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The Density Gradient Inside Molecular-Gas Clumps as a Booster of their Star Formation Activity

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Star Formation Rate

- The process of star formation is quantified by the star formation rate (SFR), that is, how much gas mass is turned into stars per time unit

How long a gas reservoir is able to sustain star formation

SFR [$M_\odot Myr^{-1}$]

Amount of nucleosynthetic products injected into the ISM

Amount of kinetic energy injected into the ISM

Star Formation Rate / Star Formation Efficiency per Free-Fall Time

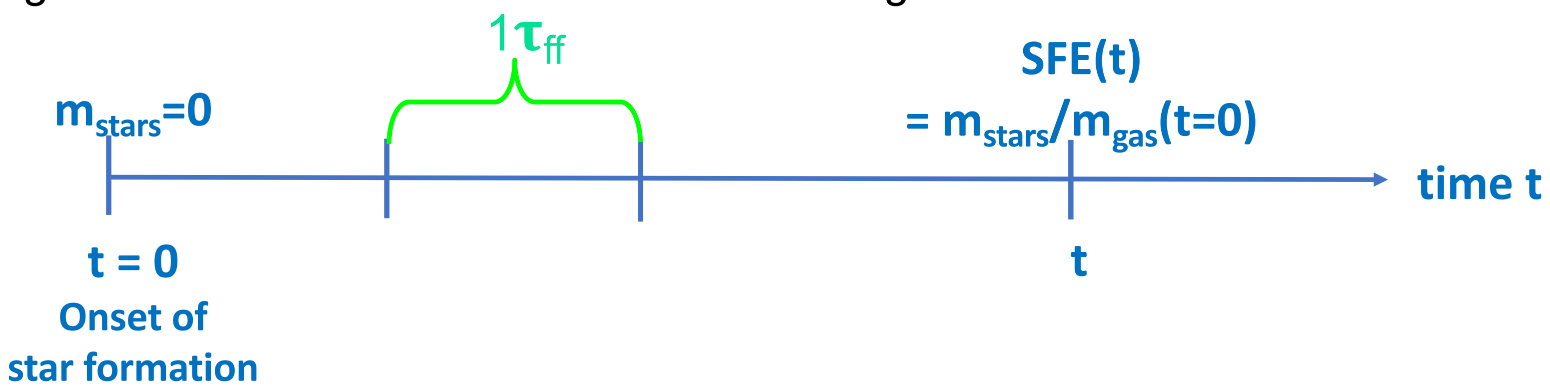
- Krumholz & McKee (2005) → empirical parameterization of the SFR of a gas reservoir :
  - m_{gas} is the mass of the gas reservoir
  - τ_{ff} is the freefall time of the gas reservoir, calculated at the mean density of the gas $\langle\rho_{gas}\rangle$
  - ε_{ff} is the star formation efficiency per free-fall time (= gas mass fraction turned into stars per free-fall time)

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

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

SFE and SFE per Free-Fall Time

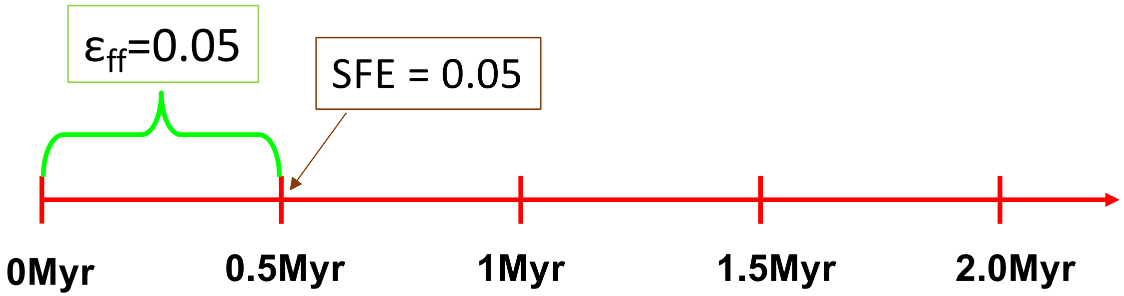
- Do not confuse:
  - The Star Formation Efficiency SFE: mass fraction of gas which has been turned into stars at a given time *t*



  - Star Formation Efficiency per Free-Fall Time ε_{ff}: mass fraction of gas which is being turned into stars over one free-fall time τ_{ff}

Star Formation Rate / Star Formation Efficiency per Free-Fall Time

ρ_{gas}=300$M_{\odot}$.pc^{-3}
$\tau_{ff,init} \cong$ 0.5Myr

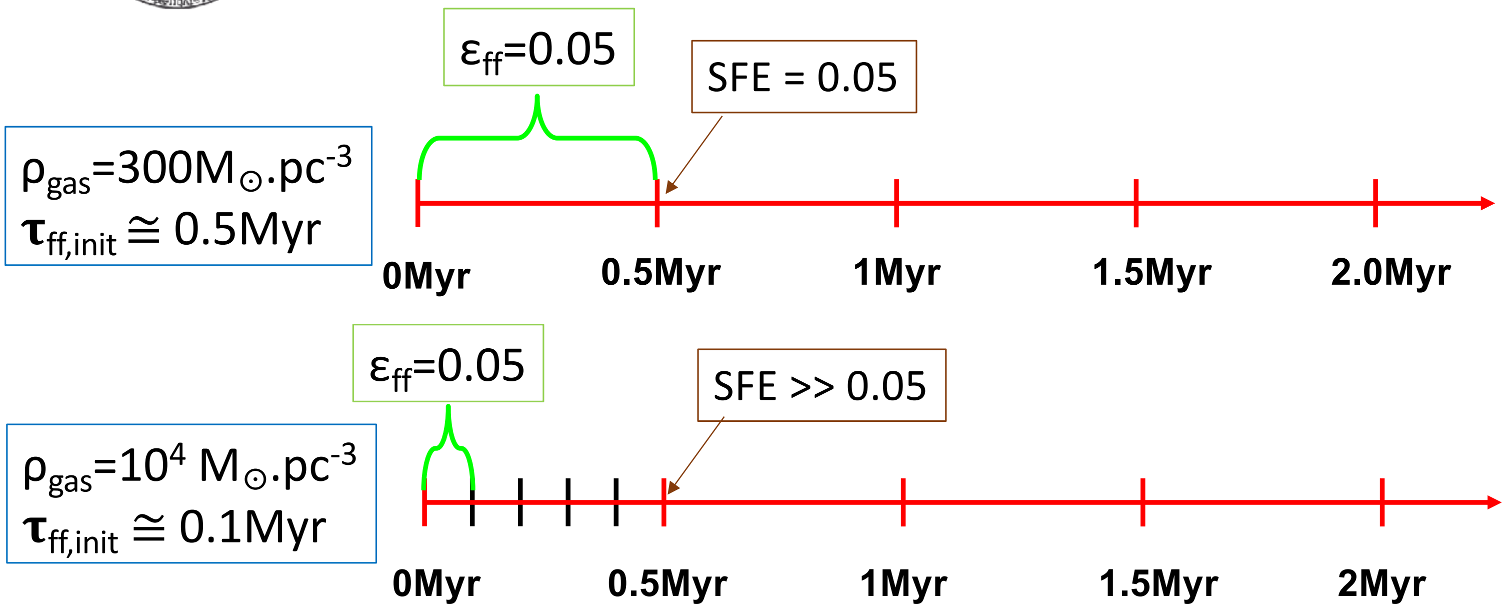


$$SFR = \frac{\varepsilon_{ff} m_{gas}}{\tau_{ff}}$$

$$\tau_{ff} = \sqrt{\frac{3\pi}{32\boldsymbol{G}\langle\rho_{gas}\rangle}}$$

G = 0.0045
[$M_{\odot}$, Myr, pc]

Star Formation Rate / Star Formation Efficiency per Free-Fall Time



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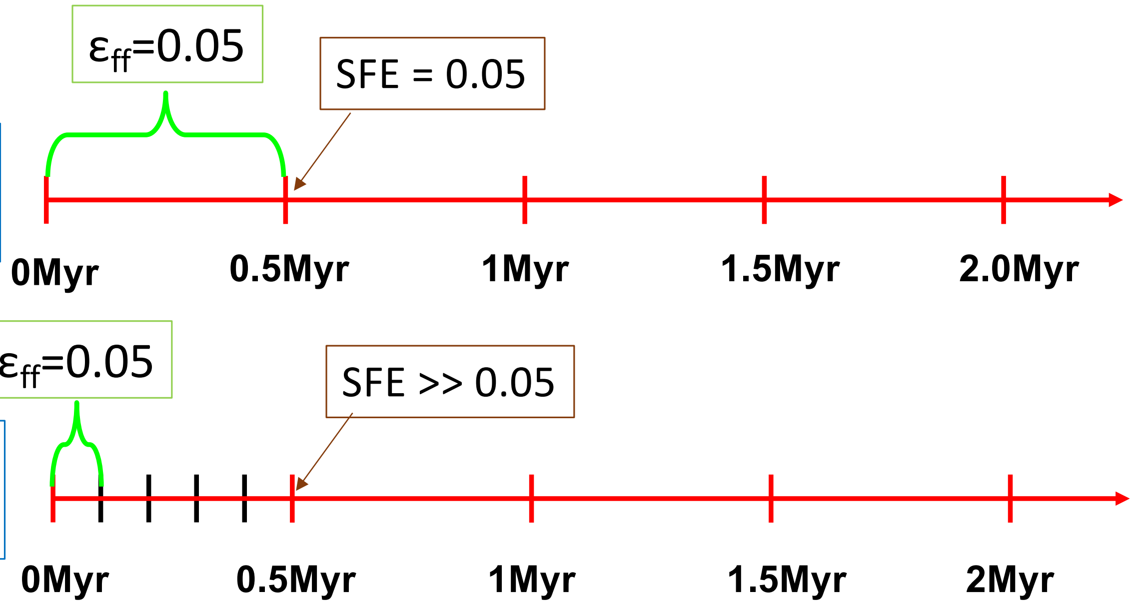
Star Formation Rate / Star Formation Efficiency per Free-Fall Time

ρ_{gas}=300M$_\odot$.pc^{-3}
$\tau_{ff,init} \cong$ 0.5Myr

ρ_{gas}=10^4 M$_\odot$.pc^{-3}
$\tau_{ff,init} \cong$ 0.1Myr



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G = 0.0045 [M$_\odot$, Myr, pc]

- **For any given physical time-span after the onset of star formation, molecular-gas regions of higher density achieve higher SFEs ("<u>denser is faster</u>")**
- **Star formation does not care about the Earth orbital period around the Sun !**

Star Formation Rate / Star Formation Efficiency per Free-Fall Time

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"**denser is faster**"

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"**denser is faster**"

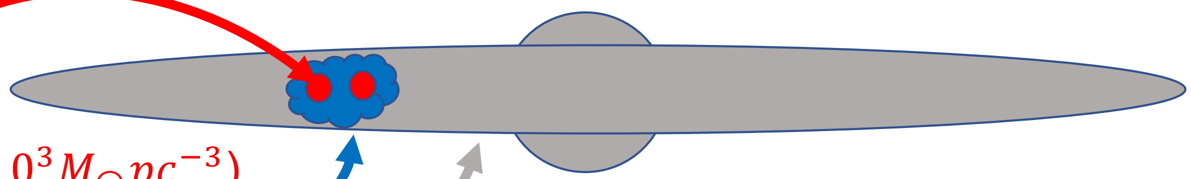
- How much is ε_{ff} ?
- Observers measure ε_{ff} as:

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

measured star formation efficiency per freefall time

Star Formation Rate / Star Formation Efficiency per Free-Fall Time

- Approach applied to
  - molecular clumps (≅ pc-scale),
    aka dense molecular gas ($\rho \cong 10^3 M_\odot pc^{-3}$)
  - molecular clouds (≅ 50-pc scale),
    aka diffuse molecular gas ($\rho \cong 10 M_\odot pc^{-3}$)
  - entire galaxies (>10kpc scale)



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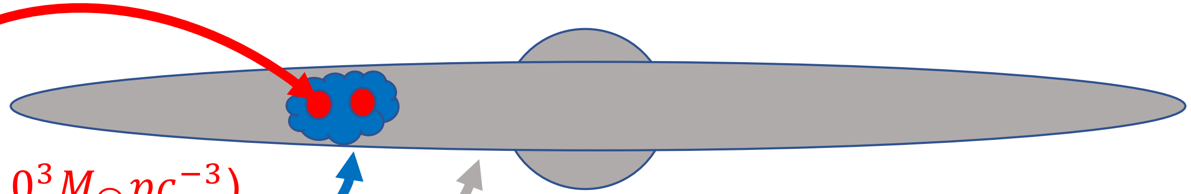


measured star formation efficiency per freefall time

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

- with a diversity of results being produced, e.g.:
  - Krumholz & Tan (2007): $\varepsilon_{ff,meas}$ about constant in the Galactic disk, from the diffuse CO-mapped gas to the dense HCN/CS-mapped gas
  - Lee+(2016), Ochsendorf+(2017): $\varepsilon_{ff,meas}$ varies among molecular clouds of the Galactic disk and of the Large Magellanic Cloud

