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Star Clusters as Crucial Tracers of Galaxy Evolution and Probes into Star Formation

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Star Clusters: Fast Facts

- Most stars in the local Universe are born in star clusters
→ clusters are at the heart of many astrophysical key-issues

  Ø young star clusters tell us about star formation
  Ø star clusters with an age range tell us about the evolution of their host galaxy over that age range

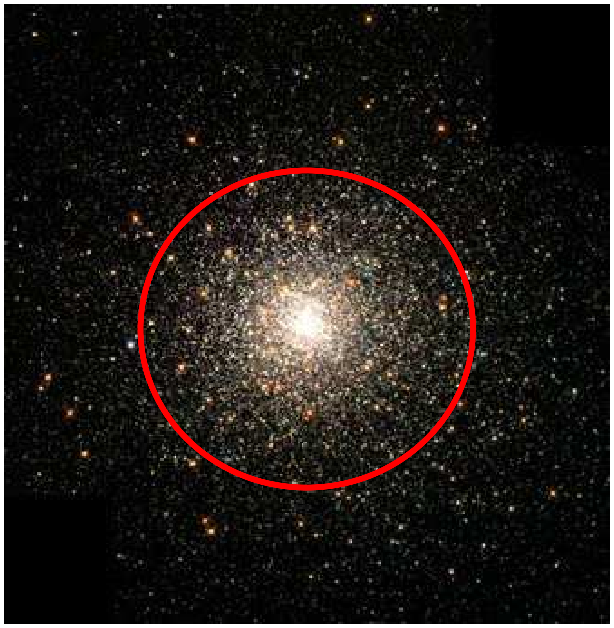
Most stars are born in star clusters, but observed as field stars.

Star clusters go through a lifecycle: they evaporate, until complete dissolution

Cluster lifecycle includes 2 phases:

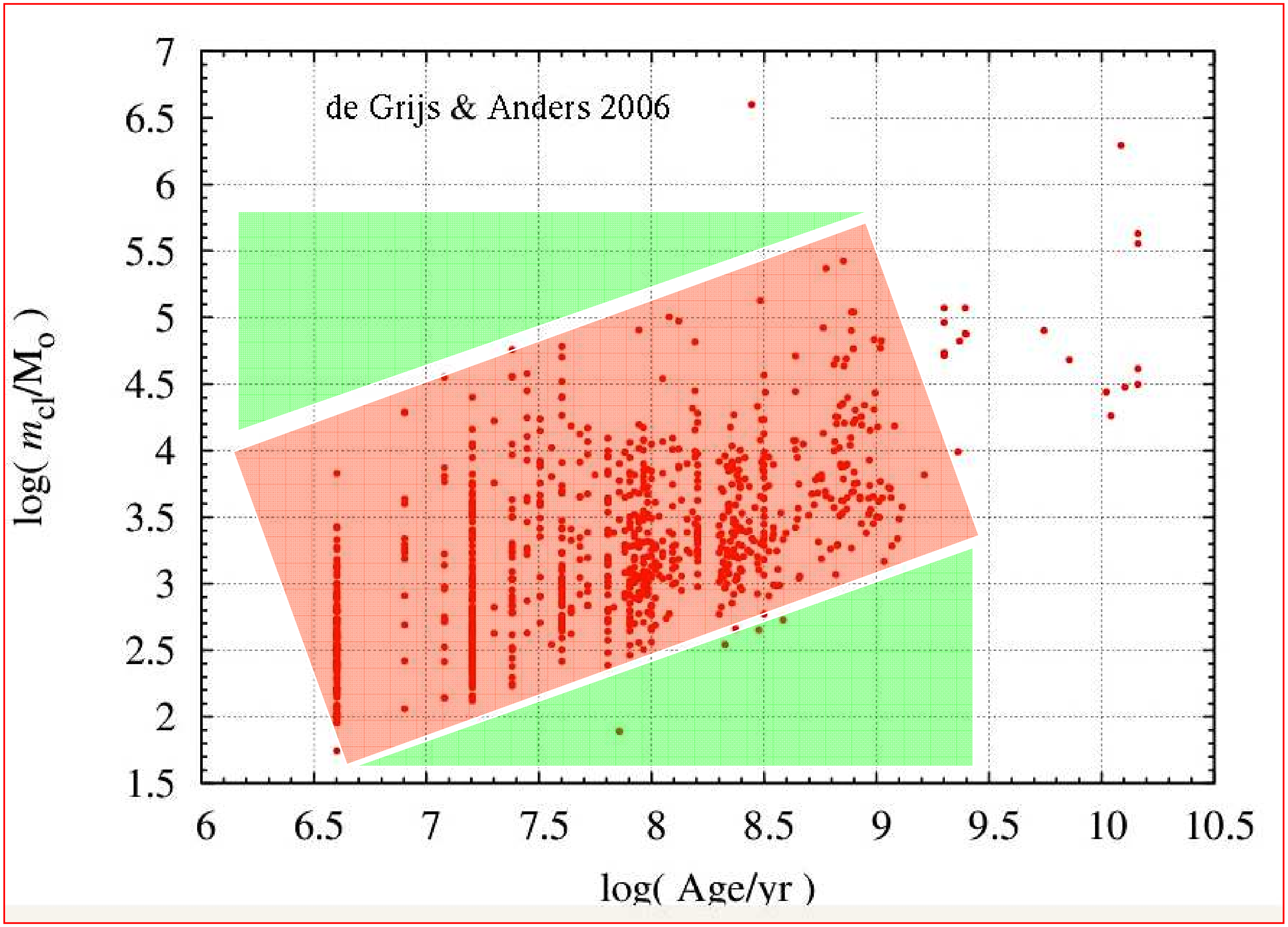
Ø gas expulsion and violent relaxation: very short (10-50 Myr),

Ø secular evolution/gas free evolution



A Vital Diagnostic Tool: the Age-Mass Diagram

Cluster mass vs cluster age for a sample of ≅1,000 clusters in the **Large Magellanic Cloud**



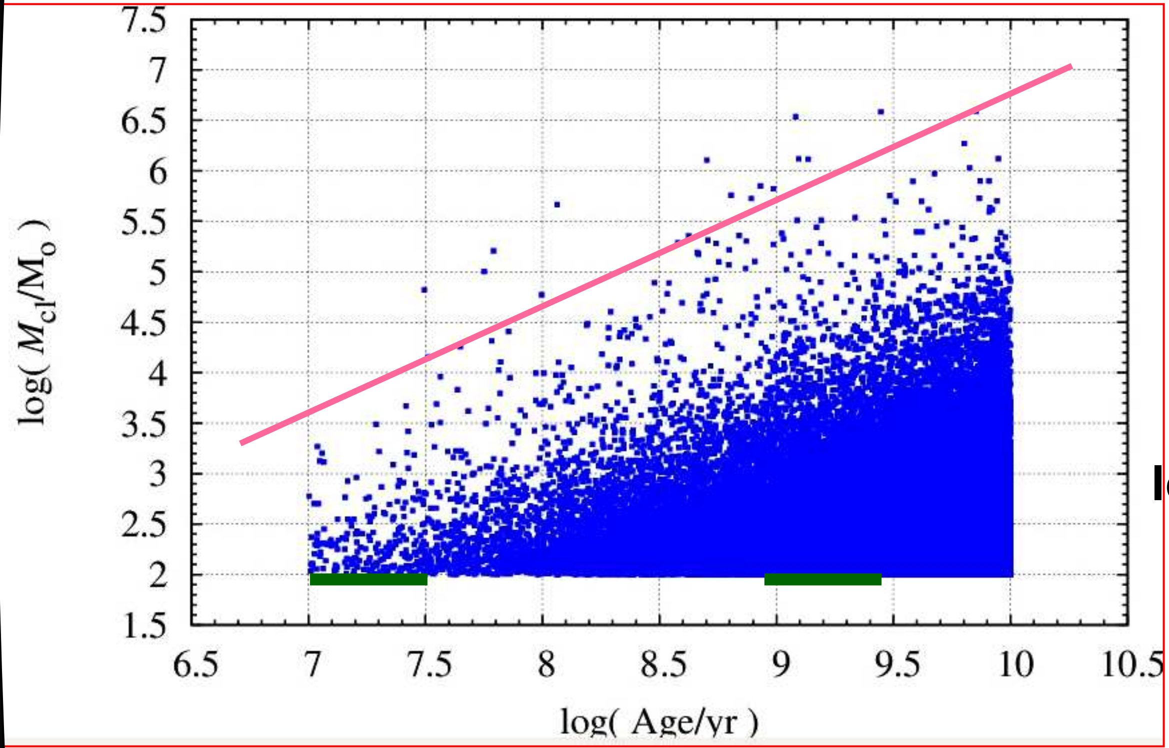
Age-Mass Diagram and Size-of-Sample Effect

Synthetic population of clusters:

- Cluster Formation Rate (CFR) constant with time,
- Initial Cluster Mass Function (ICMF):

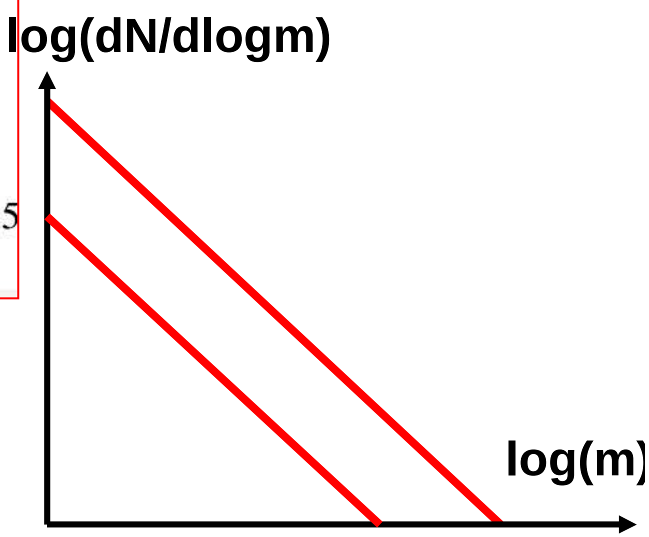
$$\frac{dN}{dm} \propto m^{-2}$$

$$\equiv \frac{dN}{d\log m} \propto m^{-1}$$



Δt=20Myr

Δt=2Gyr
(100× more SCs if CFR=cst)



