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Connecting the Local Star Formation Law and the Growth of Embeded Clusters

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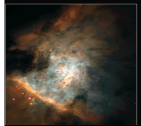
Germany

Setting the Scene: Star Clusters (SC) as Powerful Tracers of Galaxy Evolution




Star Clusters (SC):

- **Compact groups of coeval stars bound together by gravity**
- **Identified on a one-by-one basis against the background of their host galaxy**

Multi-band imaging of SC systems
(→ cluster magnitudes, colours)

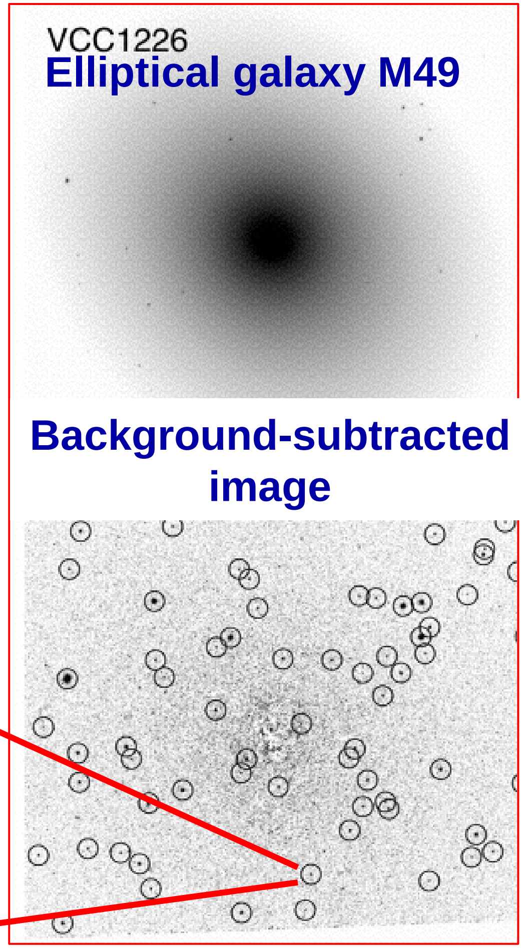
- **feasible out to Virgo Galaxy Cluster distances and beyond (≈ 60Mpc)**
- **combined to Simple Stellar Population models → estimates of cluster age, mass, metallicity**

Comprehensive view of galaxy-:

- **chemical enrichment history,**
- **interaction history,**
- **star formation history**

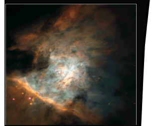
over the past Hubble-Time

Jordan+04 (ACS Virgo Galaxy Cluster Survey II, fig6)



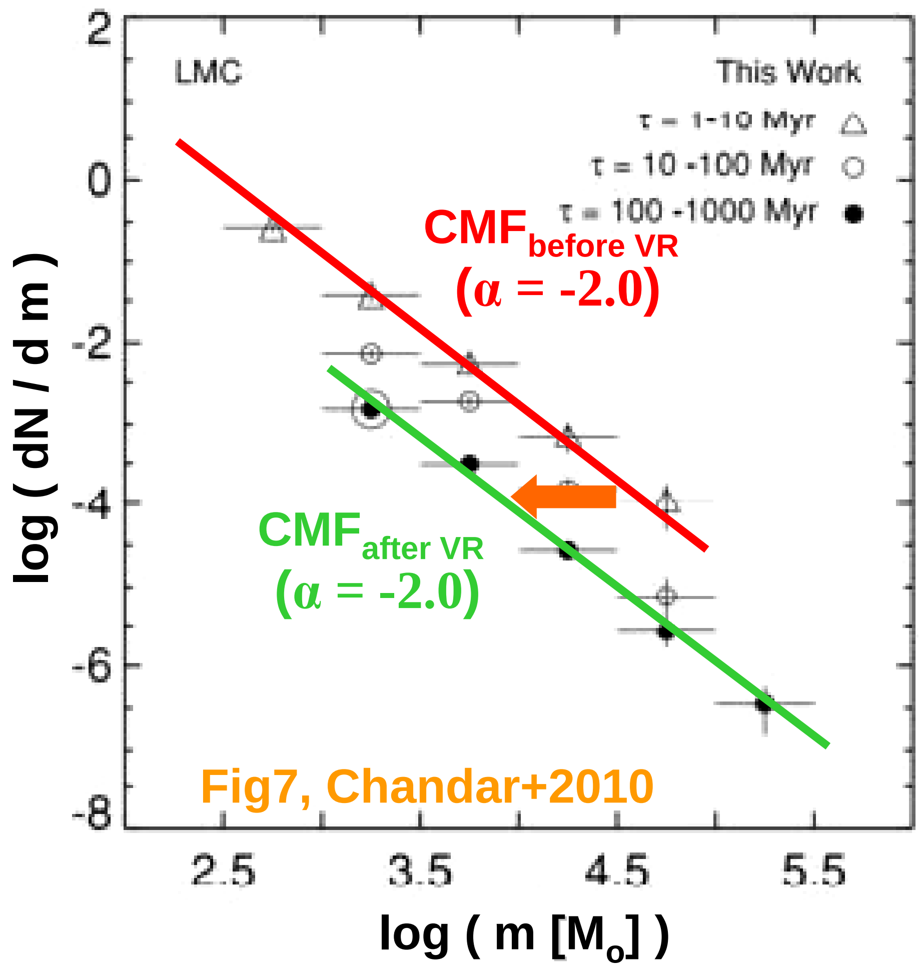
But SCs = encoded record of the SFH of their host galaxy

Observed Young Star Cluster Mass Functions



Macroscopic: **galaxy-wide, or multi-kpc scale**

→ mass distribution of star clusters



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

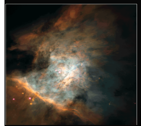
What observers tell us ...

No evolution of the CMF shape over the first few 10Myr

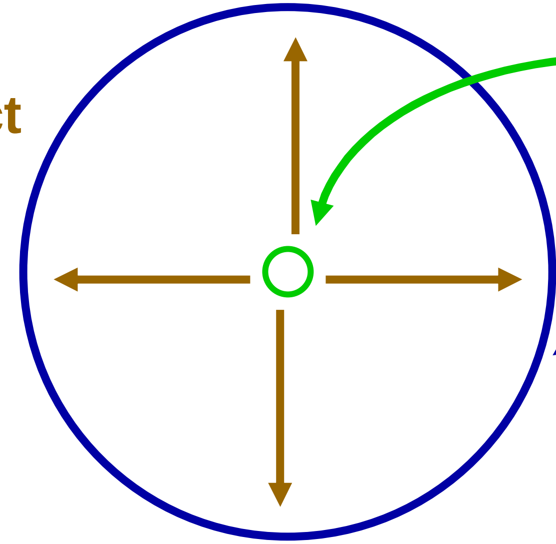
Cluster mass-loss is mass-independent

Note: what happens after 100Myr remains disputed …

Evolution of Young SC Mass Functions
1/2 - Tidal Field Impact: r_{hm}/r_t



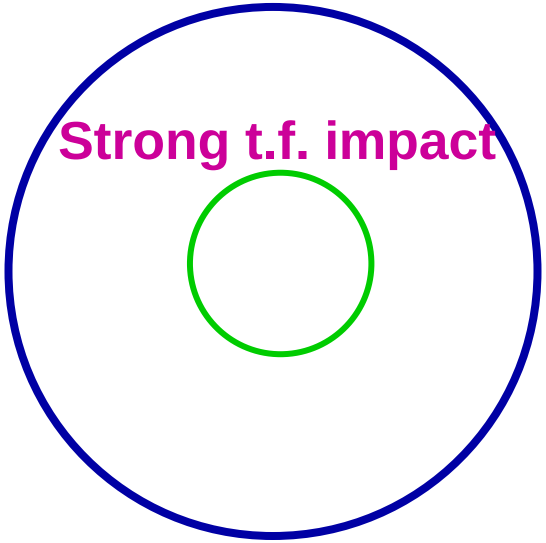

Weak t.f. impact



$$\frac{r_{half-mass}}{r_{tidal}} = f_{env} \times \left(\rho_{CFRg}\right)^{-1/3}$$

Cluster environment

Baumgardt & Kroupa (2007) parametrization



For a given environment,
- **higher mass-losses due to gas expulsion**
- **for higher tidal field impact**
- **for smaller CFRg densities**

Diapositive 4

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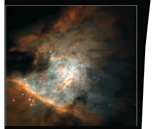
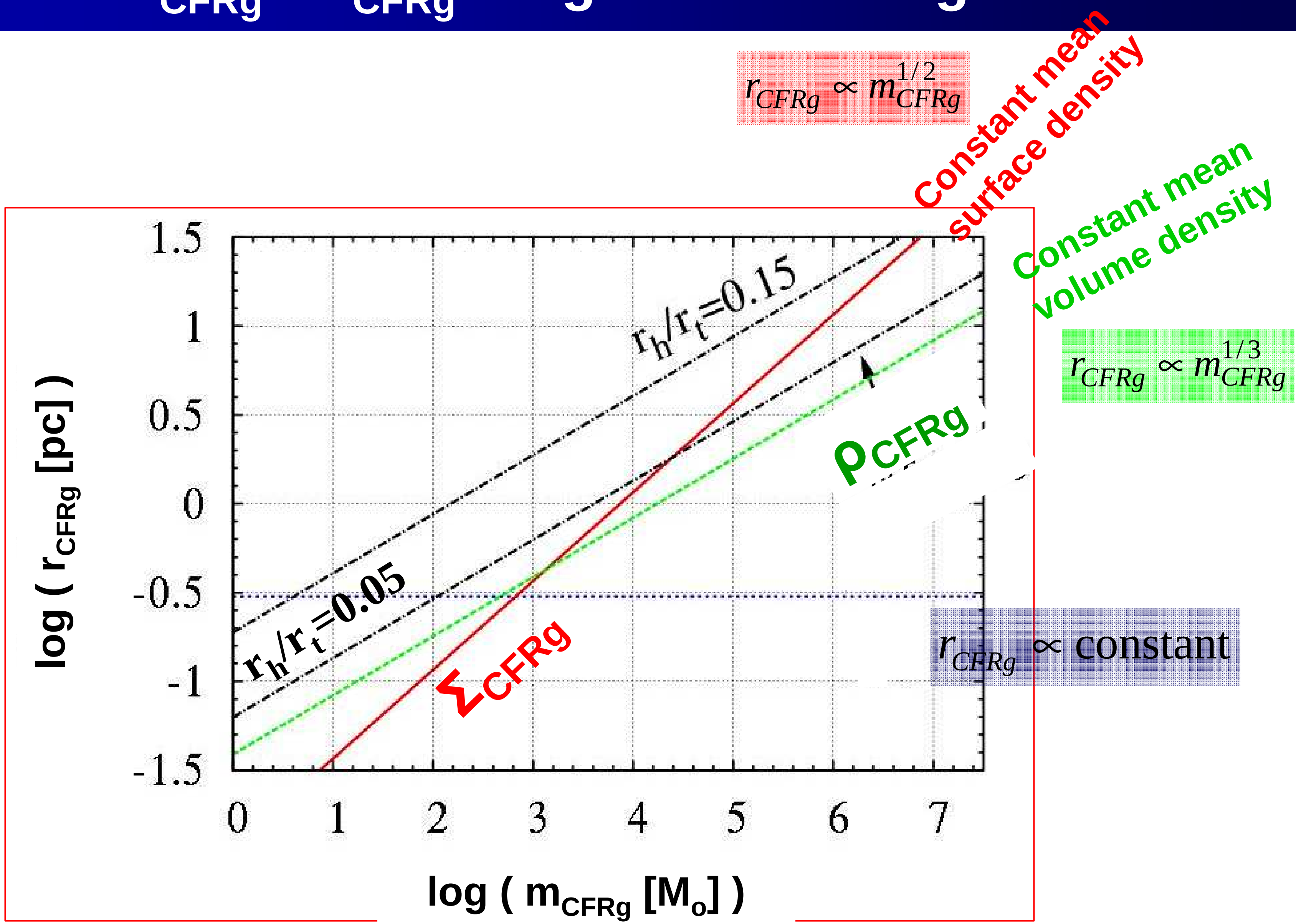
g4 gparm; 21/04/2011

