Volume-Density-Driven Star Formation in the Galaxy

Geneviève Parmentier

Astronomisches-Rechen Institut
Zentrum für Astronomie Heidelberg

Germany

Stellar Feedback and Cluster Evolution

- **Stellar feedback responsible for expelling the residual star-forming gas out of embedded star clusters**

- **At what stage of cluster development does it happen? On what time-scale?**
  - **Numerous parameters involved**
    - **Nature of the feedback: protostellar outflows, stellar winds, ionizing radiations, Type II Supernovae, …**
    - **Stellar IMF sampling at high mass, embedded-cluster mass**
    - **Depth of the gravitational potential well**
    - **…**

- **Stellar feedback modelling requires cluster formation modelling**

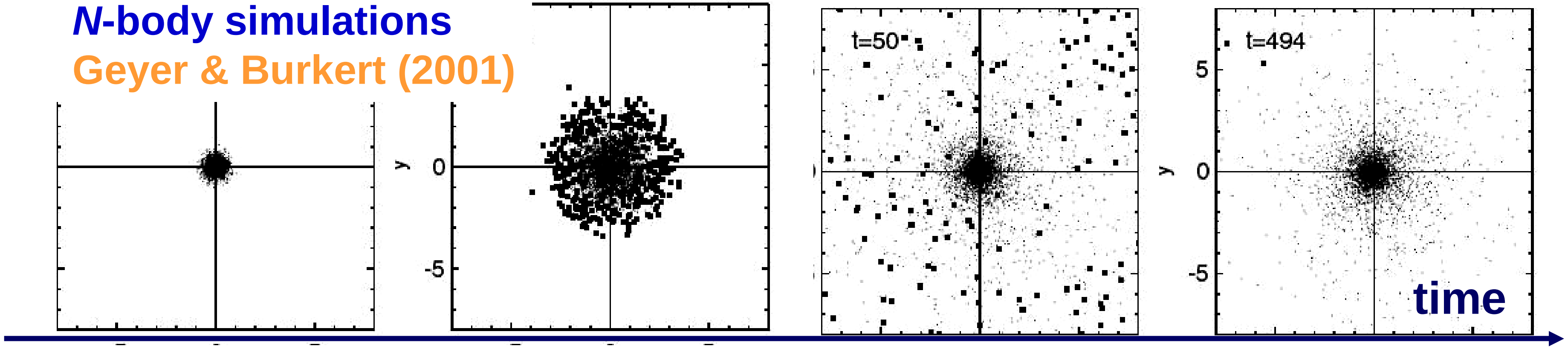
- **Talks at this Symposium (e.g. Rahner's talk)**

Post-Gas-Expulsion Cluster Evolution

➤ **Dynamical response of a star cluster to the expulsion of its residual star-forming gas**

- **Cluster expansion**
- **Star loss, or complete cluster dissolution**

***N*-body simulations**
Geyer & Burkert (2001)



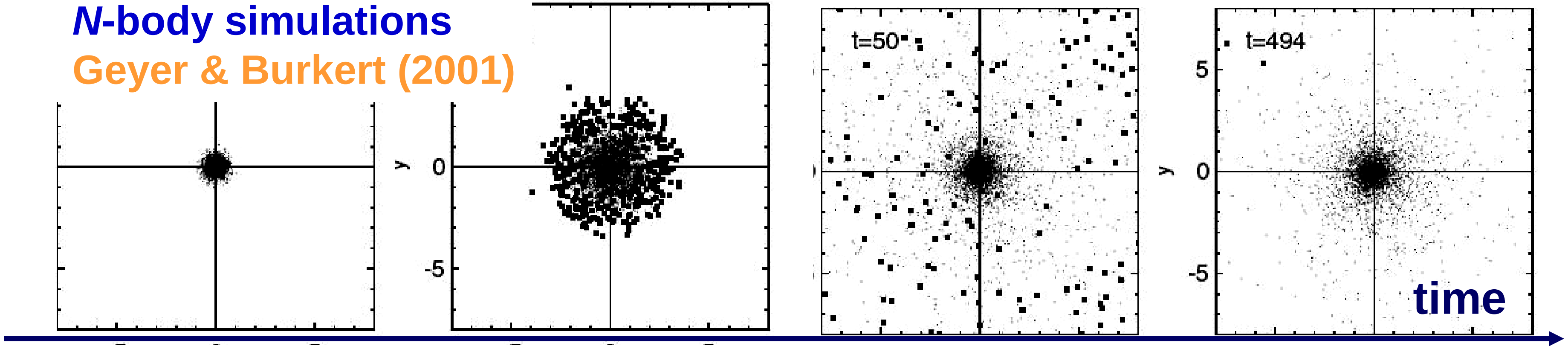
➤ **Cluster mass-loss and expansion depend on:**

- **Global star formation efficiency *(Hills 1980)***
- **Gas expulsion time-scale *(Lada+ 1984)***
- **Star-cluster dynamical state *(Goodwin 2009)***
- **Star-cluster environment (e.g. tidal field, *Renaud+ 2008*)**
- **…**

Post-Gas-Expulsion Cluster Evolution

- **Dynamical response of a star cluster to the expulsion of its residual star-forming gas**
  - **Cluster expansion**
  - **Star loss, or complete cluster dissolution**

***N*-body simulations**
Geyer & Burkert (2001)

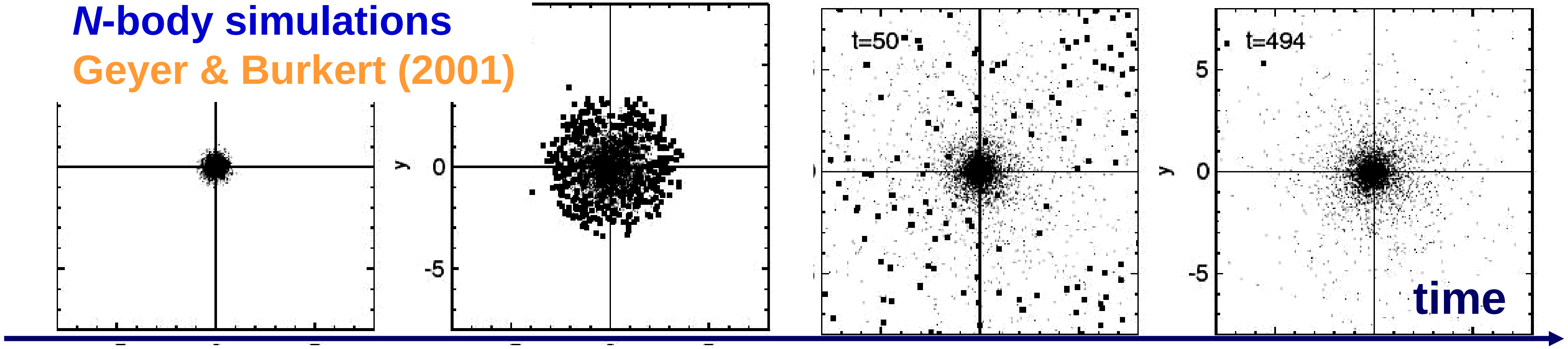


- **Cluster mass-loss and expansion depend on:**
  - **Global star formation efficiency *(Hills 1980)***
  - **Gas expulsion time-scale *(Lada+ 1984)***
  - **Star-cluster dynamical state *(Goodwin 2009)***
  - **Star-cluster environment (e.g. tidal field, *Renaud+ 2008*)**
  - **…**

Post-Gas-Expulsion Cluster Evolution

- **Dynamical response of a star cluster to the expulsion of its residual star-forming gas**
  - **Cluster expansion**
  - **Star loss, or complete cluster dissolution**

***N*-body simulations**
Geyer & Burkert (2001)



- **Cluster mass-loss and expansion depend on:**
  - **Global star formation efficiency** *(Hills 1980)*
  - Gas expulsion time-scale (Lada+ 1984)
  - Sta cluster d
  - Sta cluste er
  - …

How are the gas and stars of a nascent cluster distributed with respect to each other at gas expulsion?

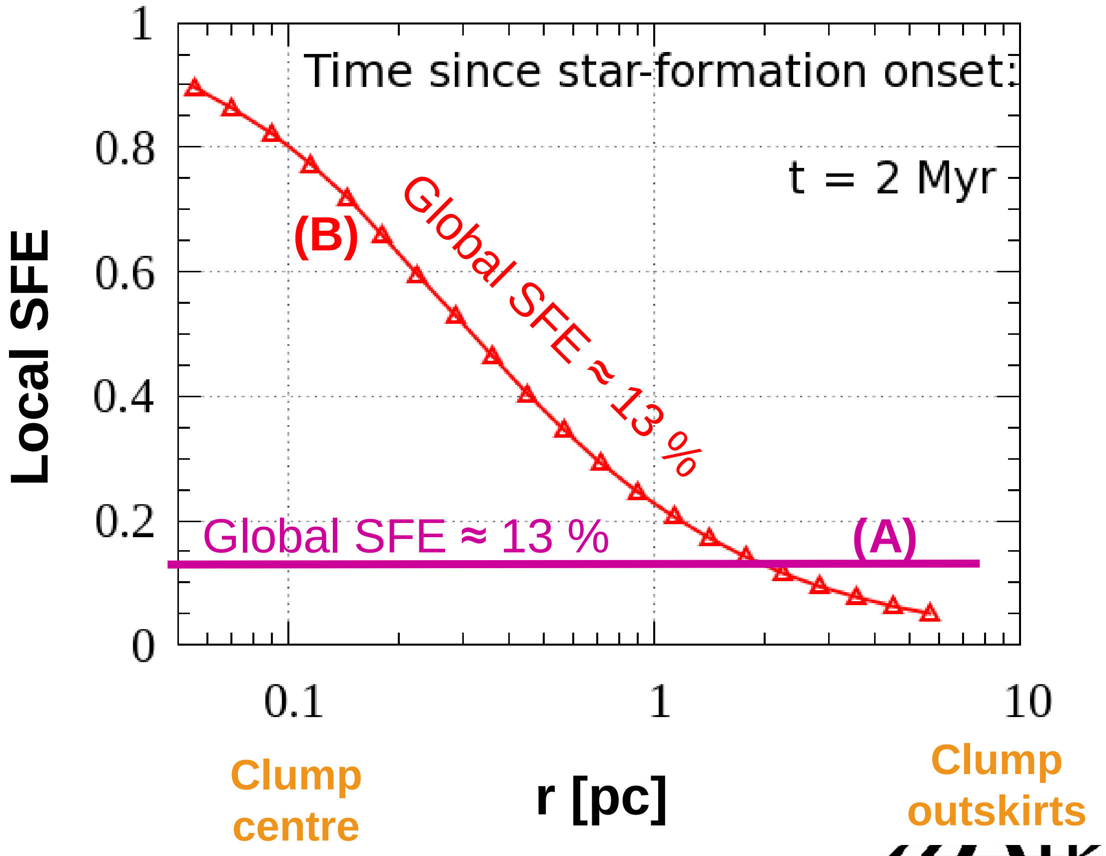
SFE Radial Profile inside a Forming Cluster

- Knowledge of the global star formation efficiency is not enough
- How are the gas and stars of a nascent cluster distributed with respect to each other at gas expulsion? A or B ?
- Clump of molecular gas

