MPIfR/AIfA Hauptkolloquium, 19 November 2010

From Molecular Clump Properties to Galaxy Evolution with Star Clusters

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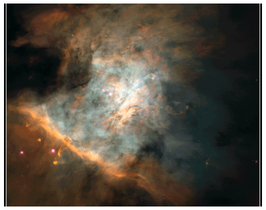
Star Clusters: at the crossroad between star formation and galaxy evolution




a few kpc - 100kpc:
systems of
star clusters
and galaxies

10pc:
individual
gas-free
star clusters

1-pc:
star formation
in embedded
star clusters

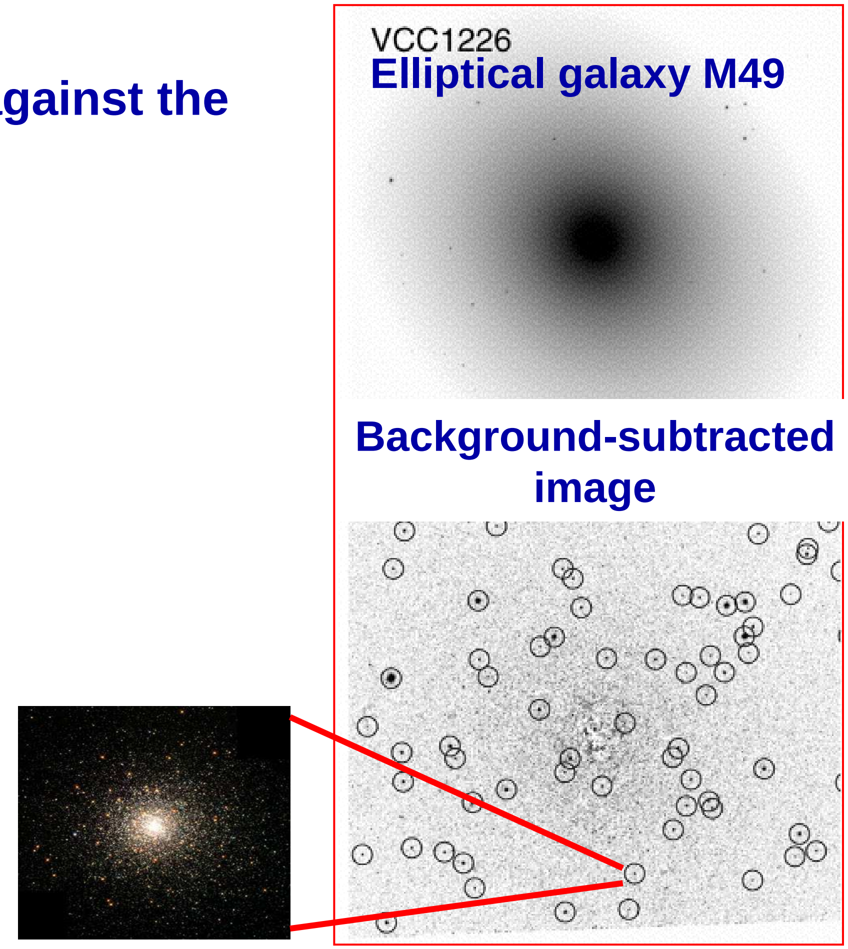


Setting the Scene: Star Clusters (SC) as Powerful Tracers of Galaxy Evolution

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**

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



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

- feasible out to Virgo Galaxy Cluster distances (≈ 20Mpc)
- combined to Simple Stellar Population models → estimates of cluster age, mass, metallicity

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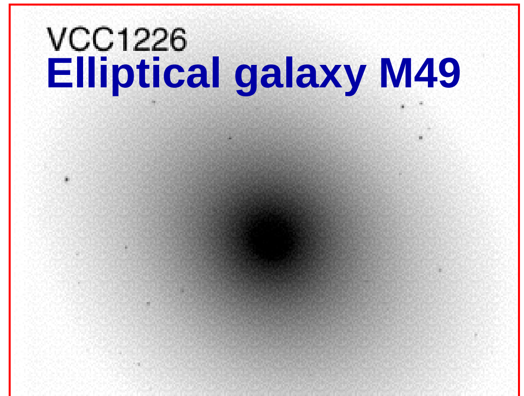
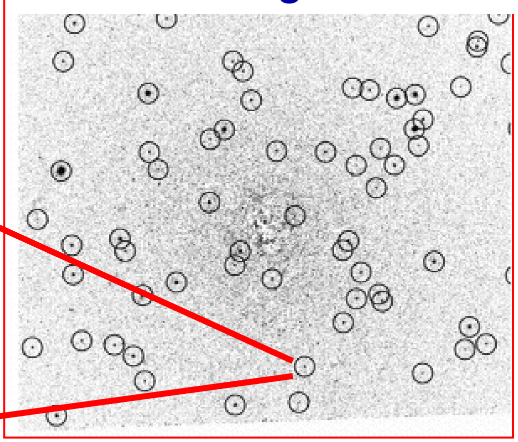
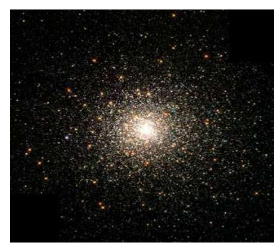


Background-subtracted image





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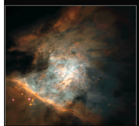

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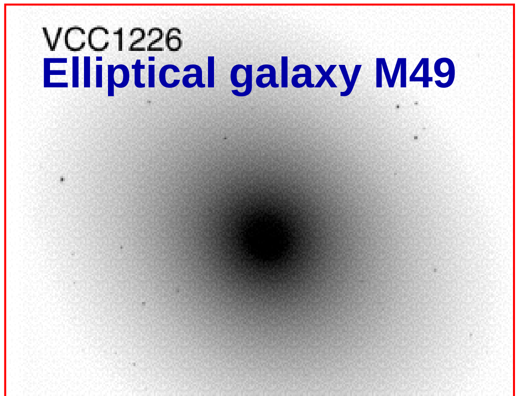
  → estimates of **cluster age, mass, metallicity**

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)



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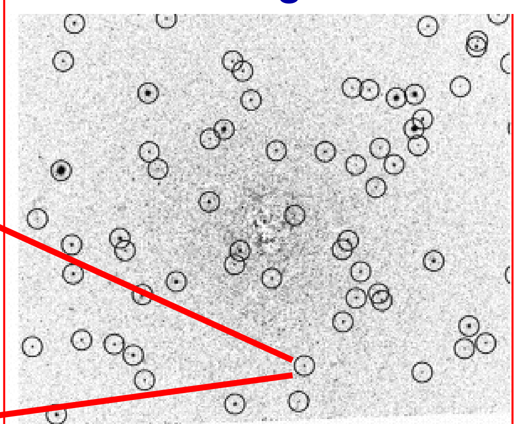
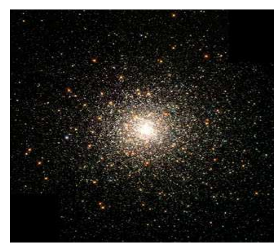
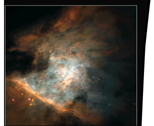




Star clusters are at the very heart of many astrophysical topics



The Big Issue: SCs versus field stars

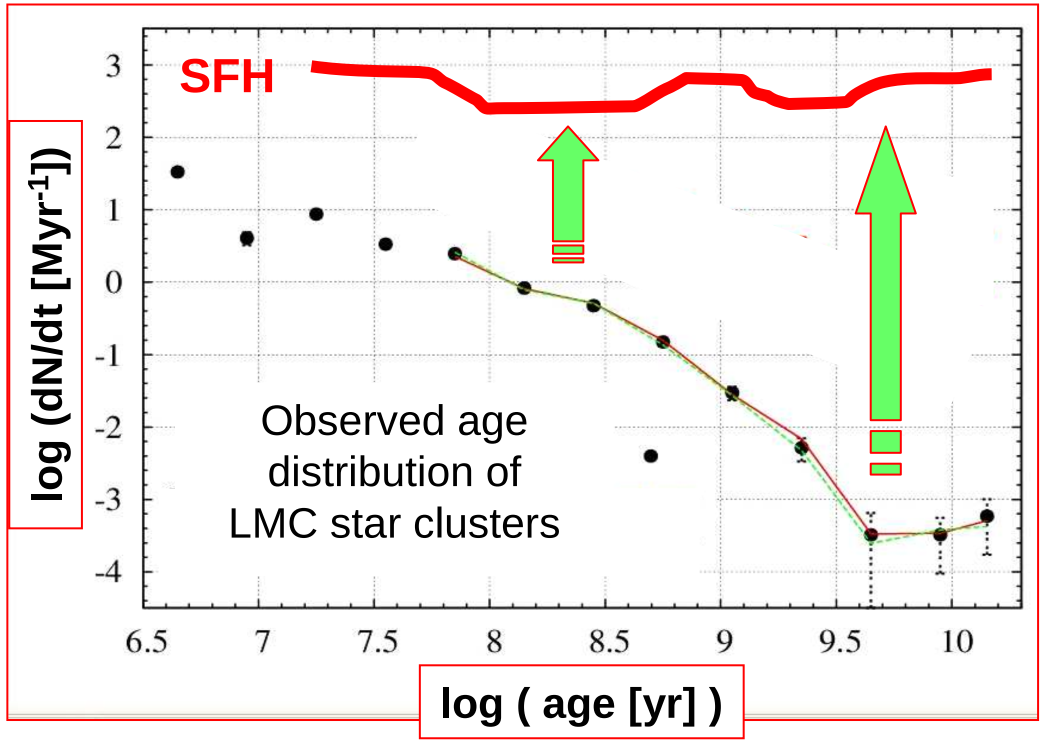
Most stars in our Galaxy:

- **are born in star clusters** → young star clusters tell us about star formation
- **but are observed as field stars**

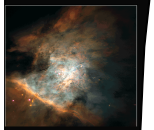
Star clusters have the potential of tracing

➤ **galaxy star formation histories**

provided we get a firm handle on the ratio of star formation still residing in (observed) star clusters as a function of age



Star Cluster Dynamical Evolution: Fast Facts

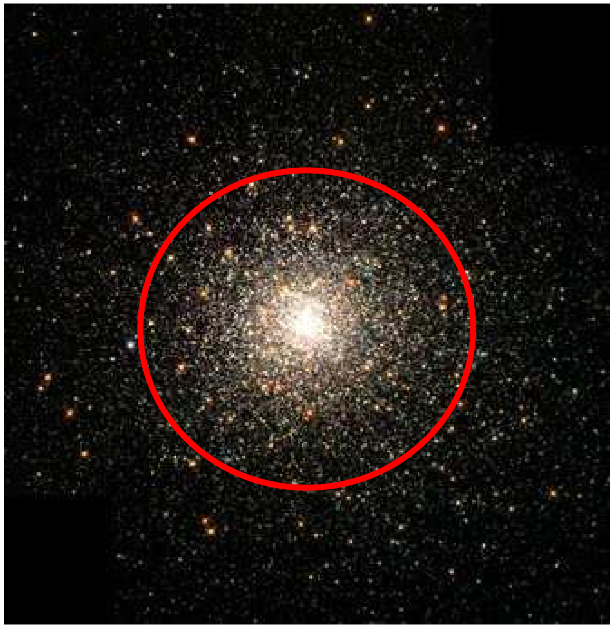


SCs go through a lifecycle: they <u>evaporate</u>, until complete dissolution

Cluster lifecycle includes 2 phases:

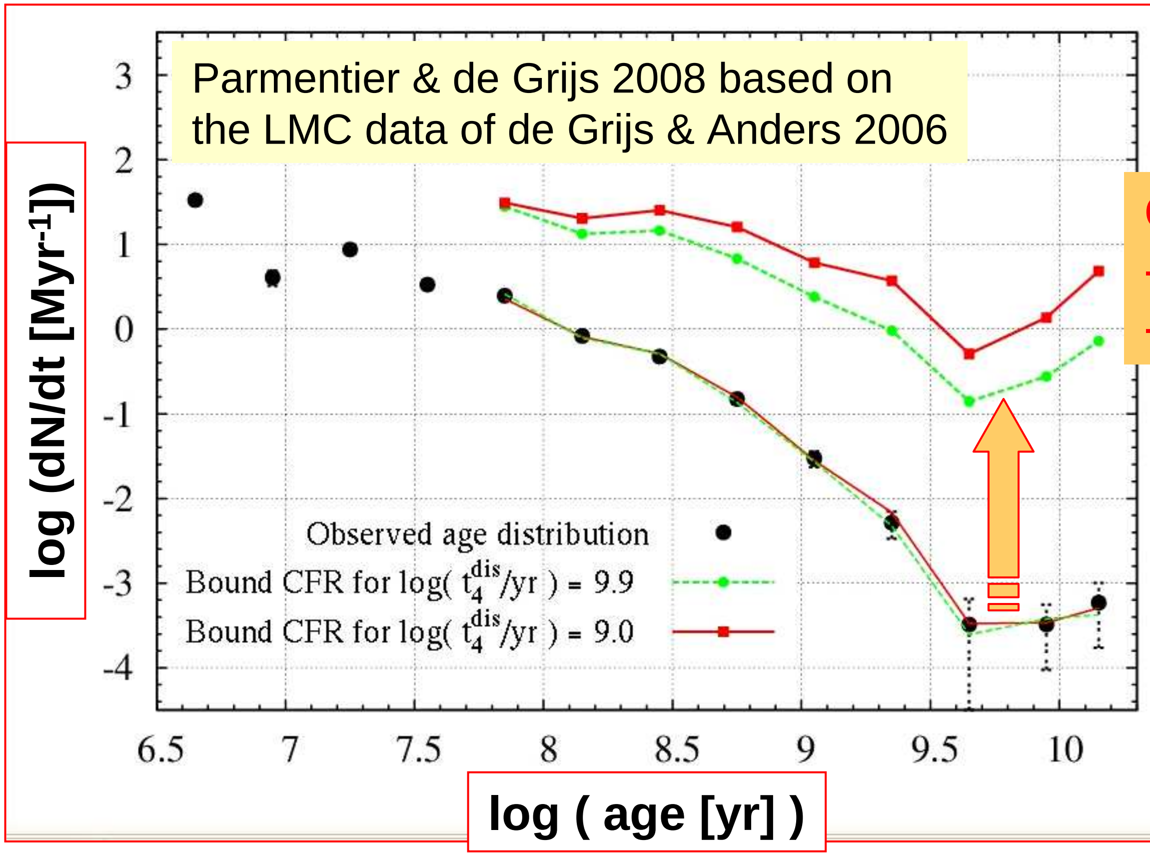
1. Violent relaxation:
Ø Very short (10-50 Myr)
Ø Dynamical response of star clusters to the expulsion of their residual star-forming gas

2. Secular evolution
Ø Until cluster dissolution
Ø Tidal-stripping of (preferentially low-mass) stars combined to internal two-body relaxation



Secular Evolution Modelling: SC Dissolution Time-Scale in the Large Magellanic Cloud



Cluster formation rate:
- Onset of Secular Evolution
- End of Violent Relaxation

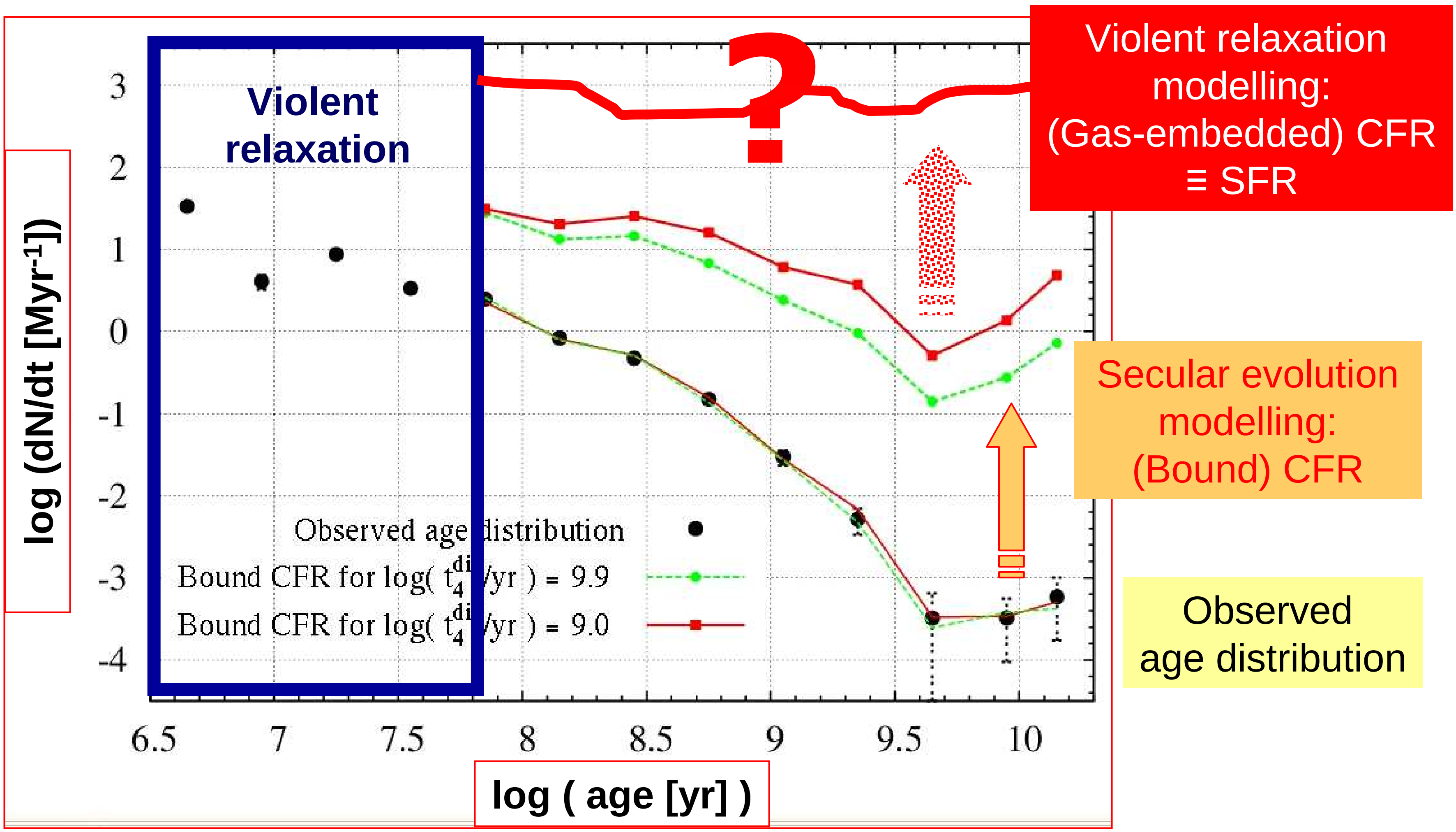
t_4^{dis} = 1Gyr

t_4^{dis} = 8Gyr

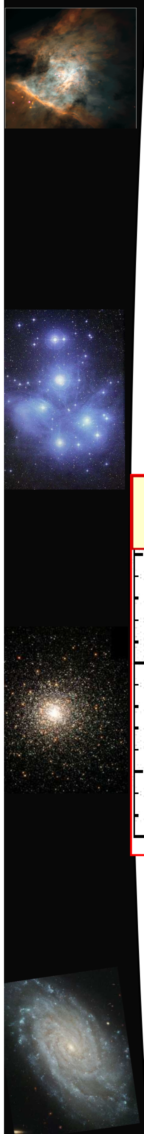
Observed age distribution

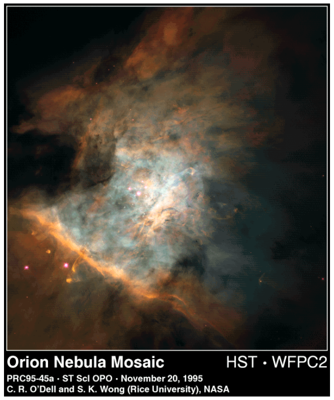
Secular evolution modelling + observed cluster age distribution → history of the formation rate of clusters which survived their violent relaxation

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

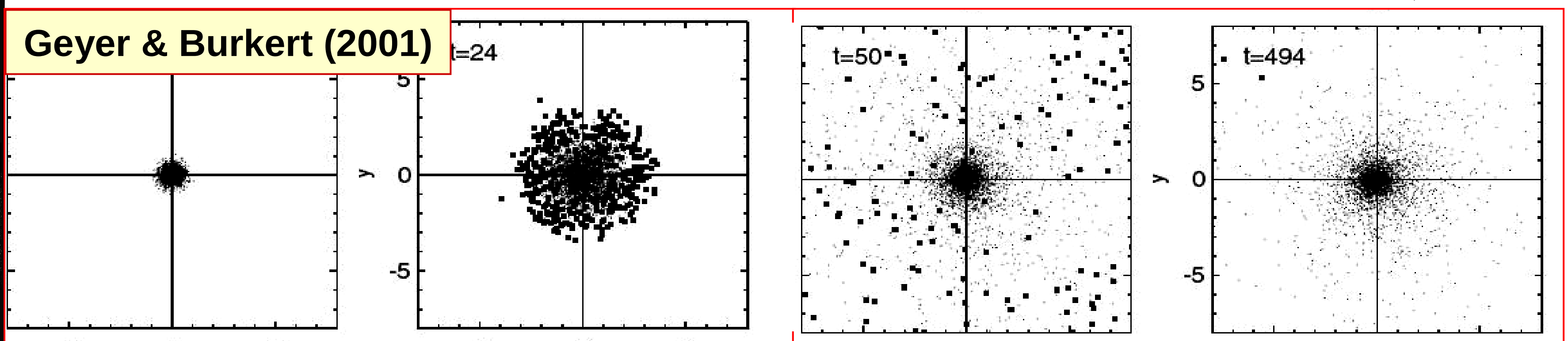


Intra-Cluster Gas-Expulsion and Violent Relaxation





time



Effects of gas expulsion - VIOLENT RELAXATION

- **Cluster expansion**
- **Star loss (infant weight-loss), or**
- **Cluster dissolution (infant mortality)**

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

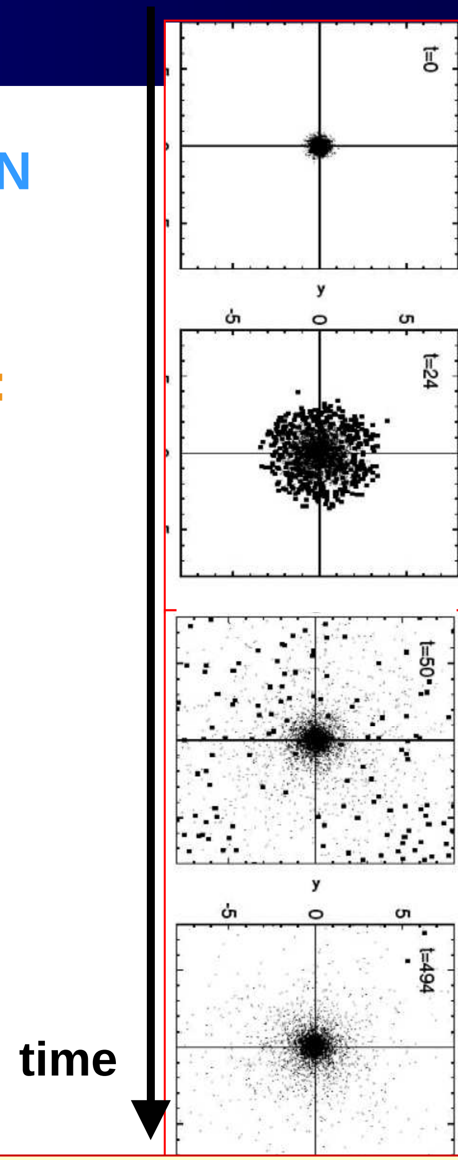
Prime parameters: (e.g. Baumgardt & Kroupa 2007)

- SFE in the Cluster Forming-Region (CFRg)

