4 Star Formation Relations

(+ Strengthened Cluster Survival)

With One Single Model

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SFB 881

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Young Star Cluster Group Meeting in Bonn:

Do All Stars Form in Compact Clusters ?
From Certainties to Doubts

15 - 17 March 2010

http://www.astro.uni-bonn.de/~ycbonn/

The web site provides an up-to-date list of all participants

Argelander-Institut für Astronomie (AIfA)

Max Planck Institut für Radio-Astronomie (MPIfR)

SOC:

- Pavel Kroupa (AIfA)
- Karl Menten (MPIfR)
- Geneviève Parmentier (AIfA; Chair)
- Hans Zinnecker (Potsdam; co-Chair)


SFB
881
Star Clusters:
From Infancy to Teenagehood
Max-Planck Haus, Heidelberg, Germany, 8 - 12 August 2016
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Participants
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Traveling to and Staying in Heidelberg
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Invited Speakers
Joana Ascenso (Porto)
Peter Berczik (Beijing)
Eugenio Carretta (Bologna)
Nicola Da Rio (Gainesville)
Walter Dehnen (Leicester)
Jan Forbrich (Wien)
Rationale
Star cluster research is experiencing a very exciting decade. With the Atacama Large Millimeter / submillimeter Array and the Gaia astrometric satellite, we are now equipped to probe the full lifecycle of star clusters, from the properties of the molecular gas in which they form, to the properties of the stellar streams which dying clusters leave in their wake. To exploit fully and meaningfully these huge data flows, the active collaboration of observers and modellers is critically needed. What theoretical predictions are we able to make? What are the observable quantities? How well do we
SOC
Geneviève Parmentier
(co-Chair; Heidelberg)
Franca D'Antona
(co-Chair; Roma)
Christian Boily (Strasbourg)
Thomas Henning (Heidelberg)

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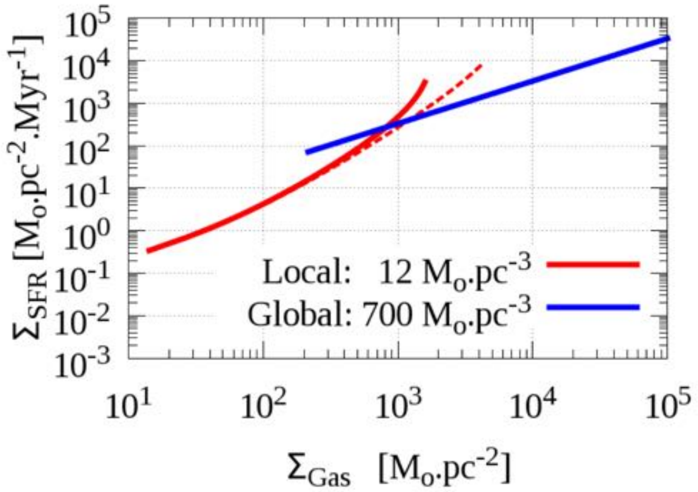
Outline

Star cluster formation in centrally-concentrated molecular clumps

A. Gas-embedded systems

- **What star formation relations characterize such systems?**



Outline

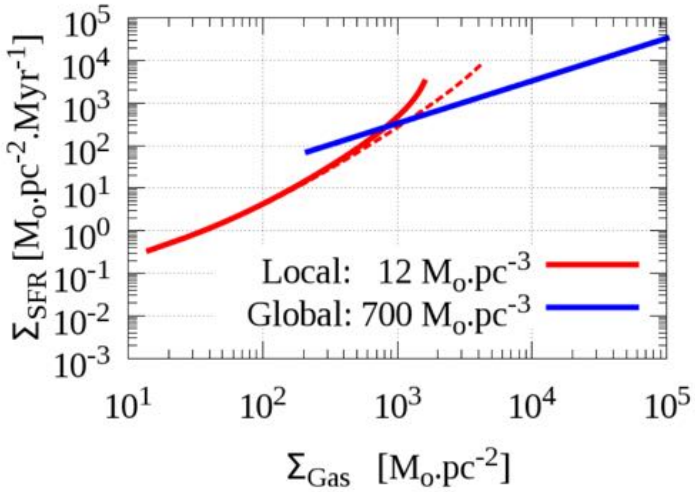
Star cluster formation in centrally-concentrated molecular clumps

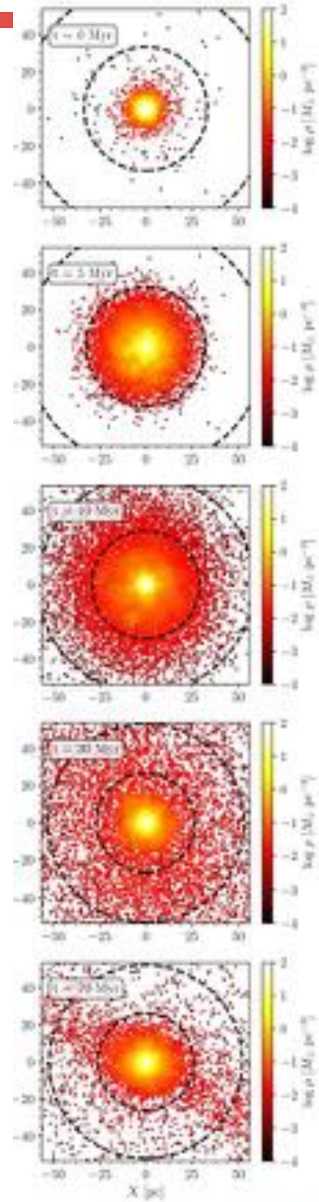
B. Gas-free systems

- **When the residual star-forming gas is gone, how do such systems evolve ?**

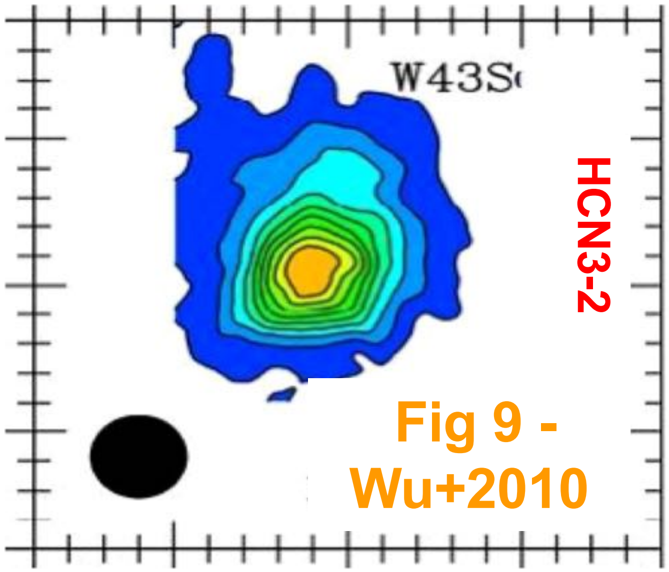
A. Gas-embedded systems

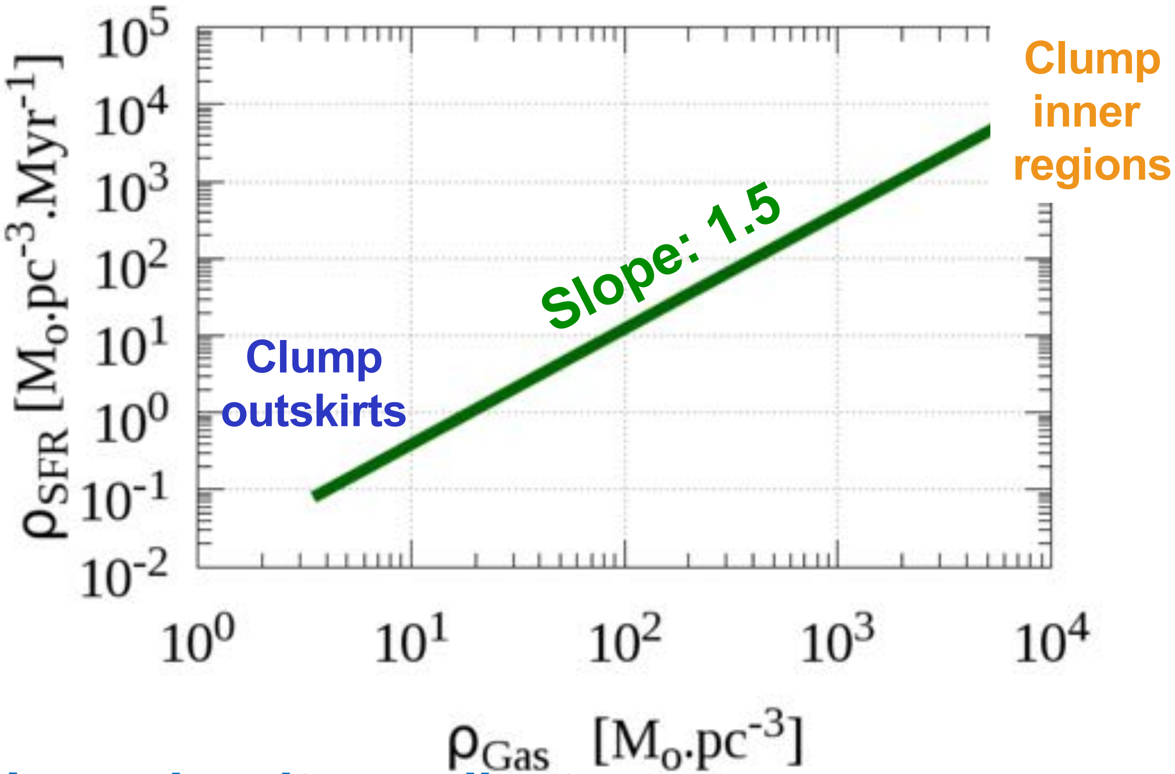
- **What star formation relations characterize such systems?**





