STAR FORMATION

An Overview

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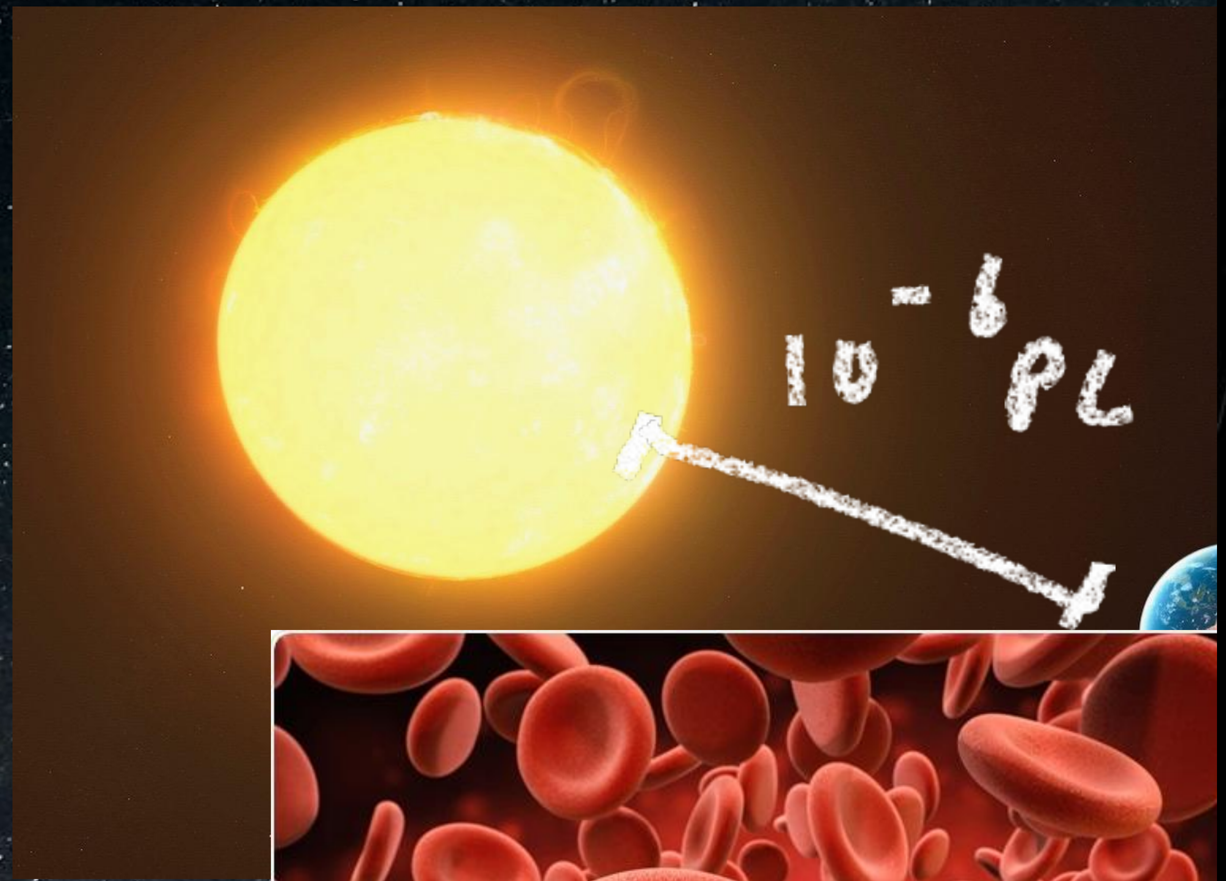
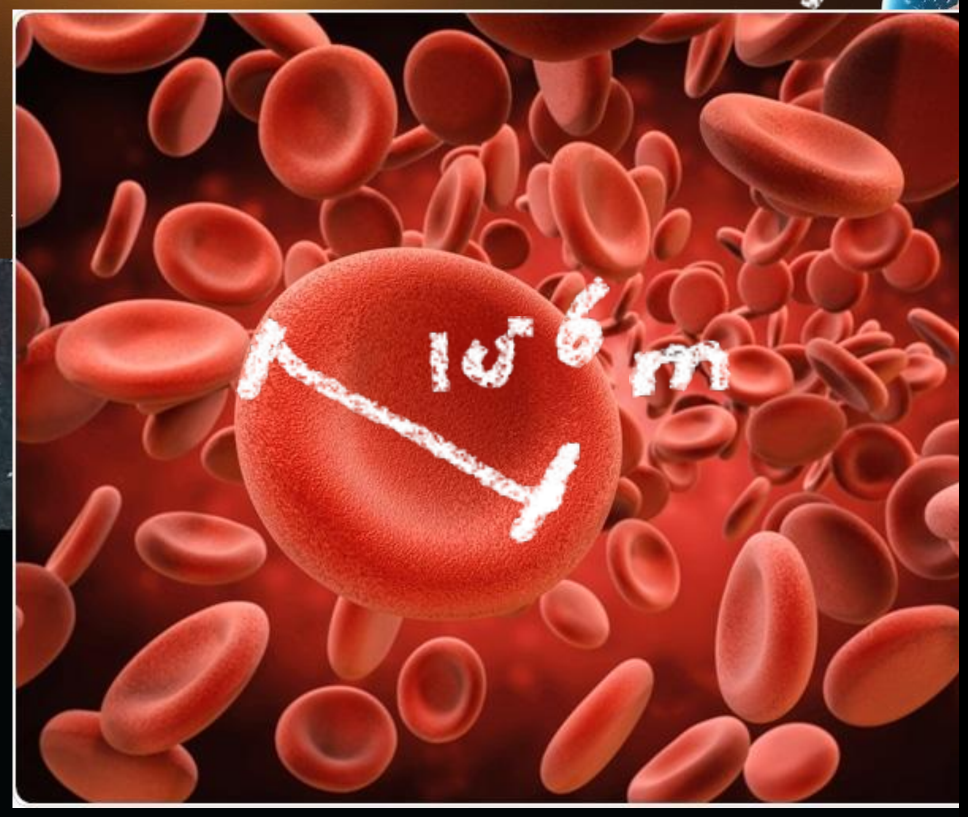
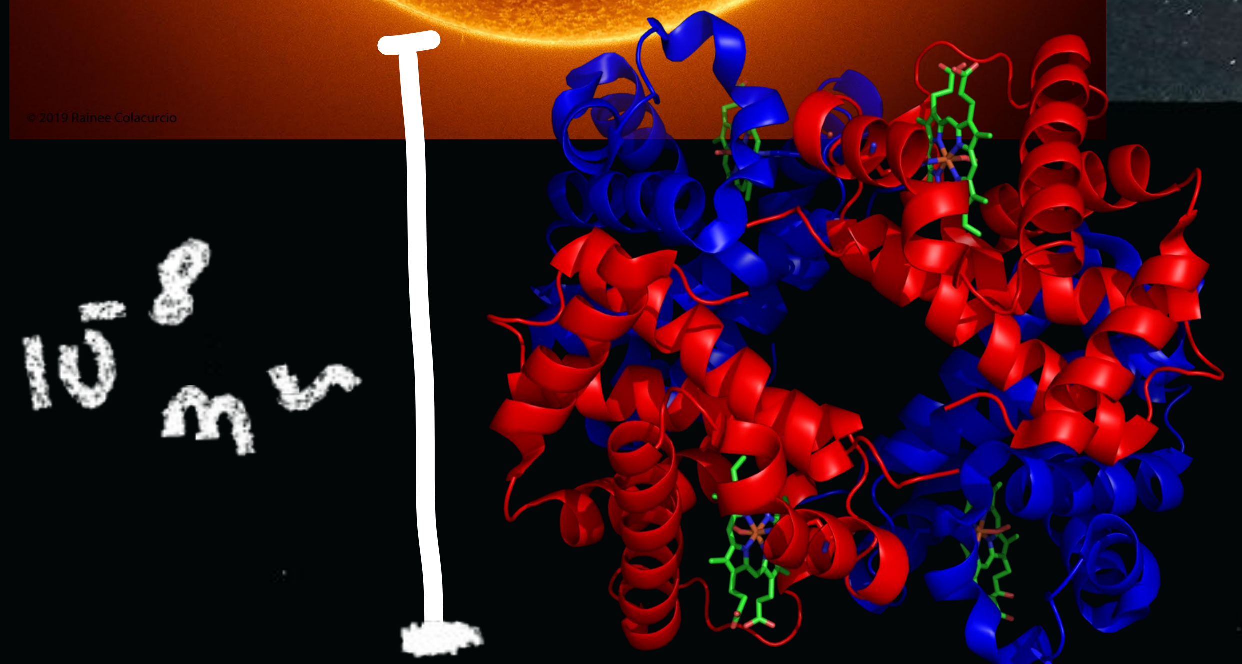
Outline