$\varepsilon_{ff,meas} \cong 10^{-2}$

$10^{-3} < \varepsilon_{ff,meas} < 1$

Molecular Clouds of the Solar Neighbourhood

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

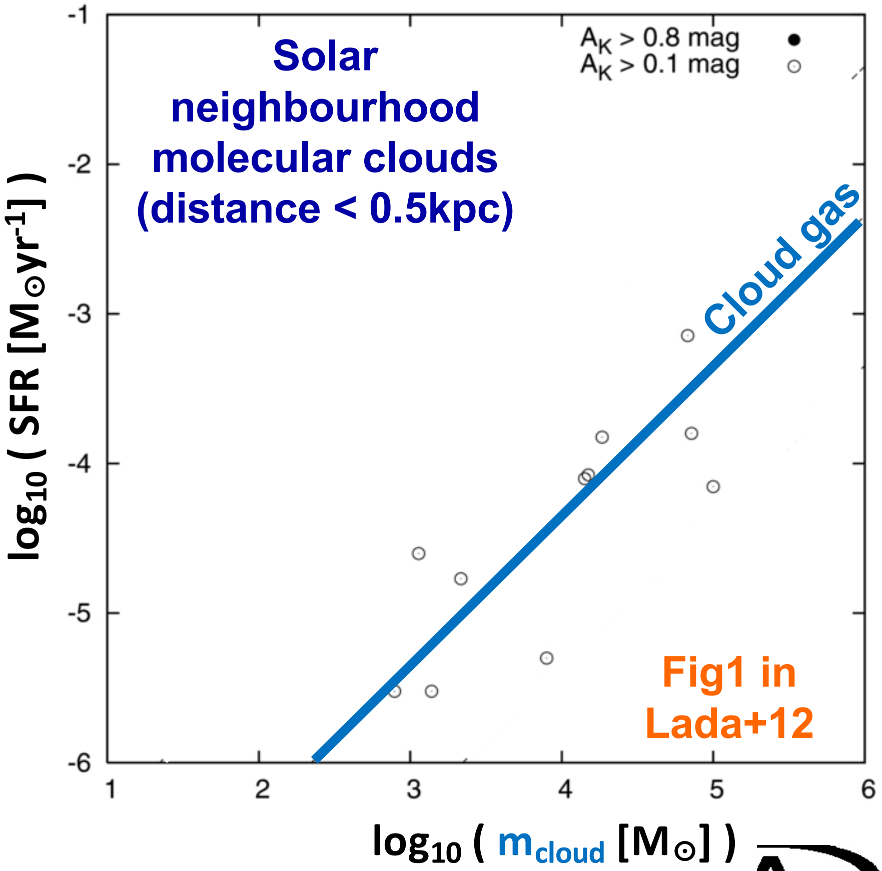
- Does the SFR depend only on the mass of gas available and on its volume density (i.e. its free-fall time) ?
- Insights from nearby molecular clouds. Their mean volume density does not vary very much ($\langle\rho_{cloud}\rangle \cong 10 M_{\odot} pc^{-3}$)

Molecular Clouds of the Solar Neighbourhood

- Correlation between the mass and SFR of a sample of nearby molecular clouds (Lada+2010/2012)
  (open symbols/blue line)

- To first order, the SFR of a cloud increases with its mass (i.e. more gas mass, more star formation activity)

- There is, however, a lot of scatter, implying that an additional parameter must play a pivotal role in setting the cloud SFR

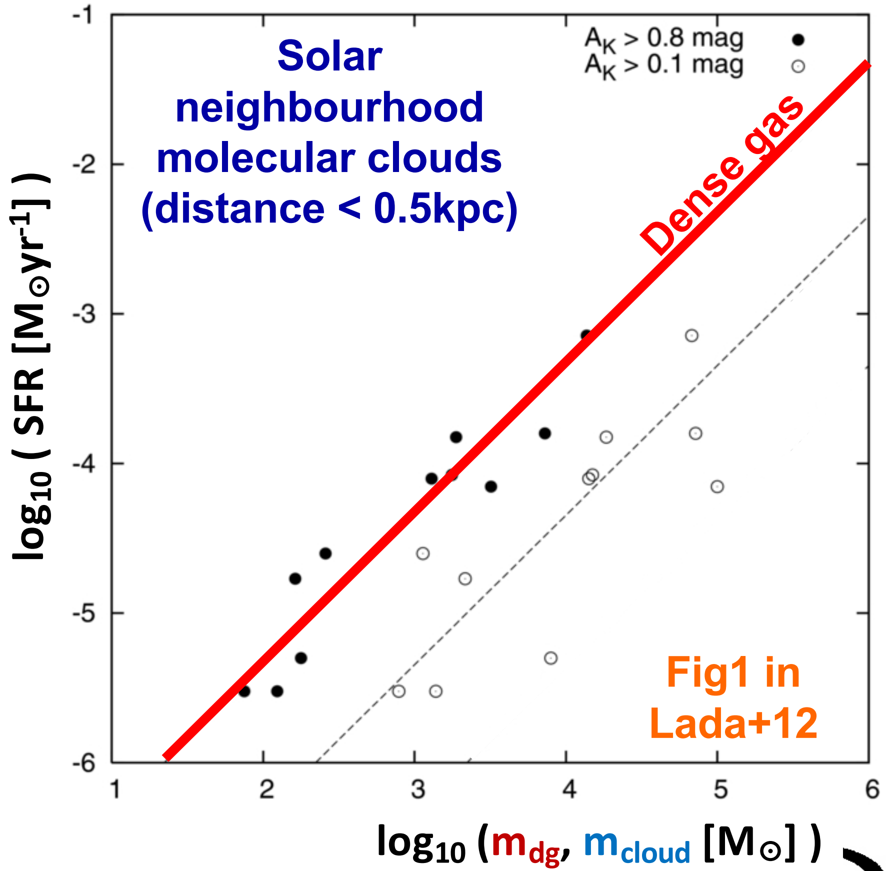


Molecular Clouds of the Solar Neighbourhood

- This additional parameter is the cloud internal structure

- Clumps of dense gas (plain symbols/red line)

- The cloud SFR is more tightly correlated with the cloud dense-gas mass than with the cloud total mass

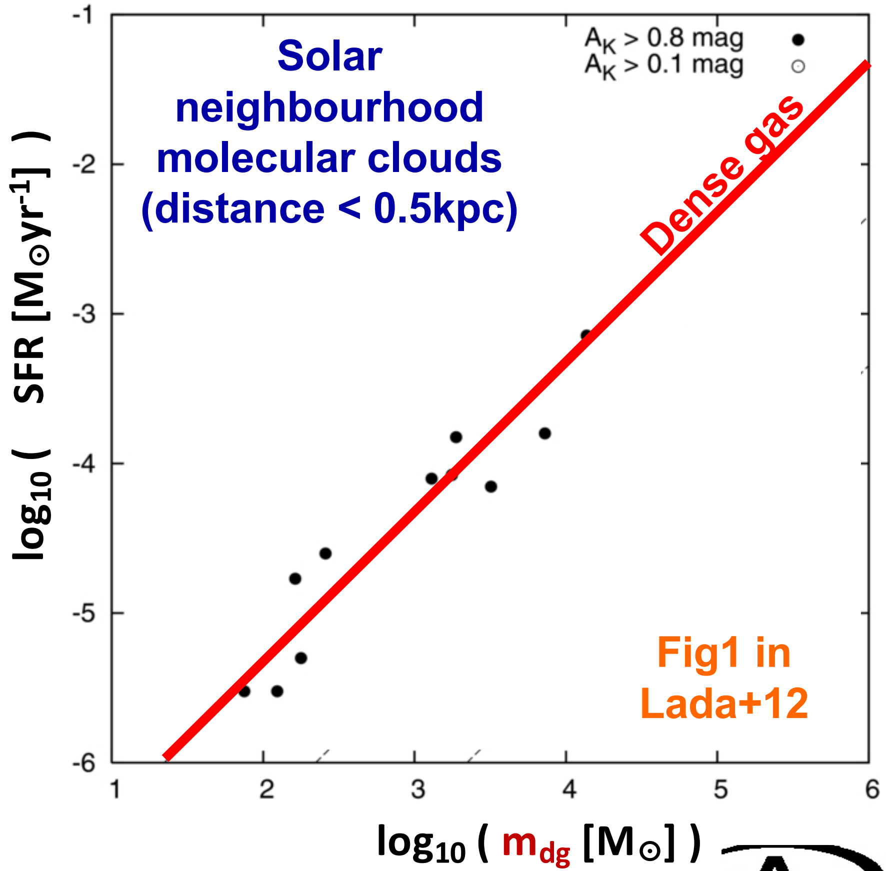


Molecular Clouds of the Solar Neighbourhood

- Uncertainties in the several parameters needed to build the SFR can account for the residual scatter:

$$SFR = \frac{N_{YSO}\langle m_{YSO}\rangle}{t_{SF}}$$

YSO = Young Stellar Object



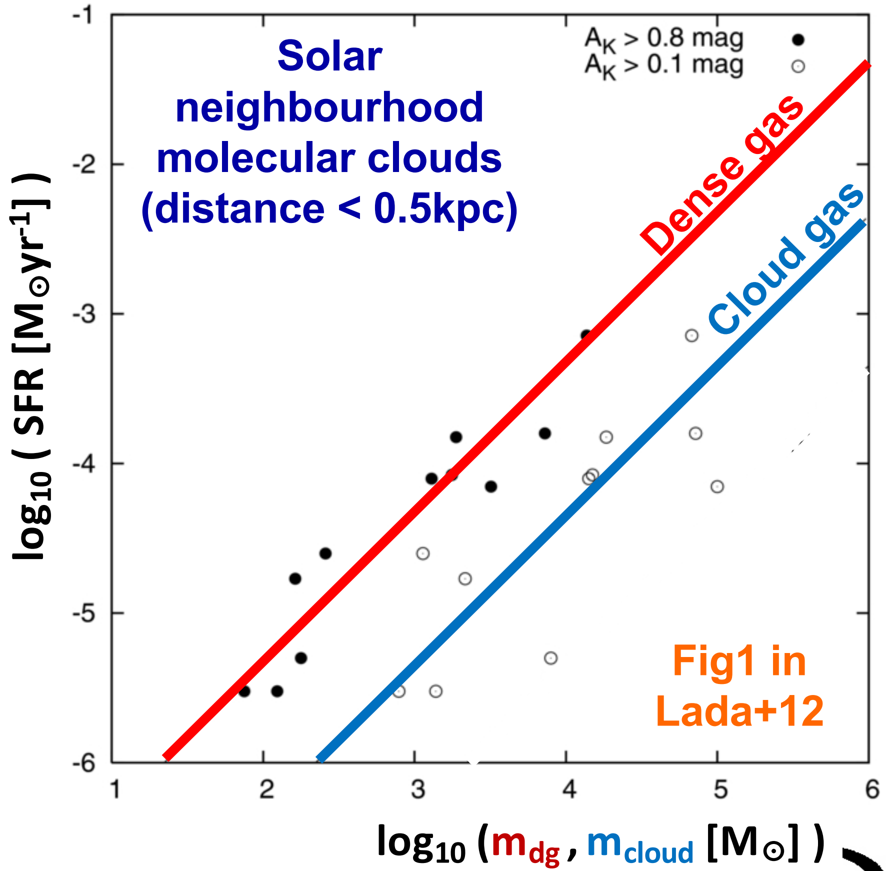
- Any additional physical parameter ?
- The idea that the scatter may still bear some physical meaning was hardly brought forward

Molecular Clouds of the Solar Neighbourhood

Observers are well-cognizant of the inner structure ↔ star formation activity connection for giant molecular clouds

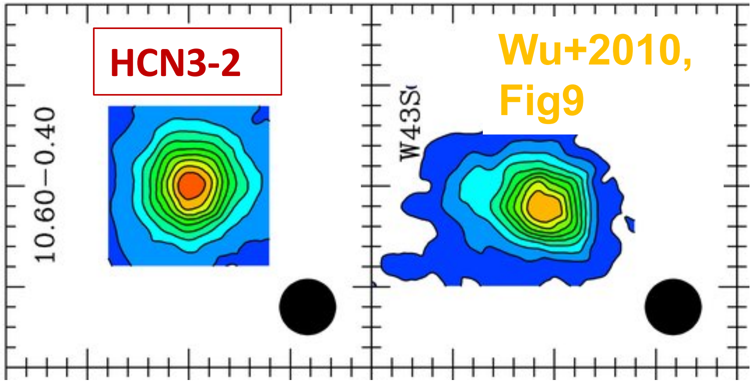
Yet, that a similar connection may exist at the level of the smaller-scale denser molecular clumps was hardly put forward

Could the clump structure be a factor contributing to their SFR?