First Star Formation Relation (Volume/Theory)



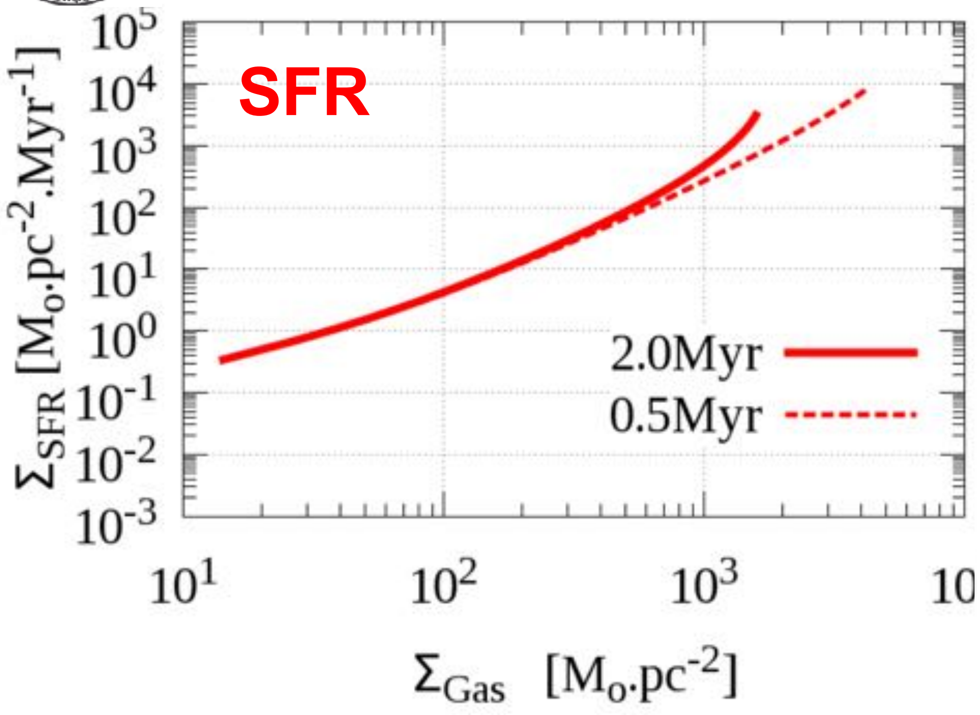


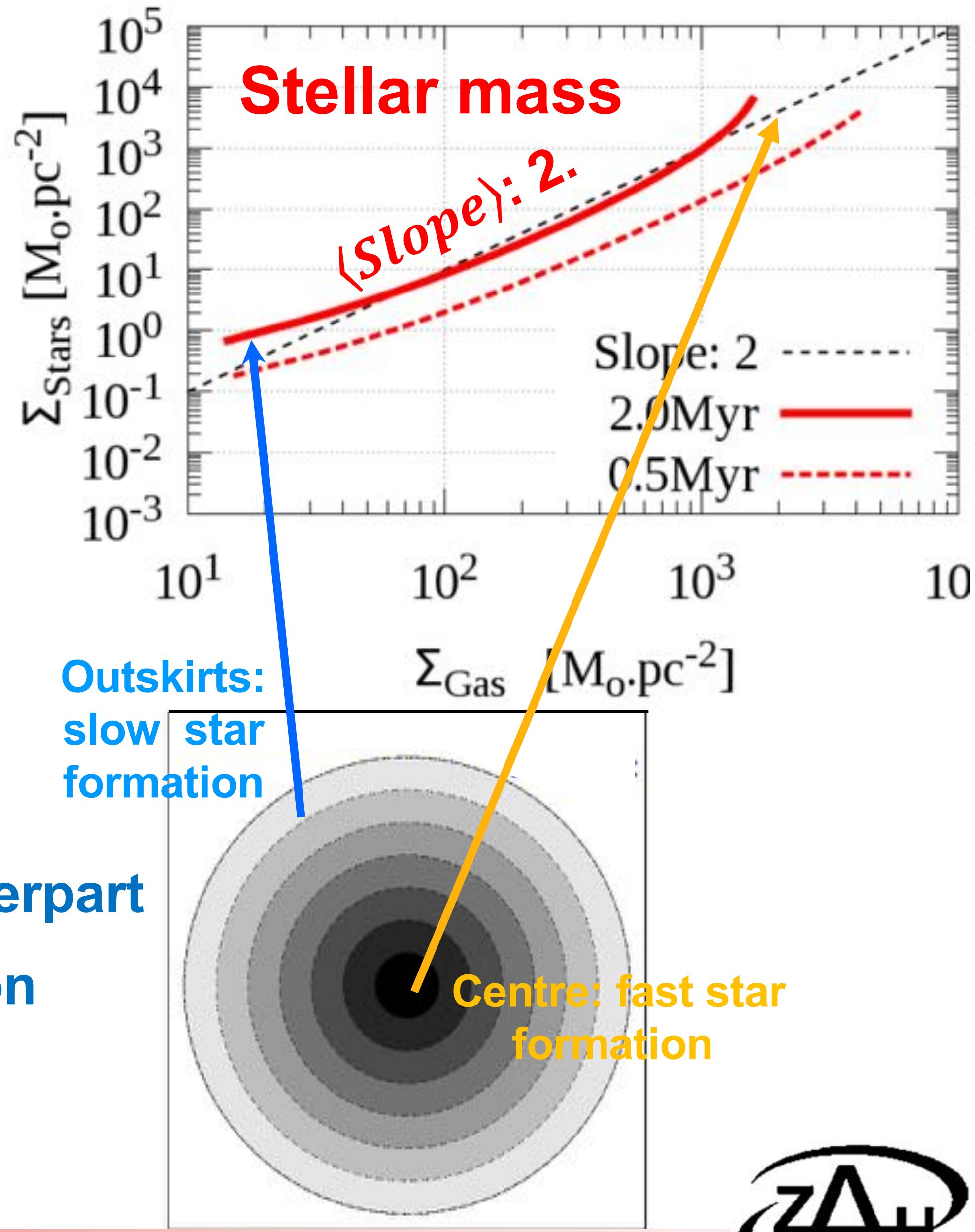
- Molecular clumps have volume density gradients
- If stars form with a constant star formation efficiency per free-fall time, ε_{ff}, the volumetric star formation relation is a power-law of slope 3/2
- Shell-by-shell representation
- Local star formation relation

$$\rho_{SFR} = \frac{\varepsilon_{ff}\,\rho_{gas}}{\tau_{ff}}$$

I. $\rho_{SFR} \propto \rho_{gas}^{1.5}$

Second Star Formation Relation (Surface/Observ.)





$$\underline{\textbf{II.}}\ \Sigma_{SFR} \propto \Sigma_{gas}^2$$

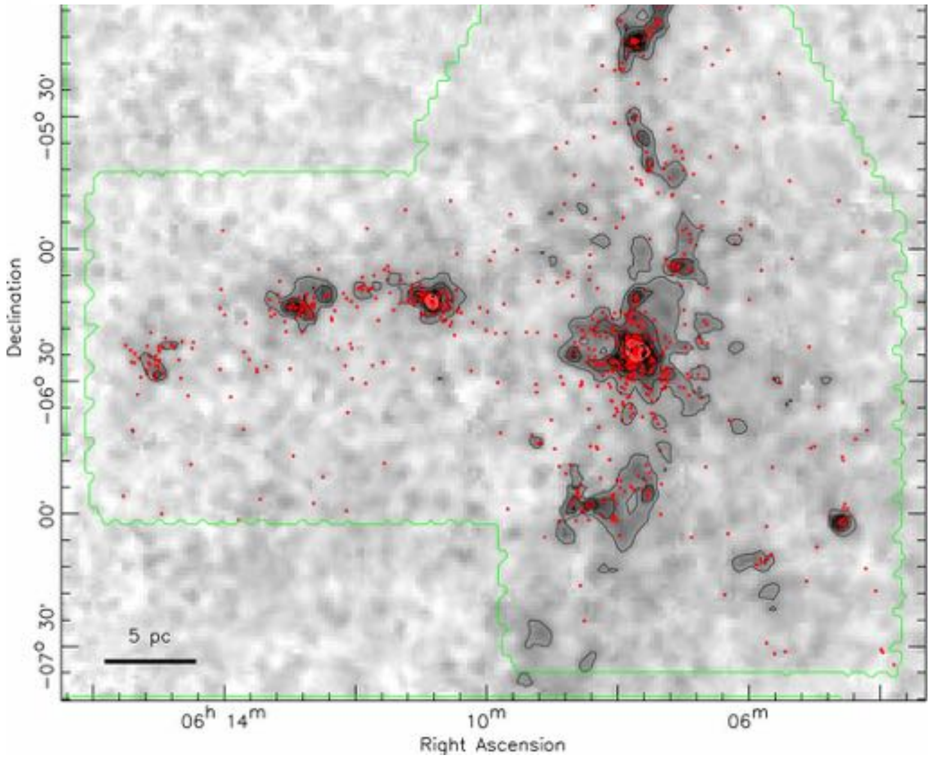
- Steeper than its volumetric counterpart
- Contour-by-contour representation
- **Local** star formation relation

Parmentier & Pfalzner (2013)

Sol. N. Molecular Clouds Show Quadratic SF Relations

Fig. 1, Gutermuth+ (2011)

