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Building on the Macroscopic to understand the Microscopic: from Systems of Star Clusters to Individual Star-Forming Regions

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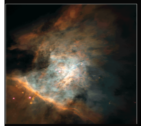
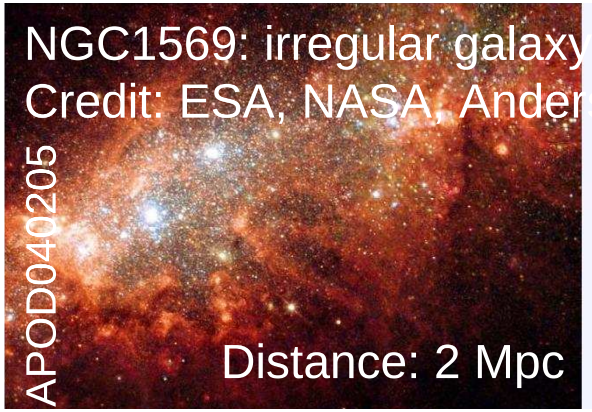
Setting the Scene: Star Clusters (SC) as Powerful Tracers of Galaxy Evolution

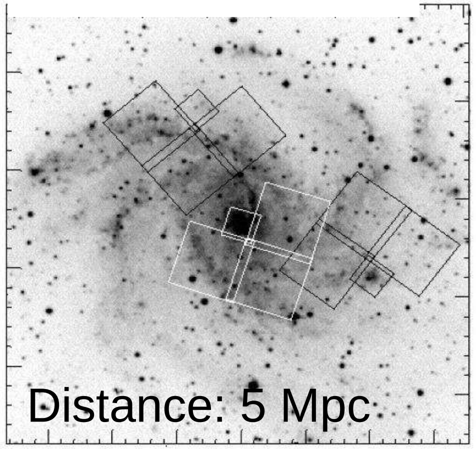


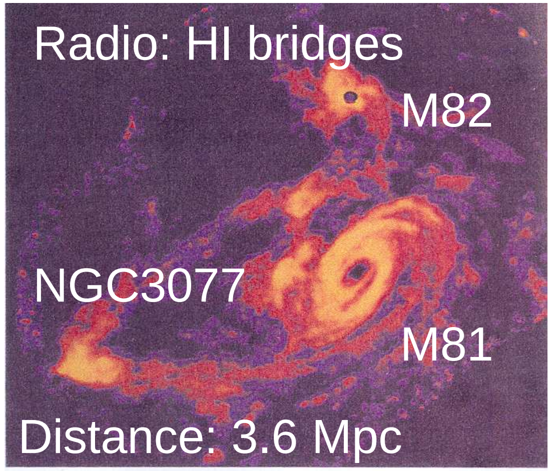
Star Clusters (SC):

- **Groups of coeval gravity-bound stars**
- **Help us probe the Universe in both space and time**

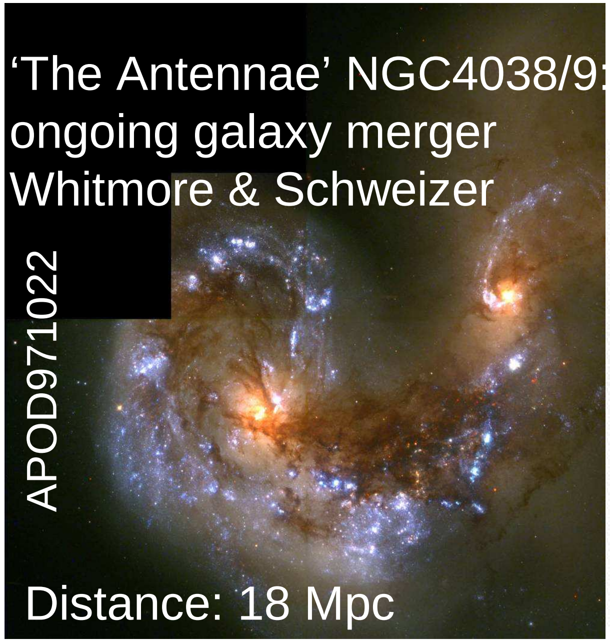


Spiral NGC 6946
Larsen 2002

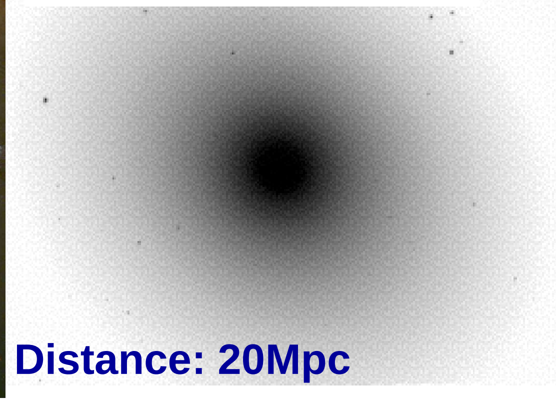




Yun, Ho & Lo 1994



Elliptical galaxy M49
Jordan+04



Distance: 20Mpc

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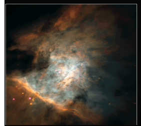


Star Clusters (SC):

- Compact groups of stars → identified on a one-by-one basis against the background of their host galaxy

Multi-band imaging of SC systems:

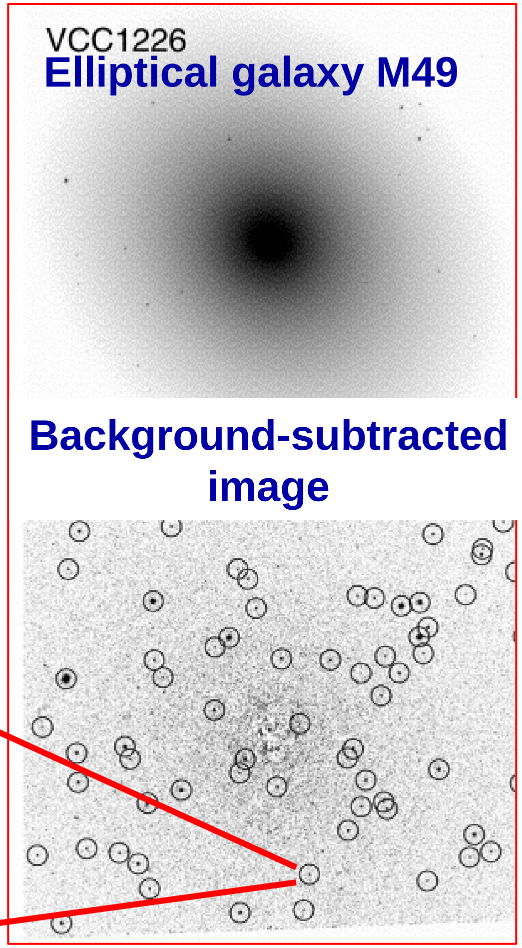
- Cluster magnitudes & colours combined to Stellar Population Synthesis Models
  → cluster age, mass, metallicity estimates

Comprehensive view of galaxy-:

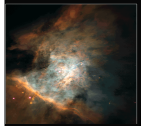
- chemical enrichment history,
- interaction history,
- star formation history (SFH)