Molecular Clumps (pc-scale)

Clumps are centrally-concentrated

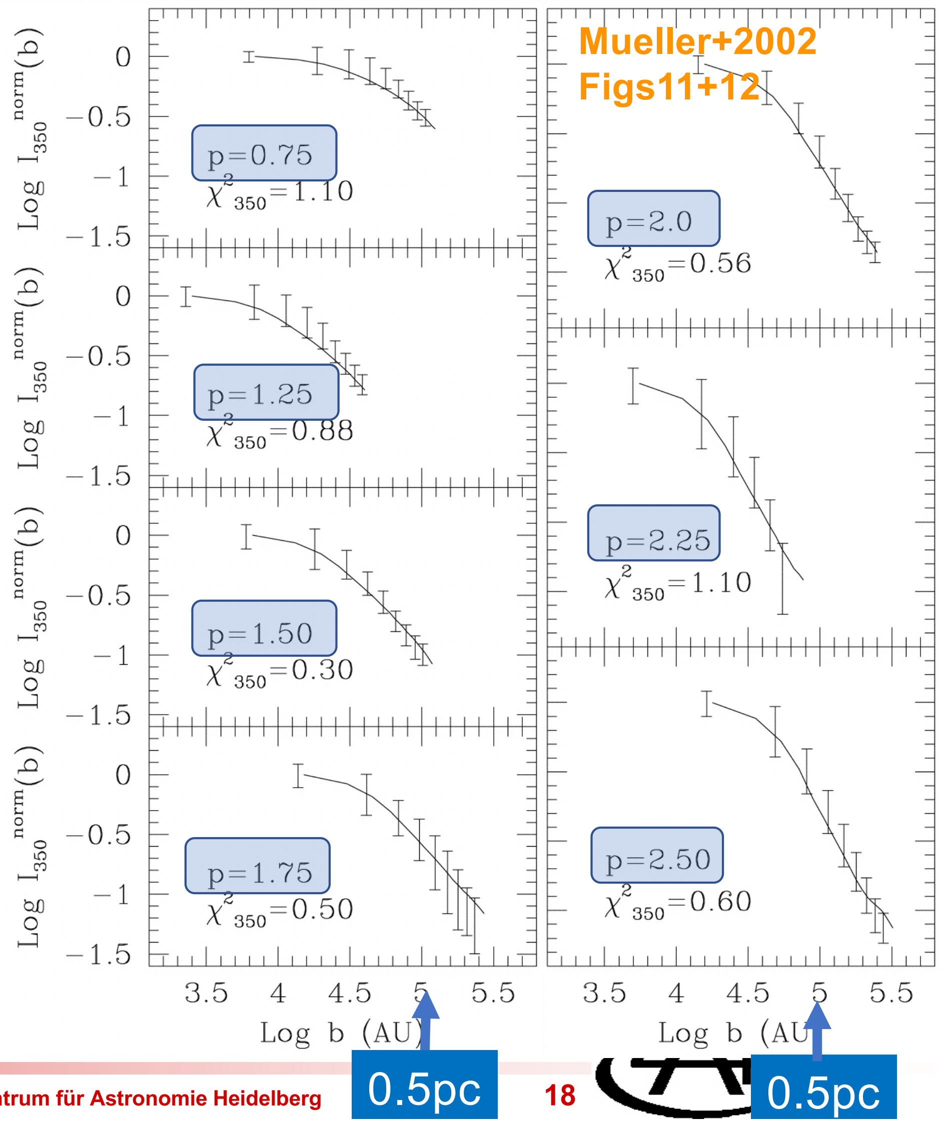


- Clump volume density profile often parameterized as:

$$\rho_{gas}(r) \propto r^{-p}$$

  - r: distance to the clump center
  - p: steepness of the density profile

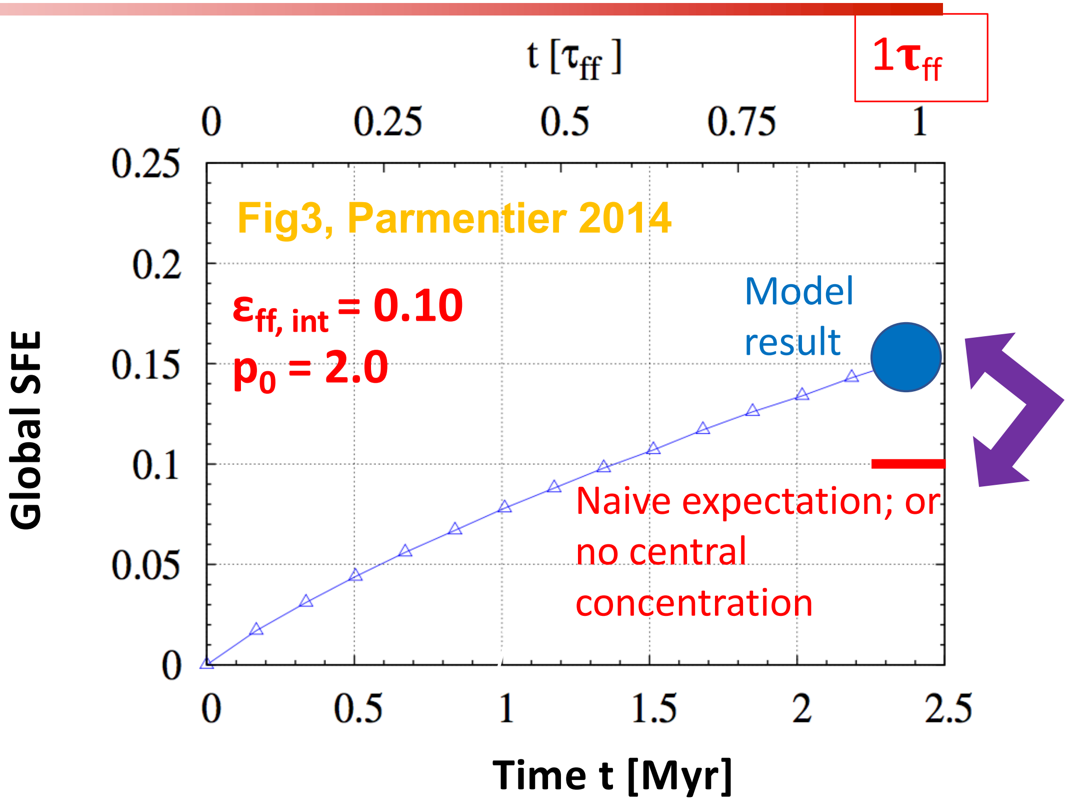
What role does their density gradient play?



Impact of Clump Density Gradient

- Parmentier & Pfalzner (2013), Parmentier (2014), and subsequent publications
- Semi-analytical model of cluster-forming clump:
  - E.g.: Power-law density profile of initial steepness p_0=2 with central core:

The global SFE of a clump increases faster if the clump is more centrally-concentrated



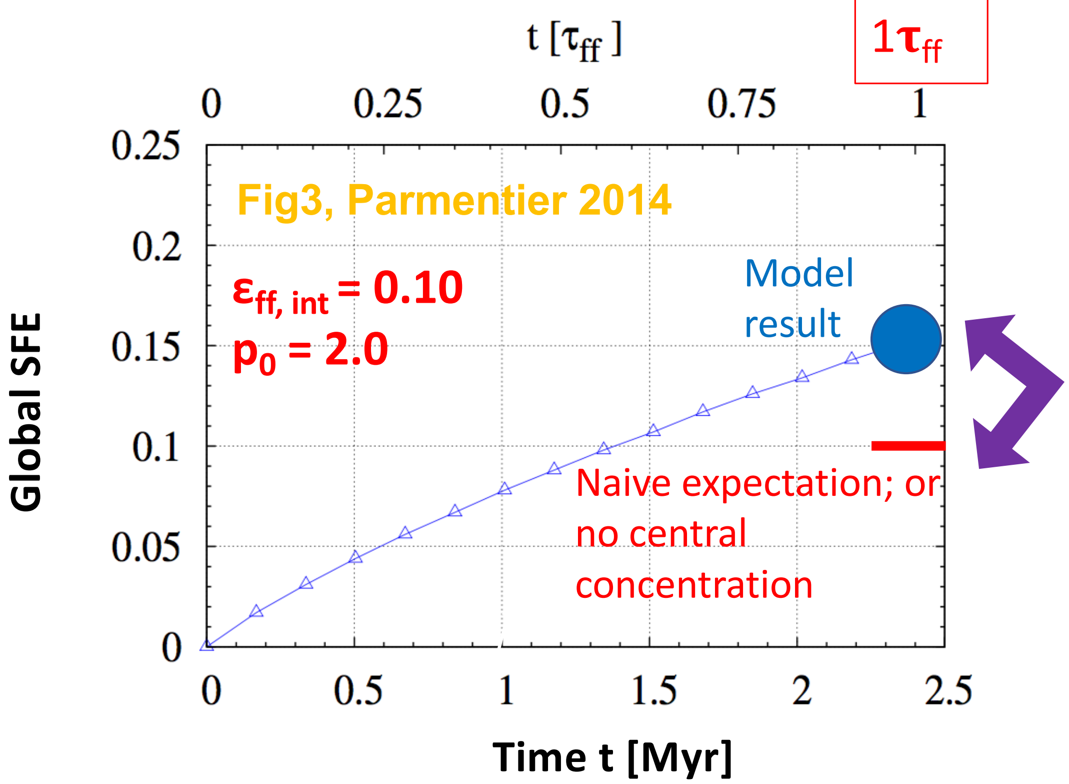
Impact of Clump Density Gradient

- Effect anticipated by Tan+2006 already
  - For a pure power law with p<2:

$$SFR_{clump} = \frac{(3-p)^{3/2}}{2.6(2-p)} SFR_{TH}$$

TH = Top-Hat (i.e. uniform gas volume density)

- Also confirmed by:
  - Girichidis+2011 (hydro),
  - Cho & Kim 2011 (hydro),
  - Elmegreen 2011 (semi-analytical)



When Gas Density Gradients Get (Much) Steeper

➤ More recent observations (Schneider+2015) have reported much steeper density profiles in dense-gas clumps (size ≅ 1pc) of two (less) nearby molecular clouds:

- MonR2 (distance ≅ 0.8kpc): $p_{equiv} = 2.9$
- NGC6334 (distance ≅ 1.4kpc): $p_{equiv} = 4.2$

Owing to their larger distances, these clouds were not included in the data set of Lada+2010/12

Dust-emission map of MonR2

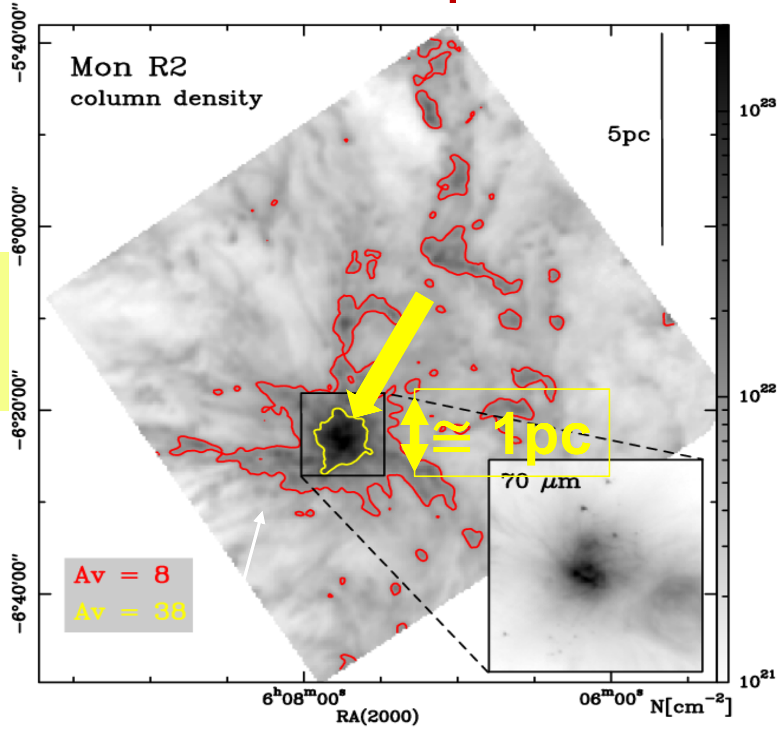
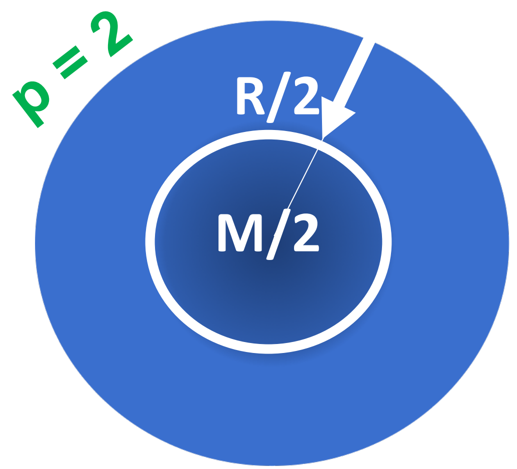


Fig 1, Schneider+2015

From Shallow to Highly Centrally-Concentrated Profiles

- Clump (M,R): How does the clump mass fraction enclosed within half the clump radius vary as a function of p?

