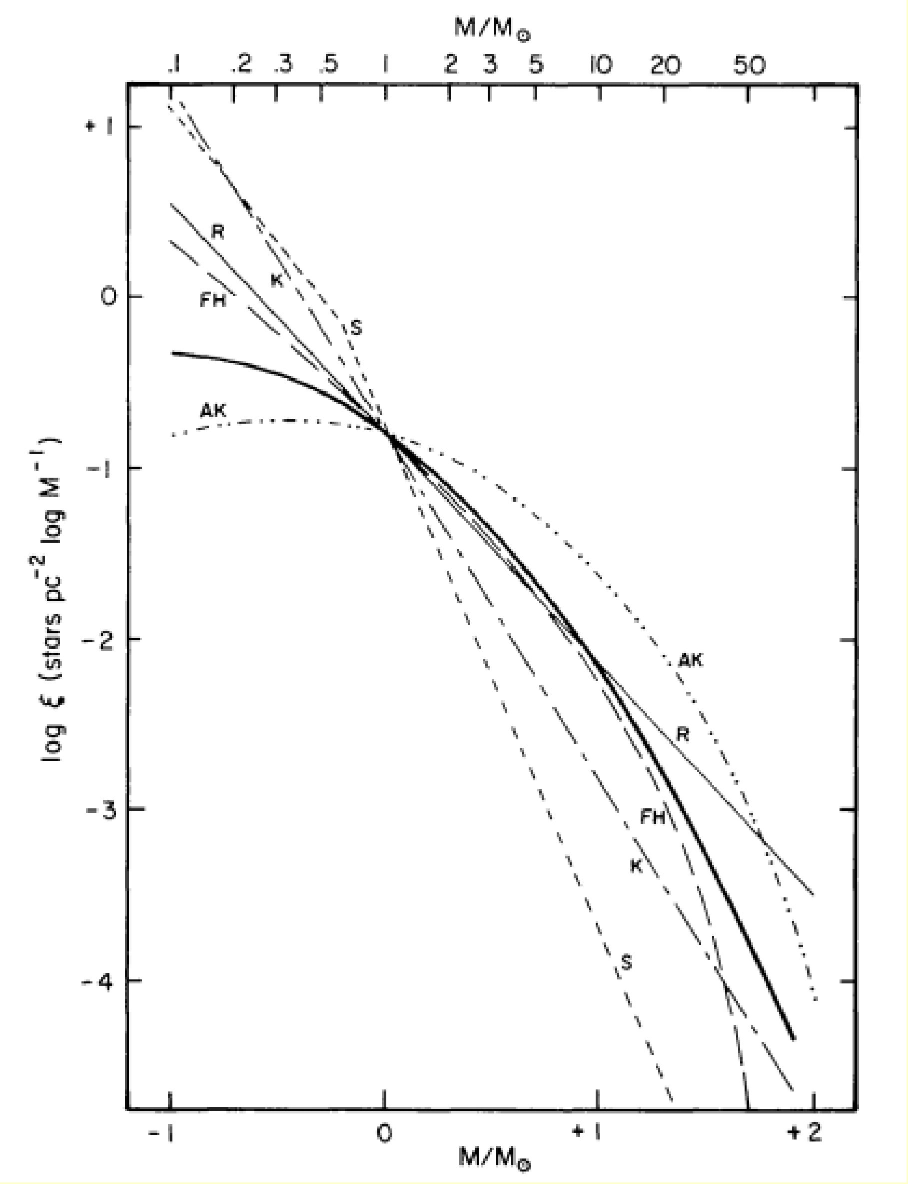
IMFs in other places



Distant regions/sources:
- technique: compare CMDs with population synthesis models (assume IMF, SFR(t))

Kroupa2002:
- some differences seen in clusters and other regions, also LMC, SMC
- but assumption of universal IMF remains sensible

Theoretical IMFs …



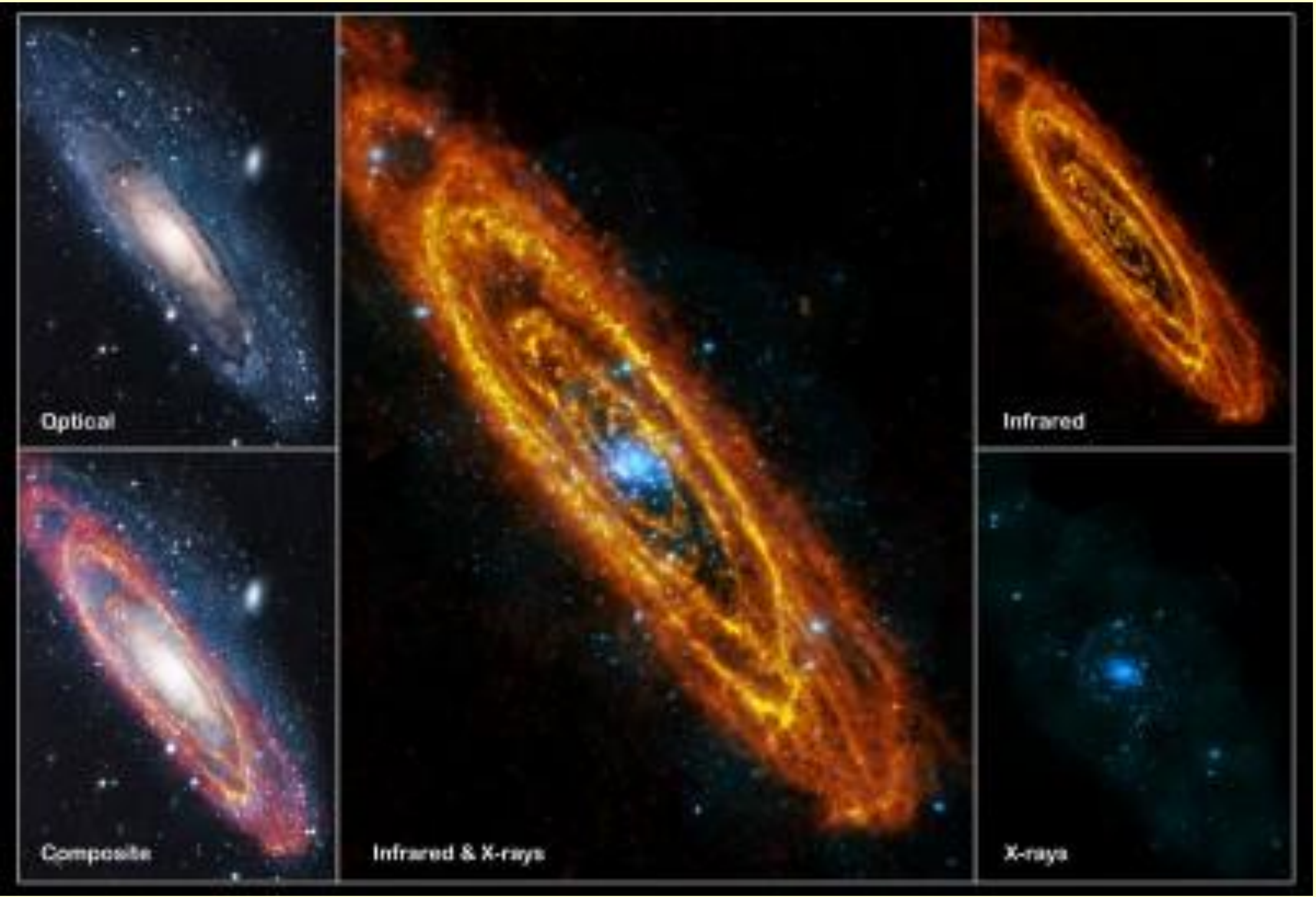
Miller+Scalo 1979

IMF conclusions

- Assumption of universal IMF is useful
- Use of Salpeter’s IMF is reasonable
- Theoretical derivations of IMF (from fragmentation of clouds) too uncertain to have predictive power

