ARI Colloquium – 30.07.2020

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

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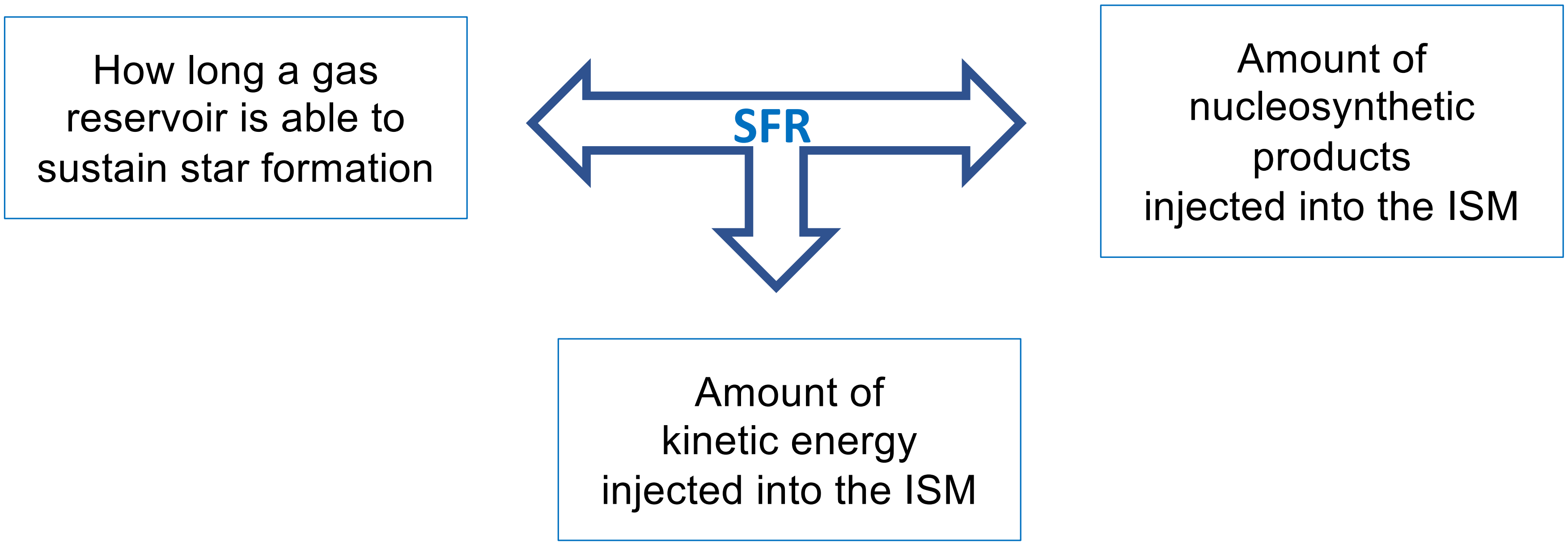
Star Formation Rate / Star Formation Efficiency per Free-Fall Time

- 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



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)

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

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

- **"denser is faster" effect**

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

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

- "denser is faster" effect
- 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,
  - molecular clouds,
  - galaxies,
- with a diversity of results being produced:
  - 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
- In the framework of my cluster-forming clump model, what do I expect?

measured
star formation efficiency per freefall time

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

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

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

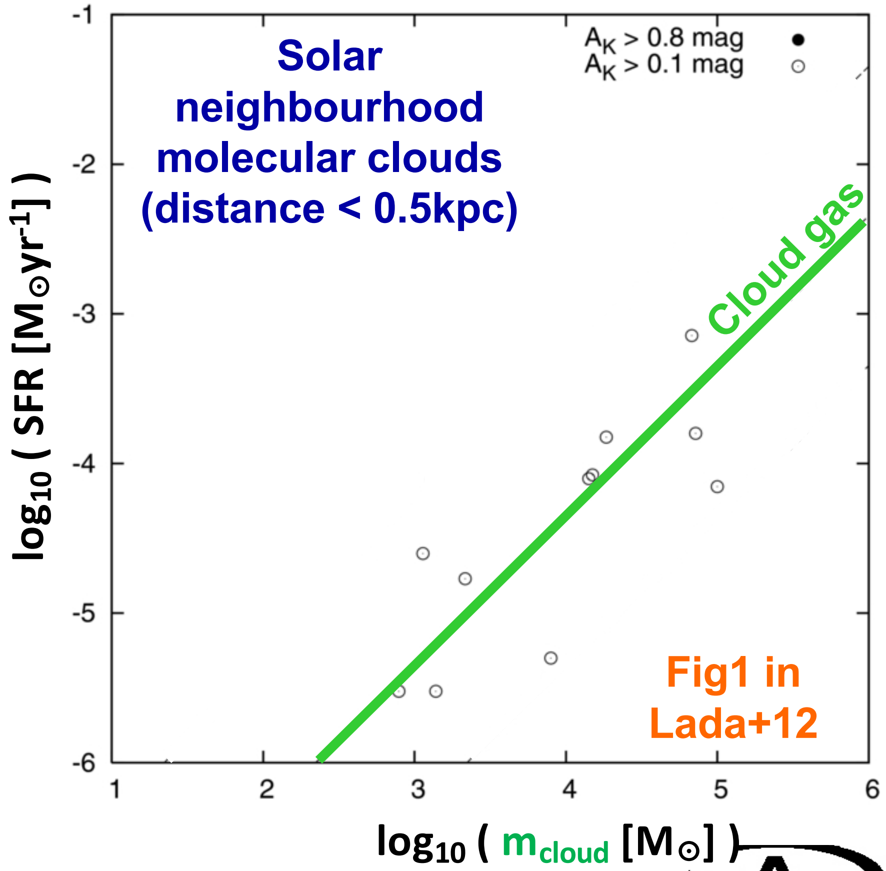
Molecular Clouds of the Solar Neighbourhood

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

- Here, the cloud mass is defined as the projected gas mass above a K-band extinction threshold:

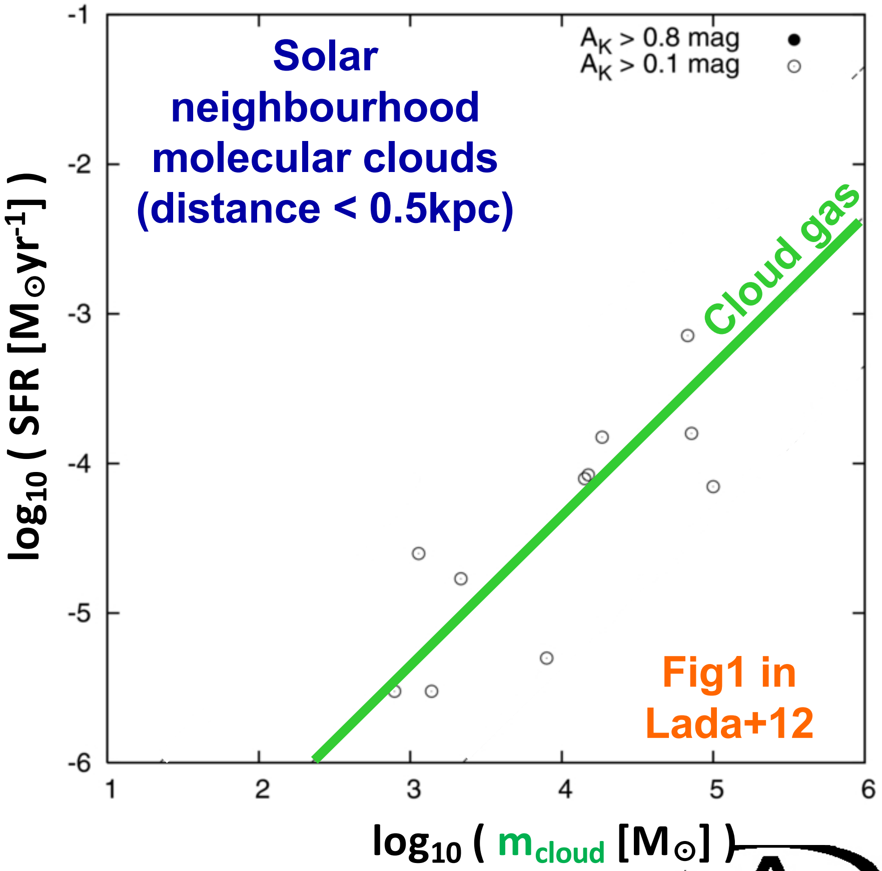
$$A_K = 0.1mag \equiv \Sigma_{gas} = 20\ M_{\odot} pc^{-2}$$

(open symbols/green line)



Molecular Clouds of the Solar Neighbourhood

- 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



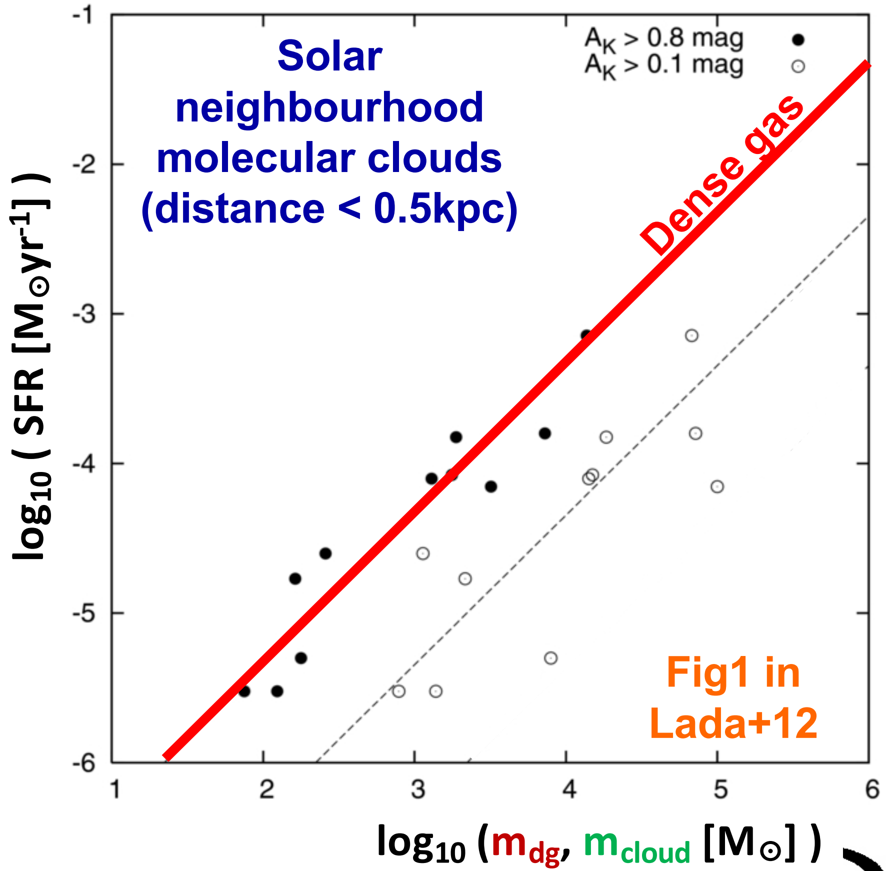
Molecular Clouds of the Solar Neighbourhood

