Linking numerical simulations of molecular cloud structure with observations

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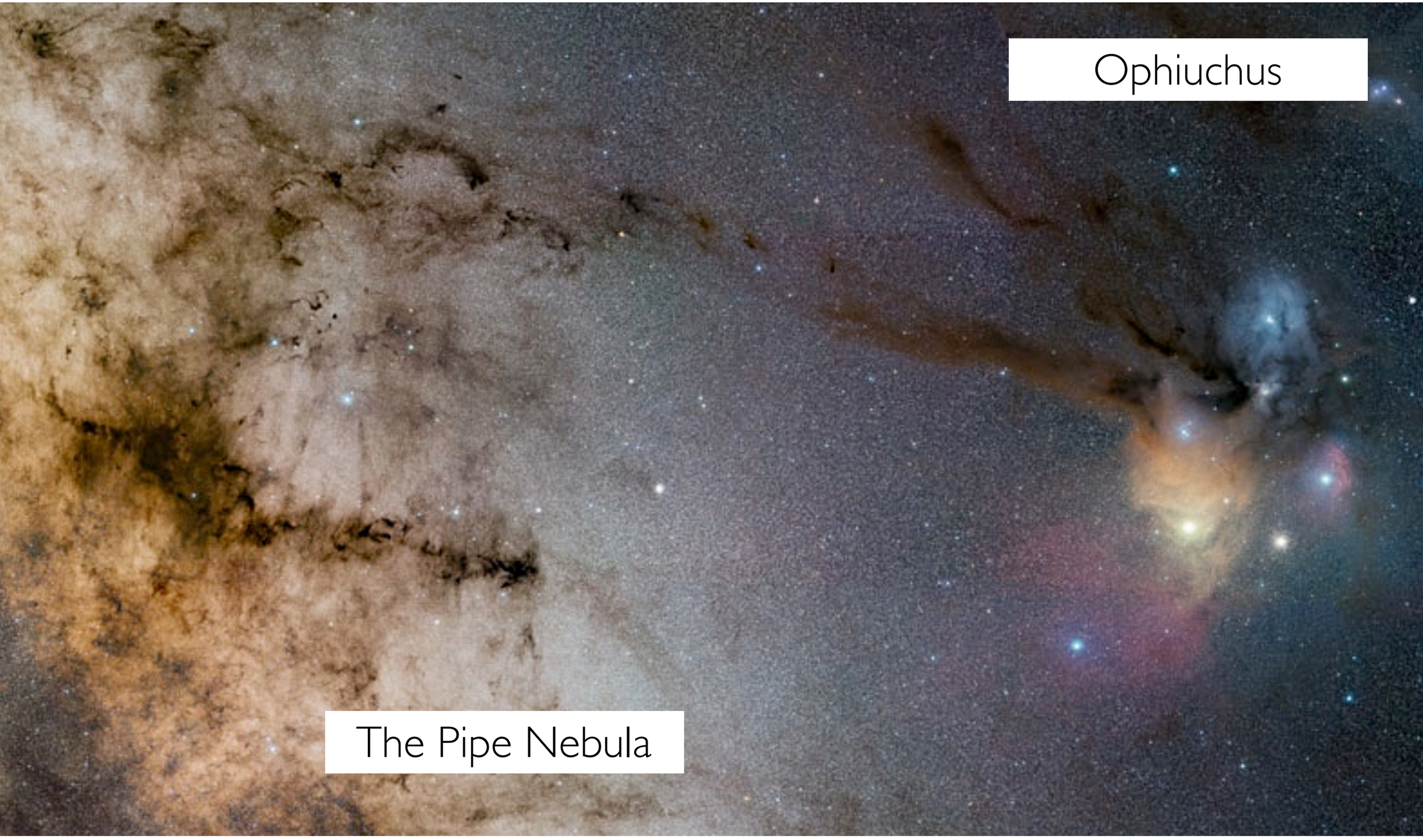
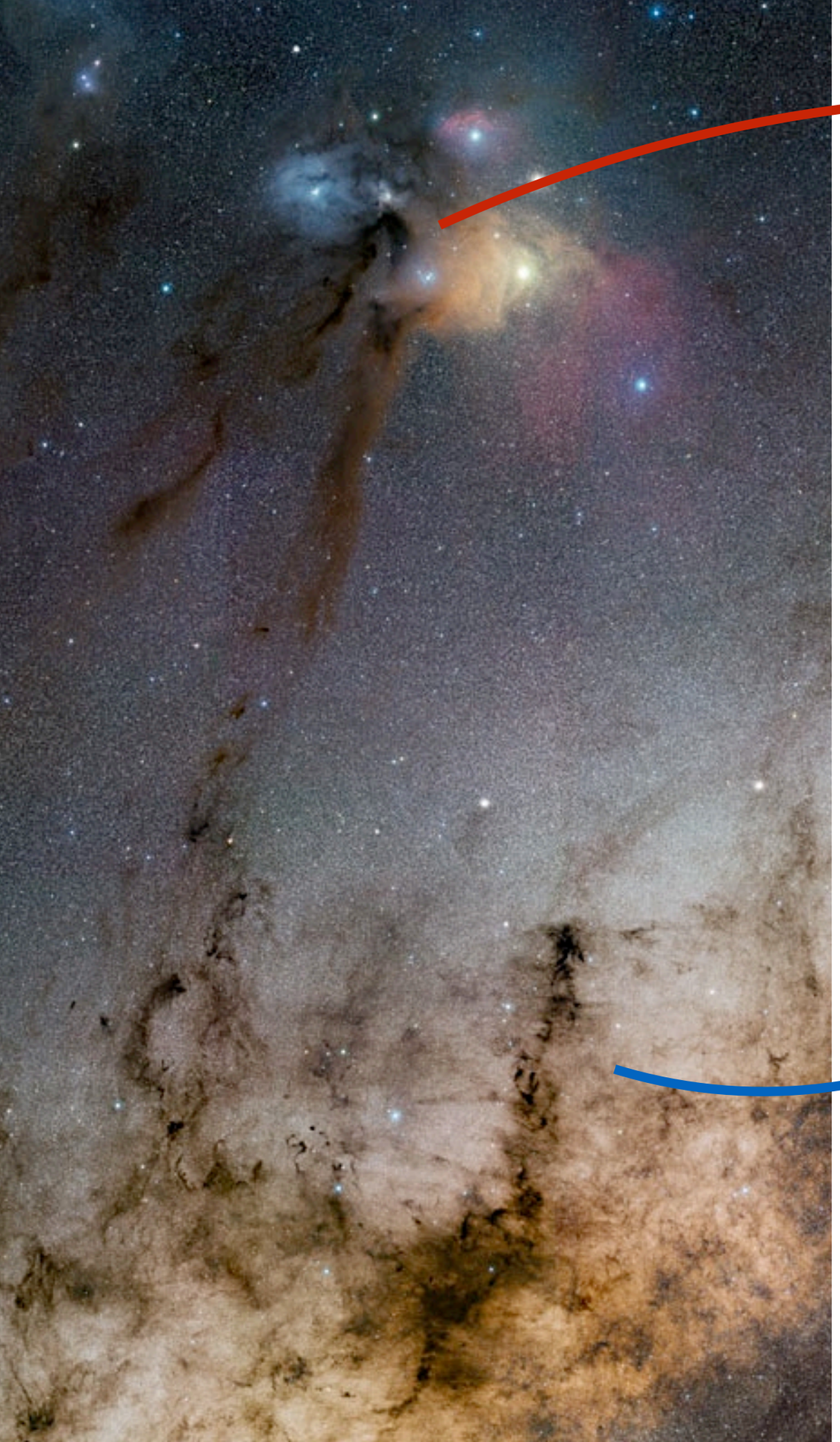
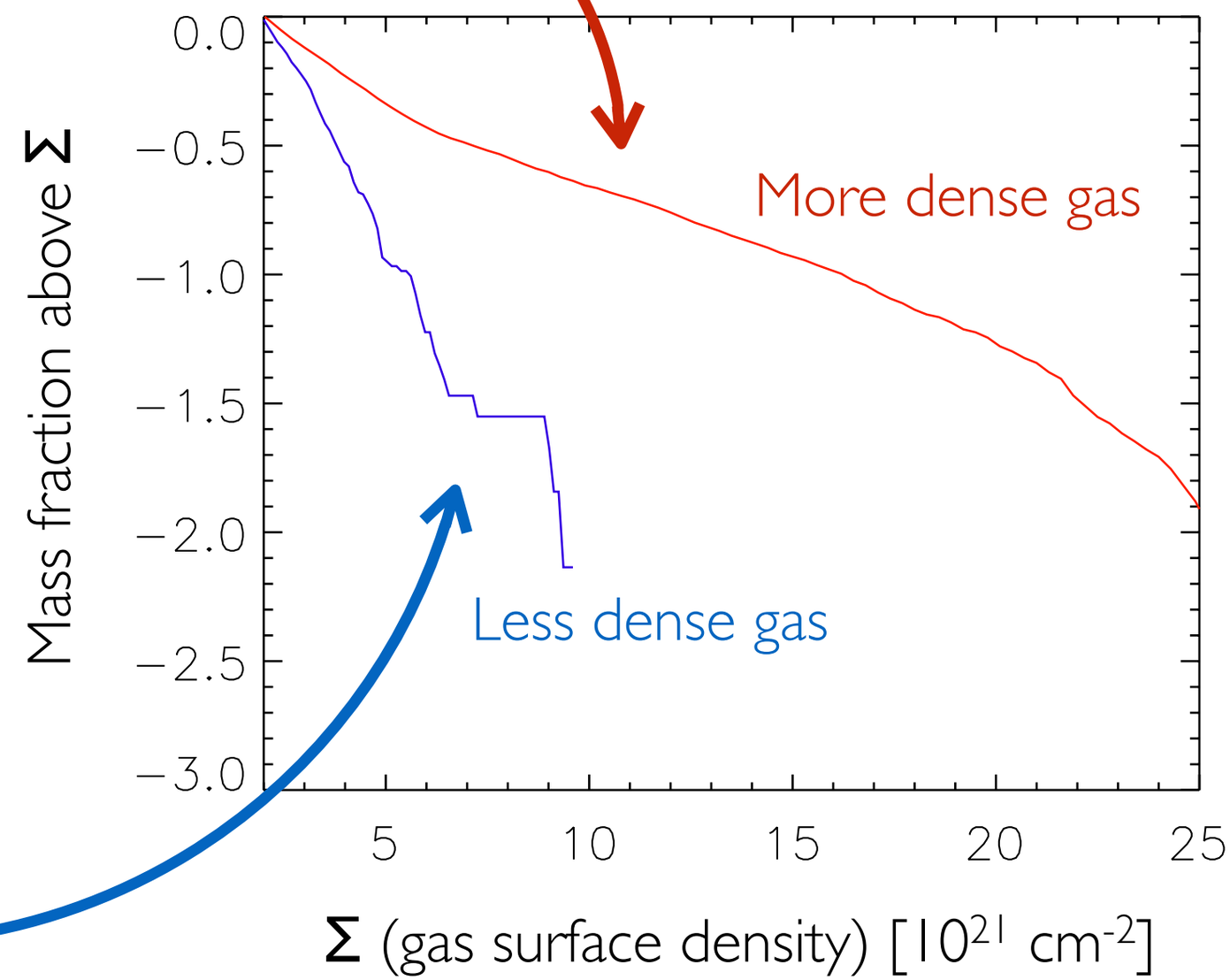
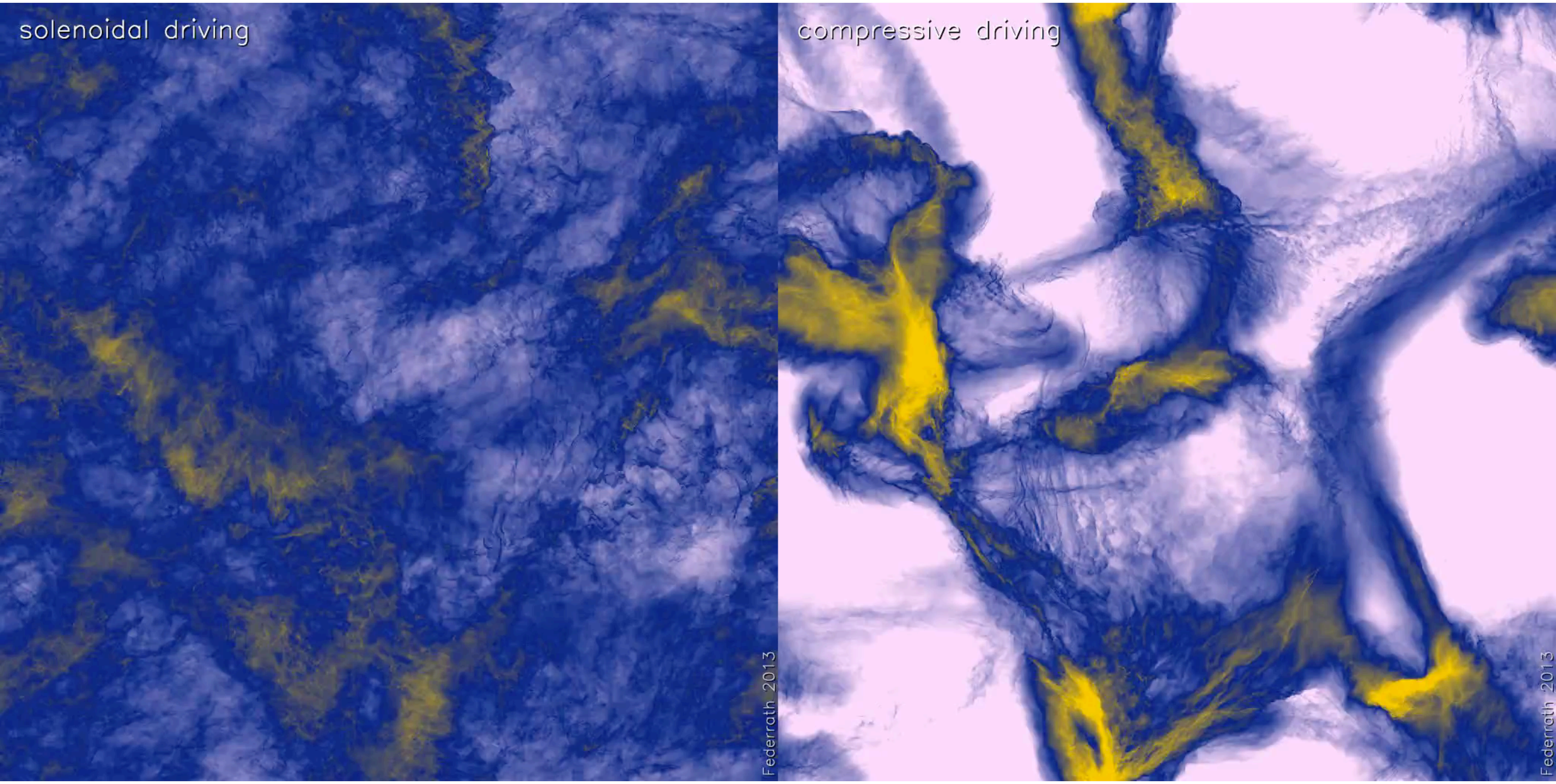
With:
Federrath, C., Alves, J., Tan J C., Beuther H., Stutz, A., Henning T., Abreu Vicente, J., Hacar, A., Mattern M.