From Shallow to Highly Centrally-Concentrated Profiles



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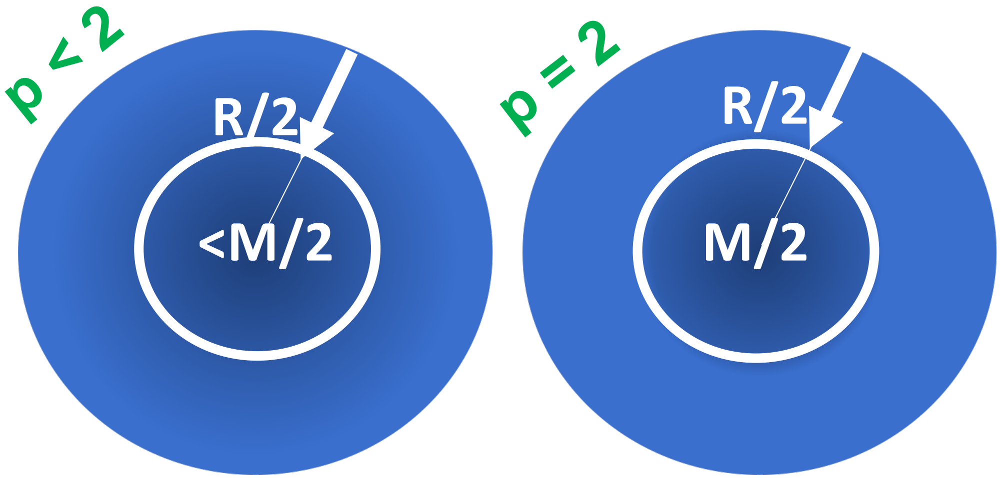

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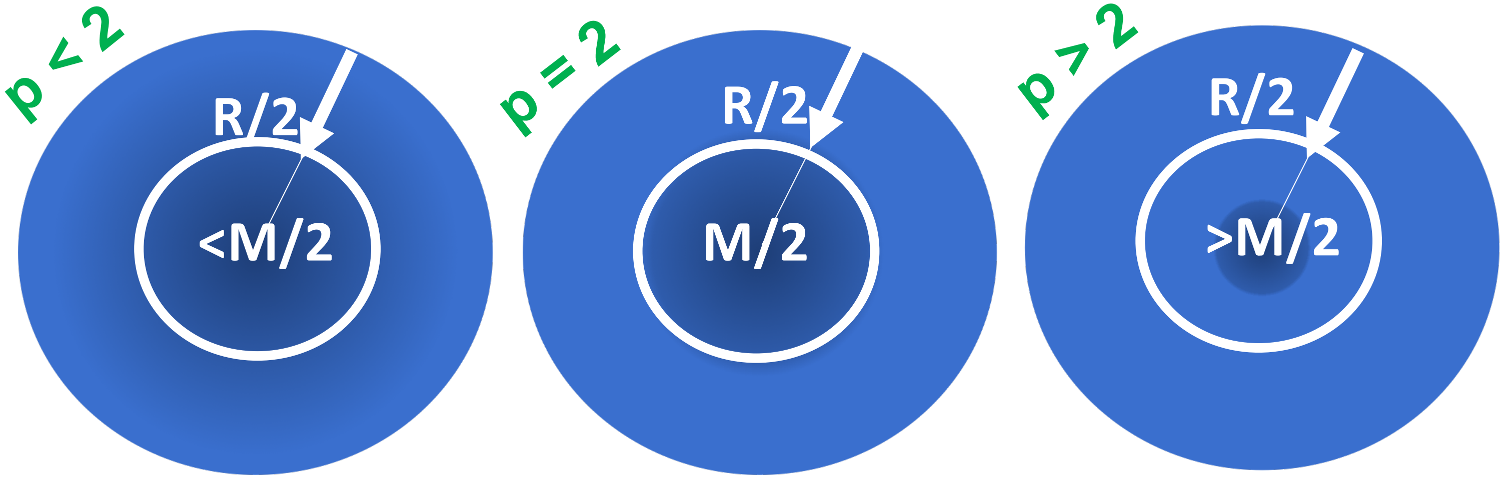

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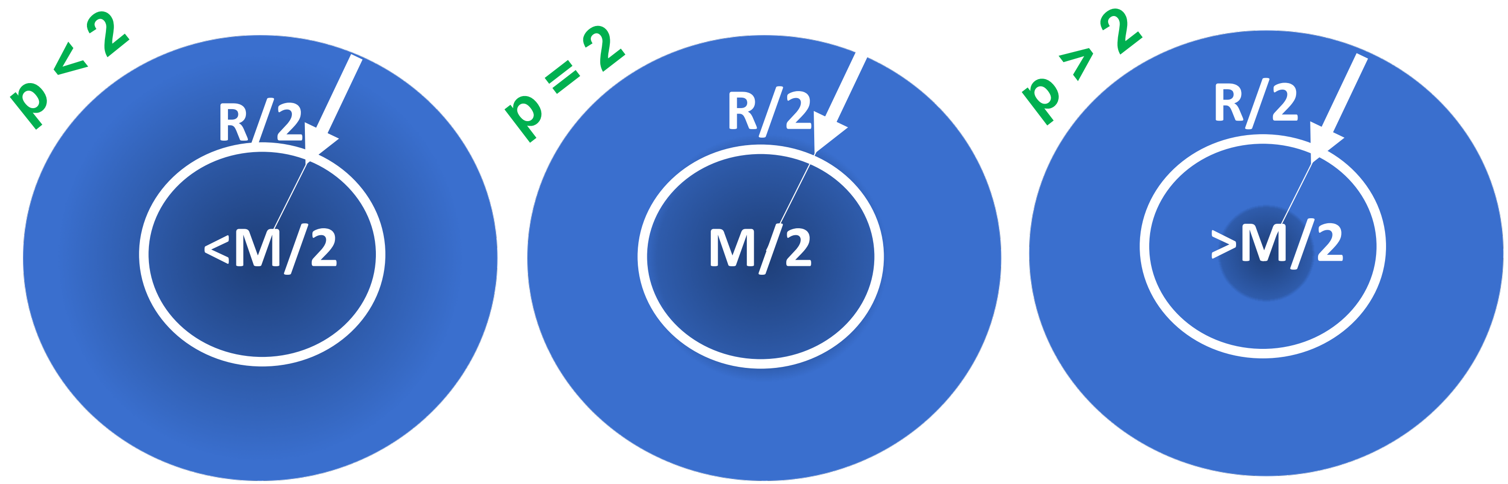


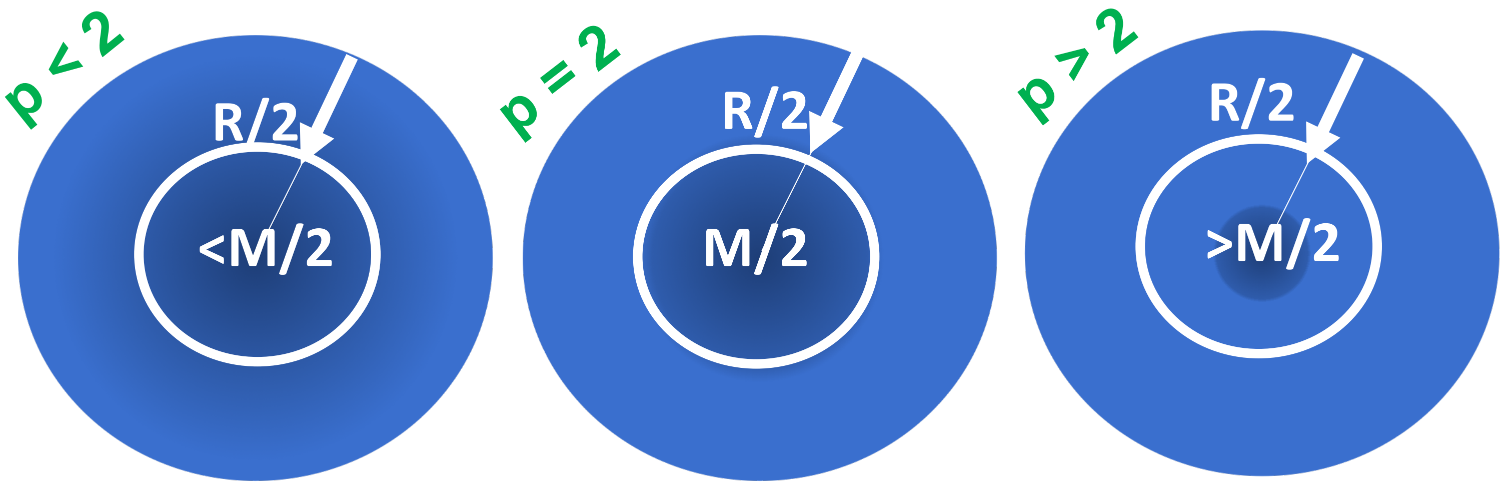
When 0 < p < 2:

➤ SF proceeds faster in the higher-density central regions of the clump, BUT that does not affect much of the gas mass since the gas is not strongly centrally-concentrated

When p > 2:

➤ SF proceeds faster in the higher-density central regions of the clump AND this affects the bulk of the clump gas mass

From Shallow to Highly Centrally-Concentrated Profiles



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When $p > 2$:

➤ SF proceeds faster in the higher-density central regions of the clump AND this affects the bulk of the clump gas mass

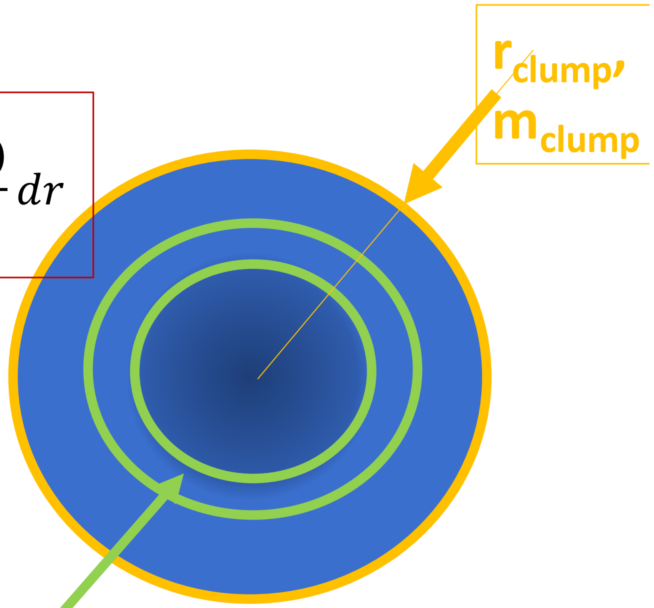
Unlock a regime of SF far more efficient than what has been chartered so far with $p \leq 2$. How much more efficient?

Clump SFR: Centrally-Concentrated vs. Top-Hat

- Gas clump: mass m_{clump}, radius r_{clump}, density profile $\rho_{gas}(r)$

$$SFR_{clump} = \int_0^{r_{clump}} \varepsilon_{ff,int} \frac{dm_{gas}(r)}{\tau_{ff}(r)} = \varepsilon_{ff,int} \int_0^{r_{clump}} \frac{4\pi\, r^2\, \rho_{gas}(r)}{\tau_{ff}(r)} dr$$

Faster in clump inner regions than in outskirts



$$dSFR_{shell} = \varepsilon_{ff,int} \frac{dm_{gas}(r)}{\tau_{ff}(r)}$$

$\varepsilon_{ff,int}$ = constant

Clump SFR: Centrally-Concentrated vs. Top-Hat

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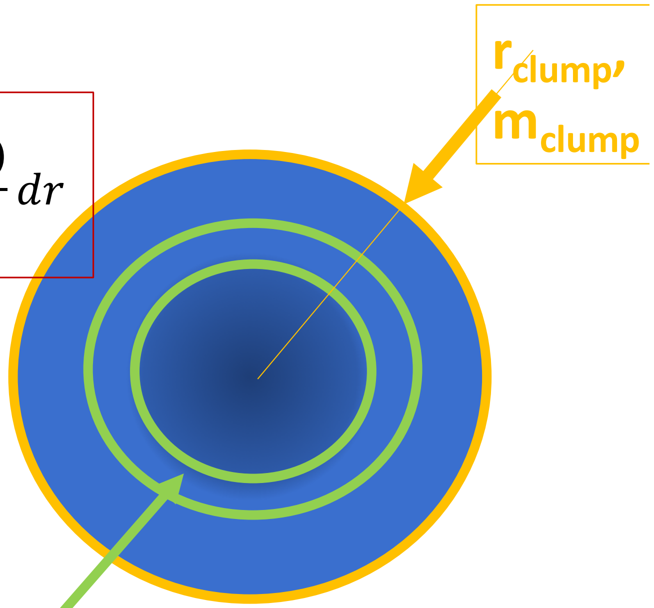

$$dSFR_{shell} = \varepsilon_{ff,int} \frac{dm_{gas}(r)}{\tau_{ff}(r)}$$

$\varepsilon_{ff,int}$ = constant

- Top-Hat Equivalent (m_{clump}, r_{clump}, $\rho_{gas}(r)$ = constant)

$$SFR_{TH} = \int_0^{r_{clump}} \varepsilon_{ff,int} \frac{dm_{gas}(r)}{\tau_{ff}(r)} = \varepsilon_{ff,int} \frac{m_{clump}}{\tau_{ff}}$$

Magnification Factor ζ

- Magnification factor ζ:

  → quantify by how much a given density profile amplifies the SFR of a clump compared to the SFR of its top-hat equivalent (Parmentier 2019)

$$\zeta = \frac{SFR_{clump}}{SFR_{TH}}$$

Magnification Factor ζ

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  → quantify by how much a given density profile amplifies the SFR of a clump compared to the SFR of its top-hat equivalent (Parmentier 2019)

$$\zeta = \frac{SFR_{clump}}{SFR_{TH}}$$

- Armed with a power-law profile with a flat central core (i.e. no density singularity at the clump center)

$$\rho_{init}(r) = \frac{\rho_c}{\left(1 + \left(\frac{r}{r_c}\right)^2\right)^{p_0/2}}$$

ρ_c: central density
r_c: central core

- let us map a wider range of the parameter space, in particular, cover p > 2

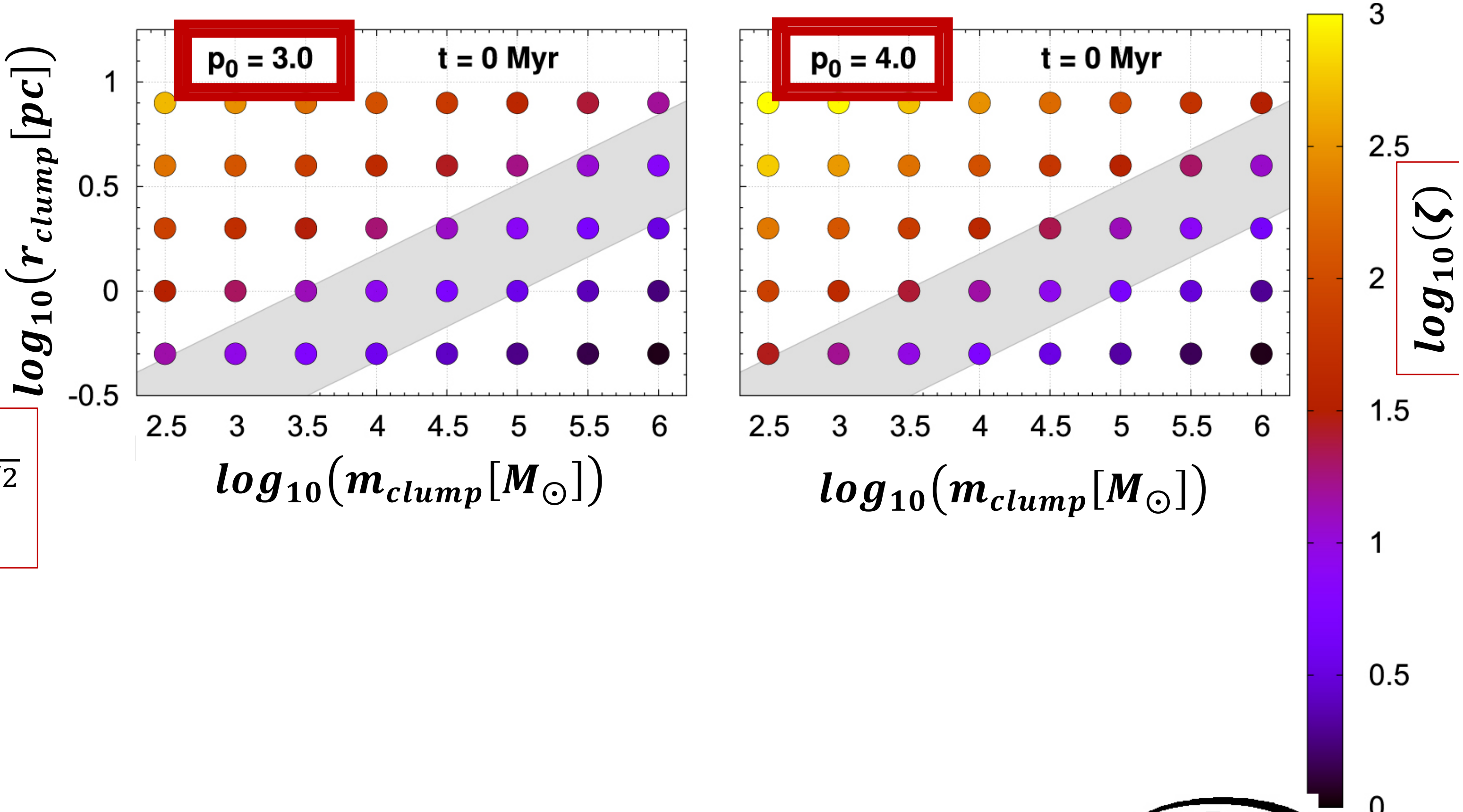
Magnification Factor ζ Mapping

Fig7, Parmentier'19

$$\zeta = \frac{SFR_{clump}}{SFR_{TH}}$$

- $\rho_c = 7.10^6\, M_{\odot} pc^{-3}$
- $r_c \leftarrow m_{clump}$ enclosed within r_{clump}

$$\rho_{init}(r) = \frac{\rho_c}{\left(1 + \left(\frac{r}{r_c}\right)^2\right)^{p_0/2}}$$



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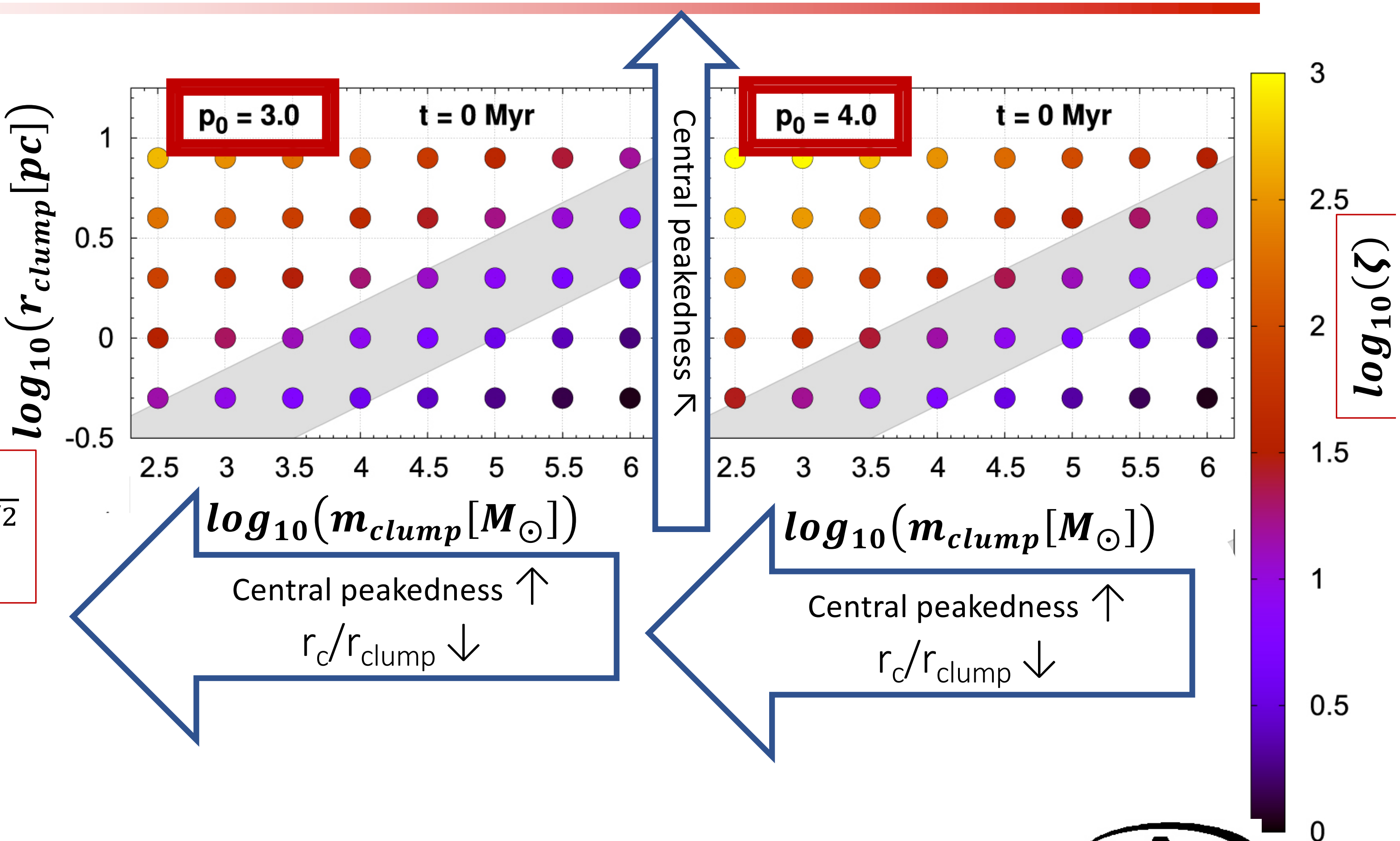

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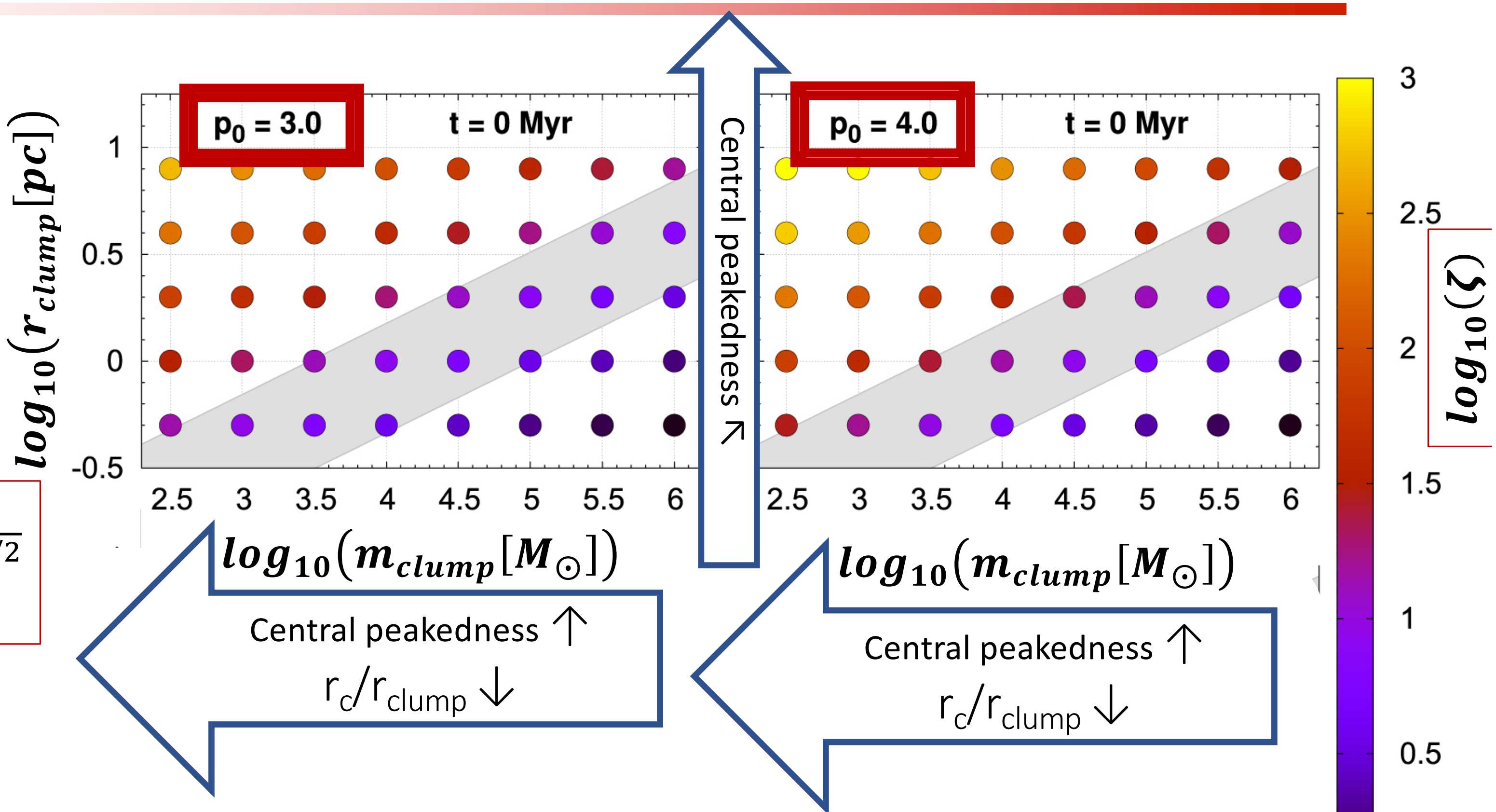

ζ reaches an order of magnitude in the density regime for which density profiles steeper than p=2 have been observed (grey stripe)

Star Formation vs. Structure Degeneracy

- If the SFR of a clump is high,
  - is it due to an intrinsically high star formation efficiency per free-fall time ($\varepsilon_{ff,int}$),
  - or is the clump SFR amplified by the clump structure (ζ)?

$$SFR_{clump} = \zeta\, SFR_{TH} = \zeta\, \varepsilon_{ff,int} \frac{m_{clump}}{\langle \tau_{ff} \rangle}$$

Star Formation vs. Structure Degeneracy

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- The measured star formation efficiency per free-fall time $\varepsilon_{ff,meas}$, being inferred from clump <u>global</u> quantities:
  - its total SFR,
  - its total gas mass and,
  - its mean volume density,

$$\varepsilon_{ff,meas} = SFR_{clump} \frac{\langle \tau_{ff} \rangle}{m_{clump}} = \zeta \, \varepsilon_{ff,int}$$

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$$\varepsilon_{ff,meas} = SFR_{clump} \frac{\langle \tau_{ff} \rangle}{m_{clump}} = \zeta \, \varepsilon_{ff,int}$$

- What are the respective contributions to $\varepsilon_{ff,meas}$ of
  - the shell star formation activity ($\varepsilon_{ff,int}$),
  - the clump centrally-condensed structure (ζ)?

