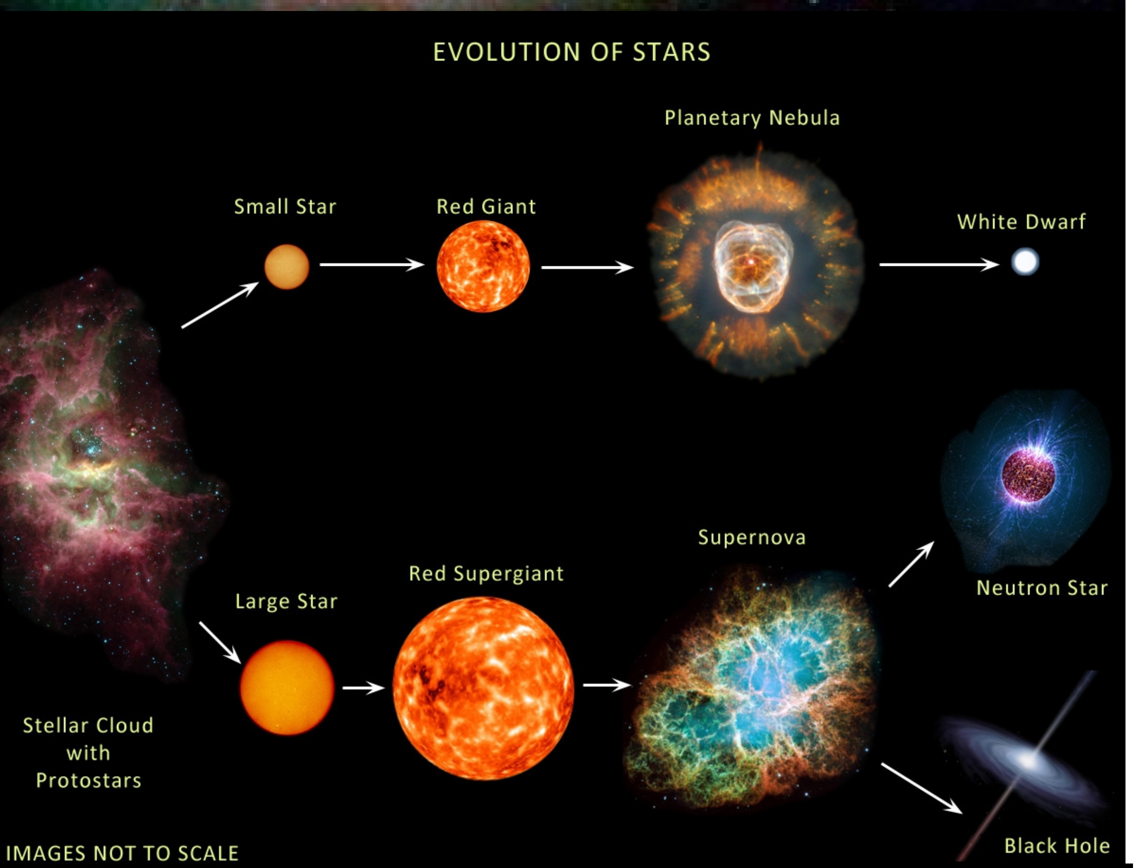
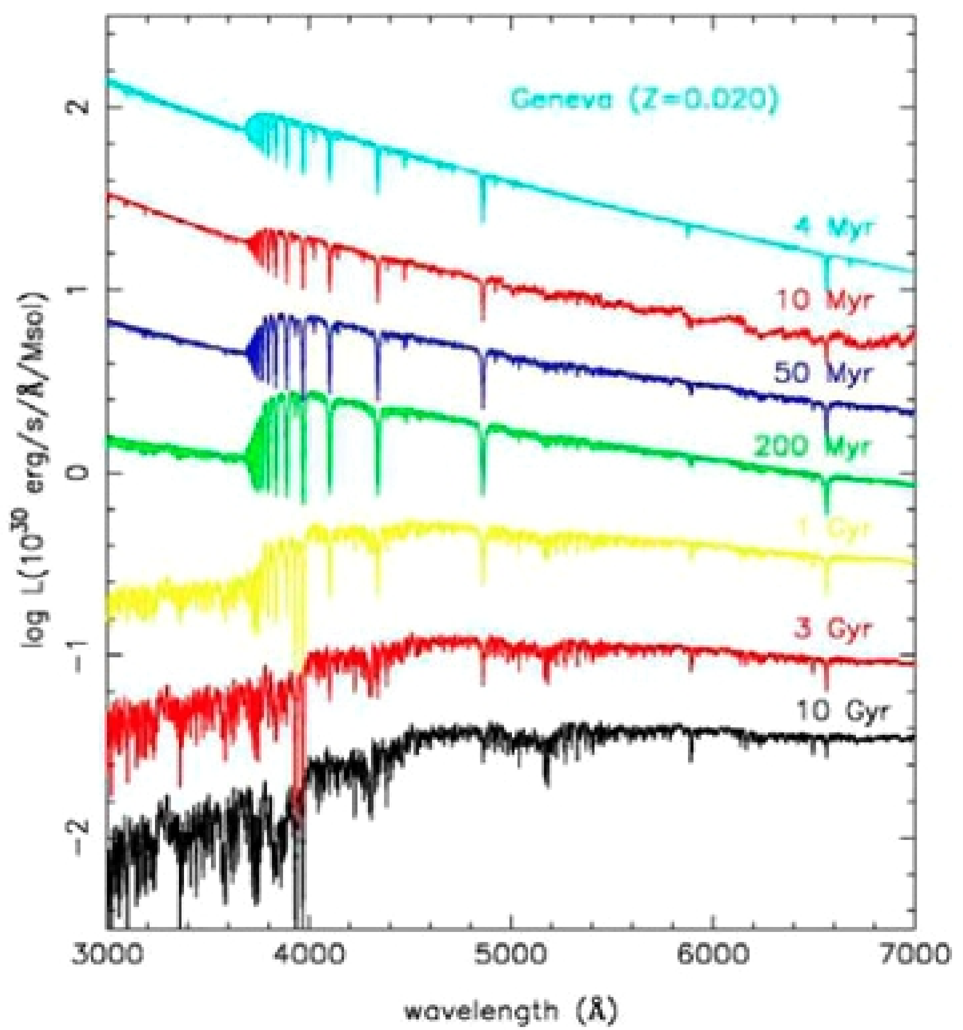
STAR FORMATION AND EVOLUTIONARY STELLAR POPULATION SYNTHESIS

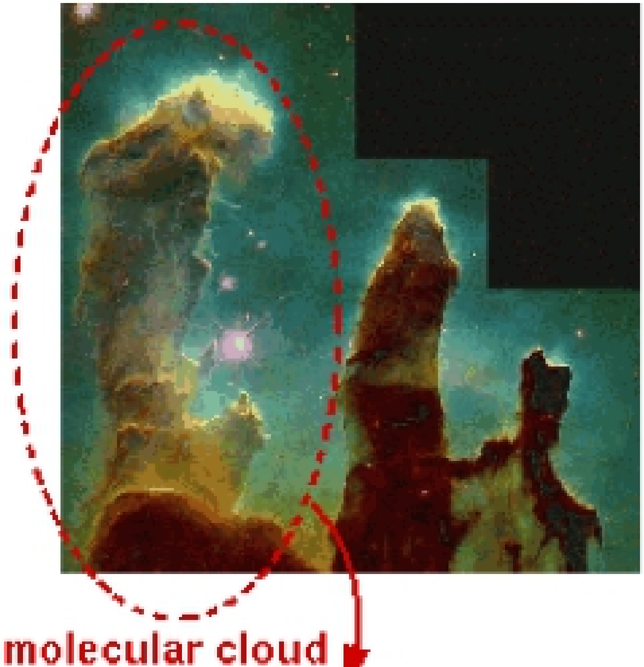


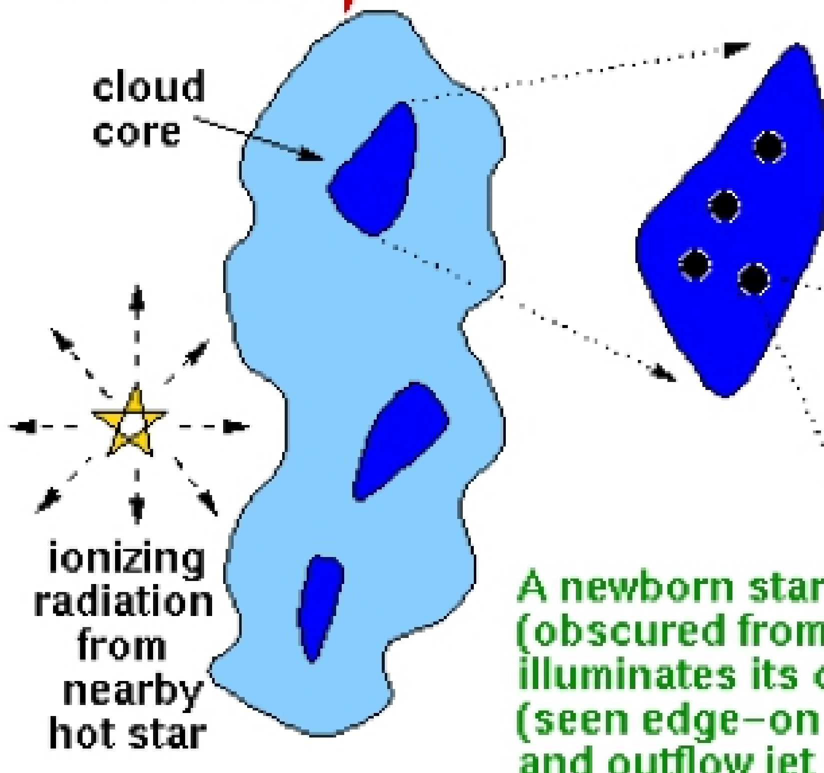


Molecular clouds are cold, dark, giant condensations of dust and molecular gas which serve as "stellar nurseries".

All stars are born in molecular clouds, including our Sun. Molecular clouds are the "stuff" we're made of!

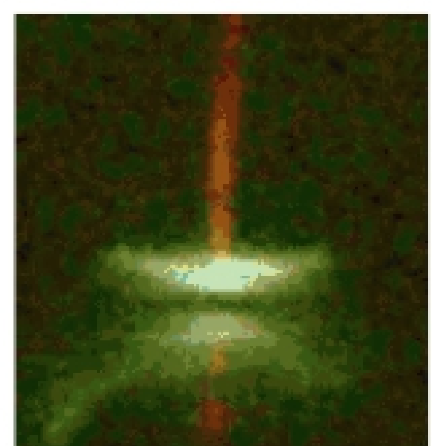
Because of their dusty content, visible light cannot penetrate into a molecular cloud. Thus, infrared and submillimeter observations are needed to "see" the star-forming process.





Dense fragments collapse under gravity, making protostars. These accumulate infalling matter and form circumstellar disks and powerful outflows and jets.

A newborn star (obscured from view) illuminates its disk (seen edge-on here) and outflow jet



Molecular Cloud Properties

Composition: H_2, He, dust (1% mass), CO (10^{-4} by number), and many other molecules with low abundances.

Sizes: 10-100 pc

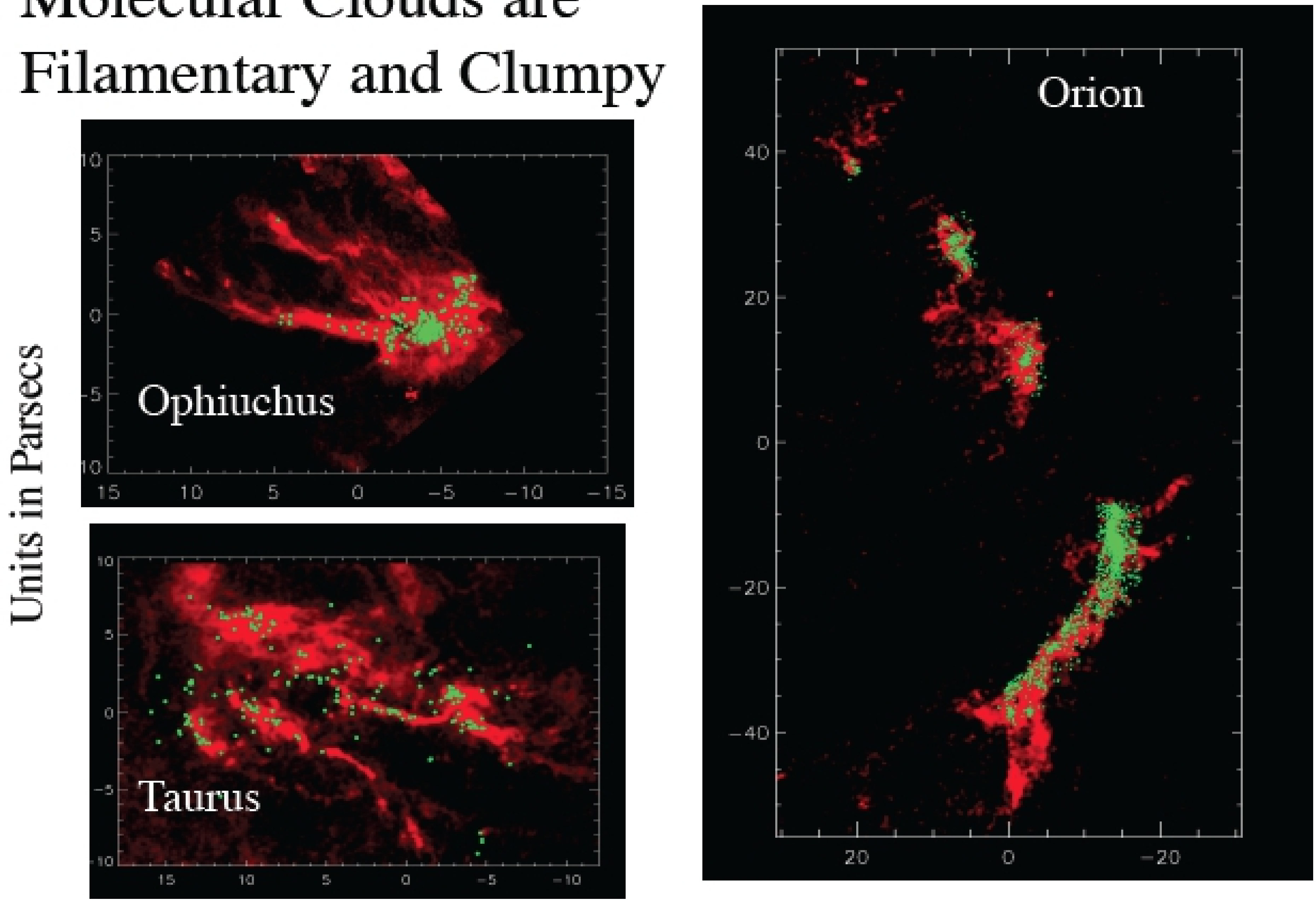
Masses: 10 to 10^6 Msun. Most of the molecular gas mass in galaxies is found in the more massive clouds.

Average Density: 100 cm^{-3}

Lifetimes: < 10 Myr

Issue: it is hard to separate individual clouds - not well defined.

Molecular Clouds are Filamentary and Clumpy



H_2 makes up the bulk of the mass of the molecular cloud, but cannot be directly detected (only quadrople transitions). Existing data is for trace molecules, CO being the most common.

Determining Cloud Mass With the X-Factor

Measure for each pixel of cloud the quantity W_{CO}:

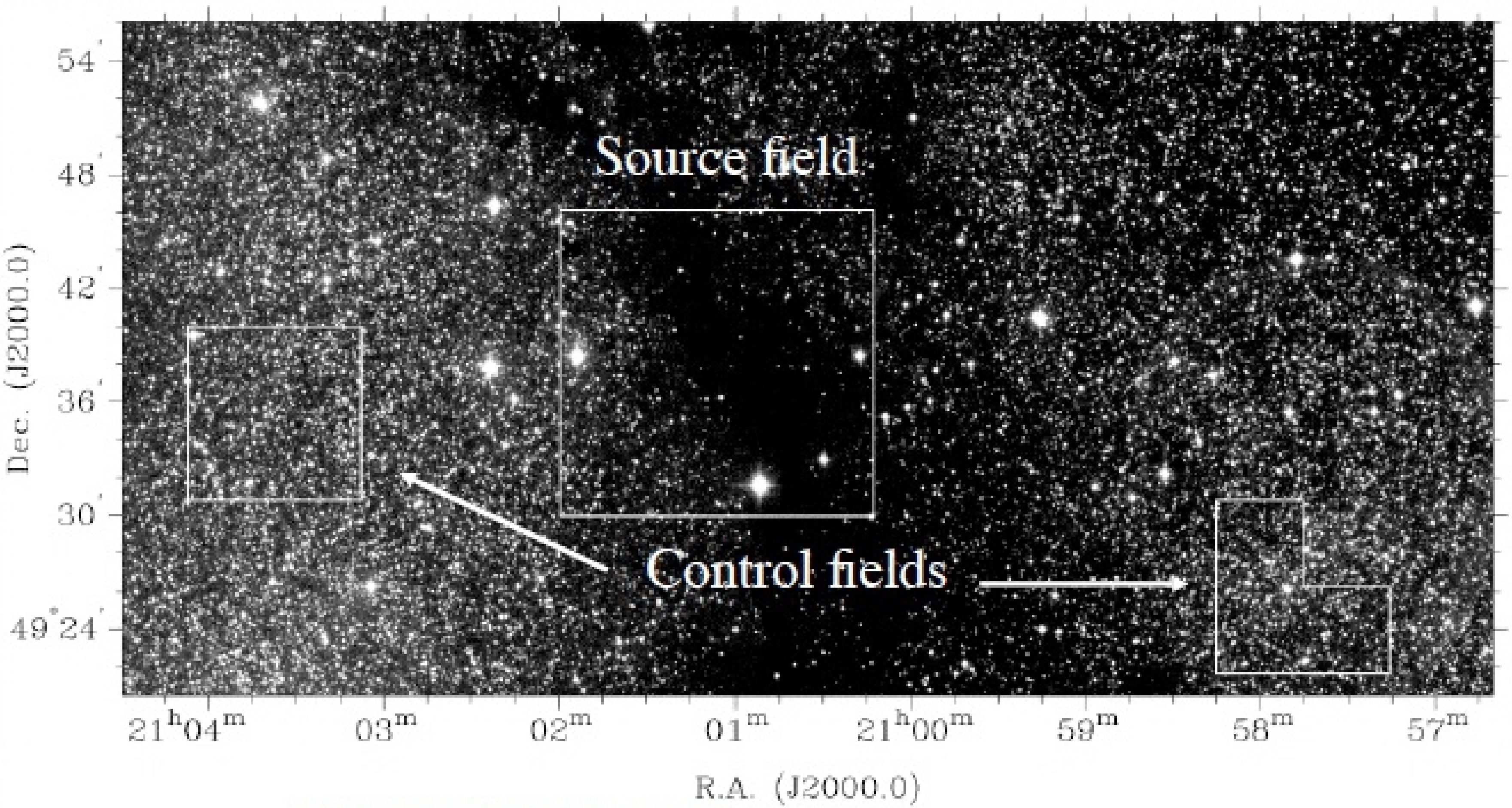
$$W_{CO} = \int T_{CO}\, dv \; [K\ km\ s^{-1}]$$

