# Star Formation Relations in the Galactic Disc

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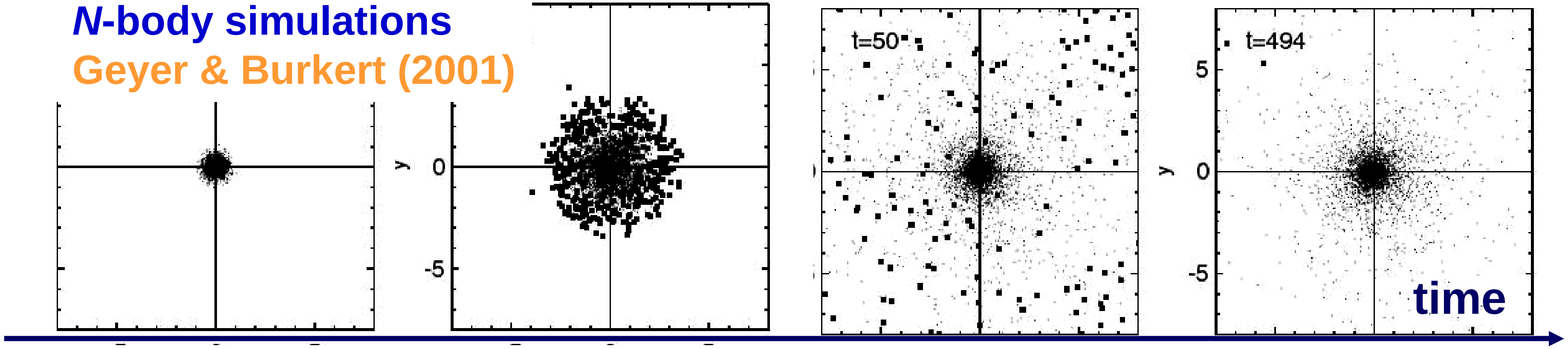
# Post-Gas-Expulsion Cluster Evolution

- **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 dynamical response depends 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*)**
  - **Star cluster structure (e.g. hierarchical, *Farias+ 2015*)**
  - **…**

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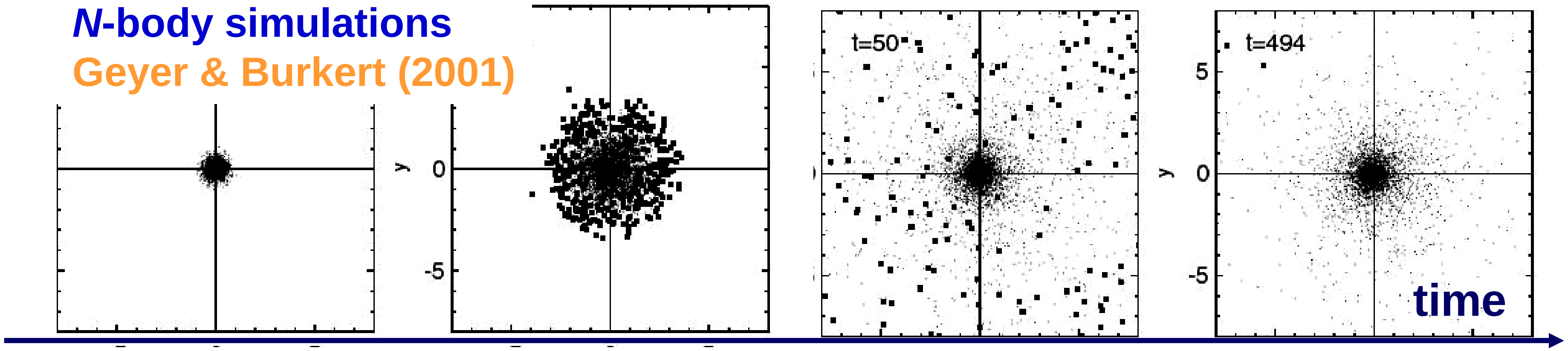


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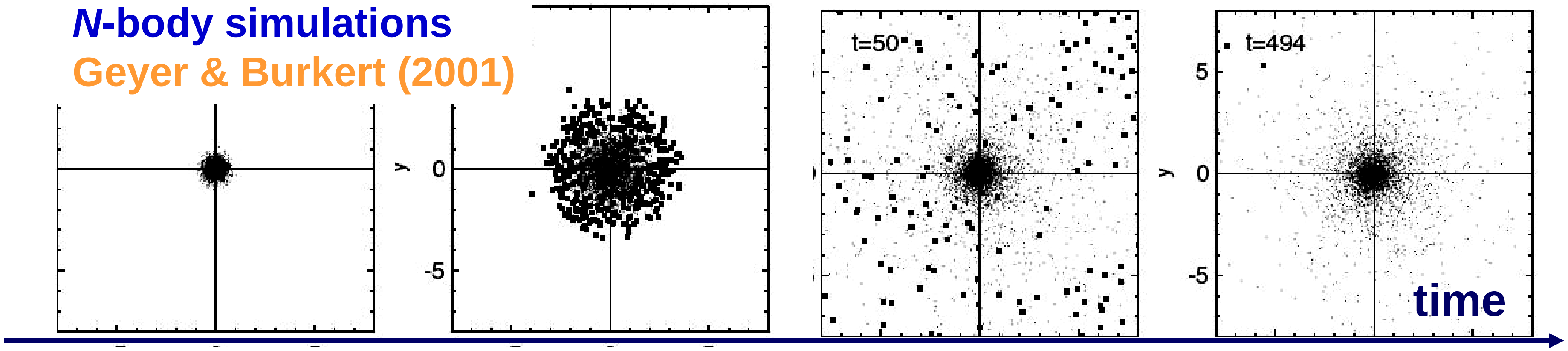


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**How are the gas and stars of a nascent cluster distributed with respect to each other at gas expulsion?**

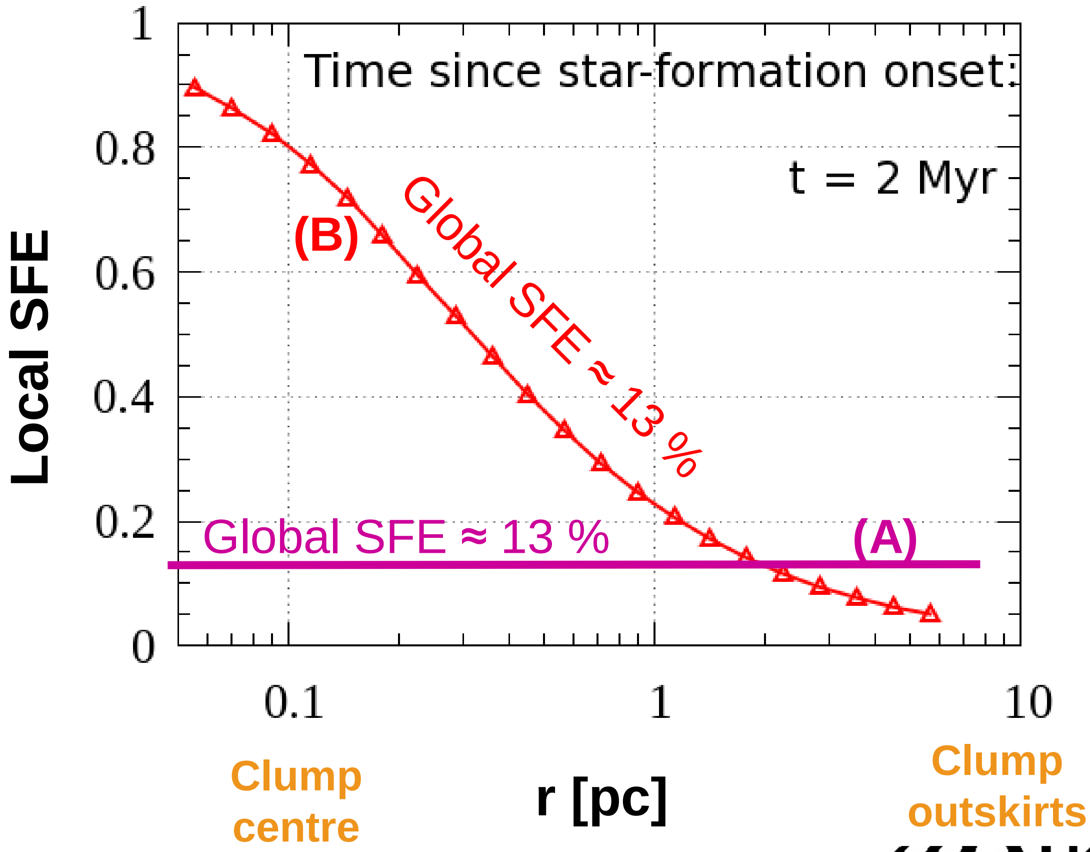
# SFE Radial Profile inside a Forming Cluster

- 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

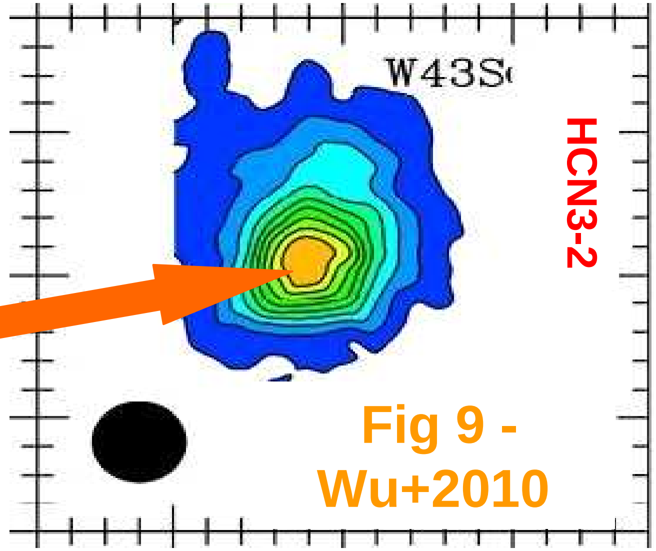
Parmentier & Pfalzner 2013, Fig10



# 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**




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

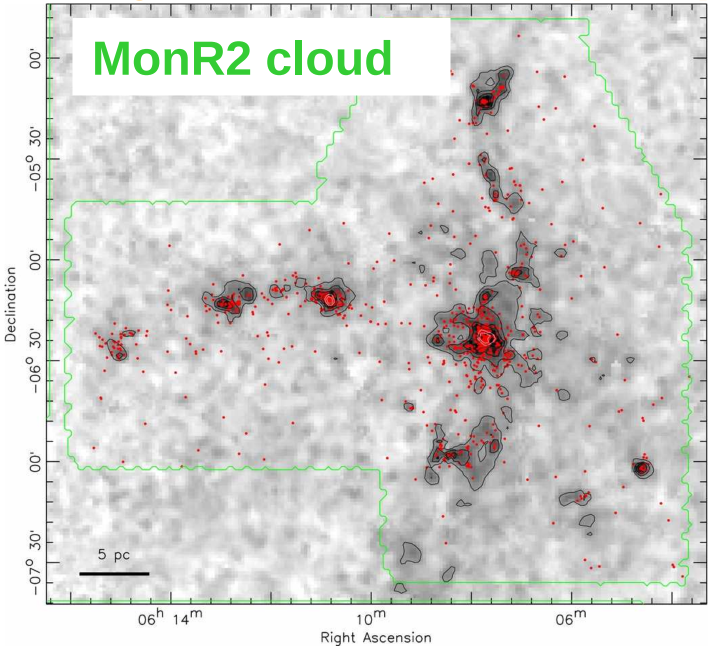
Free – fall time :

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

- **Denser**
- **Faster**

# Scenario A or B? Insights from Observations

Fig. 1, Gutermuth+ (2011)




**Molecular clouds in the Solar neighbourhood:**

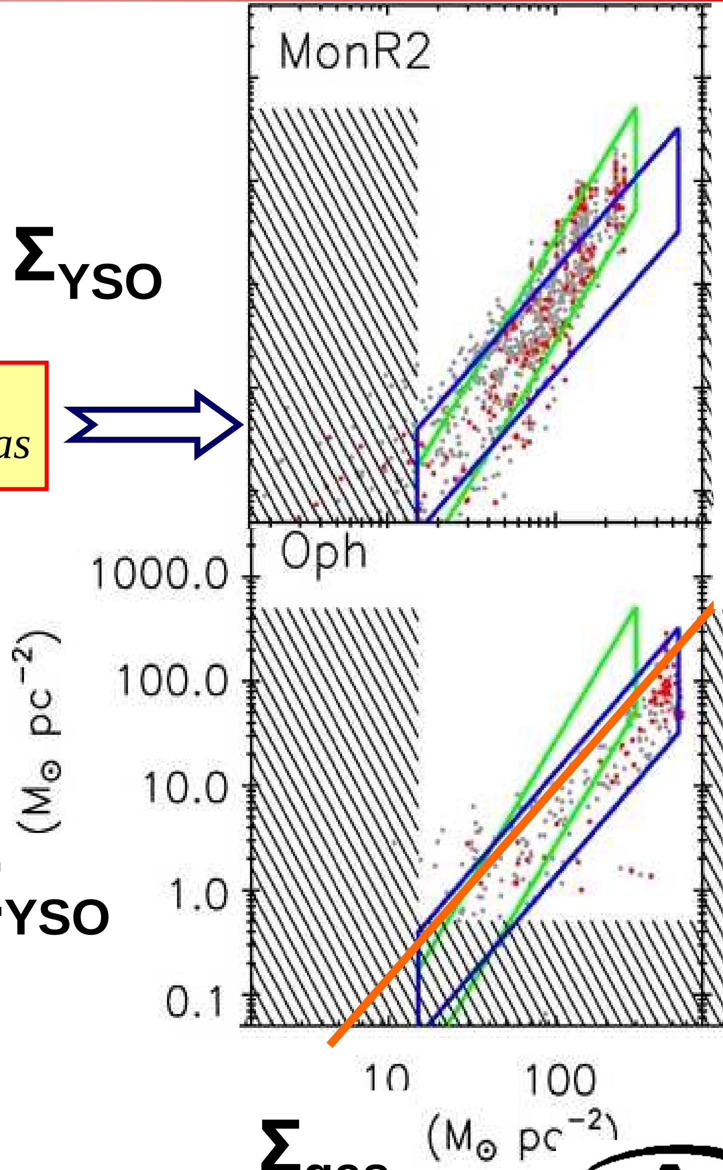
- **The local star formation efficiency depends on gas density**