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



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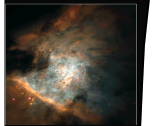
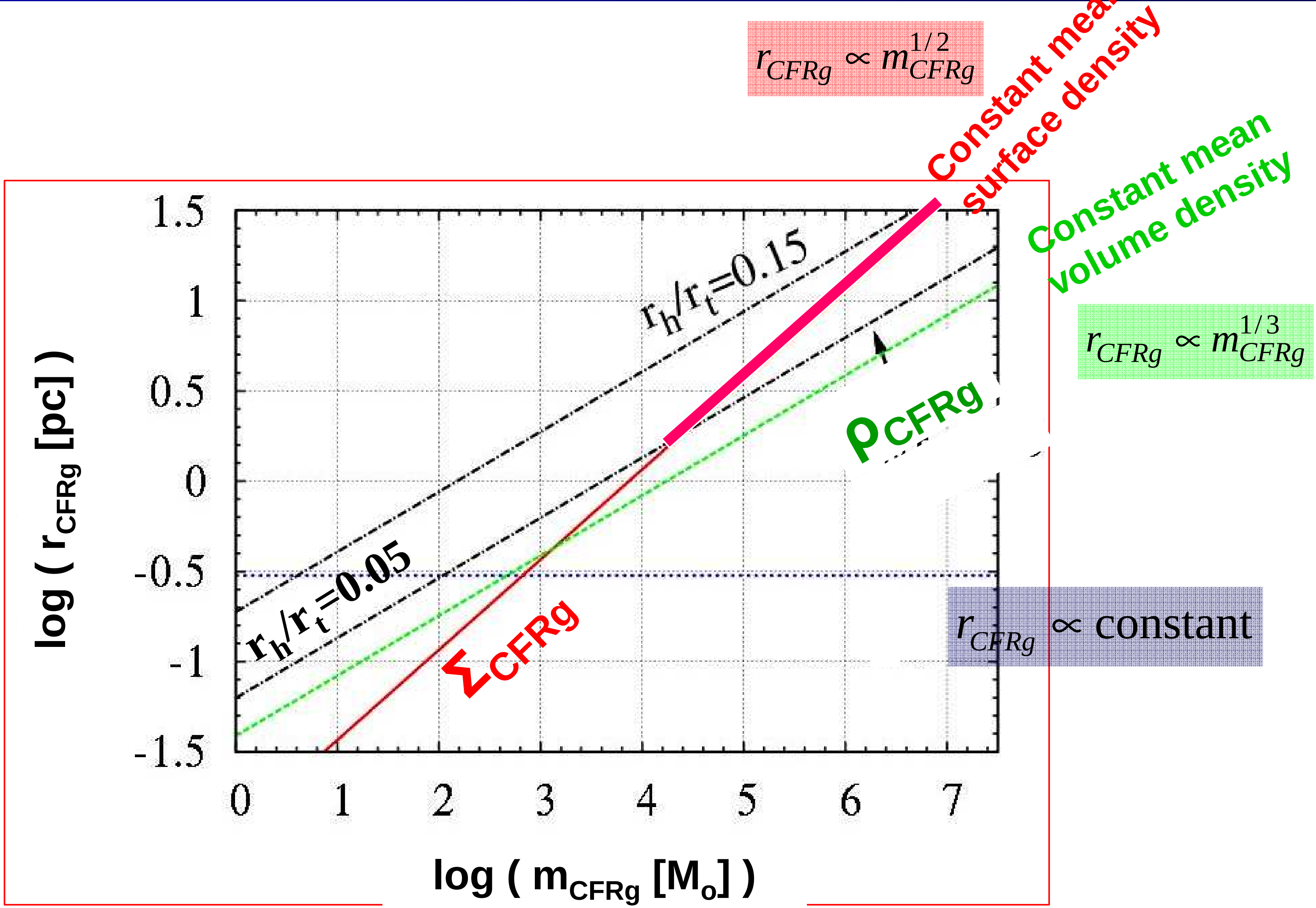
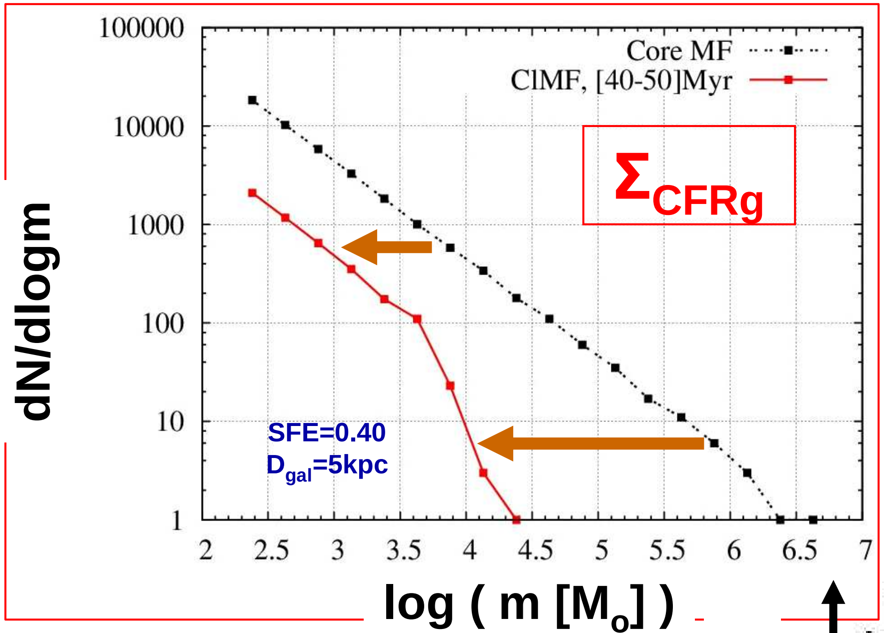


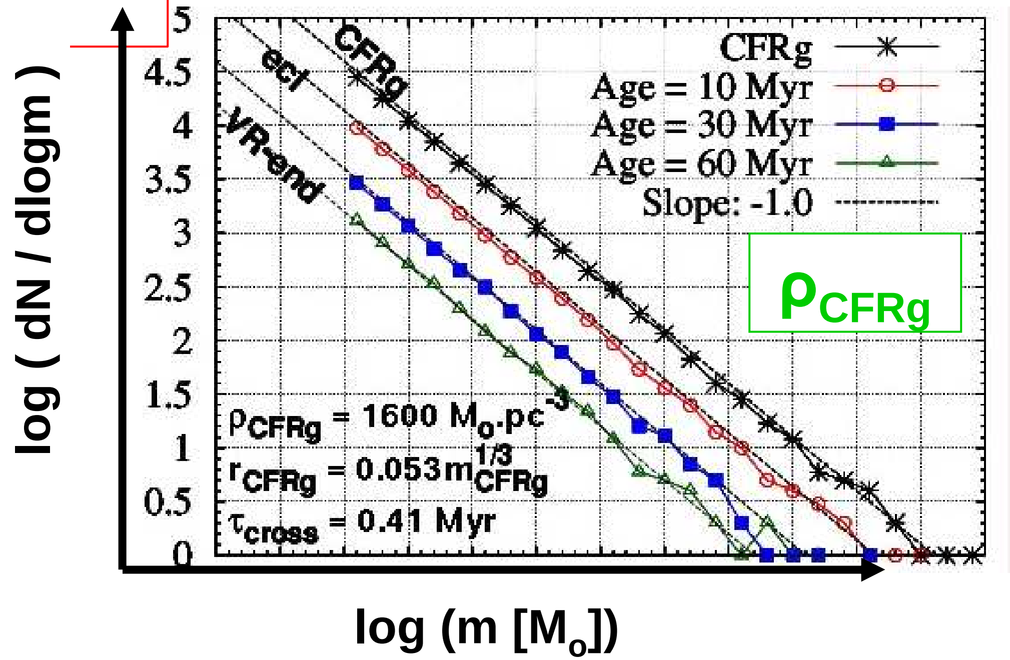



Young SC Mass Functions - Tidal Field Impact



Constant Mean Surface Density CFRgs: When more massive means more vulnerable ...

Constant Mean Volume Density CFRgs: mass-independent infant weight-loss



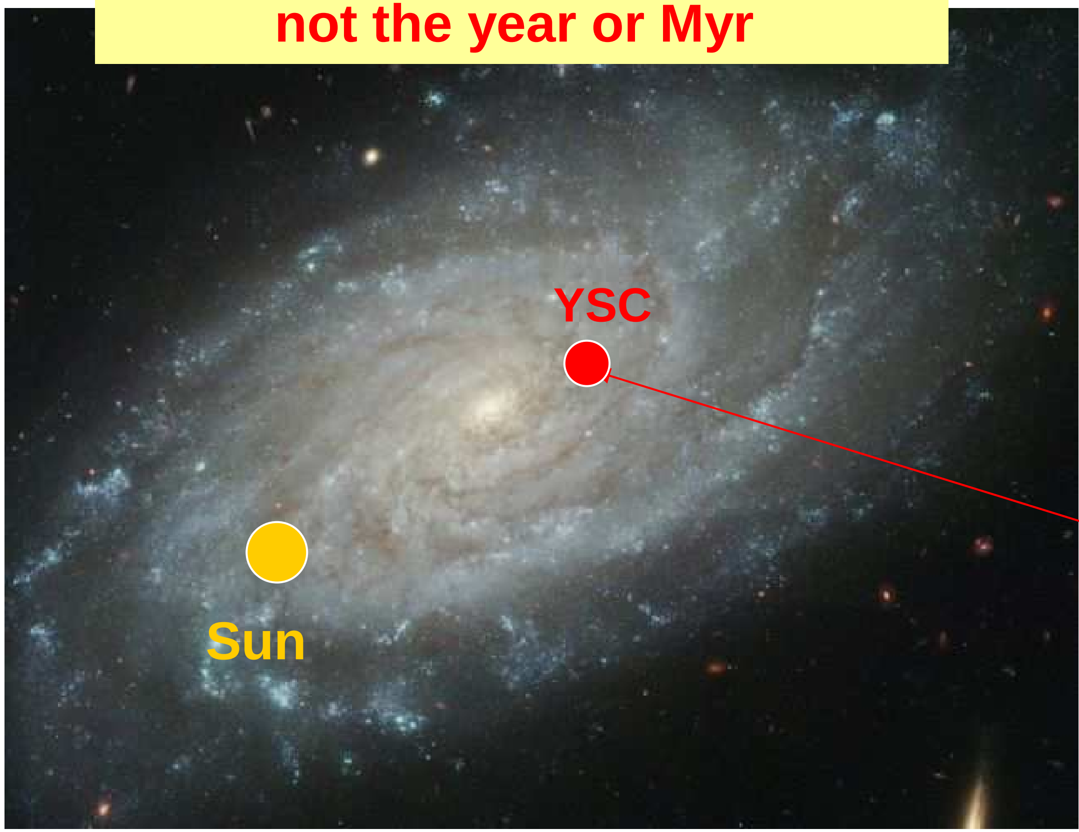
The cluster crossing-time: your basic time-unit!

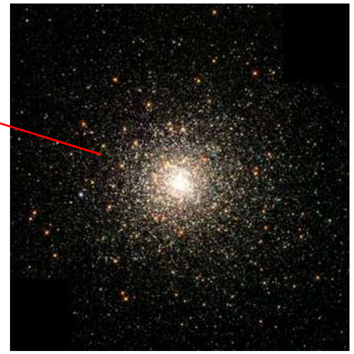
A star cluster does not care about how long it takes for the earth to revolve around the sun! The basic time-unit is the <u>cluster initial crossing-time</u>, not the year or Myr

$$\tau_{cross} \propto \rho_{CFRg}^{-1/2}$$

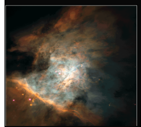
$$\tau_{cross} \cong 30\sqrt{\frac{(r_{CFRg})^3}{m_{CFRg}}}$$