Then convert to column density:

$$N(H_2) = X\, W_{CO} \text{ where } X = 1.7 \times 10^{20}\ cm^{-2}/K\ km\ s^{-1}$$

The Dark Cloud L977

Alves et al. 1998 ApJ 506, 292



Visible light image

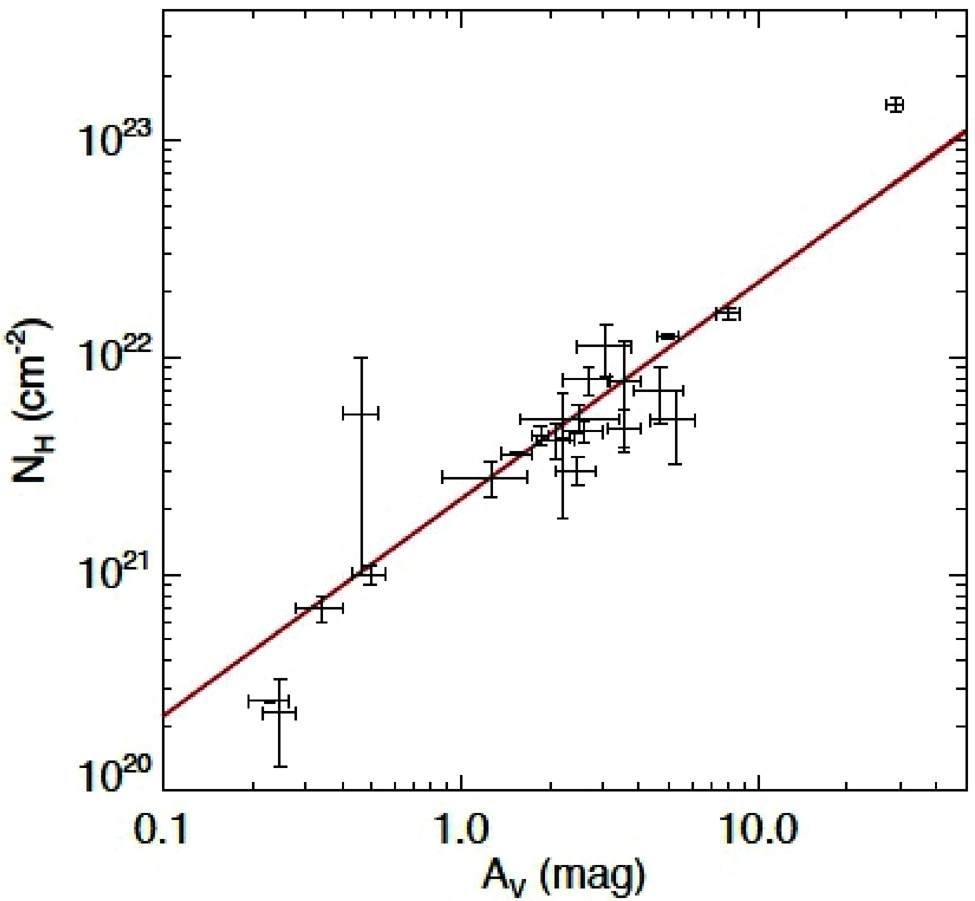
Color Excess

$$m_{\lambda_1} - m_{\lambda_2} = M_{\lambda_1} - M_{\lambda_2} + A_{\lambda_1} - A_{\lambda_2}$$

Observed color

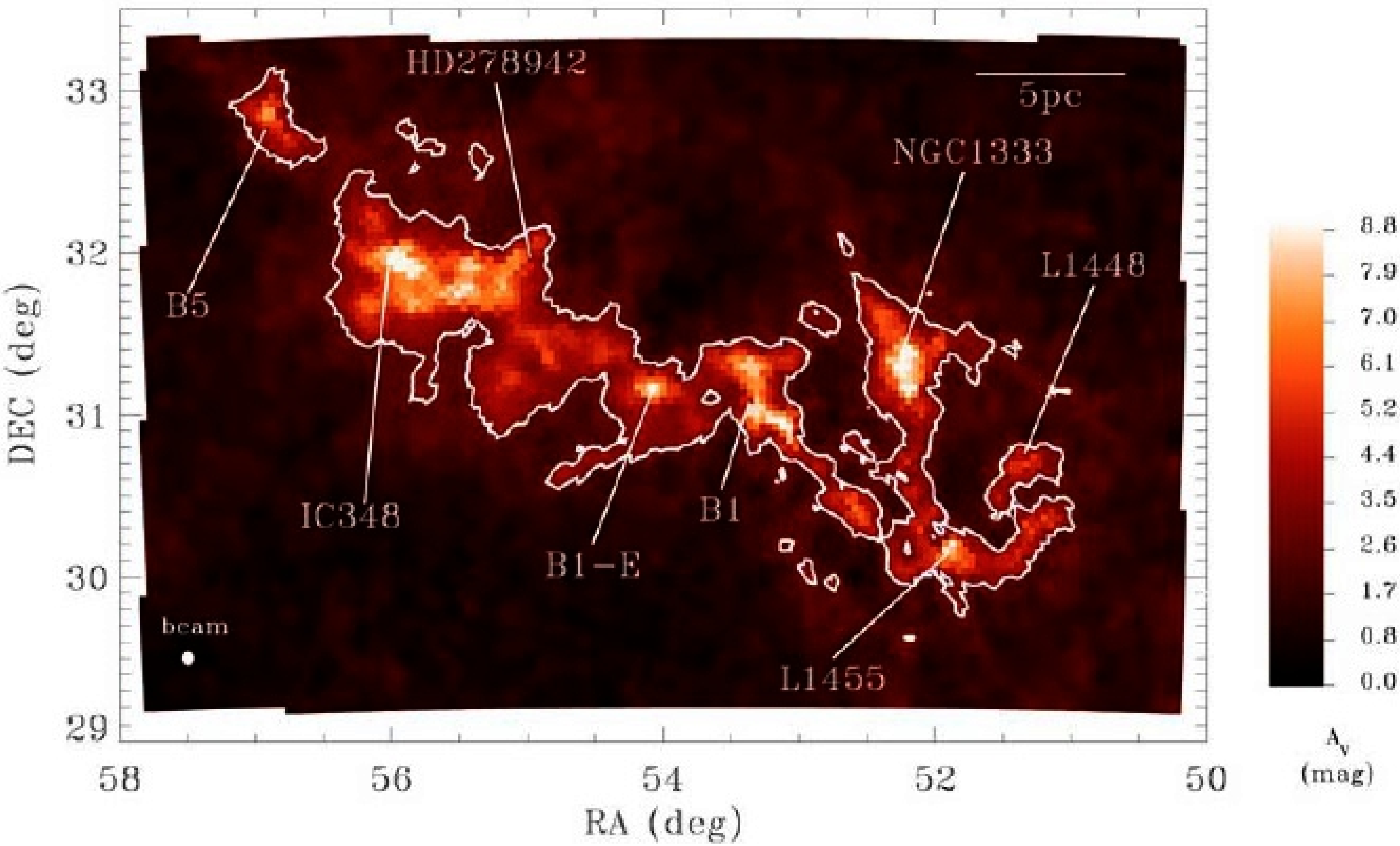
Intrinsic color

Color Excess due to interstellar dust



Relation between measured extinction due to dust and total hydrogen column density from x-ray spectroscopy of SN remnants

Extinction Map



Correlation of extinction map with CO map allows determination of “X factor”

The Formation of Molecular Hydrogen

The rate of H_2 formation in the gas phase is very low.

H_2 can form on the surfaces of dust grains (from Stahler & Palla):

Collision rate with grains: $1/t_{coll} = n_{HI}\,\sigma_d\,V_{th}$

H moves around grains through quantum tunneling, may find defect in lattice and stick. When another H comes along, the two atoms bind. Some of that energy kicks the H_2 off the grain.

Formation rate: $R_{H2} = 1/2\,\gamma_H\,n_d\,/\,t_{coll}$

$$= 1/2\,\gamma_H\,n_d\,n_{HI}\,\sigma_d\,V_{th}$$

γ_H is the sticking probability, n_d is density of grains, n_{HI} is density of hydrogen, σ_d is cross section of grains, V_{th}= thermal velocity of gas

Dissociation of Molecular Hydrogen

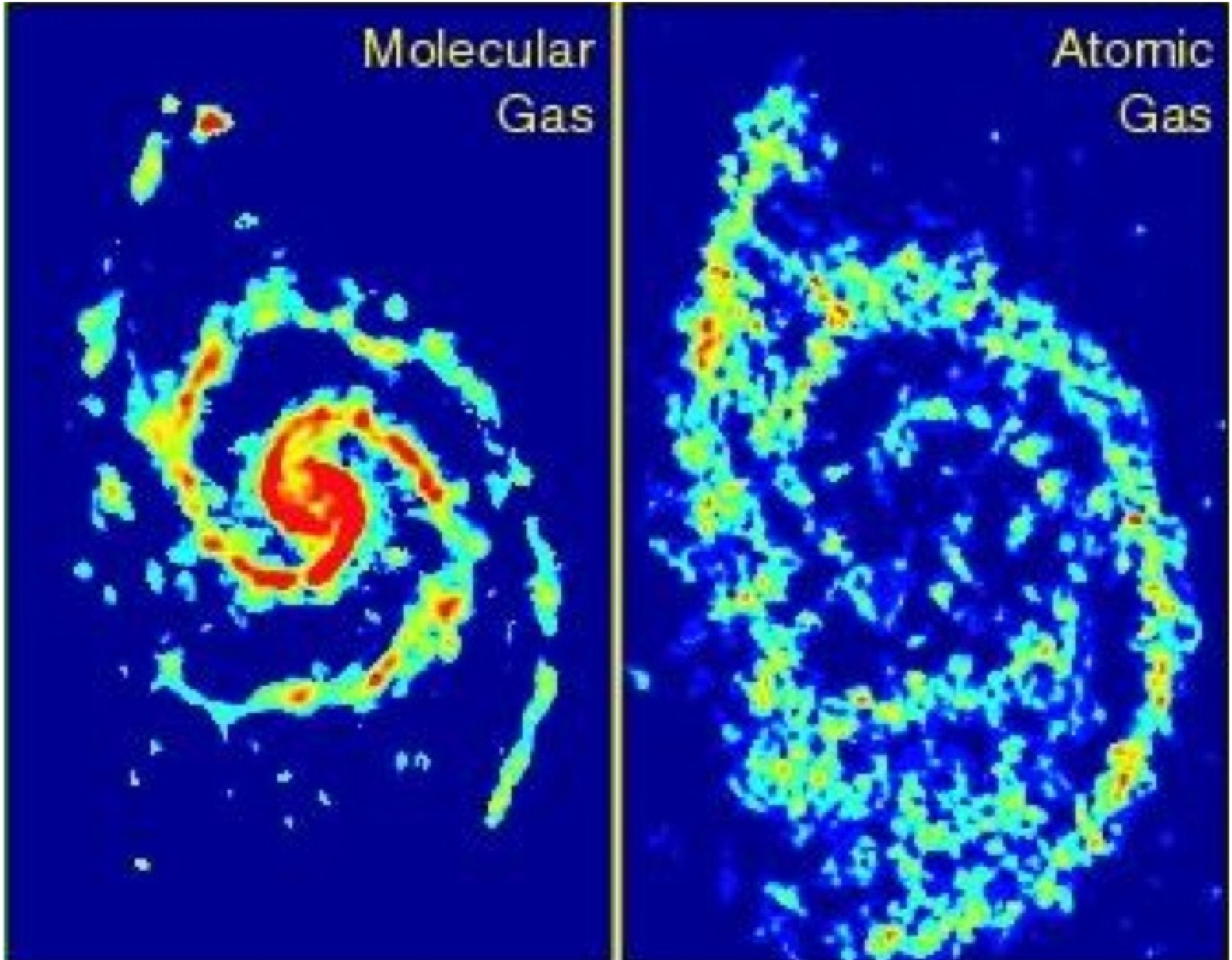
1. Absorption of UV photons with energies of 4.48-13.6 ev

2. The photons raises molecule to excited electronic state.

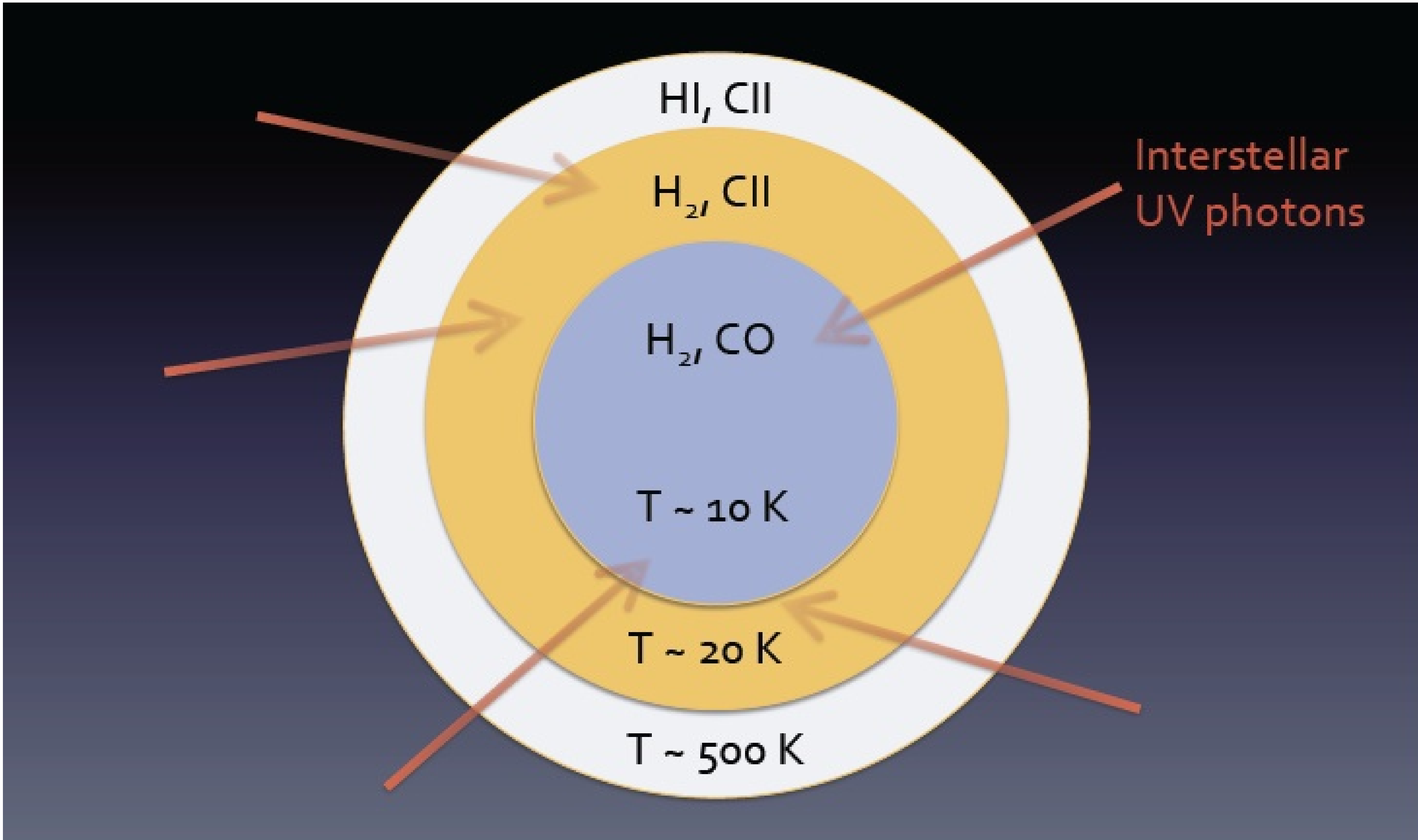
3. This energy can be exchanged to vibrational and rotational modes.

4. A fraction of these excited molecules will dissociate into two H.

Two prevent dissociation, molecules must be shielded from UV radiation from external starlight. This is done by dust and self shielding of the molecule.