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

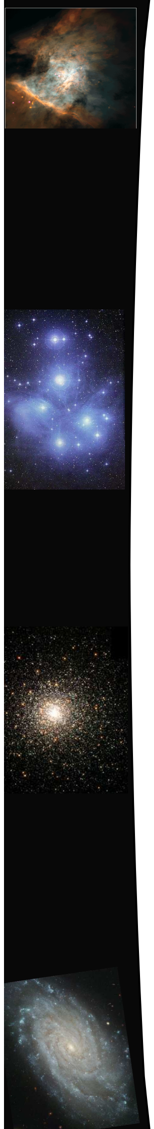
- Impact of external tidal field (environment)

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

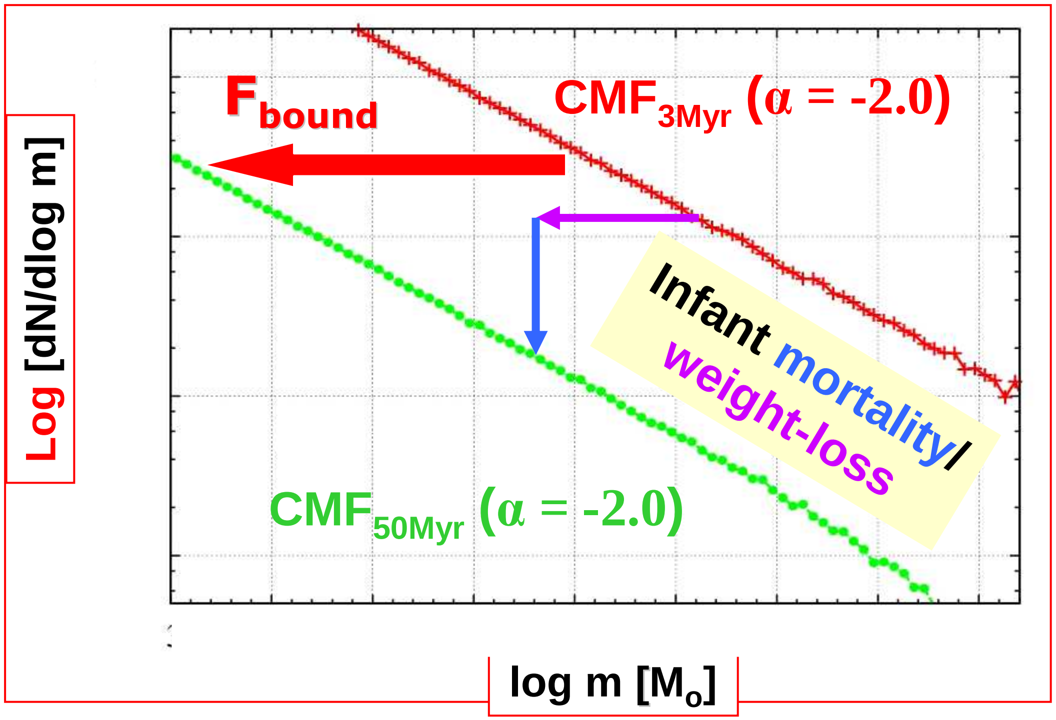


Geyer & Burkert (2001)

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

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

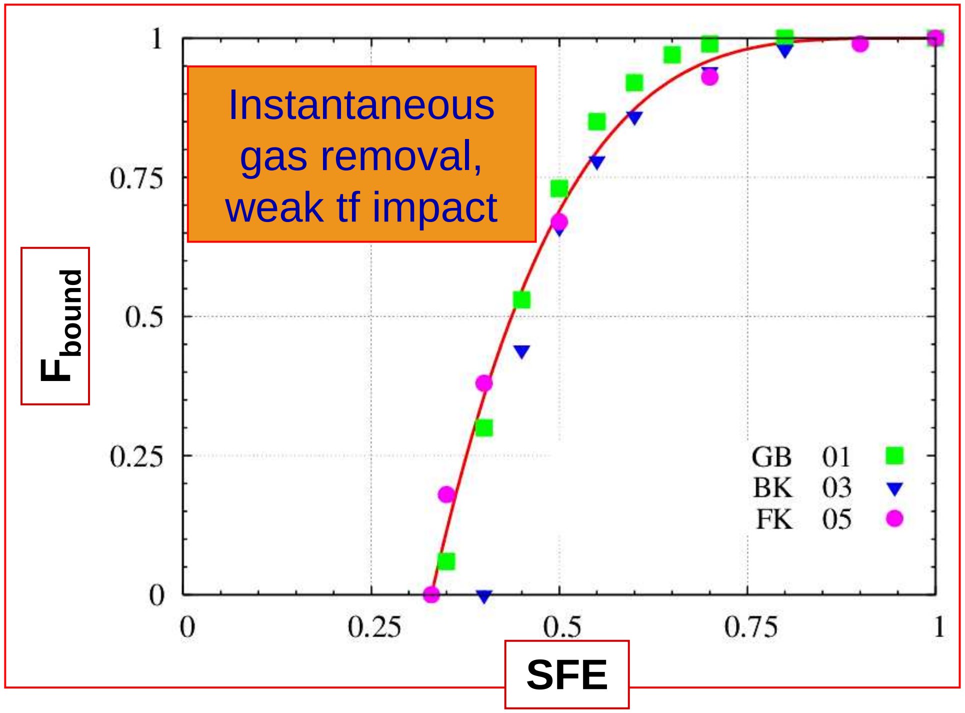
SFE and Cluster Mass Functions

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

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

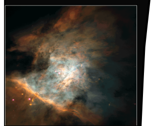
SFE
= fraction of gas ending up in stars

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



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

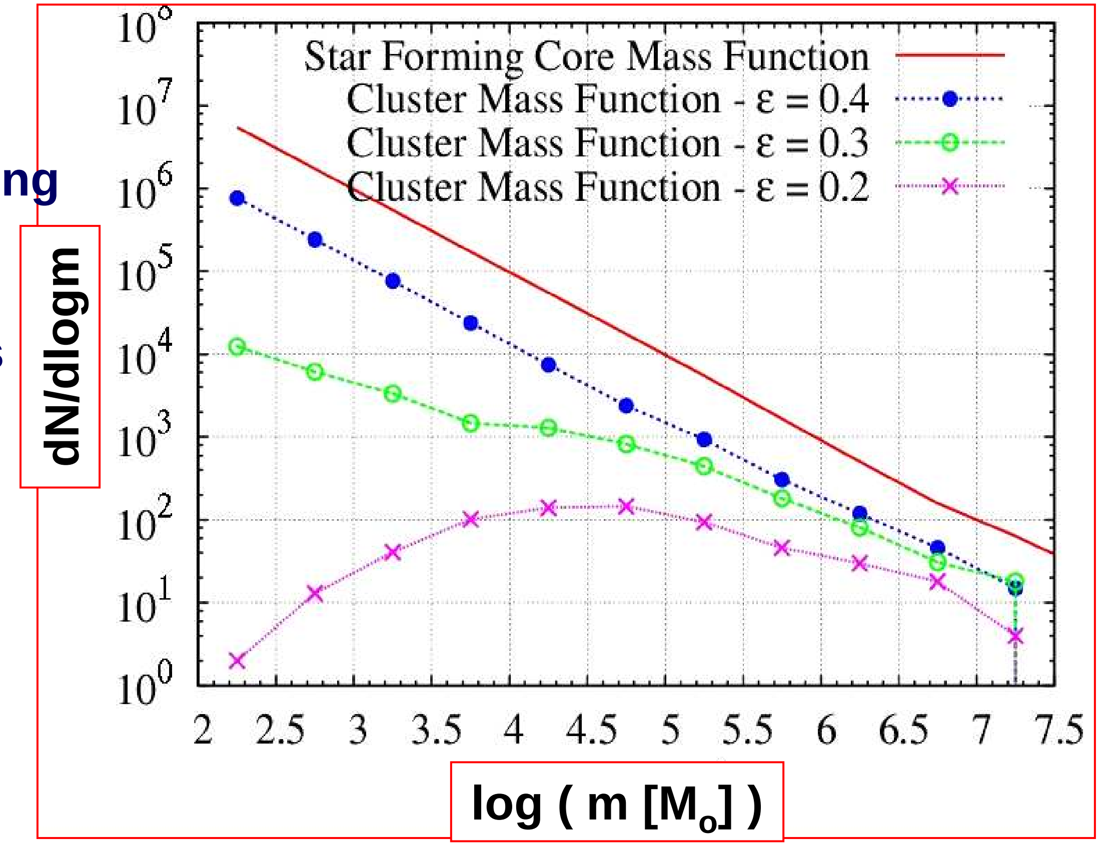
τ_{GExp}/τ_{cross} and Cluster Mass Functions



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

Parmentier, Goodwin et al. (2008)
Kroupa & Boily (2002)

Constant radius:
more massive cluster-forming regions (CFRg) have
- **a deeper potential well**
- **a slower gas-expulsion t-s**
- **can survive despite a low SFE of, say, 20%**

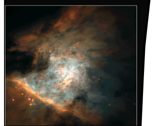


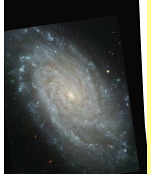
F_{bound} is mass-independent

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

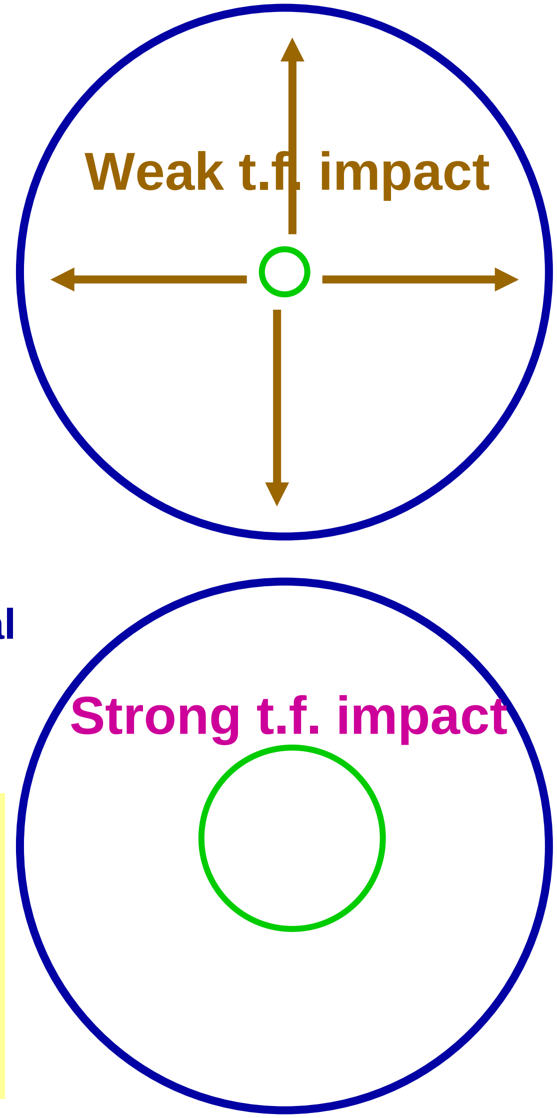
but looser constrain

Tidal Field Impact and Cluster Mass Functions



$$\text{SFE } \varepsilon, \frac{\tau_{GExp}}{\tau_{cross}}, \frac{r_{half-mass}}{r_{tidal}}$$



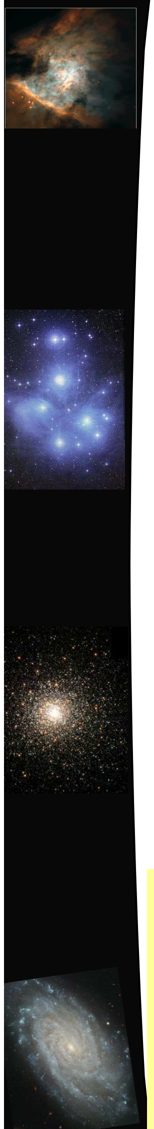
- Half-mass radius $r_{half\text{-}mass} \approx r_{CFRg}$
- Circular velocity of iso-T potential V_c
- Galactocentric distance D_{gal}
- Embedded cluster mass m_{ecl}

} r_{tidal}

Limiting tidal radius:

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

Tidal Field Impact and Cluster Mass Functions



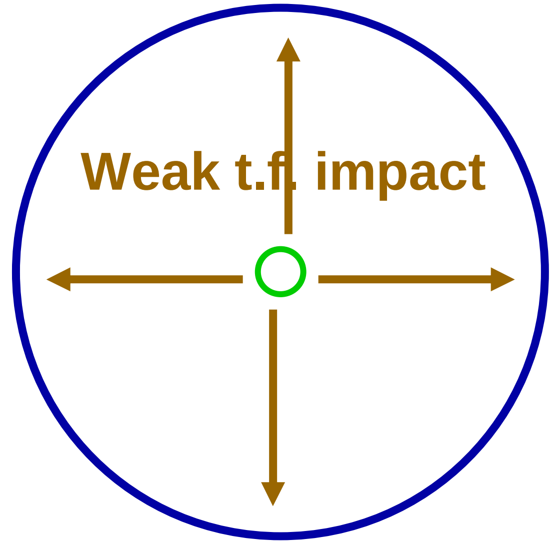
$$\text{SFE } \varepsilon, \frac{\tau_{GExp}}{\tau_{cross}}, \frac{r_{half-mass}}{r_{tidal}}$$

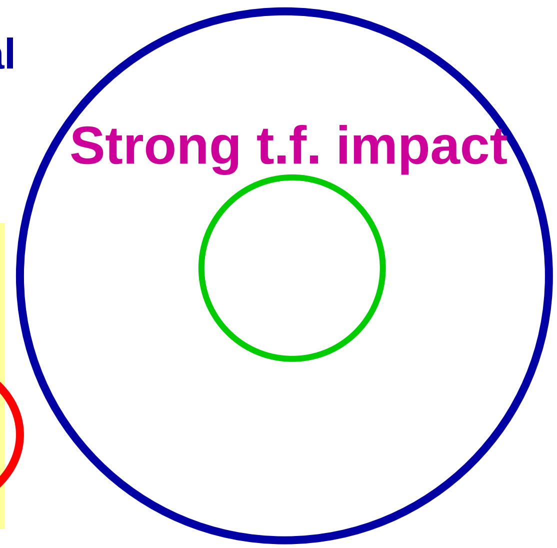
- Half-mass radius $r_{half\text{-}mass} \approx r_{CFRg}$
- Circular velocity of iso-T potential V_c
- Galactocentric distance D_{gal}
- Embedded cluster mass m_{ecl}

(Circular velocity, galactocentric distance and embedded cluster mass } r_{tidal})

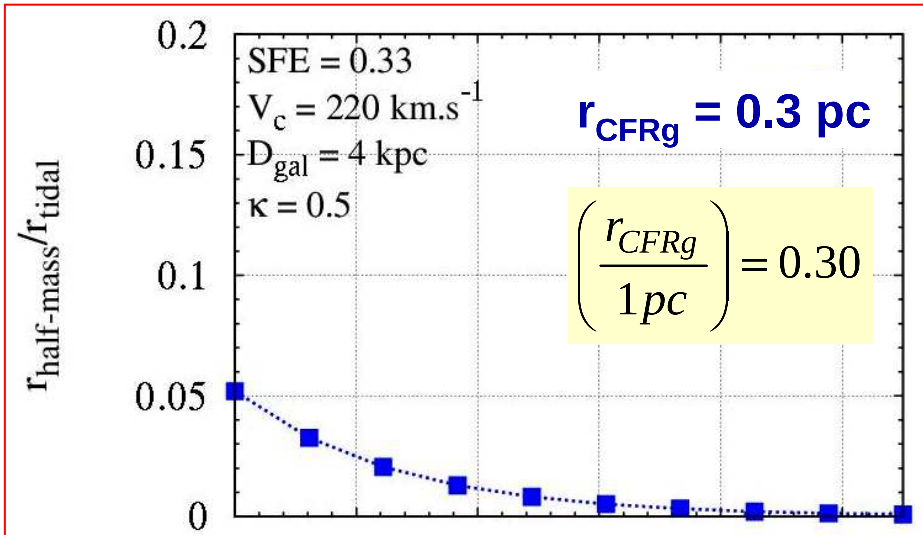
Limiting tidal radius:

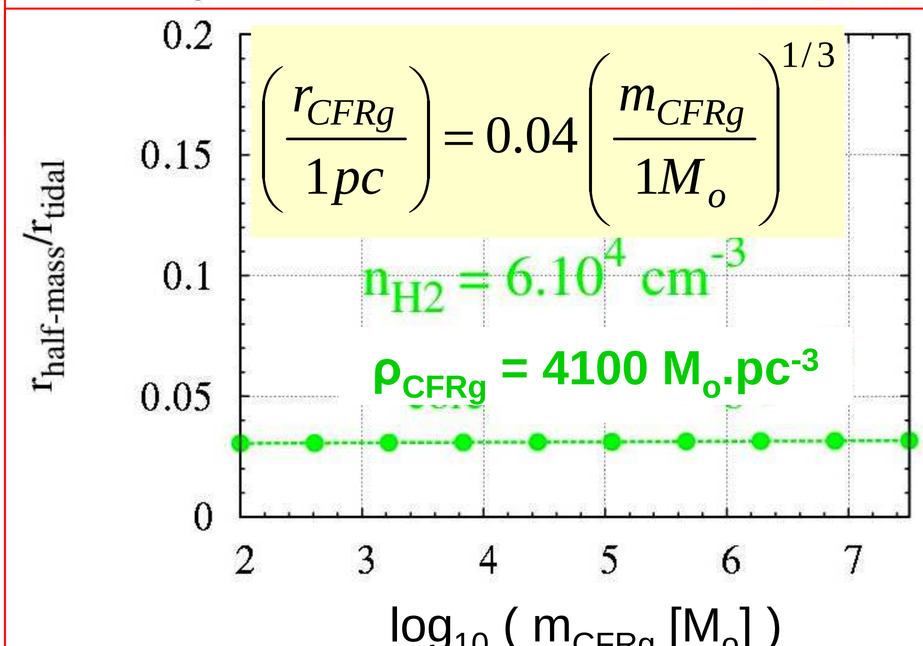
$$r_{tidal} = \left(\frac{G\, m_{ecl}}{2V_c^2}\right)^{1/3} D_{gal}^{2/3}\text{, with } m_{ecl} = SFE\, m_{CFRg}$$

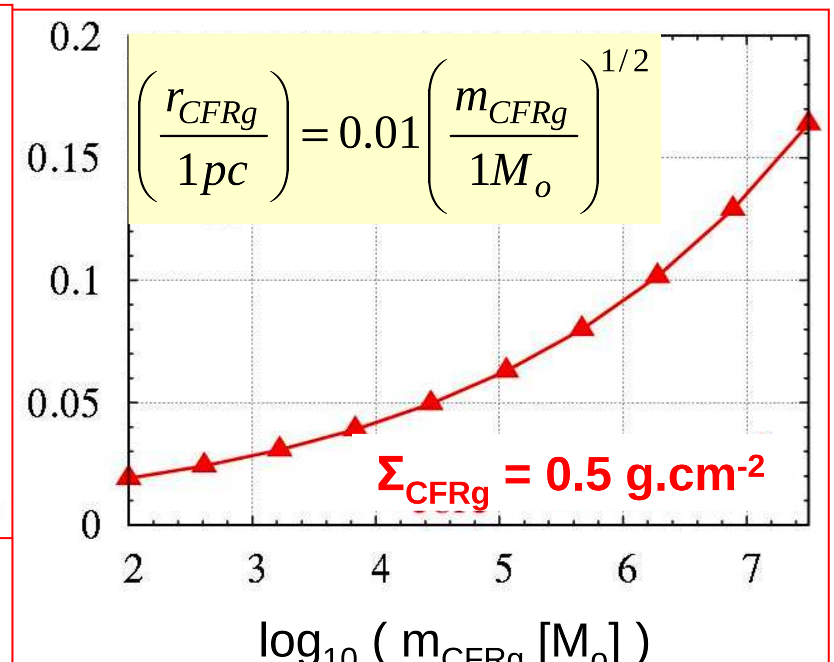




Half-mass radius—to—tidal radius ratio





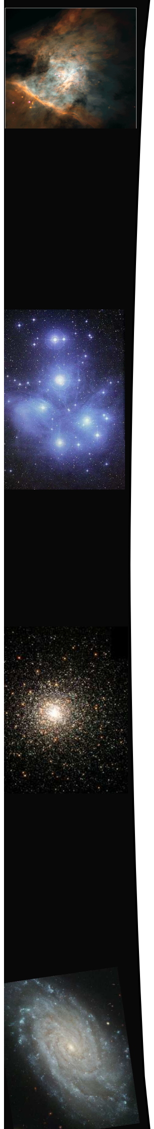


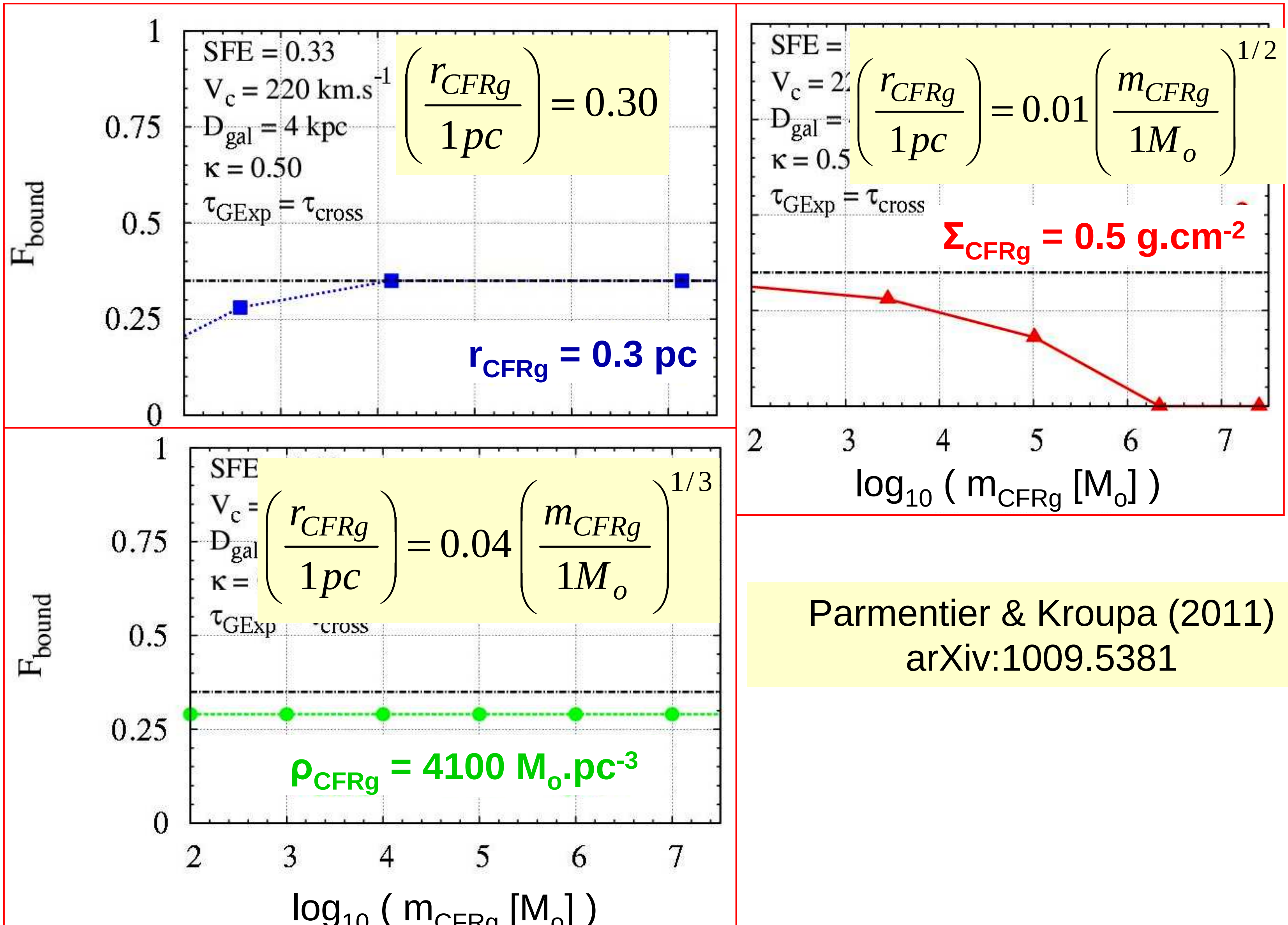
$$r_{CFRg} \propto r_{half-mass} \propto m_{CFRg}^{\delta}$$