SFR = star formation rate

M31 in optical, IR, Xrays



current SFR: count young objects

- HII regions:

$$F(H\alpha) \propto SFR(today) \int_{20}^{100} IMF \, dm$$

obscuration by dust (radio cont., Bracket lines IR)

- OB stars (UV 1550A, blue continuum)
- Warm dust (FIR, 10…100μm…) heated by stars
- Radio continuum (thermal+nonthermal)
- TTau stars
- SNR (optical, Xrays)

Solar neighbourhood

- Direct star counts (M >2 Msun)

  $\int SFR\, dz \approx$ 3 Msun/Gyr/pc²

  with gas surface density $\Sigma_g = \int \rho_g dz$ = 5..10 Msun/pc²

  $\tau_{SFR} = \rho_g / SFR$ = 2..3 Gyr

- Spiral galaxies: Ha (Kennicutt 1989+98)

Solar neighbourhood

- Direct star counts (M >2 Msun)

$$\int SFR\, dz \approx 3 \text{ Msun/Gyr/pc}^2$$

with gas surface density $\Sigma_g = \int \rho_g dz$ = 5..10 Msun/pc²

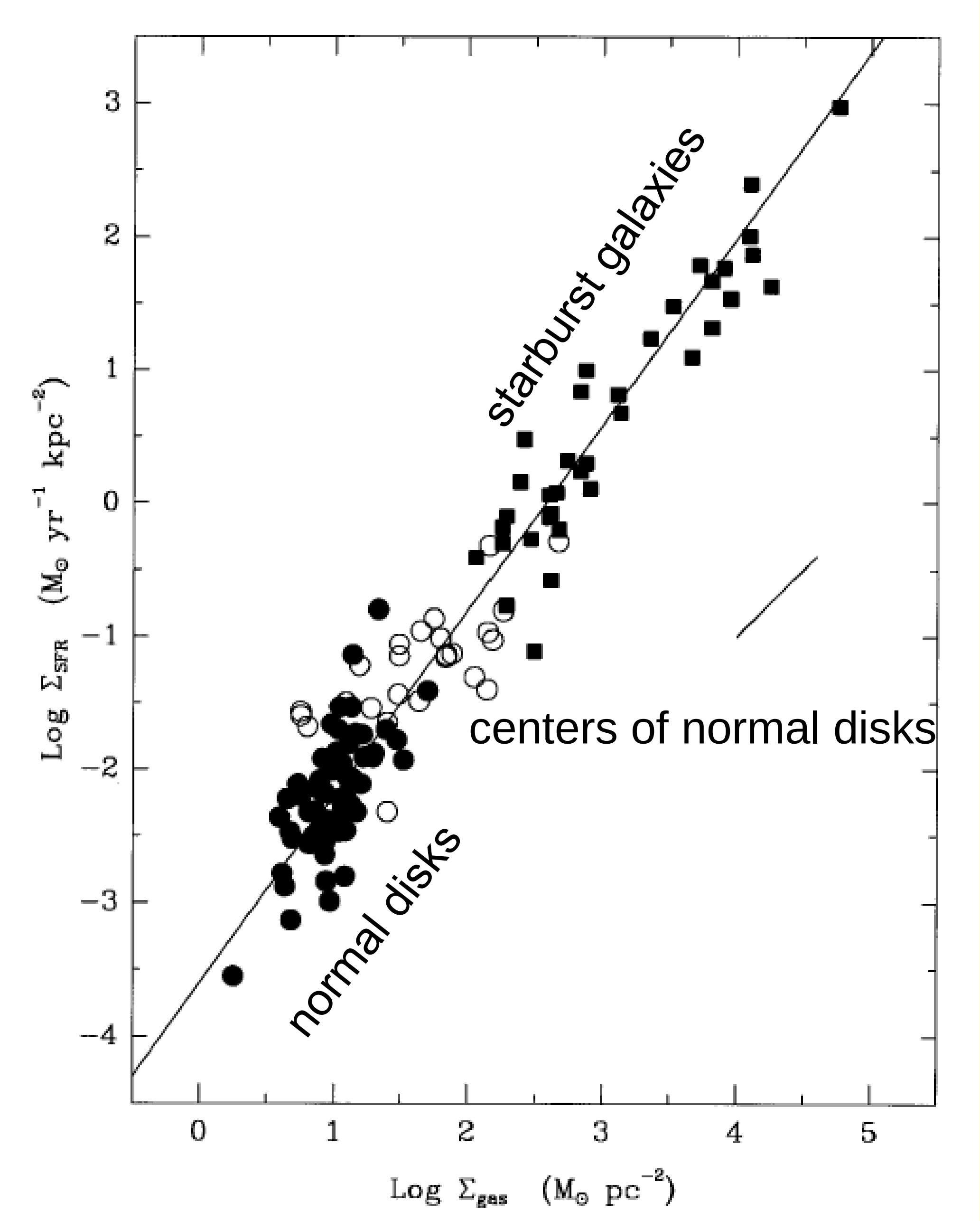
$\tau_{SFR} = \rho_g / SFR$ = 2..3 Gyr

Spiral galaxies

Kennicutt 1989+98:

$$\int SFR\, dz \;\propto\; (\Sigma_{gas})^{1.4\pm0.3}$$

M.Schmidt 1959: $(\Sigma_{gas})^2$



Past SFR = count old objects

- mass surface density in solar nh'd: Oort limit : vertical oscillations of stars → grav.potential → Σ_{stars} = 80 … 100 Msun/pc²
- Σ_{gas} = 5..10 ➔ gas fraction = 0.1 .. 0.2
- Simple model of gas consumption:
  - $\dot{g} = -\psi + (1-\alpha) * \psi$ with $\psi = g/\tau_{SFR}$ and $\alpha \approx 0.8$
  - gives $f_{gas} = \frac{g}{g_0} = \exp(-\alpha t/\tau_{SFR})$
  - SFR timescale = 4 … 6 Gyr

SFR on physical parameters?

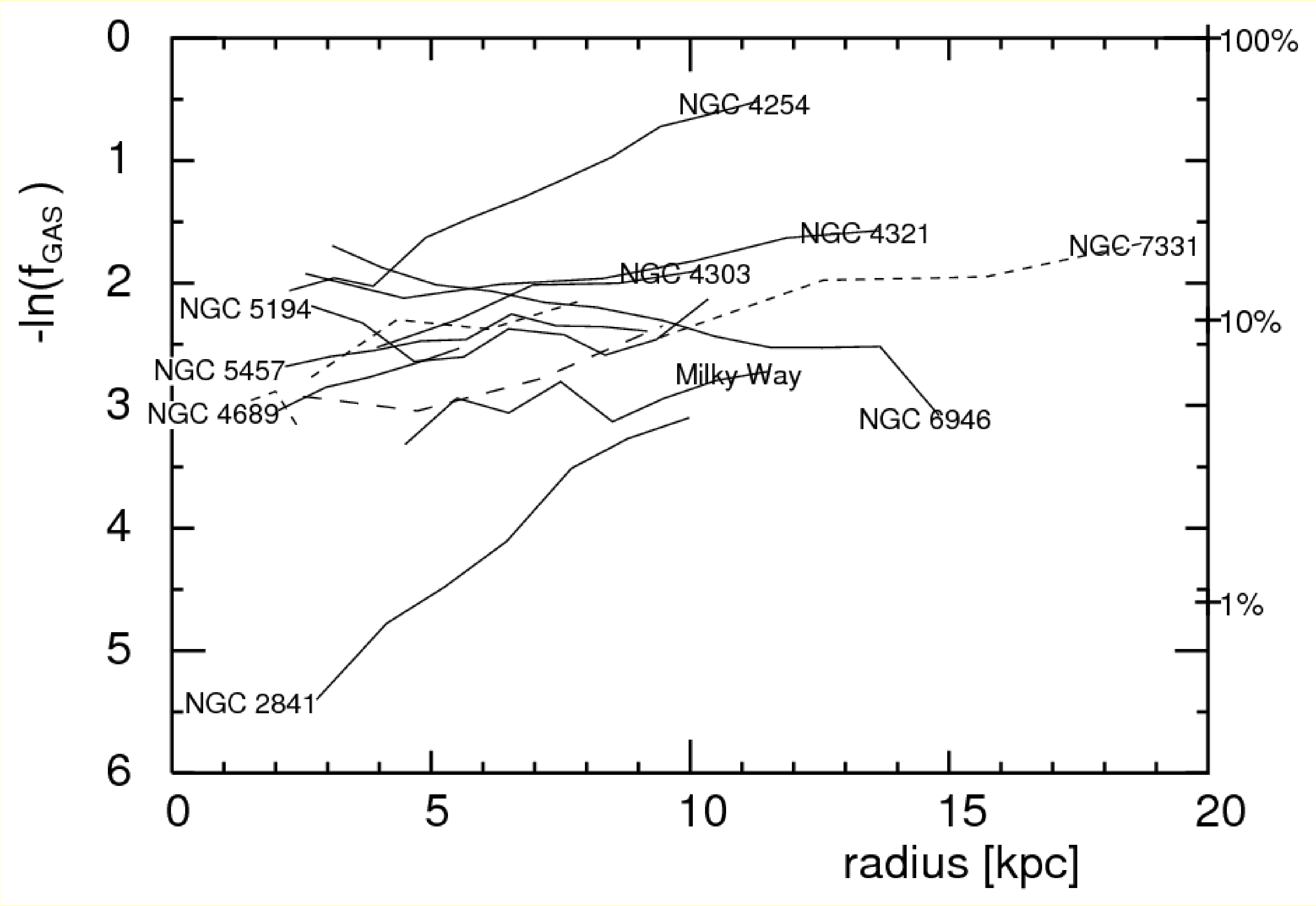
- SF associated with dense, cold, dusty regions
- Gas density:

  ? volume ρ or surface **Σ**

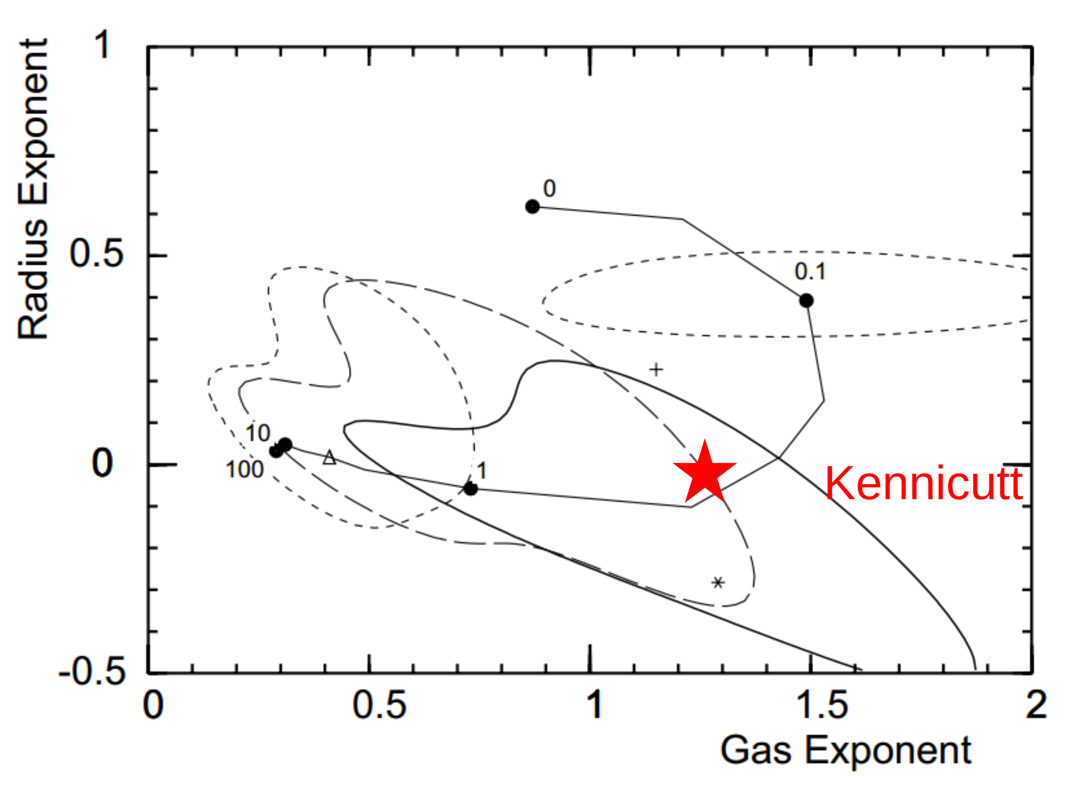
  ? dependence, **power law**, what exponent (**1.4** Kennicutt)

  ? what gas: HI or H2 = CO or **HI + H2**
- Other parameters
  - Differential rotation → spiral arms pass more often thru regions closer to centre (radial depend., Talbot 1980, Wyse+Silk 1989)
  - Galactic potential: keeps gas together so it forms stars: galactic mass (Dopita 1985)
  - Induced (stimulated) star formation: SN explosions trigger clouds into collapse → SF waves (SSPSF Gerola+Seiden 1980, cellular automaton)

Spirals: gas fraction increases outward

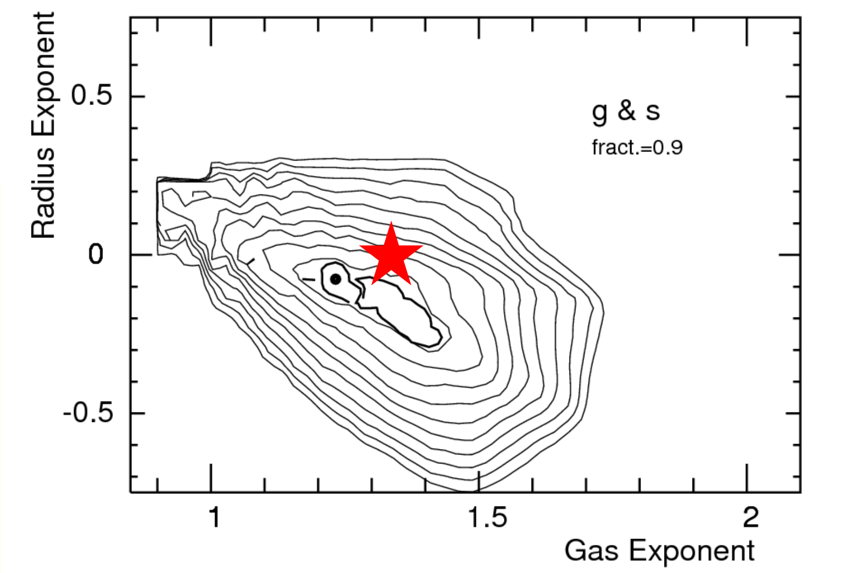


Most likely form of SFR?



$$\psi \propto \Sigma^{x}\, r^{-y}$$

average past SFR



Current SFR from Hα & gas:

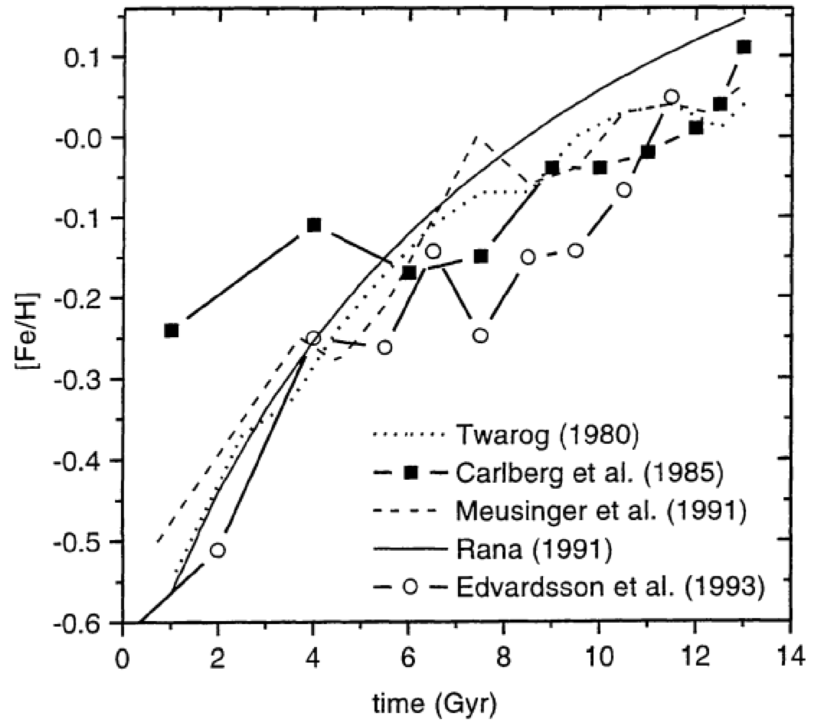
no explicit radial dependence

Köppen+Fröhlich 1997

Star Formation History

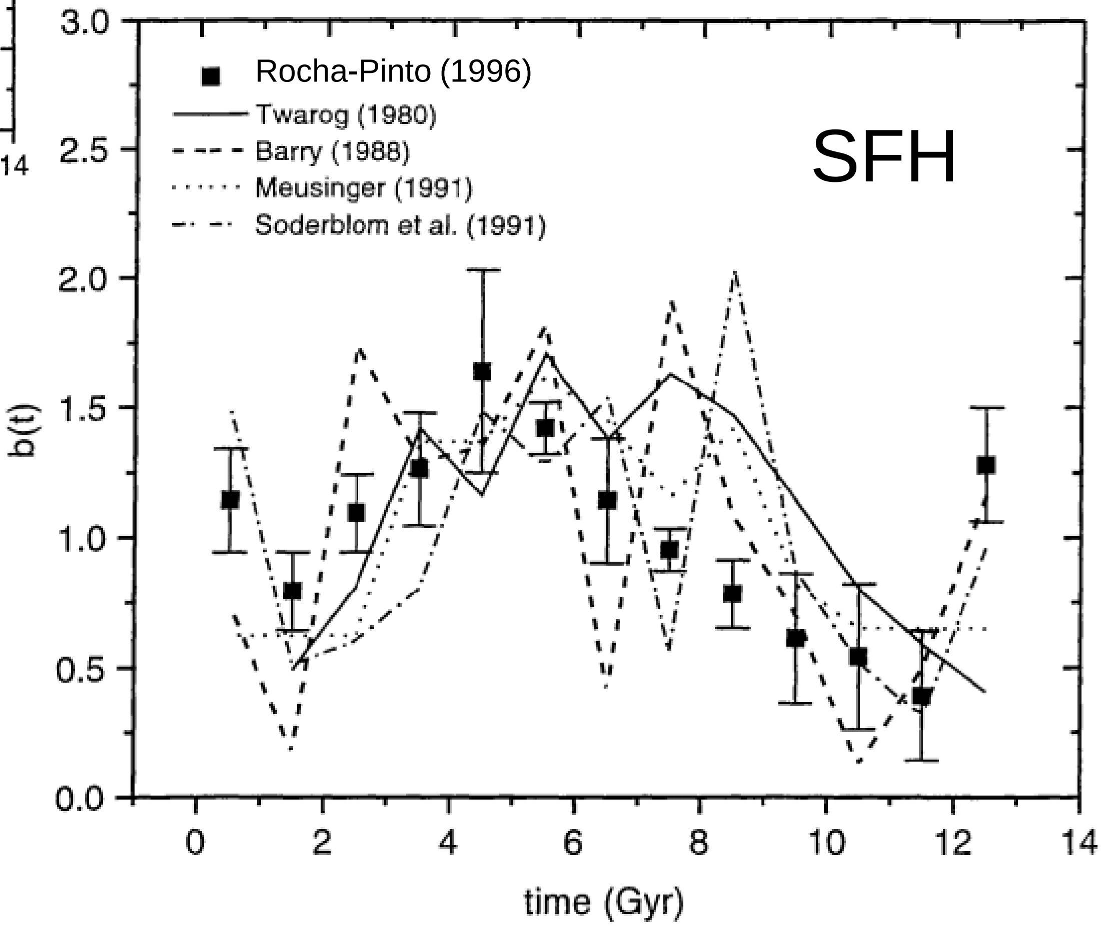
Star formation history (SFH)

- Solar neighbourhood
  - IMF determination ➔ SFR/<SFR>
  - [Fe/H] + (kinematics → stellar ages) ➔ AMR (age-metallicity relation) … chemical evolution model constrains possible SFHs (Twarog ‘80, Meusinger ‘91, Rocha-Pinto ‘96)
  - Match observed HRD or CMD by synthetic stellar populations (Vergely ’02 : inverse method!)



[Fe/H]
time (Gyr)
Twarog (1980)
Carlberg et al. (1985)
Meusinger et al. (1991)
Rana (1991)
Edvardsson et al. (1993)

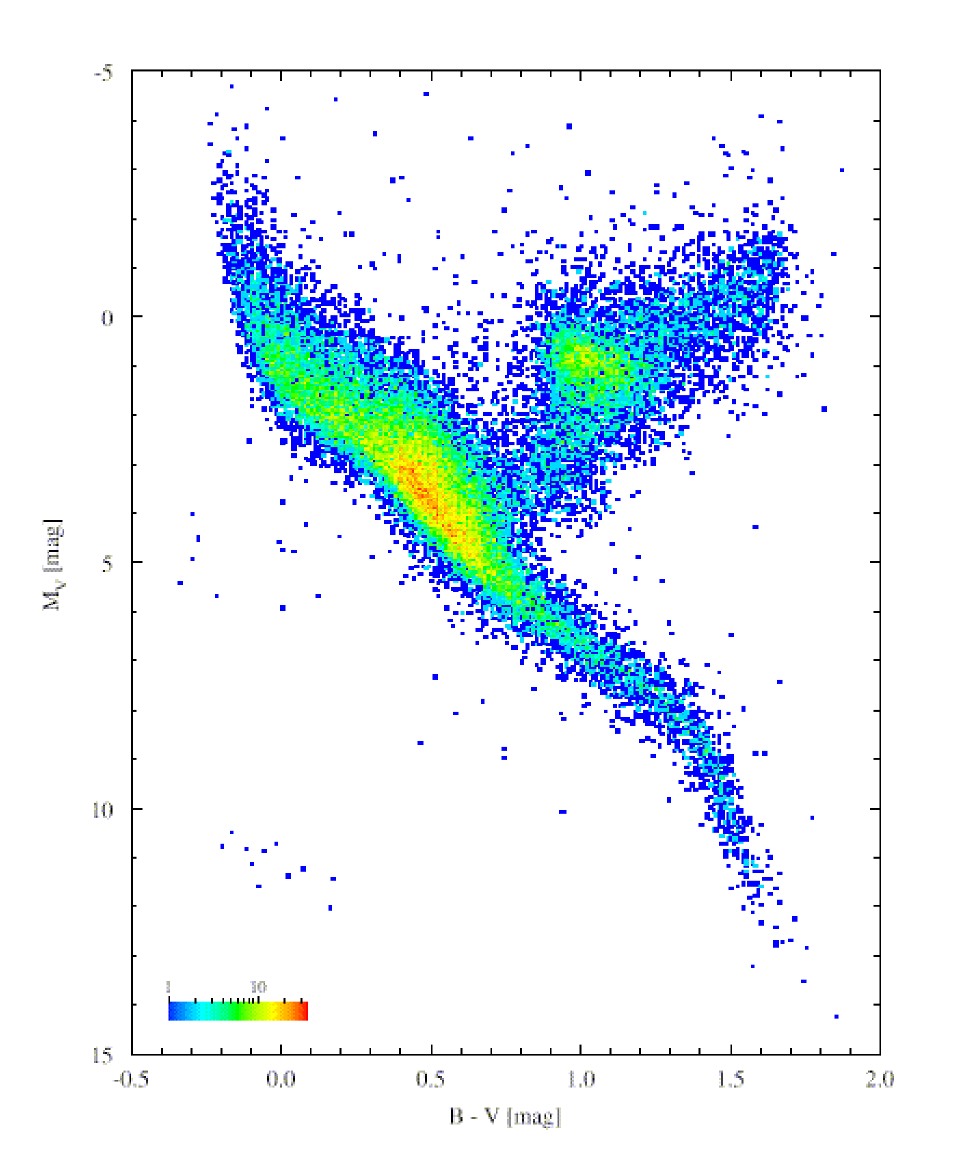
AMR



b(t)
time (Gyr)
Rocha-Pinto (1996)
Twarog (1980)
Barry (1988)
Meusinger (1991)
Soderblom et al. (1991)