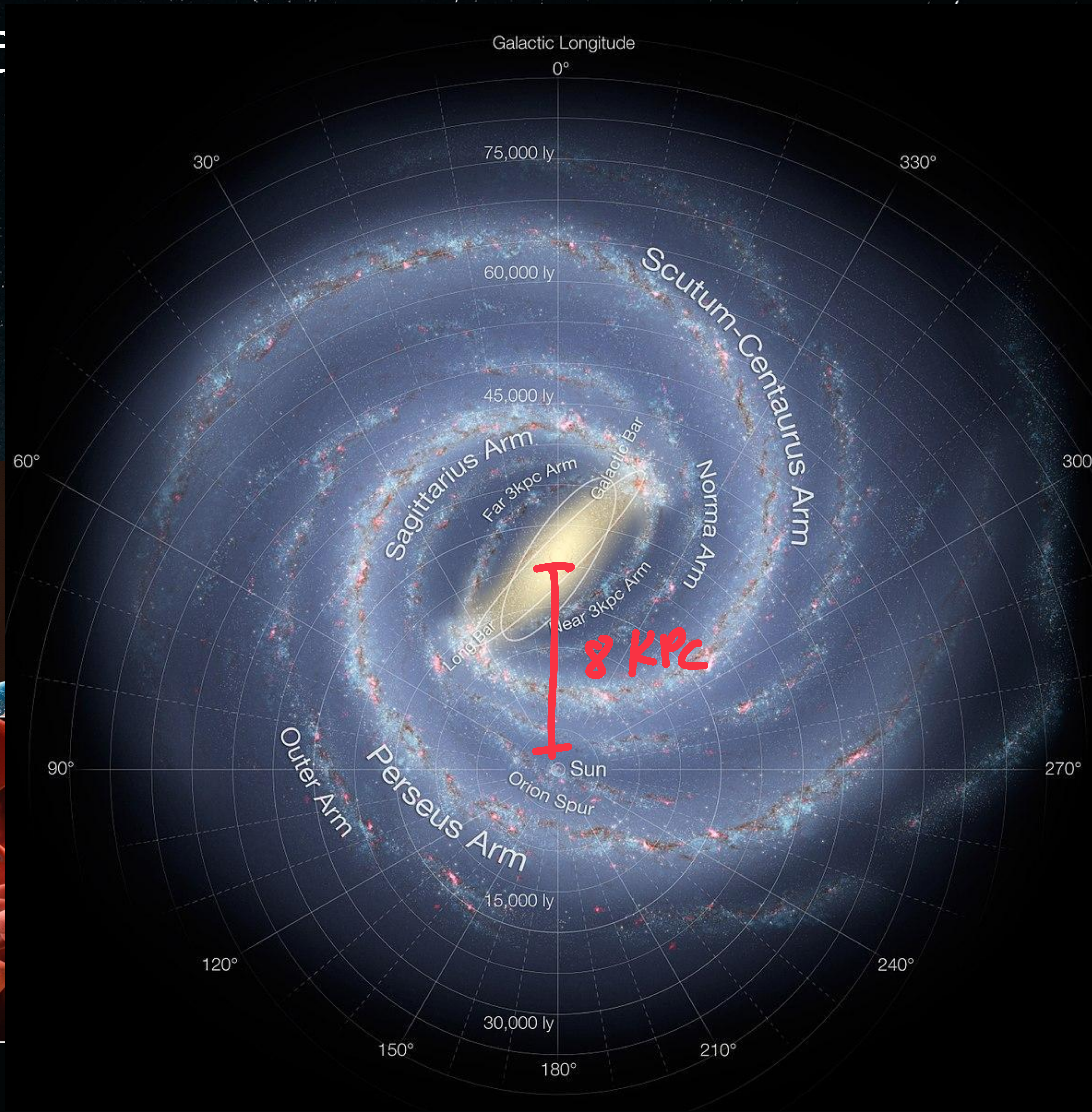
- Star formation laws.
- Initial Mass Function.
- Stochasticity and it’s effects.

Relevant Scales (the parsec meter)

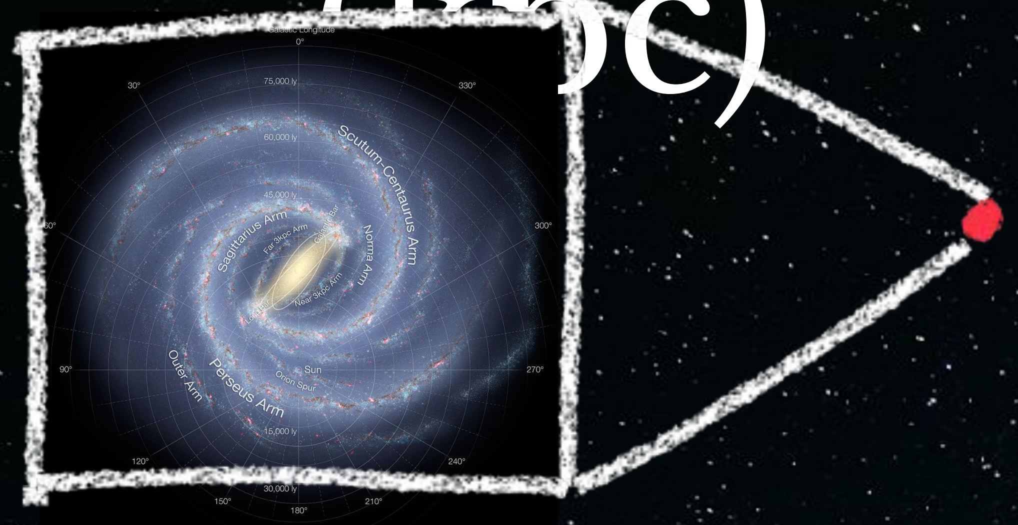








Galactic Scales (kpc)



- How fast do stars form form in a galaxy?
- Historically it was Schmidt(1959) who proposed a correlation with the gas density of the form -

$\Sigma_{SFR} \propto (\Sigma_{gas})^{N}$

- Kennicut (1998) verified the relation. This has been one of the most cited papers in Astrophysics.

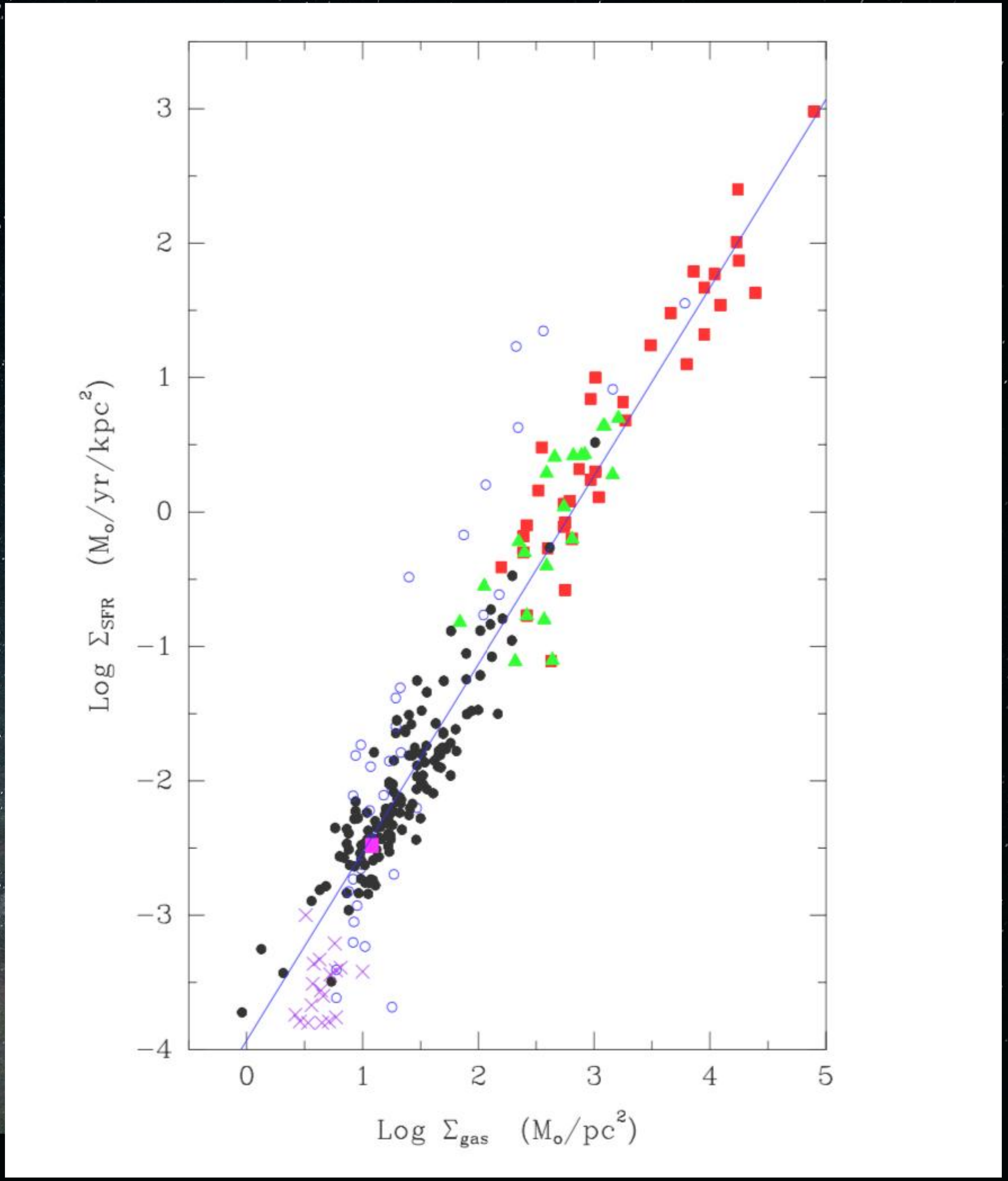


Figure: Relation between SFR per unit area and the total (HI +H2) surface gas density. Kennicut & Evans 2012.

Galactic Scales (kpc)

What do we see when we zoom-in?

Image: NGC 5055 (credits : NASA)

Galactic Scales (kpc)

- Where does star formation occur in a galaxy?