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

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

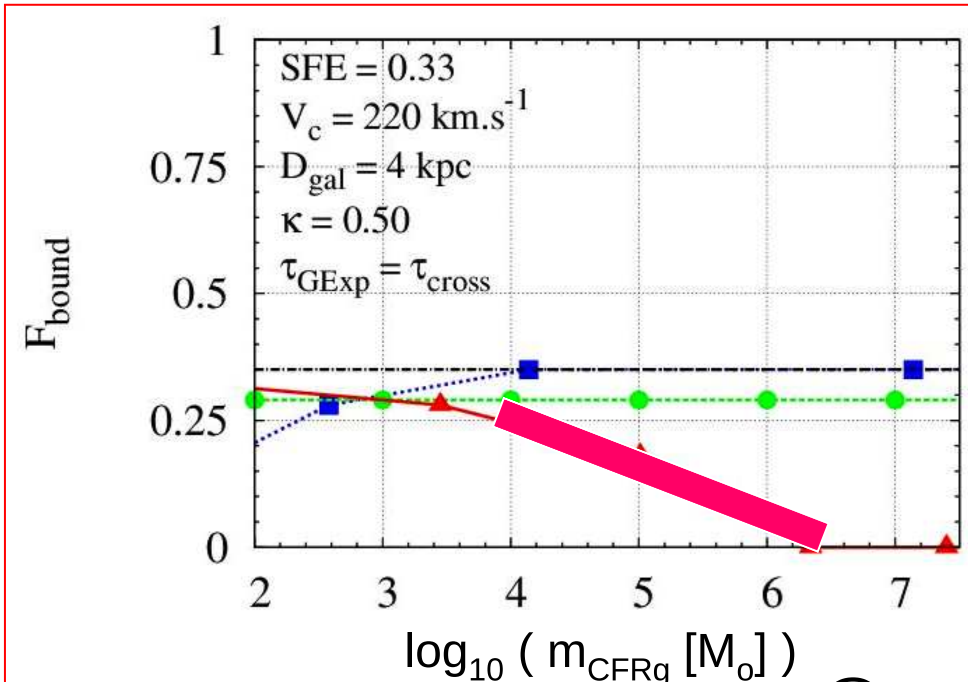
F_{bound} and Tidal Field Impact





Parmentier & Kroupa (2011)
arXiv:1009.5381

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



Σ_{CFRg}

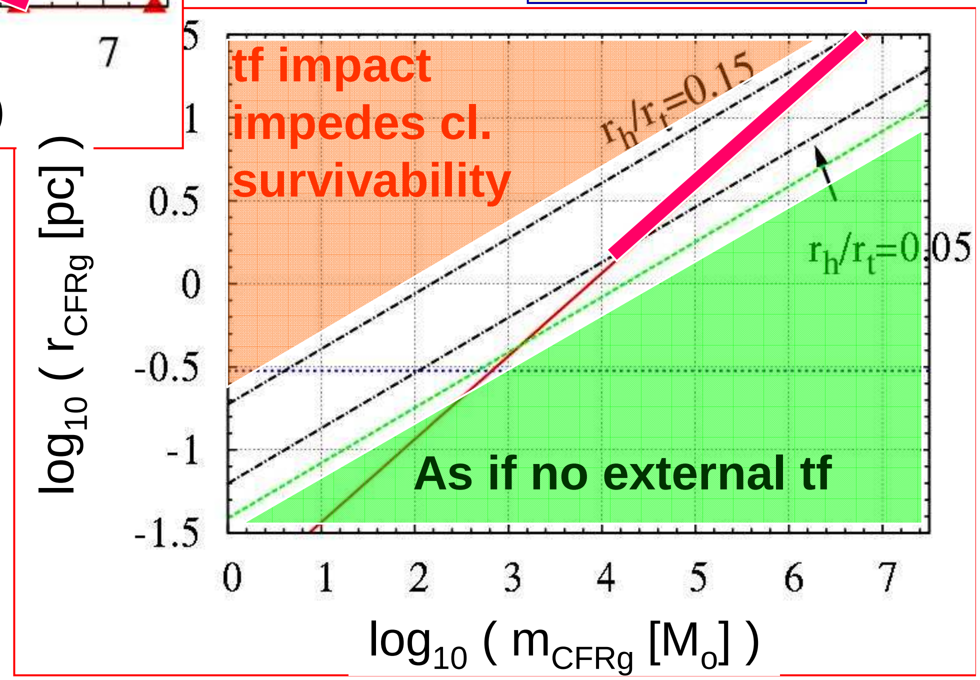
$$\left(\frac{r_{CFRg}}{1pc}\right) = 0.01\left(\frac{m_{CFRg}}{1M_o}\right)^{1/2}$$

ρ_{CFRg}

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

r_{CFRg}

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



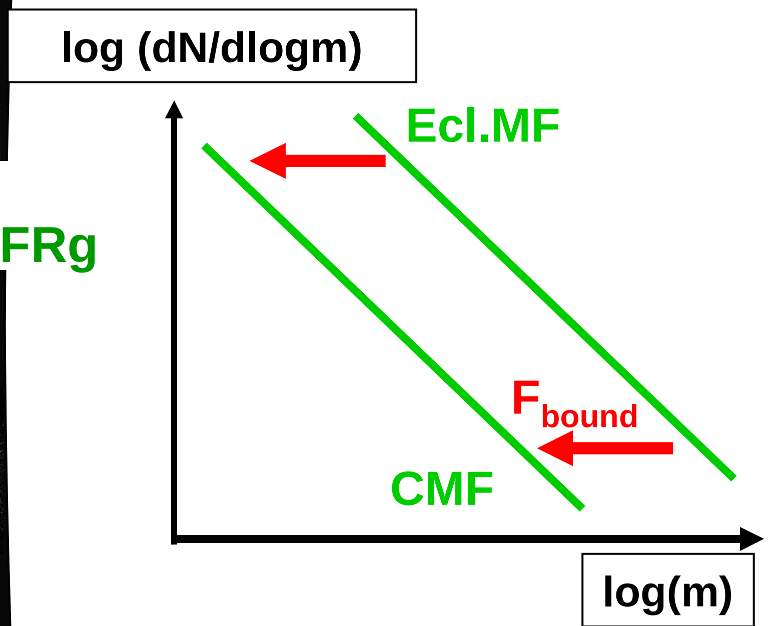
External tidal field strength:
(V_c, D_{gal}) → rh/rt in [log(r),log(m)]

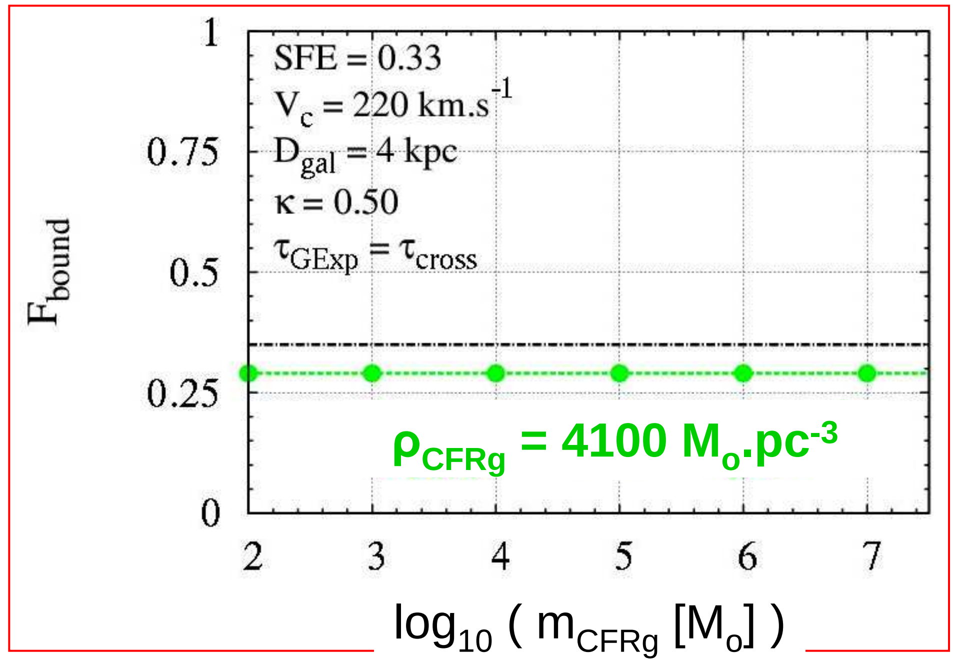
- **rh/rt < 0.05: tf does not matter**
  (<u>does not necessarily imply weak tf</u> !)
- **rh/rt > 0.15: cluster survivability demands long τ_{GExp} /τ_{cross} and high SFE**

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

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

ρ_{CFRg}

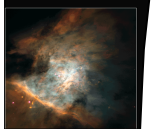


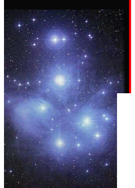


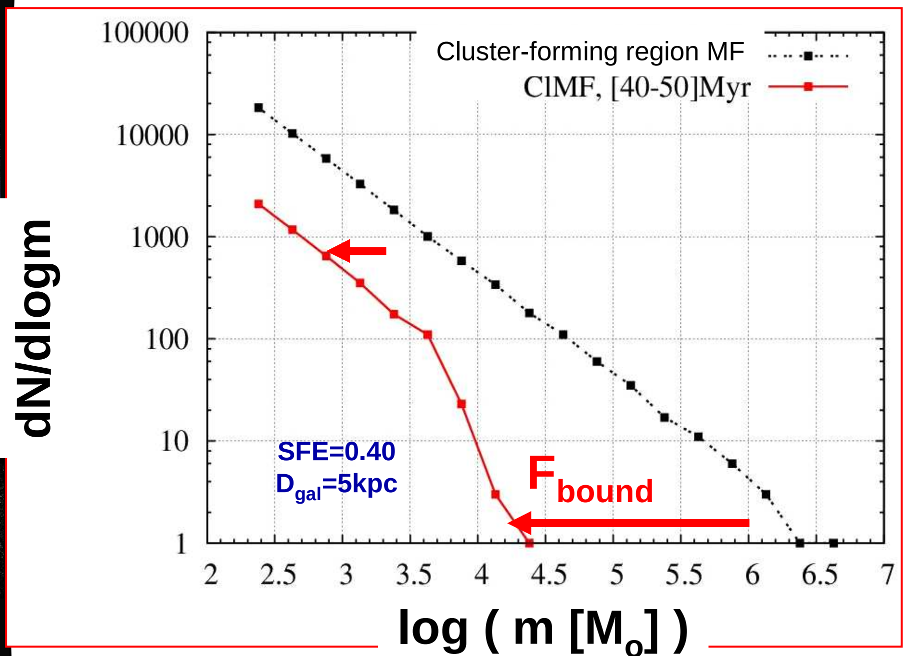
Cluster-forming regions with constant mean volume density: mass-independent infant weight-loss

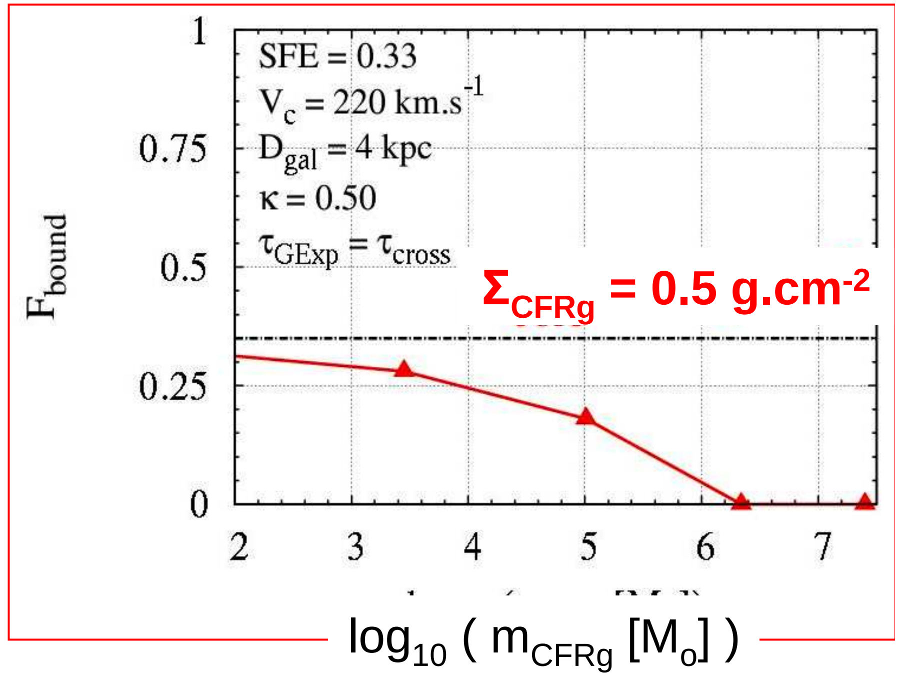
$$\left(\frac{r_{CFRg}}{1pc}\right) = 0.04\left(\frac{m_{CFRg}}{1M_o}\right)^{1/3}$$

