Vienna Institute of Astronomy - 16 May 2011

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

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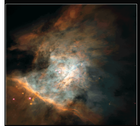
Image Credit

- **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

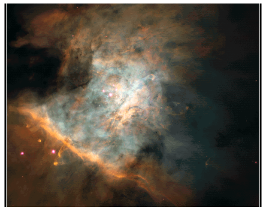
Star Clusters: at the crossroad between star formation and galaxy evolution

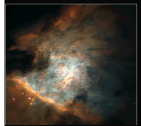



a few kpc - 100kpc:
systems of
star clusters
and galaxies

10pc:
individual
gas-free
star clusters

1-pc:
star formation
in embedded
star clusters



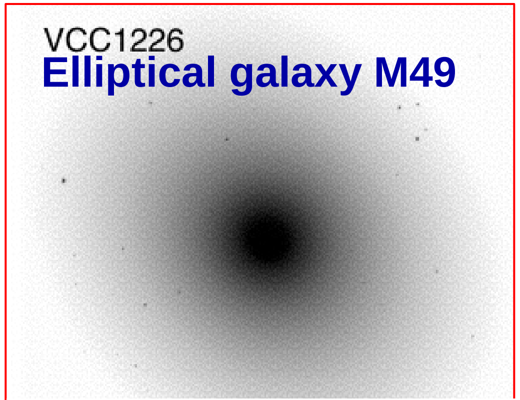


Setting the Scene: Star Clusters (SC) as Powerful Tracers of Galaxy Evolution

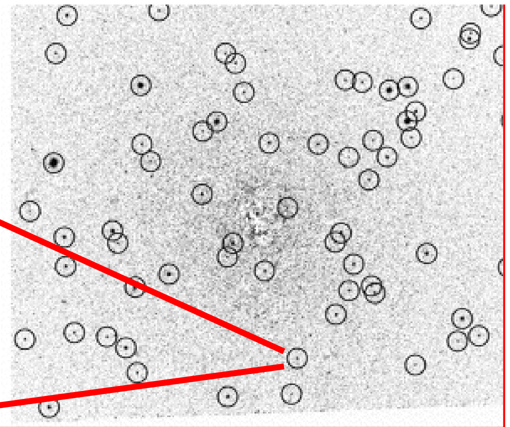
Star Clusters (SC):

- **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)



Background-subtracted image



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**

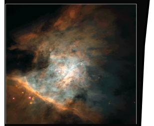
Comprehensive view of galaxy-:

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

over the past Hubble-Time

Star clusters are at the very heart of many astrophysical topics

The Big Issue: SCs versus field stars



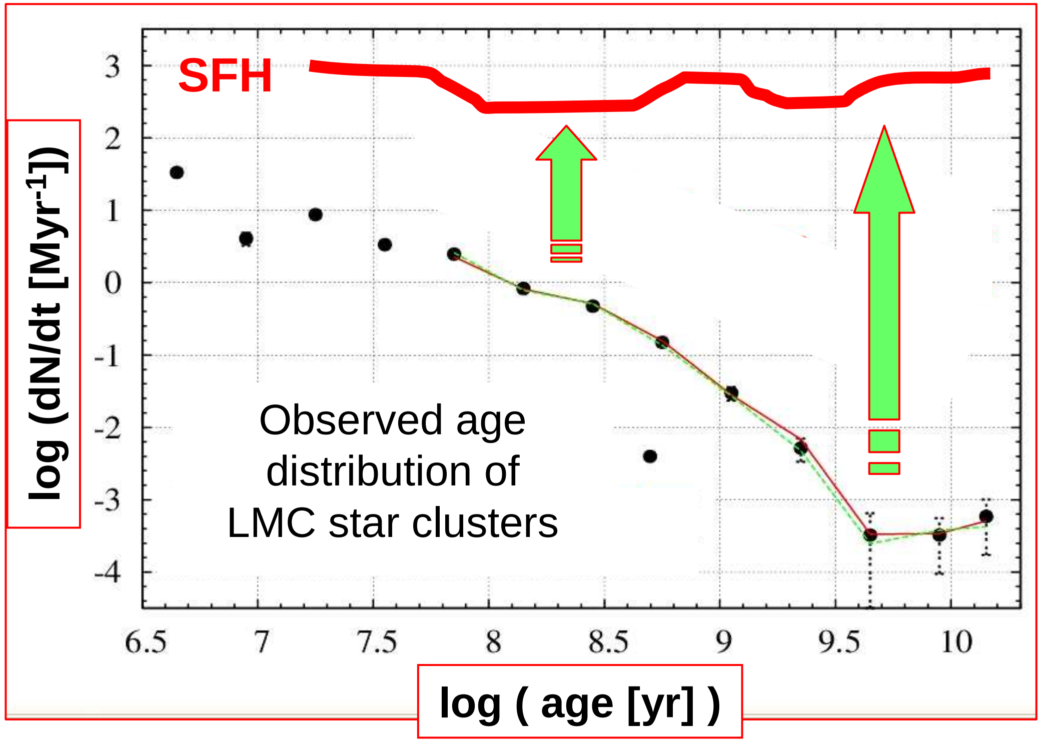
Most stars in our Galaxy:

- **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**

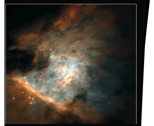
provided we get a firm handle on the ratio of star formation still residing in (observed) star clusters as a function of age

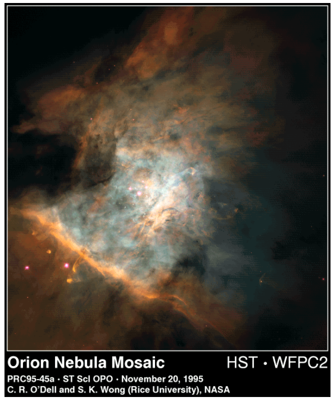


Violent relaxation = Most traumatizing phase

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

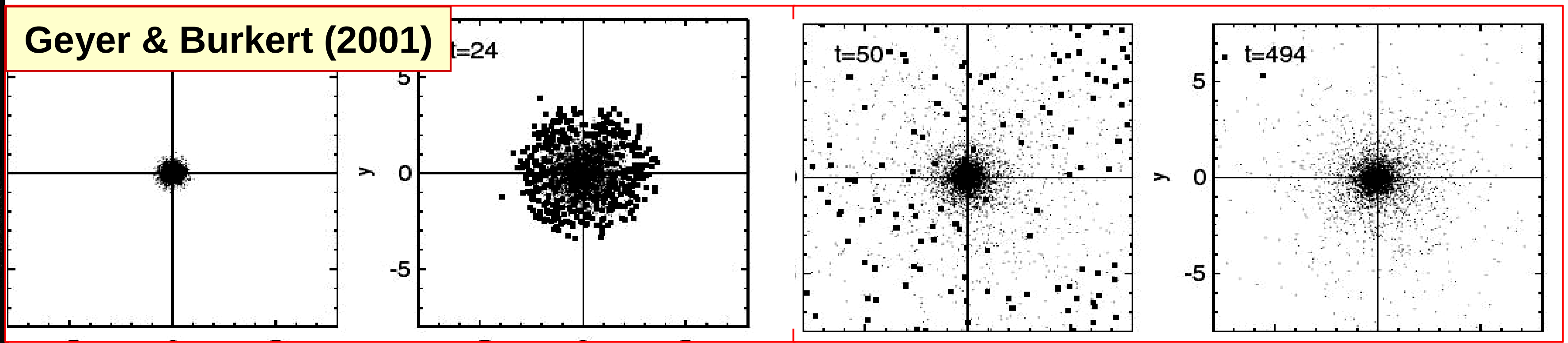
Intra-Cluster Gas-Expulsion and Violent Relaxation



time

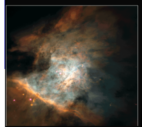
Geyer & Burkert (2001)



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,

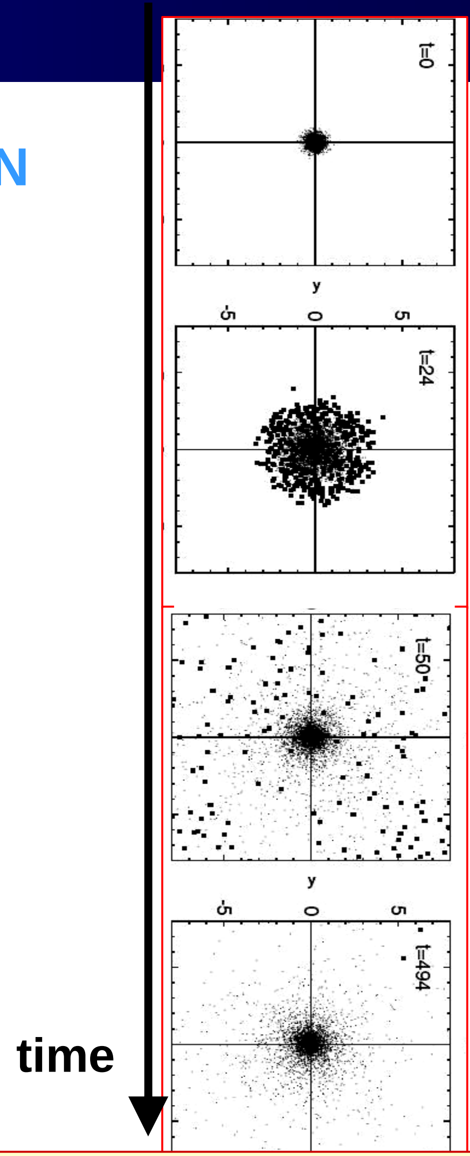
Prime parameters: (e.g. Baumgardt & Kroupa 2007)

- SFE in cluster-forming region (CFRg)

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

- Impact of external tidal field (environment)