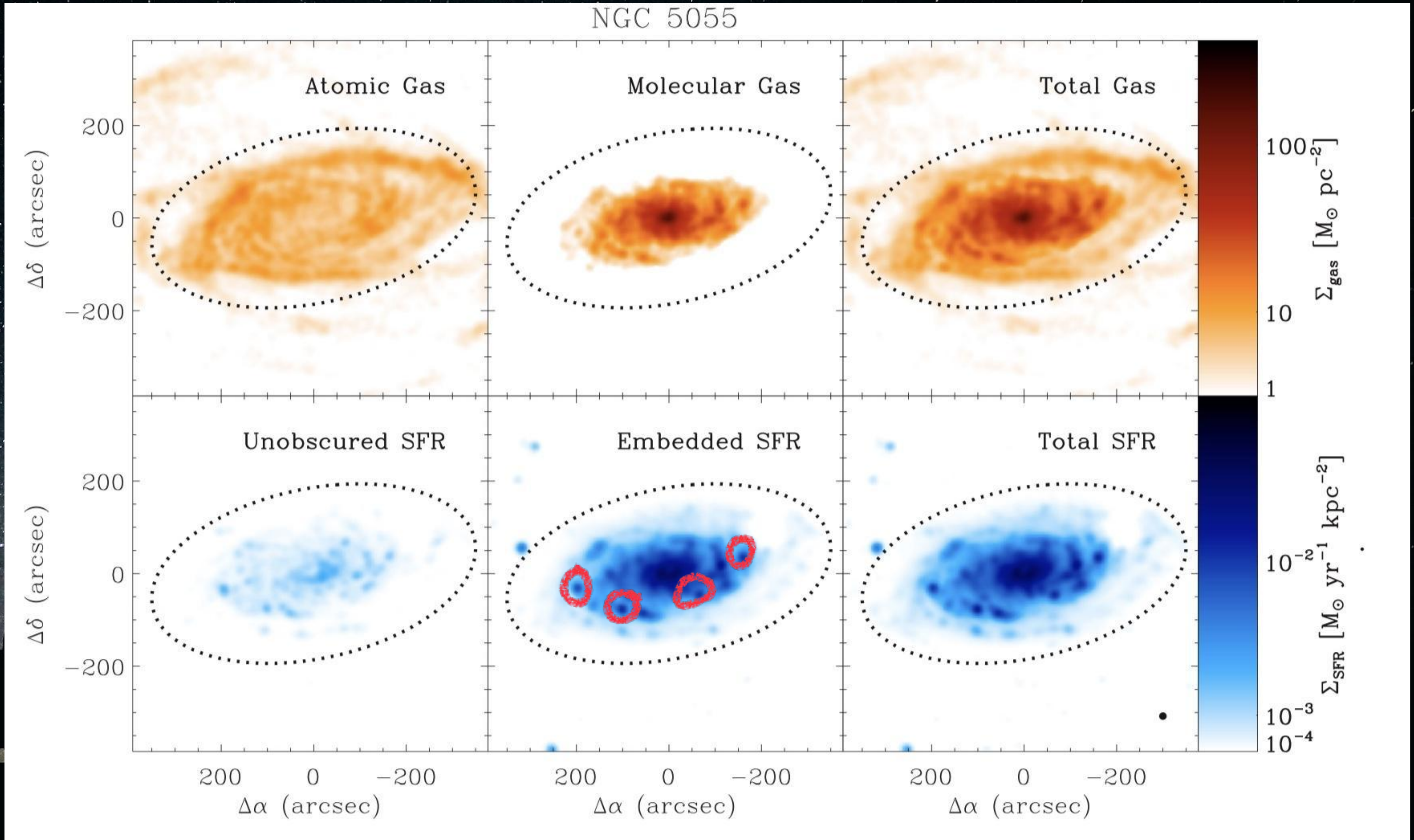
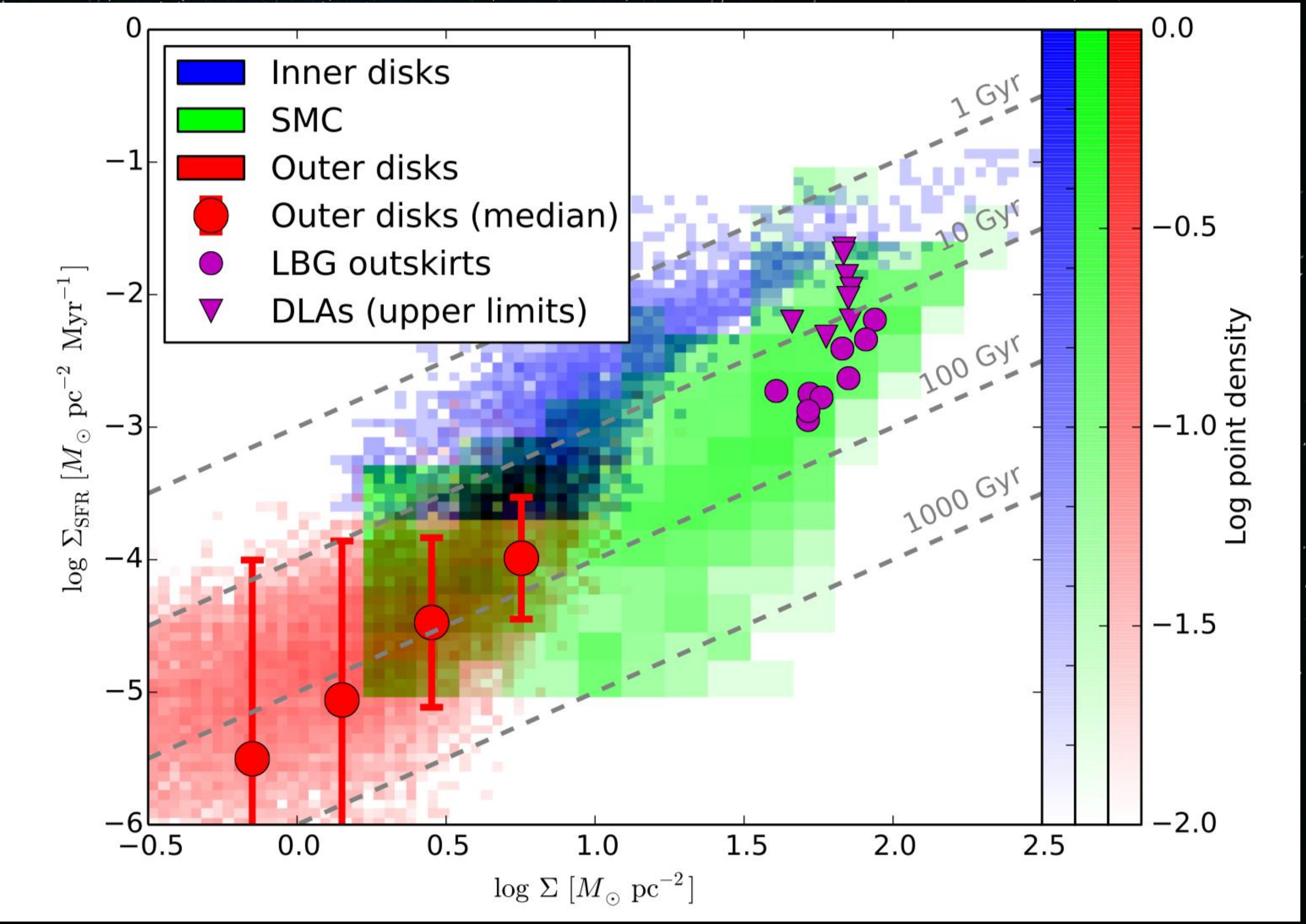


Figure: NGC 5055, column density map and star formation rate
(Leroy et. al. (2008)).