Tidal Field Impact and Cluster Mass Functions







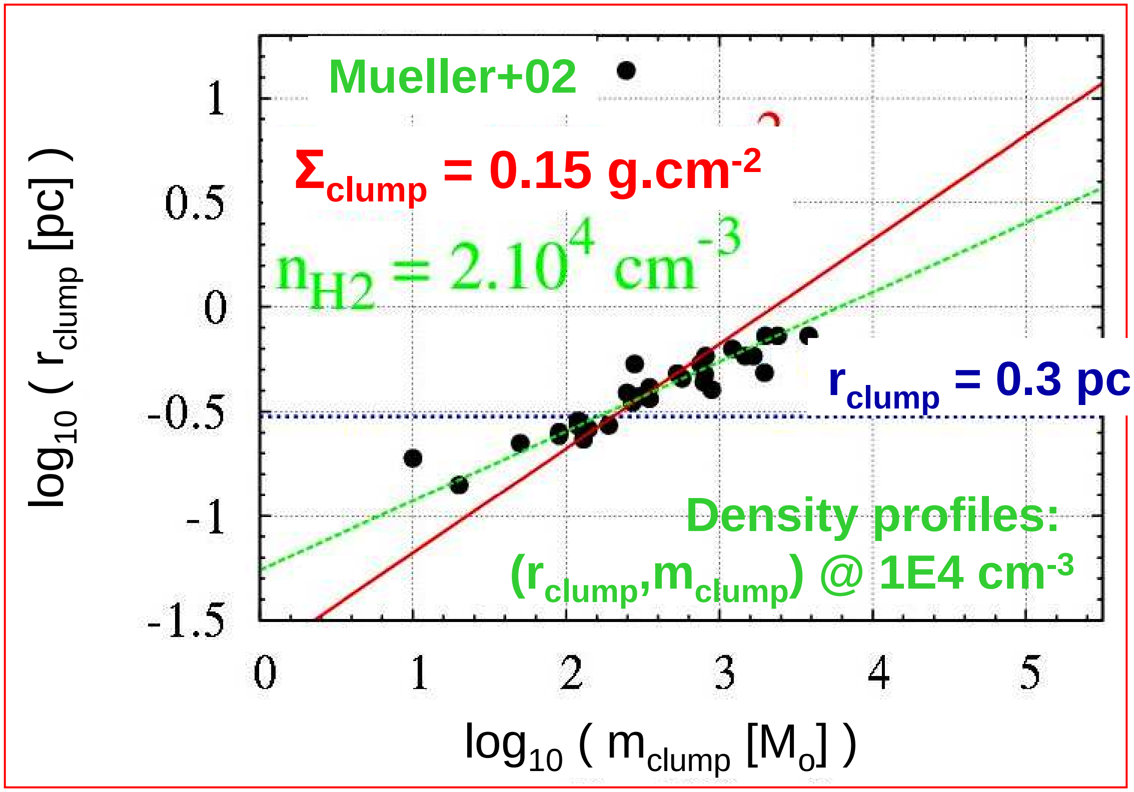


Cluster-forming regions with constant mean surface density When more massive means more vulnerable ...

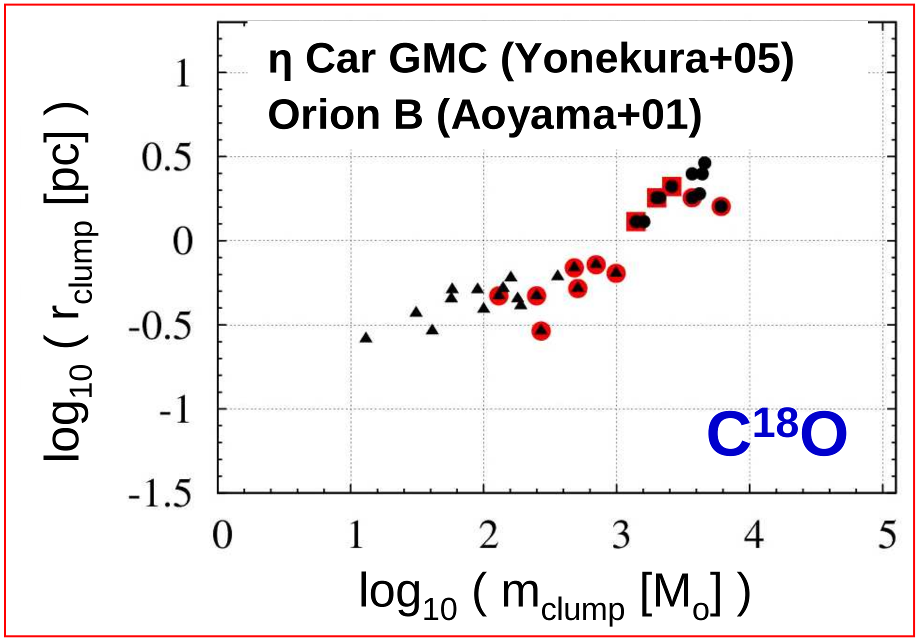
$$\Sigma_{CFRg}: \left(\frac{r_{CFRg}}{1pc}\right) = 0.01 \left(\frac{m_{CFRg}}{1M_o}\right)^{1/2}$$

Clump mass-radius relations: observations

- Clump mass-radius diagram: imprint of
- cluster-formation physics, or of
- measurement method ?
- Lack of high-mass data
- Does the whole clump form a star cluster ?

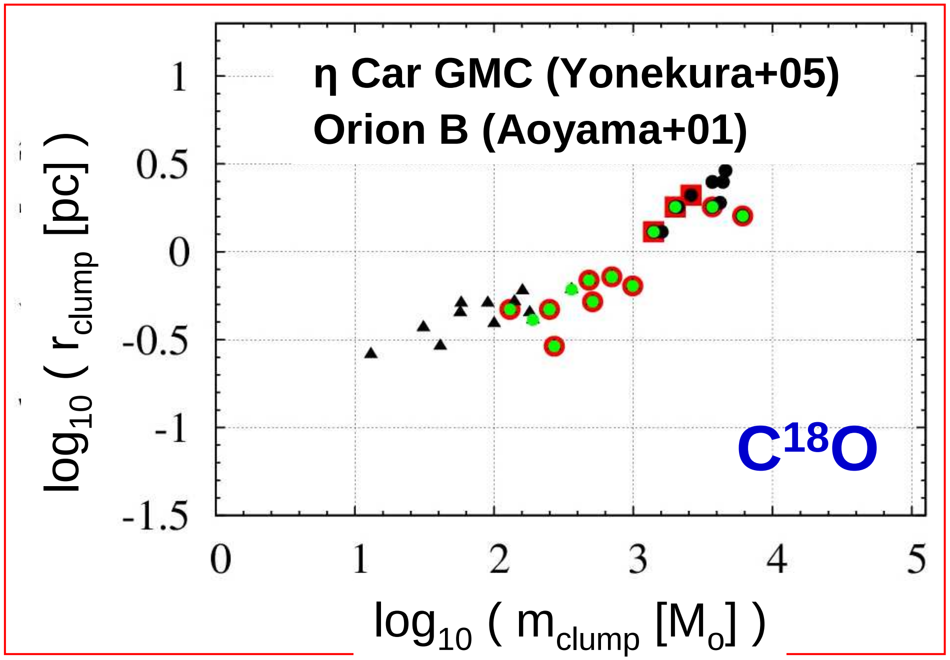


Cluster-forming region mass-radius relation: so what ... ?



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

Cluster-forming region mass-radius relation: so what ... ?



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

- Most of them also host a sub-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 $C^{18}O$ clumps

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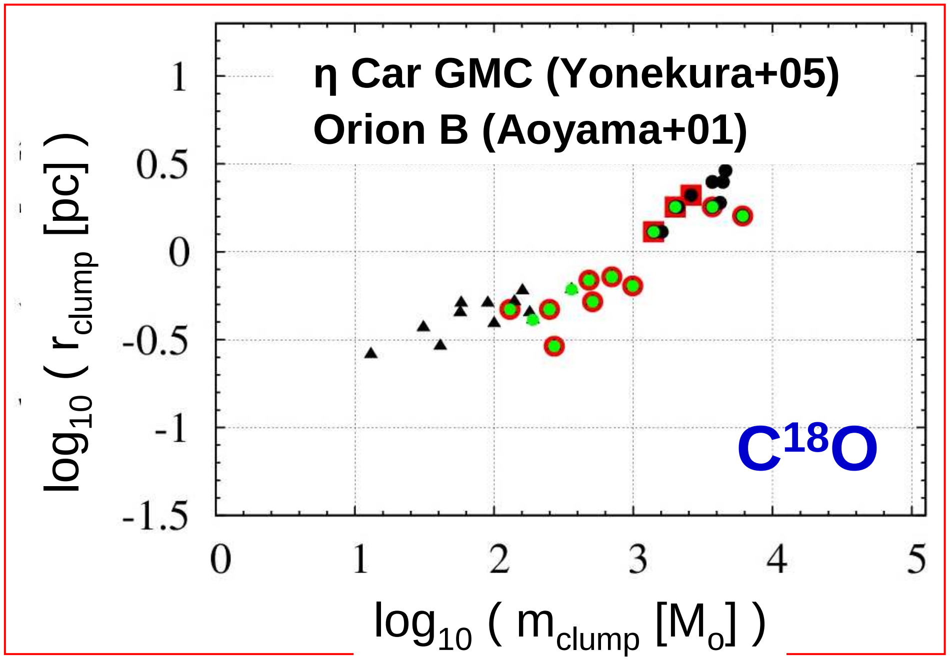

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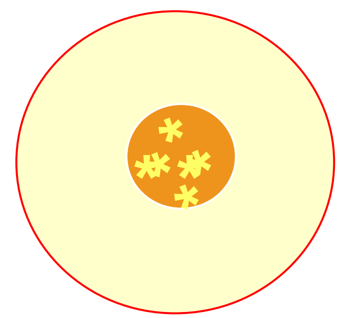
→ SF takes place in regions where the density is higher than a threshold, i.e. only in the densest regions of $C^{18}O$ clumps

Consequence: the local SFE must be measured over the cluster-forming volume, not over the whole $C^{18}O$ clump