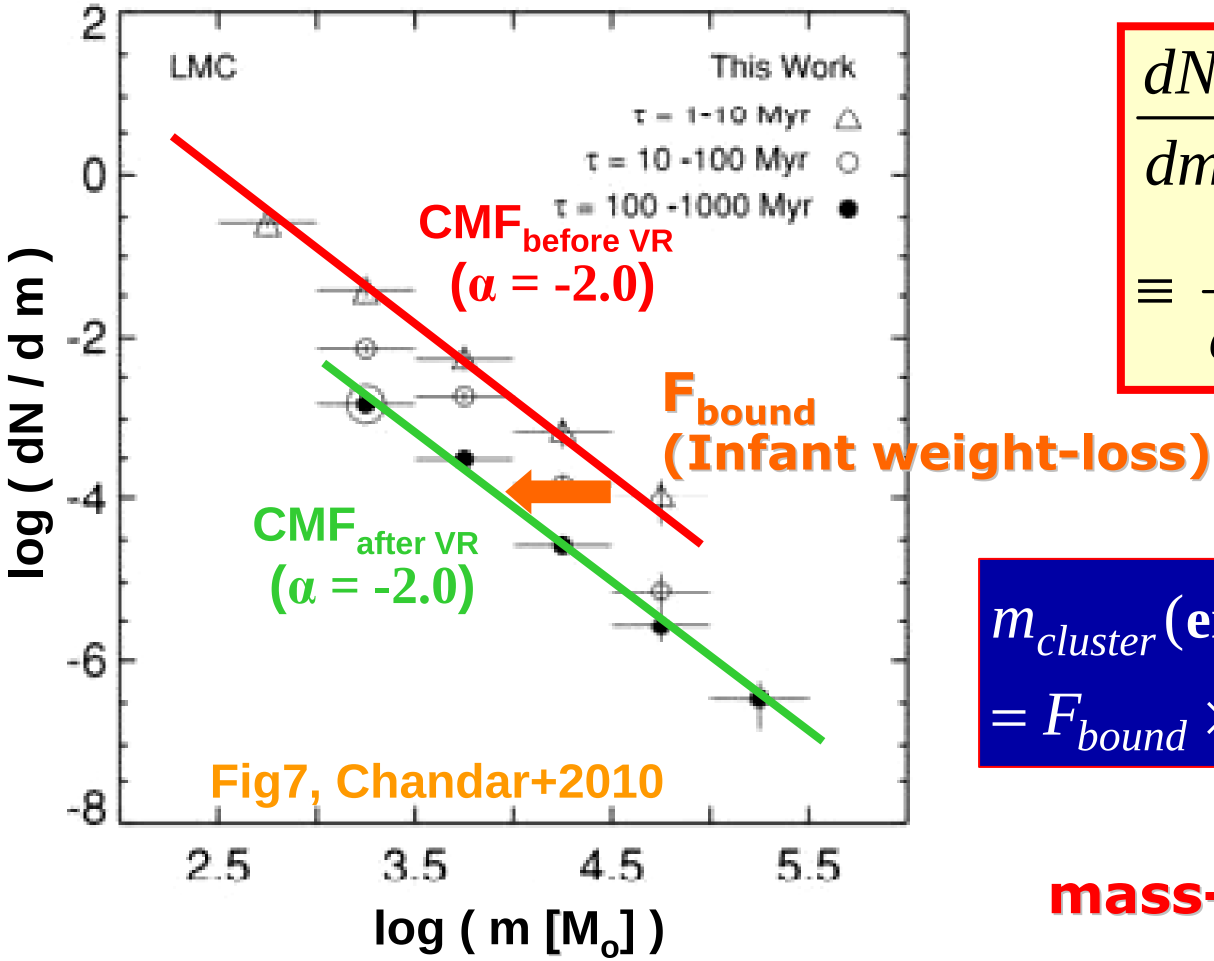
See also Adams (2000), Vesperini et al (2009), …



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



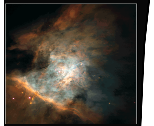
$$\frac{dN}{dm} \propto m^{-2} \equiv \frac{dN}{d\log m} \propto m^{-1}$$

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

F_{bound} is mass-independent

Note: what happens after 100Myr remains disputed …

SFE and SC Mass Functions

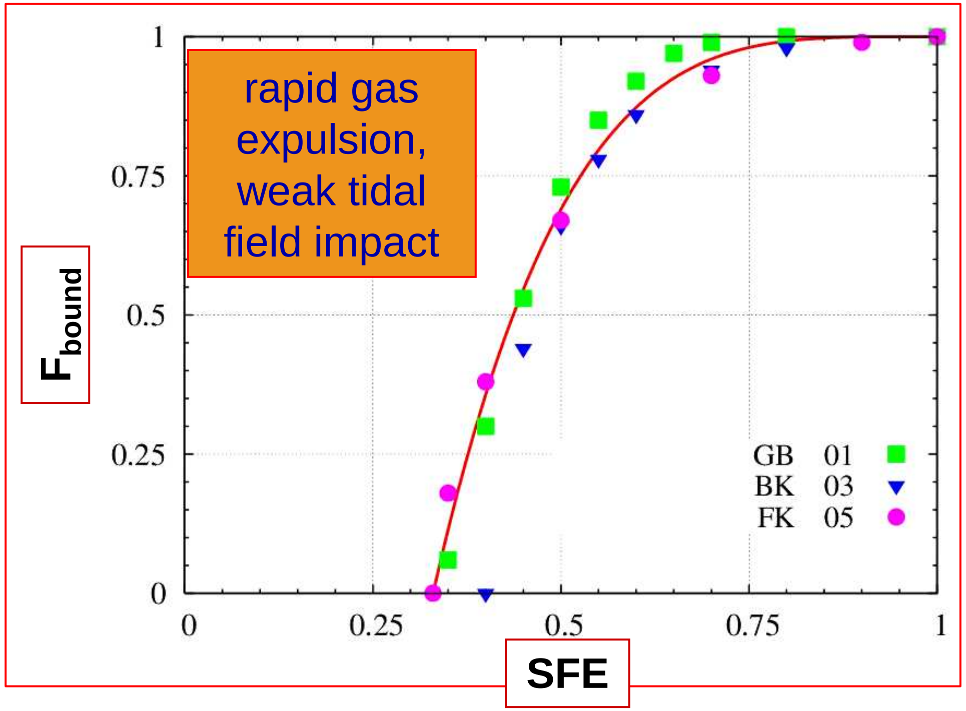



$$m_{cluster}(\text{end of VR}) = F_{bound}(SFE) \times SFE \times m_{CFRg}$$

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

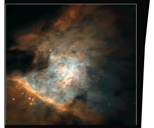
SFE
= fraction of gas ending up in stars

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



F_{bound} is mass-independent
→ SFE is mass-independent

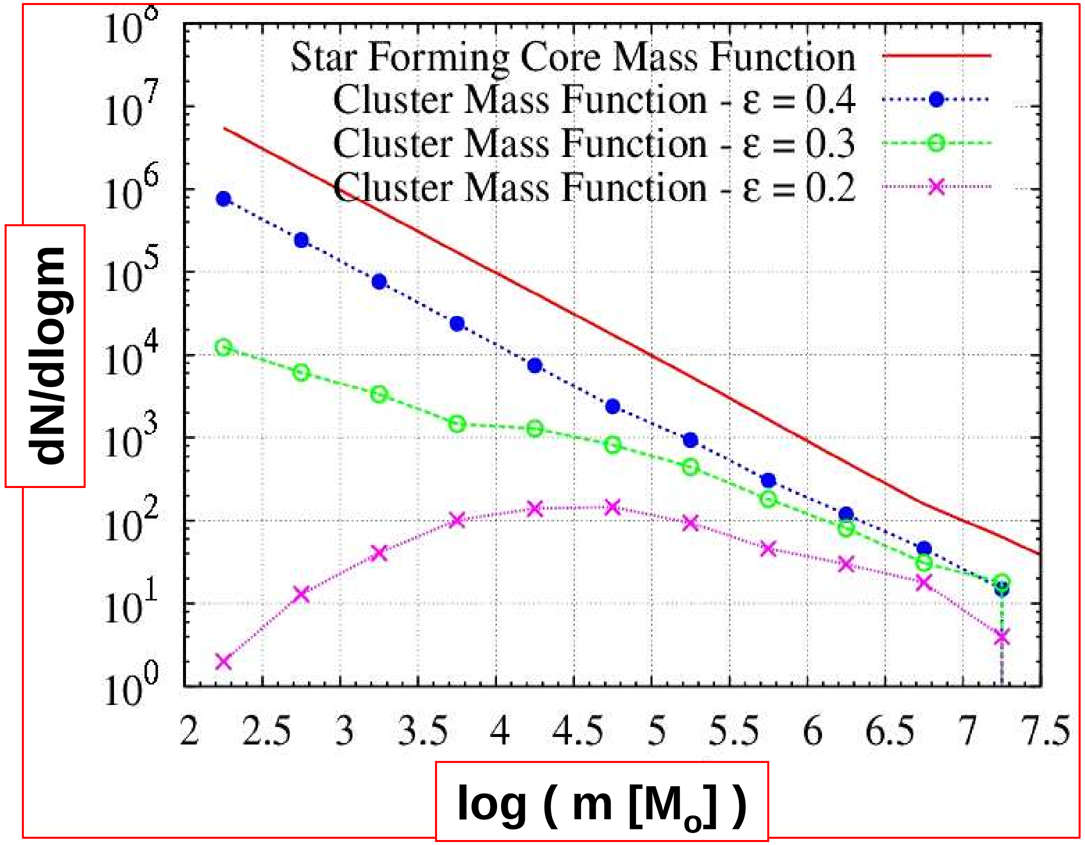
τ_{GExp}/τ_{cross} and SC Mass Functions




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

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

Constant radius:
more massive 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

Tidal Field Impact

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

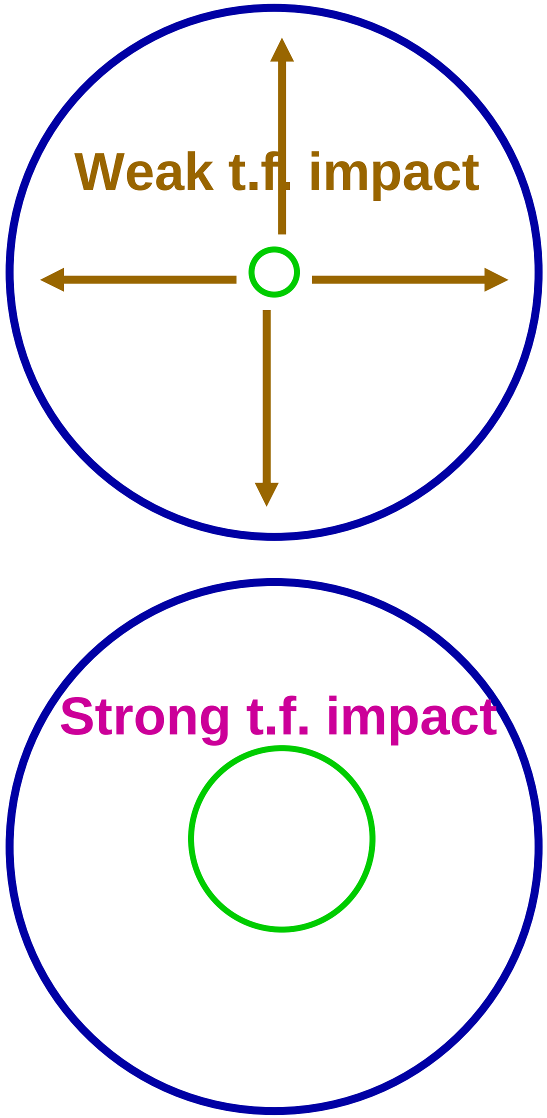
Half-mass radius $r_{half\text{-}mass} \approx r_{CFRg}$

Limiting tidal radius :

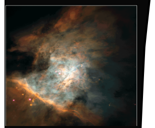
$$r_{tidal} = \left(m_{ecl}\right)^{1/3}\left(\frac{G\,D_{gal}^2}{2V_c^2}\right)^{1/3} \propto \left(SFE.m_{CFRg}\right)^{1/3}$$