- This additional parameter is the cloud internal structure
- Dense gas mass: projected gas mass above a K-band extinction threshold

$$A_K = 0.8mag \equiv \Sigma_{gas} = 160\ M_{\odot}pc^{-2}$$

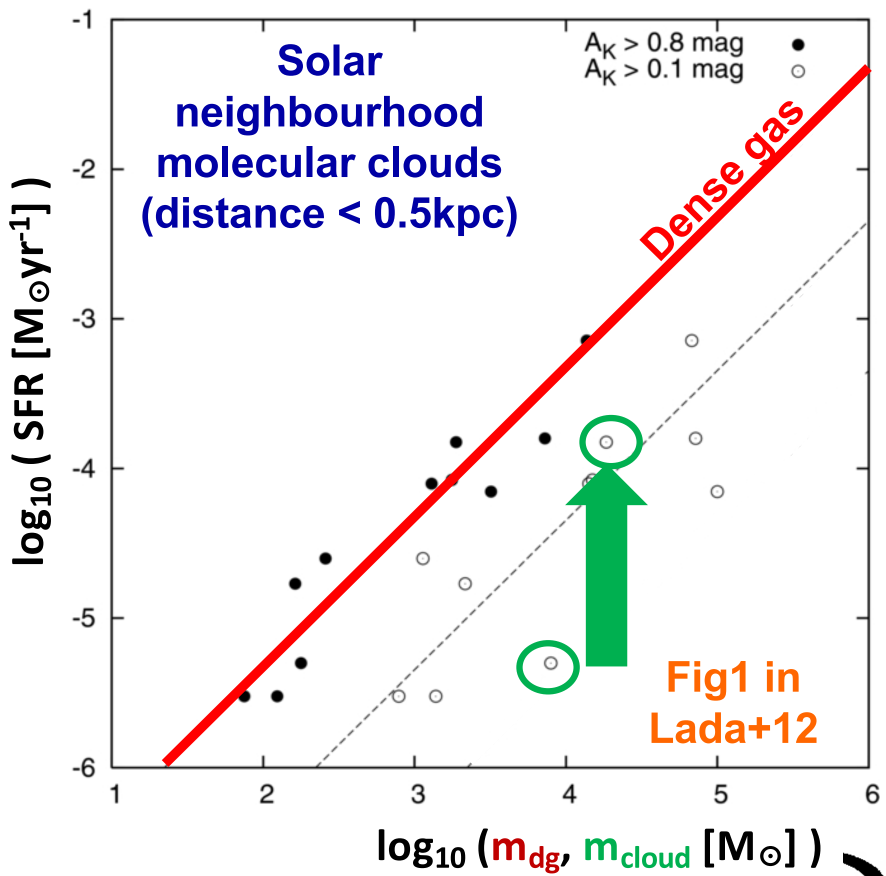
(plain symbols/red line)

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



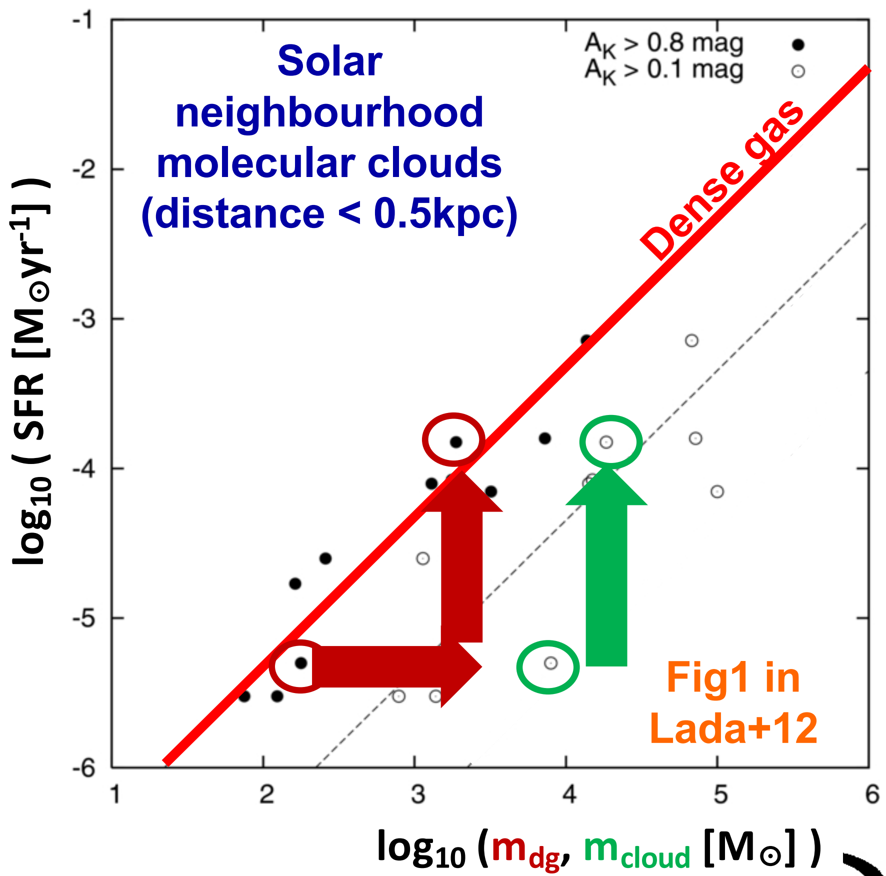
Molecular Clouds of the Solar Neighbourhood

- Example:
  - Two clouds with similar total masses but SFRs differing by more than an order of magnitude (green circles)



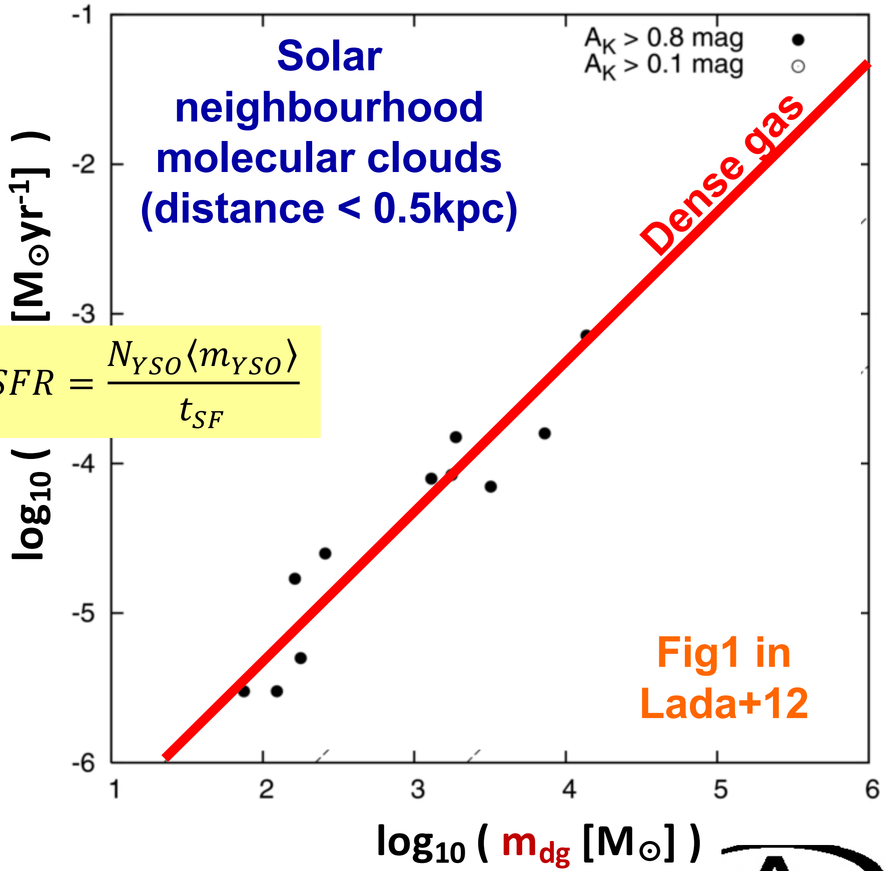
Molecular Clouds of the Solar Neighbourhood

- Example:
  - Two clouds with similar total masses but SFRs differing by more than an order of magnitude (green circles)
  - The more active cloud is the one with the higher dense-gas content (red circles)



Molecular Clouds of the Solar Neighbourhood

- The residual scatter can be due to:
  - Uncertainties in the YSO counting N_{YSO}
  - Variations in the <u>assumed</u> SF time-span from one dense-gas region to another t_{SF}
  - Uncertainties in the dense-gas mass
    - m_{dg} is here a projected mass (i.e. it over-estimates the actual/3D dense-gas mass)



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

Molecular Clouds of the Solar Neighbourhood

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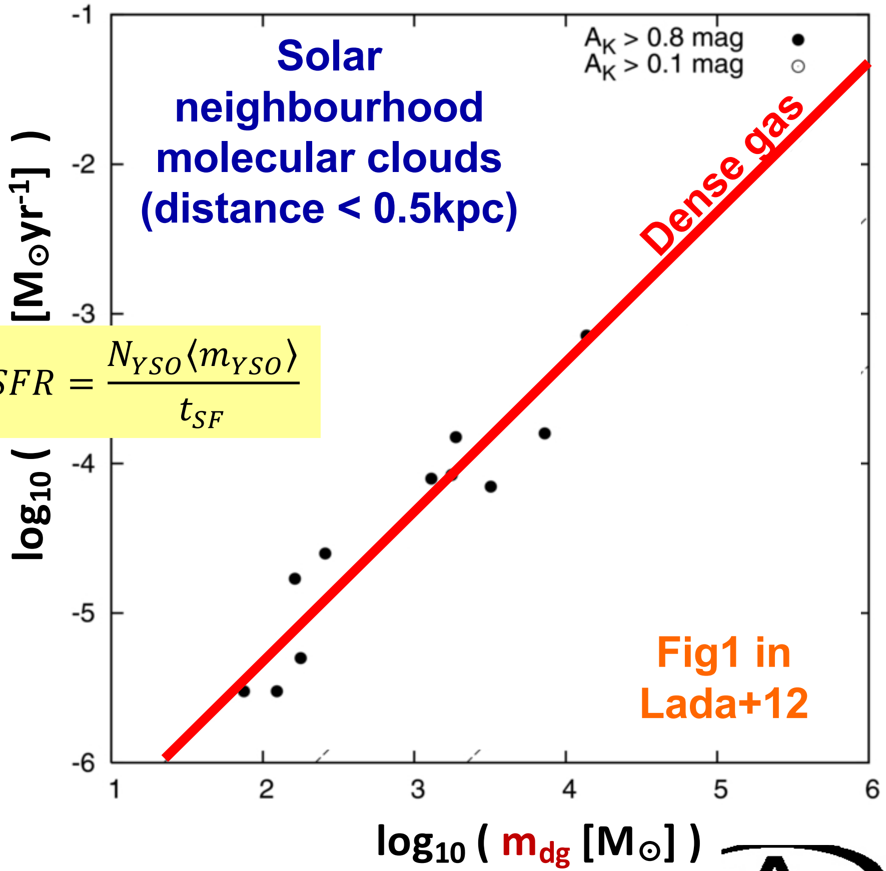
  - Uncertainties in the dense-gas mass
    - m_{dg} is here a projected mass (i.e. it over-estimates the actual/3D dense-gas mass)
  - Any additional physical parameter ?