Exact coefficient depends on density profile





Evolution of Young SC Mass Functions
2/2 – Cluster Evolutionary Rate



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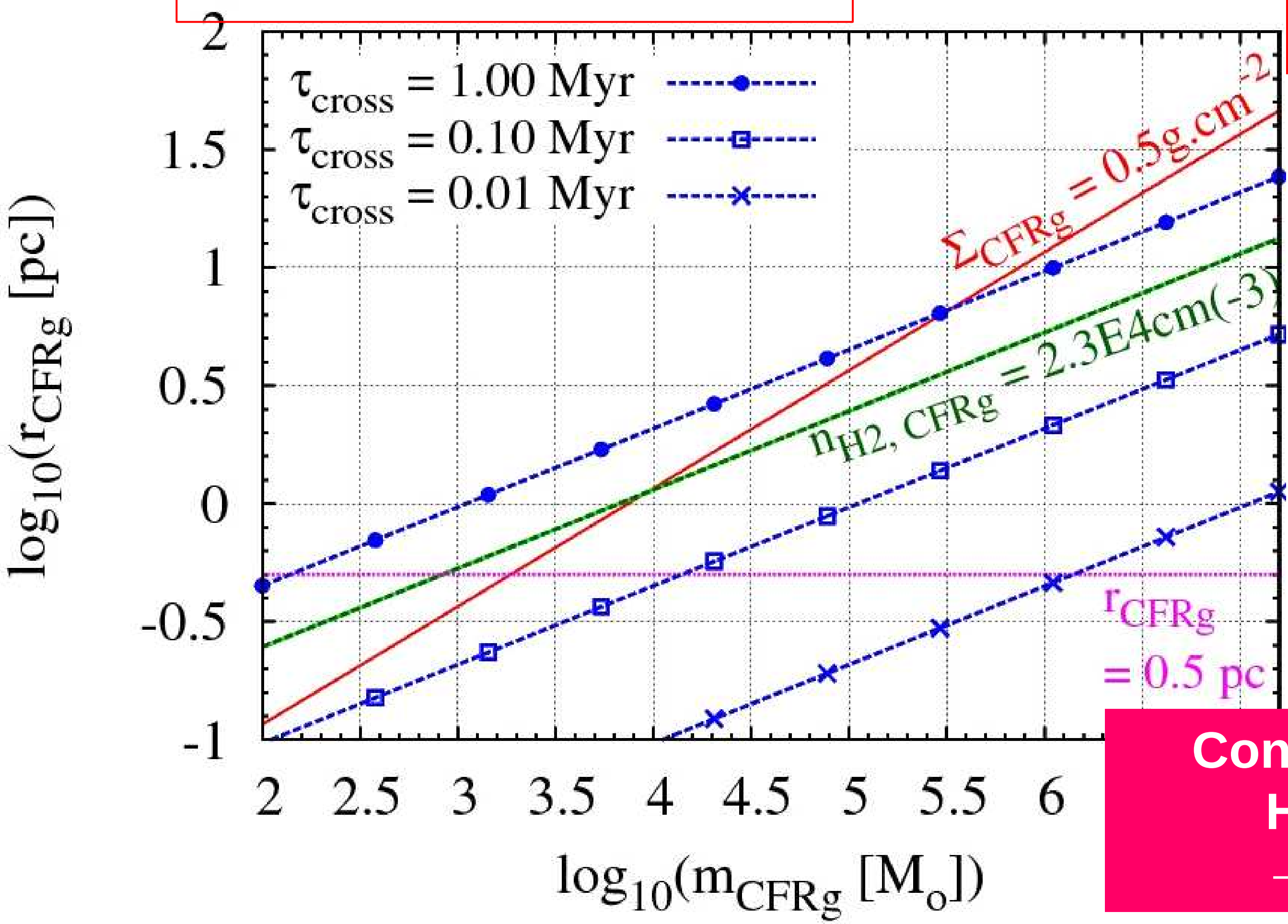

Constant mean surface density: high mass → slower

Constant mean volume density: no mass dependence

Constant radius: High mass → quicker

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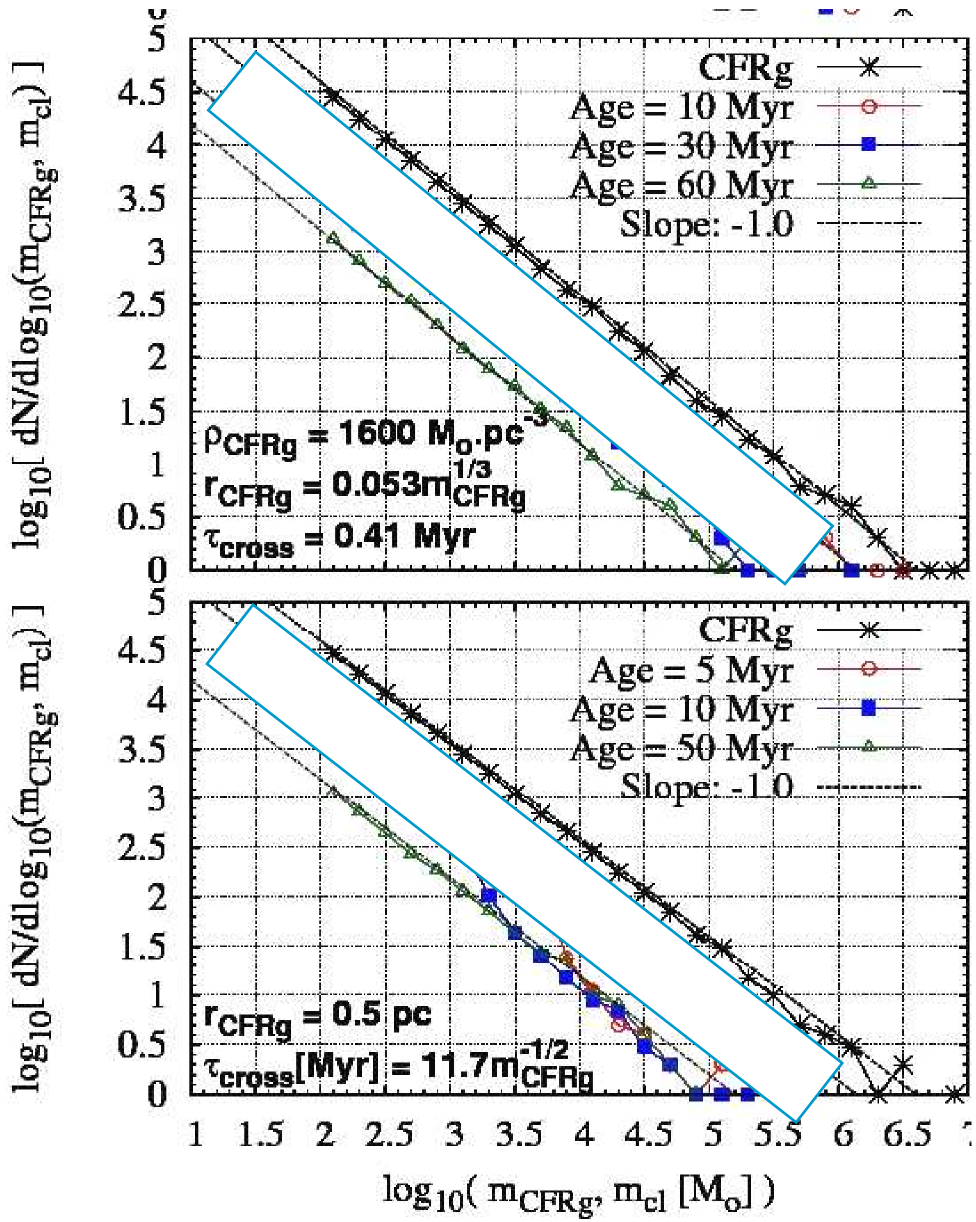

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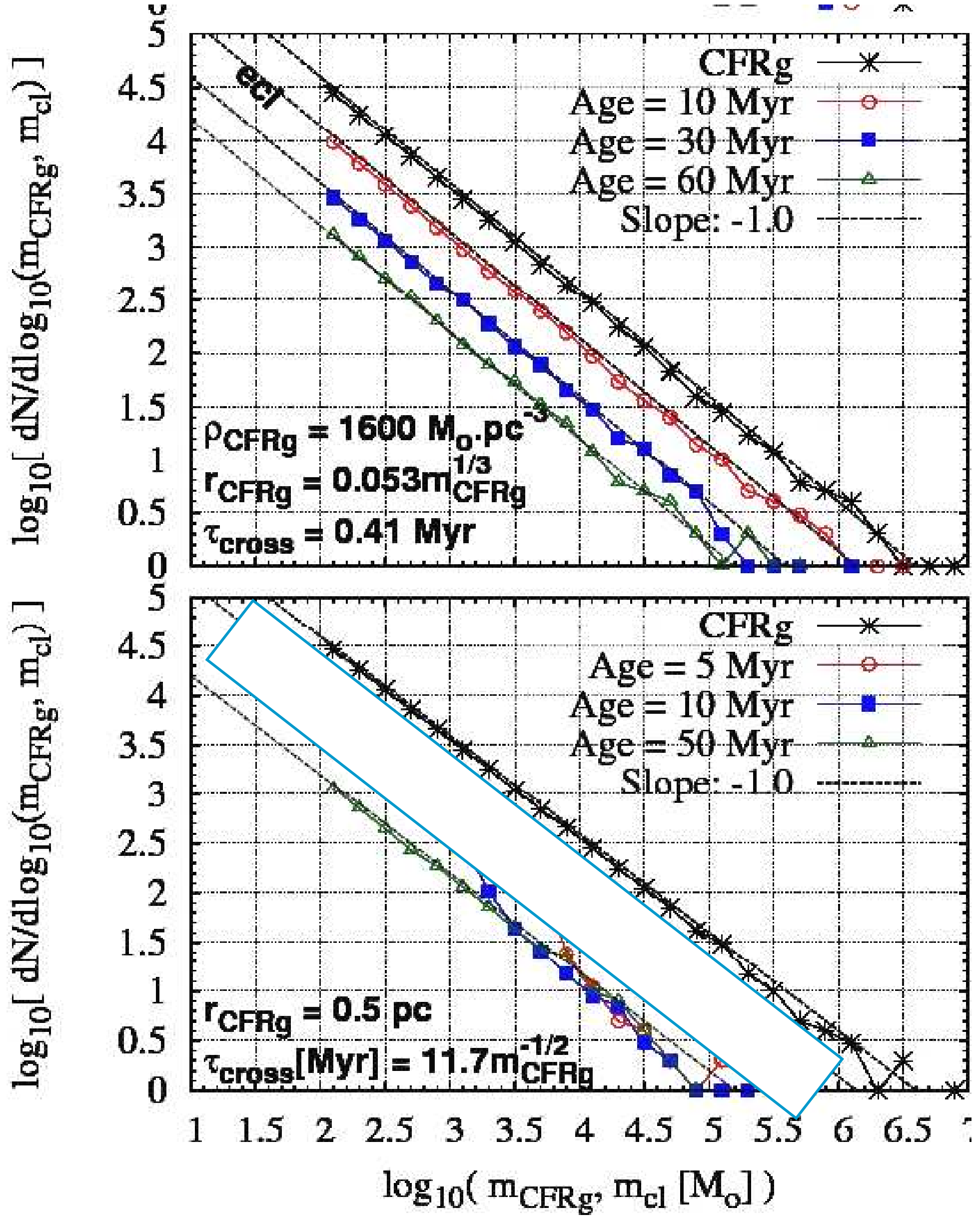
Parmentier & Baumgardt (2012)

Young SC Mass Functions



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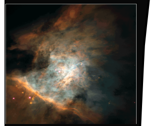


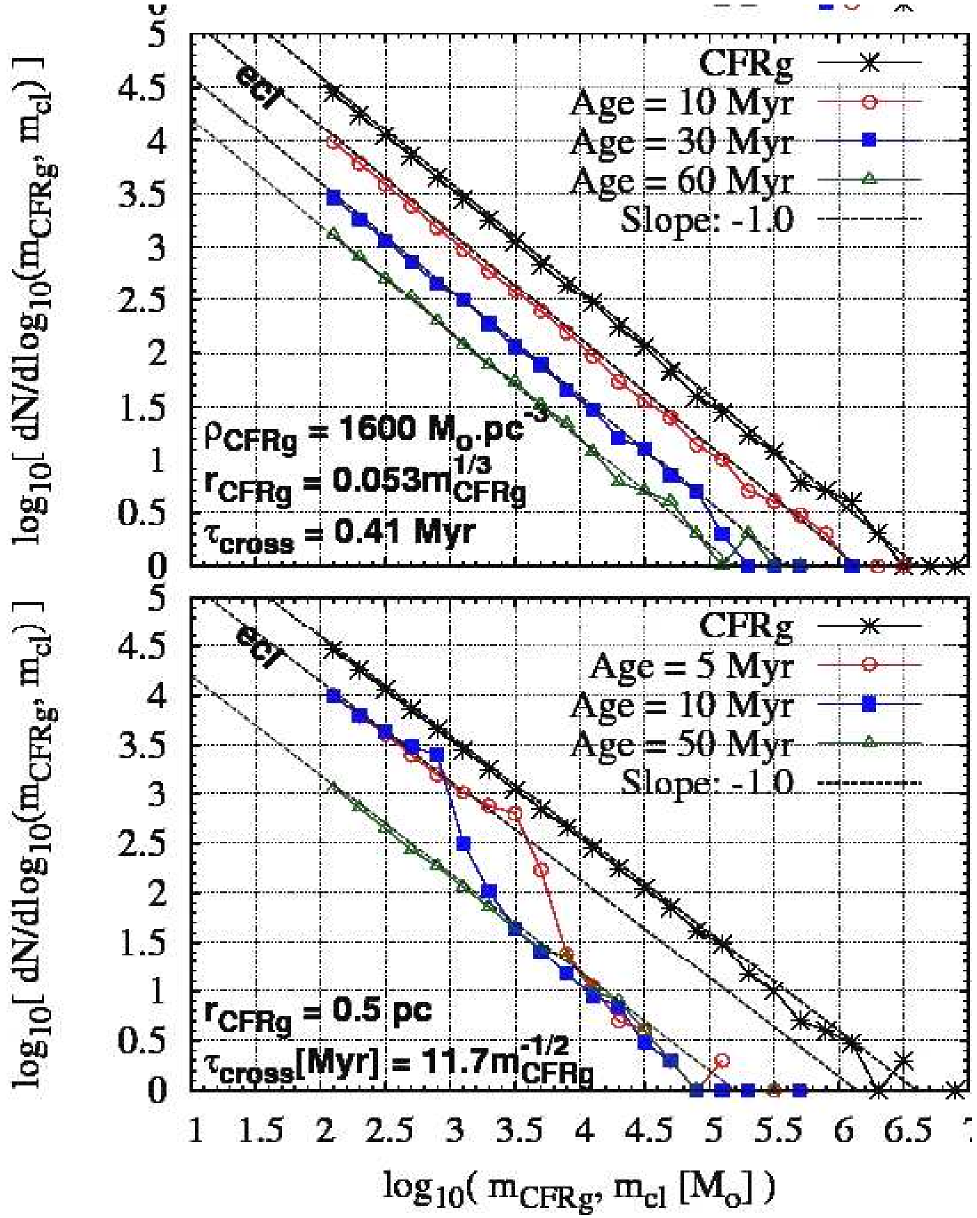

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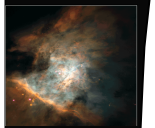
Parmentier & Baumgardt 2012

A Volume Density Threshold for the SF Gas ?