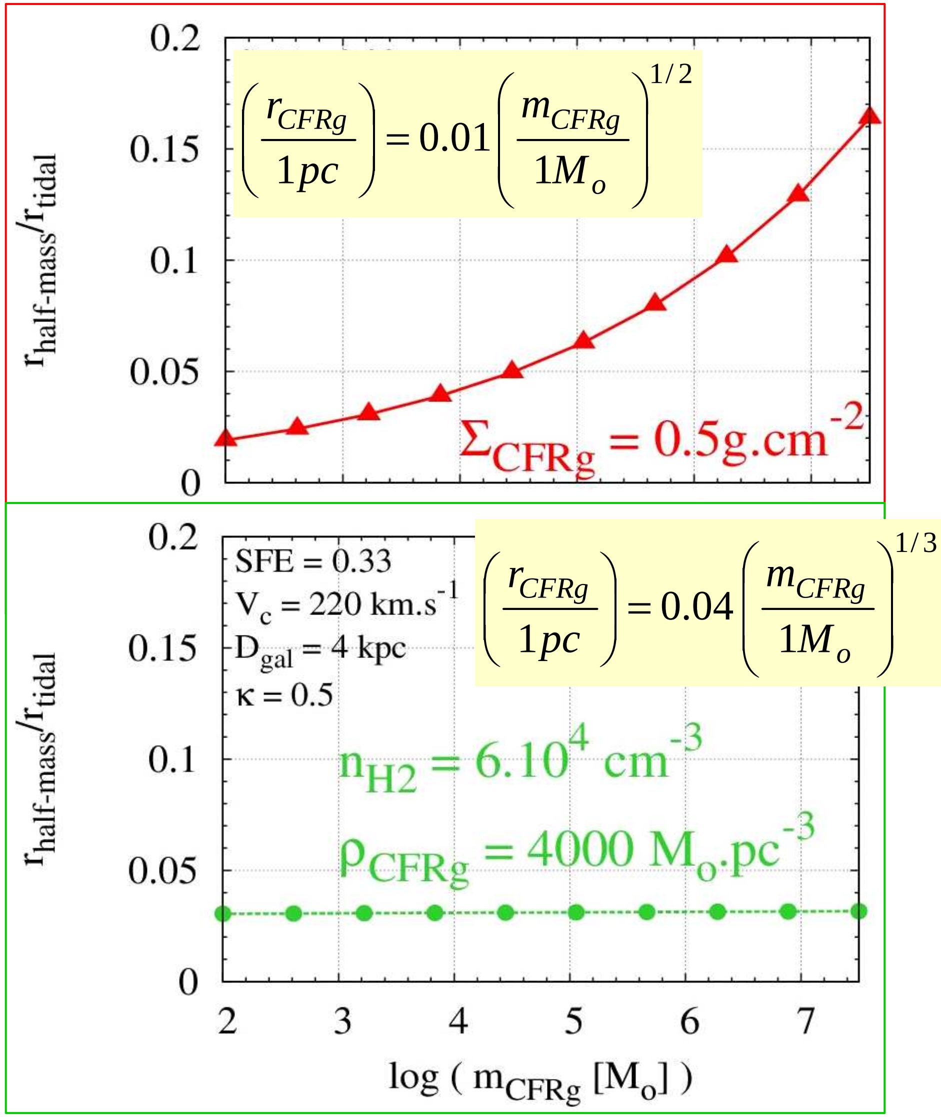
Embedded cluster mass

SC environment



Half-Mass Radius—to—Tidal Radius Ratio



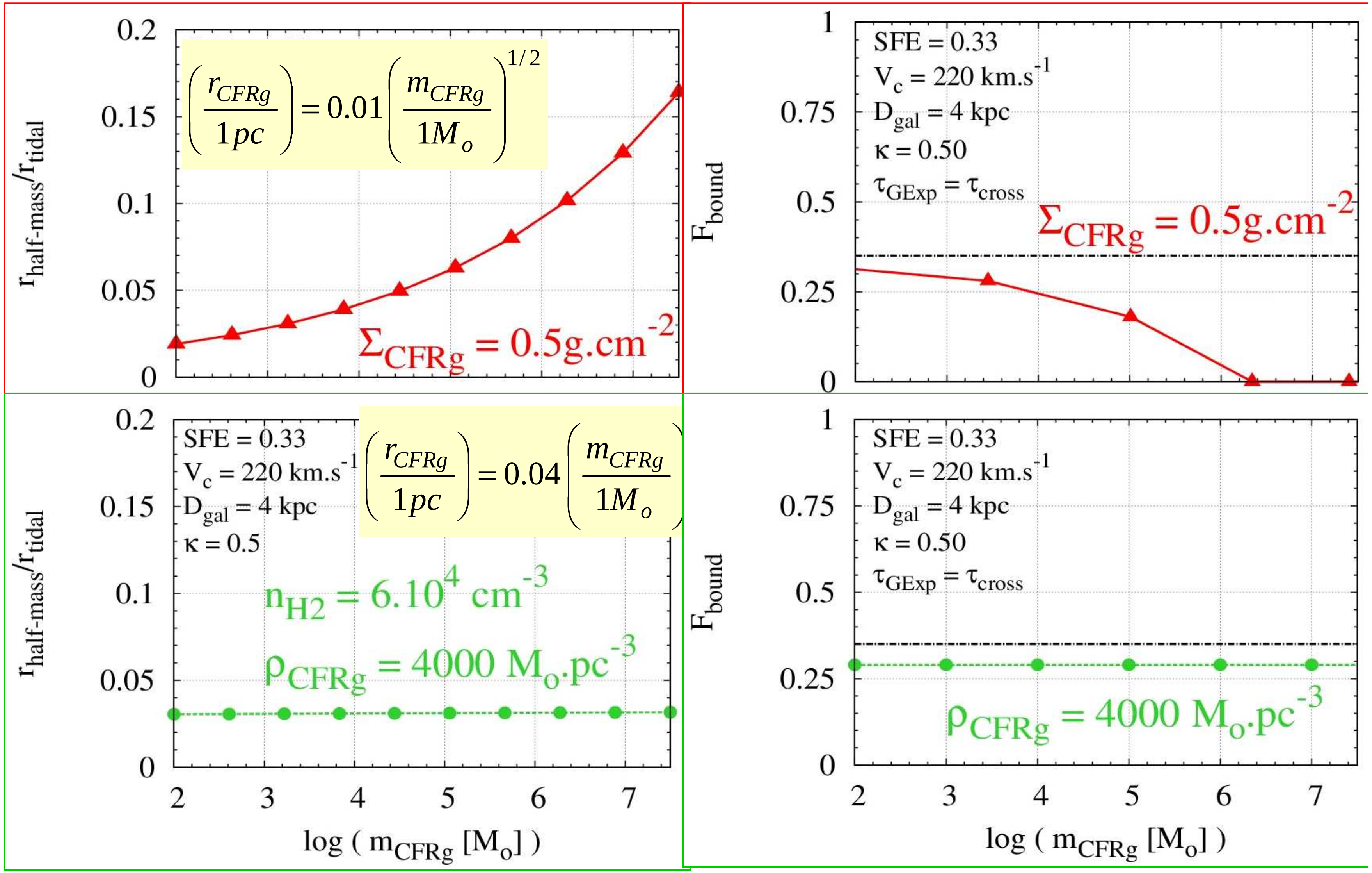



$$r_{CFRg} \propto r_{half-mass} \propto m_{CFRg}^{\delta}$$

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

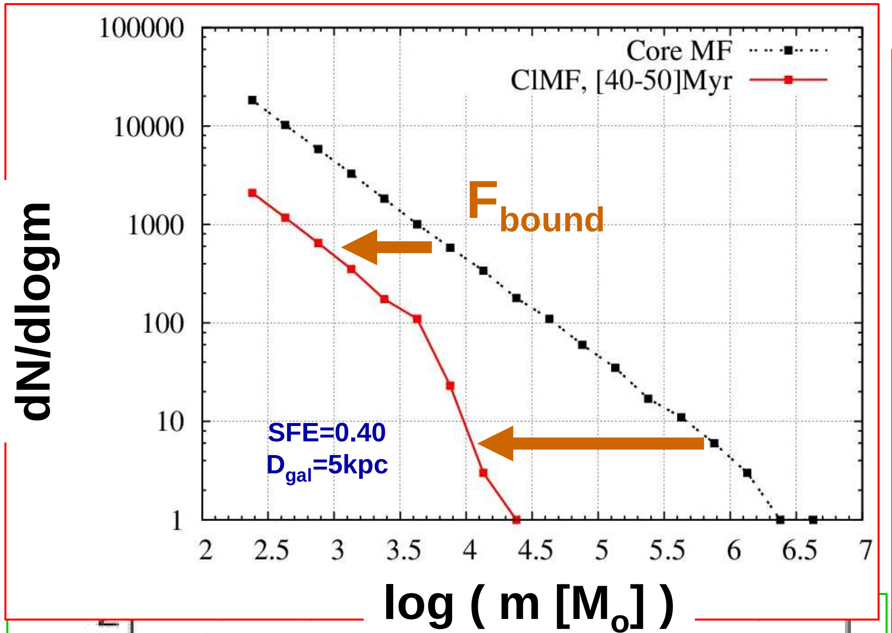
$$\frac{r_{half-mass}}{r_{tidal}} = m_{CFRg}^{\delta-1/3}$$

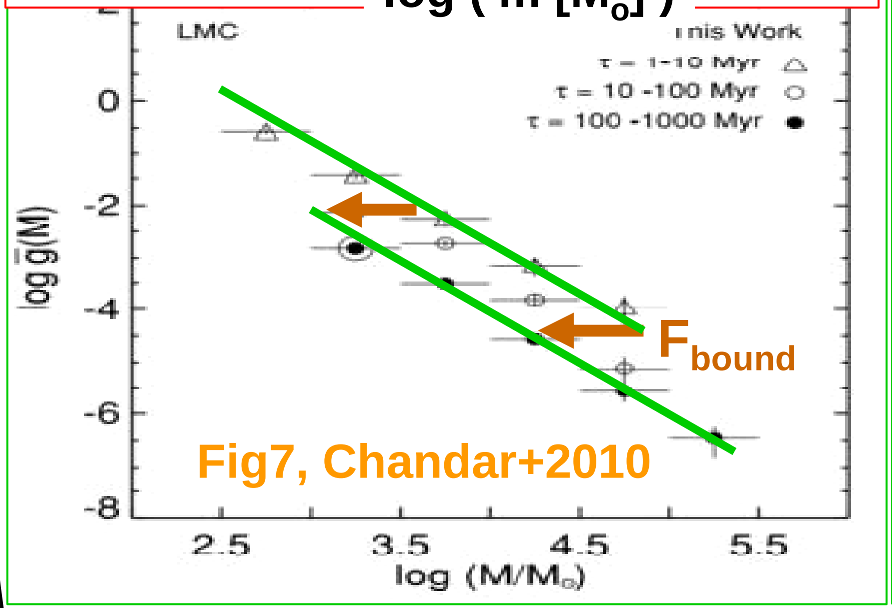
Bound Fractions at the End of Violent Relaxation

