Geneva Observatory - 14 June 2011

From
Cluster-Forming Region Properties
to Galaxy Evolution
with Star Clusters

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Image Credit

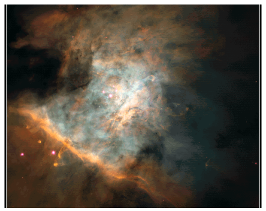
- **Elliptical galaxy M87** (APOD 16.06.2004):
  - Canada-France Hawaii Telescope, J.-C. Cuillandre
- **Globular Cluster M10** (APOD 30.06.2001):
  - Till Credner, Sven Kohle (Bonn University), Hoher List Observatory
- **Orion Nebula Mosaic** (HST – WFPC2):
  - O'Dell and S.K. Wong (Rice University), NASA
- **Open Cluster Pleiades M45** (APOD 01.12.2002):
  - Anglo-Australian Observatory/Royal Observatory, Edinburgh
- **Open Cluster Hyades**:
  - http://stars.astro.illinois.edu/sow/hyades-p.html , by Jim Kaler
- **Spiral galaxy NGC3370** (APOD 14.05.2005):
  - Hubble Heritage Team, A. Riess (STScI) NASA

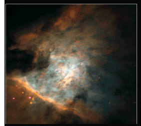
Star Clusters: at the crossroad between star formation and galaxy evolution

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

10pc:
individual
gas-free
star clusters

1-pc:
star formation
in embedded
star clusters



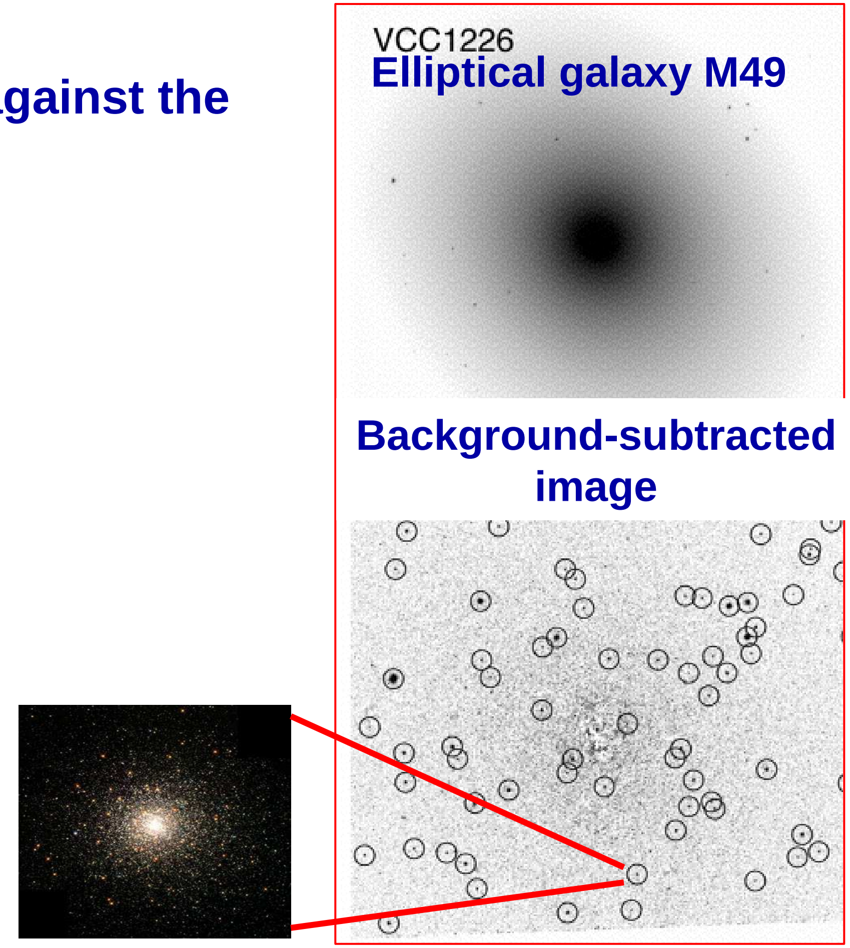


Setting the Scene: Star Clusters (SC) as Powerful Tracers of Galaxy Evolution

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 (Virgo Galaxy Cluster ACS Survey II, fig6)



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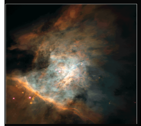

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Multi-band imaging of SC systems
(→ cluster magnitudes, colours)

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

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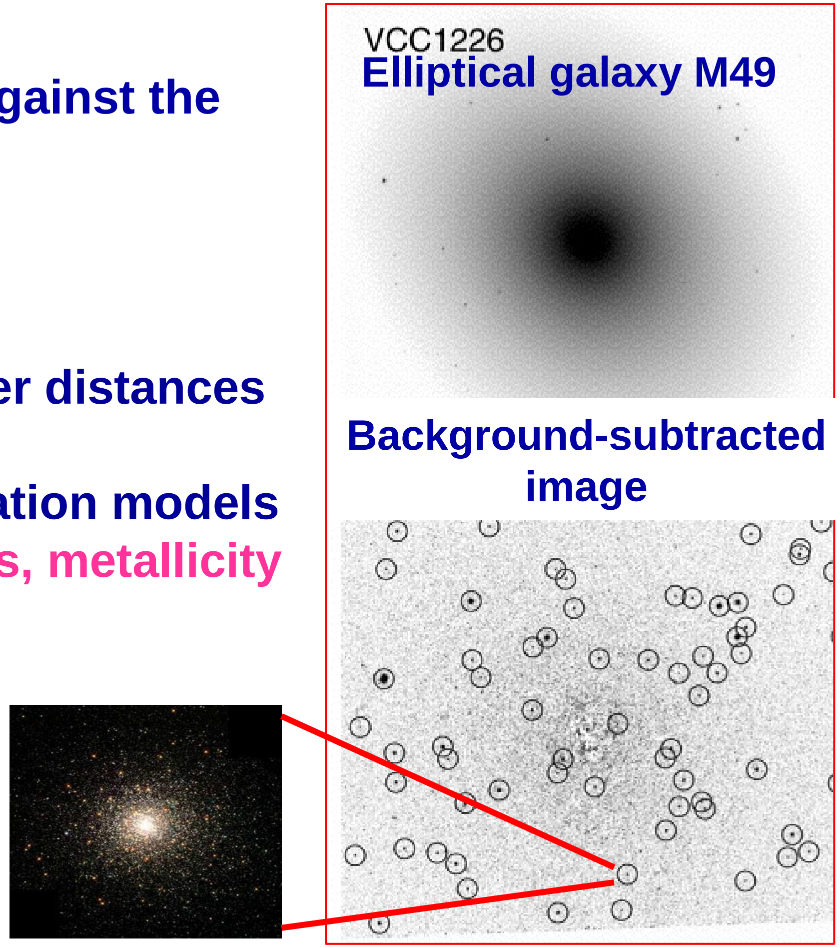

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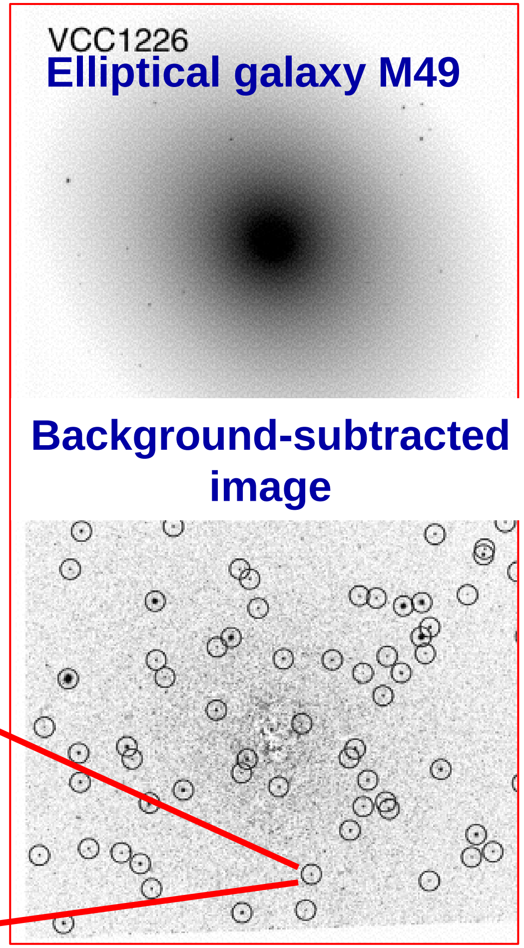
Comprehensive view of galaxy-:

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

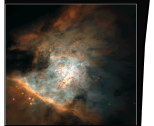
over the past Hubble-Time

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



Star clusters are at the very heart of many astrophysical topics

The Big Issue: SCs versus field stars

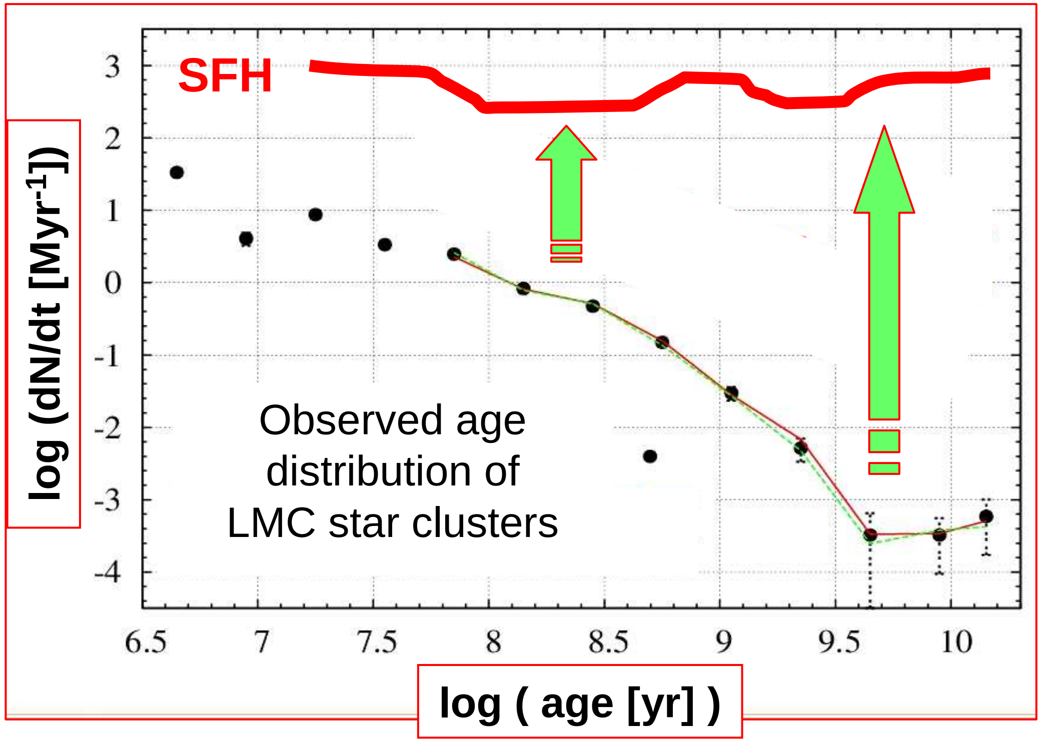



Most stars in our Galaxy:

- **are born in SCs** → young SCs tell us about star formation
- **but are observed as field stars**
- **SCs start losing stars as soon as they are born ...**

Star clusters have the potential of tracing

➤ **galaxy star formation histories**



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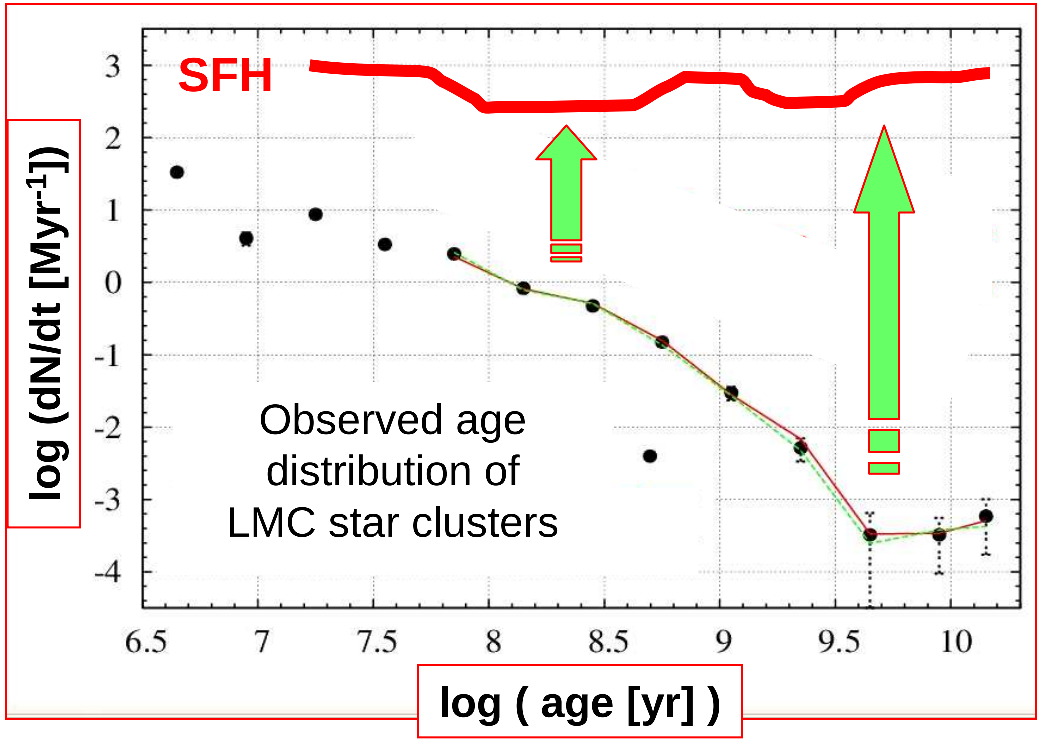

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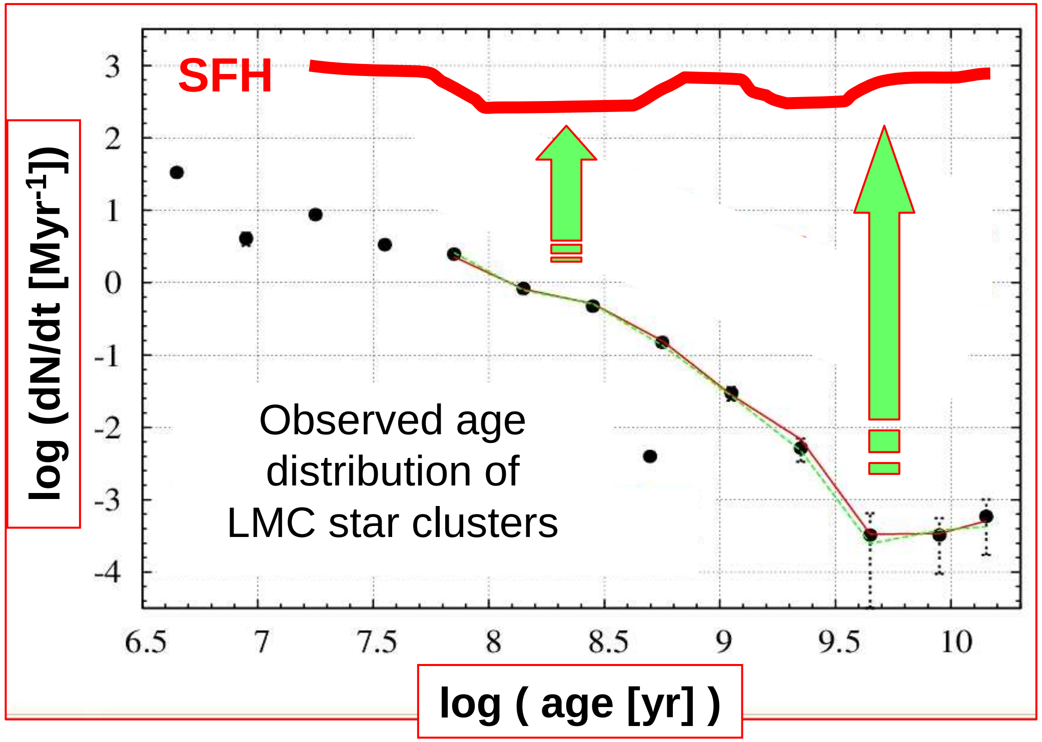
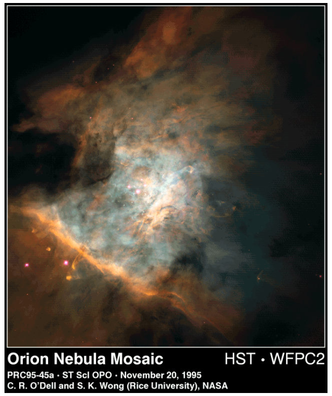


