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Why the Cluster Initial Mass Function, the Molecular Core Mass-Radius Relation and the Local SFE are all Related Issues

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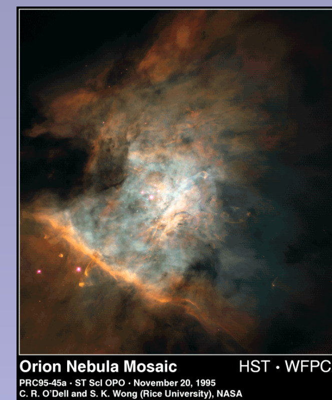
Phase 1: Gas Expulsion and Violent Relaxation

- Formation of a star cluster:
  conversion of a gas core into stars

- Protostellar cluster
  = gas + stars = gas-embedded cluster

- SNII activity
  - → removes left-over star forming gas
  - → terminates star formation
  - → weakens protocluster gravitational potential
  - → **escape of stars or**
    complete disruption of the protocluster



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Phase 1: Gas Expulsion and Violent Relaxation

Geyer & Burkert (2001)

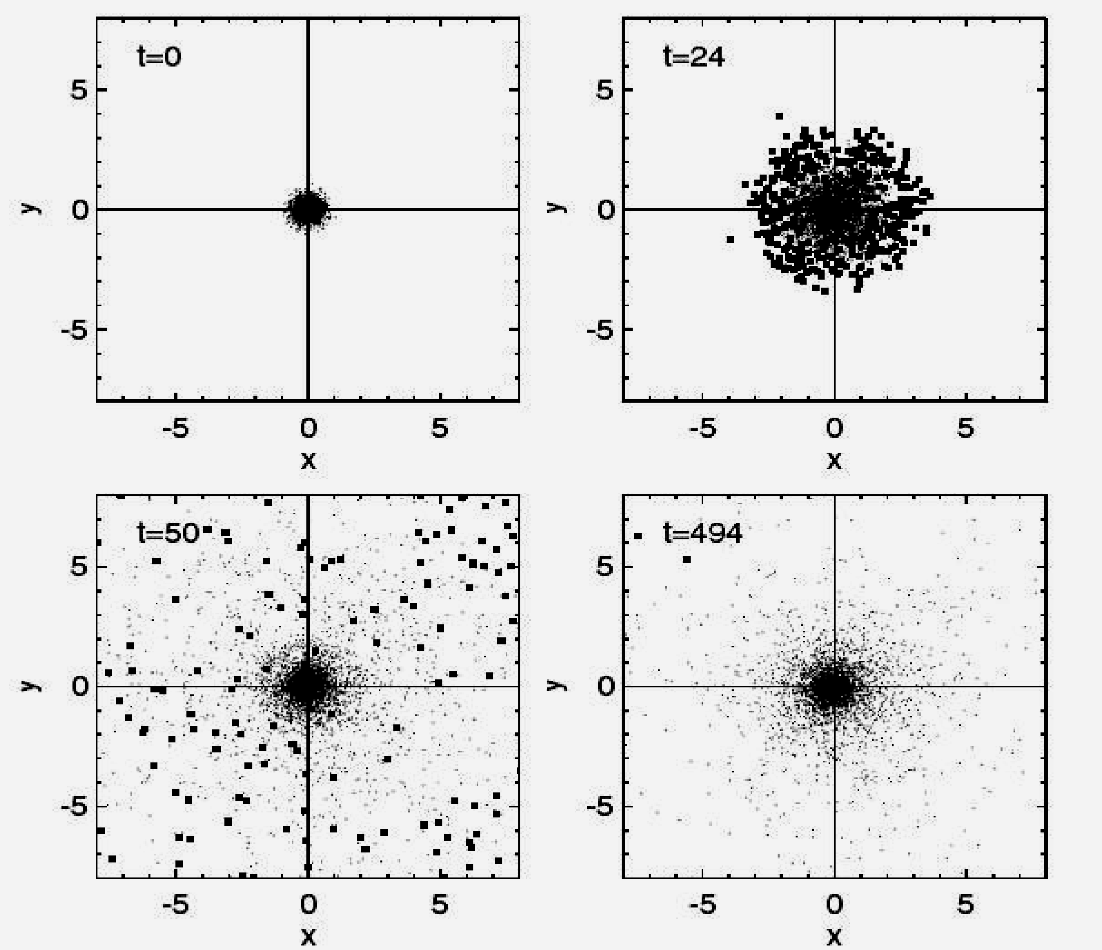
Stars + gas initially

in virial equilibrium :

$$\sigma_{stars} \cong \sqrt{\frac{G\left(M_{stars} + M_{gas}\right)}{R}}$$

(Instantaneous) gas removal :

$$\sigma_{stars} > \sqrt{\frac{GM_{stars}}{R}}$$



e evolution of model N3. The time t is given in dimensionless units. The SFE is $\epsilon = 0.4$, expulsion time $t_{exp} = 2$. The plots sh
l dots) projected on to the x–y-plane; unbound particles are indicated by squares.

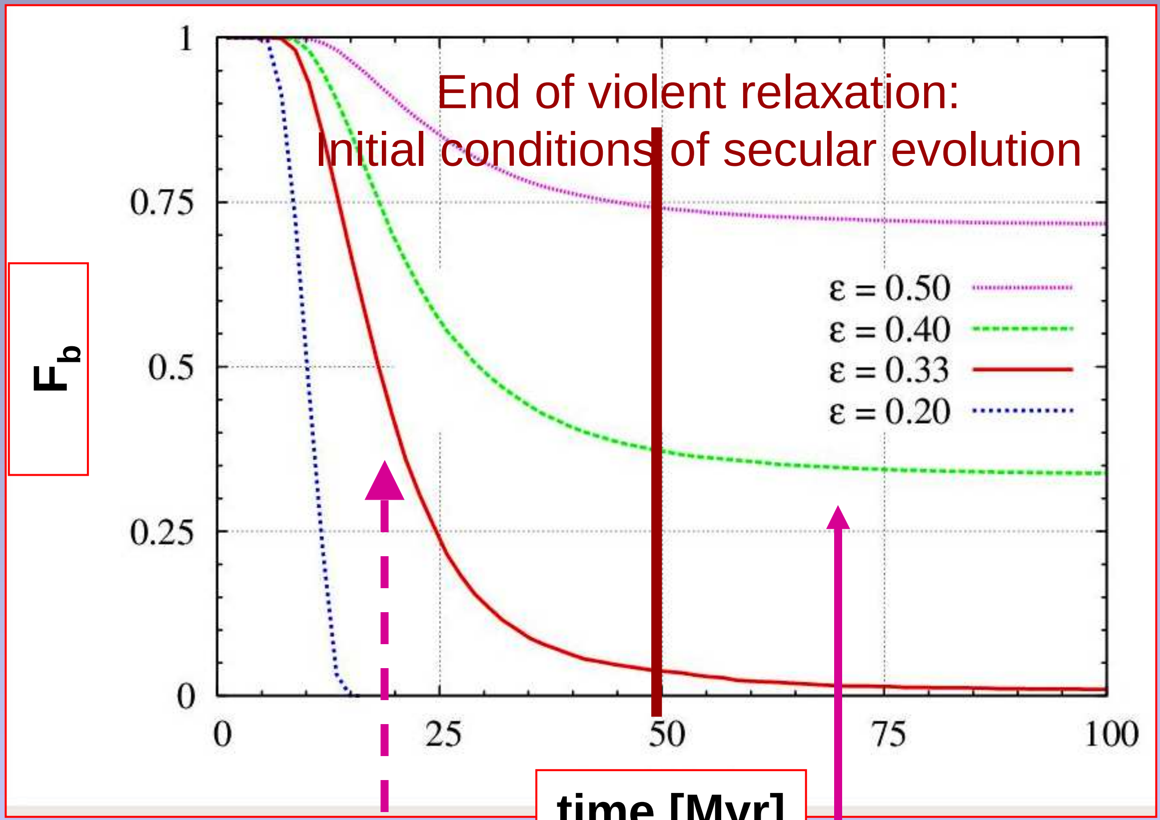
Effects of gas expulsion:
wider spatial configuration, escape of stars with the hottest kinematics, reduced mass in clustered stars

Phase 1: Gas Expulsion and Violent Relaxation

SFE ε = fraction of gas ending up in stars

F_b = fraction of stars remaining bound to the cluster after gas expulsion

Baumgardt & Kroupa 2007: Weak tidal field, instantaneous gas expulsion $\tau_{GR} << \tau_{cross}$



Initial conditions: for clusters gas-free and terminated infant weight-loss (age about 50Myr)