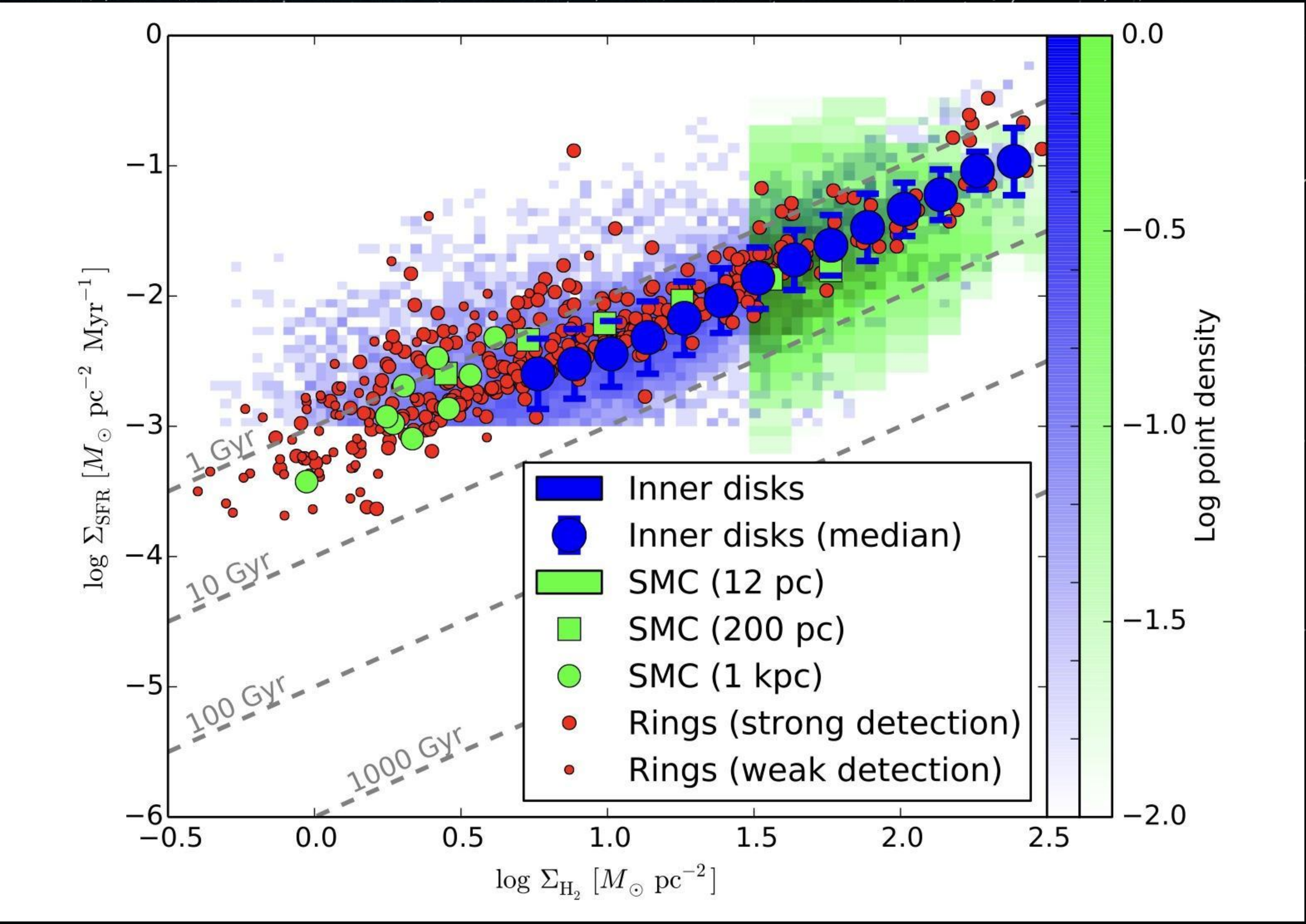
Sub kpc scales

Figure: Different regions of various galaxies. on the y-axis and total gas density () on the x-axis. Magenta circles-outskirts of lyman break galaxies (z=3) (Rafelski et. al. 2011), magenta triangles - upper SFR in DLAs (Wolfe & Chen 2006), blue pixels are inner parts of galaxies (Bigiel et. al. 2008), red pixels are outer parts of local universe spiral (Bigiel et. al. 2010) and dwarf galaxies. Green pixels are the SMC (Bolatto et. al. 2011). The dashed gray lines represent constant depletion times. Figure taken from Krumholz et. al. 20



Sub kpc scales

Figure: Similar to the last figure, the y-axis shows the but the x-axis only shows the surface gas density. Blue pixels show the inner part of galaxies in the local universe (Leroy et. al. 2013), the circles and the error bars show the median and the scatter of this data set. Green pixels represents SMC with data of Bolatto et. al. 2011. Red points are azimuthal rings of nearby spiral galaxies Schruba et. al. 2011. Image taken from Krumholz et. al. 2014.



Star Formation Efficiency

(ϵ_{ff})

- Free-fall Time ()

  The characteristic time-scales at which a system would collapse if no forces were present to oppose gravity.

- Depletion Time ()

  The actual time-scales at which the system is expected to run out of gas.

$$\dot{\rho}_* = \frac{\rho}{t_{ff}} \times \epsilon_{ff}$$

$$\dot{\Sigma}_{SFR} = \frac{\Sigma_{H_2}}{t_{ff}} \times \epsilon_{ff} \quad \text{—} \quad (1)$$

$$\frac{t_{ff}}{t_{dep}} = \epsilon_{ff} \quad ; \quad t_{dep} = \frac{\dot{\Sigma}_{SFR}}{\Sigma_{H_2}}$$

Krumholz et. al. 2012

New Star Formation Law (1)

- The figure combines many scales - kilo parsec galactic scales (unresolved galaxies), resolved molecular clouds (Milky Way) and some nearby galaxies too (resolved galaxies).
  - Notice the value of
  - Can you guess why star formation is so inefficient?

1) Pressure
2) Magnetic Pressure
3) Turbulence
4) Feedback

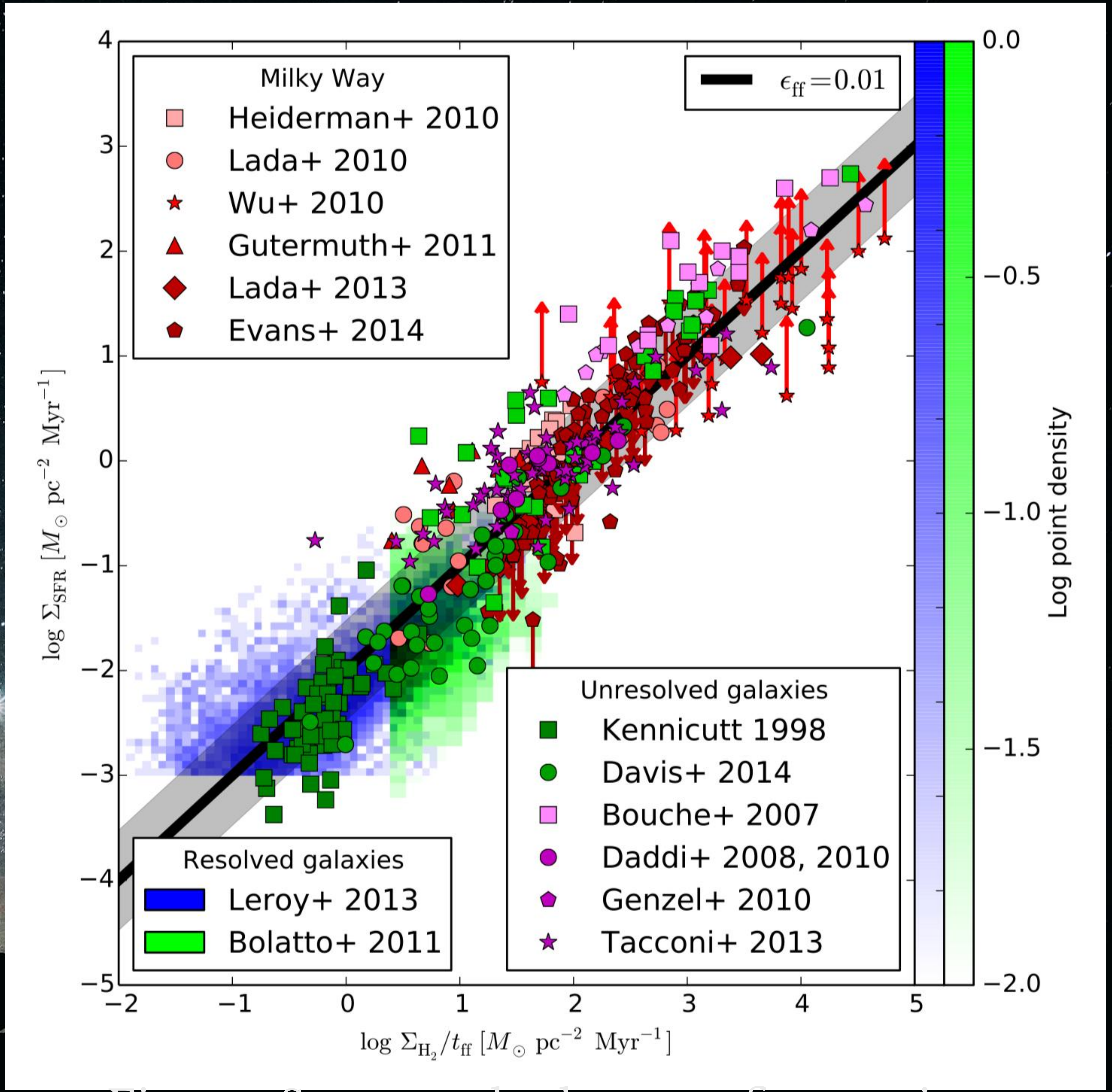


Figure: Same as the last two figures, just that the horizontal axis shows instead of the gas densities.
Image taken from Krumholz et. al. 2014.

New Star Formation Law (2)

- When we zoom-in further inside molecular clouds we see even more substructure.
- Instead of measuring the mean , we get a better result when we take into account the density structures of the clouds (Salim et. al. 2015).
- This density structure depends upon physical properties such as the Mach number (), the magnetic field and on the turbulence parameters.

