Lecture 7. Galaxy Formation

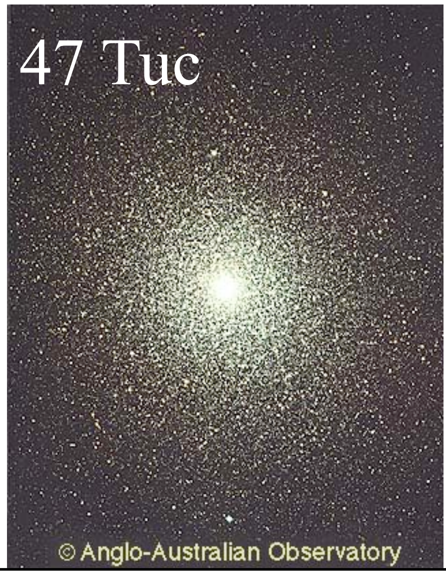
After decoupling, overdense regions collapse IF

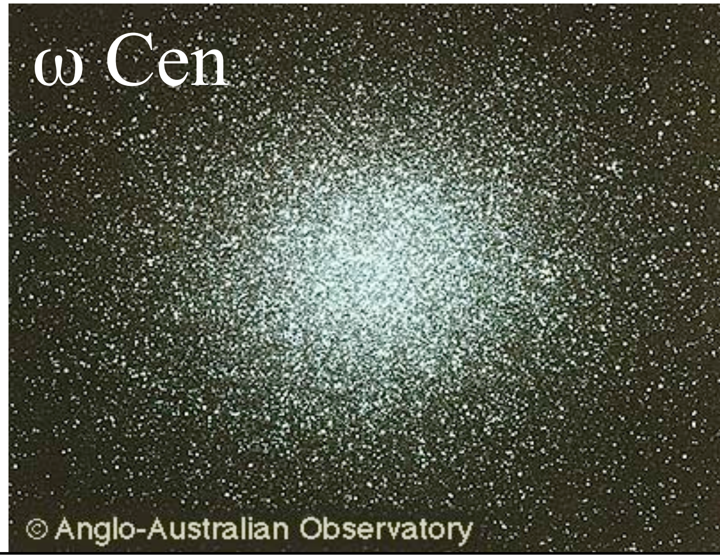
$$L > L_J \sim \left(\frac{k\,T}{G\,m\,\rho} \right)^{1/2} \sim 50 \text{ pc} \qquad M > M_J \sim \rho\, L_J^{\;3} \sim 10^6 \text{ M}_{\text{sun}}$$

Collapse time $t_G \sim (G\,\rho)^{-1/2} \sim 10^7\,\text{yr}$ for all sizes.

More small ripples than large waves.

--> Universe dominated by globular clusters (?!)





Caveats

Dimensional Analysis --> scaling laws
leaving out dimensionless factors (e.g.~10).

We ignored:

angular momentum -- slows and can halt the collapse
--> Spiral Galaxies.

cosmological expansion -- delays collapse until
expansion time > collapse time.

$$t > \left(G\rho\right)^{-1/2}$$

--> Need "Dark Matter halos" (which begin collapsing
before decoupling) into which baryon gas falls.

The Dark Ages (1100 < z < 20)

Uniform neutral IGM
(*Inter-Galactic Medium*)

Proto-globular clusters.

Rare larger objects:

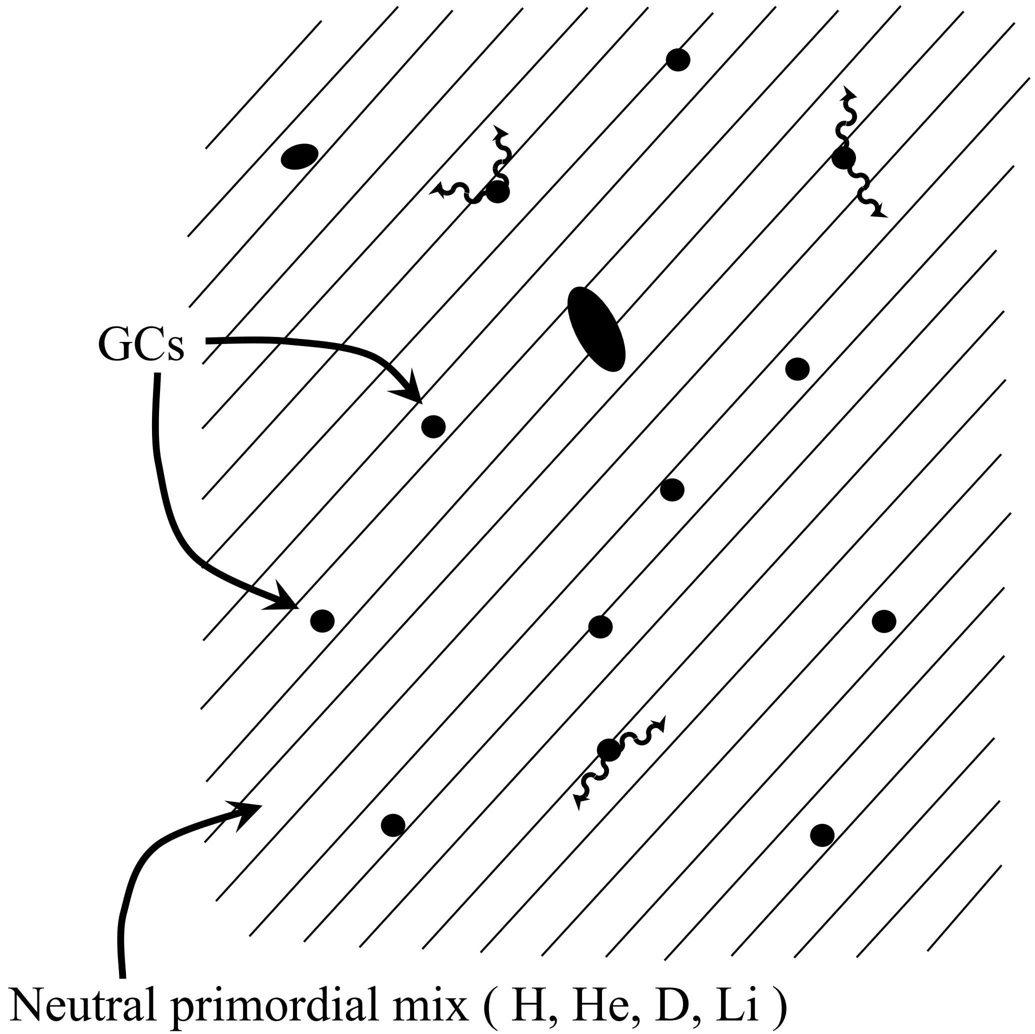
proto-galaxies

proto-clusters

T_{CMB}=*2.7(1+z)* K

No stars!

As regions collapse and merge, stars form, and their ultra-violet light can *re-ionise* the IGM.



Redshift of Galaxy Formation

Recombination:

$$t_{\mathrm{Rec}} = 3 \times 10^5 \text{ yr} \qquad \mathrm{z}_{\mathrm{Rec}} = 1100$$

Galaxy formation (collapse time):

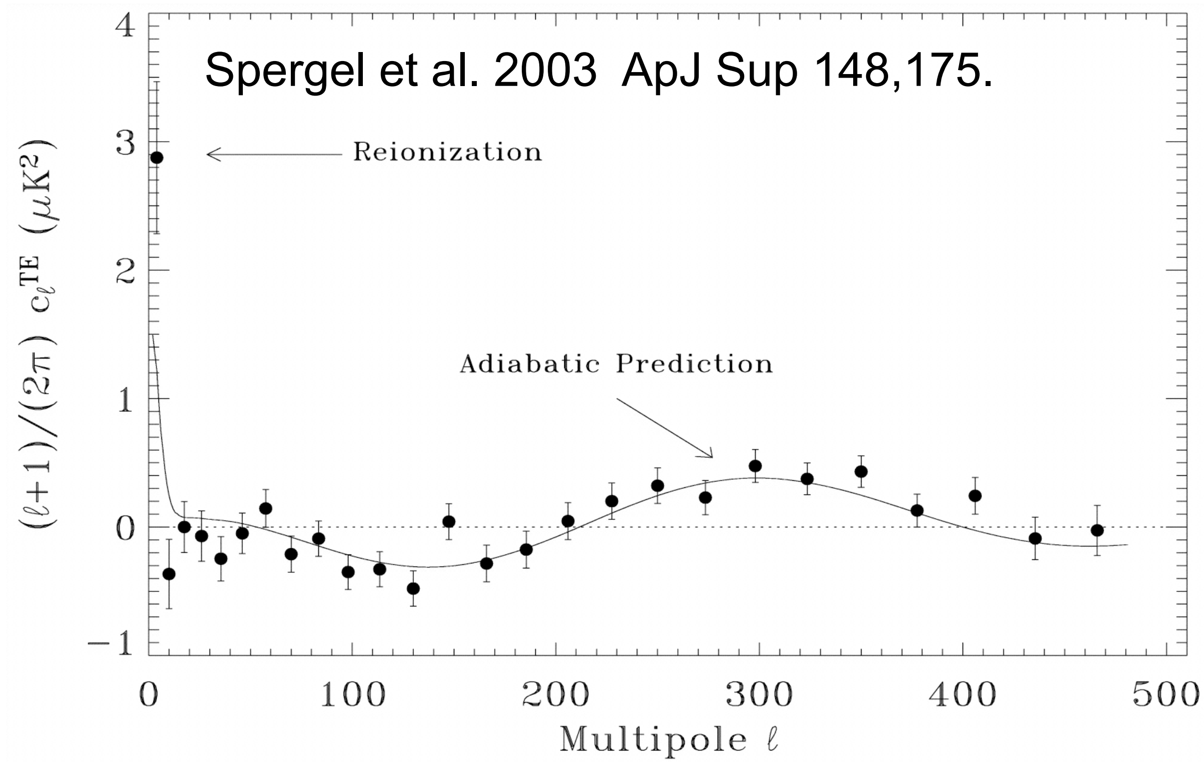
$$t_G = 10^7 \text{ yr} \qquad \mathrm{z}_{\mathrm{G}} = ?$$

CMB ~15% Polarised

2003 WMAP discovery.

Free electrons have scattered ~15% of CMB photons.

--> ***<u>IGM was re-ionised by redshift z ~ 20.</u>***



History of Galaxy Formation

CMB (z ~ 1100)

⇓

First (smaller) galaxies form (GCs?)