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

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

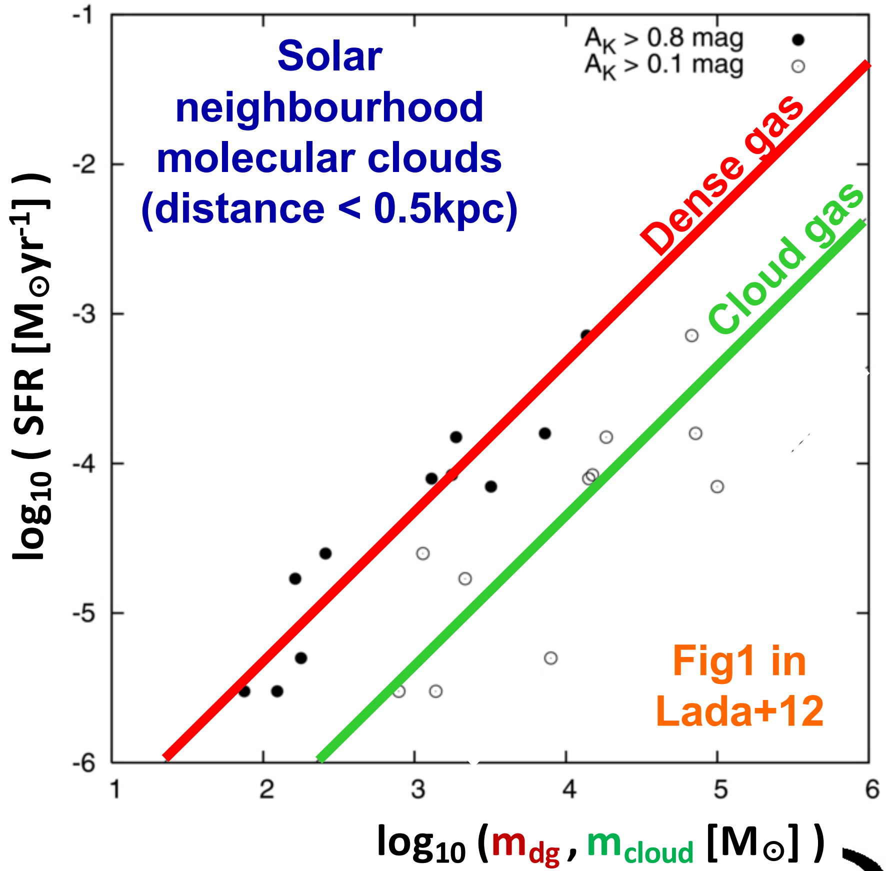


Molecular Clouds of the Solar Neighbourhood

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

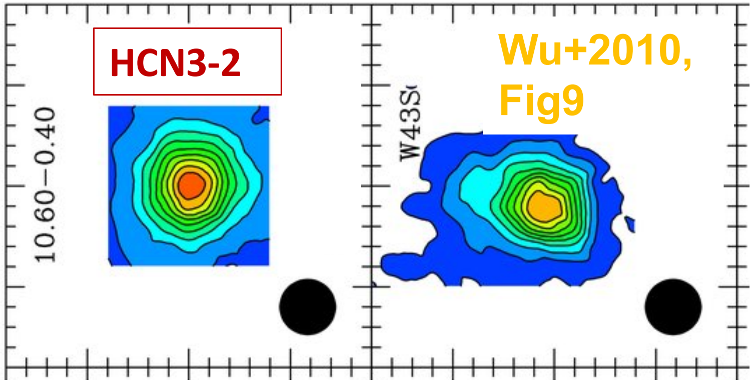
Yet, that a similar connection may exist at the level of the smaller-scale denser molecular clumps was hardly put forward

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



Molecular Clumps

$\rho_{gas}(r) \propto r^{-p}$ Clumps are centrally-concentrated

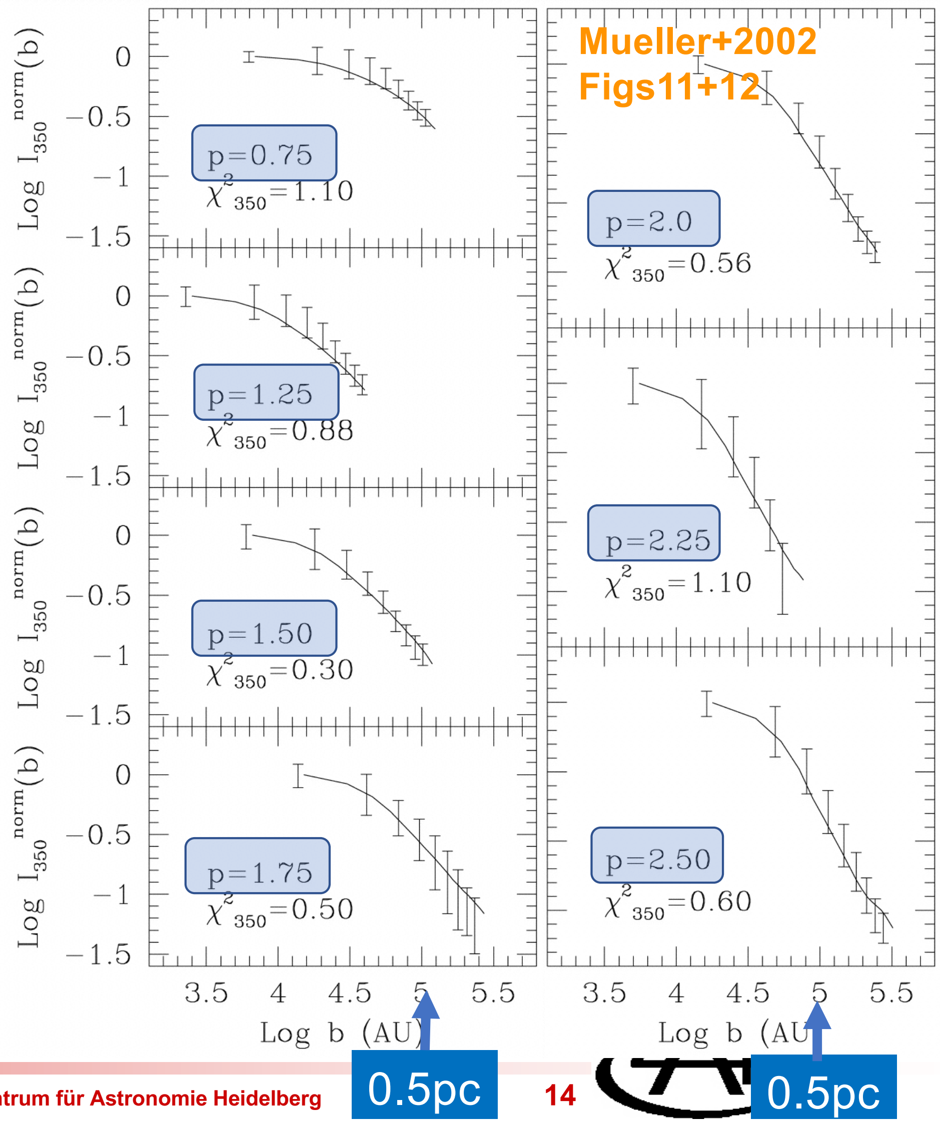


- Clump volume density profile often parameterized as:

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

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

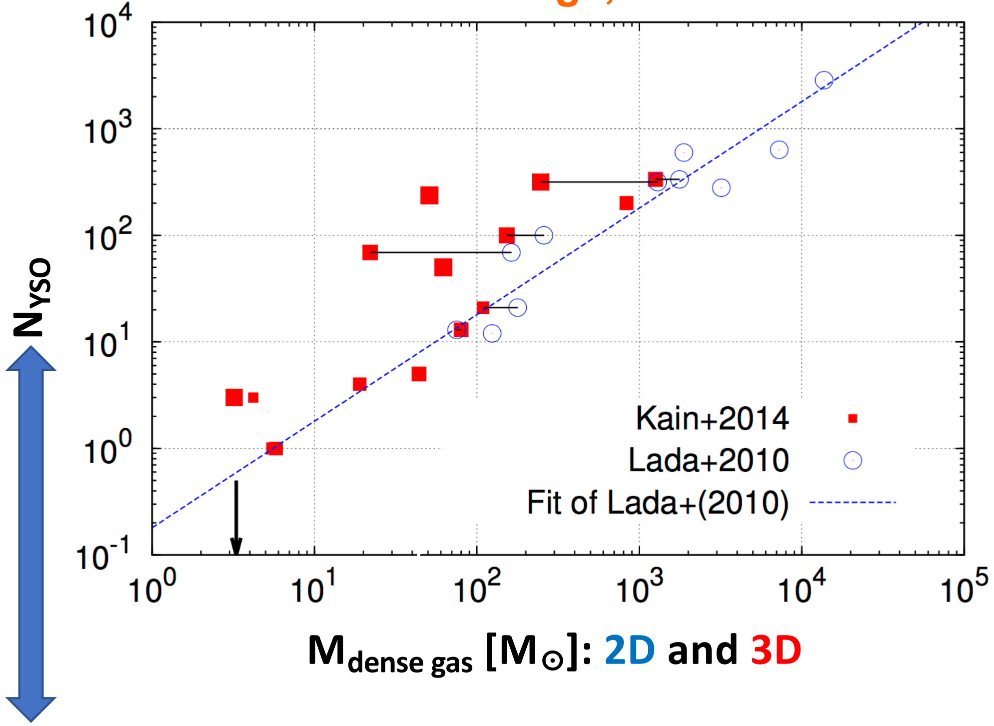
What role does their density gradient play?