- **ρ_{CFRg} = constant :**

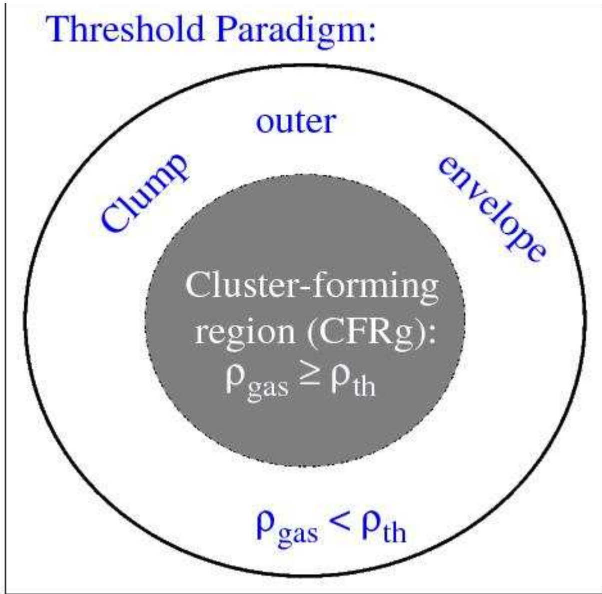
  provides the most robust solution to the time-invariant shape of the cluster mass function

- **Interesting since:**

  SFR and dense molecular gas mapping in:
  - **Entire galaxies …………………….. Gao & Solomon 2004**
  - **Galactic molecular clumps ……... Wu+ 2005**

  ➨ **SFR scales as the mass of dense molecular gas: $n_{H2} > 10^4 cm^{-3}$**

  ➨ **CFRgs of about constant mean volume density (n_{H2} = few n_{th})**



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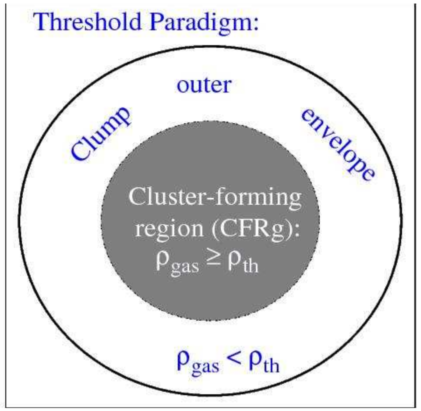


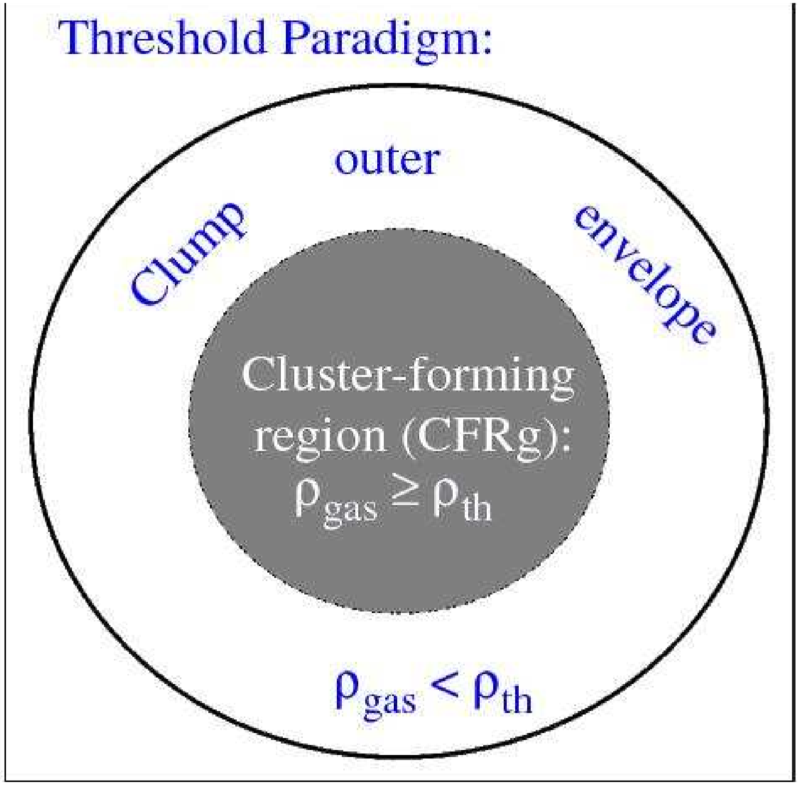
- **Same scaling (constant mean volume density) as from:**
  - the tidal field impact analysis (Parmentier & Kroupa 2011)
  - the crossing-time analysis (Parmentier & Baumgardt 2012)

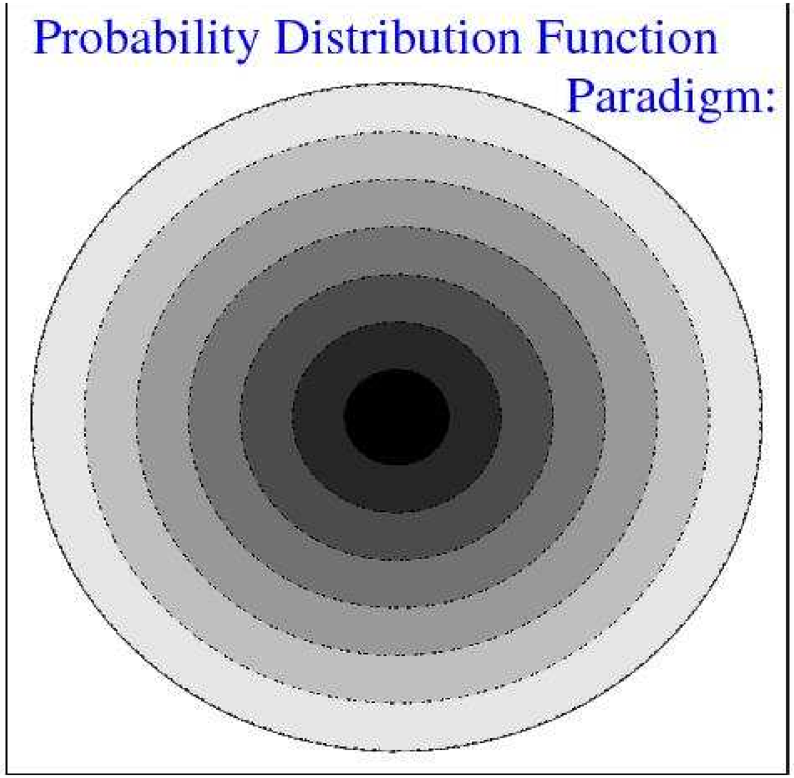
… cannot be the only explanation

But what for the star-forming regions of the Solar Neighbourhood?

Spitzer-telescope observations: star formation can proceed in <u>low-density</u> environments too …

(Allen et al. 2007, Evans et al. 2009, …)





Star Formation Efficiency per Free-Fall Time: ε_{ff}

Star Formation Efficiency ε_{ff} per Free-Fall Time τ_{ff}

$$\tau_{ff} = \sqrt{\frac{3\pi}{32\, G\, \rho_g}}$$

Krumholz & McKee 2005

For any given time-span after the onset of star formation: molecular-gas regions of higher density achieve higher SFEs

- **Global scale - galaxies**
  - **Spirals vs. ULIRGs**
  - **Central regions vs. outskirts of spirals**

- **Denser**
- **Faster**
- **Higher SFE**

- **Local scale – individual molecular clumps**
  - **volume density gradients** ⟶⟶
  - **SFE_{centre} >> $SFE_{outskirts}$**
    - **Consequences and observational signatures ?**

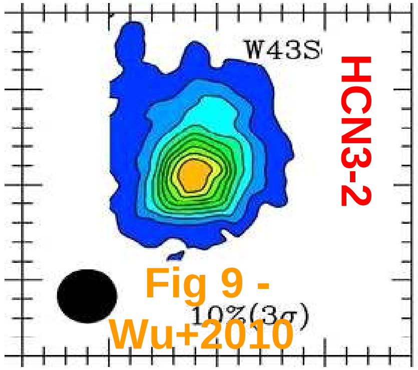
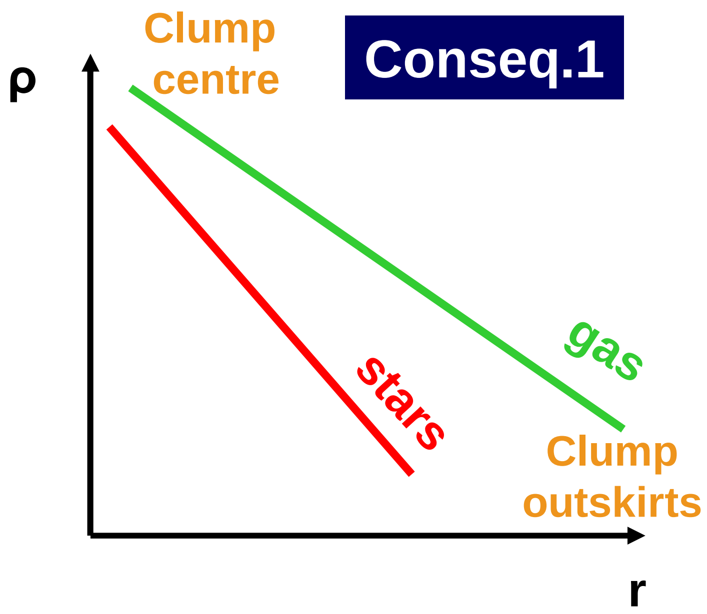


Fig 9 - Wu+2010

Immediate consequences of the ε_{ff} concept

Conseq.1



- **Density profiles:**
  $\rho_*(r)$ steeper than $\rho_g(r)$
-
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Immediate consequences of the ε_{ff} concept

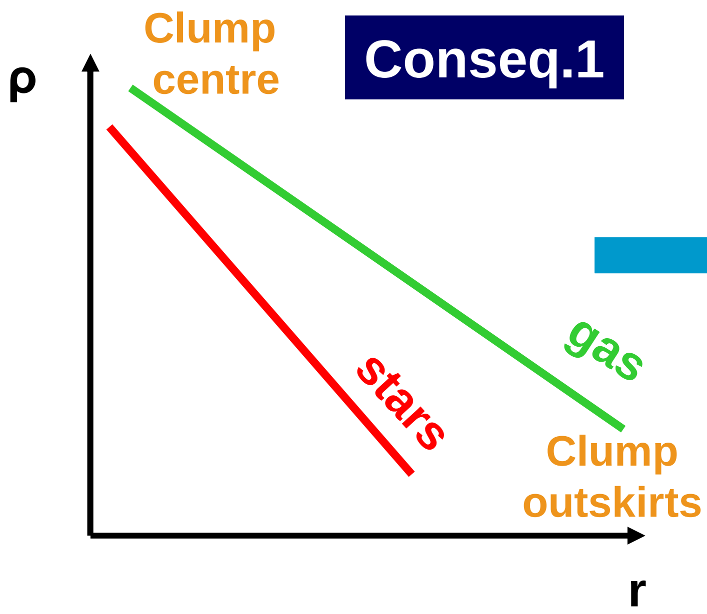
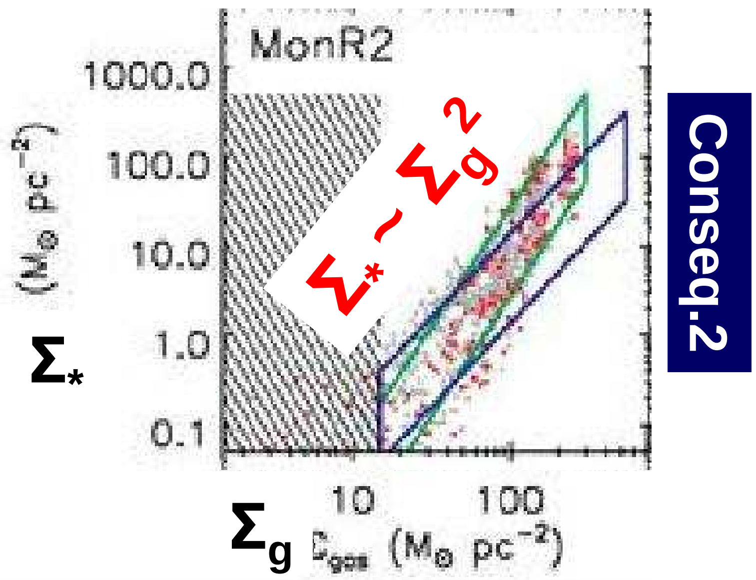