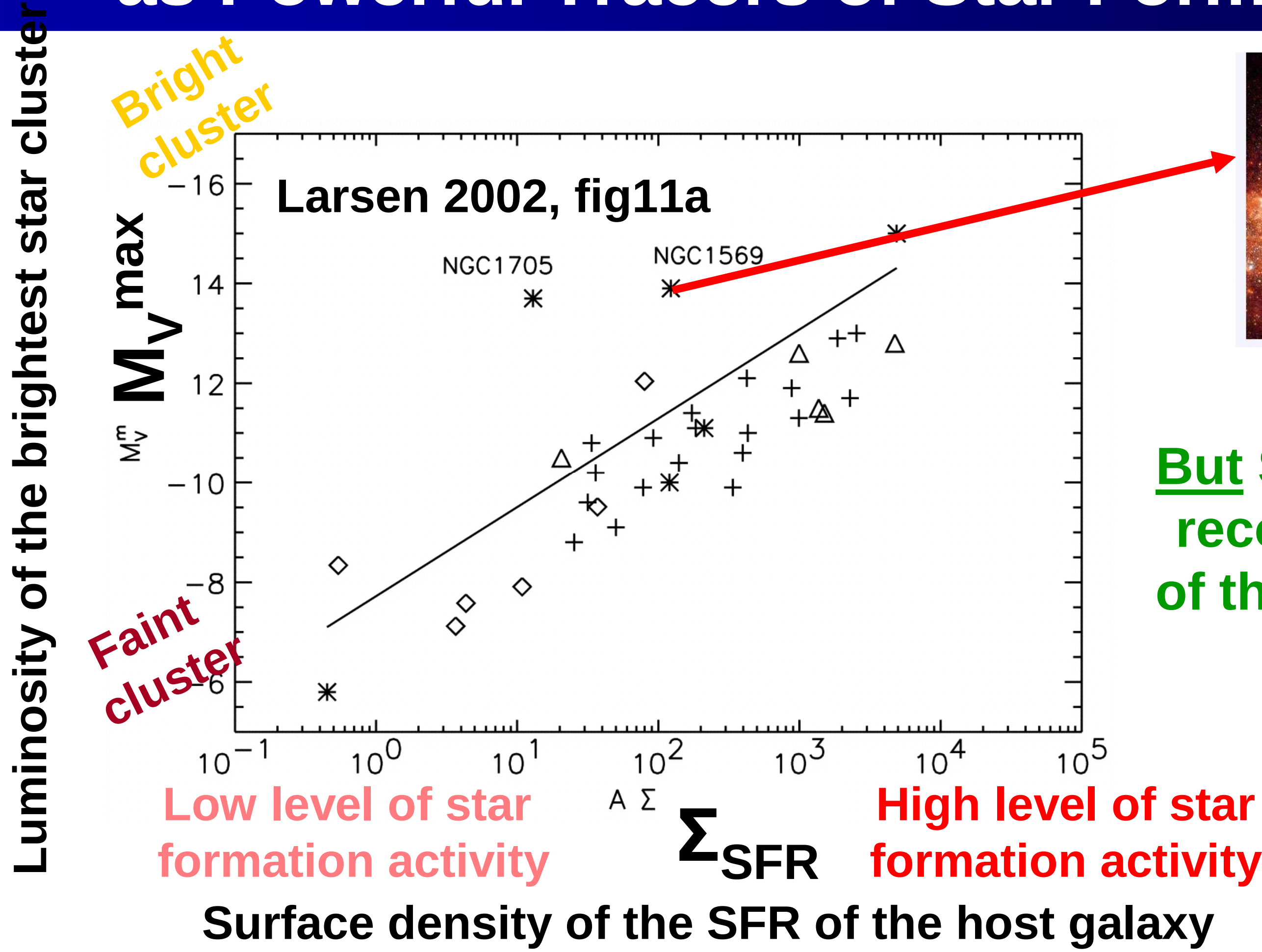
over the past Hubble-Time

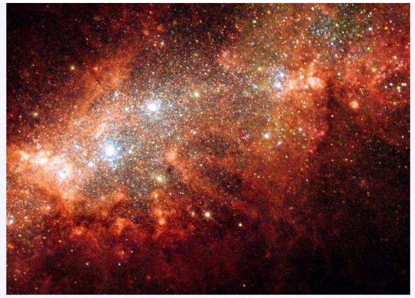
Jordan+04 (ACS Virgo Galaxy Cluster Survey II, fig6)



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





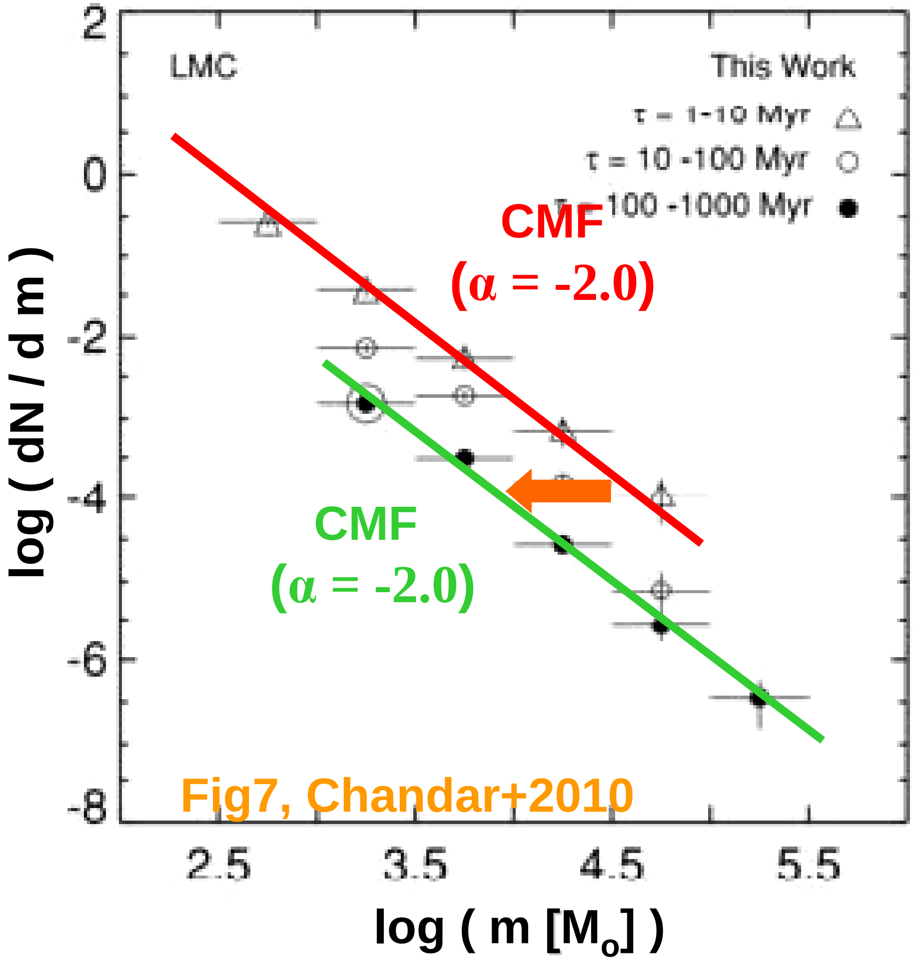


<u>But</u> SCs = encoded record of the SFH of their host galaxy

- **Do most stars form in clusters ?**
- **Or does it exist two modes of star formation (diffuse and clustered) but with some correlation between the two modes?**

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

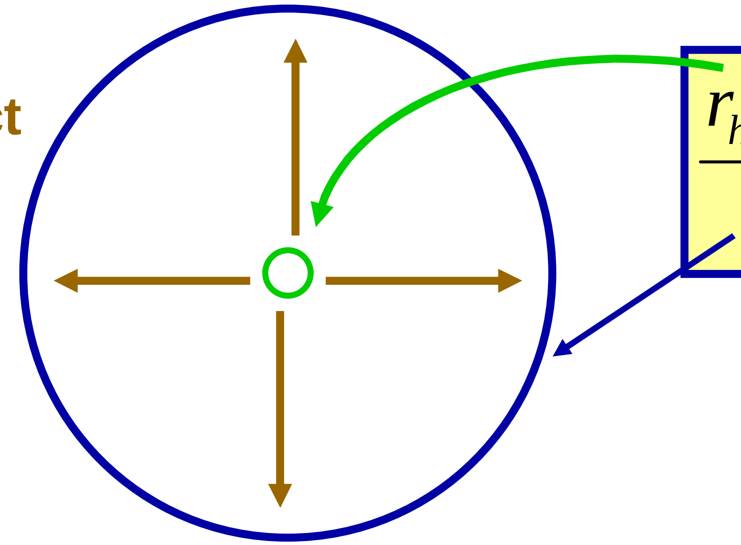
Cluster mass-loss is mass-independent

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



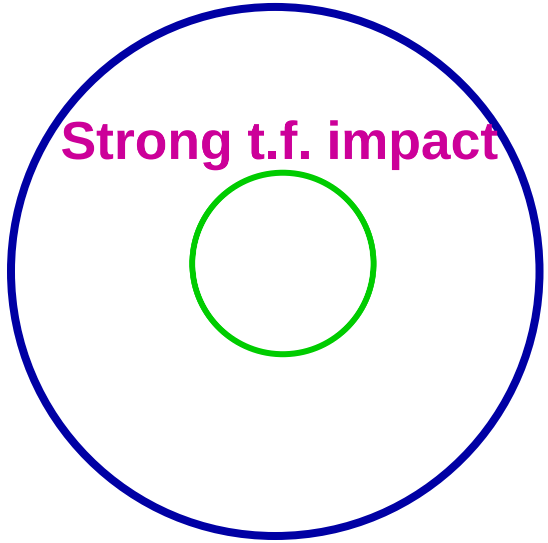
$$\frac{r_{half-mass}}{r_{tidal}} = f_{env} \times (\rho_{CFRg})^{-1/3}$$