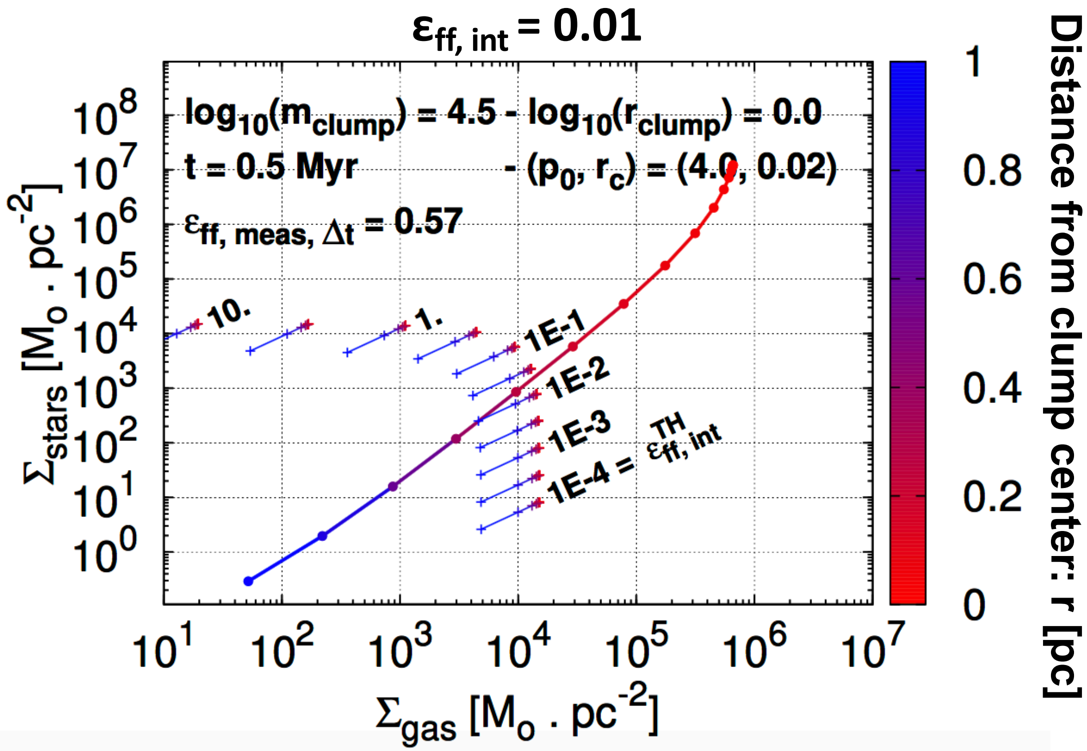
- **Can we get out of this degeneracy ?**

The Way Out: Resolved Observations

Fig3, Parmentier 2020

- Local star formation relation:
  - local stellar surface densities vs local gas surface densities

$\Sigma_{stars}(r_{proj})$ vs $\Sigma_{gas}(r_{proj})$



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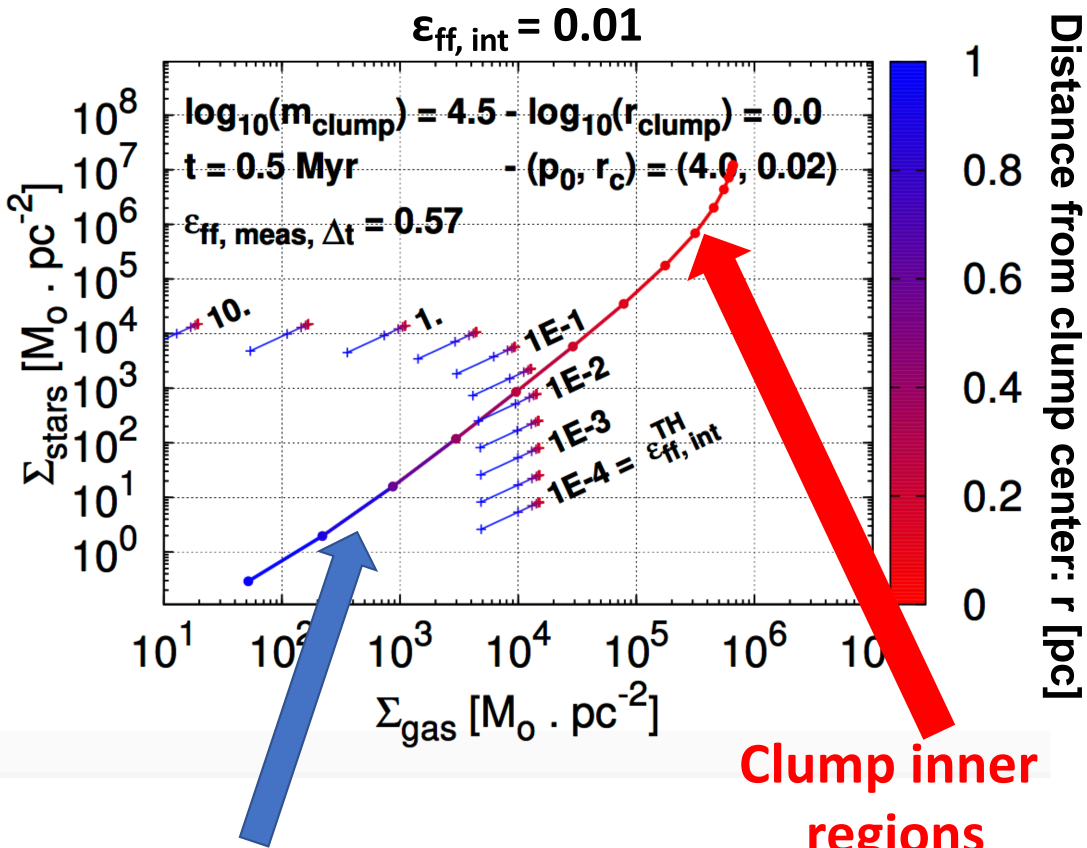

Clump outskirts

Clump inner regions

Fig3, Parmentier 2020

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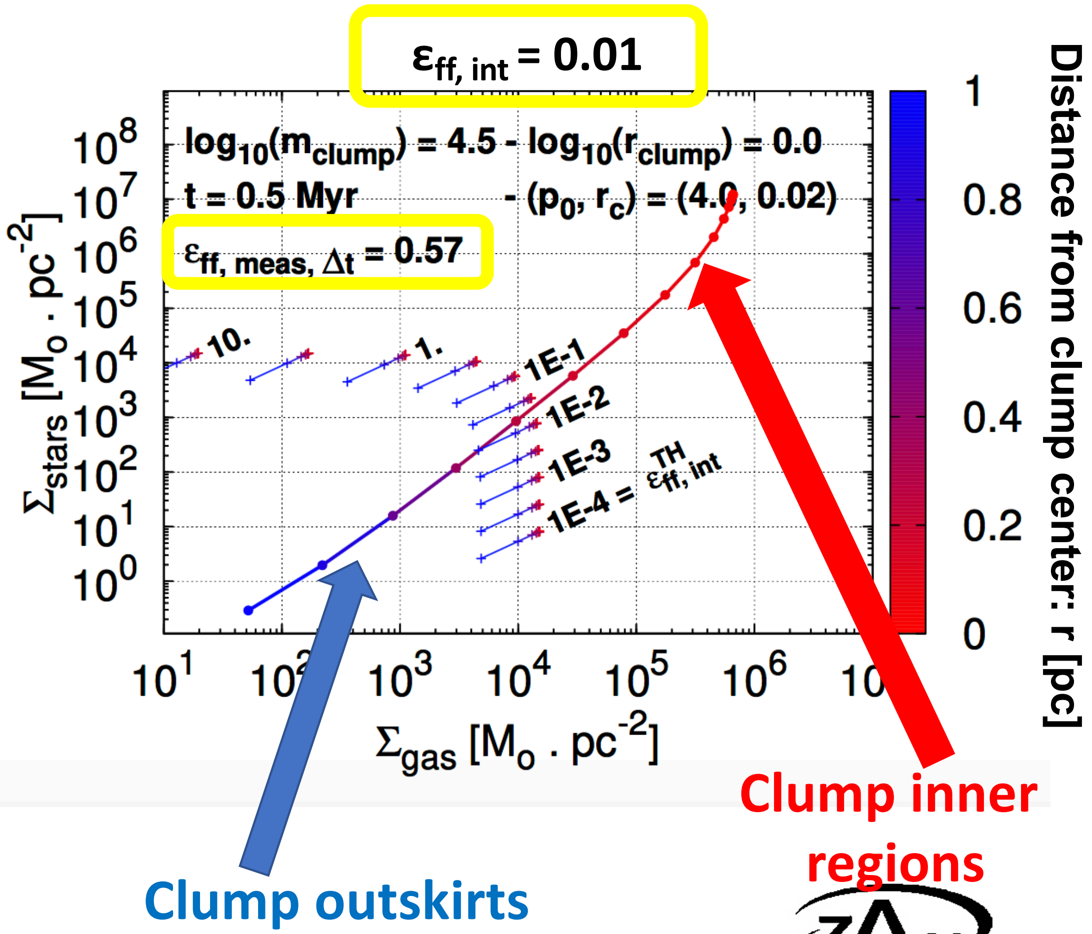

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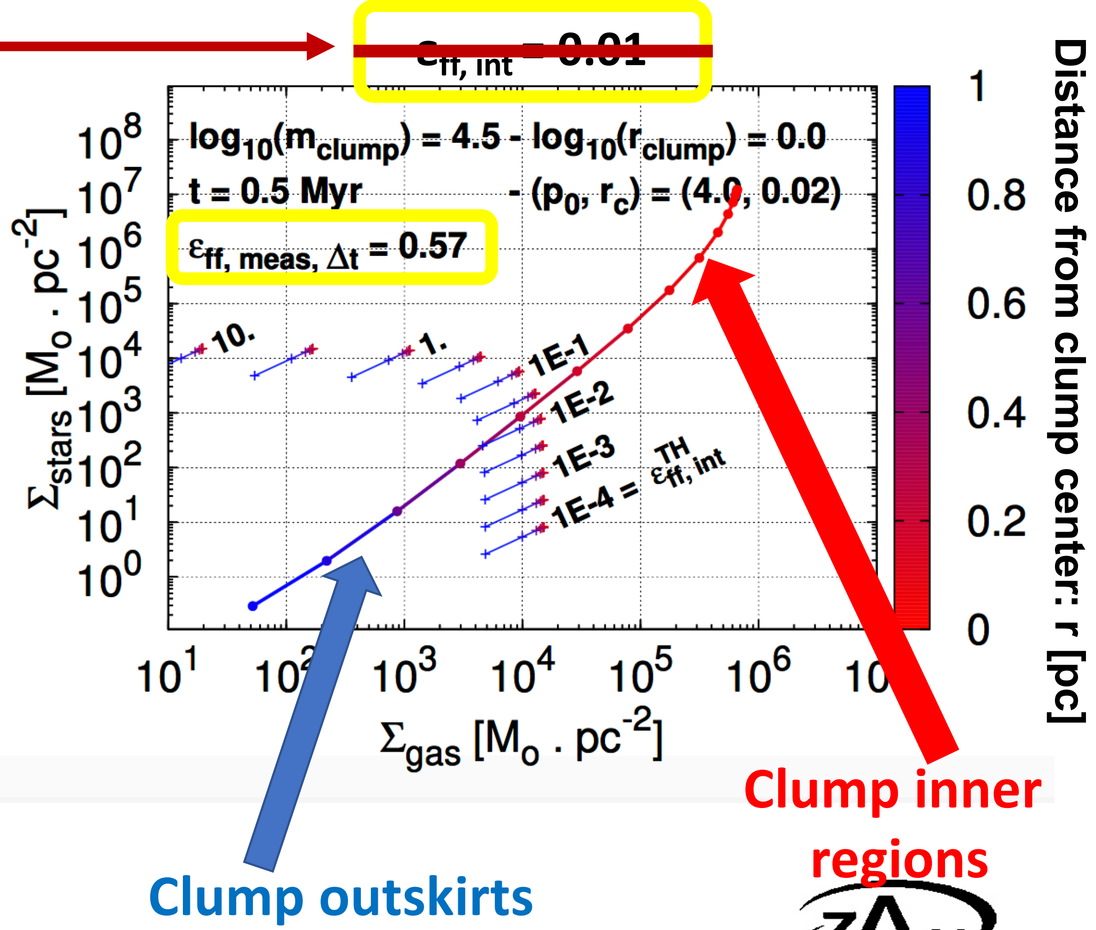
$\Sigma_{stars}(r_{proj})$ vs $\Sigma_{gas}(r_{proj})$

- What if we did not know the intrinsic SFE per free-fall time $\varepsilon_{ff,int}$?
  - Use a ladder! A ladder of top-hat profile models.