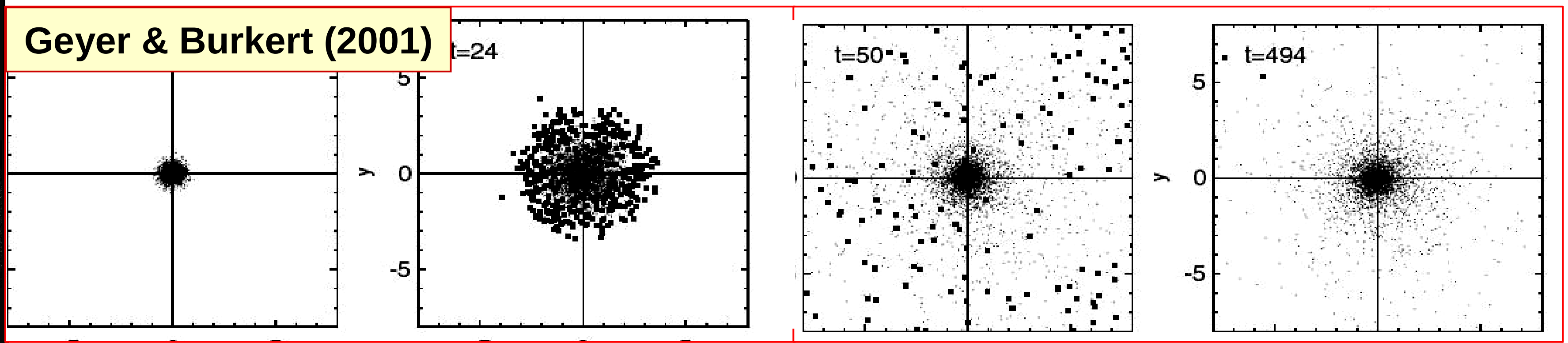
Violent relaxation = Most traumatizing phase

- ➤ **Very short (10-50 Myr)**
- ➤ **SC Dynamical response to residual star-forming gas expulsion**

Intra-Cluster Gas-Expulsion and Violent Relaxation



time



Effects of gas expulsion - VIOLENT RELAXATION

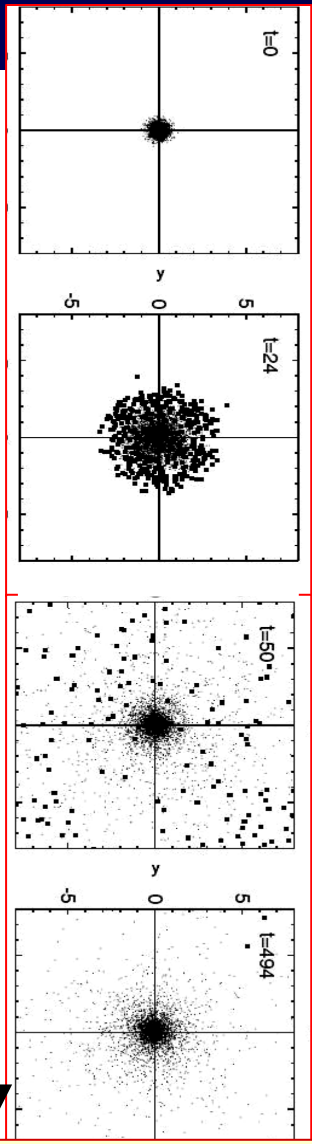
- **Cluster expansion**
- **Star loss (infant weight-loss), or**
- **Cluster dissolution (infant mortality)**

Violent Relaxation (VR): Observable Signatures and Prime Parameters

Effects of gas expulsion - VIOLENT RELAXATION

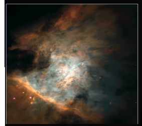
- **Cluster expansion**
- **Cluster infant weight-loss and infant mortality**

time



Geyer & Burkert (2001)

Violent Relaxation (VR): Observable Signatures and Prime Parameters

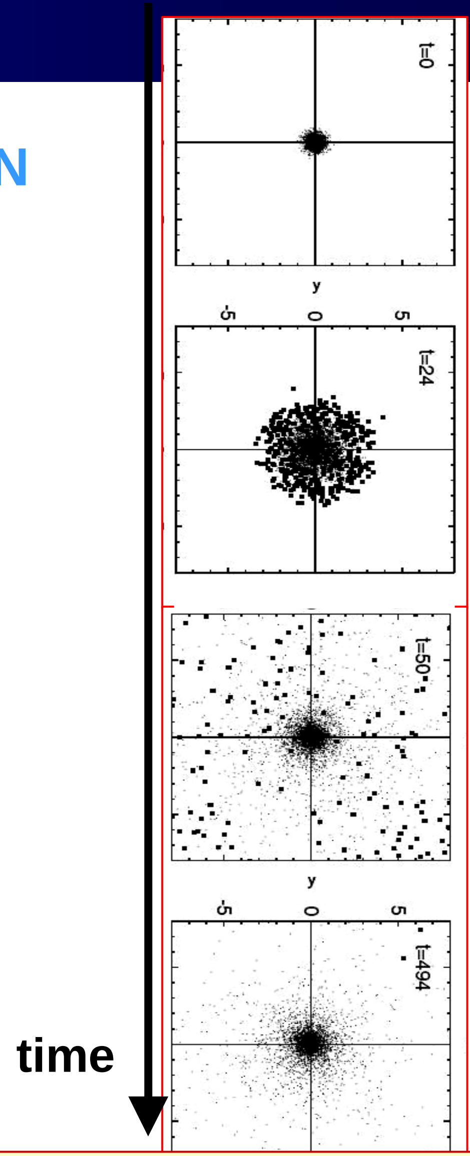



Effects of gas expulsion - VIOLENT RELAXATION

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

Observable Imprints upon Star Cluster Systems :

- Cluster mass distribution,
- Cluster age distribution,
- Cluster radius distribution,



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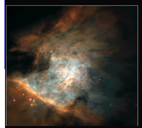

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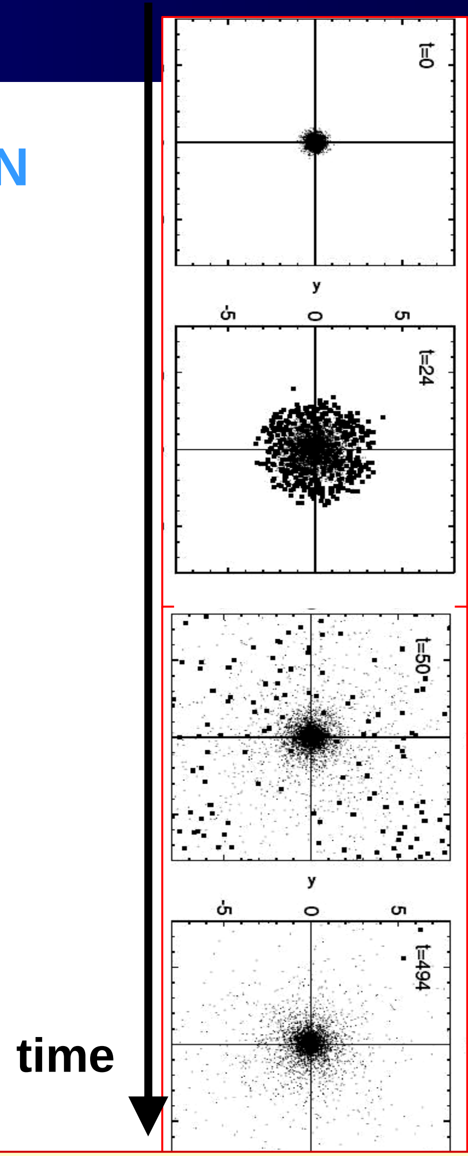
- Cluster mass distribution,
- Cluster age distribution,
- Cluster radius distribution,

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

- **SFE in cluster-forming region (CFRg)**
- **Gas expulsion time-scale: $\tau_{GExp} / \tau_{cross}$**
- **Impact of external tidal field (environment)**

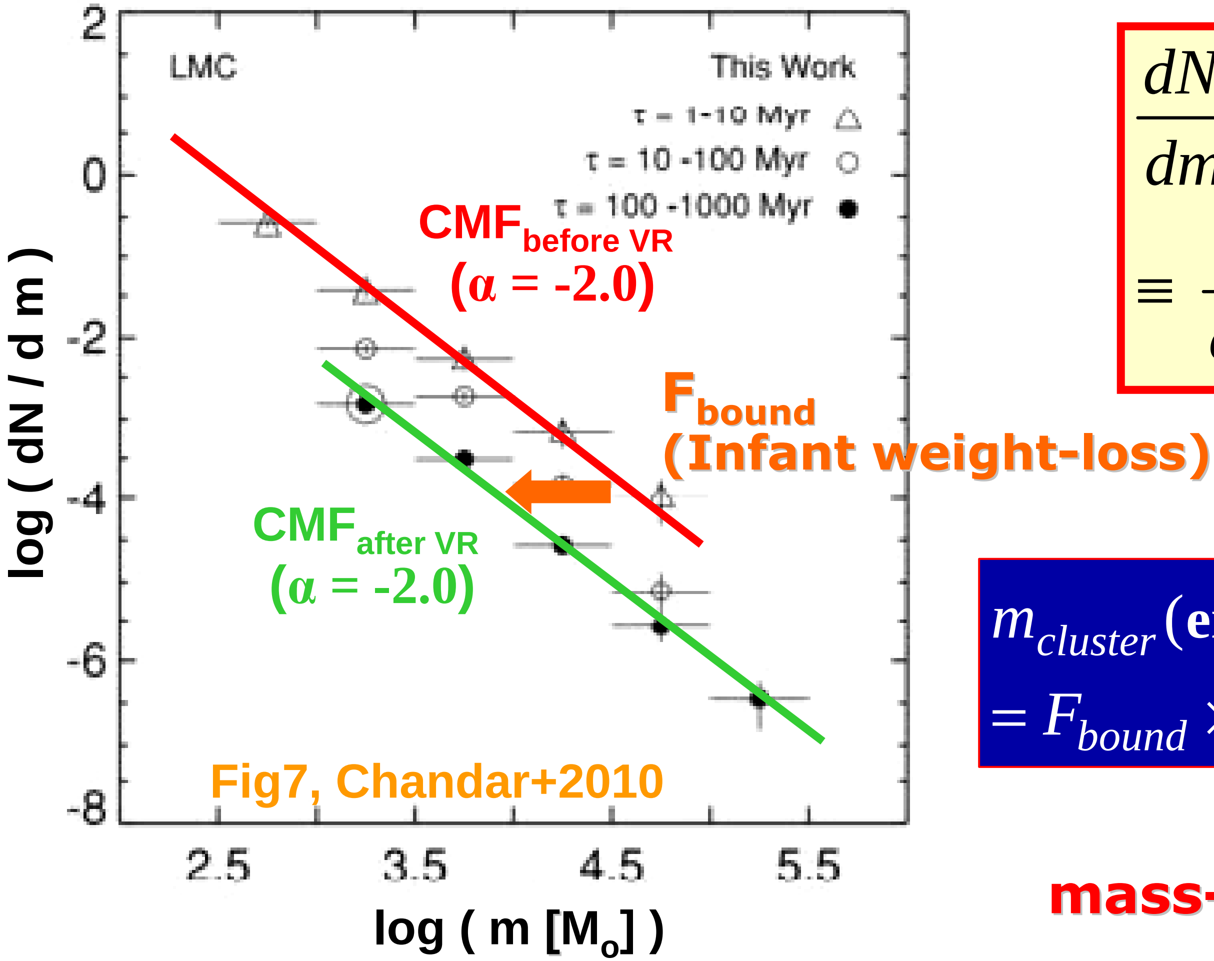
See also Adams (2000), Vesperini et al (2009), …



Geyer & Burkert (2001)

Violent Relaxation (VR): SC Mass Functions

Time-Evolution of SC Mass Functions: What observers tell us …
No evolution of the MF shape over the first few 10Myr



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

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

F_{bound} is mass-independent

Note: what happens after 100Myr remains disputed …

SFE and SC Mass Functions

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

$$F_{bound}(\mathrm{SFE})$$

SFE
= fraction of gas ending up in stars

F_{bound}
= fraction of stars remaining bound to the cluster at the end of VR

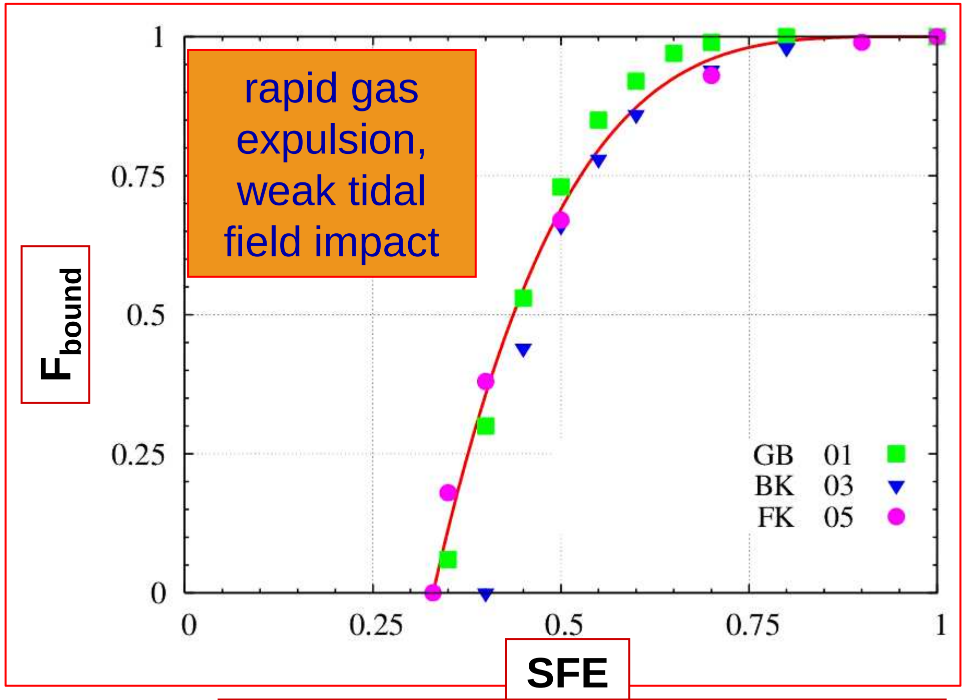
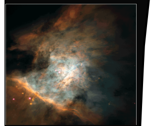


Fig1, Parmentier & Gilmore (2007)

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

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




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

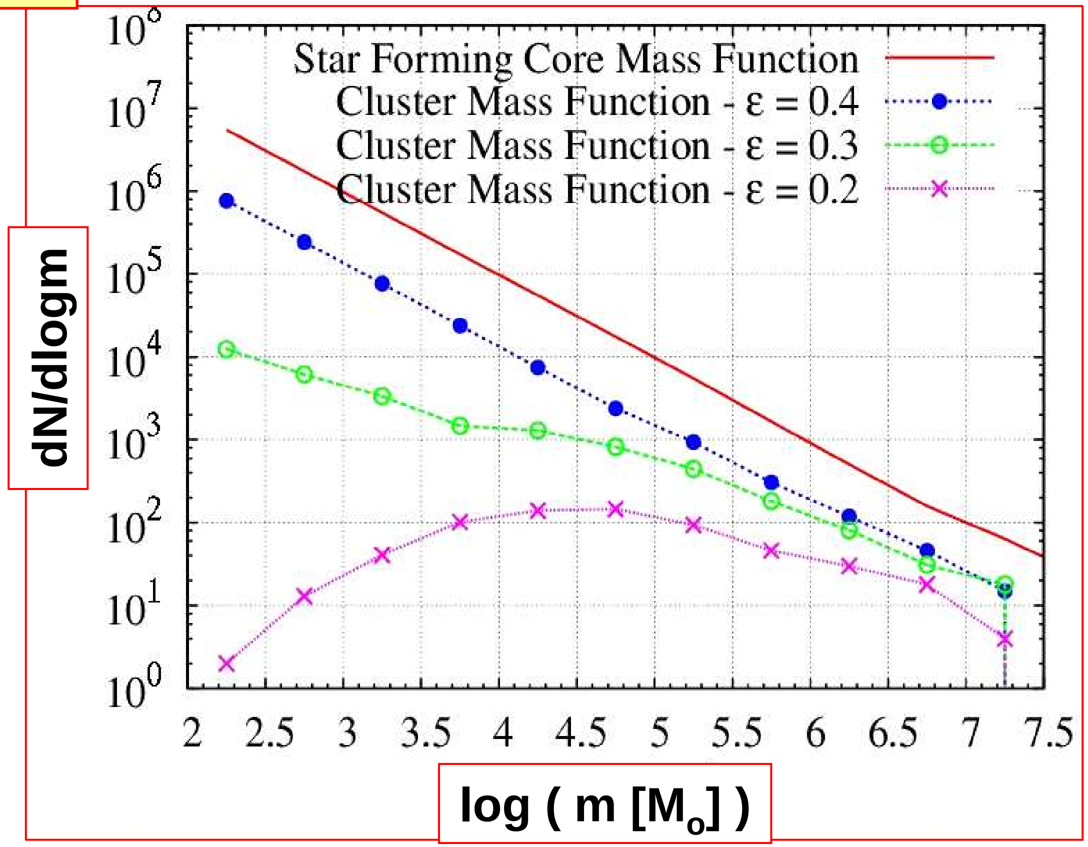
Constant radius:
more massive star cluster progenitors have
- **a deeper potential well**
- **a slower gas-expulsion t-s**
- **can survive despite a low SFE of, say, 20%**