⇓

Reionisation (z ~ 20) by first UV sources

(first stars and/or accreting black holes)

⇓

Main phase of galaxy formation (z ~ 2-3)

⇓

Today (z = 0)

Star-Formation Rates (SFR)

Consider a condensation of primordial mix [$X=0.75,\ Y=0.25,\ Z=0.0$]

Total mass: M_{gas}

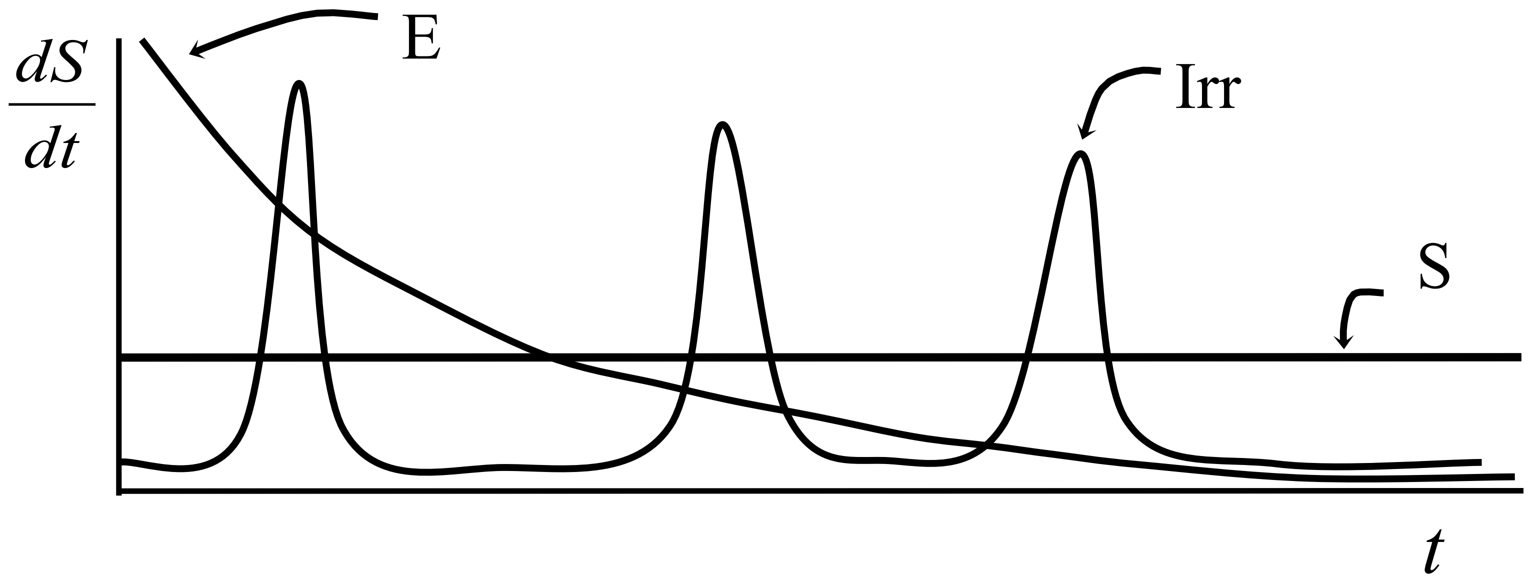
Star formation: $M_{gas} \longrightarrow M_{stars}$

How quickly? With what efficiency?

Star Formation Histories

Stellar populations (old vs young stars) reveal SF histories. Three main galaxy types:

Elliptical	exponential SFR
Spiral	constant SFR
Irregular	episodic SFR



Ellipticals

Red ⇒ Old stars

Few emission lines ⇒ Low SFR

Little dust or gas ⇒ Gas converted to stars.

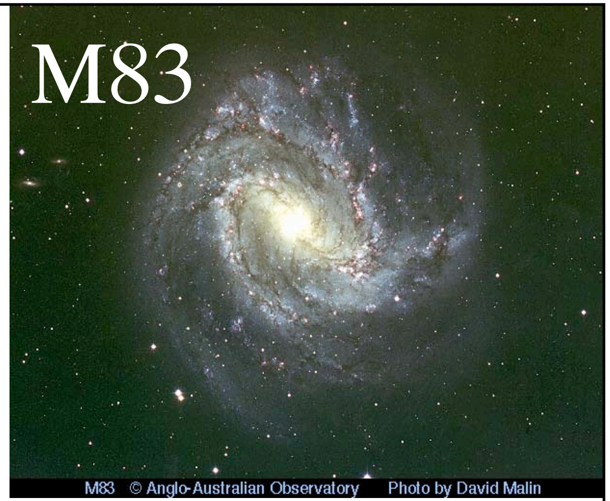
High surface brightness ⇒ Form via mergers

No net rotation ⇒ with low net

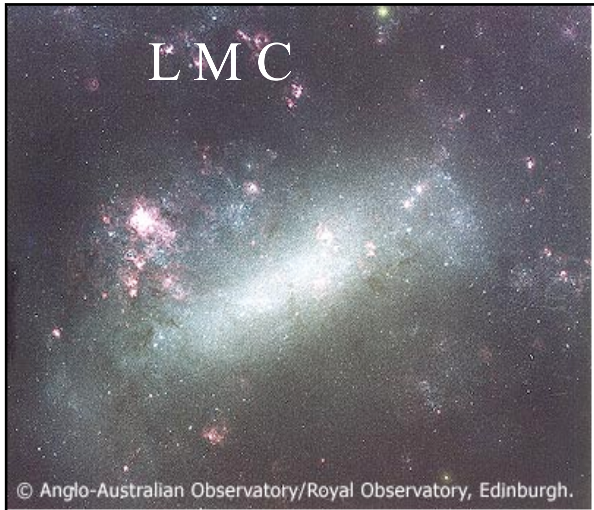
Found in clusters ⇒ angular momentum.