Molecular
Gas
Atomic
Gas

Models of uniform, spherical clouds of given composition, bathed in a uniform field of UV photons



Chemical and Thermal Balance

H_2 formation $\quad$ H_2 photodissociation

$$n_{\rm HI} n \mathcal{R} = n_{\rm H_2} \int d\Omega \int d\nu \, \sigma_{\rm H_2} f_{\rm diss} I_\nu / (h\nu)$$

$$\hat{e} \cdot \nabla I_\nu = -(n_{\rm H_2} \sigma_{\rm H_2} + n \sigma_{\rm d}) I_\nu$$

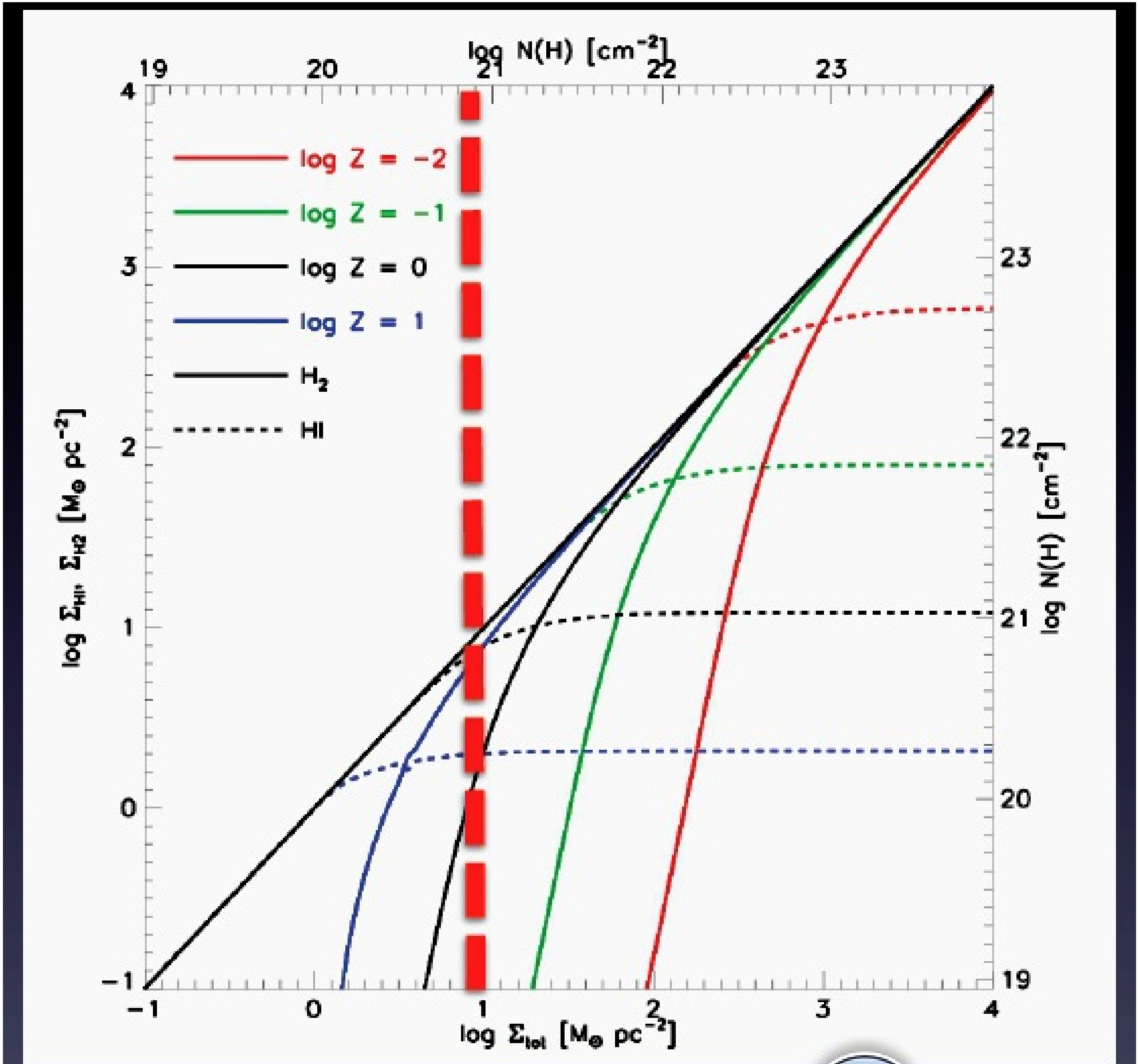
Decrease in rad. intensity $\quad$ Absorption by dust, H_2

Line cooling $\quad$ Photoelectric heating

$$n^2 \Lambda = n \int d\Omega \int d\nu \, \sigma_d E_{\rm PE} I_\nu / (h\nu)$$

$$\hat{e} \cdot \nabla I_\nu = -n \sigma_{\rm d} I_\nu$$

Decrease in rad. intensity $\quad$ Absorption by dust



The balance between atomic and molecular hydrogen in the cloud can be expressed in terns of its column density and its metallicity (dust content and metallicity are assumed to scale linearly)

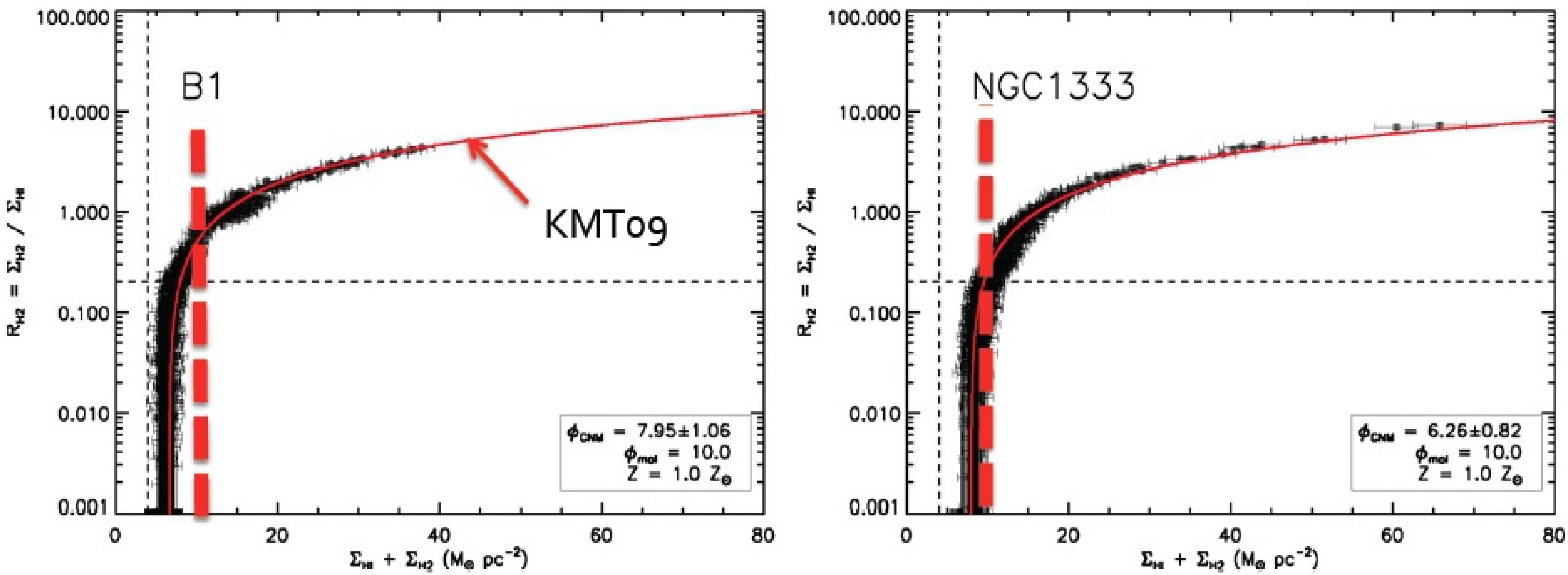
- Approximate solution:

$$f_{\mathrm{H_2}} \approx 1 - \frac{3}{4}\left(\frac{s}{1+0.25s}\right)$$

$$s \approx \frac{\ln(1+0.6\chi+0.01\chi^2)}{0.04\left(\frac{Z}{Z_\odot}\right)\left(\frac{\Sigma}{M_\odot\ \mathrm{pc}^{-2}}\right)}$$

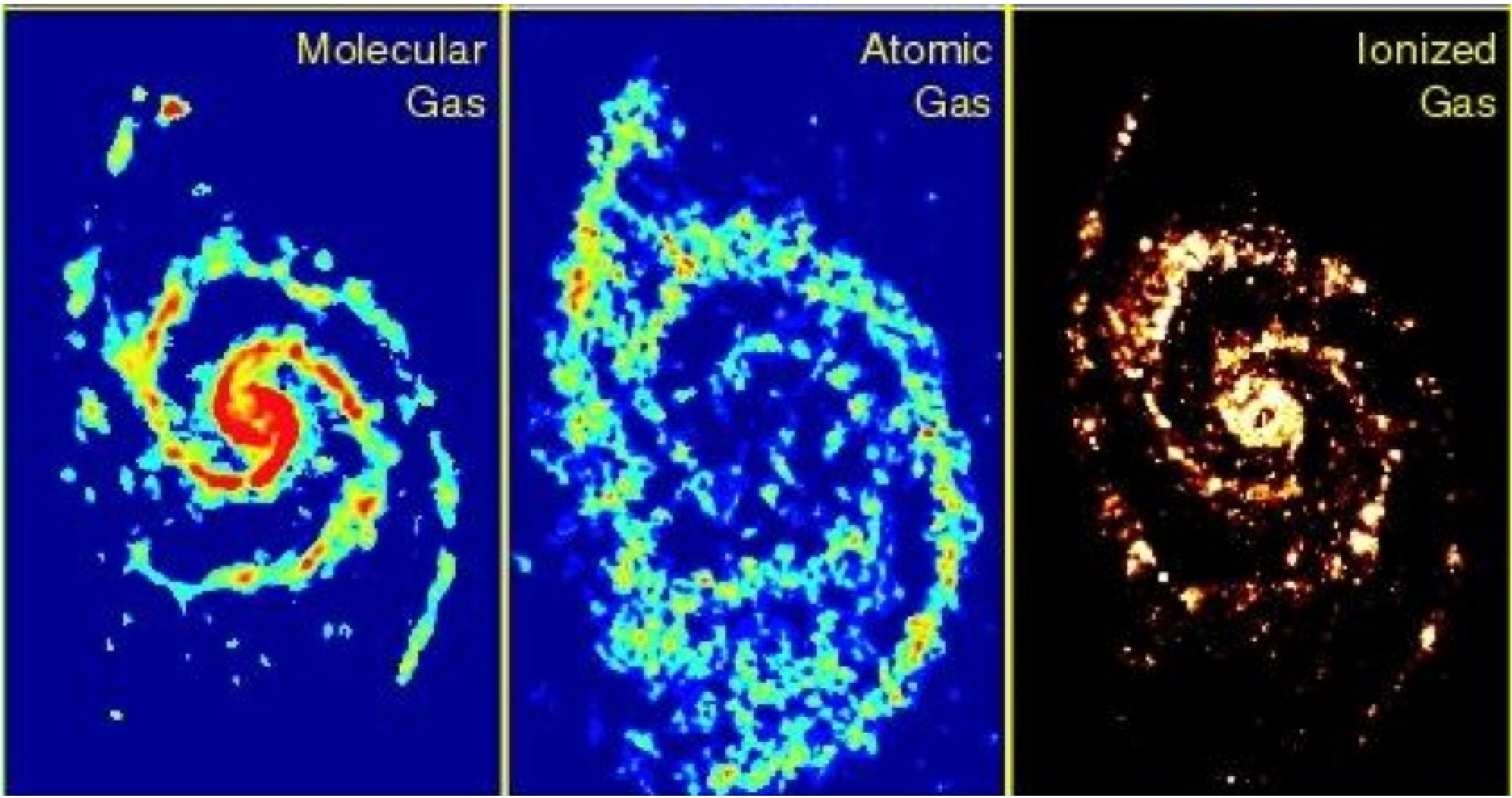
$$\chi \approx 3.1\frac{1+3.1\left(\frac{Z}{Z_\odot}\right)^{0.365}}{4.1}$$

Main result: f_{H2} is predicted to transition suddenly from ~0 to ~1 when Σgas ~ 10 M_{sun} pc^{-2}



Lee+ 2012

How rapidly is gas converted into stars in galaxies?



Empirical Star Formation "Laws"

$$\dot{\Sigma}_\star = \dot{M}_\star/\mathrm{area}$$

SFR, Σ, in terms of mass in stars formed per unit area per unit time

$$\tau_{\mathrm{SF}} = \Sigma_{\mathrm{gas}}/\dot{\Sigma}_\star$$

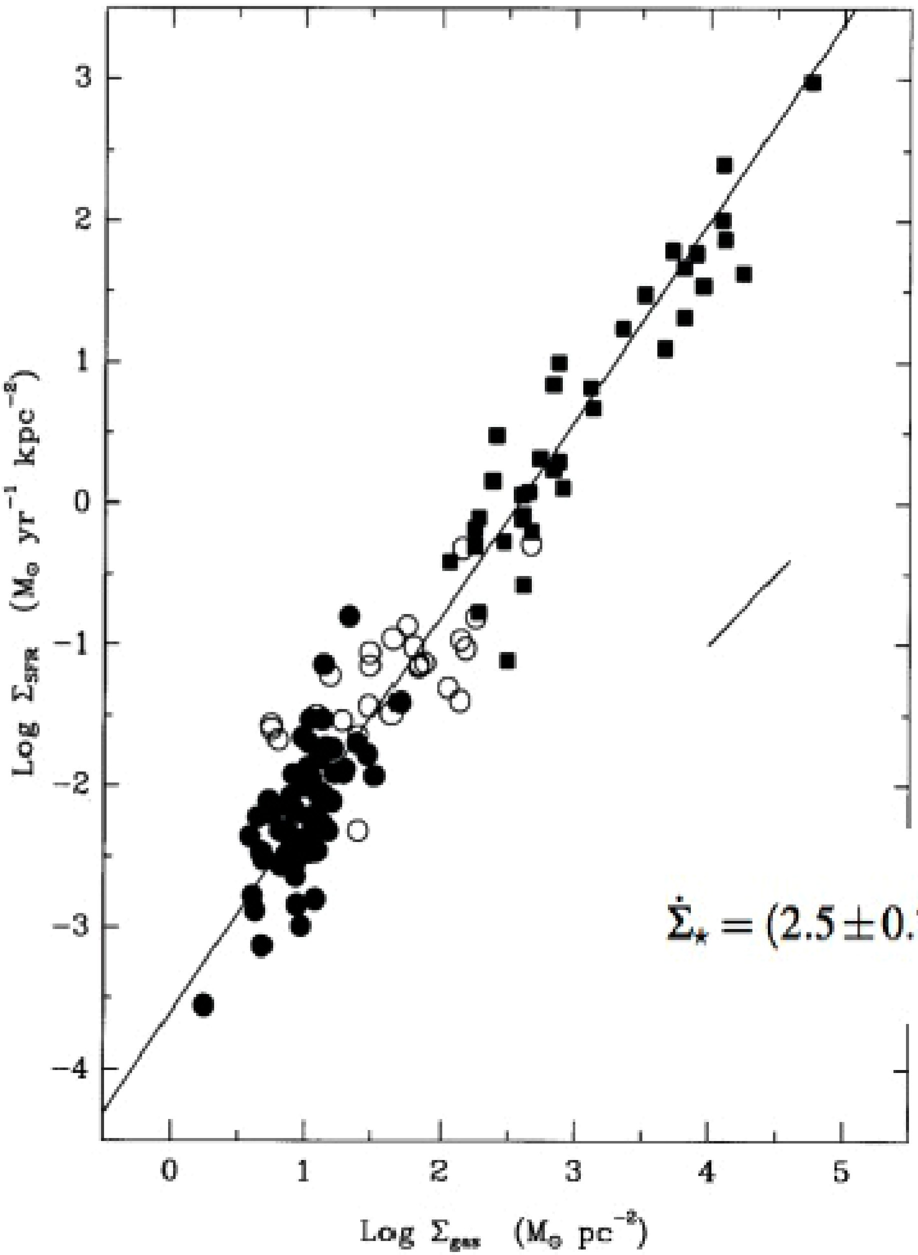
Gas consumption time, τ

Since the most obvious requirement for star formation is the presence of gas, it is only logical to look at the relation between SFR and surface density of gas:

$$\dot{\Sigma}_\star \propto \Sigma_{\mathrm{gas}}^{\mathrm{N}}$$

Schmidt (1959)

