Cloud structure and high-mass star formation in HOBYS, the *Herschel* imaging survey of OB Young Stellar objects

Frédérique Motte and Nicola Schneider
(AIM Paris-Saclay, Obs. Bordeaux)

http://hobys-herschel.cea.fr

SPIRE PACS esa

SAG3

HOBYS

Coordinated by Frédérique Motte, Annie Zavagno, and Sylvain Bontemps

- 50 researchers from 10 institutes
- Management team: P. André, J. di Francesco, F. Motte, S. Pezzuto, D. Ward-Thompson
- Special credit to: S. Bontemps, P. Didelon, M. Hennemann, T. Hill, A. Men'shchikov, V. Minier, Q. Nguyen-Luong, N. Schneider, A. Zavagno

Herschel HOBYS survey

- Target all molecular cloud complexes forming OB-type stars at $d_{Sun} < 3$ kpc
- Wide-field PACS/SPIRE imagings (70, 160, 250, 350, 500 μm) with 20''/sec

HPBW = 6''-36.9'' @ 0.7-3 kpc ➔ down to 0.03-0.2 pc dense cores

⇒ census of intermediate- to high-mass protostars

Symp #315, 316

⇒ link between cloud structure and (high-mass) SF

Div H

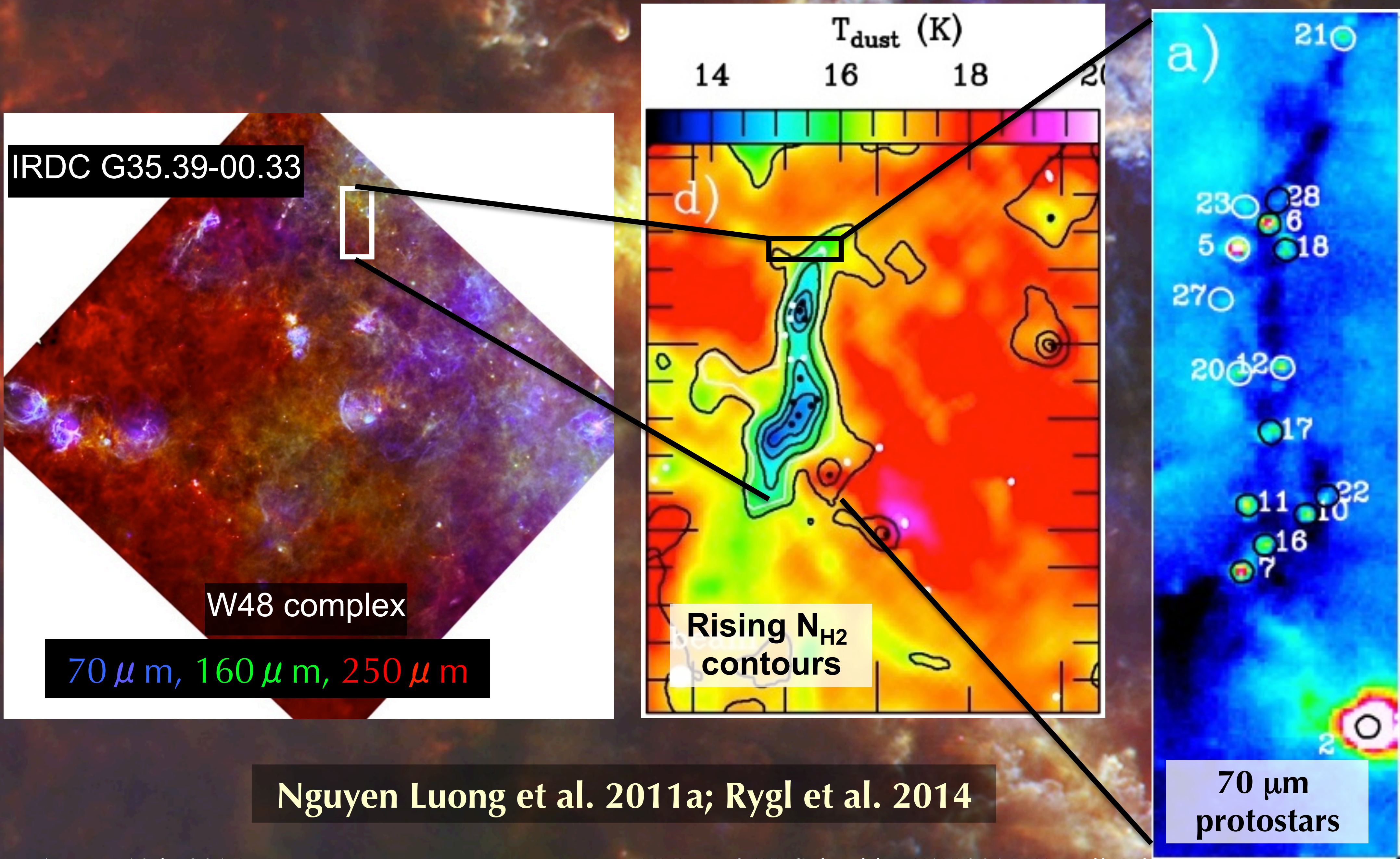
⇒ feedback effects

- Complementary to other *Herschel* KPs:
  - high-mass dense cores (small and isolated clouds) - EPOS (Krause et al.)
  - low-mass cores (~0.02 pc) – HGBS, Cold Cores and HOPS surveys (André et al.; Juvela, Ristorcelli et al.; Megeath et al.)
  - protoclusters (~1 pc clumps) - Hi-GAL (Molinari et al.)

Cloud structure and high-mass star formation in HOBYS, the *Herschel* imaging survey of OB Young Stellar objects

1. Short introduction for HOBYS
2. Cloud structures associated to high-mass star formation: from hyper-massive clumps to feedback effects
3. What can we learn from Probability Distribution Functions (PDFs)?
4. Conclusion, warnings, and future work…

Hyper-massive clump forming a massive star cluster



Nguyen Luong et al. 2011a; Rygl et al. 2014

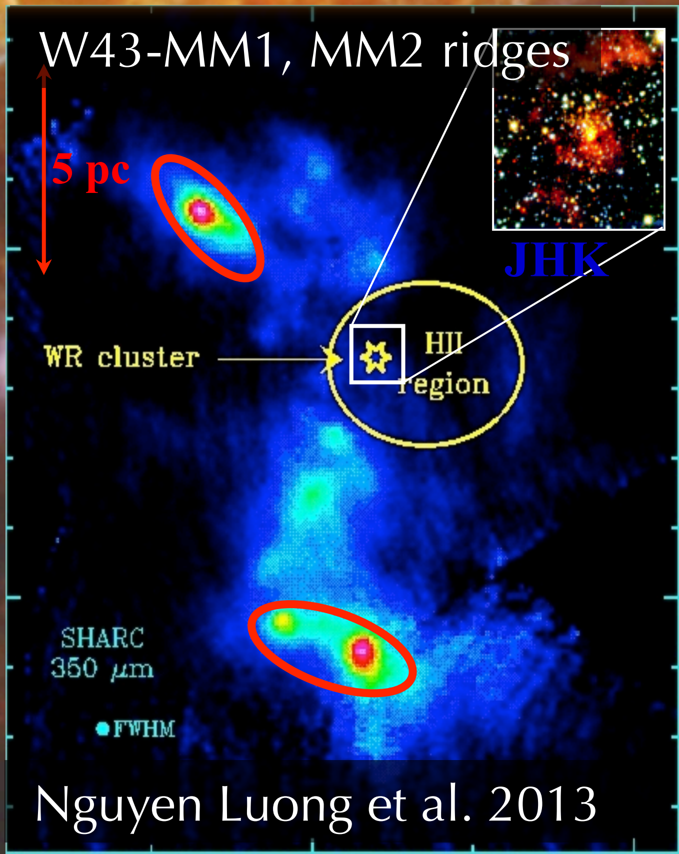
Ridges/Hubs are extreme clumps forming clusters of high-mass stars

- ~50% of the high-mass stars form in clusters within high-density elongated ridges, the other 50% form in spherical high-density hubs

⇒ Ridge/Hub definition: 5-10 pc^3 /1 pc^3 above 10^4-10^5 cm^{-3}

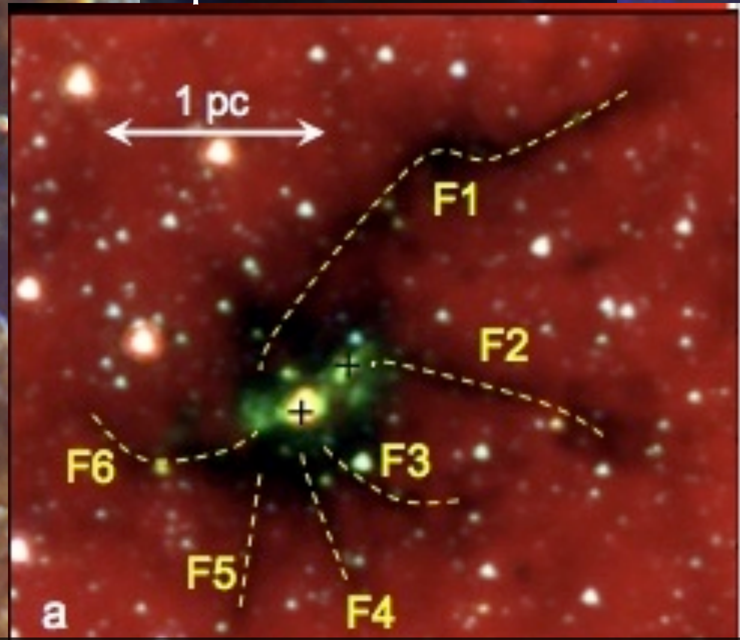
We use the 100 A_V level to identify them but it is not a physical threshold.