Ophiuchus
The Pipe Nebula





Kainulainen et al. (2009)

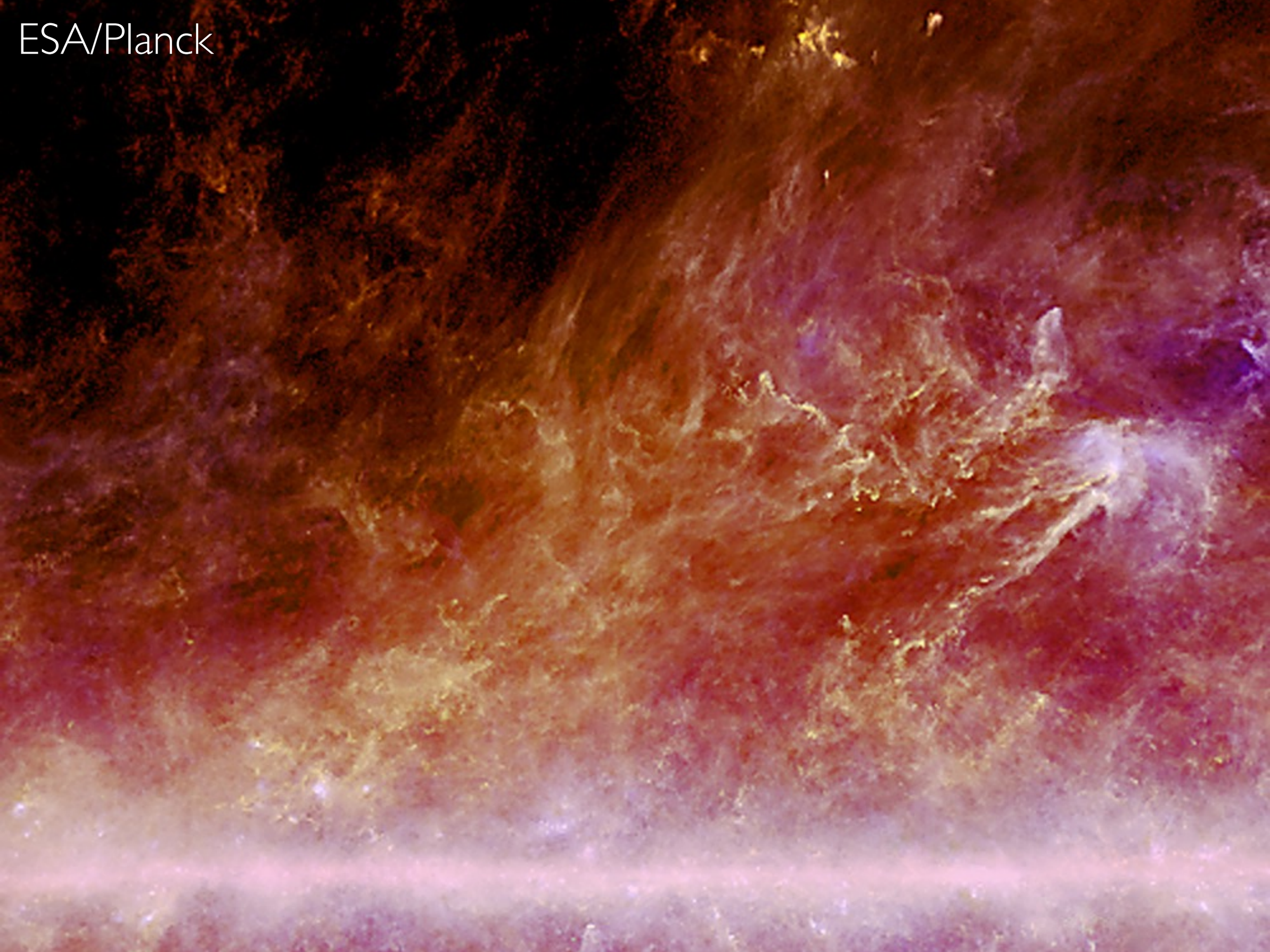


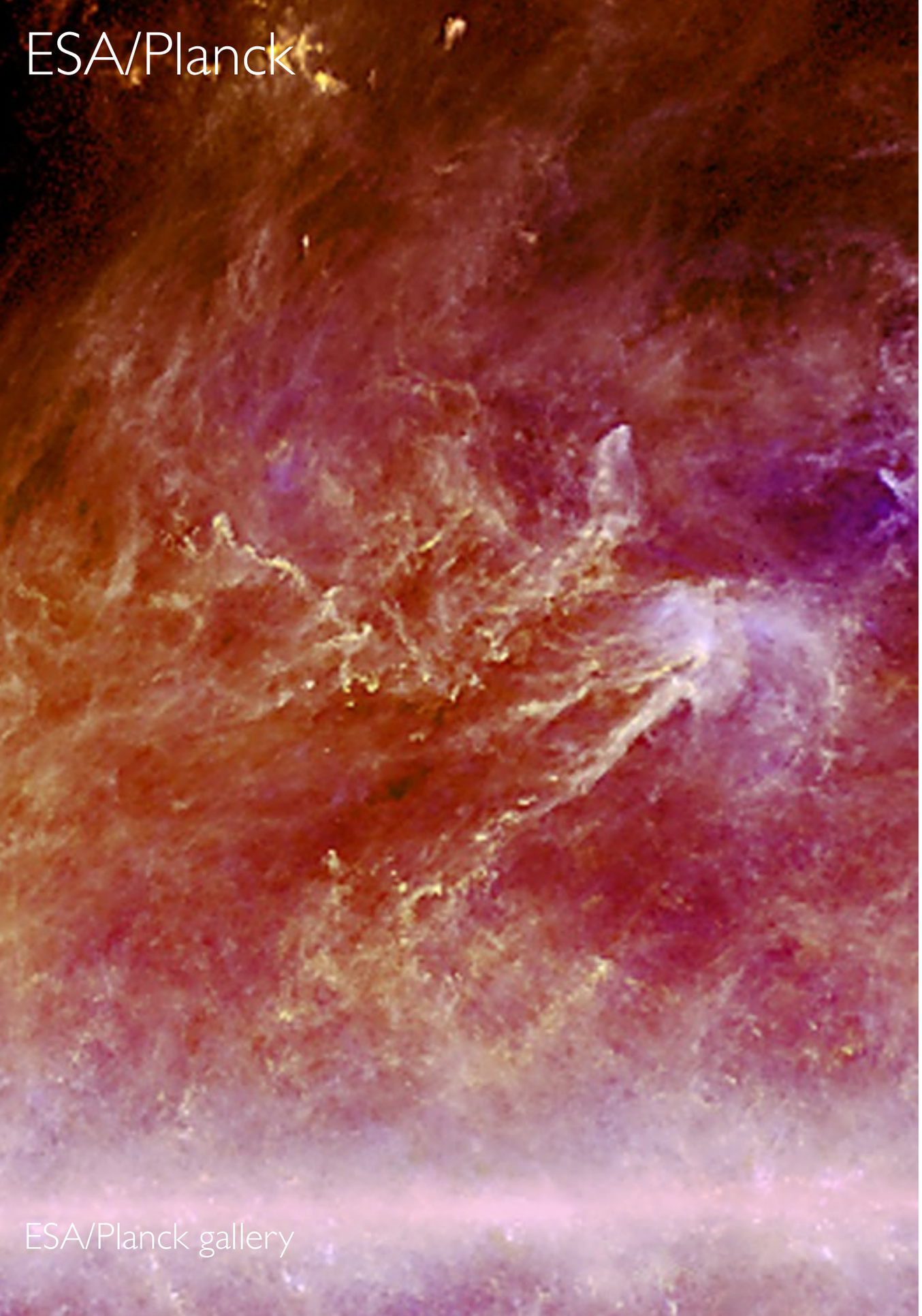
Federrath (2013)

Why do we need to understand molecular cloud structure?