SFH

Hipparcos HRD (i.e. CMD)

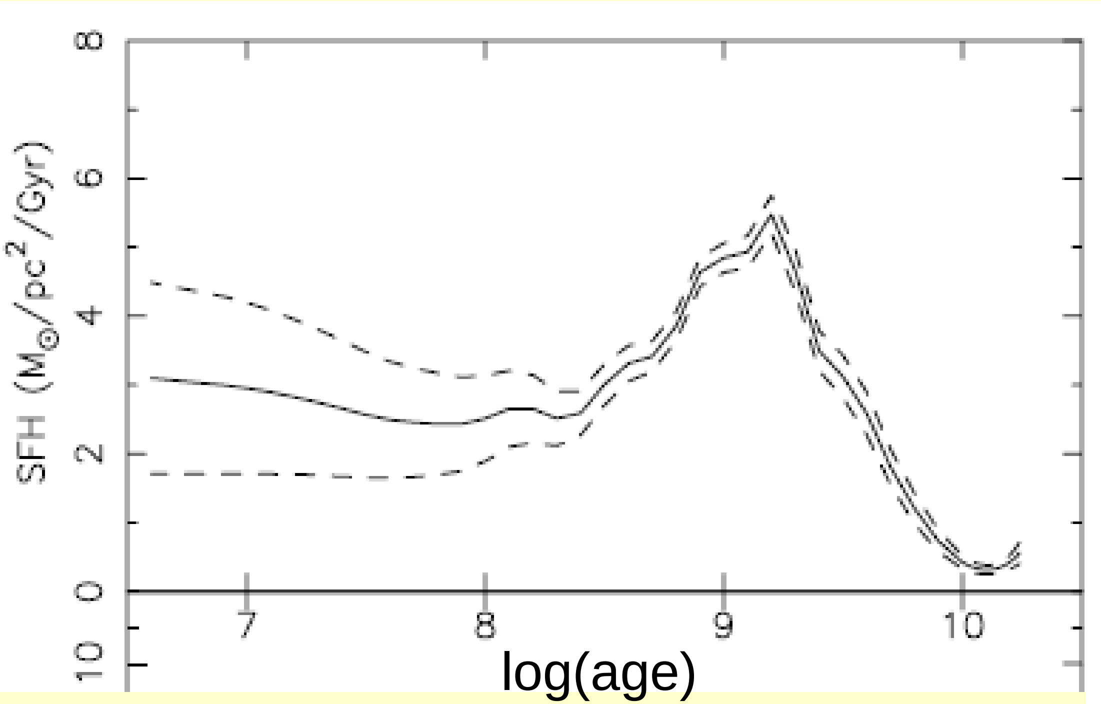


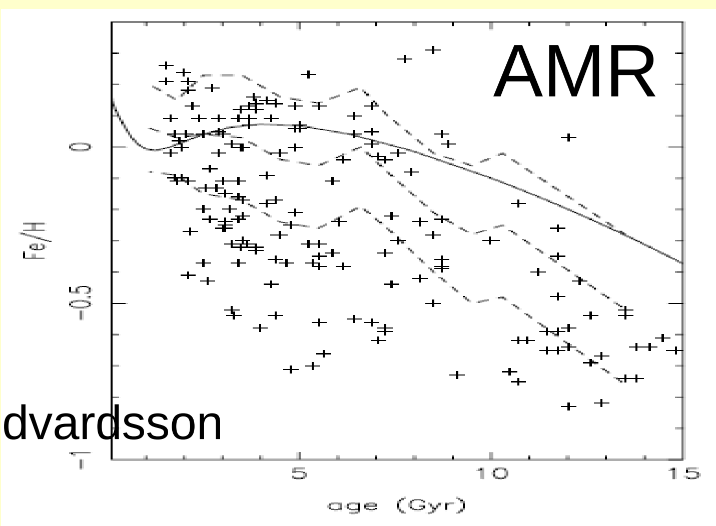
This mixture of stars of all masses, all ages and all metallicities contains all the information about IMF, SFH, AMR …

With the base of stellar isochrones one can use an inverse method to extract this information