  A. Is the gas converted into stars in a uniform manner?

  B. Is star formation more efficient in the central regions of the protocluster?
     - Helps cluster survival

Parmentier & Pfalzner 2013, Fig10



Scenario A or B? Insights from Theory

- Cluster-forming molecular clumps have volume density gradients

- Therefore, their inner regions
  - Are denser
  - Have a shorter free-fall time

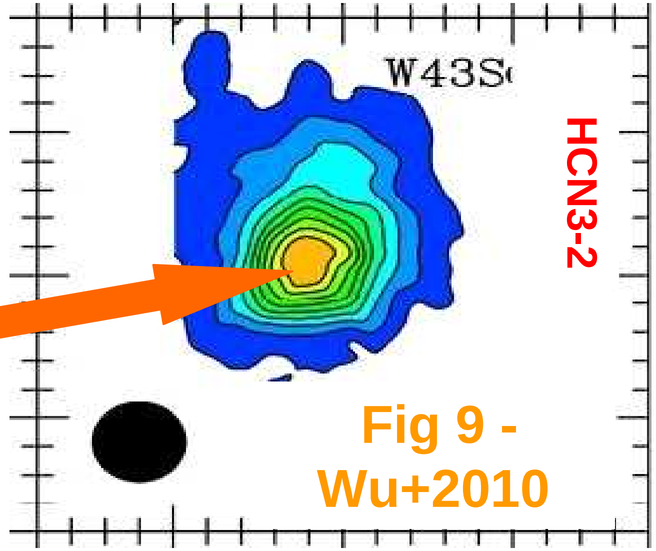


Fig 9 - Wu+2010

- For a constant star formation efficiency per free-fall time, ε_{ff} (Krumholz & McKee 2005), clump inner regions experience faster star formation
  - ➧ $SFE_{inner} >> SFE_{outskirts}$
  - ➧ Scenario B expected

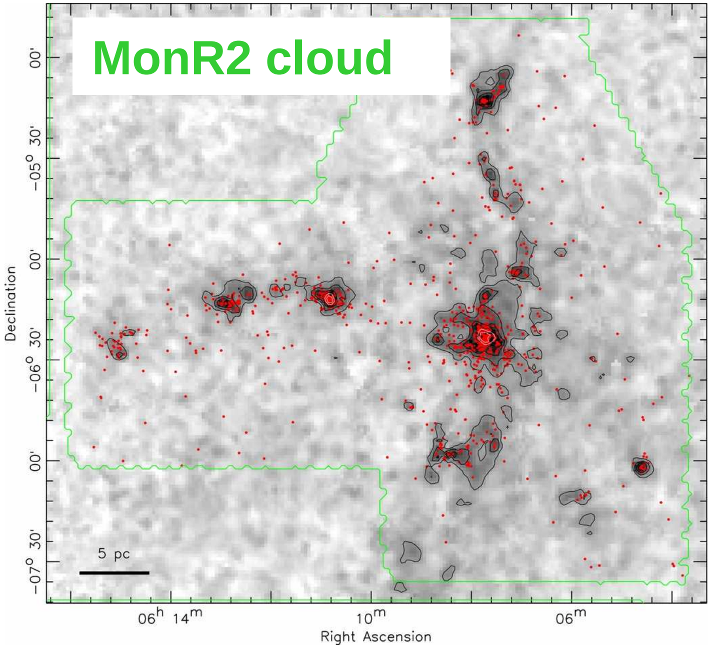
Free – fall time :

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

- Denser
- Faster

Scenario A or B? Insights from Observations

Fig. 1, Gutermuth+ (2011)



Molecular clouds in the Solar neighbourhood:

- **The local star formation efficiency depends on gas density**
- **Scenario B expected**

$$\Sigma_{YSO} \propto \Sigma_{gas}^2$$

$$\Sigma_{gas} \propto \frac{\Sigma_{YSO}}{\Sigma_{gas}} \propto \varepsilon_{2D}$$

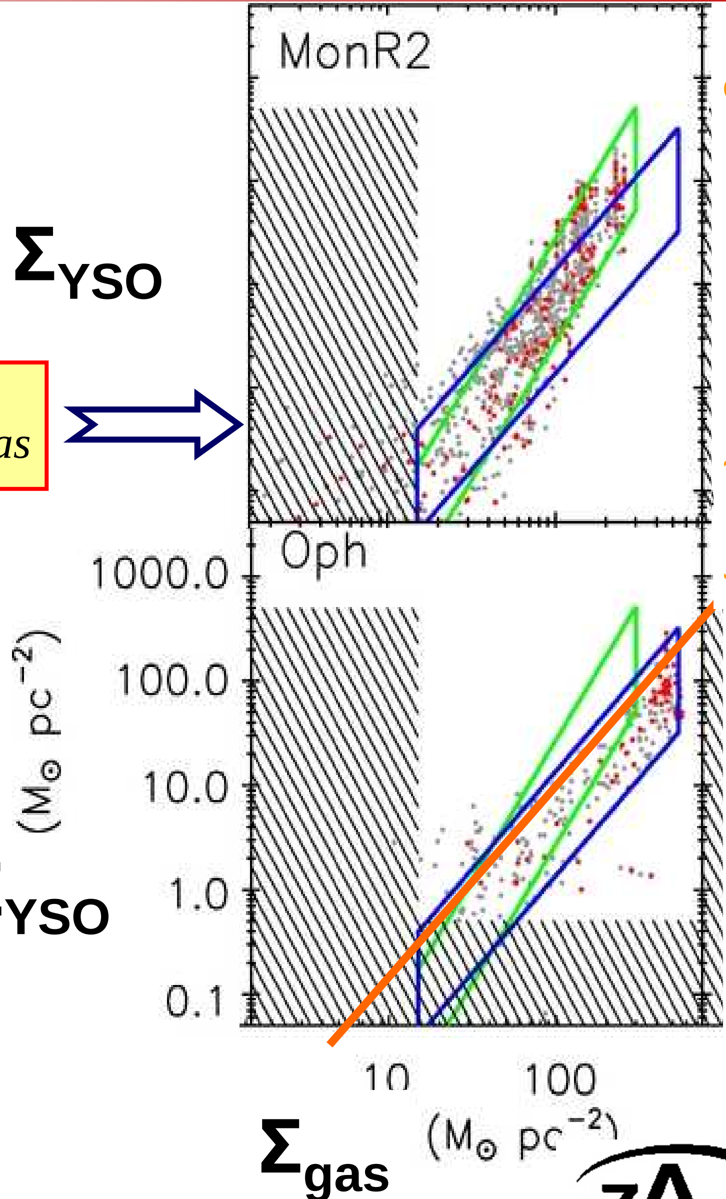
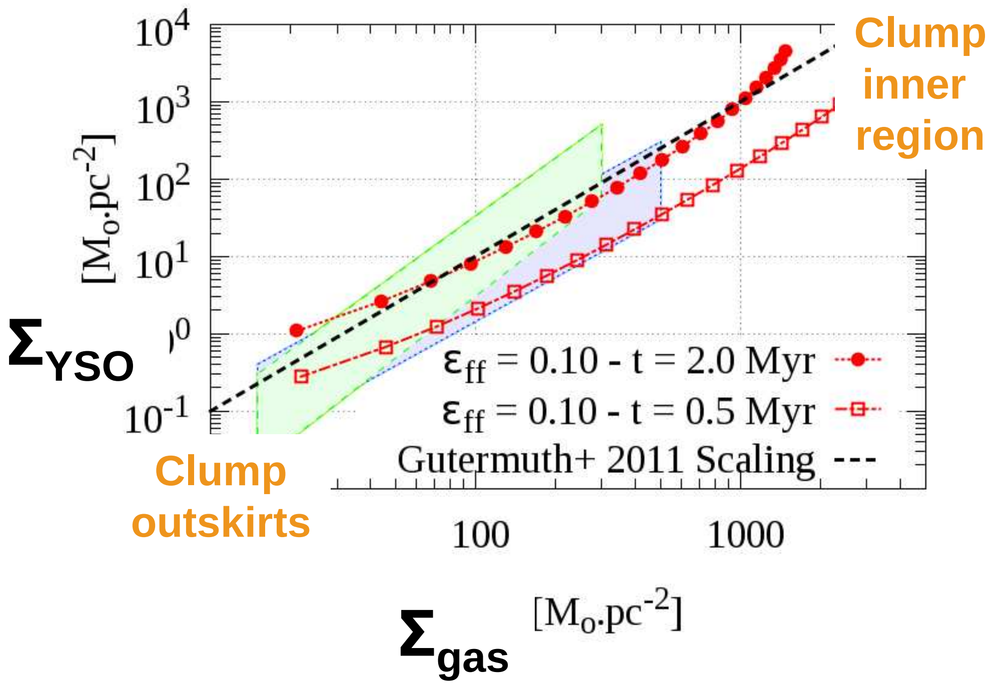


Fig. 9, Gutermuth+ (2011)