See Hill+ 2011, Nguyen Luong+ 2011, Hennemann+ 2012, Didelon+ 2015, …



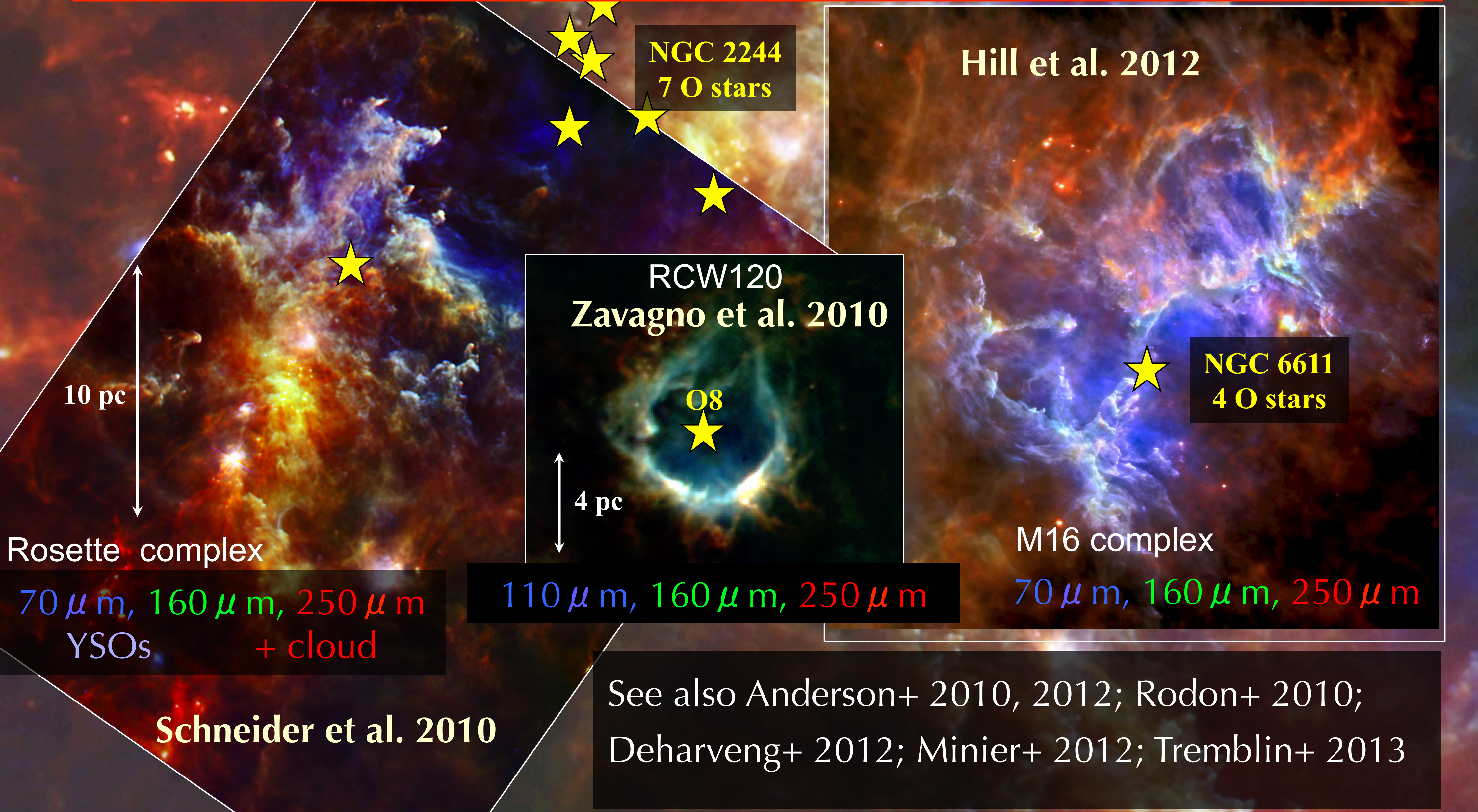
Nguyen Luong et al. 2013

Spitzer IRDC hub



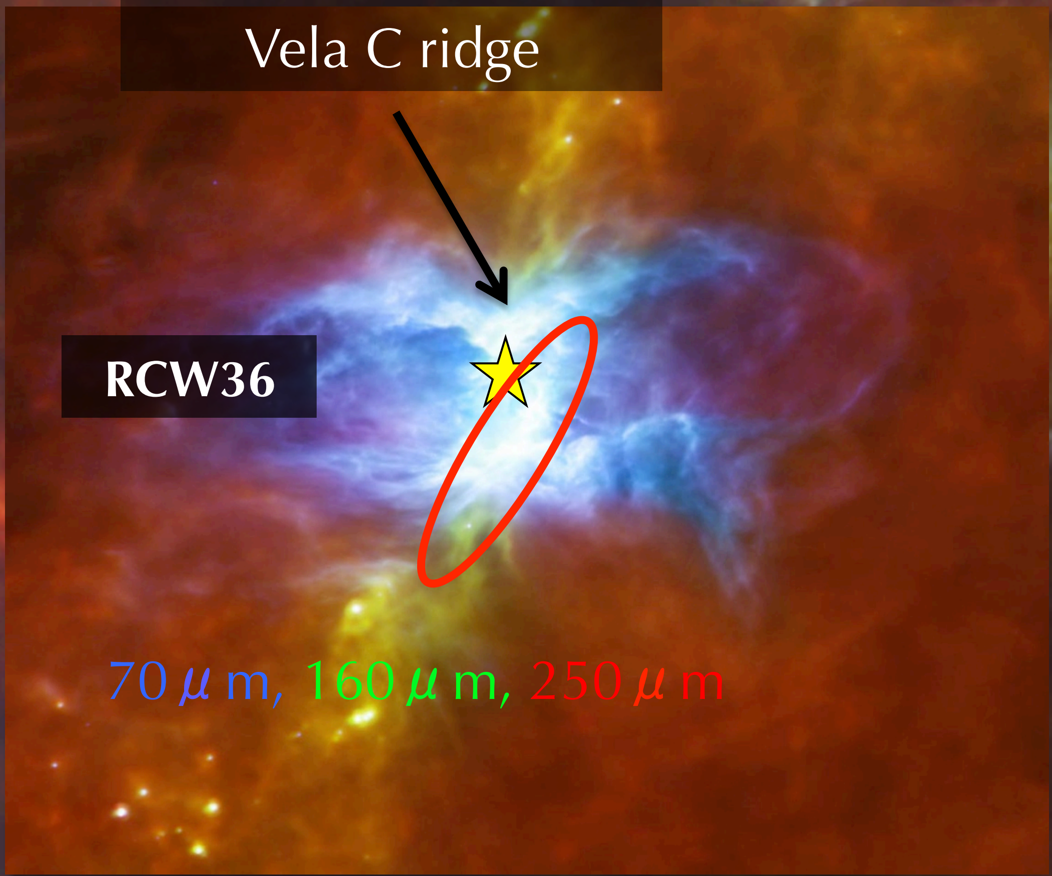
SDC335; Peretto et al. 2013

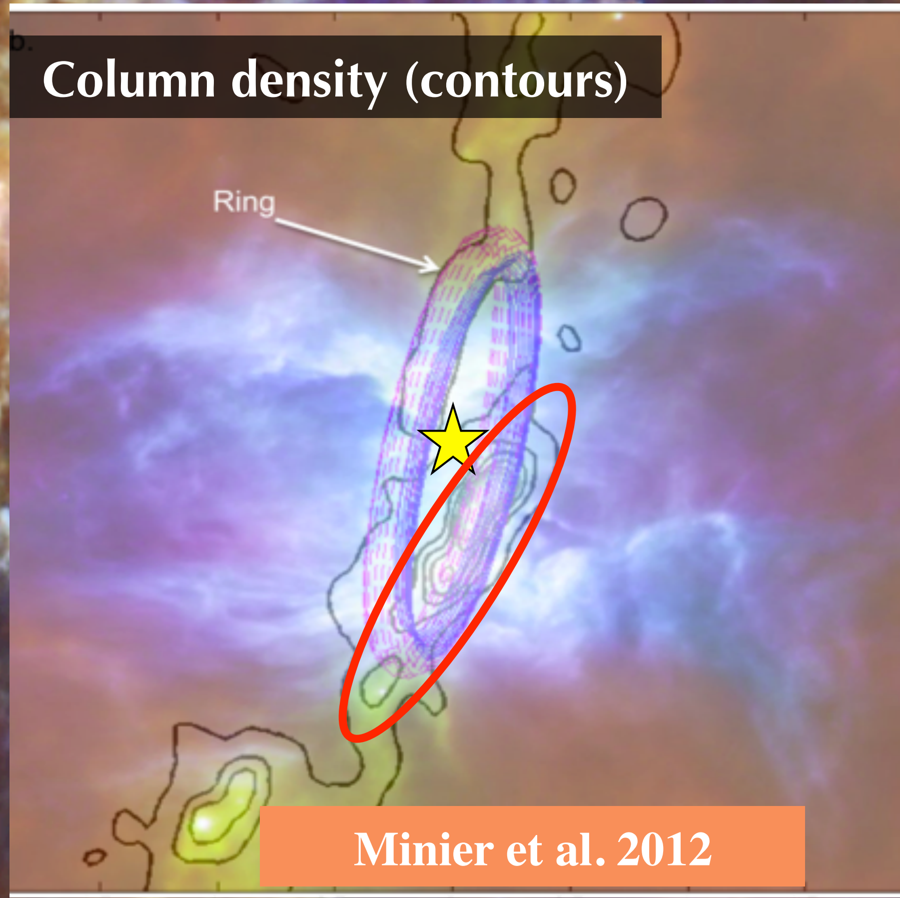
Feedback effects of OB star clusters: Heating, UV compression (pillars, ridges), and triggered star formation



