Nanchong, China, June 12-16, 2006

Primordial vs. Dynamical Mass Segregation in Massive Star Clusters

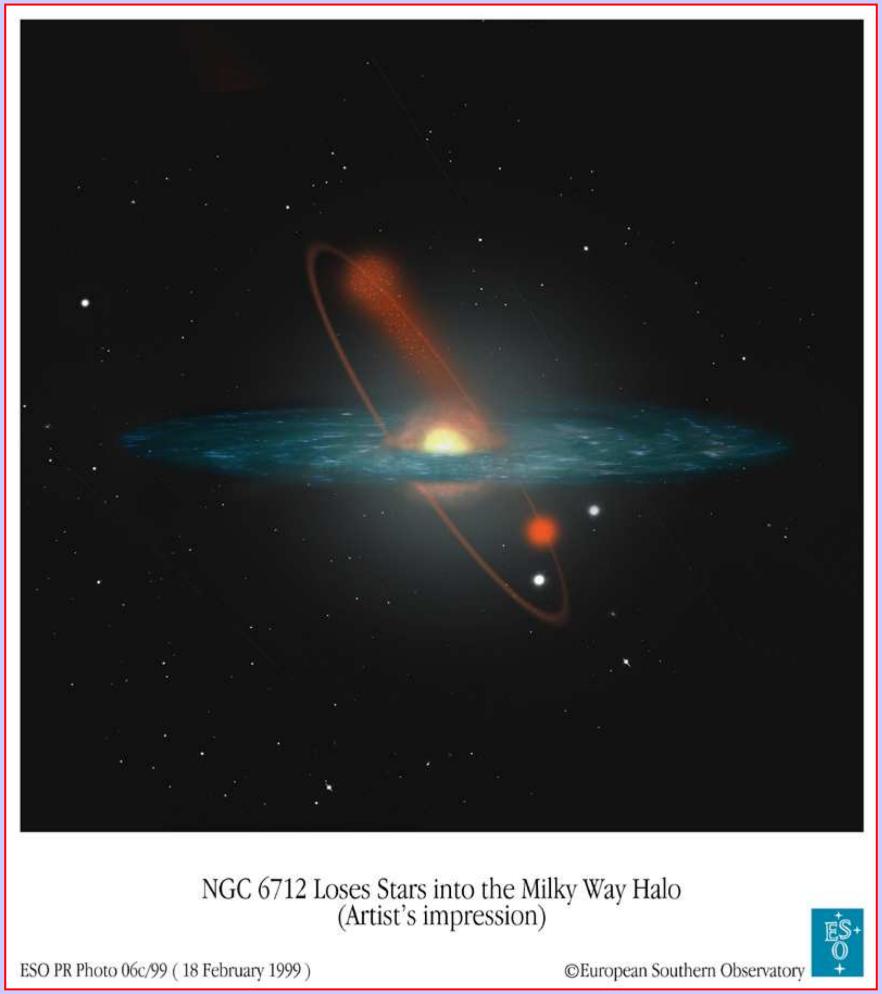
The Initial Mass Function of Old Globular Cluster Systems

Geneviève Parmentier(*) & Gerard Gilmore

(*) Intra-European *Marie Curie* Fellow

IoA UNIVERSITY OF CAMBRIDGE

- **Halo** GCs of the Milky Way: the oldest bound stellar structures, fossil records of the early Galactic evolution
- Massive stellar clusters ($M \cong [10^4\ M_o\ ,\ 10^6\ M_o]$)



Present-day mass distribution

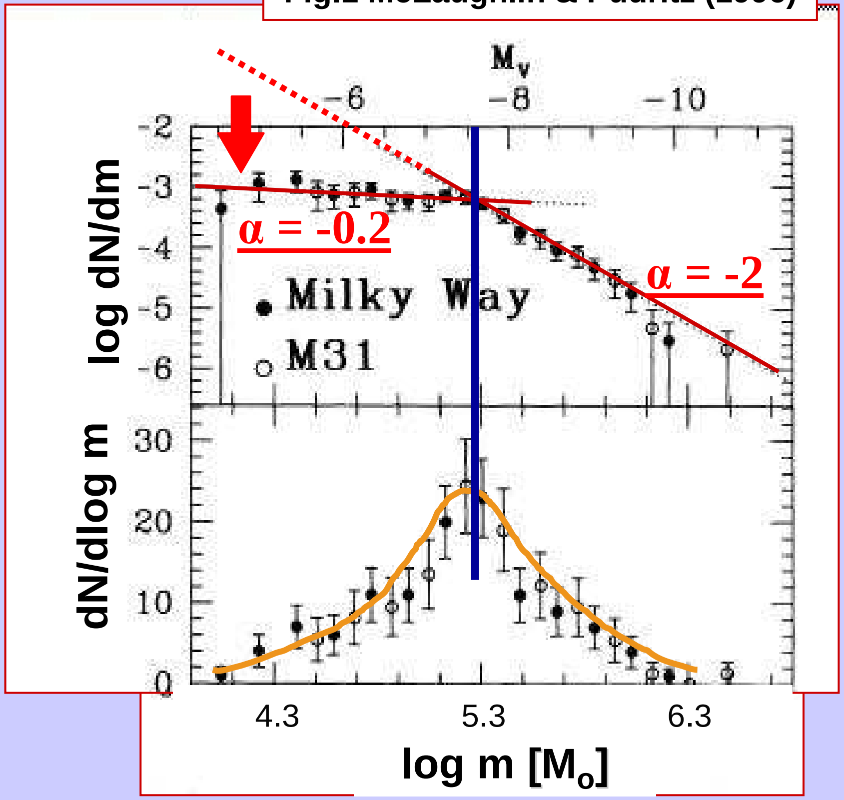
Mass Spectrum dN/dm

Two-index power-law

Mass Function dN/dlogm

Bell-shaped (Gaussian)

Fig.1 McLaughlin & Pudritz (1996)



Initial mass distribution ?

Hyp. 1: power-law dN/dm = k m^α (α = -2)

- Preferential removal of low-mass globular clusters (FZ01)

Hyp. 2: Gaussian dN/dlogm

- Gaussian = equilibrium state (Vesperini 1998)

Evolved and Observed OH GC Mass distributions

- **Constraints on P(SFE) ≡ P(ε): [δ, r_c]**

$$\bar{\varepsilon} = \frac{[M_{Halo}]_{init}}{[M_{Gas}]_{init}} = \frac{0.7^{-1}[M_{Halo}]_{13Gyr}}{[M_{Stars+Gas\ in\ MW}]_{13Gyr}} = 2.5\,\%$$

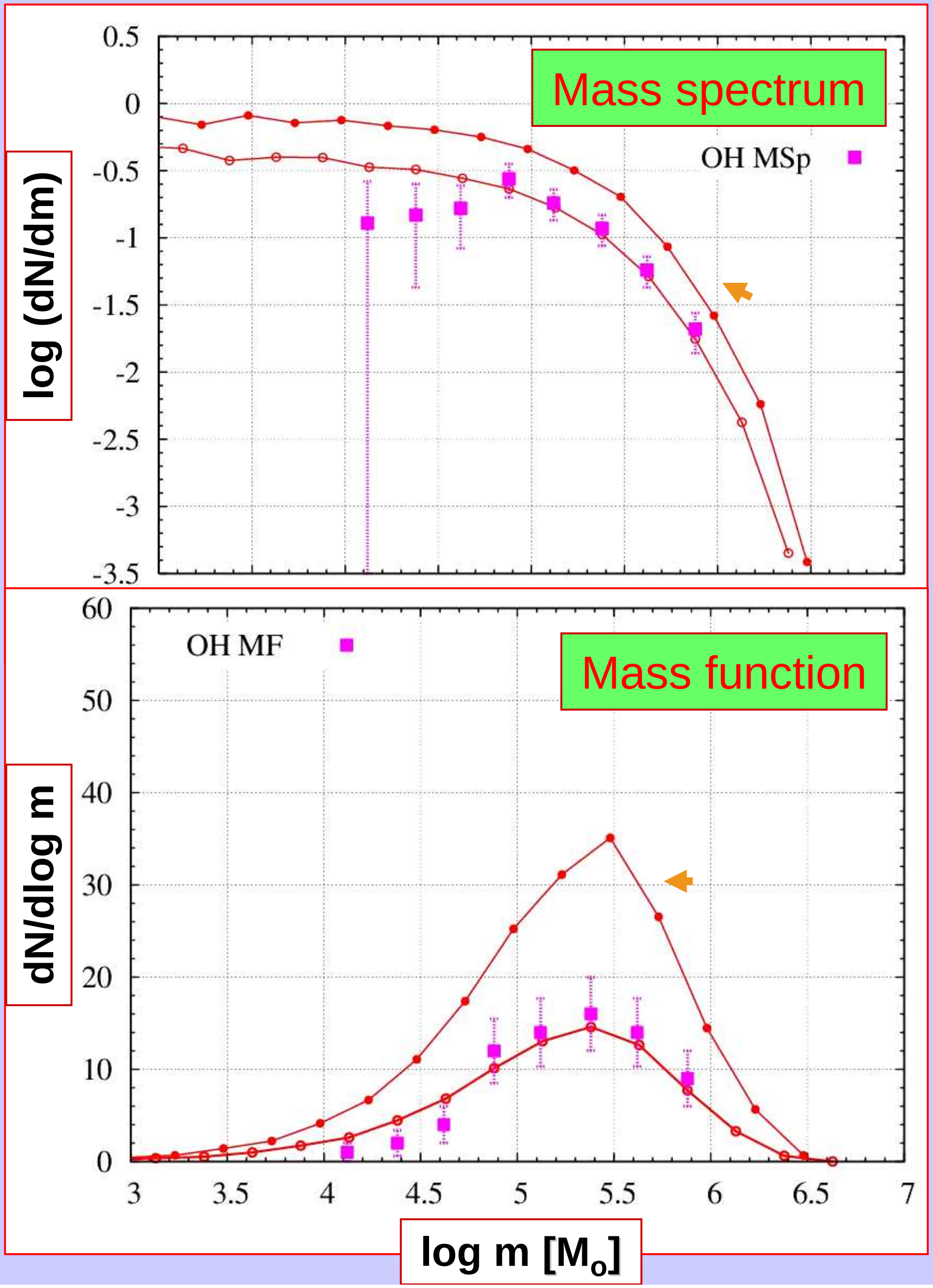
$$f_{GC} = \left[\frac{M^{tot}_{GC}}{M_{Halo}}\right]_{13Gyr} = 2\%$$

!! *Neglect later mergers*

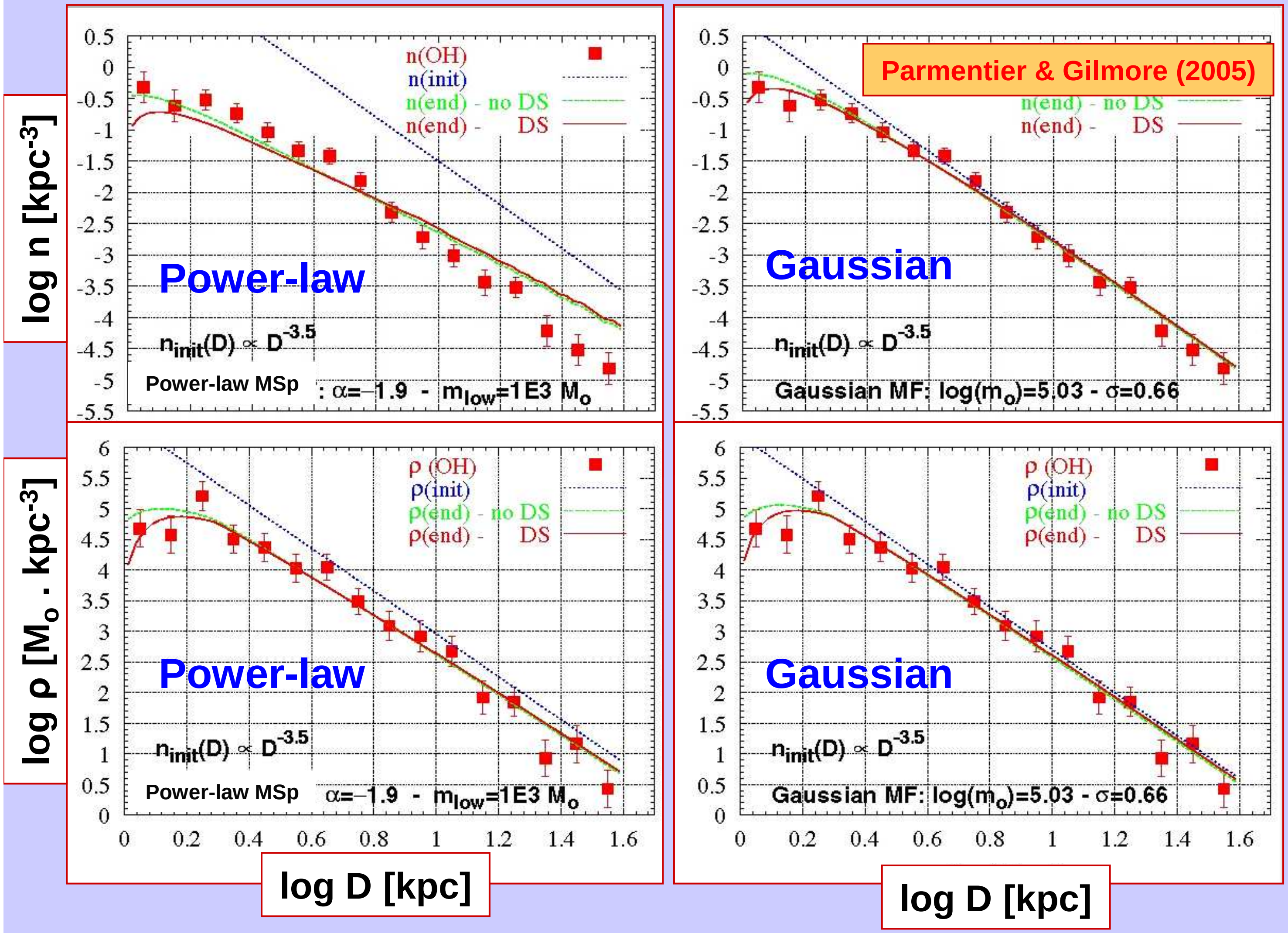
- **Good (Q ≅ 0.1) fit of the**

  OH GC mass function

  - δ = -2.9
  - r_c = 0.025
  - $m_{low} = 6 \times 10^5\ M_o$
  - $m_{up} = 5 \times 10^6\ M_o$



Evidence for a Gaussian cluster IMF in the Galactic Halo



n(D, 13 Gyr): depends sensitively on the GC IMF

ρ(D, 13 Gyr): well-preserved, irrespective of the GC IMF

Power-law GC IMSp: 10^3 - 10^4 M_o → $F_N = 0.85$, $F_M = 0.20$

Evidence for a Gaussian cluster IMF in M82 B

M82 B

- ≈ 50 1-Gyr old massive clusters
- MF: TO at $\log(m/M_o) \approx 5.15$

Power-law IMSp, $\alpha = -2$:

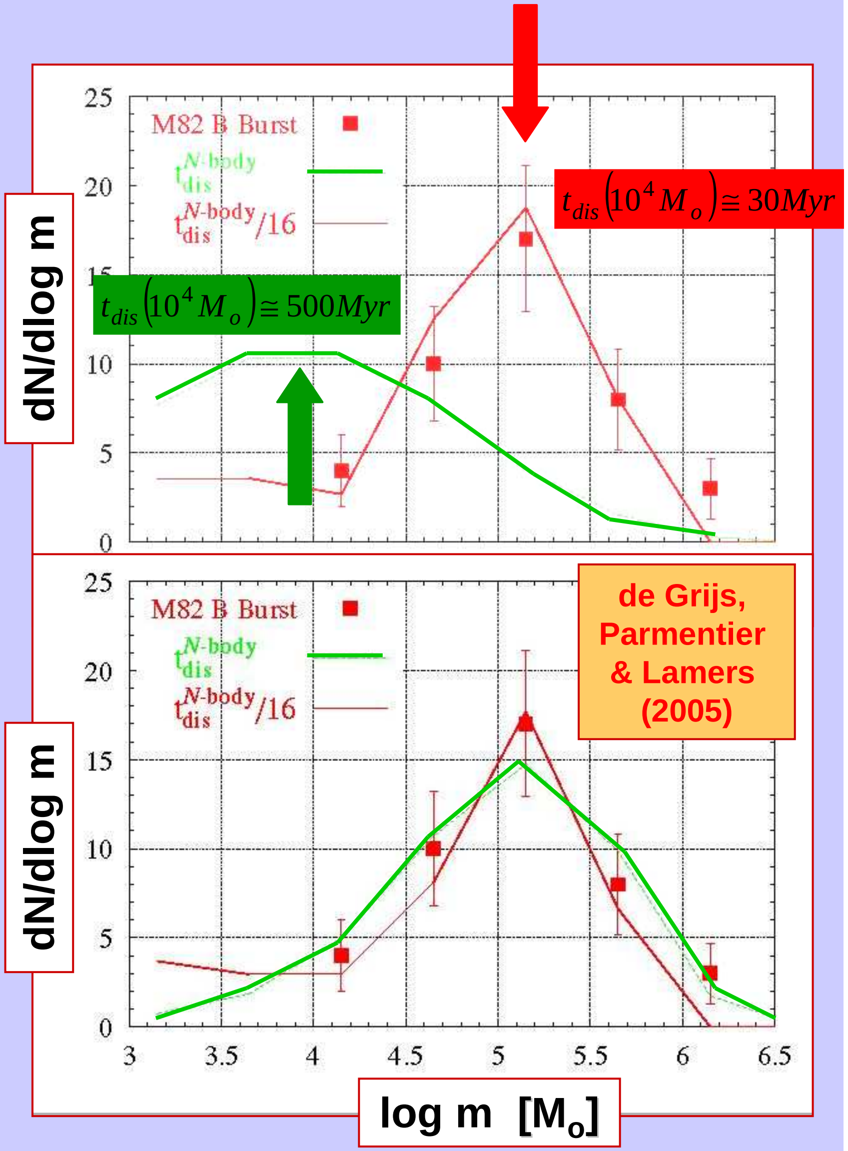
- de Grijs, Bastian & Lamers (03)

  TO at $\log(m/M_o) \approx 5.15$

- Baumgardt & Makino (03) (*N*-body simulations)

  TO at $\log(m/M_o) \approx 4.0$

- N^{init} = 80,000 clusters



Gaussian IMF: good job irrespective of t_{dis}

The cluster IMF and the gaseous progenitor MF

- Soon after star formation: removal of unprocessed gas by SNeII

→ weakens gravitational potential

→ escape of stars

- Hills (1980): SFE > 0.5 F_{bound} = 1

  SFE ≤ 0.5 F_{bound} = 0

$$0.5 m_{cloud} < m_{cluster}^{init} < m_{cloud}$$

cluster IMF ≈ cloud MF

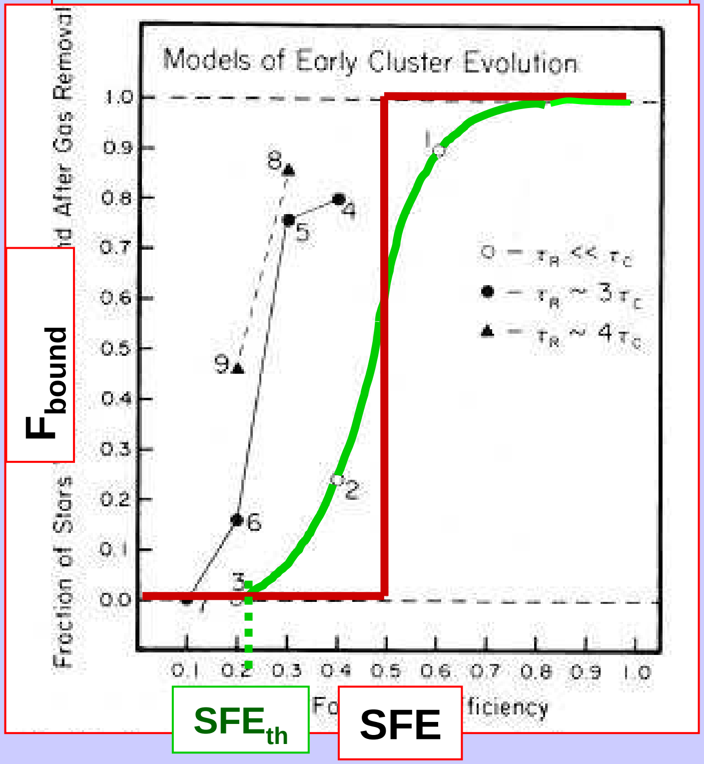
- Lada, Margulis & Deaborne (1984):

  F_{bound} (SFE) ≠ step function

$$m_{cluster}^{init} = F_{bound} \times SFE \times m_{cloud}$$

cluster IMF ≡ f(ranges of SFE and F_{bound}, cloud MF)

Fig.2 Lada, Margulis & Deaborne (1984)



Questions worth being investigated:

What is the contribution of

- $F_{bound} \times SFE$ variations to the shape of the cluster IMF ?
- the gas removal driven escape of stars to the field population ?

$$SFE < SFE_{th} \Rightarrow 1 \qquad \Rightarrow \text{infant mortality}$$
$$SFE \geq SFE_{th} \Rightarrow \left(1 - F_{bound}\right) \Rightarrow \text{infant weight-loss}$$
$$\Bigg\} \text{ Field stars}$$

?

Galactic stellar halo: $M_{Halo}^{tot} = 10^9\,\mathrm{M_o} = M_{FS}^{tot}(98\%) + M_{GC}^{tot}(2\%)$

- Overwhelming contribution of FSs does not arise from the evaporation+disruption of GCs over a Hubble-time
- Yet, star formation operates mostly in a clustered mode

Steps of the model:

- **Cloud mass distribution:**

  Power-law mass spectra $\frac{dN}{dm} \propto m^{\alpha}$ with

  α = [-2.5, -2, -1.5], as is observed for the GMCs in the LG

- **Star formation:**

  Not all clouds are subjected to the same SFE

  → Probability distribution for the SFE $P(SFE) = P(\varepsilon) = \frac{dN}{d\varepsilon}$

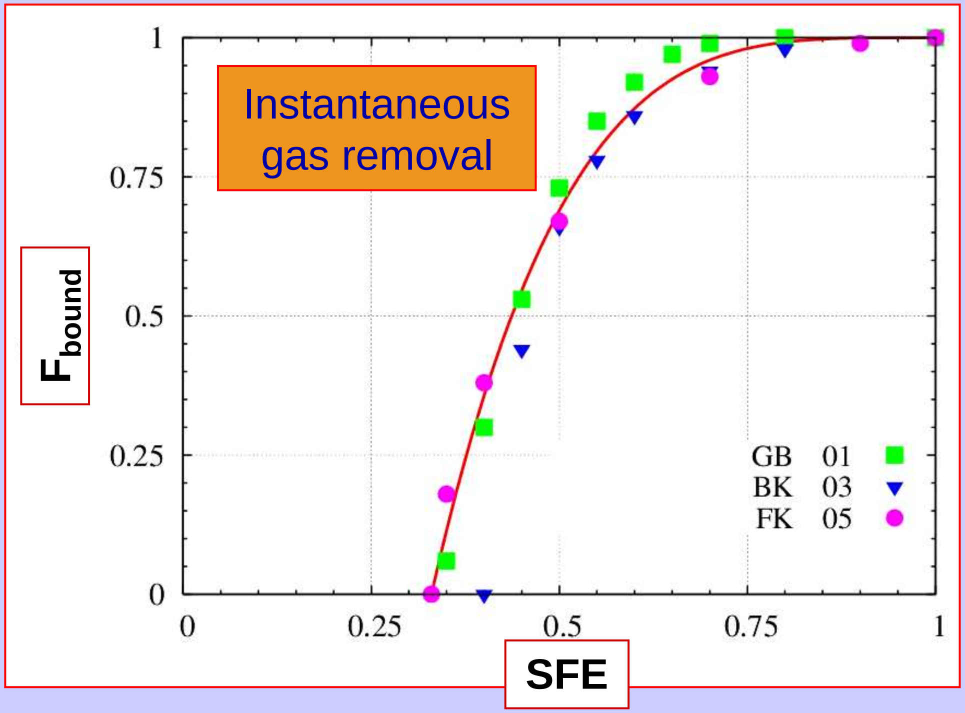
  = decreasing power-law

  $(\text{slope}\ \delta, \text{core}\ \text{r}_c)$ such that $\overline{SFE} = 1\%$

■ Gas removal impact: F_{bound} (SFE)

SFE
= fraction of gas ending up in stars

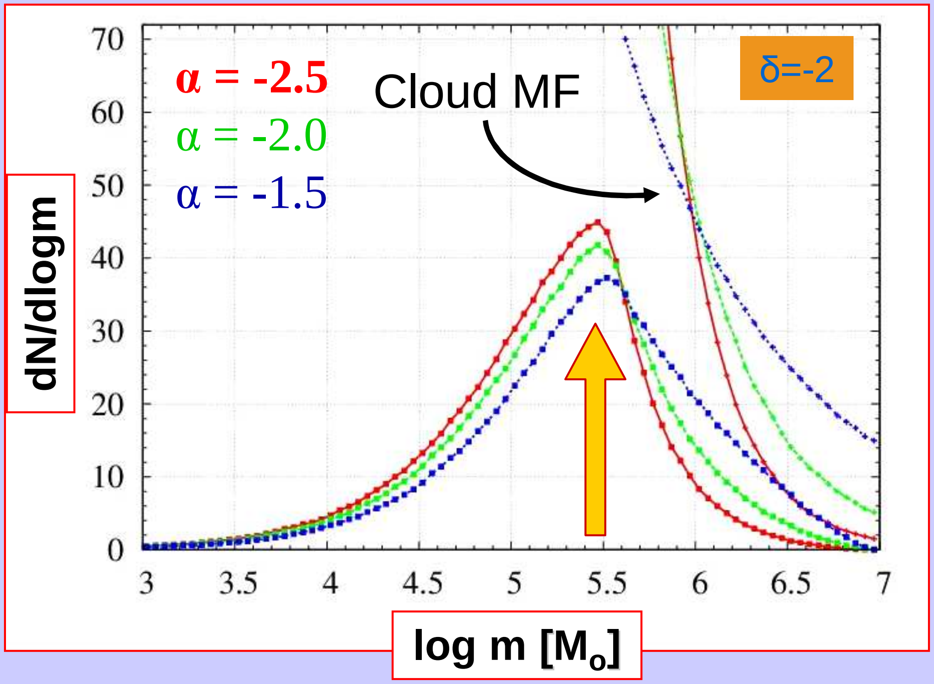
F_{bound}
= fraction of stars remaining bound to the cluster after gas removal

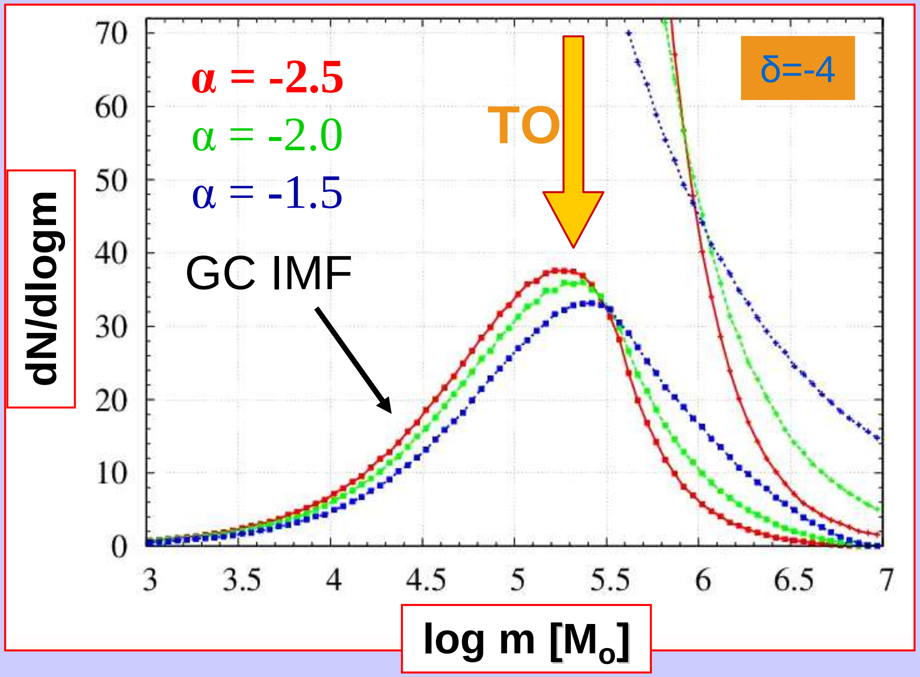


■ The GC Initial Mass Function is then derived from

$$m_{GC}^{init} = F_{bound} \times SFE \times m_{cloud}$$

- Cloud mass range: 4E5 – 1E7 M_o (Jeans' mass range)
- P(SFE): power-laws with slopes δ = -2 and δ = -4





- Bell-shaped GC IMF: memory of the cloud MF is lost

A bell-shaped GC IMF results from the GC formation process, even though the cloud mass function is a featureless power-law

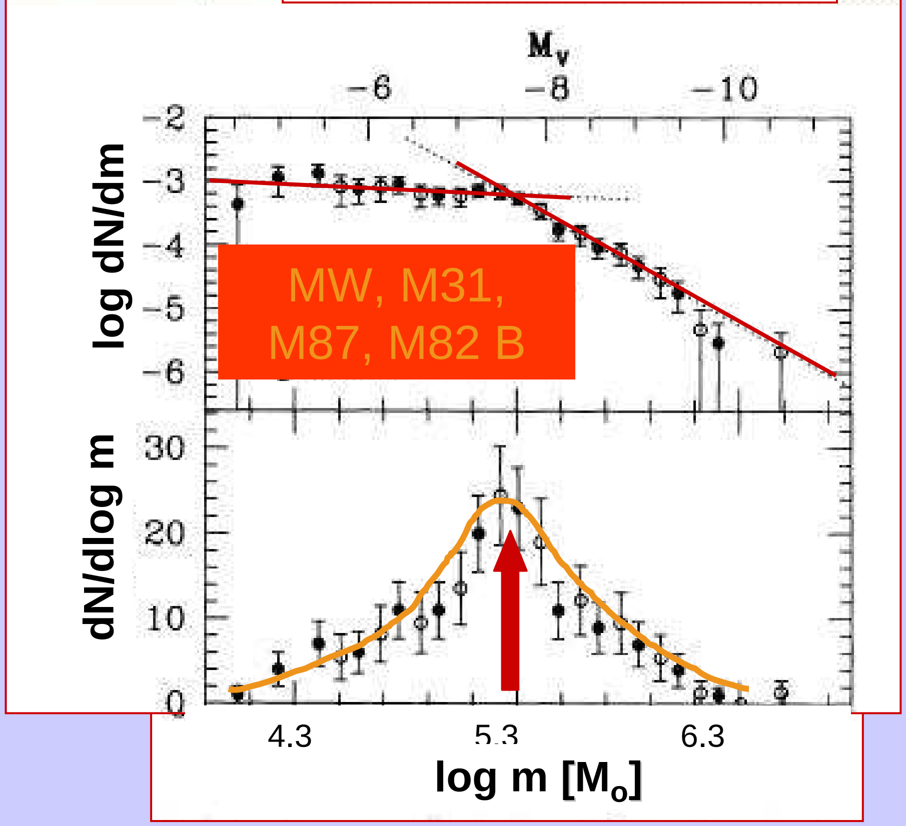
A long-standing issue:
The universality of the GC MF turnover