Age-Mass Diagram - Do Not Trust Your Eyes: 1/2

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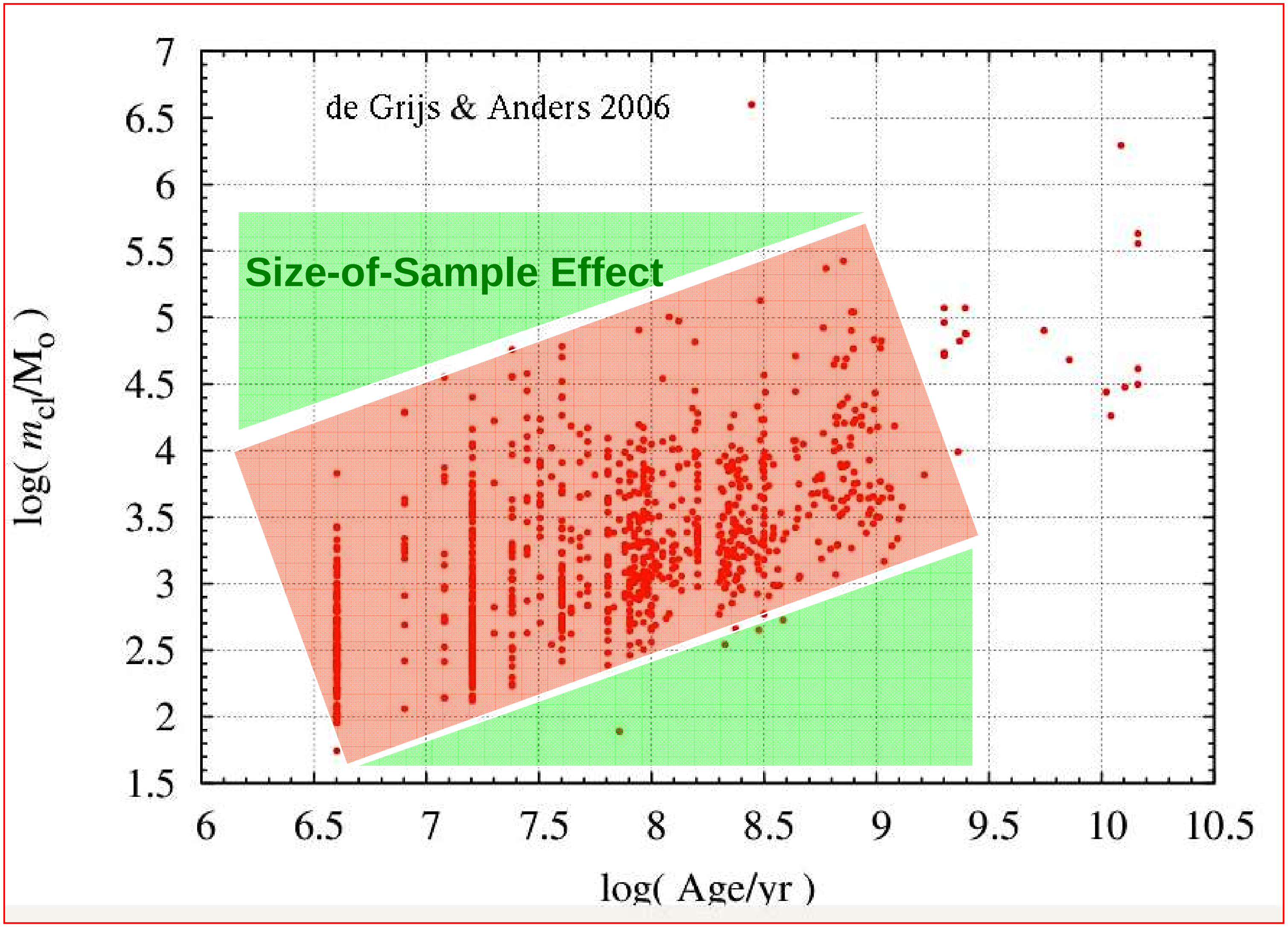
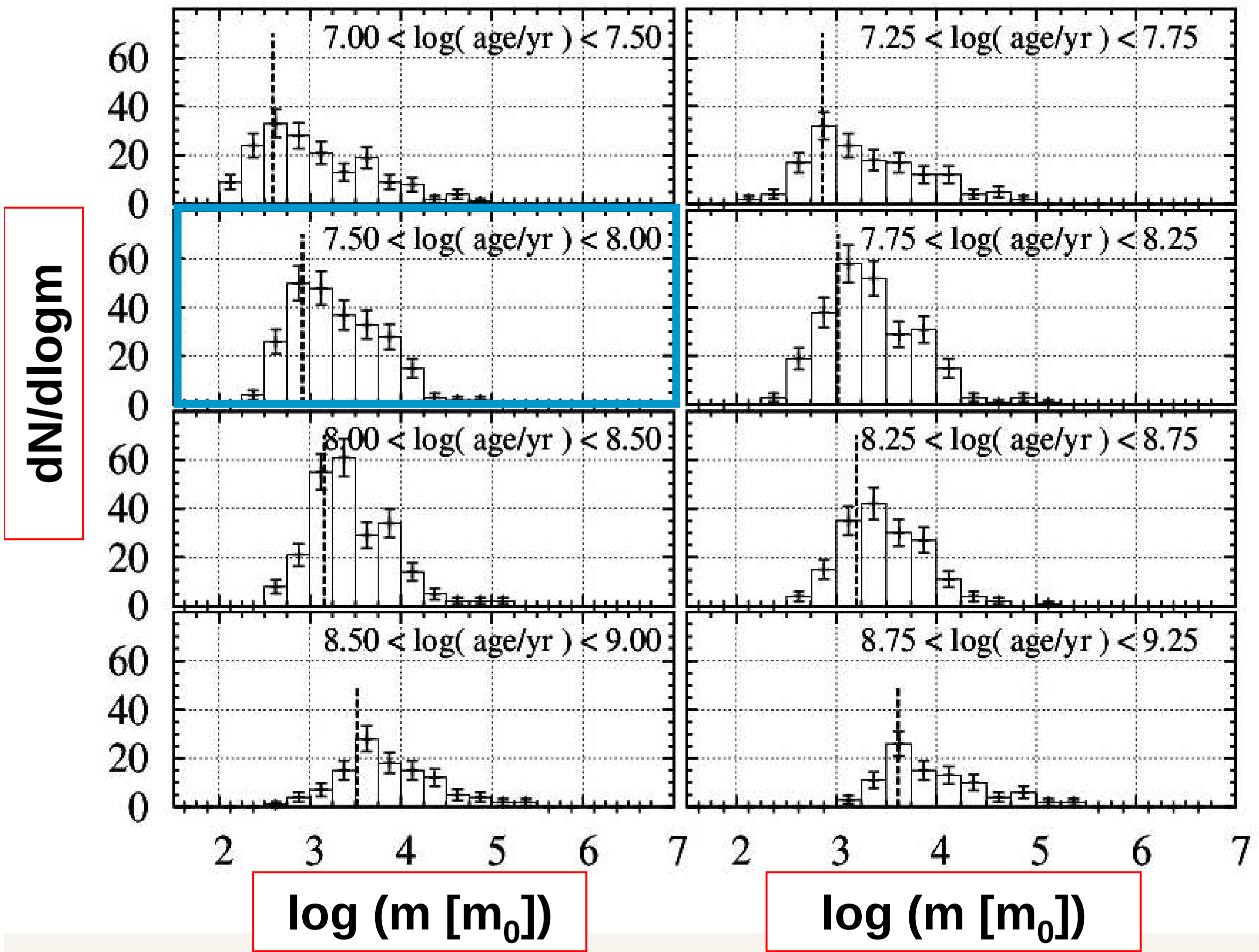
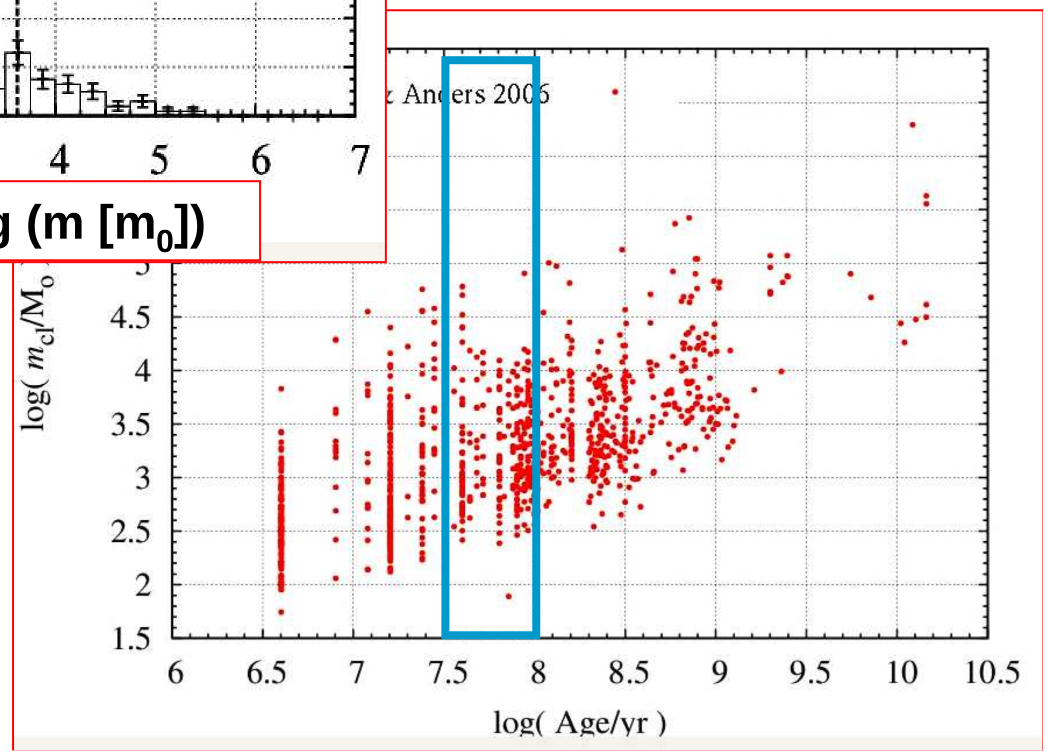


Large Magellanic Cloud
cluster sample:
Fading limit





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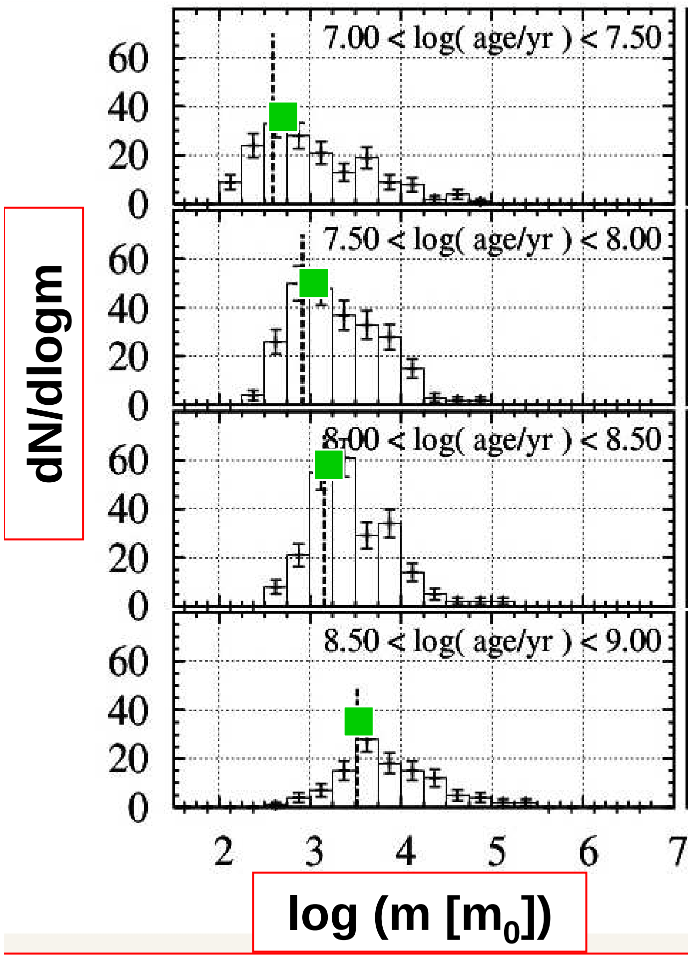
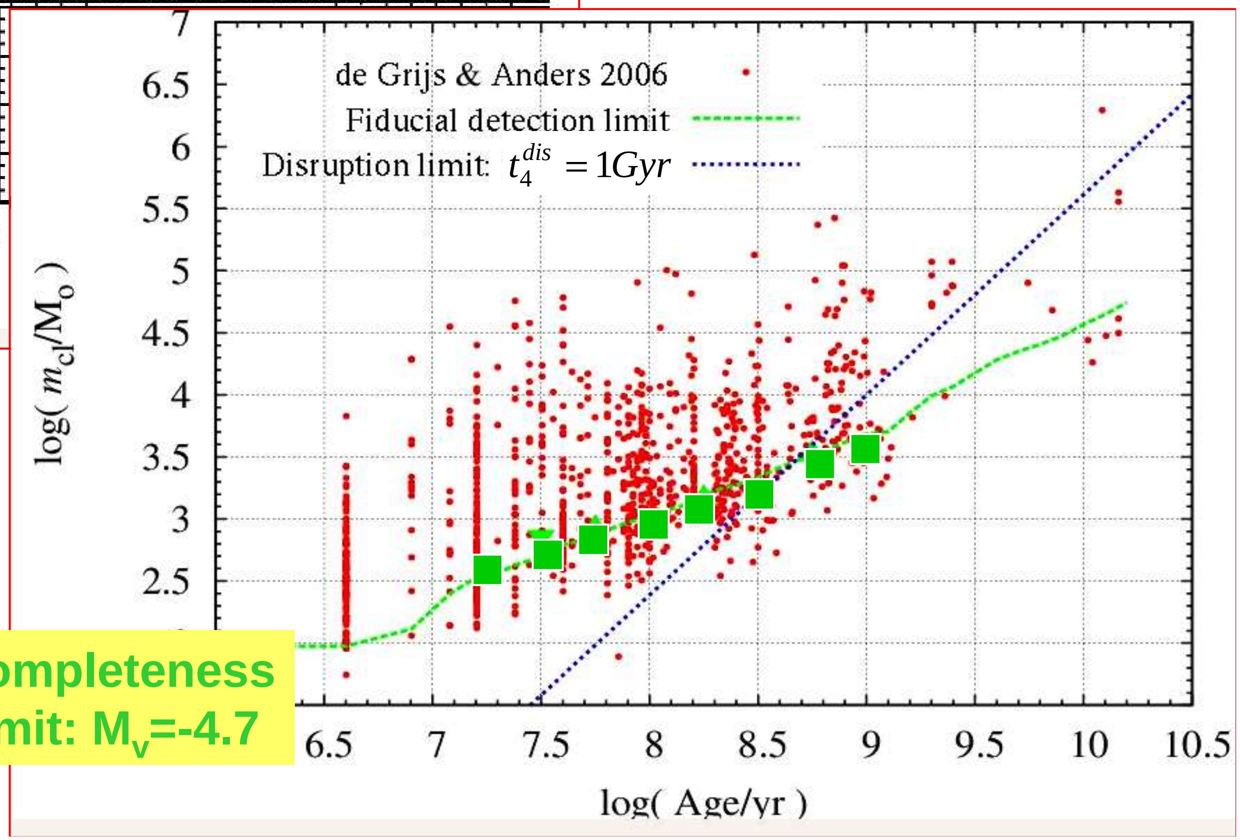
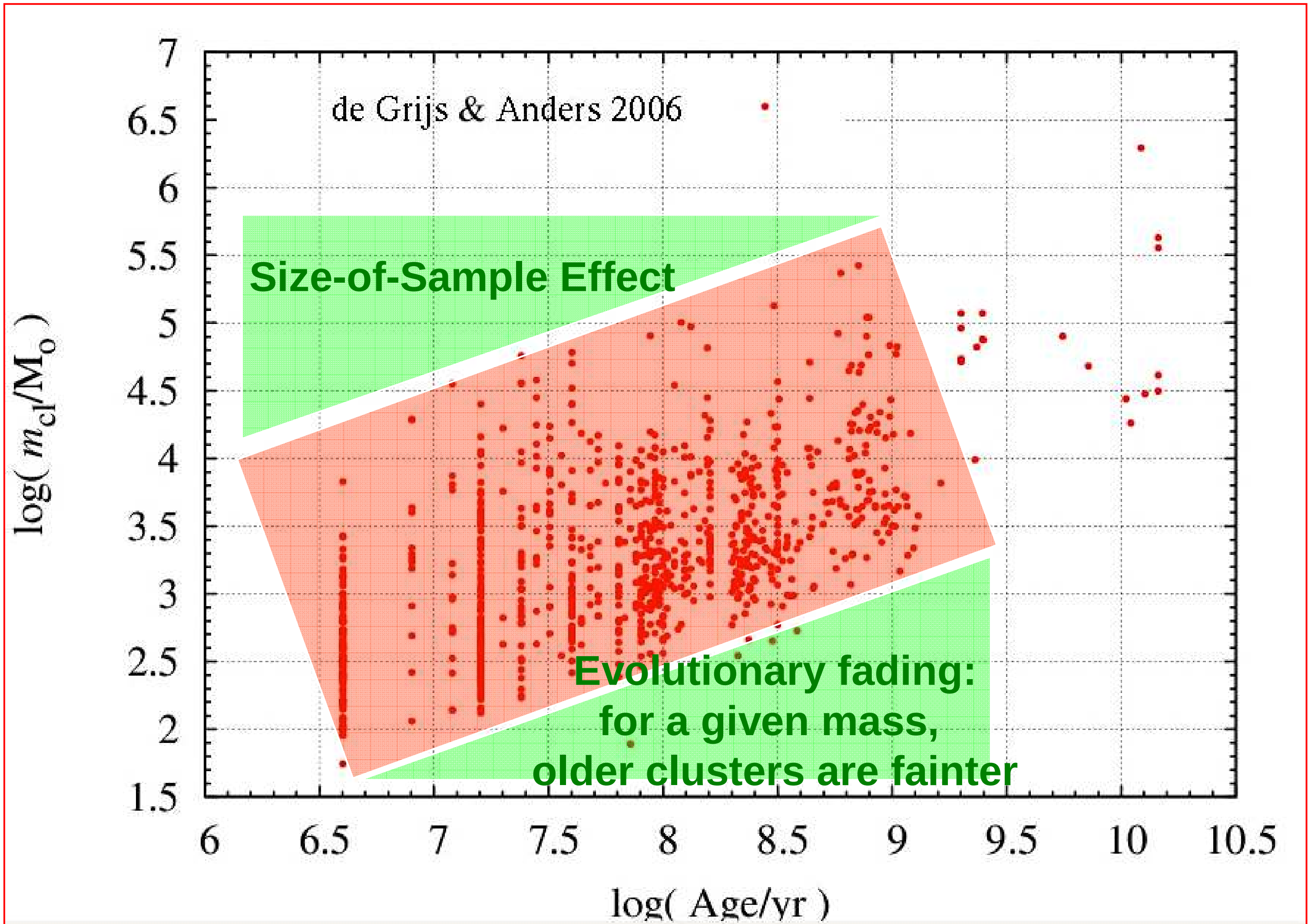