See also Anderson+ 2010, 2012; Rodon+ 2010; Deharveng+ 2012; Minier+ 2012; Tremblin+ 2013

Some ridges could have formed by compression by UV radiation…





A model of ridge formation within a sheet compressed by the OB cluster UV radiation explains the observed structure and kinematics (Minier, Tremblin, Hill et al. 2012; Tremblin et al. 2014)

Cloud structure and high-mass star formation in HOBYS, the *Herschel* imaging survey of OB Young Stellar objects

1. Short introduction for HOBYS

2. Cloud structures associated to high-mass star formation: from hyper-massive clumps to feedback effects

3. What can we learn from Probability Distribution Functions (PDFs)?

4. Conclusion, warnings, and future work…

Probability Distribution Functions (PDFs), powerful tools to study cloud structure and thus indirectly follow the star formation process

PDFs trace the transformation of the gas from cloud to stars:

- Disentangling various physical processes in molecular clouds:
  Turbulence, gravity, stellar feedback, magnetic field, rotation, …

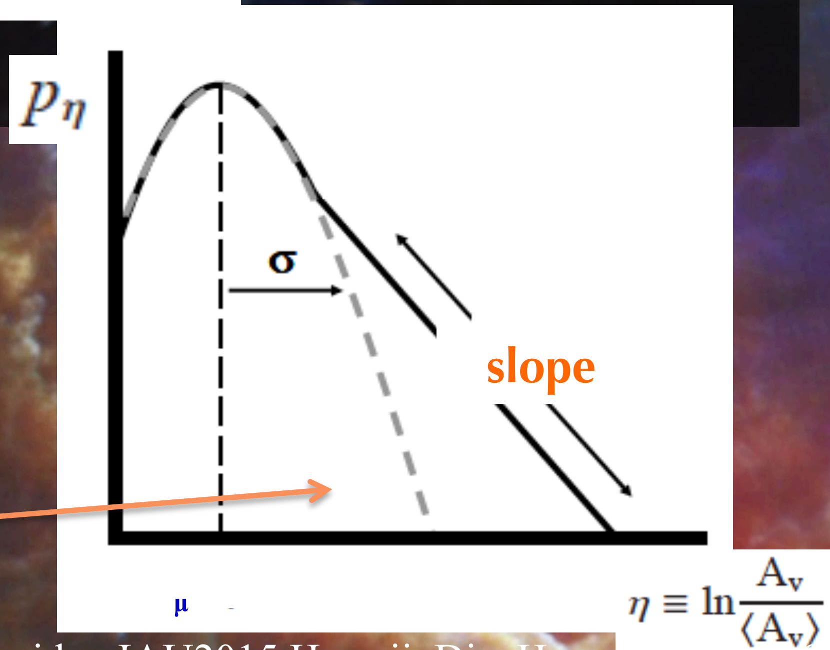
- Easy to compare to simulations.

- Can be applied to all tracers and constrain the chemistry and excitation conditions of molecular clouds.

Probability distribution functions of (column) density

- Statistical tool to describe the probability of a variable η to have a value between η and $\eta + \Delta\eta$.
- For molecular cloud analysis, η can be related to the density $\eta = \ln(\rho/<\rho>)$ or column density $\eta = \ln(N/<N>)$.
- How to make a N-PDF:

1. determine <N> of the map (noise, 'border' of the cloud/subregions)
2. determine $\eta = \ln(N/<N>)$ for each pixel of the map
3. bin η
4. normalization, e.g. $\int_{-\infty}^{+\infty} p_\eta \mathrm{d}\eta = \int_0^{+\infty} \mathrm{p}_{\mathrm{A_v}} \mathrm{dA_v} = 1\,.$
5. plot p = normalized #pixels vs η

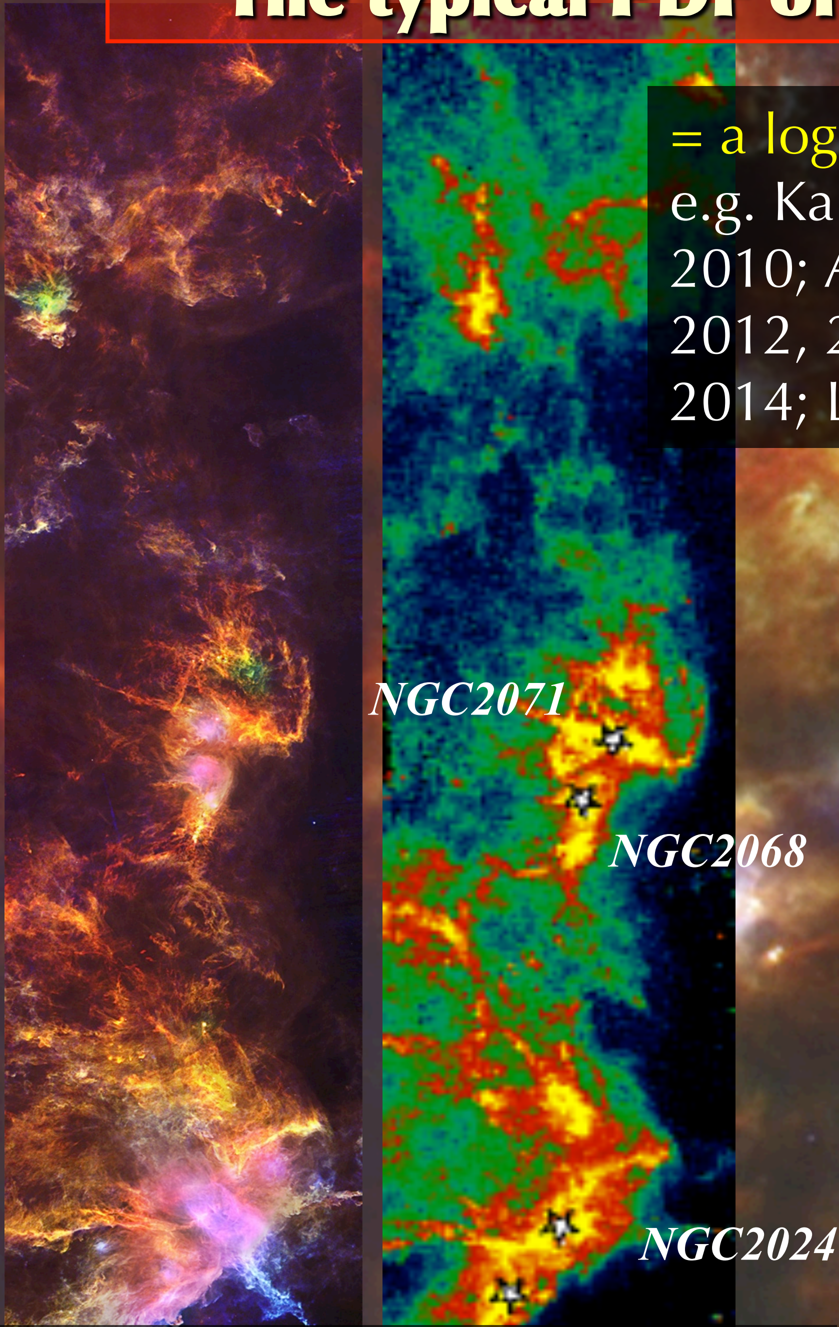


for a purely lognormal distribution:

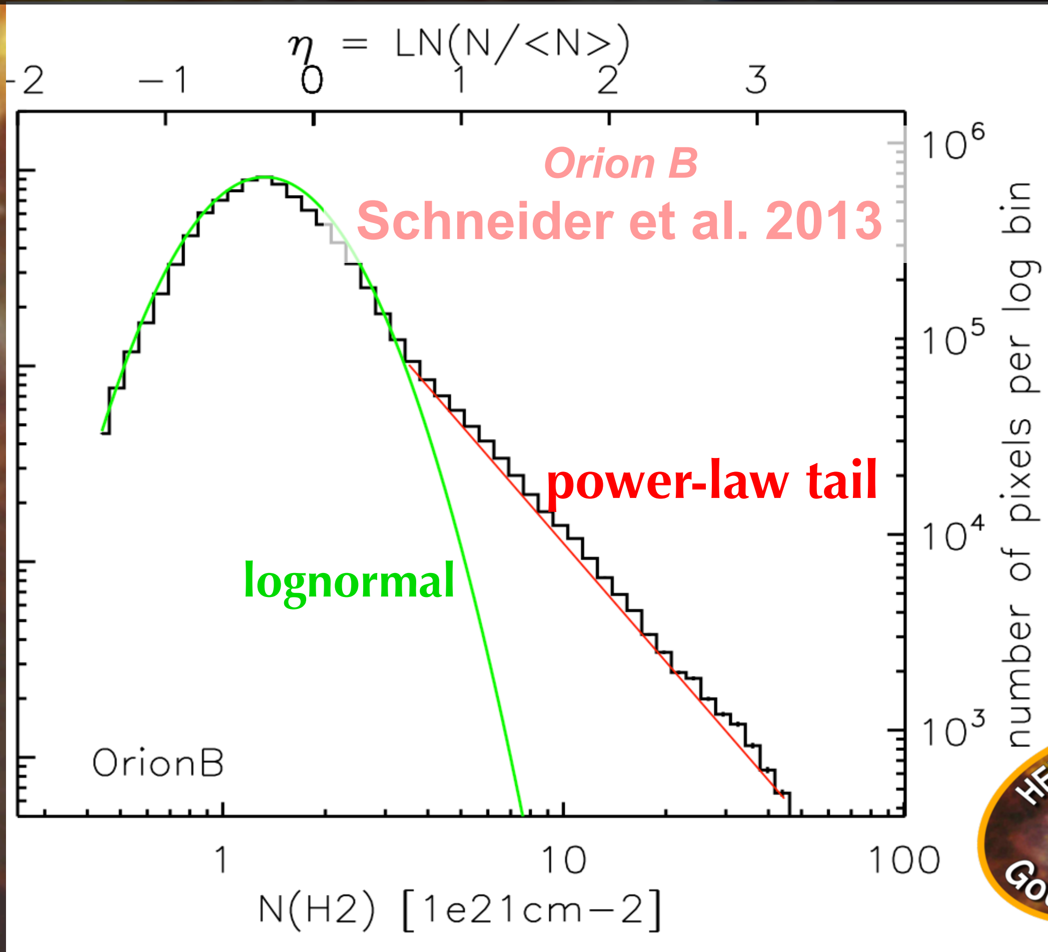
$$p_\eta \,\mathrm{d}\eta = \frac{1}{\sqrt{2\pi\sigma_\eta^2}} \exp\left[-\frac{(\eta-\mu)^2}{2\sigma_\eta^2}\right] \mathrm{d}\eta$$

The typical PDF of a star-forming molecular cloud

= a lognormal distribution plus a power-law tail
e.g. Kainulainen et al. 2009, 2011; Froebrich & Rowles 2010; André et al. 2011; Russeil et al. 2013; Schneider et al. 2012, 2013, 2015a-b; Tremblin et al. 2013; Sadavoy et al. 2014; Lombardi et al. 2014; Stutz & Kainulainen 2015 ….

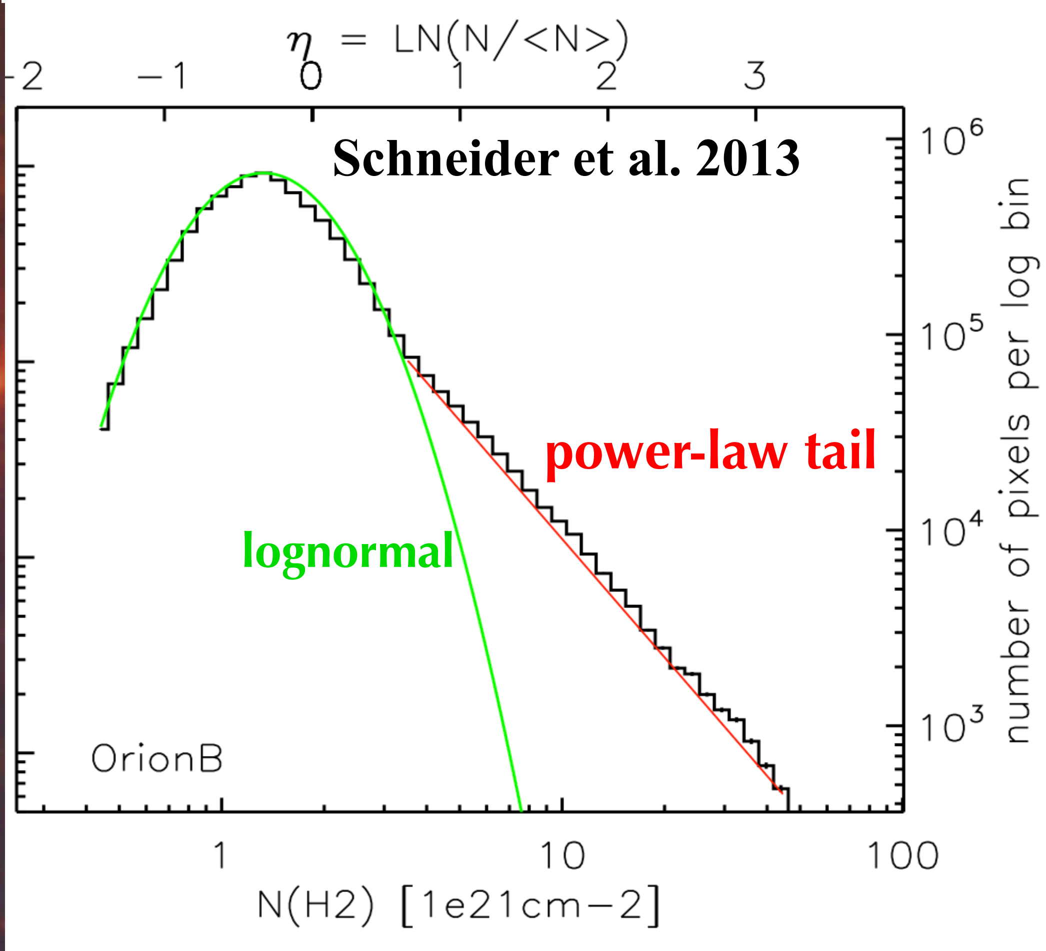


Herschel 3 color image + column density map



Interpretation of the different regimes of a PDF

PDF of the column density measured in OrionB from *Herschel* data



Lognormal = turbulence

Theory: Vazquez-Semadeni 1994; Nordlund & Padoan 1999; Ostriker et al. 2001; Hennebelle & Chabrier 2008; Kritsuk et al. 2011; Collins et al. 2012; Federrath & Klessen 2013; Ward et al. 2014. See however Tassis et al. 2012.

Power-law tail = gravity

Theory: Ballesteros-Paredes, Vazquez-Semadeni et al. 2011; Kritsuk et al. 2011; Girichidis et al. 2014.
Observations: Froebrich & Rowles 2010; Schneider et al. 2013, 2015a-b.

or pressure

Theory: Passot & Vazquez-Semadeni 1998.
Observations: Kainulainen et al. 2011; Tremblin et al. 2013, 2014.

Slope of the power-law tail and density structure constraints

PDFs with pixels on filaments have a power-law tail
⇒ gravitational boundedness or gravitational collapse

- From the slope 's' of the power-law tail to the exponent 'α' of the radial density distribution:

$\rho(r) \sim r^{-\alpha}$ spherical geometry $\alpha = -2/(s+1)$

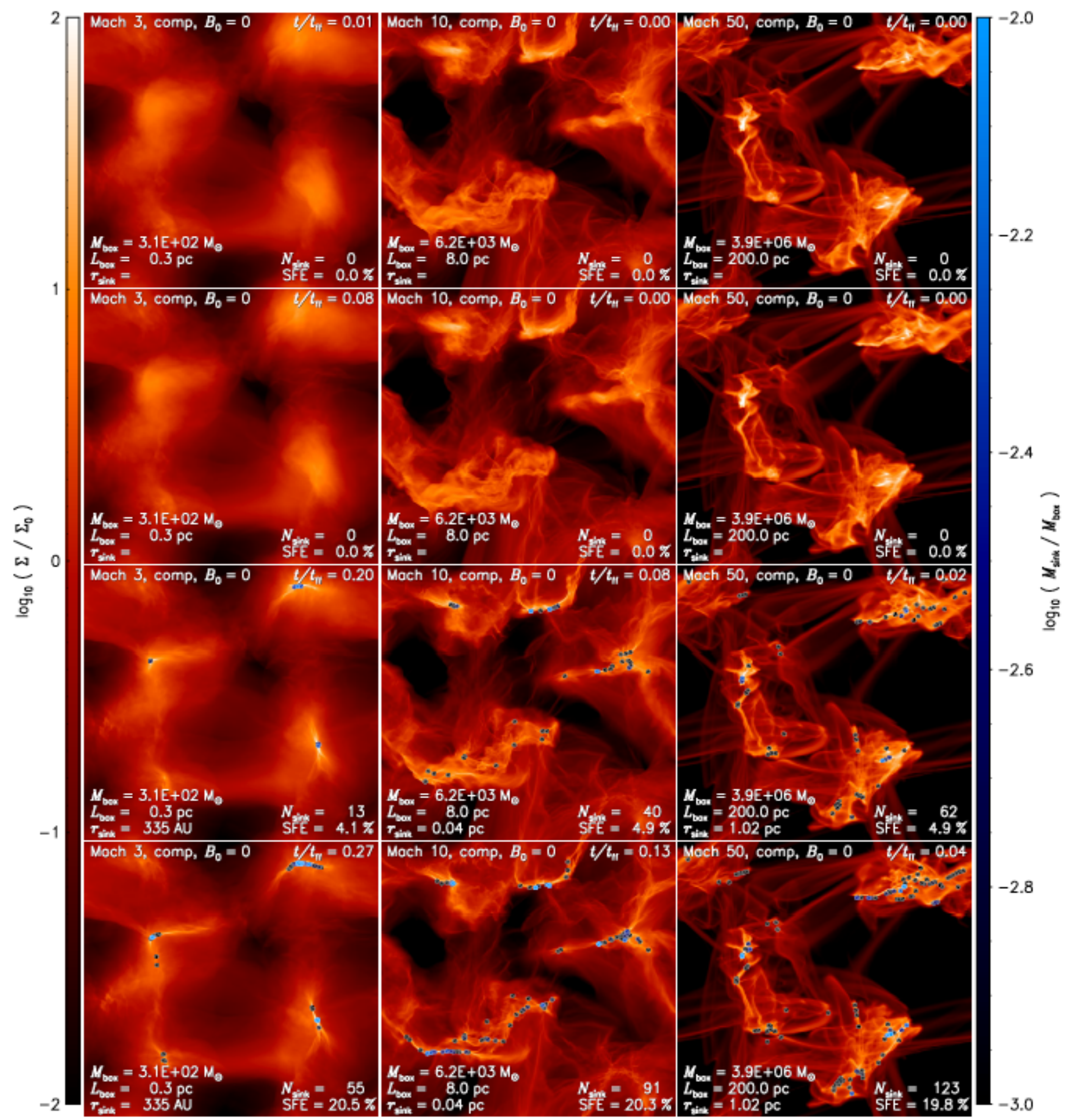
cylindrical geometry $\alpha = -1/(s+1)$