Cluster environment

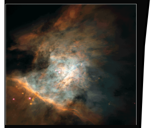
Baumgardt & Kroupa (2007) parametrization

For a given environment,

- **higher mass-losses due to gas expulsion**
- **if higher tidal field impact**
- **e.g. smaller CFRg densities**



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



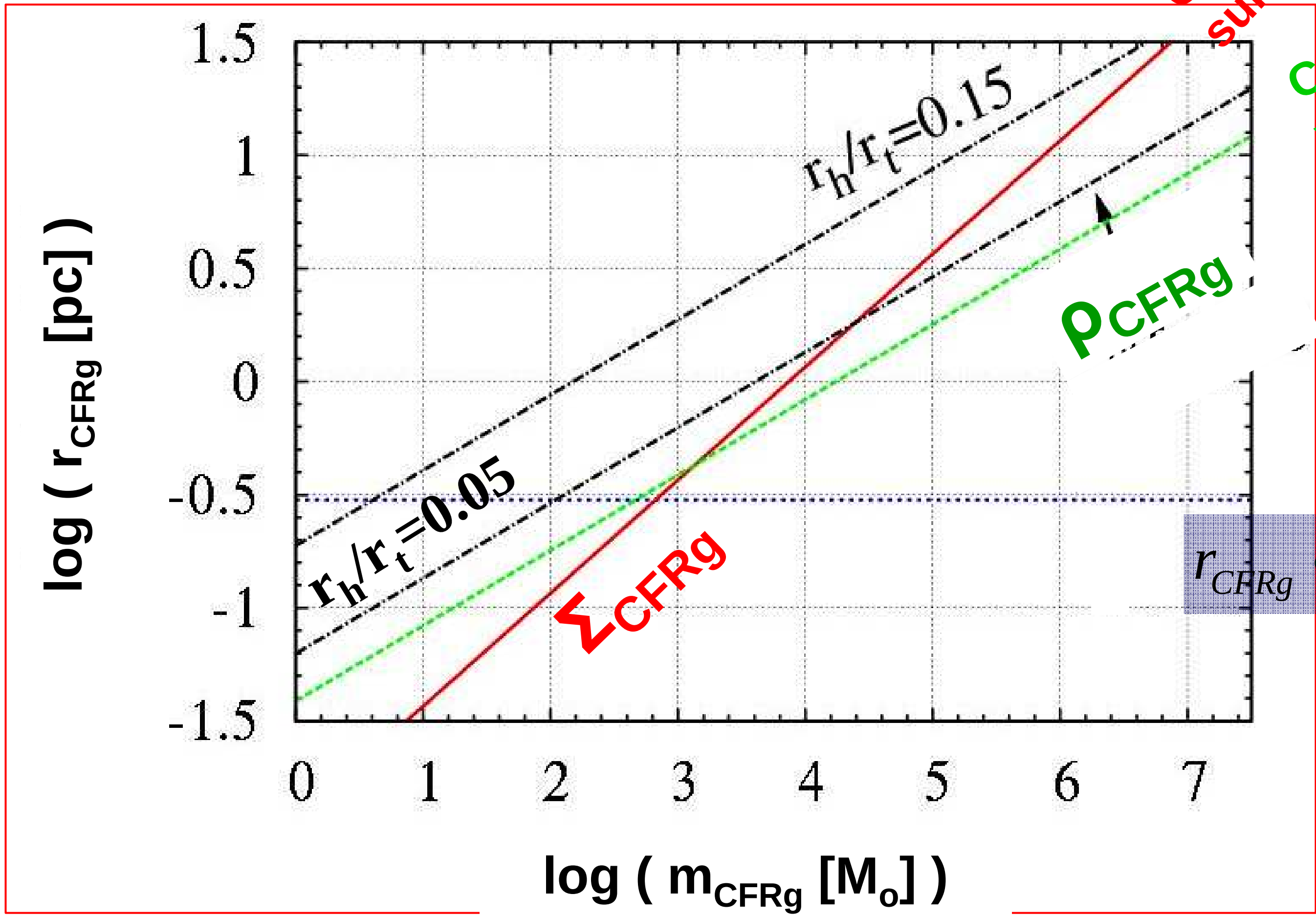

$$\frac{r_{half-mass}}{r_{tidal}} = f_{env} \times (\rho_{CFRg})^{-1/3}$$

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

Constant mean surface density

Constant mean volume density

$r_{CFRg} \propto m_{CFRg}^{1/3}$



$r_{CFRg} \propto$ constant

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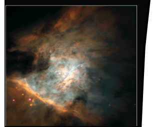


$$\frac{r_{half-mass}}{r_{tidal}} = f_{env} \times \left(\rho_{CFRg}\right)^{-1/3}$$