Completeness limit: M_V=-4.7

Age-Mass Diagram - Do Not Trust Your Eyes: 2/2

Cluster mass vs cluster age for a sample of ≅1,000 clusters in the **Large Magellanic Cloud**



Age-Mass Diagram - Do Not Trust Your Eyes: 2/2

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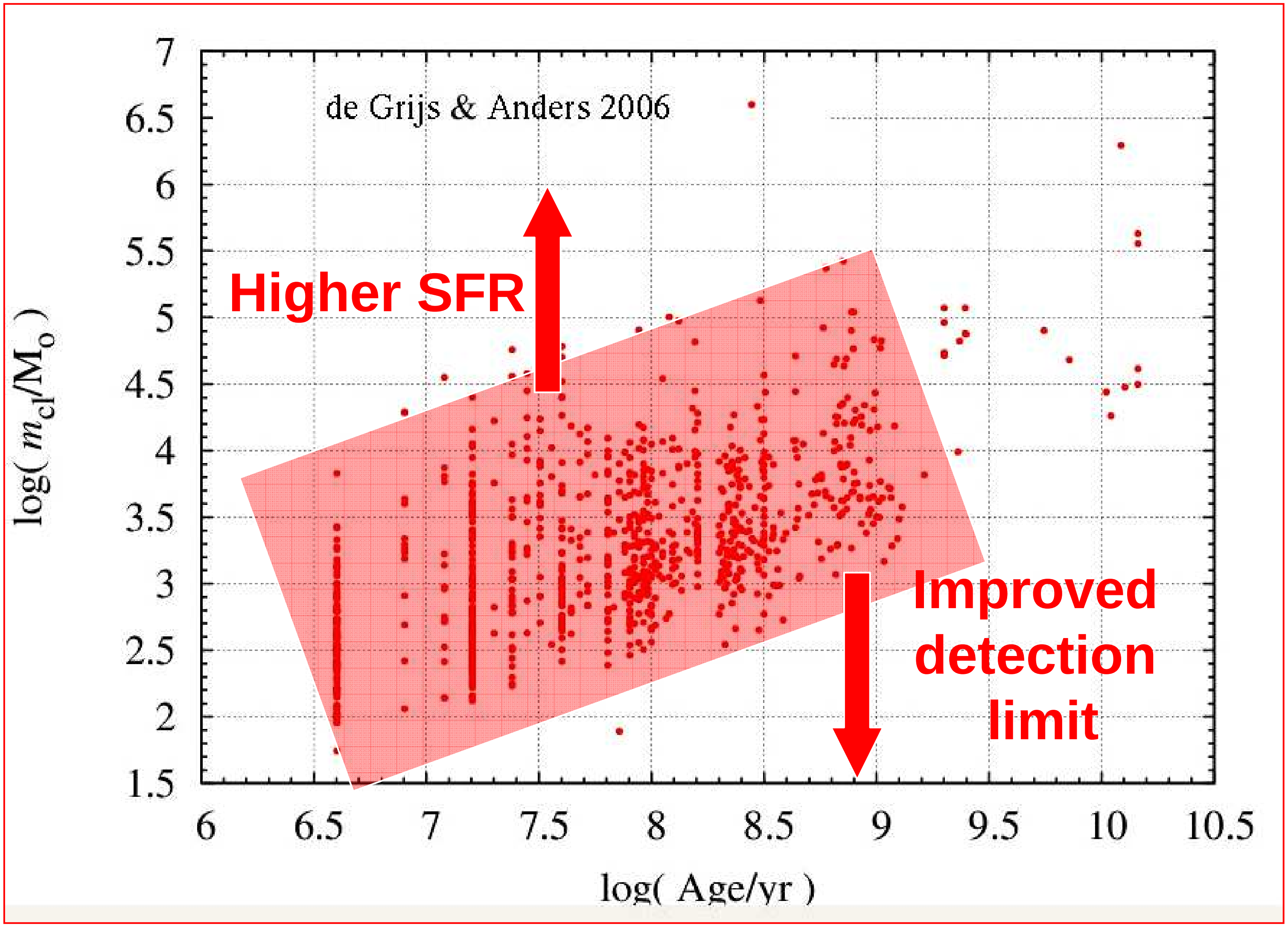

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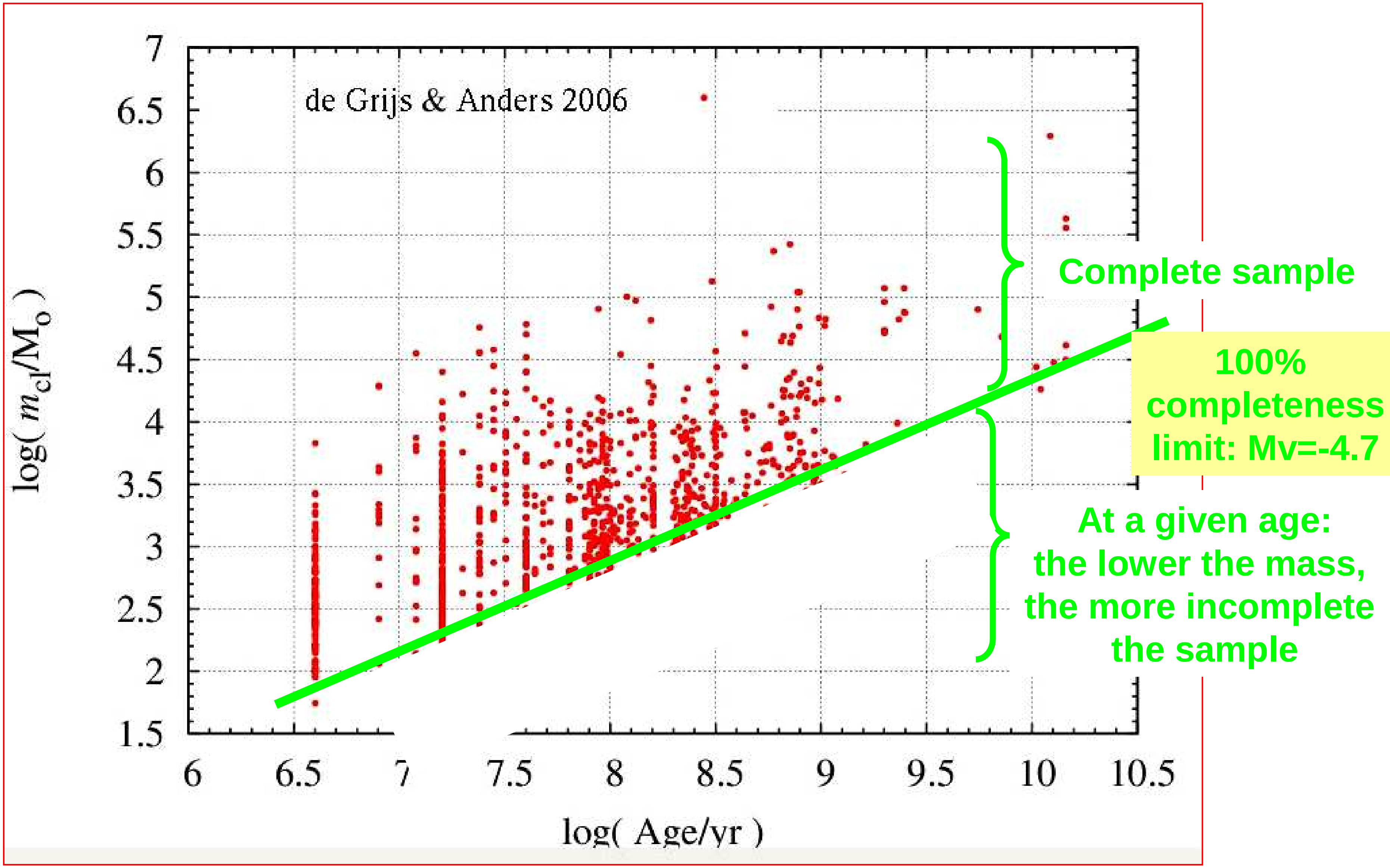

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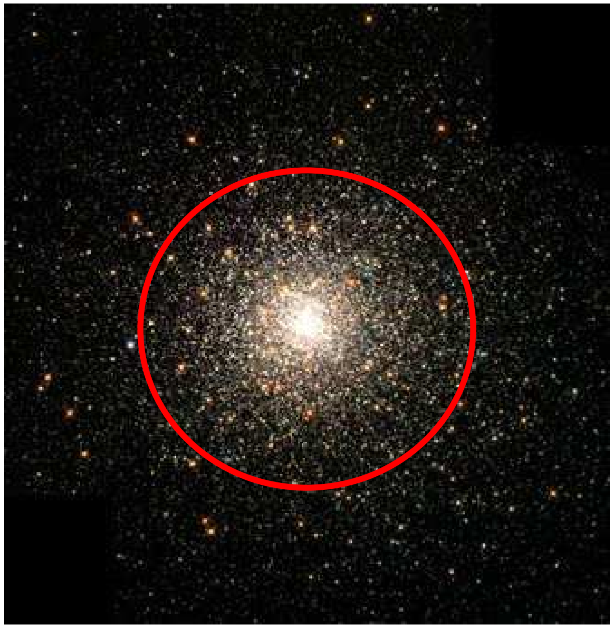

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Cluster lifecycle includes 2 phases:

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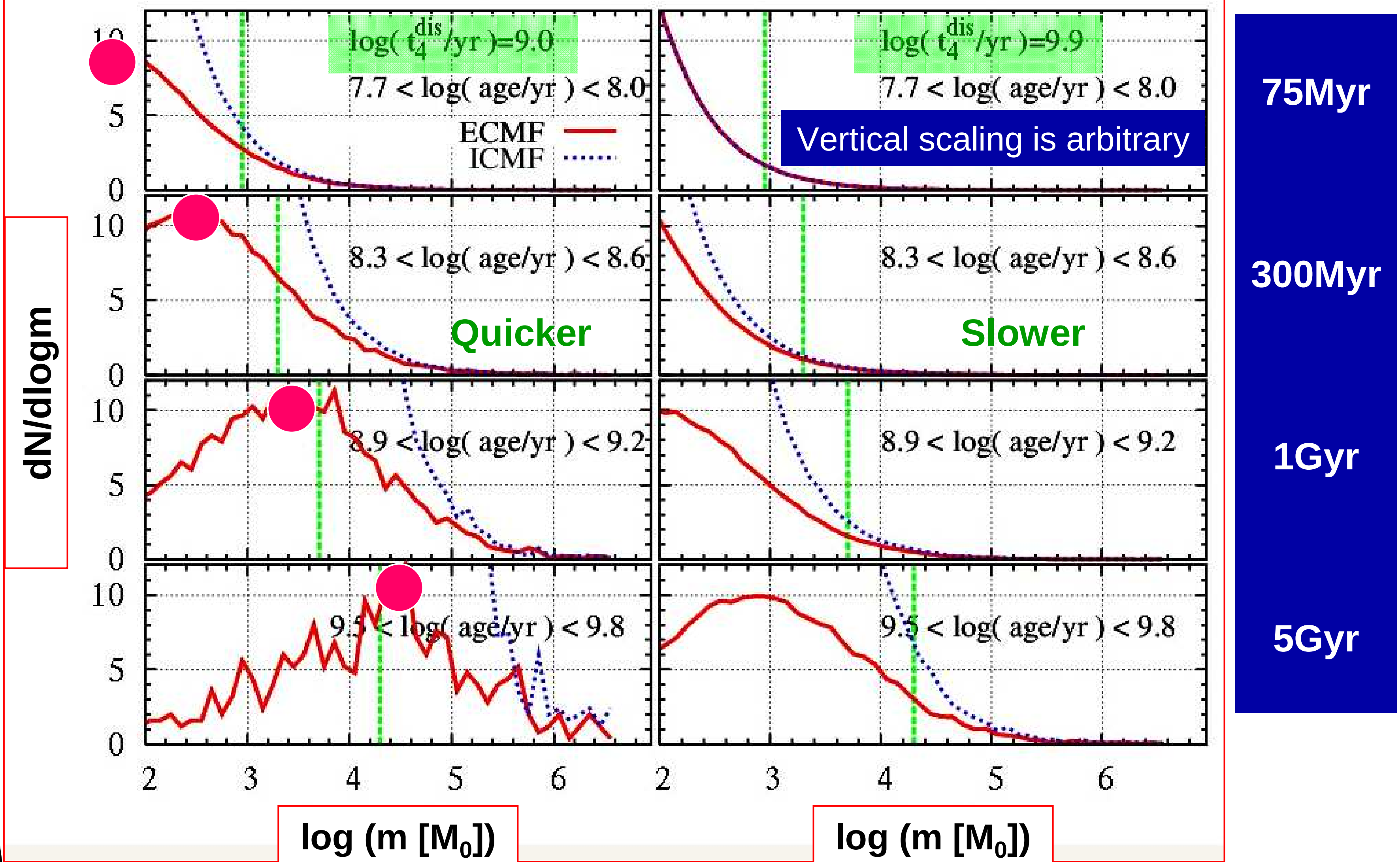
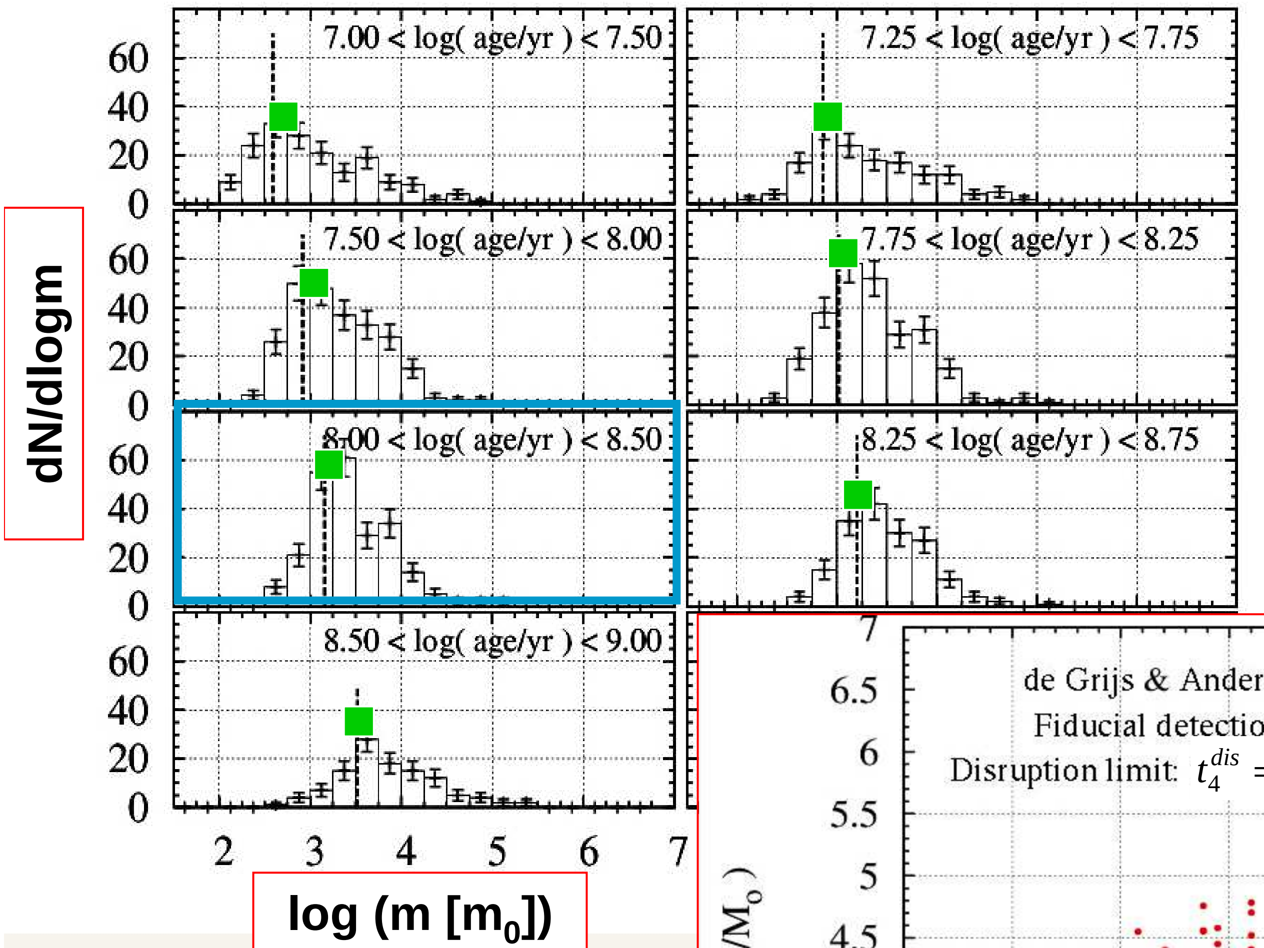
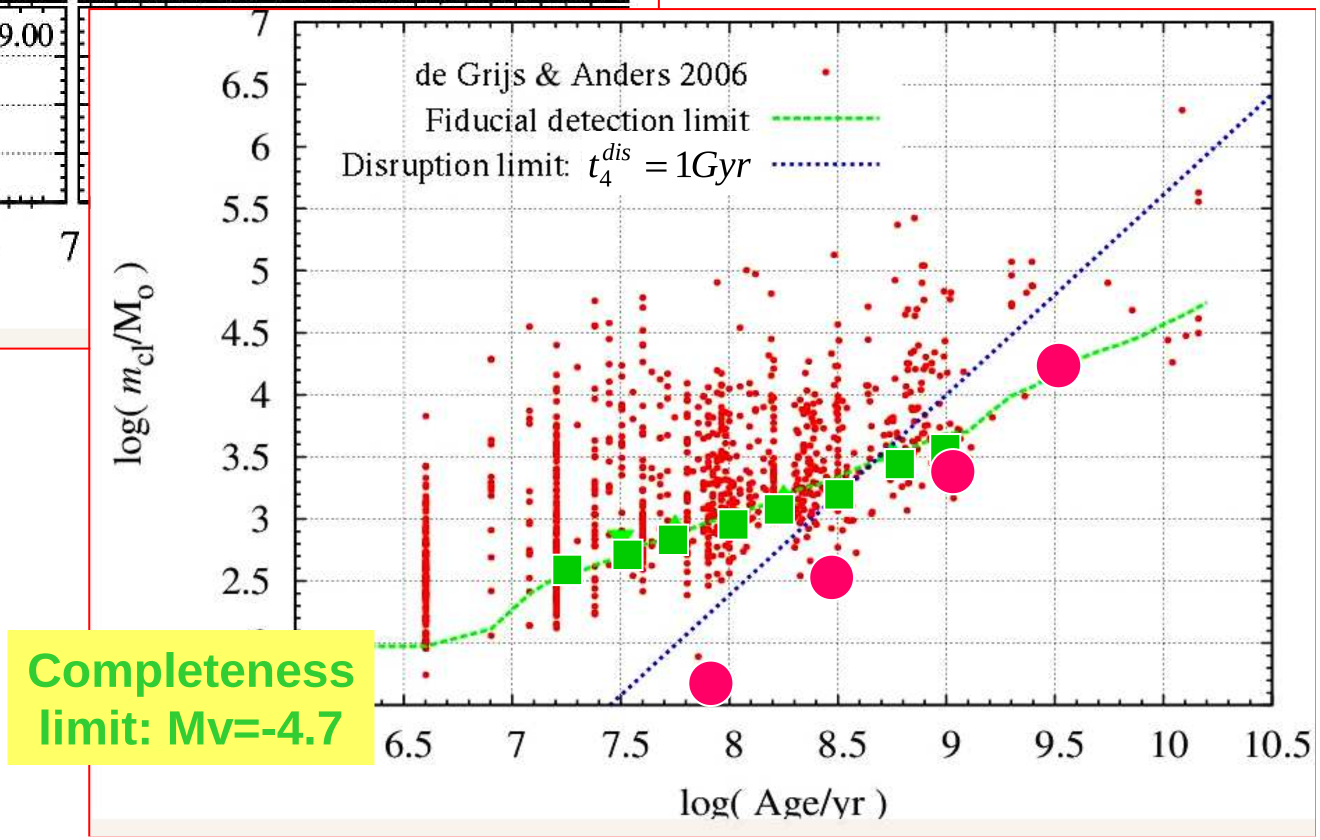
- Ø secular evolution/gas free evolution

Secular Evol.: Carving a Turnover in the ICMF

Modelling of Secular Evolution: Fig.17 in Parmentier & de Grijs (2008), based on the models of Baumgardt & Makino (2003) and Lamers et al (2005)

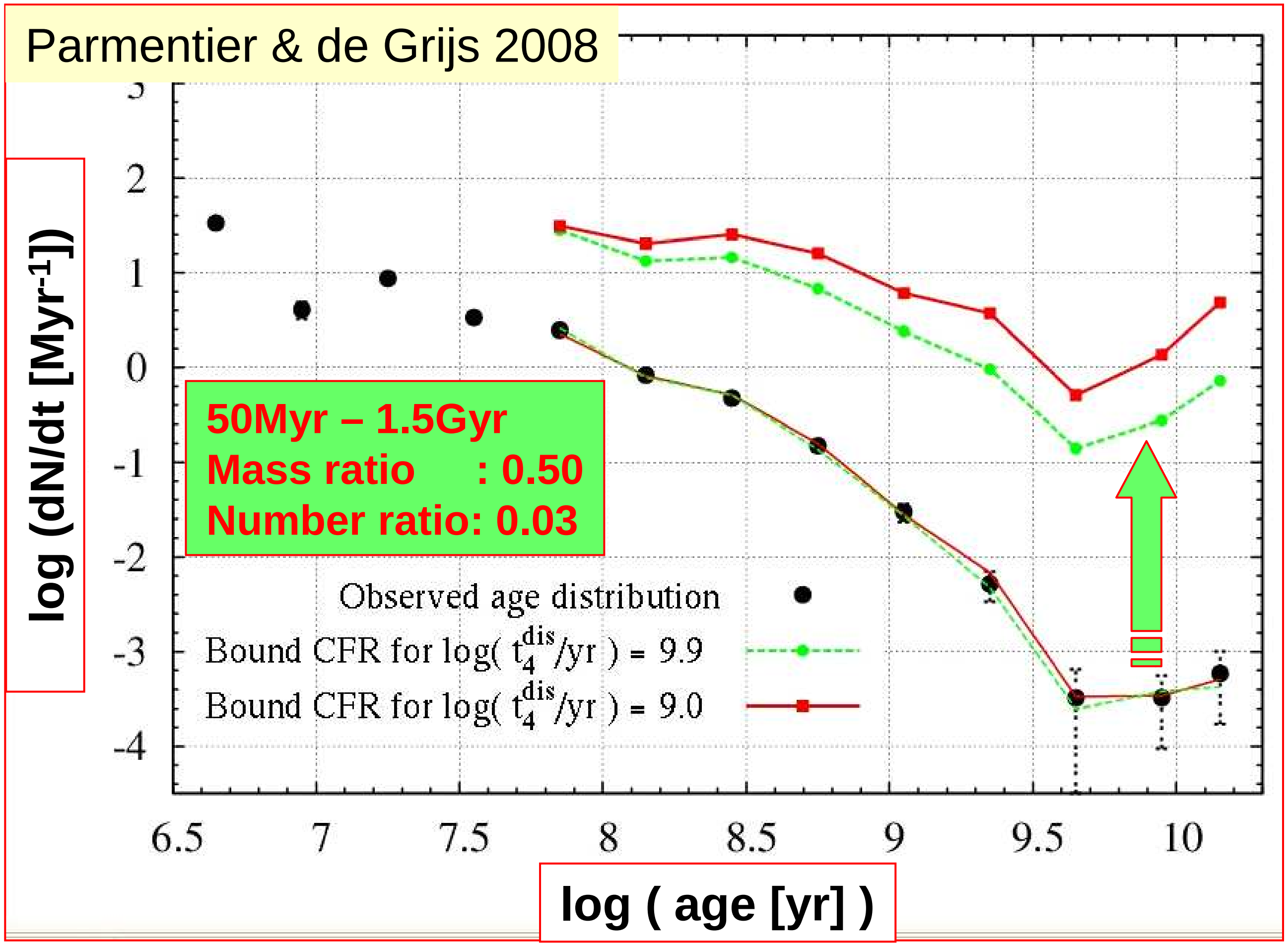



dN/dlogm
7.00 < log(age/yr) < 7.50
7.25 < log(age/yr) < 7.75
7.50 < log(age/yr) < 8.00
7.75 < log(age/yr) < 8.25
8.00 < log(age/yr) < 8.50
8.25 < log(age/yr) < 8.75
8.50 < log(age/yr) < 9.00
0
20
40
60
2
3
4
5
6
7
log (m [m0])


de Grijs & Anders 2006
Fiducial detection limit
Disruption limit: $t_4^{dis} = 1Gyr$
log(m_{cl}/M$_o$)
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
6.5
7
7.5
8
8.5
9
9.5
10
10.5
log(Age/yr)
Completeness
limit: Mv=-4.7

Bound Cluster Formation History and Cluster Dissolution Time-Scale in the LMC

Parmentier & de Grijs 2008



Predicted Bound CFR

t_4^{dis} = 1Gyr

t_4^{dis} = 8Gyr

Observed age distribution

Secular evolution modelling
→ Bound Cluster Formation History from the observed cluster age distribution

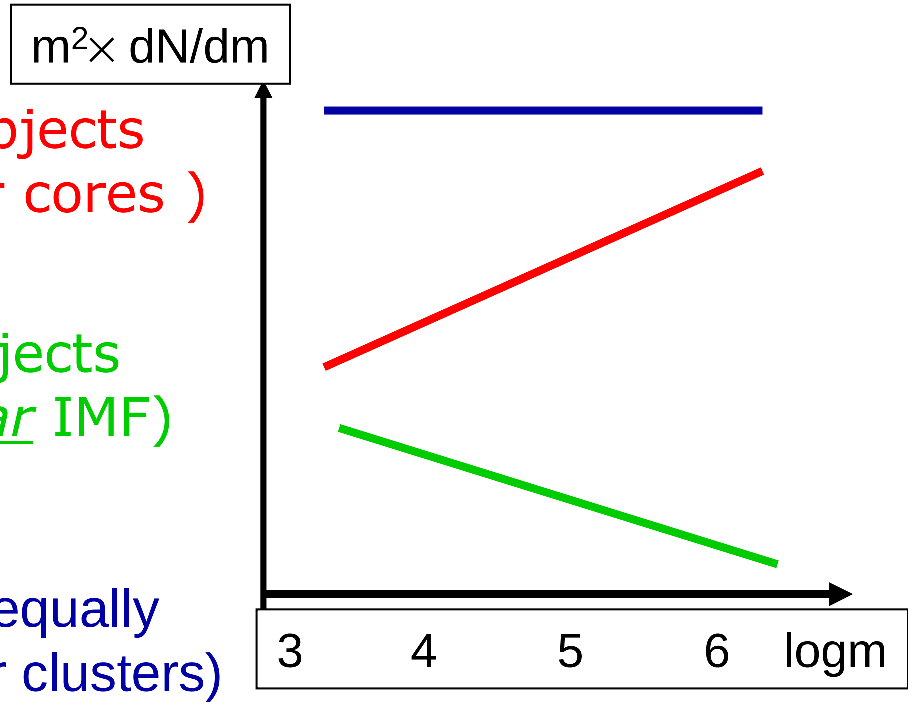
Cluster Mass Functions: mass versus number

Power - Law Mass Function: $\frac{dN}{dm} \propto m^{-\alpha}$

- $\alpha < 2$
  → 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)

- $\alpha = 2.0$
  → low- and high-mass clusters equally contribute to the total mass (star clusters)