- Gravitational collapse $\alpha = 1.5\text{-}2$

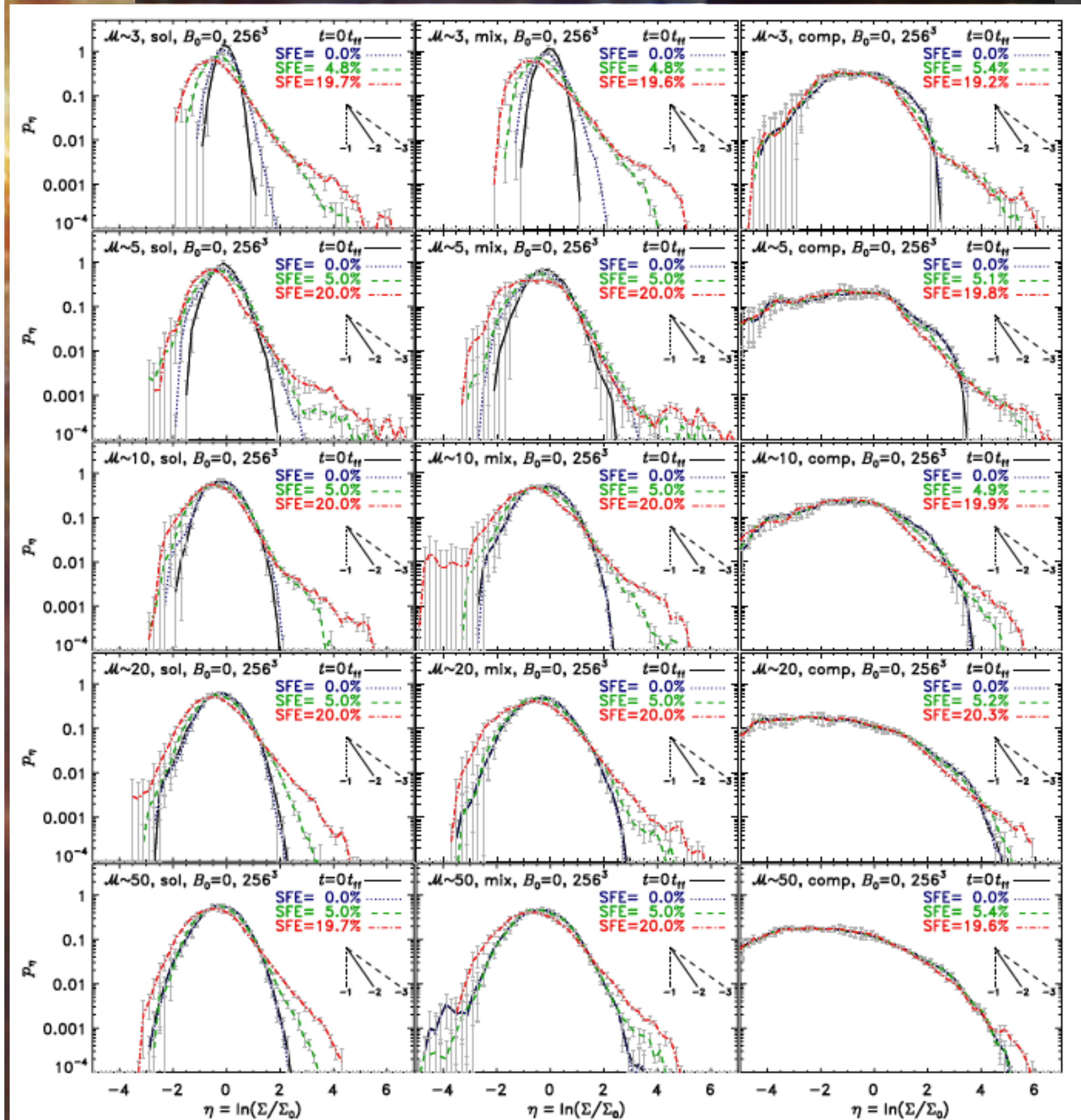
(Shu 1977, Whitworth et al. 1985)

Column density PDFs of numerical simulations

Federrath & Klessen 2013: MHD simulations.