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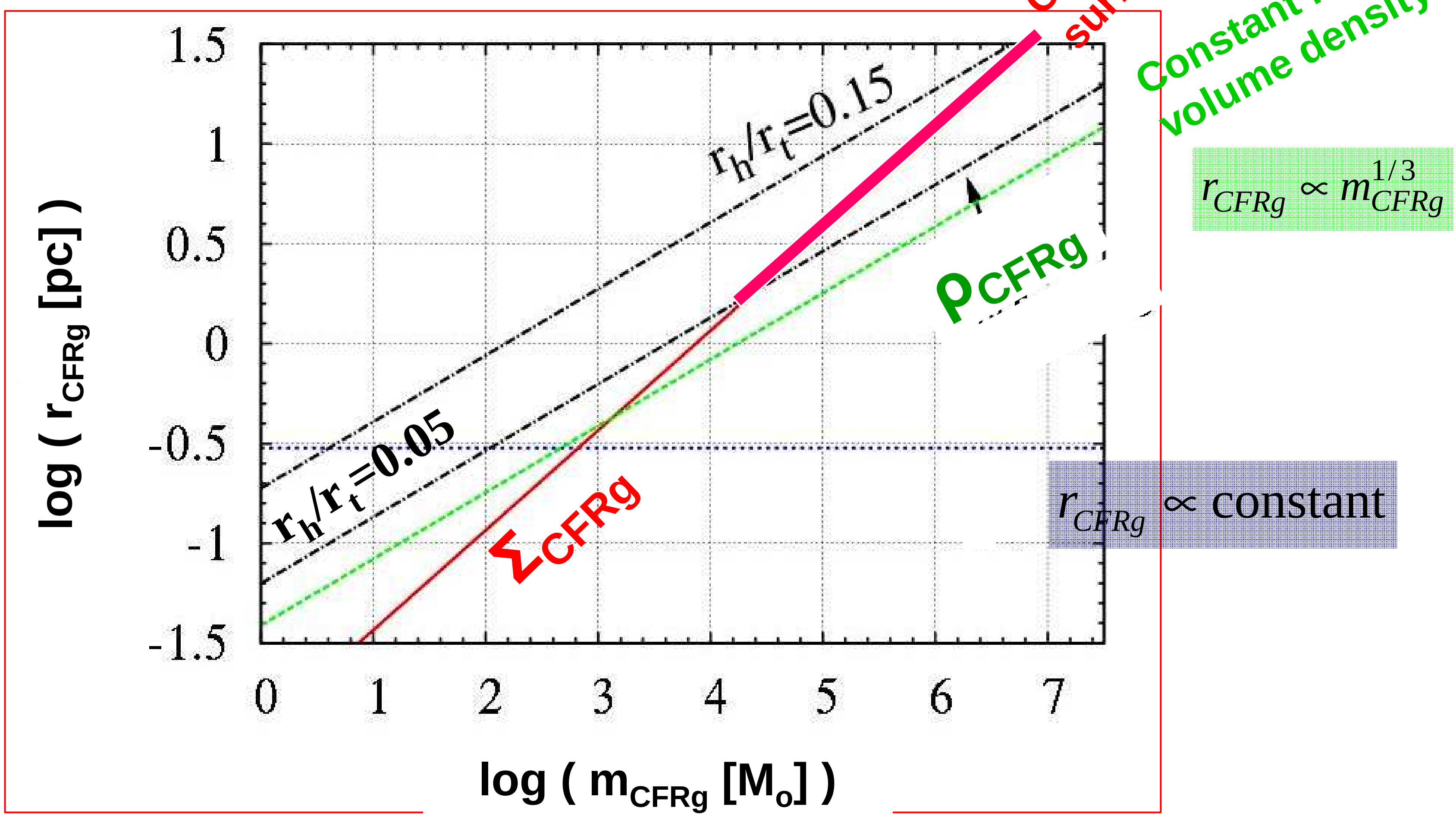
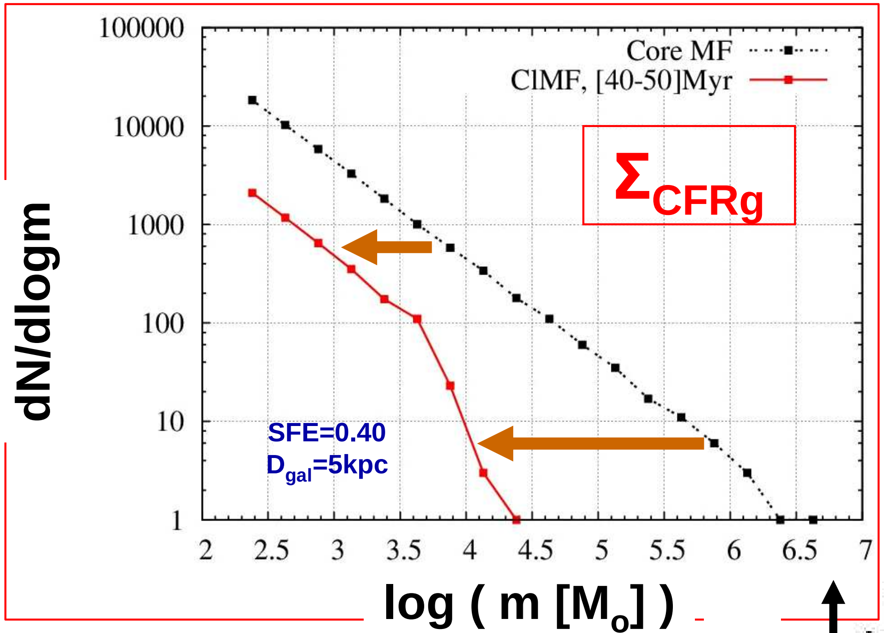
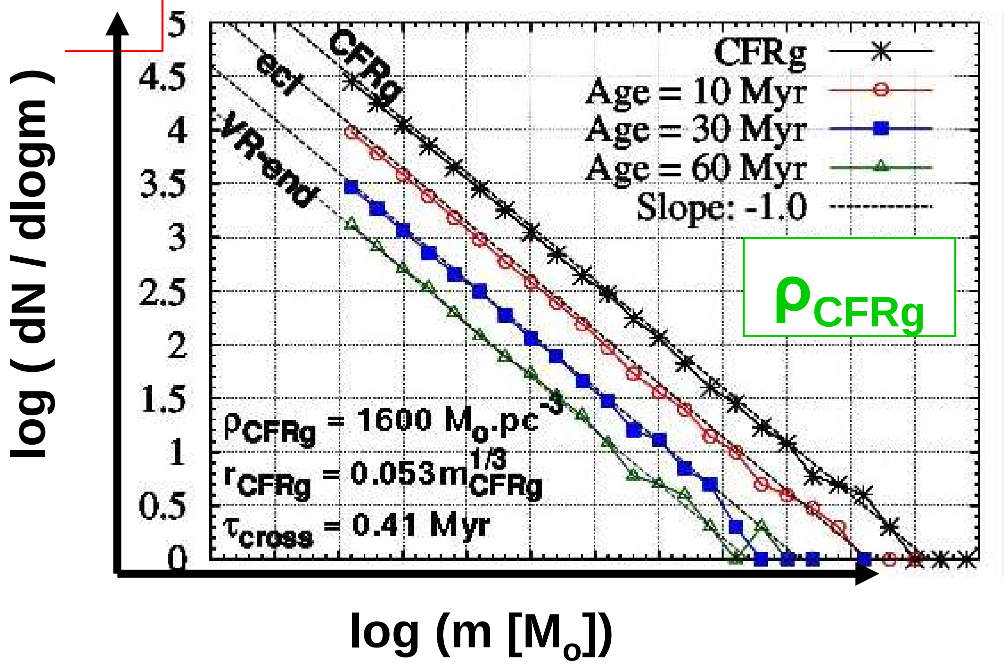


Young SC Mass Functions - Tidal Field Impact



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!

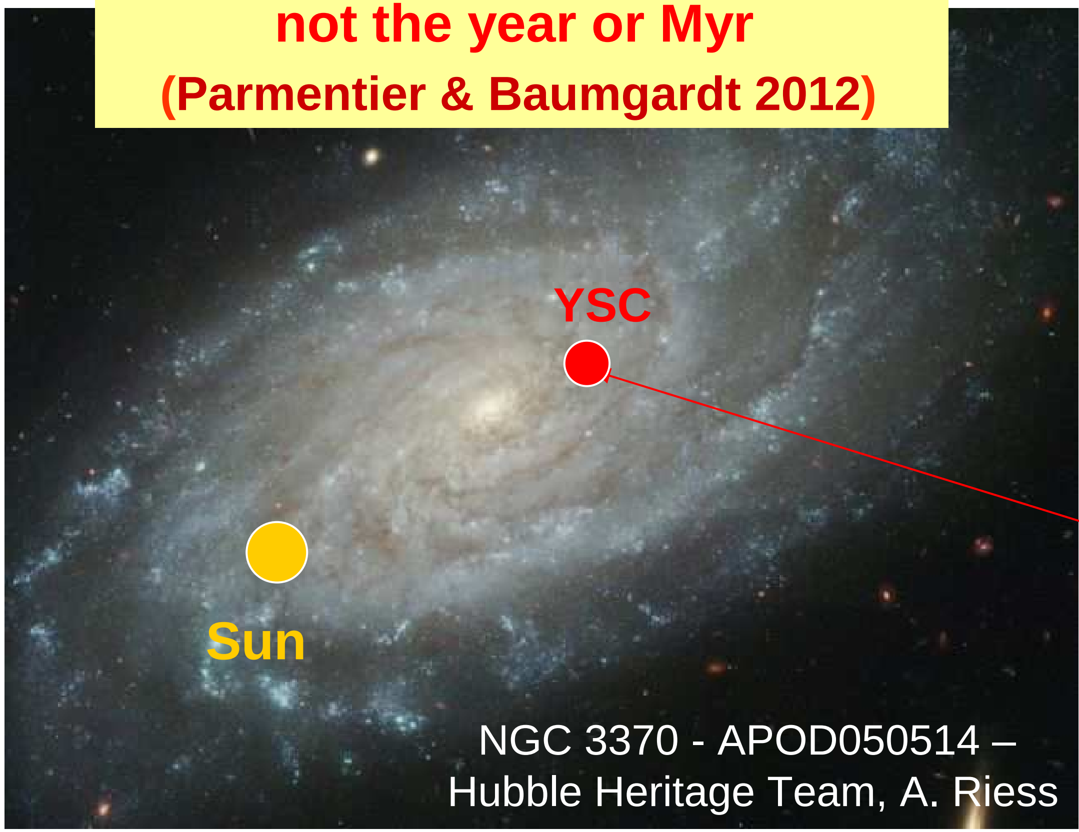
A star cluster does not care about how long it takes for the earth to revolve around the sun! The basic time-unit is the <u>cluster initial crossing-time</u>, not the year or Myr

(Parmentier & Baumgardt 2012)

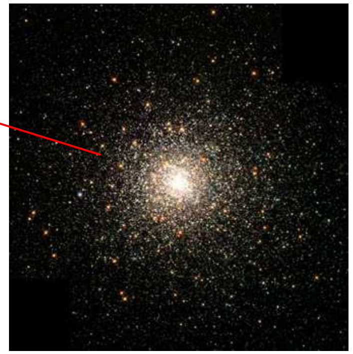
$$\tau_{cross} \propto \rho_{CFRg}^{-1/2}$$