- **The observations:**

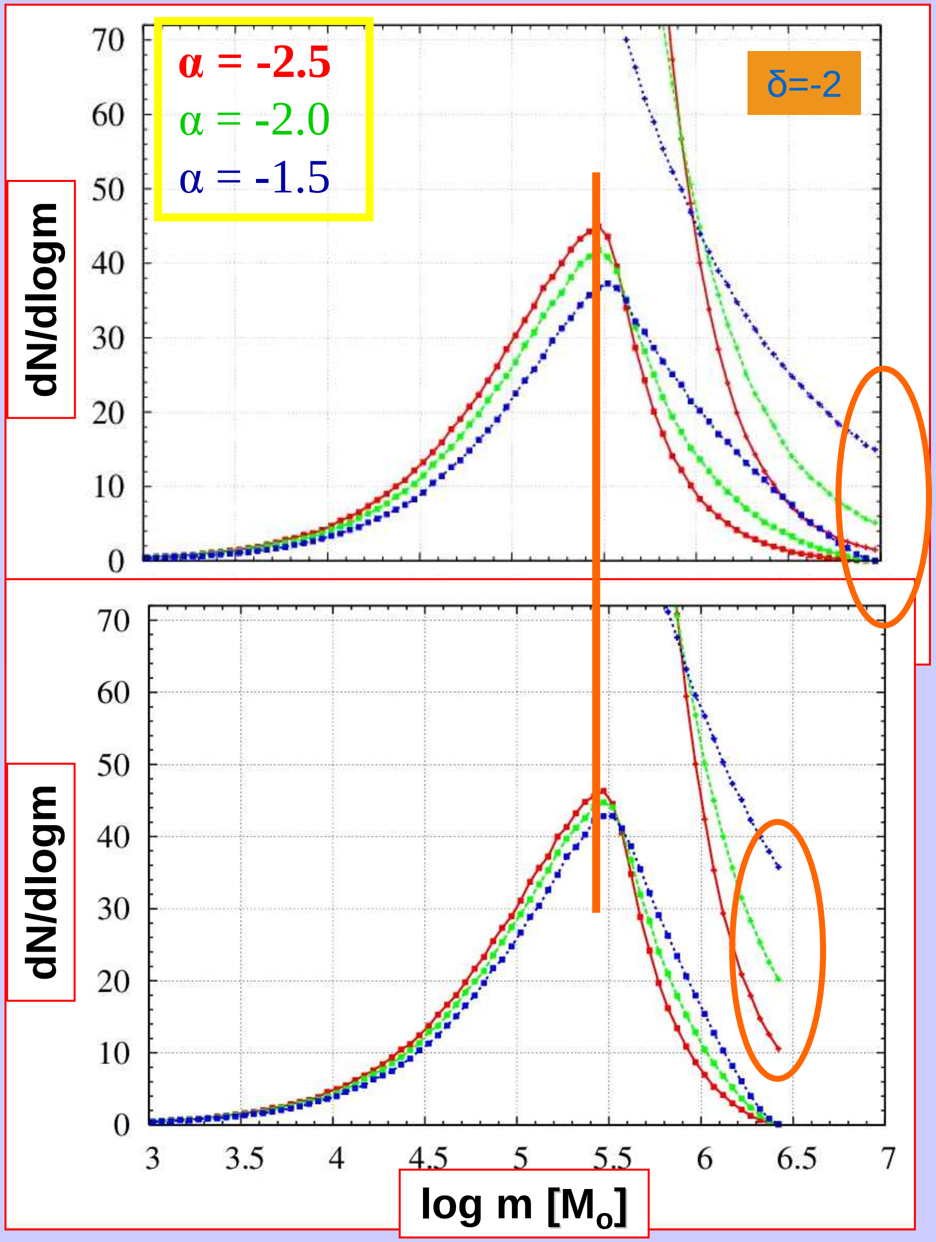
  the GC mass at the TO is almost universal

- *IF* the GC IMF is bell-shaped/Gaussian, then the TO universality is a fossil imprint of the cluster formation process

Fig.1 McLaughlin & Pudritz (1996)



What does the GC IMF turnover depend on ?

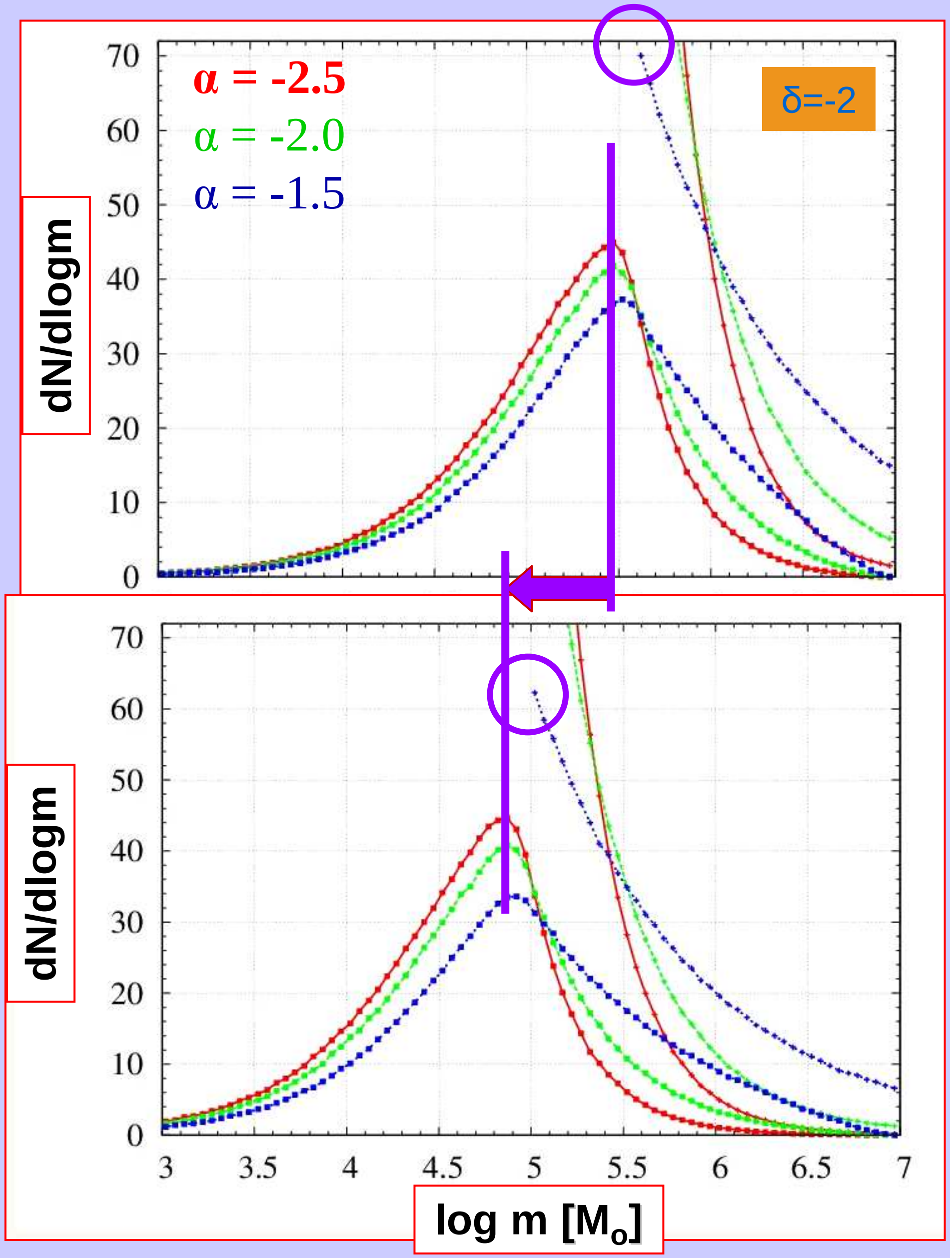


$$m_{GC}^{init} = F_{bound} \times SFE \times m_{cloud}$$

[3] [2] [1]

[1]
- Spectral index **α** of cloud MF,
- Upper limit of cloud mass range

What does the GC IMF turnover depend on ?

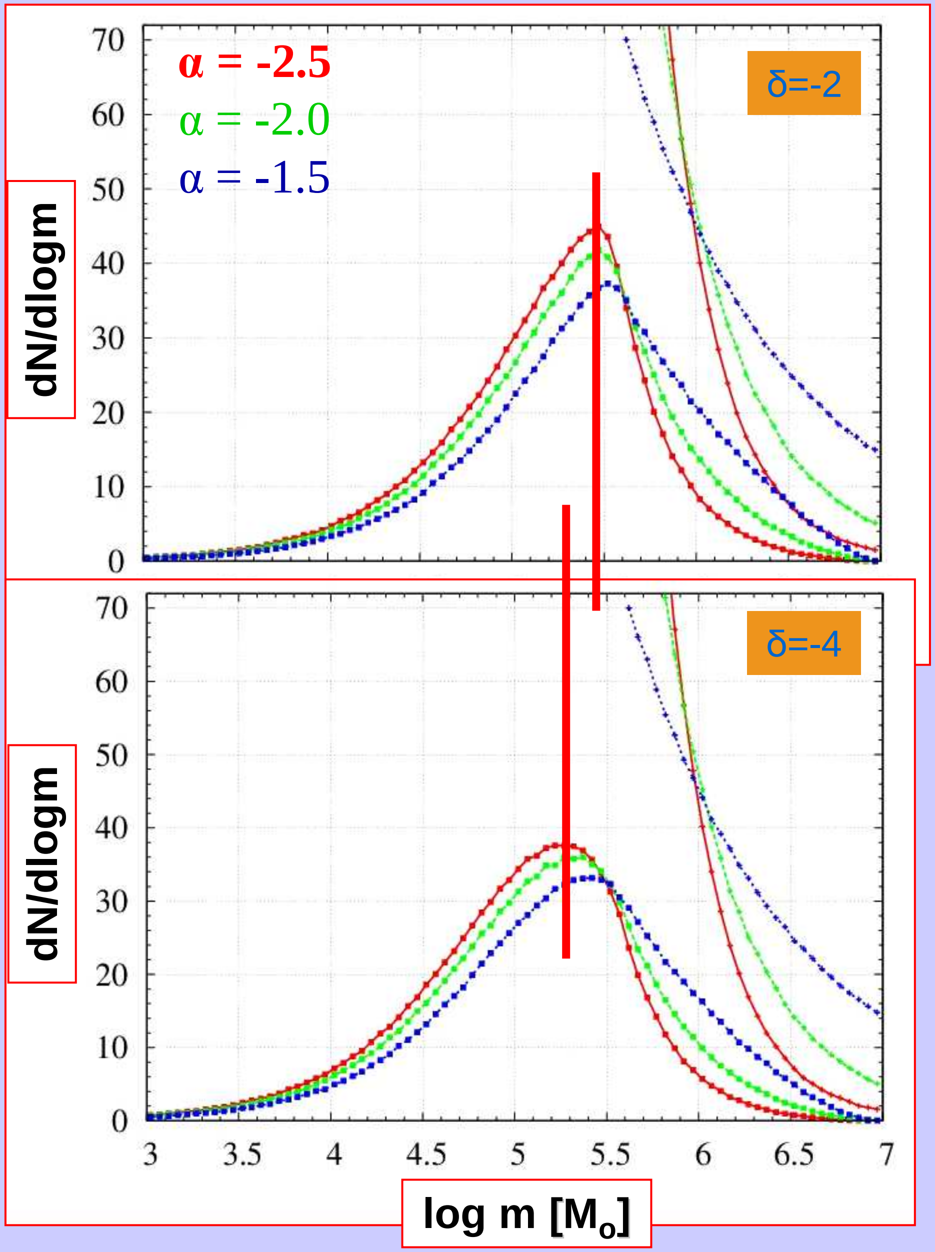


$$m_{GC}^{init} = F_{bound} \times SFE \times m_{cloud}$$

[3] [2] [1]

[1]
- Spectral index **α** of cloud MF,
- Upper limit of cloud mass range,
- Lower limit of cloud mass range,

What does the GC IMF turnover depend on ?



$$m_{GC}^{init} = F_{bound} \times SFE \times m_{cloud}$$

[3] [2] [1]

[1] Spectral index **α** of cloud MF,

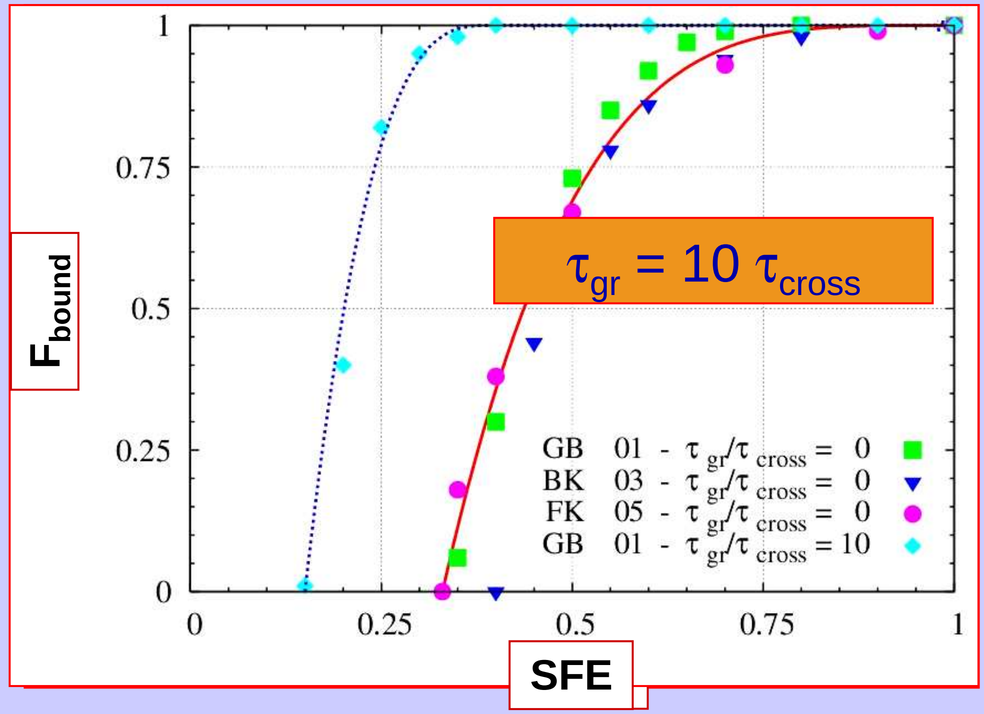
- Upper limit of cloud mass range,
- Lower limit of cloud mass range,

[2] Slope δ of the P(SFE),

■ Impact of a slower gas removal: F_{bound} (SFE)

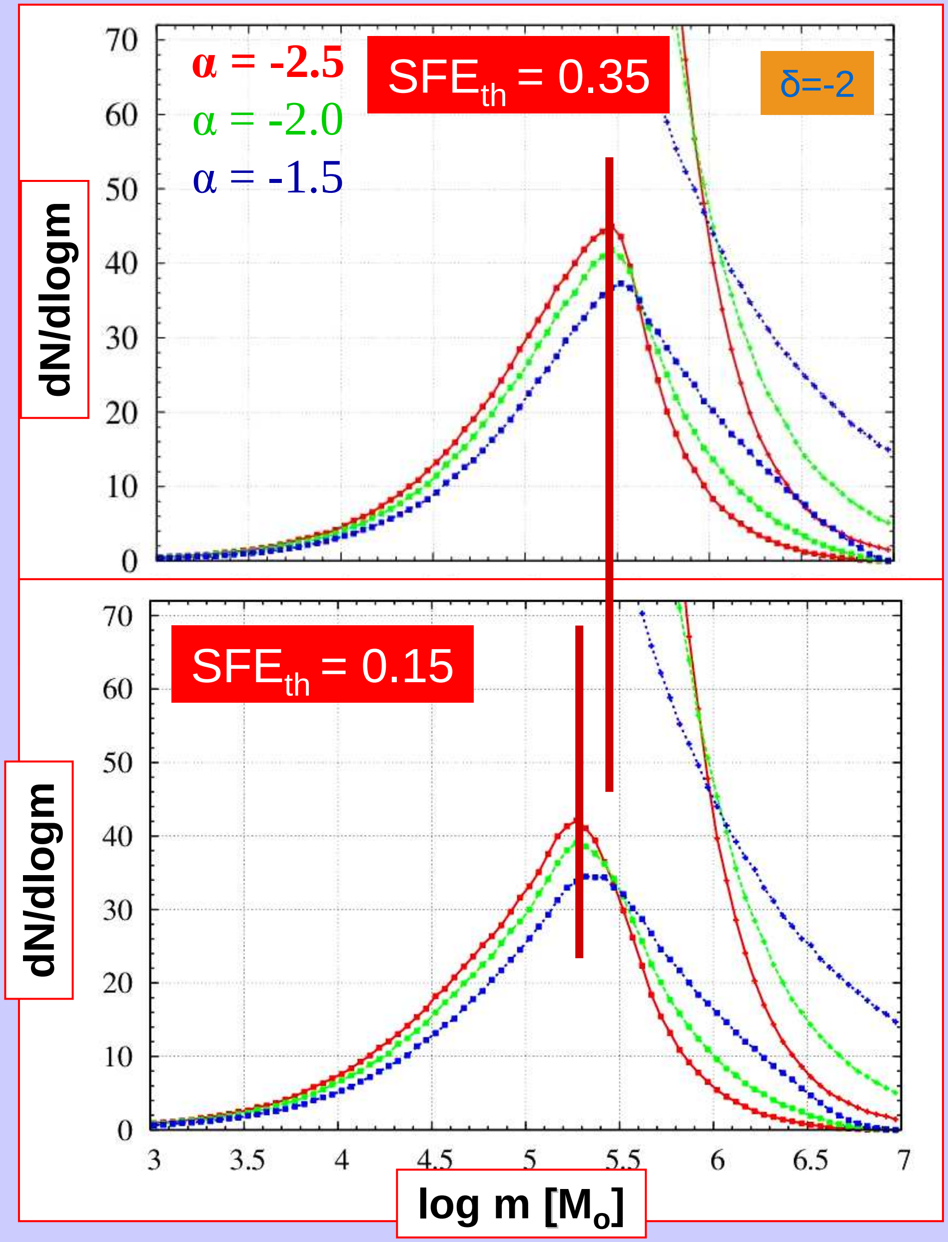
SFE
= fraction of gas ending up in stars