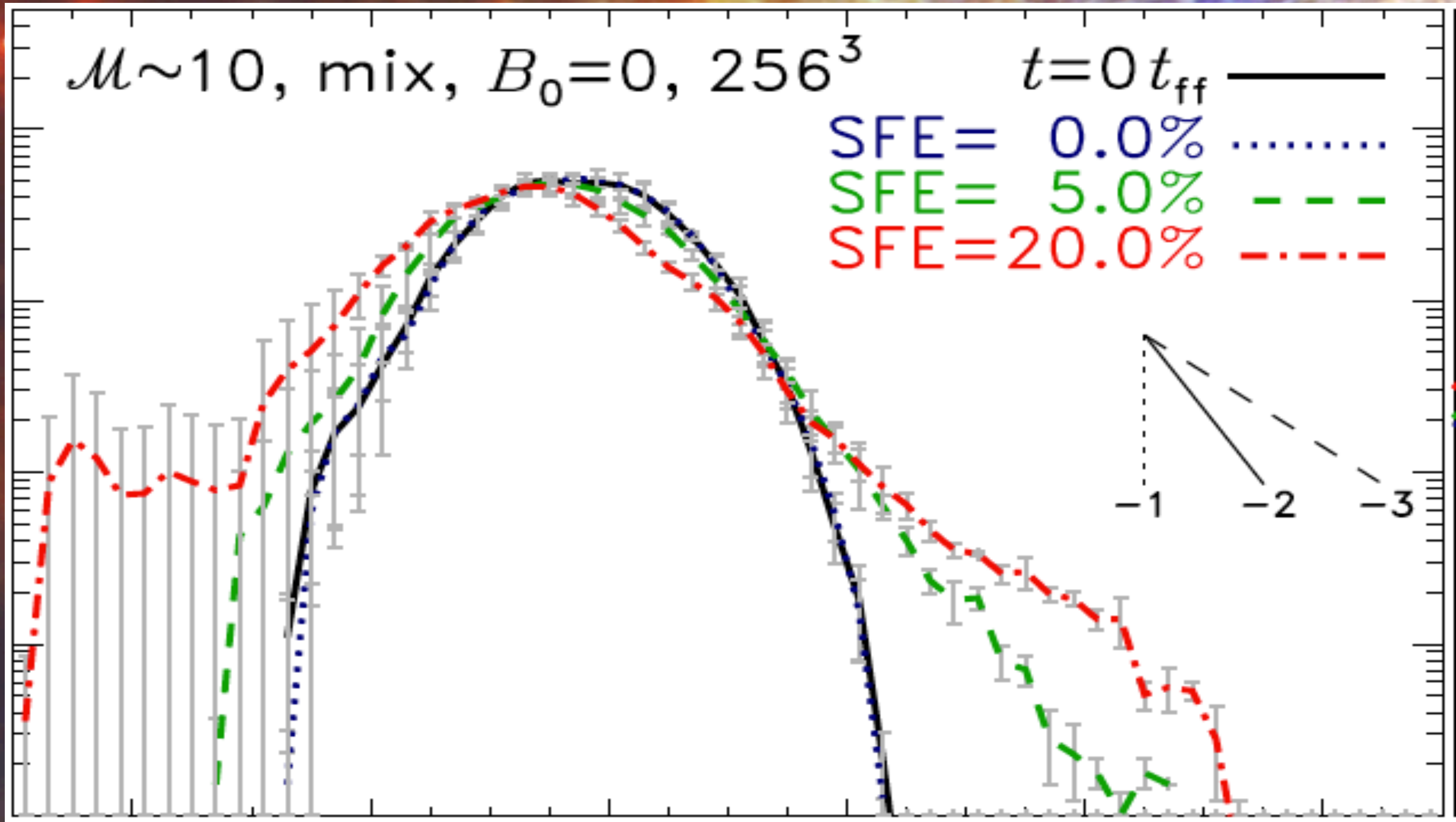


solenoidal mixed compressive



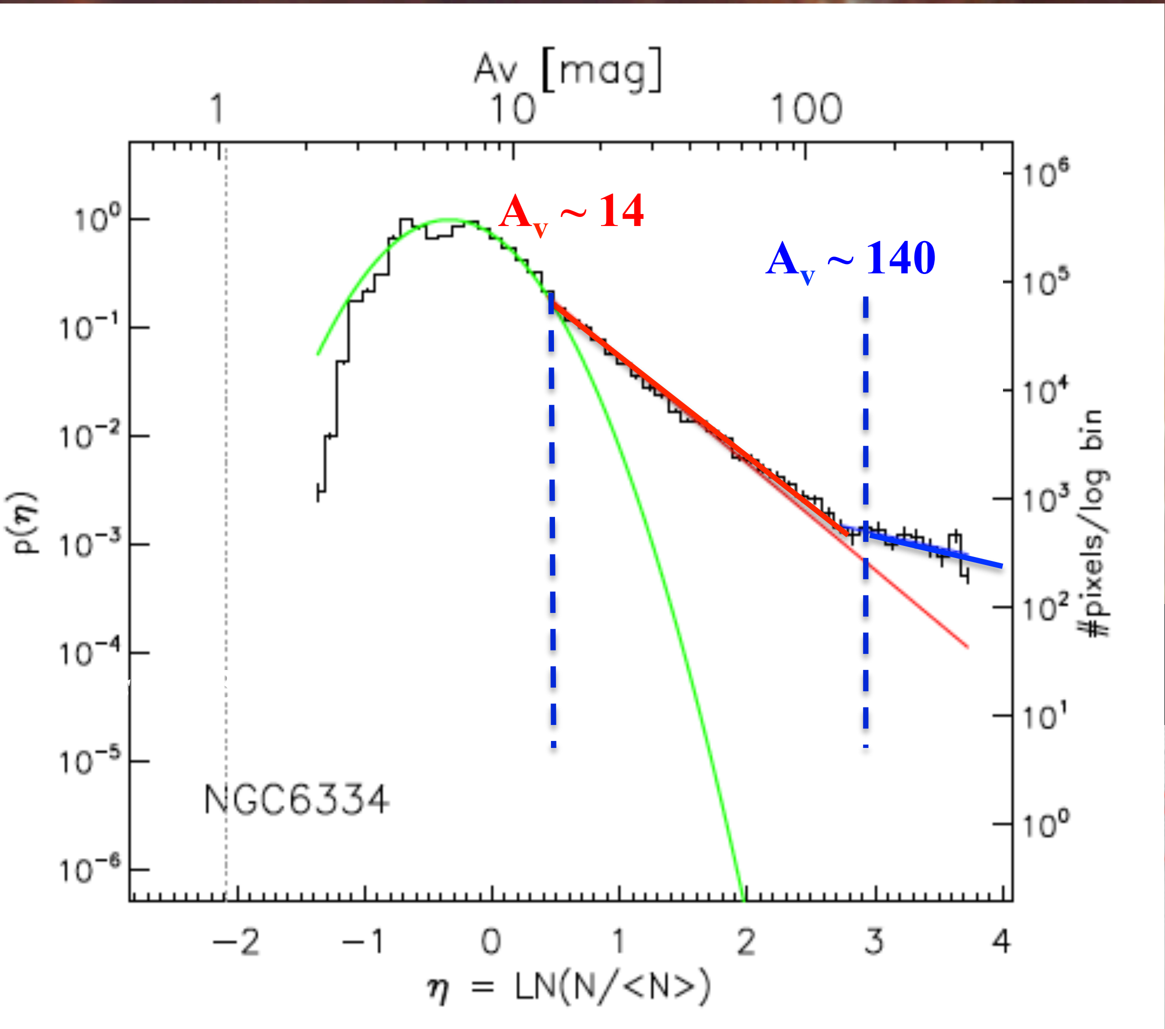
PDF power-law tails in numerical simulations

Federrath & Klessen 2013: MHD simulation of magnetized, turbulent, and self-gravitating gas.



For typical molecular clouds, a power-law tail develops and the slope depends on the star formation efficiency.

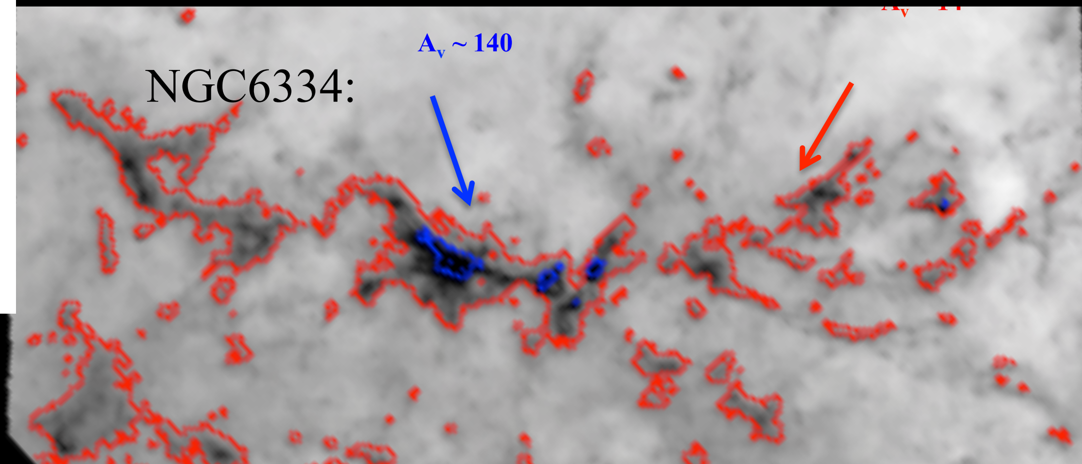
A second power-law tail in PDFs of high-mass SF clouds



Schneider et al. 2015c (MNRAS Letter)

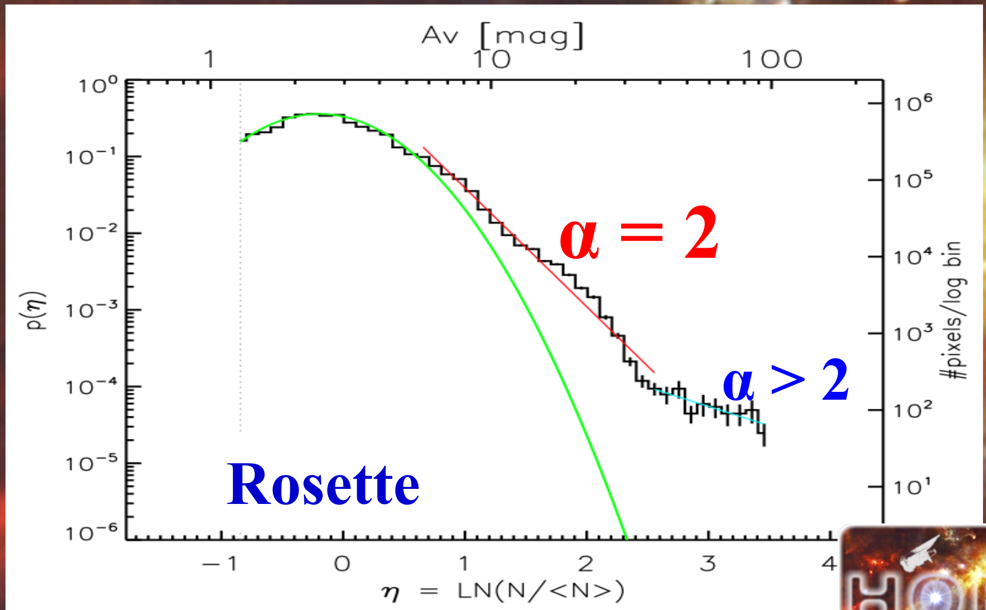
A second power-law tail is observed at high column densities.

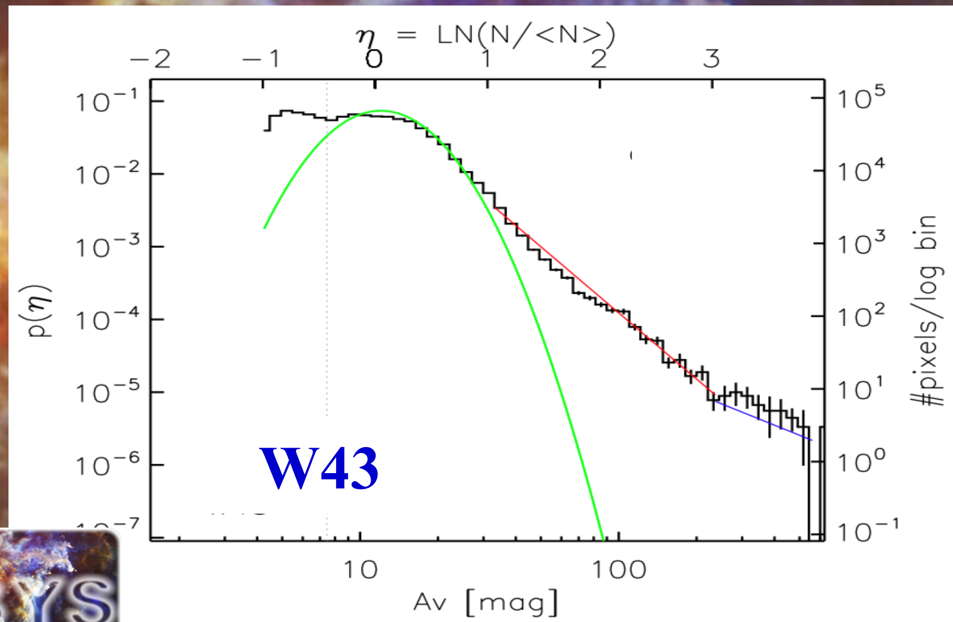
- Excess emission confined to central ridges/hubs (Hill et al. 2011; Hennemann et al. 2012; Nguyen-Luong et al. 2011, 2013; Rayner et al. in prep.)
- size scale ~1 pc
- densities ~10^4-10^5 cm^{-3}