$$\tau_{cross} \cong 35 \sqrt{\frac{\left(r_{CFRg}\right)^3}{m_{CFRg}}}$$

Exact coefficient depends on density profile

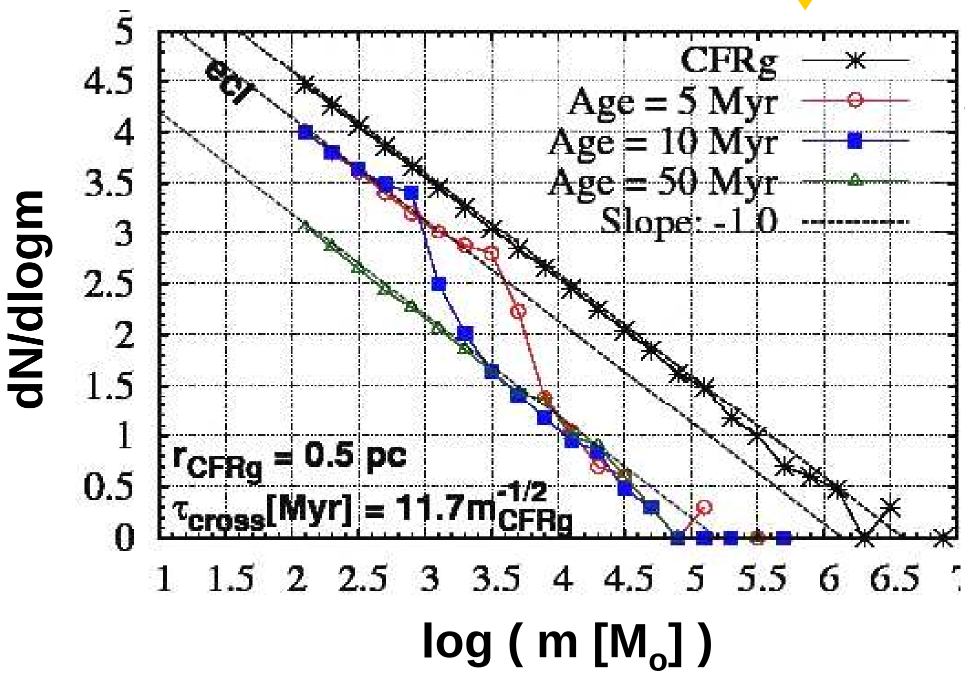


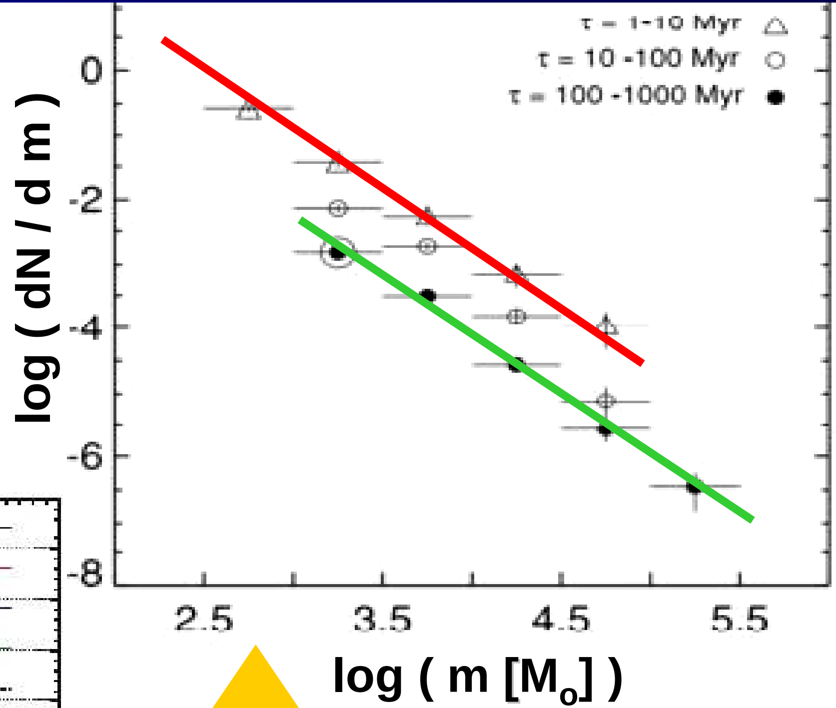
NGC 3370 - APOD050514 – Hubble Heritage Team, A. Riess



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

Simulations of star clusters with the most massive clusters the densest ones (constant radius) → higher mass objects evolve at a quicker rate. Parmentier & Baumgardt (2012)





Observations of star clusters in the Large Magellanic Cloud (Chandar+ 2010)

A Volume Density Threshold for the SF Gas ?

- **ρ_{CFRg} = constant :**

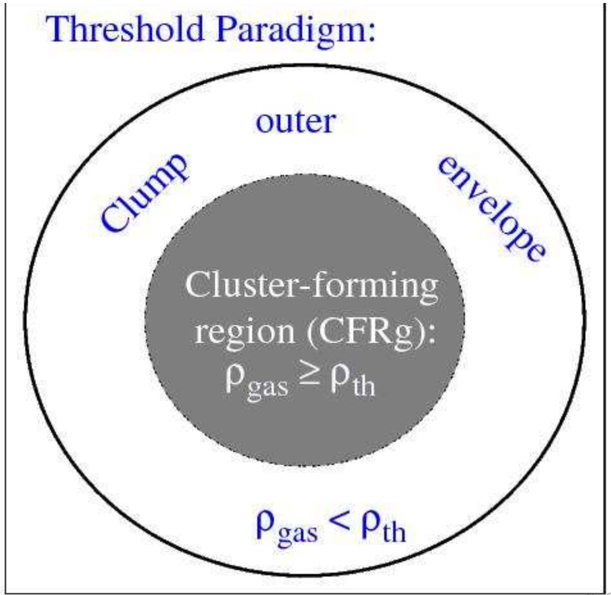
  provides the most robust solution to the time-invariant shape of the cluster mass function

- **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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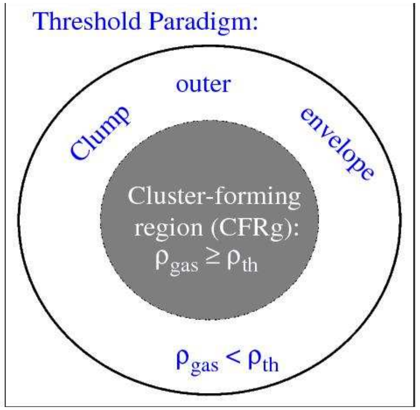
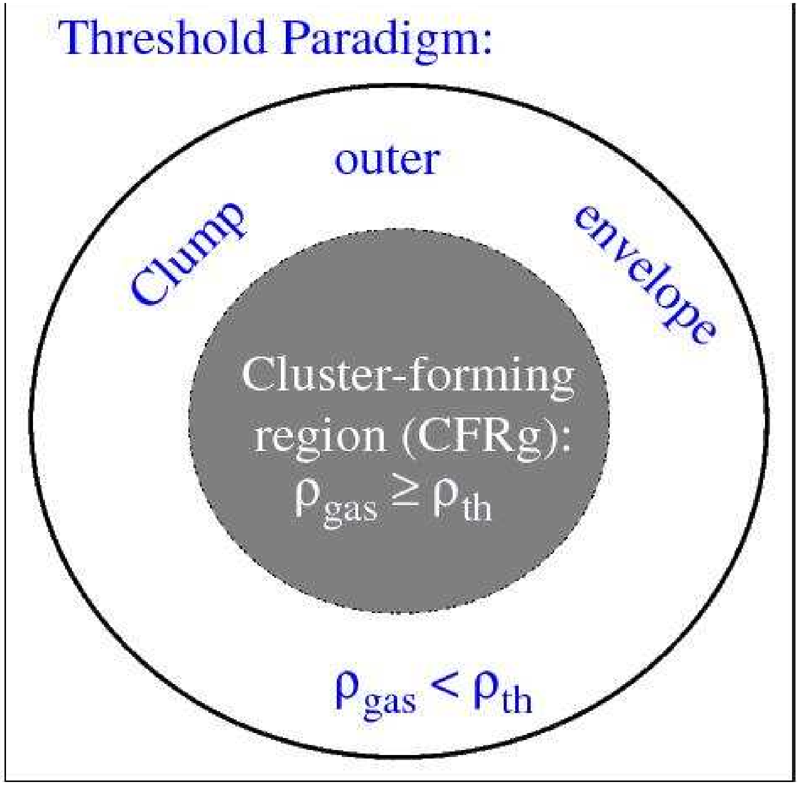