- **Scenario B expected**

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

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

$\Sigma_{YSO}$

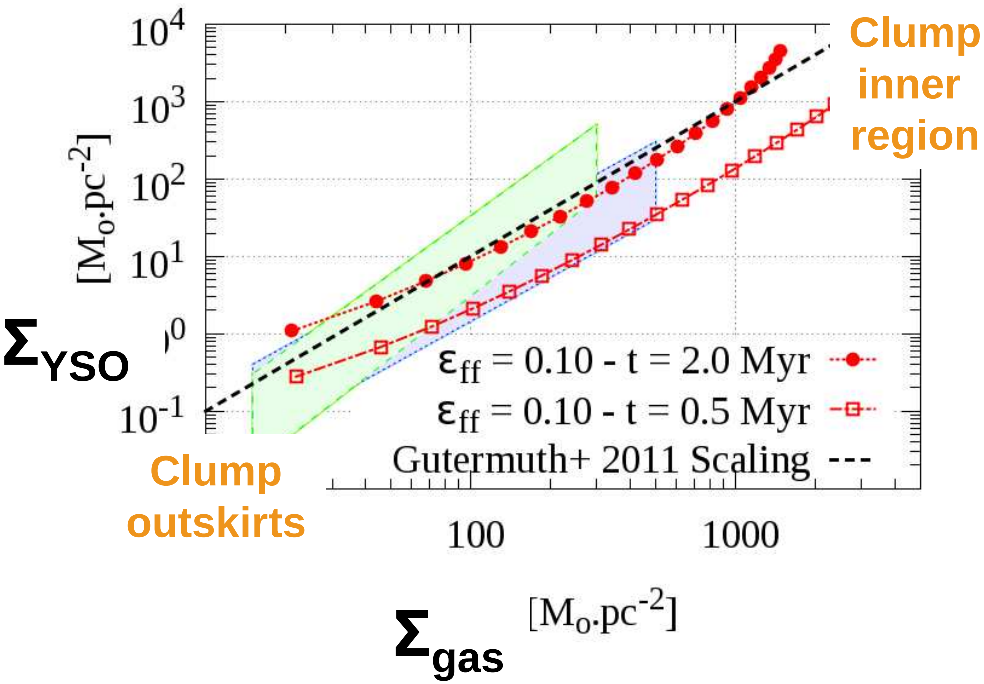



$\Sigma_{gas}$

Fig. 9, Gutermuth+ (2011)

# 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)**

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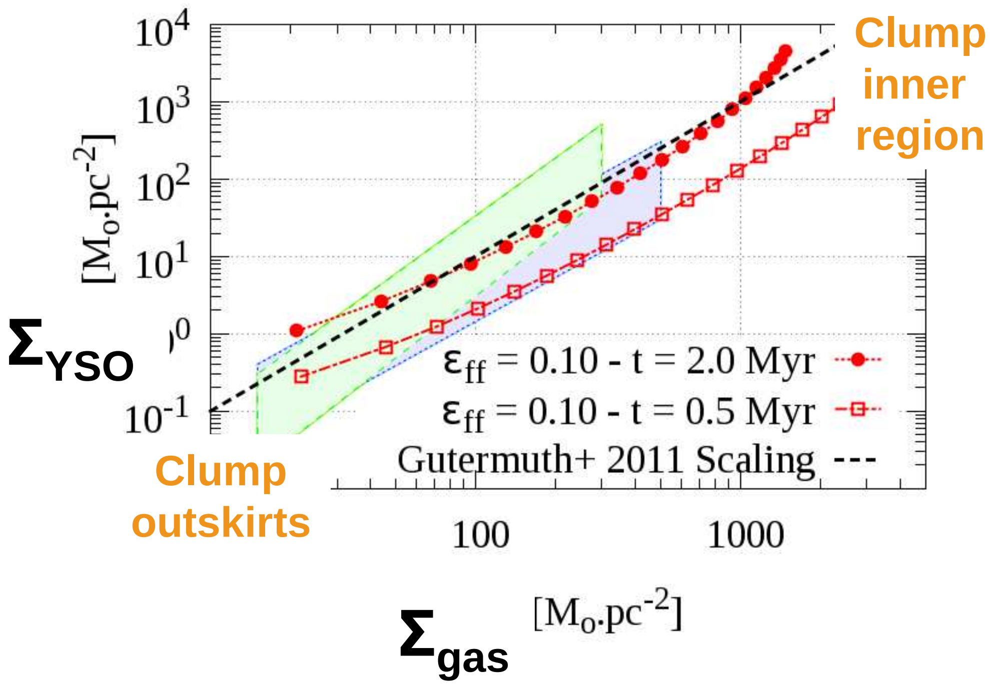


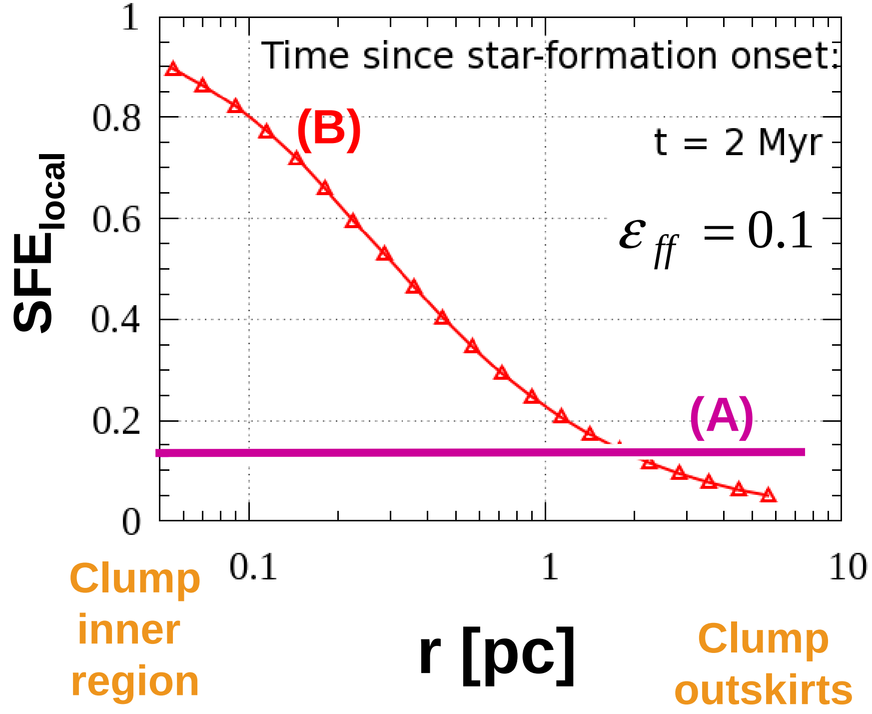


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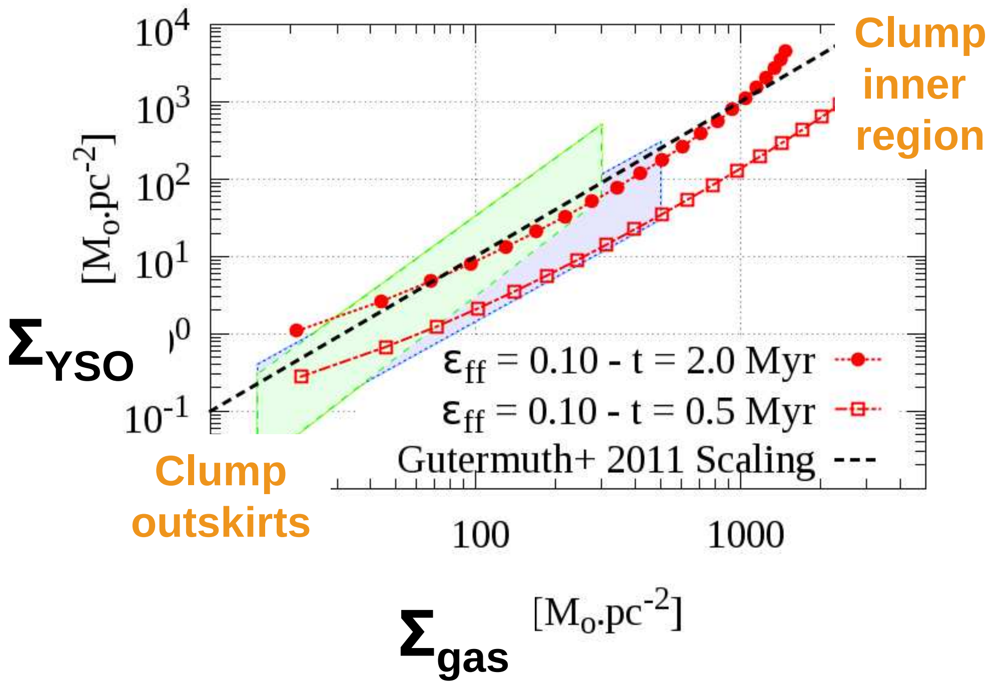


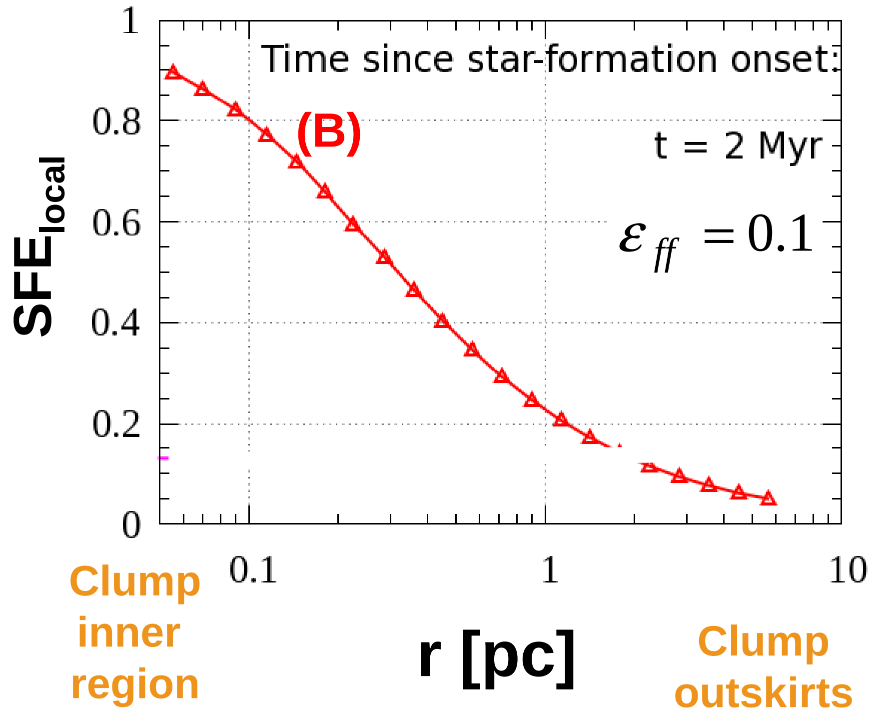


**Local Star Formation Relation:**

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**See also Lombardi+2013, Lada+2013**

**Local star formation efficiency :**

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

**Figs 3 and 10, Parmentier & Pfalzner (2013)**

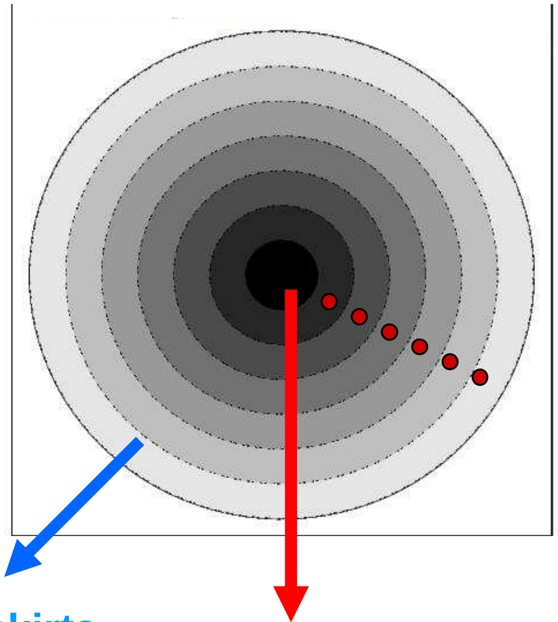
# Take-Away Messages

- If star formation proceeds with a constant $\varepsilon_{ff}$:
  - Quadratic local star formation relation
    Parmentier & Pfalzner (2013)
  - Improved star cluster survival after residual star-forming gas expulsion
    Shukirgaliyev+ 2017 (see also Adams 2000)