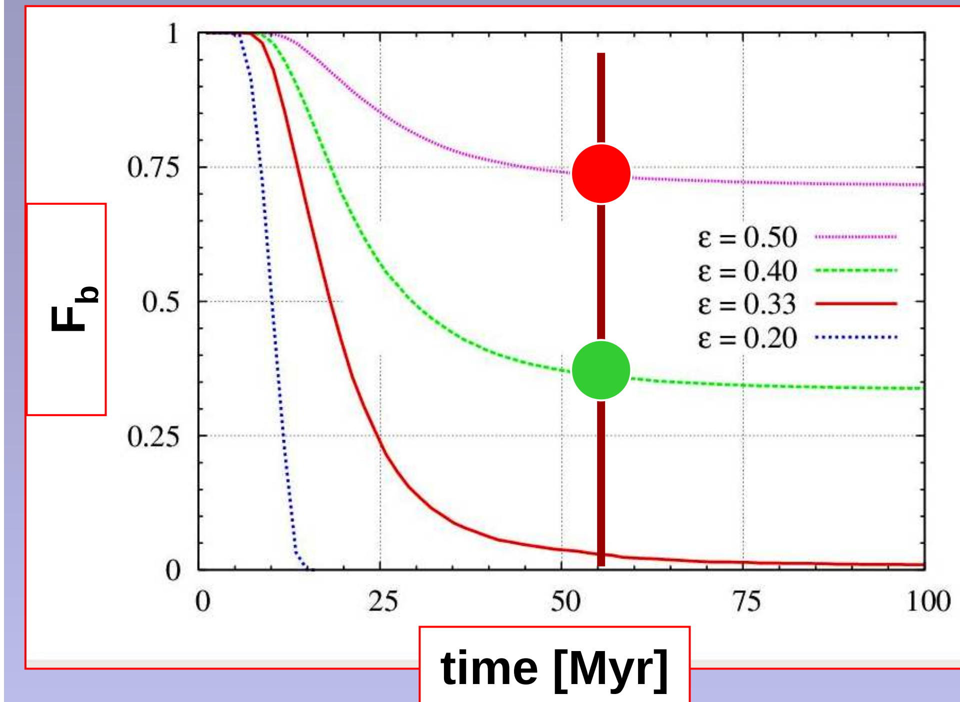
$$m_{cluster} = F_b(Age) \times \varepsilon \times m_{core}$$

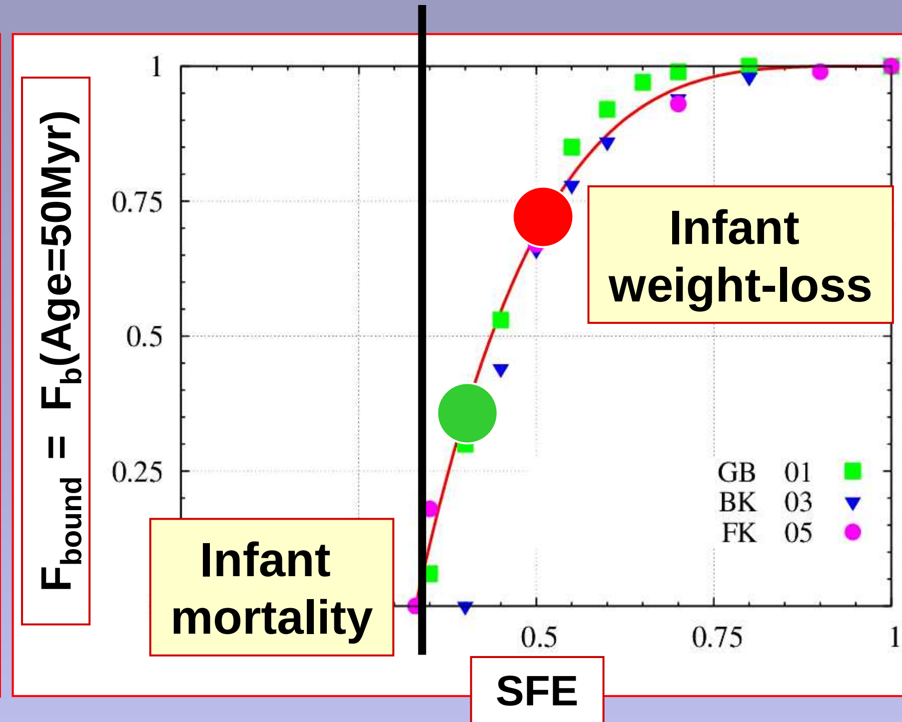
$$m_{cluster}^{init} = F_{bound} \times \varepsilon \times m_{core}$$

Cautionary note: the 50 Myr time-scale for the end of cluster violent relaxation indicated on several of my slides is intended to be an indicative one only.
The actual time-scale required by a protocluster to reach the end of its violent relaxation depends on its crossing-time when still embedded and on the tidal field impact on the protocluster.

See Fig.4 in Parmentier (2009, Astro-ph:0901/3140) and slide 22.

Phase 1: Notion of Initial Cluster Mass





Parent core : m_{core}

Star Formation $\rightarrow$ **Gas - embedded cluster :**

$$m_{ecl} = SFE \times m_{core} \qquad \textbf{[time = 0Myr]}$$

Gas expulsion $\rightarrow$ **Gas - free bound cluster in equilibrium :**

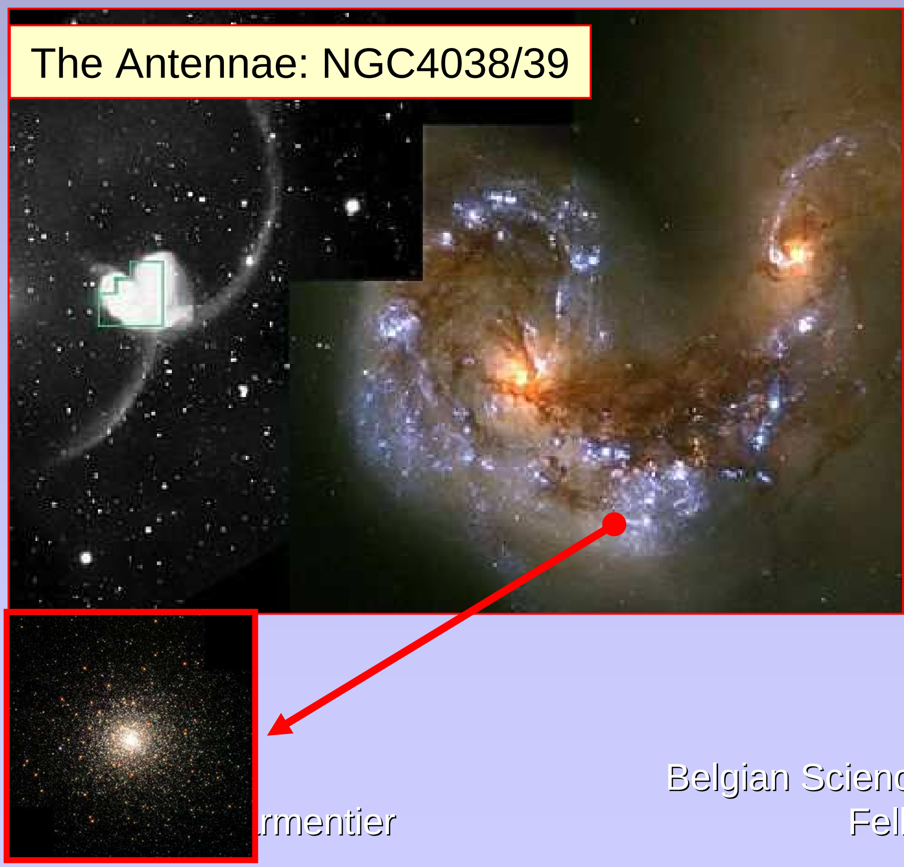
$$m_{cluster}^{init} = F_{bound} \times SFE \times m_{core} \qquad \textbf{[time = 50Myr]}$$

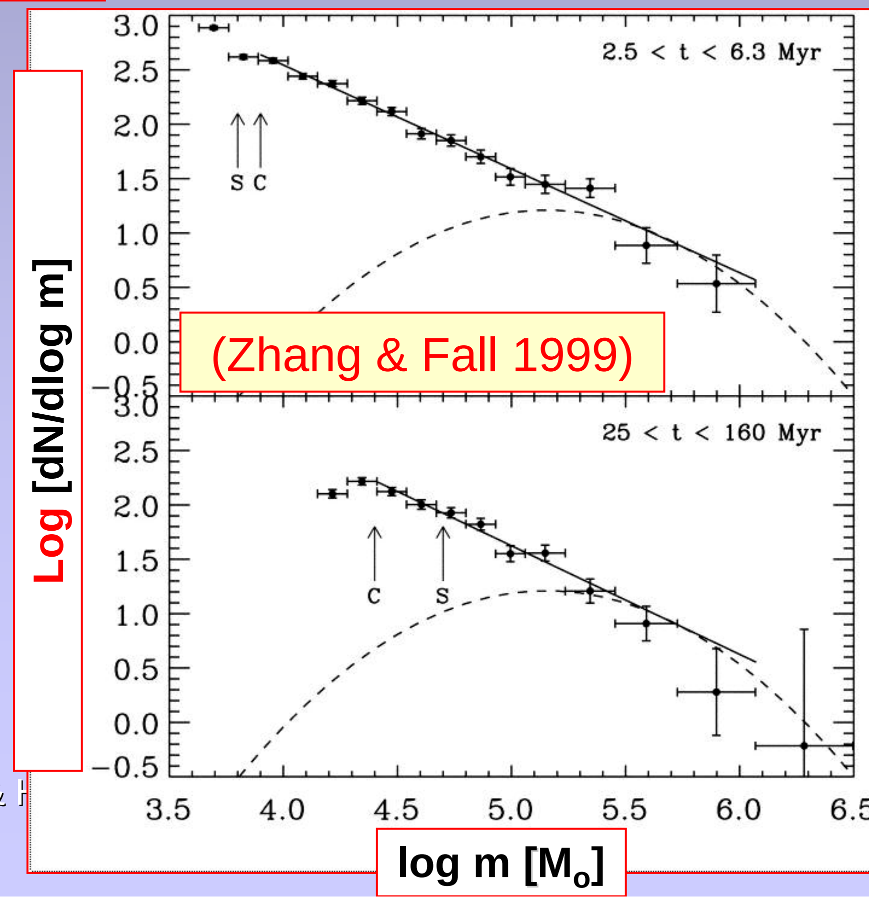
Observationally derived Cluster Mass Functions (CMF) of Young Clusters

Hubble Space Telescope
⇒ Young star clusters
with mass and compactness ~ old GCs
in violent star forming environments