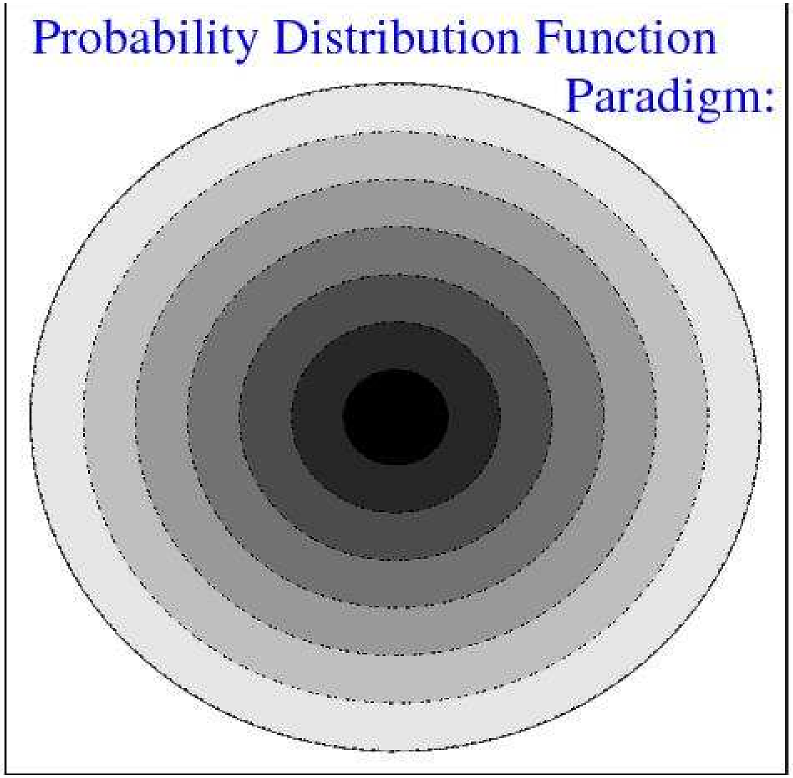
- Same scaling (constant mean volume density) as from:
  - the tidal field impact analysis (Parmentier & Kroupa 2011)
  - the crossing-time analysis (Parmentier & Baumgardt 2012)

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

Spitzer-telescope observations: star formation can proceed in low-density environments too …

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





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

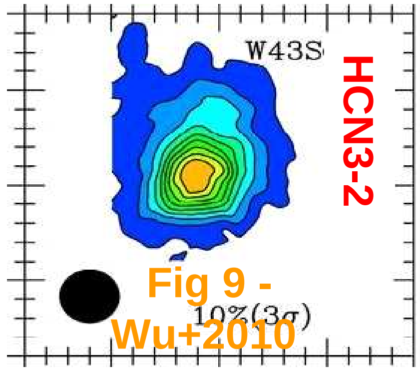
Star Formation Efficiency ε_{ff}
per Free-Fall Time τ_{ff}

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

Krumholz & McKee 2005

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

- **On the scale of individual molecular clumps**
  - **volume density gradients** ⟶⟶
  - **$SFE_{centre} >> SFE_{outskirts}$**
    - Consequences?

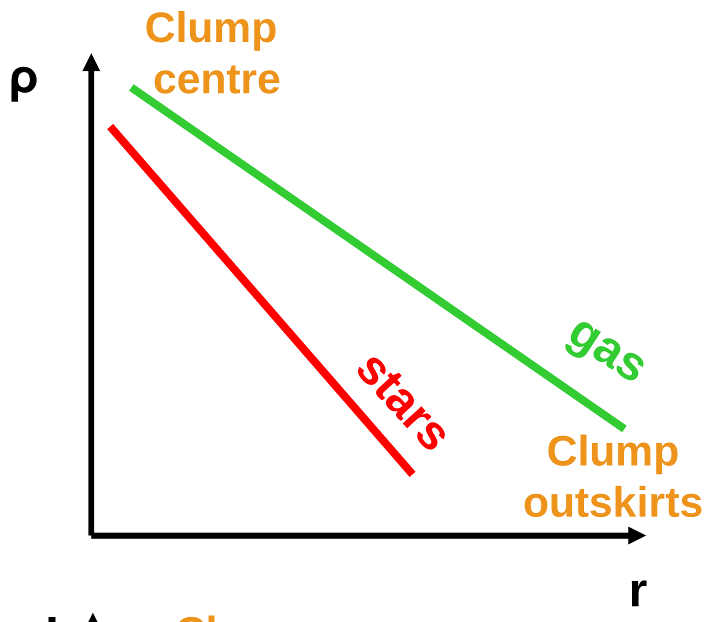


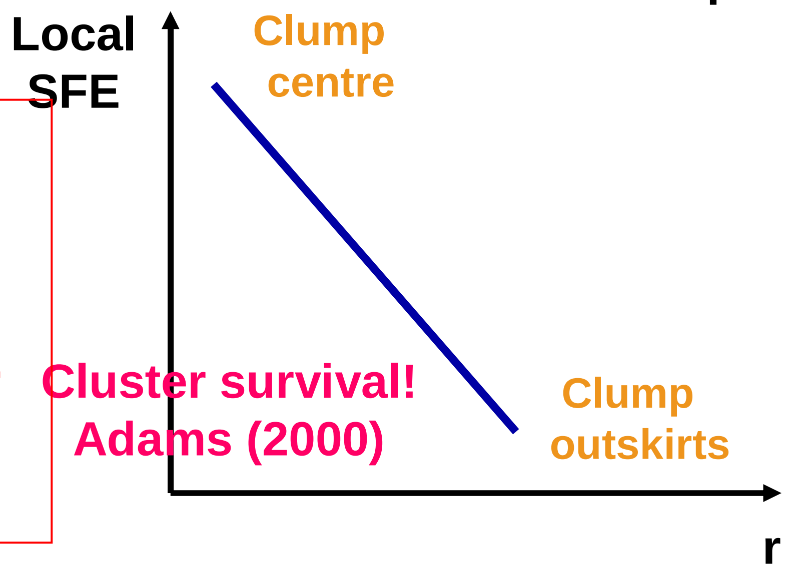
- **Denser**
- **Faster**
- **Higher SFE**

Immediate consequences of the ε_{ff} concept

Conseq.1

- **Density profiles:**
  $\rho_*(r)$ steeper than $\rho_g(r)$
- **Radially-dependent local SFE**
-

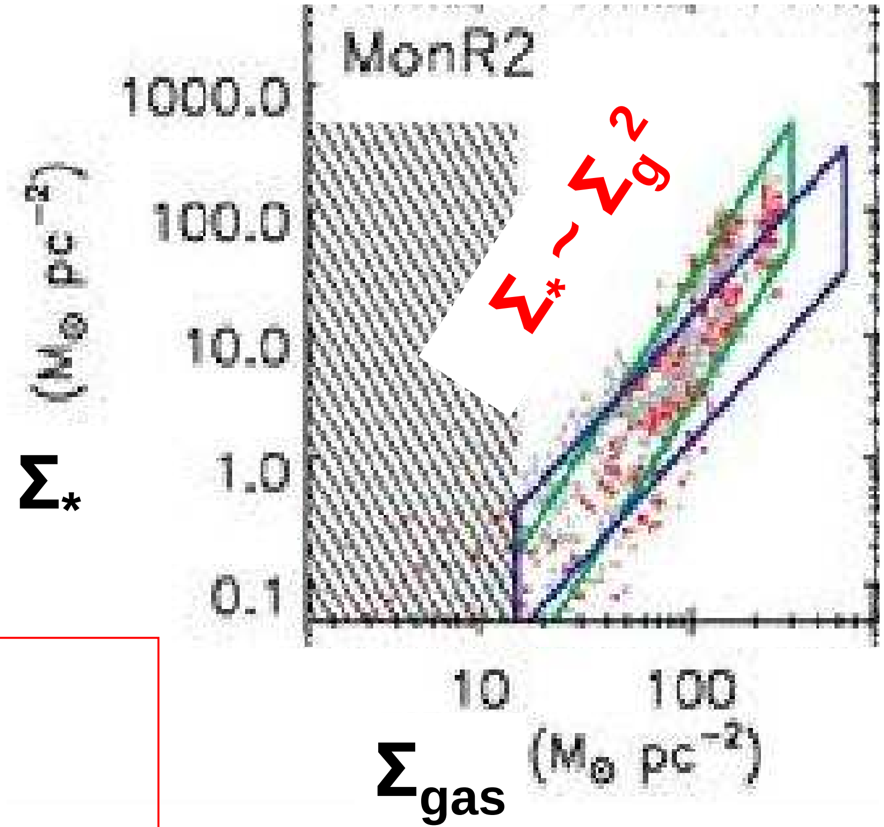




Immediate consequences of the ε_{ff} concept

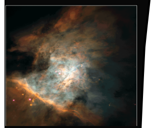
Fig9, Gutermuth+ (2011)

Conseq.2



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

Star and Gas Volume Density Profiles [Conseq.1]