F_{bound}
= fraction of stars remaining bound to the cluster after gas removal



- Smaller SFE threshold: $SFE_{th} \cong 15\%$
- Larger **F_{bound}** for a given **SFE**

What does the GC IMF turnover depend on ?



$$m_{GC}^{init} = F_{bound} \times SFE \times m_{cloud}$$

[3] [2] [1]

[1] ■ Spectral index **α** of cloud MF,

■ Upper limit of cloud mass range,

■ Lower limit of cloud mass range,

[2] ■ Slope δ of the P(SFE),

[3] ■ SFE threshold

Fitting the Galactic Old Halo GC Mass Function

Evolving the GC Initial Mass Function over a Hubble-Time

BM03 ´s model: **$m_{GC}(t)$ [m_{GC}^{init}, D_{GC}]** ,

which requires:

- a cluster initial spatial distribution:
  - $n_{init}(D)$ scales as $D^{-3.5}$
  - Circular orbits (ellipticity through **0.5** T_{diss})
- a cluster initial mass function:
  - provided by this protocluster gas removal model
    - Cloud mass spectrum: **α = -1.7**
    - Instantaneous gas removal: **SFE_{th} = 0.33**
    - 4 free parameters:
    - Cloud mass range: **[m_{low}, m_{up}]**
    - Slope and core of P(SFE): **[δ, r_c]**

Evolved and Observed OH GC Mass distributions

- **Constraints on P(SFE) ≡ P(ε): [δ, r_c]**

$$\bar{\varepsilon} = \frac{[M_{Halo}]_{init}}{[M_{Gas}]_{init}} = \frac{0.7^{-1}[M_{Halo}]_{13Gyr}}{[M_{Stars+Gas\ in\ MW}]_{13Gyr}} = 2.5\,\%$$

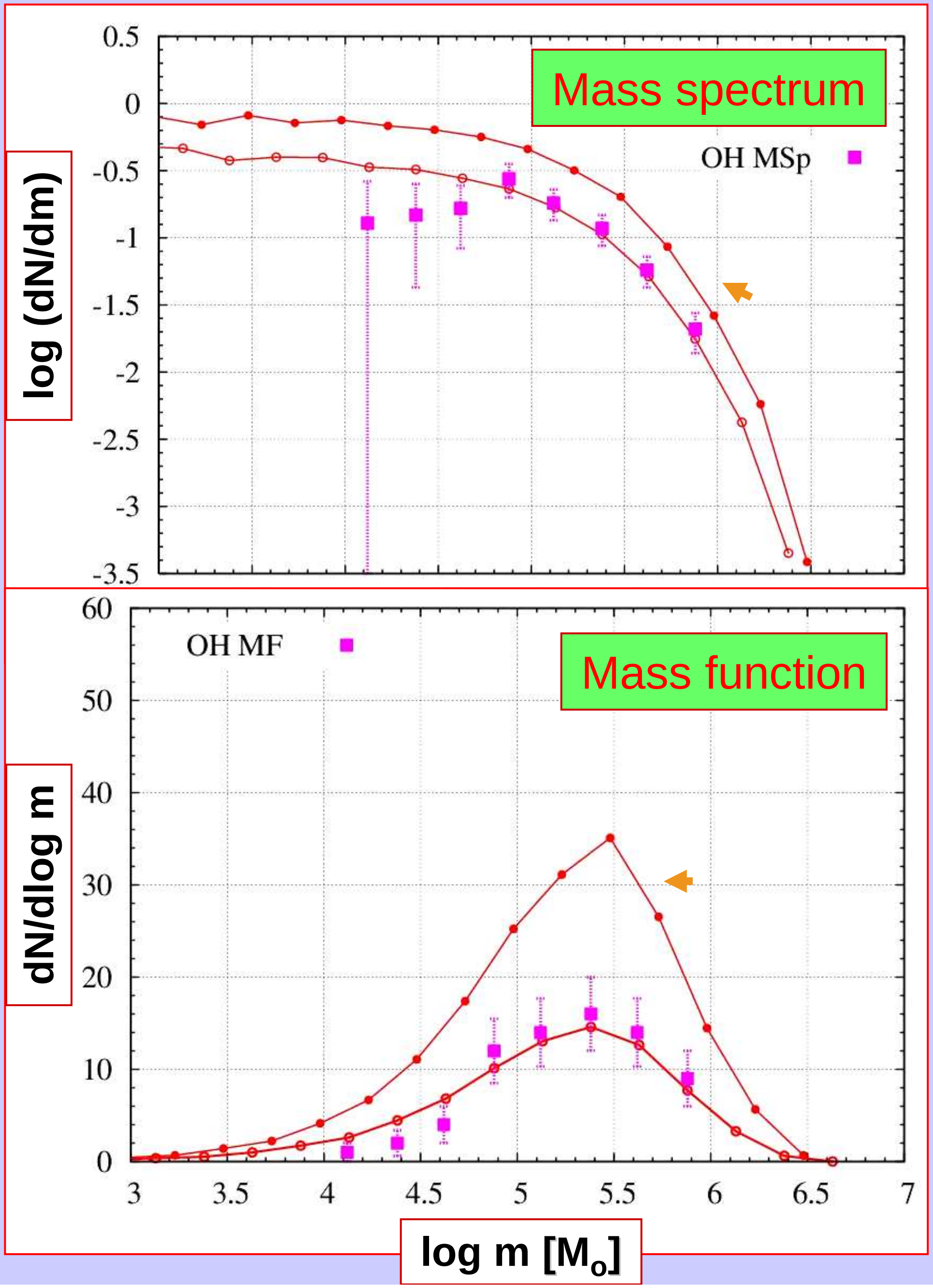
$$f_{GC} = \left[\frac{M_{GC}^{tot}}{M_{Halo}}\right]_{13Gyr} = 2\%$$

!! *Neglect later mergers*

- **Good (Q ≅ 0.1) fit of the**

  OH GC mass function

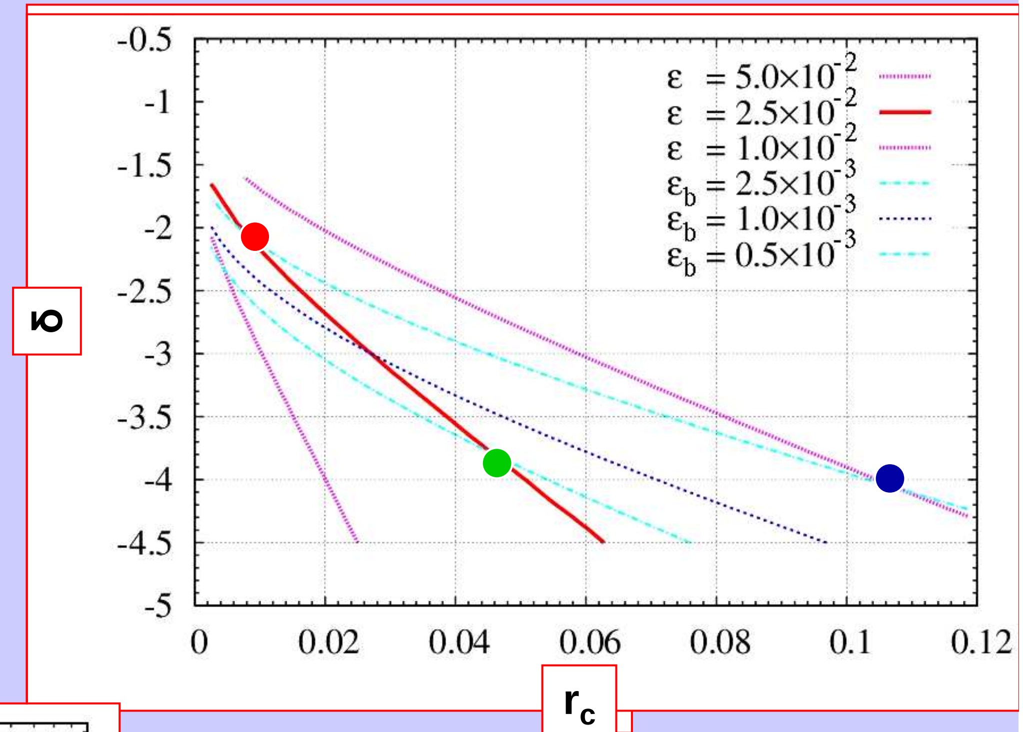
  § δ = -2.9
  § r_c = 0.025
  § m_{low} = 6 × 10^5 M_o
  § m_{up} = 5 × 10^6 M_o

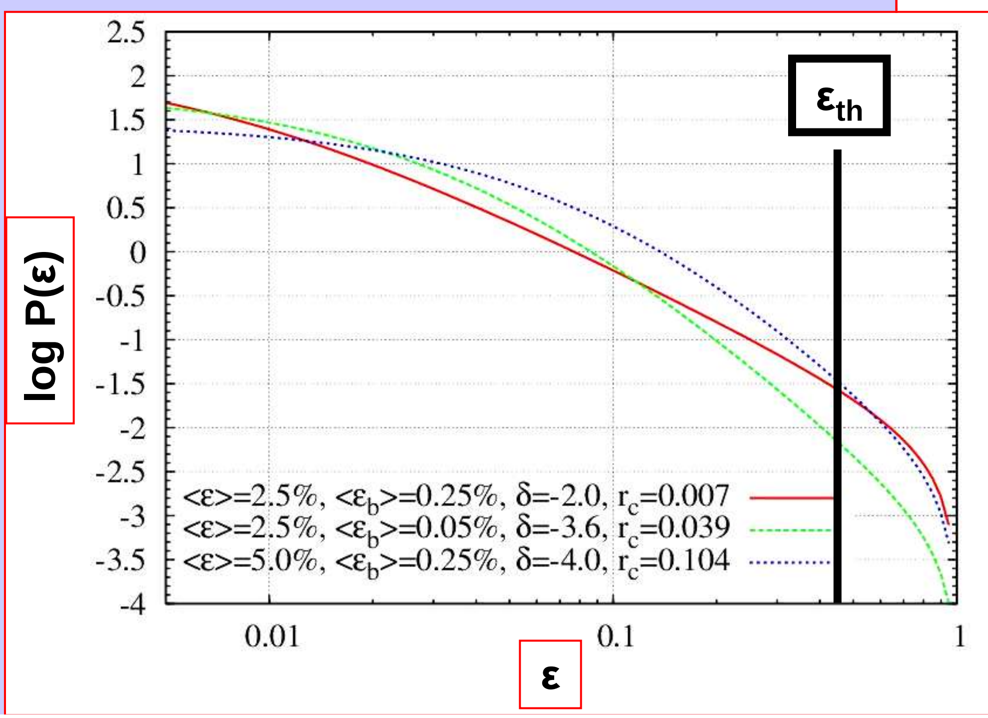


Obtaining the parameters can be done this way (I):

- First estimate of P(SFE)

$$\bar{\varepsilon} \ \text{and} \ \bar{\varepsilon}_b \ \Leftrightarrow \ [\delta, r_c]$$





$$\bar{\varepsilon} = \int_0^1 \varepsilon \, \mathrm{d}N(\varepsilon)$$

$= \text{fract. of gas ending up in stars}$

$$\bar{\varepsilon}_b = \int_{\varepsilon_{th}}^1 [\varepsilon \times F_{bound}(\varepsilon)] \, \mathrm{d}N(\varepsilon)$$

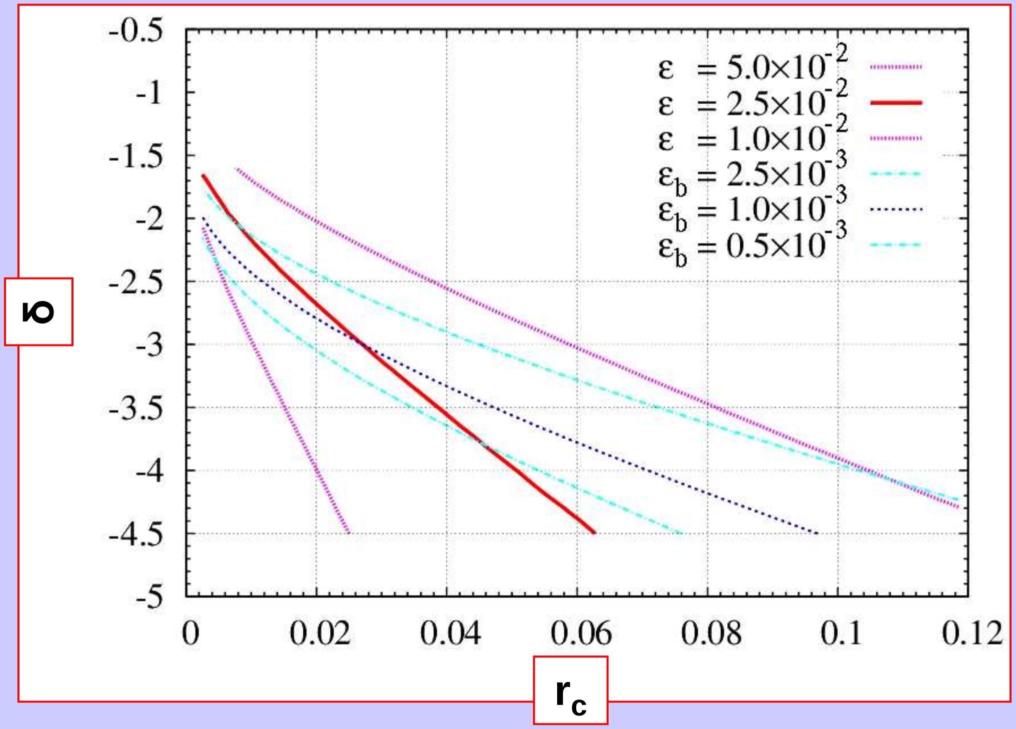
$= \text{fract. of gas ending up in}$ *clustered* stars

Obtaining the parameters can be done this way (II):

$\bar{\varepsilon}$ and $\bar{\varepsilon}_b \Leftrightarrow [\delta, r_c]$

$\bar{\varepsilon} = 2.5\%$ ——

$$f_{GC} = \frac{M_{GC}^{tot}}{M_{Halo}} = 2\%$$



$$f_{GC} = \frac{\left[M_{GC}^{tot}\right]_{13Gyr}}{\left[M_{Halo}\right]_{13Gyr}} = \frac{F_M \times \left[M_{GC}^{tot}\right]_{init}}{0.7 \times \left[M_{Halo}\right]_{init}}$$

$$= \frac{F_M \times \bar{\varepsilon}_b \times \left[M_{Gas}\right]_{init}}{0.7 \times \bar{\varepsilon} \times \left[M_{Gas}\right]_{init}} = \frac{F_M \times \bar{\varepsilon}_b}{0.7 \times \bar{\varepsilon}}$$