Power - law CMFs :

$$\frac{dN}{dm} \propto m^{-2} \equiv \frac{dN}{d\log m} \propto m^{-1}$$





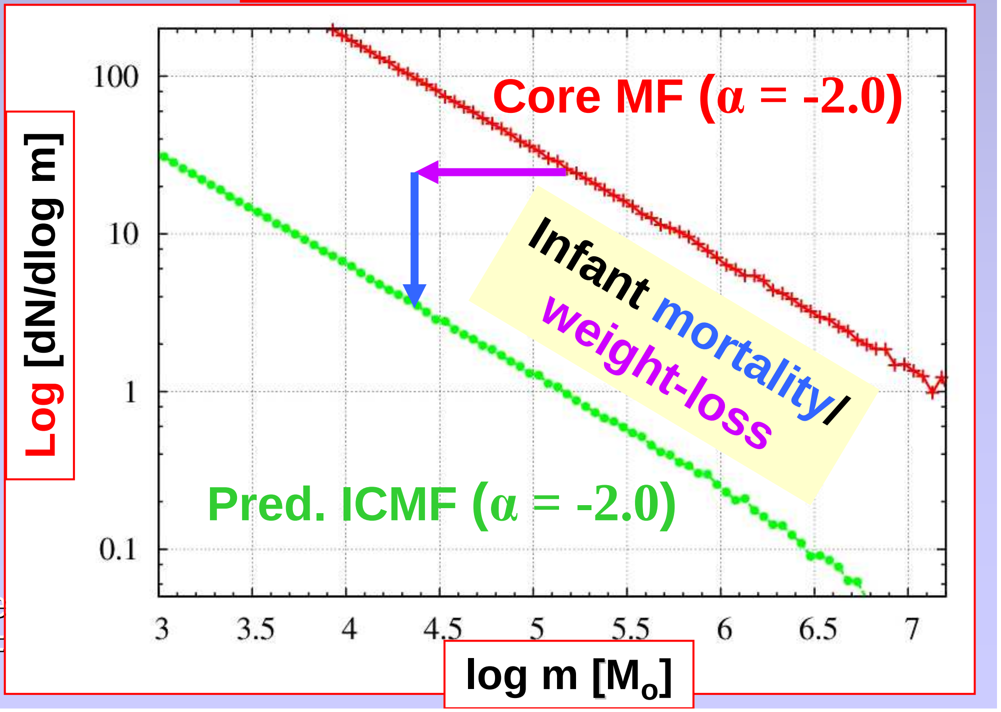
The Initial Cluster Mass Function (ICMF) and the cluster gaseous progenitor MF

A featureless power-law core mass function is conducive to the same ICMF, provided that neither F_{bound} nor (SFE) ε show core mass dependence

$$\frac{dN}{dm} \propto m^{-2} \equiv \frac{dN}{d\log m} \propto m^{-1}$$

Is it really true ?

$$m_{cluster}^{init} = F_{bound} \times \varepsilon \times m_{core}$$



Henny 's input at conference panel discussion:

- Core mass function is a power-law

- Embedded cluster mass function is a power-law
  - ⇒ SFE is core mass-independent
  - But the opposite may be expected from a theoretical point of view (Elmegreen)

- Cluster mass function is a power-law
  - ⇒ F_{bound} is core mass-independent
  - Conditions for this ?

Core

$$m_{core}$$

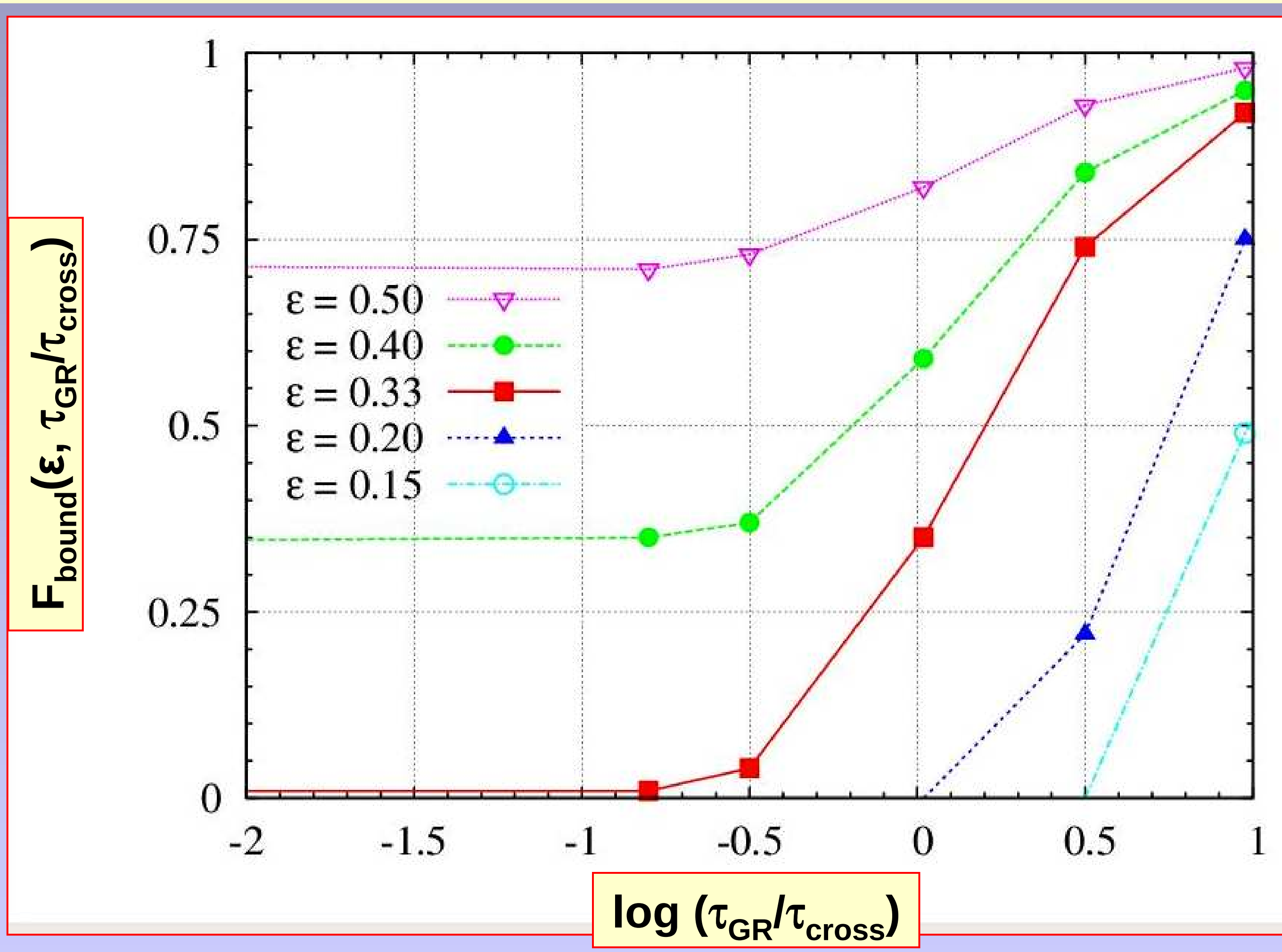
Gas - embedded cluster :

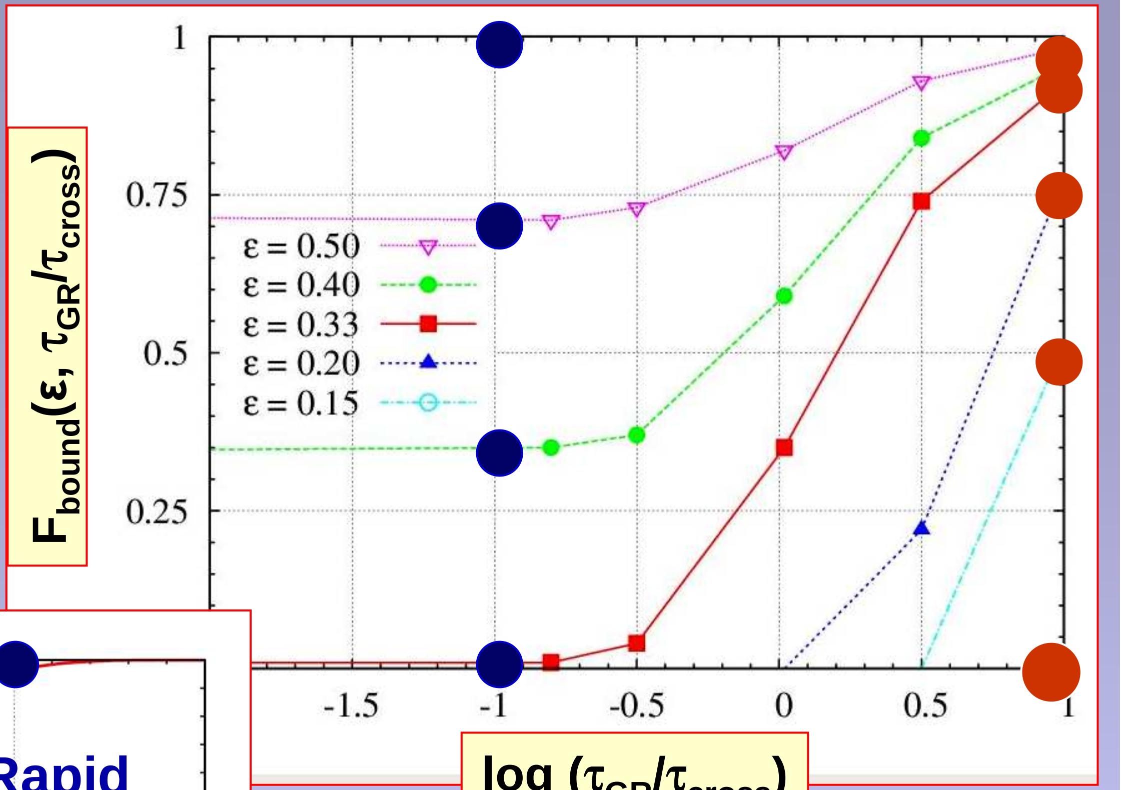
$$m_{ecl} = SFE \times m_{core}$$

Gas - free bound cluster :