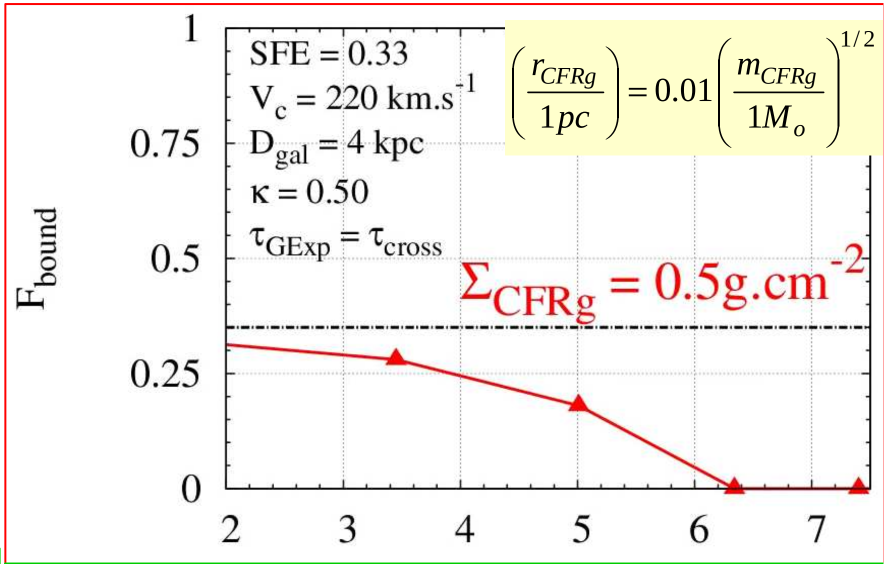


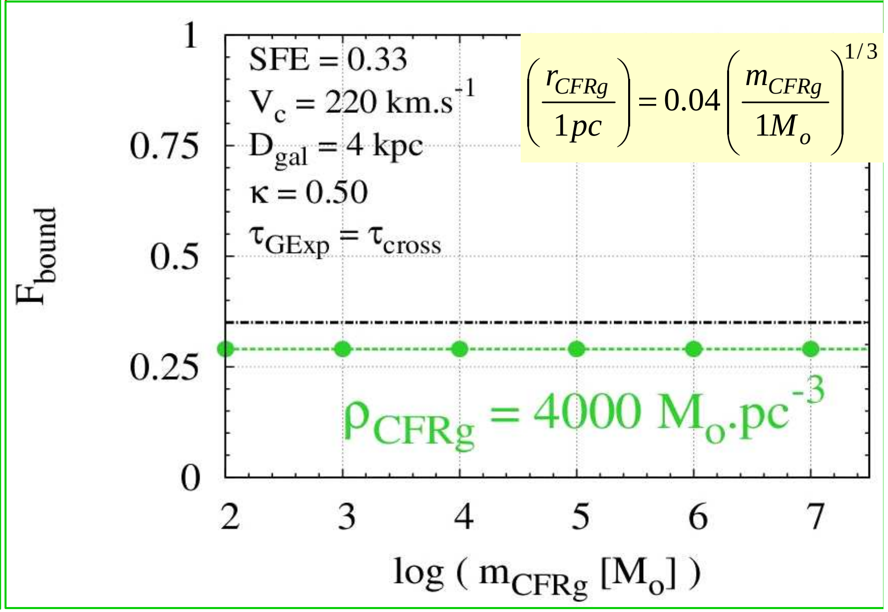
Parmentier & Kroupa (2011)

Young SC Mass Functions

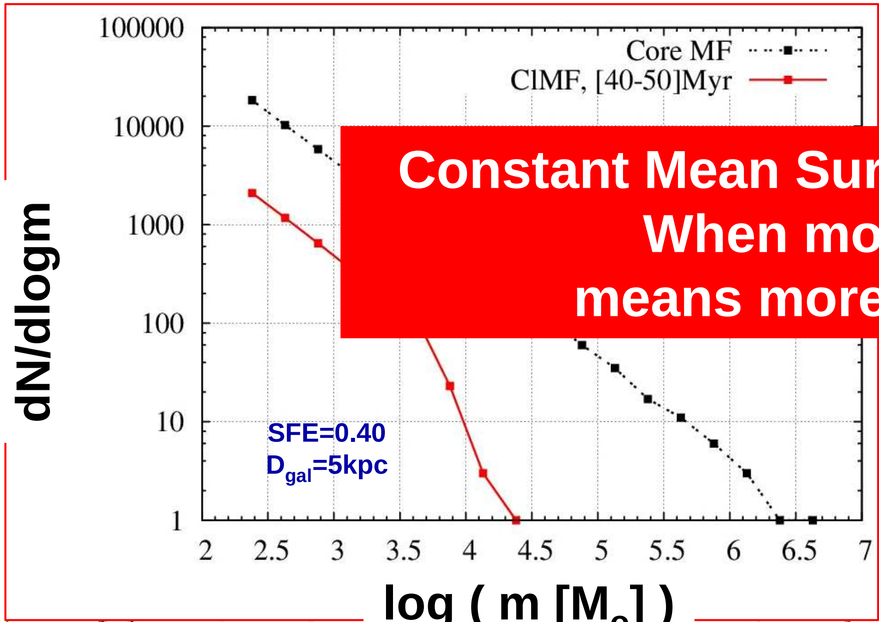


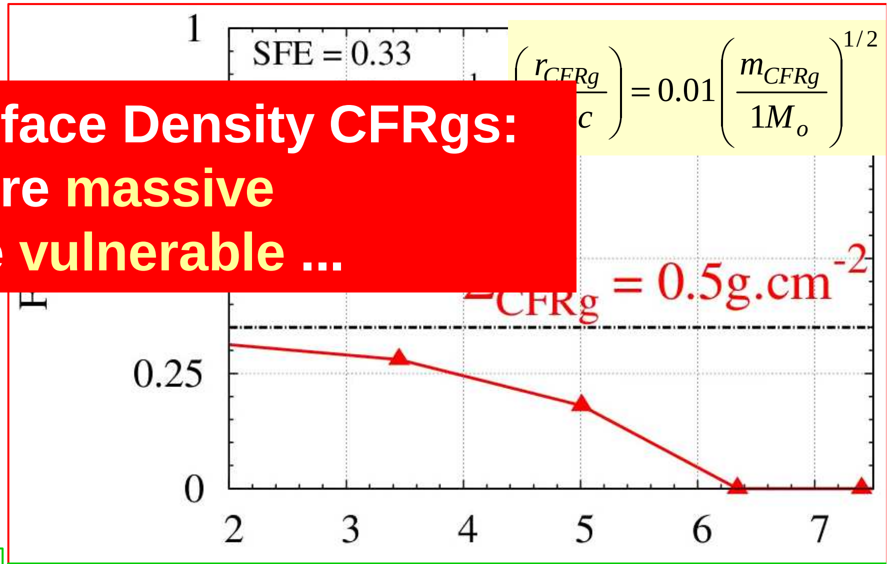




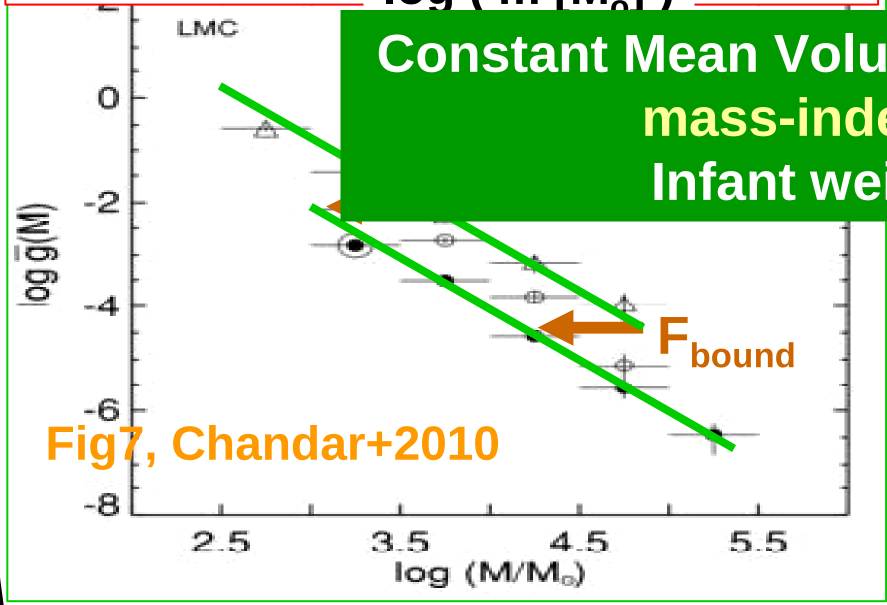


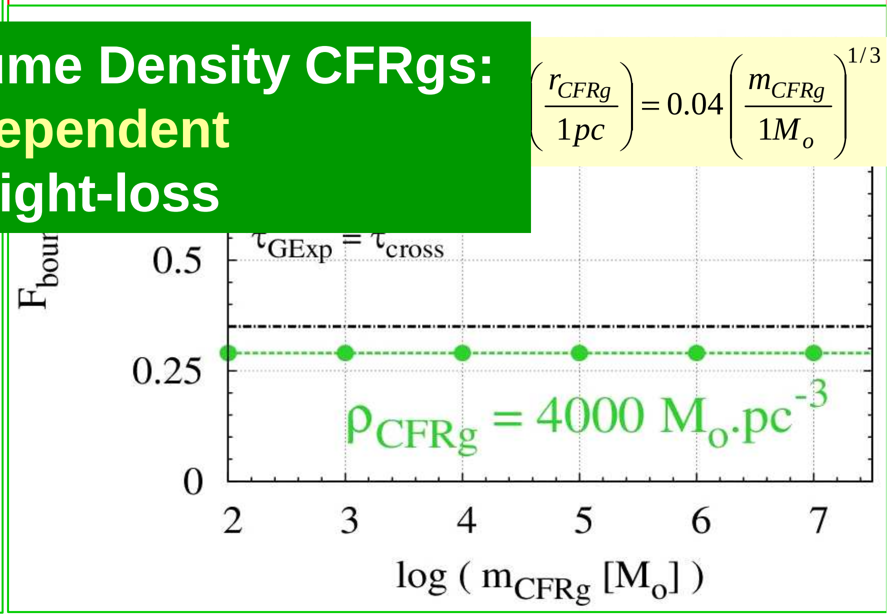
Young SC Mass Functions





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





Constant Mean 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: $n_{H2} > 10^4 cm^{-3}$