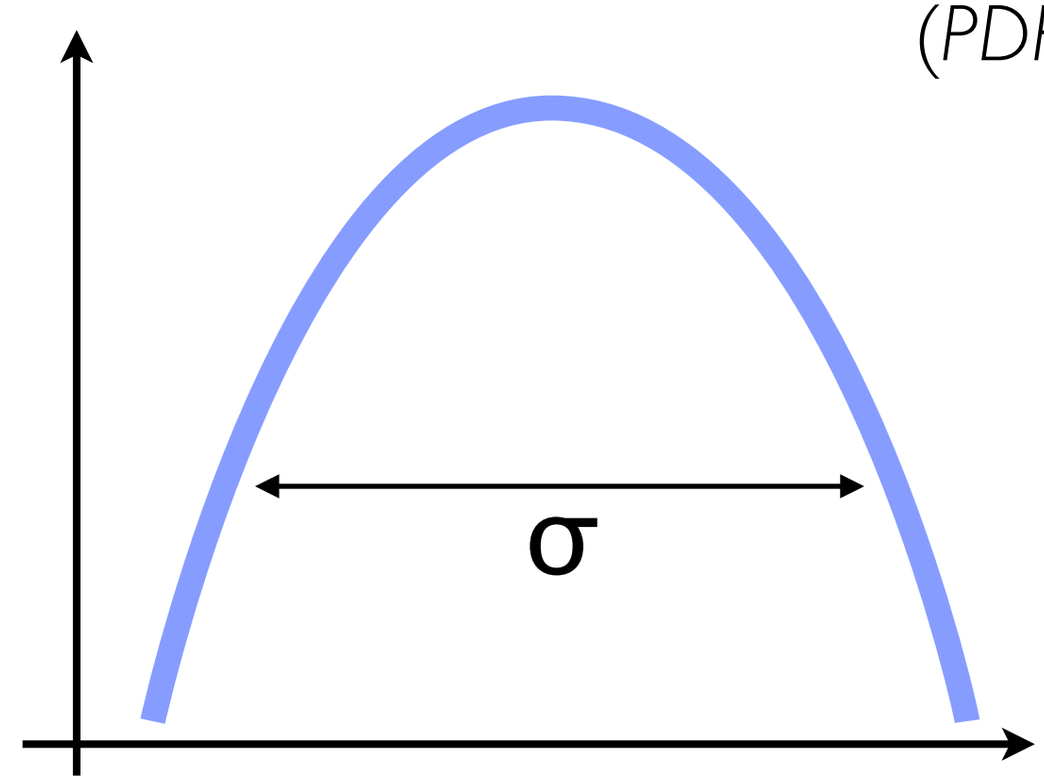
I: **Star formation** is linked to the **internal cloud structure**.

II: Cloud structure **carries imprints** of fundamental physical processes.


ESA/Planck



Log Probability Distribution Function (*PDF*)



Log (density, ρ), or
Log (projected density, *N*)

$$\sigma_s^2 = \ln\left(1 + b^2\mathcal{M}^2\frac{\beta}{\beta+1}\right)$$

Molina et al. (2012)

M ~ turbulence energy, *b* ~ compression,
β ~ magnetic field energy

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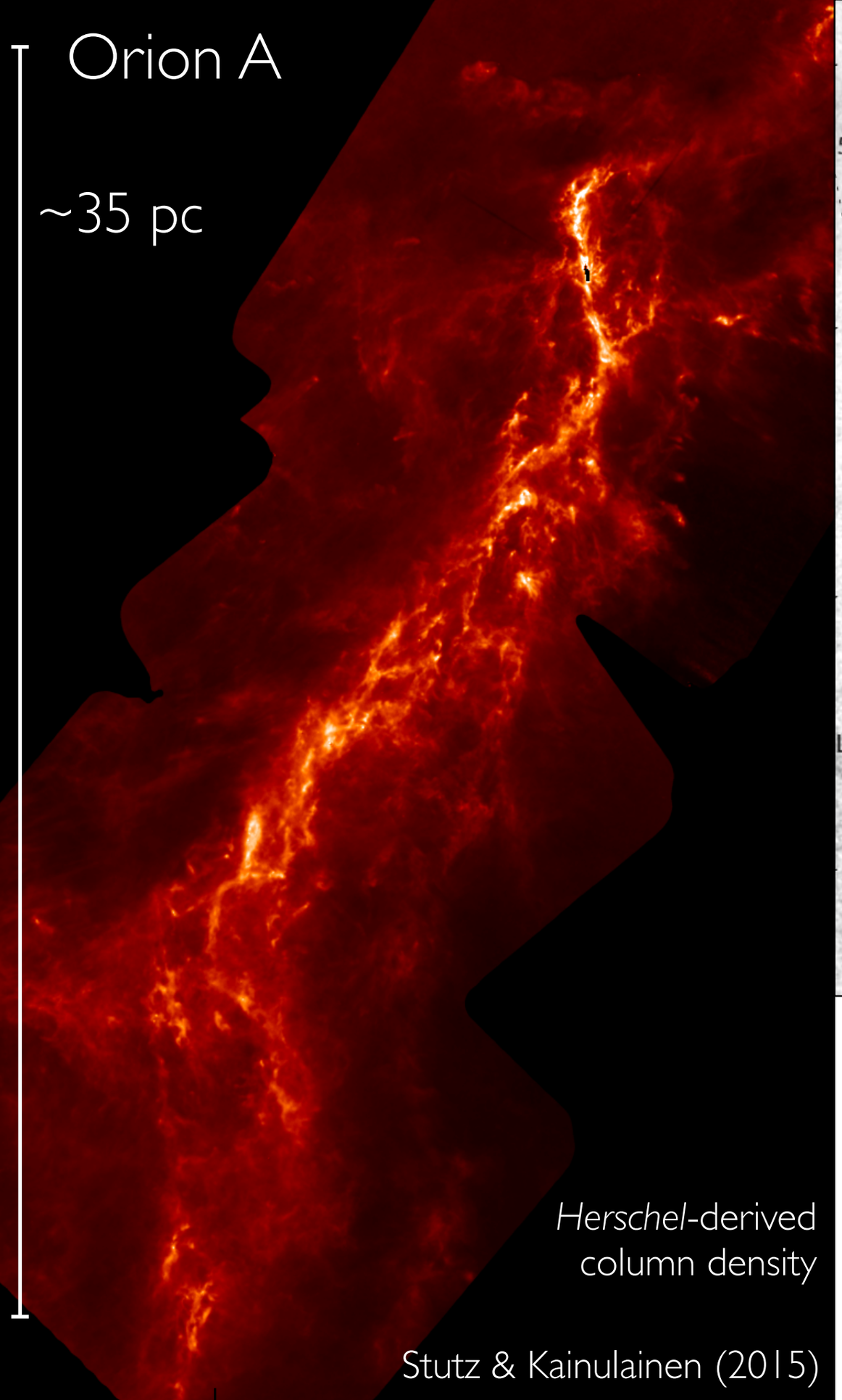
see also, e.g., Vazquez-Semadeni et al. (1994); Padoan et al. (1997); Ostriker et al. (2001); Federrath et al. (2008); Federrath & Klessen (2013a, b)

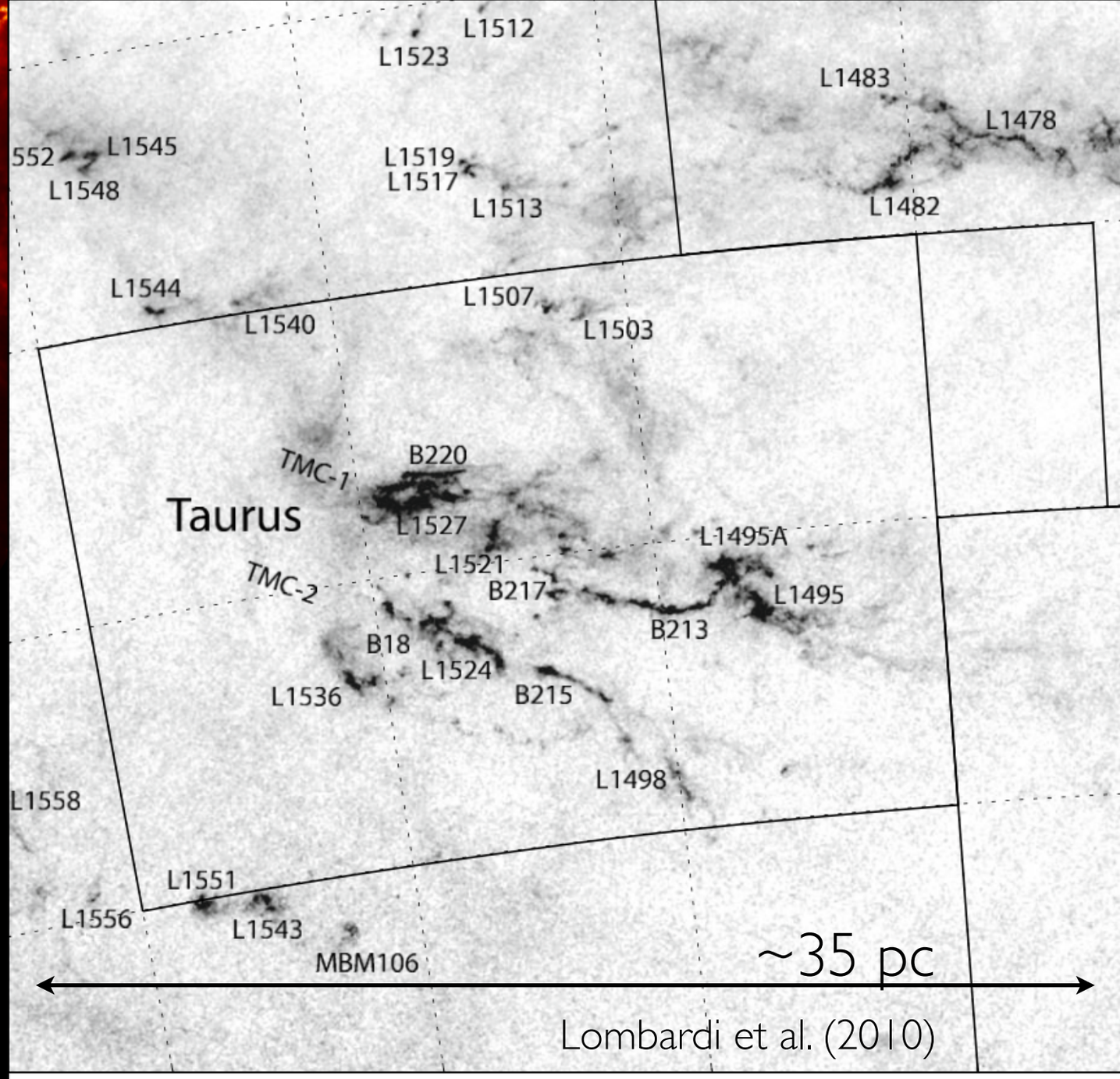
Understanding (column) **density statistics** of molecular clouds

Understanding (column) **density statistics** of molecular clouds

Now — building a comprehensive observational view:

1 pc —— 10 pc —— 100 pc —— 1 kpc —— 10 kpc





Dust extinction mapping in near-infrared

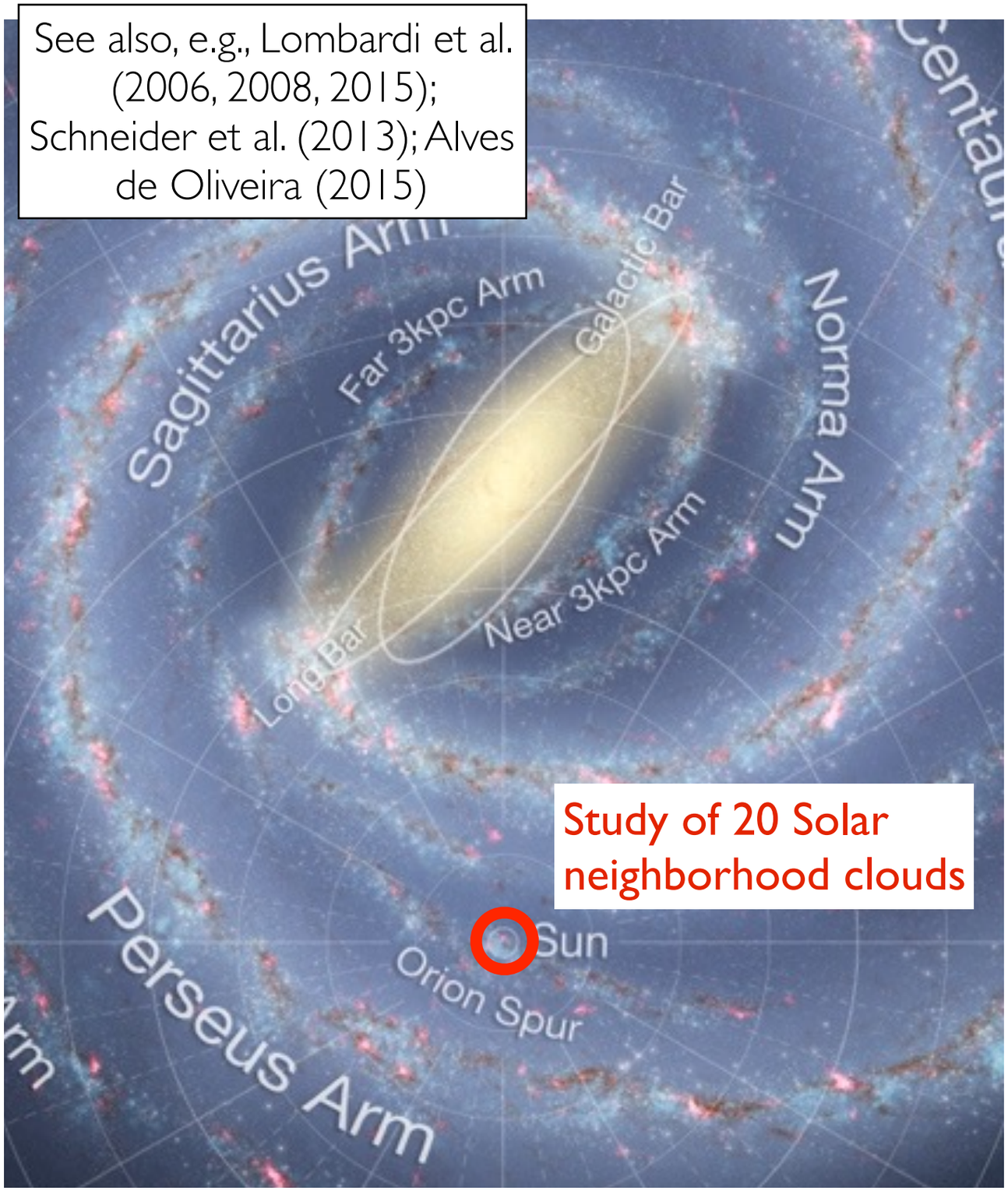
(e.g., Lombardi et al. 2006; Kainulainen et al. 2009; Rowles & Froebrich 2011; Schneider et al. 2011)

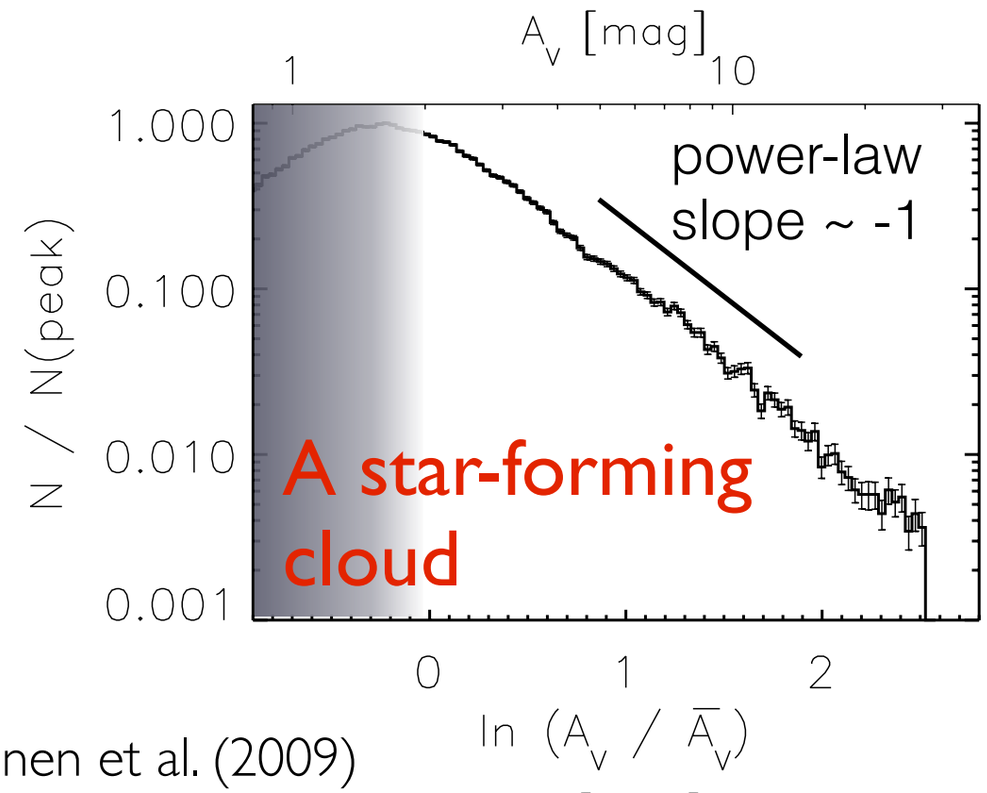
Dust emission measurements with *Herschel*

(e.g., Andre et al. 2011; Hill et al. 2011; Schneider et al. 2013; Alves de Oliveira 2014; Sadavoy et al. 2014; Lombardi et al. 2015)

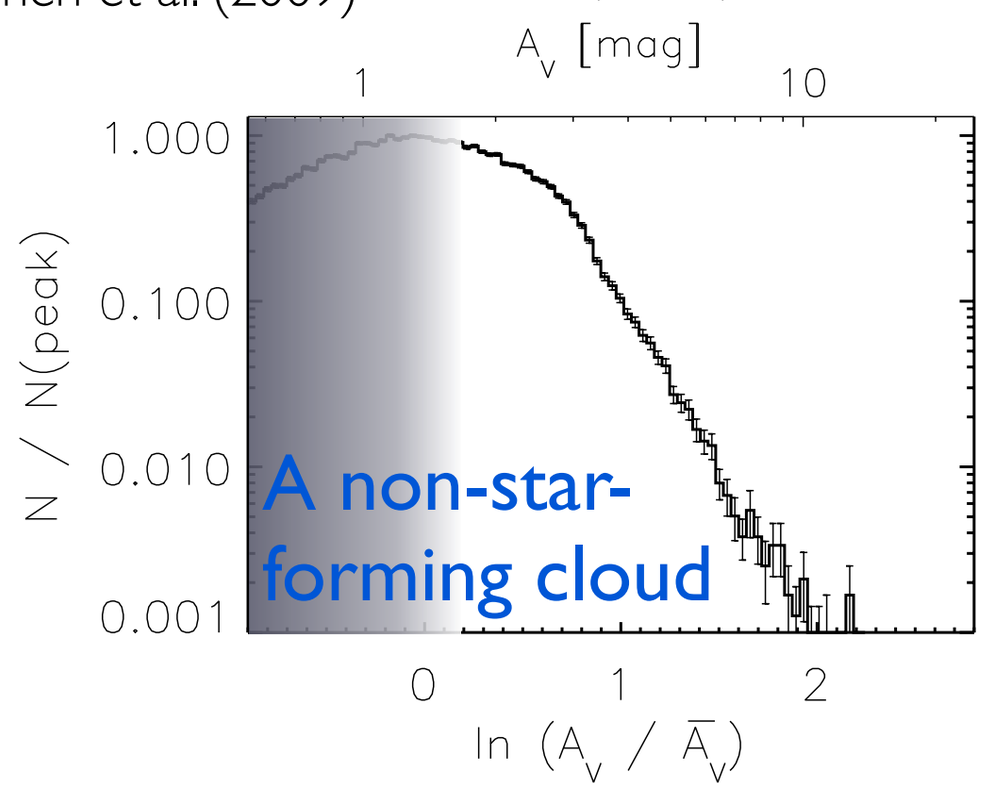
1 pc —— 10 pc —— 100 pc —— 1 kpc —— 10 kpc

See also, e.g., Lombardi et al. (2006, 2008, 2015); Schneider et al. (2013); Alves de Oliveira (2015)