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

Fig.1 in Parmentier et al.2008 (based on the N-body model grid of Baumgardt & Kroupa 2007):
Case of SCs subjected to weak tidal fields (ie $r_h/r_t <= 0.01$)




1
0.75
0.5
0.25
ε = 0.50
ε = 0.40
ε = 0.33
ε = 0.20
ε = 0.15
-1.5
-1
-0.5
0
0.5
1
$F_{bound}(\varepsilon, \tau_{GR}/\tau_{cross})$
log (τ_{GR}/τ_{cross})

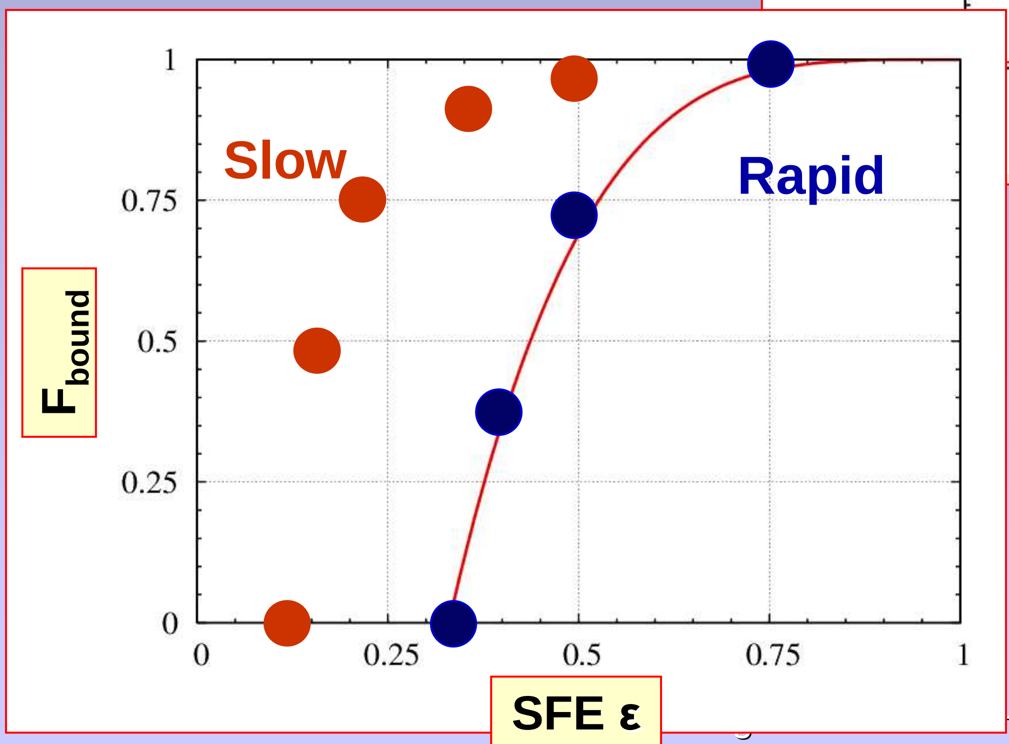
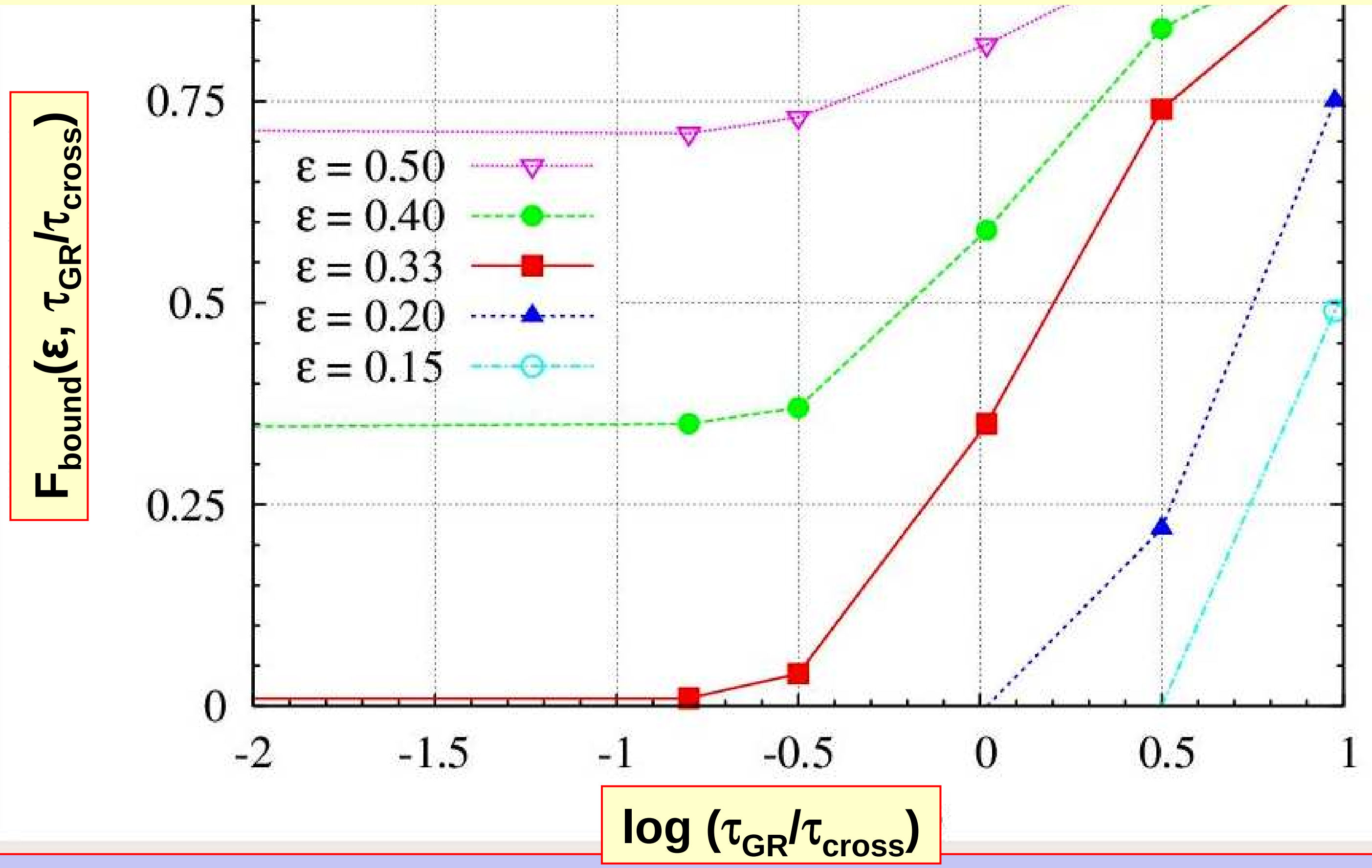

1
0.75
0.5
0.25
0
0
0.25
0.5
0.75
1
Slow
Rapid
F_{bound}
SFE ε

Fig.1 in Parmentier et al.2008

Case of SCs subjected to weak tidal fields (ie $r_h/r_t <= 0.01$)



If the core gravitational pull increases, gas is removed on a slower time-scale and τ_{GR}/τ_{cross} may increase …
Substantial observations (see Kroupa & Boily 2002) show that $r_{core} \cong 1$pc regardless of the mass

→ **relation between m_{core} and F_{bound}**

How to quantify the relation between τ_{GR}/τ_{cross} and m_{core} ?

Removal of intracluster gas via the expansion of a supernova-driven supershell
→ compute temporal evolution of supershell radius: $r_s(t)$

$$r_S(t) = \left(\frac{125}{154\pi} \frac{dE_0}{dt} \frac{1}{\rho_{gas}} \right)^{1/5} t^{3/5}$$