Have many GCs

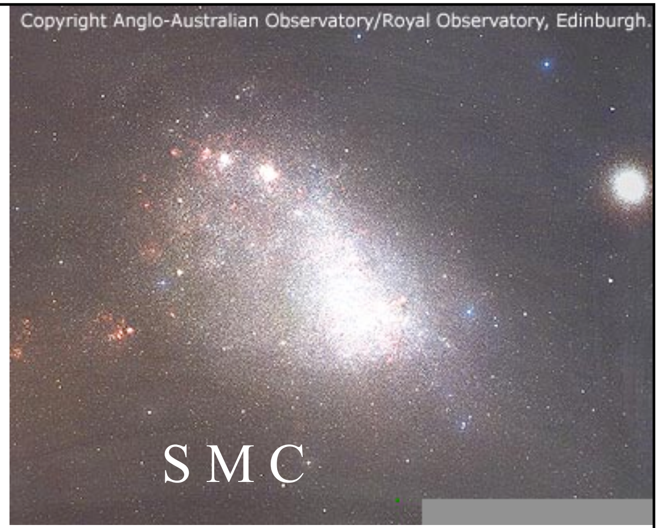
Spirals



Red halo, blue disc	⇒	Old and young stars.
Emission & absorption lines	⇒	Star formation + old stars
Dust lanes & HI	⇒	Gas available to form stars
Moderate surface brightness	⇒	Form via collapse with
Rotating disk	⇒	high angular momentum.
Fewer spirals in clusters.	⇒	Destroyed by mergers.



Irregulars



Blue	$\Longrightarrow$	Young stars
Strong emission lines	$\Longrightarrow$	High SFR
Very dusty	$\Longrightarrow$	Large gas reservoir
Low surface brightness	$\Longrightarrow$	High angular momentum
Rotating	$\Longrightarrow$	Form via collapse.
Have few GCs	$\Longrightarrow$	“
Mainly in field	$\Longrightarrow$	Easily disrupted.

Closed Box Model

M_0 = initial gas mass

$M_G(t)$ = gas mass at time t

$M_S(t)$ = mass converted to stars

β = fraction of M_S returned to gas
(supernovae, stellar winds, PNe)

$$\begin{aligned} M_G &= M_0 - M_S + \beta\, M_S \\ &= M_0 - \alpha\, M_S \end{aligned}$$

α = 1- β = fraction of M_S retained in stars

= ***star formation efficiency***

In densities: $$\rho_G = \rho_0 - \alpha\, \rho_S$$

In dimensionless form

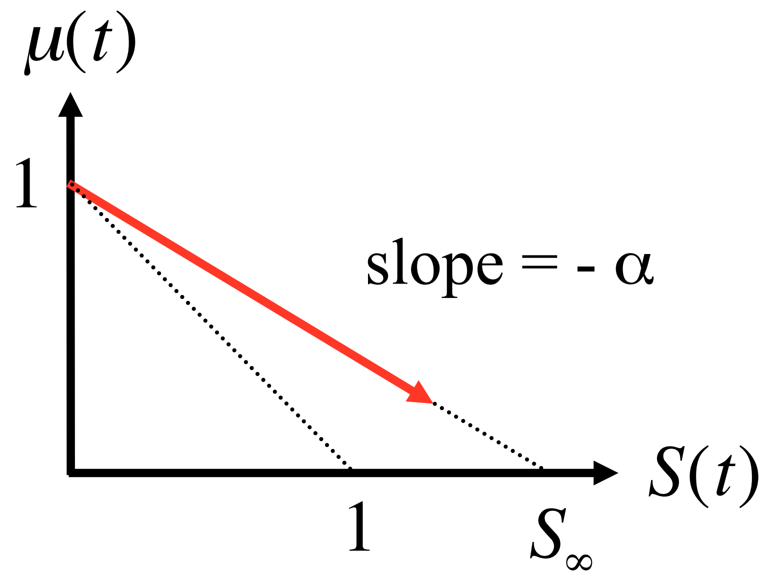
$$\mu(t) \equiv \frac{M_G(t)}{M_0}$$ = fraction of M_0 in gas

$$S(t) \equiv \frac{M_S(t)}{M_0}$$ = fraction of M_0 that has been turned into stars

$$M_G = M_0 - \alpha\, M_S$$
$$\mu = 1 - \alpha\, S$$

Since $\alpha < 1$, $S(t) \rightarrow S_\infty > 1$

OK, since some gas is recycled.



SFR in Ellipticals

Assume $dS/dt \propto \mu$ (more gas -> more stars form)

$$\mu(t) = 1 - \alpha \ \ S(t)$$

$$\frac{d\mu}{dt} = -\alpha \frac{dS}{dt} = -\alpha \, C \, \mu \qquad \frac{dS}{dt} = C \, \mu$$

$$\frac{d\mu}{\mu} = -\alpha \, C \, dt = -\frac{dt}{t_*} \qquad t_* \equiv \frac{1}{\alpha C}$$

$$\ln \mu = -\frac{t}{t_*} + A \qquad A = \ln \mu(0) = 0 \text{ for } \mu(0) = 1$$

gas $\mu(t) = \ e^{-t/t_*}$

stars $\alpha \ S(t) = \ 1 - e^{-t/t_*}$

Star Formation Timescale

t_* = "e-folding time"