MonR2 cloud of Solar Neighbourhood



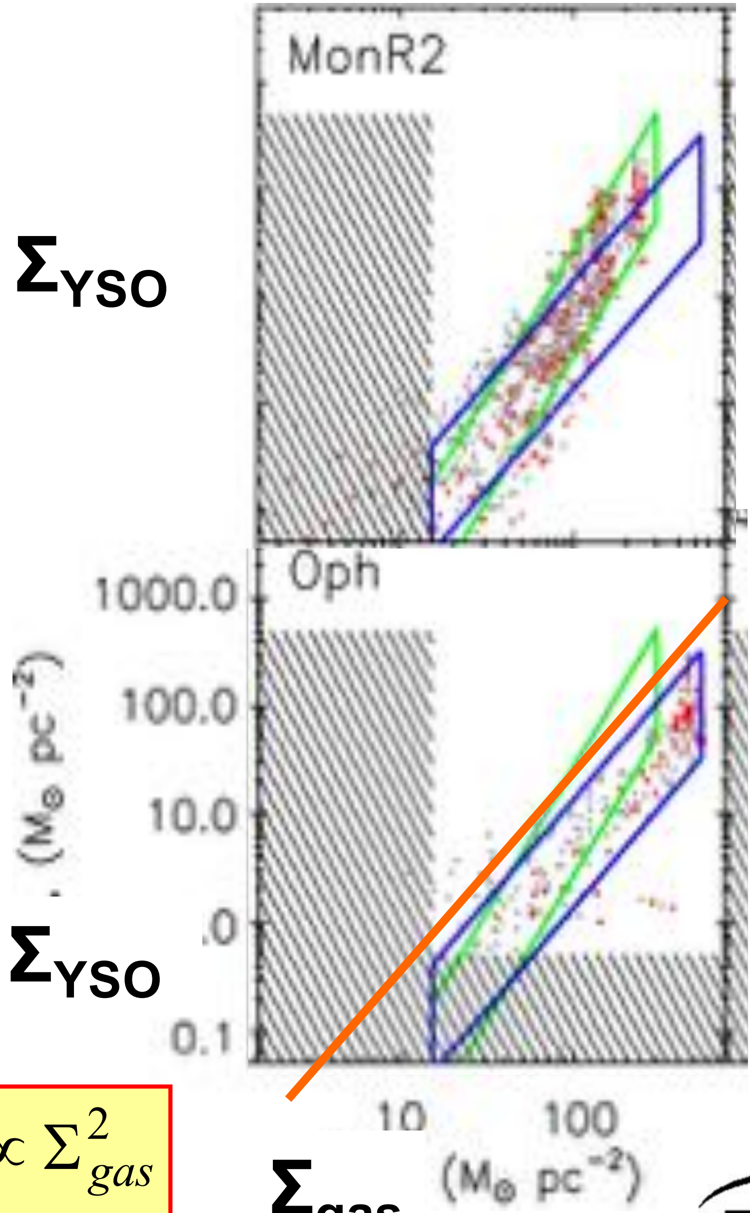


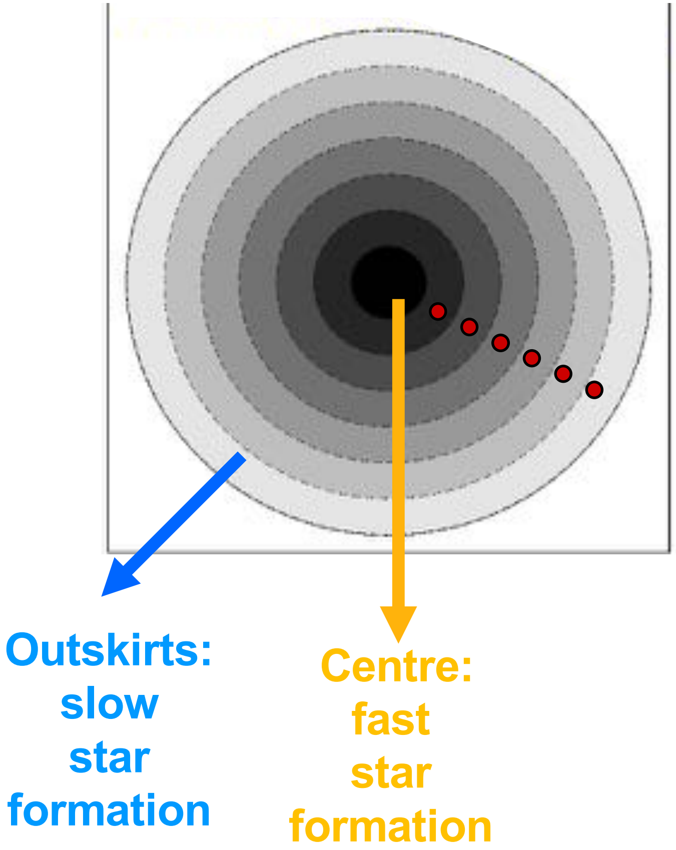
Fig. 9, Gutermuth+ (2011)

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

From a Local SF Relation …

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

Clump distance: e.g. 500 pc



… to a Global (= Third) SF Relation

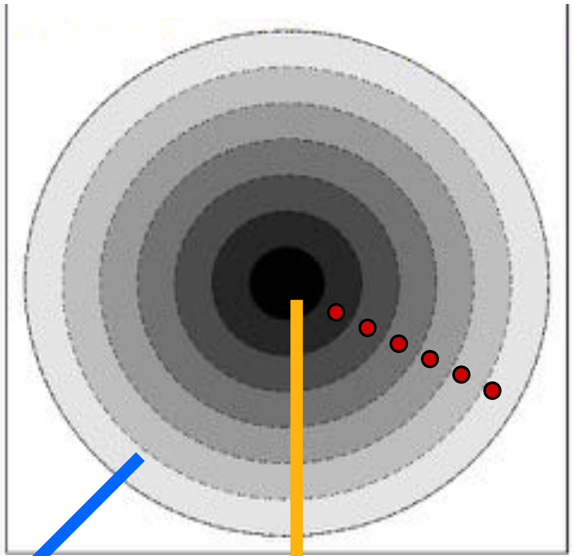
Clump at a distance where it cannot be resolved

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

Local perspective:

- **Contour-by-contour basis**
- **One clump is enough**

Clump distance: e.g. 500 pc



Outskirts: slow star formation

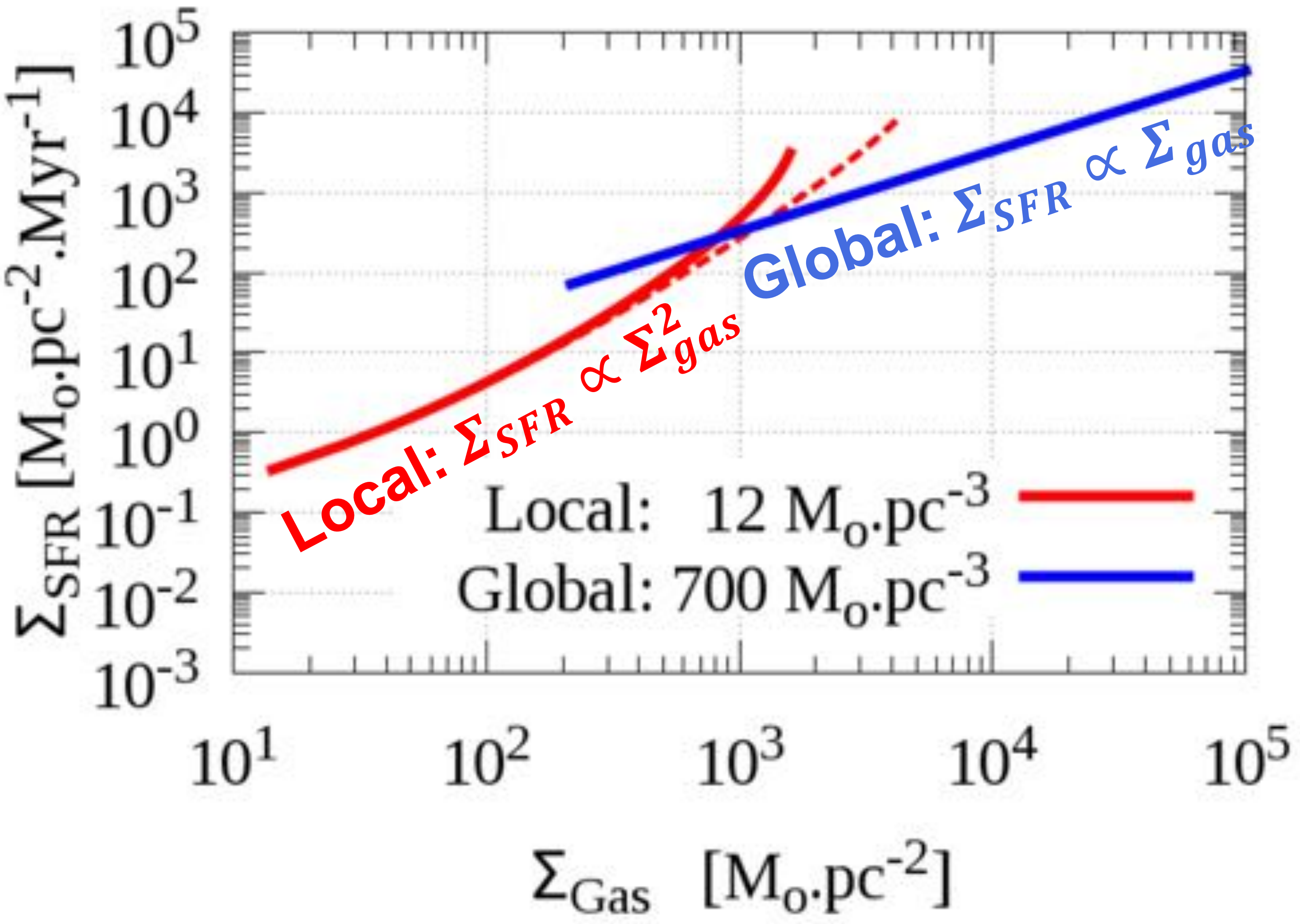
Centre: fast star formation

Global perspective:

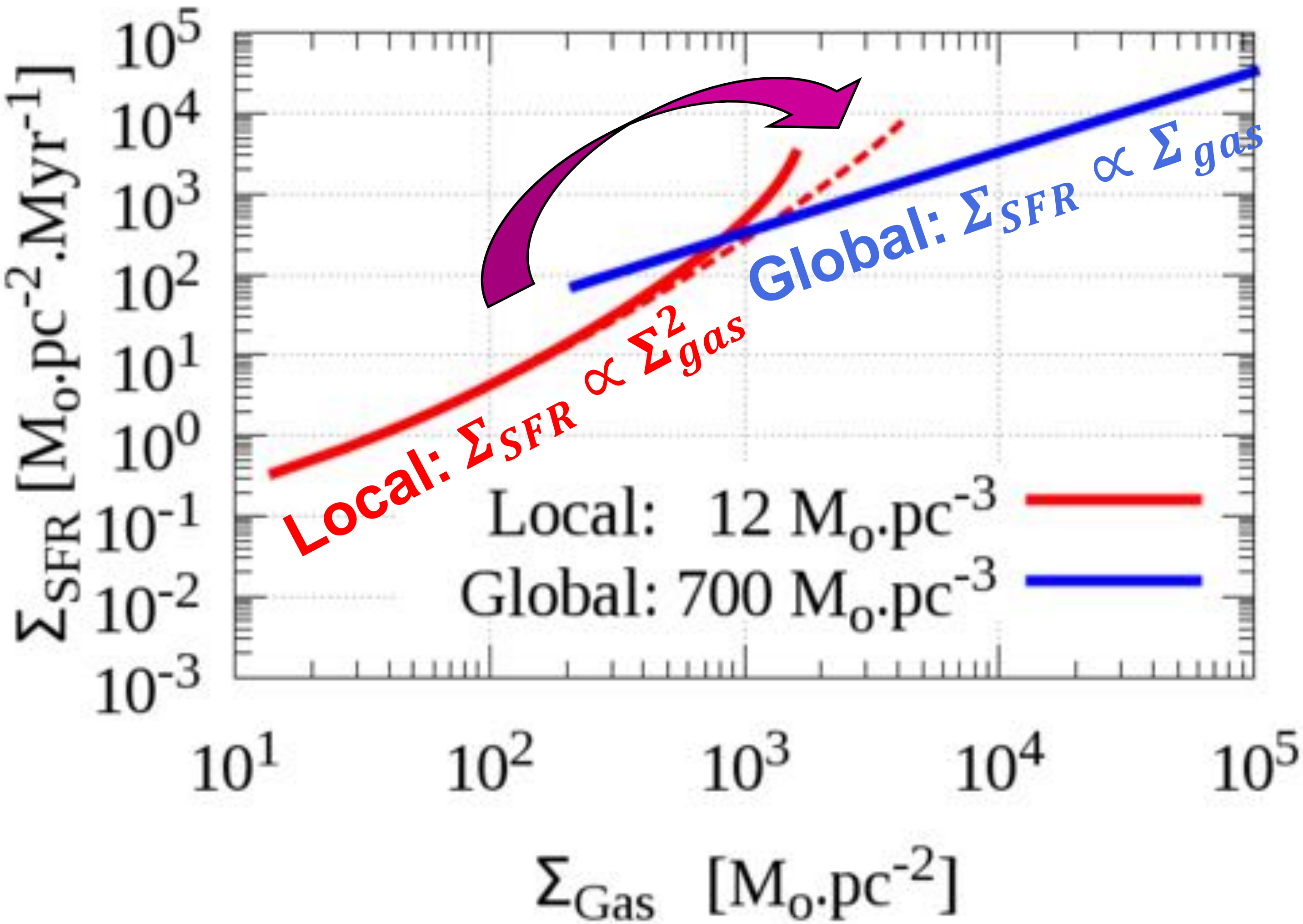
- A population of clumps is needed
- e.g. HCN(1-0) molecular clumps
- To first order: common free-fall time
  - → Slope: 1
  - → Third / linear SF relation

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

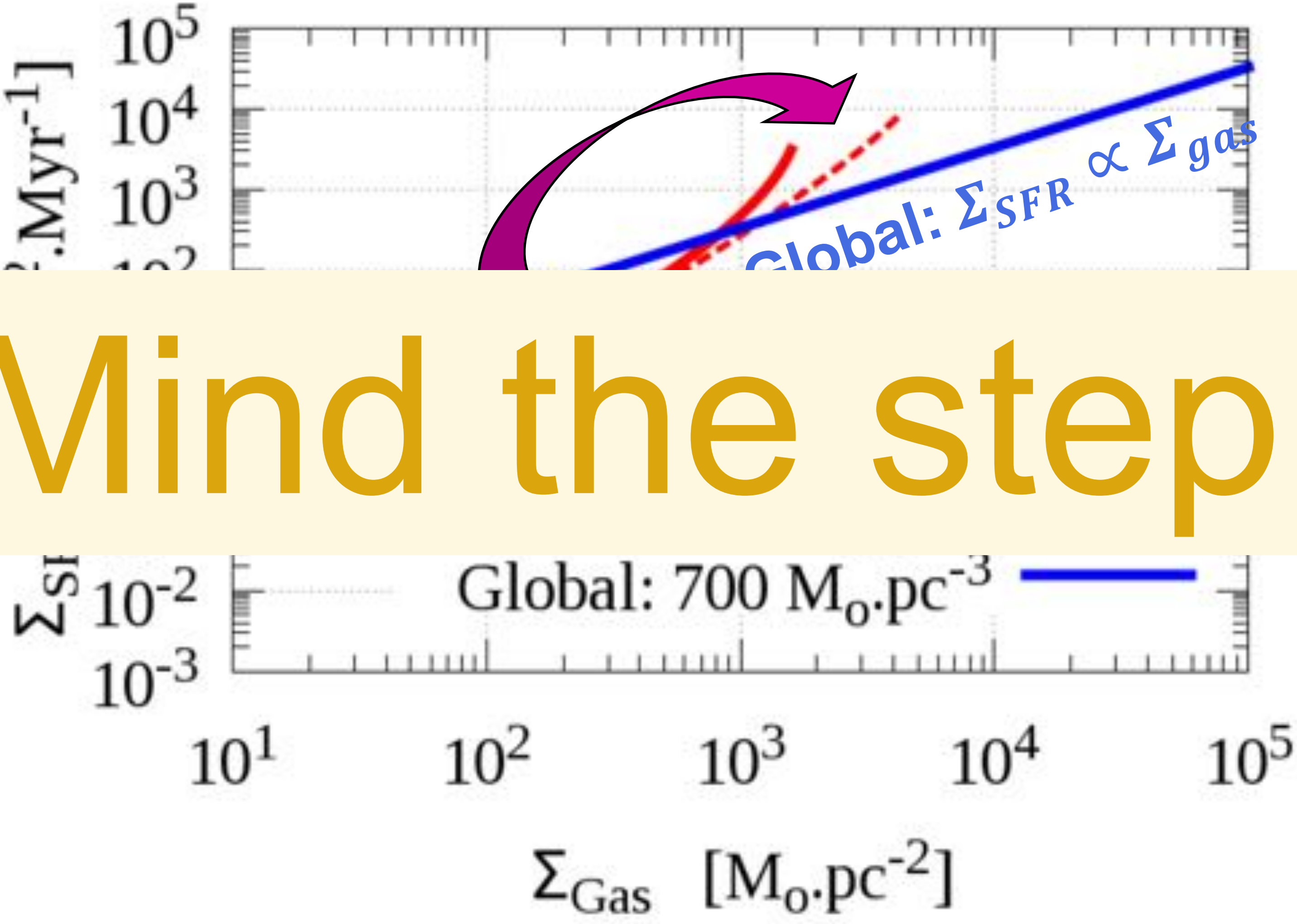
Composite SF Relation: II + III



Break-Point in Composite SF Relation



Break-Point in Composite SF Relation



Mind the step !