Fig9, Gutermuth+ (2011)



- **Density profiles:**
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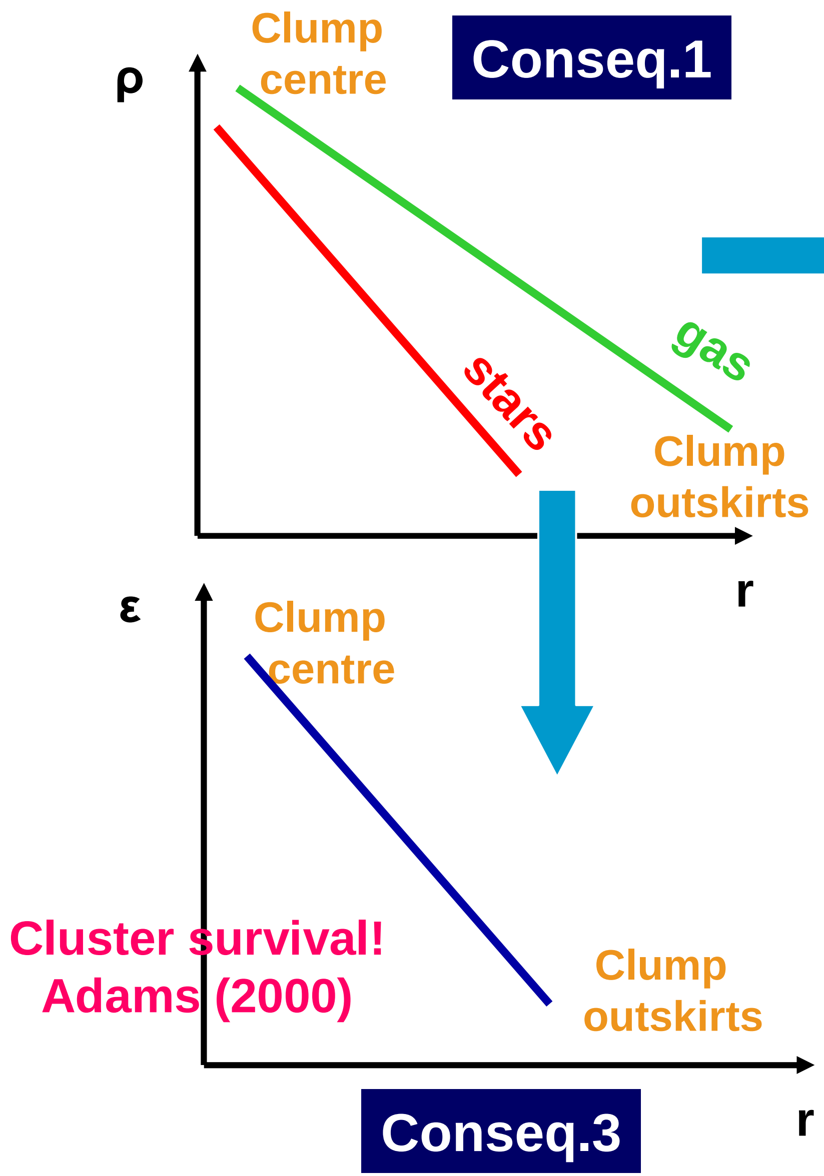

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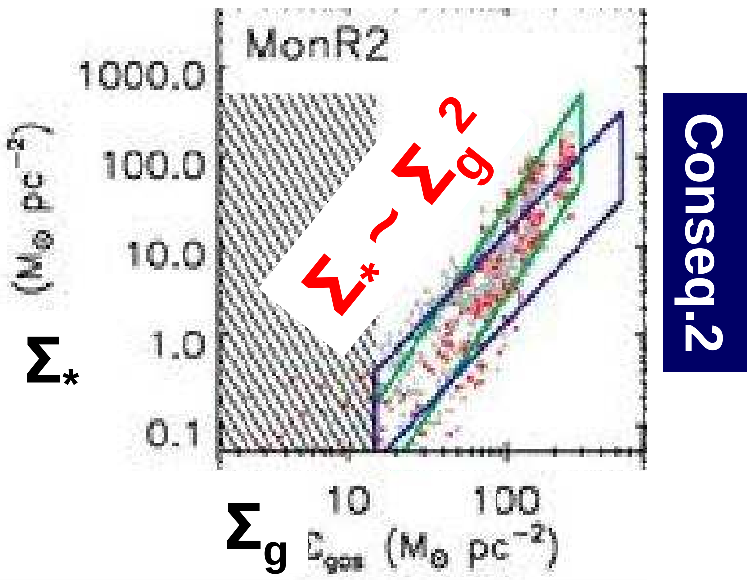


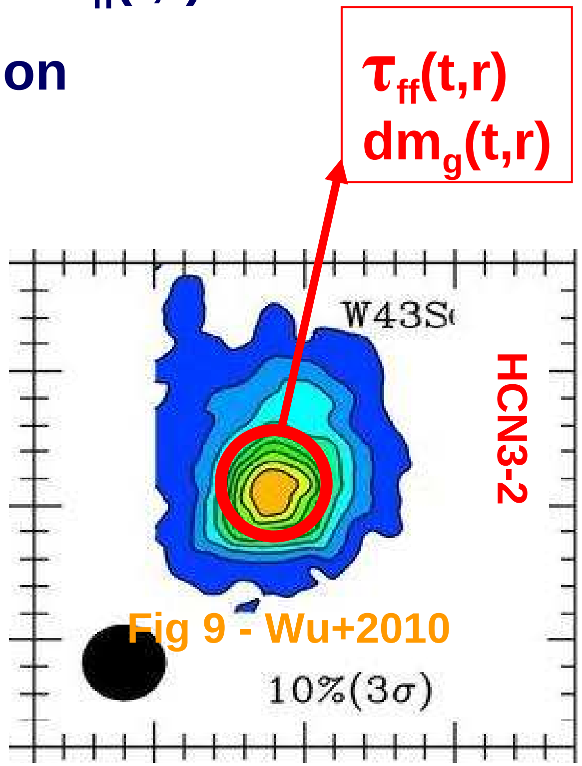
- Density profiles: $\rho_*(r)$ steeper than $\rho_g(r)$
- Local star formation law
- Radially-dependent local ε

Model

- **Molecular clump and YSOs - Hypotheses**
  - **Molecular clump:**
    - **Spherical symmetry – power-law density profile**
    - **Static clump - No global collapse**
    - **Local collapse on a time-scale $\tau_{ff}(t,r)$**
  - **YSOs: no migration after formation**

- **Model – For a shell of radius r,**
  gas mass $dm_g(t,r)$,
  at each time-step Δt,
  its stellar mass increases by:

$$+\varepsilon_{ff}\,\frac{\Delta t}{\tau_{ff}(t,r)}\,dm_g(t,r)$$



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- **Model consequence: SF slows down**
  - **$\tau_{ff}(t,r)$ ↑**
  - **$dm_g(t,r)$ ↓**

$\tau_{ff}(t,r)$
$dm_g(t,r)$

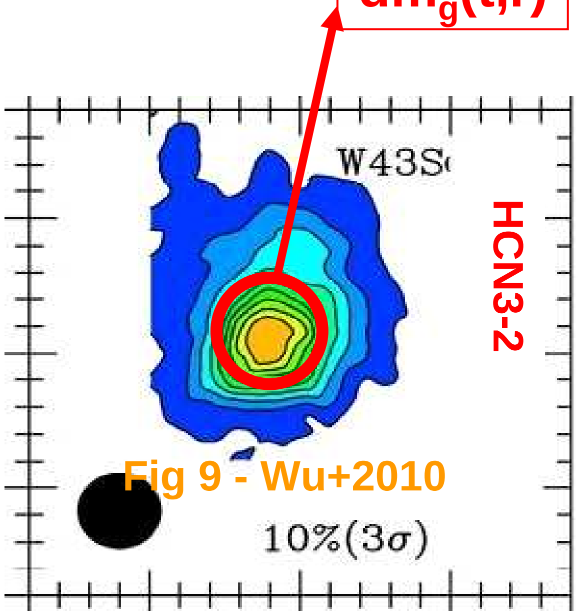


Fig 9 - Wu+2010

Star and Gas Volume Density Profiles [Conseq.1]

$$\rho_g(t=0,r) \propto r^{-p_0} \quad - \quad \varepsilon_{ff} = 0.1$$

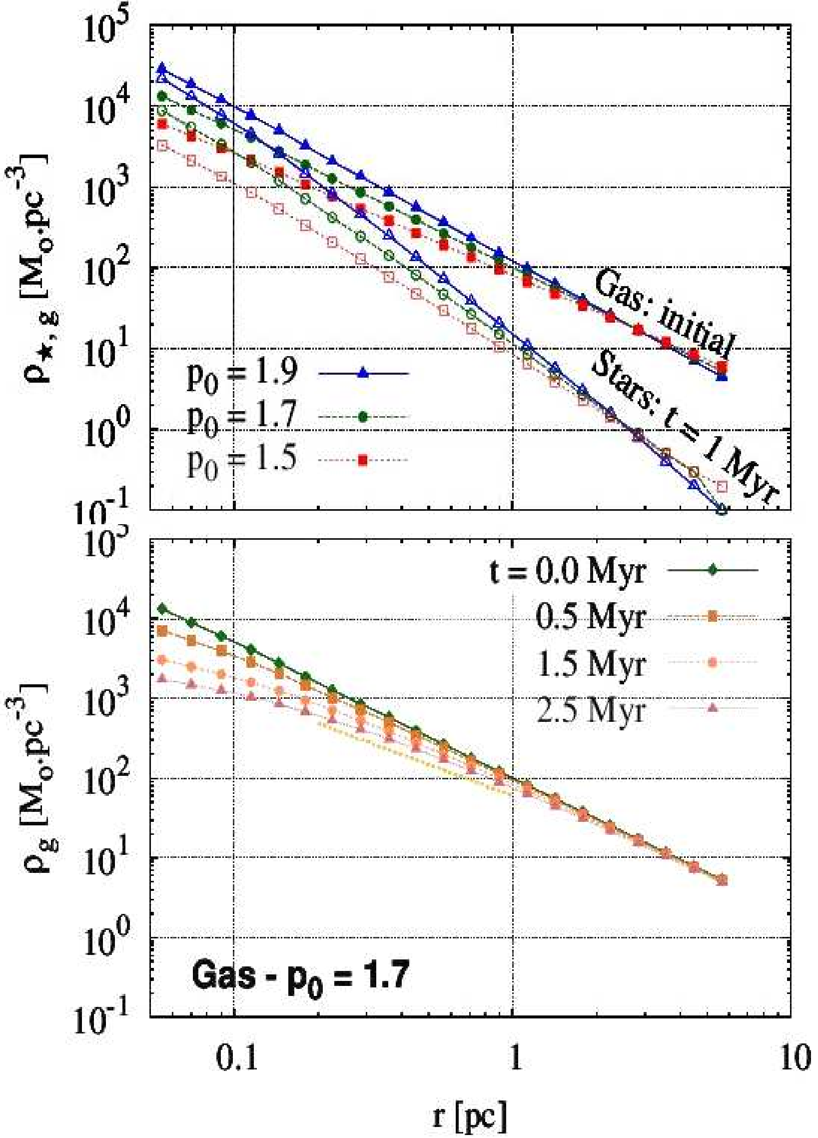
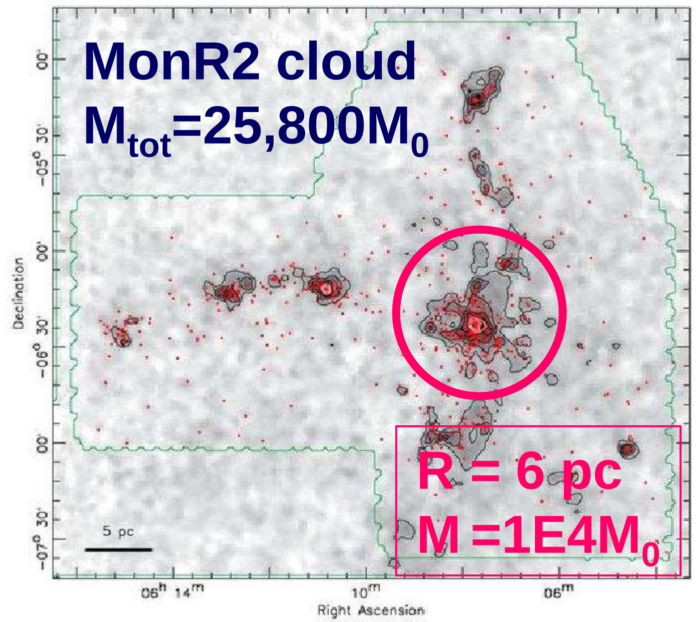