# Local SF Relation

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

Clump distance: e.g. 500 pc



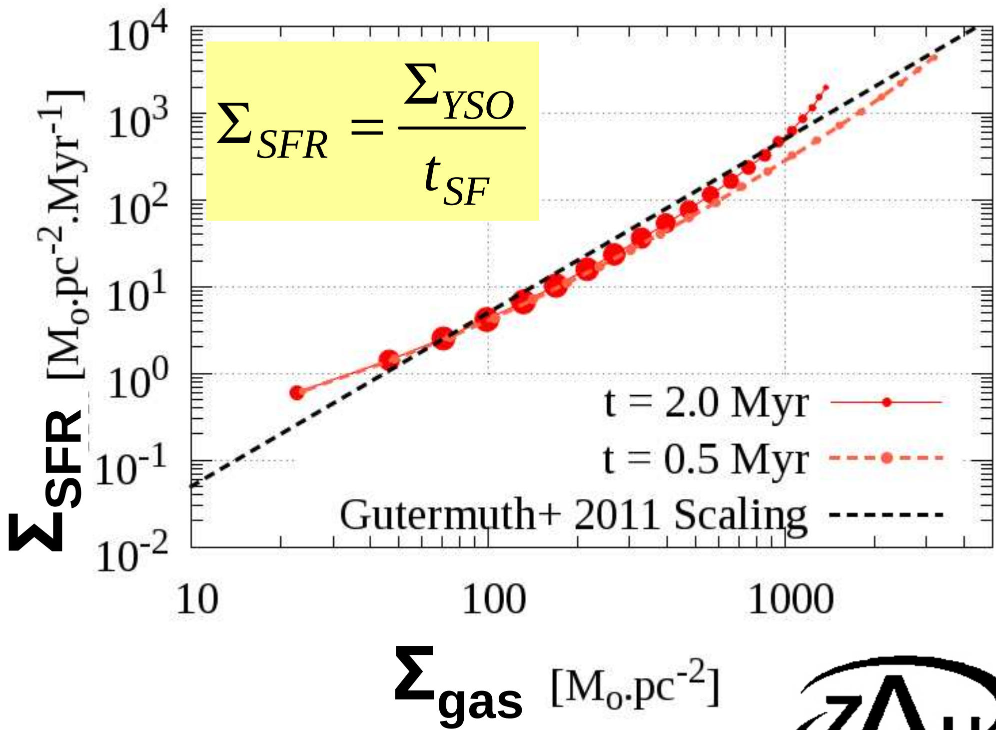
**Outskirts: slow star formation**

**Centre: fast star formation**

**Local (contour-by-contour) SF relation:**

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

***Slope of 2***



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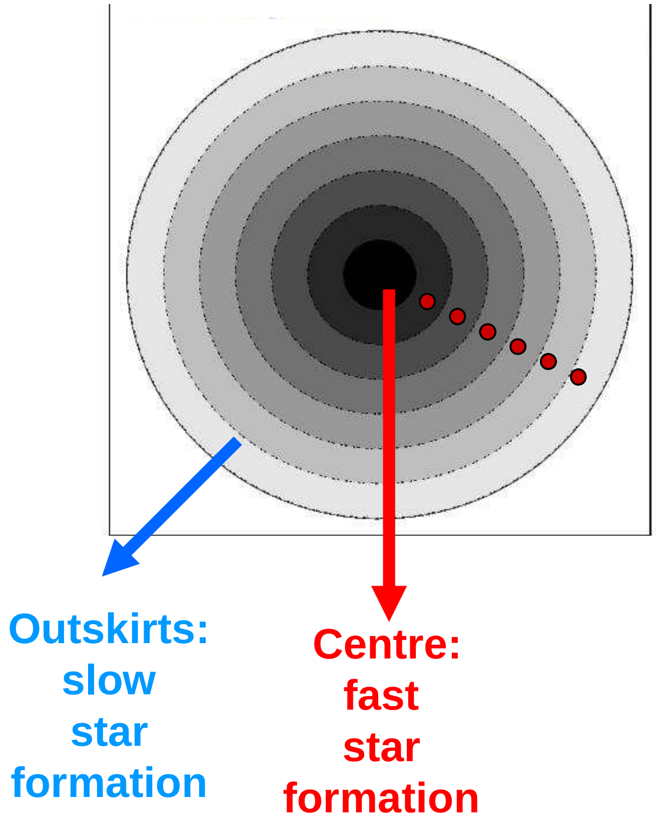

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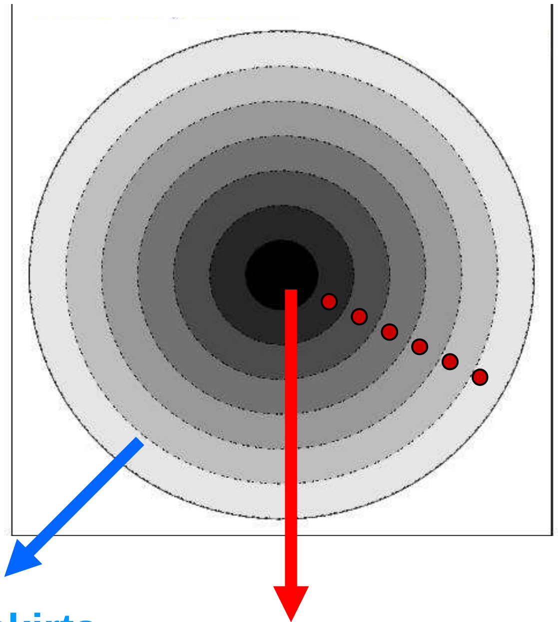

**Outskirts: slow star formation**

**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**

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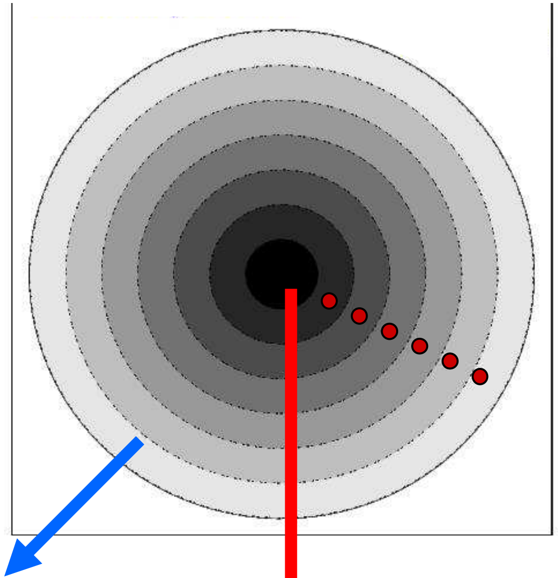

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- **A population of clumps is needed**
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**Global (clump-by-clump) SF relation:**

For one clump :

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

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

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

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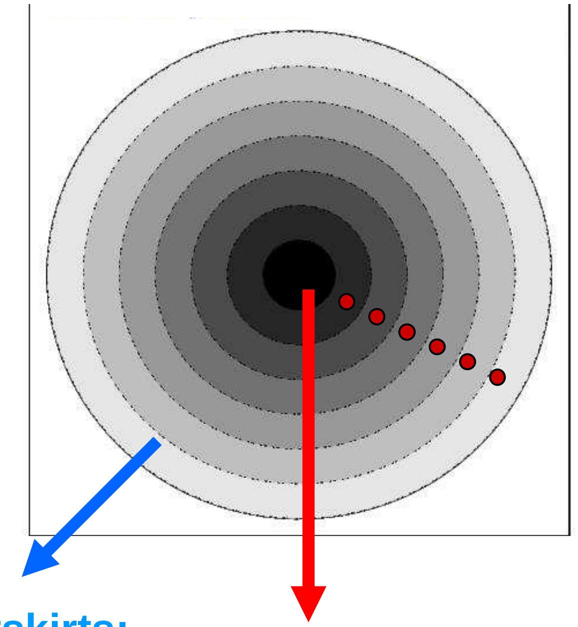


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$$\Sigma_{SFR} \cong \frac{\varepsilon_{ff} \cdot \Sigma_{gas}}{\tau_{ff}}$$