Break-Point in Composite SF Relation

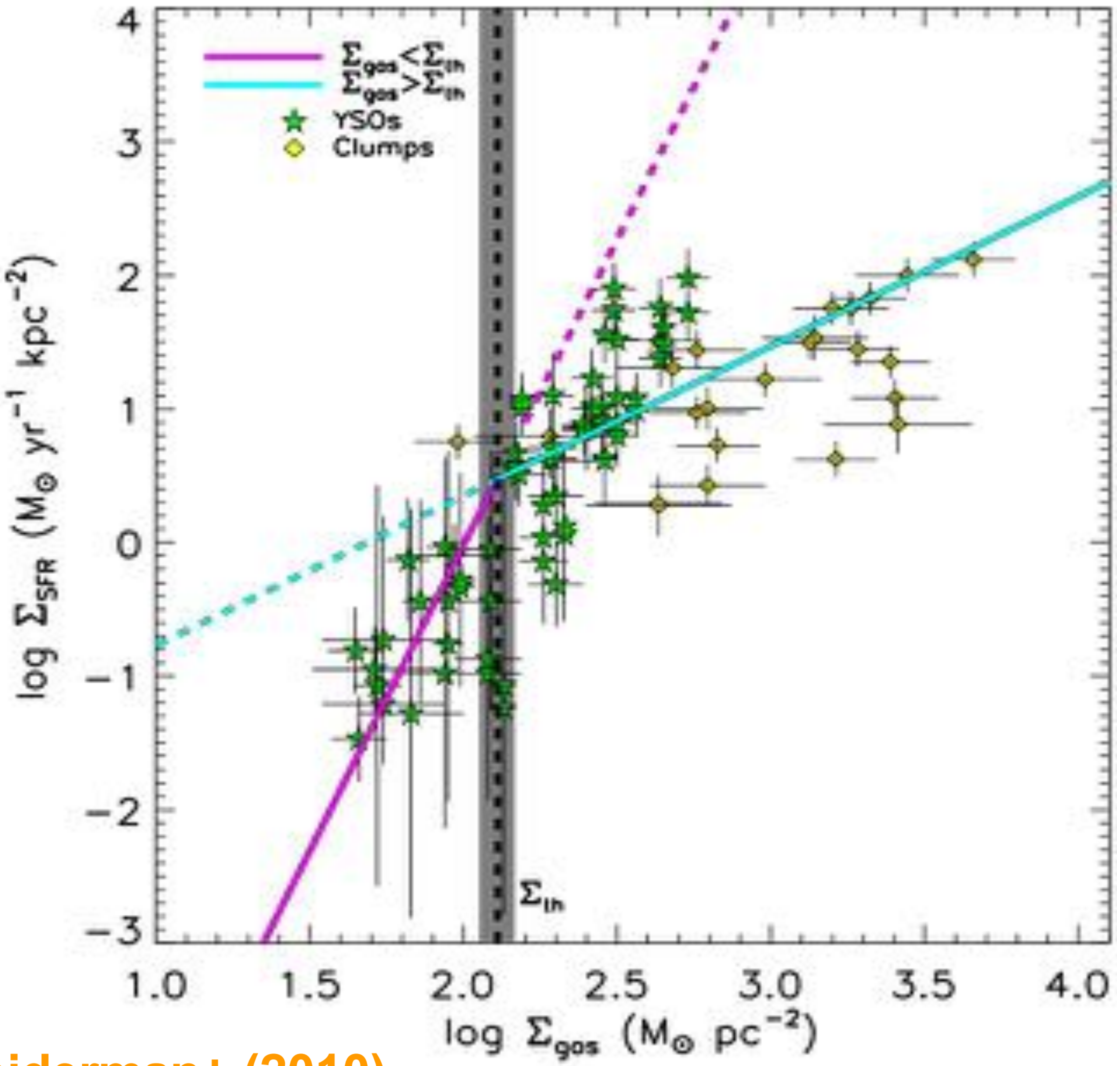


Fig. 10, Heiderman+ (2010)

Break-Point in Composite SF Relation

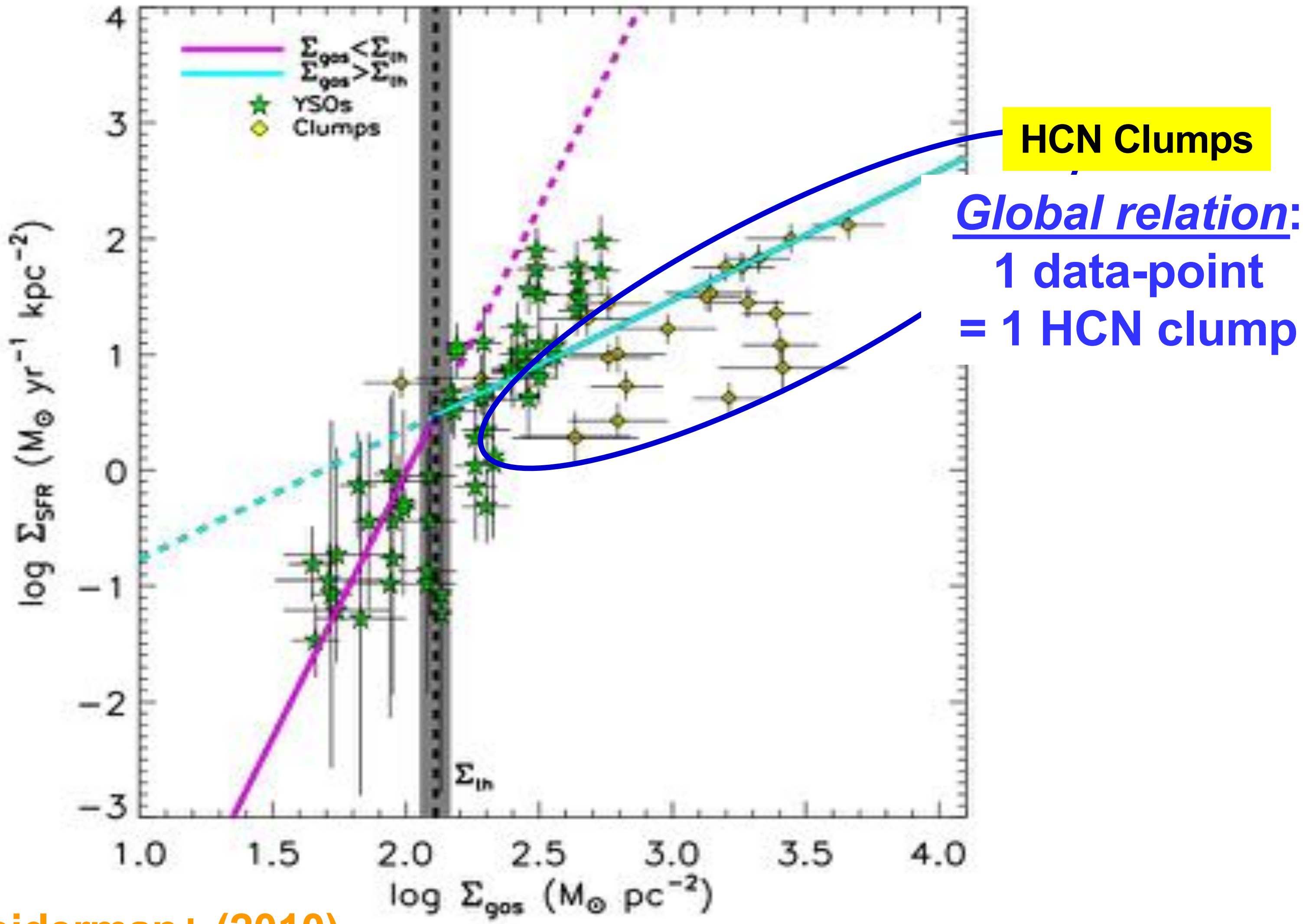
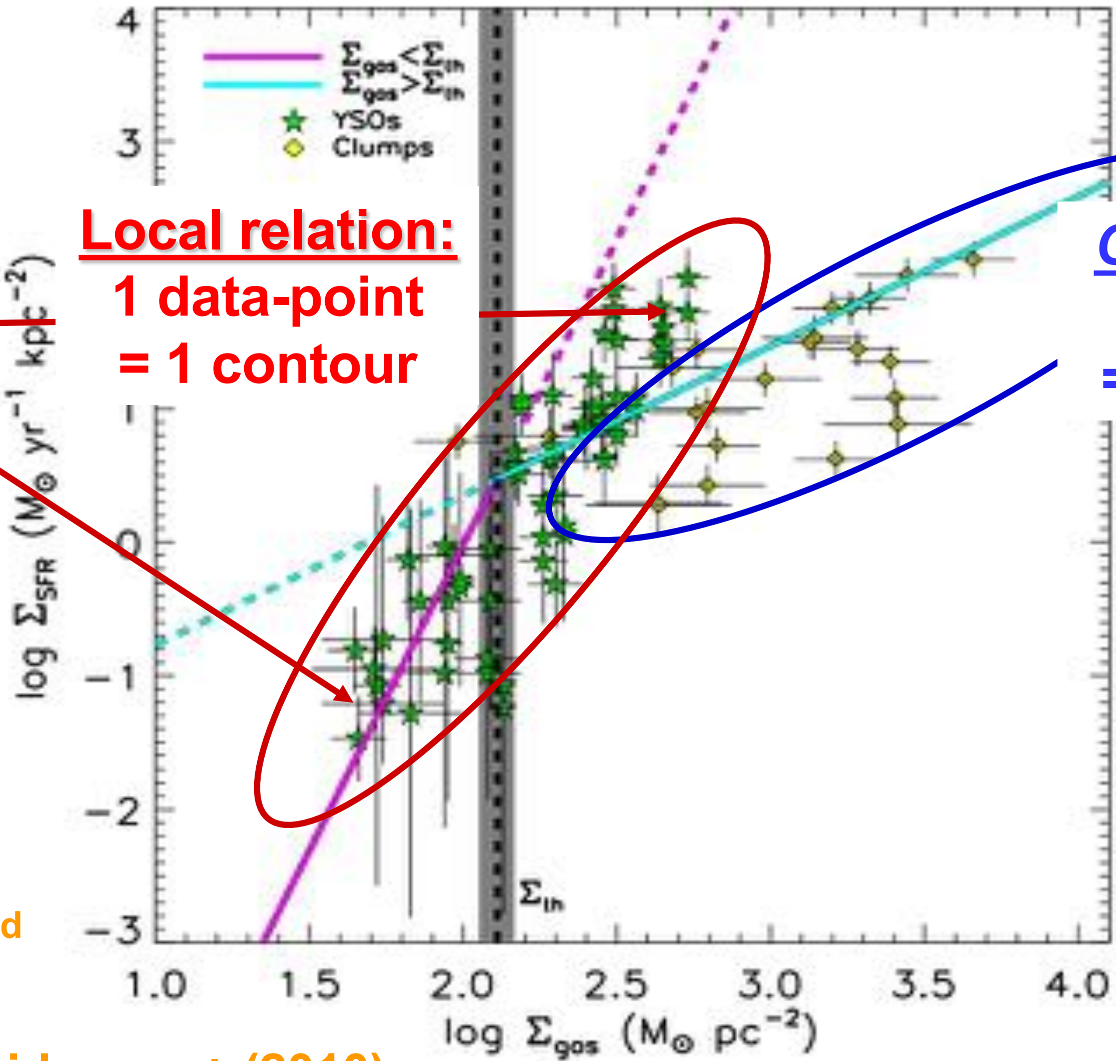