Star Formation Relation and SFE Radial Variations

$$\text{Centrally-concentrated clump}: \rho_{clump}(r) \propto r^{-2}$$



<u>**Local Star Formation Relation:**</u>

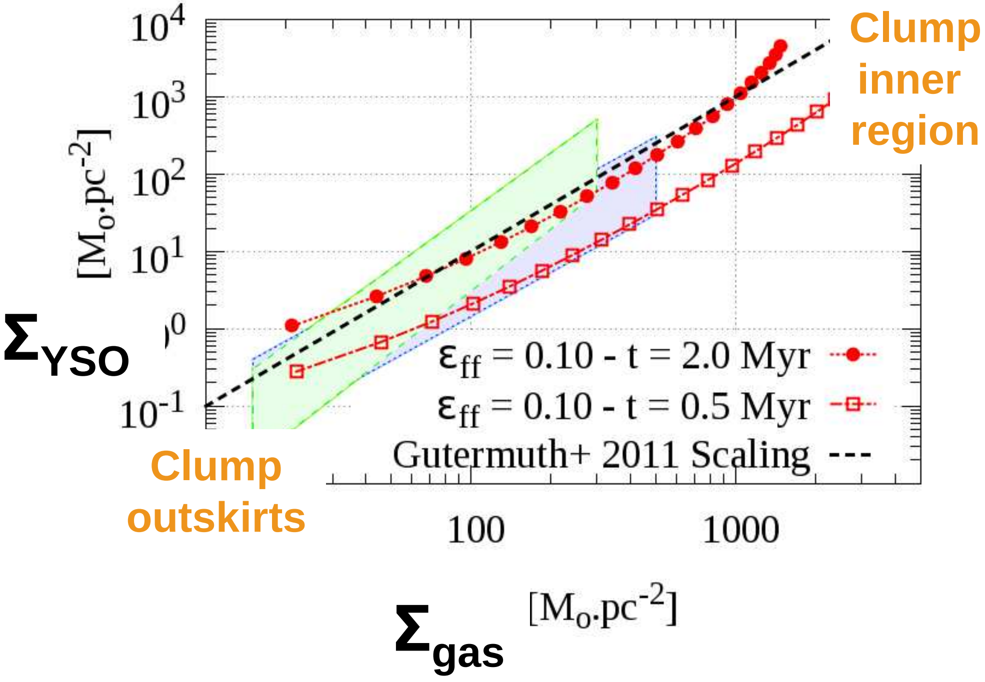
Superlinear / Quadratic

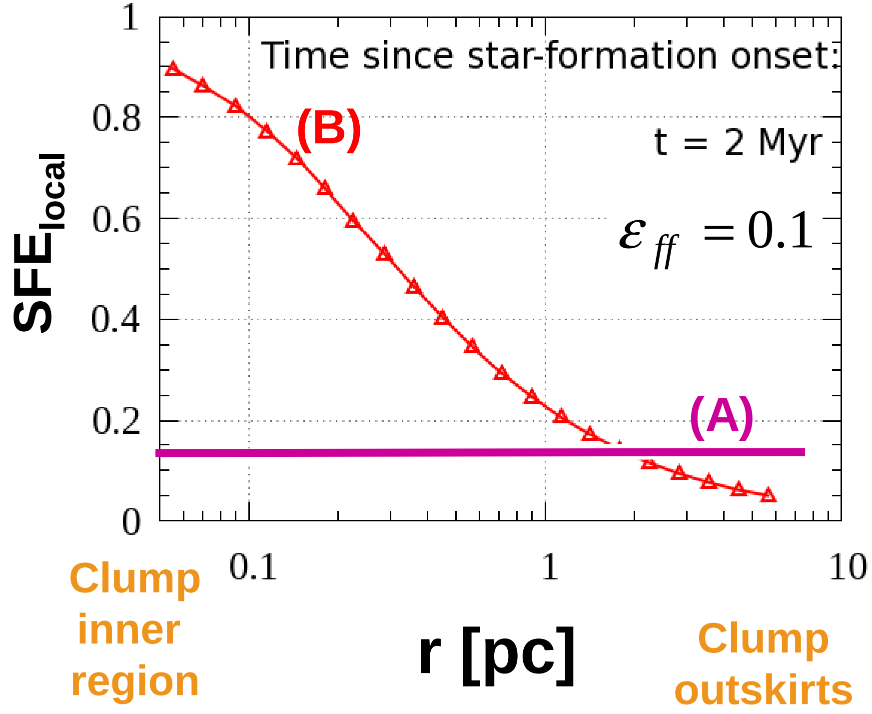
See also Lombardi+2013, Lada+2013

Figs 3 and 10, Parmentier & Pfalzner (2013)

Star Formation Relation and SFE Radial Variations

$$\text{Centrally-concentrated clump}: \rho_{clump}(r) \propto r^{-2}$$





Local Star Formation Relation:

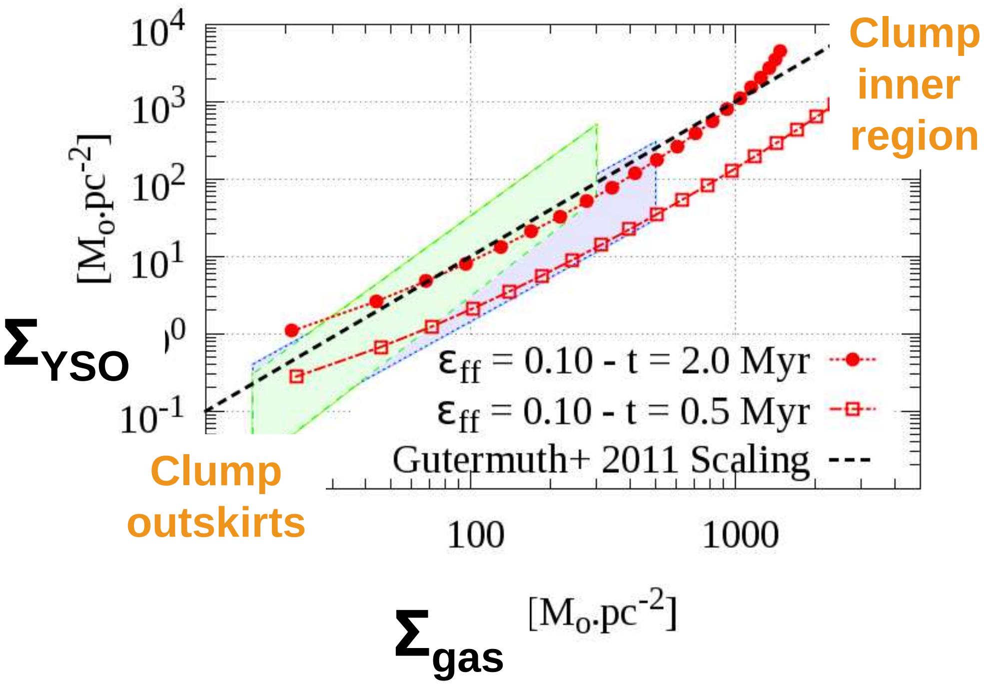
Superlinear / Quadratic

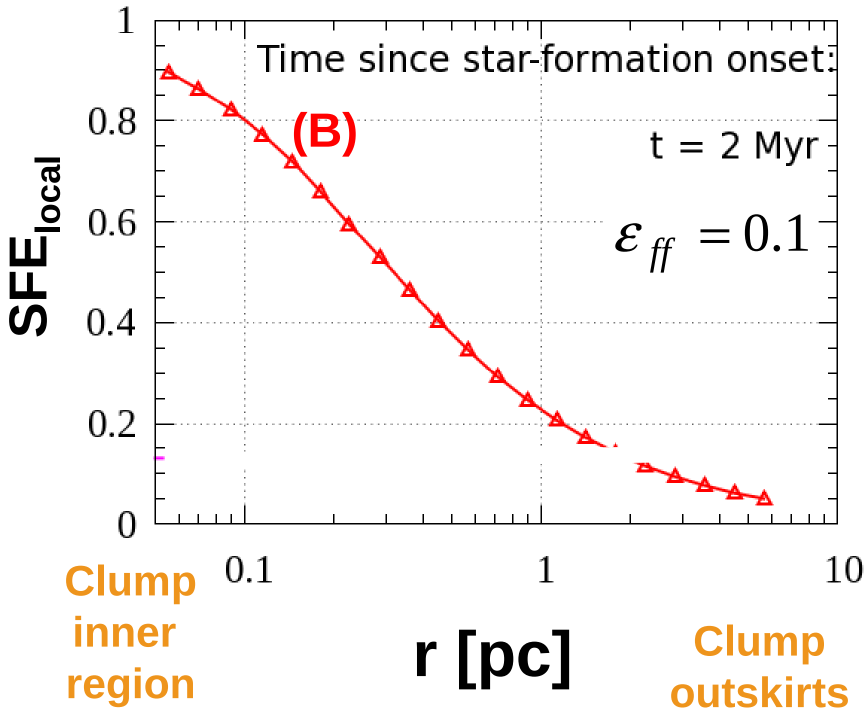
See also Lombardi+2013, Lada+2013

Figs 3 and 10, Parmentier & Pfalzner (2013)

Star Formation Relation and SFE Radial Variations

$$\text{Centrally-concentrated clump}: \rho_{clump}(r) \propto r^{-2}$$





<u>Local Star Formation Relation:</u>

Superlinear / Quadratic

<u>Local star formation efficiency :</u>

SFE_{local}(inner) > SFE_{local}(outer)

See also Lombardi+2013, Lada+2013

Figs 3 and 10, Parmentier & Pfalzner (2013)

Scenario B – the Rescuer – is the Winner

Cluster survivability is strengthened (despite tidal-field inclusion!)

Bekdaulet Shukirgaliyev

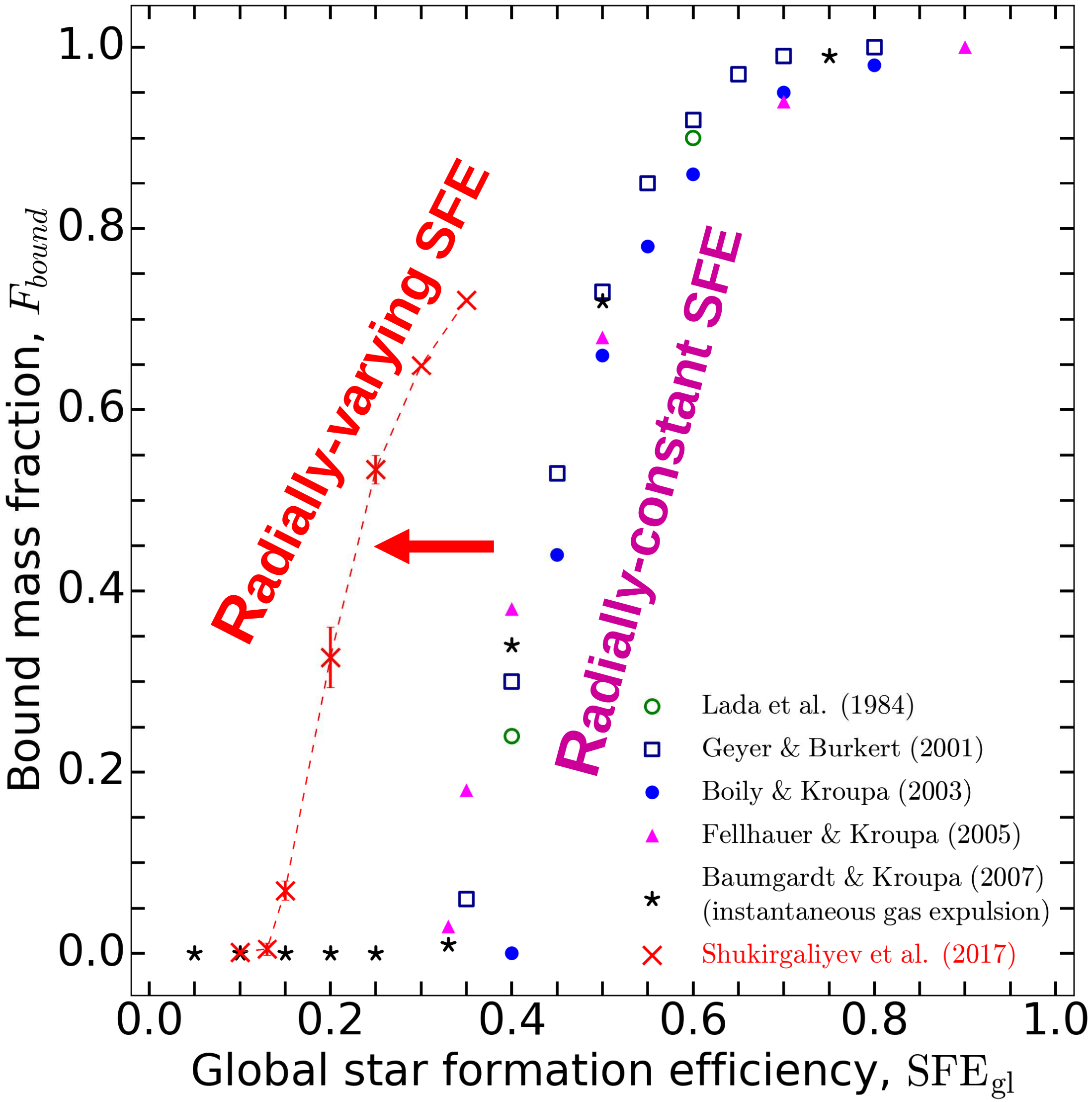
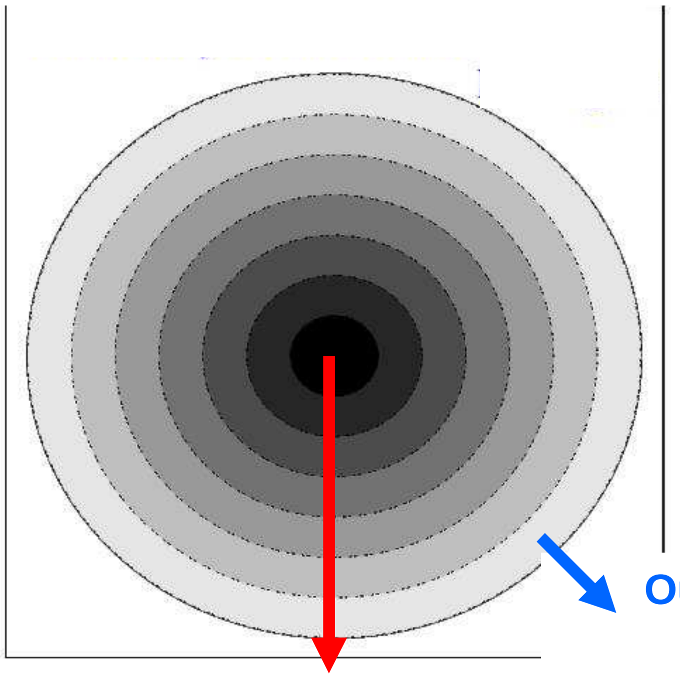