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

***Slope of 1***

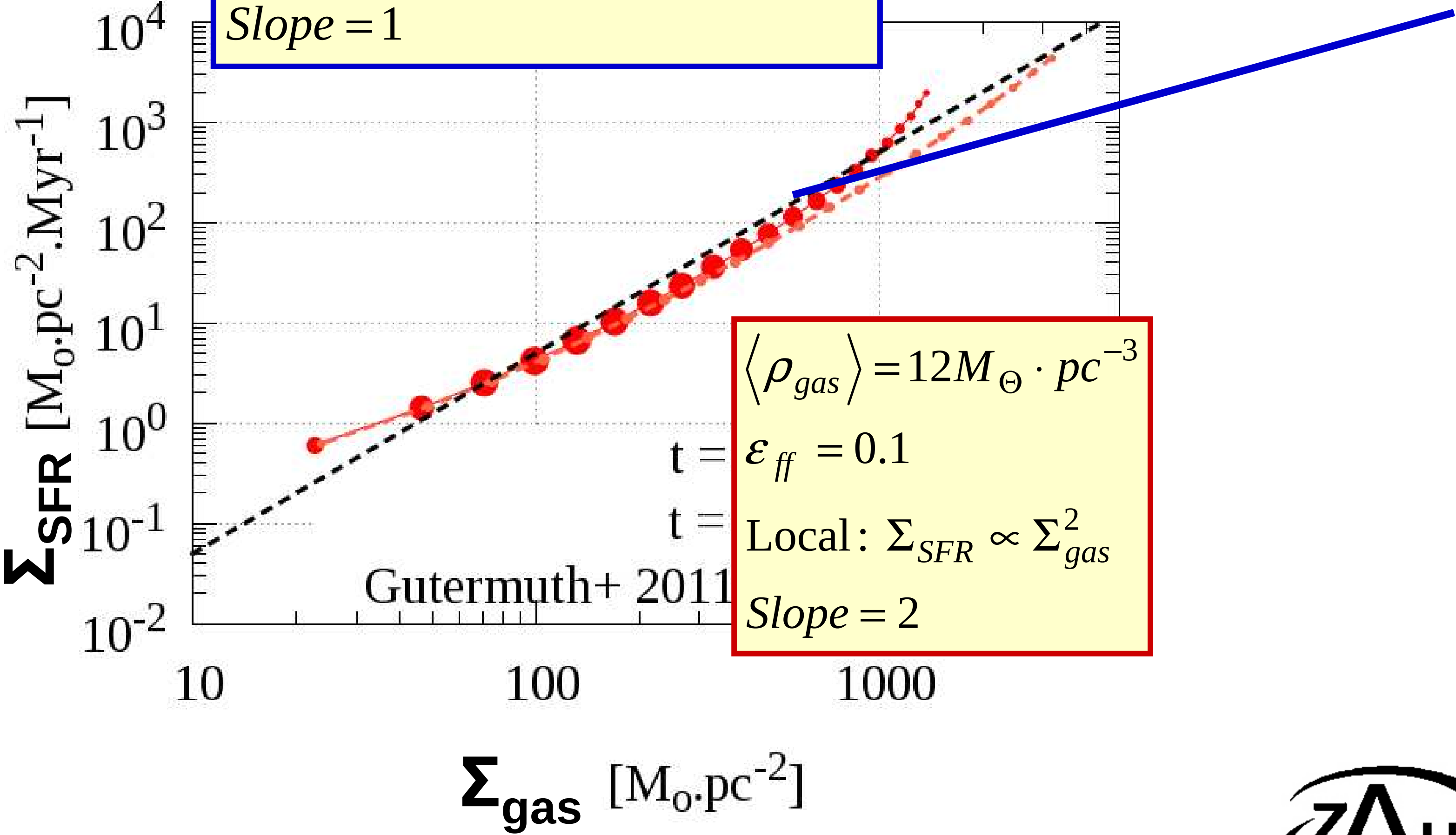
# Break-Point in Composite SF Relation

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

$$\varepsilon_{ff} = 0.1$$

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

$$Slope = 1$$




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

$$\varepsilon_{ff} = 0.1$$

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

$$Slope = 2$$

# Break-Point in Composite SF Relation

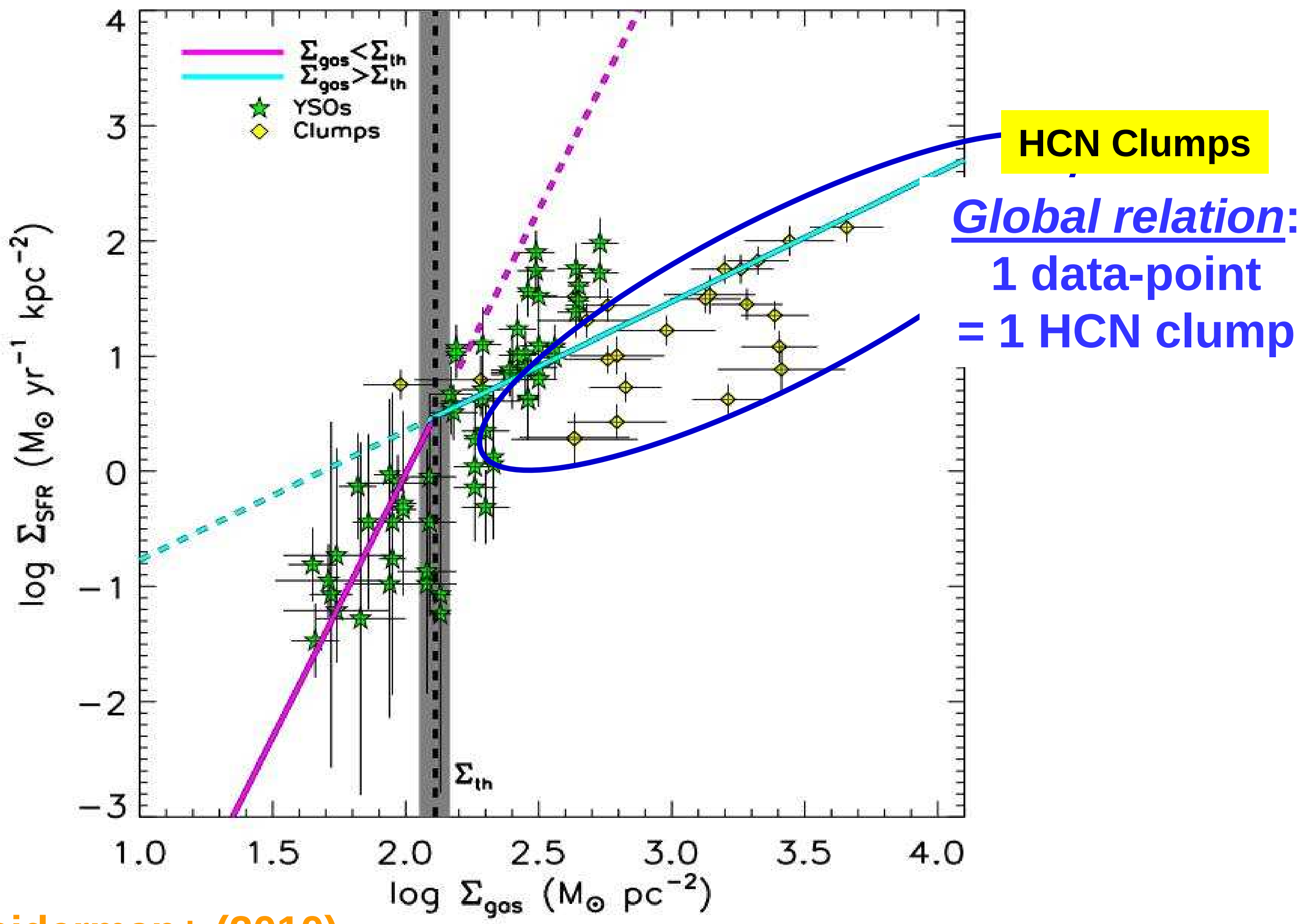
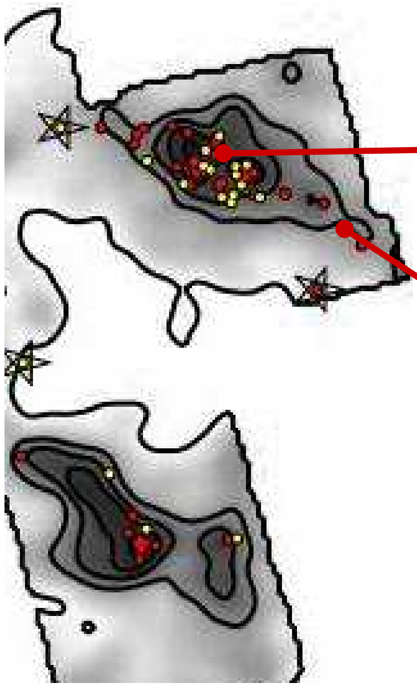
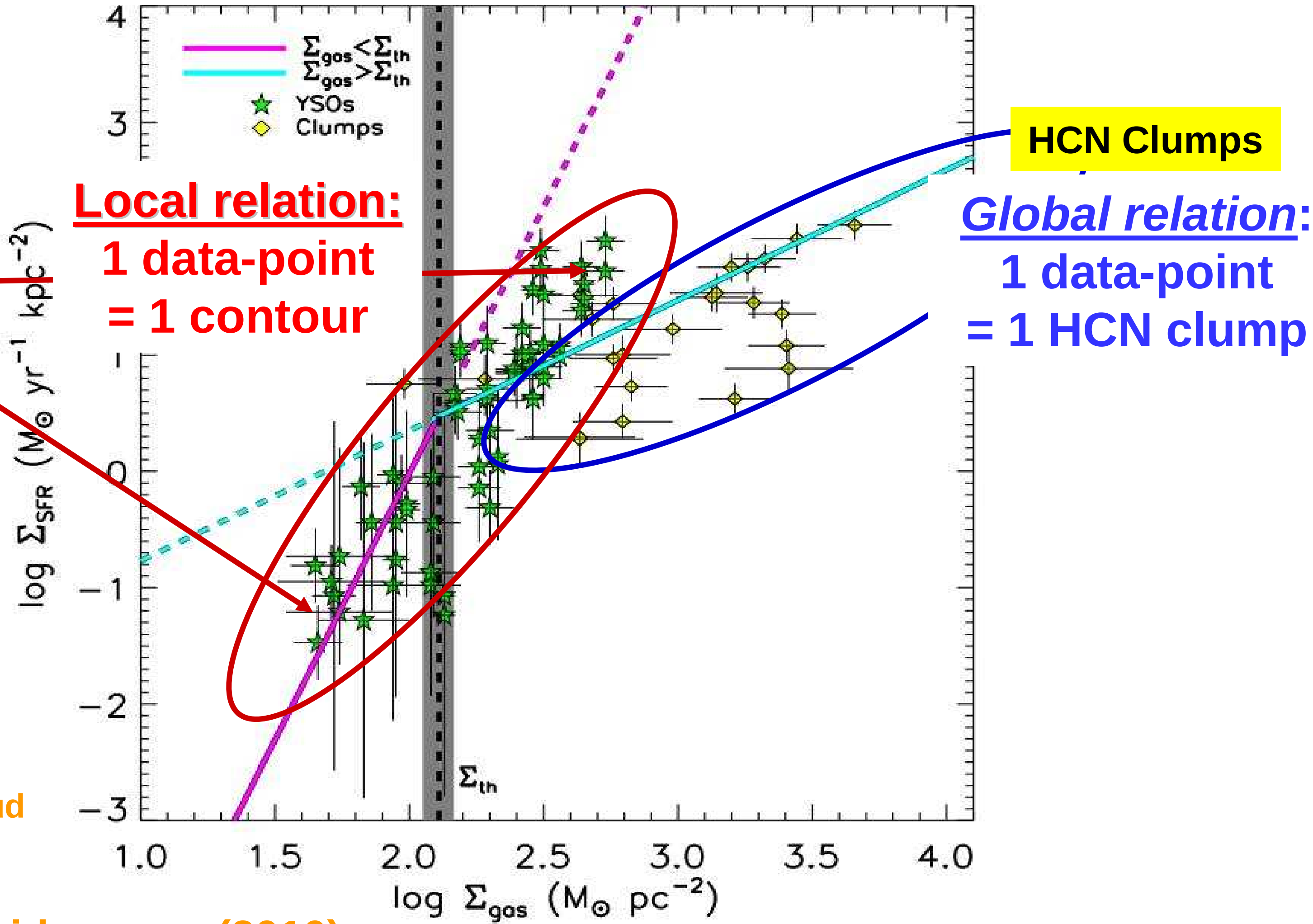



Fig. 10, Heiderman+ (2010)

# Break-Point in Composite SF Relation

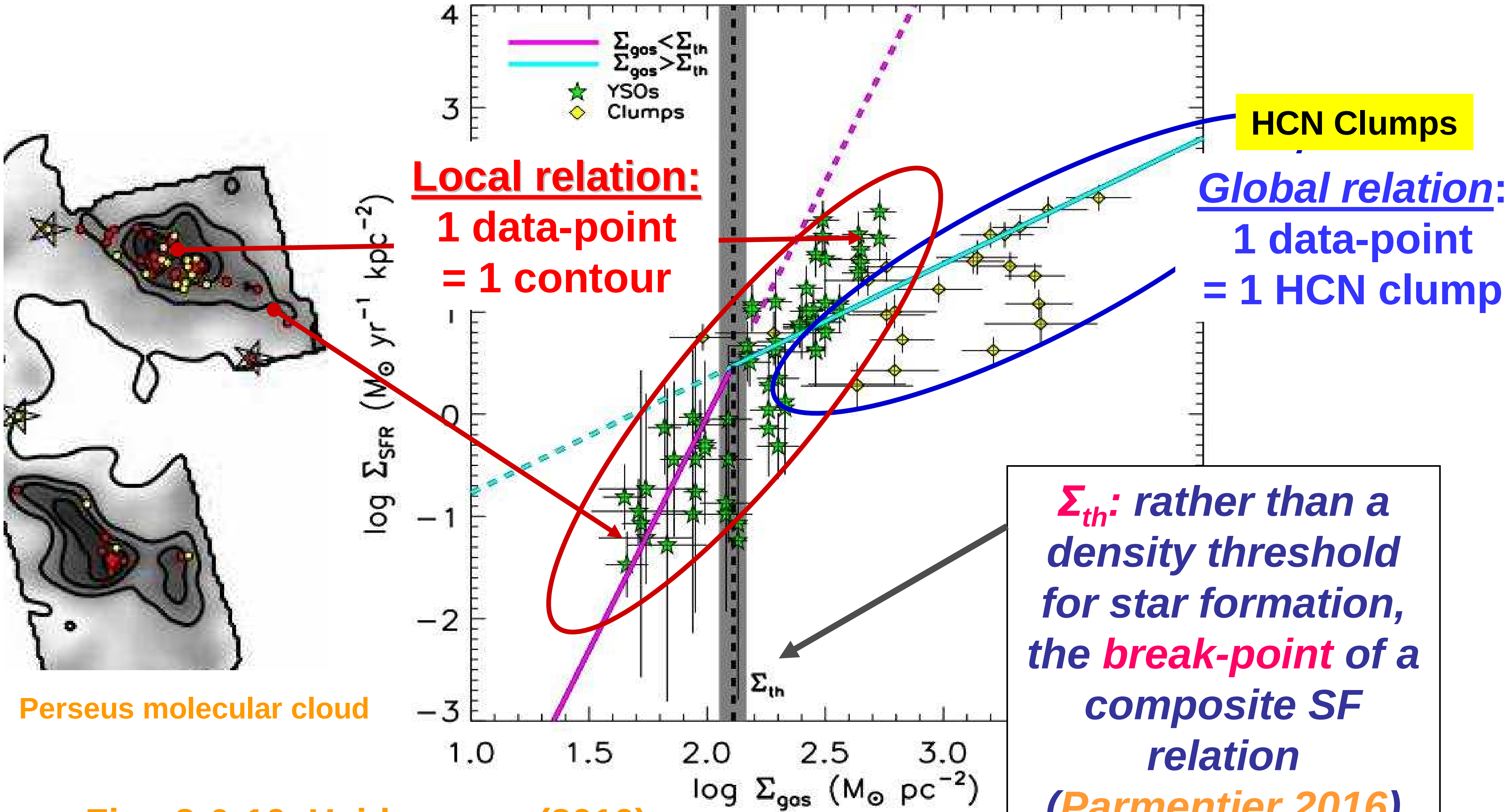


Perseus molecular cloud




Figs 2 & 10, Heiderman+ (2010)

# Interpretation of Break-Point




Perseus molecular cloud

Figs 2 & 10, Heiderman+ (2010)

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

# Star Formation Relations and Co.

$$\text{Contour} - \text{by} - \text{contour}:$$

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

$$\text{Clump} - \text{by} - \text{clump}\,(\text{constant}\,\langle \rho_{gas} \rangle):$$

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

# 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 :

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

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

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- **$\varepsilon_{ff}$: the slope is not necessarily 1.5**
- **Slope ≠ 1.5 does not necessarily discard a scenario in which star formation proceeds with a constant $\varepsilon_{ff}$**