F_{bound} is mass-independent

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

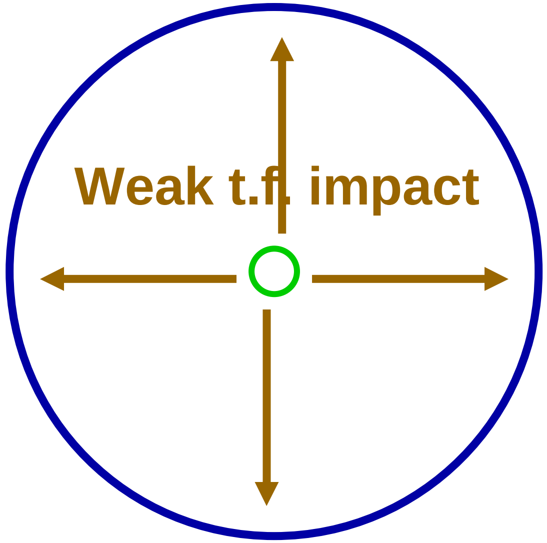
but looser constrain

Parmentier, Goodwin et al. (2008), Fig2a



Tidal Field Impact

$$F_{bound}\left(\mathbf{SFE}, \frac{\tau_{GExp}}{\tau_{cross}}, \frac{r_{half-mass}}{r_{tidal}}\right)$$



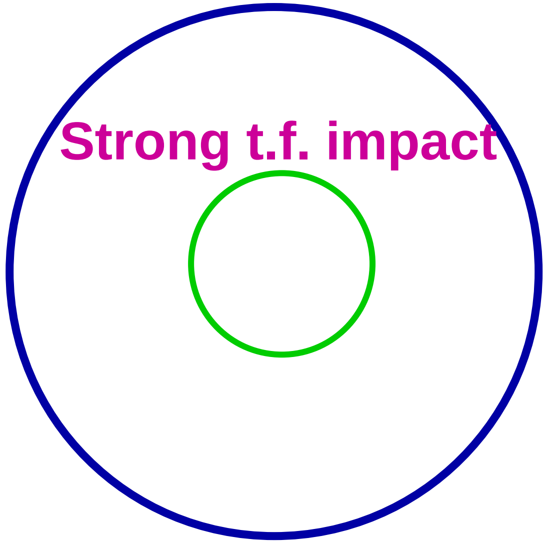
$$Half-mass\ radius:\ r_{half-mass} \propto r_{CFRg}$$

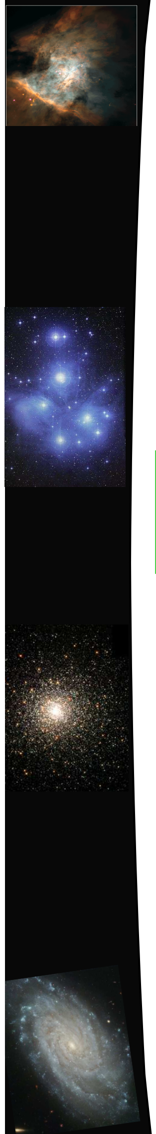
Limiting tidal radius:

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

Embedded cluster mass

SC environment





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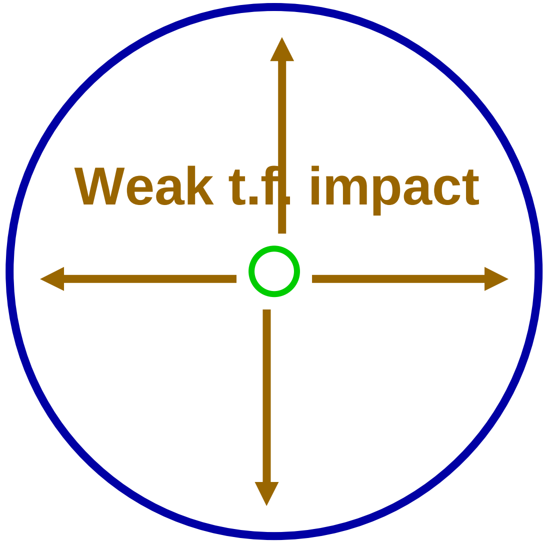

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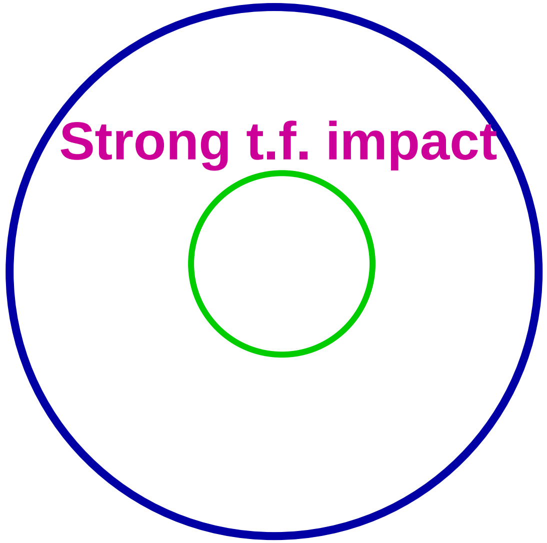
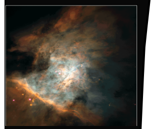
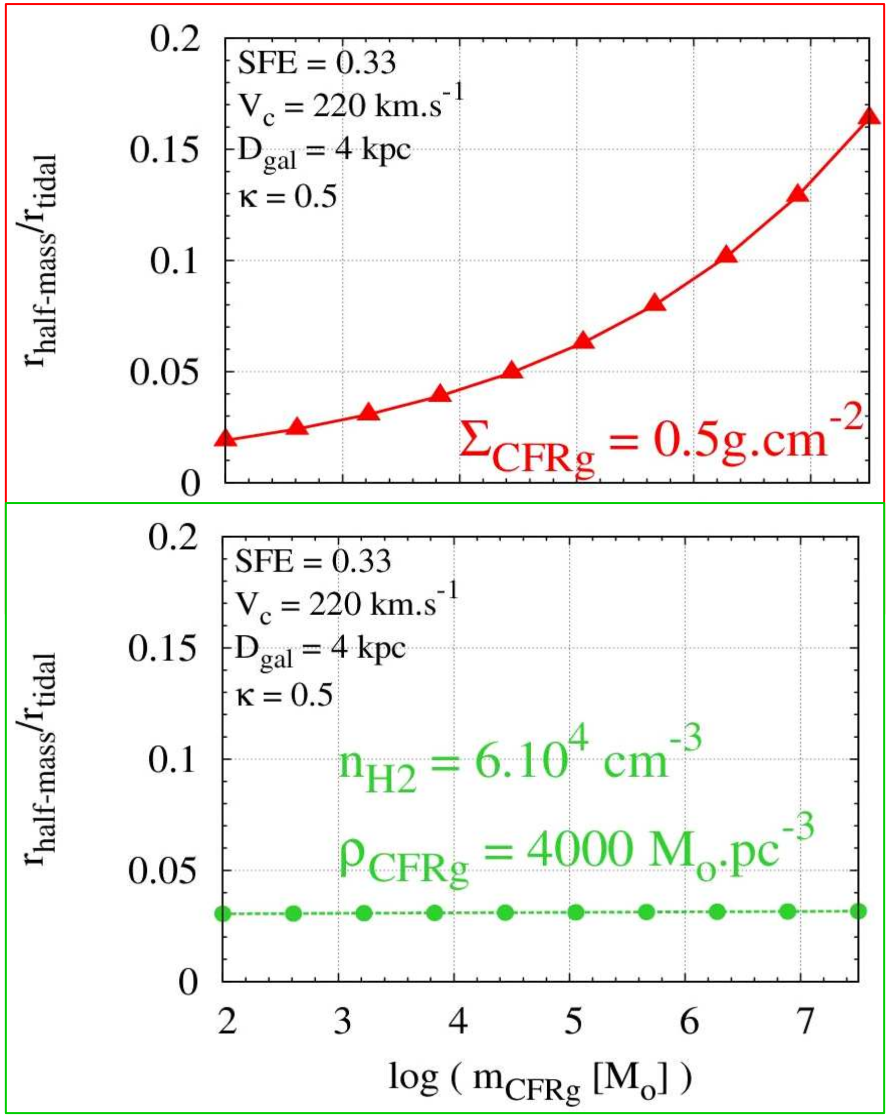


Half-Mass Radius—to—Tidal Radius Ratio





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

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

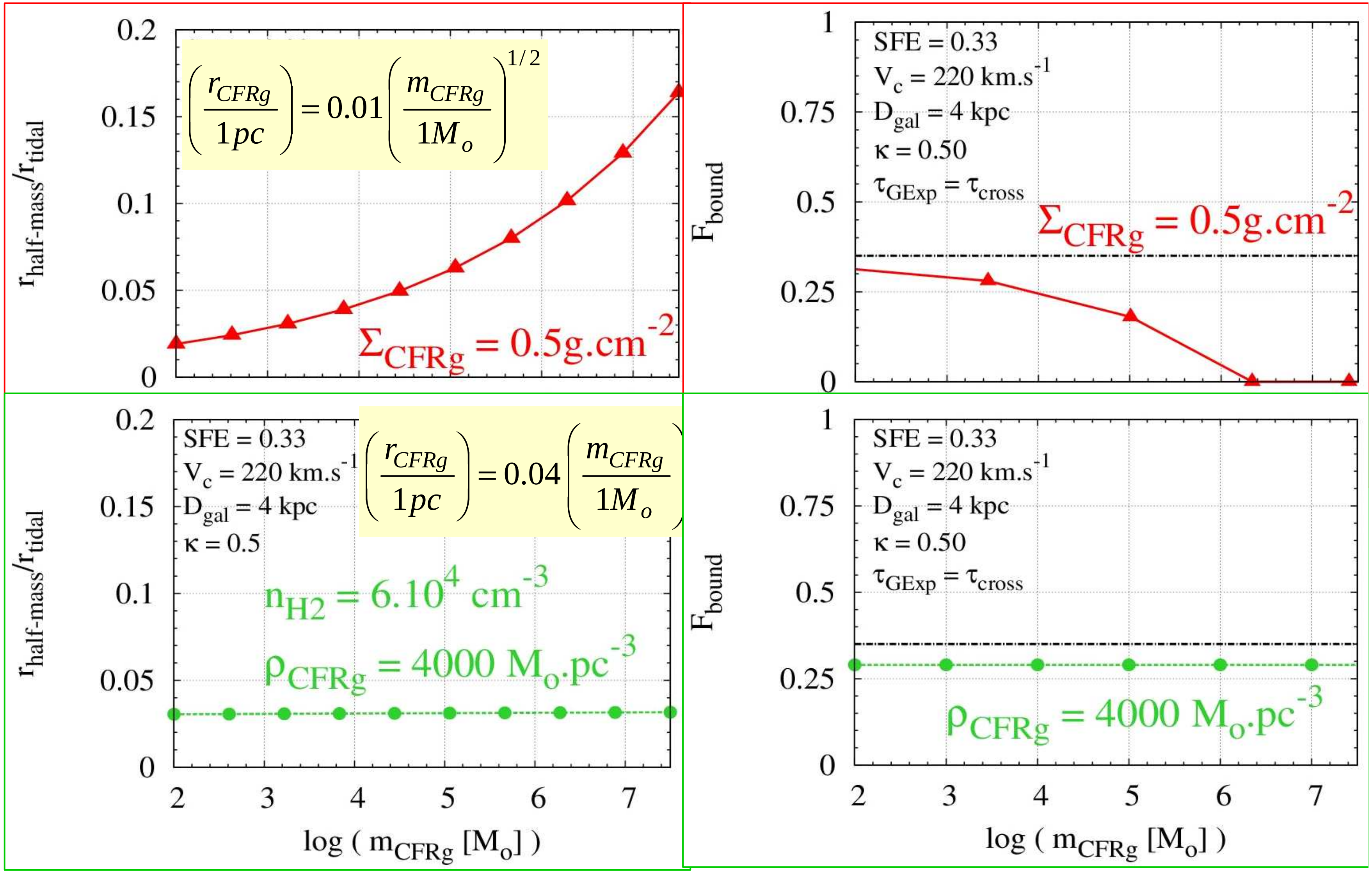
$$\frac{r_{half-mass}}{r_{tidal}} \propto m_{CFRg}^{1/6}$$

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

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

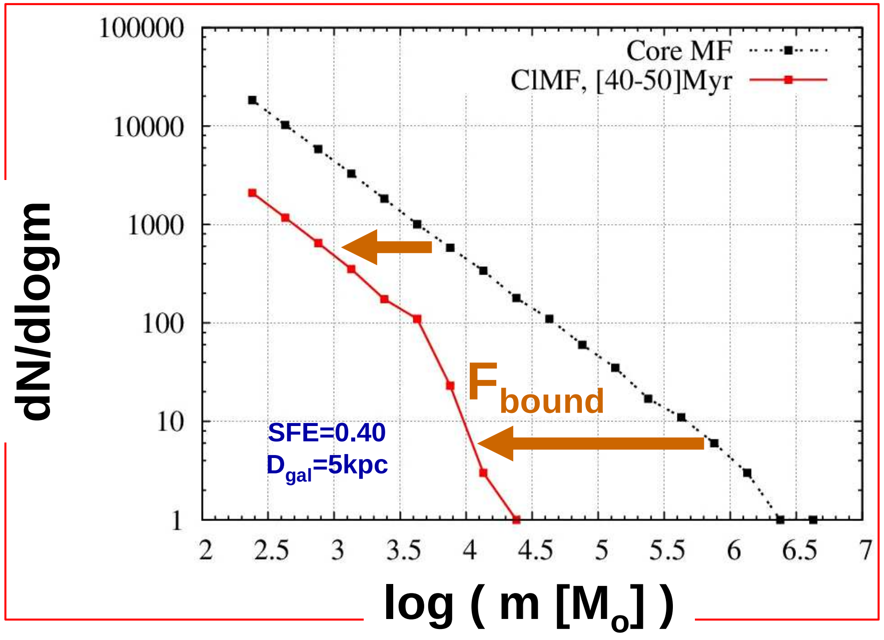
$$\frac{r_{half-mass}}{r_{tidal}} \propto m_{CFRg}^{0}$$

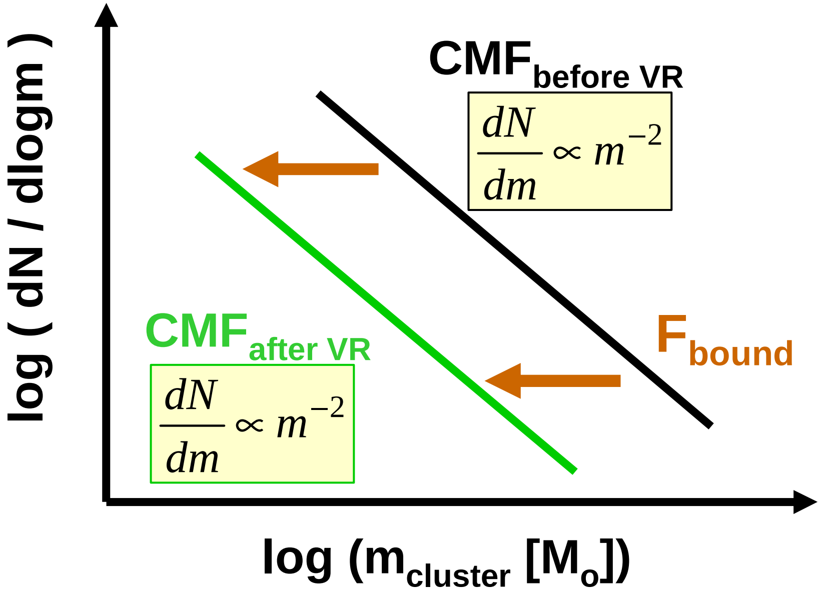
Bound Fractions at the End of Violent Relaxation

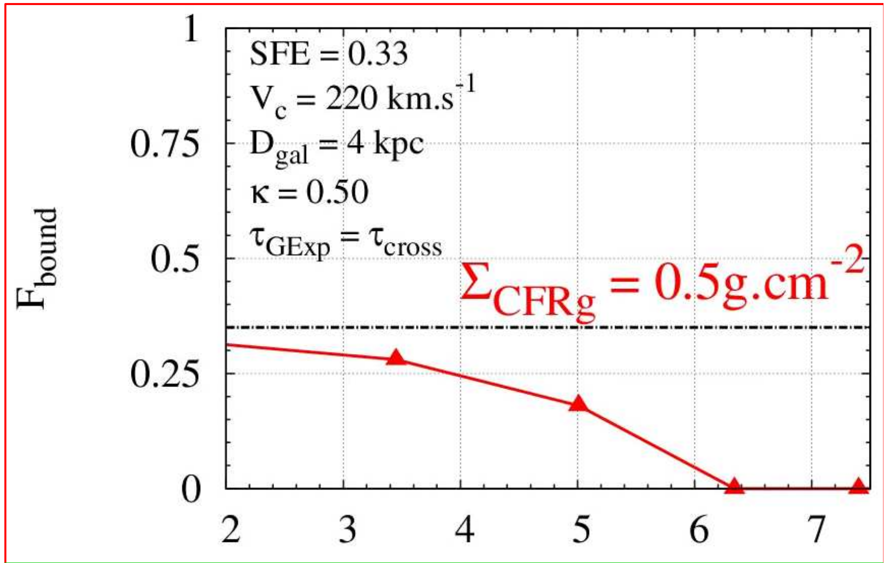


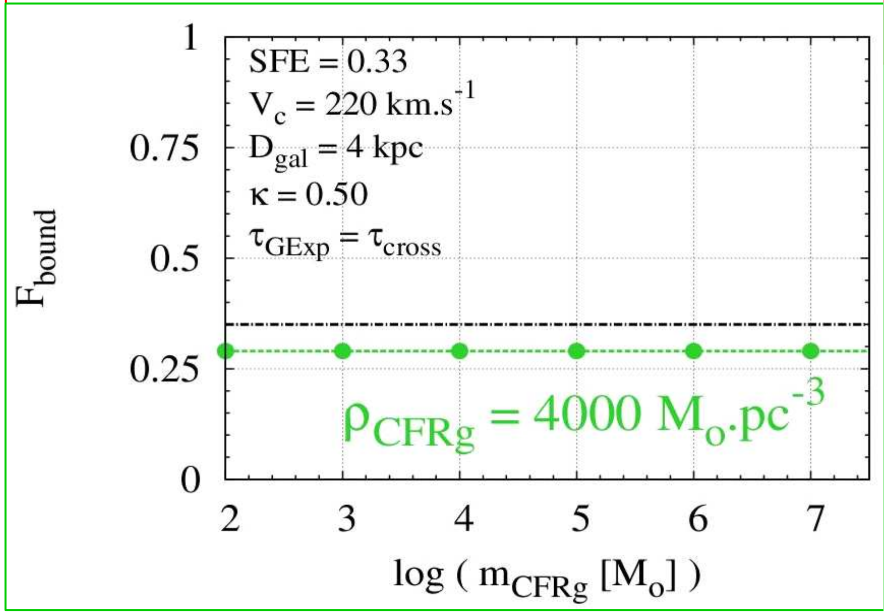
Parmentier & Kroupa (2011)