Impact of Clump Density Gradient

- New version of the (M_{dg}, N_{YSO}) relation
- Open circles: projected/2D dense-gas masses of Lada+2010/12
- Plain squares: 3D dense-gas masses of Kainulainen+2014, for a sample of 16 molecular clouds with distances < 260pc
  - Shift to lower dense-gas mass compared to Lada+2010/12 likely due to losing the fore- and background contribution of the cloud gas
  - Data still correlated but with much greater scatter

Based on Fig1, Parmentier 2019

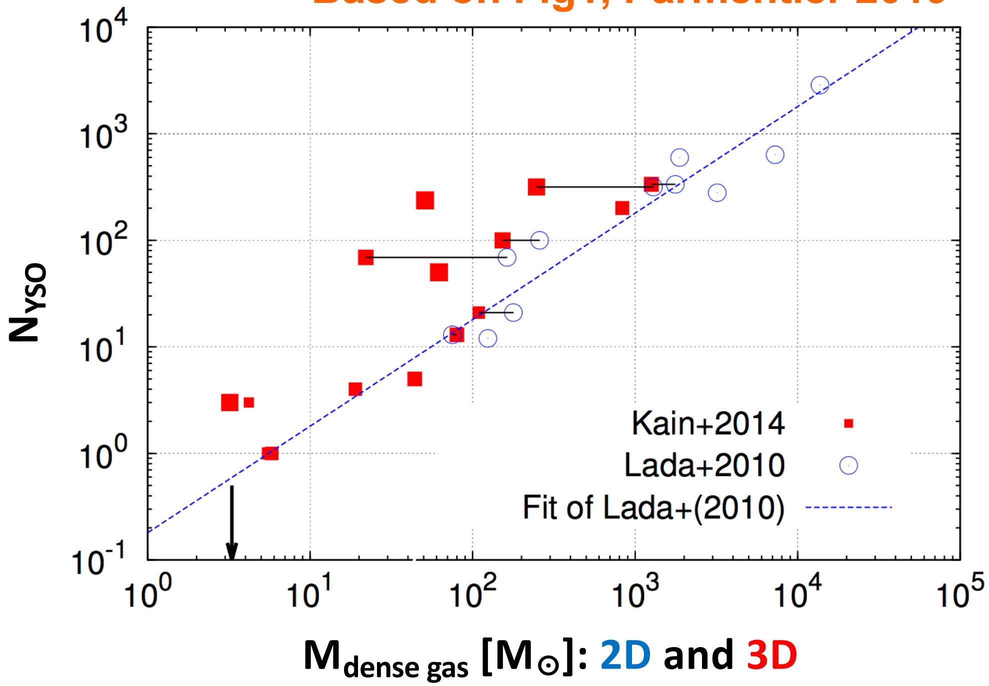


$$SFR = \frac{N_{YSO}\langle m_{YSO}\rangle}{t_{SF}}$$

Impact of Clump Density Gradient

- The red-square size codes the steepness of the underlying gas density profile: larger symbols depict steeper gas density profiles (i.e higher p with $\rho_{gas} \propto r^{-p}$)
- Sample of Kainulainen+2014:
  1.15 < p < 2.05
- Slight tendency for the steeper density profiles to top the data (i.e. to be more efficient at forming YSOs)
- Effect predicted by Tan+2006:
  - For a pure power law with p<2:

Based on Fig1, Parmentier 2019



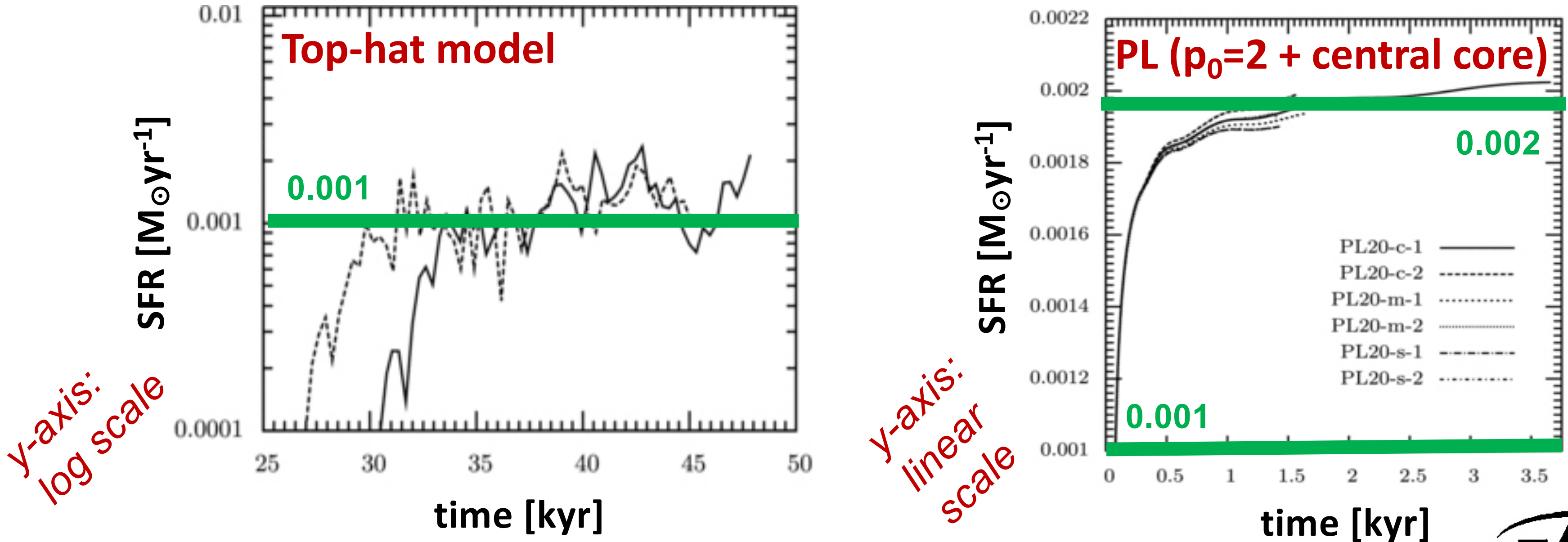
$$SFR_{clump} = \frac{(3-p)^{3/2}}{2.6(2-p)} SFR_{TH}$$

→ For p=1.5: $SFR_{clump} = 1.4 \times SFR_{TH}$

Impact of Clump Density Gradient

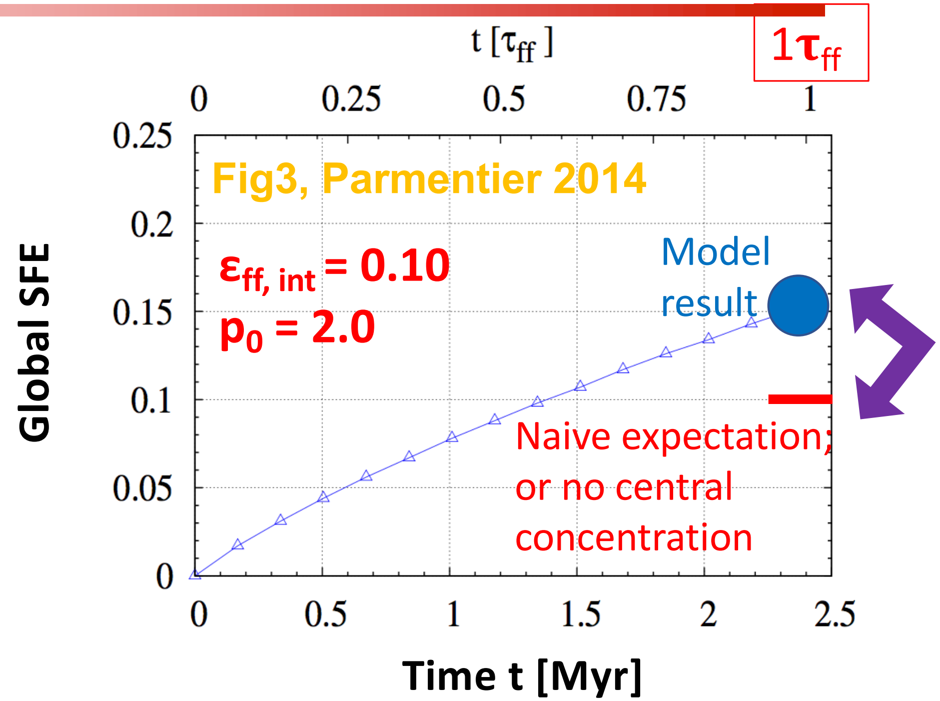
- Hydrodynamical simulations of clumps with m=100M$_\odot$ and r=0.1pc - Girichidis+2011
- SFR twice as high in right panel (PL: p_0=2) as in left panel (p_0=0;TH)

Figs 7 (left panel) and 14 (right panel) from Girichdis+2011



Impact of Clump Density Gradient

- Also consistent with Parmentier 2014
- Clump model:
  - Power-law density profile of steepness p_0=2 with central core;



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

- That the impact of the density profile of molecular clumps on their SFR has remained largely ignored may be due to it being predicted a fairly small effect (factors from 1.4 to 2)
- ***UNTIL NOW …***

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 included neither in the data set of Lada+2010/12, nor in that of Kainulainen+2014