# Take-Away Messages

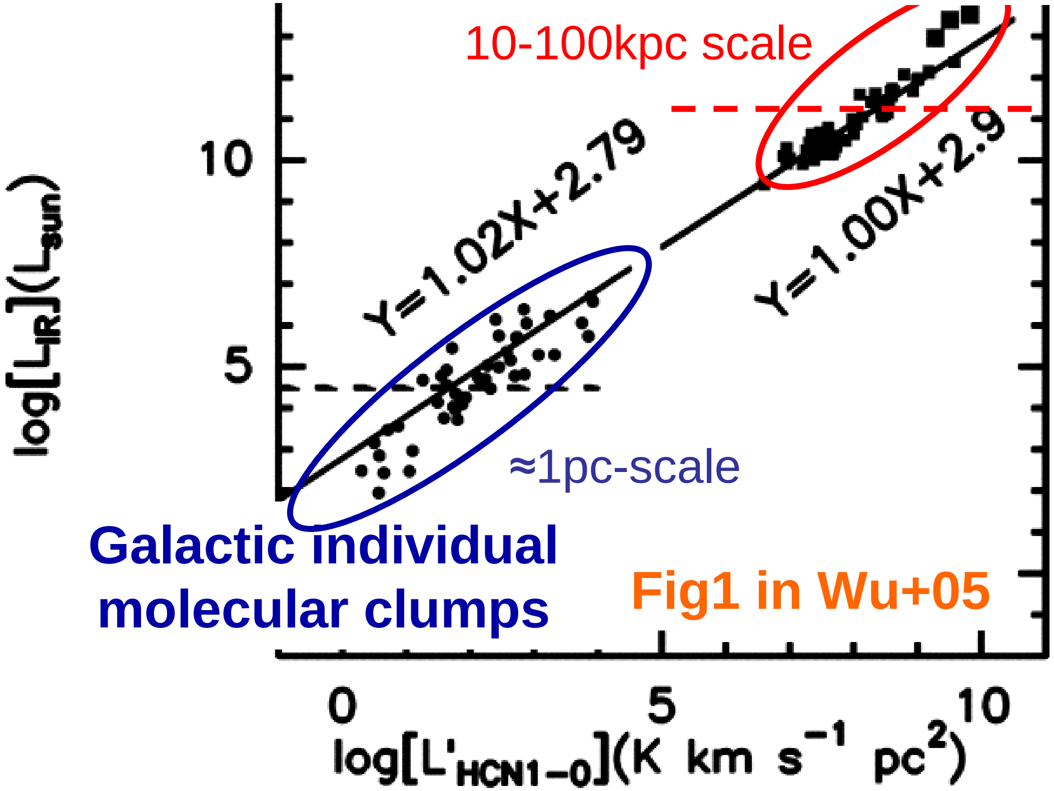
- A composite SF relation is not an appropriate tool to decide on the existence of a density threshold for star formation (Parmentier 2016)

- 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 $L_{IR}$ - $L_{HCN}$ Star Formation Relation

$L_{IR} \propto SFR$

**Galaxies**
**(Spirals, LIRGS/ULIRGS)**
**Gao & Solomon 2004**




$L_{HCN} \propto m_{dense\ gas}$

- **HCN(1-0) traces gas**
  - $\rho > 700 M_o.pc^{-3}$
  - $n_{H2} > 10^4\ cm^{-3}$

# The Dense Gas Mass - Star Formation Rate Relation

$L_{IR} \propto SFR$

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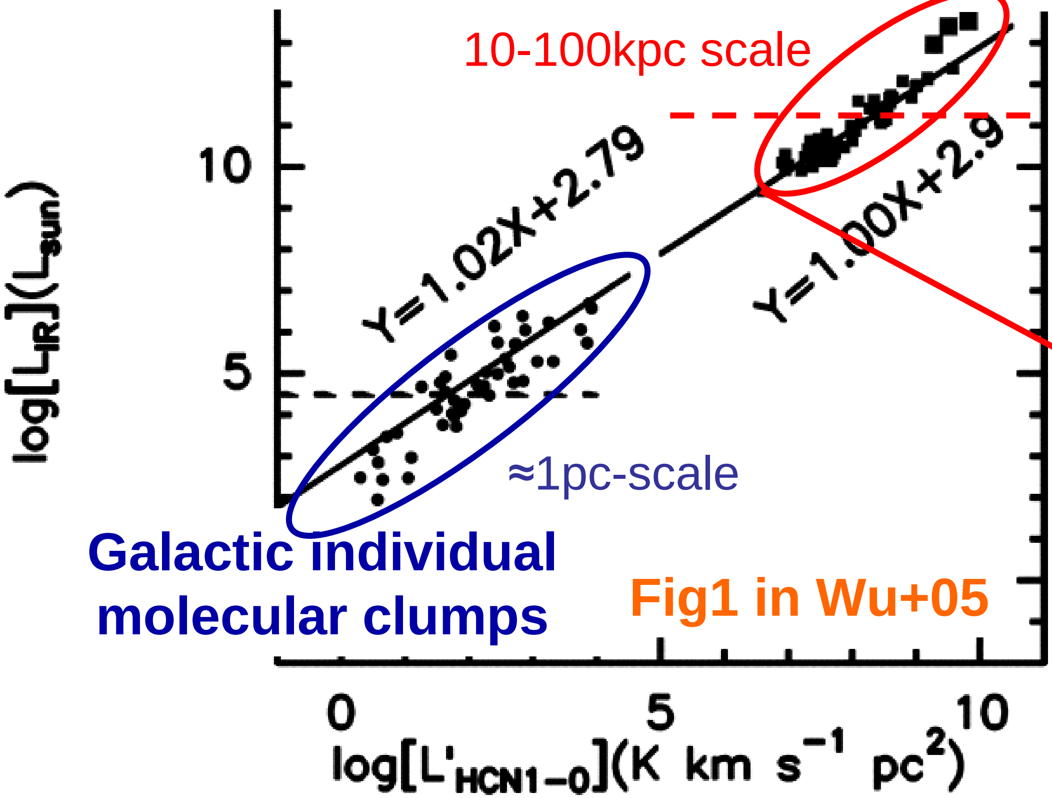


**Galactic individual molecular clumps**

**Fig1 in Wu+05**

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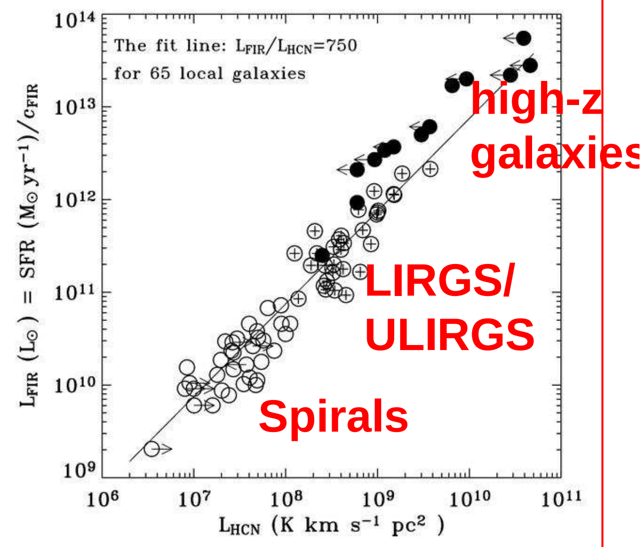


**Fig2 in Gao+07**

- **HCN(1-0) traces gas**
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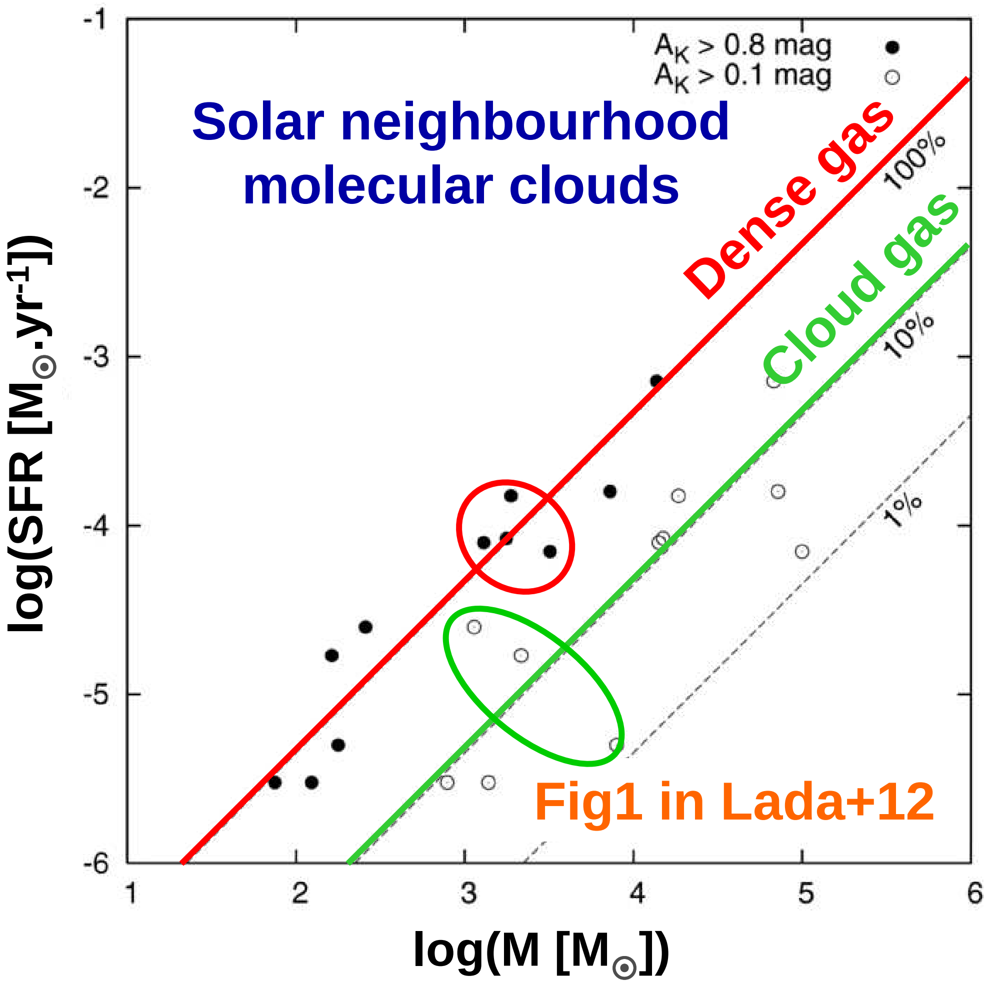
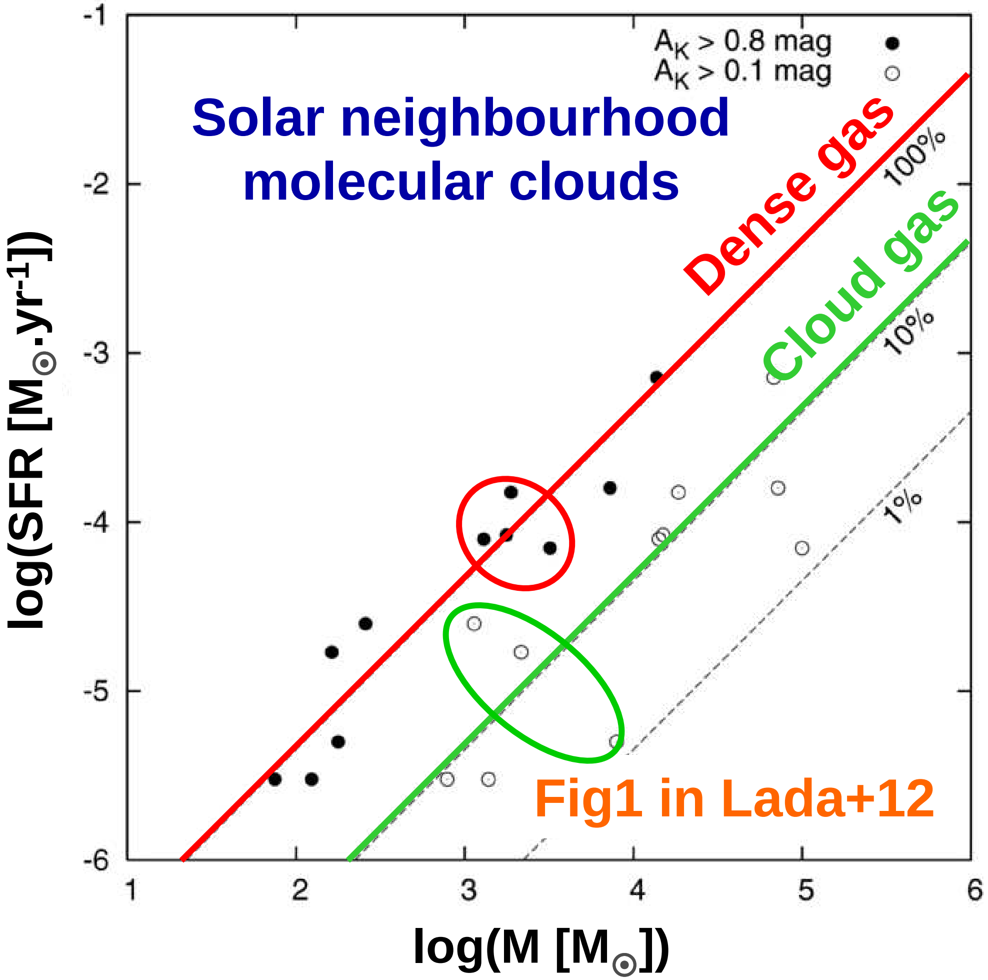
# The (Dense) Gas Mass - Star Formation Rate Relation




➤ **Molecular clouds of the Solar neighbourhood. Their SFR is:**

- **tightly correlated with their dense gas mass (•)**
- **loosely correlated with their total mass (○)**