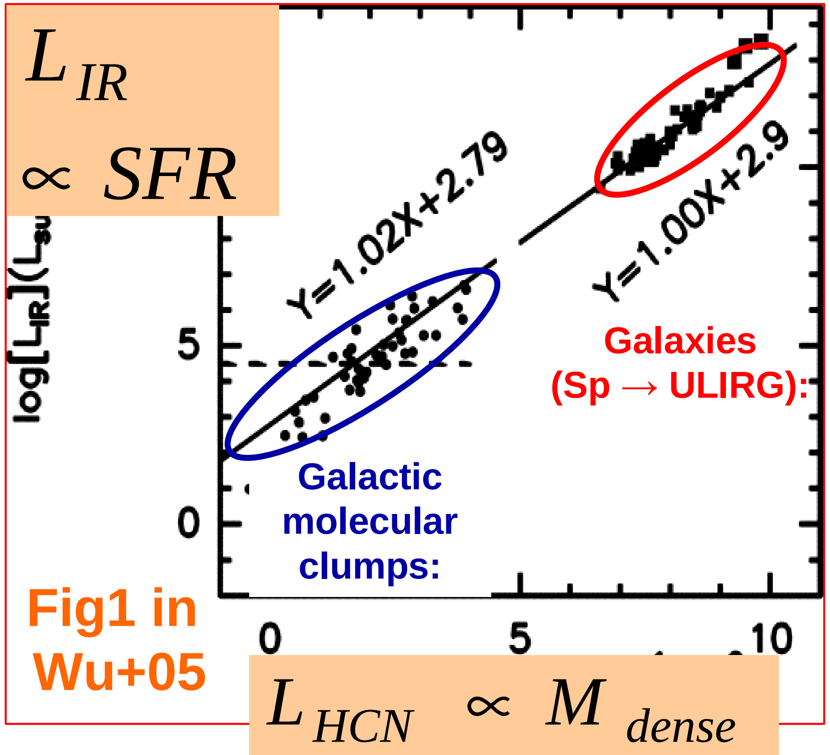


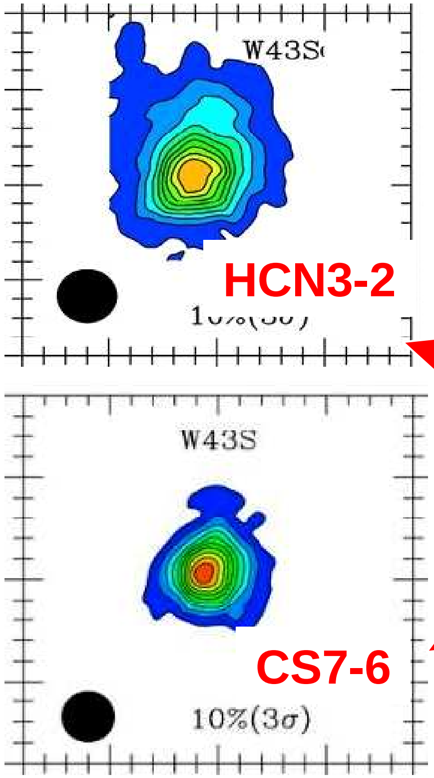
Fig1 in Wu+05

- 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)

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

CFRgs - Molecular Clump Mapping: Do Not Mix !

Figs 9 and 21 Wu+2010



Star-forming region: W43S

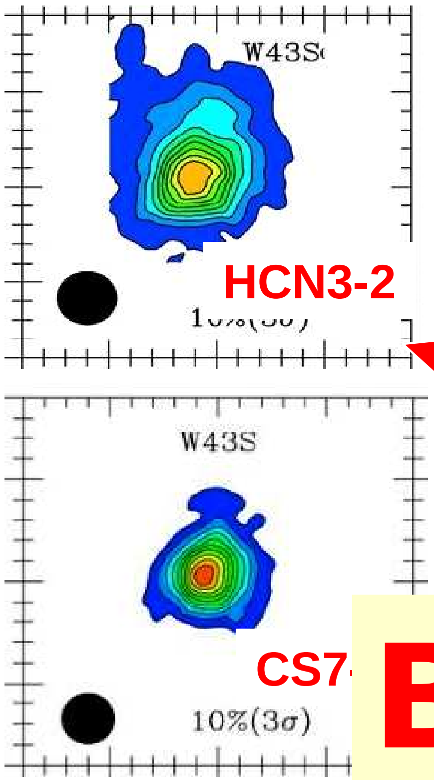
Tracers	FWHM [pc]	log(n [cm^{-3}])
HCN1-0	1.8	3.46
CS2-1	1.4	3.68
HCN3-2	0.6	4.50
CS7-6	0.3	5.21

- **≠ tracers probe ≠ molecular clump regions, with higher densities corresponding to inner, smaller regions.**

- **To identify a mass-radius diagram of molecular clumps as the mass-radius diagram of the star clusters they are forming is not as straightforward as sometimes quoted in the literature**

CFRgs - Molecular Clump Mapping: Do Not Mix !

Figs 9 and 21 Wu+2010



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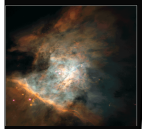
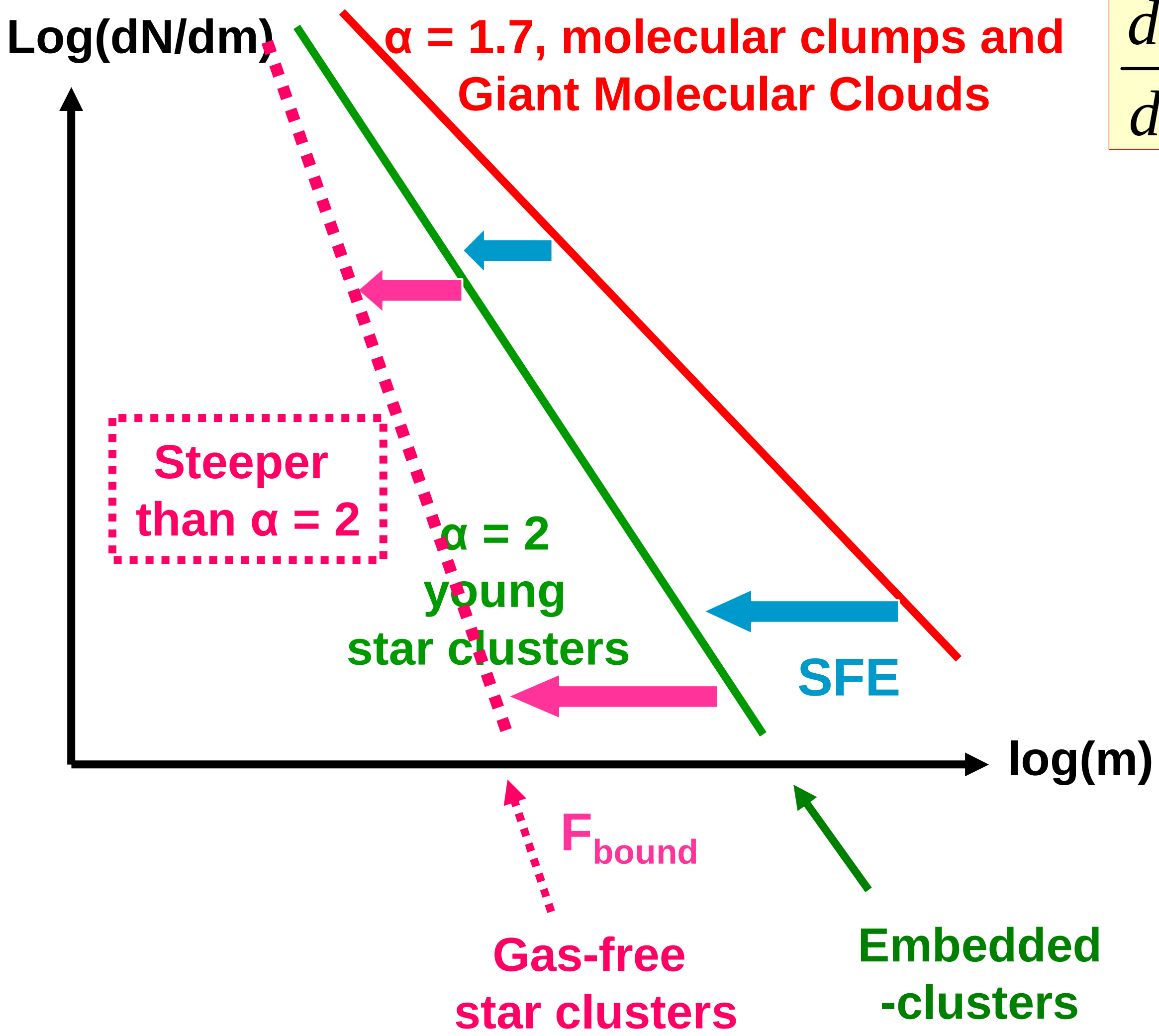
BEWARE !!

ecular clump
sities
smaller regions.

To identify a mass-radius diagram of molecular clumps as the mass-radius diagram of the star clusters they are forming is not as straightforward as sometimes quoted in the literature

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



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

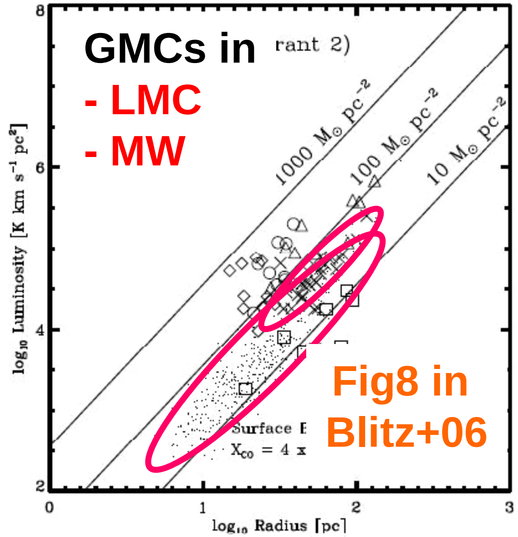
Mass-varying SFE: lower SFE at higher cloud/clump mass ??

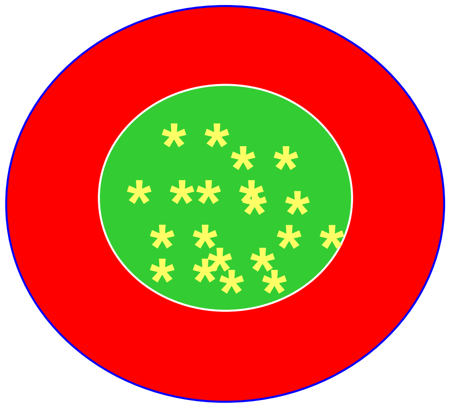
But then mass-varying F_{bound} too ??