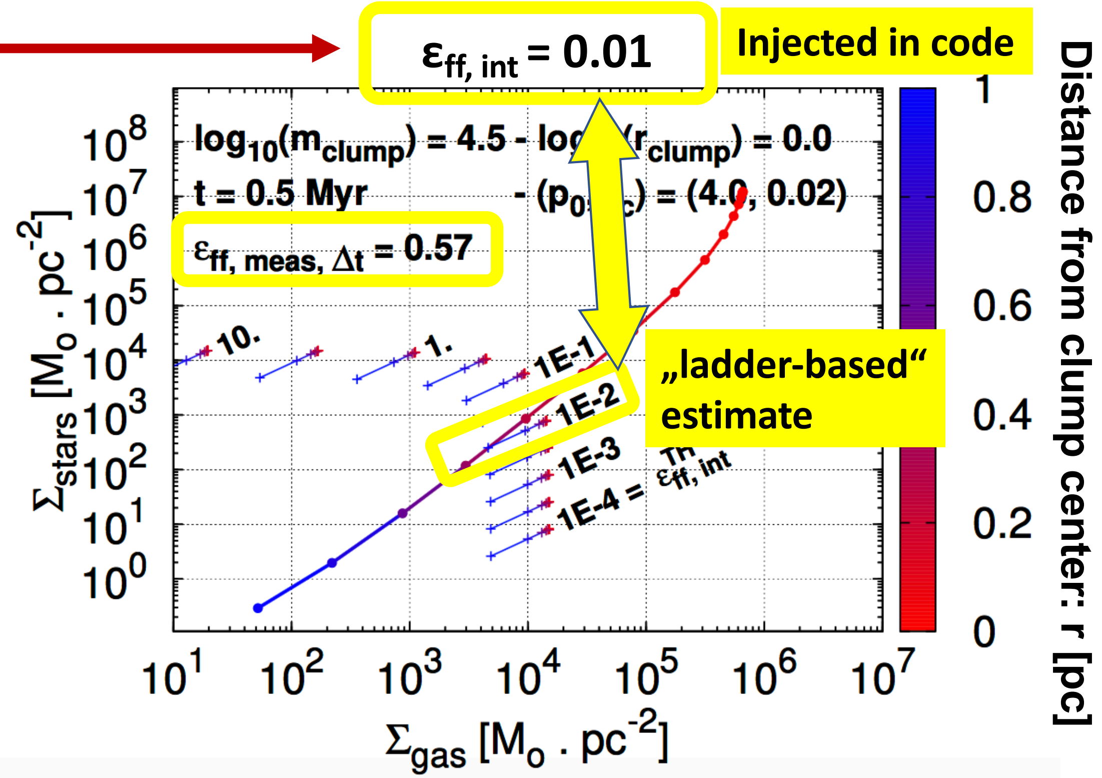
The Way Out: Resolved Observations

Fig3, Parmentier 2020

- Local star formation relation:
  - local stellar surface densities vs local gas surface densities

$$\Sigma_{stars}(r_{proj}) \text{ vs } \Sigma_{gas}(r_{proj})$$

- What if we did not know the intrinsic SFE per free-fall time $\varepsilon_{ff,int}$?
  - Use a ladder! A ladder of top-hat profile models.

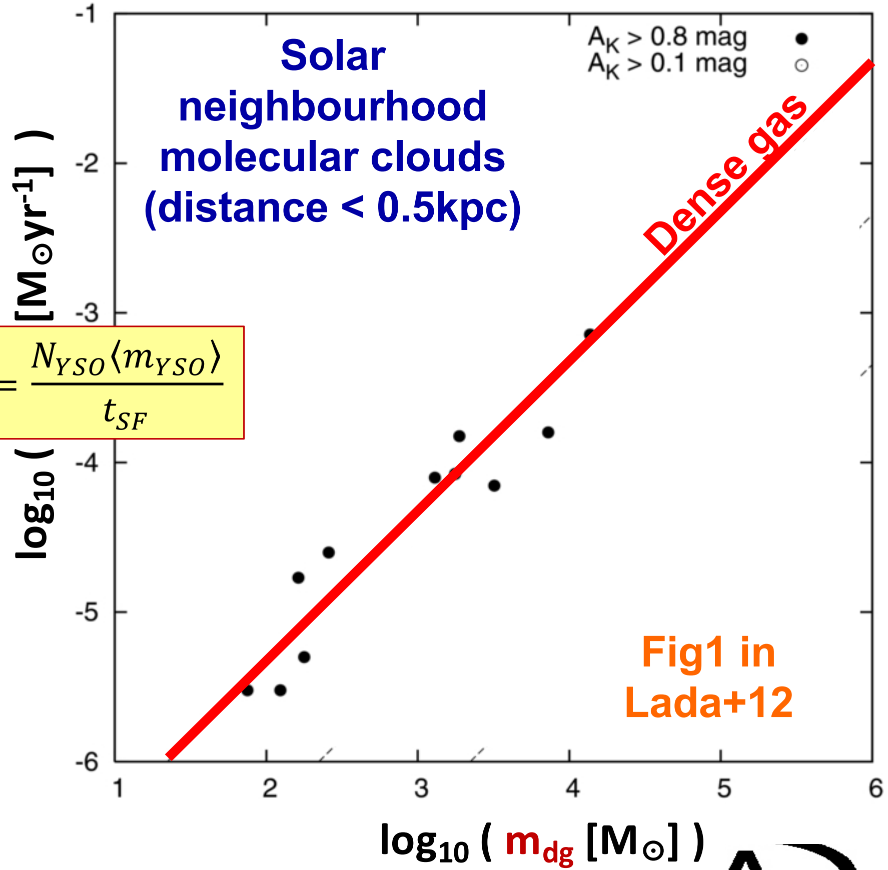


Dense gas relation of nearby clouds: an update

- Recall the dense-gas mass – SFR relation of nearby molecular clouds (Lada+2010/12):
  - $SFR_{cloud} \propto m_{dg}$
  - If star formation confined to the dense gas:

$$SFR_{dg} \propto m_{dg}$$
$$\equiv$$
$$\frac{SFR_{dg}}{m_{dg}} \propto constant$$

$$SFR = \frac{N_{YSO}\langle m_{YSO}\rangle}{t_{SF}}$$



Dense gas relation of nearby clouds: an update

- Lada+2010/12 (Open circles)

$$\frac{SFR_{dg}}{m_{dg}} \propto constant$$

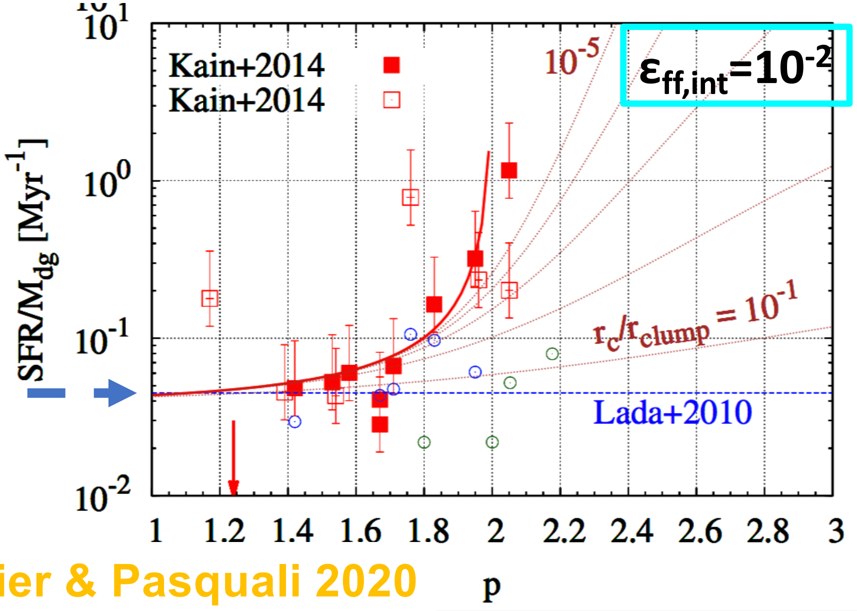


Fig4, Parmentier & Pasquali 2020

Dense gas relation of nearby clouds: an update

- Lada+2010/12 (Open circles)

$$\frac{SFR_{dg}}{m_{dg}} \propto constant$$

- Kainulainen+2014 (Red squares)
  - $\frac{SFR_{dg}}{m_{dg}} \neq constant$
  - $\frac{SFR_{dg}}{m_{dg}} \nearrow$ as $p \nearrow$

as expected (see red thick line: prediction for a pure power-law)