# 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 ($m_{dg}$)

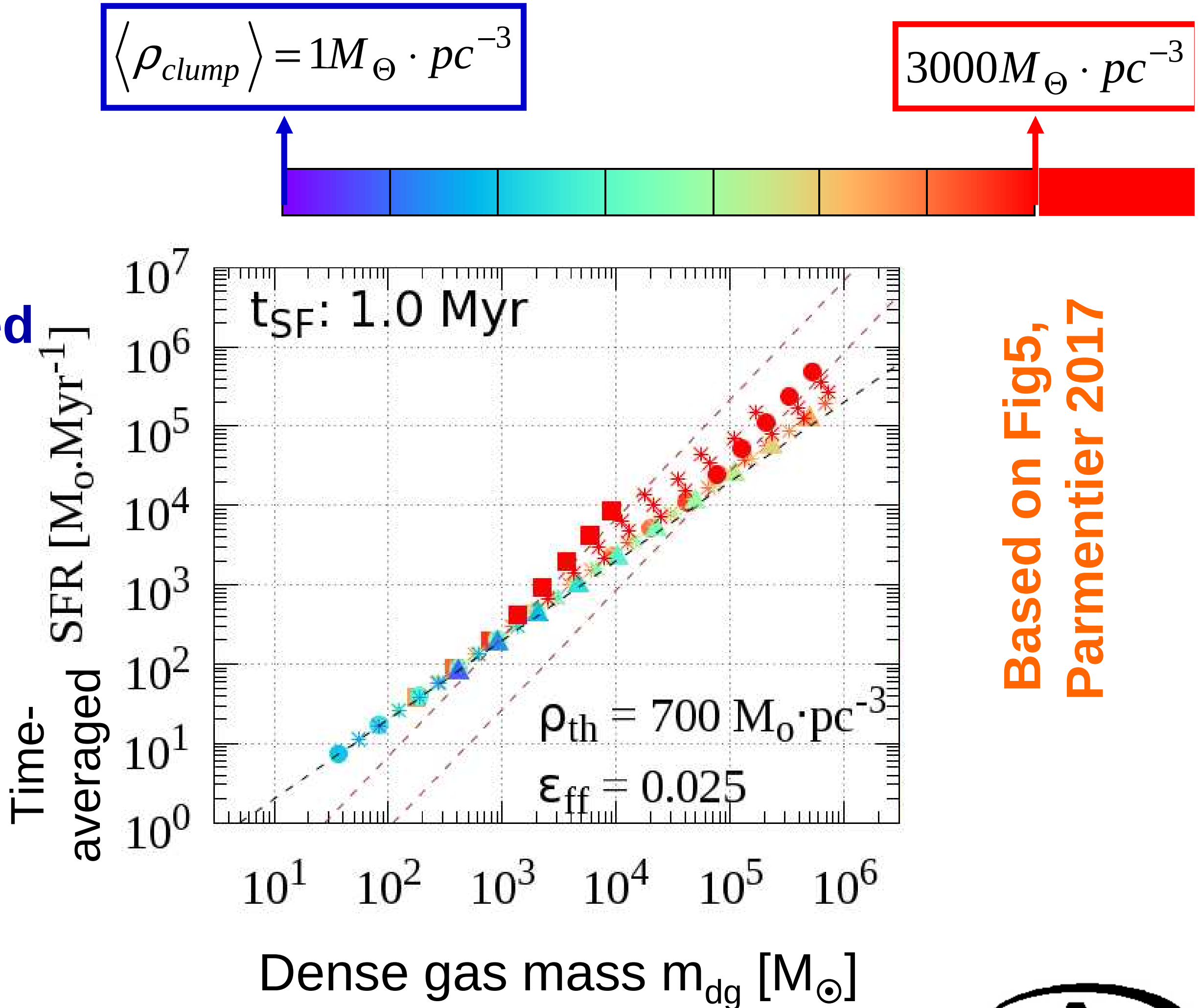
➤ **Consider a grid of model clumps ($m_{clump}$, $r_{clump}$)**

- **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**

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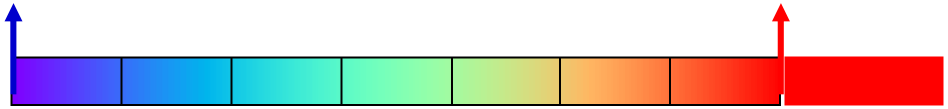
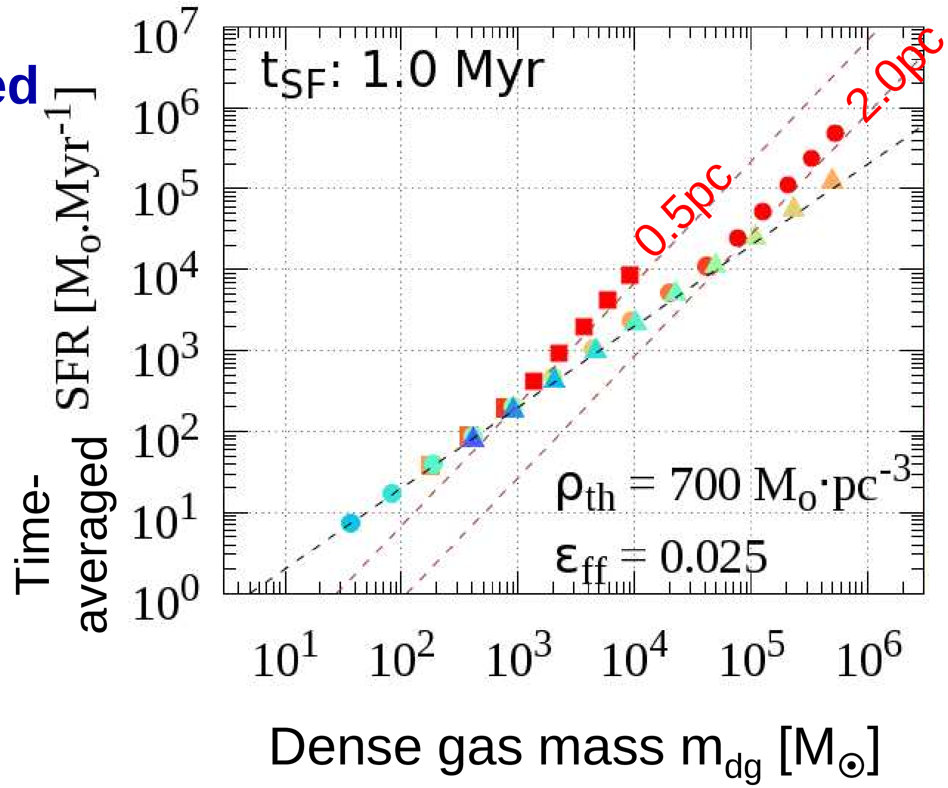
$$\rho_{clump}(r) \propto r^{-2}$$

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

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






Based on Fig5, Parmentier 2017

- **Two 'families':**
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# Very Dense Clumps – A Superlinear Relation

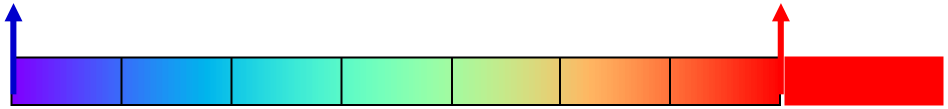
- **Very dense clumps**

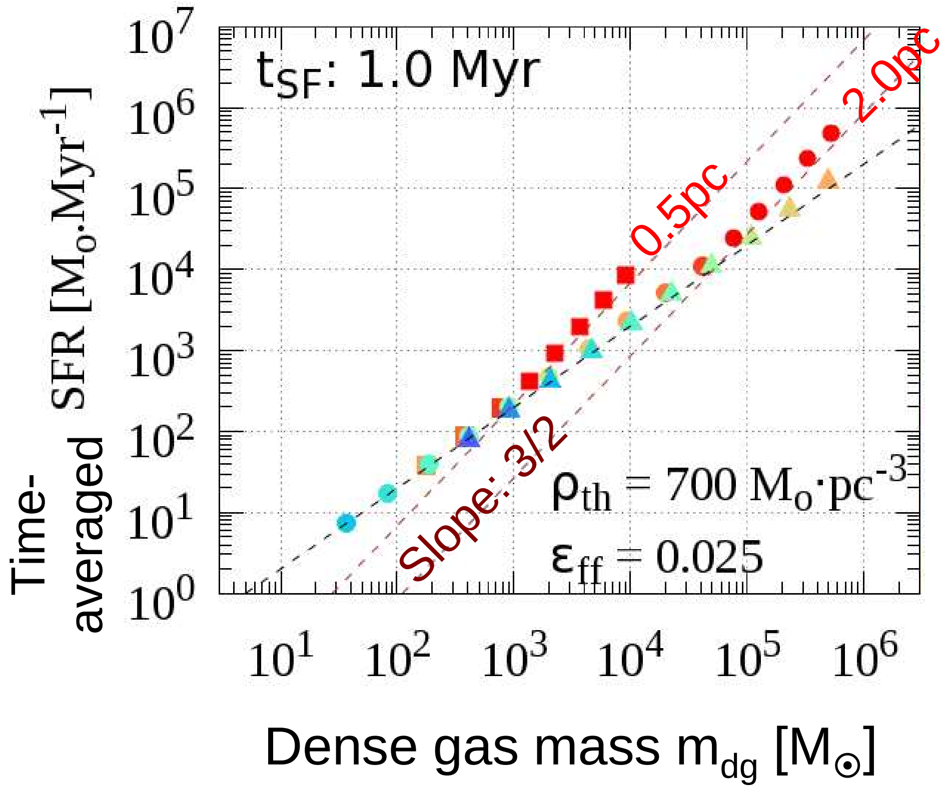
$$\langle \rho_{clump} \rangle \geq 2100 M_{\Theta} \cdot pc^{-3}$$

- **Slope of SF relation: 1.5**

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

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






Based on Fig5, Parmentier 2017

## ‘Not-So-Dense’ Clumps – A Linear Relation

- **Very dense clumps**

$$\left\langle \rho_{clump} \right\rangle \geq 2100 M_\Theta \cdot pc^{-3}$$

  - **Slope of SF relation: 1.5**

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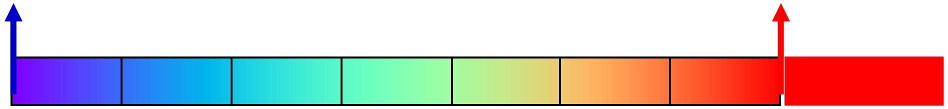
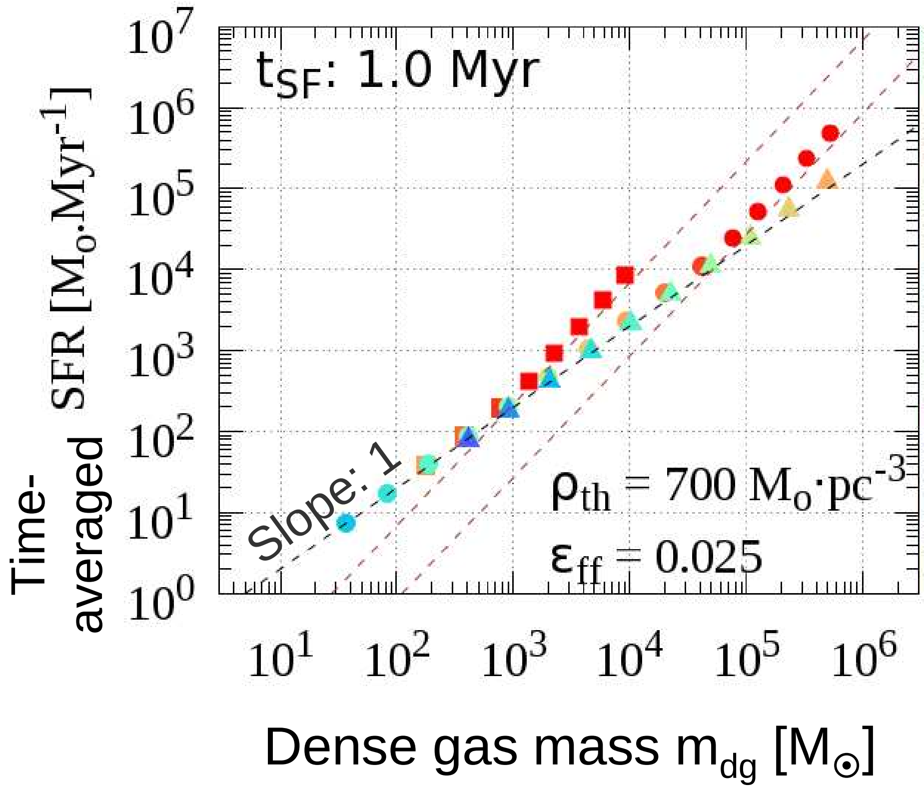
$$3000 M_\Theta \cdot pc^{-3}$$