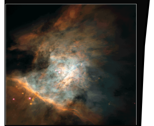
Fig1, Gutermuth+ (2011)

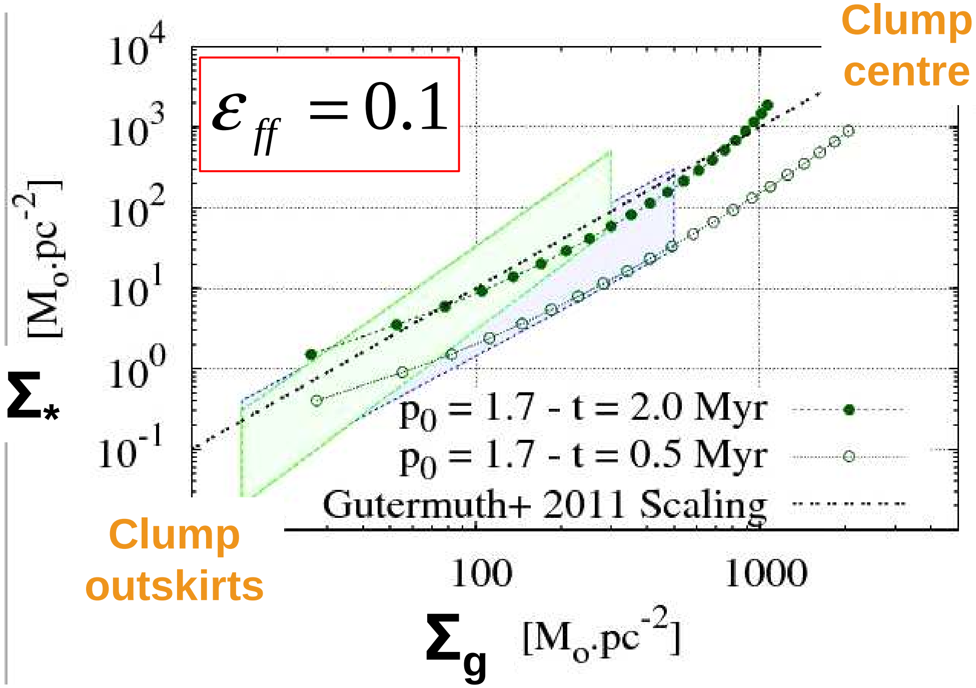


Density profiles:

- $\rho_*(t,r)$ steeper than $\rho_g(t,r)$
- $\rho_g(t,r)$ shallower than $\rho_g(t=0,r)$

Local Star Formation Law [Conseq. 2]





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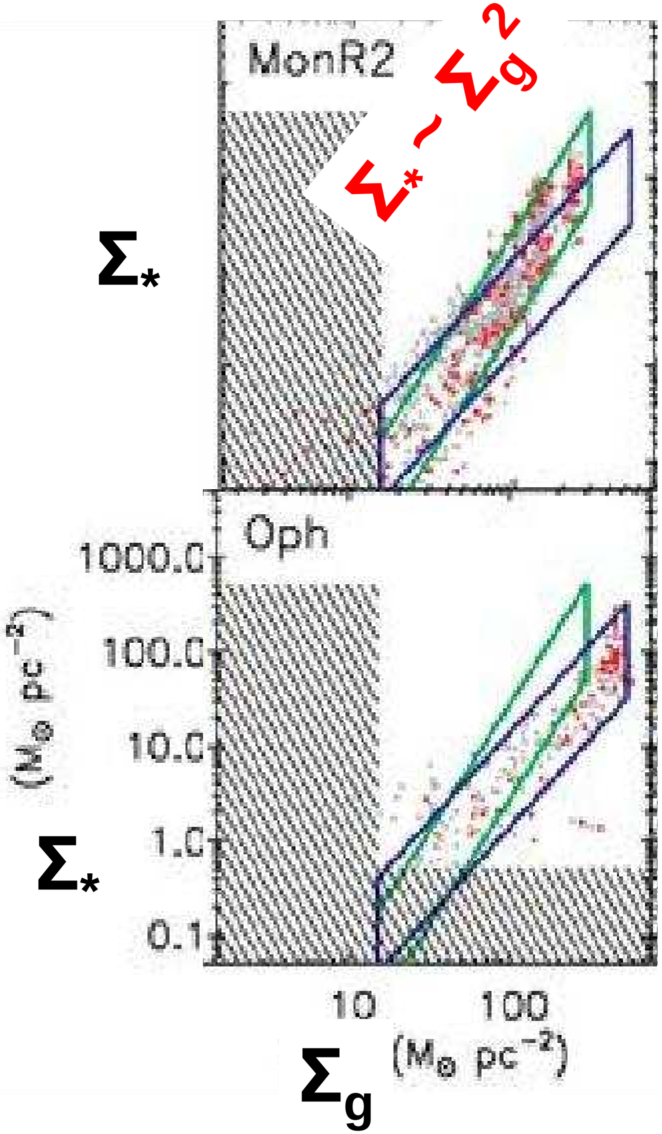


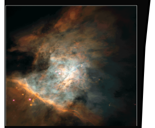
Relation between the local surface densities of YSOs and of the residual gas:

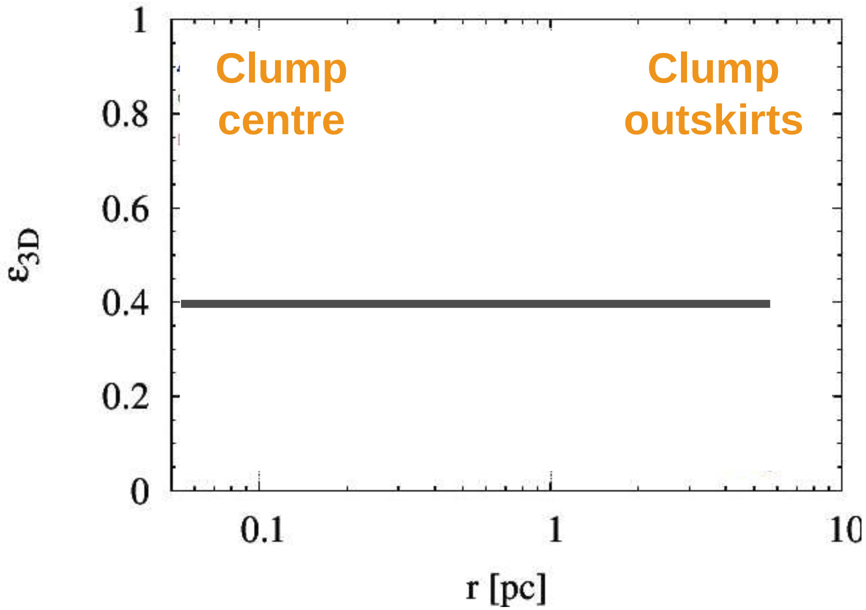
$$\Sigma_* \approx 10^{-3}\ \Sigma_g^{\ 2} \quad \text{at } t = 2\text{Myr}$$

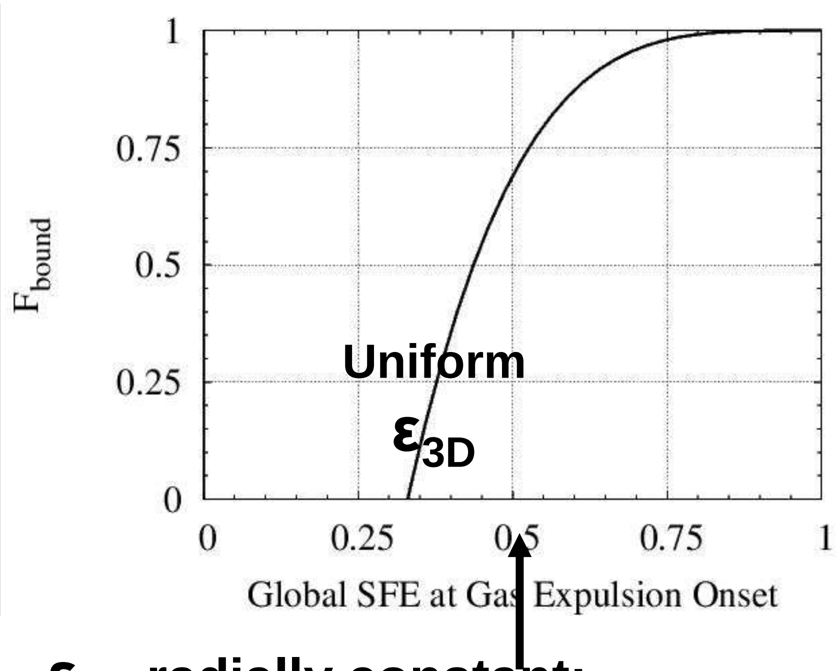
for the adopted M, R, ε_{ff}

(Parmentier & Pfalzner, in press)

Cluster Survival Made Easier [Conseq. 3]



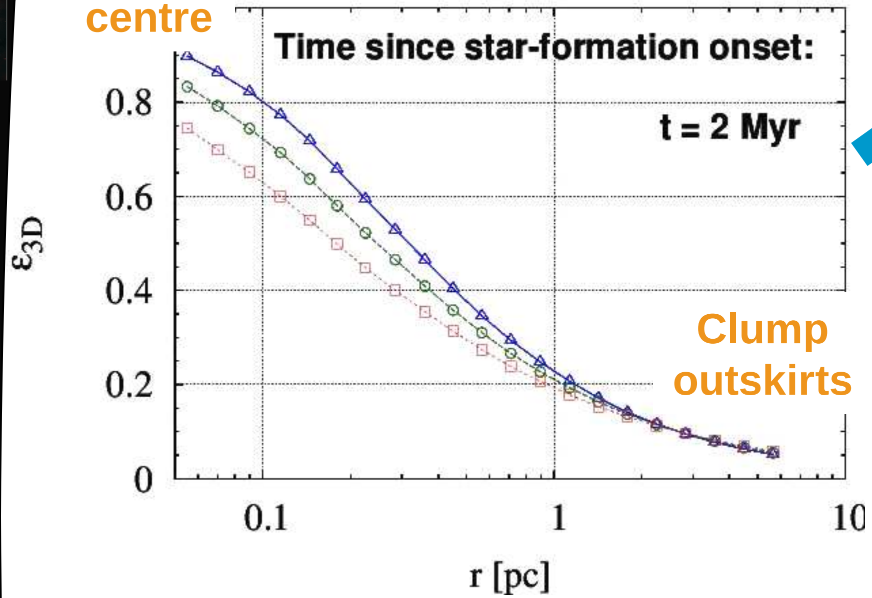





ε_{3D} **radially constant:**

- ε_{3D} **= SFE (local ≡ global)**
- **Cluster survival requires global SFE > 0.33**

Cluster Survival Made Easier [Conseq. 3]



$$\varepsilon_{3D}(t,r) = \frac{\rho_*(t,r)}{\rho_g(t,r)+\rho_*(t,r)}$$

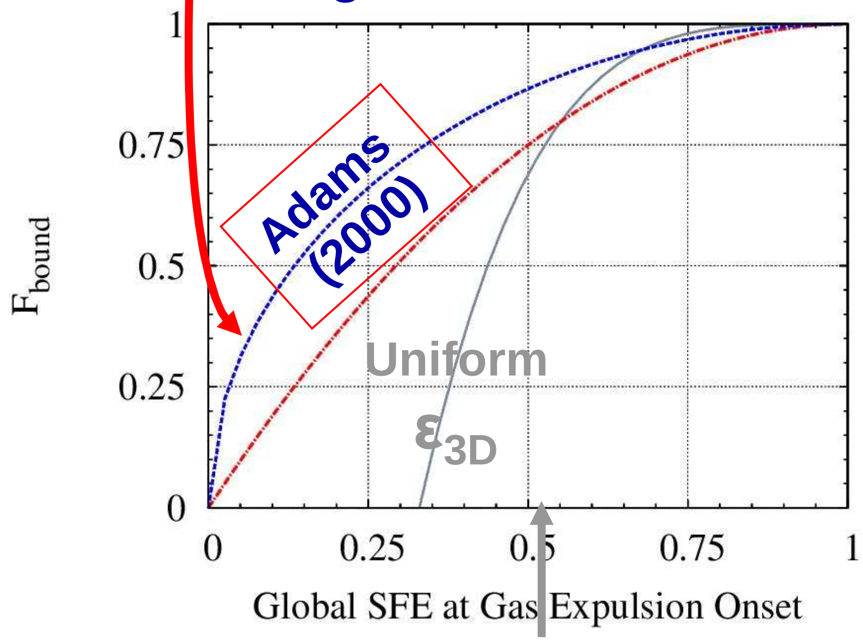
Caution!