Fig 8a, Shukirgaliyev, Parmentier, Berczik & Just 2017

Denser Is Faster – True Locally and Globally

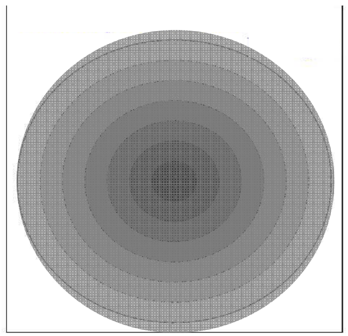
Local perspective:
Compare inner and outer regions of a clump



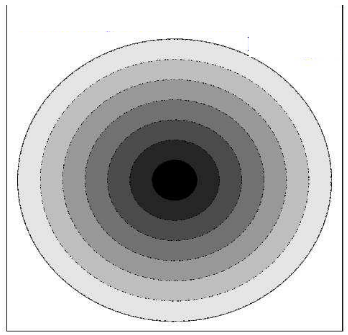
Outskirts: slow star formation

Centre: fast star formation

Global perspective:
Compare two clumps with different densities



High-density clump: fast star formation

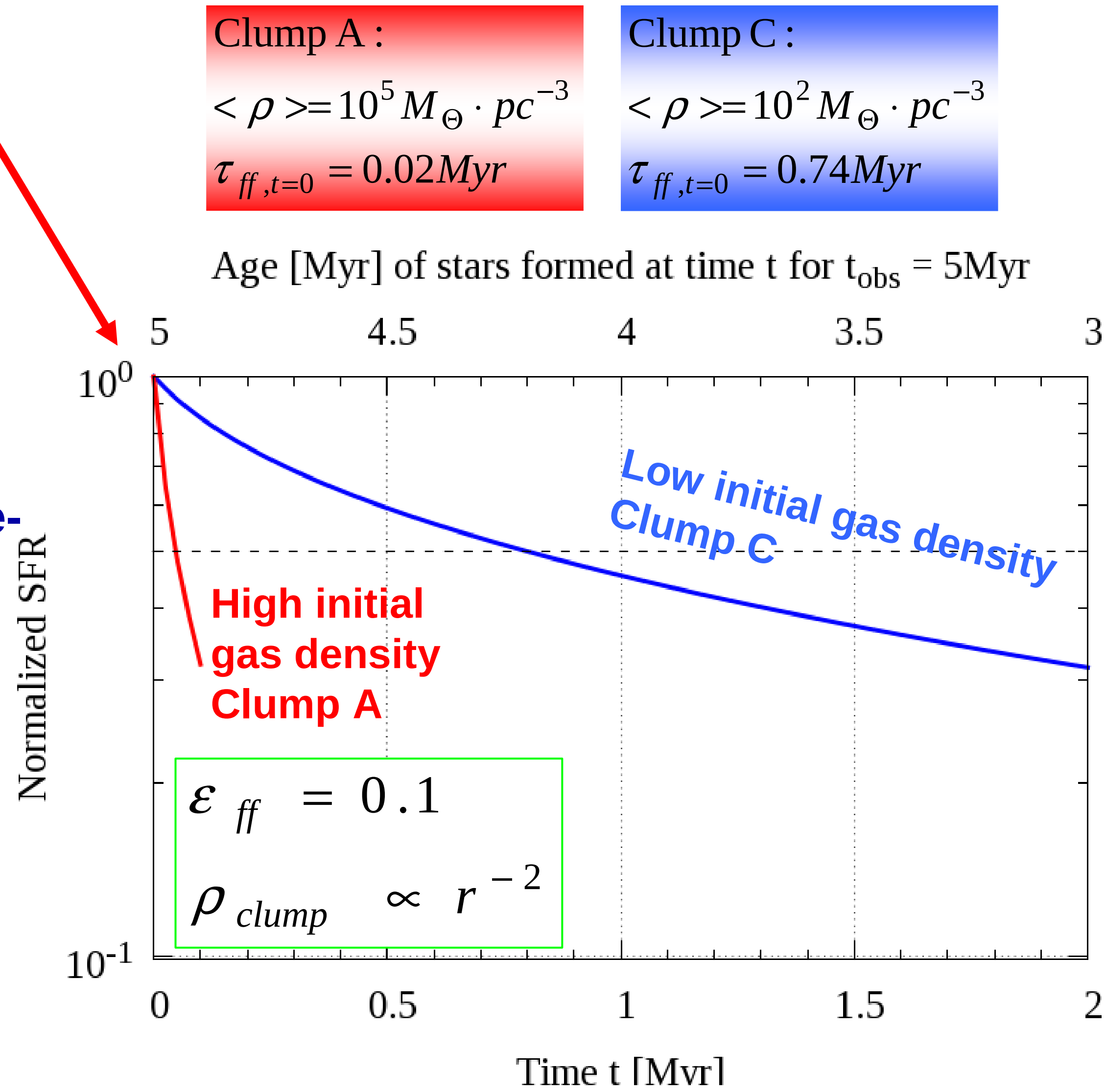


Low-density clump: slow star formation

Denser Is Faster – Cluster Stellar Age Spreads

- **Clump SFR evolution normalized to initial value**
- **SFR decreases with time**
  - $M_{gas}(t)$ decreases
  - $\tau_{ff}(t)$ gets longer

- **Luhman (2007)**
  Isochronal ages of pre-main sequence stars
- **Belloche+ 2011,**
- **Hatchell+ 2005**
  Counting of Class 0, Class I and Class II objects
- **Evans+ 2014**
  'no obvious evidence for acceleration'



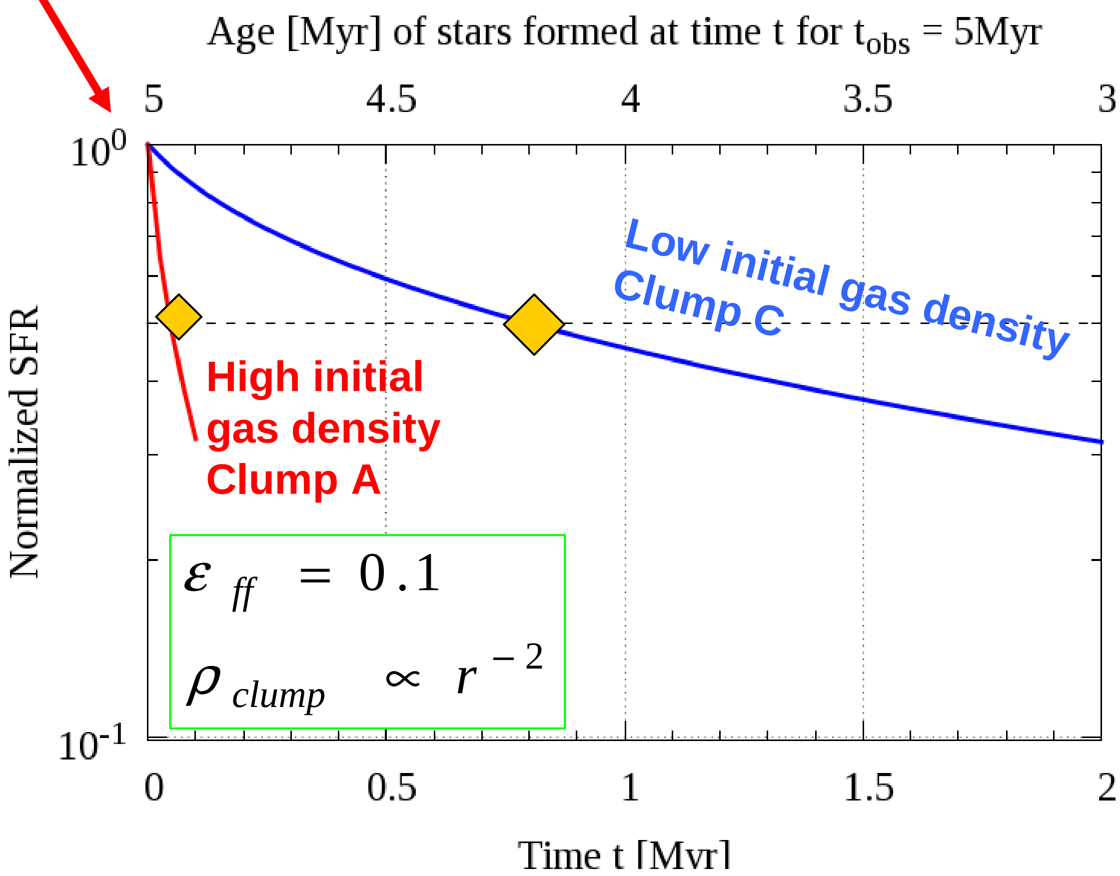
Parmentier, Pfalzner & Grebel (2014), Fig. 3

Denser Is Faster – Cluster Stellar Age Spreads

- **Clump SFR evolution normalized to initial value**
- **SFR decreases with time**
  - **$M_{gas}(t)$ decreases**
  - **$\tau_{ff}(t)$ gets longer**
- **Low-density Clump C:**
  - **slow decrease**
  - **wide stellar age distribution**
- **High-density Clump A:**
  - **steep decrease**
  - **narrow stellar age distribution**
- **Stellar age spread = clump density indicator**