- **‘Not-So-Dense’ Clumps**
  - **Linear SF relation**




Based on Fig5, Parmentier 2017

# The 'Not-So-Dense' Clumps – Inner Region SF Relation

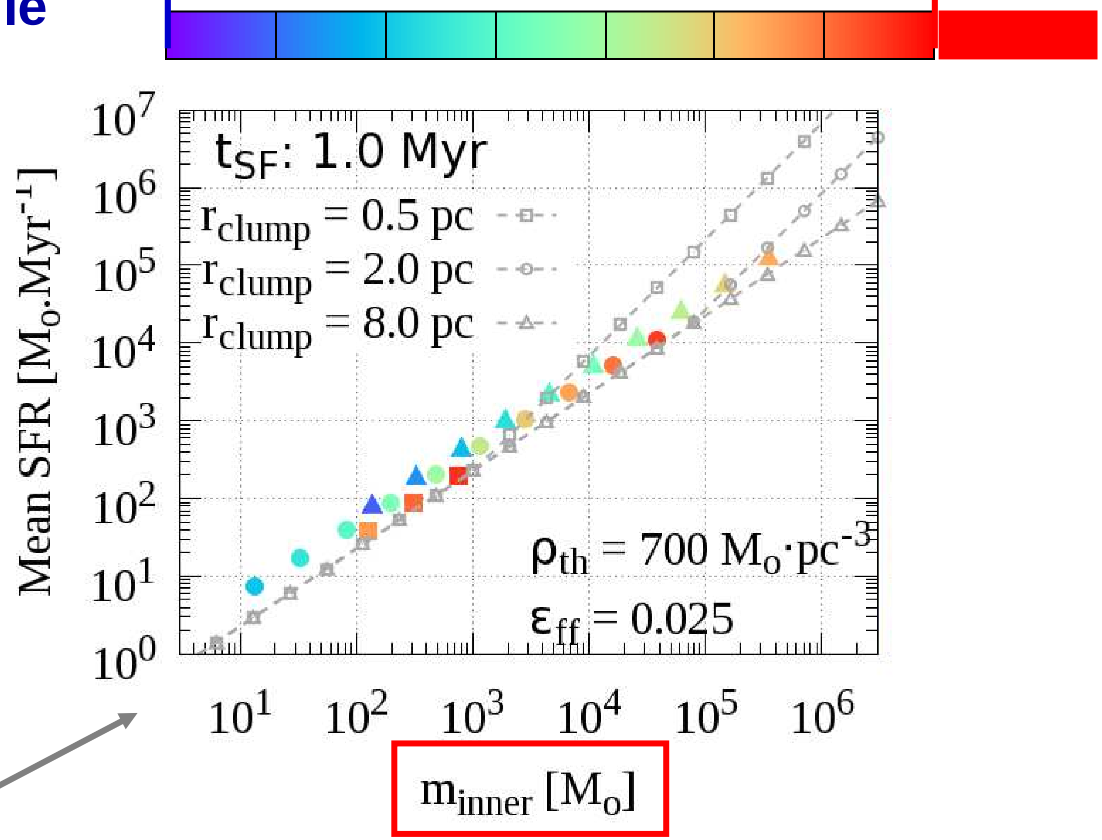
- Dense gas of the 'not-so-dense' clumps
  - Dense Inner Region:
  - Analytical insights, based on the clump density profile

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

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

$$SFR_{clump} \approx 4\varepsilon_{ff} \sqrt{\frac{2G\rho_{th}}{\pi}} m_{inner}$$

**Eq. 13 in Parmentier (2017)**



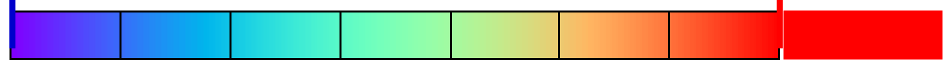

**Based on Fig4, Parmentier 2017**

## ➤ Dense gas of the 'not-so-dense' clumps

- **Dense Inner Region:**
- **Analytical insights, based on the clump density profile**

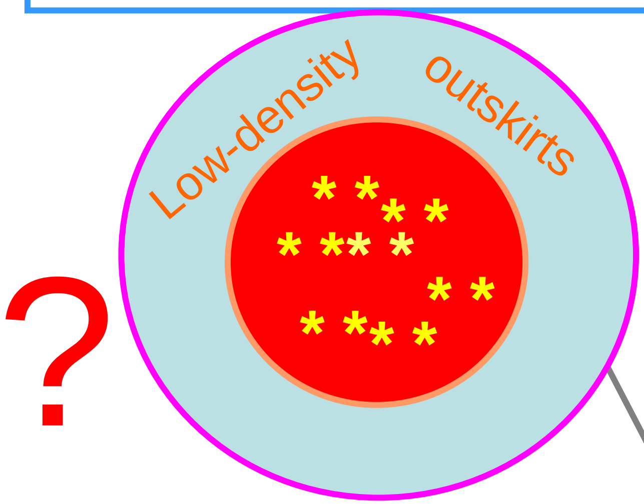
$\langle \rho_{clump} \rangle = 1 M_\Theta \cdot pc^{-3}$

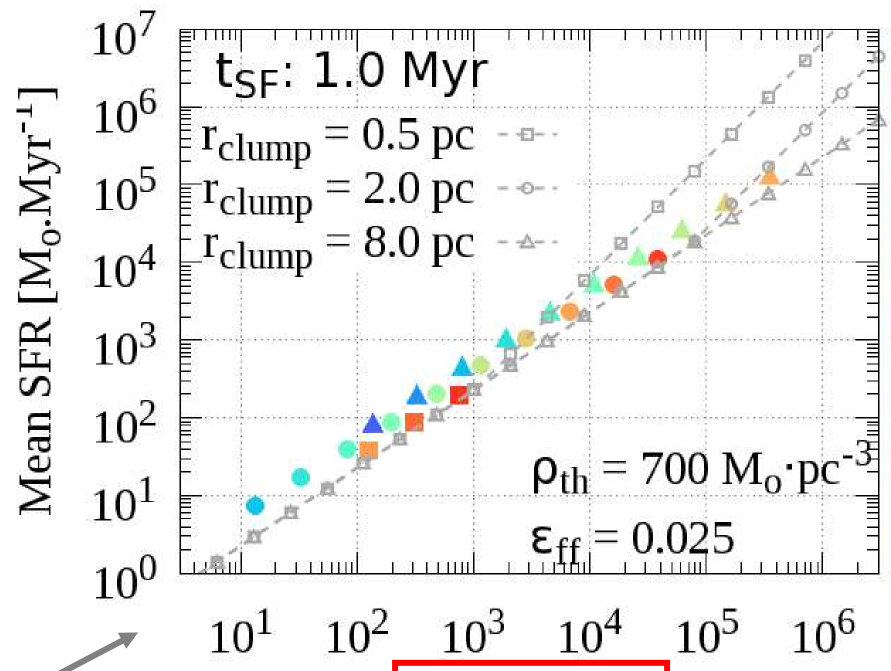
$3000 M_\Theta \cdot pc^{-3}$



$$SFR_{clump} \approx 4\varepsilon_{ff} \sqrt{\frac{2G\rho_{th}}{\pi}} m_{inner}$$

**Eq. 13 in Parmentier (2017)**

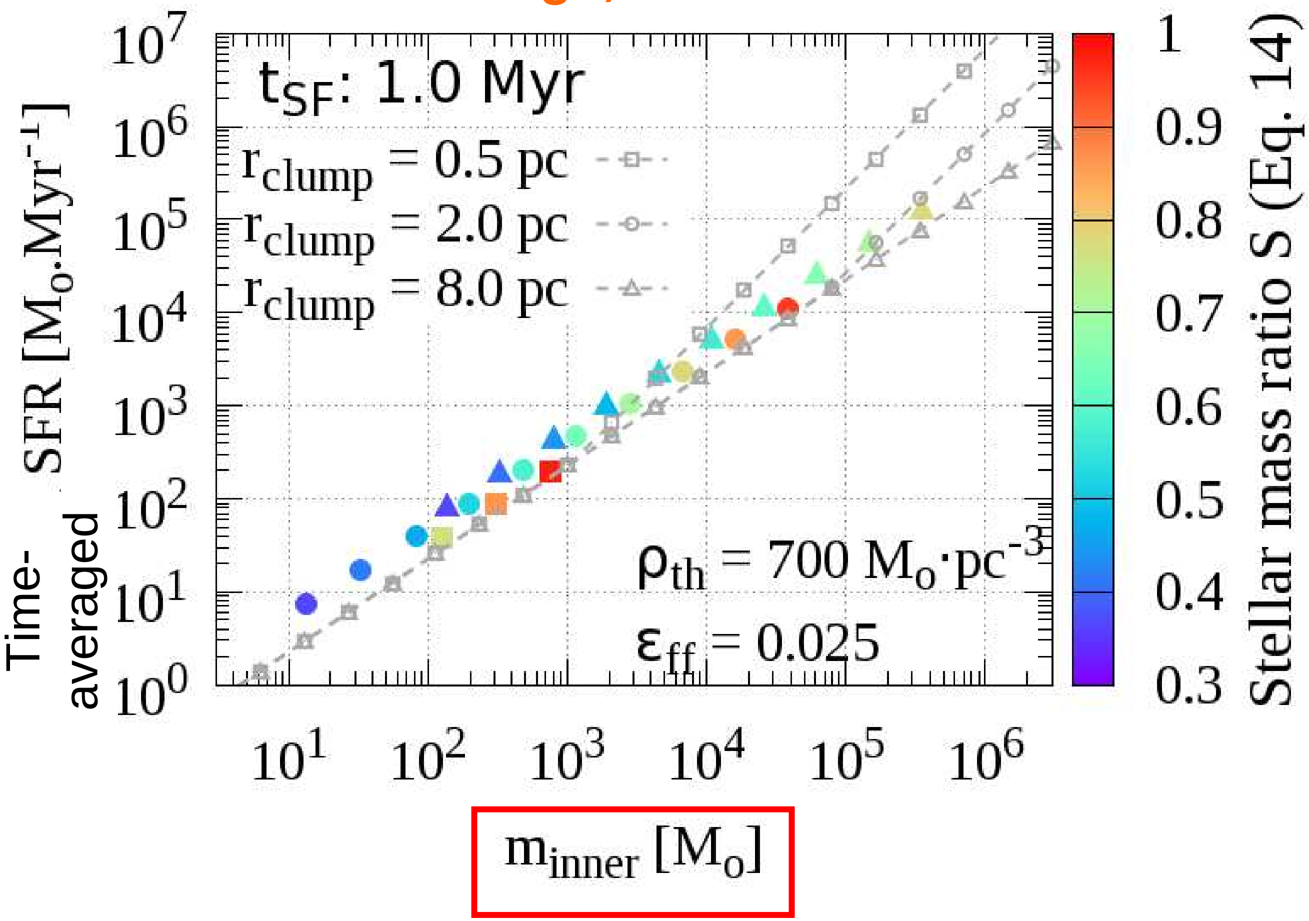



**Based on Fig4, Parmentier 2017**

# Where Does the Bulk of Star Formation Takes place?

**Based on Fig4, Parmentier 2017**



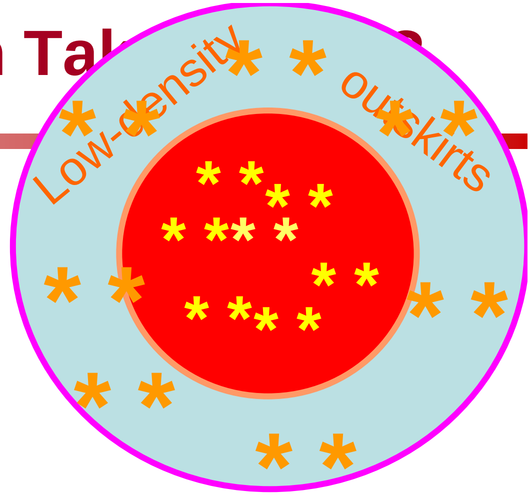

Most of star formation in clump inner region

Color - coded ratio :

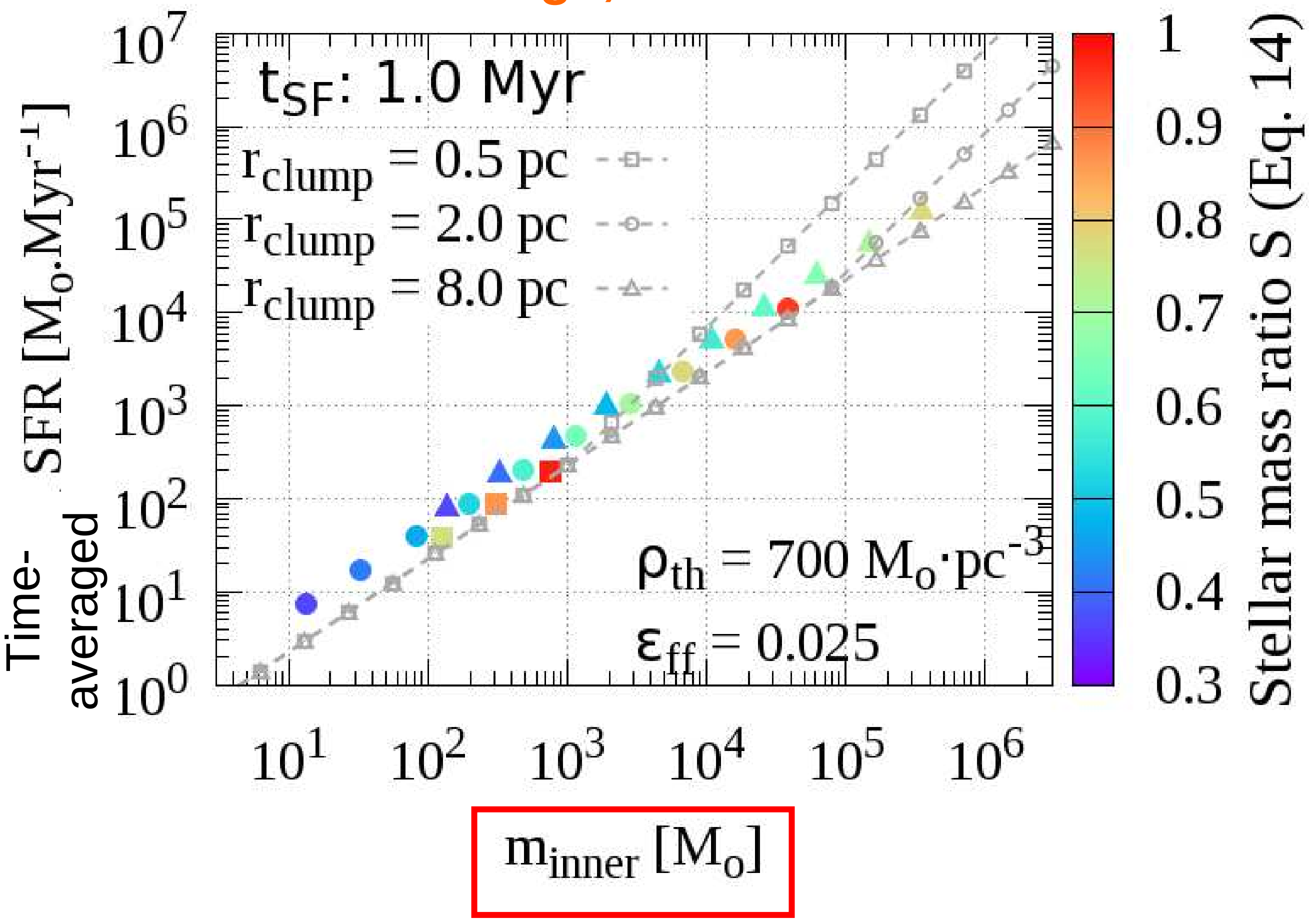
$$\frac{m_{stars,inner}}{m_{stars,whole\,clump}}$$