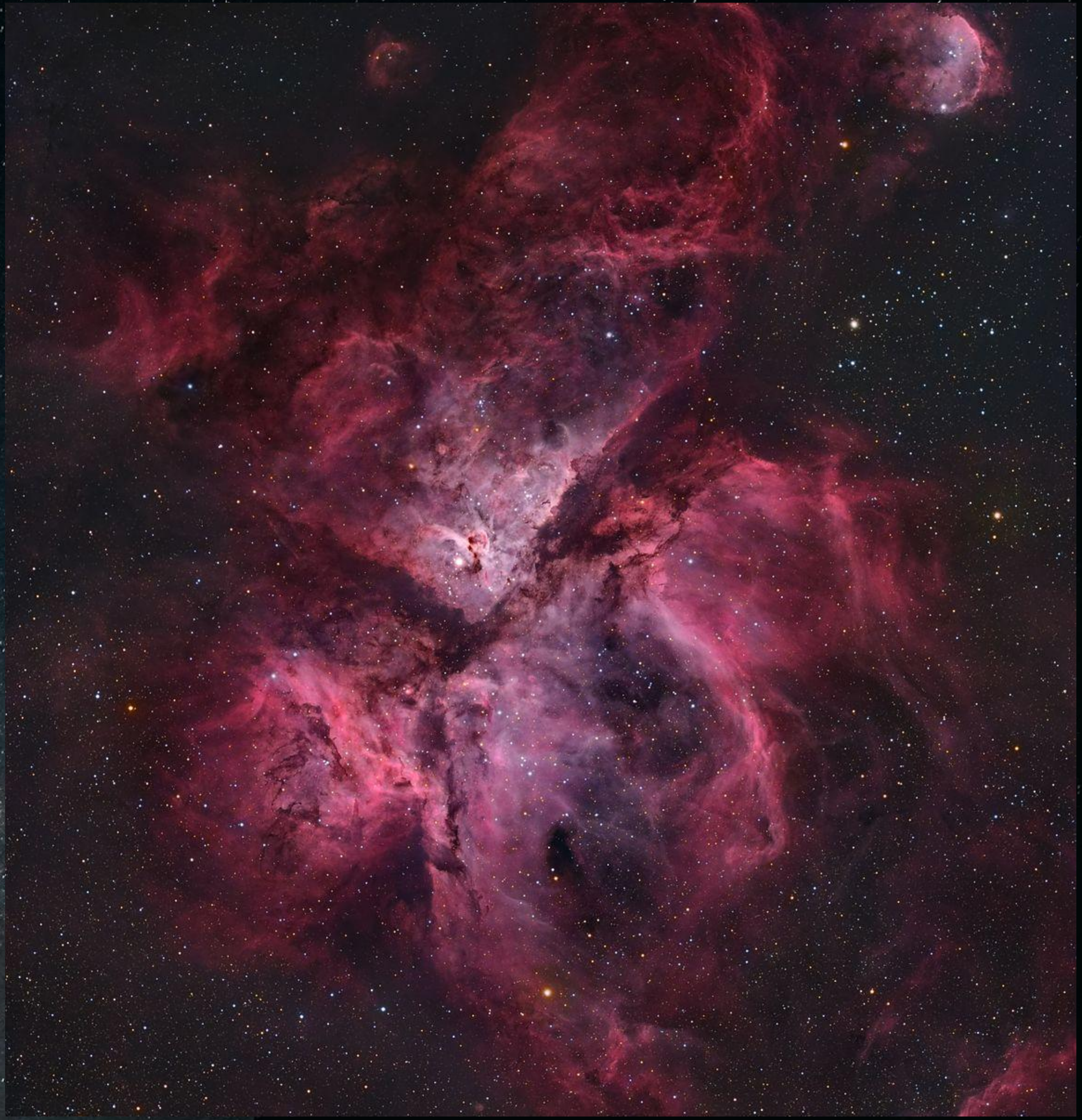


Figure: Carina Nebula. Image Credits : Harel Boren.

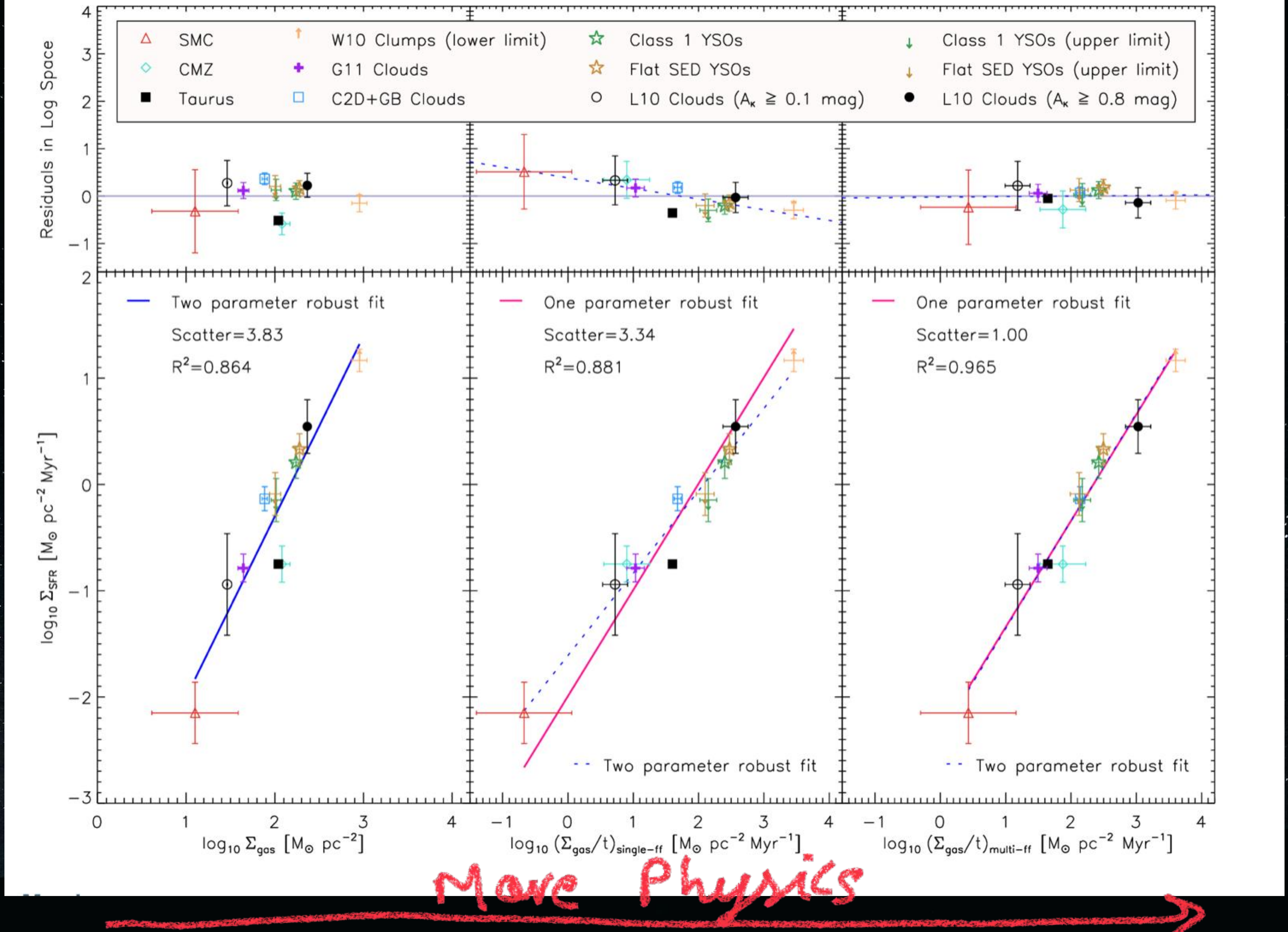
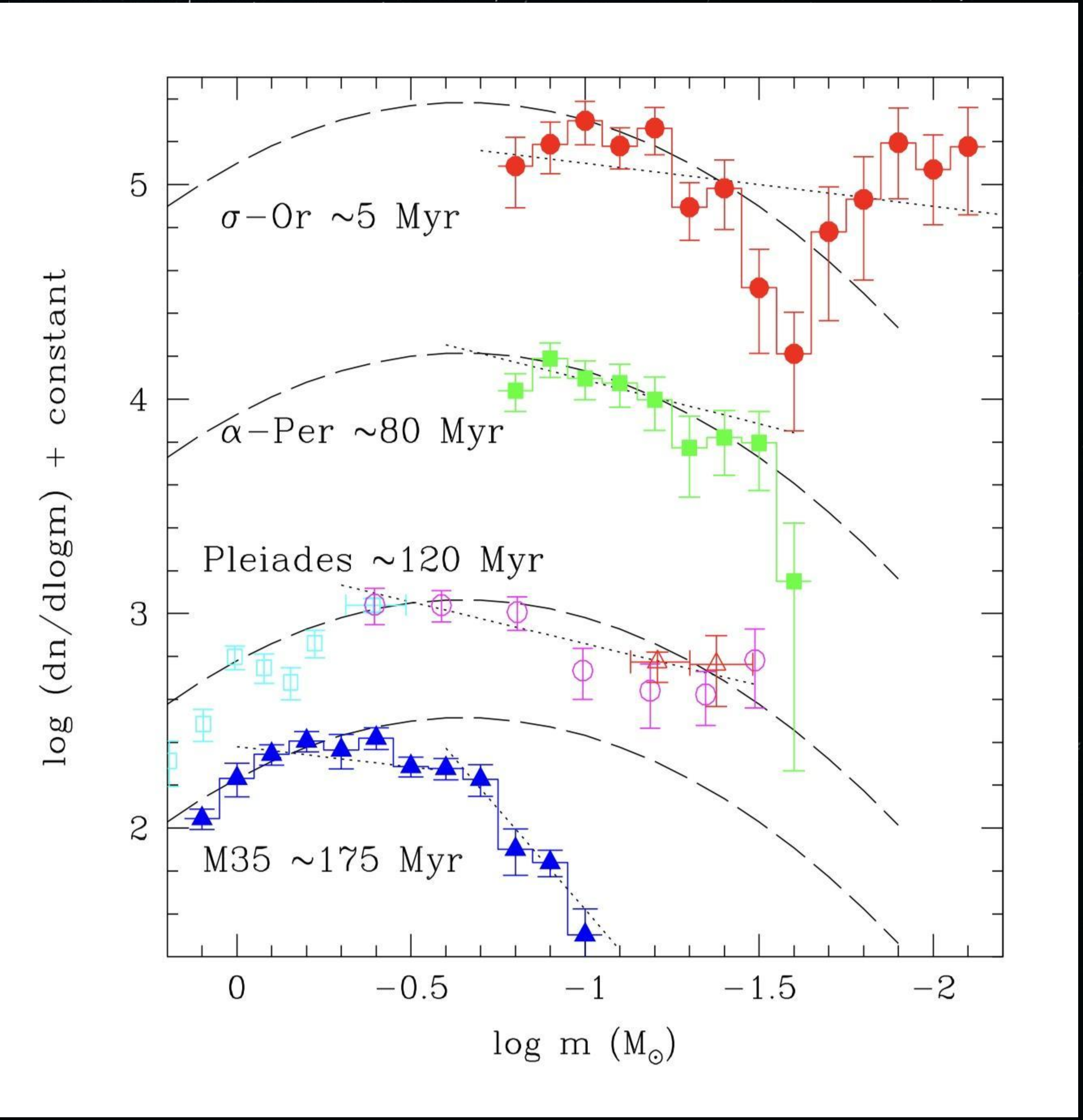


Figure: Left most panel: kennicutt-schmidt relation, middle panel: krumholz et. al 2012. Right panel: multi free-fall SFR law. Figure taken from Salim et. al. 2015.