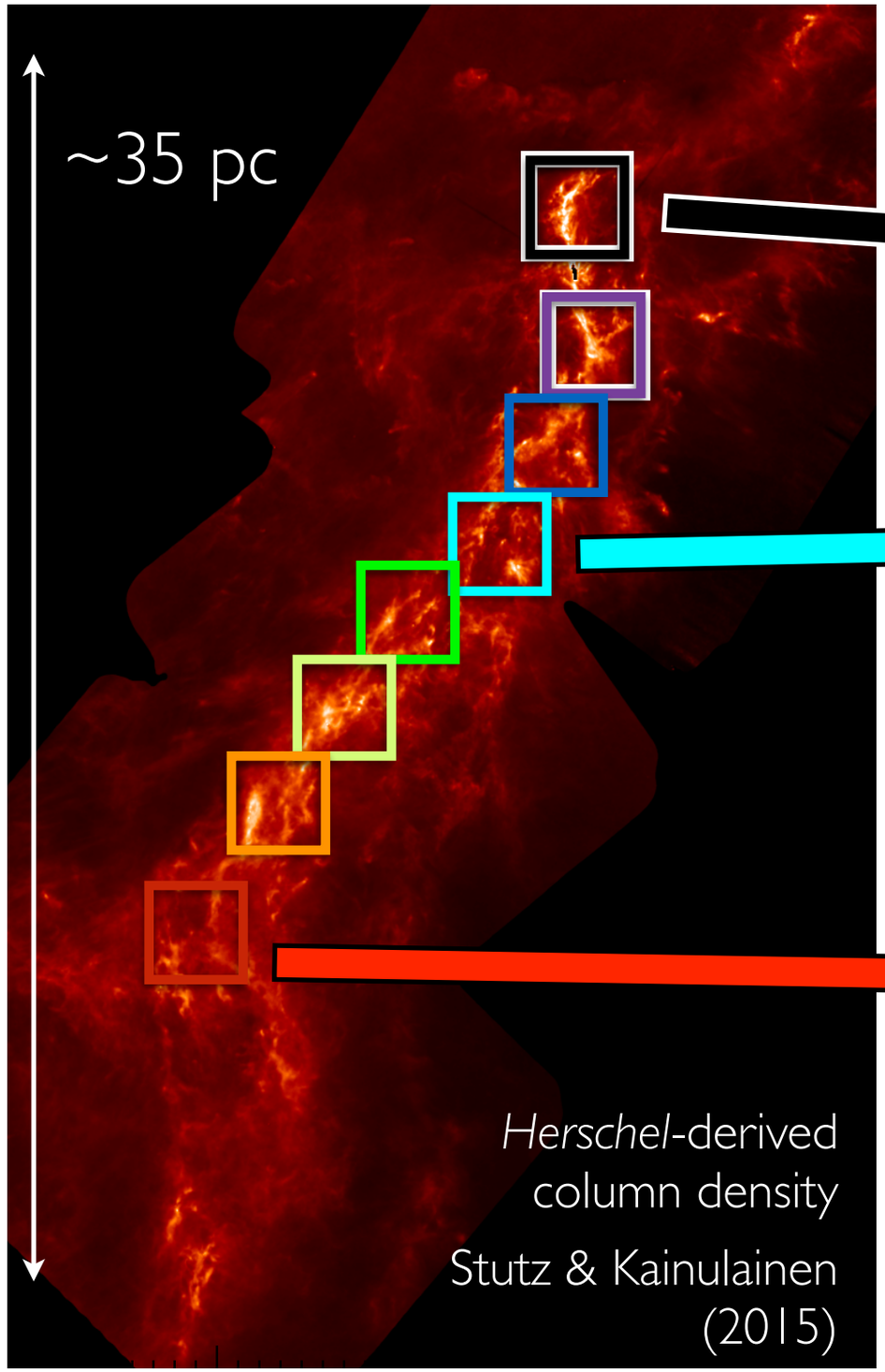


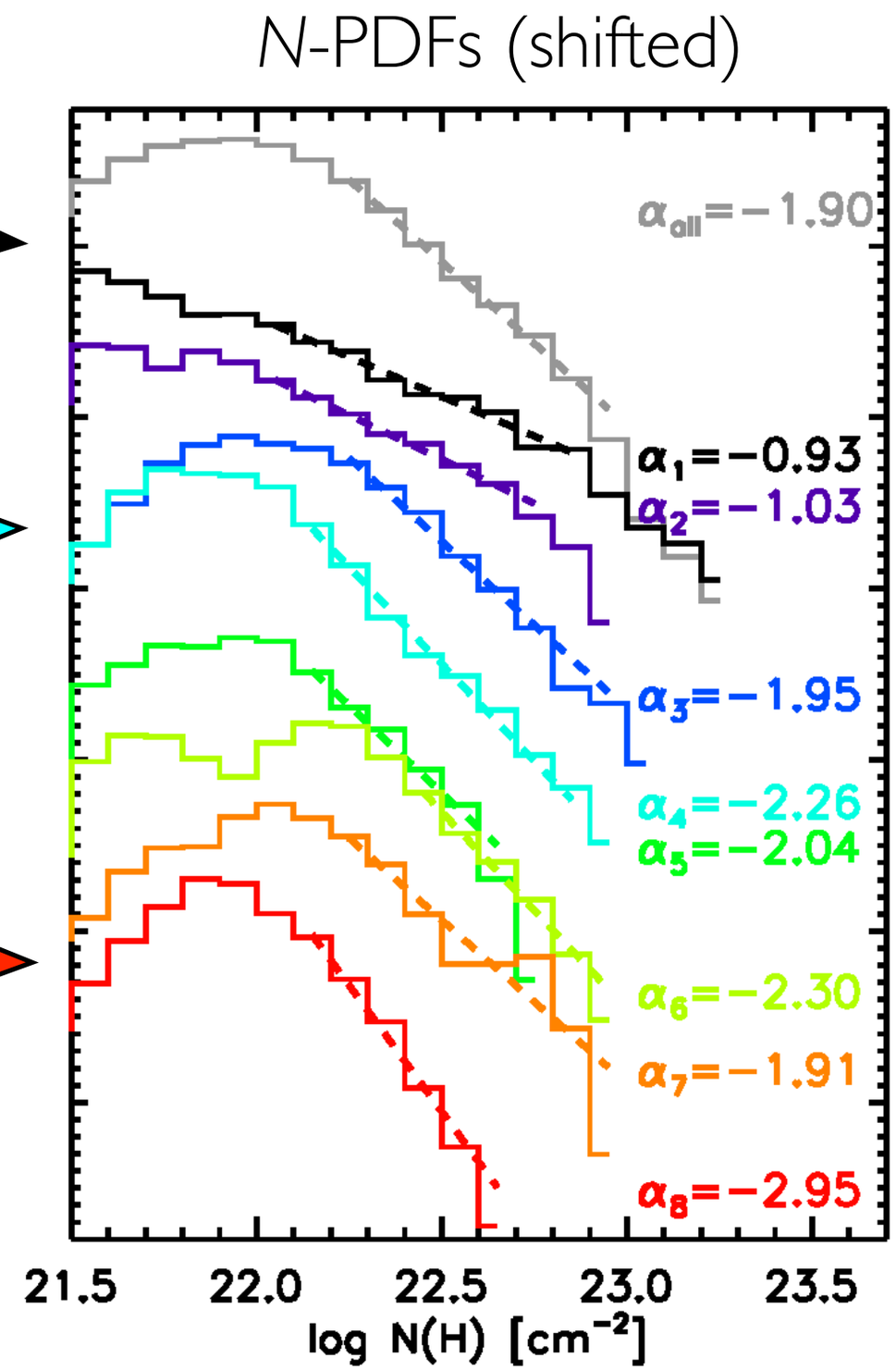


Kainulainen et al. (2009)