Young SC Mass Functions









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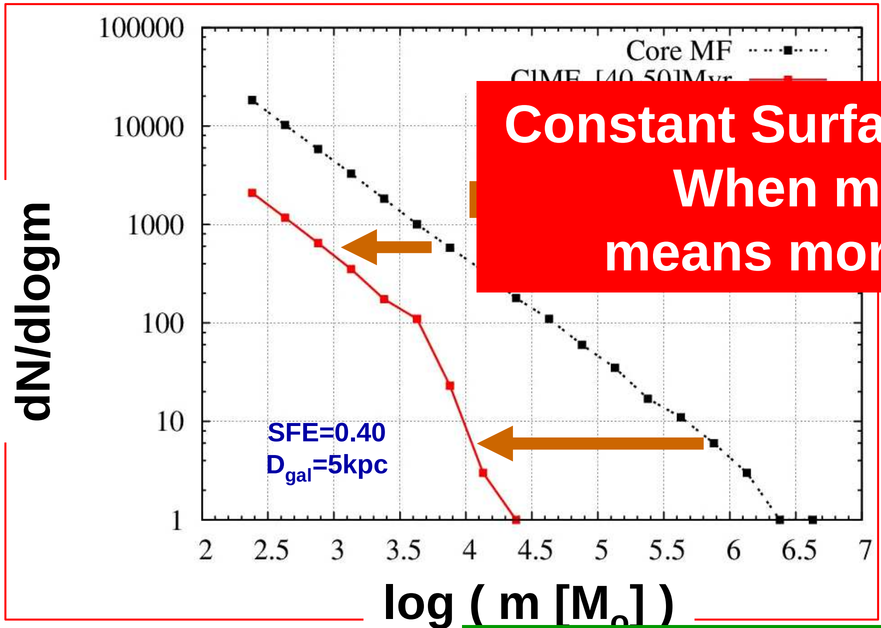
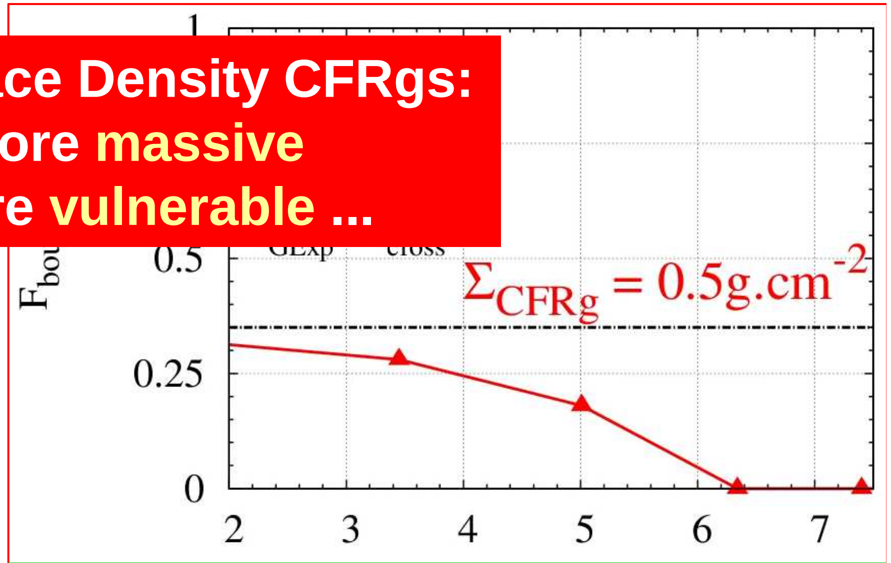
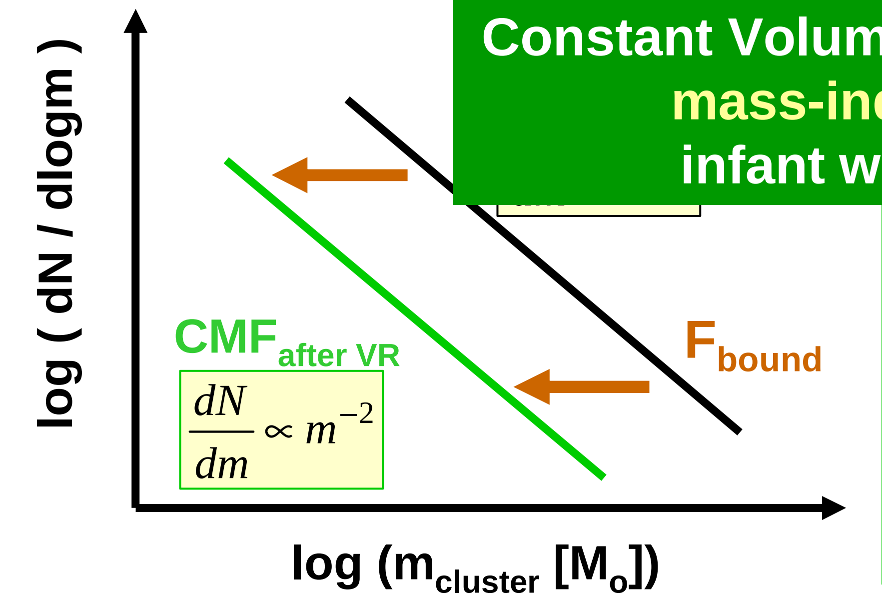
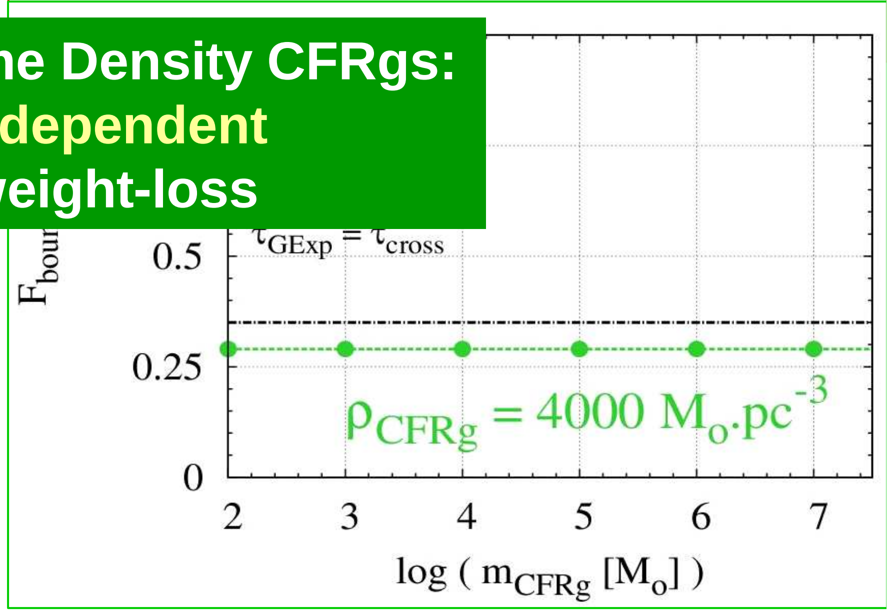




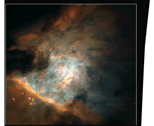
Constant Surface Density CFRgs:
When more massive
means more vulnerable ...





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

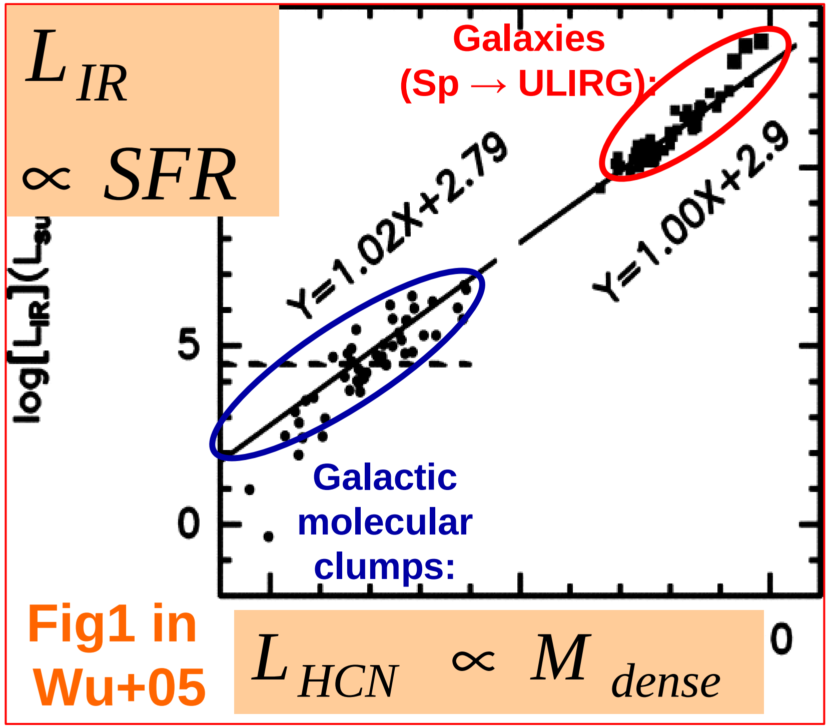
A Volume Density Threshold for the Star-Forming Gas



- Gao & Solomon (2004), Wu+2005

→ HCN mapping of entire galaxies
+ Galactic individual molec clumps

➡ the SFR scales as the mass of dense molecular gas: $n_{H2} > 3.10^4 cm^{-3}$



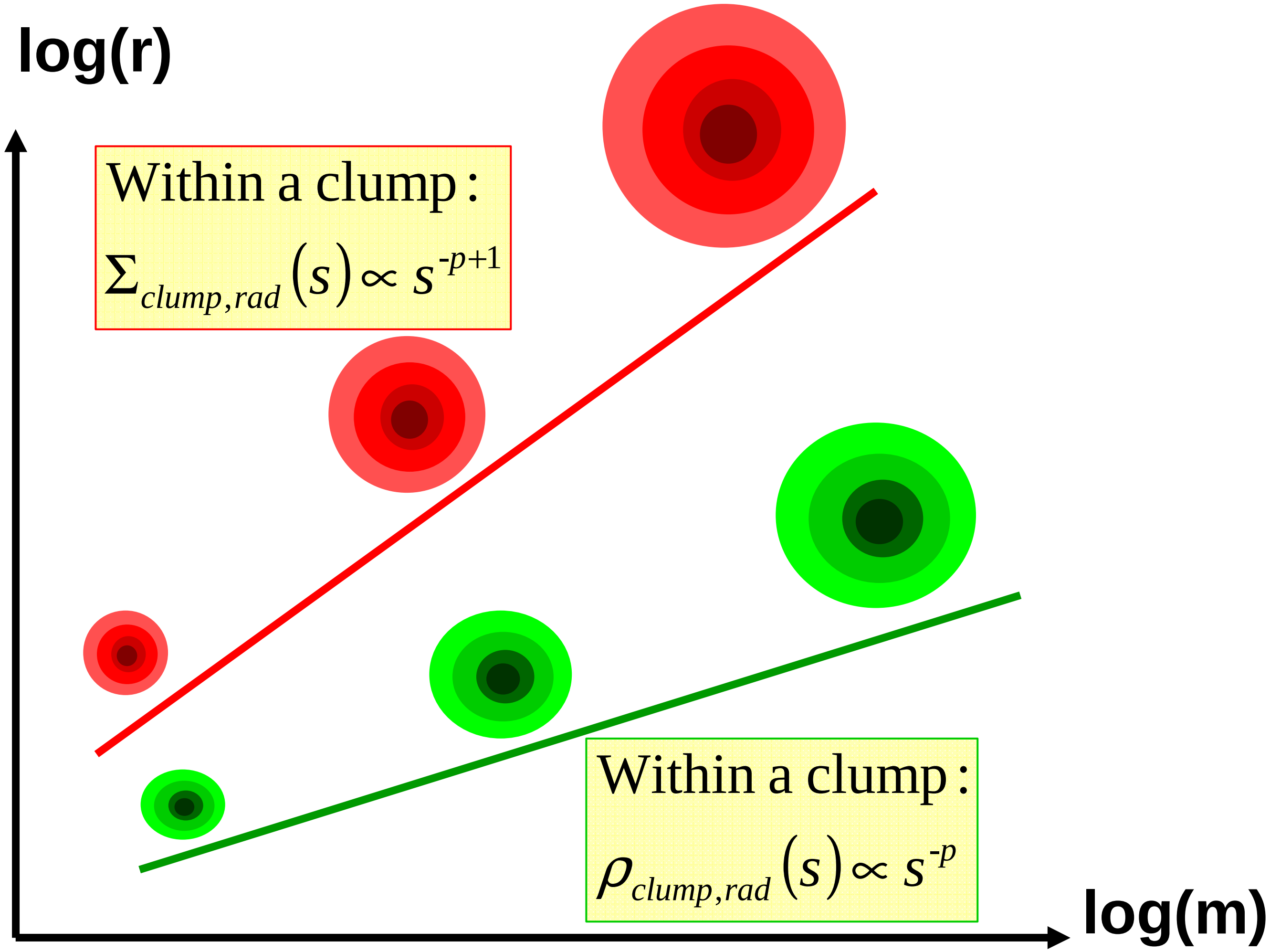
- Lada, Lombardi & Alves (2010)

→ comparison of IR extinction maps of molecular clouds with their census of Young Stellar Objects

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

➤ CFRgs of about <u>constant mean volume density</u> (n_{H2} = few n_{th})
➤ Conclusion identical as for the tidal field impact analysis
(Parmentier & Kroupa 2011)

Constant 'mean' volume or surface density, NOT 'uniform' volume or surface density



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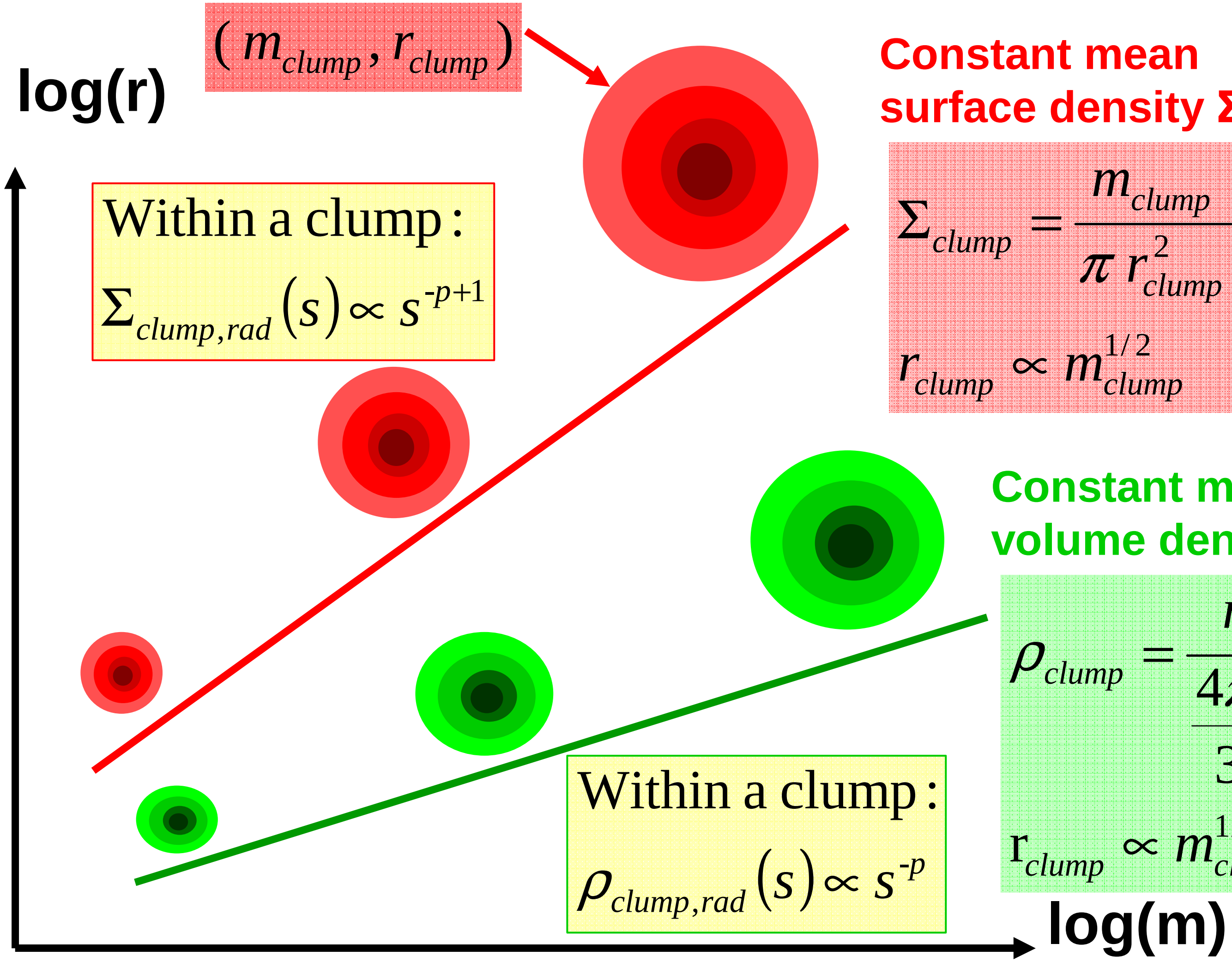