Both

- $H^{13}CO^{+}$ observations and

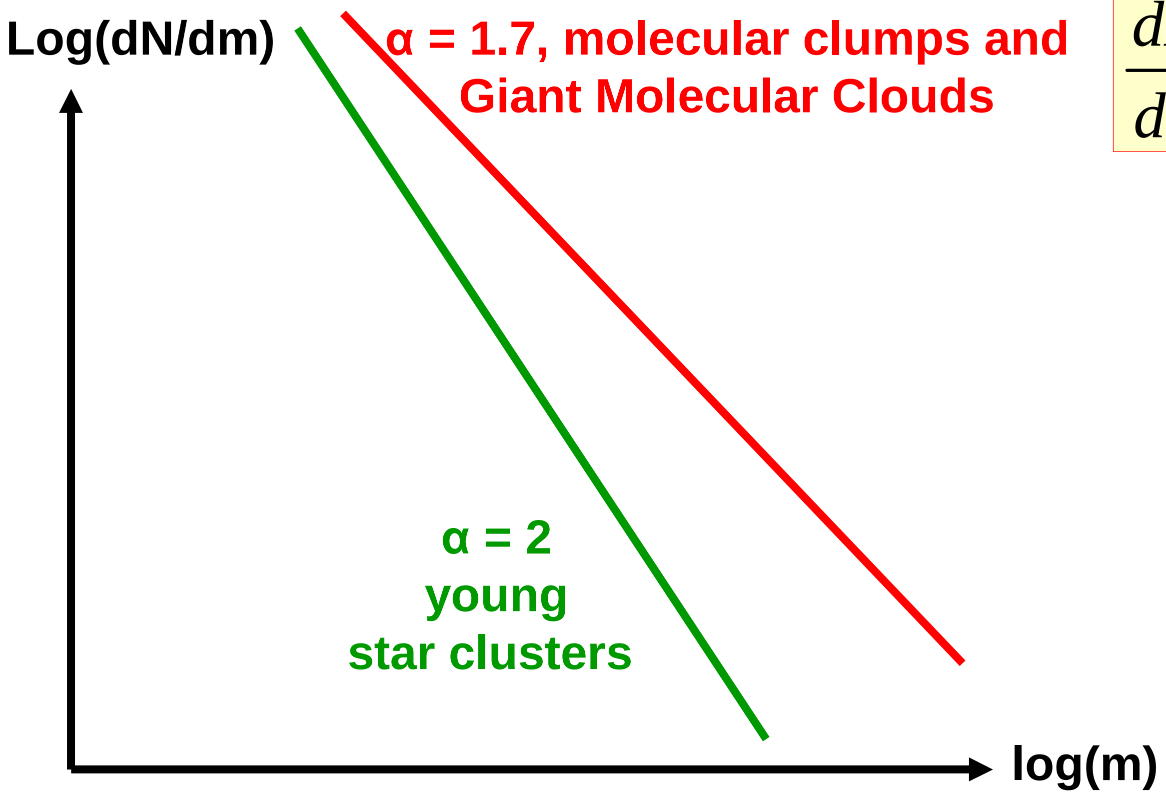
- the tidal field impact analysis

suggest: cluster-forming regions of <u>constant mean volume density</u>

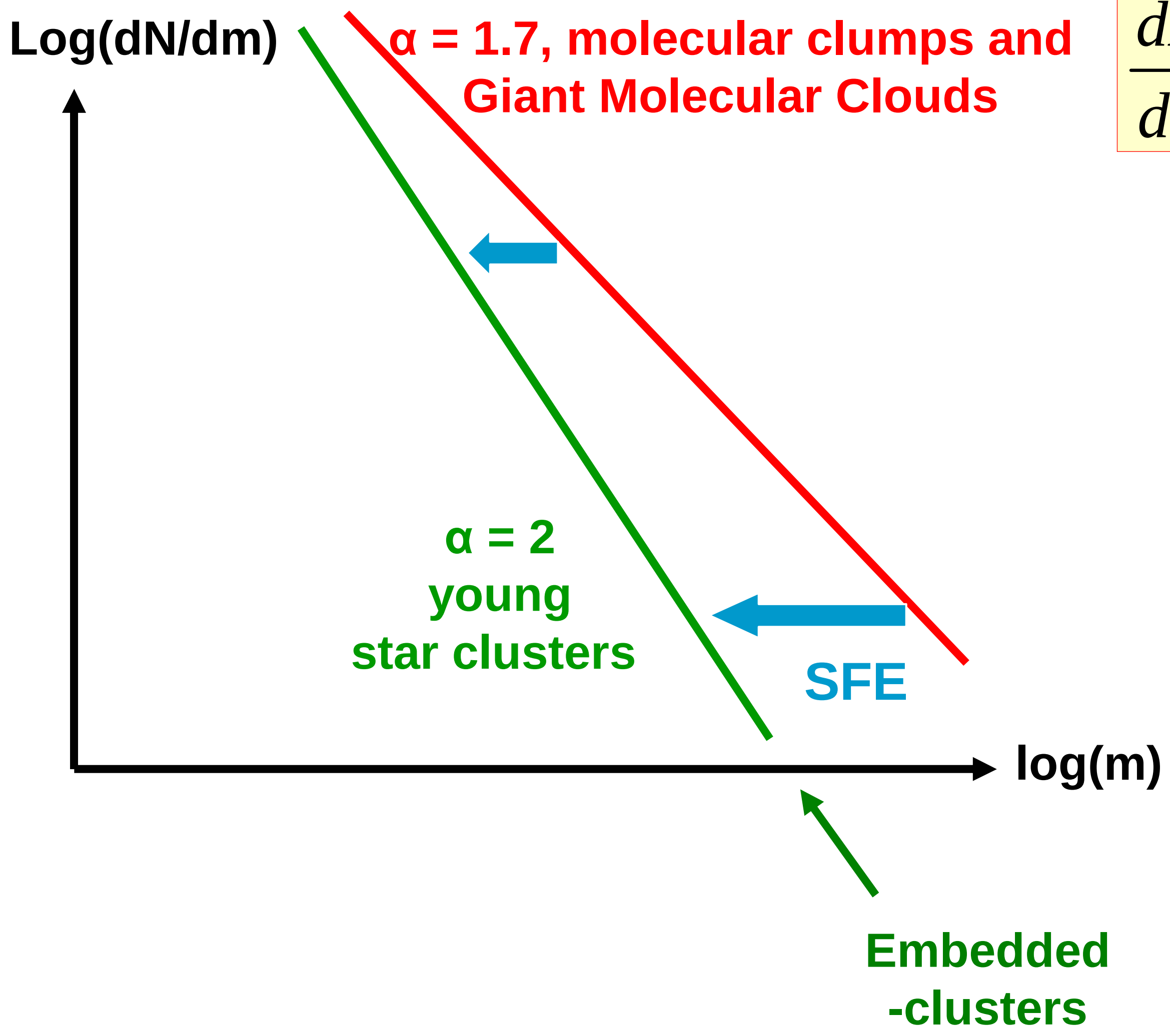
(Parmentier & Kroupa 2011, arXiv:1009.5381)

From the mass function of GMCs/clumps to that of gas-free star clusters ...

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



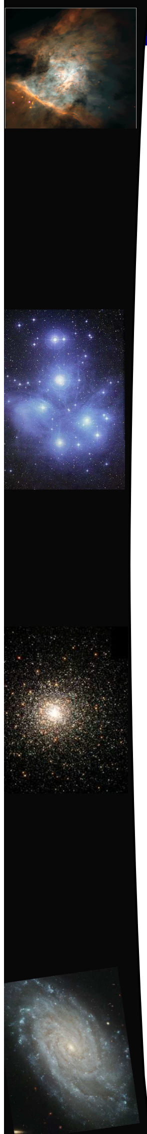
From the mass function of GMCs/clumps to that of gas-free star clusters ...



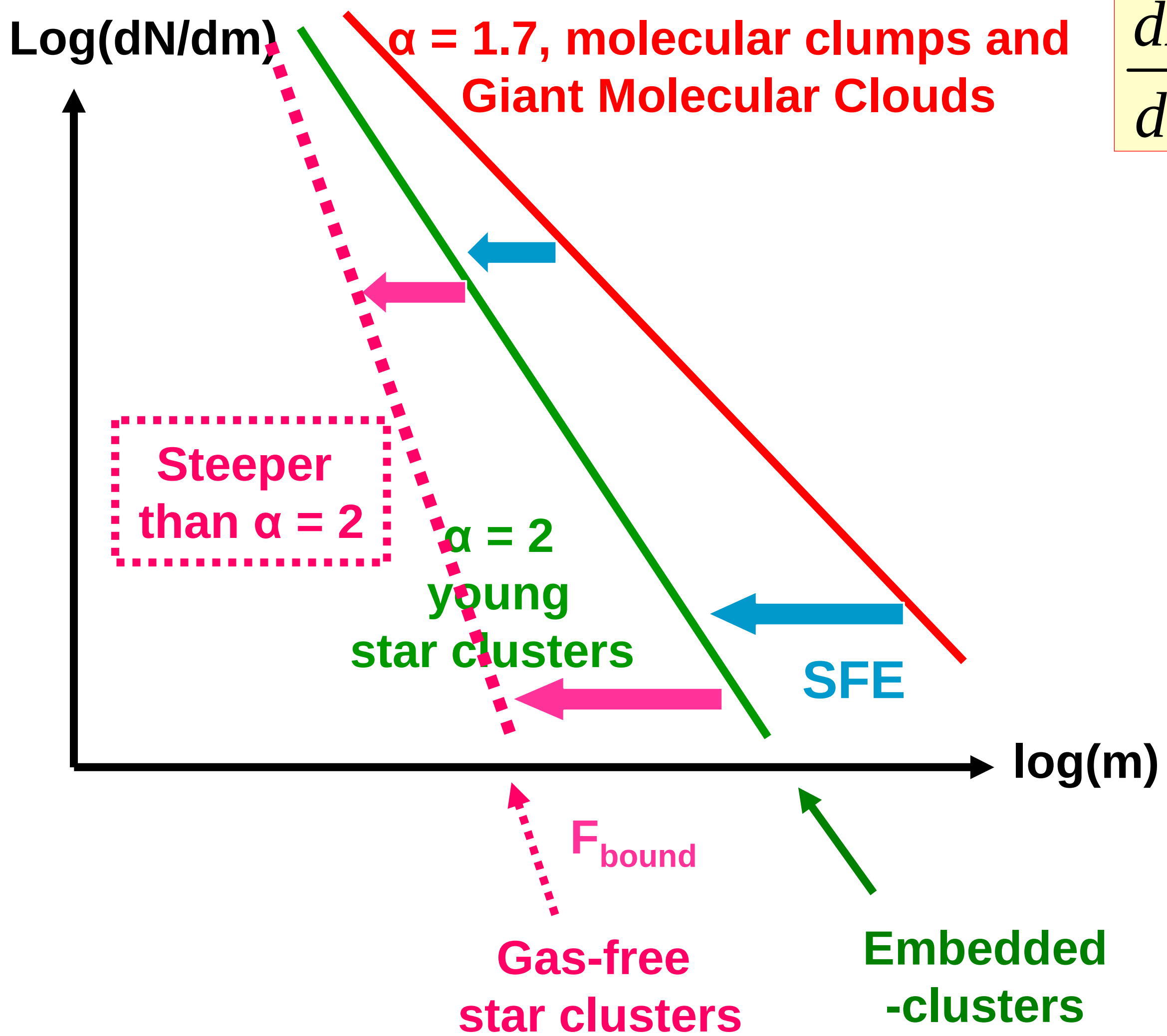
$$\frac{dN}{dm} \propto m^{-\alpha}$$

Mass-varying SFE:
lower SFE at higher
cloud/clump mass ??

From the mass function of GMCs/clumps to that of gas-free star clusters ...



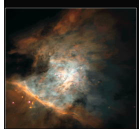
$$\frac{dN}{dm} \propto m^{-\alpha}$$



Mass-varying SFE: lower SFE at higher cloud/clump mass ??

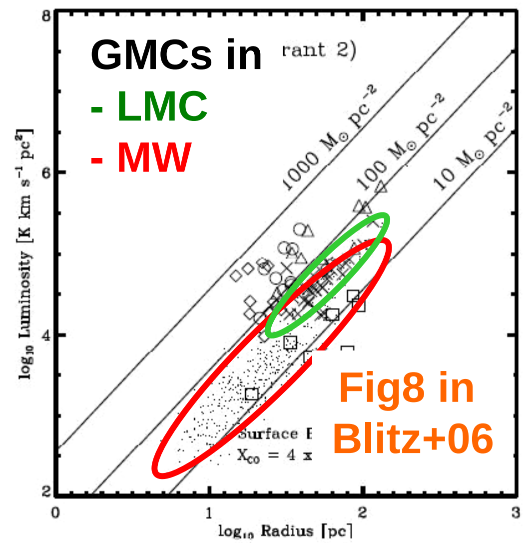
But then mass-varying F_{bound} too ??