= time to turn mass M_0/e into stars. Typically:

$$t_* \sim 1\text{ - }5\ \text{Gyr}$$

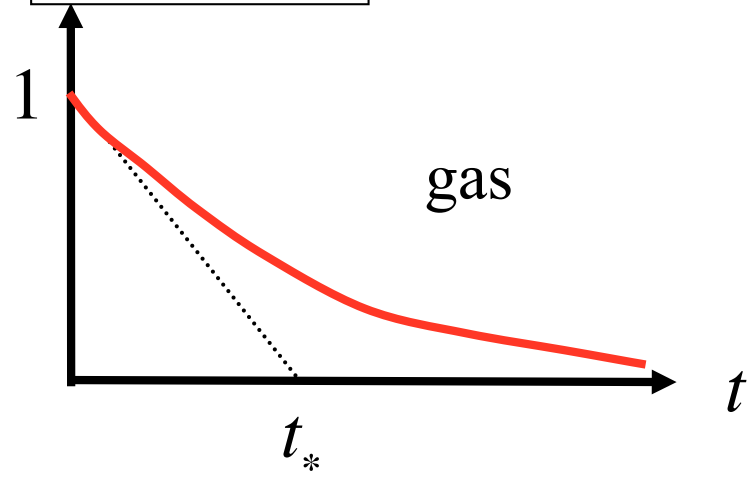
Q: If $t_* = 2$ Gyr, how long to turn 90% of gas into stars?

A: $\mu(t) = e^{-t/t_*} = 0.1$

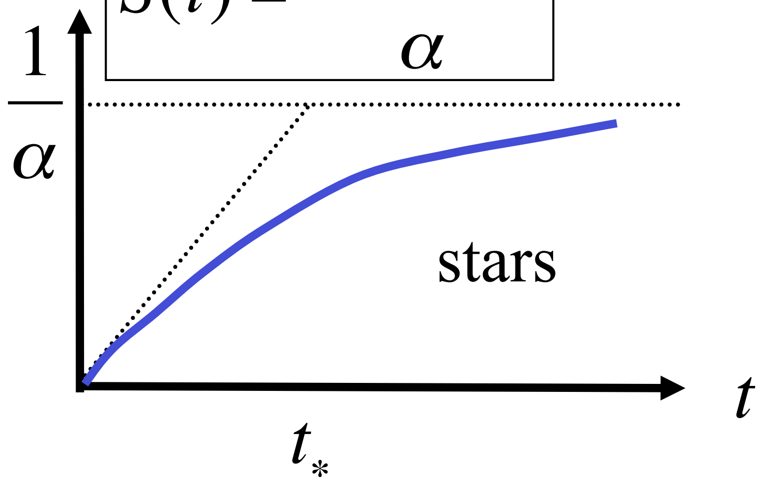
$$t = -t_* \ln(\mu)$$

$$= -2\ln(0.1) = 4.6\ \text{Gyr}$$

$$\mu(t) = e^{-t/t_*}$$



$$S(t) = \frac{1 - e^{-t/t_*}}{\alpha}$$



SFR in Spirals

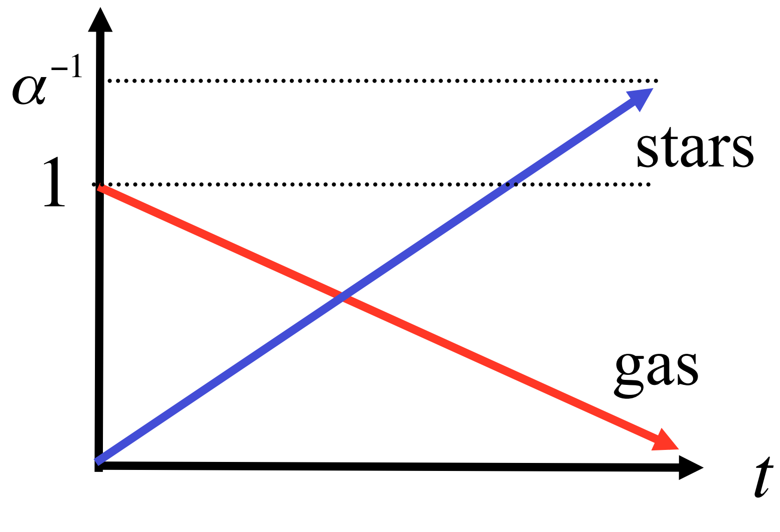
Assume *SFR* = constant

$\dot{M}$ = mass converted per year

$$\frac{dS}{dt} = \frac{\dot{M}}{M_0}$$

$$S(t) = \frac{\dot{M}}{M_0}\; t$$

$$\mu(t) = 1 - \alpha\; S(t)$$
$$= 1 - \alpha\; \frac{\dot{M}}{M_0}\; t$$



SFR in Irregulars

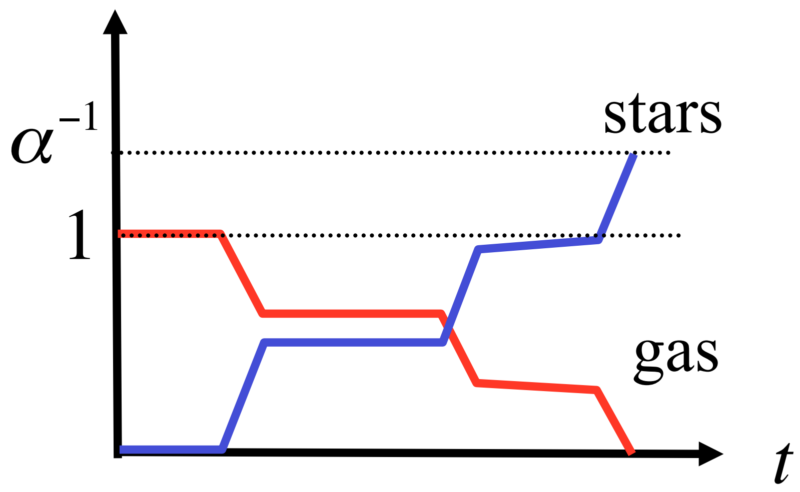
Typically bursts of 100 $M_\odot yr^{-1}$ for 0.5 Gyr at intermittent intervals