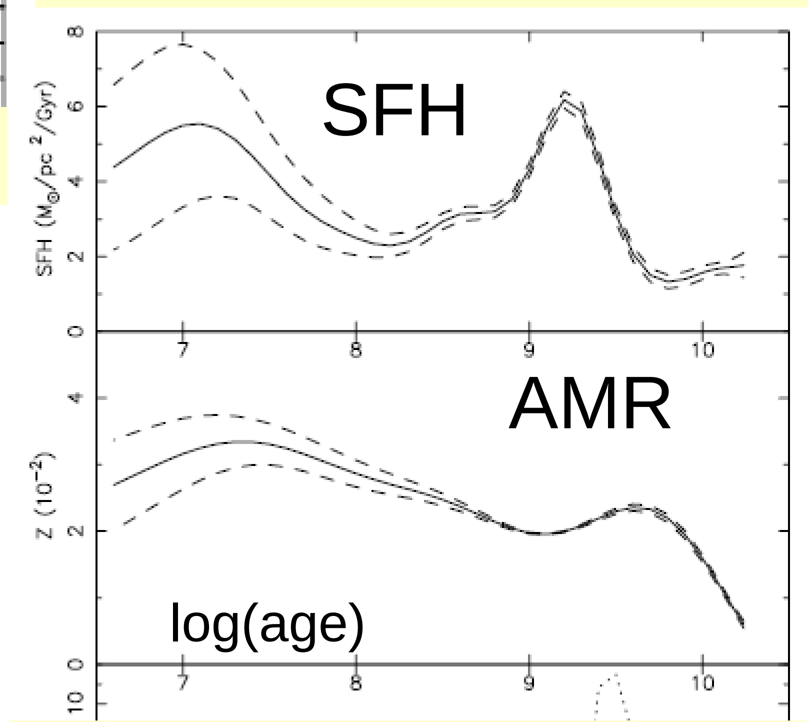
Vergely 2002

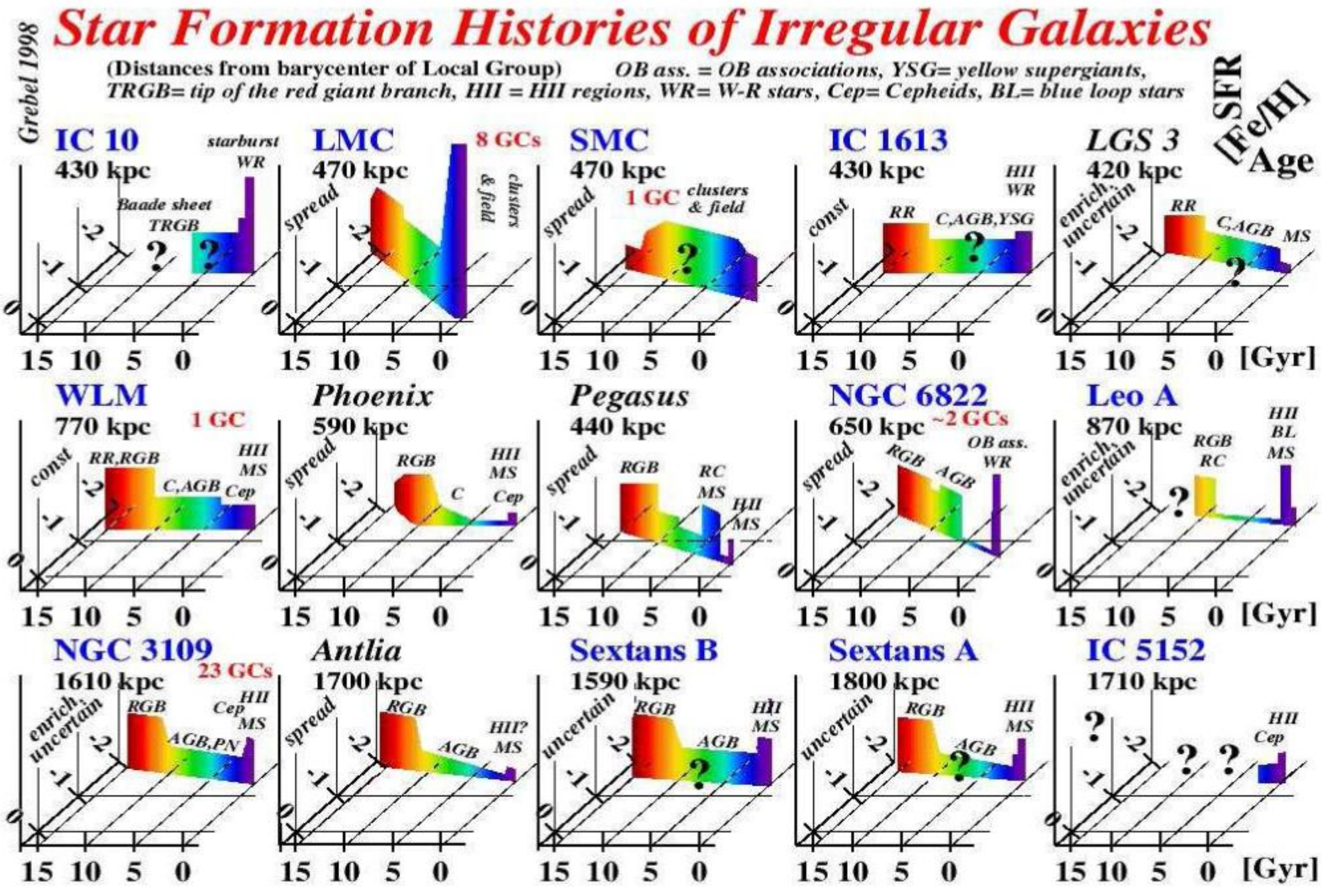
SFH (fixed IMF, fixed metallicity)



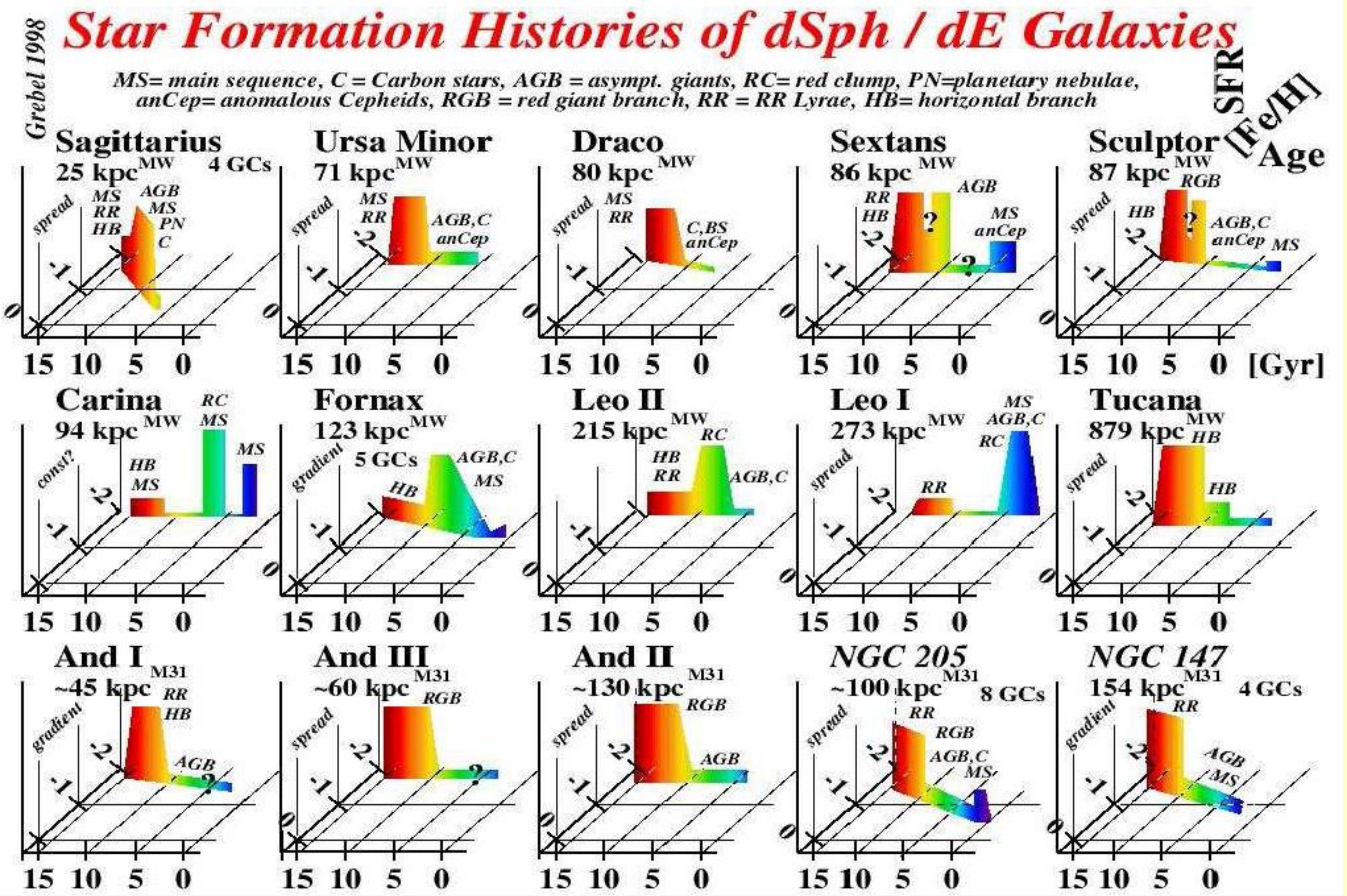


fixed IMF:





Star Formation Histories of Irregular Galaxies
Grebel 1998
(Distances from barycenter of Local Group) OB ass. = OB associations, YSG= yellow supergiants, TRGB= tip of the red giant branch, HII = HII regions, WR= W-R stars, Cep= Cepheids, BL= blue loop stars
SFR
[Fe/H]
Age
IC 10
430 kpc
LMC
470 kpc
8 GCs
SMC
470 kpc
1 GC
IC 1613
430 kpc
LGS 3
420 kpc
WLM
770 kpc
1 GC
Phoenix
590 kpc
Pegasus
440 kpc
NGC 6822
650 kpc
~2 GCs
Leo A
870 kpc
NGC 3109
1610 kpc
23 GCs
Antlia
1700 kpc
Sextans B
1590 kpc
Sextans A
1800 kpc
IC 5152
1710 kpc
15 10 5 0 [Gyr]