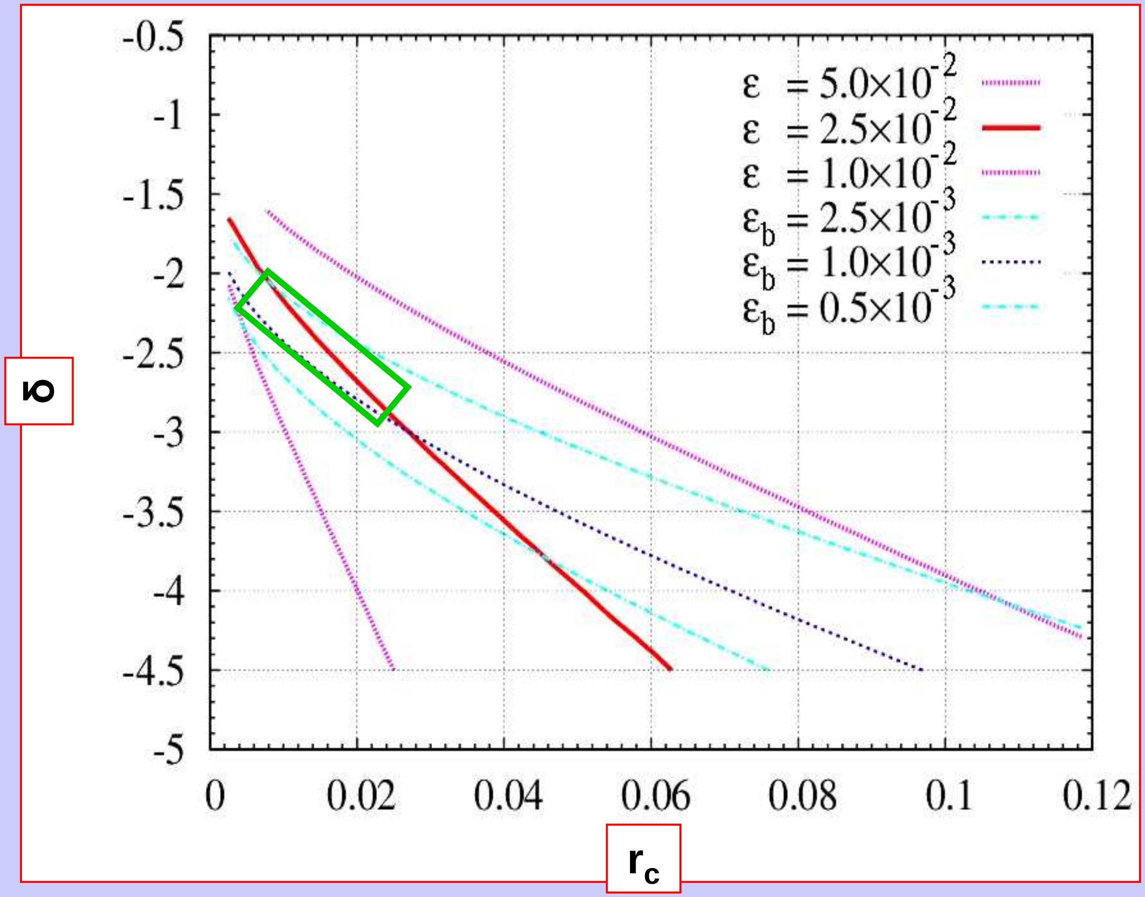
$$f_{GC} = \frac{F_M \times \bar{\varepsilon}_b}{0.7 \times \bar{\varepsilon}}$$

F_M = ? Depends on:

- cluster IMF,
- spatial distribution,
- age and T_{diss}

F_M : st., int. + ext. dyn. evolutions
0.7: stellar evolution

Obtaining the parameters can be done this way (III):



Extreme values of F_M:

- "Low"-mass clusters
  - $m_{low} = 2 \times 10^5\ M_o$
  - $m_{up} = 1 \times 10^6\ M_o$
  - $\delta = -4$
  - → **$F_M = 0.13$**
- "High"-mass clusters
  - $m_{low} = 1 \times 10^6\ M_o$
  - $m_{up} = 1 \times 10^7\ M_o$
  - $\delta = -1.5$
  - → **$F_M = 0.31$**

$$f_{GC} = \frac{F_M \times \bar{\varepsilon}_b}{0.7 \times \bar{\varepsilon}}$$

$\Rightarrow [1.1 \leq \bar{\varepsilon}_b \leq 2.8] \times 10^{-3}$

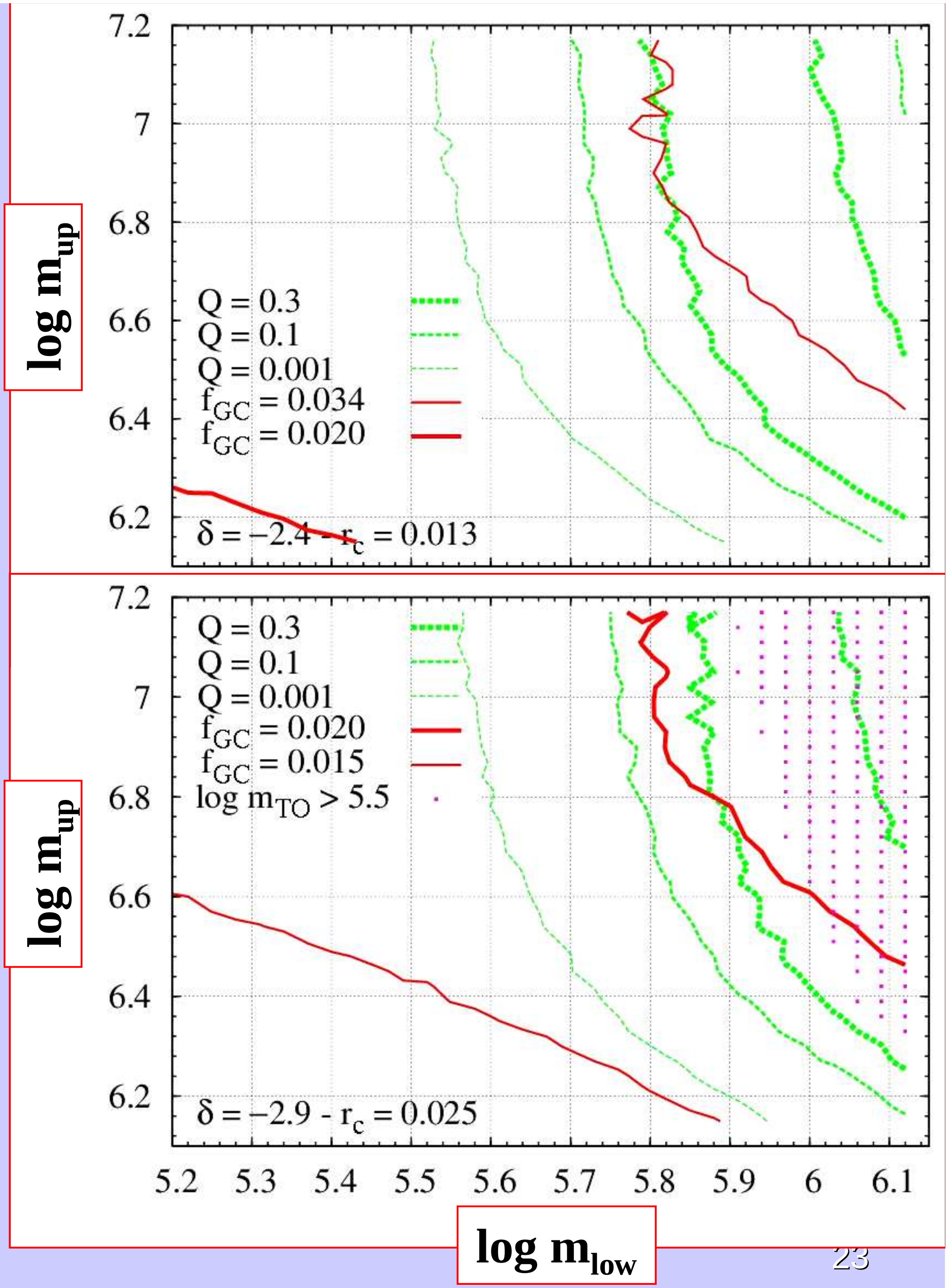
$\Rightarrow$ intervals of permitted values of $[\delta, r_c]$

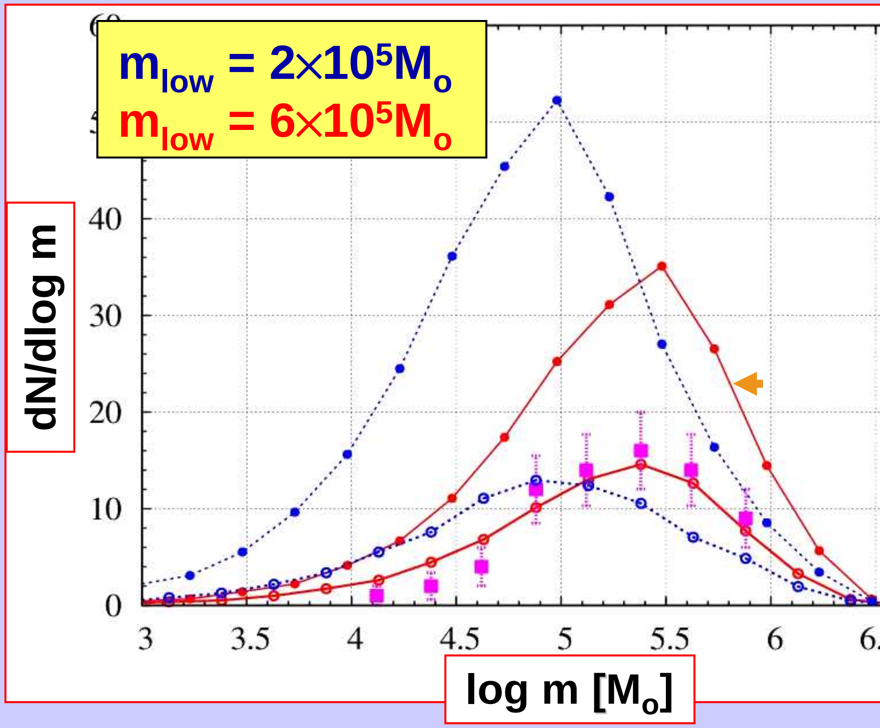
$\Rightarrow \delta \in [-2.8, -2] \quad \Rightarrow \delta_{init} = -2.4,\ r_c = 0.013$

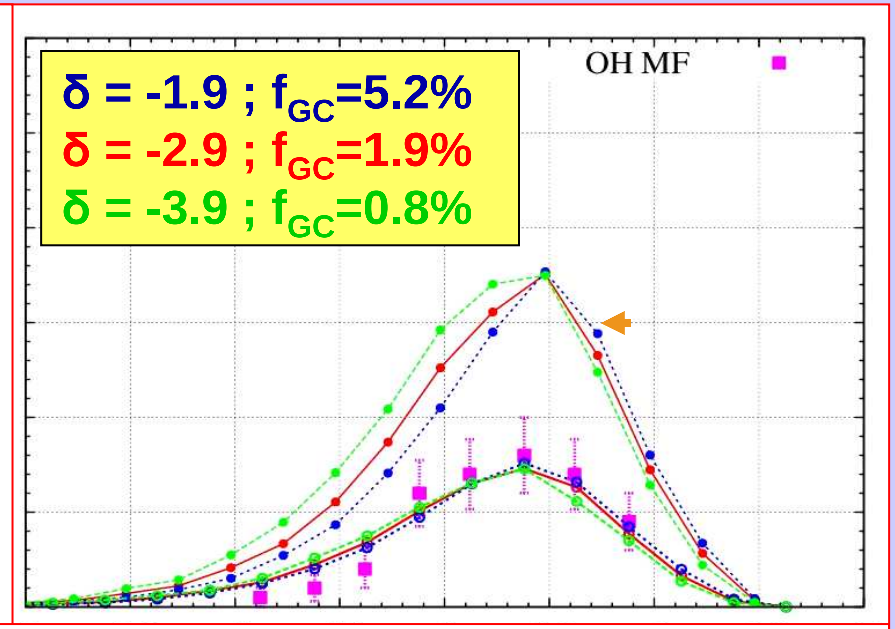
- With this first estimate of **P(SFE)**, run simulations for a grid of **[m_{low},m_{up}]**, i.e., for each couple [m_{low},m_{up}]:
  - Compute GC IMF
  - Evolve it over 13 Gyr
  - Compare with its observed counterpart
  - Compute **f_{GC}**
- **Iso-Q** and **iso-f_{GC}** curves in [log m_{low}, log m_{up}] plane
- f_{GC} too large

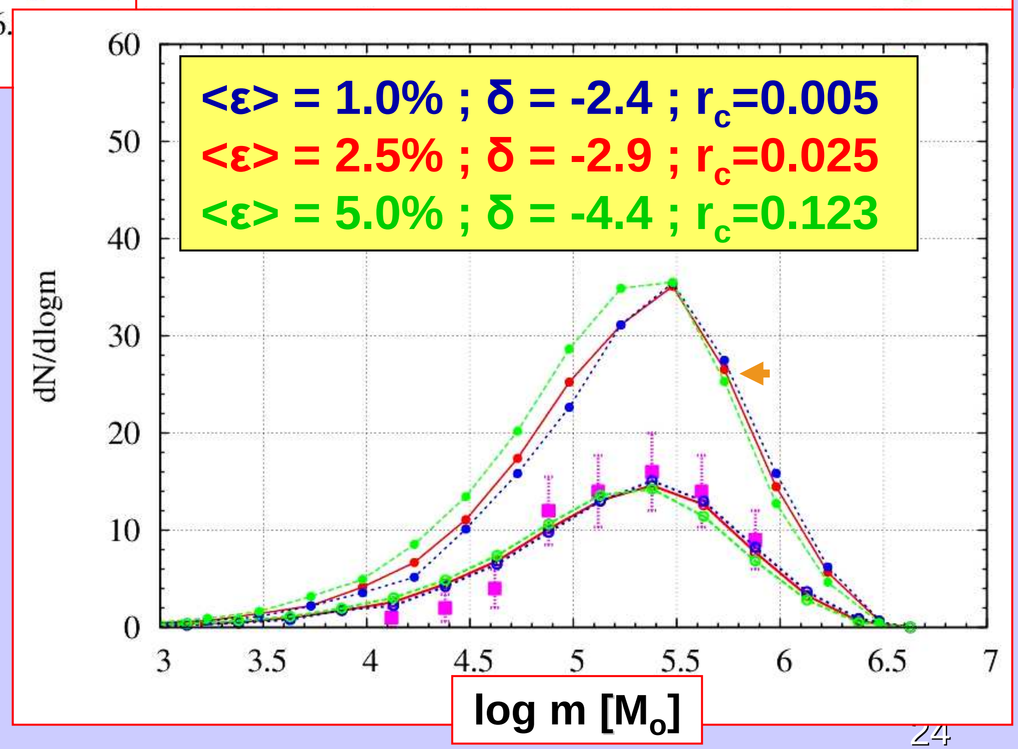
  → δ smaller, P(SFE) steeper
  → δ = -2.9:
  $\bar{\varepsilon}_b$ decreased by one third

(GC IMF not much dependent on δ
→ F_M and iso-Q curves not much affected
→ one iteration only)









Main driving parameter of the predicted GC MF at an age of 13Gyr: the cloud mass range, shape of P(SFE) is secondary.