Kennicutt-Schmidt law



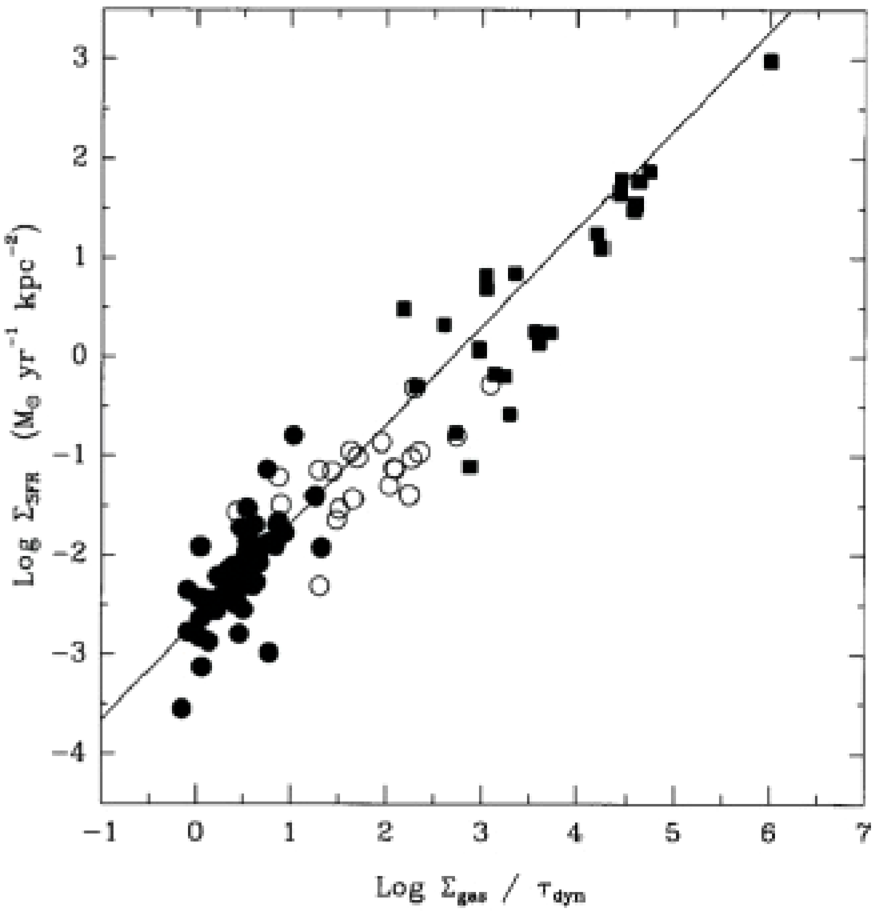
The study of star formation in normal spiral galaxies and also starbursts have shown Schmidt is a surprisingly good description of global SFRs (averaged over entire SF disc) –

$$\dot{\Sigma}_\star = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{gas}}{M_\odot \, pc^{-2}} \right)^{1.4 \pm 0.15} M_\odot \, yr^{-1} \, kpc^{-2}$$

$$\Sigma_{gas} = \Sigma_{HI} + \Sigma_{H_2}$$

Kennicutt (1998) ApJ, 498, 541

Dynamical time scale



In addition to the Schmidt law – there is an equally strong correlation between star formation rate and the gas surface density divided by the dynamical time

$$\tau_{\rm dyn} = 2\pi R / V_{\rm rot}(R)$$

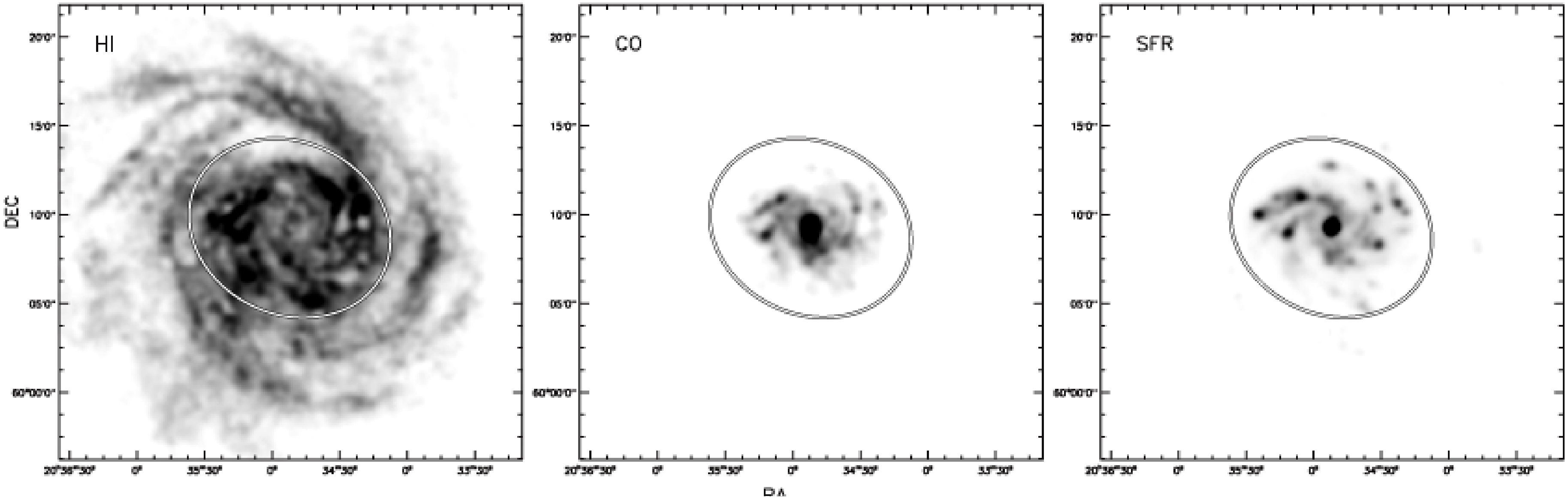
defined as the orbital time at the outer radius R of the relevant star forming region.

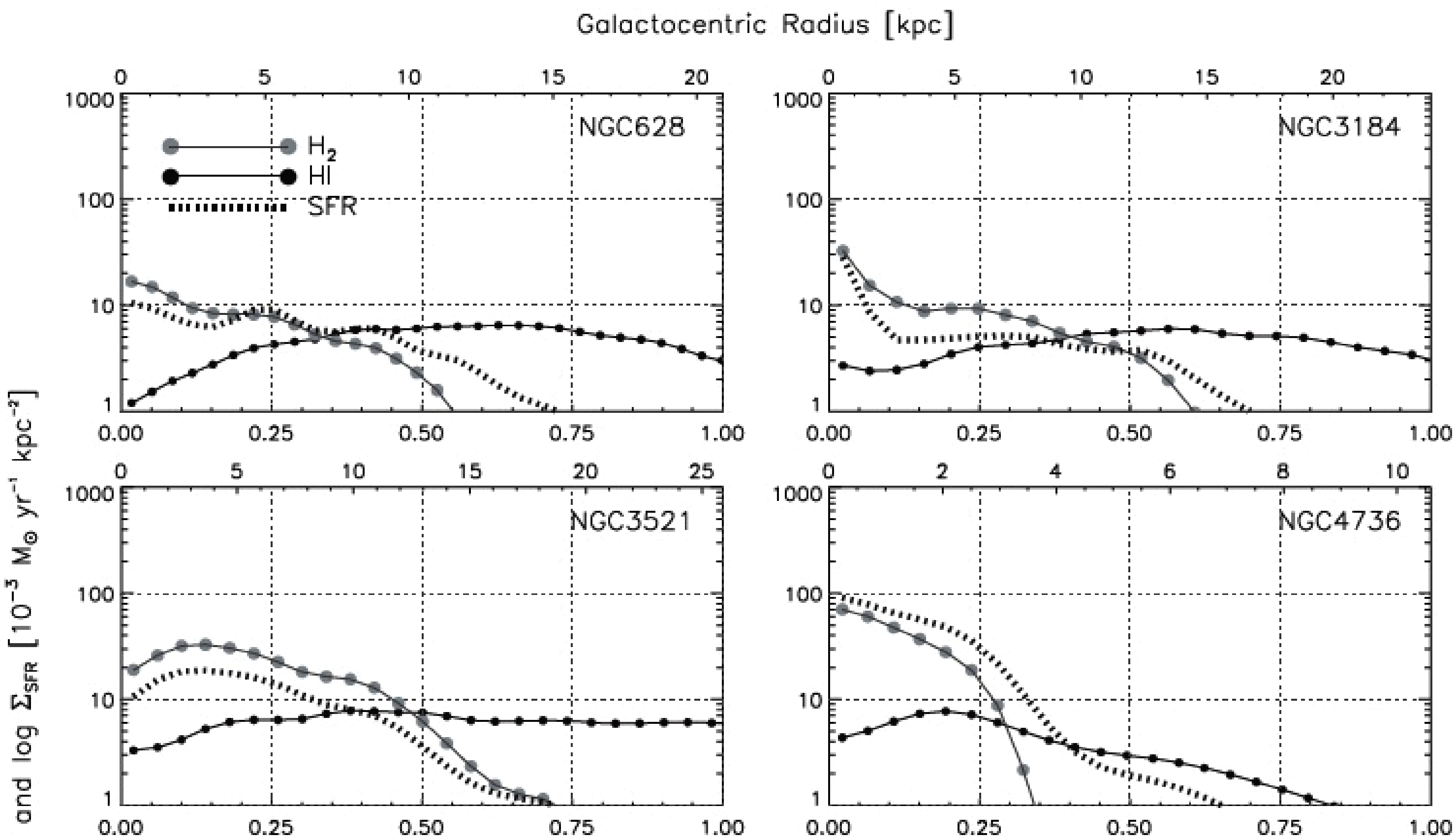
$$\dot{\Sigma}_\star \approx 0.017 \Sigma_{\rm gas} \Omega$$

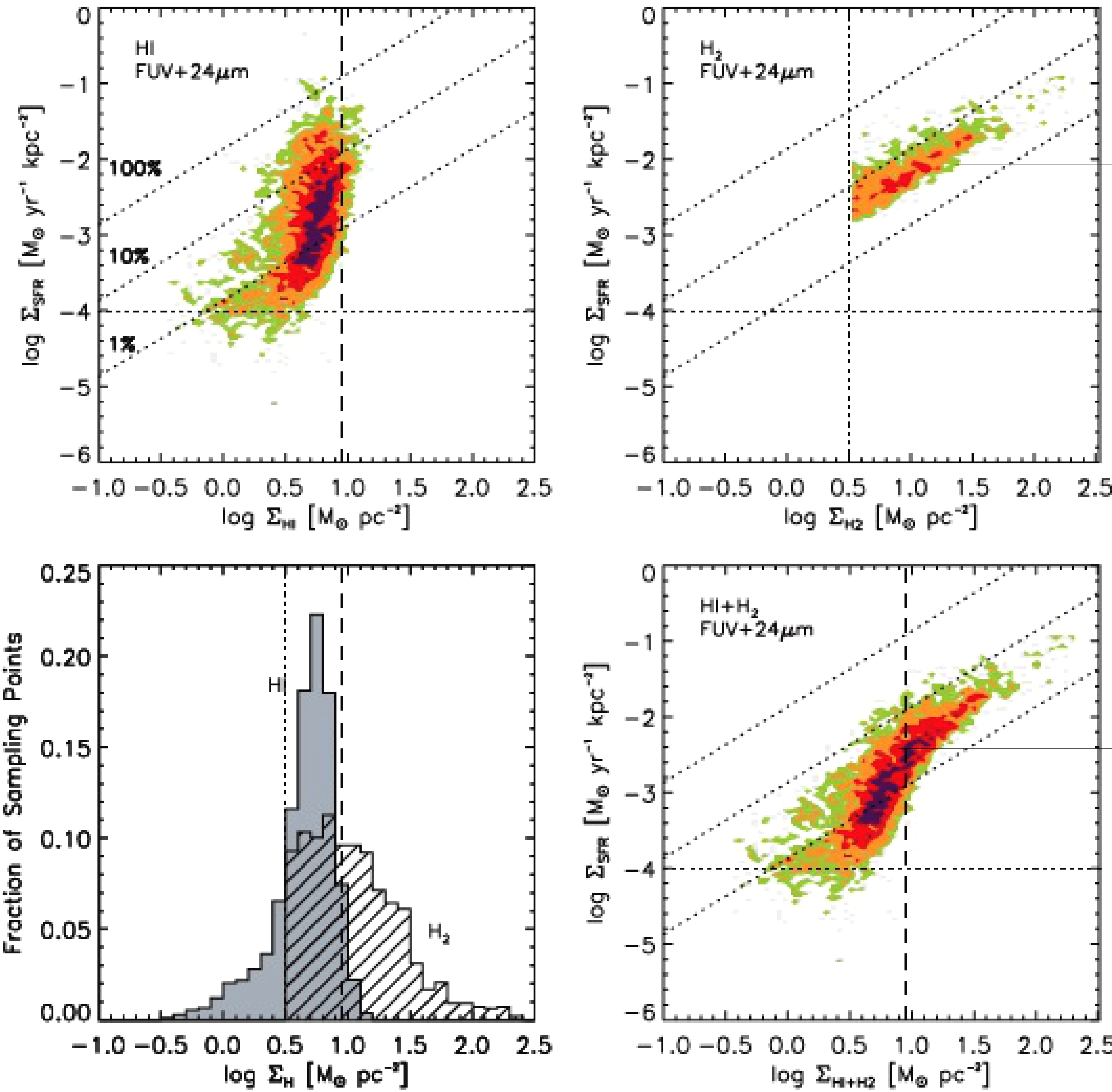
Ω is the circular frequency

This implies 10% of available gas forms stars per orbital time

Kennicutt (1998) ApJ, 498, 541

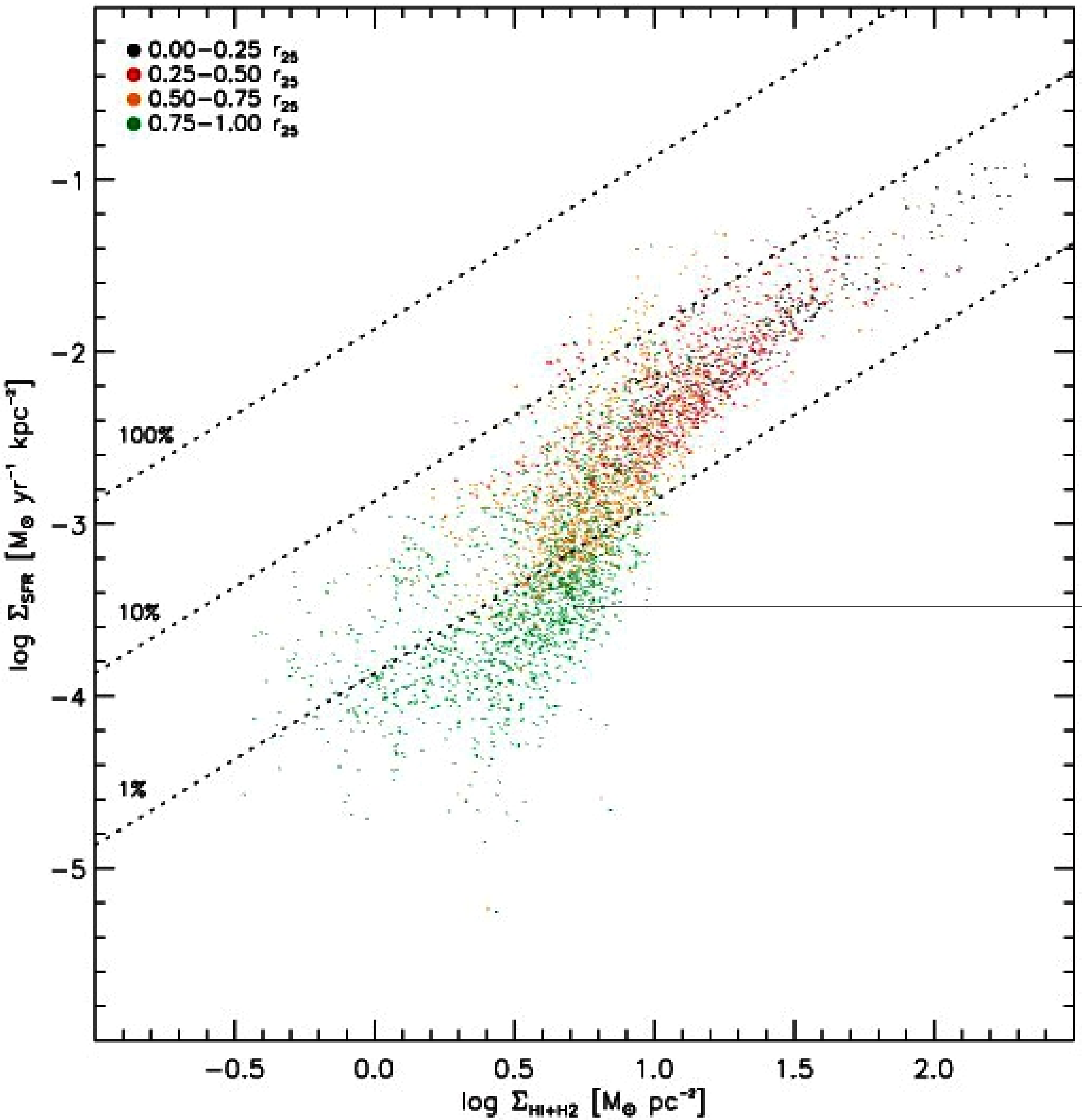

HI
CO
SFR
DEC


Galactocentric Radius [kpc]
NGC628
NGC3184
NGC3521
NGC4736
H2
HI
SFR
and log ΣSFR [10−3 M⊙ yr−1 kpc−2]

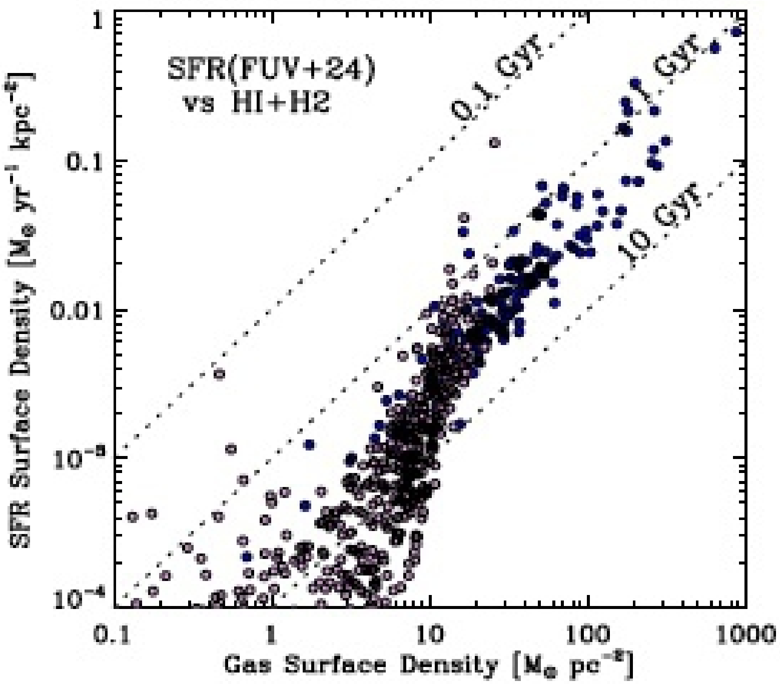


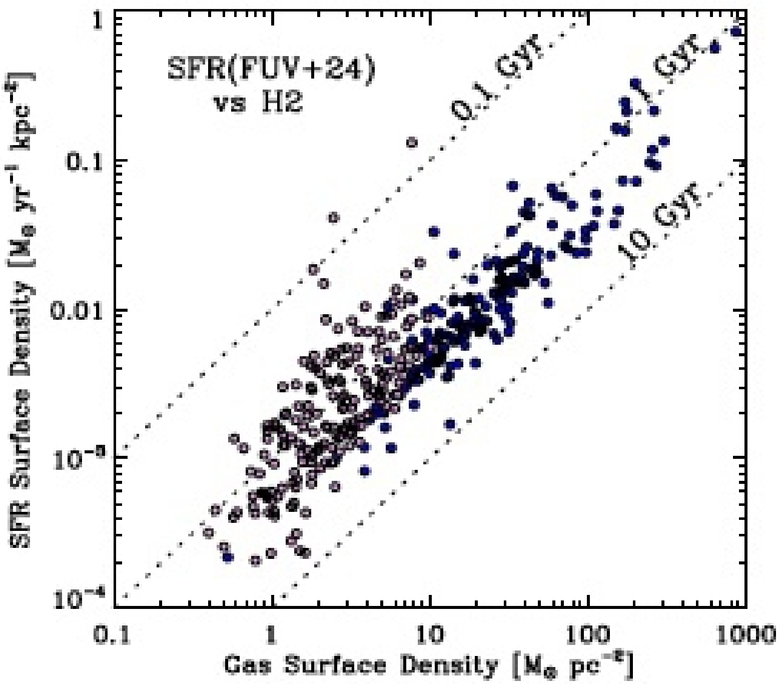
Depletion time of around 1 Gyr

Roughly the location of the atomic-to-molecuar transition.