(m_{clump} , r_{clump})

Within a clump:

$\Sigma_{clump,rad}(s) \propto s^{-p+1}$

Within a clump:

$\rho_{clump,rad}(s) \propto s^{-p}$

Constant mean surface density Σ_{clump} :

$$\Sigma_{clump} = \frac{m_{clump}}{\pi r_{clump}^2} = \mathrm{cst}$$

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

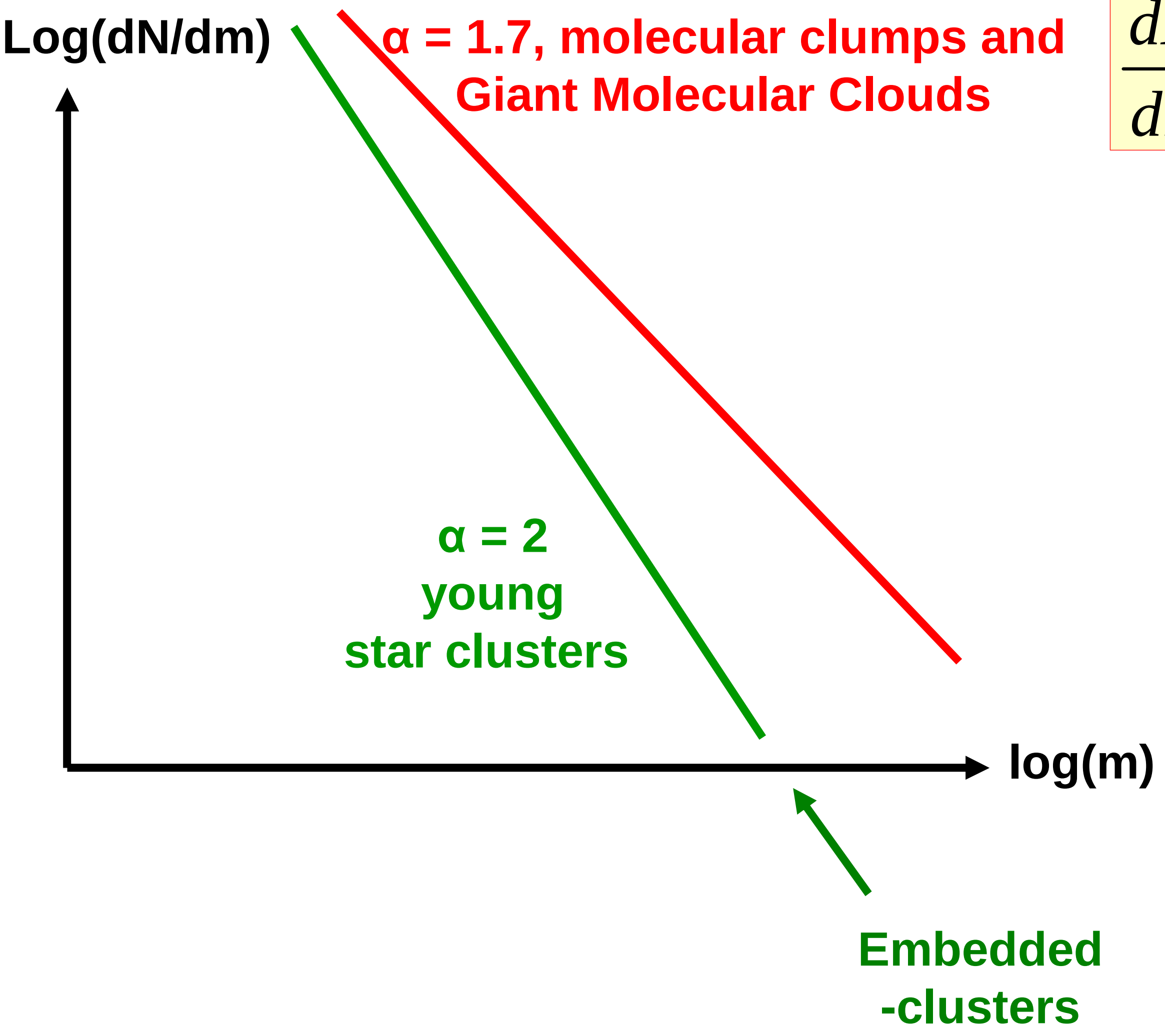
Constant mean volume density ρ_{clump}:

$$\rho_{clump} = \frac{m_{clump}}{\frac{4\pi}{3} r_{clump}^3} = \mathrm{cst}$$

$$\mathrm{r}_{clump} \propto m_{clump}^{1/3}$$

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

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



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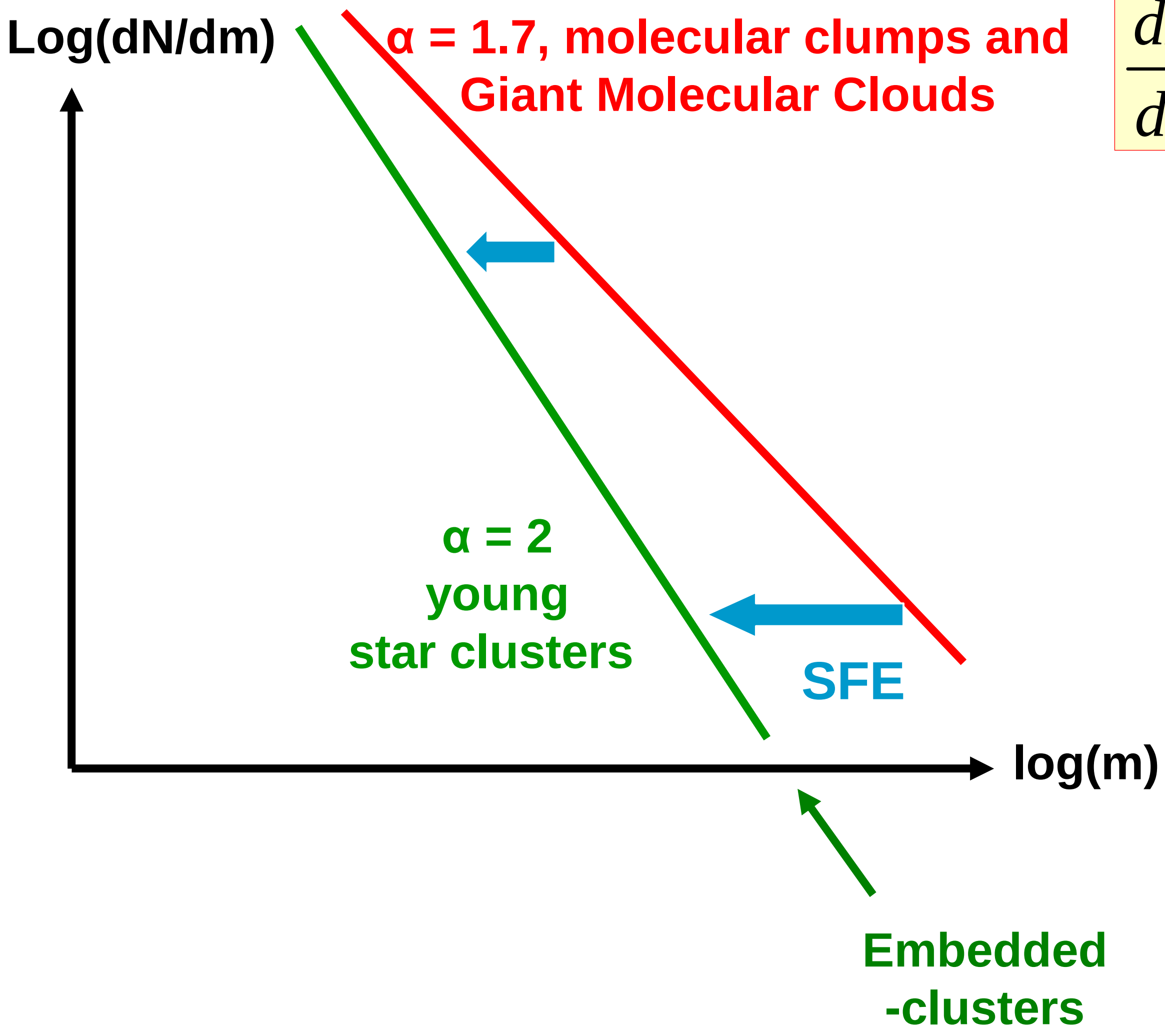

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Mass-varying SFE: lower SFE at higher cloud/clump mass ??

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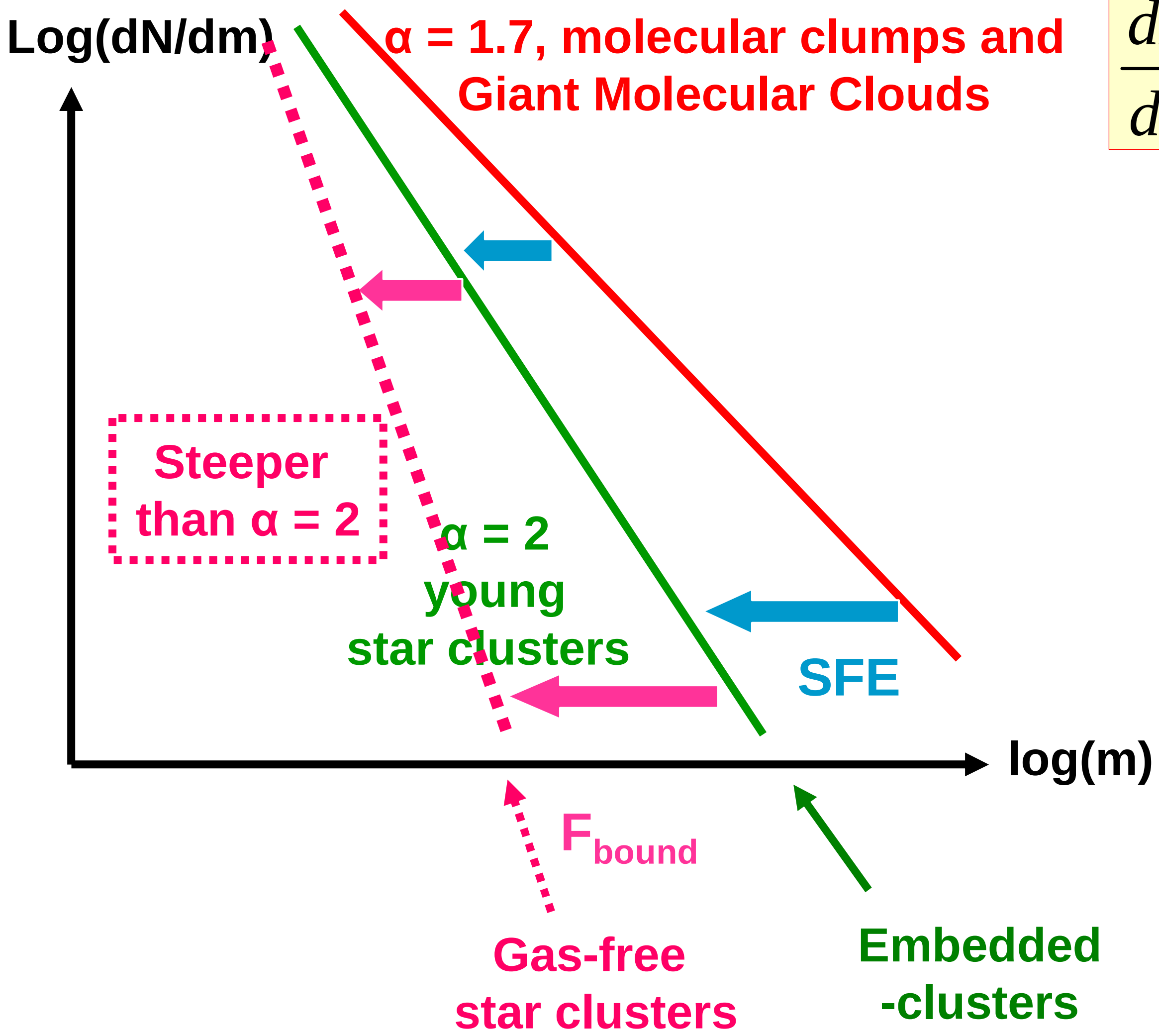


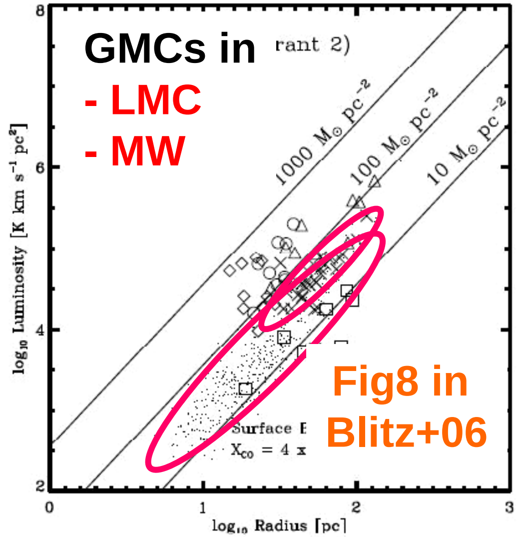
$$\frac{dN}{dm} \propto m^{-\alpha}$$

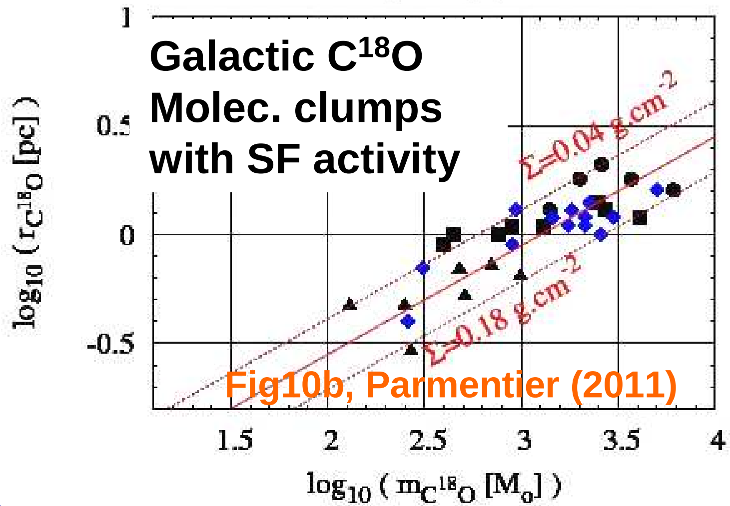
Mass-varying SFE: lower SFE at higher cloud/clump mass ??