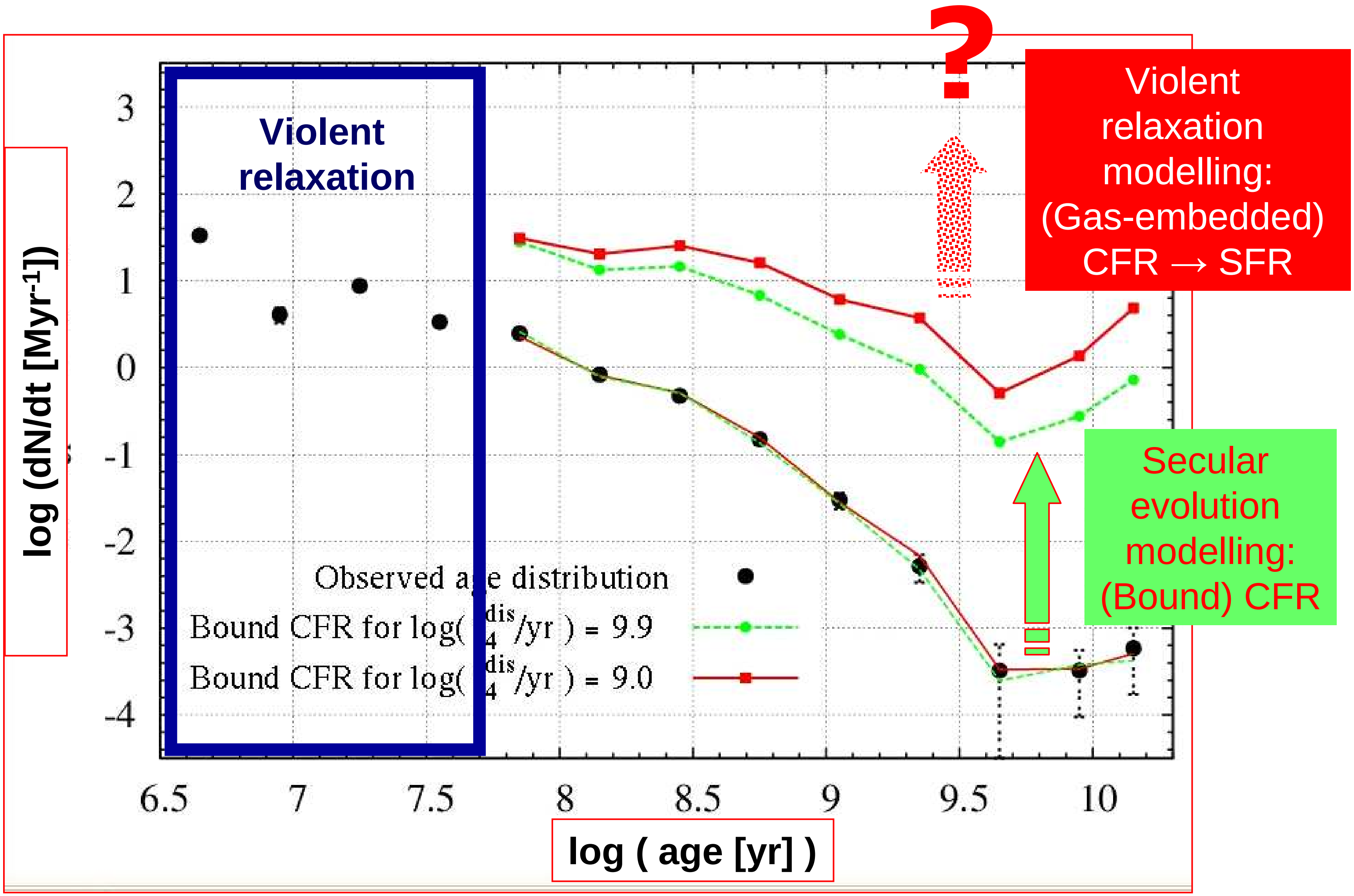


Numbers: **90%** **9%** **0.9%** **0.09%**

2 3 4 5 6 **log(m)**

Masses: **25%** **25%** **25%** **25%**

Gas-Embedded Cluster Formation History: the next step ...



Violent Relaxation (VR): Observable Signatures And Prime Parameters

Effects of Gas expulsion - VIOLENT RELAXATION

- **Cluster expansion**
- **Cluster infant weight-loss and infant mortality**

Observable Imprints upon Star Cluster Systems :

- Cluster mass distribution,
- Cluster age distribution,
- Cluster radius distribution,
- Ratio of the total mass in clusters to
  the total stellar mass in gas-embedded clusters

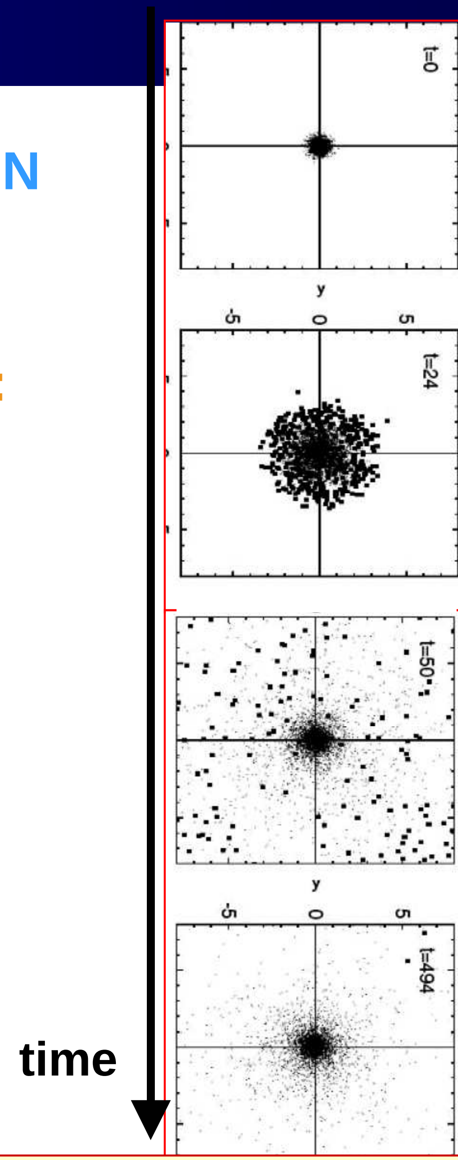
Prime parameters: (e.g. Baumgardt & Kroupa 2007)

- SFE in cluster-forming molecular cores

- Gas expulsion time-scale: $\tau_{GExp} / \tau_{cross}$

- Impact of external tidal field (environment)

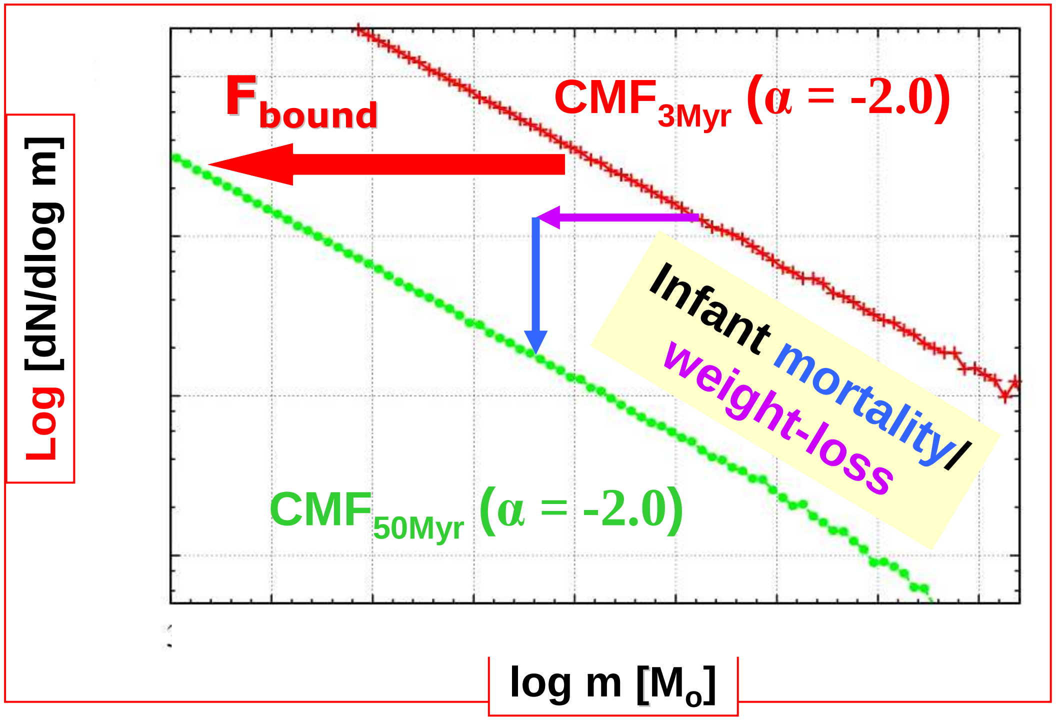
See also Adams (2000), Vesperini et al (2009), …



Geyer & Burkert (2001)

Violent Relaxation: Cluster Mass Functions

Time-Evolution of Cluster Mass Functions:
What observers tell modellers …



$$\frac{dN}{dm} \propto m^{-2}$$

$$\equiv \frac{dN}{d\log m} \propto m^{-1}$$

F_{bound} is mass-<u>in</u>dependent

$$m_{cluster}(\textbf{end of VR}) = F_{bound} \times m_{cluster}(\textbf{at Gas Exp})$$

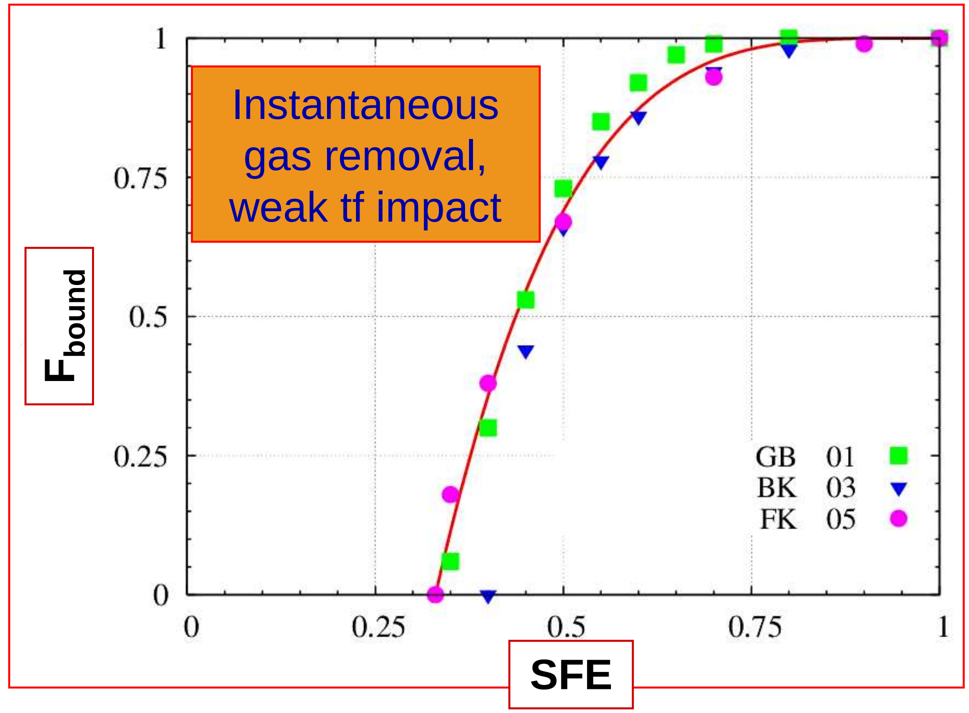
SFE and Cluster Mass Functions

$$m_{cluster}(\textbf{end of VR}) = F_{bound}(SFE) \times SFE \times m_{core}$$

$$F_{bound}(\textbf{SFE } \varepsilon)$$

SFE
= fraction of gas ending up in stars

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

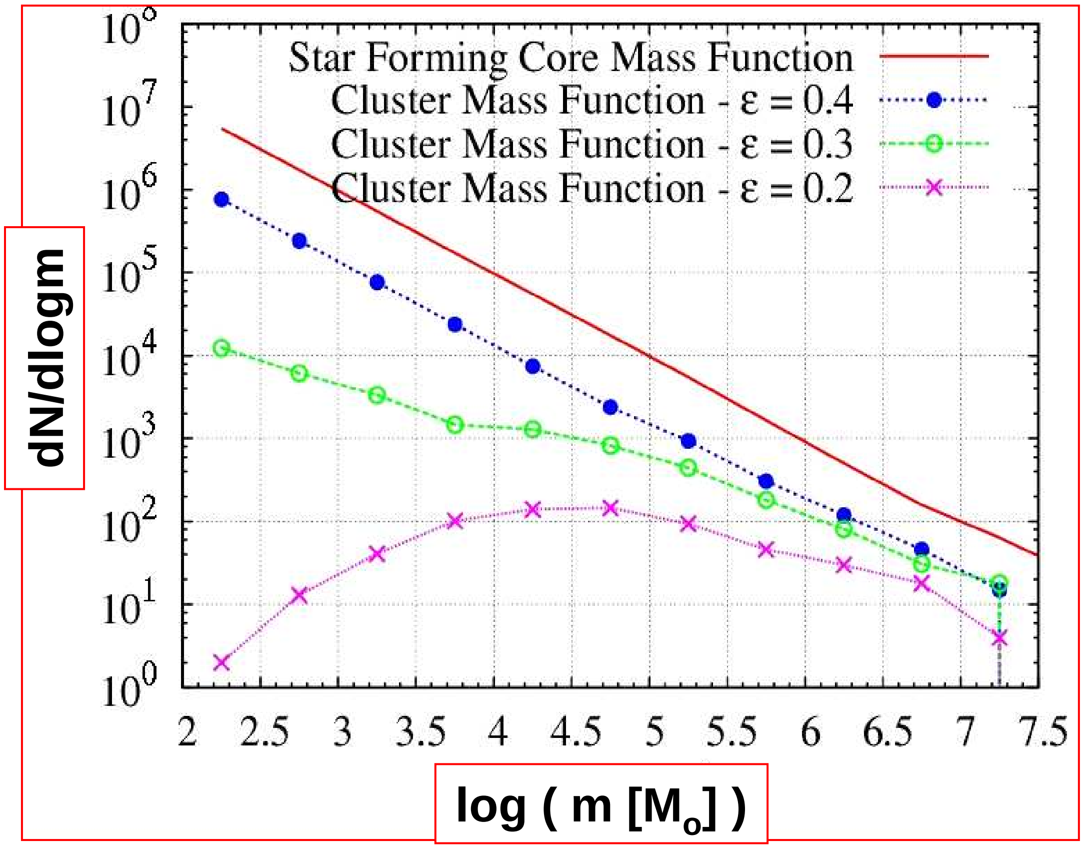


F_{bound} is mass-<u>in</u>dependent
→ SFE is mass-<u>in</u>dependent

τ_{GExp}/τ_{cross} and Cluster Mass Functions

$$F_{bound}\left(\mathbf{SFE}\ \varepsilon, \frac{\tau_{GExp}}{\tau_{cross}}\right)$$

Constant core radius:
More massive cores have
- a deeper potential well
- a slower gas-expulsion t-s
- can survive despite a low SFE of, say, 20%