$$\frac{dS}{dt} = f \, \frac{\dot{M}}{M_0}$$

$\dot{M}$: Star formation rate during star bursts.

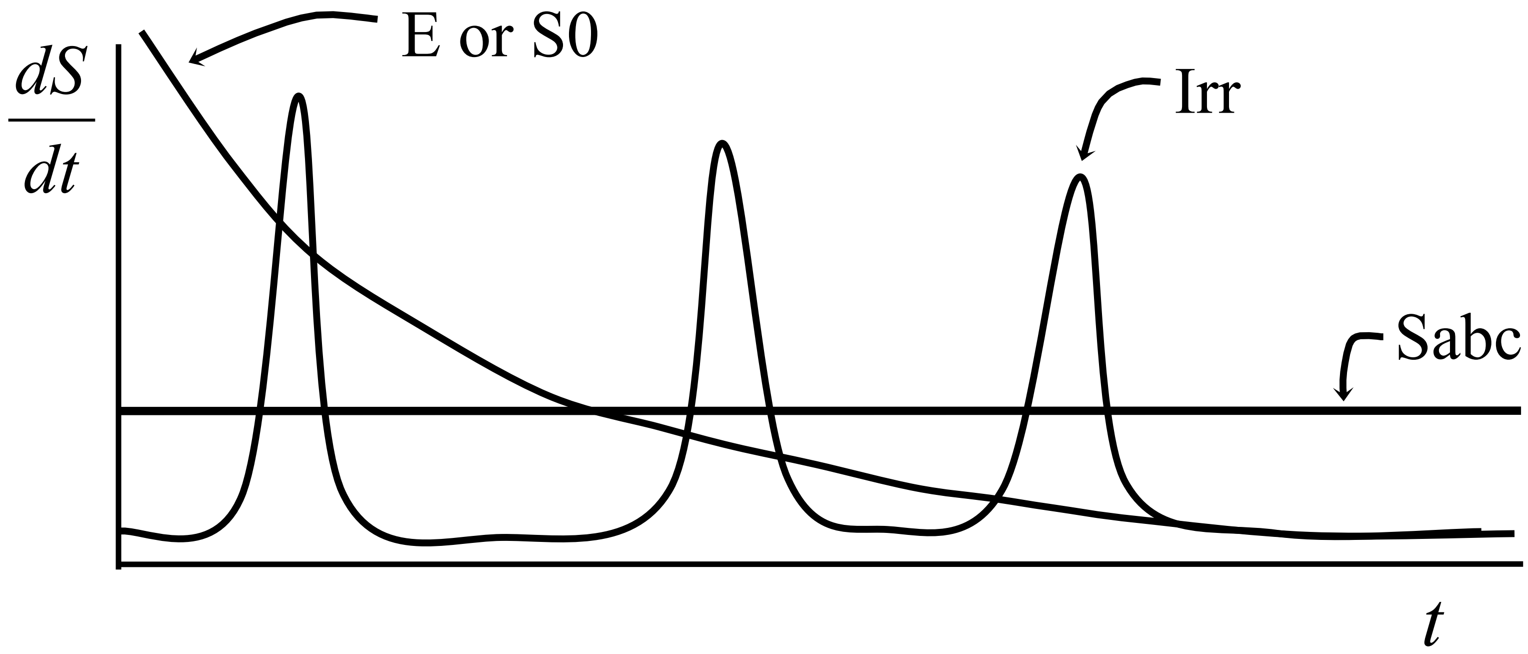
f: Fraction of time spent star-bursting

$$\mu(t) = 1 - \alpha f \, \frac{\dot{M}}{M_0} \, t$$



$$\mu(t) = 1 - \alpha \, S(t)$$

Star-formation histories



For ellipticals most stars form early on.
Stars all roughly same age (co-eval).

Ages from main-sequence turn-off stars

Main sequence lifetime:

lifetime = fuel / burning rate

$$\tau_{MS} = 7 \times 10^9 \left[\frac{M}{M_\odot}\right]\left[\frac{L}{L_\odot}\right]^{-1} \text{ yr}$$