Clump A :
$< \rho >= 10^5 M_\Theta \cdot pc^{-3}$
$\tau_{ff,t=0} = 0.02 Myr$

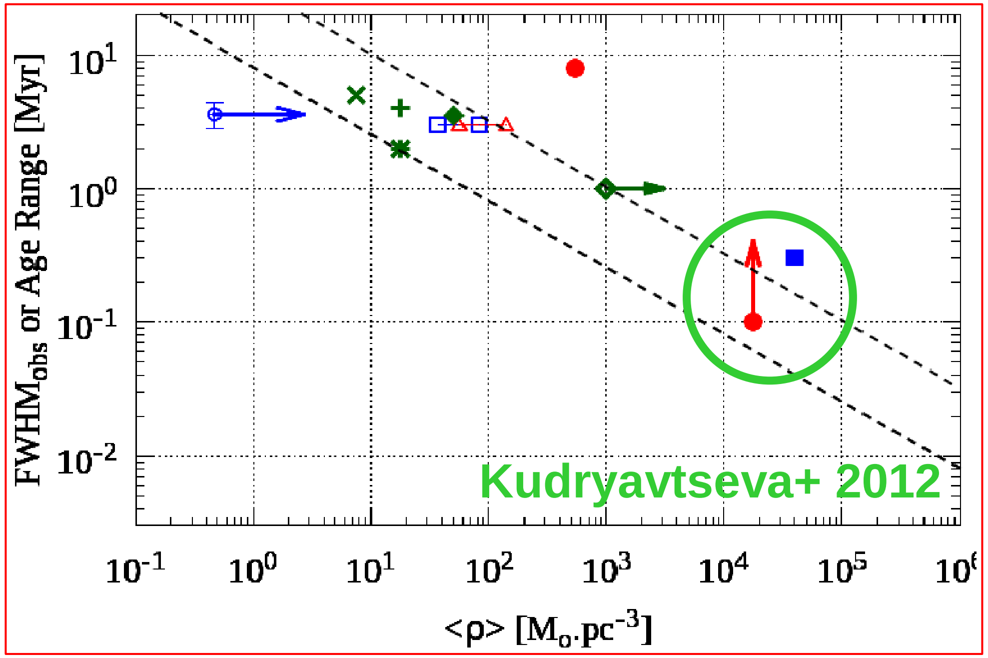
Clump C :
$< \rho >= 10^2 M_\Theta \cdot pc^{-3}$
$\tau_{ff,t=0} = 0.74 Myr$



Parmentier, Pfalzner & Grebel (2014), Fig. 3

Stellar Age Spreads: Observations

Observations



Parmentier, Pfalzner & Grebel (2014), Fig 10

- **Stellar age spreads in Wd 1 and NGC3603 YC narrower than that of the ONC (Kudryavtseva+ 2012, Reggiani+ 2011): denser is faster**

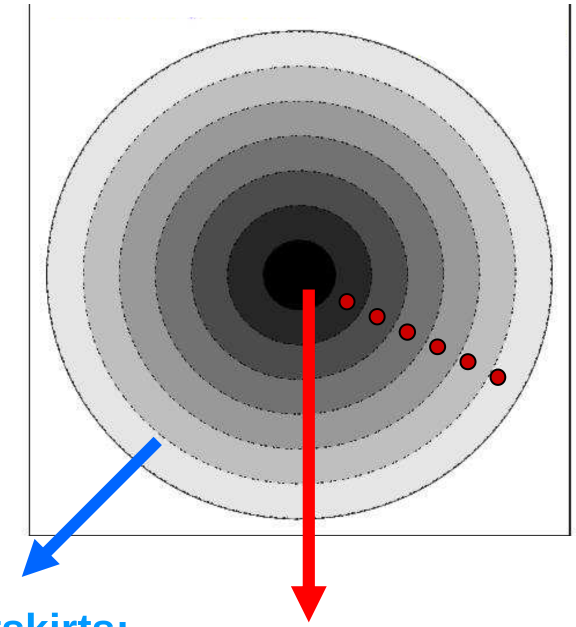
Take-Away Messages

- If star formation proceeds with a constant ε_{ff}:
  - Quadratic local star formation relation
    Parmentier & Pfalzner (2013)
  - Improved star cluster survival after residual star-forming gas expulsion
    Shukirgaliyev+ 2017 (see also Adams 2000)
  - Denser clumps yield clusters with narrower stellar age spreads than low-density clumps
    Parmentier, Pfalzner & Grebel (2014)

Local SF Relation

Local perspective:
- **Contour-by-contour basis**
- **One clump is enough**

Clump distance: e.g. 500 pc



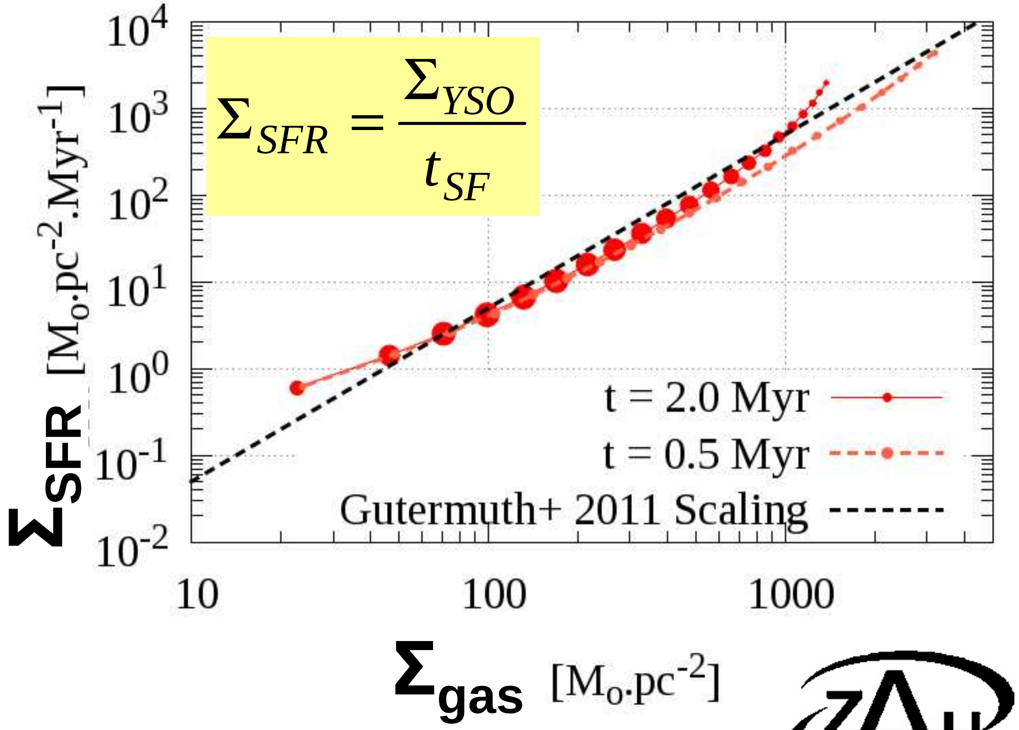
Outskirts: slow star formation

Centre: fast star formation

Local (contour-by-contour) SF relation:

$$\Sigma_{SFR} \propto \Sigma_{gas}^2$$

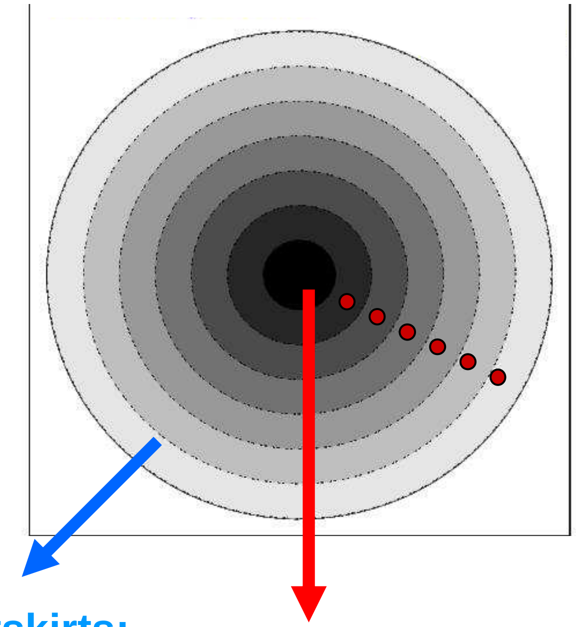
Slope of 2



Local SF Relation

Local perspective:
- **Contour-by-contour basis**
- **One clump is enough**

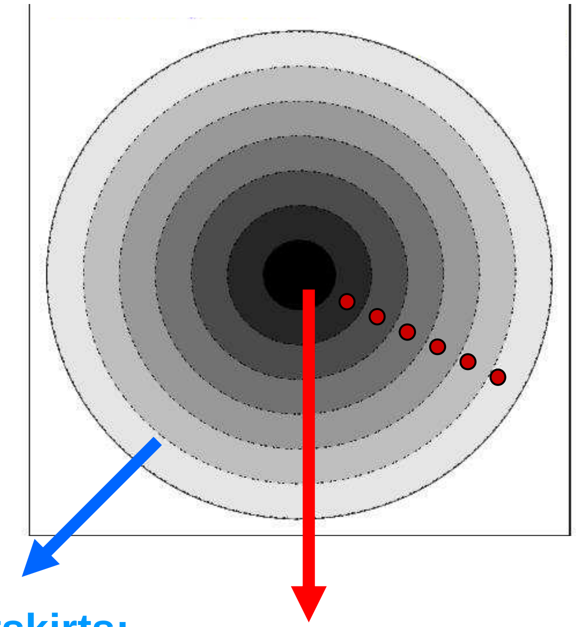
Clump distance: e.g. 500 pc



Global SF Relation

Local perspective:
- **Contour-by-contour basis**
- **One clump is enough**

Clump distance: e.g. 500 pc



Outskirts: slow star formation

Centre: fast star formation

Clump distance: e.g. 5 kpc

$(\Sigma_{gas}^{glob}, \Sigma_{SFR}^{glob})$

SFR tracers: e.g. Vutisalchavakul & Evans 2013

Global perspective:
- **A population of clumps is needed**
- **E.g. HCN(1-0) molecular clumps**
- **To first order: common free-fall time**

Global SF Relation

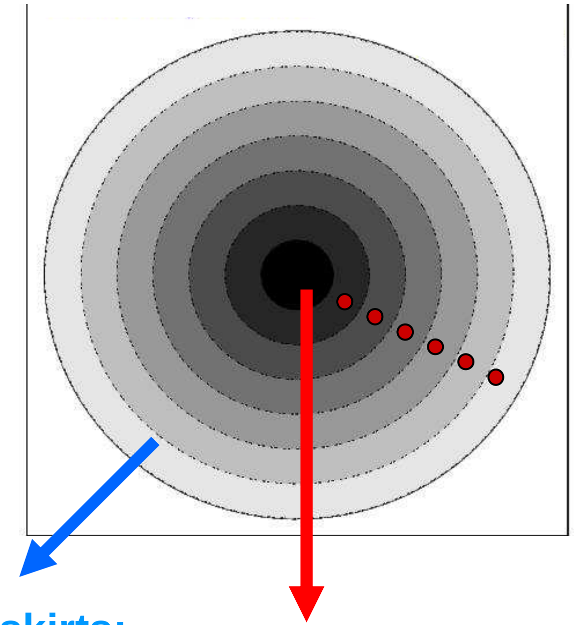
Local perspective:
- **Contour-by-contour basis**
- **One clump is enough**

Clump distance: e.g. 5 kpc

$(\Sigma_{gas}^{glob}, \Sigma_{SFR}^{glob})$

SFR tracers: e.g. Vutisalchavakul & Evans 2013

Clump distance: e.g. 500 pc



Outskirts: slow star formation

Centre: fast star formation

Global perspective:
- **A population of clumps is needed**
- **E.g. HCN(1-0) molecular clumps.**
- **To first order: common free-fall time**