All measured data points in the regime where the relation changes slope are from the outer regions of the disk, where HI dominates.





The linear relation between SFR surface density and molecular gas surface density was shown to hold an order of magnitude lower in gas surface density by Schruba and collaborators.

No clear second parameter in the relation between SFR and molecular gas

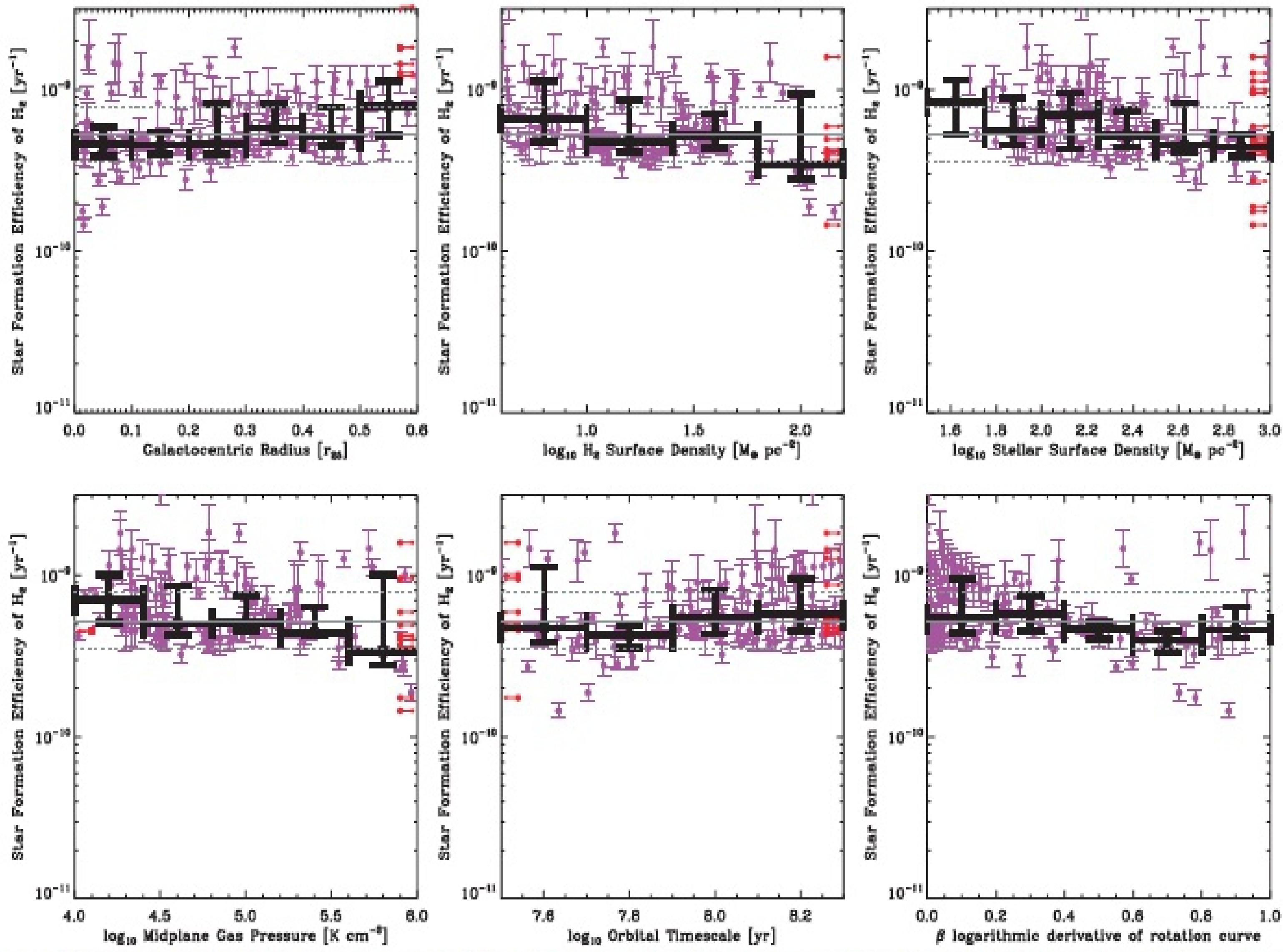
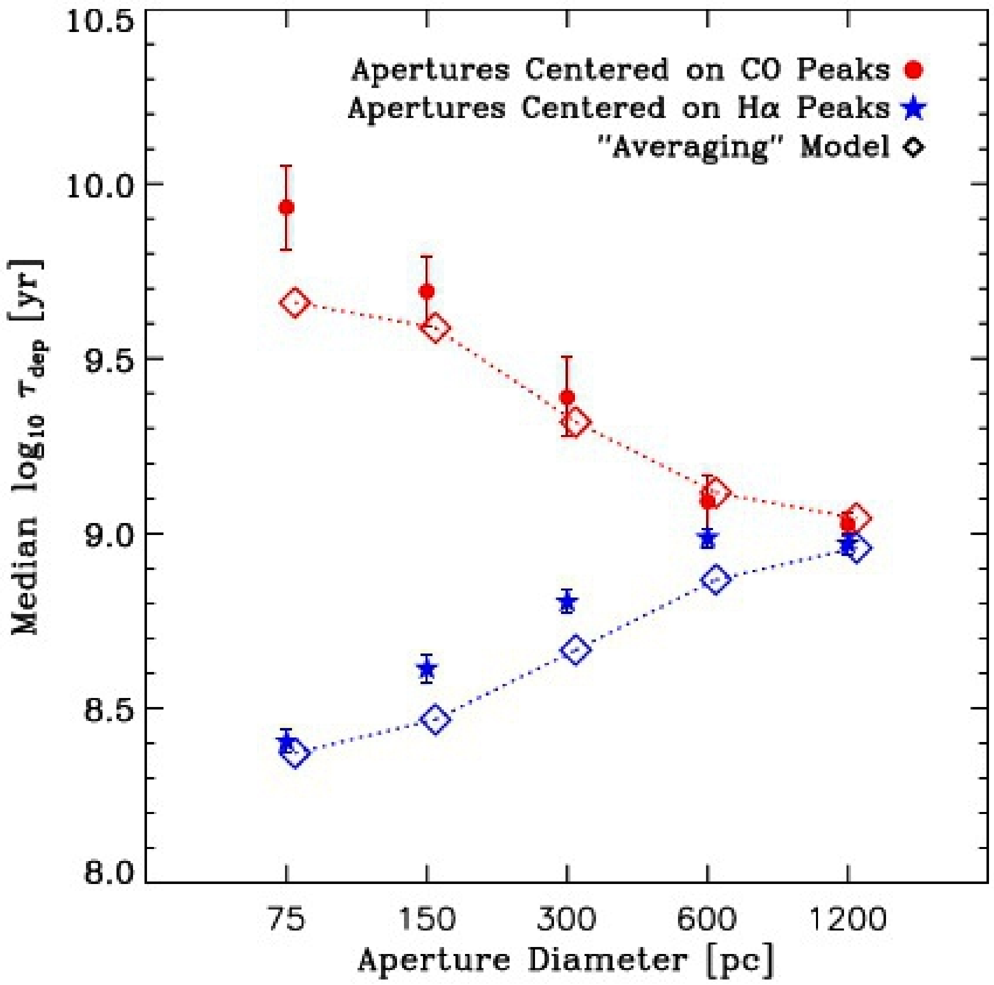
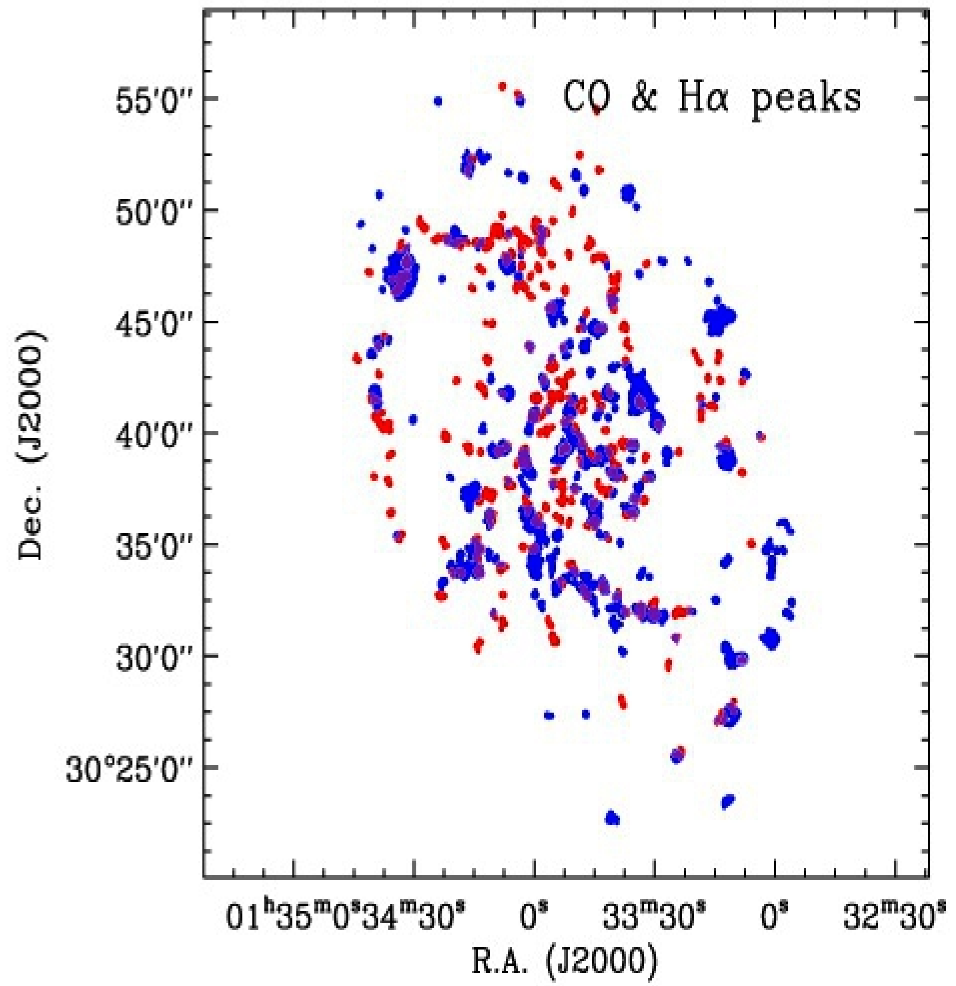


Figure 15. SFE (H_2) in individual tilted rings from spiral galaxies as a function of (top left) galactocentric radius, (top middle) H_2 surface density, (top right) stellar surface density, (bottom left) midplane pressure, (bottom middle) orbital timescale, and (bottom right) logarithmic derivative of the rotation curve. Gray lines show the median $\log_{10}$ SFE(H_2) $= -9.28 \pm 0.17$ for our data.

On what scales does the apparently “Universal” molecular gas depletion timescale hold?





The Stellar Initial Mass Function (IMF)

The initial mass function is a function describing the distribution of stellar masses in a newly formed population (i.e. none of the stars have had a chance to loose mass or undergo supernova). The initial mass function, IMF, was first derived by Ed Salpeter in 1955, who found that:

$$\xi(logM) = \frac{dN}{dlog(M)} = k_1 M^{-\Gamma} = k_1 M^{-1.35} \tag{1}$$

A similar function is the mass spectrum

$$\frac{dN}{dM} = k_2 M^{-\alpha} = k_2 M^{-2.35} \tag{2}$$

where $\alpha = \Gamma + 1$.

The total mass is then the integral of this:

$$M_{tot} = \int_{M_{min}}^{M_{max}} M k_2 M^{-2.35} dM = \frac{k_2}{0.35}(M_{min}^{-0.35} - M_{max}^{-0.35})$$

This shows that most of the stellar mass is in low mass stars. On the other hand, if we calculate the total luminosity (and assuming $L \propto M^3$), then

$$L_{tot} = \int_{M_{min}}^{M_{max}} k_3 M^3 k_2 M^{-2.35} dM = \frac{k_2 k_3}{1.65}(M_{max}^{1.65} - M_{min}^{1.65})$$

which shows that the total luminosity is driven by the most massive stars. We know now that the IMF is not a strict power law, and we will examine the variations.

The initial stellar mass distribution in young star clusters

The initial stellar mass distribution in young star clusters

Spatial distribution of stars in the Orion Nebula Cluster (ONC)

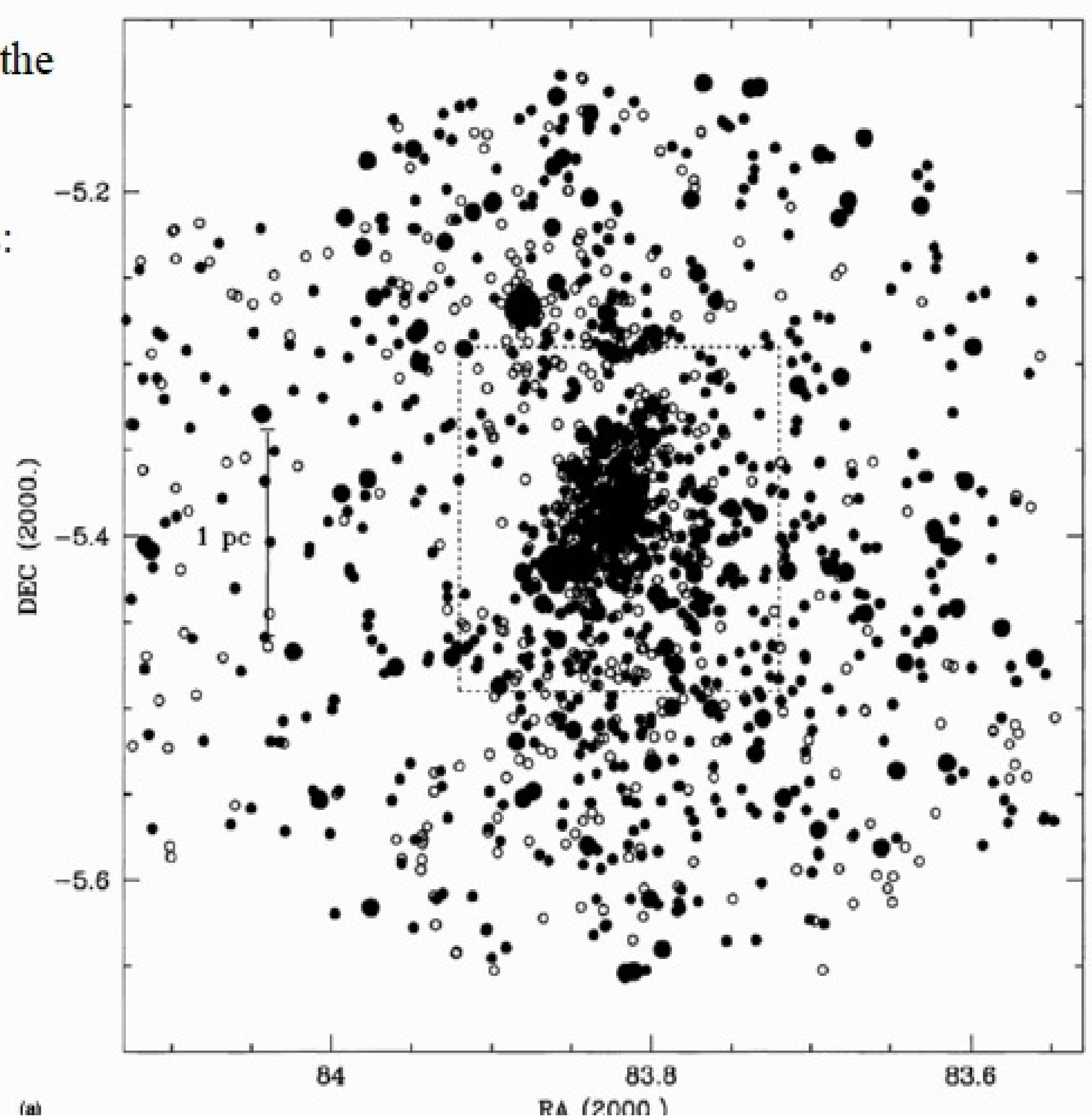
Stars are sorted into mass bins:

- M < 1 Msun
- 1 < M < 10 Msun
- M > 10 Msun

One very massive star (Theta 1 OriC)

Numerous stars 1-10 Msun

The largest fraction is of the lowest mass < 1 Msun!