From the mass function of GMCs/clumps to that of gas-free star clusters ... with a volume density threshold for star formation




- Cluster-forming regions:
  constant mean <u>volume</u> density
  (tidal field impact analysis)

- GMCs and
- Molecular clumps with signs
  of SF activity:
  Constant mean <u>surface</u> density
  - Larson 1981
  - Blitz+ 2006
  - Heyer+ 2009



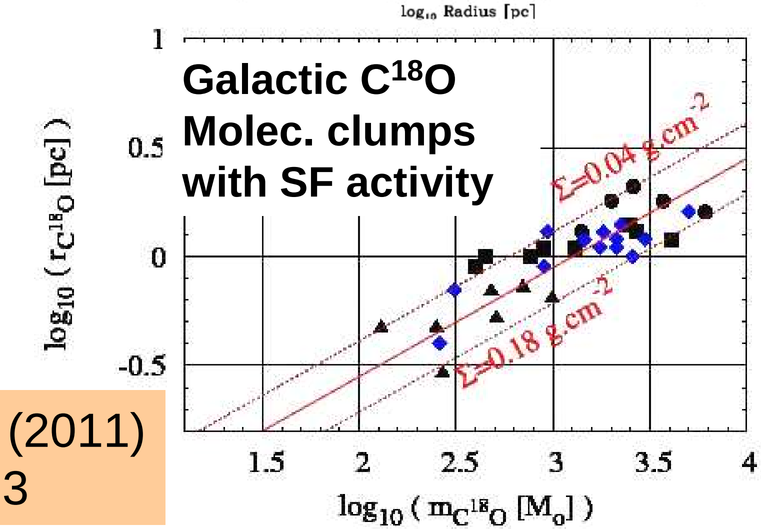
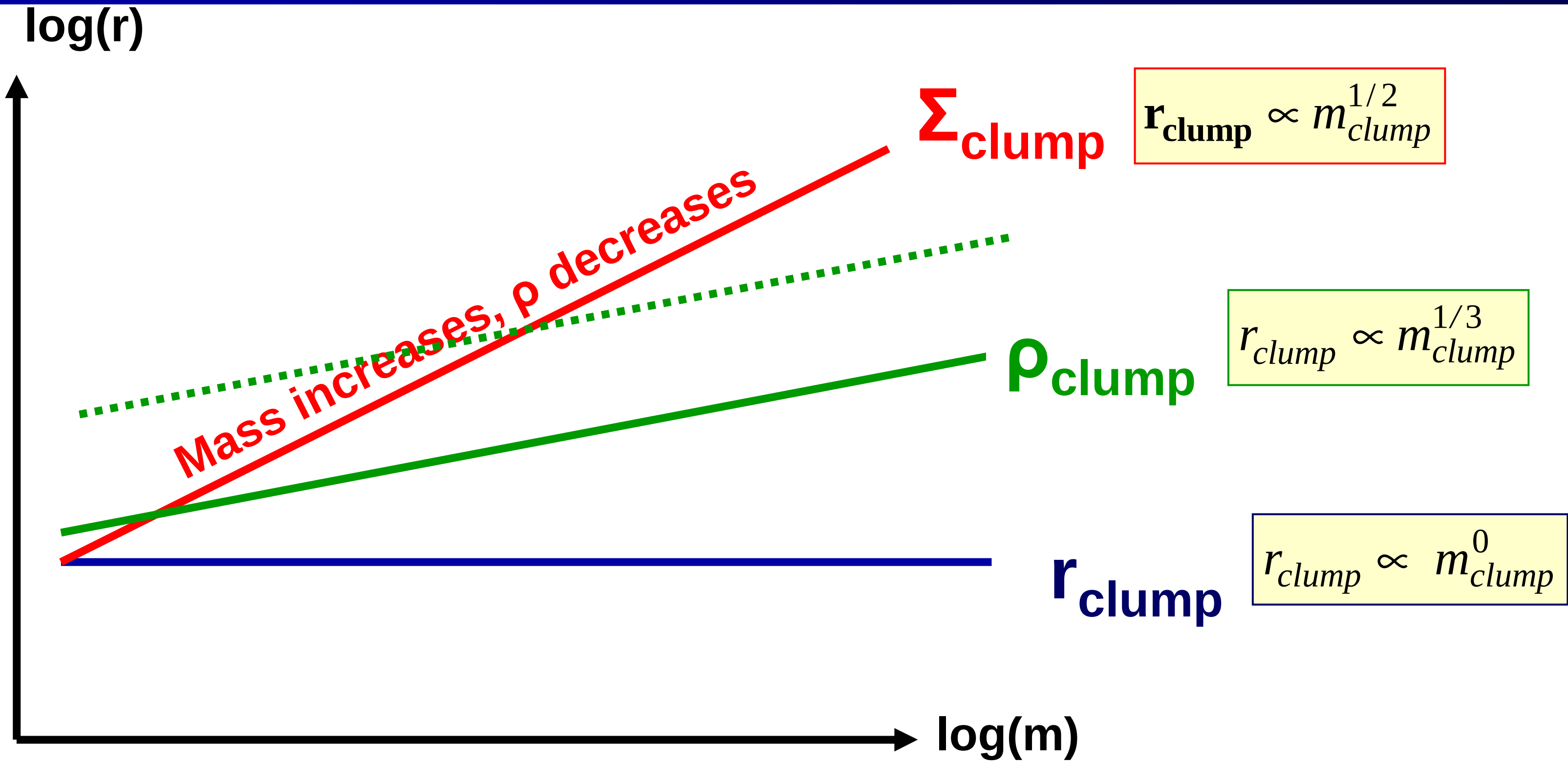


Fig 10 in Parmentier (2011)
arXiv:1101.0813

Cluster-forming regions of constant mean volume density and cloud/clump mass functions



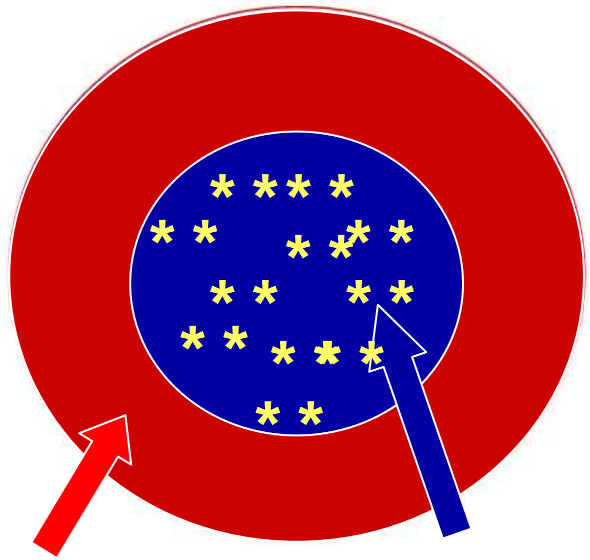
- Constant mean **surface** density clumps
→ a clump of **higher mass**
has a **lower fraction** of
its mass above a given
volume density threshold

$$\rho_{clump}(r) \propto \mathbf{r}^{\mathbf{-1.9}} :$$

$$\frac{m_{th}}{m_{clump}} \propto m_{clump}^{-0.3}$$

Cluster-forming regions of constant mean volume density and cloud/clump mass functions

Molecular clump 2-zone model

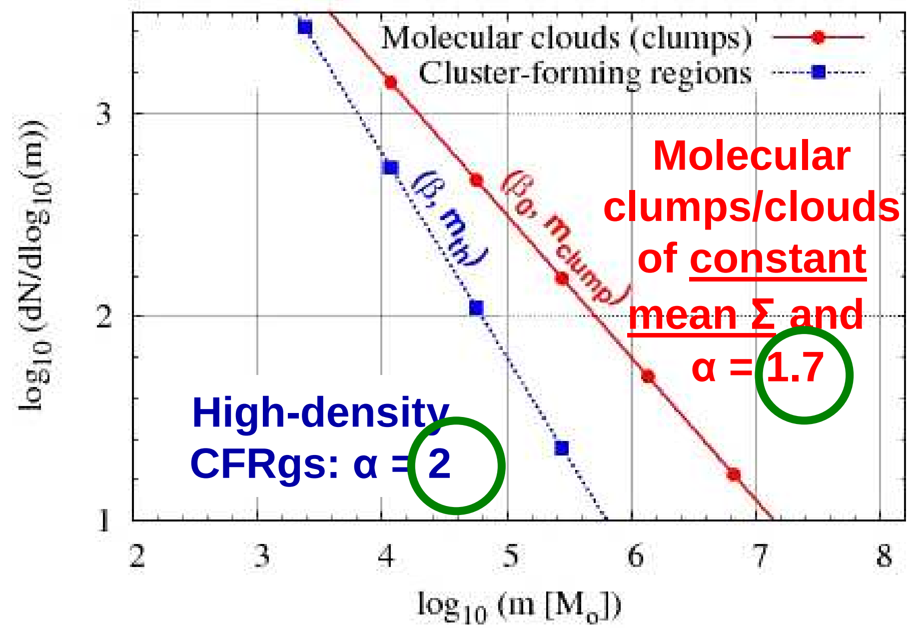


low-density outer envelope: $n_{H2} < n_{th}$

High-density CFRg of mass m_{th}: $n_{H2} > n_{th}$ → for a given density profile $\rho_{clump}(r)$, all CFRgs have identical mean volume densities (Note: $m_{th} = m_{CFRg}$)

$$\rho_{clump} \propto r^{-1.9} : \frac{m_{th}}{m_{clump}} \propto m_{clump}^{-0.3}$$

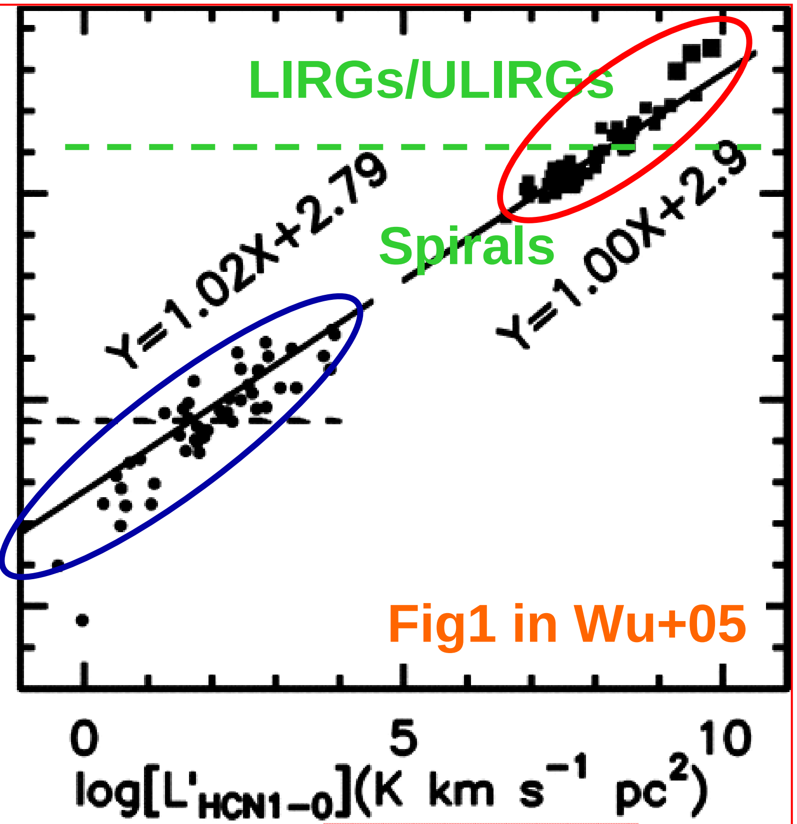
Mueller+02: density index ≈ 1.8



Parmentier (2011)
arXiv:1101.0813

The star-forming gas is the dense molecular gas

$$L_{IR} \propto SFR$$



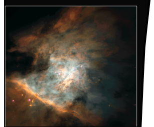
Galaxies:
$10^9 < M_{dense} < 4.10^{10}$ M$_o$

Galactic individual molecular clumps:
$10^2 < M_{dense} < 10^4$ M$_o$

$$L_{HCN} \propto M_{dense} \quad (n_{H_2} \cong 3\times10^4\, cm^{-3})$$

Dense star-forming gas vs diffuse quiescent molecular gas
- **Slopes of the cloud and cluster mass functions**
- **Slope of the Kennicutt-Schmidt law**

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 single step"
Oriental saying

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