Castor, McCray & Weaver 1975

$$N_{SNII} \leftarrow (m_{core}, \varepsilon, IMF)$$

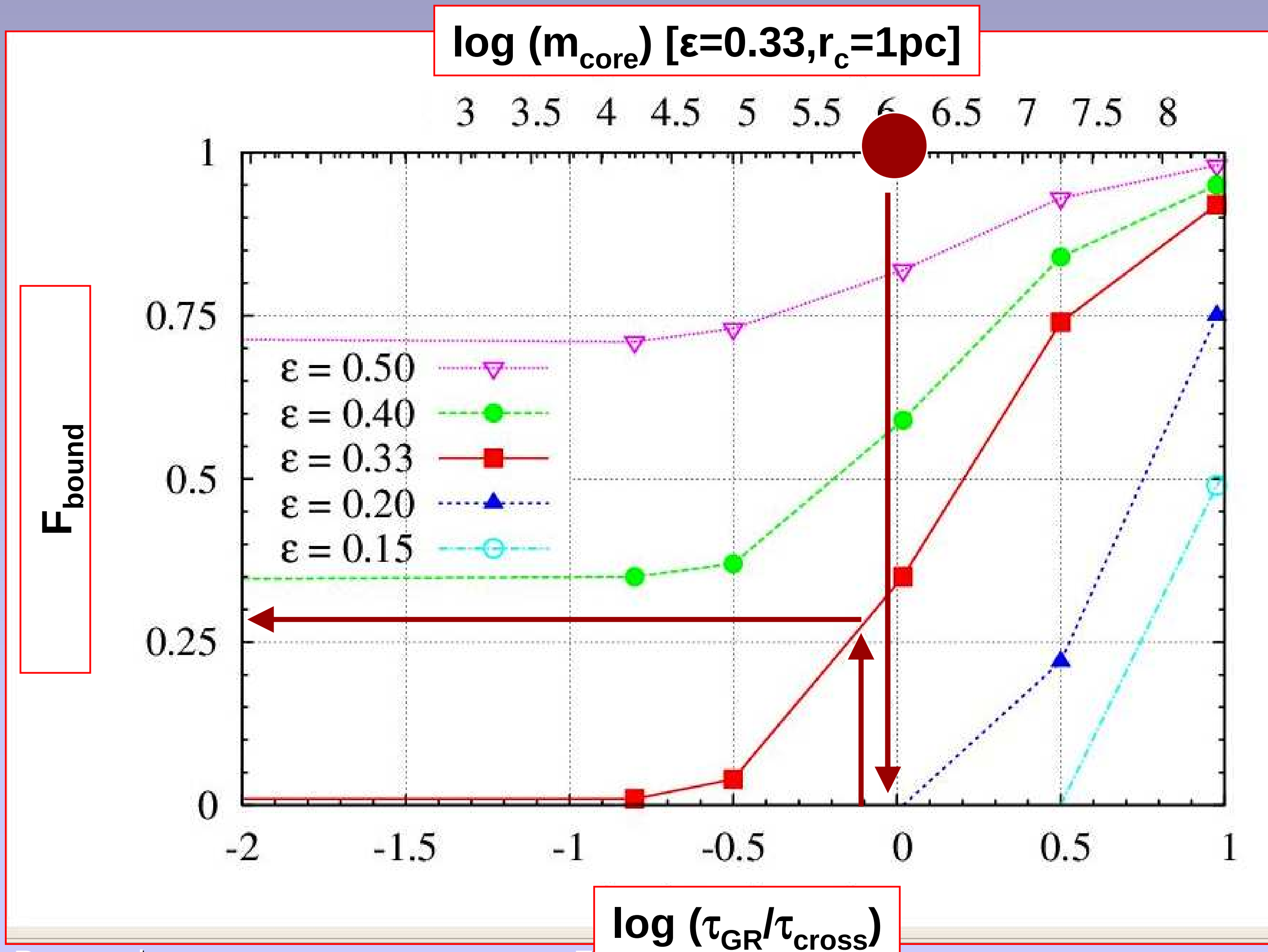
$$\rho_{gas} = (1-\varepsilon) \times \rho_{core}$$

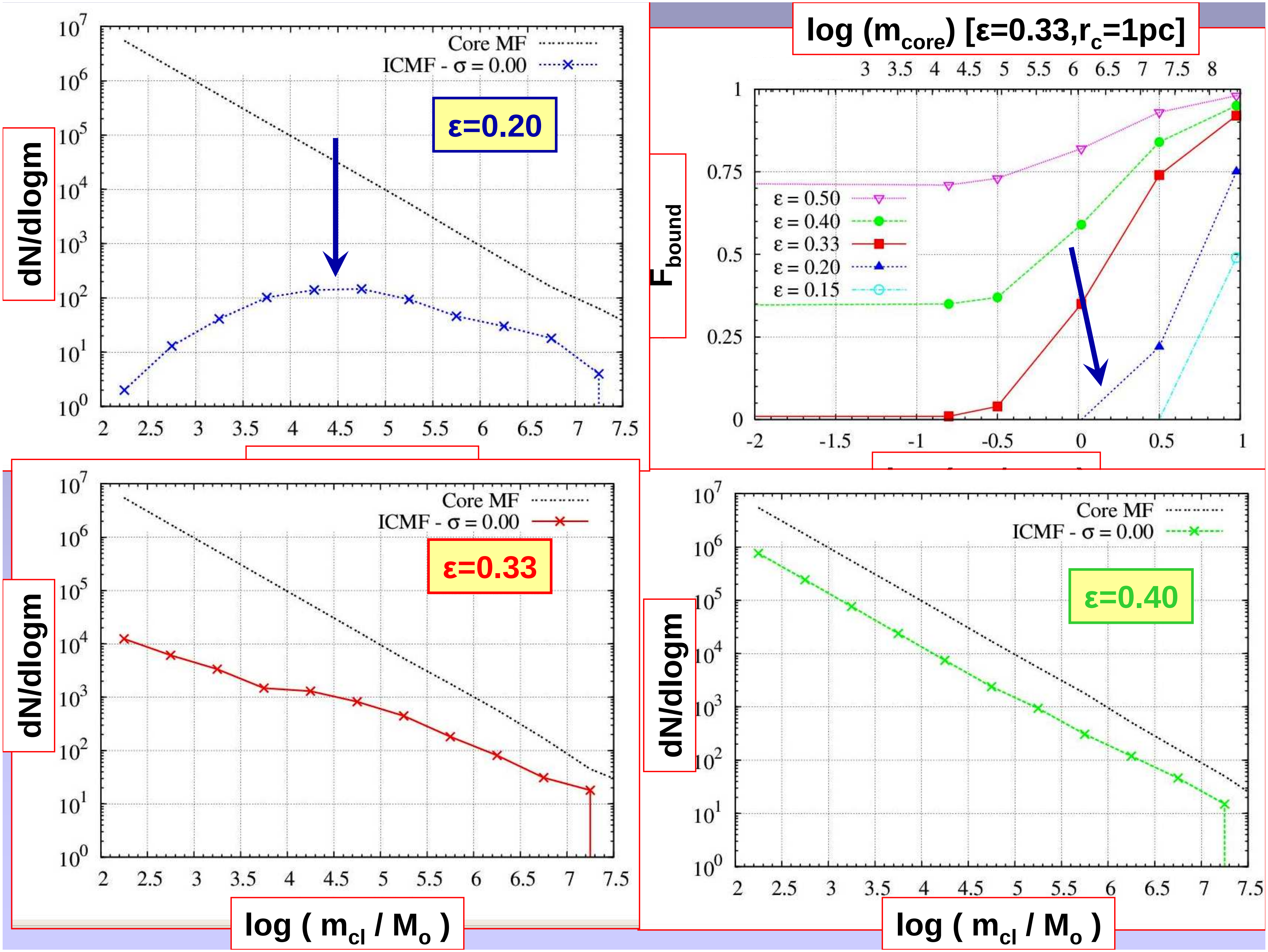
$$\tau_{GR} \leftrightarrow r_S(\tau_{GR}) = r_{core}$$

$$\frac{\tau_{GR}}{\tau_{cross}} \cong 6 \times 10^{-4} \left(\frac{1-\varepsilon}{\varepsilon} \right)^{1/3} m_{core}^{1/2} \, r_{core}^{-5/6}$$

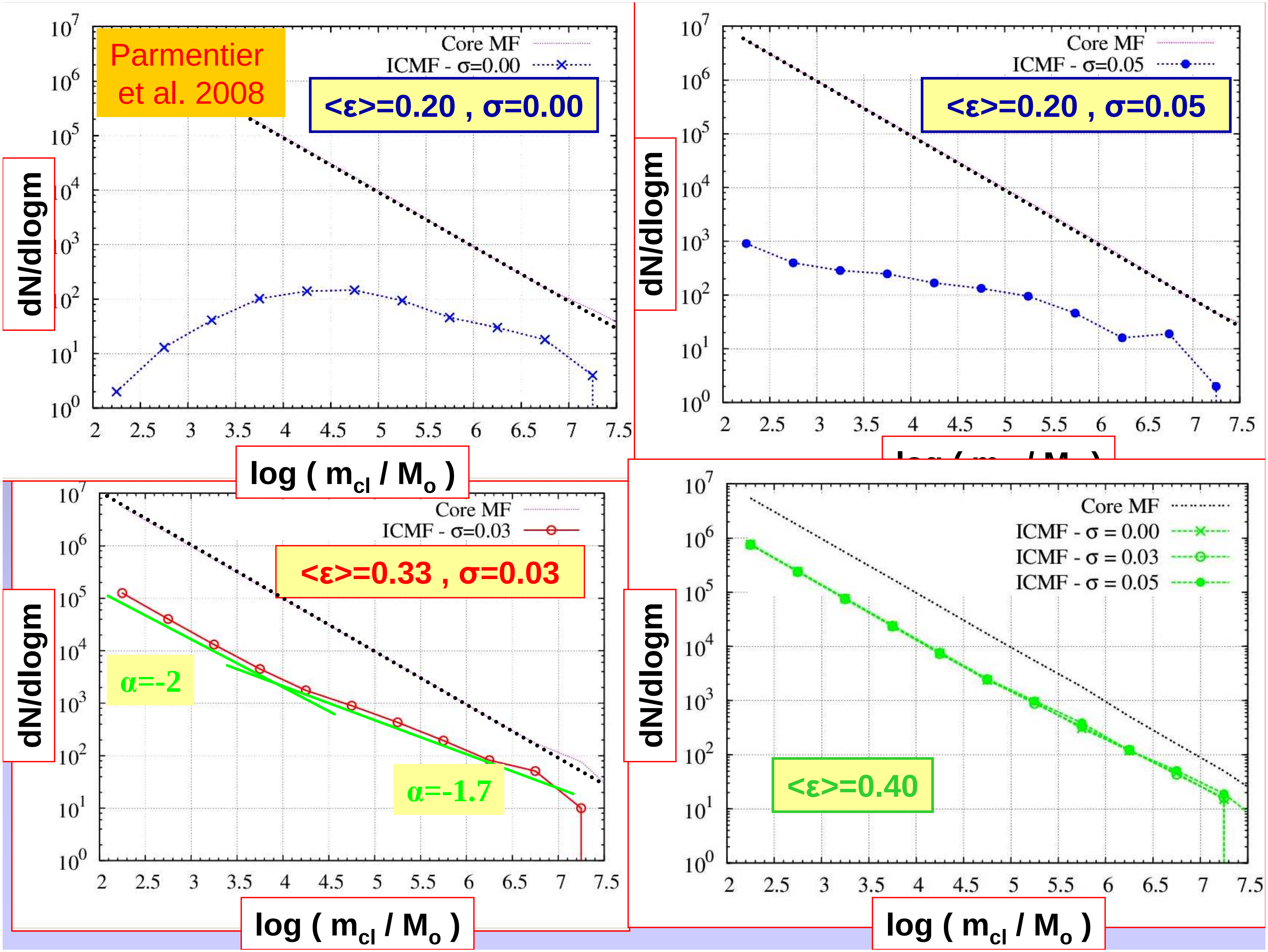
$$\frac{\tau_{GR}}{\tau_{cross}} \cong 6\times10^{-4}\left(\frac{1-\varepsilon}{\varepsilon}\right)^{1/3} m_{core}^{1/2}\ r_{core}^{-5/6}$$