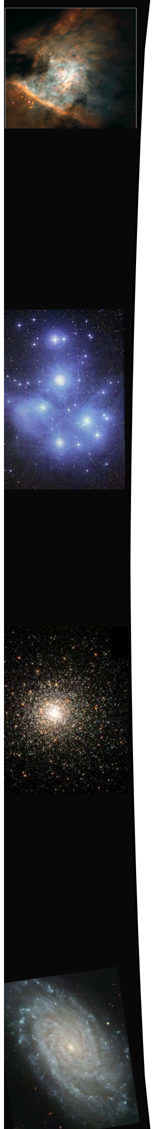
Parmentier, Goodwin et al. (2008)

F_{bound} is mass-independent

→ τ_{GExp}/τ_{cross} is mass-independent

but looser constrain

Tidal Field Impact and Cluster Mass Functions



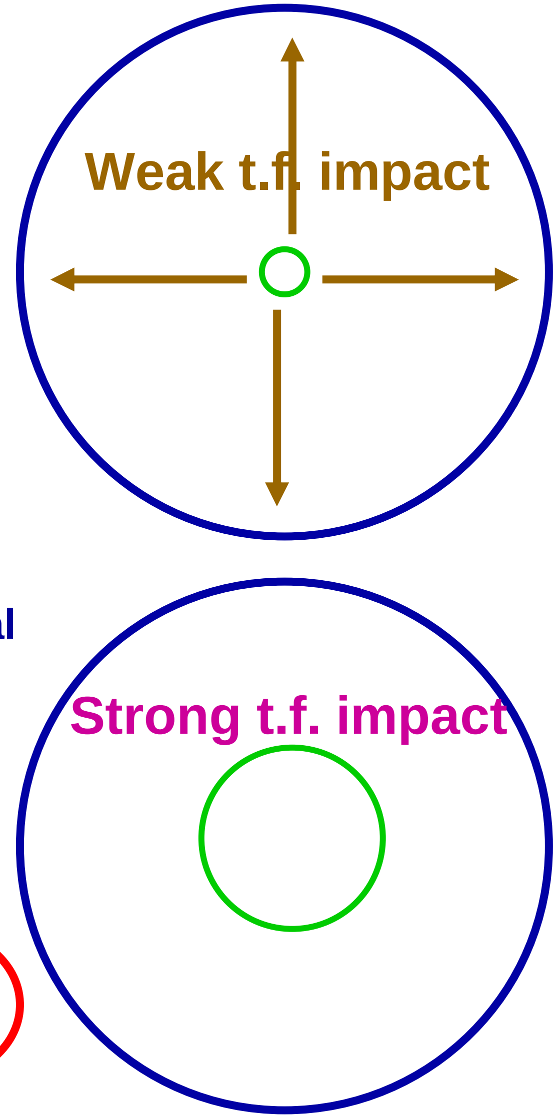
$$\textbf{SFE}\ \varepsilon, \frac{\tau_{GExp}}{\tau_{cross}}$$

- **Half-mass radius $r_{half\text{-}mass} \approx r_{core}$**
- **Circular velocity of iso-T potential V_c**
- **Galactocentric distance D_{gal}**
- **Embedded cluster mass m_{ecl}**

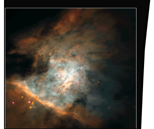
} r_{tidal}

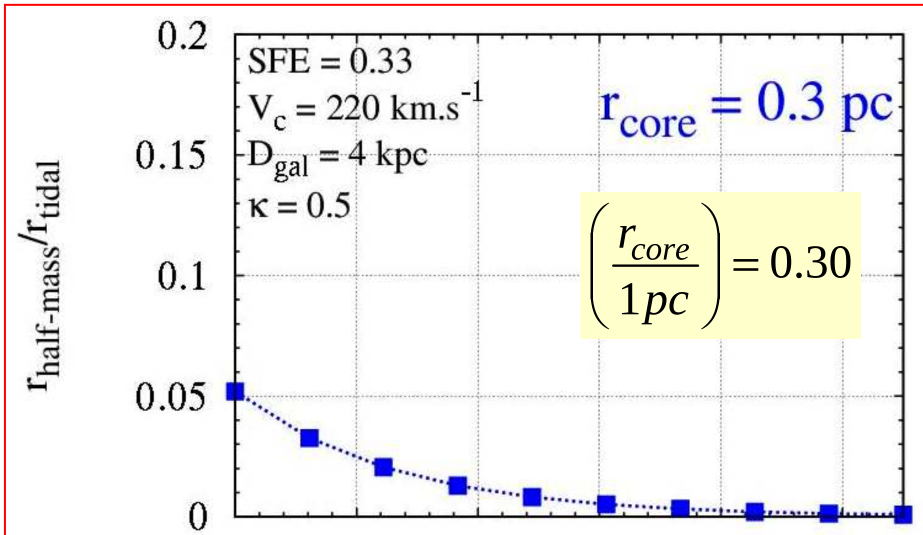
Limiting tidal radius:

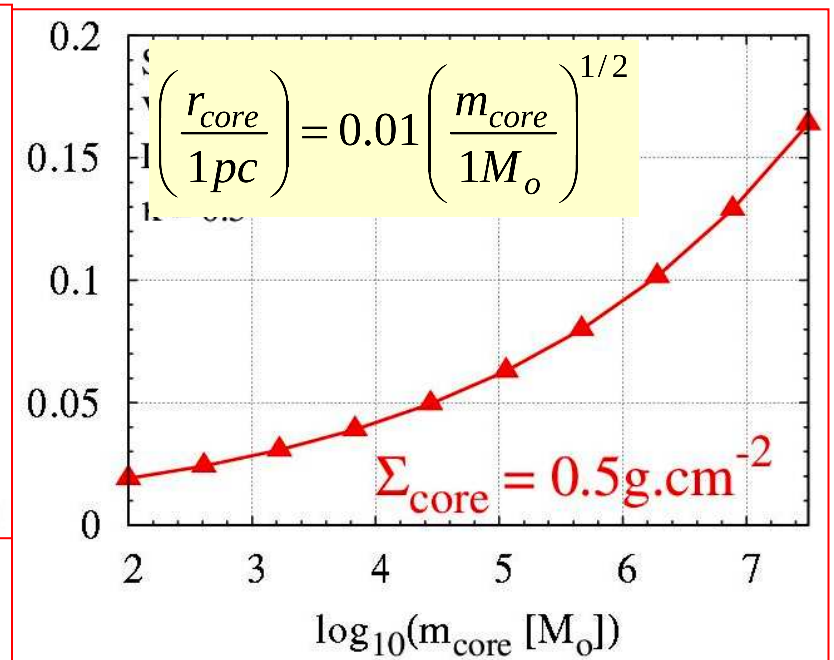
$$r_{tidal} = \left(\frac{G\, m_{ecl}}{2 V_c^2} \right)^{1/3} D_{gal}^{2/3}\ , \textbf{with}\ m_{ecl} = SFE.m_{core}$$

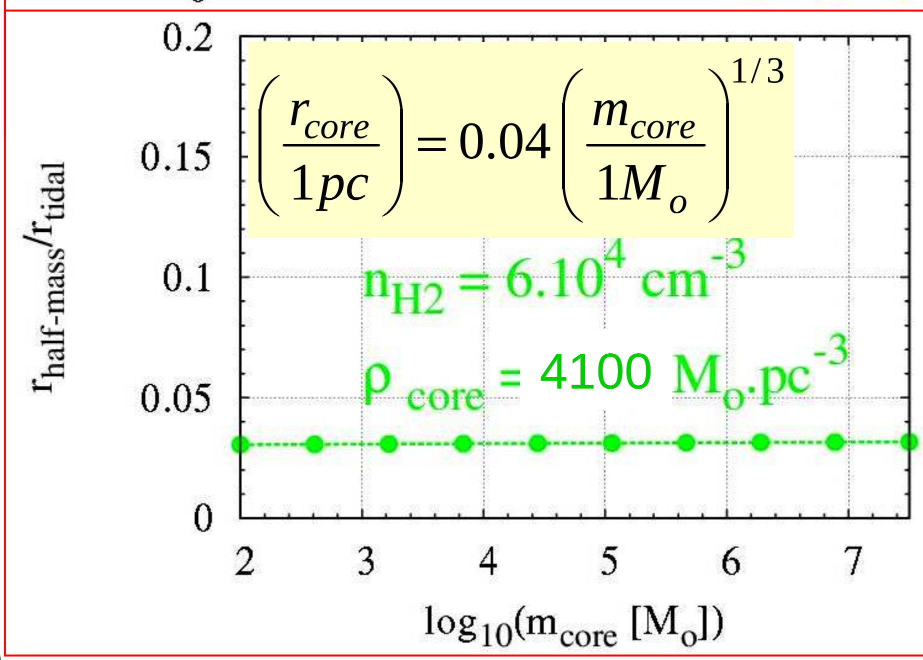


Half-mass radius—to—tidal radius ratio







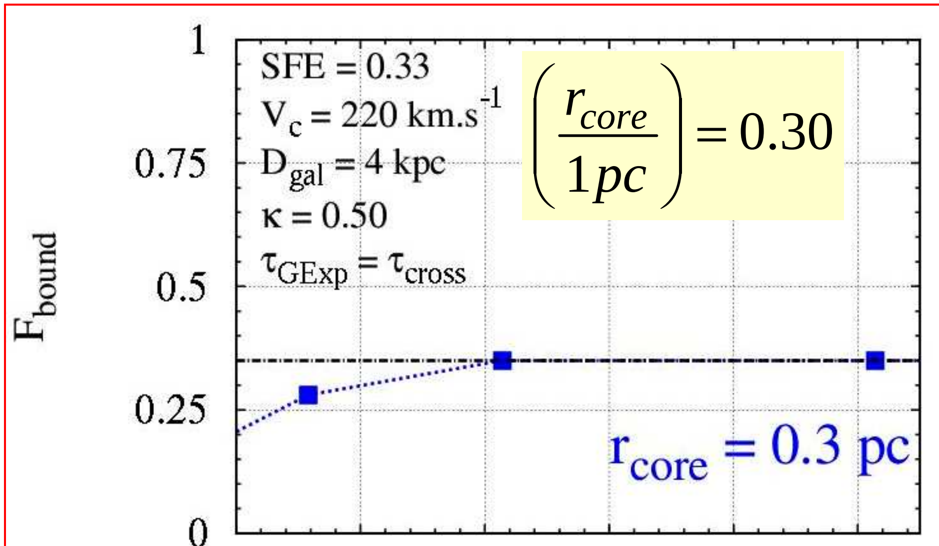


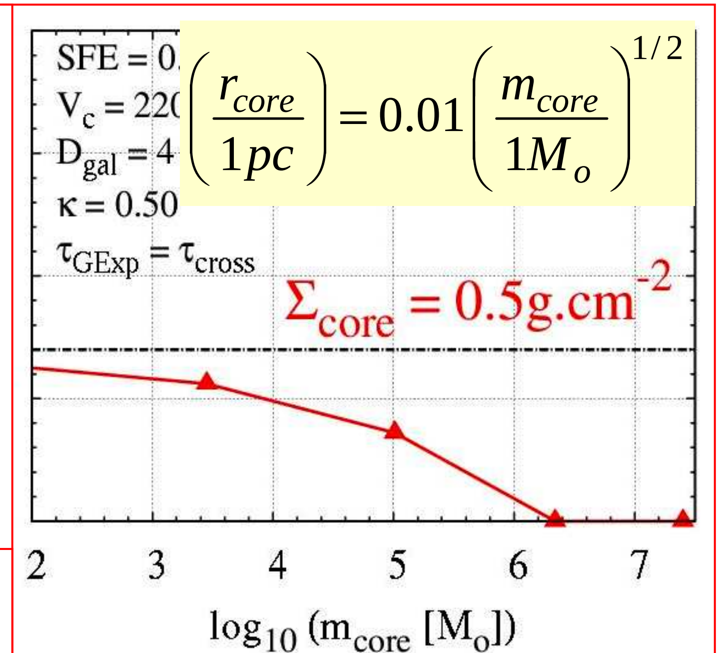
$$r_{core} \propto r_{half-mass} \propto m_{core}^{\delta}$$

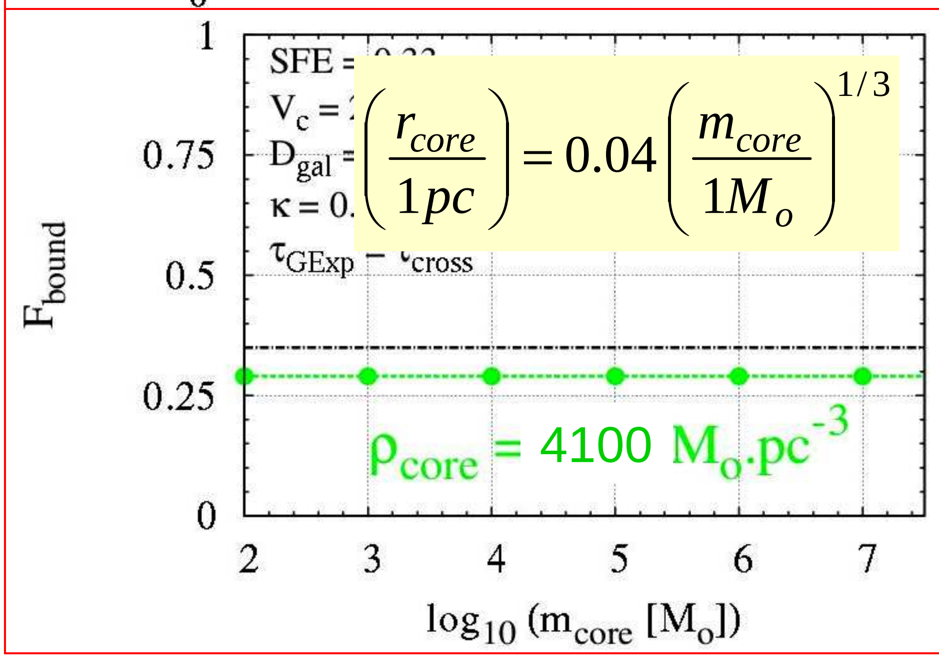
$$r_{tidal} \propto m_{ecl}^{1/3} \propto m_{core}^{1/3}$$

$$\frac{r_{half-mass}}{r_{tidal}} \propto m_{core}^{\delta-1/3}$$

F_{bound} and Tidal Field Impact

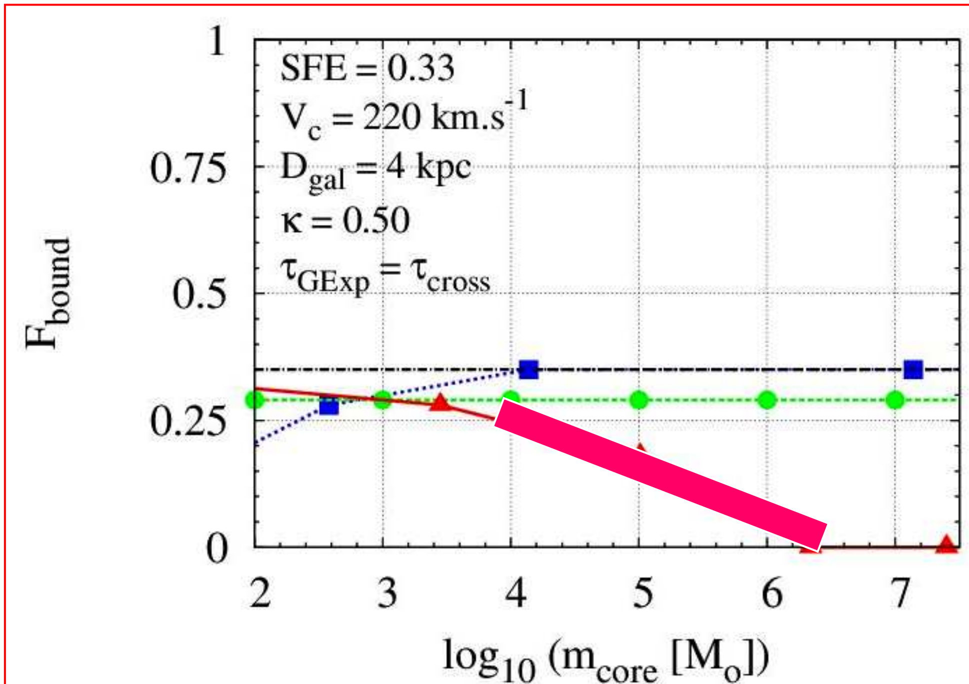






Parmentier & Kroupa (in press)