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

From the Mass Function of Molecular Clumps to that of Embedded Star Clusters

- **Cluster-forming regions:**
  constant mean volume density
  (tidal field impact analysis)



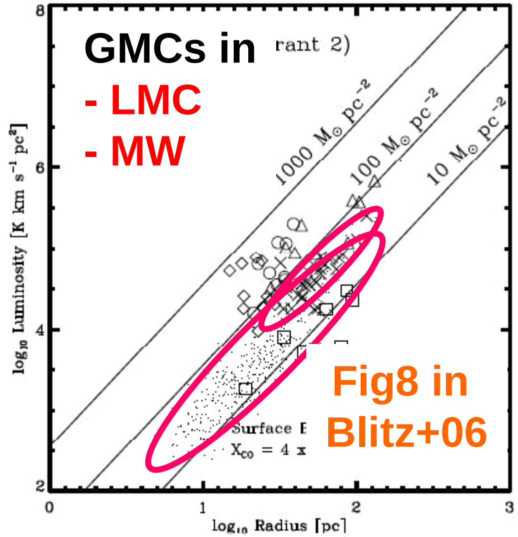


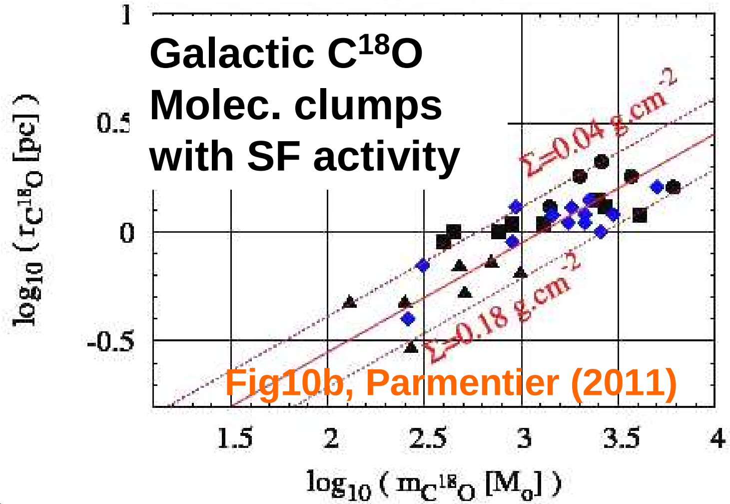
From the Mass Function of Molecular Clumps to that of Embedded Star Clusters

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

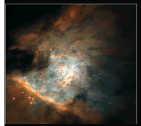
- **GMCs and Molecular clumps with signs of SF activity:**
  constant mean <u>surface</u> density
  - **Larson 1981**
  - **Blitz+ 2006**
  - **Heyer+ 2009**

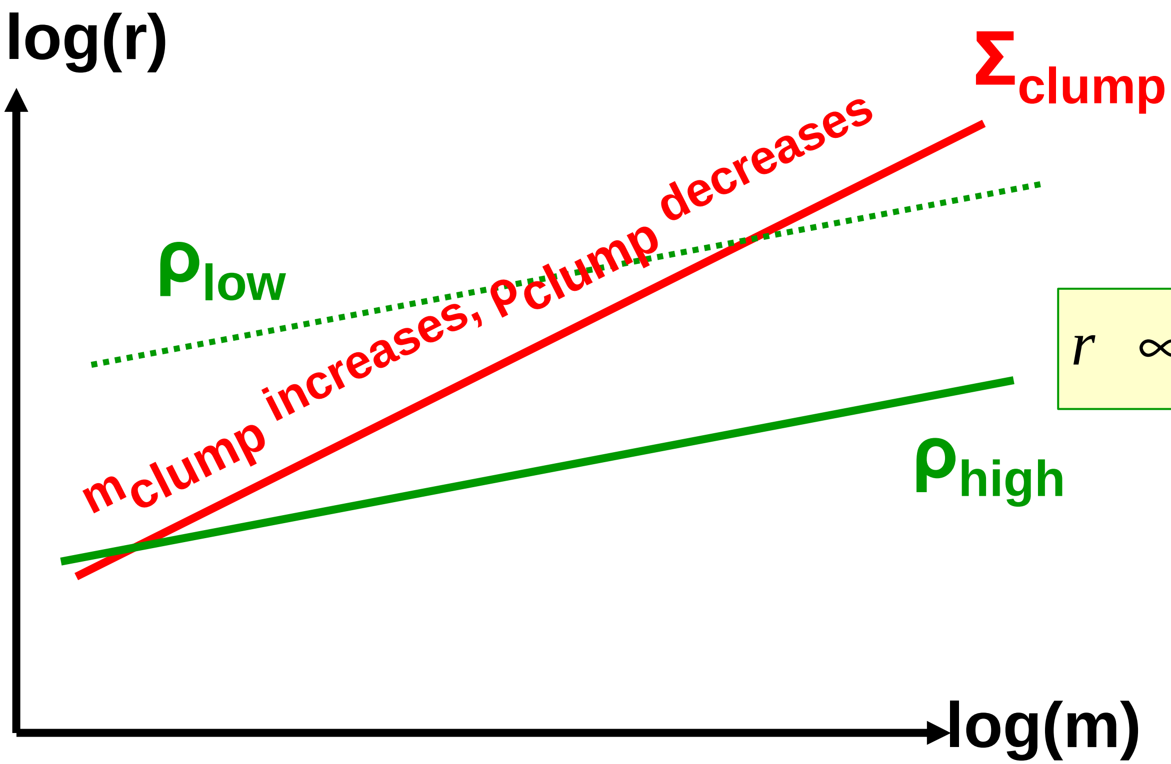
➡ **Mass-dependent effect**





From the Mass Function of Molecular Clumps to that of Embedded Star Clusters



$$r_{\mathbf{clump}} \propto m_{clump}^{1/2}$$

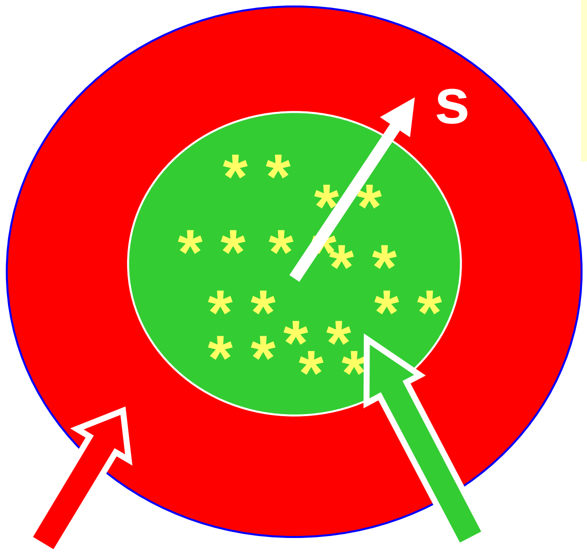
$$r \propto m^{1/3}$$

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

$$\frac{m_{CFRg}}{m_{clump}} \propto m_{clump}^{-?}$$

From the Mass Function of Molecular Clumps to that of Embedded Star Clusters

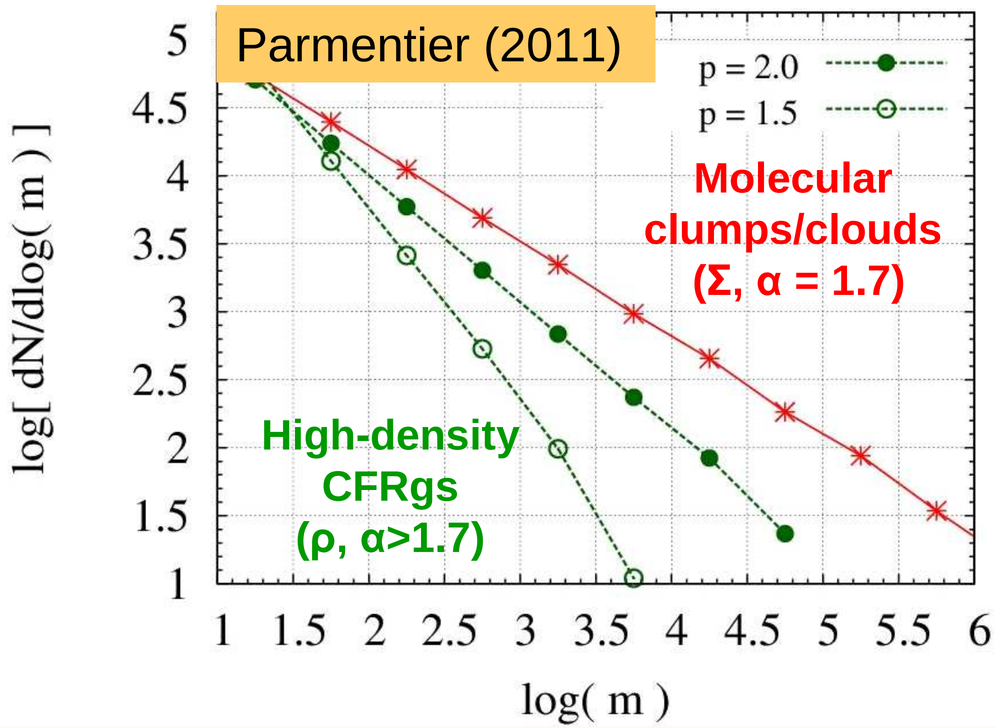
Molecular clump: 2-zone model



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

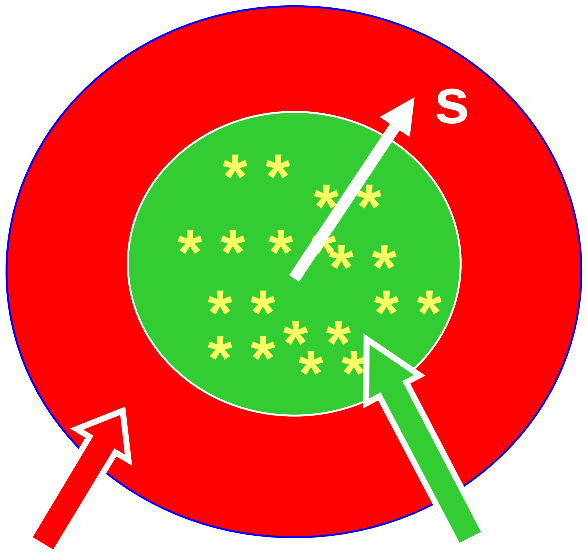
High-density cluster-forming region (CFRg): $n_{H2} > n_{th}$

$$\rho_{clump,rad}(s) \propto s^{-p} : \frac{m_{CFRg}}{m_{clump}} \propto m_{clump}^{-f(p)}$$



From the Mass Function of Molecular Clumps to that of Embedded Star Clusters

Molecular clump: 2-zone model

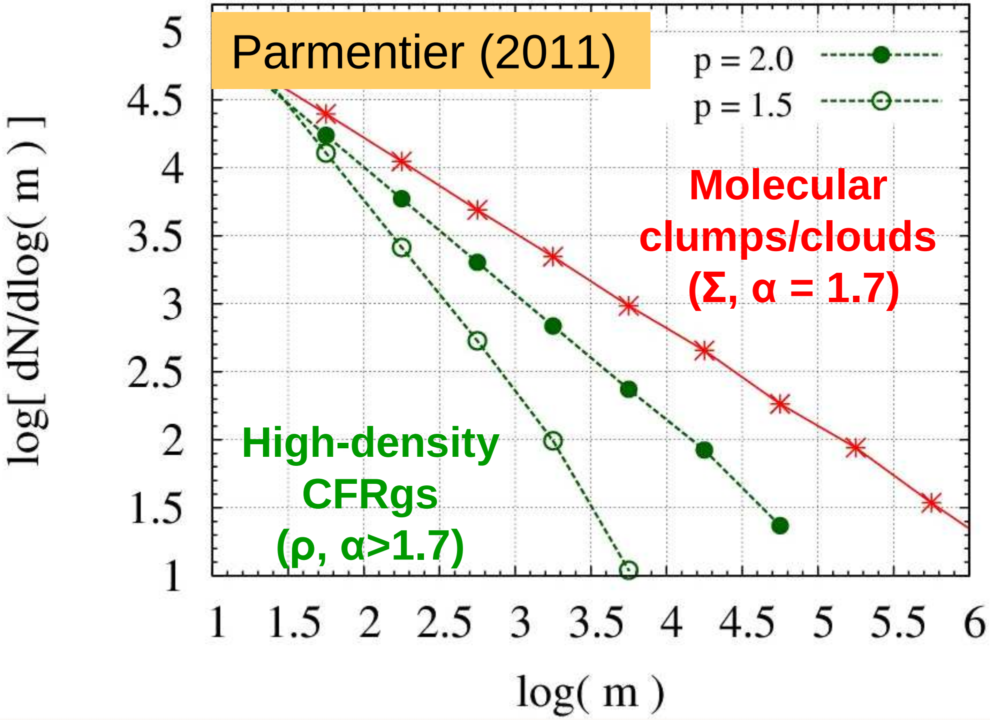


low-density outer envelope: $n_{H2} < n_{th}$

High-density cluster-forming region (CFRg): $n_{H2} > n_{th}$

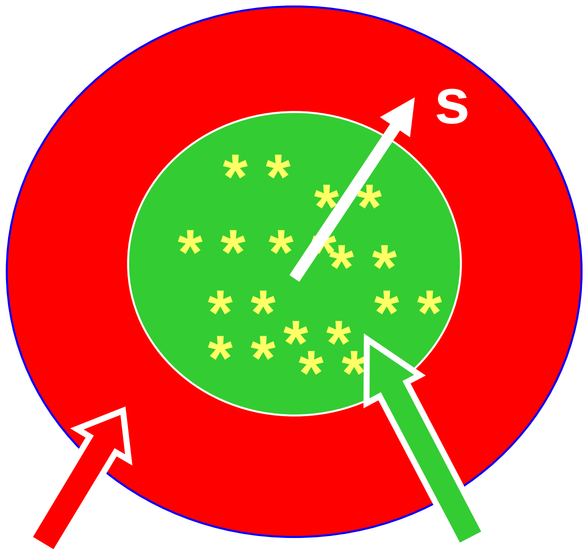
$$\rho_{clump,rad}(s) \propto s^{-1.9} : \frac{m_{CFRg}}{m_{clump}} \propto m_{clump}^{-0.3}$$

Mueller+02: density index p ≈ 1.8



From the Mass Function of Molecular Clumps to that of Embedded Star Clusters

Molecular clump: 2-zone model



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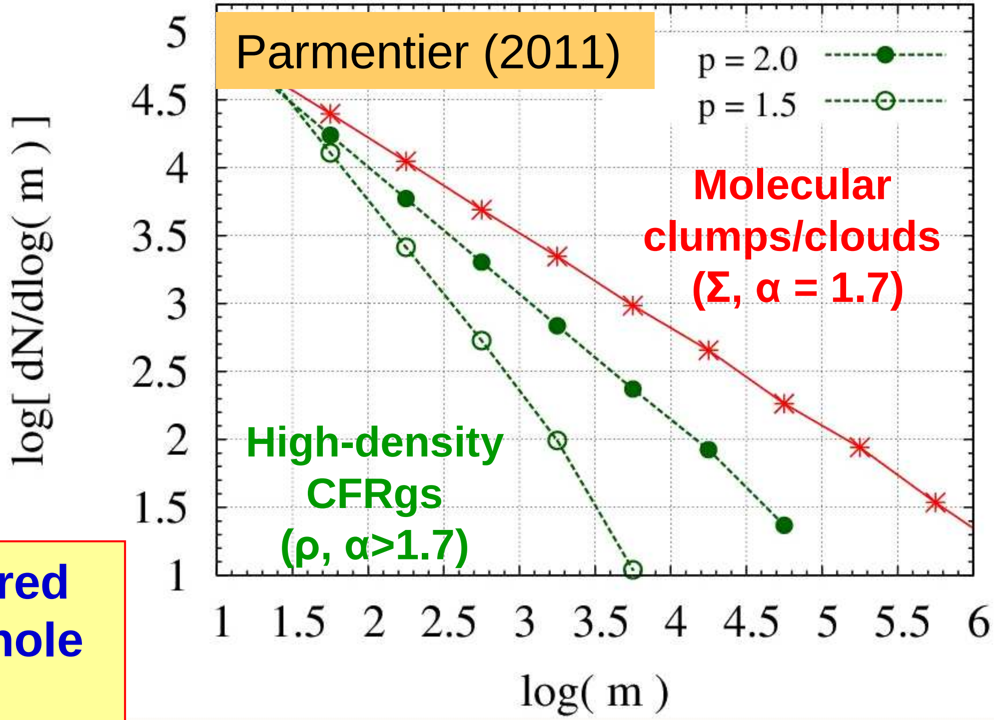


The local SFE must be measured over the CFRg, not over the whole molecular clump

Massive Star Formation (MSF) Limit

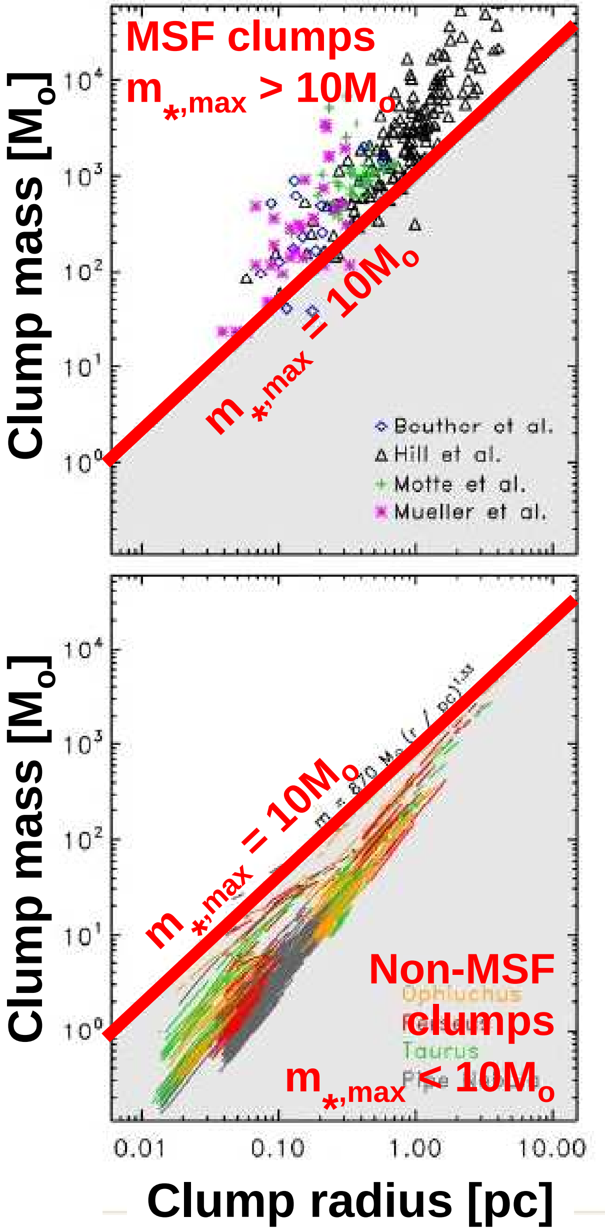


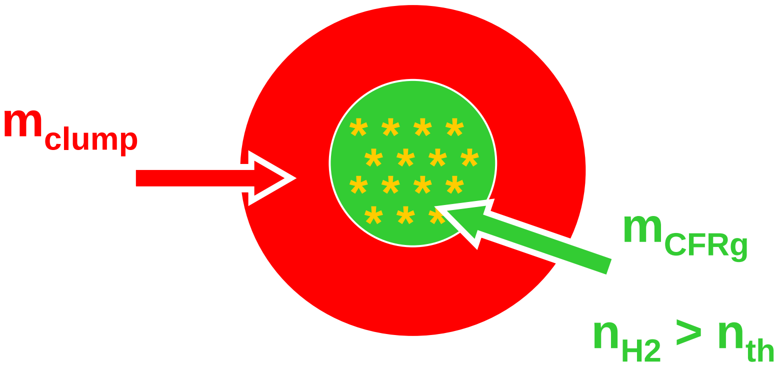
Fig2 and Eq1, Kauffmann & Pillai (2010)