Fig. 10, Heiderman+ (2010)

Break-Point in Composite SF Relation

Perseus molecular cloud



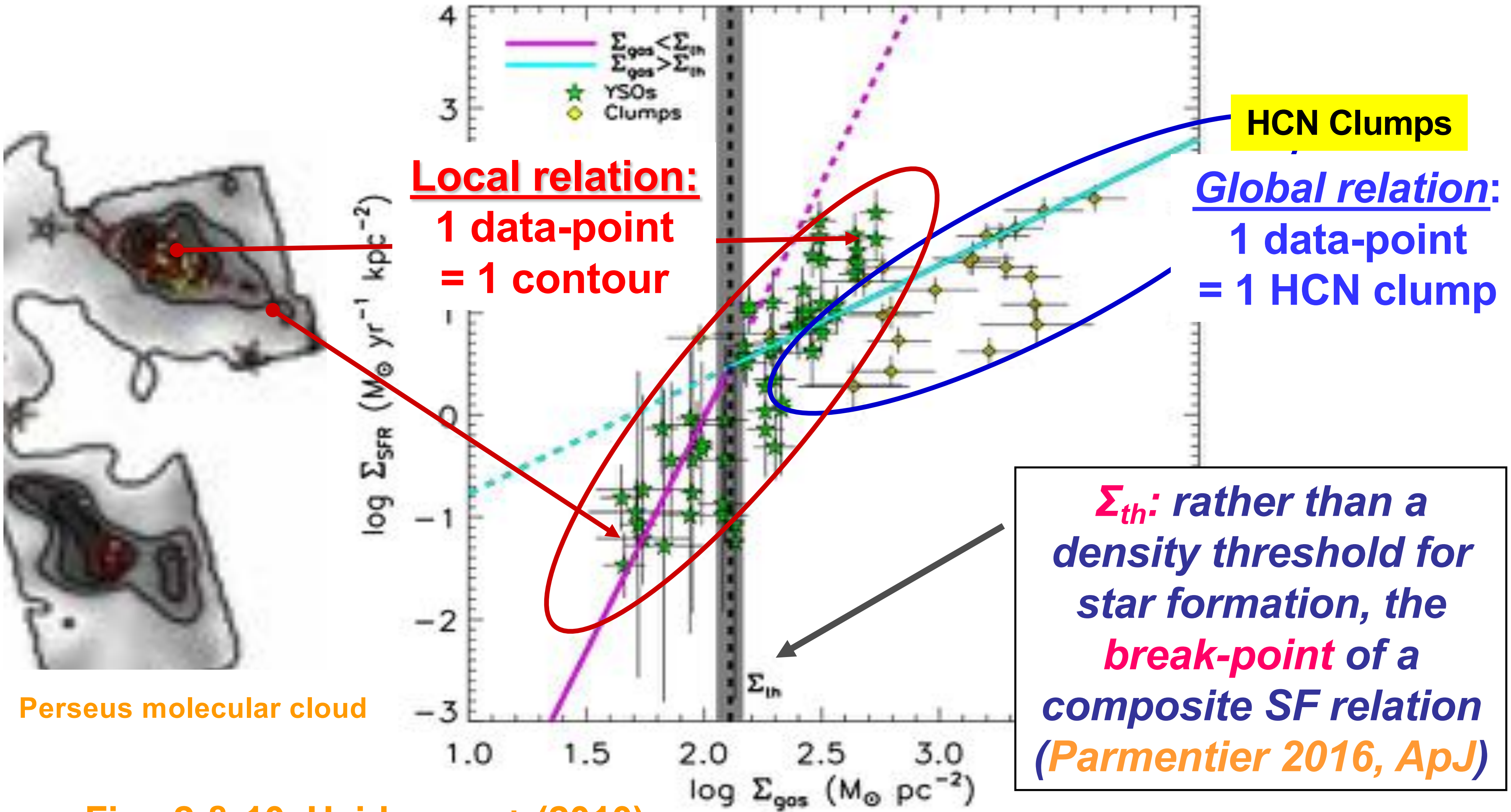
Local relation:
1 data-point
= 1 contour

HCN Clumps

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

Figs 2 & 10, Heiderman+ (2010)

Interpretation of Break-Point

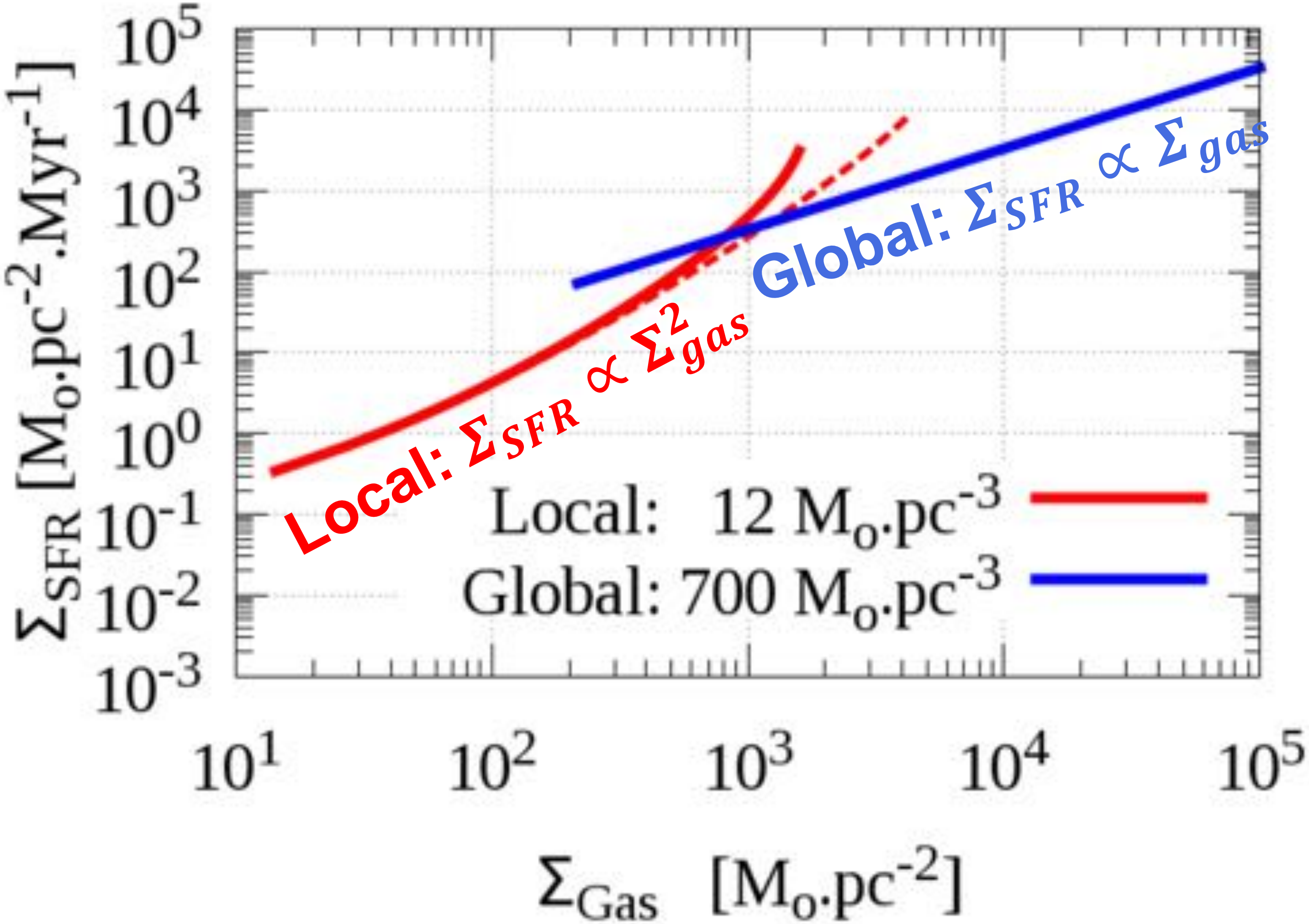


Perseus molecular cloud

Figs 2 & 10, Heiderman+ (2010)