Dust-emission map of MonR2

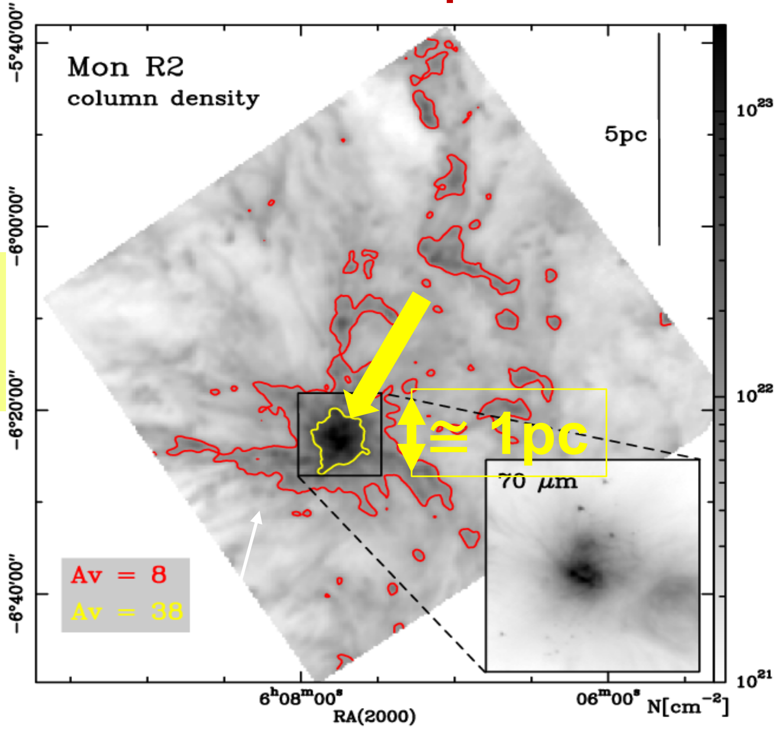
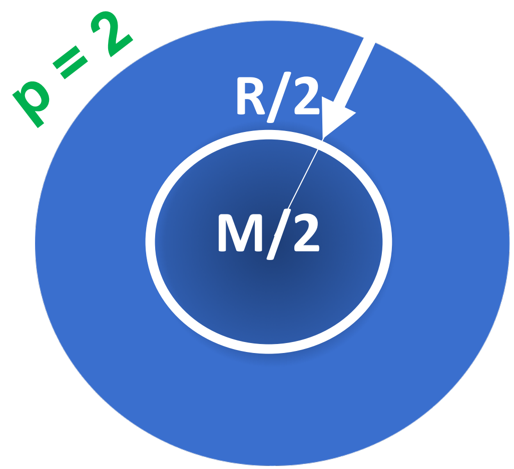


Fig 1, Schneider+2015

From Top-Hat to Highly Centrally-Concentrated: Expectations

- How does the clump mass fraction enclosed within half the clump radius vary as a function of p?

From Top-Hat to Highly Centrally-Concentrated: Expectations



- How does the clump mass fraction enclosed within half the clump radius vary as a function of p?
  - When p=2, the mass enclosed within R/2 is M/2

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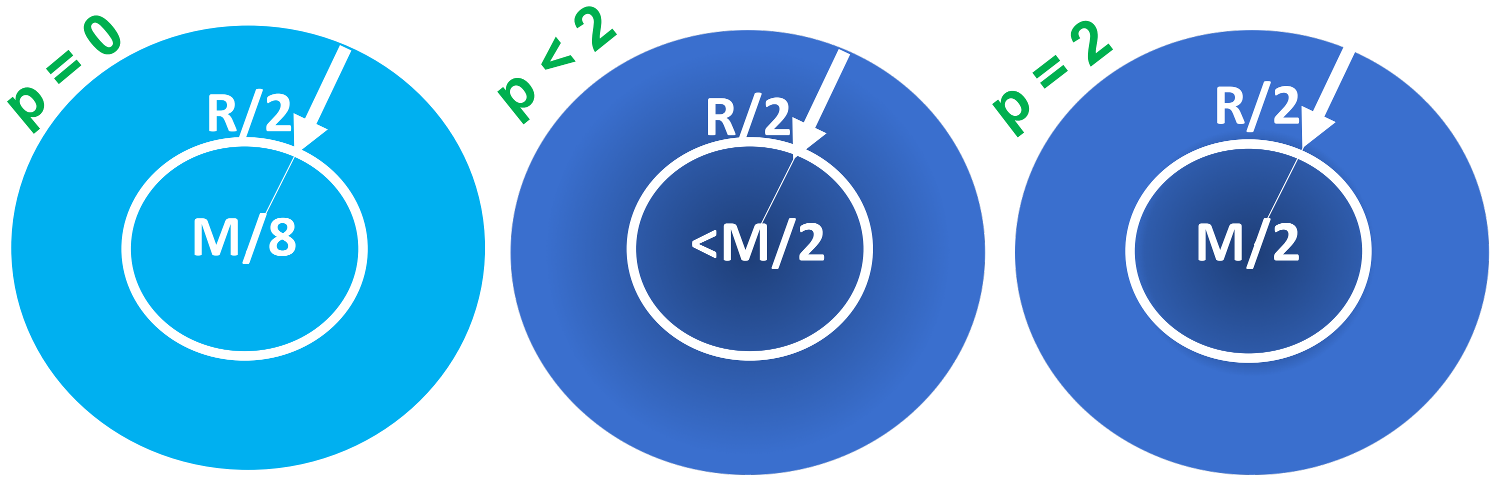
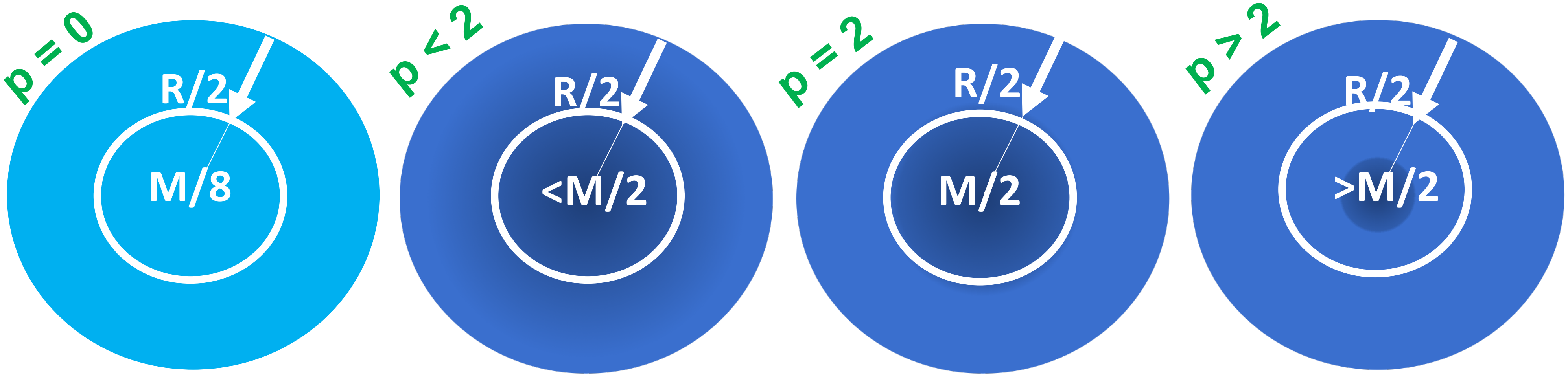


➤ How does the clump mass fraction enclosed within half the clump radius vary as a function of p?

- When p=0 (TH), the mass enclosed within R/2 is M/8
- When p<2, the mass enclosed within R/2 is less than M/2
- When p=2, the mass enclosed within R/2 is M/2

From Top-Hat to Highly Centrally-Concentrated: Expectations



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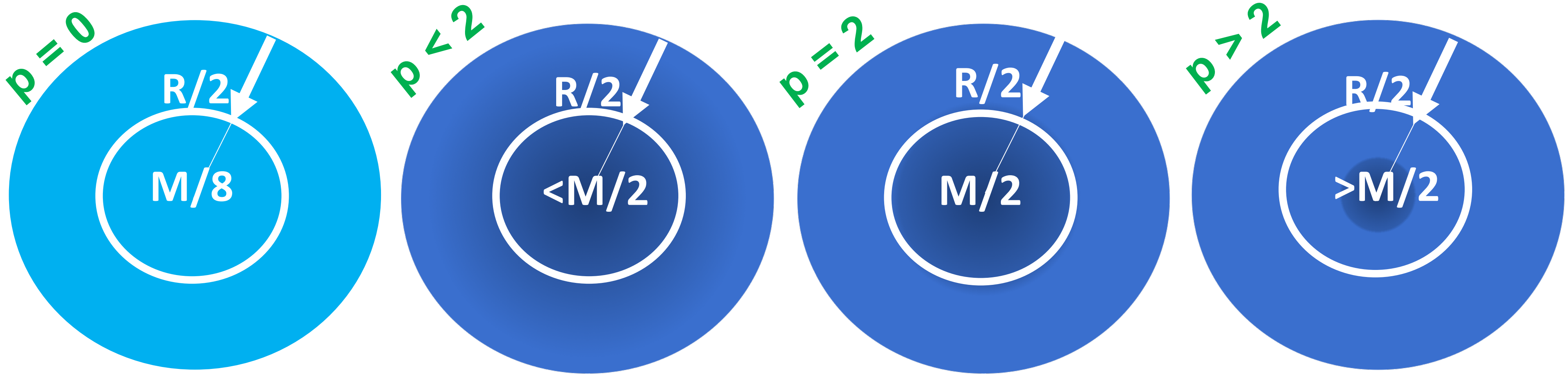
- When p<2, the mass enclosed within R/2 is less than M/2
- When p=2, the mass enclosed within R/2 is M/2
- When p>2, the mass enclosed within R/2 is larger than M/2

From Top-Hat to Highly Centrally-Concentrated: Expectations



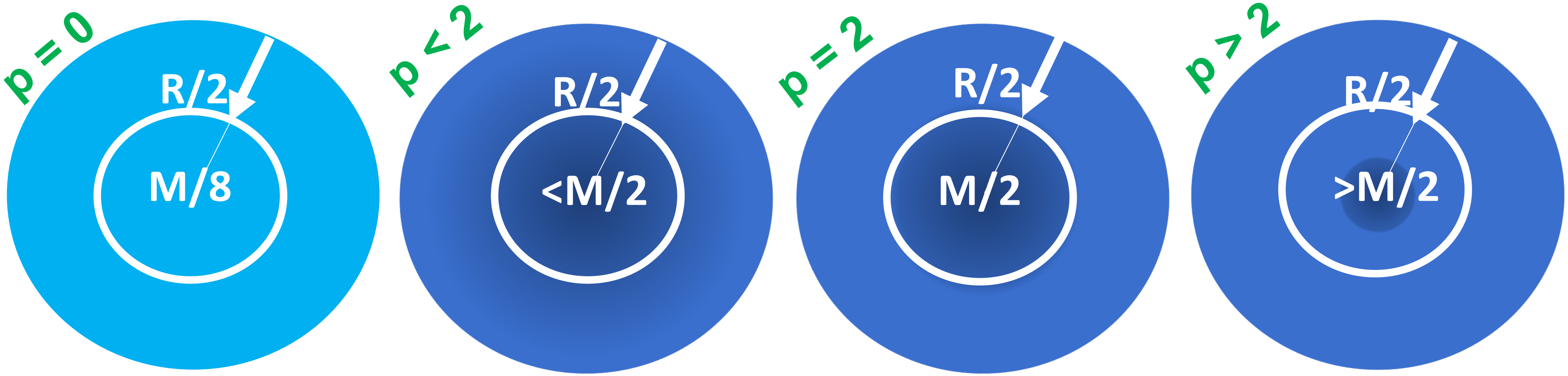
When $0 < p < 2$:

- 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 Top-Hat to Highly Centrally-Concentrated: Expectations



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

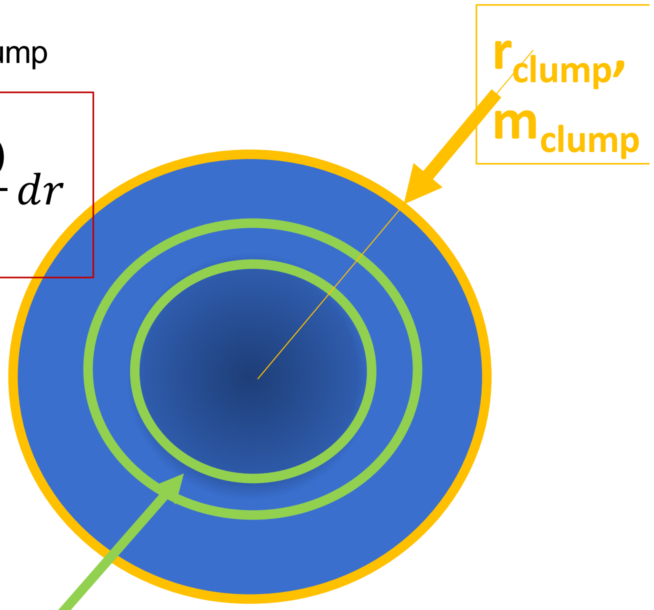
Unlock a regime of SF far more efficient than what has been chartered so far with $p \leq 2$. How much more efficient?

Clump SFR: Centrally-Concentrated vs. Top-Hat

- Density profile $\rho_{gas}(r)$ for a clump of mass m_{clump} and radius r_{clump}

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

  - Star formation faster in clump inner regions than in outskirts



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

$\varepsilon_{ff,int}$ = constant

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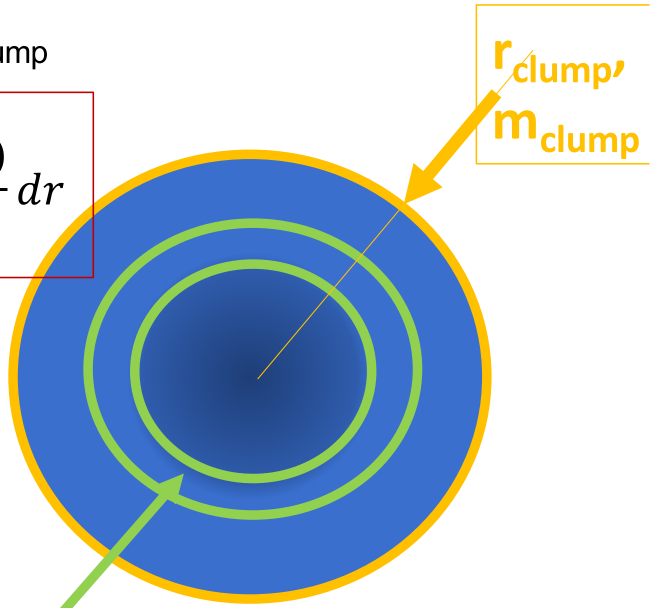

$$dSFR_{shell} = \varepsilon_{ff,int} \frac{dm_{gas}(r)}{\tau_{ff}\,(r)}$$

$\varepsilon_{ff,int}$ = constant

- Top-hat-profile clump of mass m_{clump} and radius r_{clump}

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

Magnification Factor ζ

- Magnification factor ζ: quantify by how much a given density profile amplifies the clump SFR compared to the SFR that the clump would experience with a top-hat density profile (Parmentier 2019)

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

Magnification Factor ζ

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- Tan+2006:
  - For a pure power-law gas density profile
  - Due to the central singularity: if p>=2, $SFR_{clump} \rightarrow \infty$

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

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

$$SFR_{clump} = \frac{(3-p)^{3/2}}{2.6(2-p)} SFR_{TH} = \frac{(3-p)^{3/2}}{2.6(2-p)} \varepsilon_{ff,int} \frac{M}{\tau_{ff}}$$

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  → quantify by how much a given density profile amplifies the clump SFR compared to the SFR that the clump would experience with a top-hat density profile (Parmentier 2019)

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

- Re-address the problem in a more general framework
  - Assume a power-law profile with a central core (i.e. w/o a density singularity at the clump center)
  - Browse a wider range of the parameter space
  - In particular, cover p > 2

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

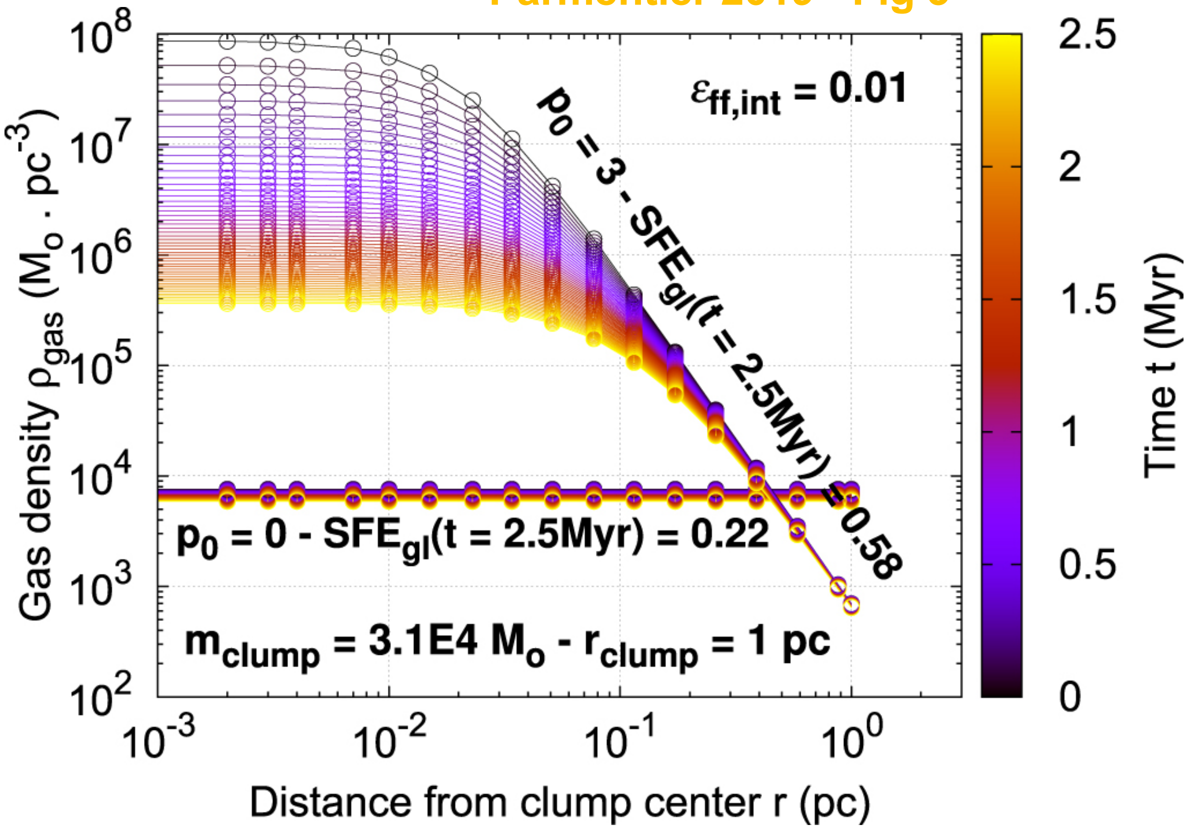
ρ_c: central density
r_c: central core

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 $\boldsymbol{\varepsilon_{ff,\,int}}$ has remained unchanged

Parmentier 2019 - Fig 3



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}

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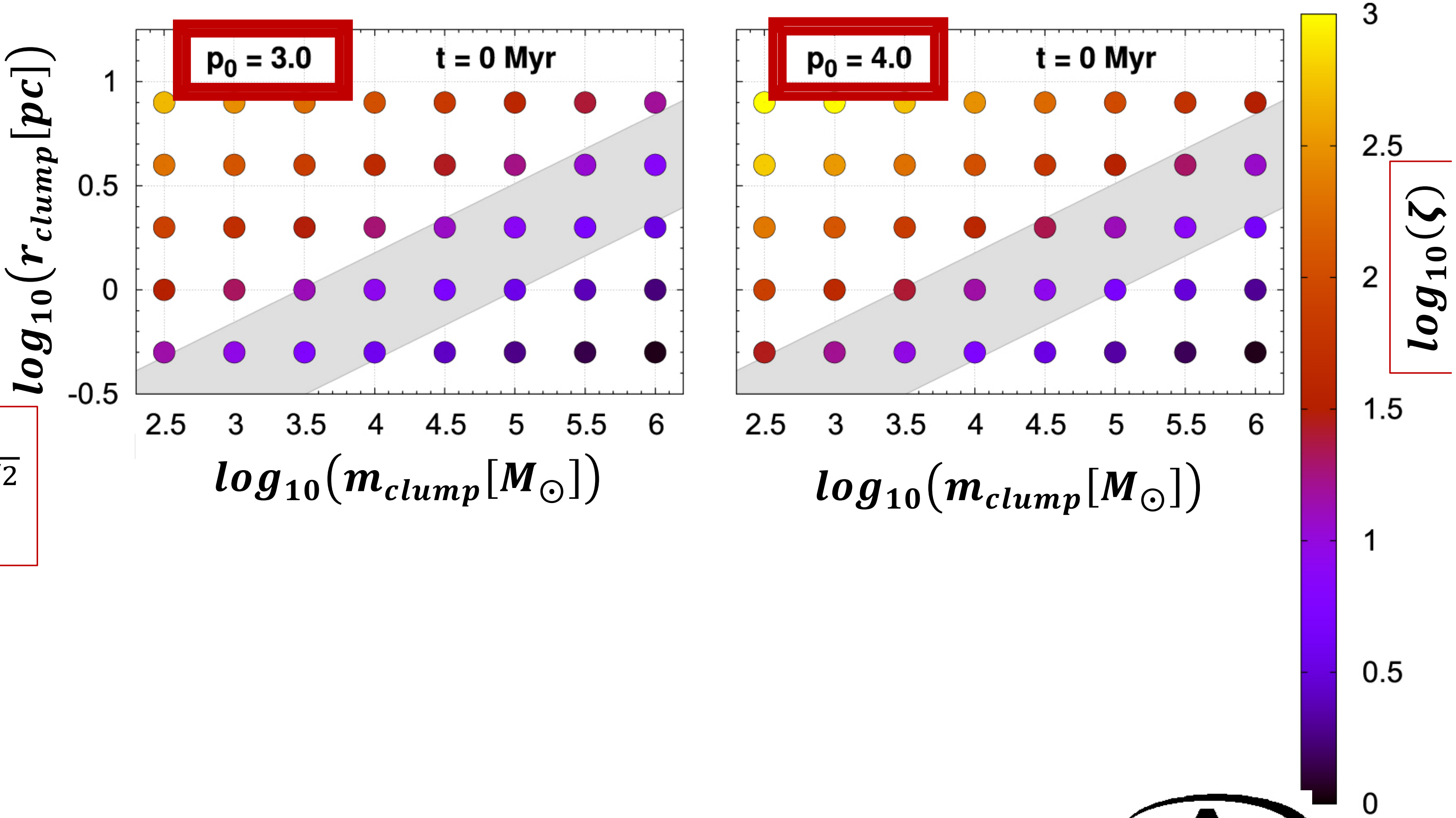