The Initial Mass Function (IMF)

- The mass distribution of the stellar population at the time of birth.

Figure: The mass function for various young clusters. Solid circles:σ-Or (B´ejar et al. 2001);filled squares :α-Per (Barrado y Navascues et al. 2002); empty symbols : Pleiades (Hamblyet al., 1999, squares; Moraux et al., 2003, circles; Dobbie et al., 2002b, triangles); filledtriangles : M35 (Barrado y Navascues et al. 2002). Ages of the clusters are annotated beside the data. Image taken from Chabrier et. al. 2003.



The Initial Mass Function (IMF)

- The mass distribution of the stellar population at the time of birth.

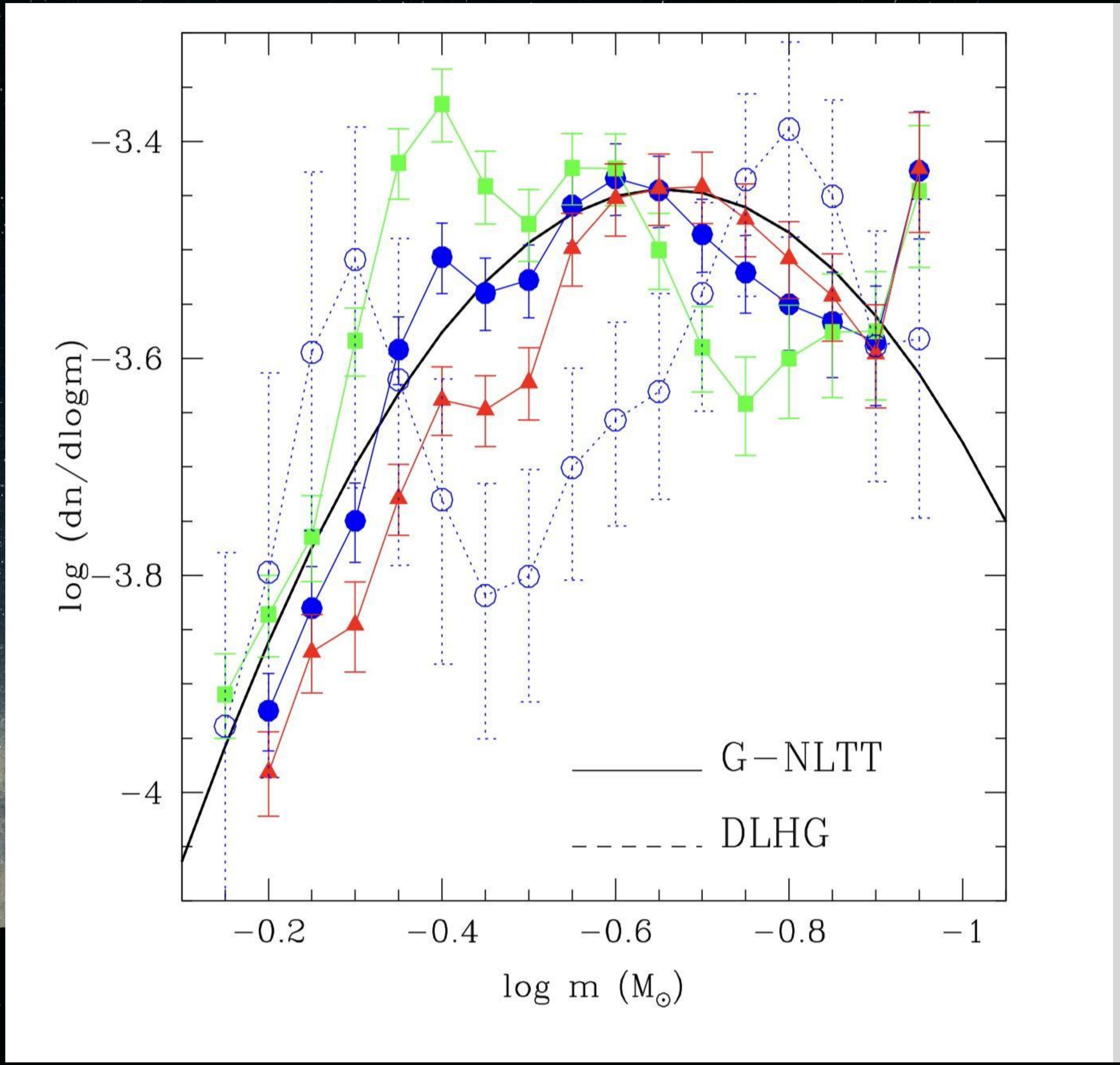


Figure: Mass function of the Galactic spheroid, based on the NLTT (Gould 2003) LF(solid lines) and the Baraffe et al. (1997) , for three metallicities:[M/H] =-1.5 (triangles), -1.0 (circles) and -0.5 (squares), respectively. Dotted line: samecalculation based on Dahn et al. (1995, 2002) LF and [M/H] =−1.0 models. Image taken from Chabrier et. al. 2013

The Initial Mass Function (IMF)

- The mass distribution of the stellar population at the time of birth.
  - Each of these have their own observational uncertainties But the universality is remarkable!

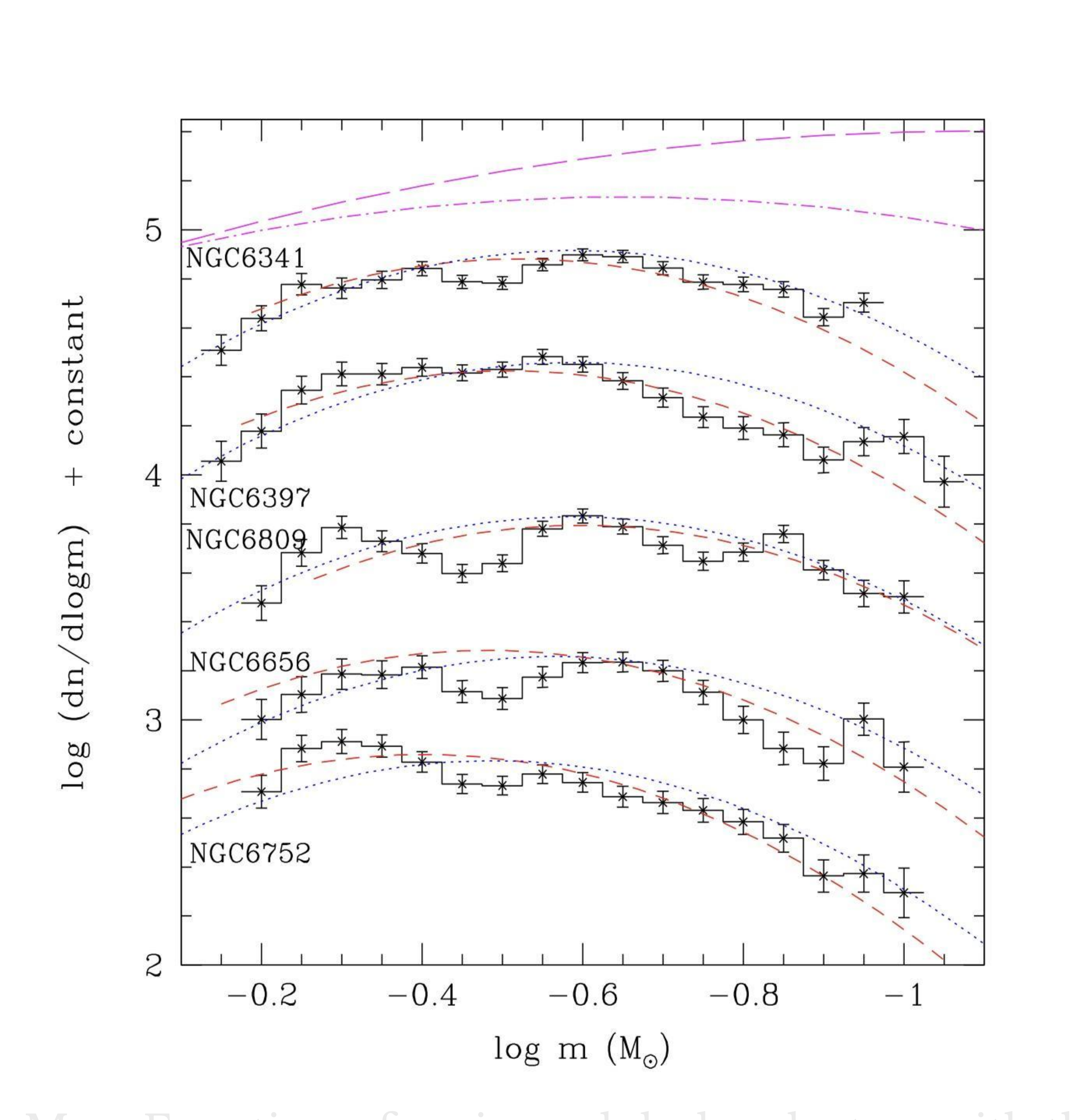


Figure: Mass Function of various globular clusters with the Baraffe et al.(1997) MMRs in several bandpasses, from the LFs of Paresce & DeMarchi (2000), spanninga metallicity range−2.0.[M/H].−1.0.

The Initial Mass Function (IMF)

- The mass distribution of the stellar population at the time of birth.
- Two universal features that we observe are - the low mass peak and the high mass slope.