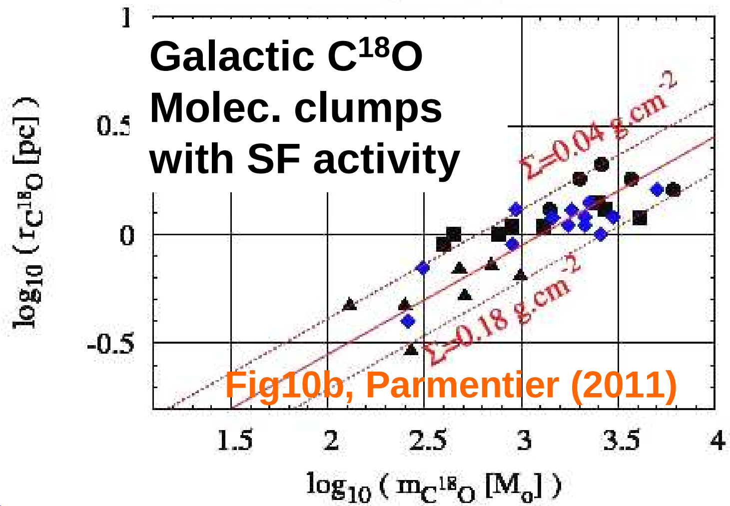
From the mass function of GMCs/clumps to that of gas-free star clusters ... with a volume density threshold for star formation

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

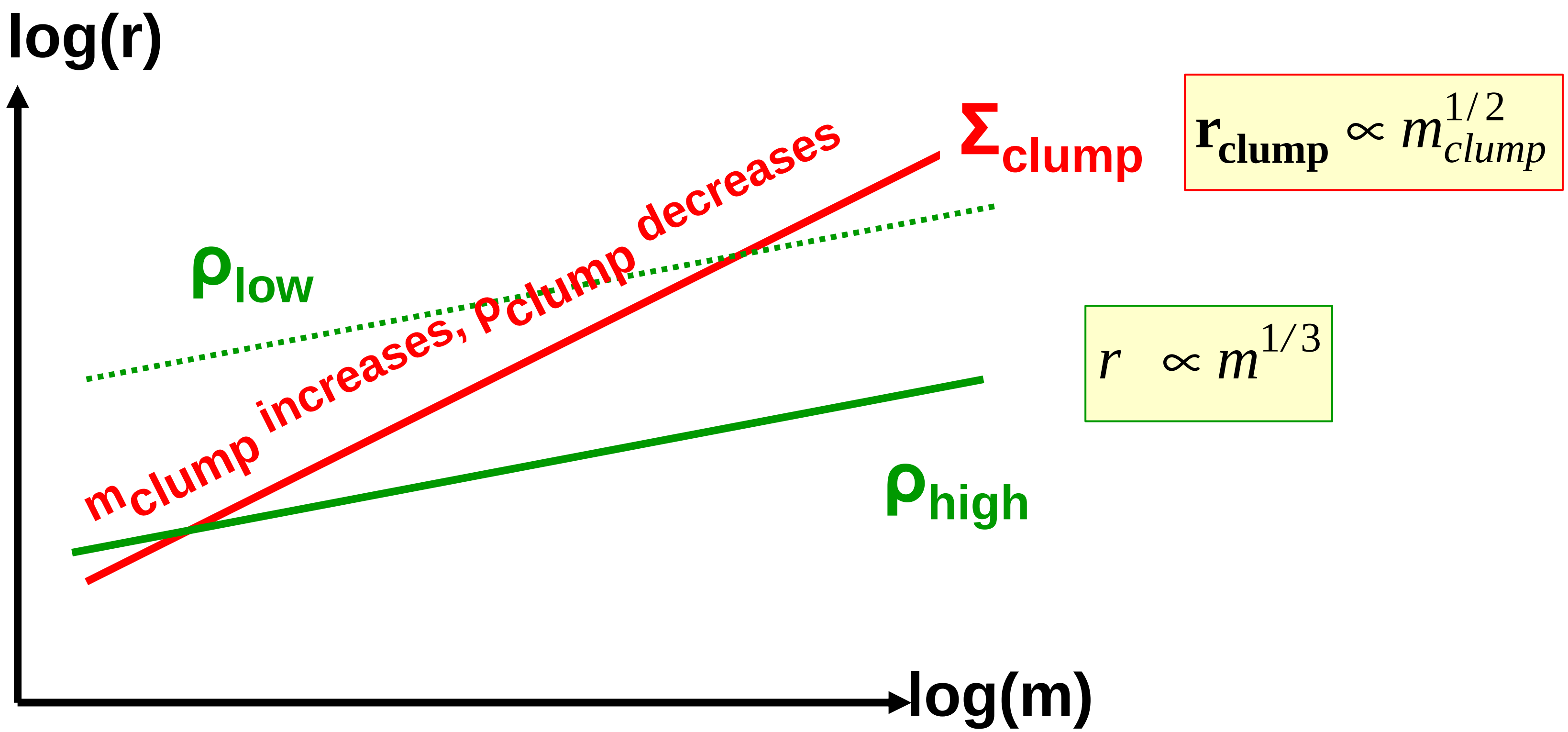
- **GMCs and**
- **Molecular clumps with signs of SF activity:**
  constant mean surface density
  - **Larson 1981**
  - **Blitz+ 2006**
  - **Heyer+ 2009**







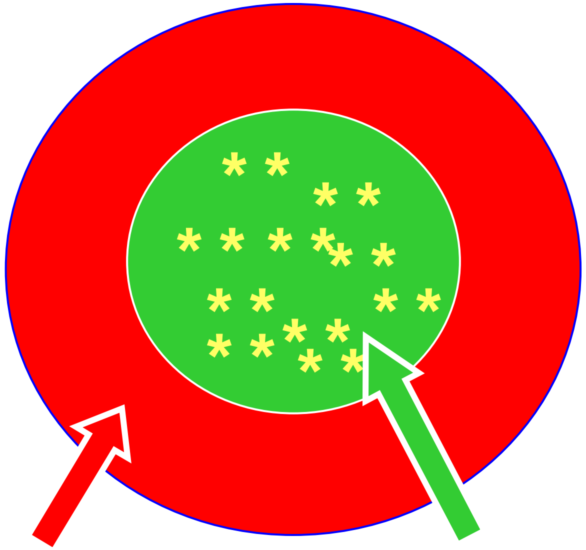
From the Mass Function of Molecular Clumps to that of Embedded Star Clusters



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

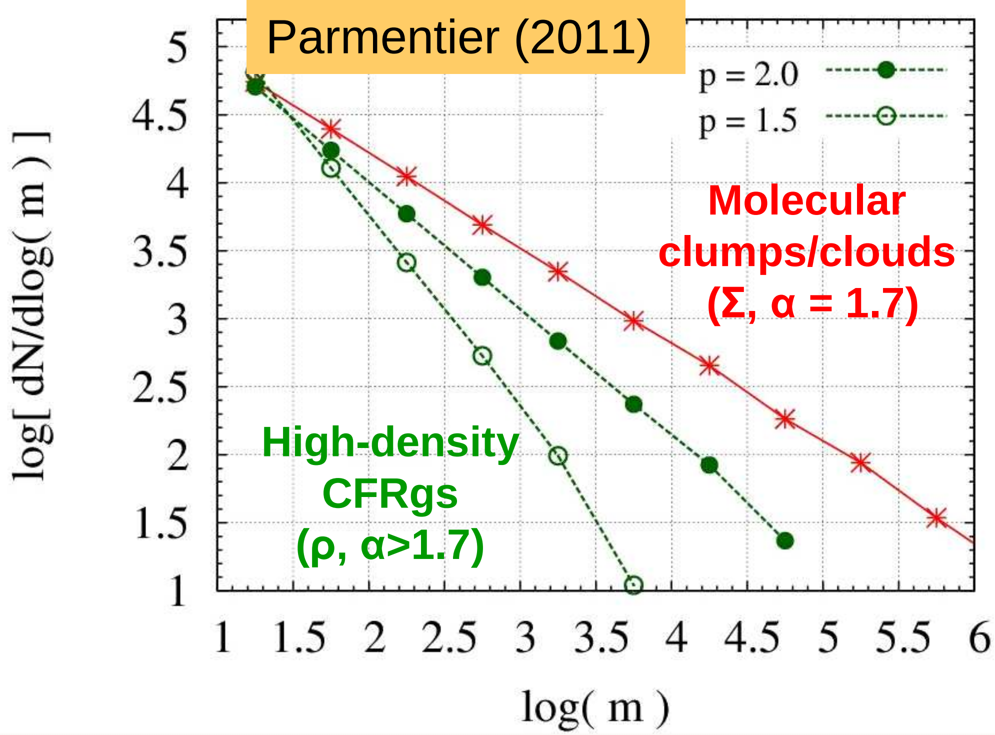
From the Mass Function of Molecular Clumps to that of Embedded Star Clusters

Molecular clumps: 2-zone model



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

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

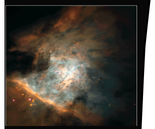


$$\rho_{clump}(r) \propto \mathbf{r}^{-1.9}; \quad \frac{m_{CFRg}}{m_{clump}} \propto m_{clump}^{-0.3}$$

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

Mueller+02: density index ≈ 1.8

Massive Star Formation (MSF) Limit



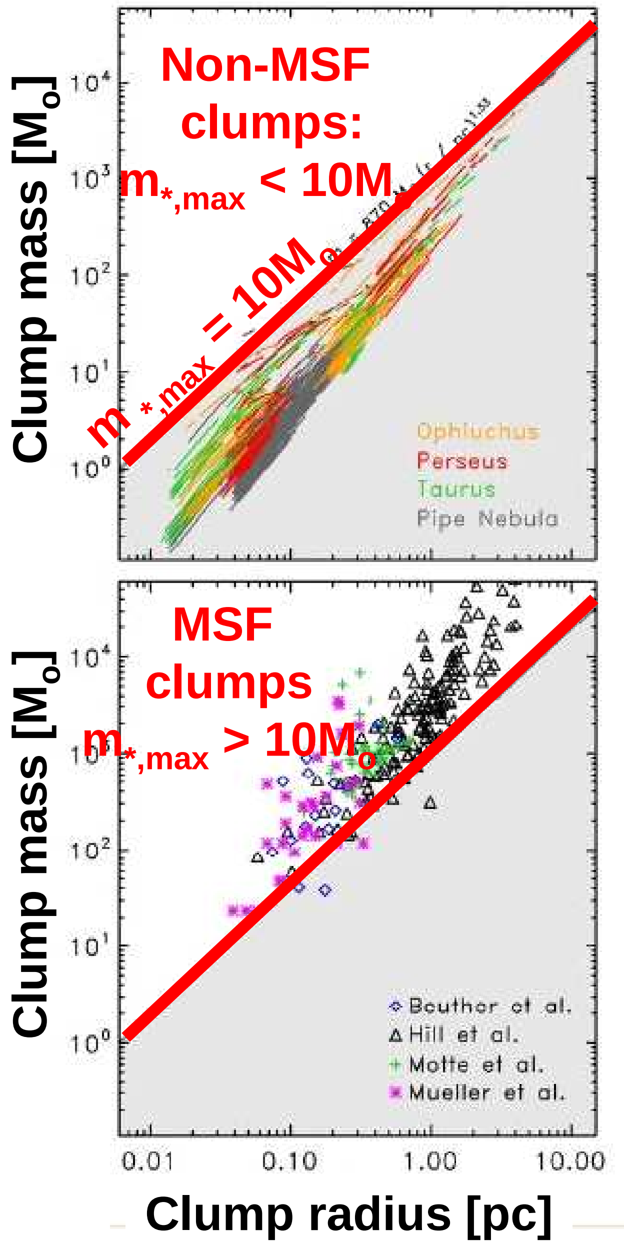



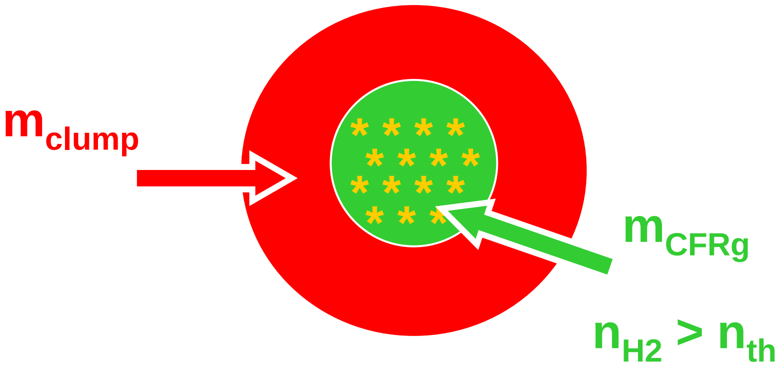
Fig2 and Eq1, Kauffmann & Pillai (2010)