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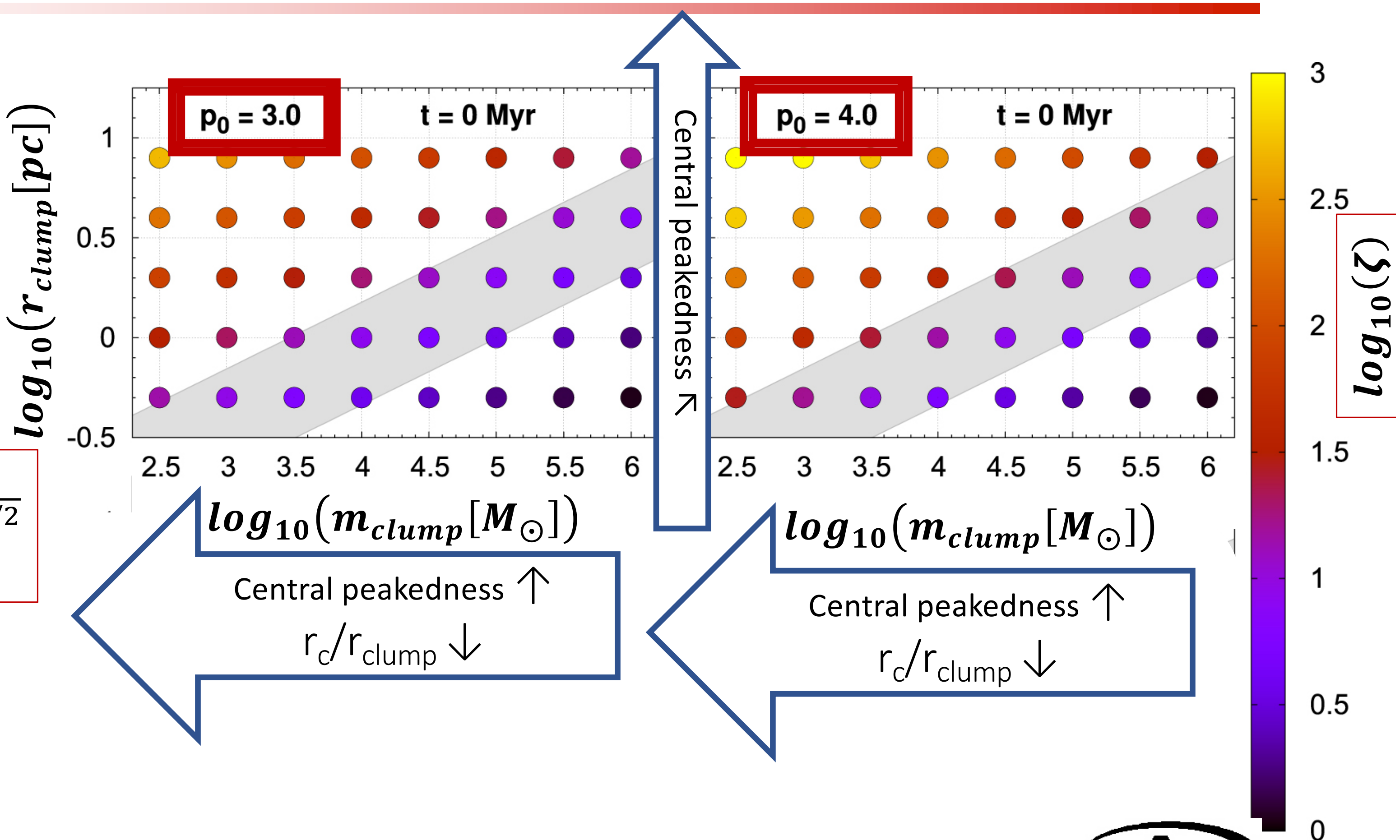

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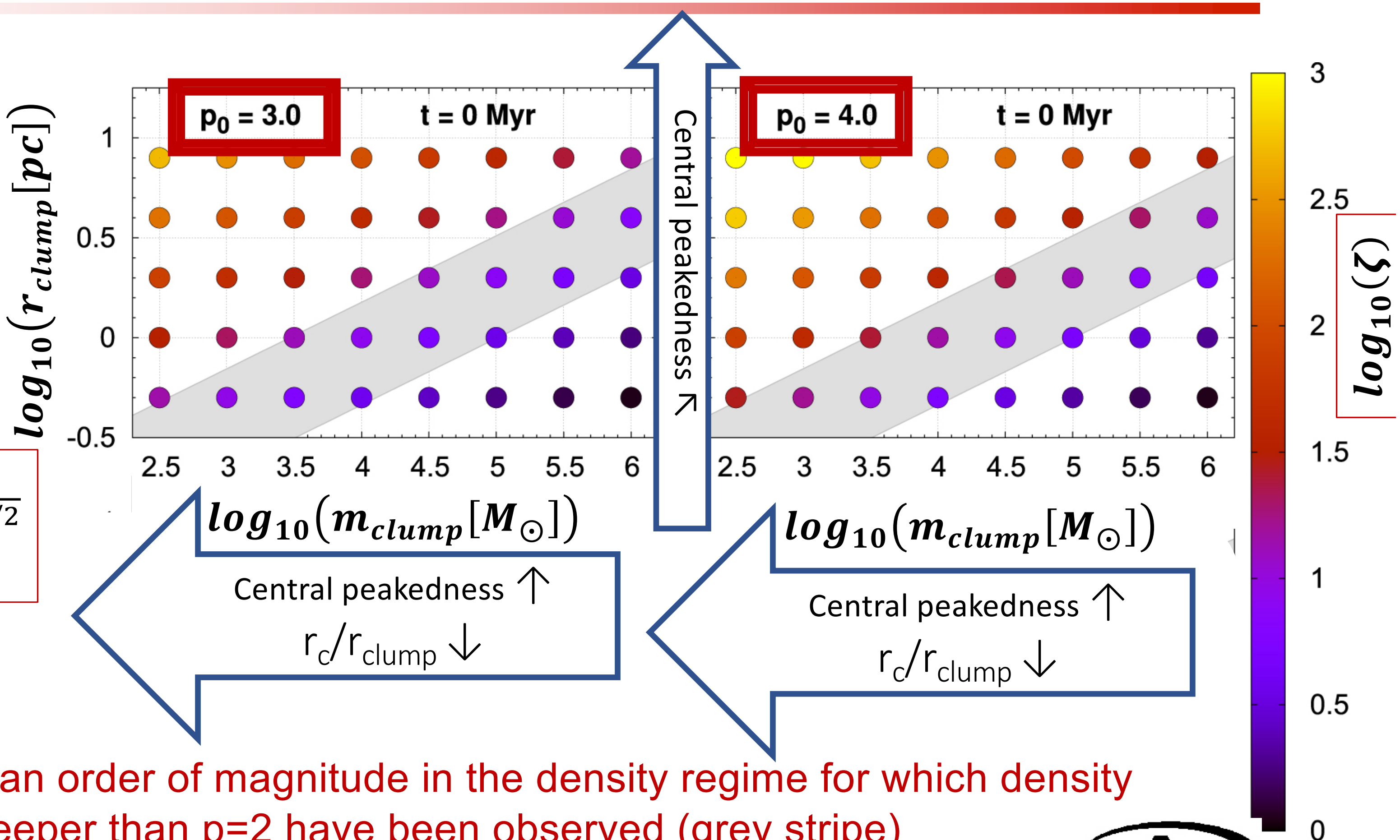

ζ reaches an order of magnitude in the density regime for which density profiles steeper than p=2 have been observed (grey stripe)

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)?

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

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

- The measured star formation efficiency per free-fall time $\varepsilon_{ff,meas}$, being inferred from clump global 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 ?**

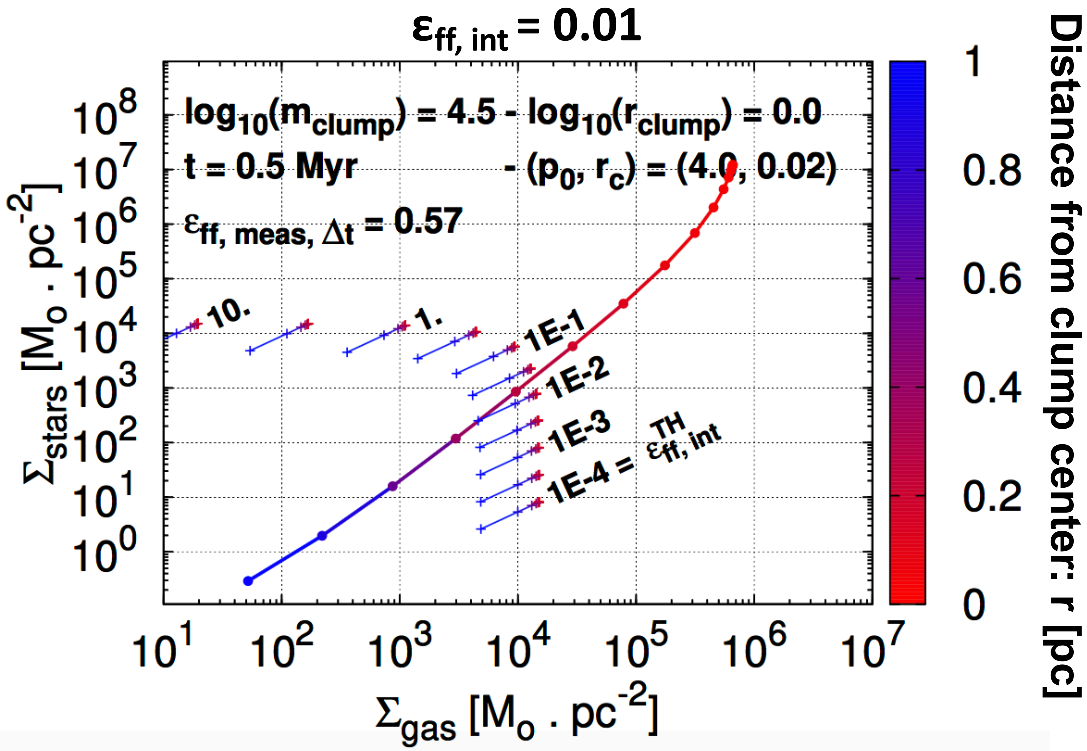
The Way Out: Resolved Observations

Fig3, Parmentier 2020

Local star formation relation:

- local stellar surface densities vs local gas surface densities

$\Sigma_{stars}(r)$ vs $\Sigma_{gas}(r)$



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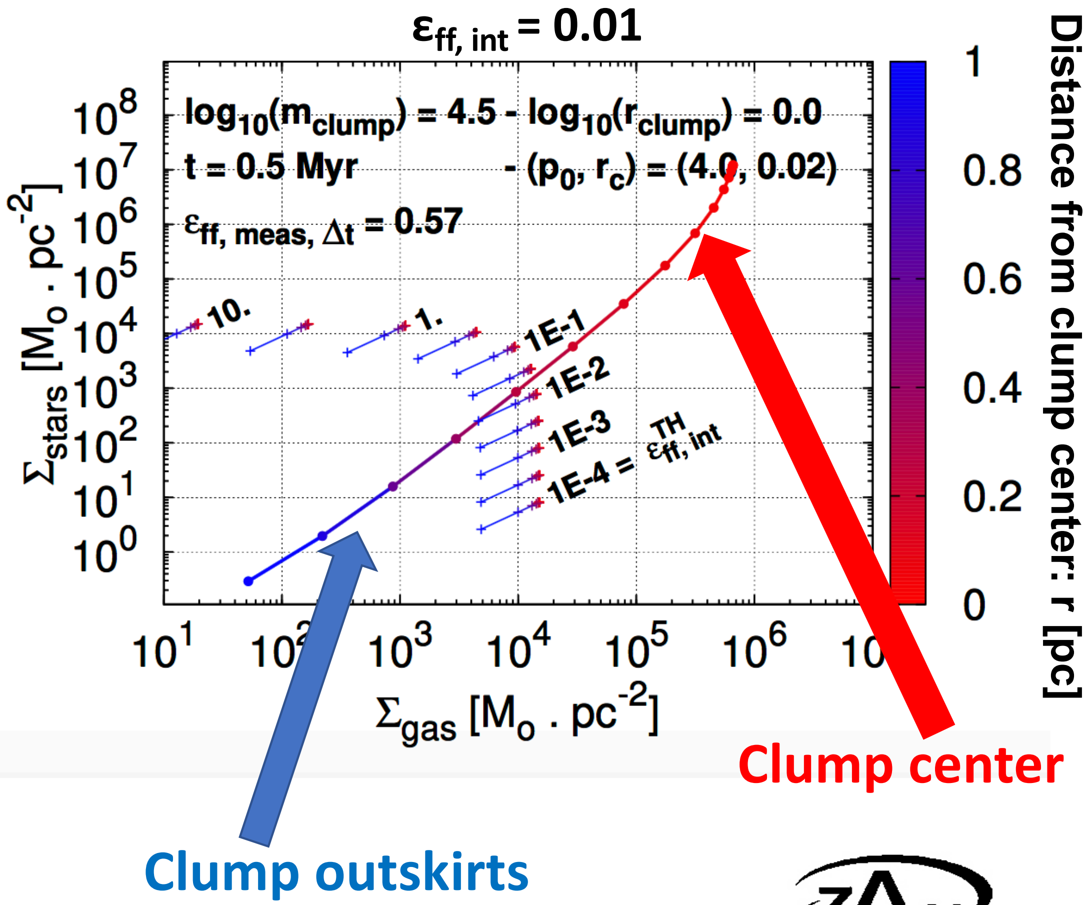

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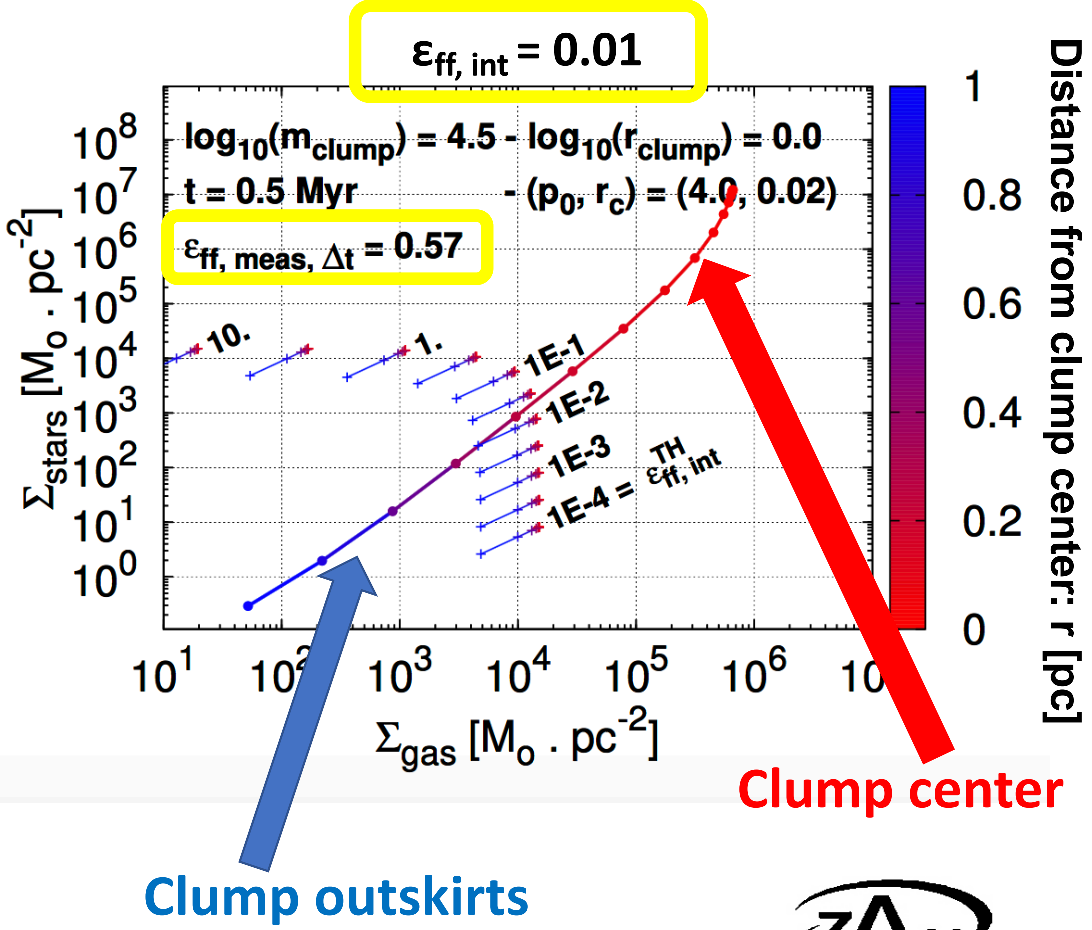
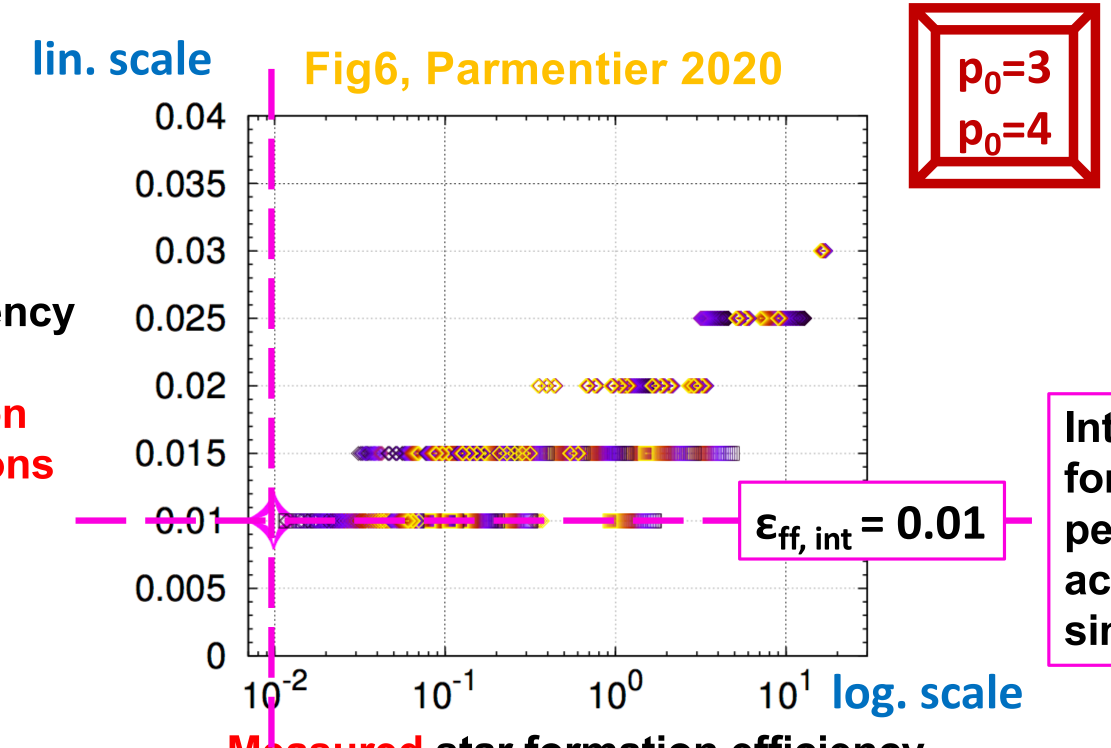
- local stellar surface densities vs local gas surface densities

$\Sigma_{stars}(r)$ vs $\Sigma_{gas}(r)$



The Way Out: Resolved Observations – Method Efficiency



Intrinsic star formation efficiency per free-fall time **estimated based on resolved observations**

Intrinsic star formation efficiency per free-fall time actually used in the simulations

Measured star formation efficiency per free-fall time inferred from global quantities (i.e., "polluted" by the density gradient)

Conclusions

- **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**