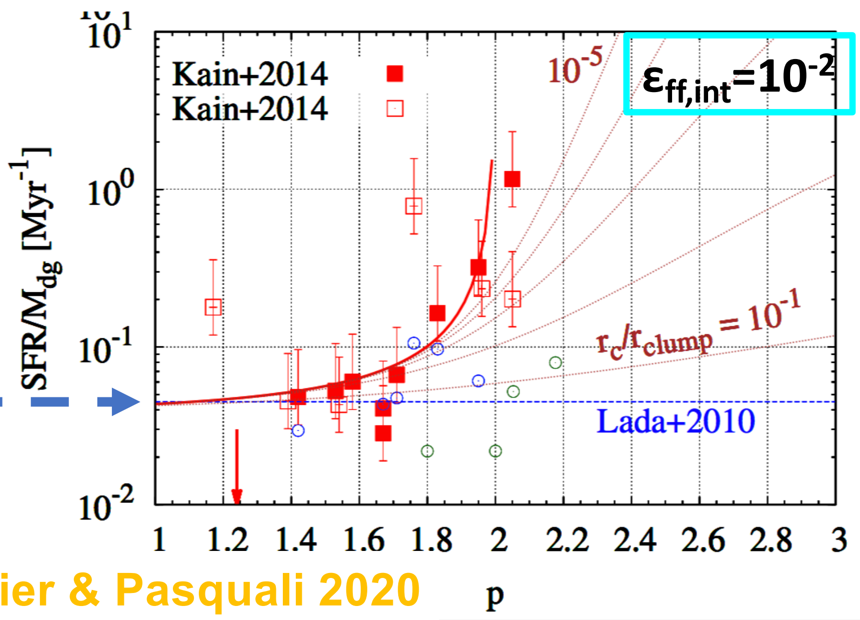


Fig4, Parmentier & Pasquali 2020

Dense gas relation of nearby clouds: an update

- Dense-gas ratio

$$\frac{SFR_{dg}}{m_{dg}} = \zeta \frac{\varepsilon_{ff,int}}{\tau_{ff,dg}}$$

← ≅0.3Myr

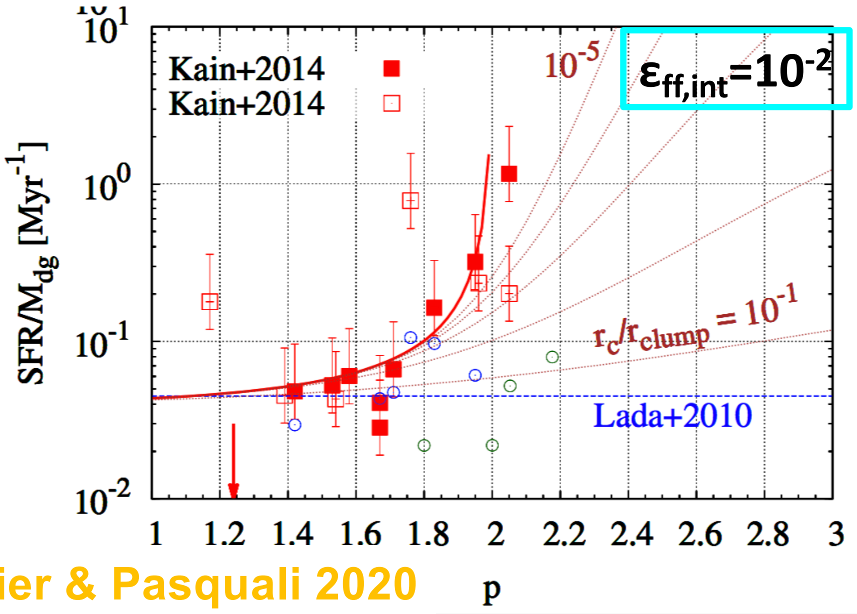


Fig4, Parmentier & Pasquali 2020

Dense gas relation: an update

- Dense-gas ratio

$$\frac{SFR_{dg}}{m_{dg}} = \zeta \frac{\varepsilon_{ff,int}}{\tau_{ff,dg}}$$

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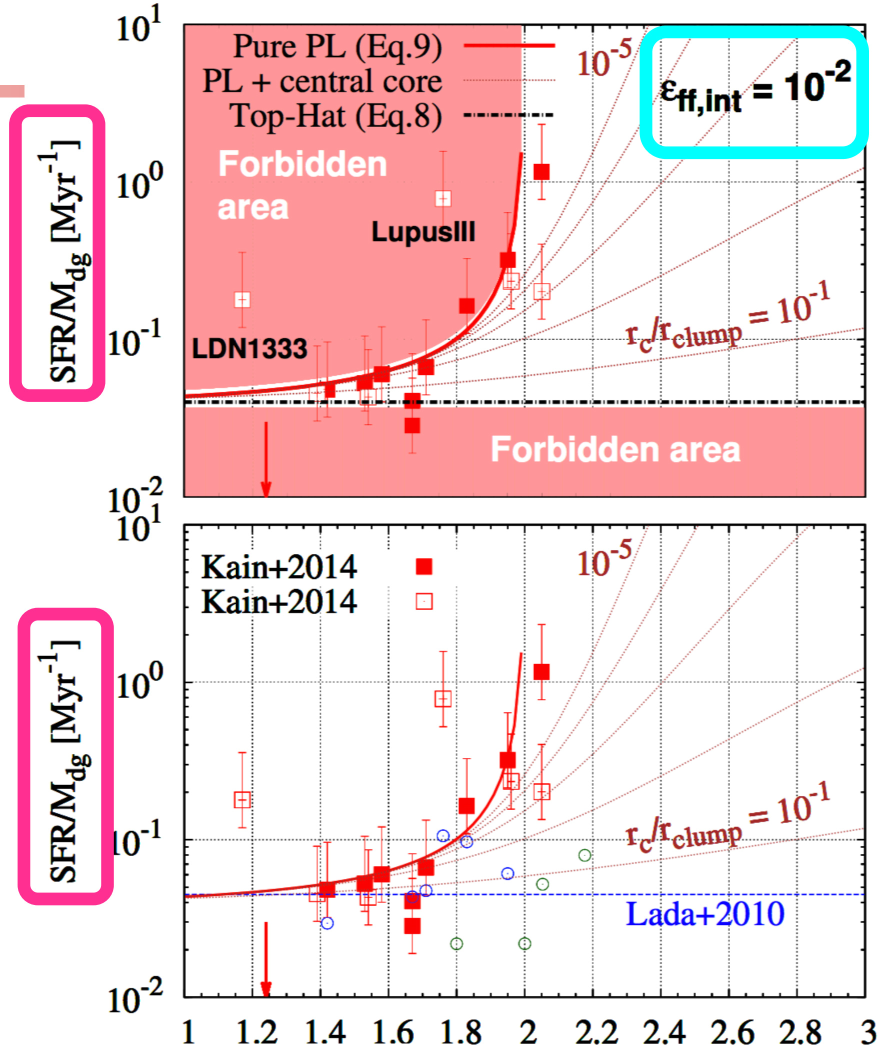


p

Fig4, Parmentier & Pasquali 2020

Dense gas relation: an update

- Dense-gas ratio

$$\frac{SFR_{dg}}{m_{dg}} = \zeta \frac{\varepsilon_{ff,int}}{\tau_{ff,dg}}$$

$\leftarrow \cong 0.3$Myr

now defined as a permitted area, rather than as a constant:

- It cannot be higher than found for a pure power-law
- It cannot be lower than found for a top-hat profile

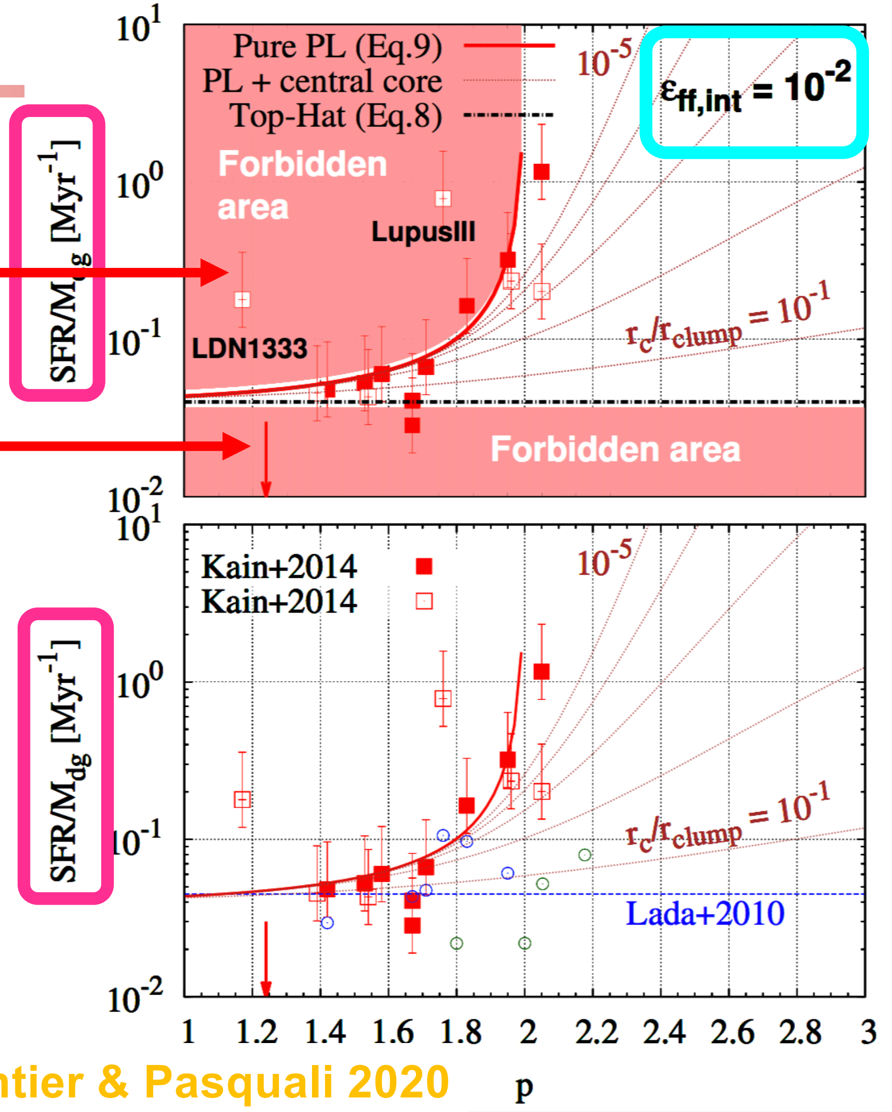


Fig4, Parmentier & Pasquali 2020

Comparison with CMZ Clouds

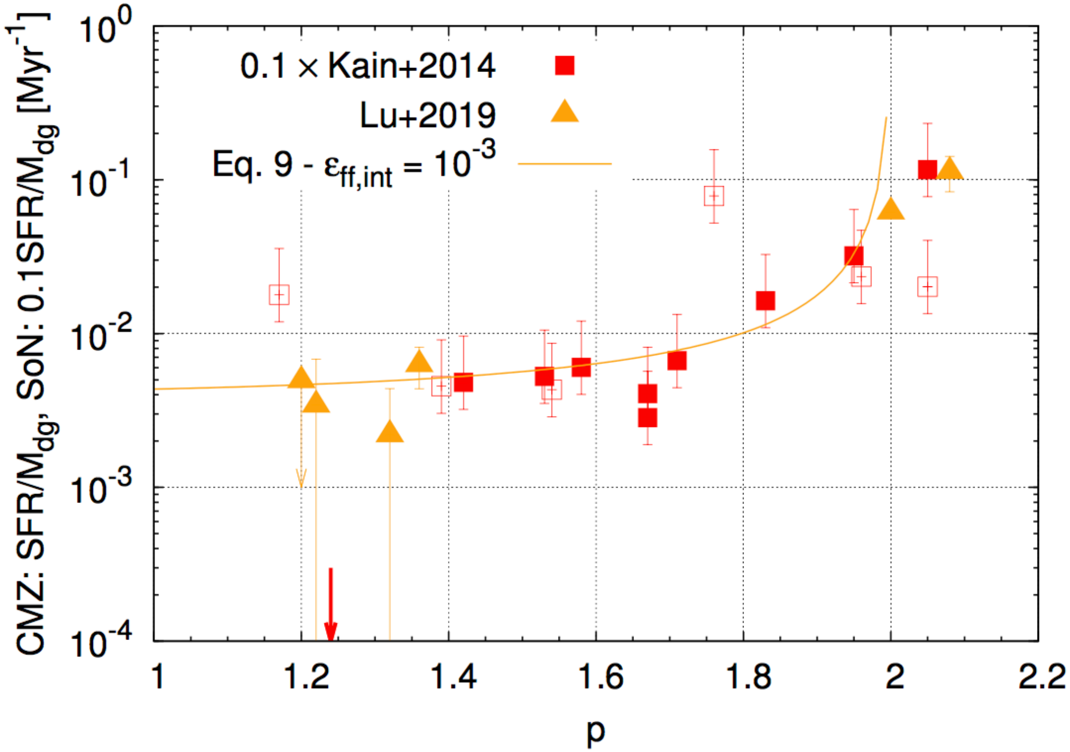


Fig7, Parmentier & Pasquali 2020

Take-away messages

- The **centrally-condensed** structure of a clump can boost its star formation rate
- The global SFR of a clump is the combination of the intrinsic star formation activity of its shells ($\epsilon_{ff,int}$) and of its structure (ζ)
- **Resolved observations** hold the potential to remove the degeneracy
- Variations among $\epsilon_{ff,meas}$ are to be expected, reflecting clump structure diversity
- The **dense-gas relation** should now be thought of as a permitted region rather than a linear correlation

Slides of talks and links to papers available at:
https://wwwstaff.ari.uni-heidelberg.de/mitarbeiter/gparm/

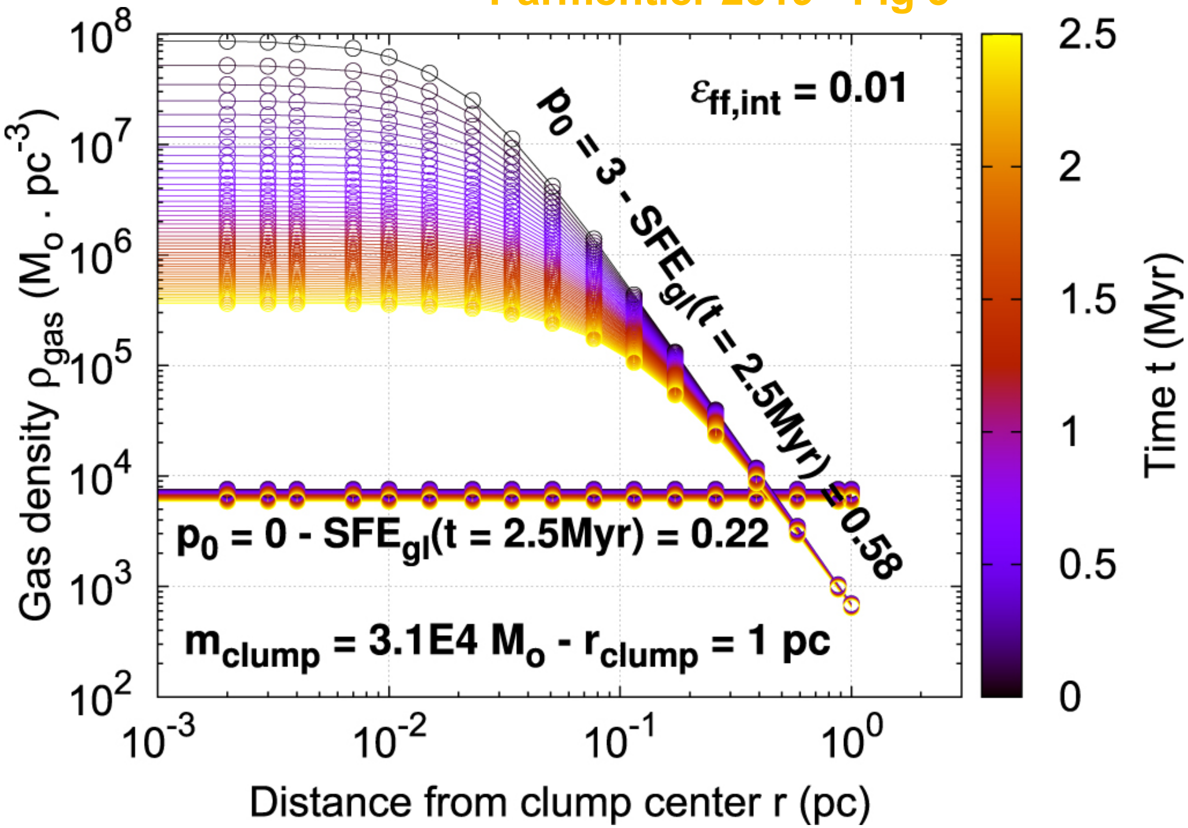
Supplementary Material

Time-Evolution of the Gas Density Profile

- Two clumps with identical masses and radii
- But two different density profiles:
  - top-hat
  - centrally-concentrated (p_0=3; central core)

A central concentration hastens SF and makes it more efficient even though $\varepsilon_{ff, int}$ has remained unchanged

Parmentier 2019 - Fig 3



The Way Out: Method Principle

Parmentier 2020, Figs1+2