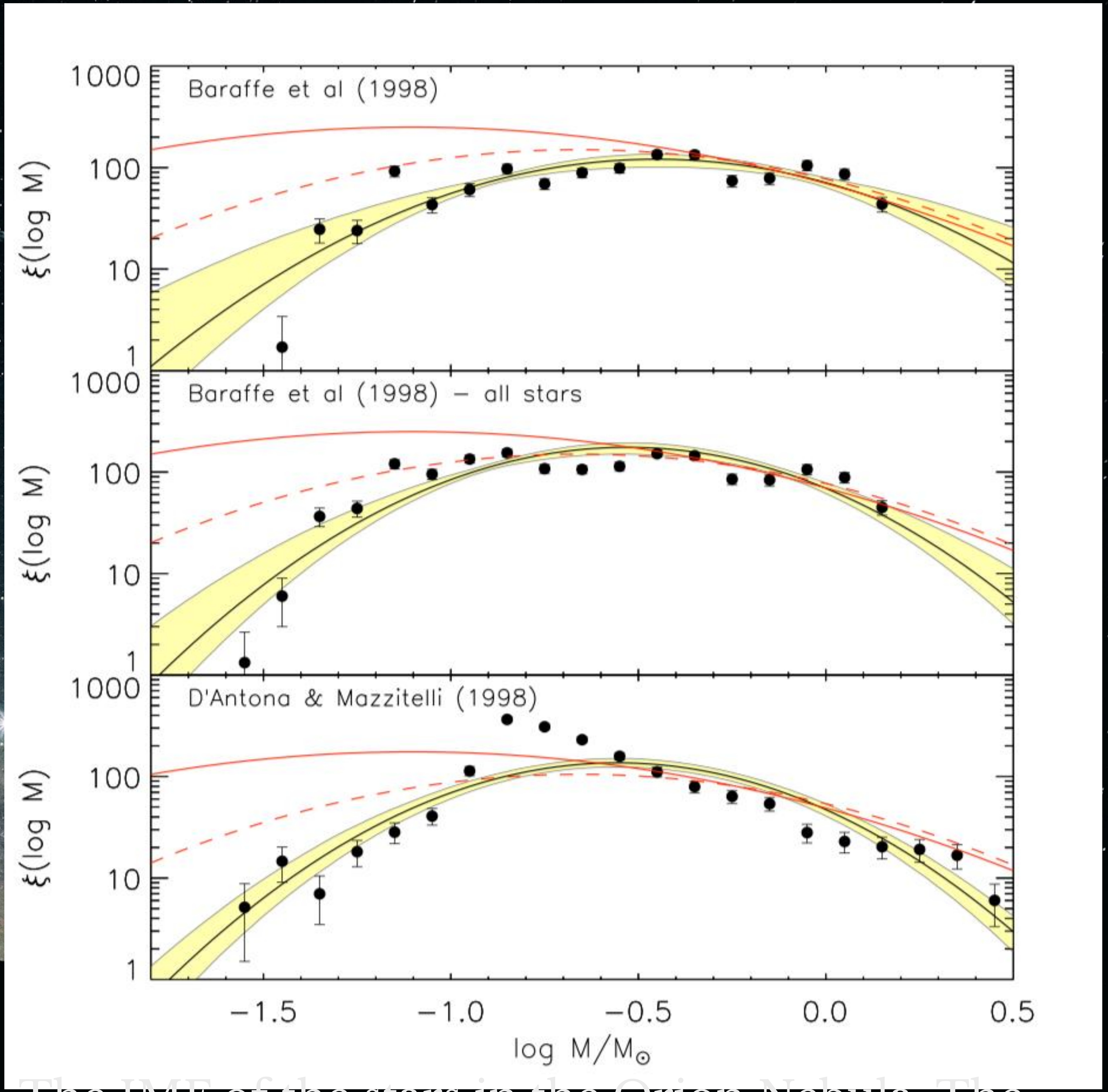
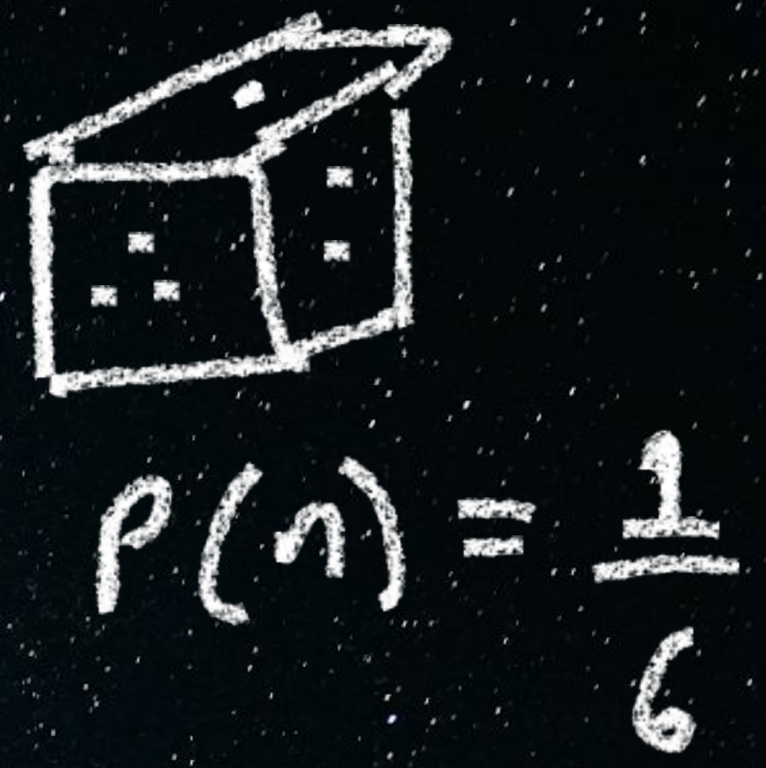


Figure: The IMF of the stars in the Orion Nebula. The photometry data is converted to the IMF using different models. Bottom Panel : Models of D'Antona & Mazzitelli (1998), top two panels: Baraffe et. al. (1998) models. Taken from Da Rio et. al. (2012)

Stochasticity

Having a random probability distribution.



- With recent developments in observational tools, we can now resolve and look more deeper in nearby galaxies than ever before!

HOWEVER

- This leads to improper sampling of the IMF.

- The mass range for a fully sampled IMF is > .

Stochasticity

Having a random probability distribution.

- An example of a low mass star forming region that is stochastic in nature - ?

  Hint - It’s one of the brightest nebula in the night sky, also visible with the naked eye!

Figure: The Orion nebula. Picture credits - Bryan Goff.

Stochasticity

Having a random probability distribution.

- So, why is stochasticity a problem?
- Many physical properties e.g. SFR, metallicity, are estimated empirically through observations. And most of these observations have been from the time when we couldn't resolve these stochastic regions very well.

~~This is where I come~~ in (~~with my prof~~).

Stochasticity

Having a random probability distribution.

- Note that this is only a problem when your observations depend strongly upon a particular part of the spectrum.
- We do Monte-Carlo runs and sample stochastically from the IMF, to simulate the variations caused by the stochasticity.

$\cdot\ M = 10^3\ M_\odot$

$P(x) = 0.3$

$10^6 \times$

$$y \begin{cases} < 0.3 \rightarrow \text{Accept} \\ \geq 0.3 \rightarrow \text{another run} \end{cases}$$

Stochasticity (Results)

Having a random probability distribution.

- Quantity of interest - Metallicity (Z):
- We can see that the error in these synthetic observations reduces as we increase our SFR and sample more number of stars to get a fully sampled IMF.
- Not all ways of measuring metallicity suffer from stochastic effects!