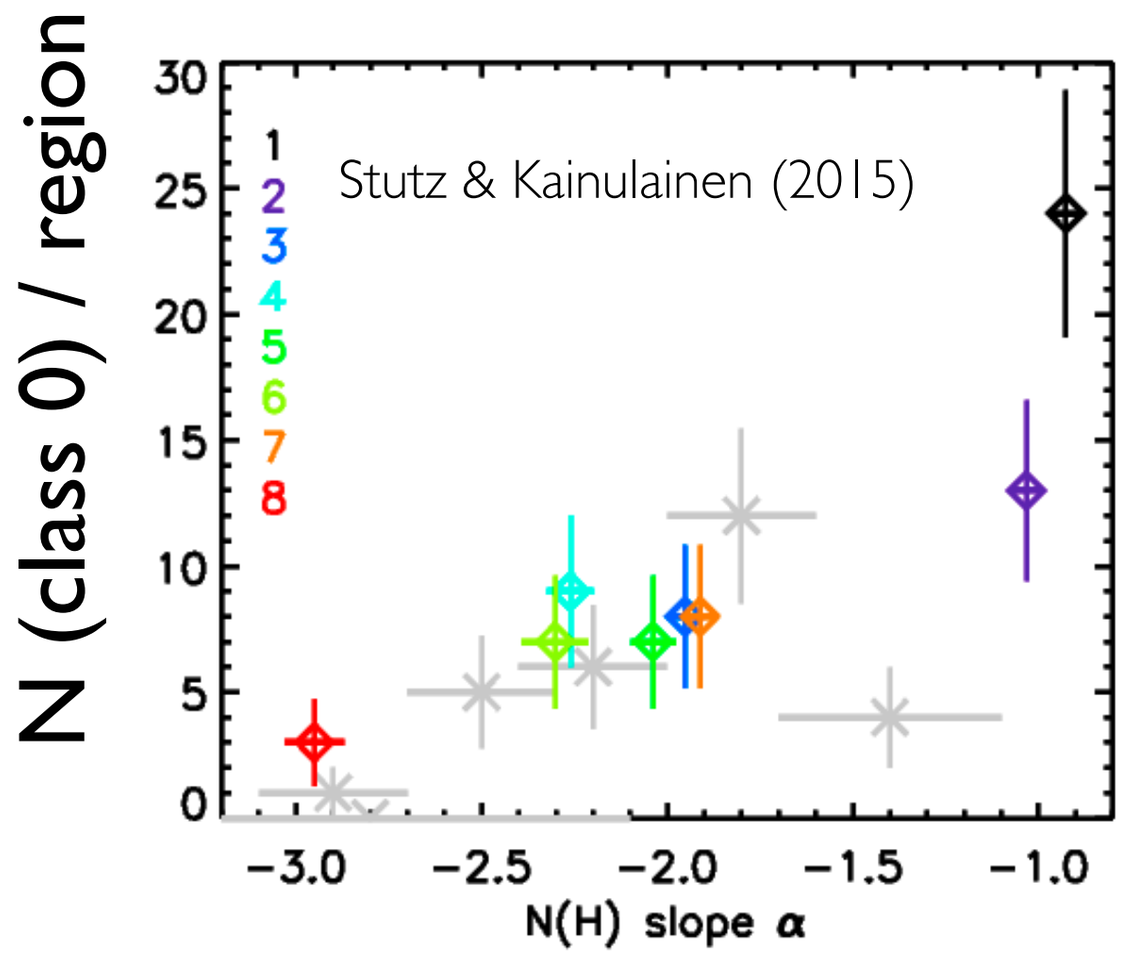
1 pc — 10 pc — 100 pc — 1 kpc — 10 kpc





1 pc — 10 pc — 100 pc — 1 kpc — 10 kpc

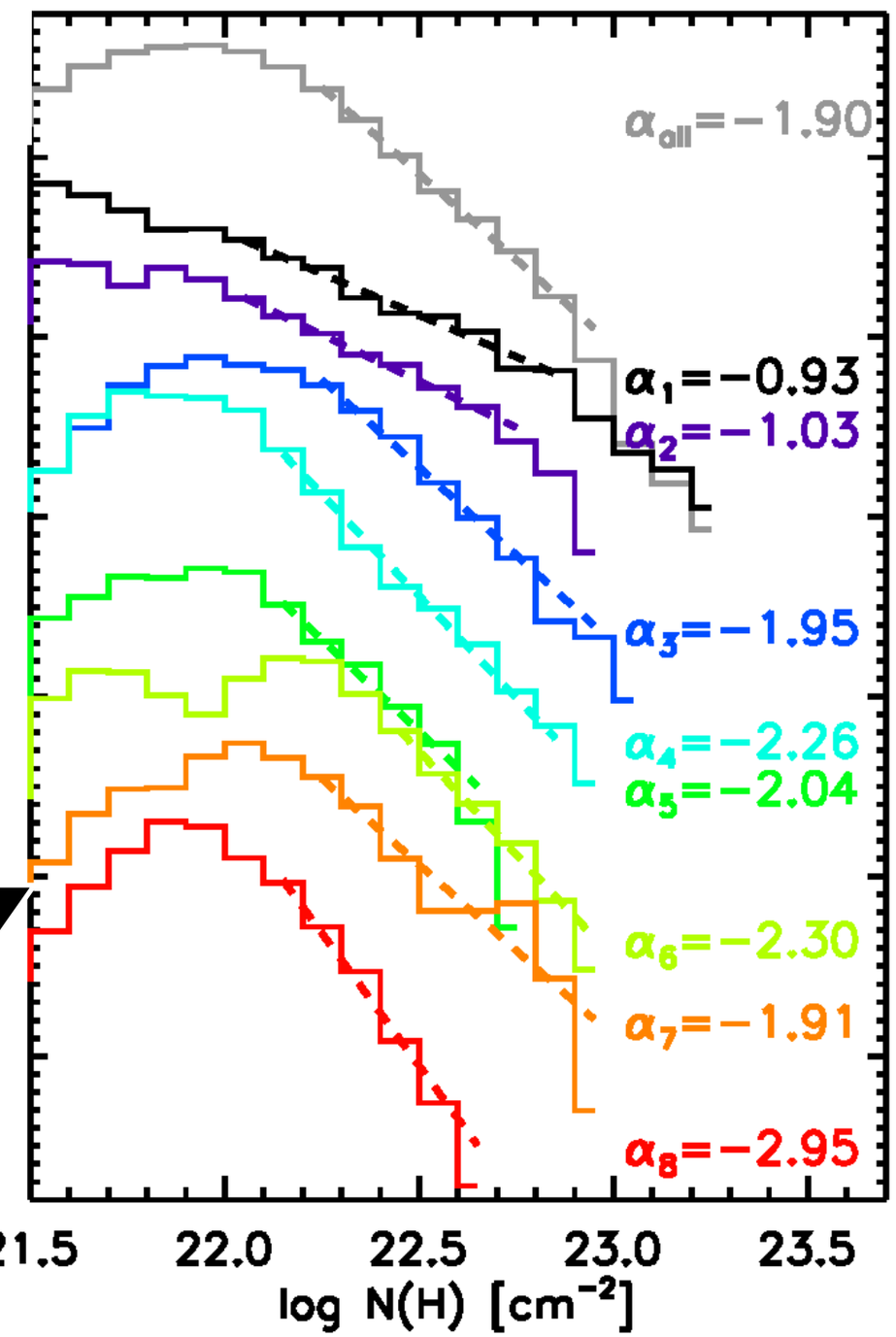
Star formation rate decreases



bottom-heavy

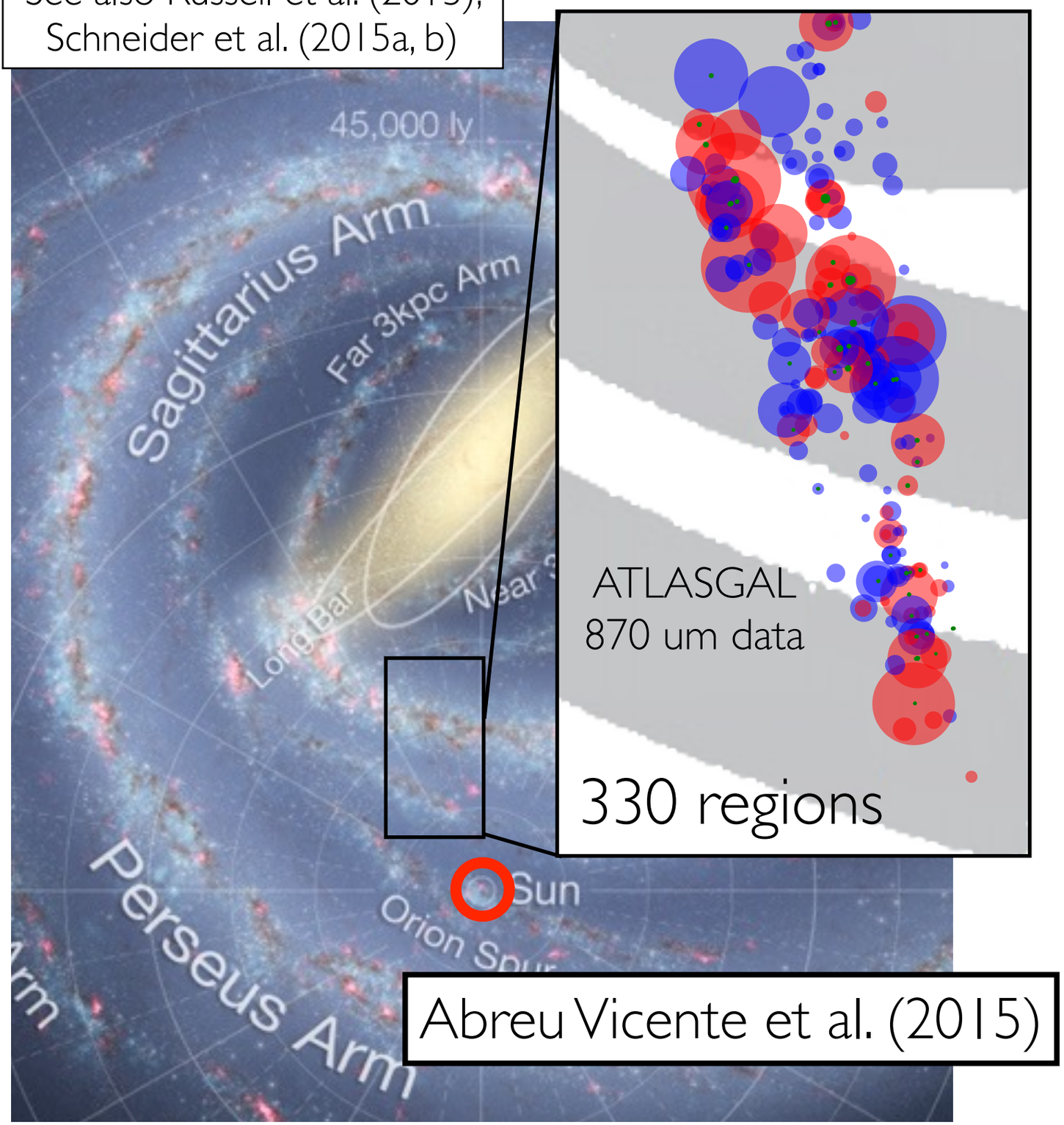
top-heavy

N-PDFs (shifted)

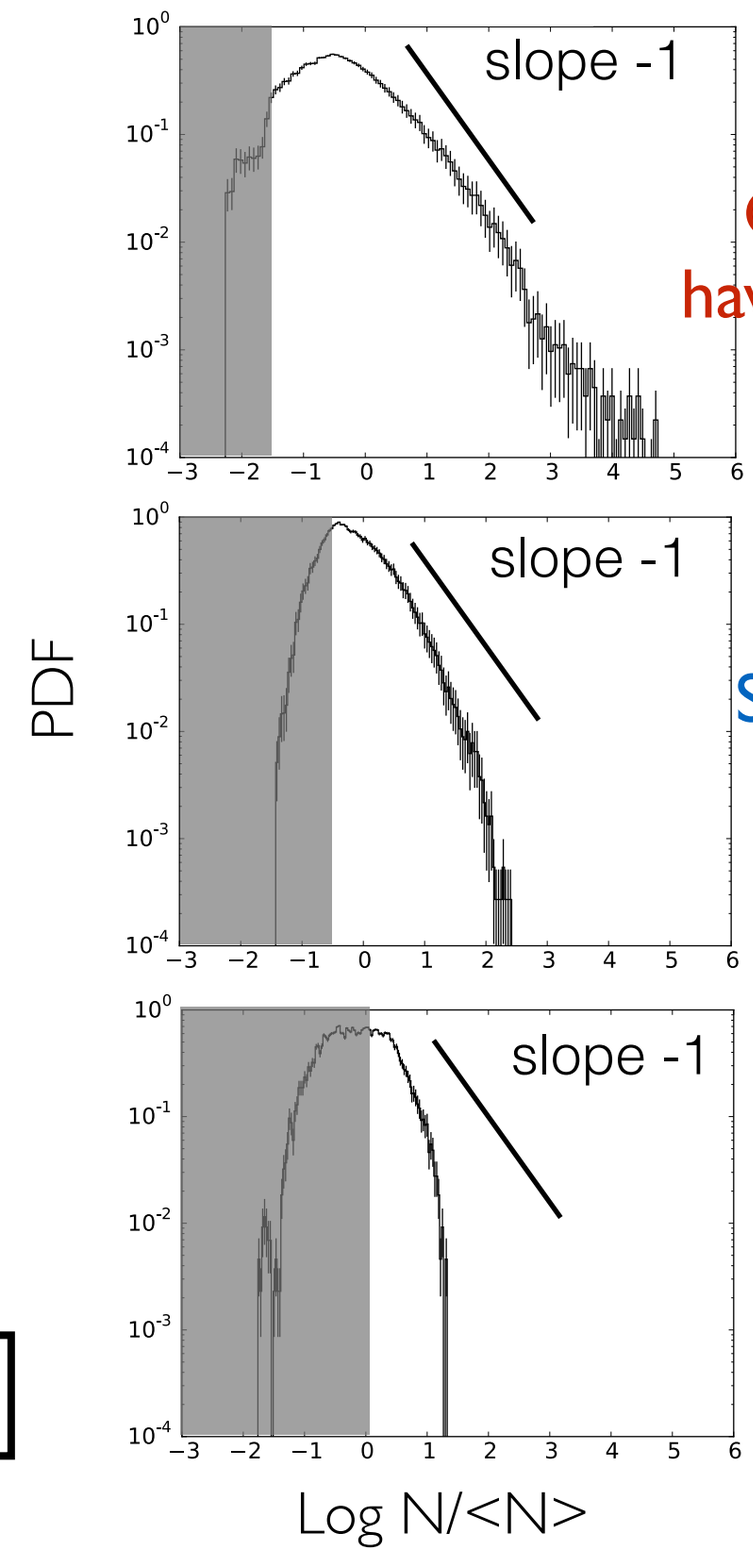


1 pc —— 10 pc —— 100 pc —— 1 kpc —— 10 kpc

See also Russeil et al. (2013); Schneider et al. (2015a, b)



Abreu Vicente et al. (2015)