Construction of the IMF

Photometry → Brightness of each star

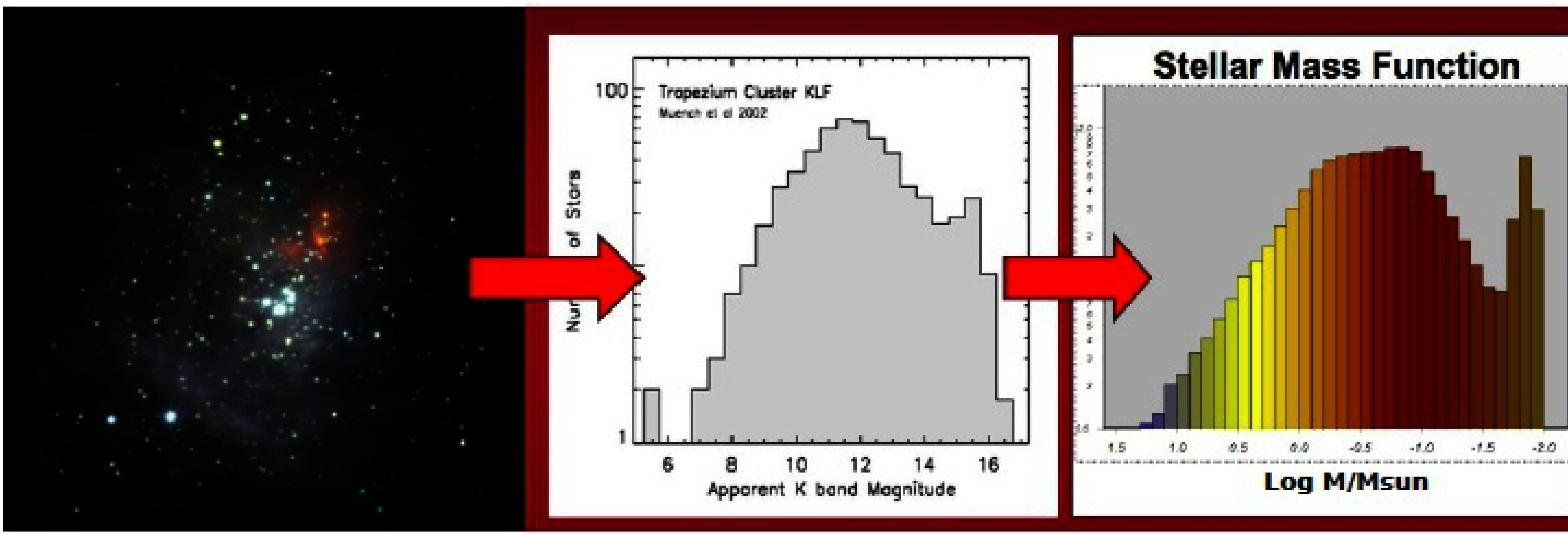
Brightness + stellar model → stellar mass + age

Counting stars into mass intervalls →

Stellar mass distribution = Initial Mass Function

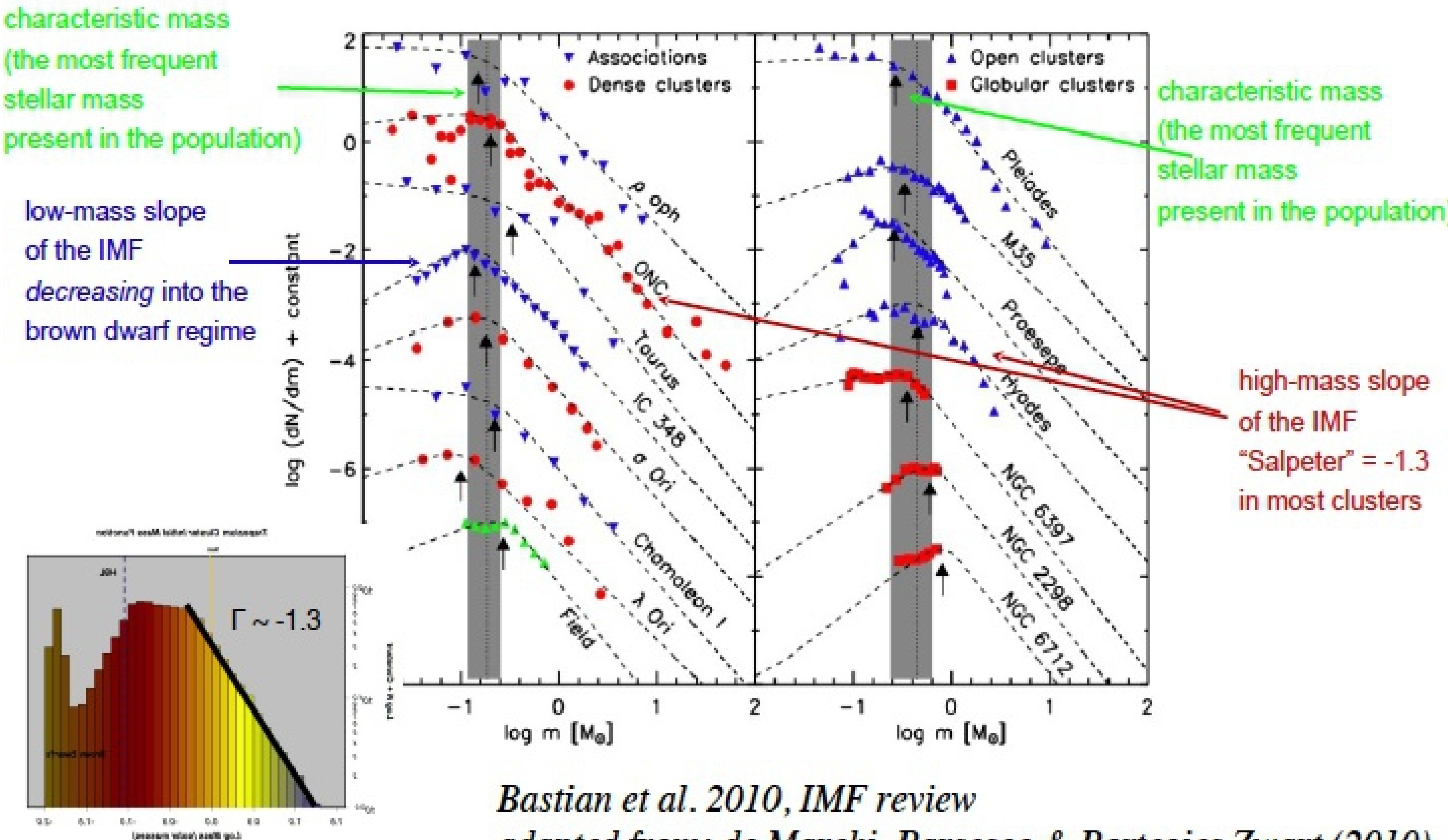
Initial = "at birth"

Outcome of the Star formation Process.



Evidence for a universal IMF in young star clusters

Mass functions from young star clusters & OB associations,
as well as open, intermediate- agen and old star clusters (globulars).



Bastian et al. 2010, IMF review
adapted from: de Marchi, Parsesce & Portegies Zwart (2010)

A theoretical construction of the "average" IMF

From a sample of young star cluster observations, Pavel Kroupa constructed a *"universal IMF"*

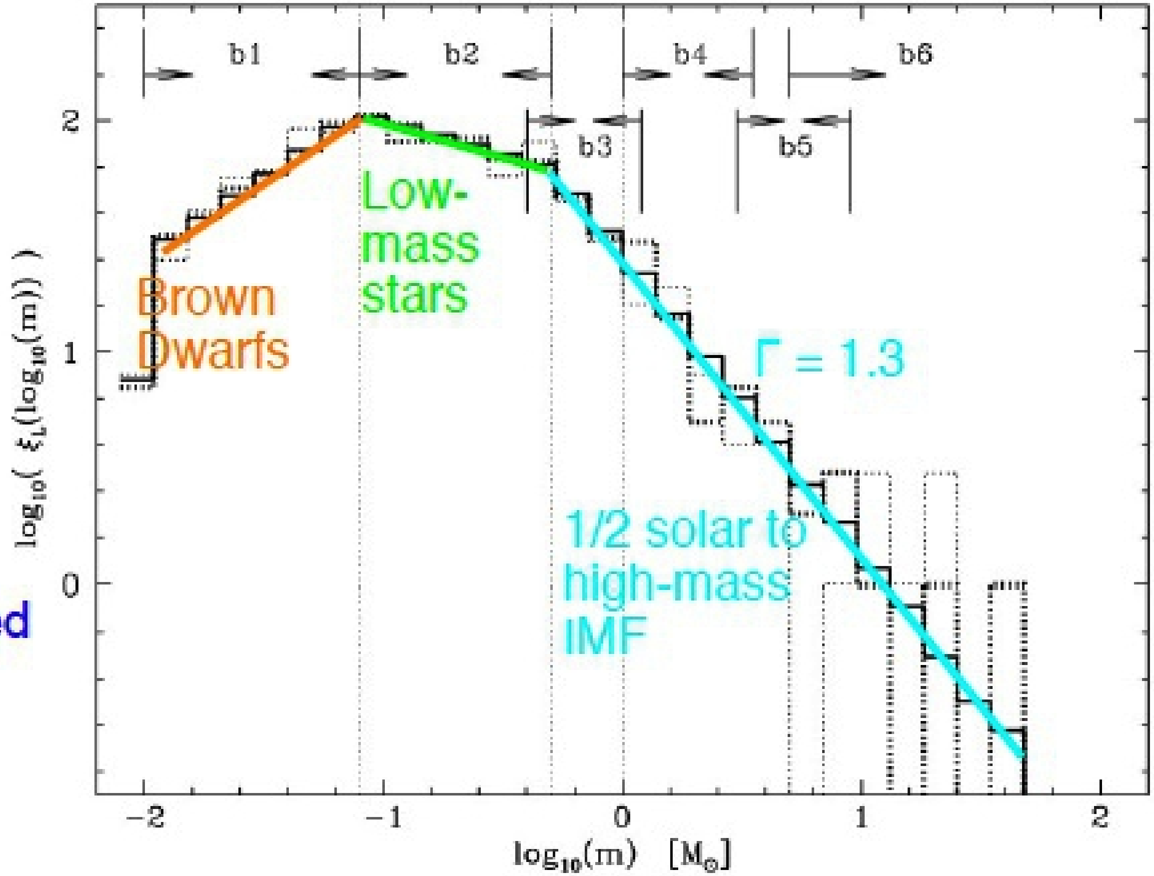
Kroupa IMF

Γ = -0.7   0.01 < M < 0.08 Msun

Γ = 0.3   0.08 < M < 0.5 Msun

Γ = 1.3 +- 0.3   M > 0.5 Msun

(Salpeter regime)



Kroupa 2001

Note: the IMF slope is defined as -Γ, so *positiv = falling*, *negativ = rising!!!*

α0 = +0.3 ± 0.7 , 0.01 ≤ m/M⊙ < 0.08,

α1 = +1.3 ± 0.5 , 0.08 ≤ m/M⊙ < 0.50,

α = +2.3 ± 0.3 , 0.50 ≤ m/M< 1.00,

The maximum stellar mass

There appears to be a linear relation between the maximum star mass in a young star-forming region (cluster or association) and the mass of the parent cloud:

$$M_{max} = 0.33\ (M_{cloud})^{0.43}$$

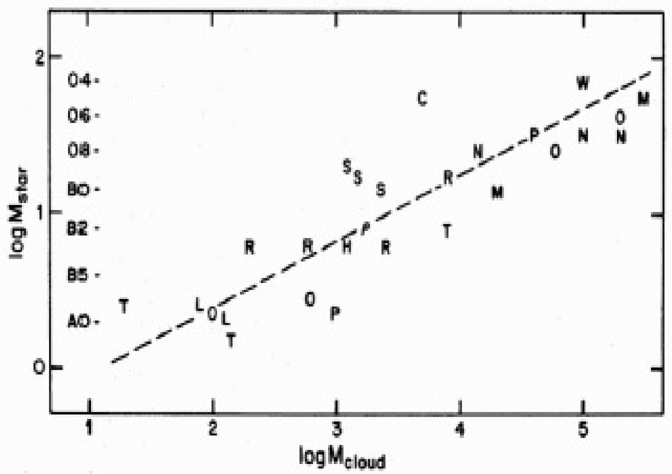


Figure 6. The mass of the most massive star in each young stellar group or region of star formation, plotted versus the mass of the associated molecular cloud. The data are from Table 1, where the symbols are identified. The main-sequence spectral types are indicated at the left of the plot. The dashed line corresponds to equation (1).

Larson 1982

However, in practice there appears to be an upper limit of 150 M_{sun} in star-forming regions in nearby galaxies.

Stellar evolution reminder

HERTZSPRUNG-RUSSELL DIAGRAM

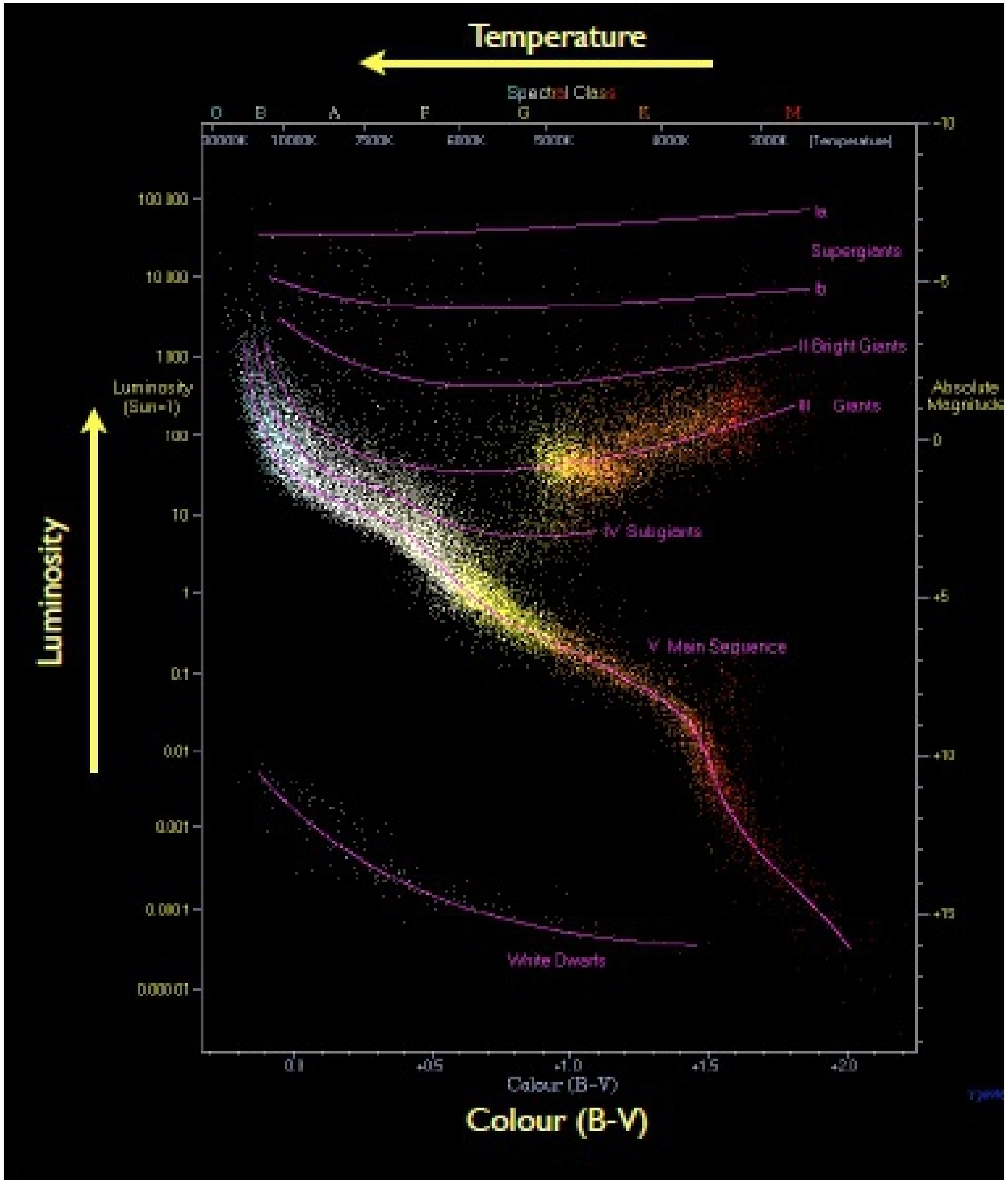
Plots luminosity of stars, versus their temperature.

Stars populate distinct regions of this plane, corresponding to particular evolutionary phases.

Terminology:

HRD is "theory" plane: temperature vs bolometric luminosity.

CMD (colour-magnitude diagram) is its empirical analogue.



Stellar evolution reminder

MAIN SEQUENCE (MS)

Core hydrogen burning phase. Longest phase of evolution.

TURN-OFF

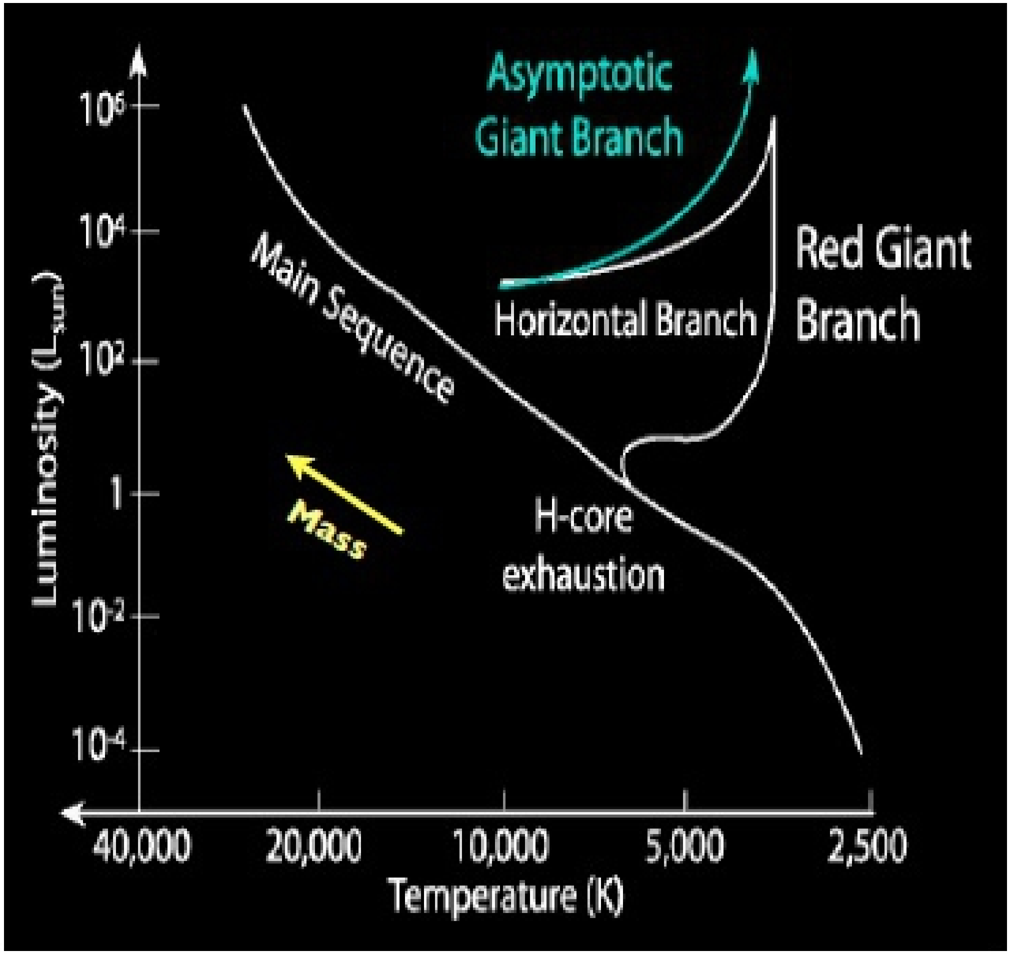
Hydrogen exhausted in core, start of "interesting" evolution.