Global (clump-by-clump) SF relation:

For one clump:

$$SFR \cong \varepsilon_{ff} \frac{m_{gas}}{\tau_{ff}}$$

$$\Sigma_{SFR} \cong \varepsilon_{ff} \frac{\Sigma_{gas}}{\tau_{ff}}$$

$$\Sigma_{SFR} \propto \Sigma_{gas}$$

Slope of 1

Global SF Relation

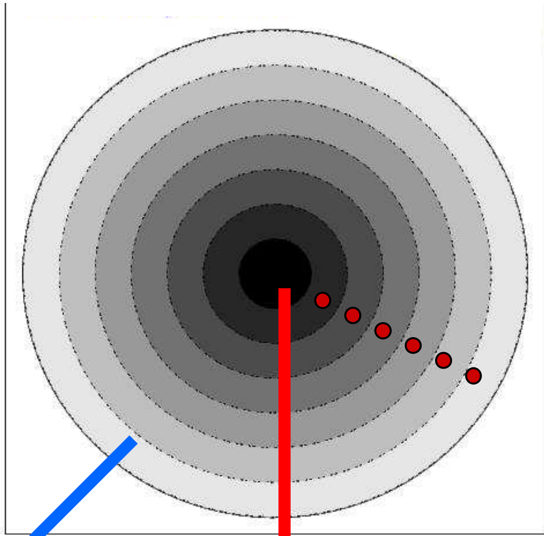
Local perspective:
- **Contour-by-contour basis**
- **One clump is enough**

Clump distance: e.g. 5 kpc

$(\Sigma_{gas}^{glob}, \Sigma_{SFR}^{glob})$

SFR tracers: e.g. Vutisalchavakul & Evans 2013

Clump distance: e.g. 500 pc



Outskirts: slow star formation

Centre: fast star formation

Global perspective:
- **A population of clumps is needed**
- **E.g. HCN(1-0) molecular clumps.**
- **To first order: common free-fall time**

Global (clump-by-clump) SF relation:

For one clump :

$$SFR \cong \varepsilon_{ff} \frac{m_{gas}}{\tau_{ff}}$$

$$\Sigma_{SFR} \cong \varepsilon_{ff} \frac{\Sigma_{gas}}{\tau_{ff}}$$

$$\Sigma_{SFR}^{global} \propto \Sigma_{gas}^{global}$$

Slope of 1

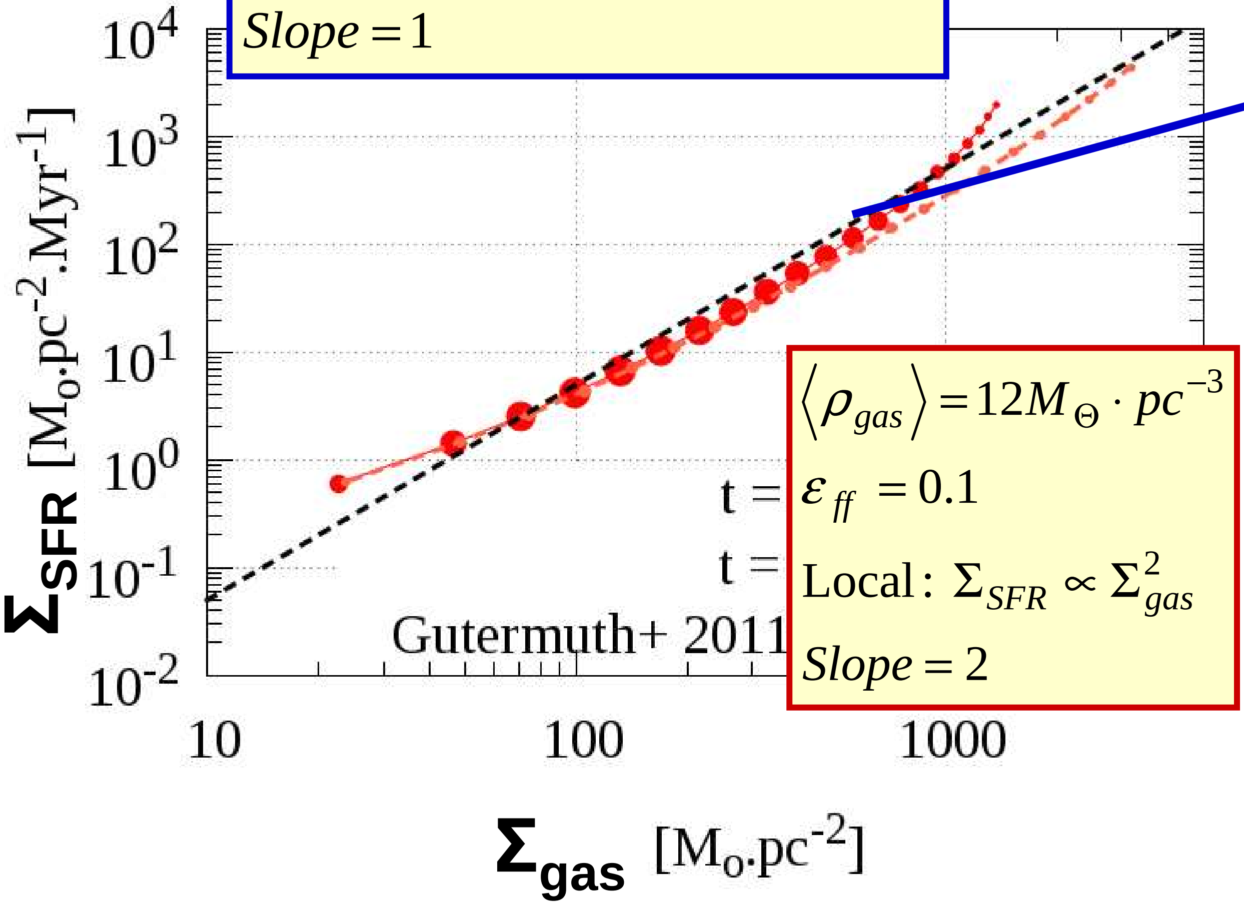
Break-Point in Composite SF Relation

$$\langle \rho_{gas} \rangle = 700 M_{\Theta} \cdot pc^{-3} \ (\mathrm{HCN}_{1\text{-}0})$$

$$\varepsilon_{ff} = 0.1$$

$$Global: \ \Sigma_{SFR} \propto \Sigma_{gas}$$

$$Slope = 1$$



$$\langle \rho_{gas} \rangle = 12 M_{\Theta} \cdot pc^{-3}$$

$$\varepsilon_{ff} = 0.1$$

$$\mathrm{Local}: \ \Sigma_{SFR} \propto \Sigma_{gas}^2$$

$$Slope = 2$$

Break-Point in Composite SF Relation

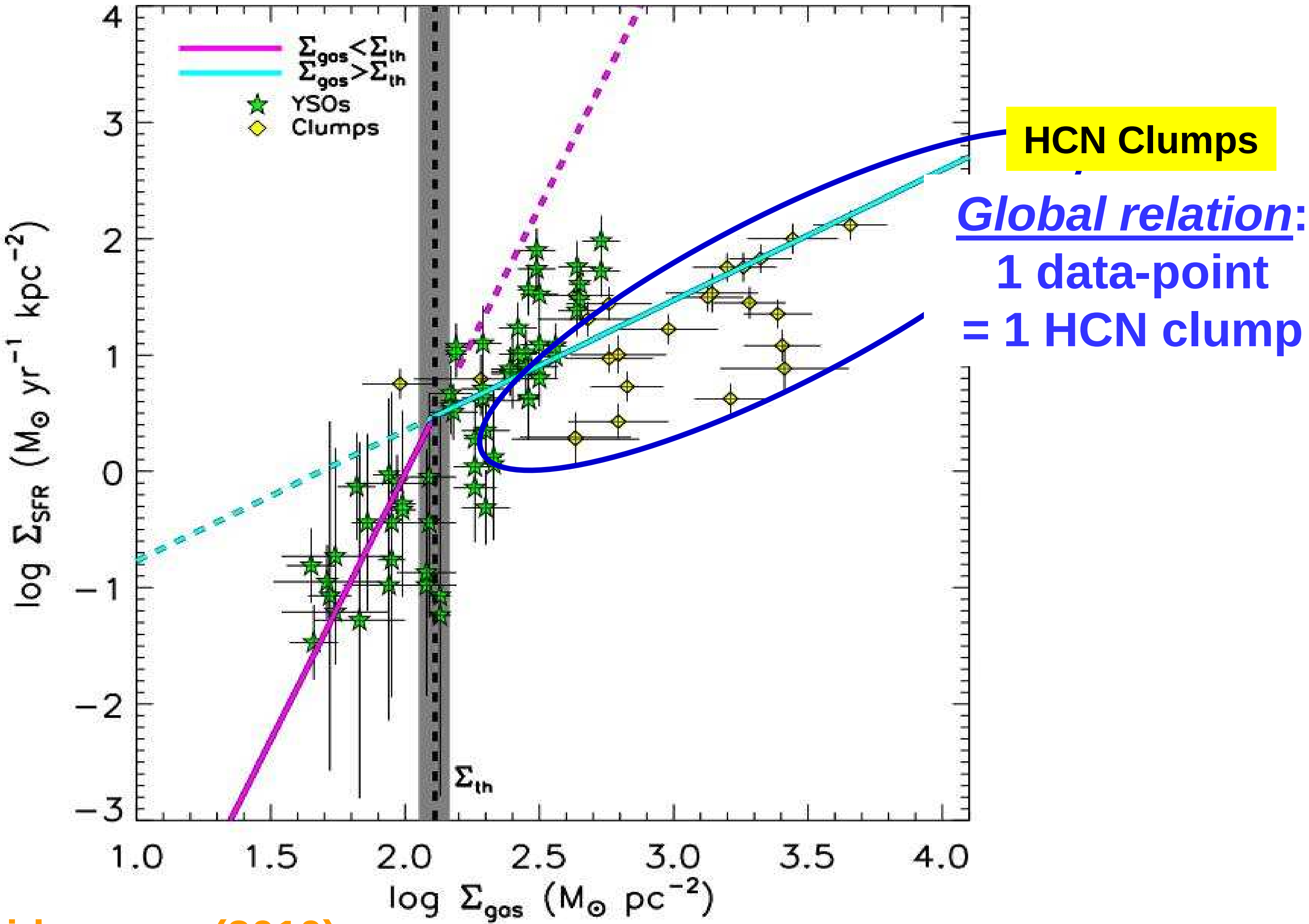
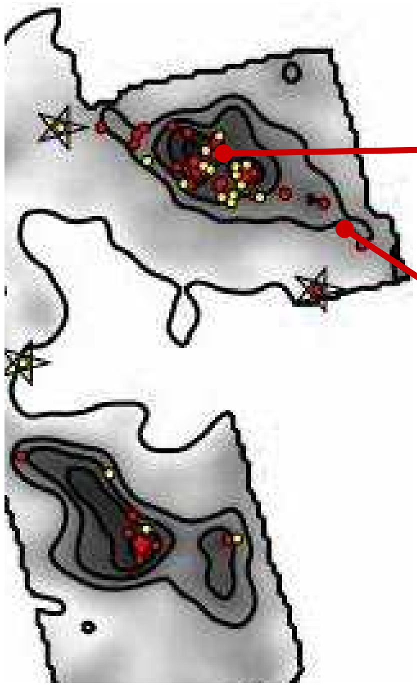
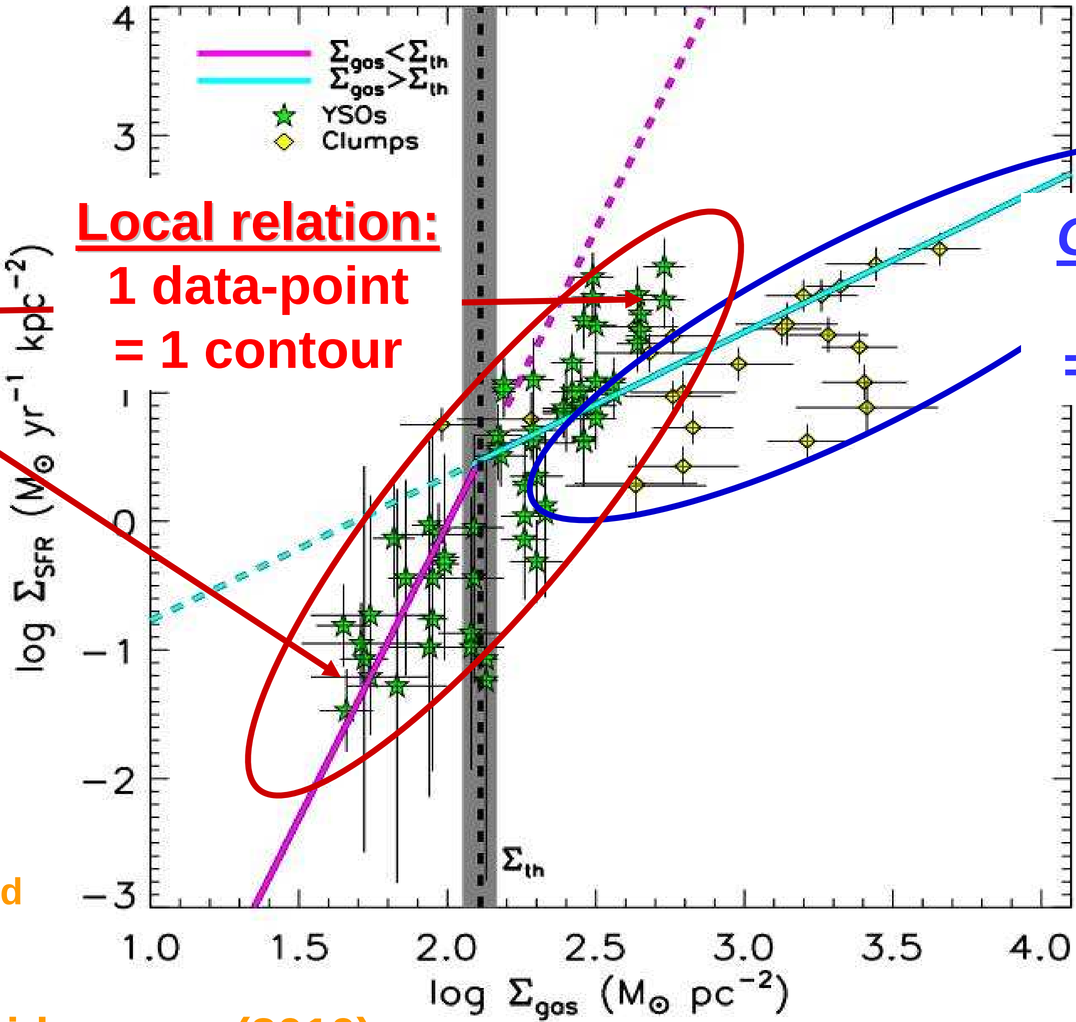