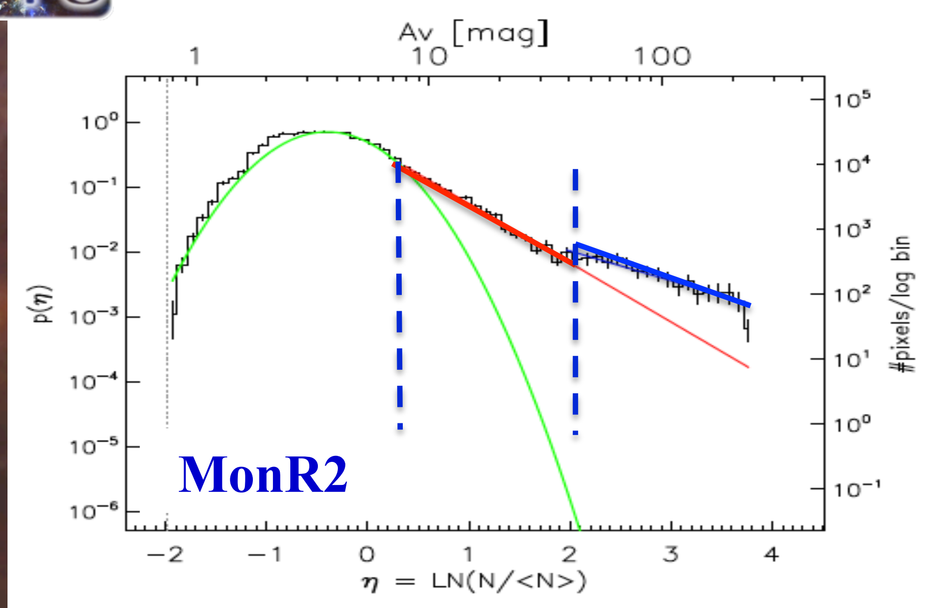


column density map Russeil, Schneider et al. 2013

PDFs with 2 power-law tails seem characteristic of high-mass SF clouds







Schneider et al. (2015c)
see also Rivera-Ingraham et al. (2015); Rayner et al. (in prep.).
Confirmed in MonR2 by direct density profile measurements (Didelon et al. 2015).
Recalls the definition of ridges by Hill et al. (2011).

Interpretation of PDF power-law tails

The first power-law tail corresponds to self-gravitating gas (filaments and cores). Its slope is consistent with $\alpha \sim 1.5\text{-}2$ for a spherical or cylindrical density distribution $\rho \sim r^{-\alpha}$.

The second power-law tail has a $\alpha > 2$ slope, which suggests that a physical process reduces the gas flow toward the highest densities (Schneider et al. 2015c; Didelon et al. 2015).

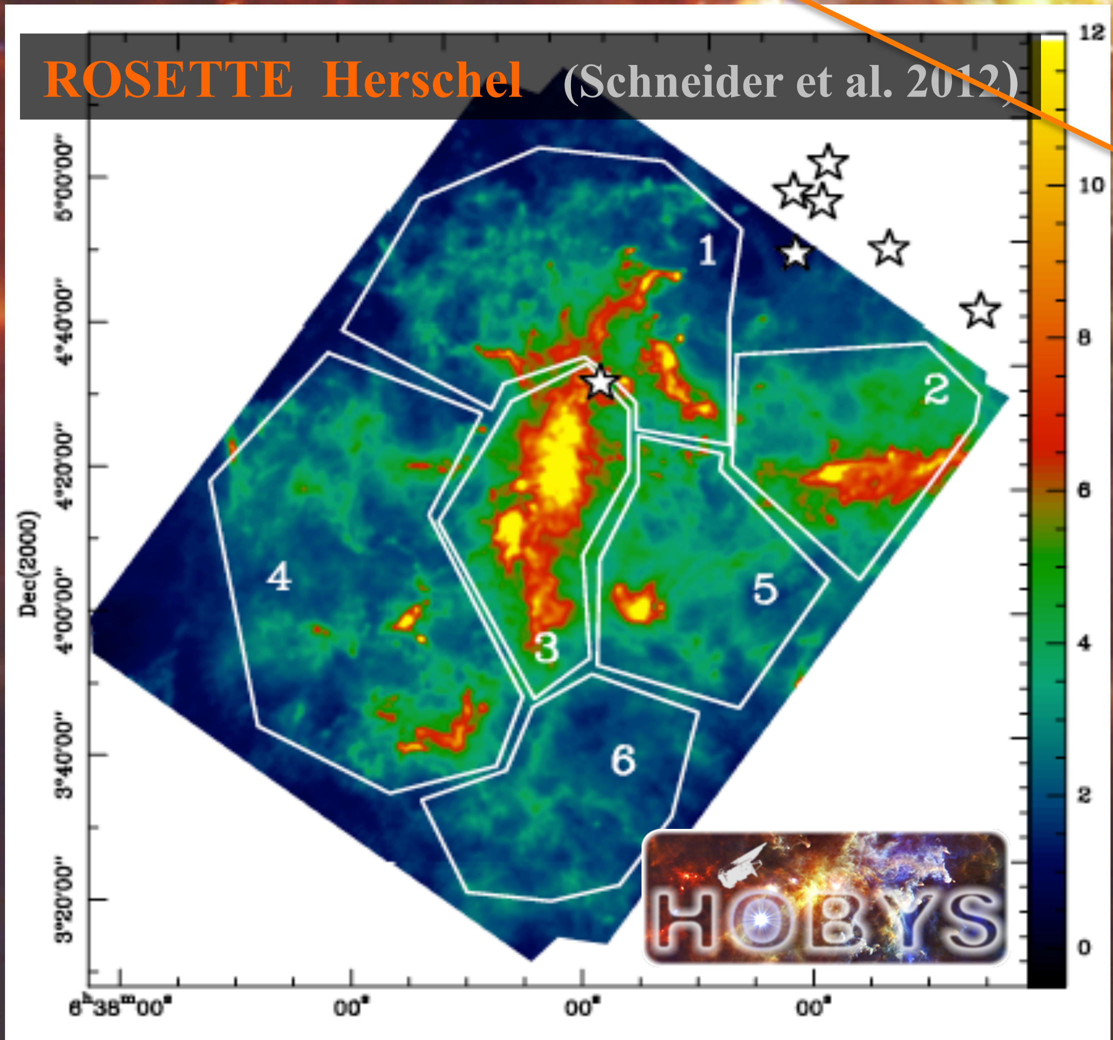
It could be:

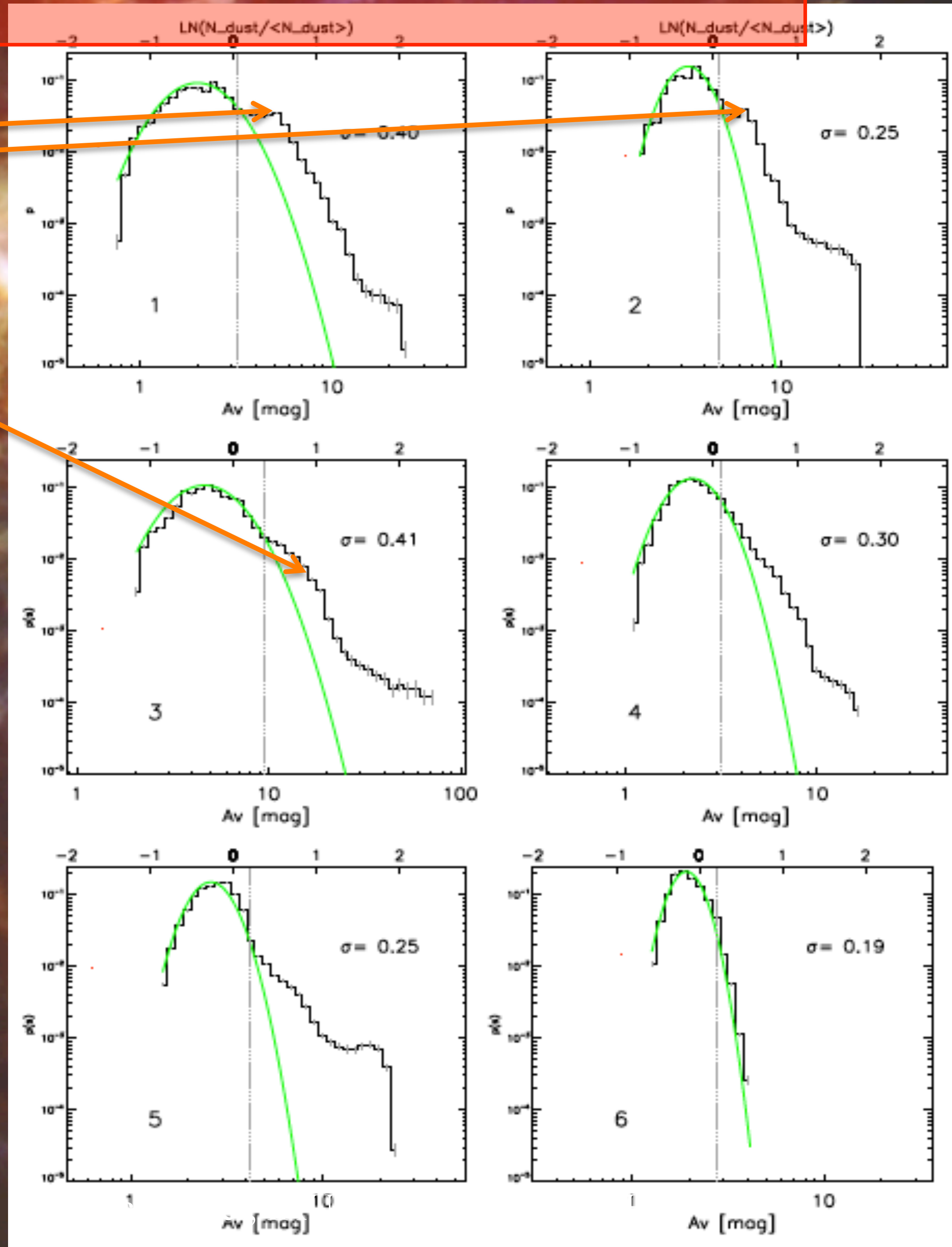
1. rotation (Kritsuk et al. 2011; Girichidis et al. 2015)
2. magnetic field (Balsara et al. 2001; Heitsch et al. 2011; Koertgen & Banerjee 2015)
3. protostellar feedback
4. longitudinal filament collapse (Toala et al. 2011; Vazquez-Semadeni et al.)
5. increasing optical depth and weaker cooling…