$$m_{cluster}^{init} = F_{bound} \times \varepsilon \times m_{core}$$





dN/dlogm
Core MF
ICMF - σ = 0.00
ε=0.20
log (m_core) [ε=0.33,r_c=1pc]
F_bound
ε = 0.50
ε = 0.40
ε = 0.33
ε = 0.20
ε = 0.15
ε=0.33
ε=0.40
log (m_cl / M_o)
log (m_cl / M_o)


Parmentier et al. 2008
<ε>=0.20 , σ=0.00
Core MF
ICMF - σ=0.00
dN/dlogm
log (m_cl / M_o)
<ε>=0.20 , σ=0.05
Core MF
ICMF - σ=0.05
dN/dlogm
<ε>=0.33 , σ=0.03
Core MF
ICMF - σ=0.03
α=-2
α=-1.7
dN/dlogm
log (m_cl / M_o)
<ε>=0.40
Core MF
ICMF - σ = 0.00
ICMF - σ = 0.03
ICMF - σ = 0.05
dN/dlogm
log (m_cl / M_o)

$$\frac{\tau_{GR}}{\tau_{cross}} \cong 6\times10^{-4}\left(\frac{1-\varepsilon}{\varepsilon}\right)^{1/3} m_{core}^{1/2}\, r_{core}^{-5/6}$$

Young CMF = PL (universally)

What about the present-day GC mass-function ? CMF in intermediate-age mergers required !

$$r_{core} \propto m_{core}^{1/2} \;\Rightarrow\; \frac{\tau_{GR}}{\tau_{cross}} \cong const$$

$$F_{bound} \cong const \;\Rightarrow\; PL \rightarrow PL$$

$$r_{cluster} \propto m_{cluster}^{1/2}$$

while $r_{cluster} \cong const$ is observed

Zepf & Ashman: SFE variations ?

$$r_{core} = const \;\Rightarrow\; \frac{\tau_{GR}}{\tau_{cross}} \cong m_{core}^{1/2}$$

$F_{bound}(m_{core})$:

$PL \rightarrow PL$ **if SFE $\cong$ 0.4**

$PL \rightarrow Bell-shape$ **if SFE $\cong$ 0.2**

Mostly infant weight-loss

Infant mortality: definition of a cluster ??

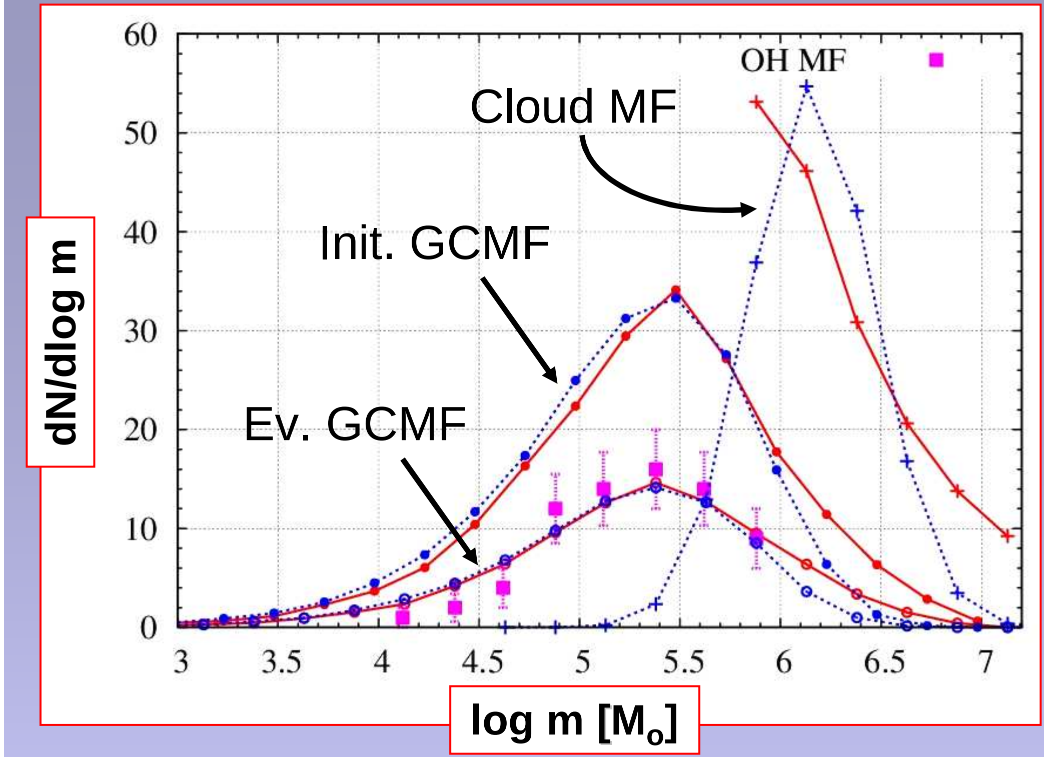


Figure adapted from Parmentier & Gilmore (2007)

Gaussian present-day GCMF = state of equilibrium
(Vesperini 1998)

Universal GC MF ?

- Gas removal (regardless of its time-scale)
- Common protoglobular cloud mass-scale ($\cong 10^6 M_o$), which may be an imprint of the protogalactic era (Fall & Rees 1985, Bromm & Clarke 2002)

See also Baumgardt, Kroupa & Parmentier (2008)

Young CMF = PL (universally): some caveats

A. Beware of CMF integrated over time
B. Be open-minded

Power-law CMF with $\alpha \cong -2$:

- NGC4038/39:
  Zhang & Fall 1999
- M51:
  Bik et al. 2003
- LMC:
  de Grijs & Anders 2006
- Milky Way disc:
  Battinelli, Brandimarti & Capuzzo-Dolcetta 1994

Bell-shaped (turnover) CMF:

- NGC5253:
  Cresci, Vanzi & Sauvage 2005
- He 2-10:
  Johnson (Granada Conference)

Bell-shaped (turnover) CLF:

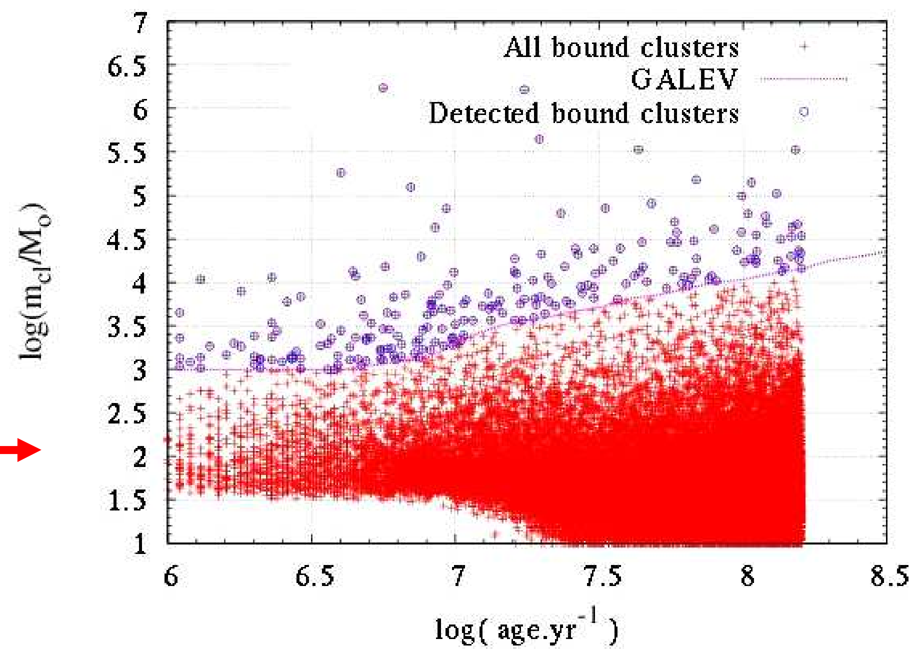
- 36 dIrr:
  Sharina, Puzia, & Makarov 2005
- NGC4038/39: Anders et al. 2007