Fig. 10, Heiderman+ (2010)

Break-Point in Composite SF Relation



Perseus molecular cloud



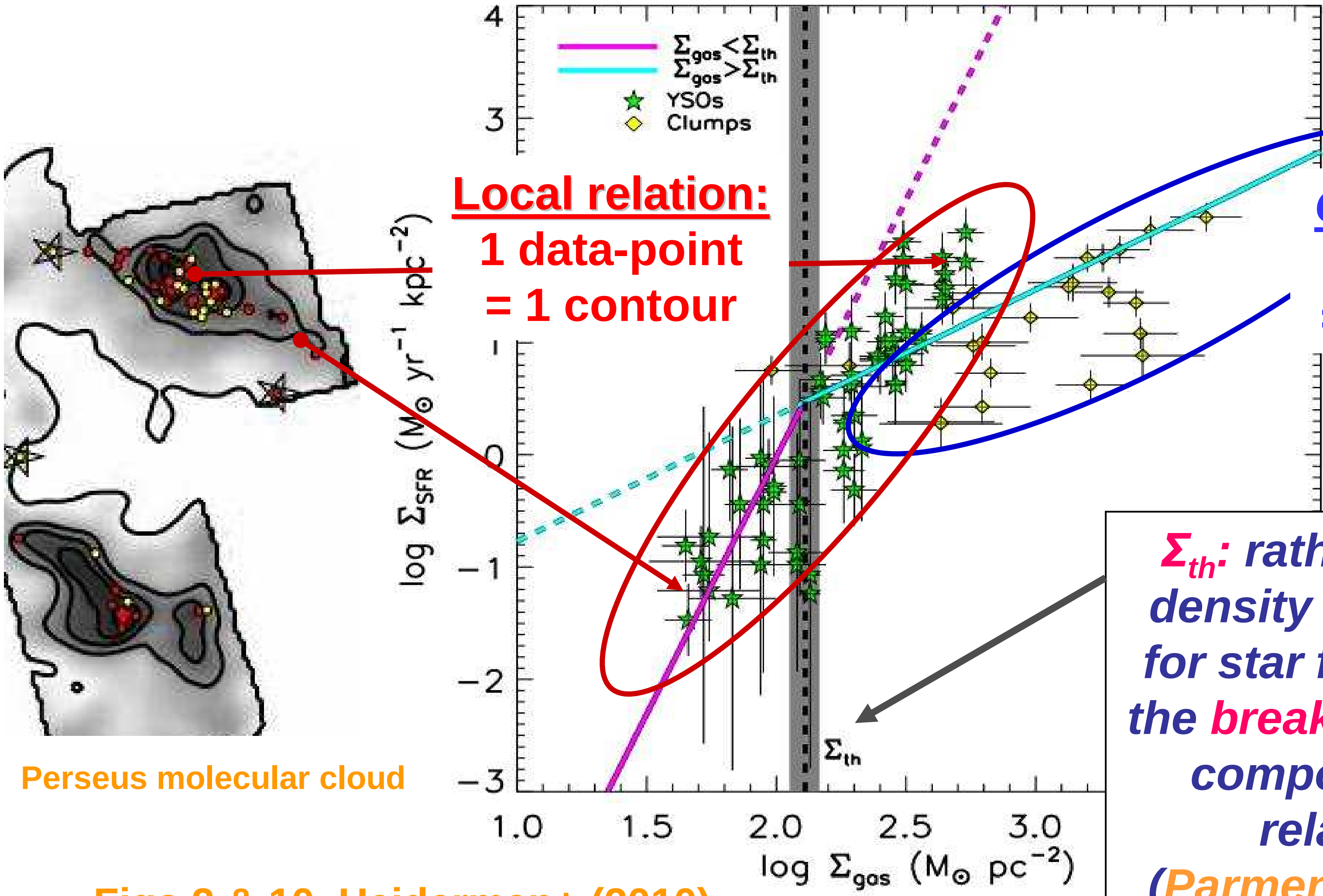
Local relation:
1 data-point
= 1 contour

HCN Clumps

***Global relation*:**
1 data-point
= 1 HCN clump

Figs 2 & 10, Heiderman+ (2010)

Interpretation of Break-Point



Perseus molecular cloud

Figs 2 & 10, Heiderman+ (2010)

HCN Clumps

***Global relation*:**
1 data-point
= 1 HCN clump

Σ_{th}: rather than a density threshold for star formation, the break-point of a composite SF relation (Parmentier 2016)

Star Formation Relations and Co.

$$\text{Contour-by-contour:}$$
$$\Sigma_{SFR} \approx \Sigma_{gas}^{2}$$

$$\text{Clump-by-clump (constant } \langle \rho_{gas} \rangle \text{):}$$
$$\Sigma_{SFR} \propto \langle \Sigma_{gas} \rangle^{1}$$

Star Formation Relations and Co.

Shell – by – shell :

$$\rho_{SFR} \cong \varepsilon_{ff} \frac{\rho_{gas}}{\tau_{ff}} \propto \varepsilon_{ff} \frac{\rho_{gas}}{(\rho_{gas})^{-1/2}} \propto \rho_{gas}^{3/2}$$

Contour – by – contour :

$$\Sigma_{SFR} \approx \Sigma_{gas}^{2}$$

Clump – by – clump (constant $\langle \rho_{gas} \rangle$) :

$$\Sigma_{SFR} \propto \langle \Sigma_{gas} \rangle^{1}$$

Star Formation Relations and Co.

Shell – by – shell :

$$\rho_{SFR} \cong \varepsilon_{ff} \frac{\rho_{gas}}{\tau_{ff}} \propto \varepsilon_{ff} \frac{\rho_{gas}}{\left(\rho_{gas}\right)^{-1/2}} \propto \rho_{gas}^{3/2}$$

Contour – by – contour :

$$\Sigma_{SFR} \approx \Sigma_{gas}^{2}$$

Clump – by – clump (constant $\langle \rho_{gas} \rangle$) :

$$\Sigma_{SFR} \propto \langle \Sigma_{gas} \rangle^{1}$$

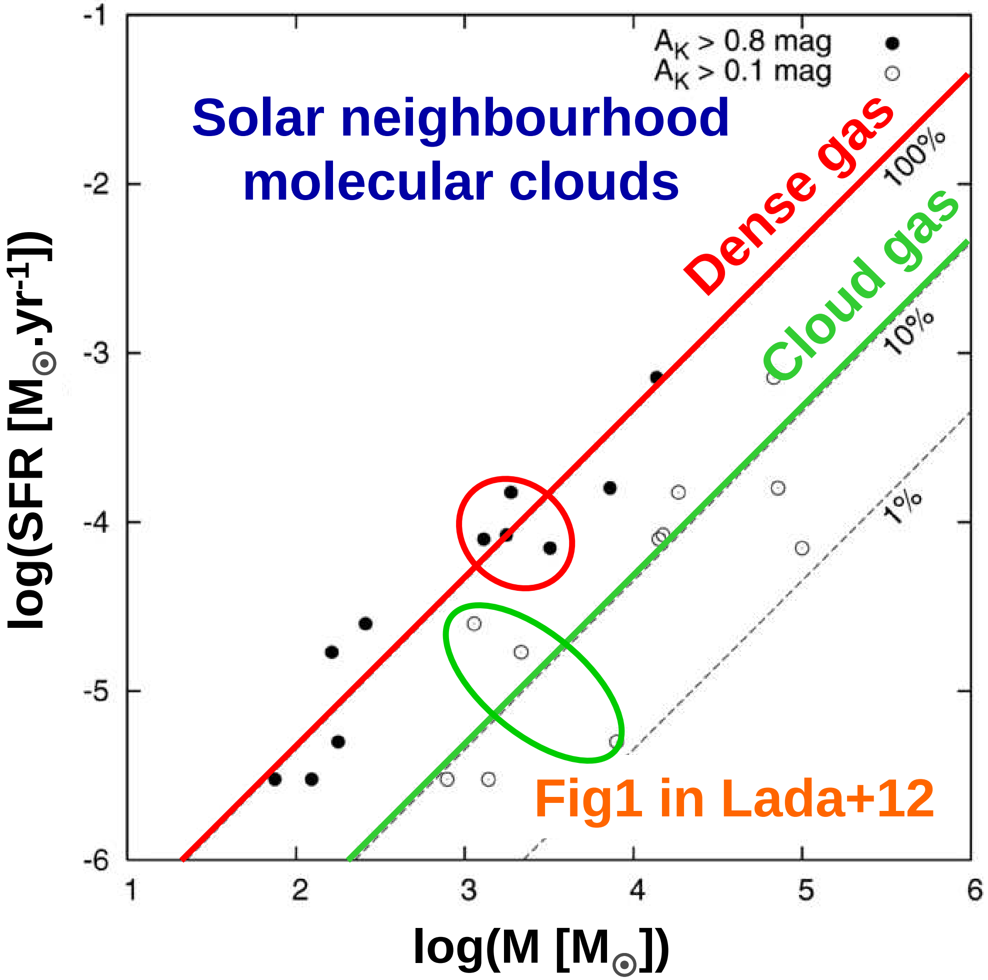
- **ε_{ff}: the slope is not necessarily 1.5**
- **Slope ≠ 1.5 does not imply that star formation does not proceed with a constant ε_{ff}**