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

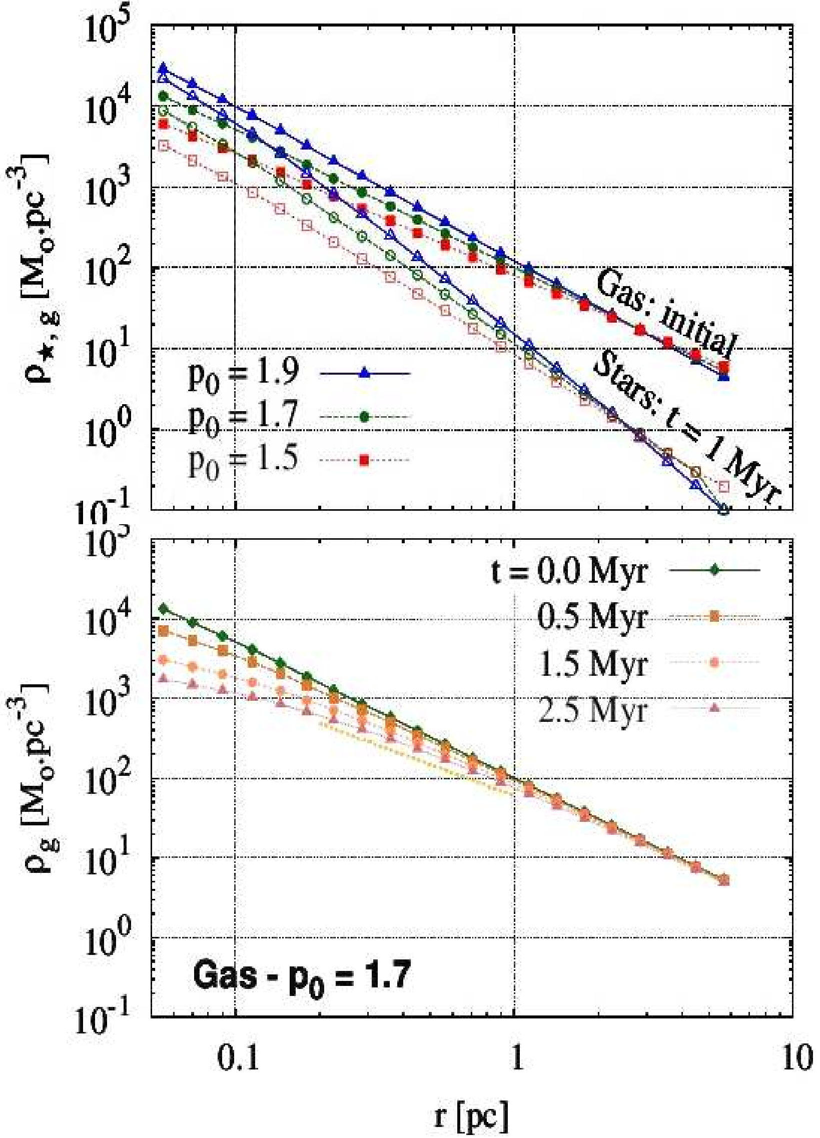
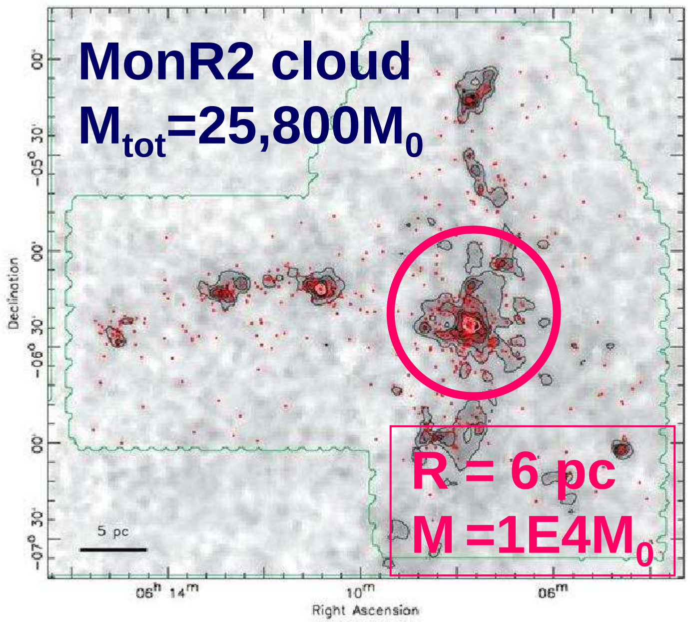


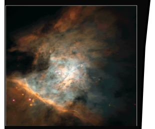
Fig1, Gutermuth+ (2011)



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]



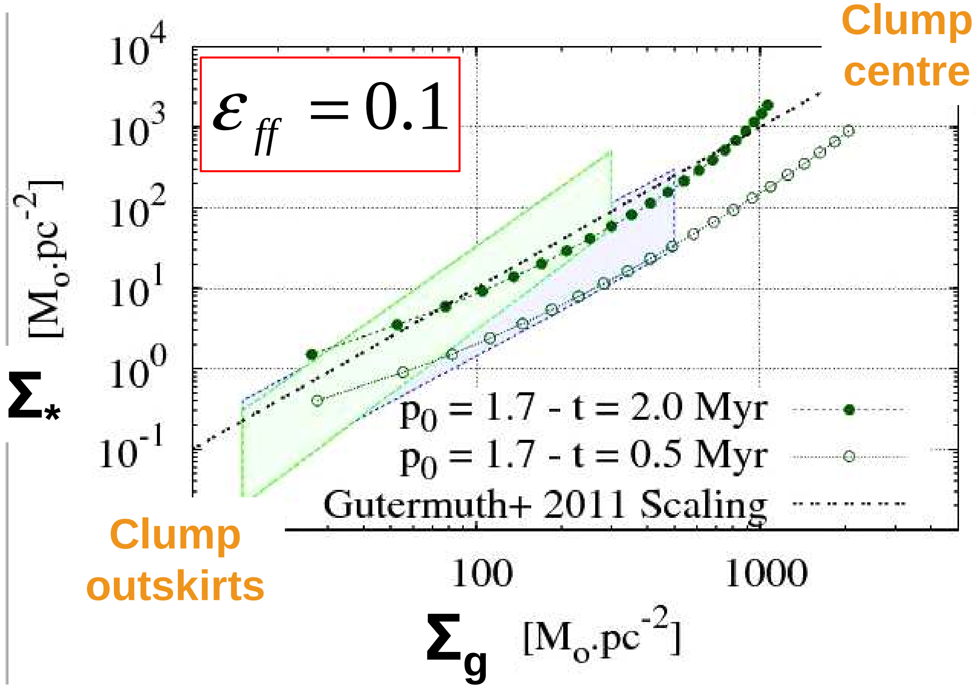
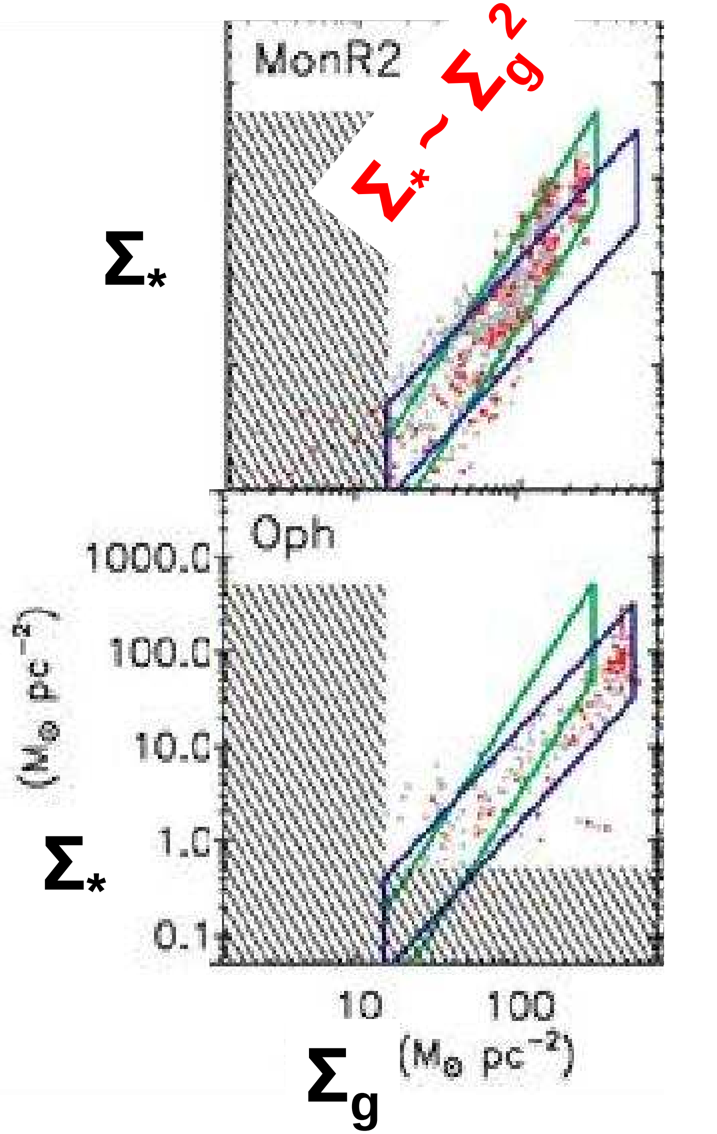