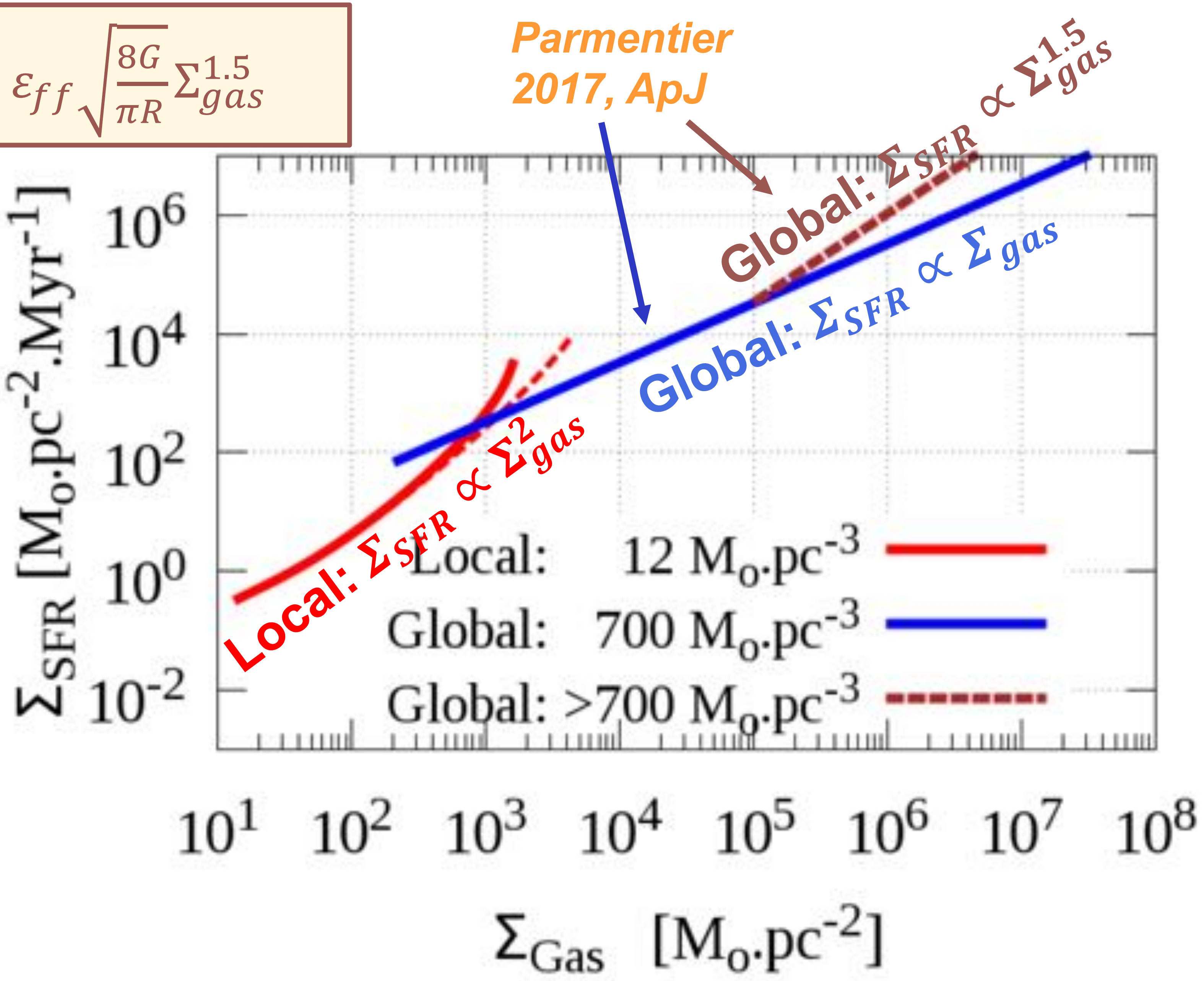
Σ_{th}: rather than a density threshold for star formation, the break-point of a composite SF relation (Parmentier 2016, ApJ)

Composite SF Relation: II + III

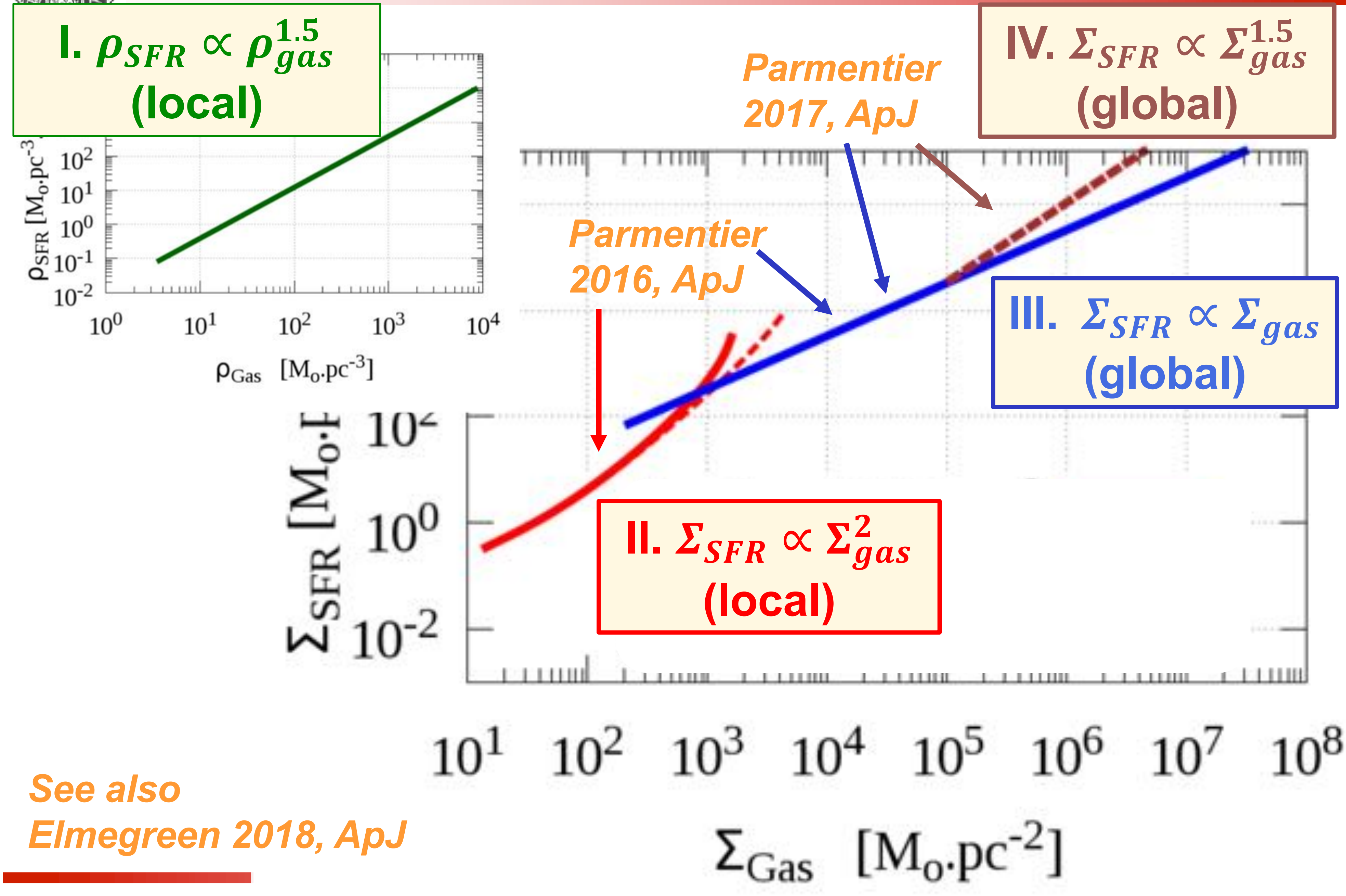


Fourth SF Relation (the very dense gas)

IV. $\Sigma_{SFR} = \varepsilon_{ff}\sqrt{\frac{8G}{\pi R}}\Sigma_{gas}^{1.5}$



4 Star Formation Relations for Molecular Clumps



See also
Elmegreen 2018, ApJ

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 $\langle \rho_{gas} \rangle$):

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

Clump-by-clump (increasing $\langle \rho_{gas} \rangle$):

$$\langle \Sigma_{SFR} \rangle \propto \langle \Sigma_{gas} \rangle^{3/2}$$

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 $\langle\rho_{gas}\rangle$):

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

Clump-by-clump (increasing $\langle\rho_{gas}\rangle$):