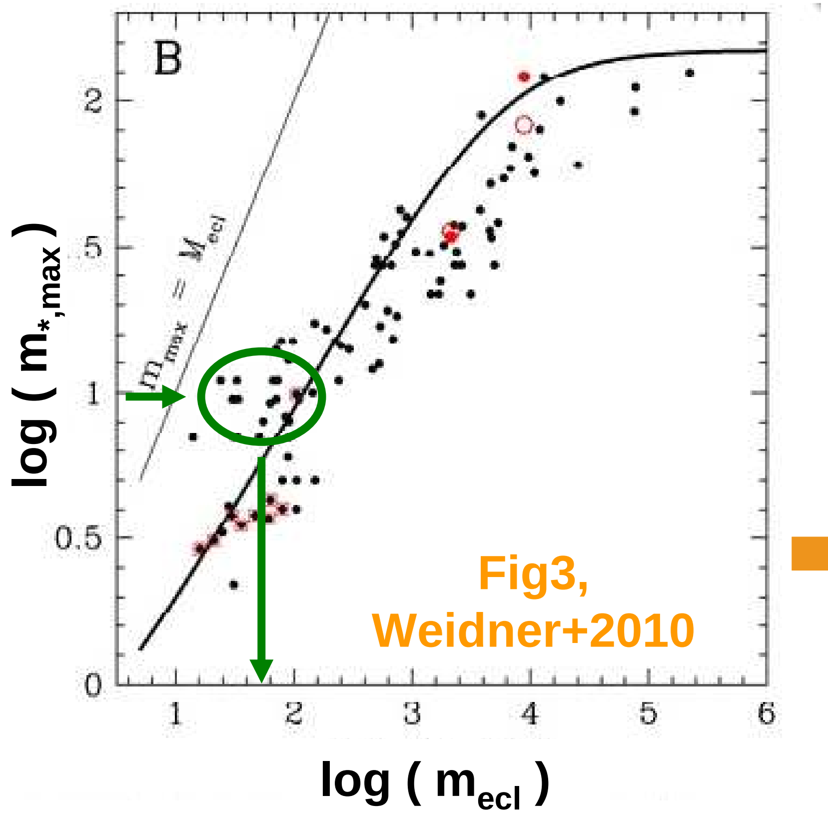
$$m_{clump} = 870 M_0 \left(\frac{r_{clump}}{pc} \right)^{1.33}$$

Tool to define ALMA targets for MSF studies

Intercept and slope?

What do we need to form a $10M_o$ star?





Molecular clump: m_{clump}

$$m_{CFRg}(p, \rho_{th}, m_{clump}, r_{clump})$$

Star-forming gas:
$m_{CFRg} > 150M_o$

SFE = 0.3

Embedded-cluster:
$m_{ecl} > 50M_o$

(m_{ecl}, $m_{*,max}$) relation

Most-massive star:
$m_{*,max} > 10M_o$

What do we need to form a $10M_o$ star?

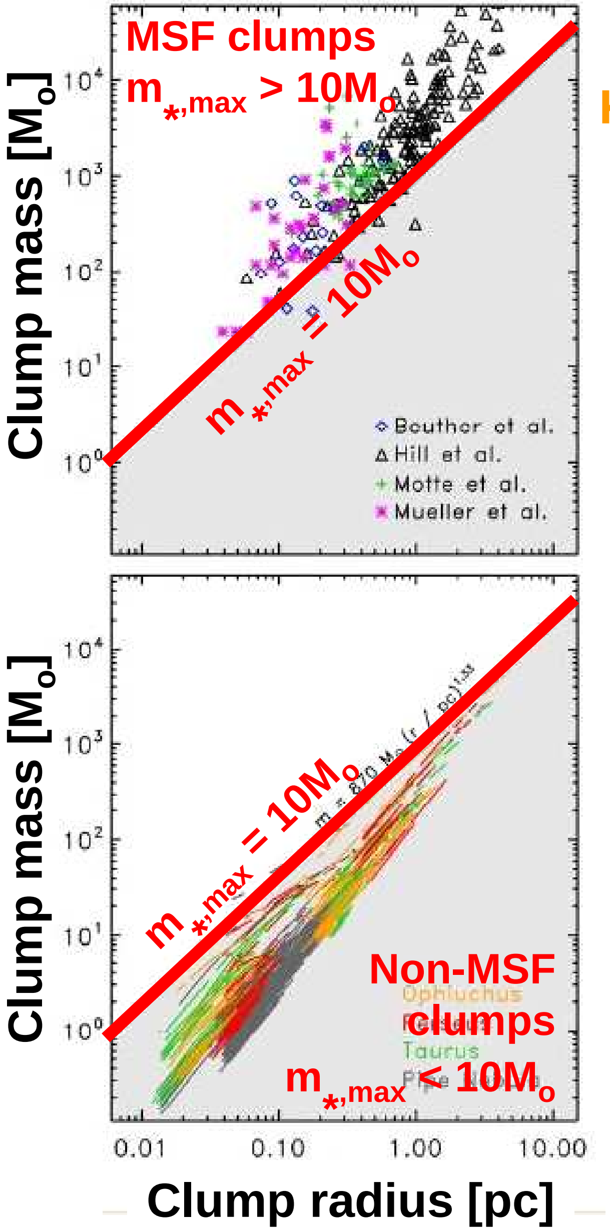


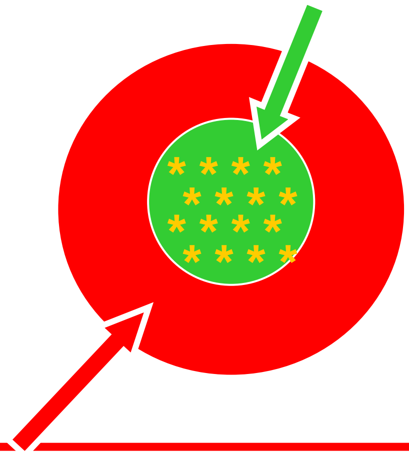
Fig2, Kauffmann & Pillai (2010)

Volume density threshold for overall star formation:

$n_{H2} > n_{th}$

$$m_* = 10M_o : \; m_{CFRg} = \frac{m_{ecl}}{SFE} \cong 150M_o$$

$$< n_{CFRg} >= few \times n_{th}$$



$$m_{clump} = 870M_0 \left(\frac{r_{clump}}{pc} \right)^{1.33}$$

Iso-m_{CFRg} in the clump mass-size space

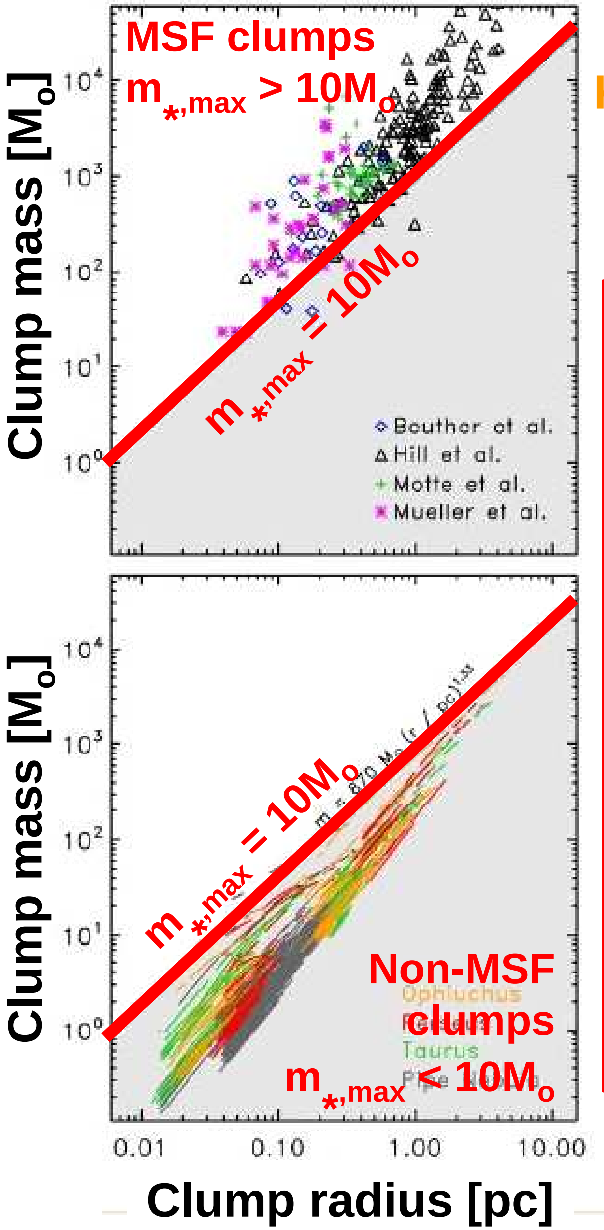
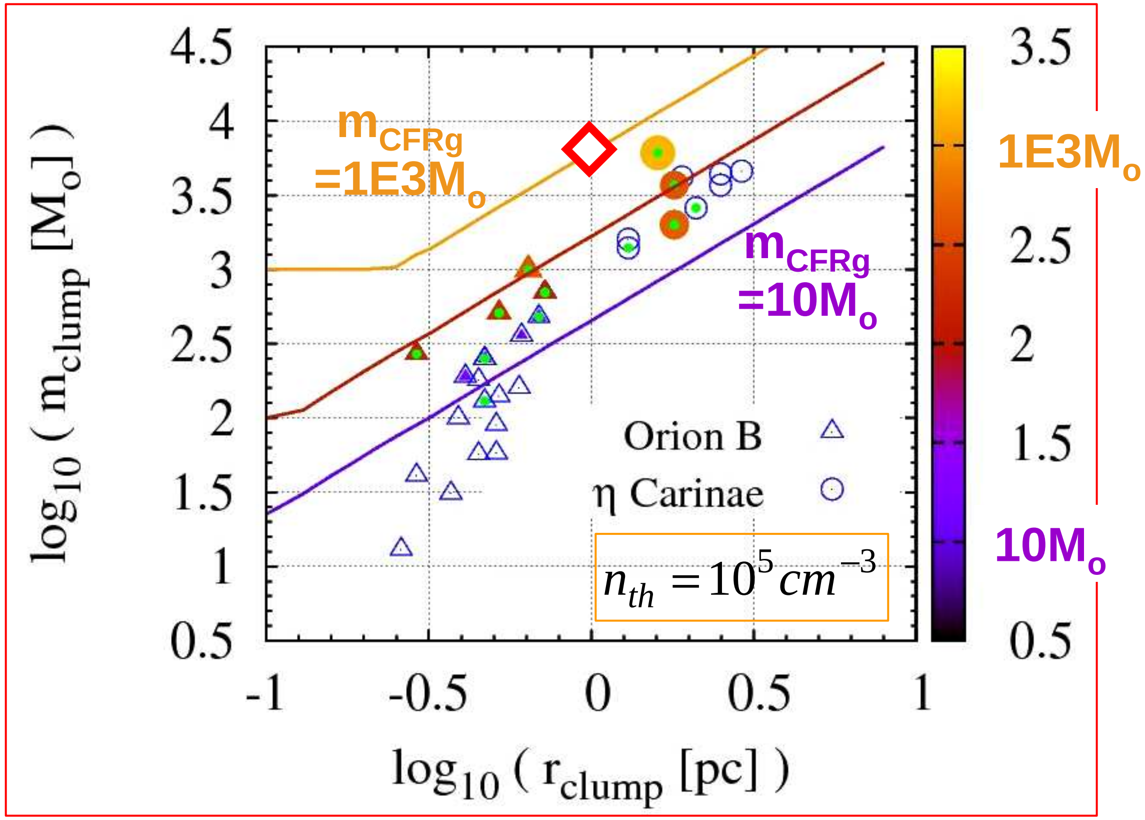


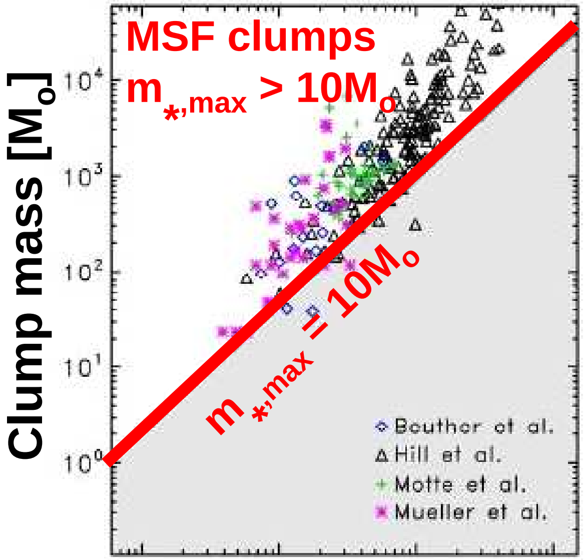
Fig2, Kauffmann & Pillai (2010)

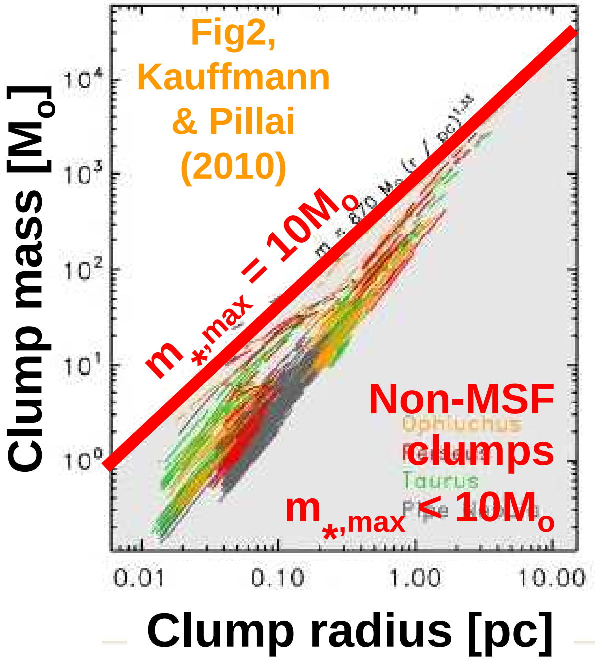
$$m_{clump} = \left(m_{CFRg}\right)^{p/3} \left(\frac{4\pi\rho_{th}}{3-p}\right)^{(3-p)/3} r_{clump}^{3-p}$$

Parmentier (2011), Eq.3



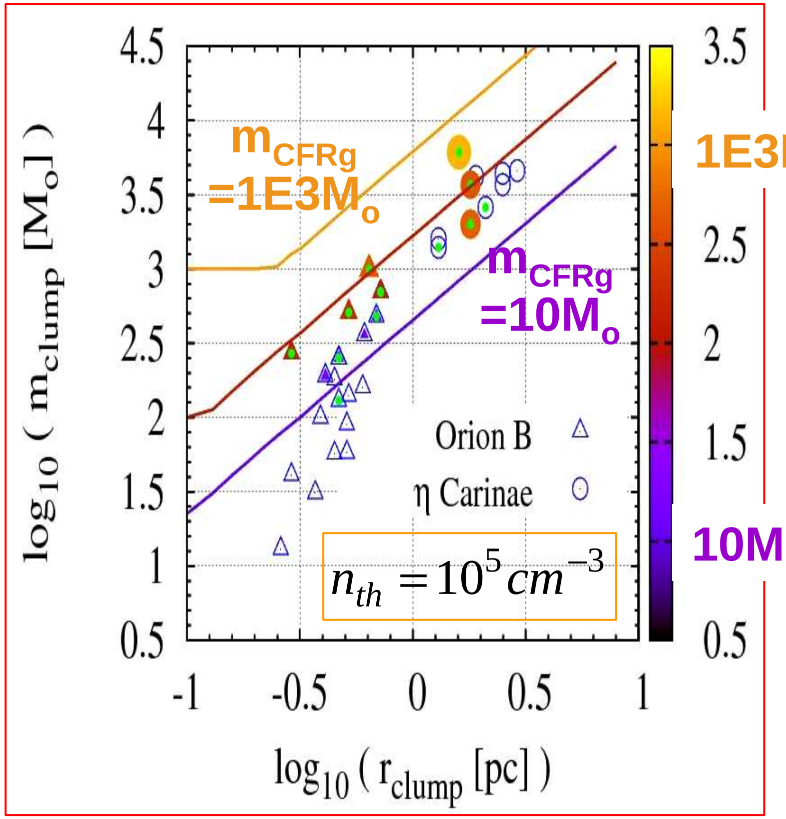
Iso-m_{CFRg} in the clump mass-size space