To be further investigated…

A second peak in PDFs of regions compressed by HII regions

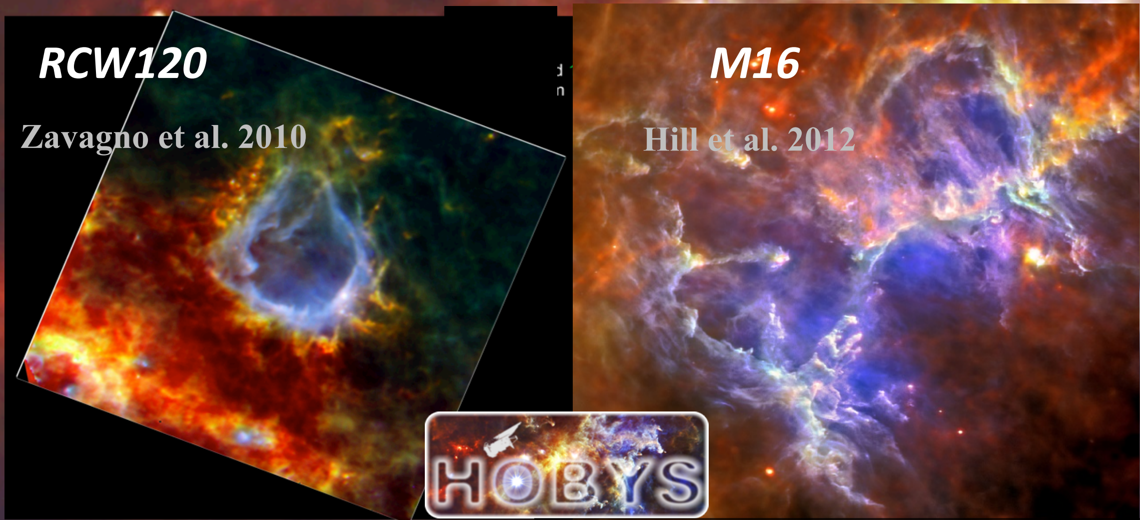
Second peak in PDF
= compressed shell

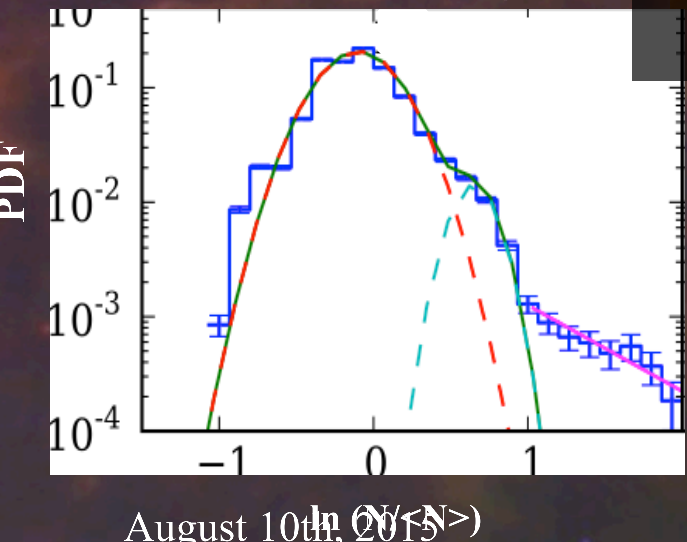


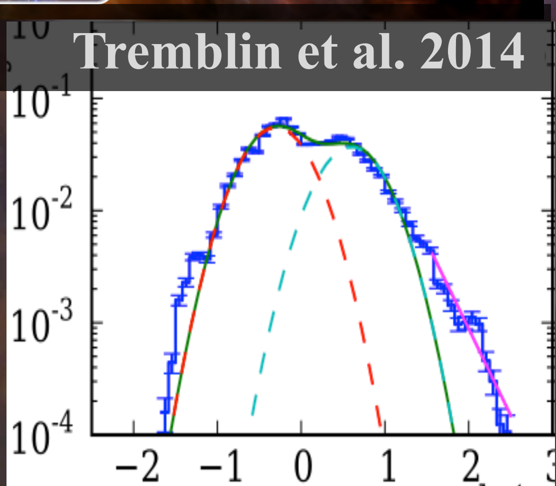


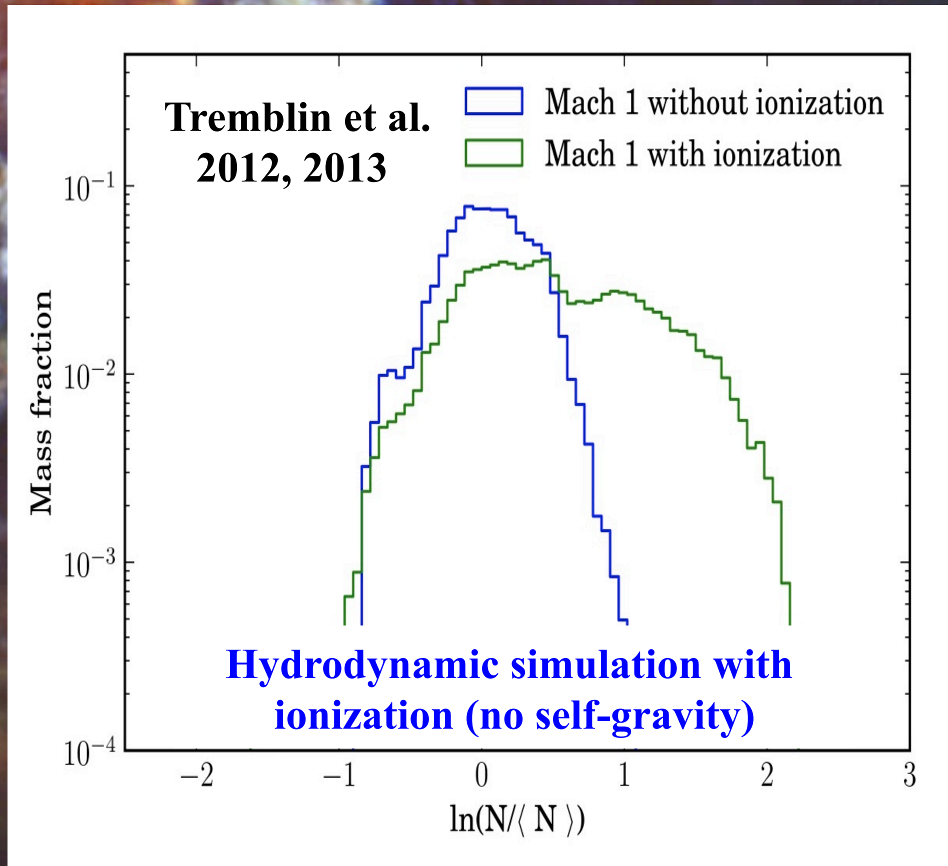
Interpretation of double-peak PDFs

Shell compressed by ionized gas of HII regions
=> PDF is either double-peaked or simply broader, depending on the relative strengths of turbulence and ionization (Tremblin et al. 2014).









Conclusion, warnings, and future work

PDFs are powerful tools to investigate cloud structure under the influence of

- Turbulence (log-normal)
- Gravity (power-law tail with α ~ 1.5-2).
- Complementary processes (rotation, B-field or…) slowing down the collapse at high densities (second power-law tail with α > 2)
- Stellar feedback (second PDF peak)

⇒ High-mass star formation shapes the cloud inside which OB stars form/formed:

- PDFs with a second power-law tail

- PDFs with a second peak

A word of caution:

- Image cropping versus good statistics
- Line-of-sight contamination

Need for:

- Direct measurements of density structure (Didelon+ 2015)
- Comparison with other tracers (e.g. molecular line PDFs, Schneider+ subm.)

Thank you for your attention!