The upper limit m_{up} of the cloud mass range and the MF substructures in the high mass regime (I)

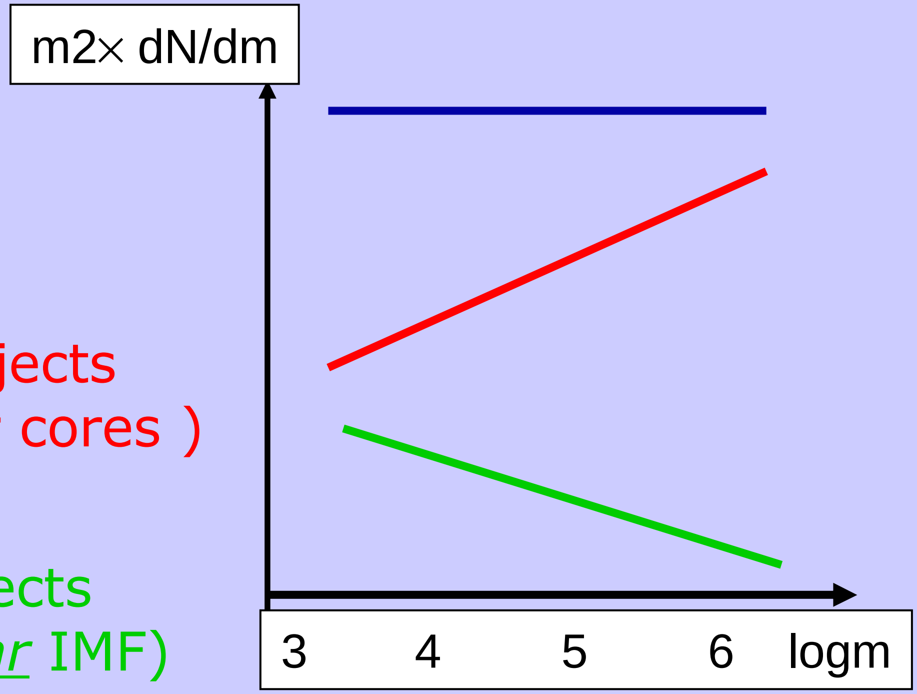
- the **mass-weighted mass function** (MWMF)

$$m^2 \frac{dN}{dm} \propto m \frac{dN}{d \log m}$$

Describes how the total mass of a population of objects is distributed between the high- and low-mass members of the population

$$\text{e.g., MSp}: \quad \frac{dN}{dm} \propto m^{\alpha}$$

- $\alpha = -2.0$
  → MWMF flat
- $\alpha > -2$
  → most mass in high-mass objects
  (e.g. $\alpha = -1.7$: GMCs and their cores)
- $\alpha < -2$
  → most mass in low-mass objects
  (e.g. $\alpha = -2.35$: Salpeter *stellar* IMF)

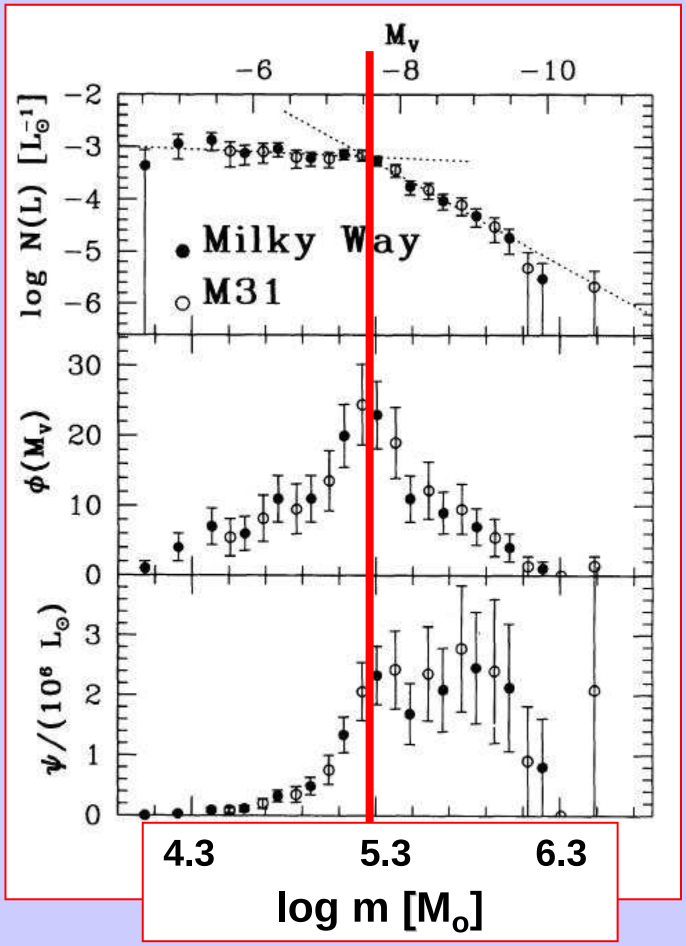


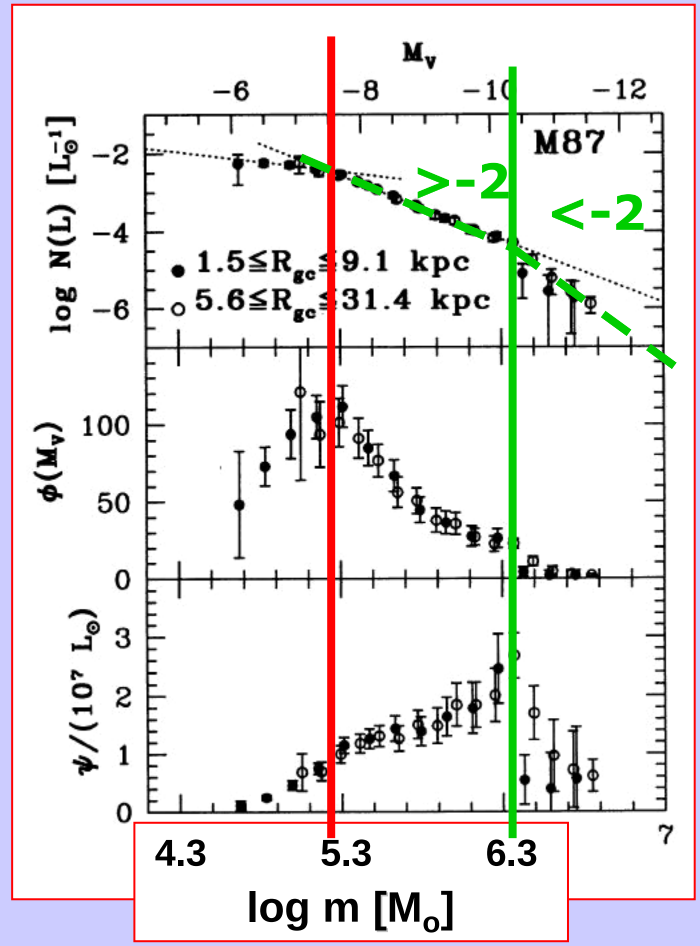
The upper limit m_{up} of the cloud mass range and the MF substructures in the high mass regime (II)

Mass spectrum

Mass function

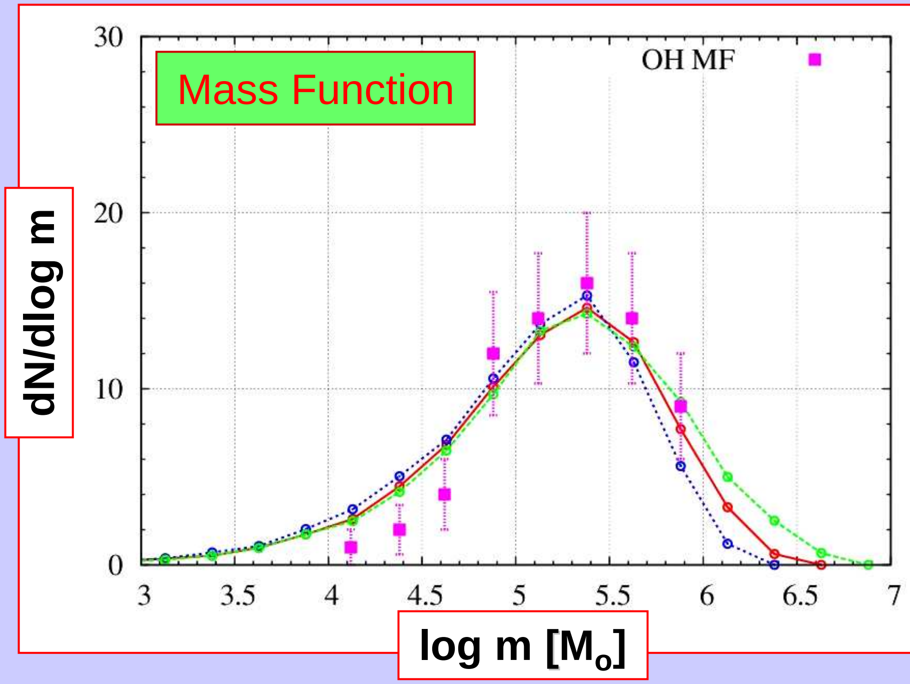
Mass-weighted mass function

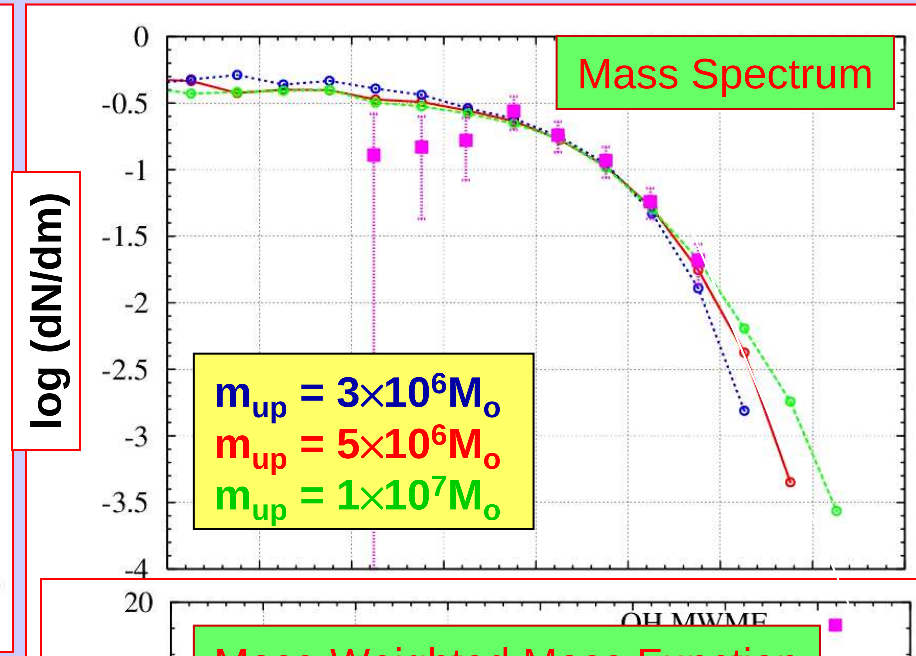


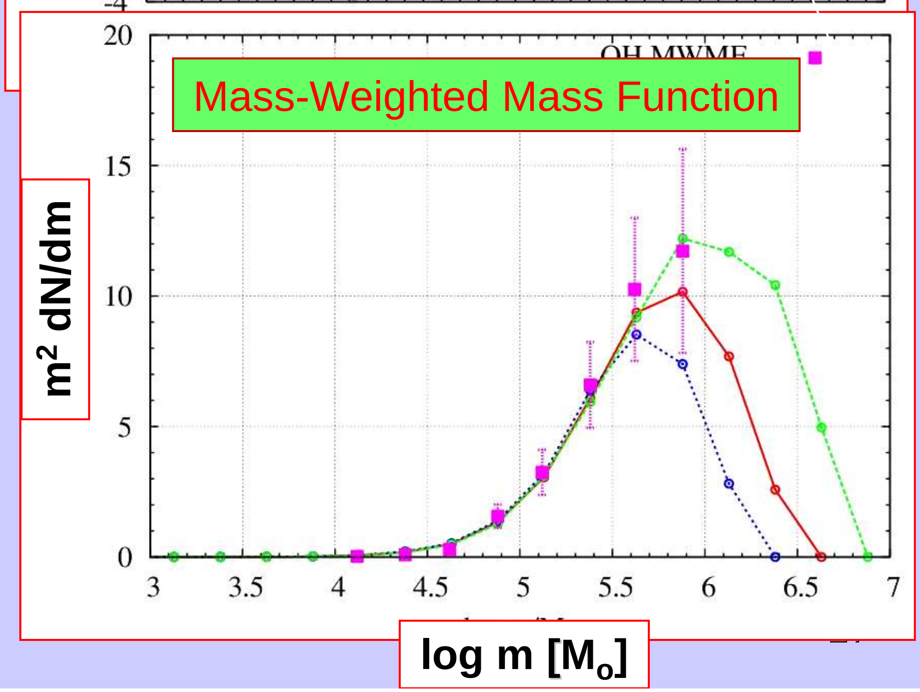


McLaughlin & Pudritz (1996): the cluster mass at the turnover is practically universal, but the shape of the MF beyond the turnover varies within galaxies, as highlighted by the MWMF.
The cluster mass at the MWMF peak varies from one galaxy to another.

The upper limit m_{up} of the cloud mass range and the MF substructures in the high mass regime (III)







m_{up} drives:

- **peak location of MWMF**
- **slope of MSp beyond TO**

m_{up}:

- **does not affect the TO location significantly**

The upper limit m_{up} of the cloud mass range and the MF substructures in the high mass regime (IV)

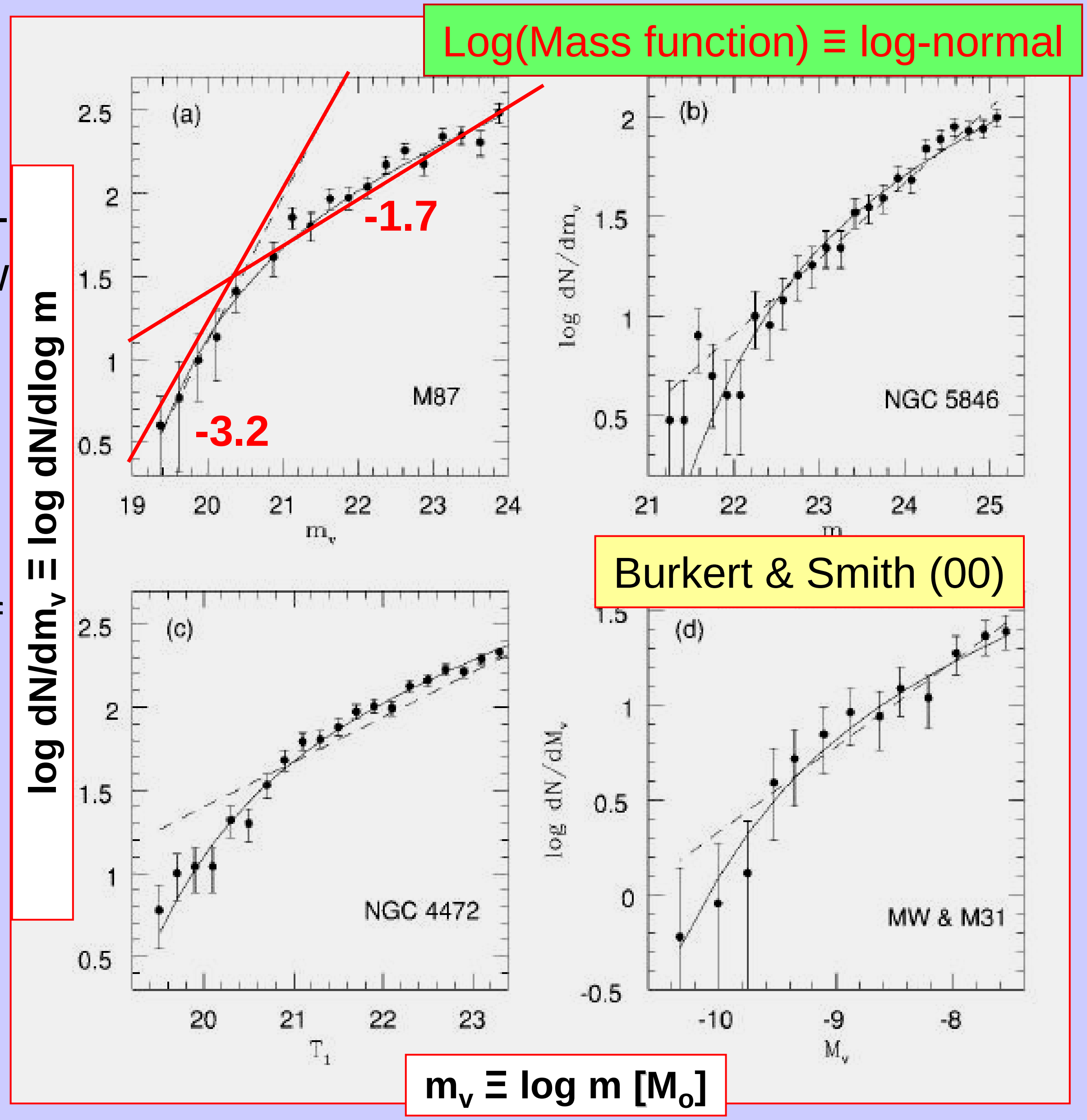
McLaughlin & Pudritz (96)

- the upper mass spectrum of GCSs in ellipticals is not well-fitted by a single power-law; double-index power-law required (e.g. M87)

Burkert & Smith (00):