$\varepsilon_{3D}(r)$ depends on ε_{ff}

Parmentier & Pfalzner, in press

$\varepsilon_{3D}(r)$ radially-varying:

- **clusters survive despite low global SFE**



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The Embedded-Cluster Growth Sequence

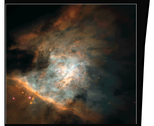
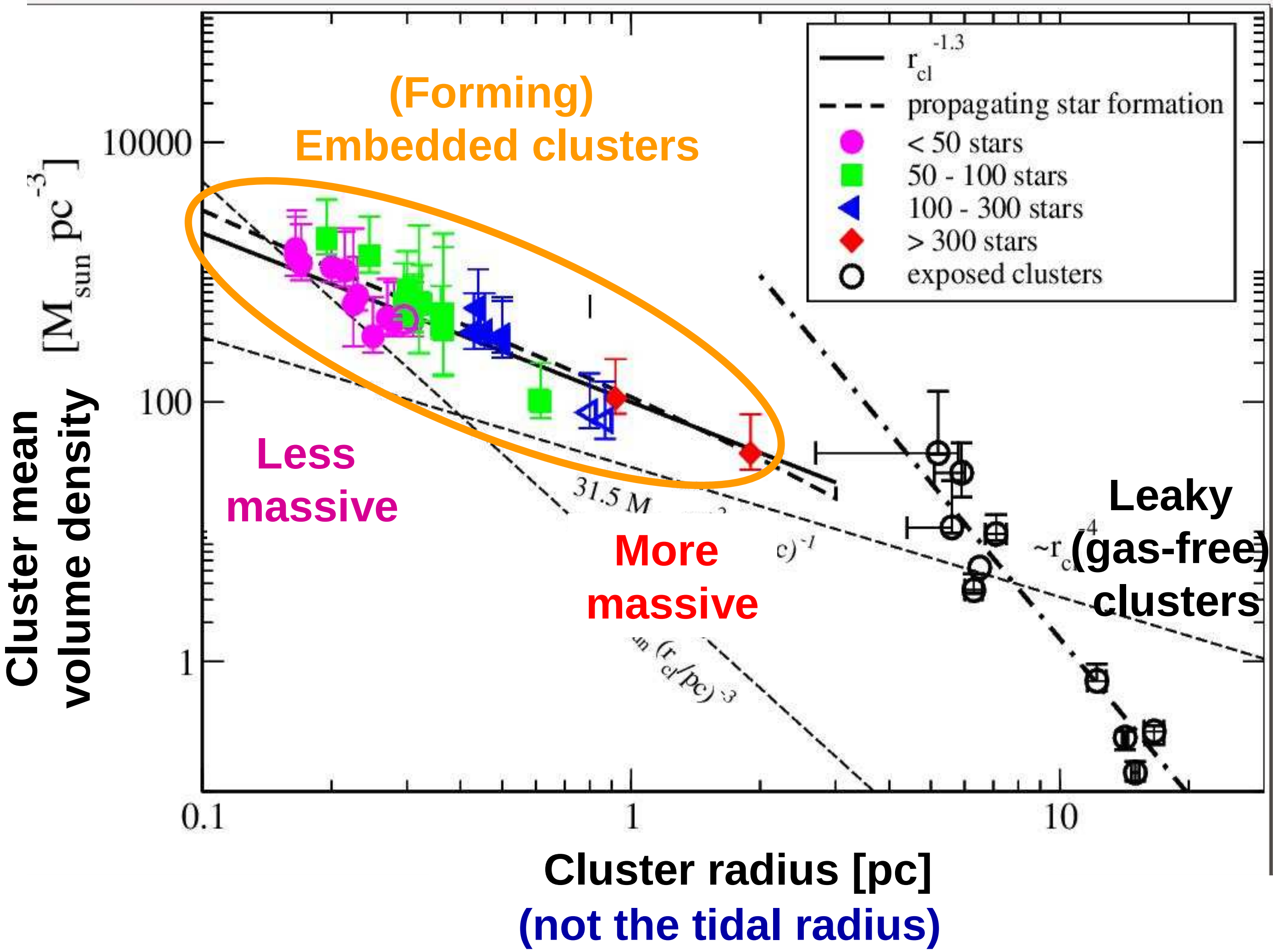


Fig2, Pfalzner (2011)



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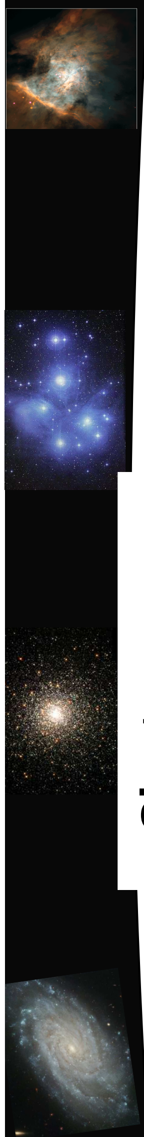

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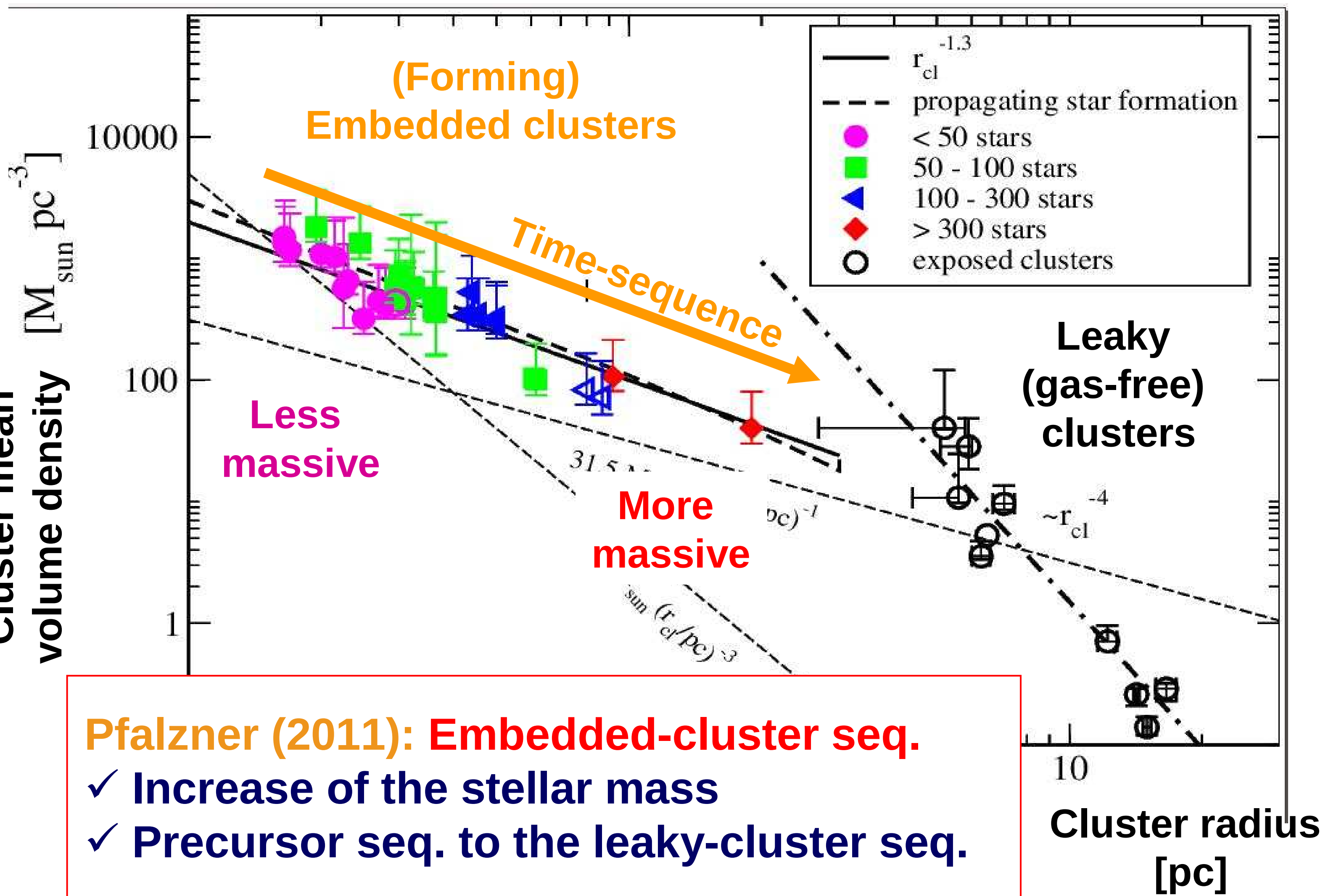


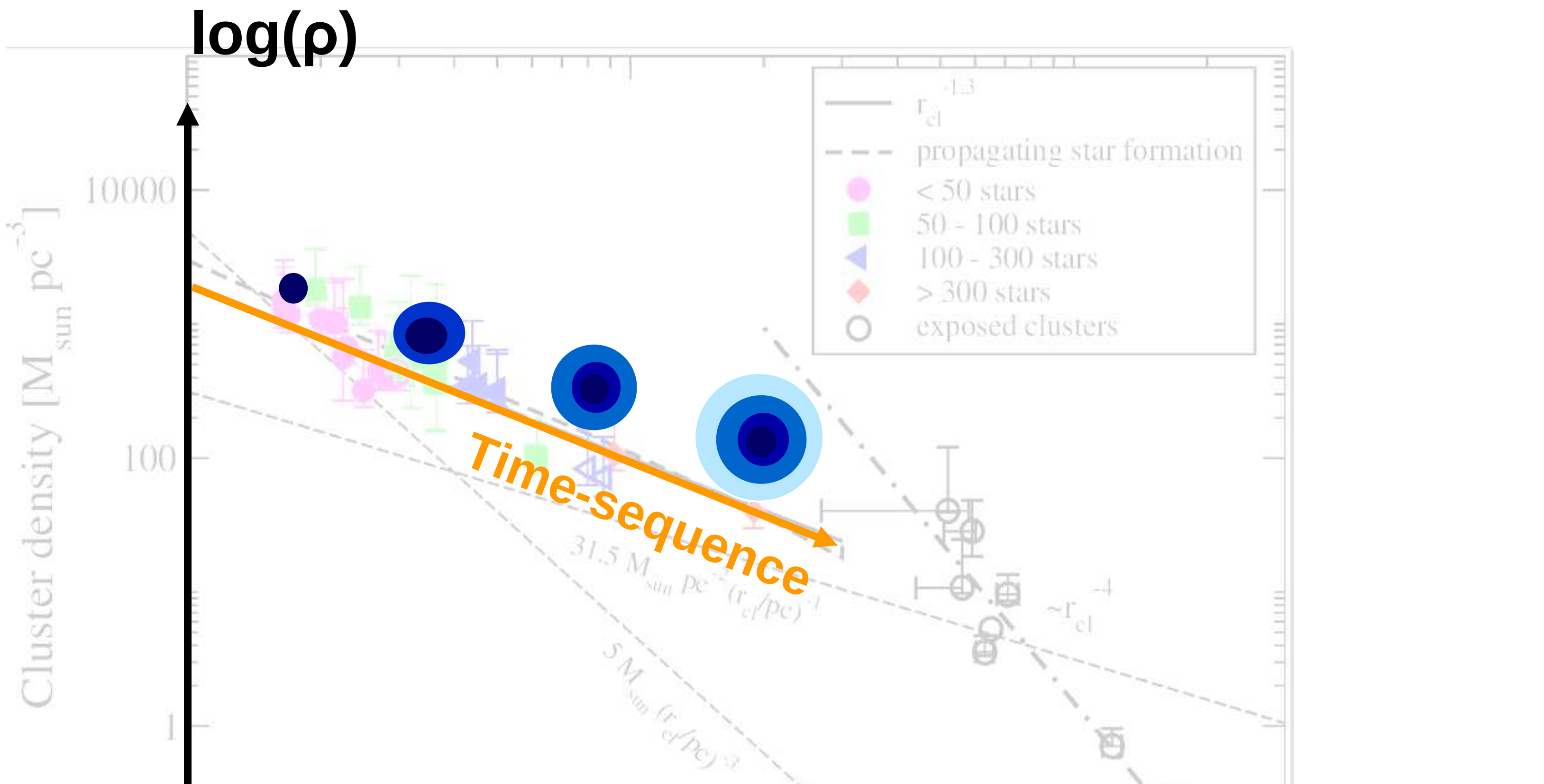
Pfalzner (2011): Embedded-cluster seq.