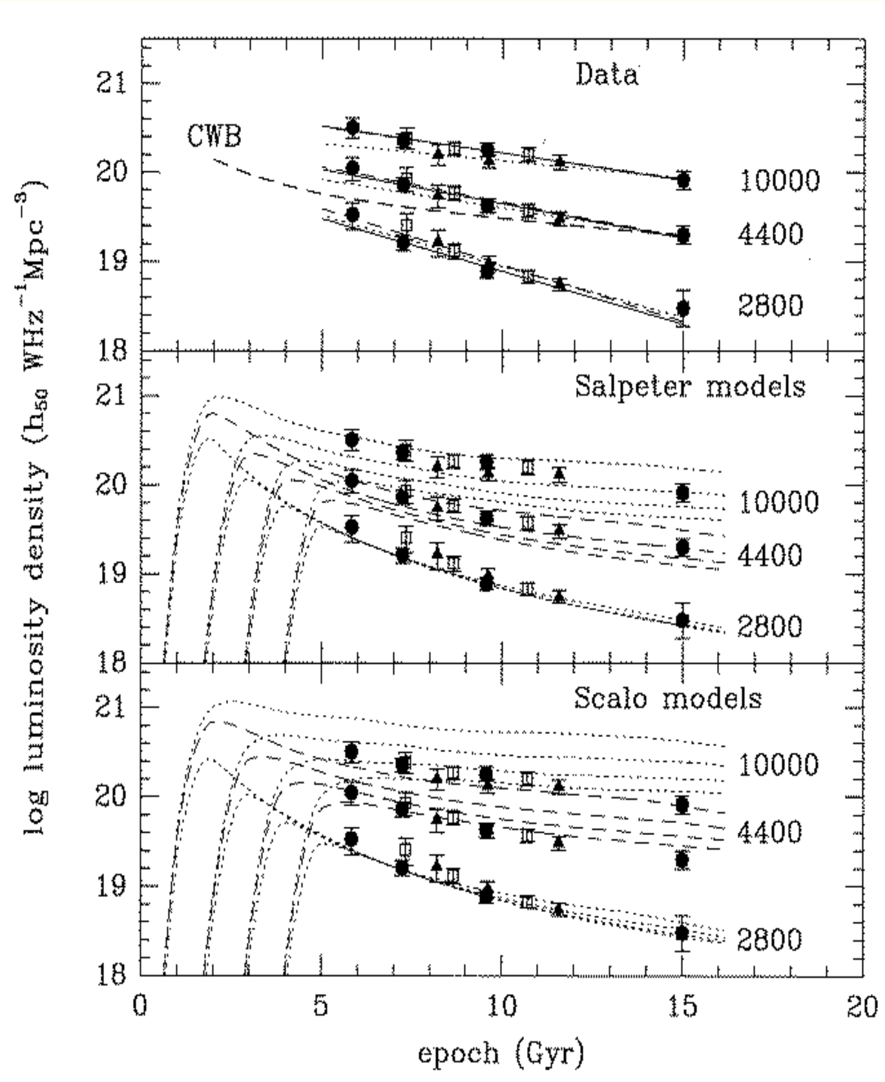


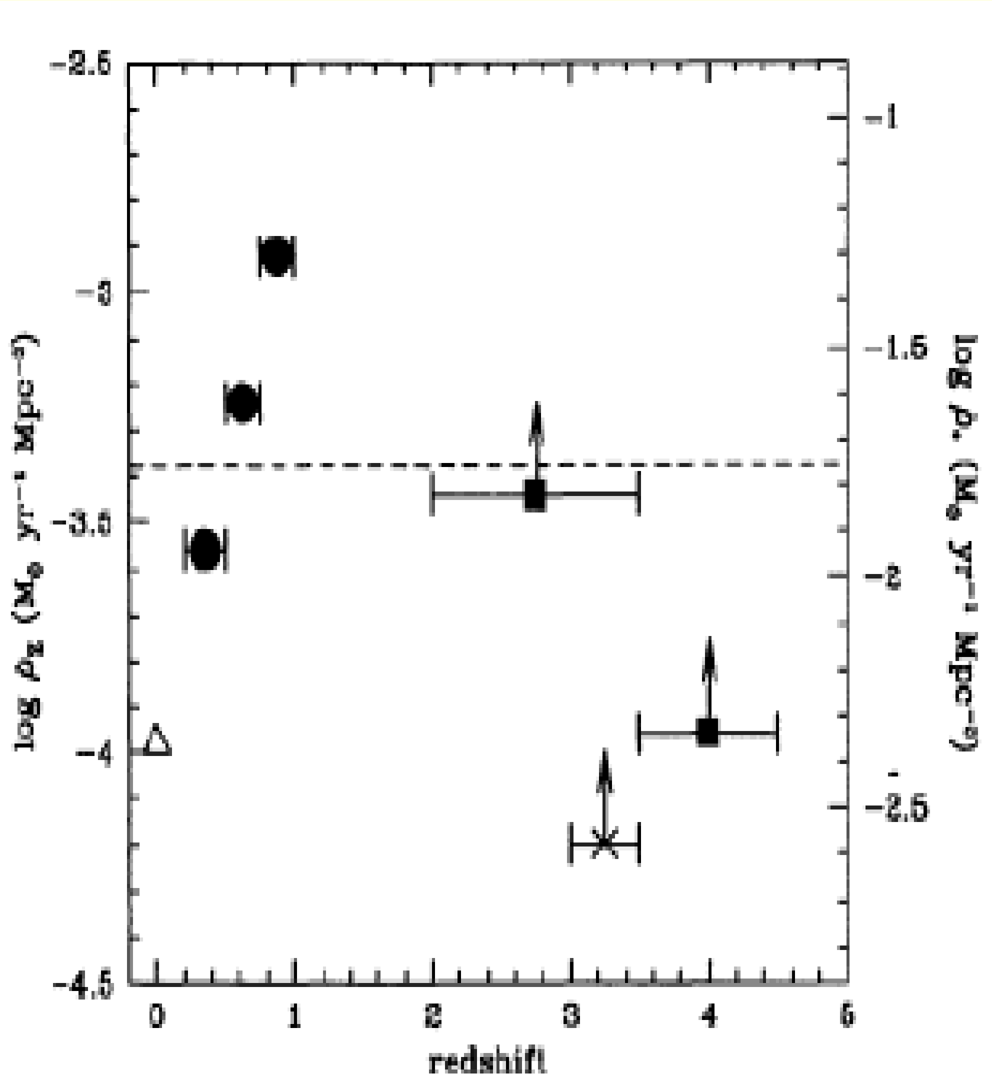
Star Formation Histories of dSph / dE Galaxies
Grebel 1998
MS= main sequence, C = Carbon stars, AGB = asympt. giants, RC= red clump, PN=planetary nebulae,
anCep= anomalous Cepheids, RGB = red giant branch, RR = RR Lyrae, HB= horizontal branch
SFR
[Fe/H]
Age
Sagittarius
25 kpc MW
4 GCs
Ursa Minor
71 kpc MW
Draco
80 kpc MW
Sextans
86 kpc MW
Sculptor
87 kpc MW
[Gyr]
Carina
94 kpc MW
Fornax
123 kpc MW
5 GCs
Leo II
215 kpc MW
Leo I
273 kpc MW
Tucana
879 kpc MW
And I
~45 kpc M31
And III
~60 kpc M31
And II
~130 kpc M31
NGC 205
~100 kpc M31
8 GCs
NGC 147
154 kpc M31
4 GCs
15 10 5 0

SFH of the Universe: Lilly/Madau plot

- SFR indicators:
  - UV: 1500 … 2800A
  - Recombination lines: Hα, Hβ
  - Forbidden lines: [OII]   (empirical relations)
  - H Lyman α
  - mid- and far-IR: 10 …1000µm
  - Radio continuum: 1.4 GHz
  - Xrays: 0.5 ..10 keV
- Proper compensation for source redshifts …