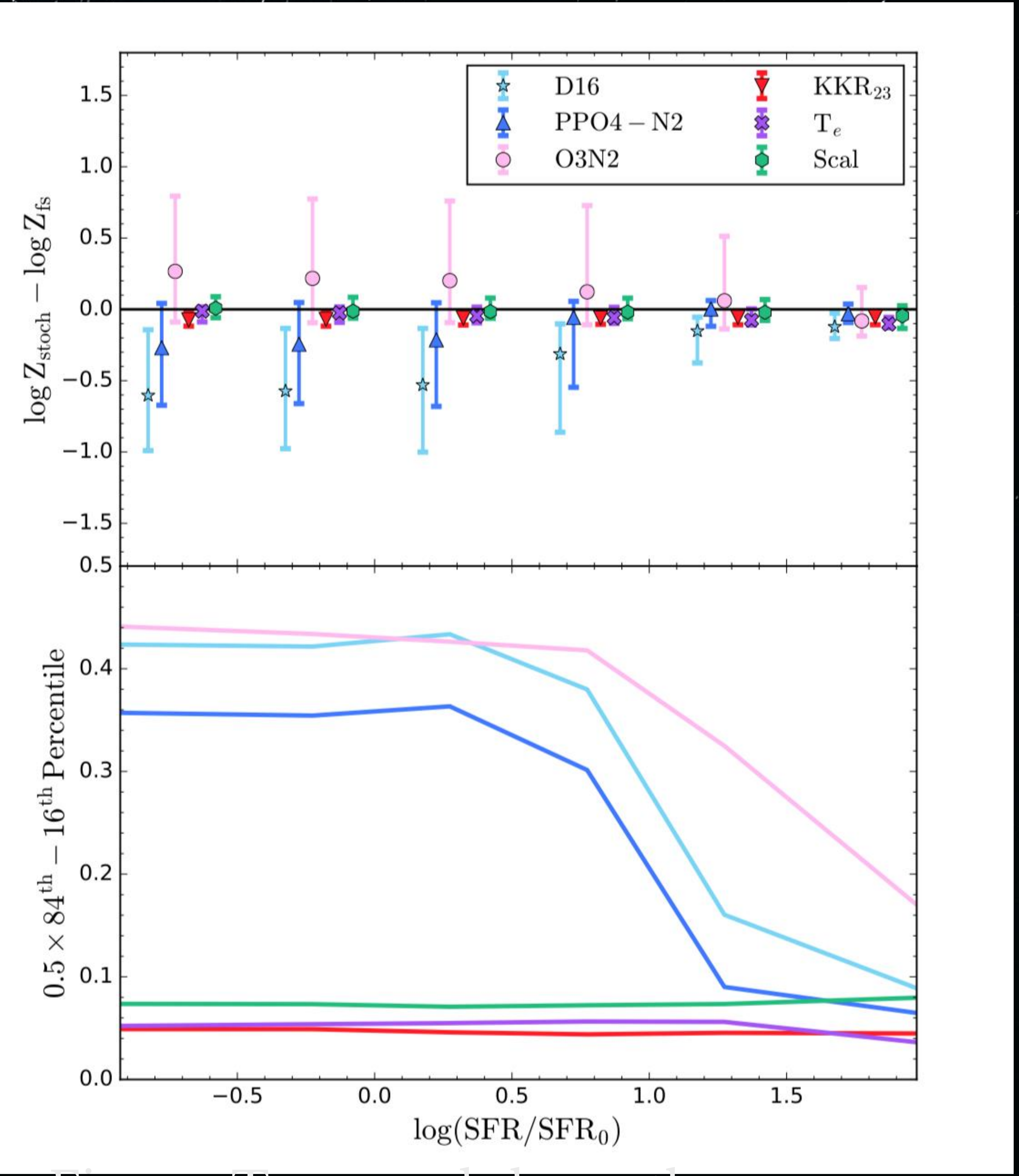
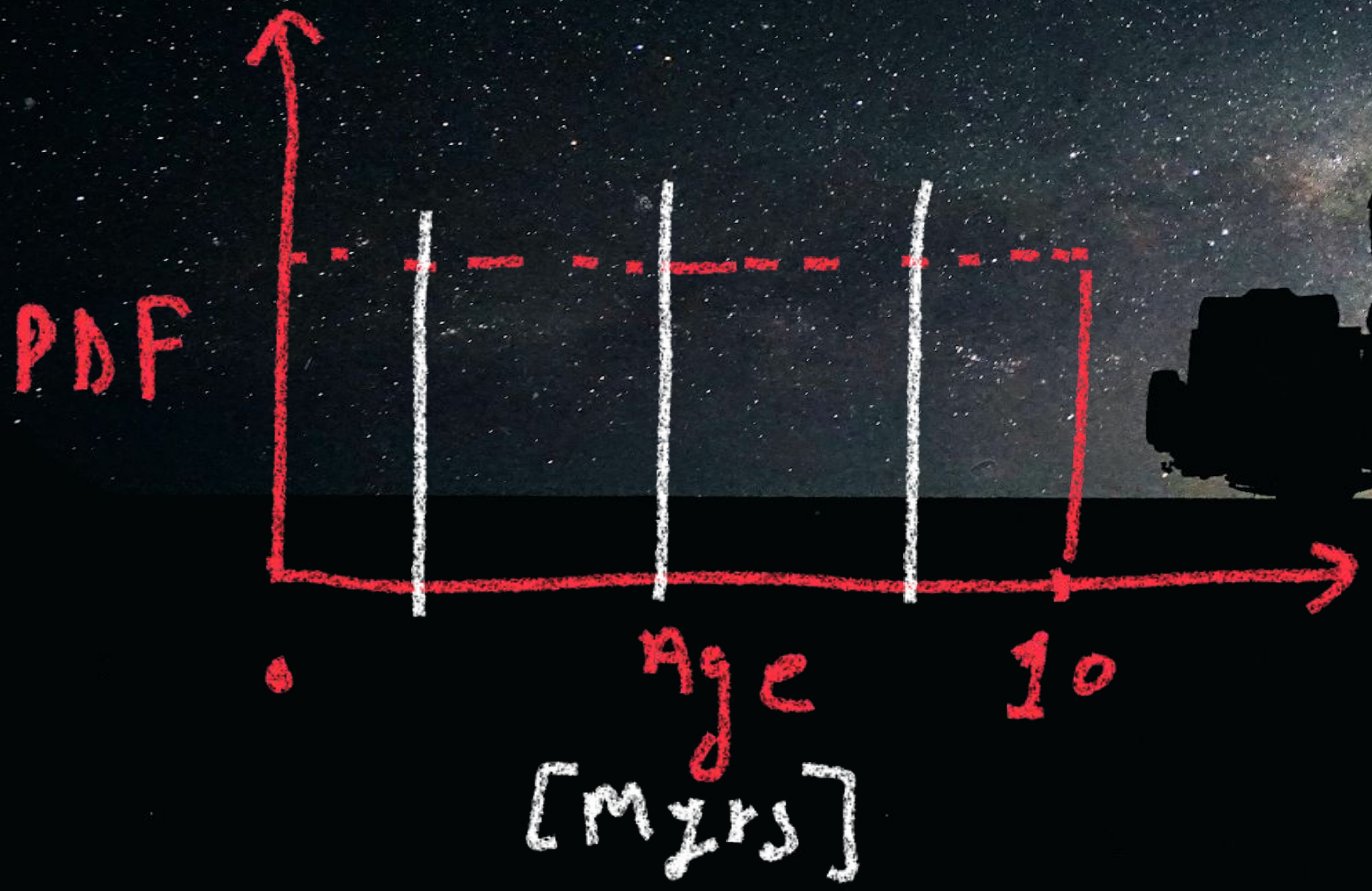


Figure: Top panel shows the metallicity values, relative to solar. And the bottom panel, the 16th - 84th percentile range of the same. (Arora et. al. 2020; under review).

Stochasticity (Results)

Having a random probability distribution.

- Stochasticity in time
  - We also found that stochasticity in time is actually more important for measuring metallicity values.



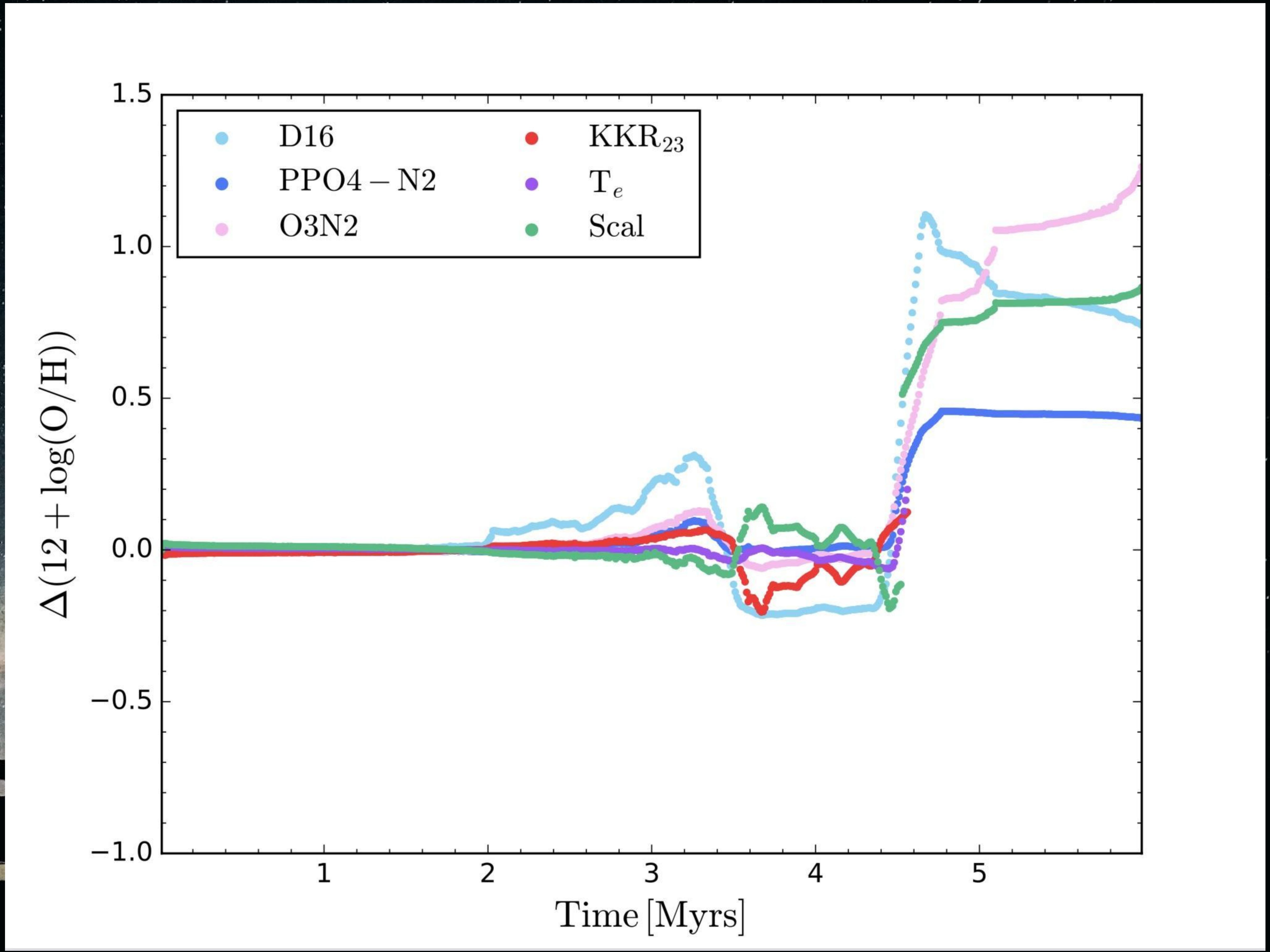


Figure: Evolution of a cluster that has a fully sampled IMF. (Arora et. al 2020; under review)

Summary

- Astronomy is a technology driven field, so we have to be on our toes for any new revisions that may be needed soon.

- Stochasticity: More resolution can sometimes come back to bite you in the ass.


Thats all folks!