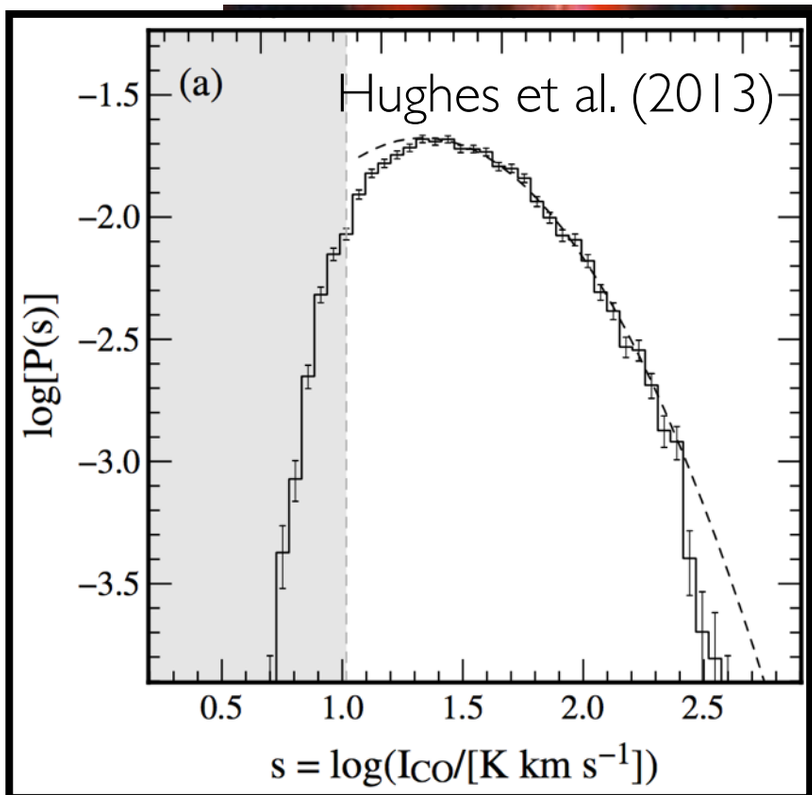


Clouds that have HII regions

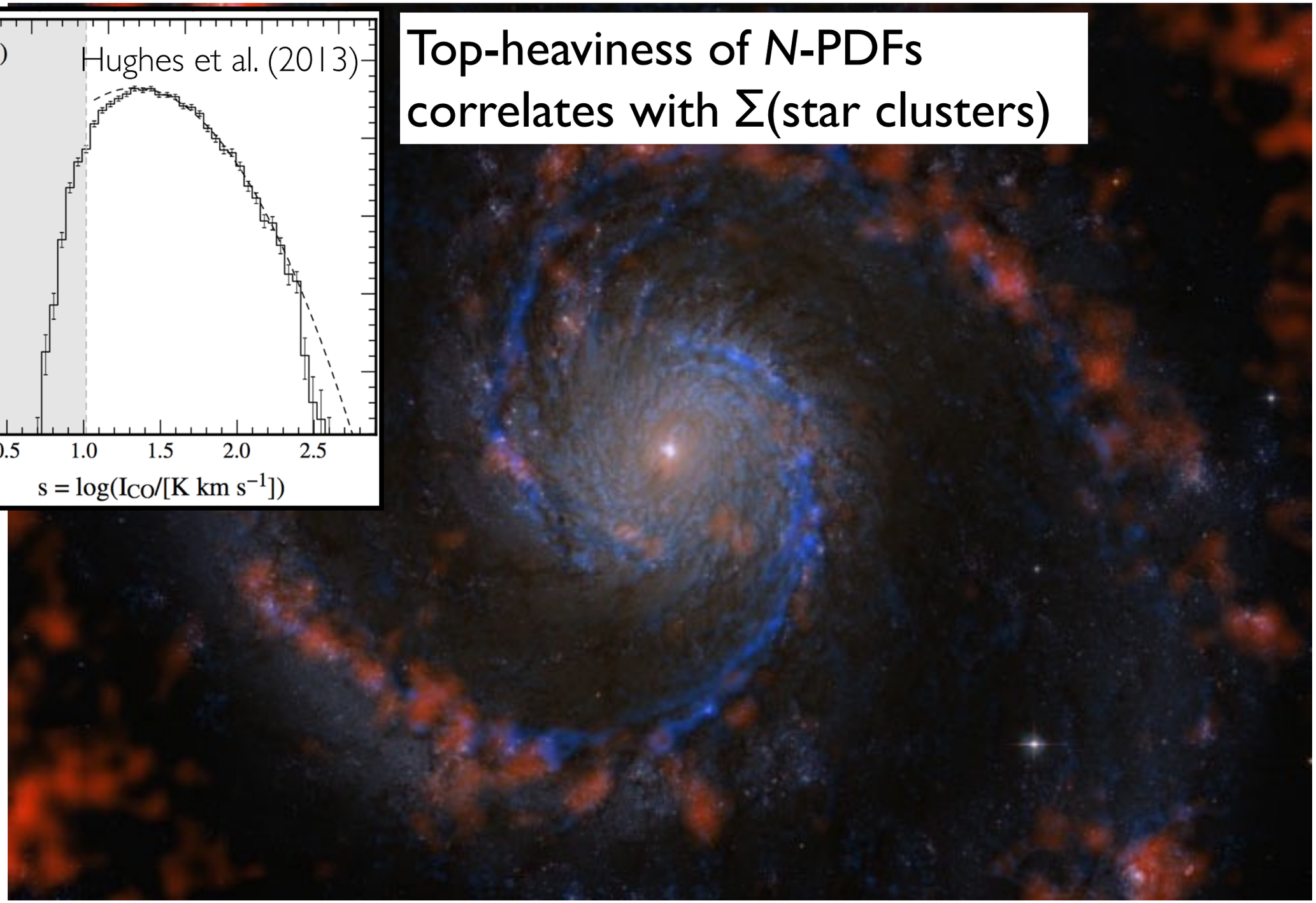
Star-forming Clouds

Starless clumps

1 pc —— 10 pc —— 100 pc —— 1 kpc —— 10 kpc

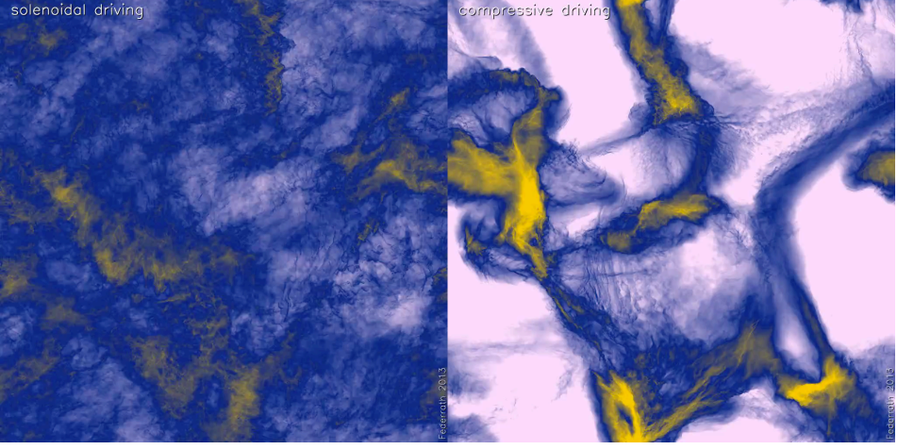


Top-heaviness of *N*-PDFs correlates with Σ(star clusters)



Credit: PAWS team/IRAM/NASA HST/T. A. Rector (University of Alaska Anchorage)

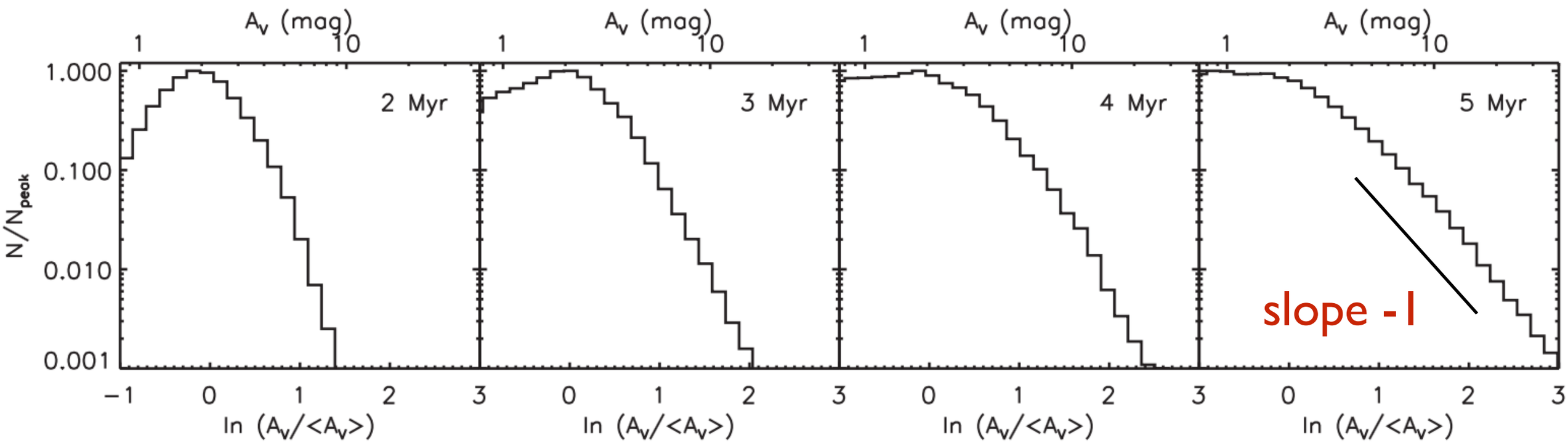
Link to ISM physics with the help of numerical simulations



Federrath (2013)

Gravo-turbulent (M)HD simulations
(continuously driven/decaying)

(e.g., Klessen 2000; Collins et al. 2010; Cho & Wang 2010; Kritsuk et al. 2011; Federrath & Klessen 2013, 2014)



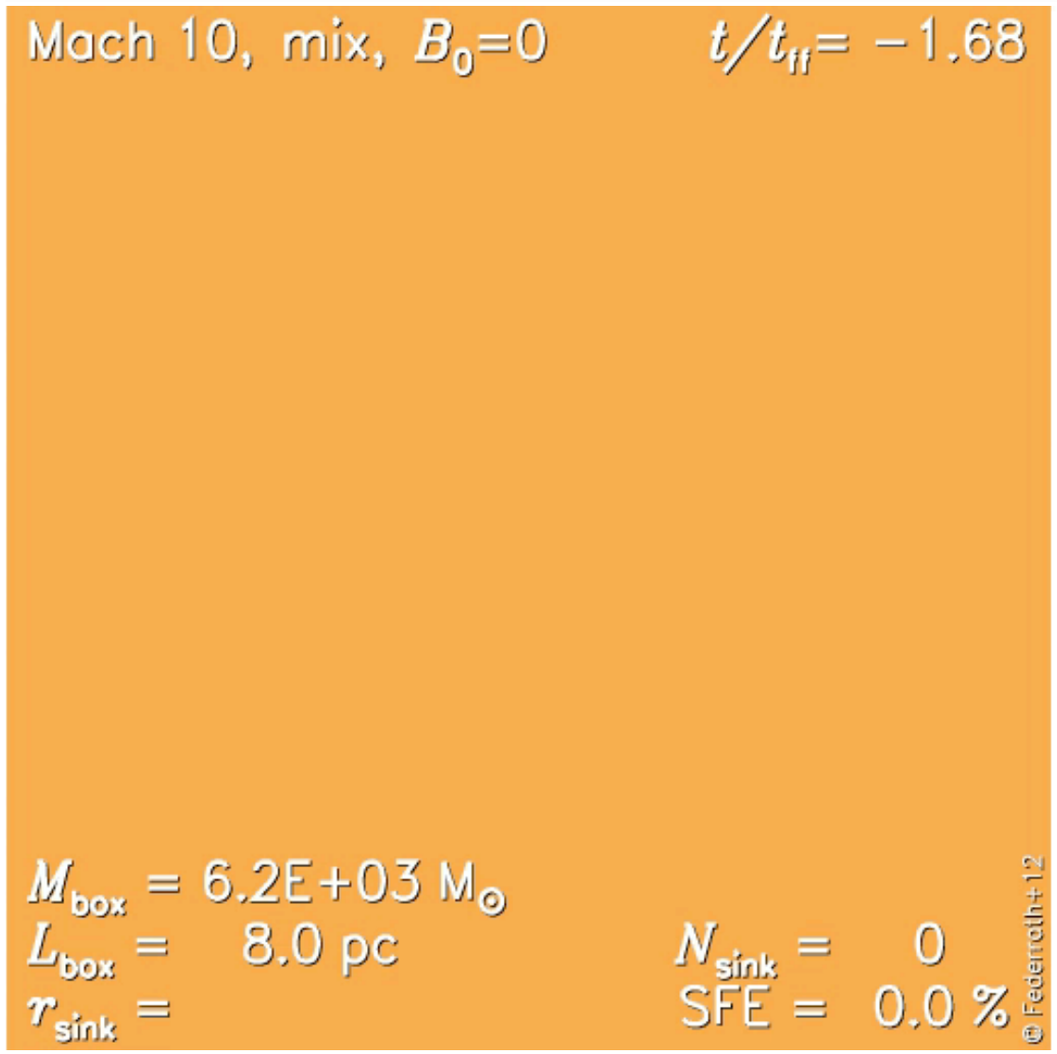
Turbulence-induced initial condition

Ward et al. (2014)

Gravity-dominated state

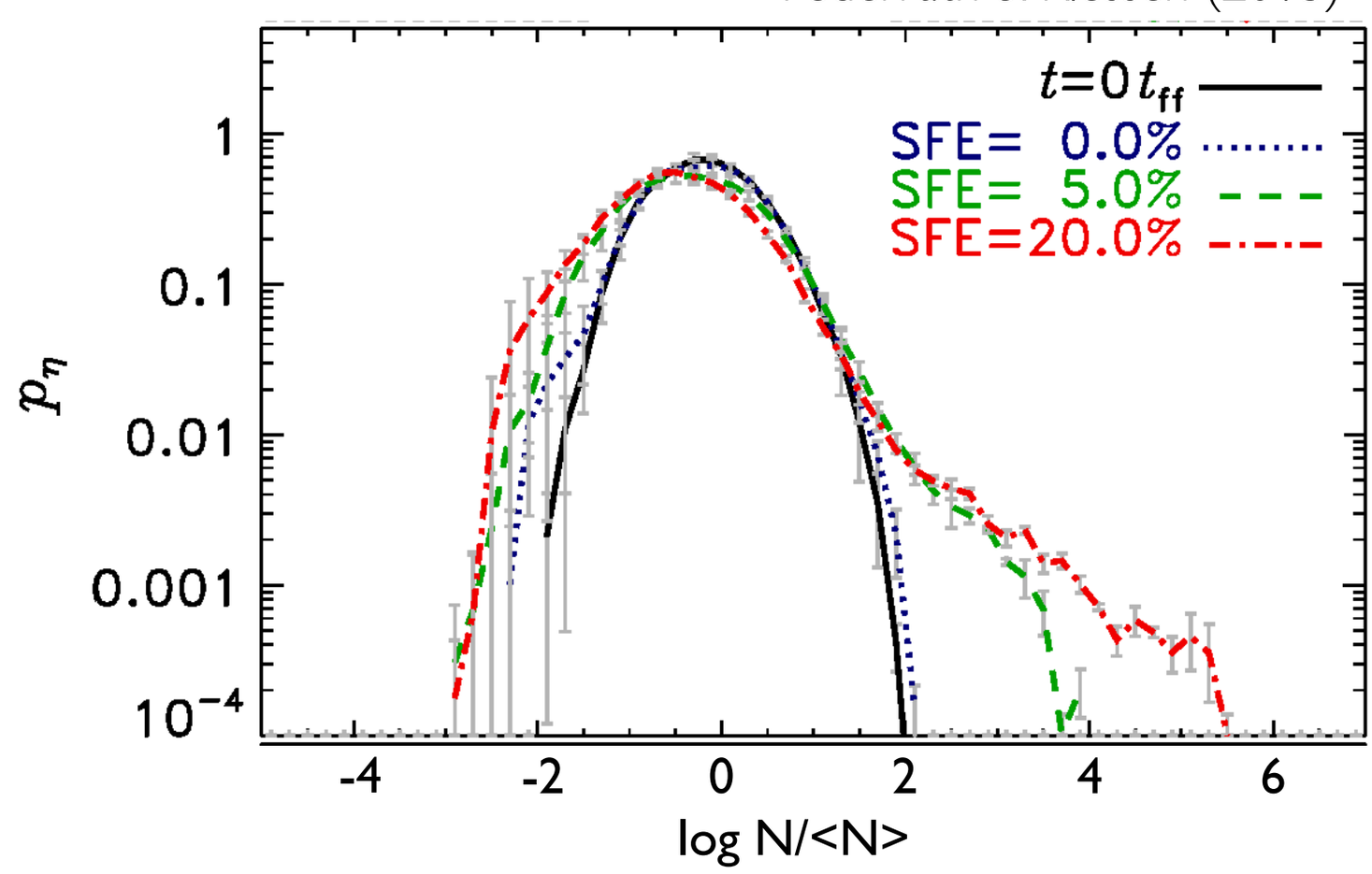
Gravity switched on

Star-formation (with sink particles)