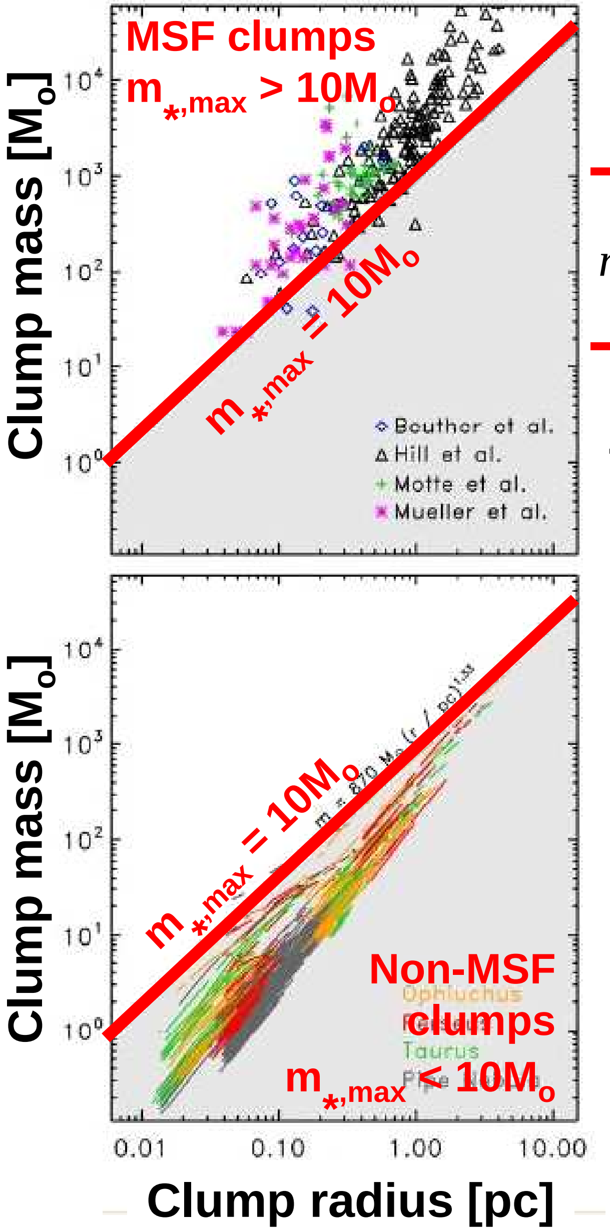


$$m_{clump} = 870 M_0 \left(\frac{r_{clump}}{pc} \right)^{1.33}$$

$$= m_{CFRg}^{p/3} \left(\frac{4\pi\rho_{th}}{3-p} \right)^{(3-p)/3} r_{clump}^{3-p}$$



Matching Observed MSF Limit & Iso-m_{CFRG} Model



Matching the slopes:

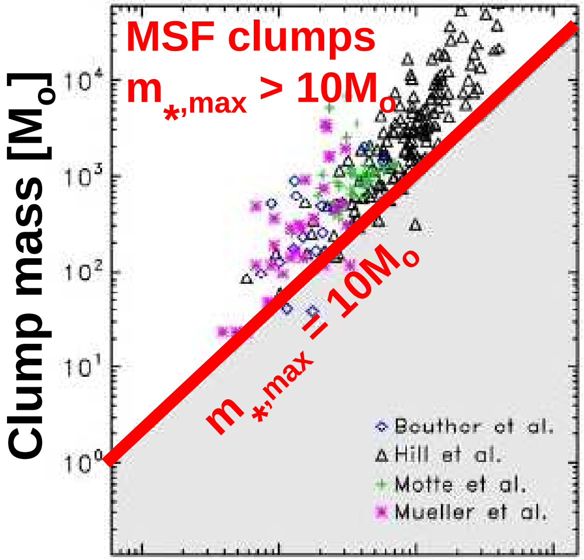
$$m_{clump} = 870 M_0 \left(\frac{r_{clump}}{pc}\right)^{1.33} = m_{CFRg}^{p/3} \left(\frac{4\pi\rho_{th}}{3-p}\right)^{(3-p)/3} r_{clump}^{3-p}$$

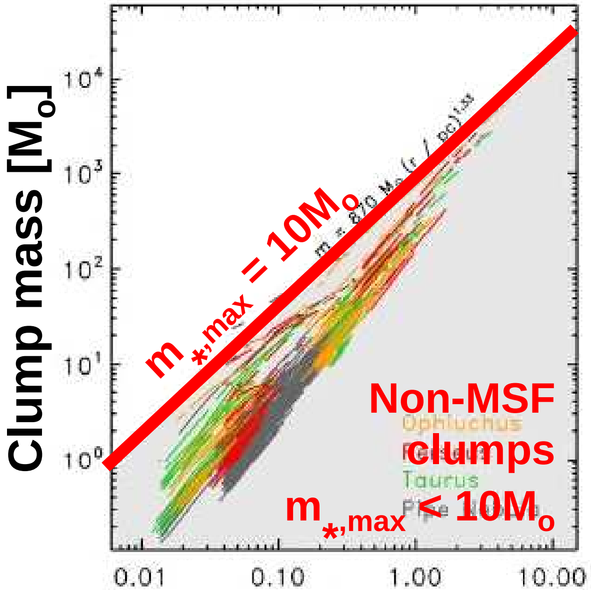
MSF limit: p=1.7 (Parmentier+ 2011)

GMC/SC MFs: p=1.9 (Parmentier 2011)

Dust Cont. mapping: p=1.8 (Mueller+ 2002)

Matching Observed MSF Limit & Iso-m_{CFRG} Model





Matching the slopes:

$$m_{clump} = 870 M_0 \left(\frac{r_{clump}}{pc}\right)^{1.33} = m_{CFRg}^{p/3} \left(\frac{4\pi\rho_{th}}{3-p}\right)^{(3-p)/3} r_{clump}^{3-p}$$

MSF limit: p=1.7 (Parmentier+ 2011)

GMC/SC MFs: p=1.9 (Parmentier 2011)

Dust Cont. mapping: p=1.8 (Mueller+ 2002)

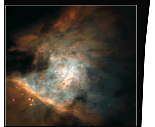
Matching the intercepts:

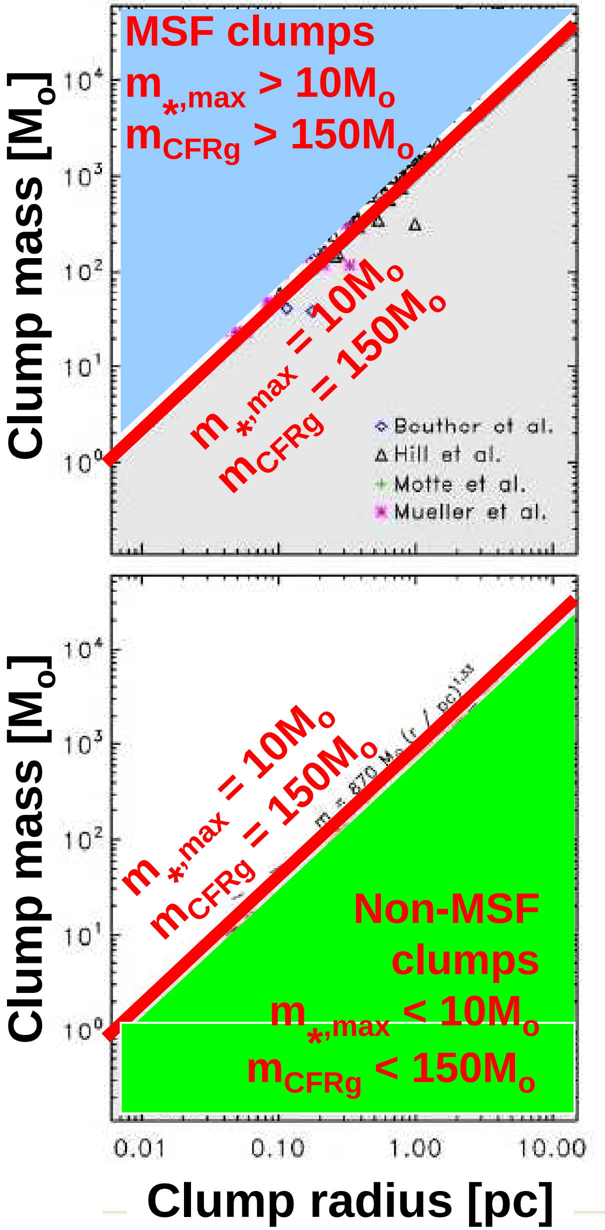
$$m_{clump} = 870 M_0 \left(\frac{r_{clump}}{pc}\right)^{1.33} = m_{CFRg}^{p/3} \left(\frac{4\pi\rho_{th}}{3-p}\right)^{(3-p)/3} r_{clump}^{3-p}$$

- **Parmentier+ (2011), m_{CFRg} = 150M_o:**
- **Lada, Lombardi & Alves (2010):**

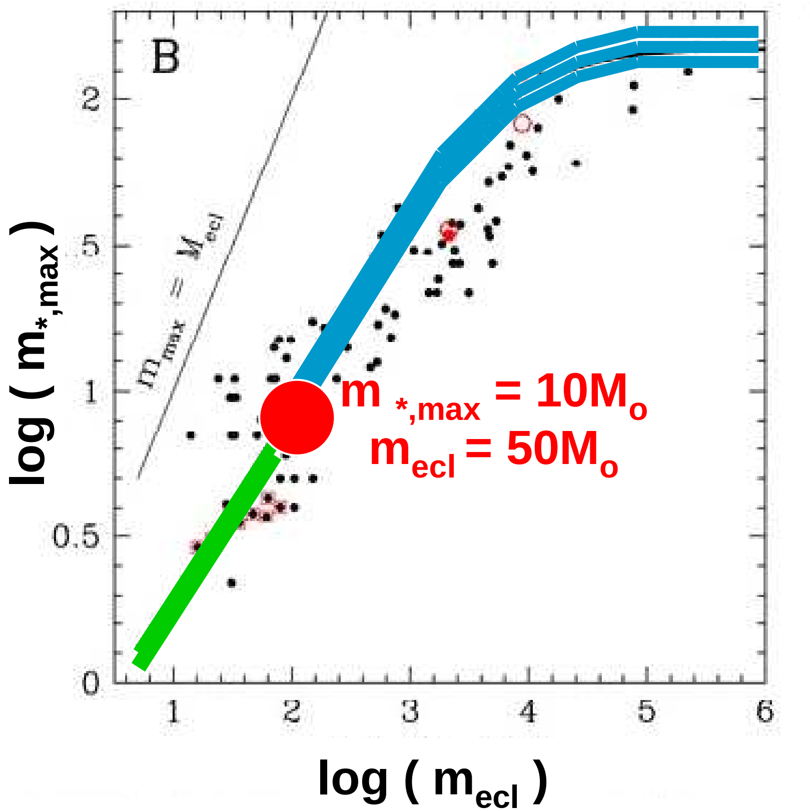
$n_{th,H2}$ = 10^4 cm^{-3}

MSF Limit: Quick overview

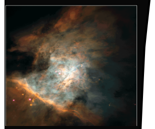


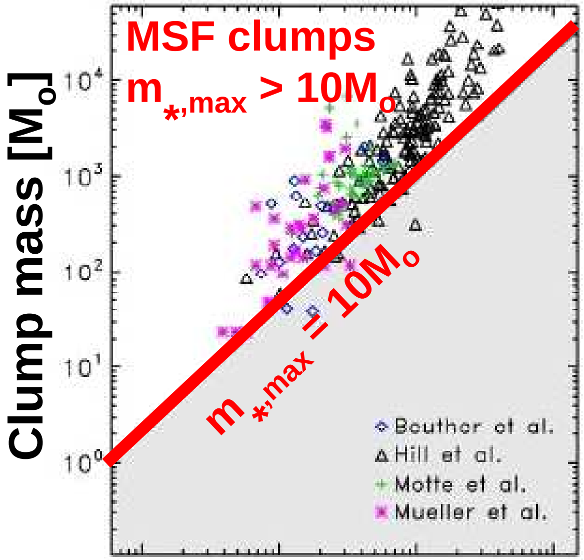



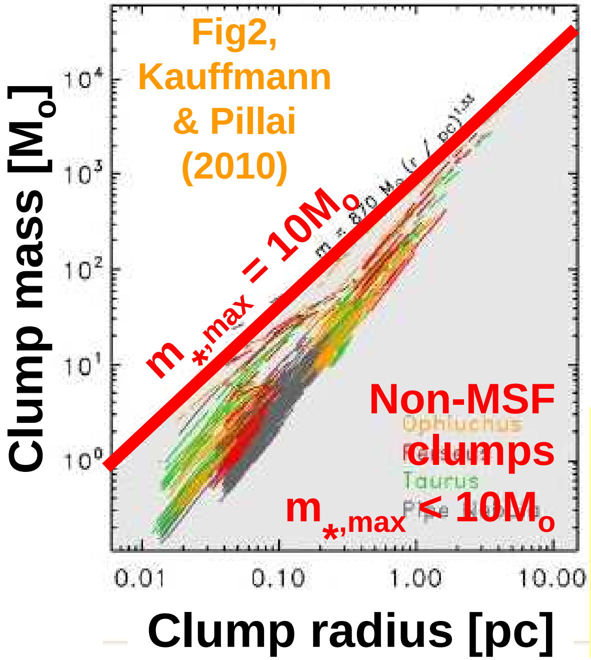
The observational MSF limit is consistent with a threshold in SF gas mass beyond which the SF gas reservoir is large enough to allow the formation of massive stars.

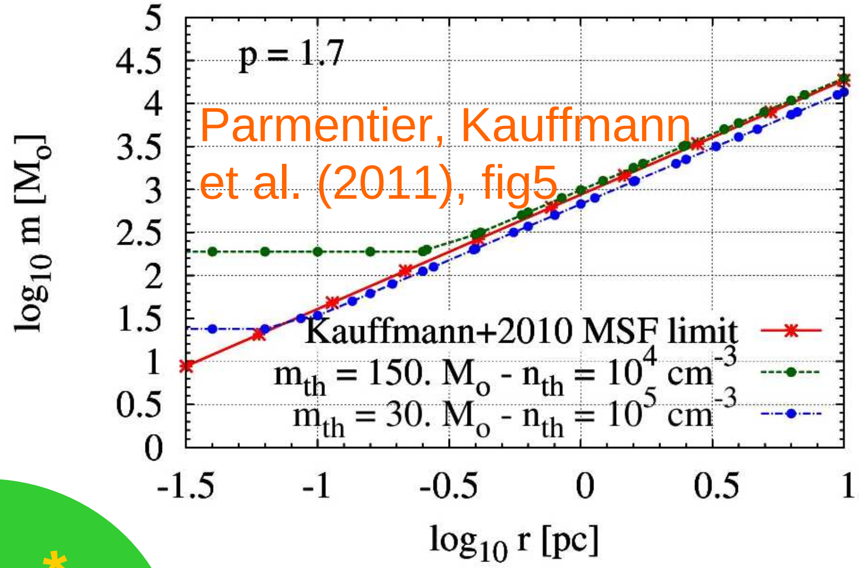


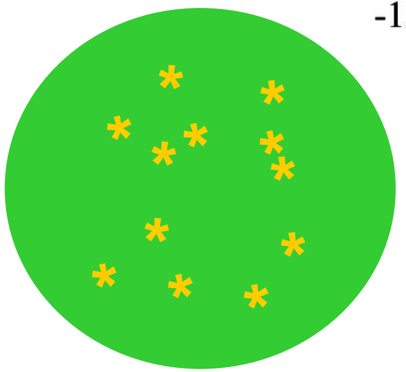
MSF Limit on Smaller Spatial Scales

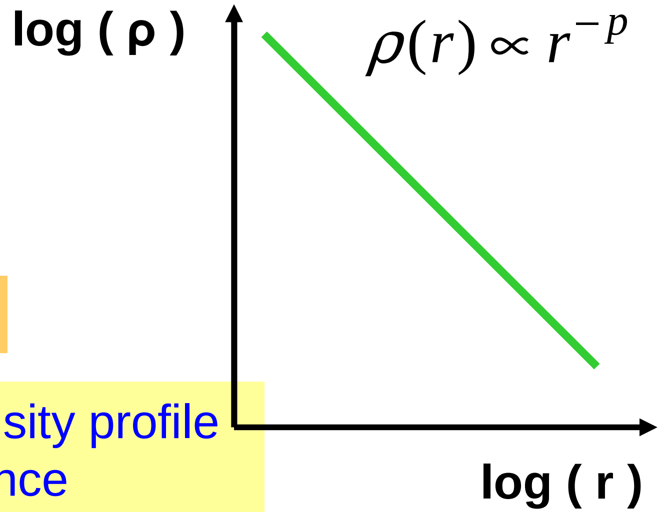












Elmegreen (2011):

Mean power-law density profile
+ supersonic turbulence
→ Density peaks 10^5 cm^{-3}
≡ pre-stellar cores:

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

An exciting era has just started:
HERSCHEL, ALMA, …