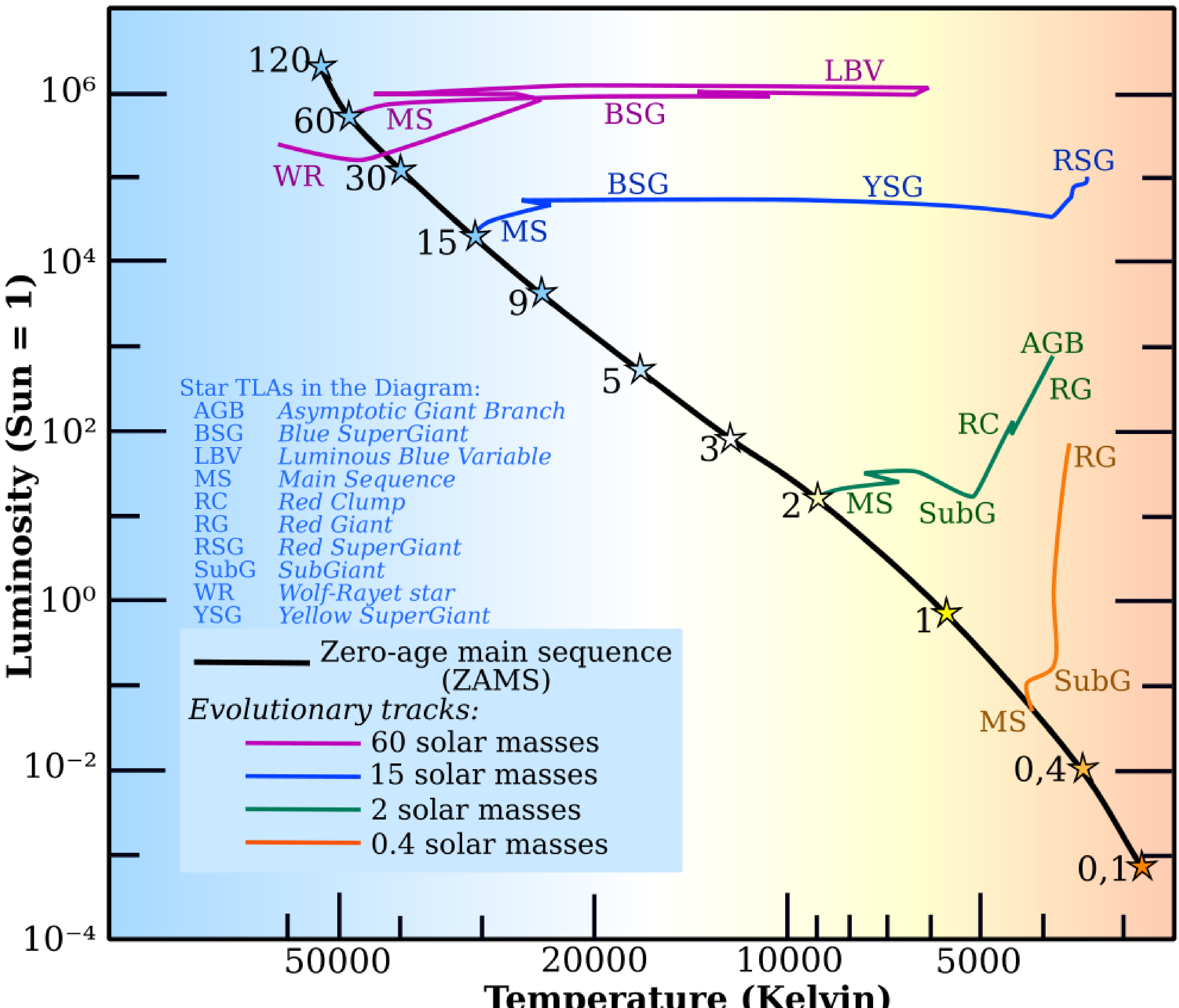
RED-GIANT BRANCH (RGB)

Hydrogen burning in shell around inert helium core. Growth of He core.

RGB TIP

End of RGB phase: core massive and hot enough to ignite He-burning (the "helium flash")





Luminosity (Sun = 1)
10⁶
10⁴
10²
10⁰
10⁻²
10⁻⁴
Temperature (Kelvin)
50000
20000
10000
5000
120
60
30
15
9
5
3
2
1
0,4
0,1
LBV
BSG
MS
WR
RSG
BSG
YSG
MS
AGB
RG
RC
RG
MS
SubG
SubG
MS
Star TLAs in the Diagram:
AGB Asymptotic Giant Branch
BSG Blue SuperGiant
LBV Luminous Blue Variable
MS Main Sequence
RC Red Clump
RG Red Giant
RSG Red SuperGiant
SubG SubGiant
WR Wolf-Rayet star
YSG Yellow SuperGiant
Zero-age main sequence (ZAMS)
Evolutionary tracks:
60 solar masses
15 solar masses
2 solar masses
0.4 solar masses

Stellar Evolution Reminder

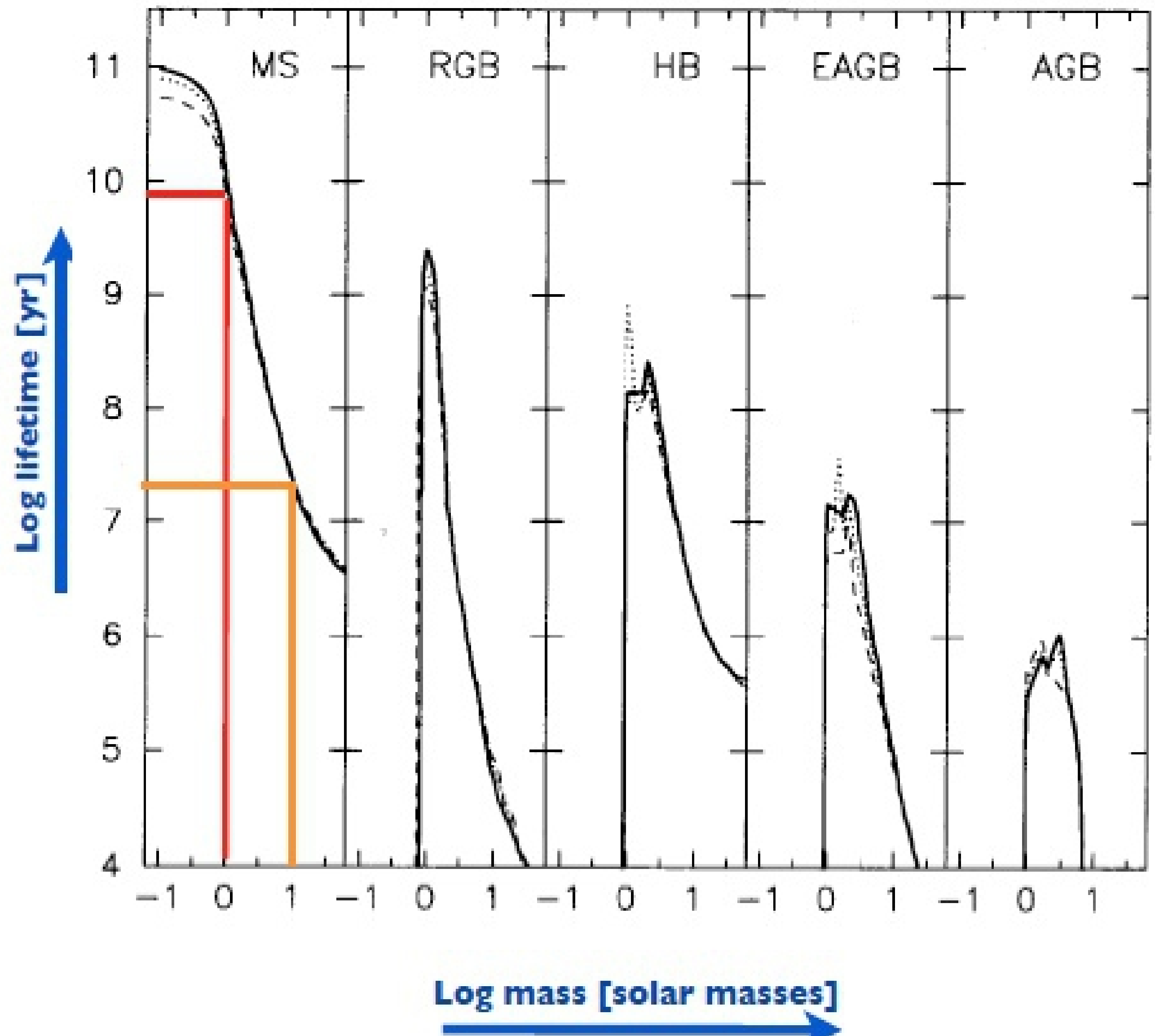
MASS-DEPENDENT LIFETIMES

Lifetime in each evolutionary phase depends sensitively on initial mass.

MS lifetime is ~10^{10} years at 1 solar mass, but only ~10^7 years for 10 Msun.

Below ~ 0.9 Msun, the MS lifetime is longer than age of Universe!

Mass-vs-lifetime relation is one of the crucial tools for age-dating populations.



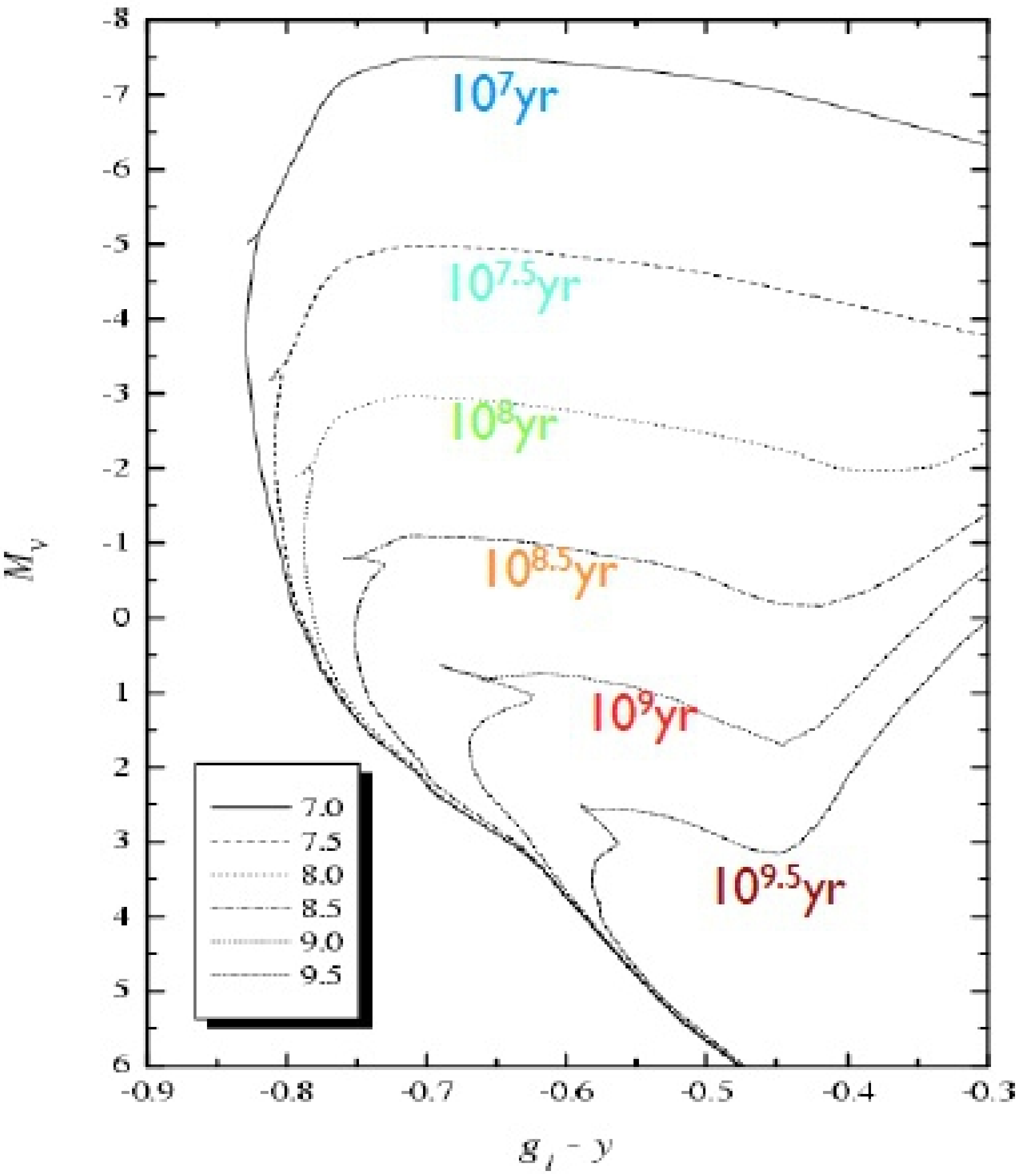
Tracks & Isochrones

ISOCHRONES

"Isochrones" are loci on the HRD populated by stars of a given time since formation, for a range of different masses.

Formed by picking a common "time" point from the track for each stellar mass.

Snapshot of a "simple" stellar population.



Tracks & Isochrones

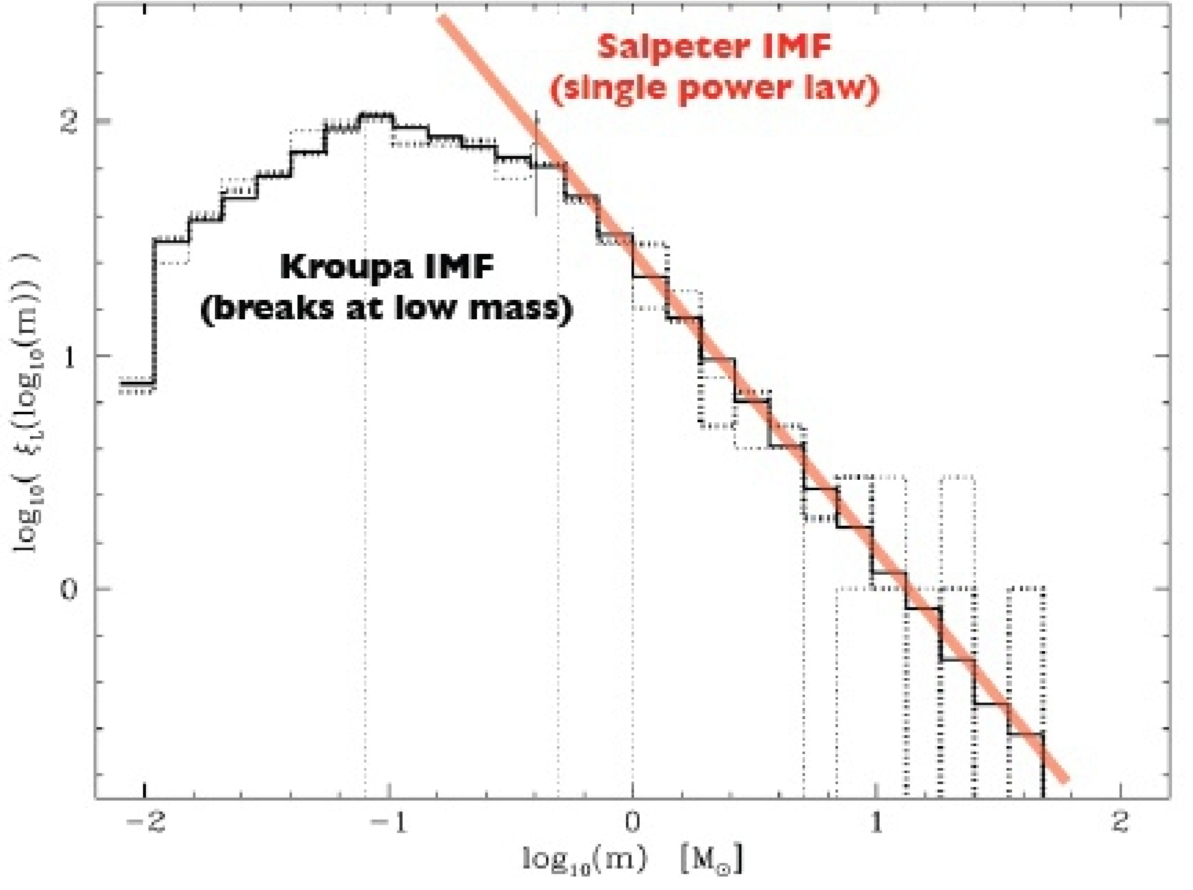
INITIAL MASS FUNCTION

How many stars formed per unit mass?

Determines number of stars expected at each point along isochrone.

Constrained from detailed observations of star-forming regions in the MW.

Applied to wide range of environments beyond MW!



Kroupa (2002)

Simple Stellar Population (SSP)

THE SIMPLEST STELLAR POPULATION MODEL

A burst of star-formation at a given time: all stars have the same age.

All stars form with the same initial chemical composition: a single "metallicity".