The m_{core} - r_{core} Diagram as a Diagnostic Tool



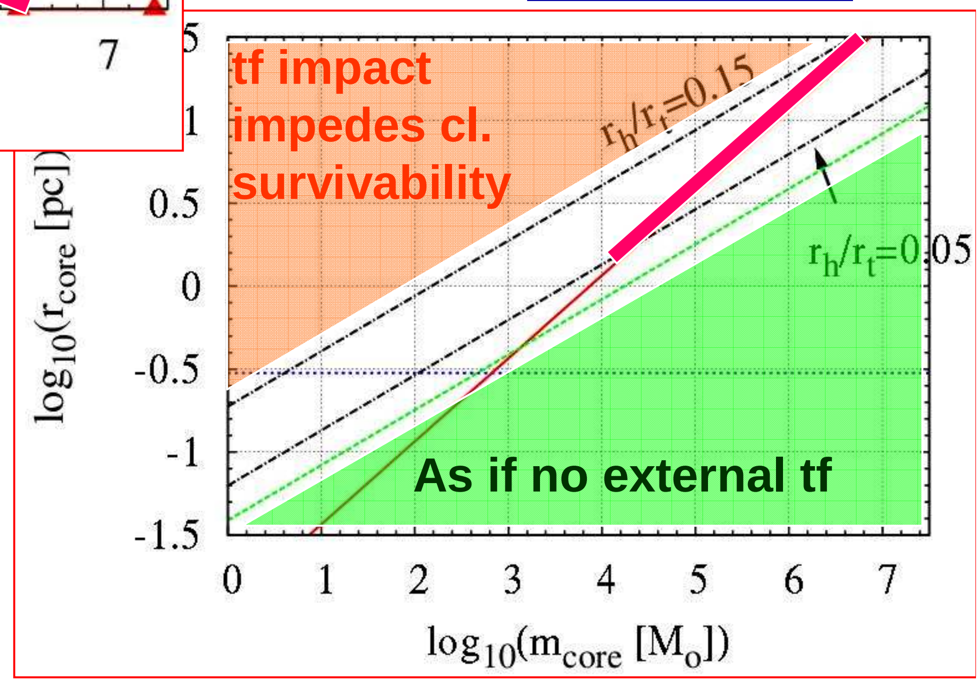
Σ_{core} $$\left(\frac{r_{core}}{1pc}\right) = 0.01\left(\frac{m_{core}}{1M_o}\right)^{1/2}$$

ρ_{core} $$\left(\frac{r_{core}}{1pc}\right) = 0.04\left(\frac{m_{core}}{1M_o}\right)^{1/3}$$

r_{core} $$\left(\frac{r_{core}}{1pc}\right) = 0.30$$

External tidal field strength:
(V_c, D_{gal}) → rh/rt in [log(r),log(m)]

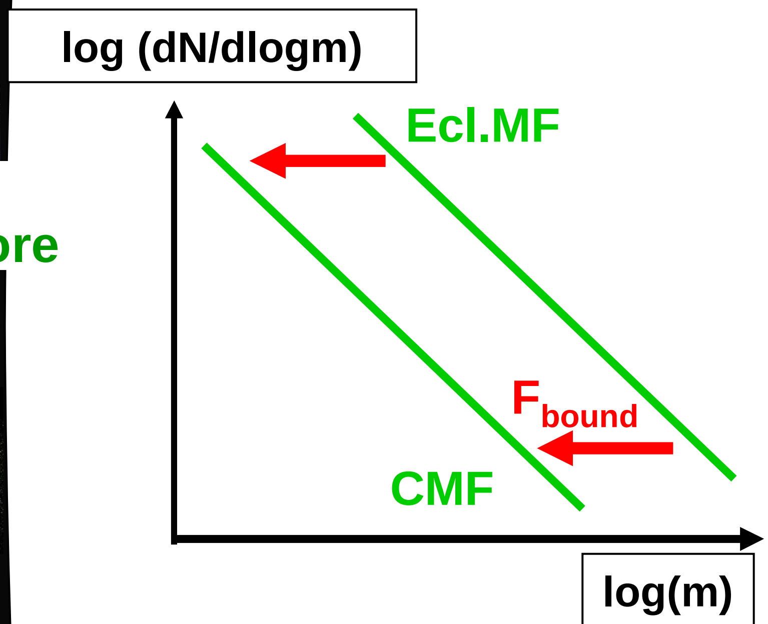
- **rh/rt < 0.05: tf does not matter**
  (<u>does not necessarily imply weak tf</u> !)
- **rh/rt > 0.15: cluster survivability demands long τ_{GExp}/τ_{cross} and high SFE**

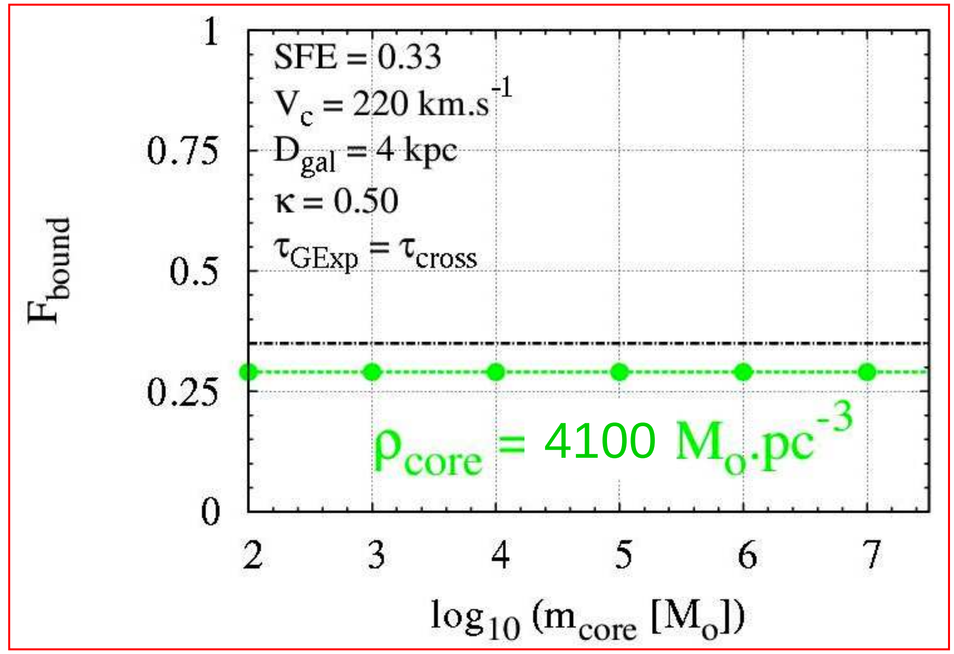


Tidal Field Impact and Cluster Mass Functions: Probing the cluster-forming core mass-radius relation

Cluster infant weight-loss is mass-independent, the shape of the cluster mass function does not evolve during VR

ρ_{core}

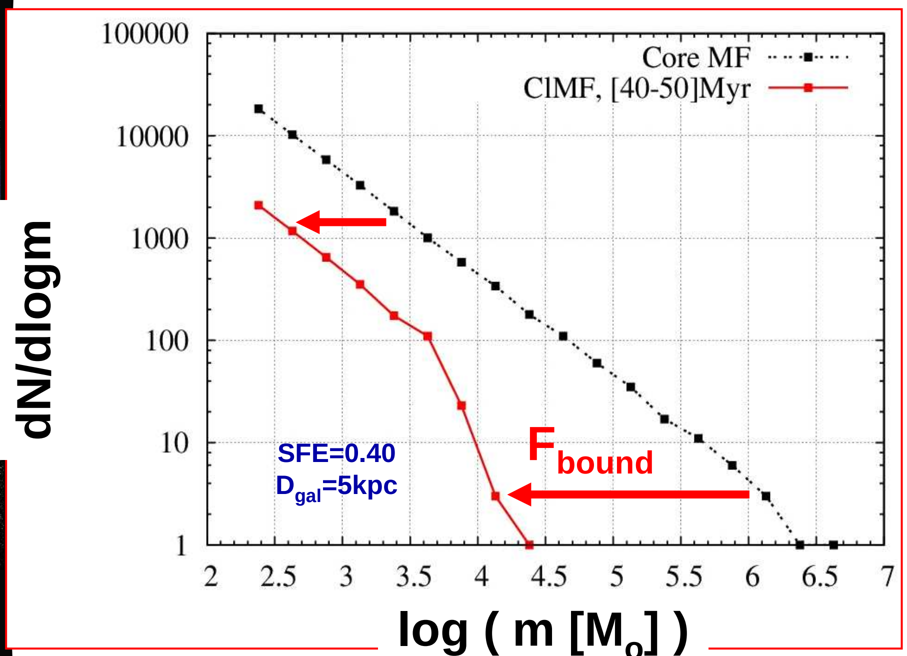


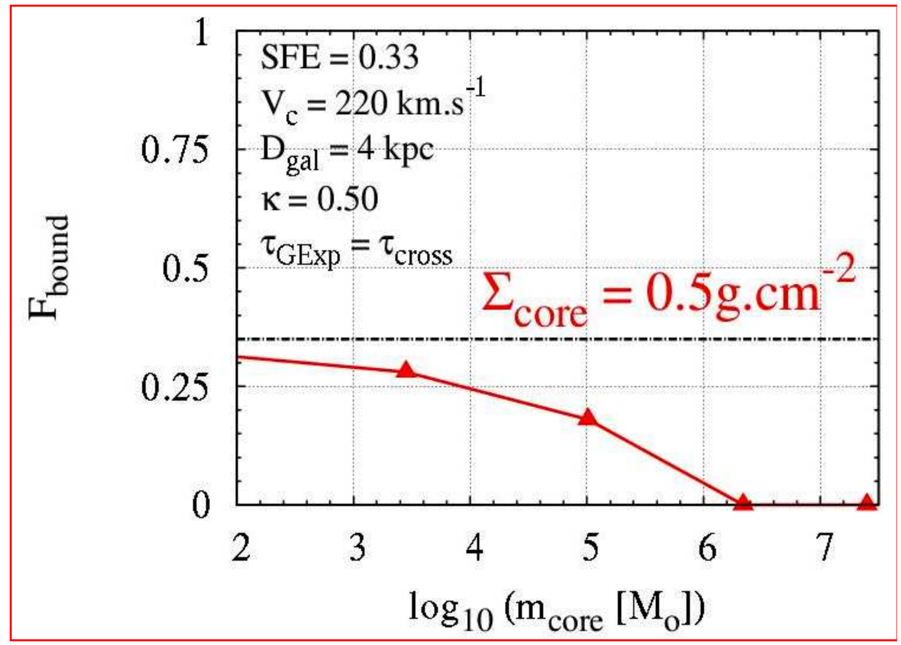


Constant Volume Density Cores:
mass-independent
infant weight-loss

$$\left(\frac{r_{core}}{1pc}\right) = 0.04\left(\frac{m_{core}}{1M_o}\right)^{1/3}$$