- a power-law having an exponential cutoff at high masses (i.e. beyond a cutoff mass, the mass spectrum drops off more steeply than a pure power-law) matches well the clear curvature evident in the figure

$$\frac{dN}{dm} \propto m^{-3/2} e^{-m/m_c}$$

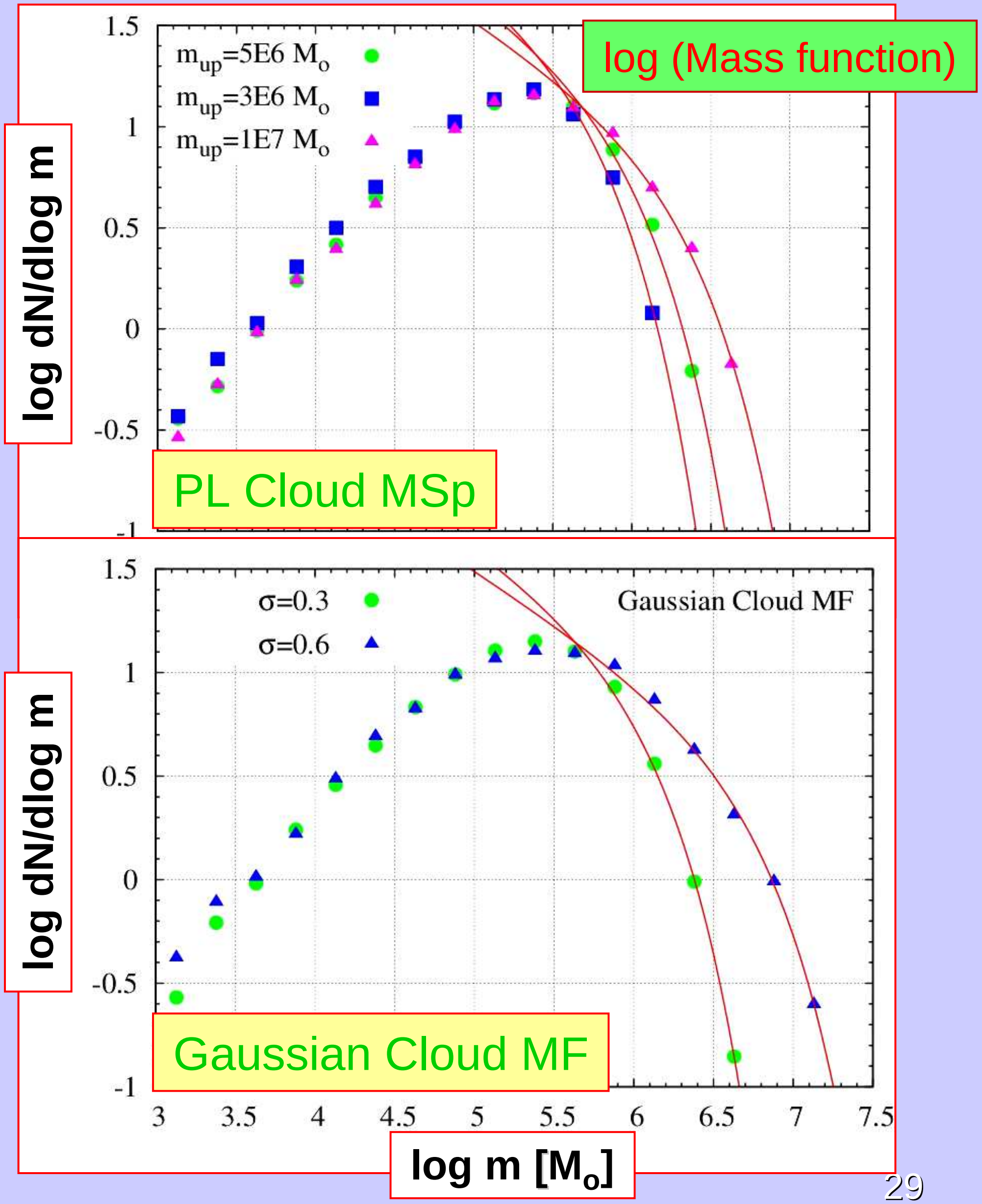


The upper limit m_{up} of the cloud mass range and the MF substructures in the high mass regime (V)

- Does our model obey to the functional form introduced by Burkert & Smith (00) to fit the GC mass distributions of elliptical galaxies ? **YES**

- It would thus be worth testing the model on the more populous GCSs of giant ellipticals, where the observed cluster mass distribution can be probed to higher GC mass.

Note:
Gaussian cloud MF:
see slide [29]

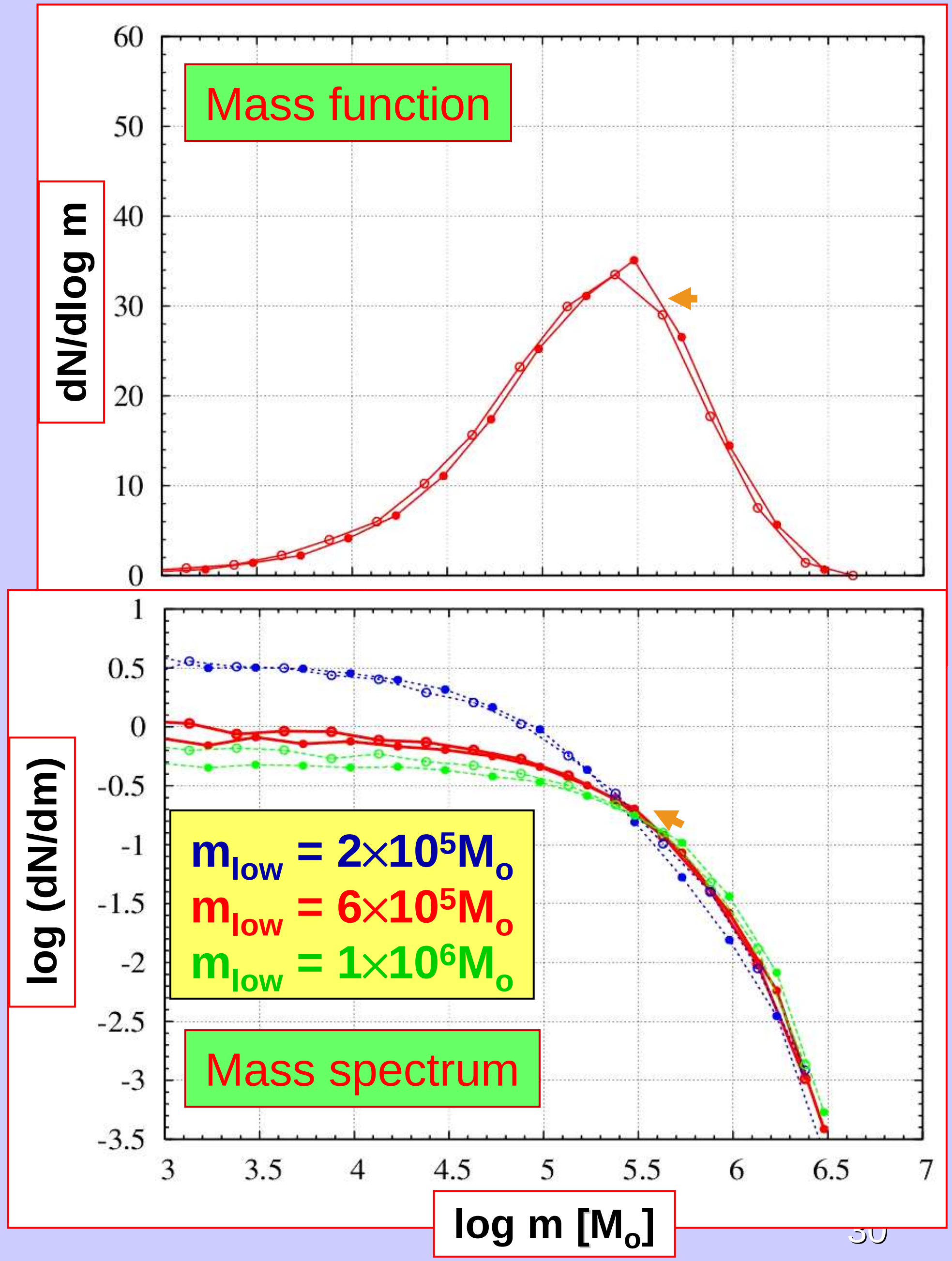


An Equilibrium Mass Distribution

- Cluster "I"MF after stellar evolution (all initial cluster mass reduced by 30%, as shown by the yellow arrow)

○ Cluster EMF at age=13Gyr and normalized to the initial GC number

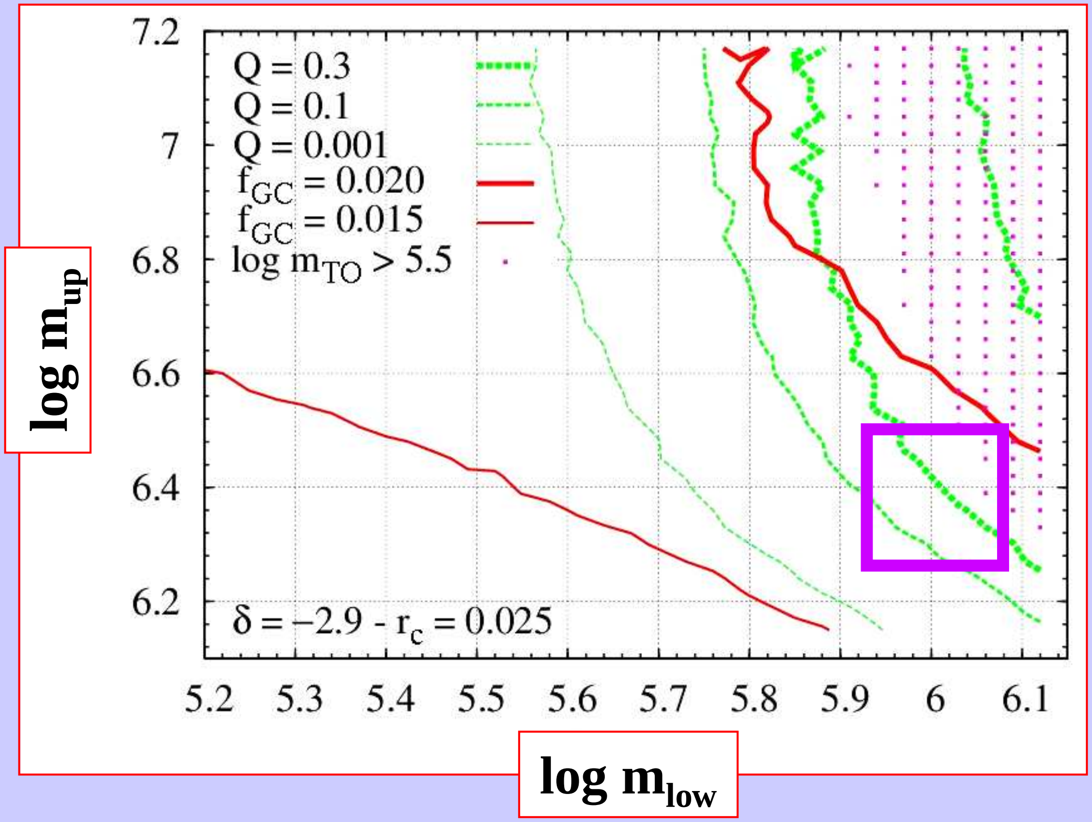
Vesperini (1998):
« ´dynamical equilibrium´ GC MF able to preserve its initial shape and parameters for one Hubble time through a subtle balance between disruption of clusters and evolution of the masses of the surviving ones. »



The Gaussian: another possible cloud mass function (I)

Power-law cloud MSp (α = -1.7):
Iso-Q and **iso-f_{GC}** curves in the [log m_{low}, log m_{up}] plane.

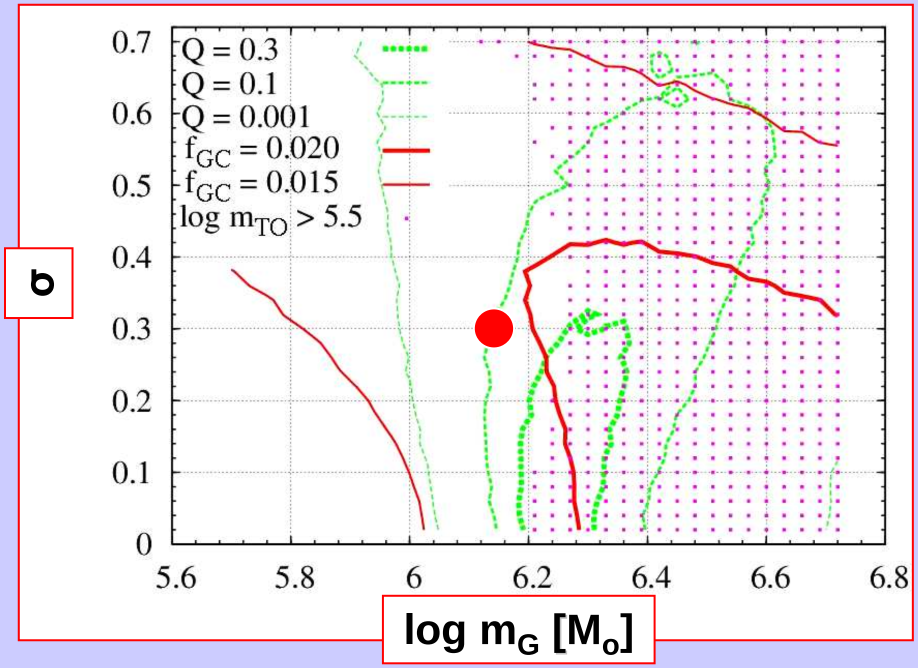
A narrow cloud mass range **($10^6 M_o$ - $3 \times 10^6 M_o$)** provides a good solution

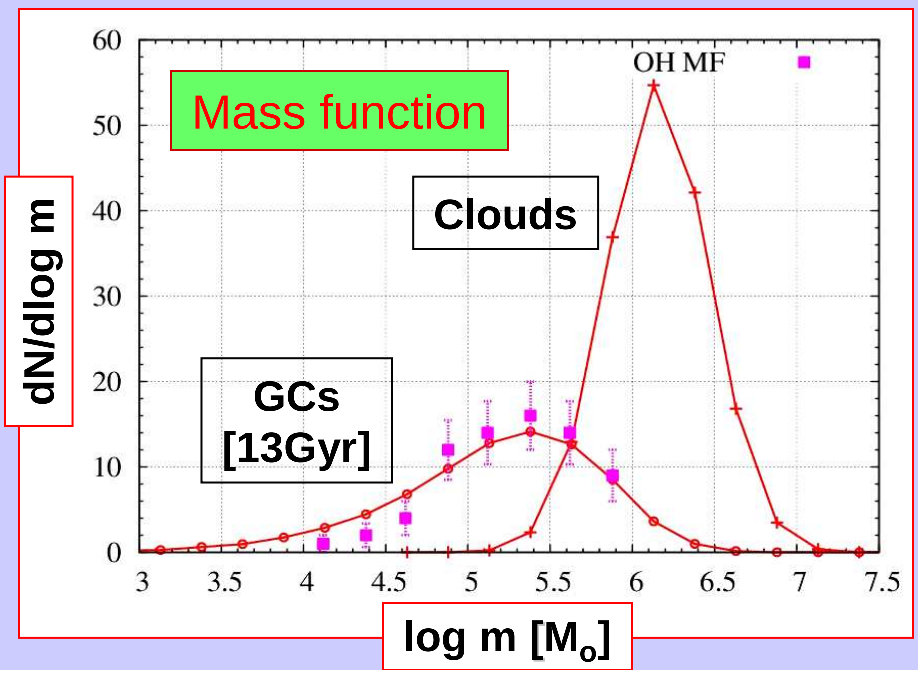


What about a peaked-shape cloud mass function (e.g. a narrow Gaussian) ?

The Gaussian: another possible cloud mass function (II)

Gaussian cloud MF:
Iso-Q and **iso-f_{GC}** curves in the [log m_G, σ] plane (same P(SFE) as for the power-law study).