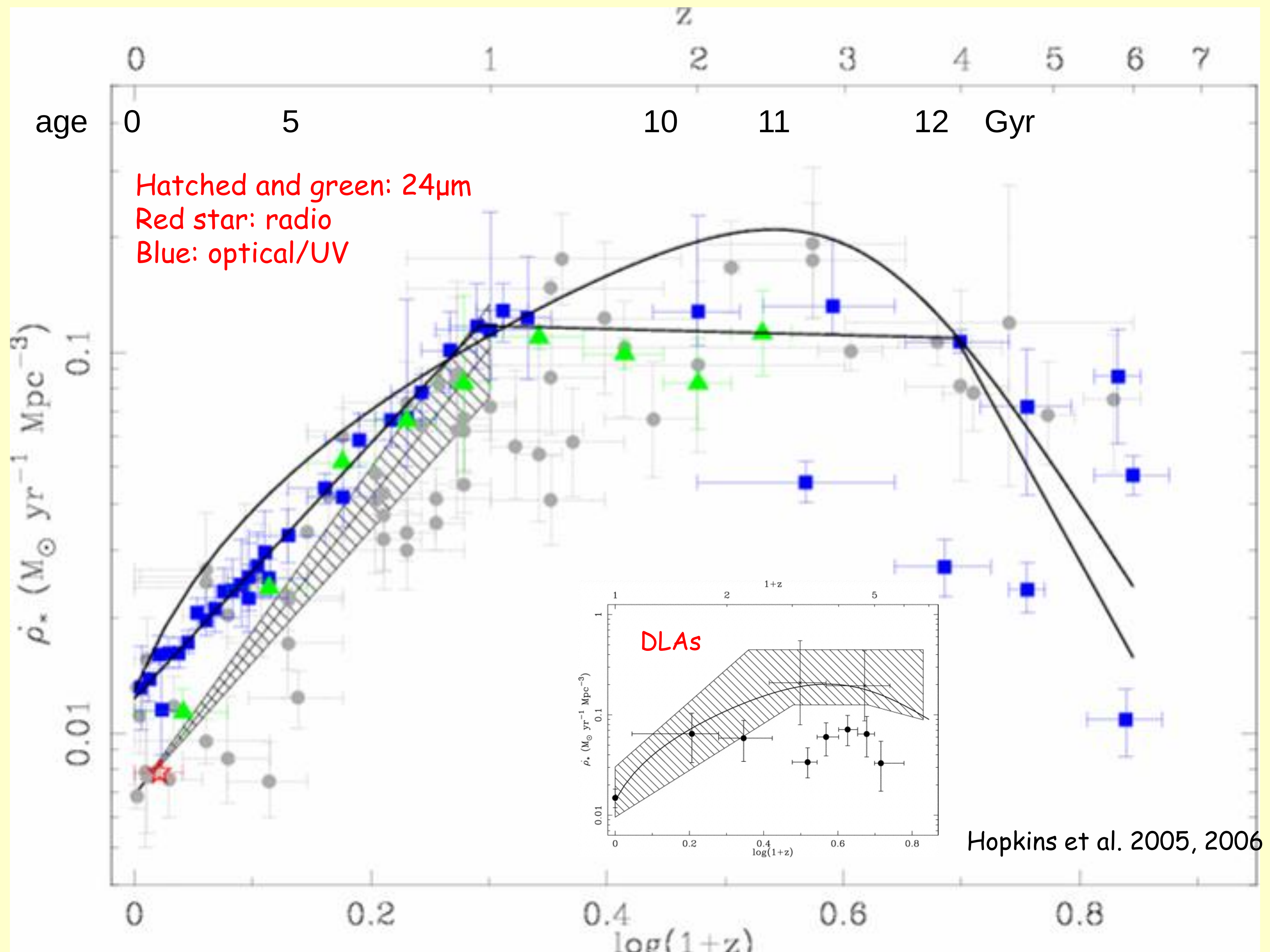
The original Lilly – Madau plots



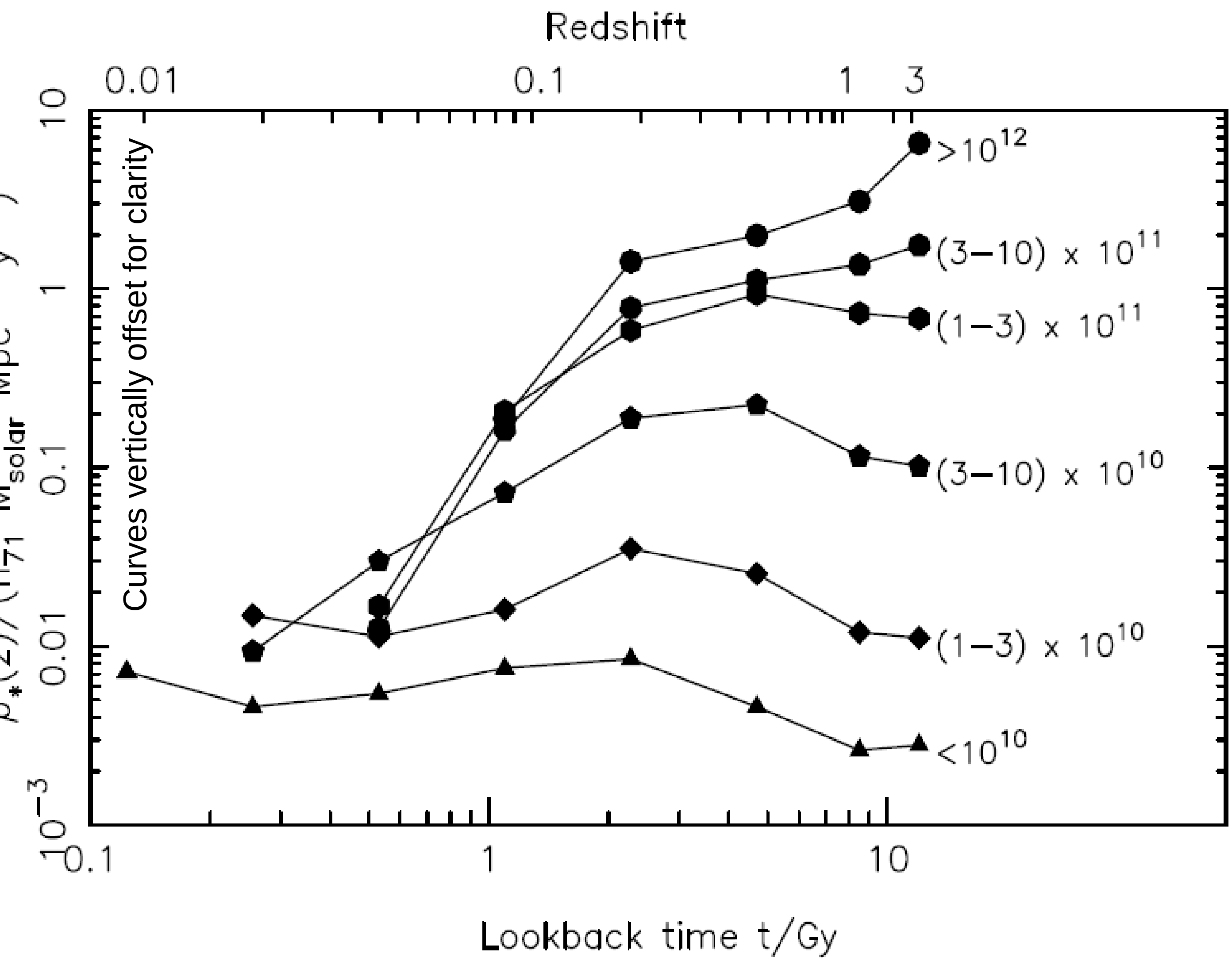


Lilly et al. 1996

Madau et al. 1996


z
0
1
2
3
4
5
6
7
age
0
5
10
11
12
Gyr
Hatched and green: 24μm
Red star: radio
Blue: optical/UV
0.1
0.01
0
0.2
0.4
0.6
0.8
log(1+z)
DLAs
1+z
log(1+z)
Hopkins et al. 2005, 2006

Downsizing:
dependence of SFH on stellar mass



Massive galaxies have formed early.

They now are in clusters, while the less massive ones Inhabit low-density regions

10^5 SSDS galaxies

Heavens 2004