Take-Away Messages

- **A composite SF relation is not an appropriate tool to decide on the existence of a density threshold for star formation (Parmentier 2016)**

- **The diversity of slopes of observed star formation relations depends on:**
  - **<u>what is measured,</u>**
  - **<u>how it is measured,</u>**
  - **on top of SF physics**

The (Dense) Gas Mass - Star Formation Rate Relation



- Molecular clouds of the Solar neighbourhood. Their SFR is:
  - tightly correlated with their dense gas mass (•)
  - loosely correlated with their total mass (○)
- Dense-gas mass vs SFR linear relation:
  - Gao & Solomon 2004
  - Wu+2005, Wu+2010
  - Lada+2012
  - Vutisalchavakul+2016
- Hints for superlinear behaviour in (U)LIRGS and high-z galaxies
  - Gao+ 2007
  - Garcia-Carpo+ 2008
  - Garcia-Burillo+ 2015

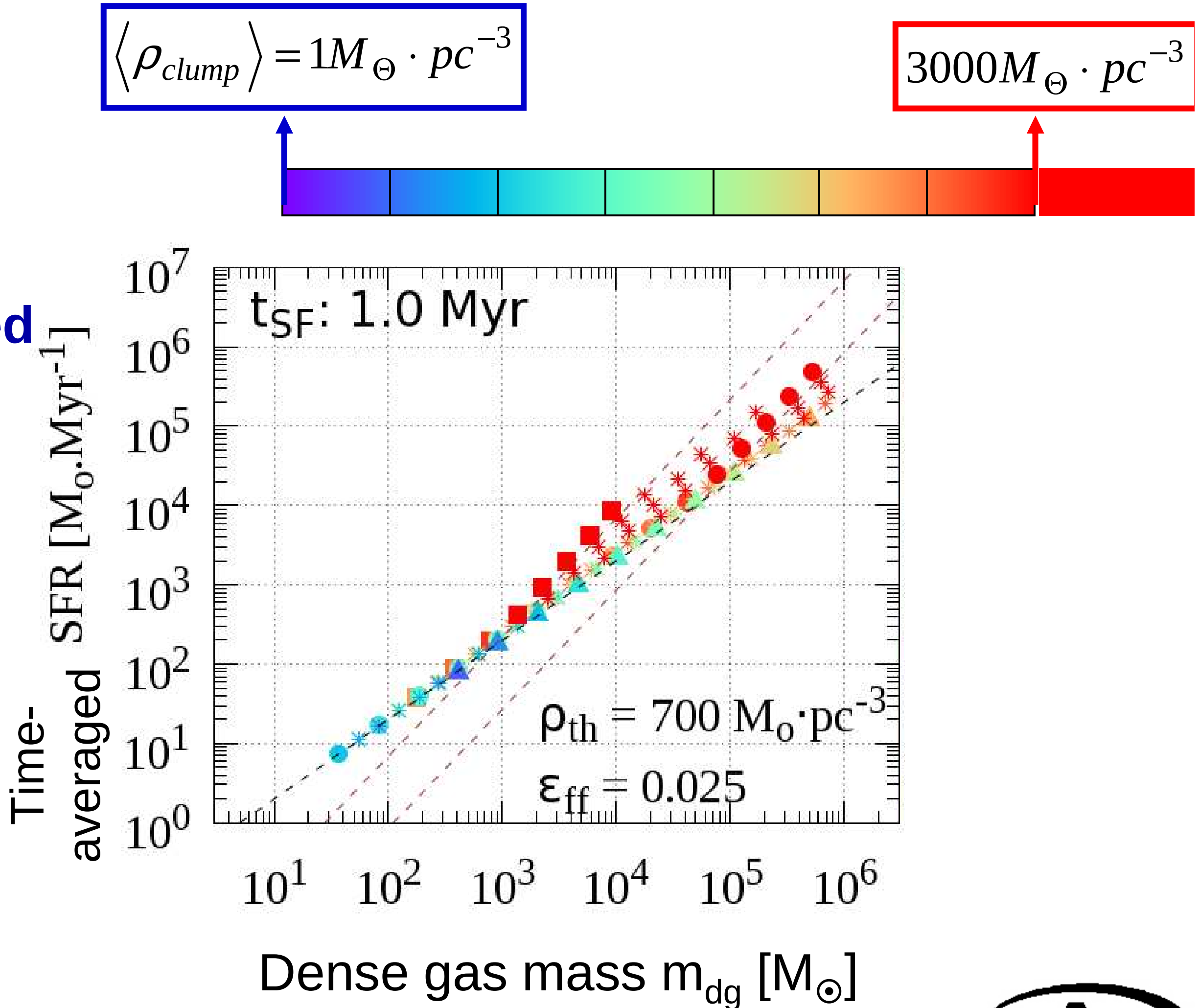
Star Formation Relation (m_{dg})

- **Consider a grid of model clumps (m_{clump}, r_{clump})**
  - **Mass m_{clump}: 250 - 10^6 $M_\odot$**
  - **Radius r_{clump}: 0.5 - 8 pc**
  - **Centrally-concentrated**

$$\rho_{clump}(r) \propto r^{-2}$$

- **Two 'families':**
  - **Very dense clumps**
  - **'Not-so-dense' clumps**

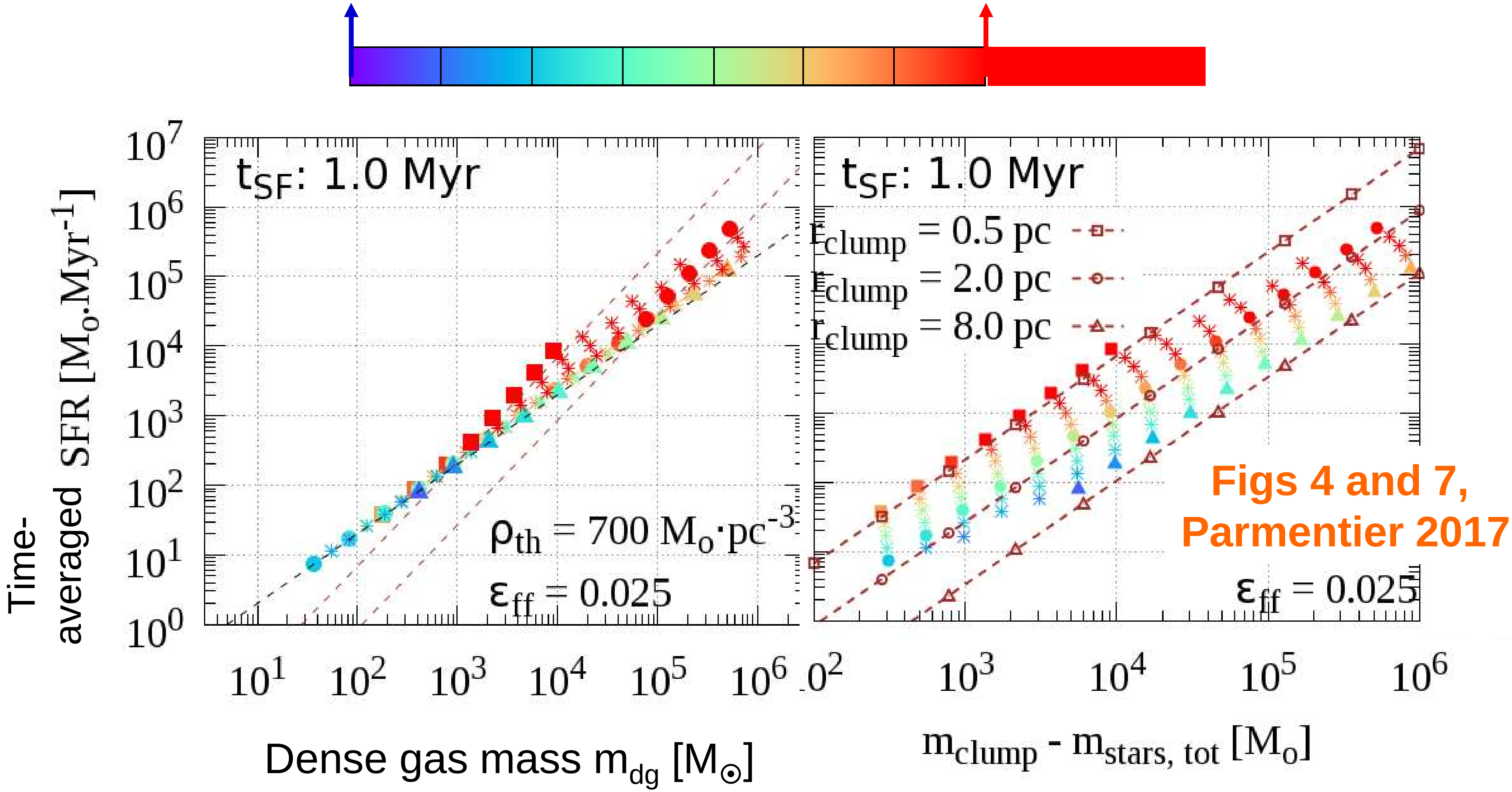
Based on Fig5, Parmentier 2017



SF Relations with Dense and Total Gas Masses

$\langle \rho_{clump} \rangle = 1 M_{\Theta} \cdot pc^{-3}$

$3000 M_{\Theta} \cdot pc^{-3}$



Figs 4 and 7, Parmentier 2017

With clump dense gas **With clump total gas**

Take-Away Message

Local-density driven cluster formation models naturally reproduce:

- **the tight linear star formation relation in terms of the clump dense-gas mass**
- **the loose star formation relation in terms of the clump total gas mass**

as was observed by Lada+2012

Parmentier (2017)