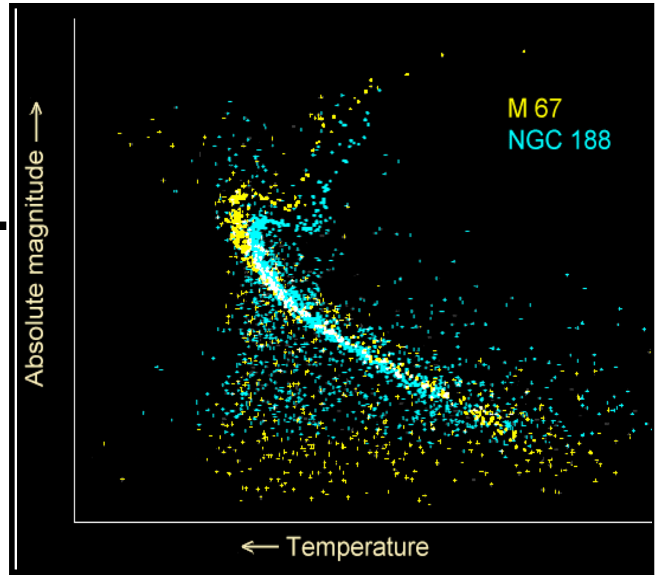
$$\tau_{MS} = 7 \times 10^9 \left[\frac{L}{L_\odot}\right]^{-\frac{3}{4}} \text{ yr}$$

(since $L \propto M^4 \rightarrow M \propto L^{1/4}$)

HR diagram

M_V

$M_V(TO)$



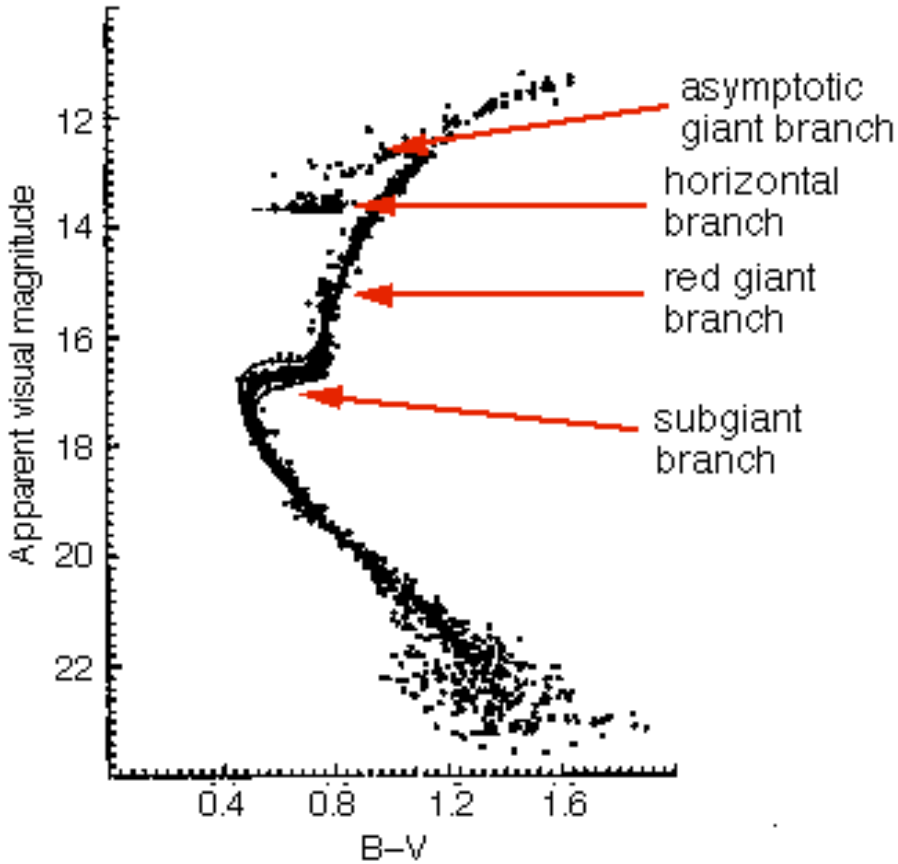
B-V

Luminosity at the top of the main sequence (turn-off stars) gives the age *t*.

Ages from main-sequence turn-off stars

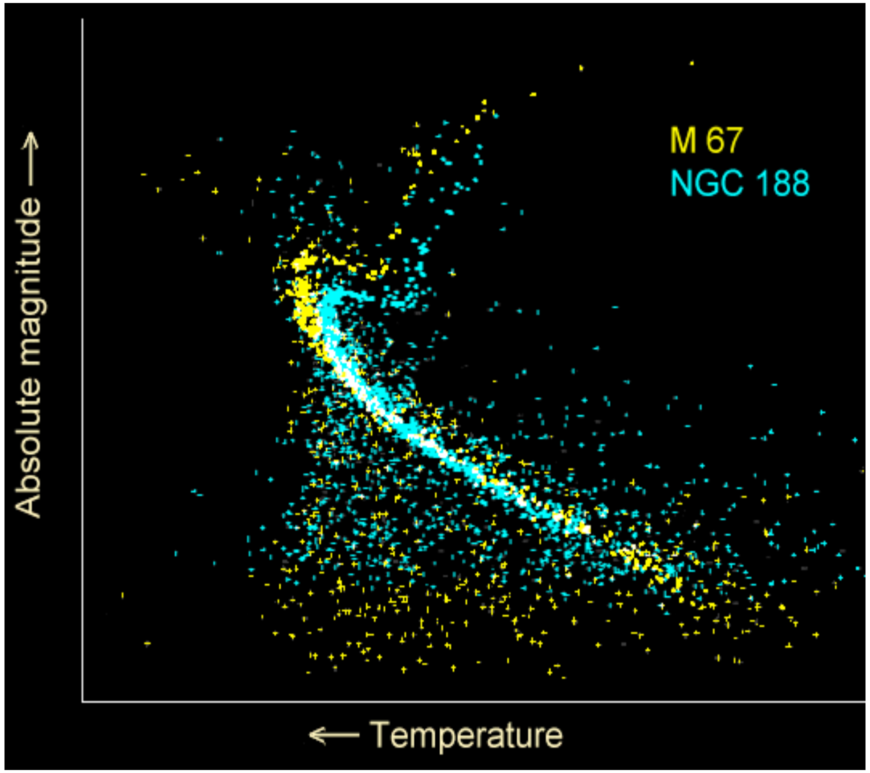
$$M_V(TO) = 2.70 \log (t / Gyr) + 0.30 [Fe/H] + 1.41$$