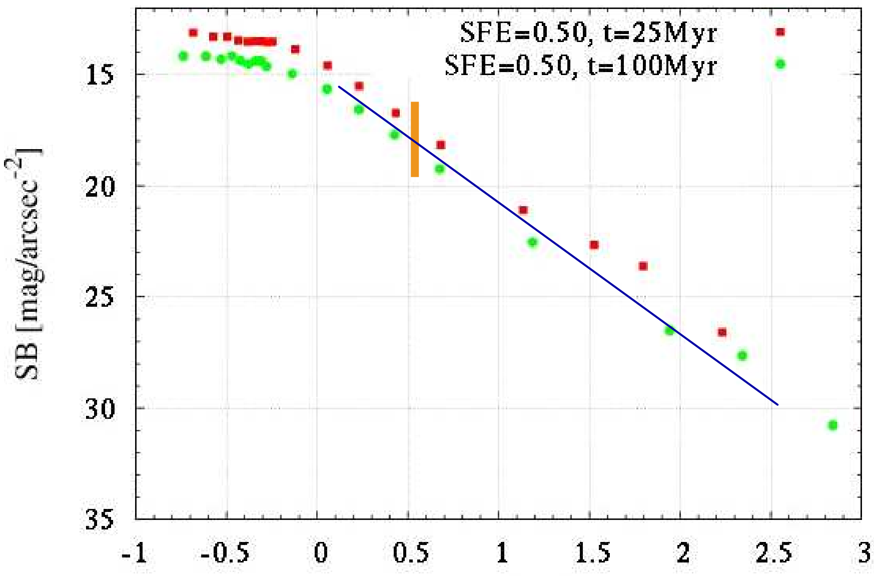
The core mass-radius relation is central to our understanding of whether infant-mortality/weight-loss is mass dependent or not

⇒ Cluster sizes to be simulated:

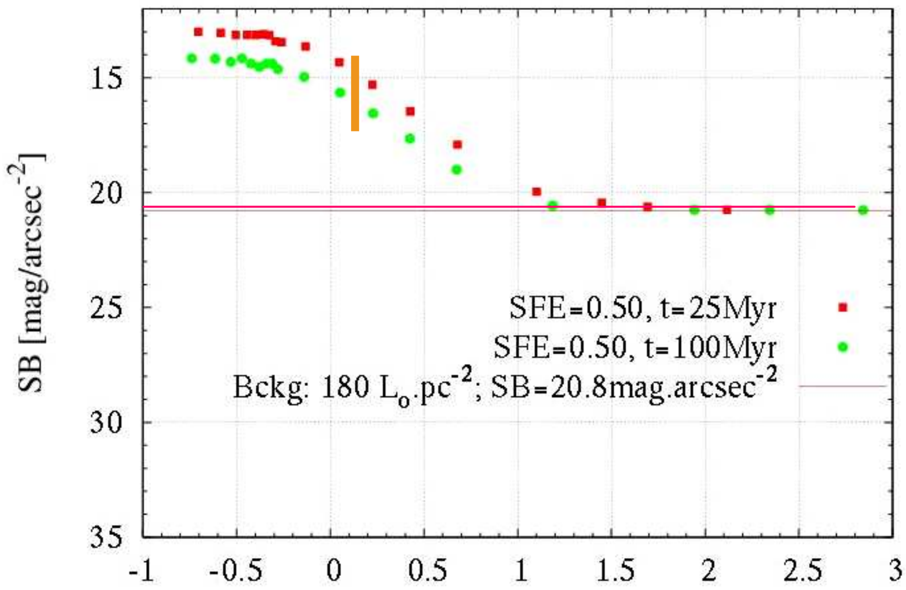
⇒ Observational biases:

1. Magnitude
2. SB





log r [pc]



log r [pc]

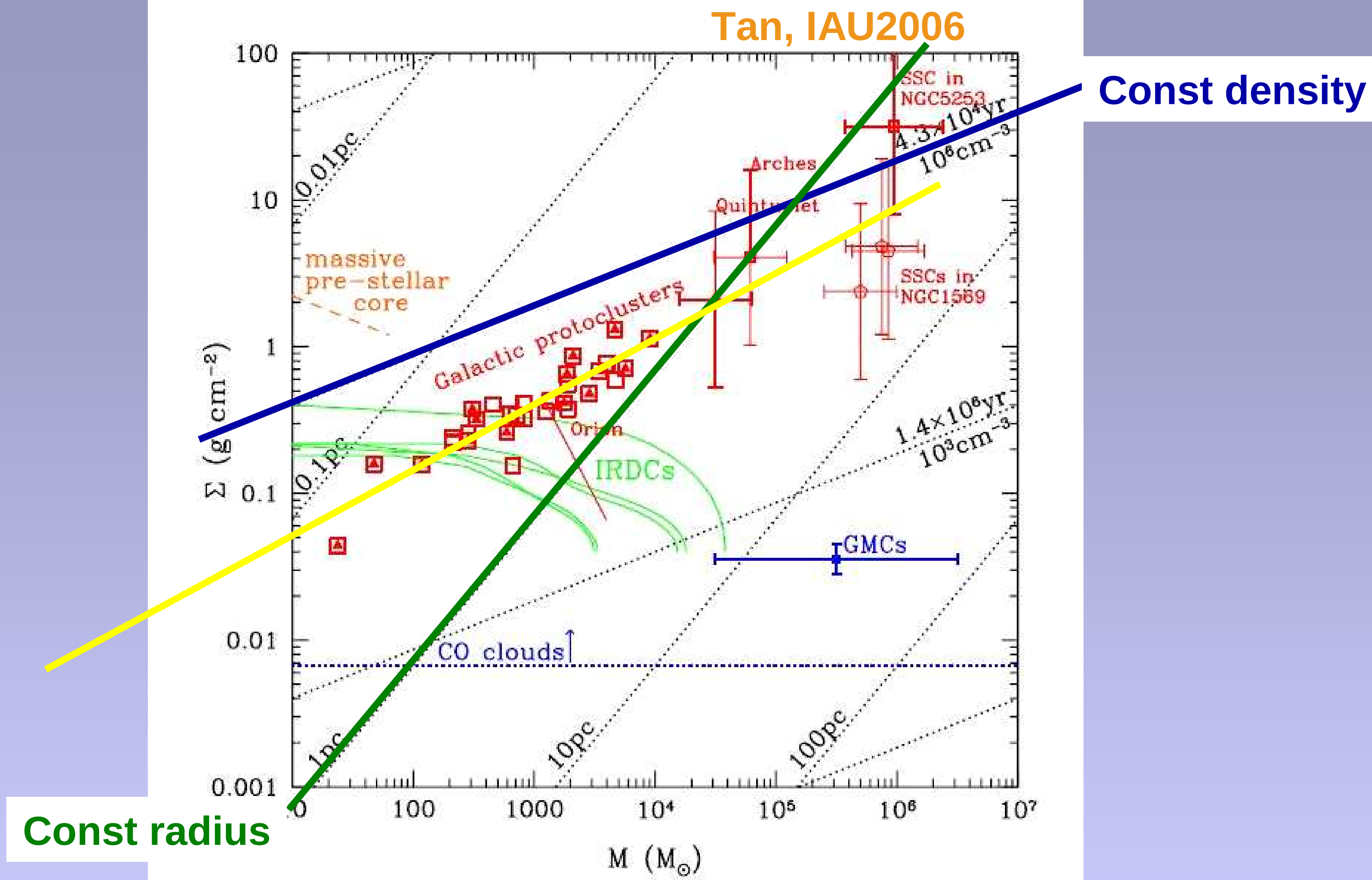
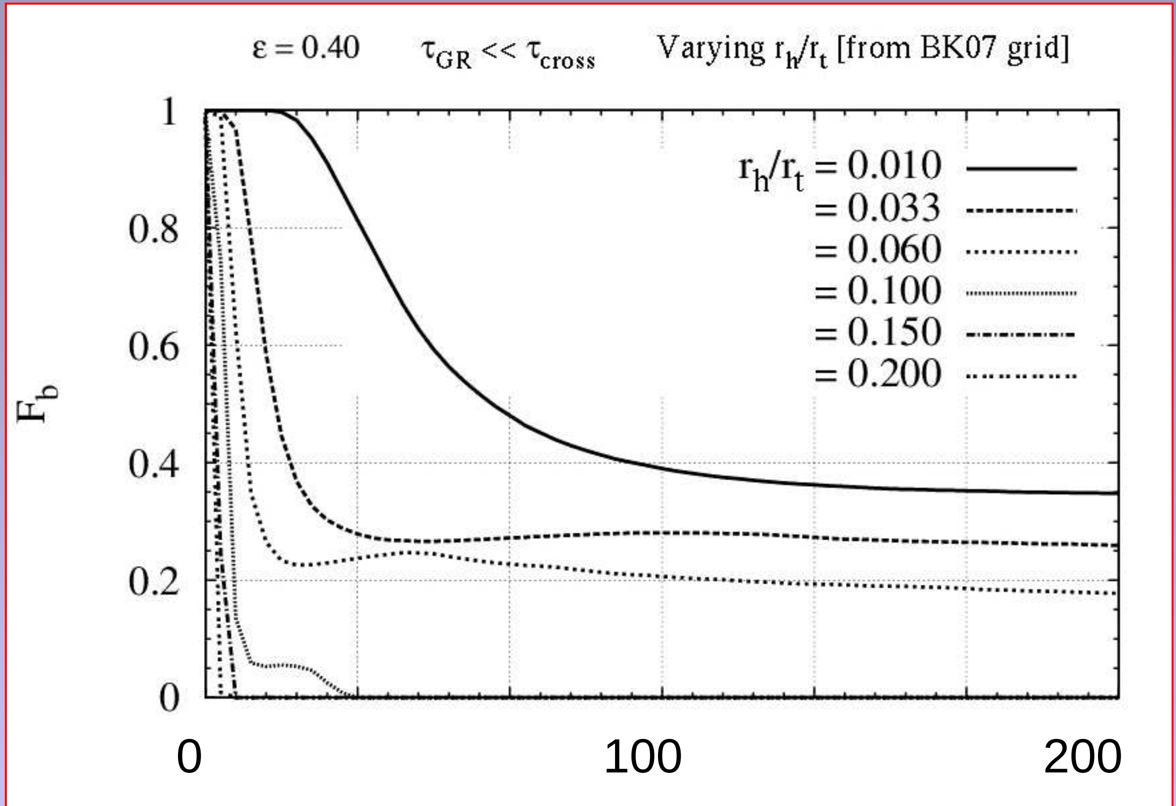