Fig9, Gutermuth+ (2011)

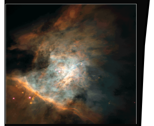


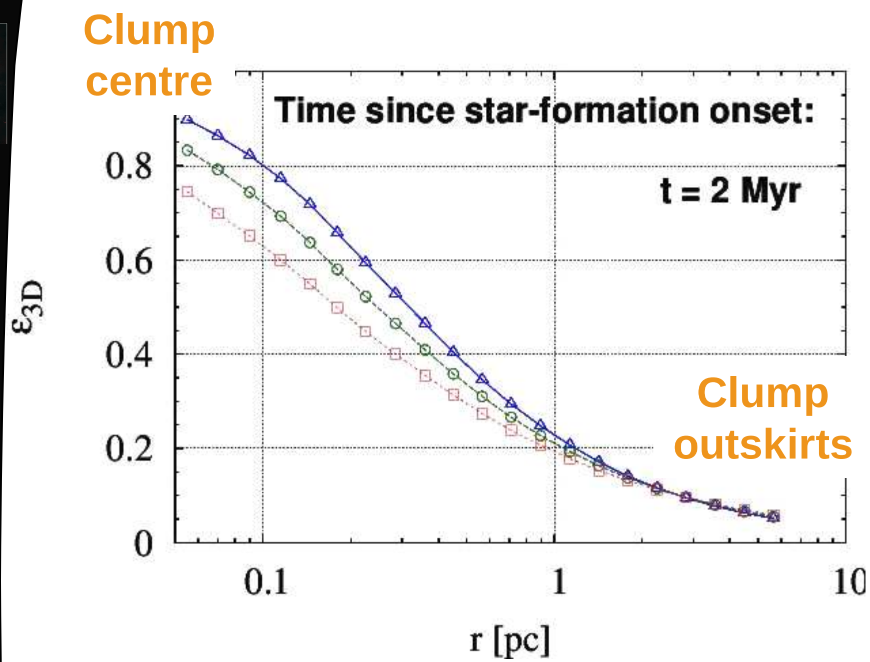
Relation between the local surface densities of YSOs and of the residual gas:

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

for the adopted M, R, ε_{ff}
(Parmentier & Pfalzner 2013)

Cluster Survival Made Easier [Conseq. 1b]



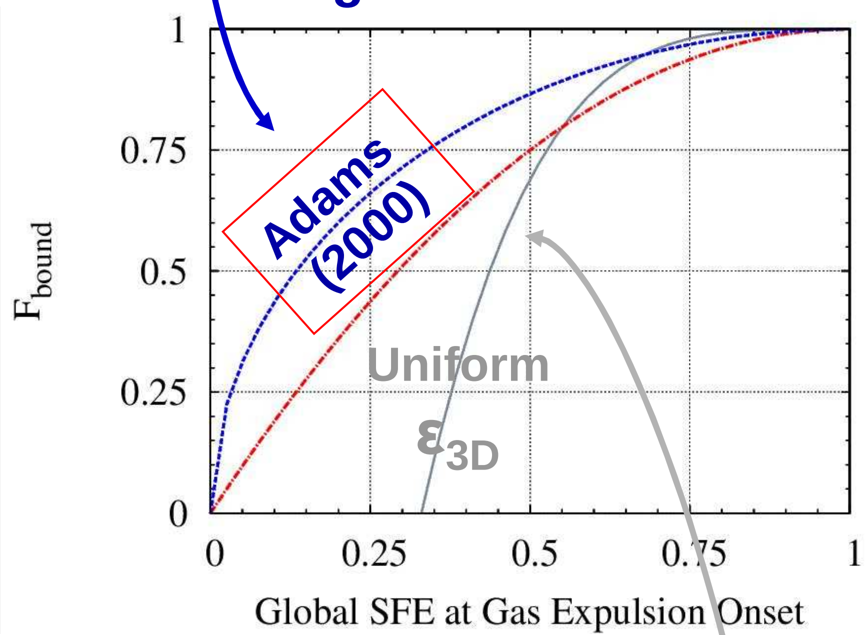



$$\text{Local SFE} = \varepsilon_{3D}(t,r) = \frac{\rho_*(t,r)}{\rho_g(t,r)+\rho_*(t,r)}$$

Parmentier & Pfalzner 2013

ε_{3D}(r) radially-varying:

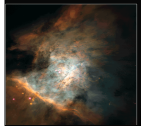
- **clusters survive despite low global SFE**



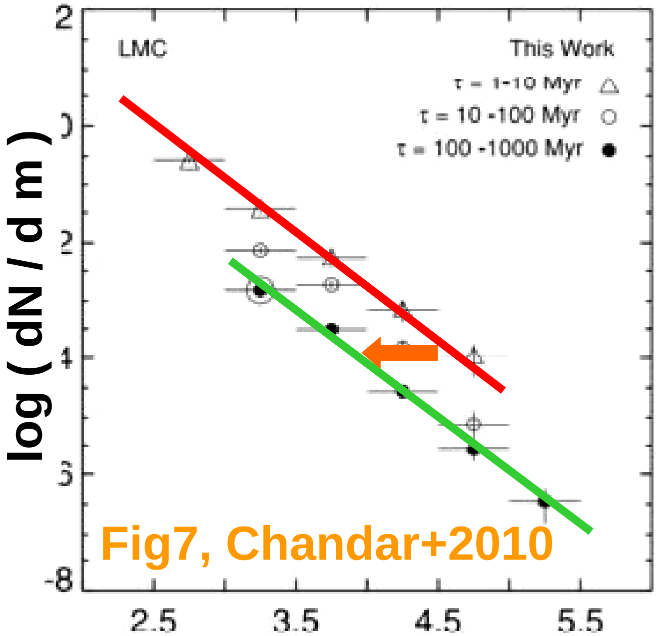
ε_{3D} radially constant:

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

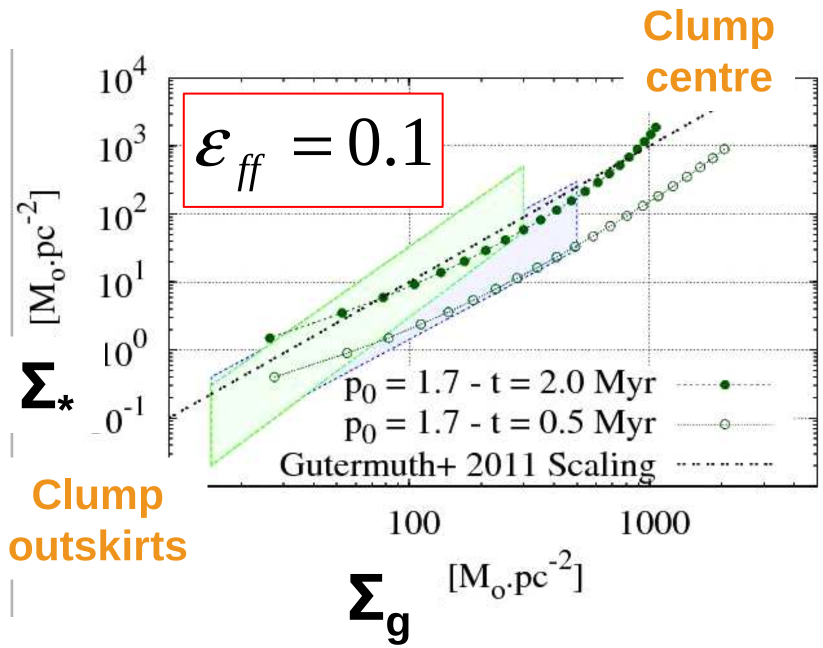
Conclusions: From the Cluster Mass Function to the Local Star Formation Law



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



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



Contact Details

- ✓ **Talk slides at:** wwwstaff.ari.uni-heidelberg.de/mitarbeiter/gparm/talks.html
- ✓ **E-mail: gparm AT ari.uni-heidelberg.de**