Tidal Field Impact and Cluster Mass Functions

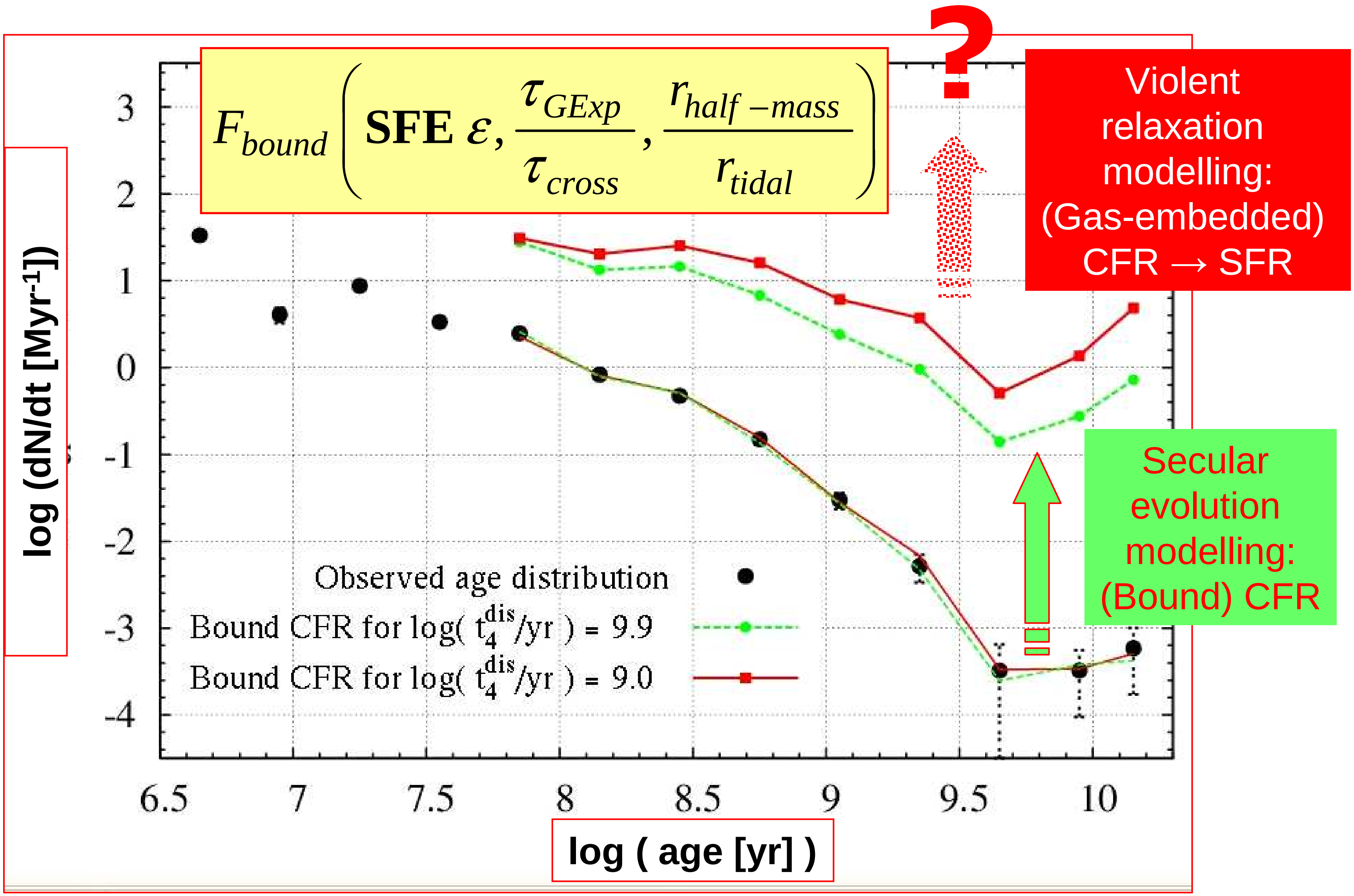




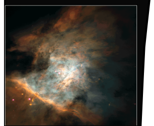
Constant Surface Density Cores:
When more massive
means more vulnerable ...

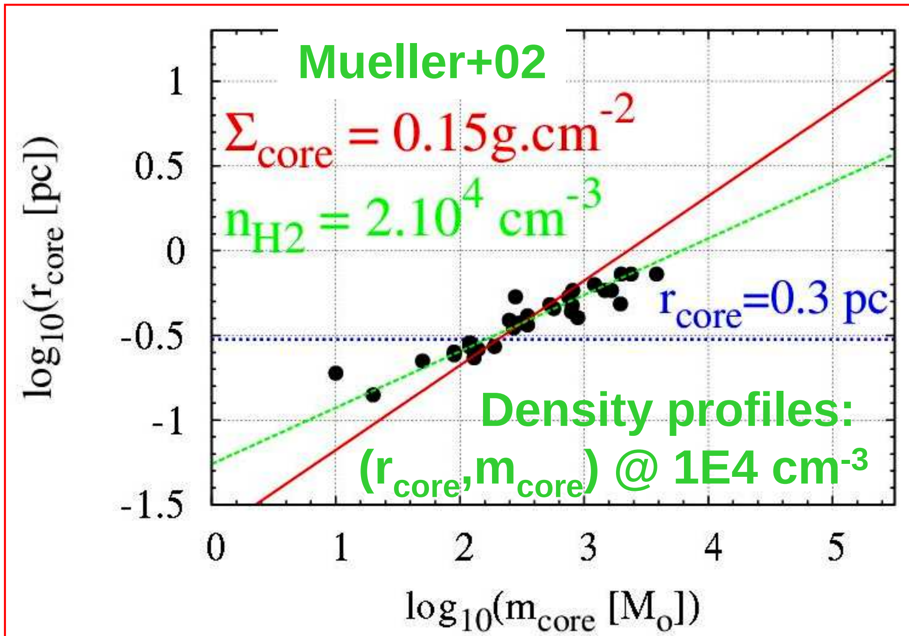
$$\Sigma_{core} : \left(\frac{r_{core}}{1pc}\right) = 0.01 \left(\frac{m_{core}}{1M_o}\right)^{1/2}$$

Galaxy Star Formation Histories: even a long journey starts with one single footstep ...



Core mass-radius relations: observations



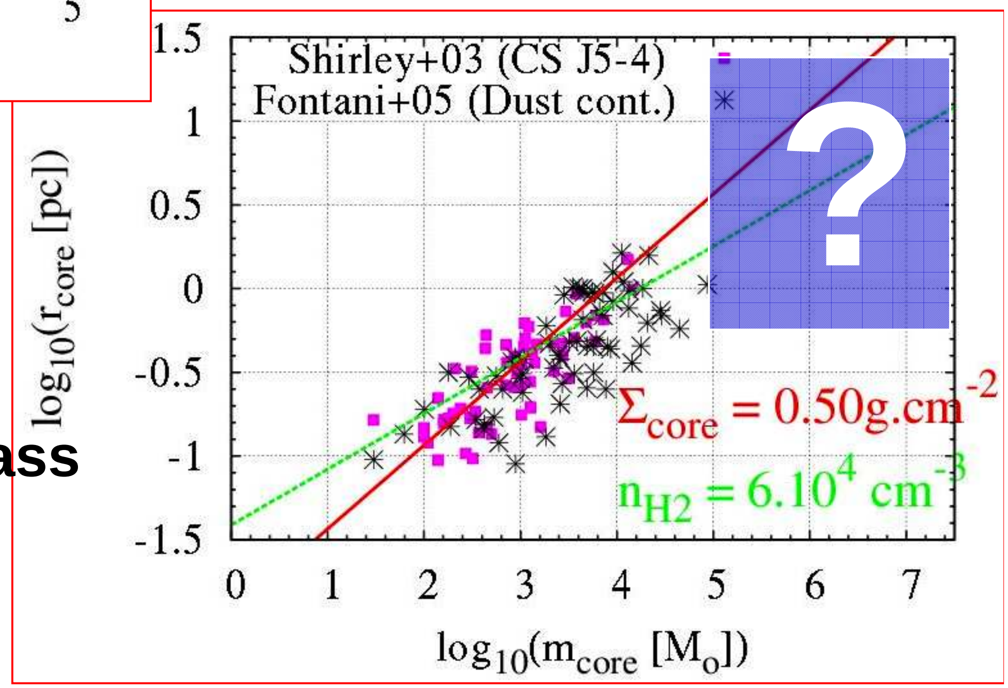


Core mass-radius diagram:
imprint of
- measurement method,
or of
- cluster-formation physics?

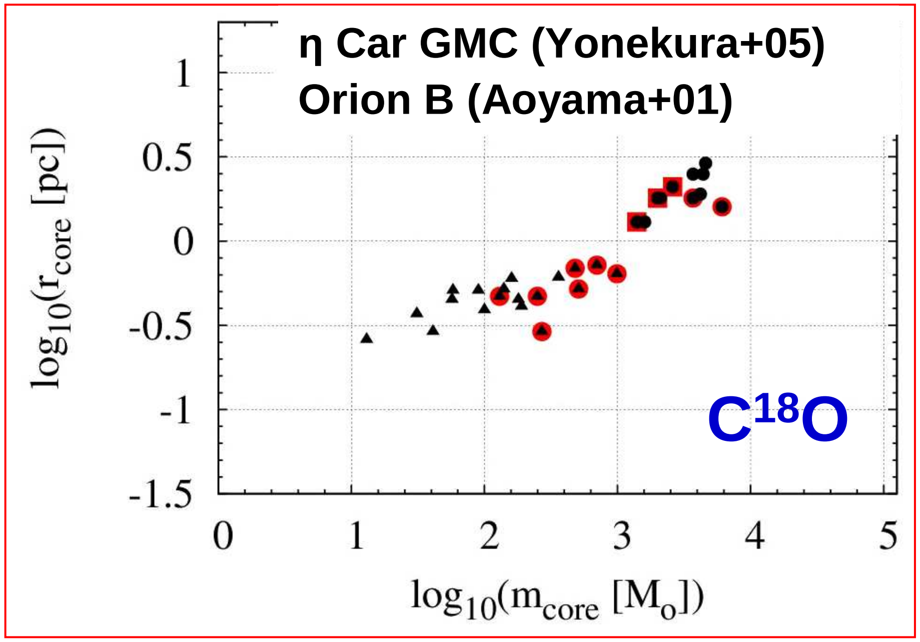
→ when picking-up obs data read (part of) the paper

Σ_{core} or ρ_{core} ?

- Limited baseline in cluster-forming core mass
- Lack of high-mass data

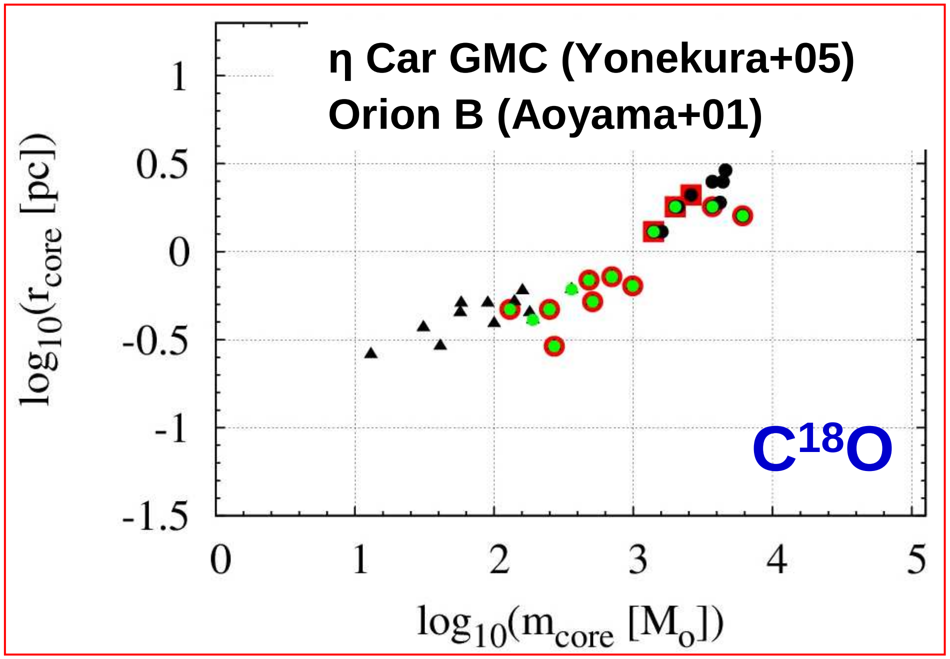


Core mass-radius relations: so what ... ?



- Red circles: $C^{18}O$ cores showing signs of SF activity

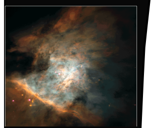
Core mass-radius relations: so what ... ?



- Red circles: $C^{18}O$ cores showing signs of SF activity

- Most of them also host a clump at 1E5 cm^{-3} ($H^{13}CO^+$)

→ SF takes place in regions where the density is higher than a threshold, i.e. only in the densest regions of $C^{18}O$ cores



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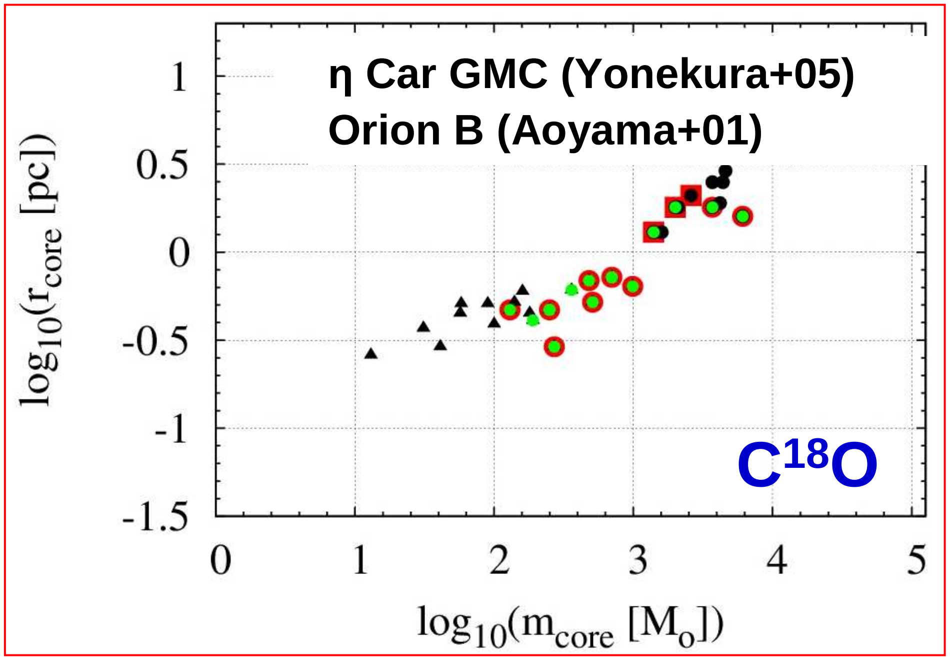

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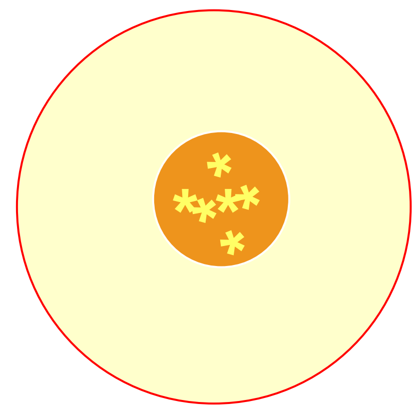
- **Why ? Efficient decay of turbulence … (Klessen 2003)**
- **Consequence: the local SFE must be measured over the cluster volume, not over the whole $C^{18}O$ core**



- **$H^{13}CO^{+}$ observations suggest:**
  <u>Constant volume density</u> cluster-forming cores, which lead to <u>mass-independent infant weight-loss (t.f. impact),</u> as suggested by observations

Parmentier & Kroupa (in press)

Conclusions

Properties of young star cluster systems
→ sharp insights into the clustered mode of star formation
→ star formation conditions determine what mass fraction clusters lose as they age
→ information needed to reconstruct galaxy SFH
→ time-variations ? (e.g. metallicity)

"Even a long journey starts with a one sinle step"
Oriental saying

Most exciting years are still to come:
HERSCHEL, ALMA, …