Globular Cluster in Halo



47 Tuc: 12.5 Gyr

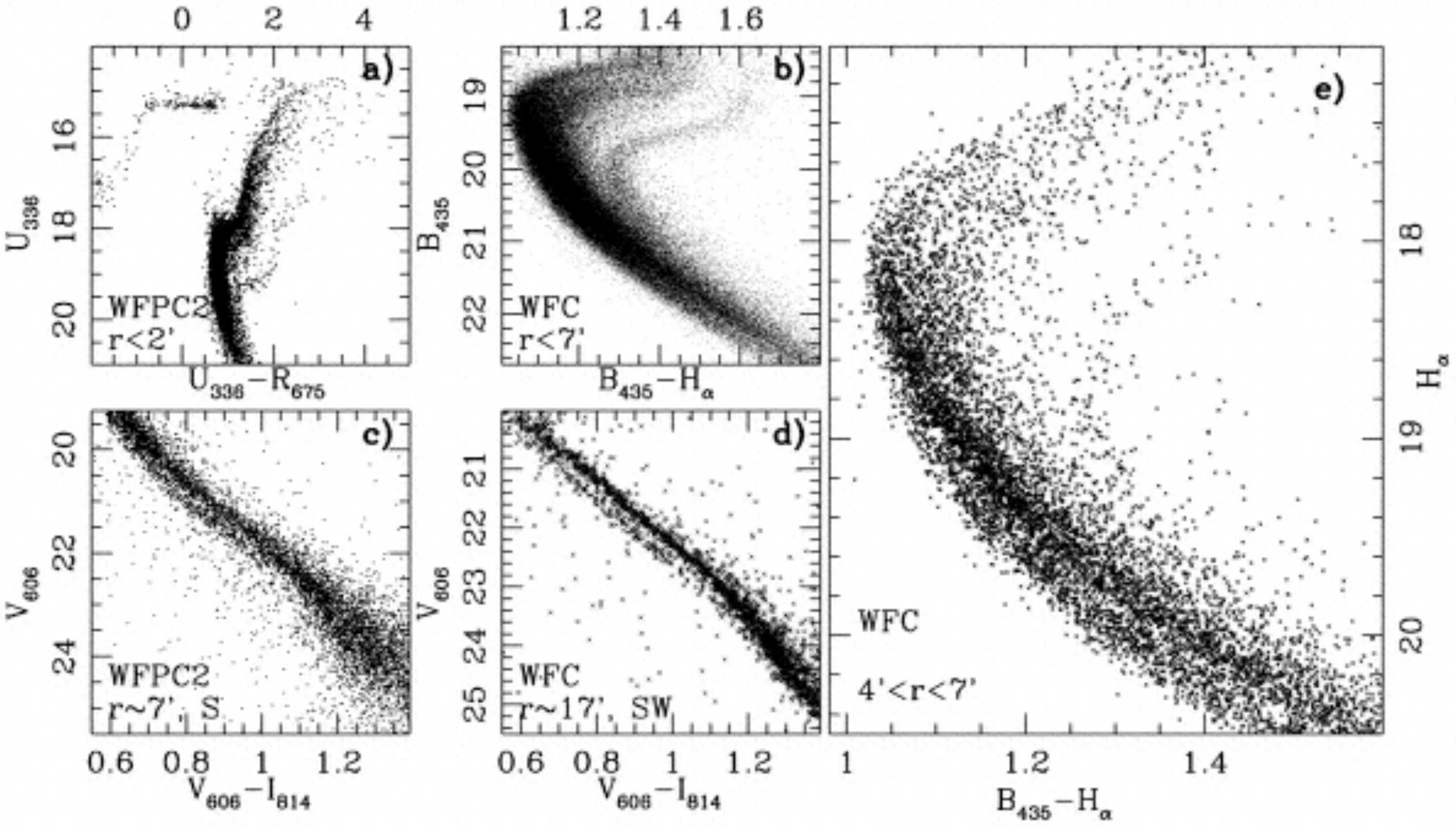
Open Clusters in Disk



M67: 4 Gyr

NGC188: 6 Gyr

Multiple Ages of stars in Omega Cen



Summary of Star Formation Models

$$\mu_{\mathrm{Ell}} = e^{-\frac{t}{t_*}}$$

t_* = e-folding time

$$\mu_{\mathrm{Sp}} = 1 - \alpha \frac{\dot{M}}{M_0} t$$

α = star-forming efficiency

$\dot{M}$ = mass conversion yr^{-1}

$$\mu_{\mathrm{Irr}} = 1 - \alpha f \frac{\dot{M}}{M_0} t$$

f = fraction of time spent star-bursting

$$\tau_{MS} = 7 \times 10^9 \left[\frac{M}{M_\odot}\right]\left[\frac{L}{L_\odot}\right]^{-1} = 7 \times 10^9 \left[\frac{L}{L_\odot}\right]^{-\frac{3}{4}} \ \mathrm{yr}$$