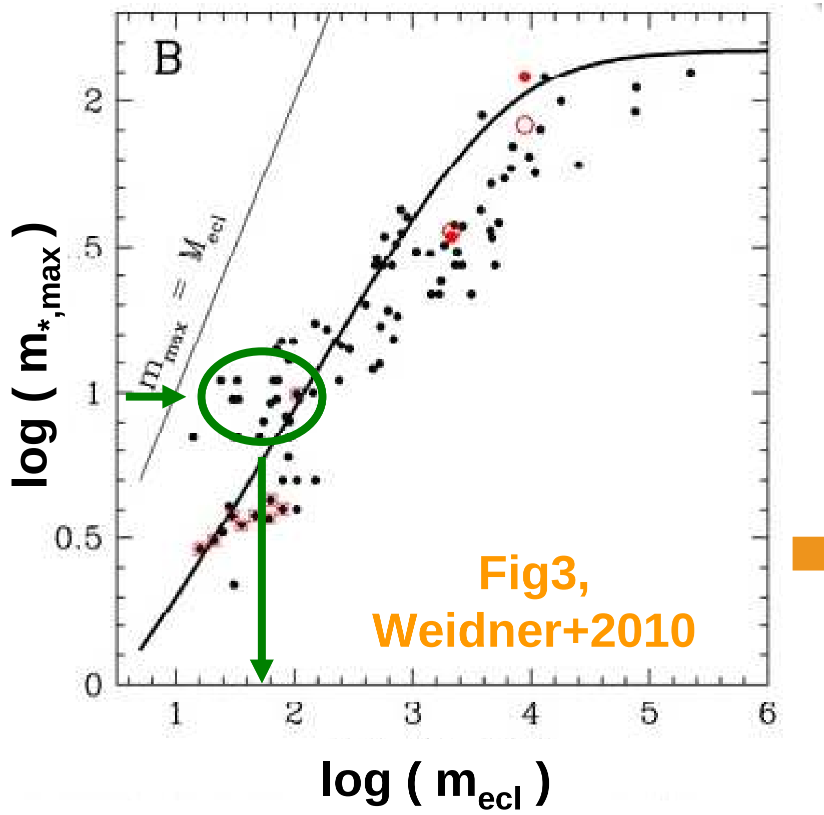
$$m_{clump} = 870 M_0 \left(\frac{r_{clump}}{pc} \right)^{1.33}$$

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:
$m_{*,max} > 10M_o$

Massive Star Formation (MSF) Limit

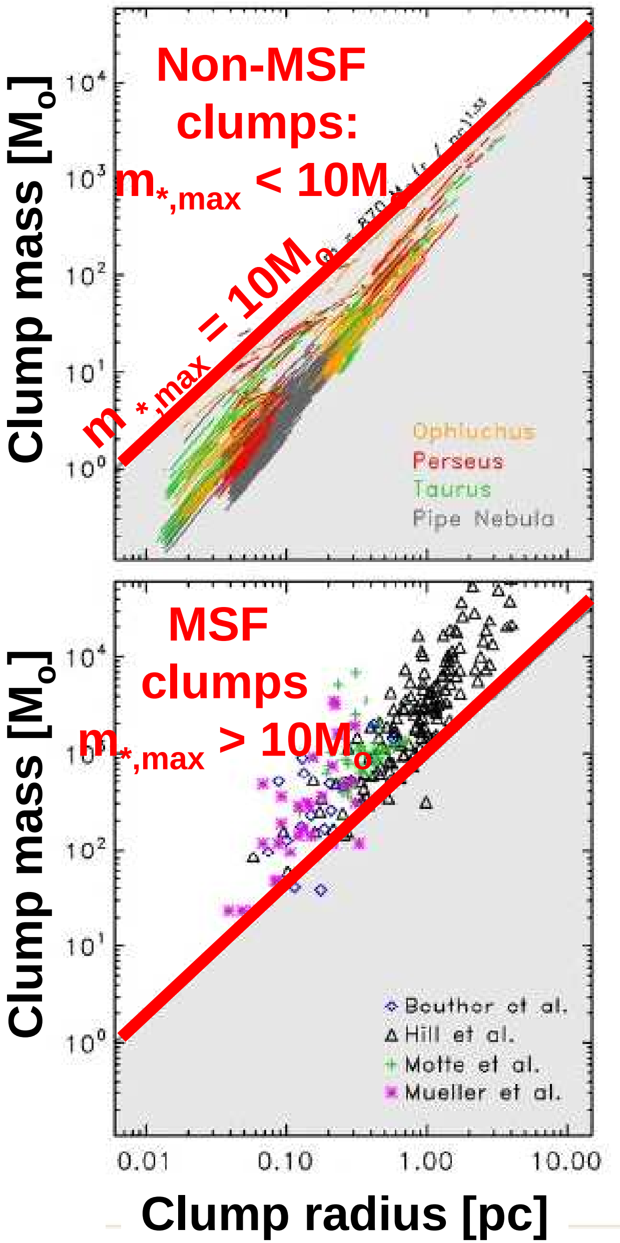
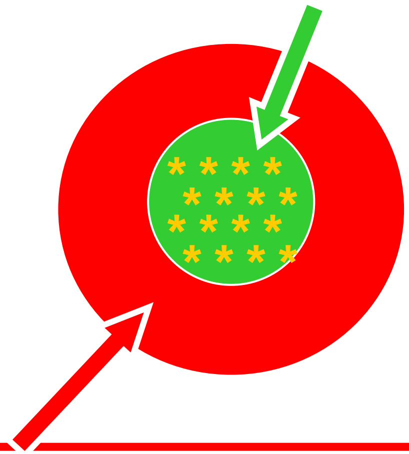


Fig2 and Eq1, Kauffmann & Pillai (2010)

Volume density threshold for overall star formation: $n_{H2} > n_{th}$

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

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



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

Massive Star Formation Limit

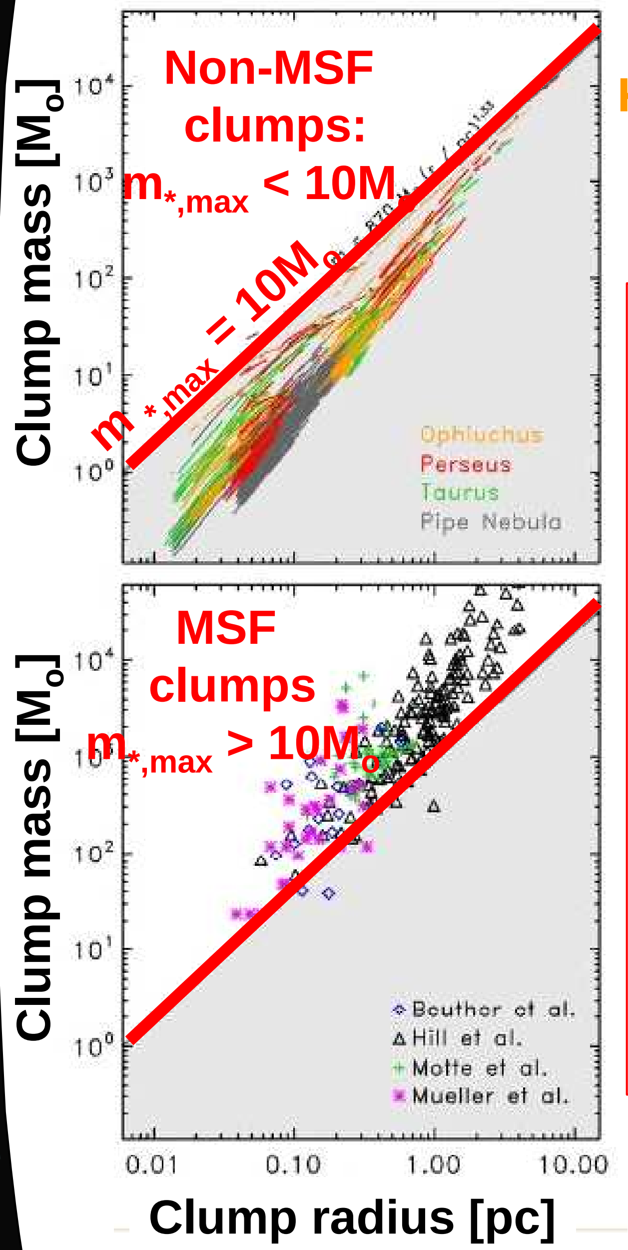
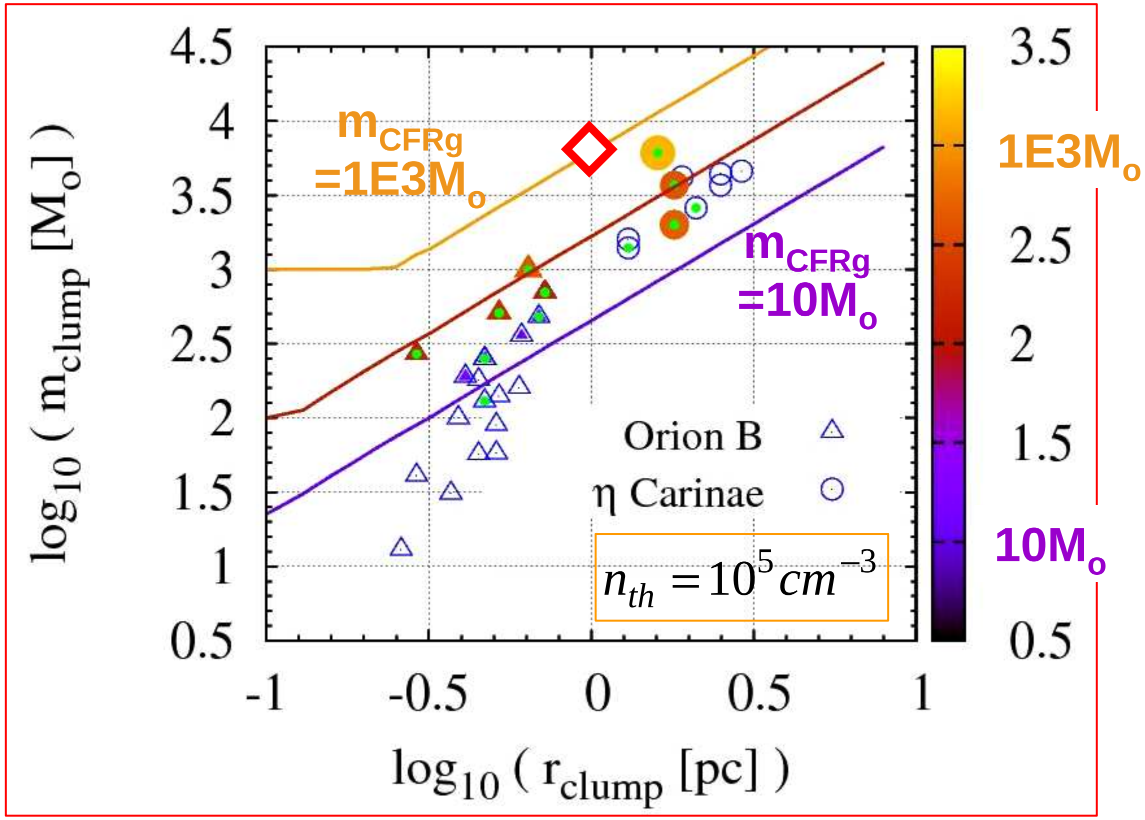