✓ **Increase of the stellar mass**

✓ **Precursor seq. to the leaky-cluster seq.**

→ **Defines a growth/time seq.**

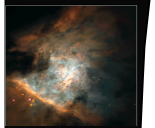
The Embedded-Cluster Growth Sequence

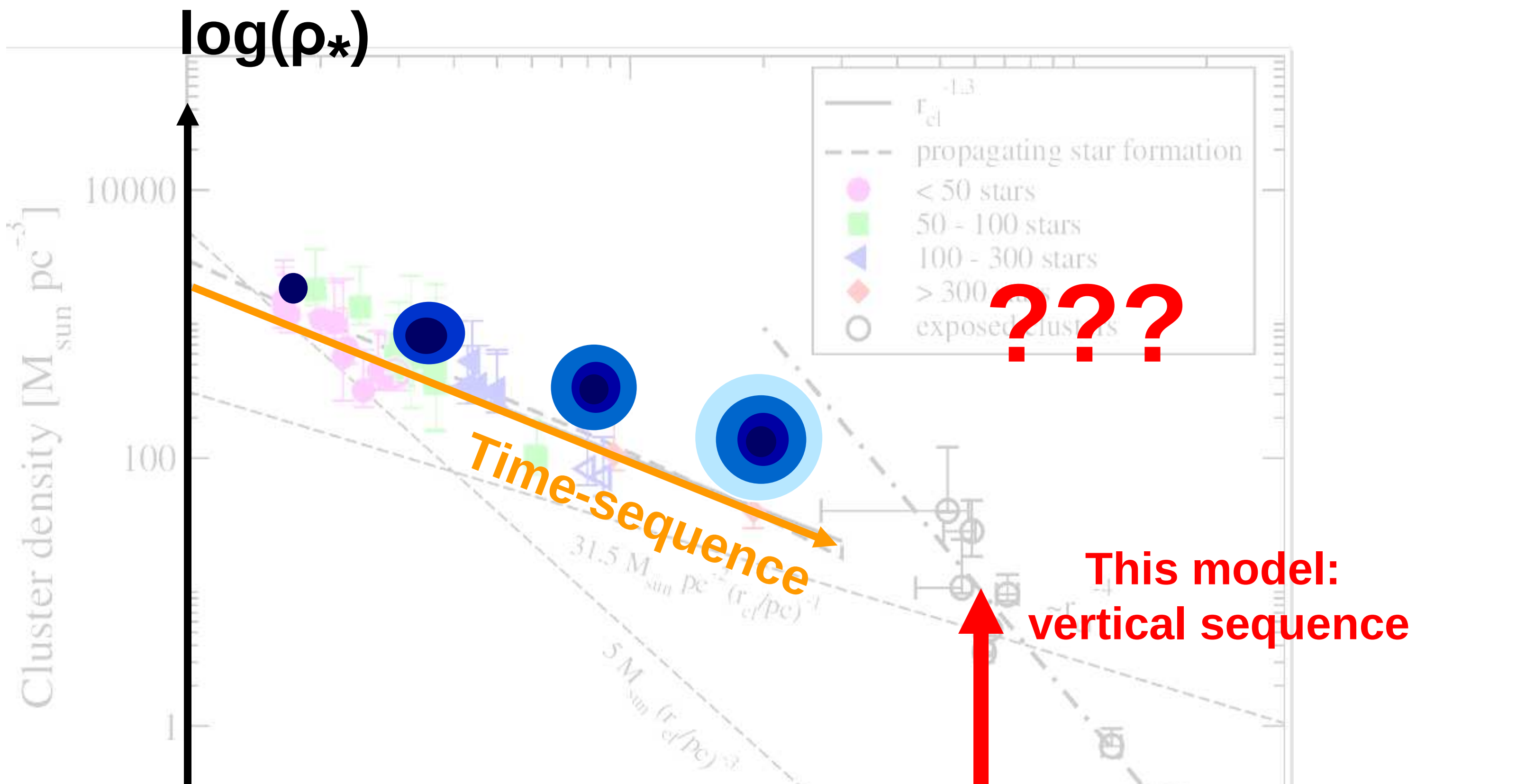


Pfalzner (2011): Embedded-cluster sequence
≡ outer shells of stars added with time
(i.e. SF is delayed in the outskirts)

- **growth of the radius with time**
- **decrease of the mean volume density with time**

The Embedded-Cluster Growth Sequence





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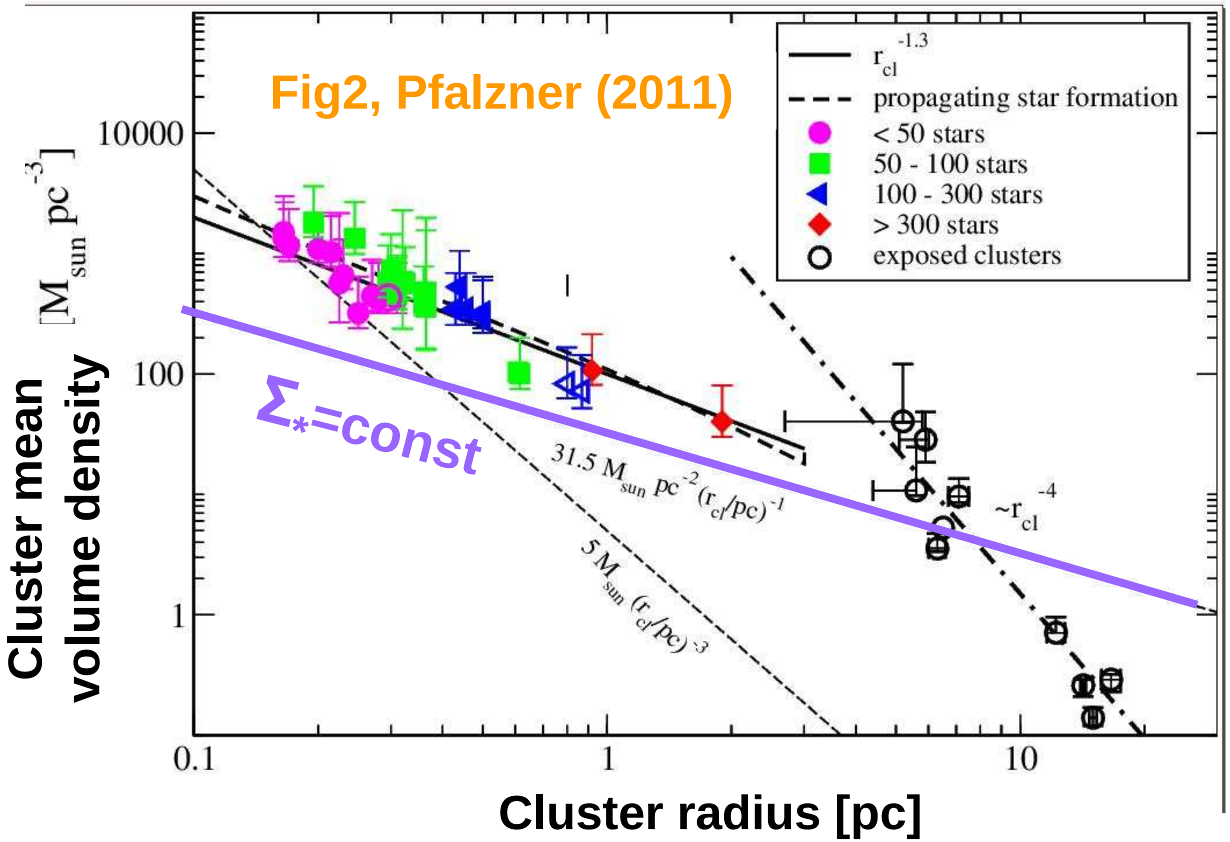
(i.e. SF is delayed in the outskirts)

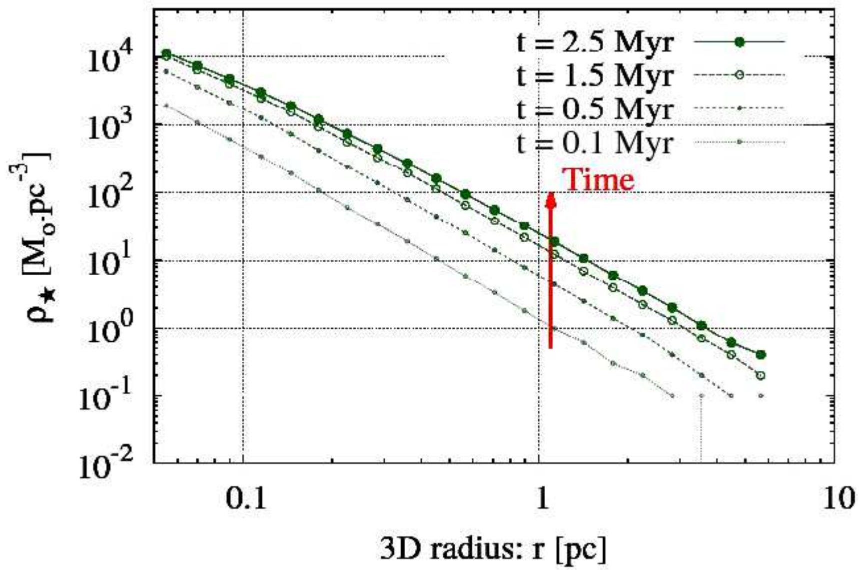
- **growth of the radius with time**
- **decrease of the mean volume density with time**

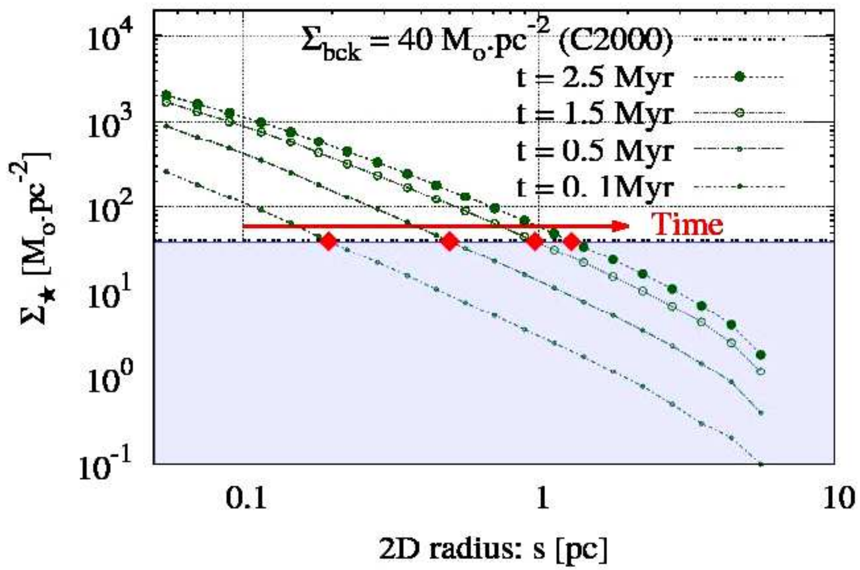
Reconciling the two scenarios with an obs. bias

Allen et al. (2007): "for the many clusters surrounded by large, low surface density halos of stars, the measured radius and density of these clusters depends on the threshold surface density used to distinguish the cluster stars from those in the halos"



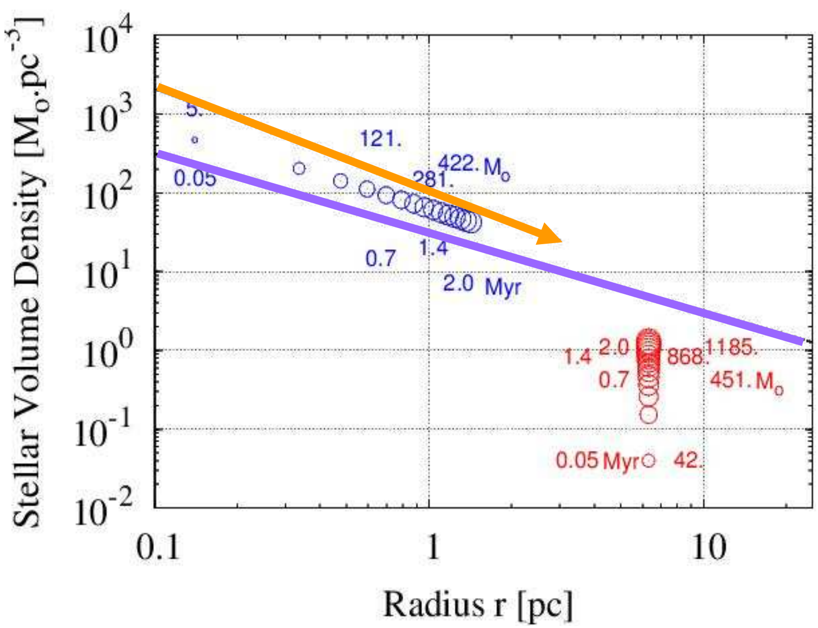
Reconciling the two scenarios with an obs. bias





A surface density threshold reconciles **the model** and the data

Parmentier & Pfalzner, in press



Conclusions: From the Cluster Mass Function to the Local Star Formation Law

Macroscopic: galaxy-wide, or multi-kpc scale
→ mass distribution of star clusters

Microscopic: star-forming region few-pc scale
→ local star formation law