Figure 1. Surface density, $\Sigma \equiv M/(\pi R^2)$, versus mass, M, for star clusters and interstellar clouds. Contours of constant radius, R, and hydrogen number density, $n_{\rm H}$, or free-fall timescale, $t_{\rm ff}$, are shown with dotted lines. The minimum Σ for CO clouds in the local Galactic FUV radiation field is shown, as are typical GMC parameters and the distributions $M(>\Sigma)$ of several IRDCs derived from extinction mapping (Butler et al., in prep.). Open squares are star-forming clumps (Mueller et al. 2002): a triangle indicates presence of an HII region. The solid straight line traces conditions from the inner to outer parts of the ONC, assuming equal mass in gas and stars. Several more massive clusters are also indicated. The fiducial massive core in the model of McKee & Tan (2003) is shown by the dashed line.

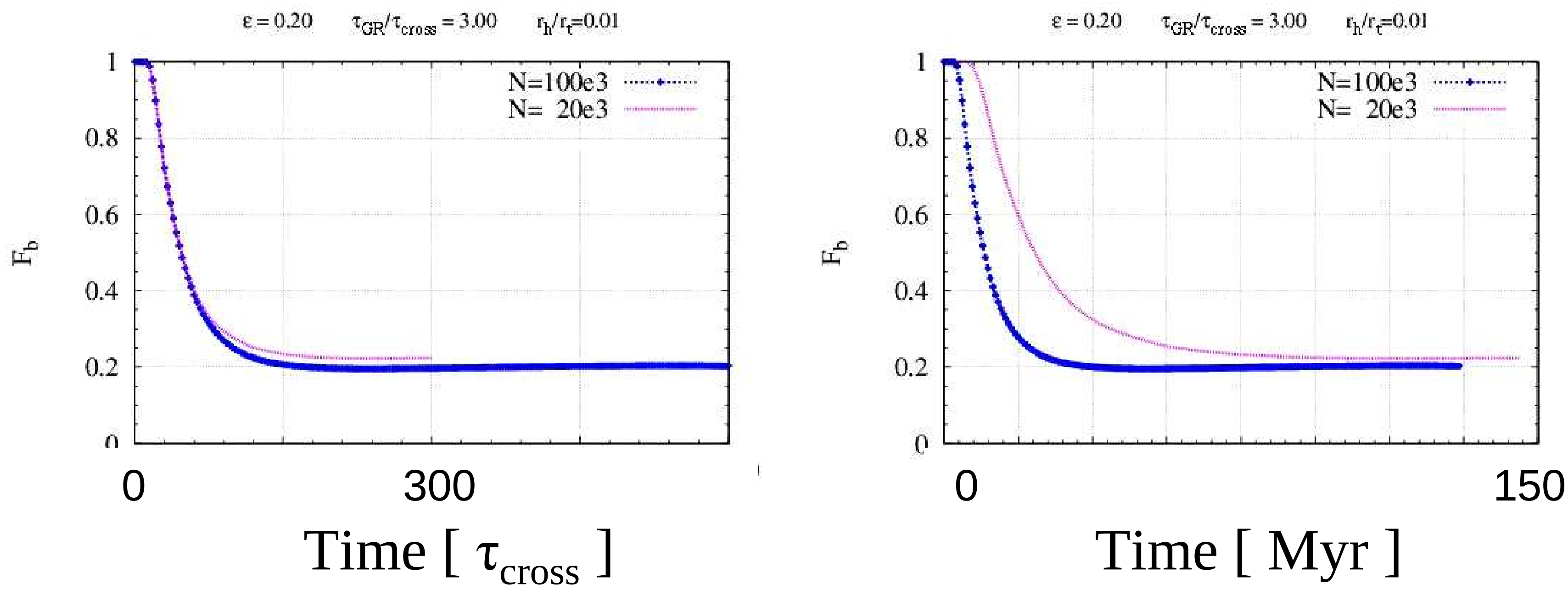
Fig.4 in Parmentier (2009, Astro-ph:0901/3140)



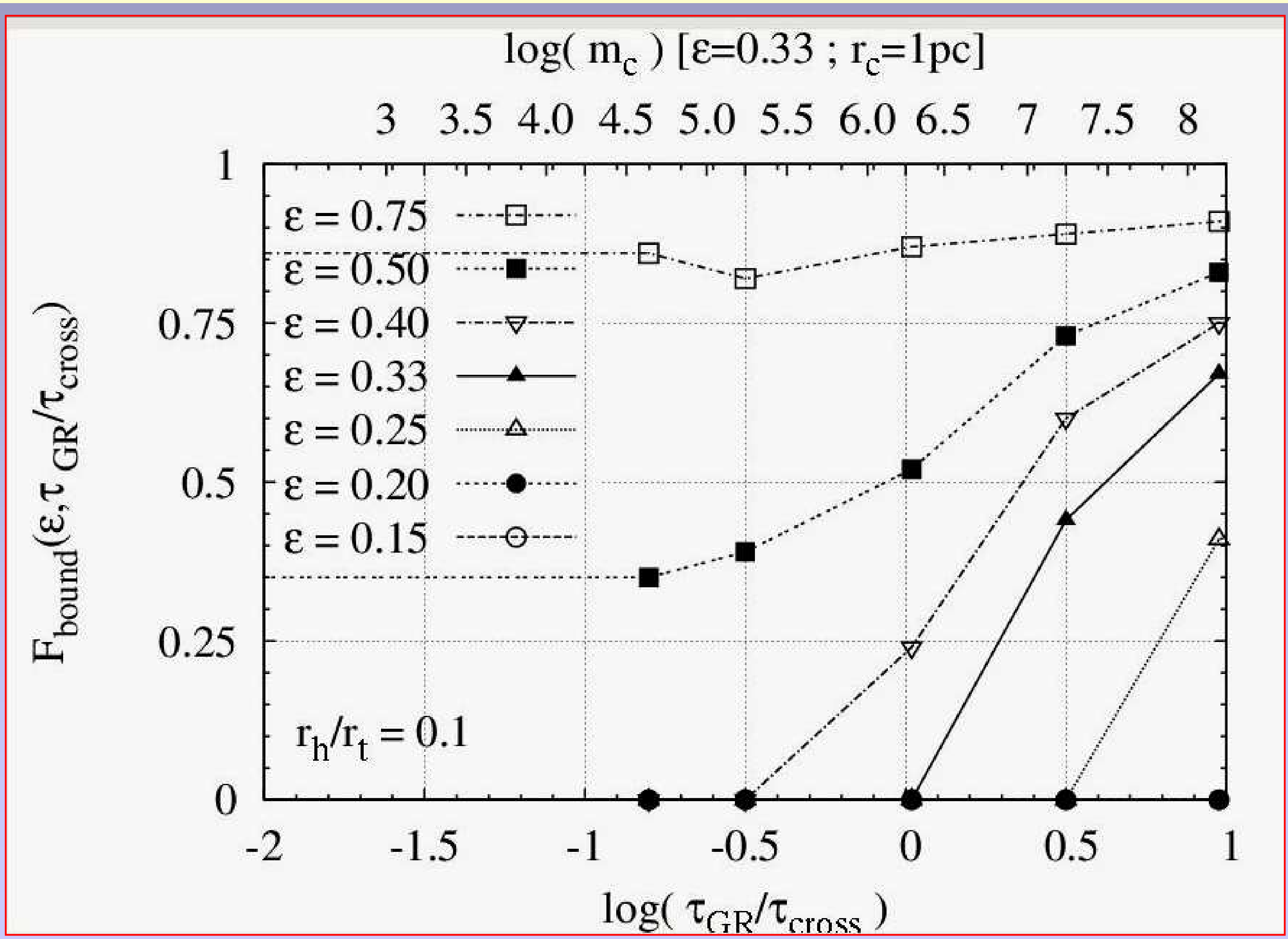
Time [τ_{cross}]

$\rho^{-1/2}$

Core mass-radius relation


ε = 0.20 τ_{GR}/τ_{cross} = 3.00 r_h/r_t=0.01
N=100e3
N= 20e3
F_b
1
0.8
0.6
0.4
0.2
0
0
300
Time [τ_{cross}]
ε = 0.20 τ_{GR}/τ_{cross} = 3.00 r_h/r_t=0.01
N=100e3
N= 20e3
F_b
1
0.8
0.6
0.4
0.2
0
0
150
Time [Myr]

Based on the N-body model grid of Baumgardt & Kroupa (2007)
Figure analogous to Fig.1 in Parmentier et al. (2008)
Case of SCs subjected to tidal fields scaling as $r_h/r_t = 0.1$



What cluster gas expulsion can tell us about star formation, cluster environment and galaxy evolution

G. Parmentier

Astro-ph:0901/3140

In: Proceedings of
"Star Clusters: Witnesses of Cosmic History",
Symposium held at JENAM 2008
To appear in Modern Reviews in Astronomy, 15 pages