$$\langle\Sigma_{SFR}\rangle \propto \langle\Sigma_{gas}\rangle^{3/2}$$

- **Constant ε_{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 ε_{ff}**

Star Cluster Evolution after Gas Expulsion

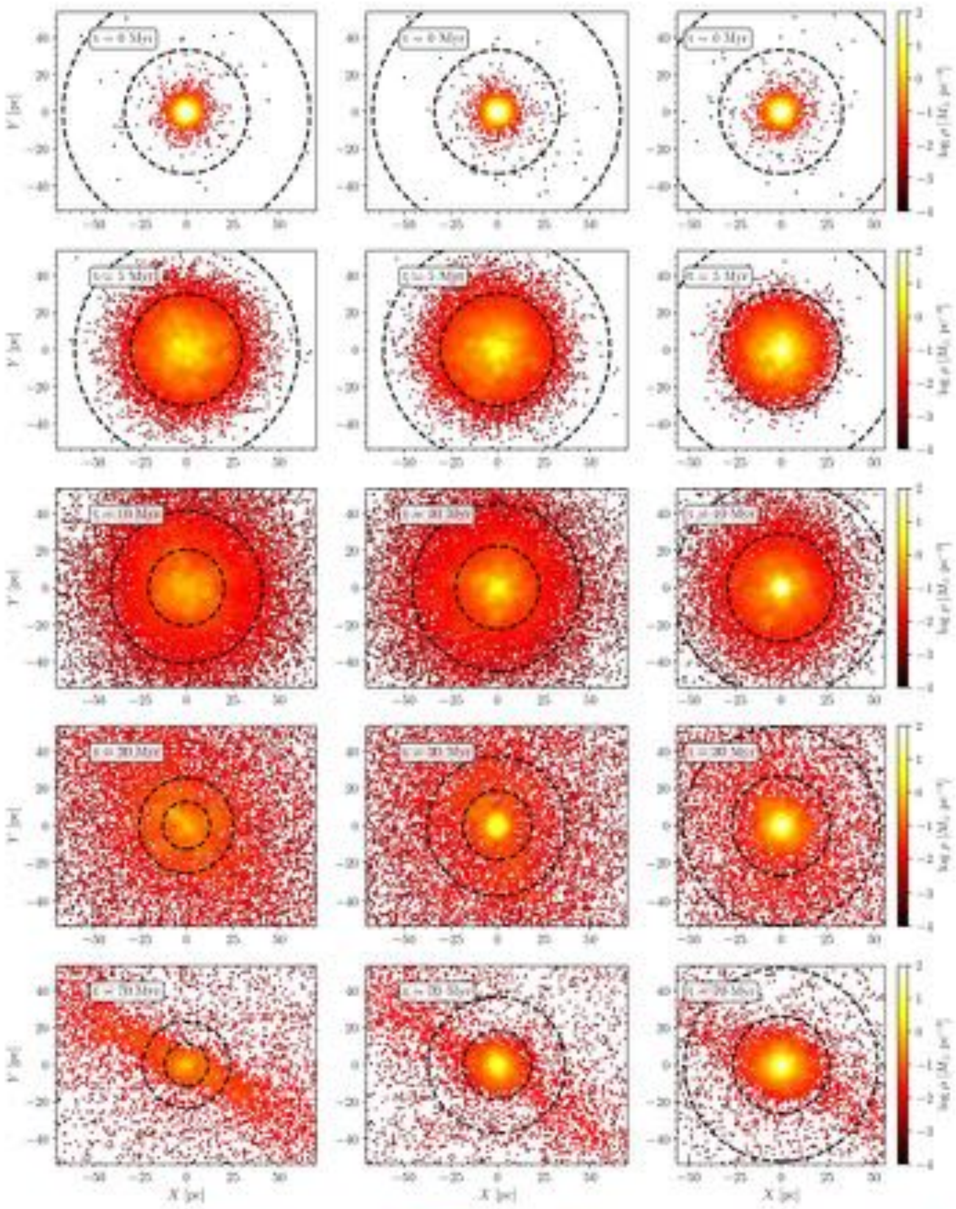
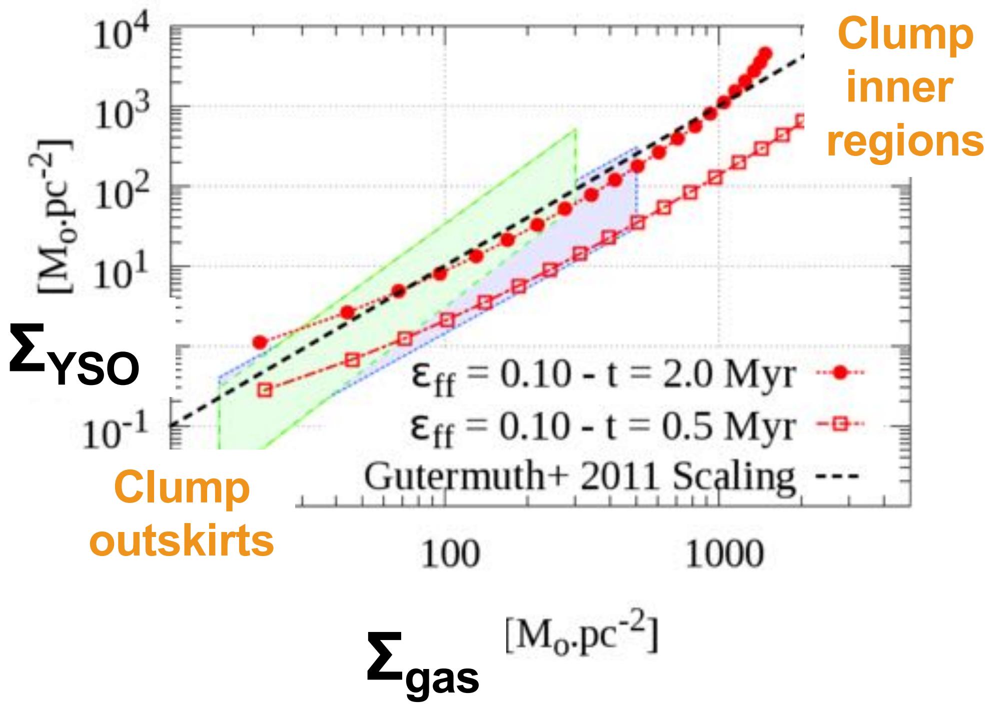
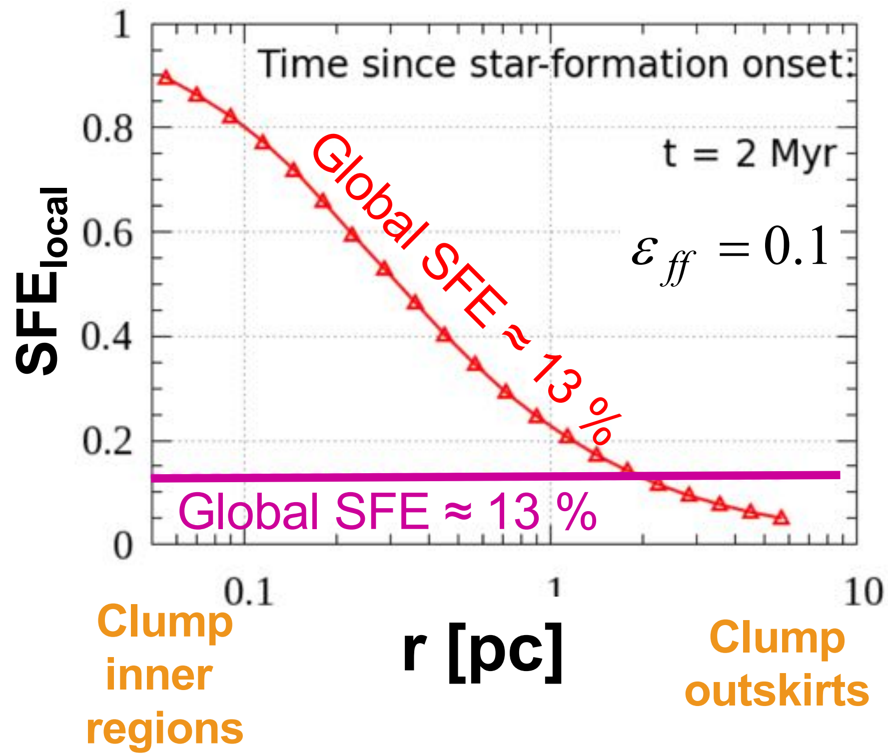


Fig 1, Shukirgaliyev, Parmentier, Just & Berczik (2018)

SFE Radial Variations





Local Star Formation Relation:

Superlinear / Quadratic

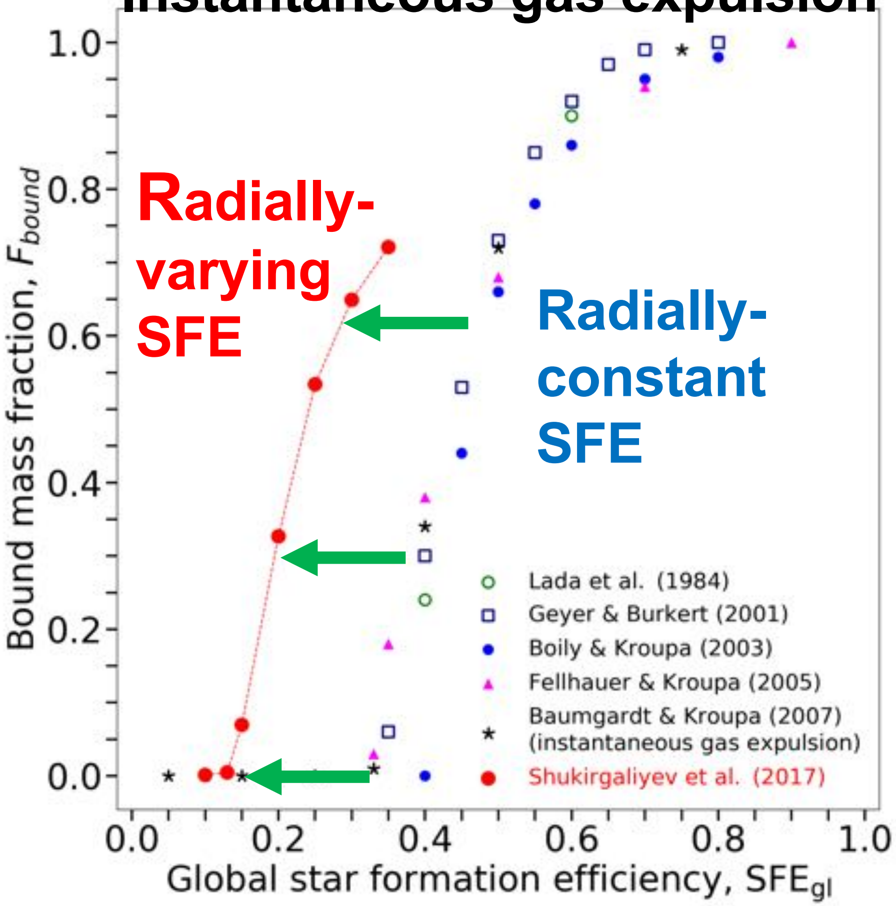
Local star formation efficiency :

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

Figs 3 and 10, Parmentier & Pfalzner (2013)

Violent Relaxation

Instantaneous gas expulsion



Based on Fig8 in Shukirgaliyev, Parmentier, Berczik & Just (2017)

- **Clusters reaching a global SFE higher than 13% do survive**

- **Strongly reduced infant mortality**
  - **Despite solar-neighbourhood tidal field inclusion!**
  - **One model cluster with a global SFE of 25% and a birth mass of 15E3M_{sun} has a dissolution time of 2.9Gyr !**

Take-Away Messages

- The slopes of star formation relations measured for molecular clumps depend on:
  - what is measured,
  - how it is measured,
  - on top of SF physics

- When interpreting star formation relations, first thought should be "pitfalls ahead"

- Cluster infant mortality

  ↳ Cluster teenage mortality