The Gaussian: another possible cloud mass function (III)

σ Variations:

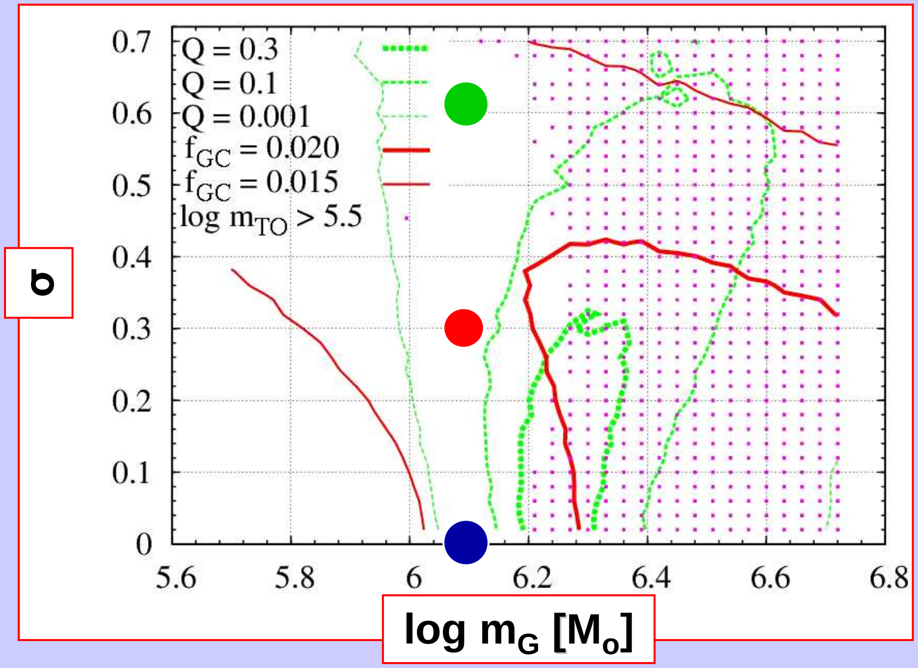
σ drives:

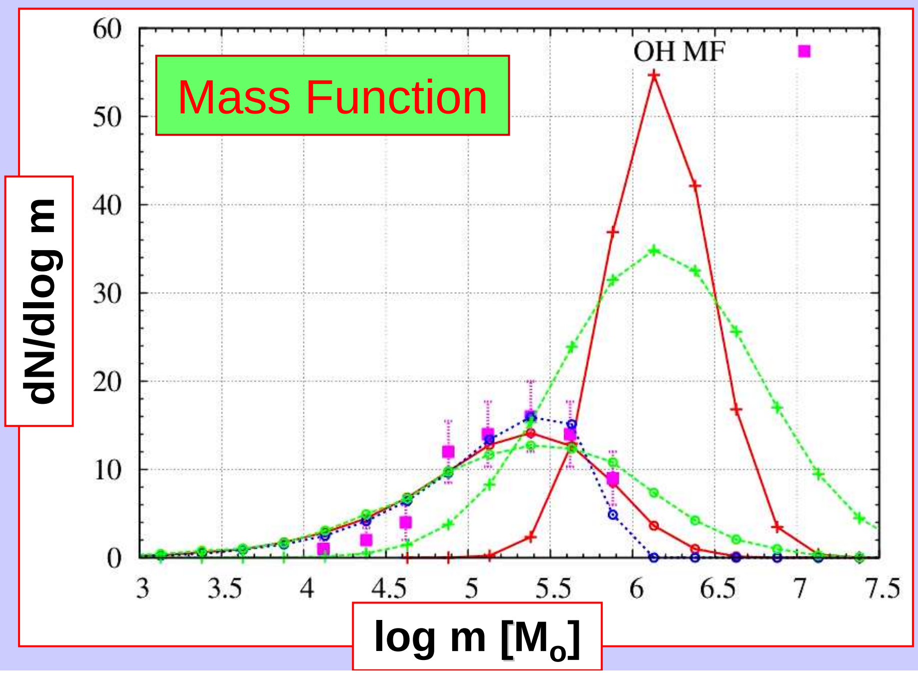
- shape of MF beyond TO
- peak location of MWMF

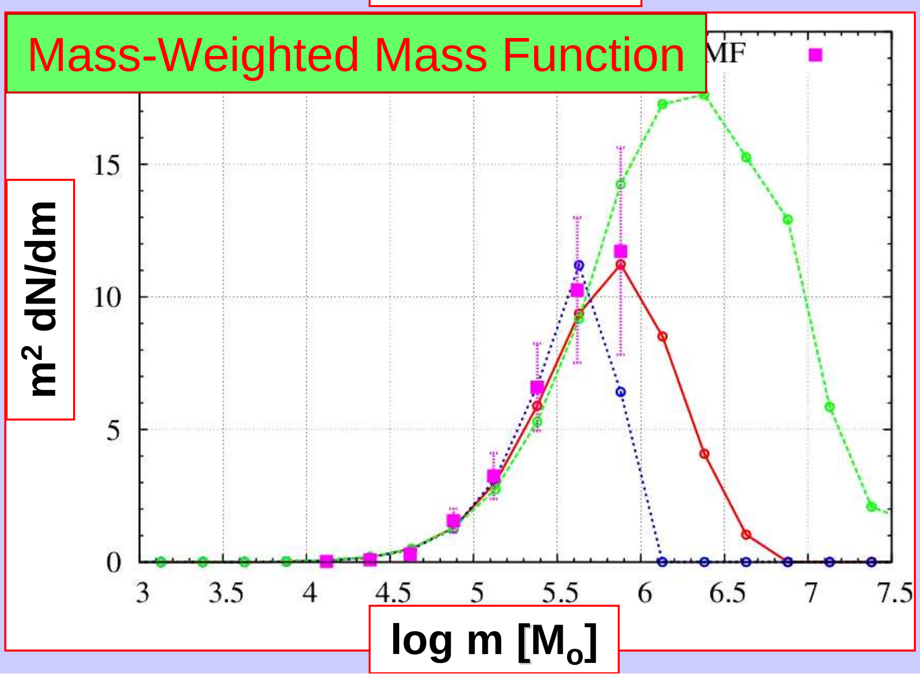
σ :

- does not affect the TO location significantly

σ : plays the role of m_{up} in the case of the PL cloud MF







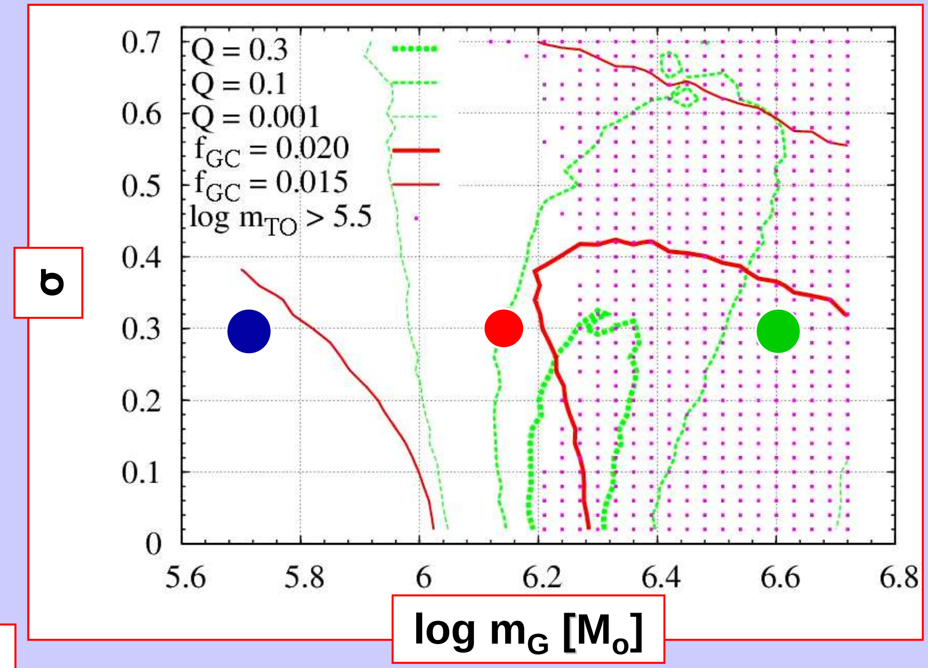
The Gaussian: another possible cloud mass function (IV)

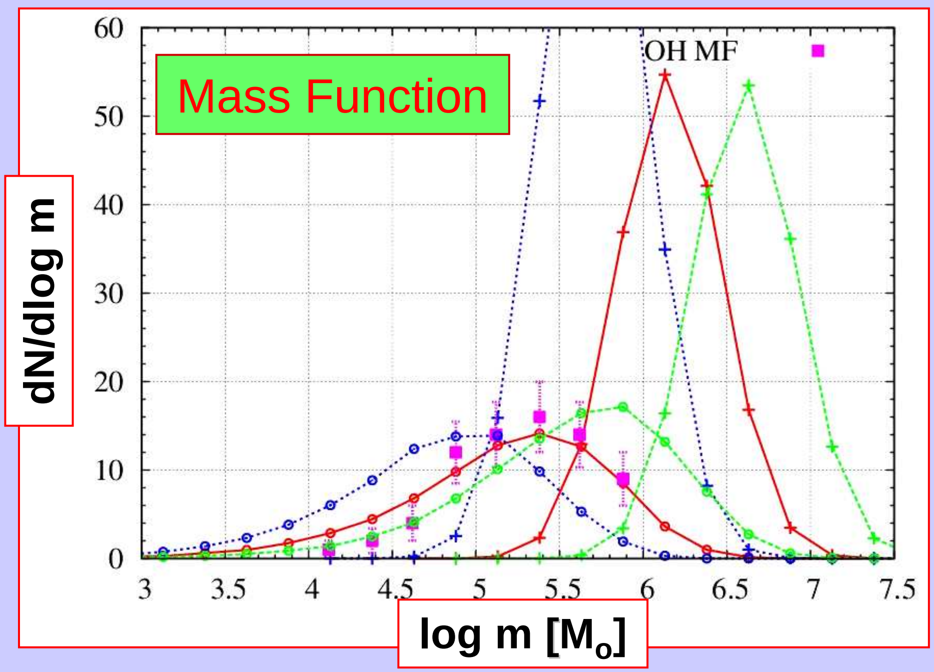
m_G Variations:

m_G drives:

- the TO location of the GC evolved MF

m_G : plays the role of m_{low} in the case of the PL cloud MF

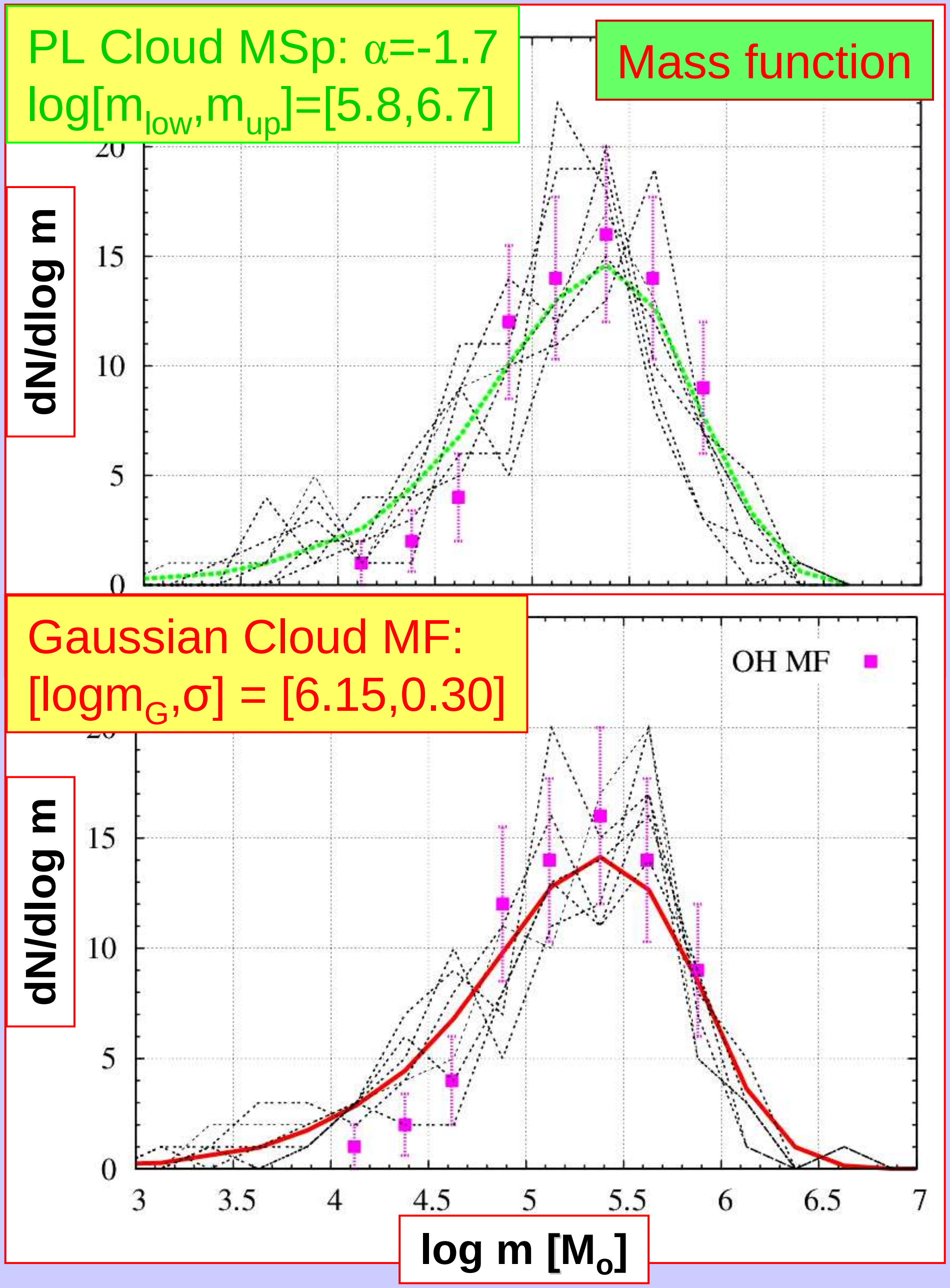




The discretness issue

- Up to now: simulations with about 10^6 clouds → no discretness issue
- What if the number of clouds is such that the predicted number of GCs at 13Gyr is the observed one? (i.e. no more vertical shift of the modelled MF)

Power-law	**Gaussian**
$N_{cloud} \cong$ 43,000	$N_{cloud} \cong$ 43,000
$N_{cloud}(\varepsilon > \varepsilon_{th}) = N_{init} \cong 190$	$N_{cloud}(\varepsilon > \varepsilon_{th}) = N_{init} \cong 190$
$N_{end}[10^4, 10^6 M_o] = [68-80]$	$N_{end}[10^4, 10^6 M_o] = [68-83]$
Old Halo: $N_{obs}[10^4, 10^6 M_o] = 72$	



The origin of field stars in the Galactic Halo

P(SFE): δ = -2.9
PL: α = -1.7
G: (6.15, 0.30)

M_{Gas}

Star formation: $\wp(SFE)$, $\overline{SFE} \cong 2.5\%$

$M_{Stars} = 0.025 \times M_{Gas}$

Gas removal: $F_{bound}(SFE)$ with $SFE_{th} \cong 0.33$

Dynamical + Stellar evolutions over a Hubble - Time

Field Stars: $SFE < SFE_{th}$, $M^{init}_{FS-a} \cong 0.92 M_{Stars}$

Field Stars: $SFE > SFE_{th}, (1 - F_{bound})$, $M^{init}_{FS-b} \cong 0.03 M_{Stars}$

Globular Clusters: $SFE > SFE_{th}, F_{bound}$, $M^{init}_{GC} \cong 0.05 M_{Stars}$

Field Stars (*ab initio*): $M^{13Gyr}_{FS-ab} \cong 0.95 M_{Halo}$

Field Stars (disr./evap. GCs): $M^{13Gyr}_{FS-c} \cong 0.03 M_{Halo}$

Globular Clusters: $M^{13Gyr}_{GC} \cong 0.02 M_{Halo}$

Conclusions

- The GC IMF (Gaussian or power-law ?) is still a much debated issue. This may have been a Gaussian
  - In the Galactic halo (mass- vs. number-related quantities)
  - In M82 B (unphysically large initial number of clusters)
- The present-day GC MF may be the imprint of the cluster formation process and not of 13 Gyr of dynamical evolution
- Simple models taking into account an SFE range coupled with the corresponding variations in F_{bound} are reproducing bell-shaped cluster IMFs

  → **theoretical support for a Gaussian cluster IMF, whose TO is mostly driven by the low-mass limit of the clouds.**

- Assuming instantaneous gas removal, the model predicts the OH GC MF and the present-day GC mass fraction in the halo if:

- Cloud MSp: $\alpha=-1.7$, $[\log m_{low}, \log m_{up}] \cong [5.8, 6.7]$
- Cloud MF : $[\log m_G, \sigma] \cong [6.15, 0.3]$
  - P(SFE): $[\delta, r_c]=[-2.9, 0.025]$