Fig2, Kauffmann & Pillai (2010)

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

Parmentier (2011), Eq.3



Massive Star Formation Limit

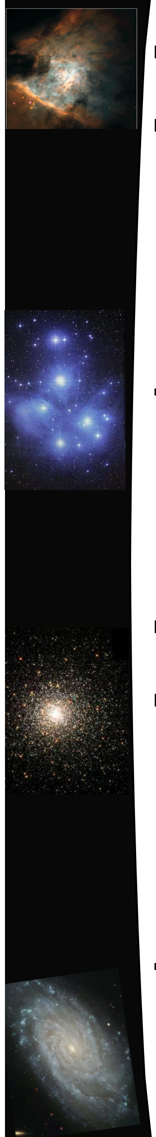
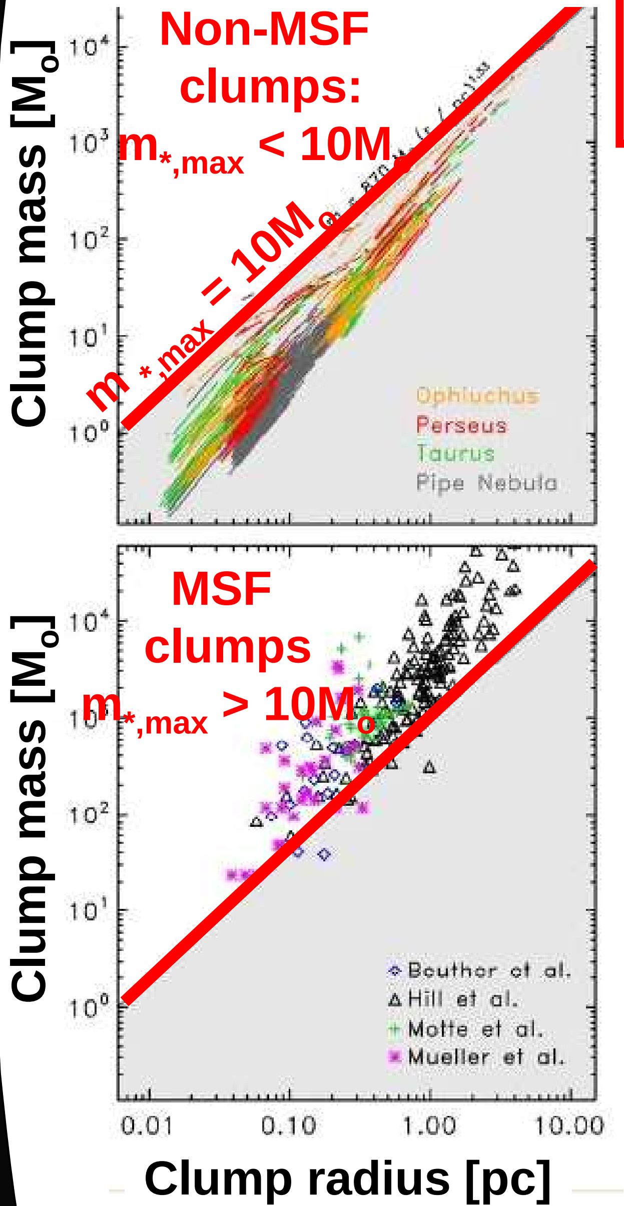
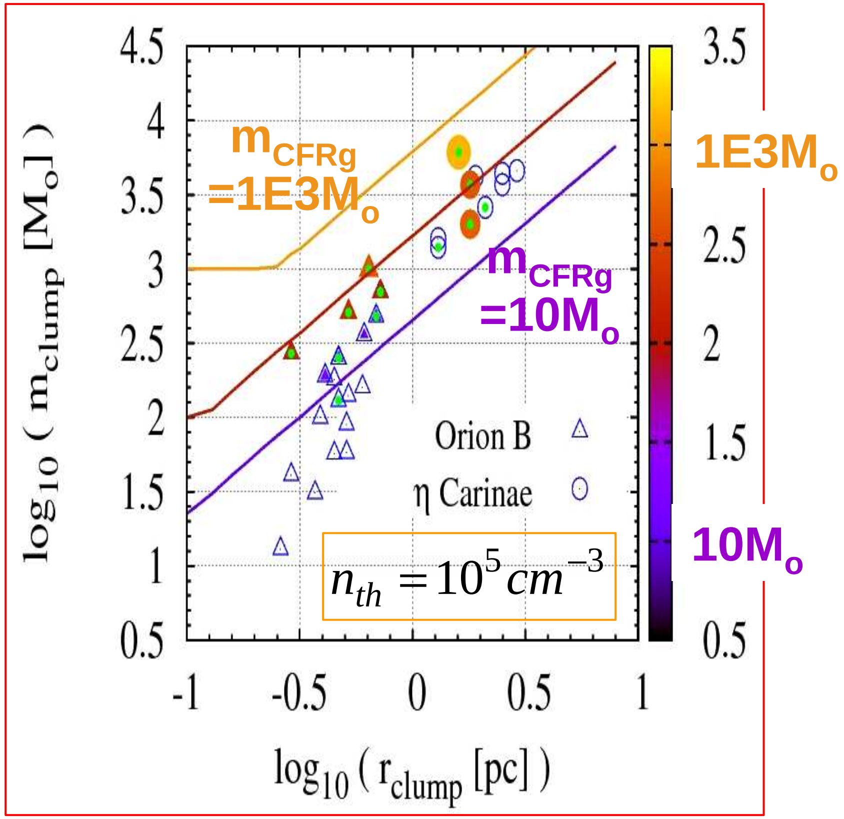


Fig2, Kauffmann & Pillai (2010)



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

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



Massive Star Formation Limit

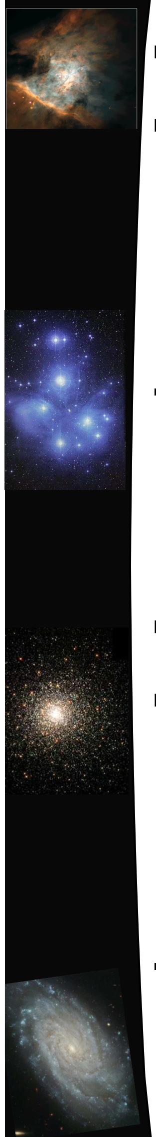
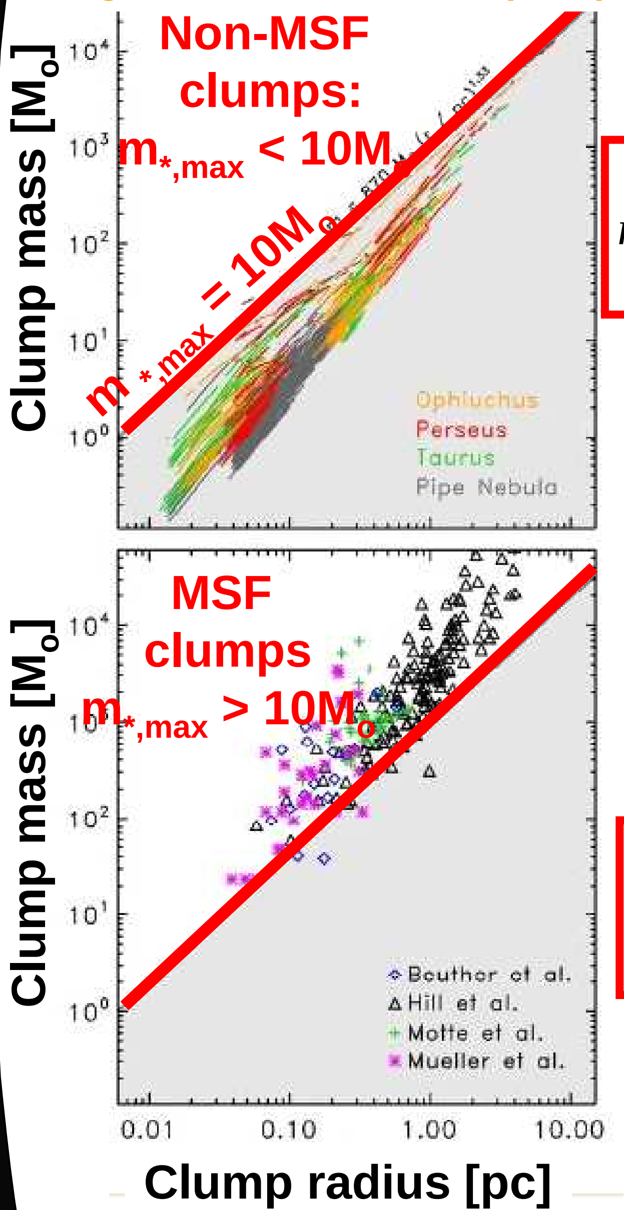


Fig2, Kauffmann & Pillai (2010)



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+, subm)

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

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

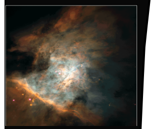
Matching the intercepts:

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

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

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

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

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