The distribution of initial masses is given by some functional form, e.g. power law $N(M)\,dM \propto M^{-x}\,dM$. Commonly assume x=2.35, the "Salpeter IMF", over $M=0.1\text{-}100\ M_{sun}$.

Modern studies show fewer low mass stars than in Salpeter, e.g. Kroupa IMF (but these make little contribution to the total light).

USEFUL BECAUSE...

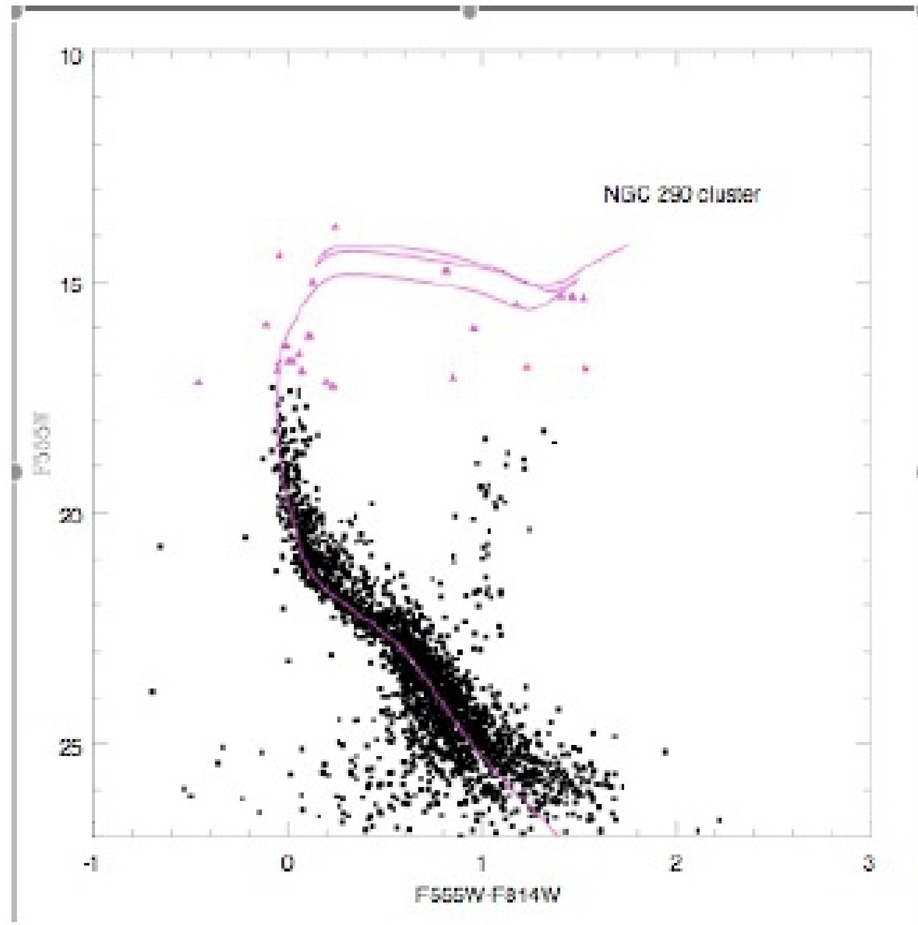
For stellar systems without much recent SF (GCs, elliptical galaxies) the SSP is probably a good approximation.

More complex systems can be modelled using combinations of SSPs.

Observed star cluster CMDs

OPEN CLUSTERS

MS dominant, few RGB or other evolved stars. Only few 100s or 1000s of stars.



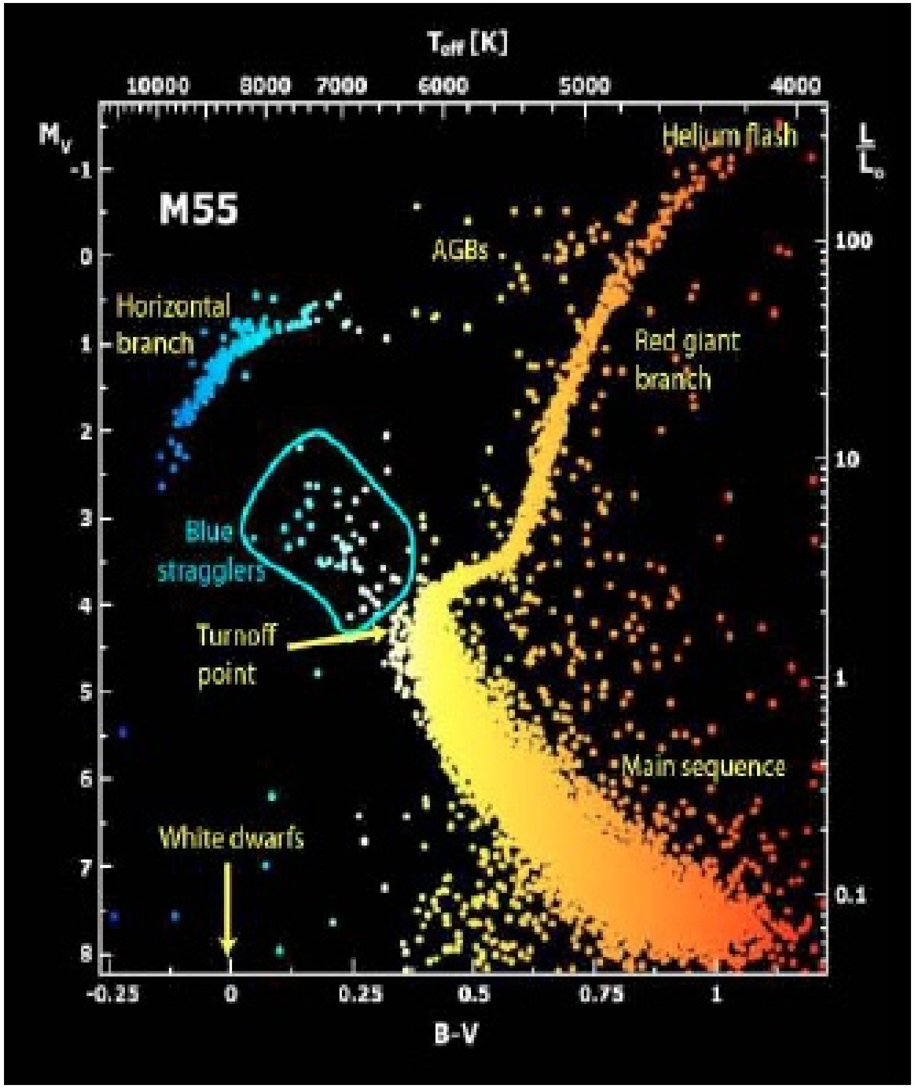
NGC 290 in the Small Magellanic Cloud (Chiosi & Vallenari 2007)

Observed star cluster CMDs

GLOBULAR CLUSTERS

De-populated upper MS. Strong RGB and HB.

1,000s to 100,000s of stars.



Population Synthesis Models

TO COMPUTE FLUX FROM AN SSP IN A GIVEN BANDPASS:

1. Choose isochrone according to desired age and metallicity (Padova, BaSTI, etc)

2. Populate isochrone with stars drawn from an assumed IMF (e.g. Kroupa, etc)

3. Map atmospheric parameters (metallicity, temperature, gravity) to flux in a given bandpass (bolometric corrections) using model or empirical spectral energy distributions.

4. Integrate along isochrone, summing contribution from stars of each initial mass:

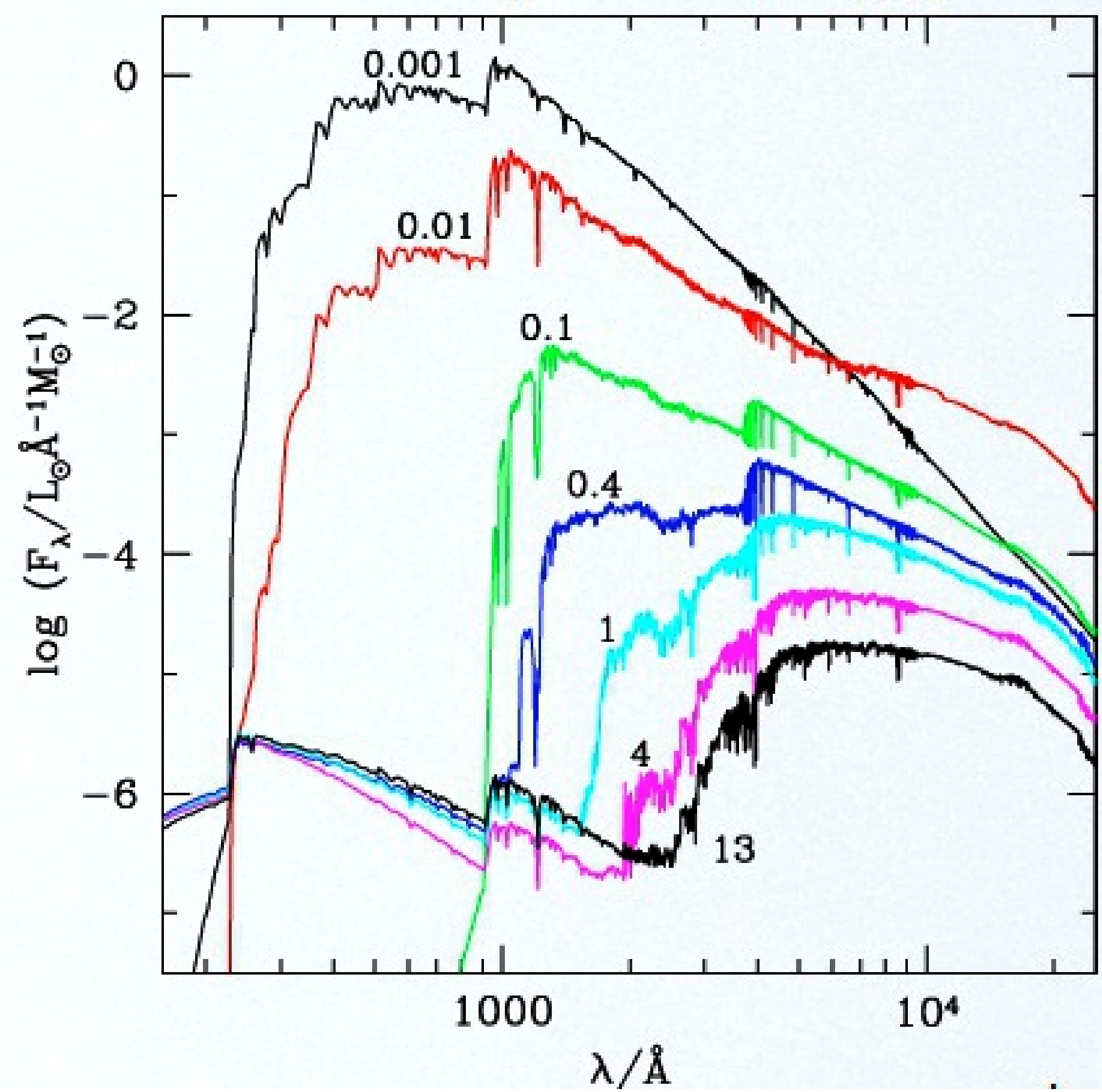
$$F_{tot} = \int L(M) \,.\, B\,(Teff(M), g(M), Z) \,.\, N(M)\, dM$$

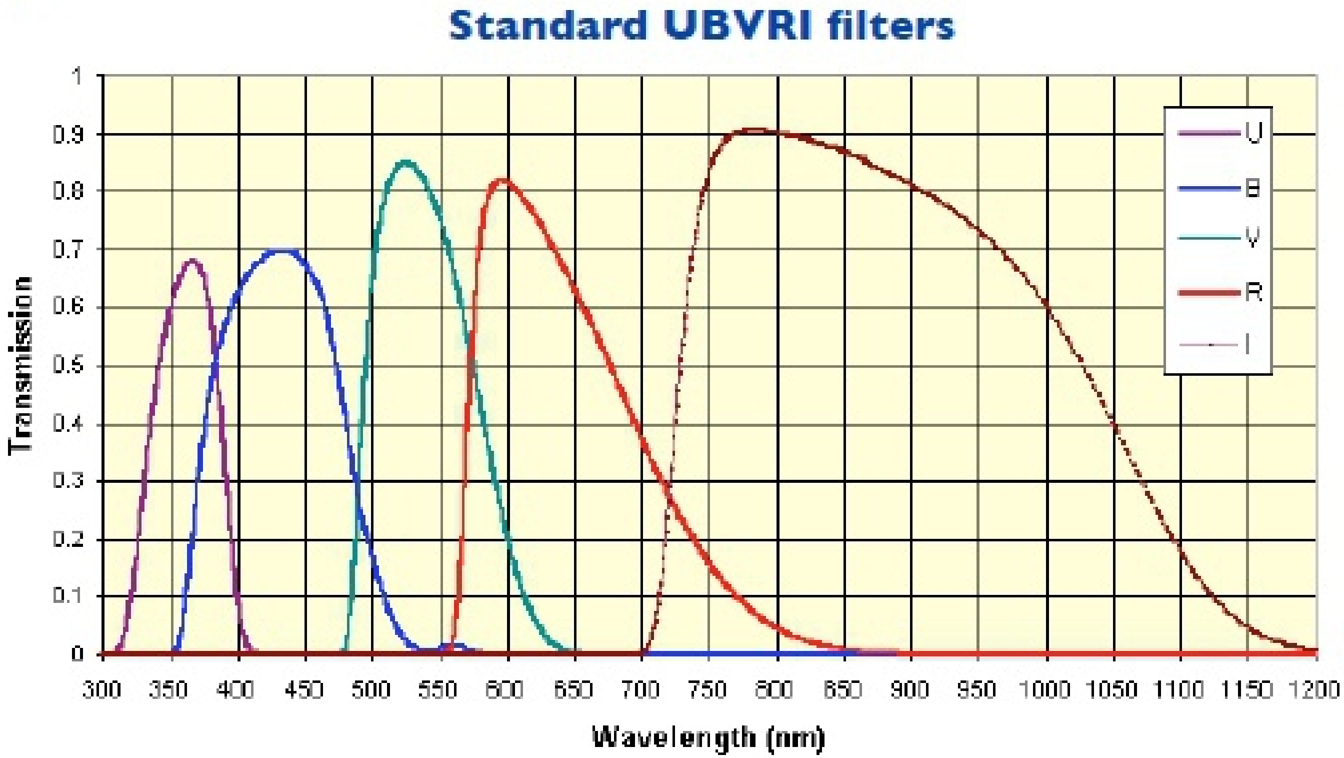
First factor is the total ("bolometric" luminosity)
Second factor is the bolometric correction for this bandpass;
Third factor is number of stars contributing for this mass.

Post RGB phases often added "by hand".

Spectral evolution of a Simple Stellar Population

Resulting SSP evolution (f_{SSP})

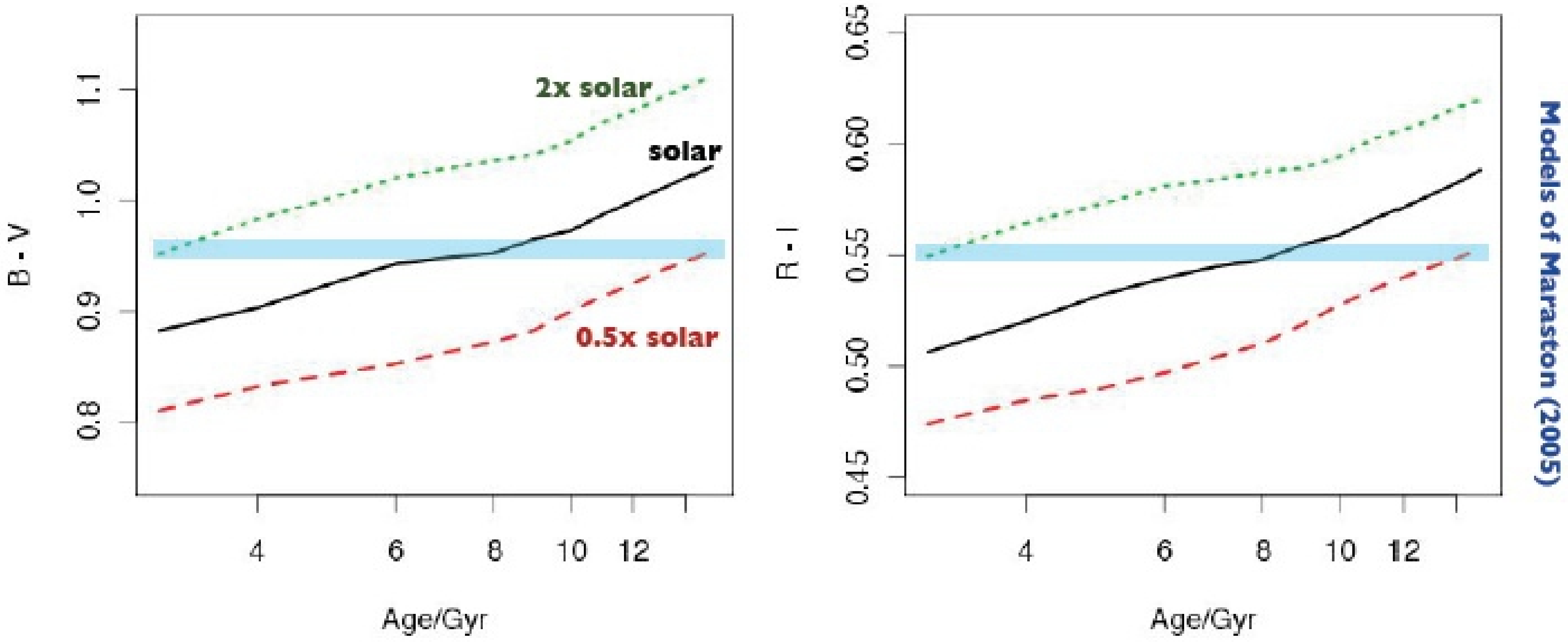




BOLOMETRIC CORRECTION

Describes how total luminosity translates to flux measured through a particular filter.

Age-Metallicity Degeneracy



Because both age and metallicity cause the population to redden, a single colour is not enough to disentangle the parameters.