Most of star formation in clump low-density outskirts

# Where Does the Bulk of Star Formation Ta




**Based on Fig4, Parmentier 2017**




Most of star formation in clump inner region

Color - coded ratio :

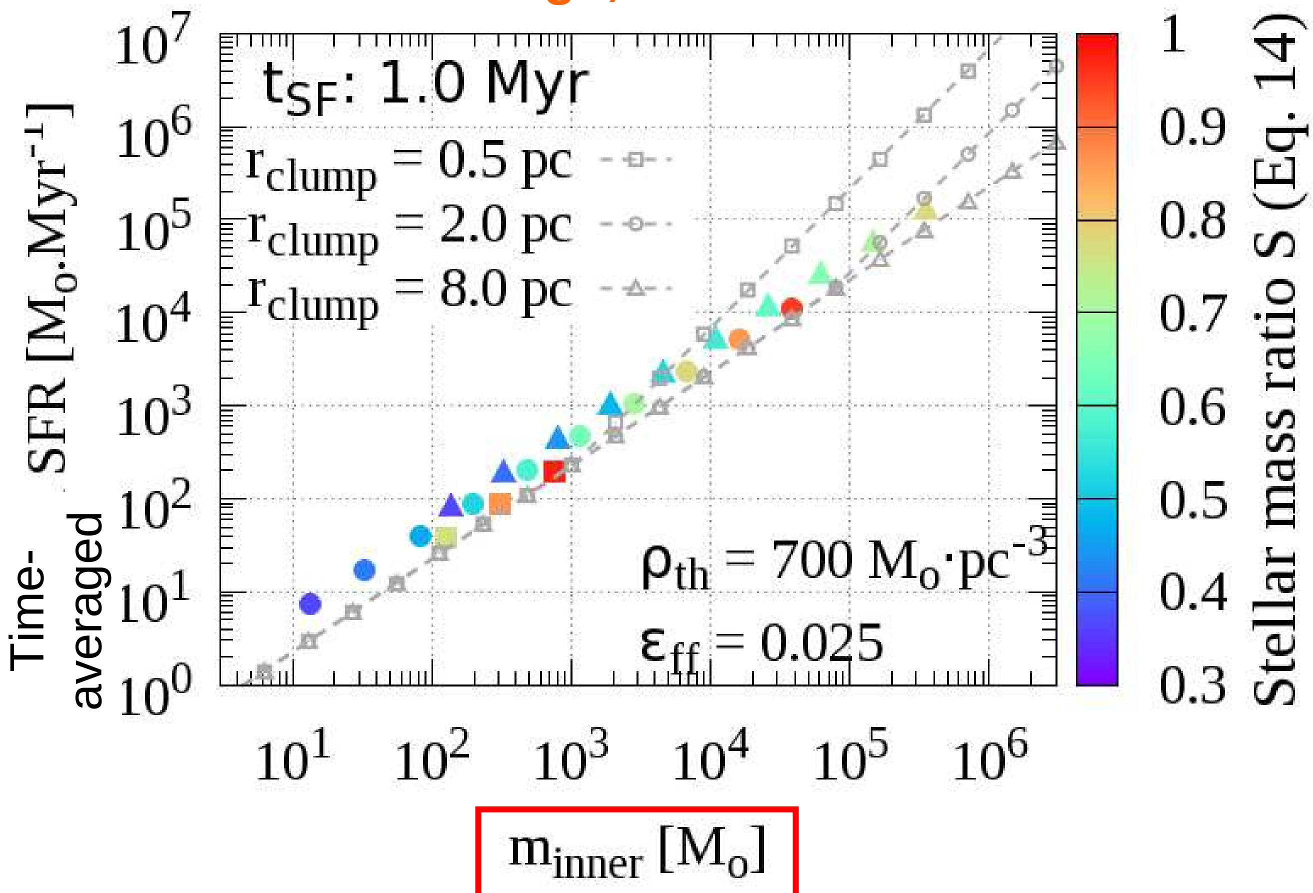
$$\frac{m_{stars,inner}}{m_{stars,whole\,clump}}$$

Most of star formation in clump low-density outskirts

# Linear Relation with Dense-Inner-Region Mass

# Yet, Dense Inner Region not Necesarily the Main Site for SF!

**Based on Fig4, Parmentier 2017**



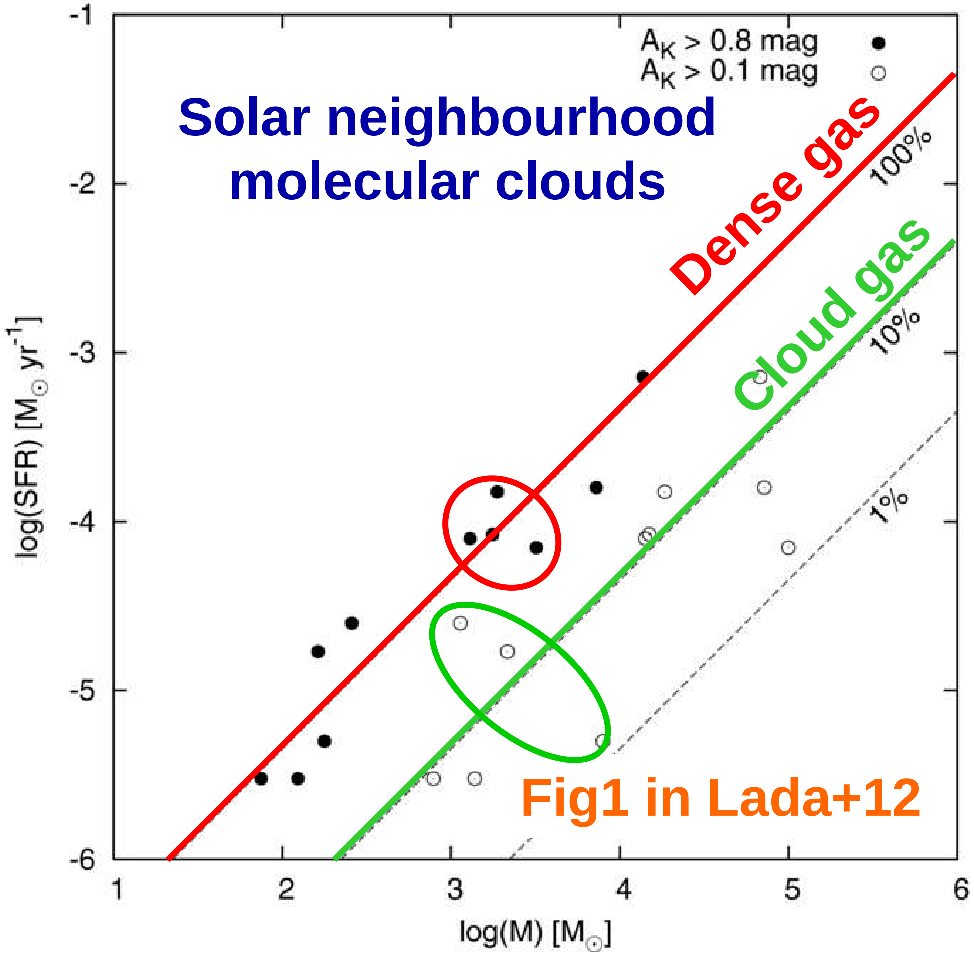

Most of star formation in clump inner region

Color-coded ratio:

$$\frac{m_{stars,inner}}{m_{stars,whole\,clump}}$$

Most of star formation in clump low-density outskirts

# The (Dense) Gas Mass - Star Formation Rate Relation



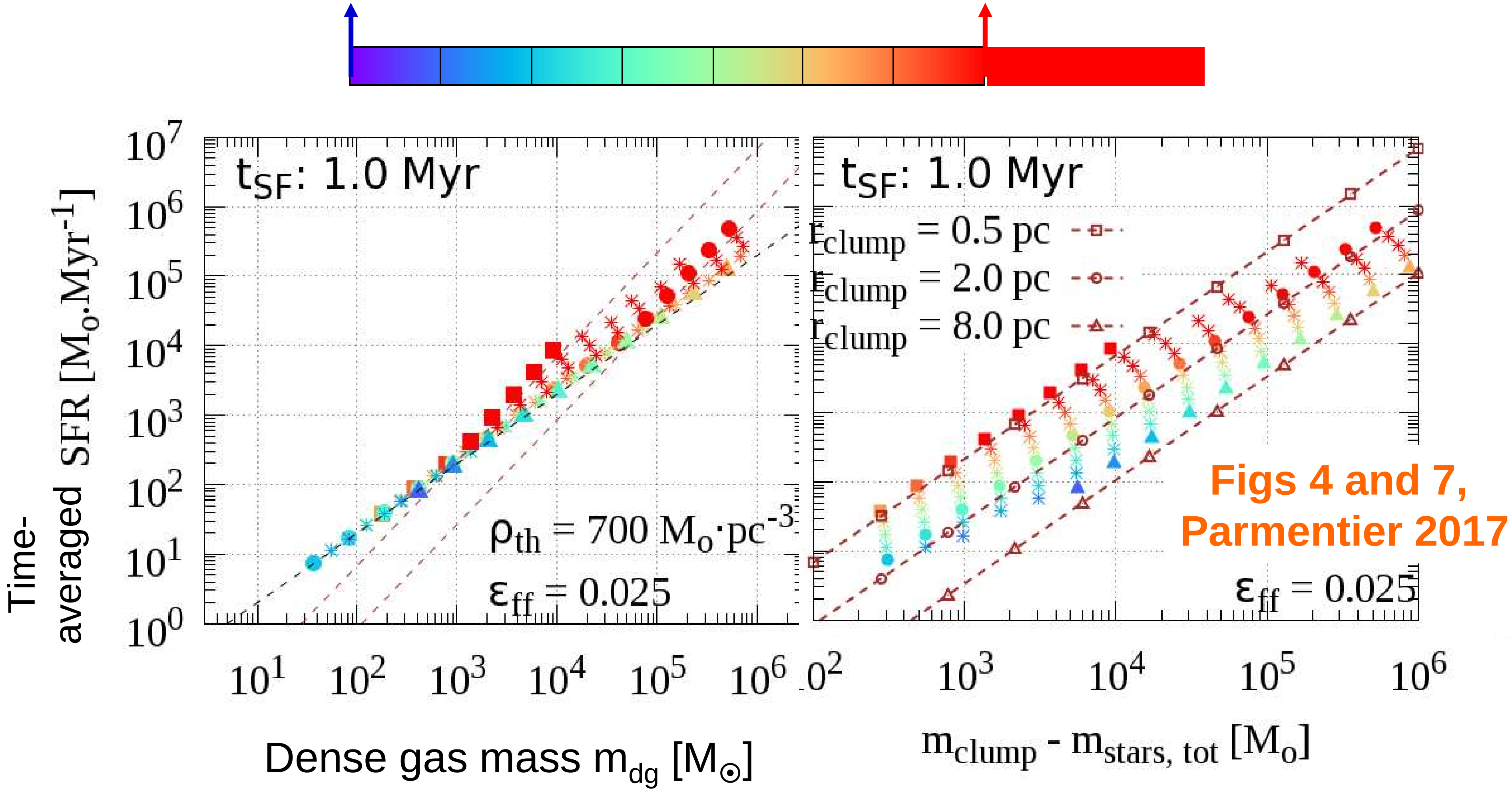

➤ **Molecular clouds of the Solar Neighbourhood. Their SFR is:**

- **tightly correlated with their dense gas mass (•)**
- **loosely correlated with their total mass (○)**

# SF Relations with Dense and Total Gas Masses

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

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




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

# Take-Away Message

**Local-density driven cluster formation models naturally reproduce:**

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

**as was observed by Lada+2012**

***Parmentier (2017)***