Evolution as a function of star formation efficiency (SFE)

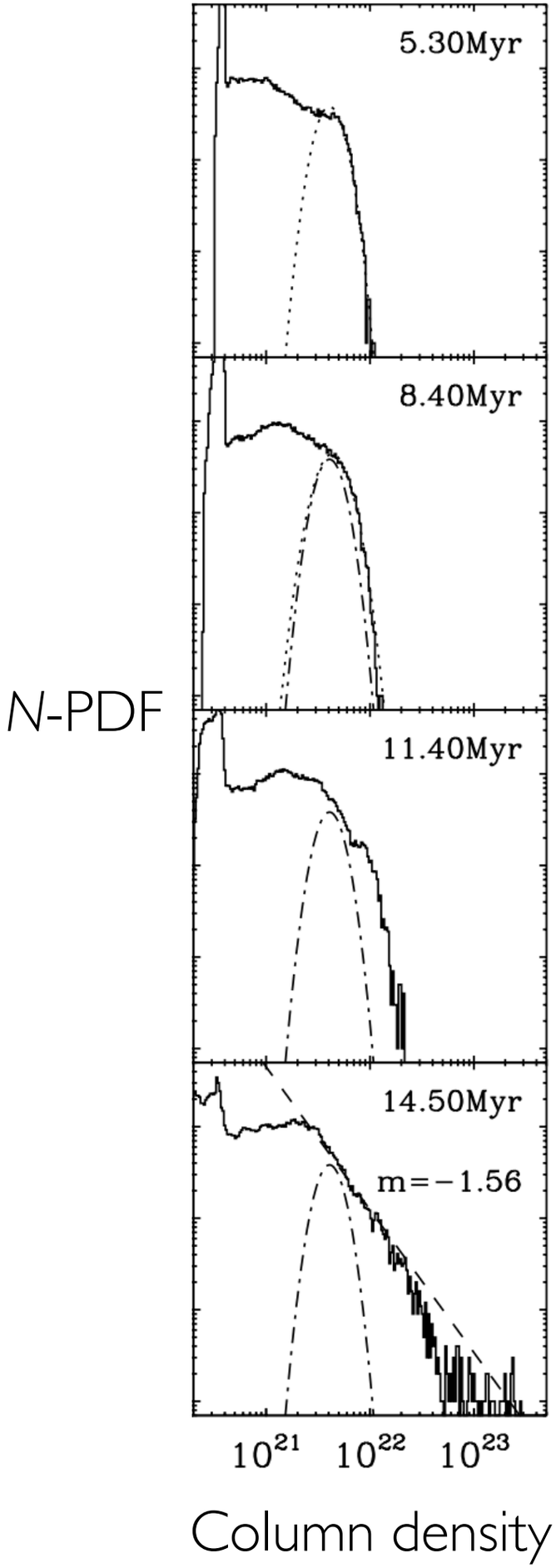
Federrath & Klessen (2013)



Highly idealised setup
(first turbulence, then gravity, no environment)

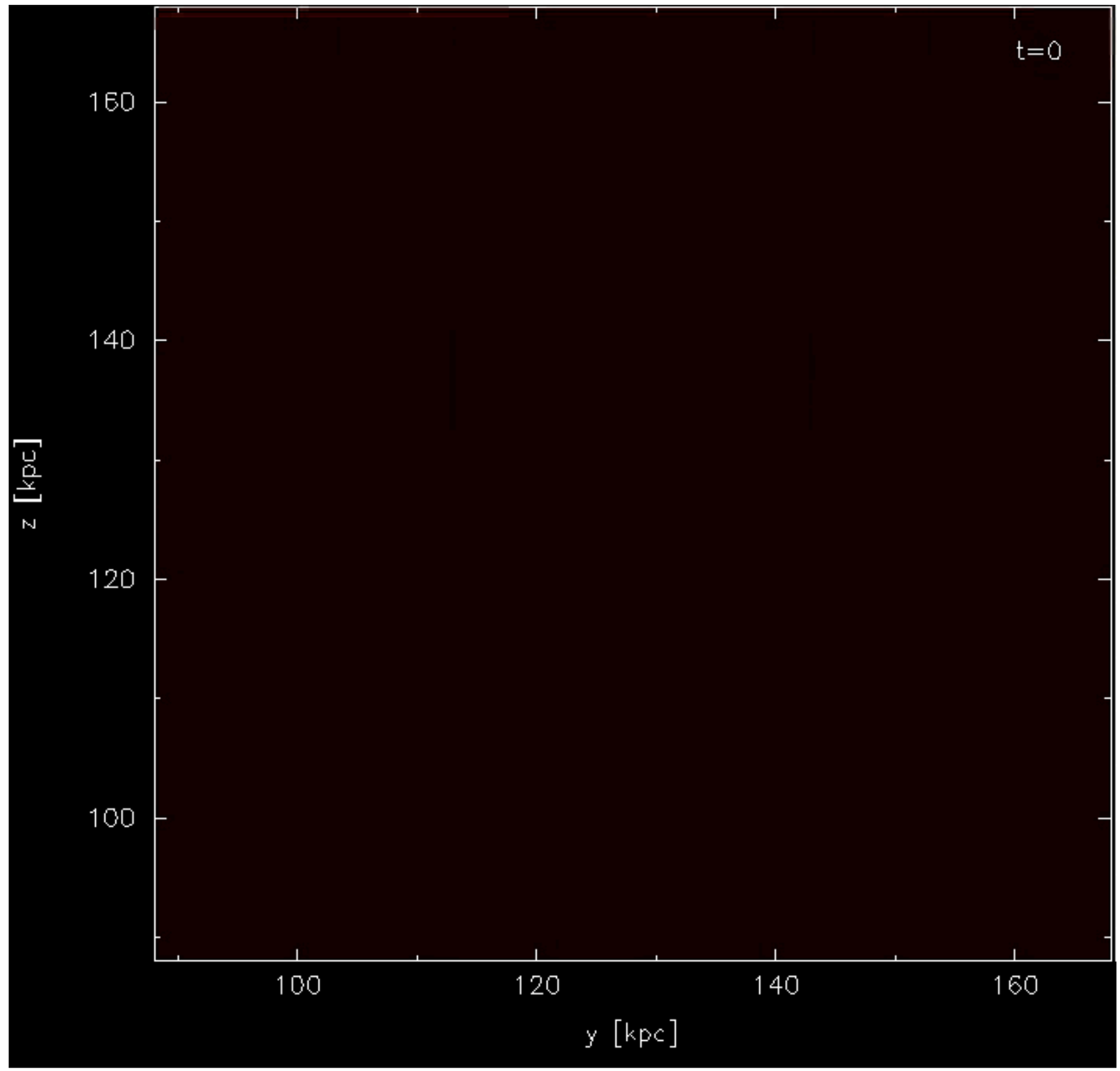
Simulations where clouds form *in situ*.

Ballesteros-Paredes et al. (2011)

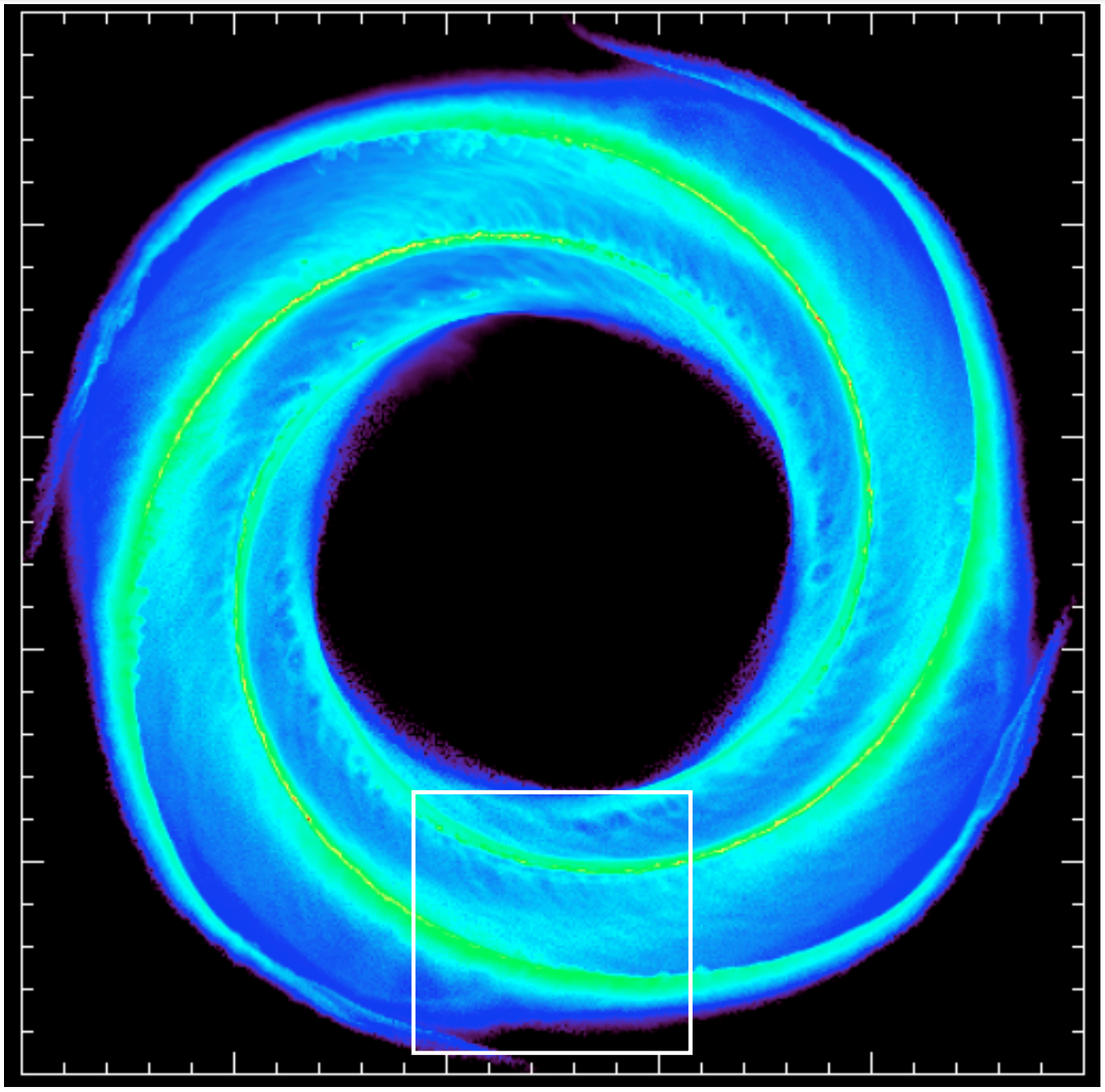


Colliding warm gas flows

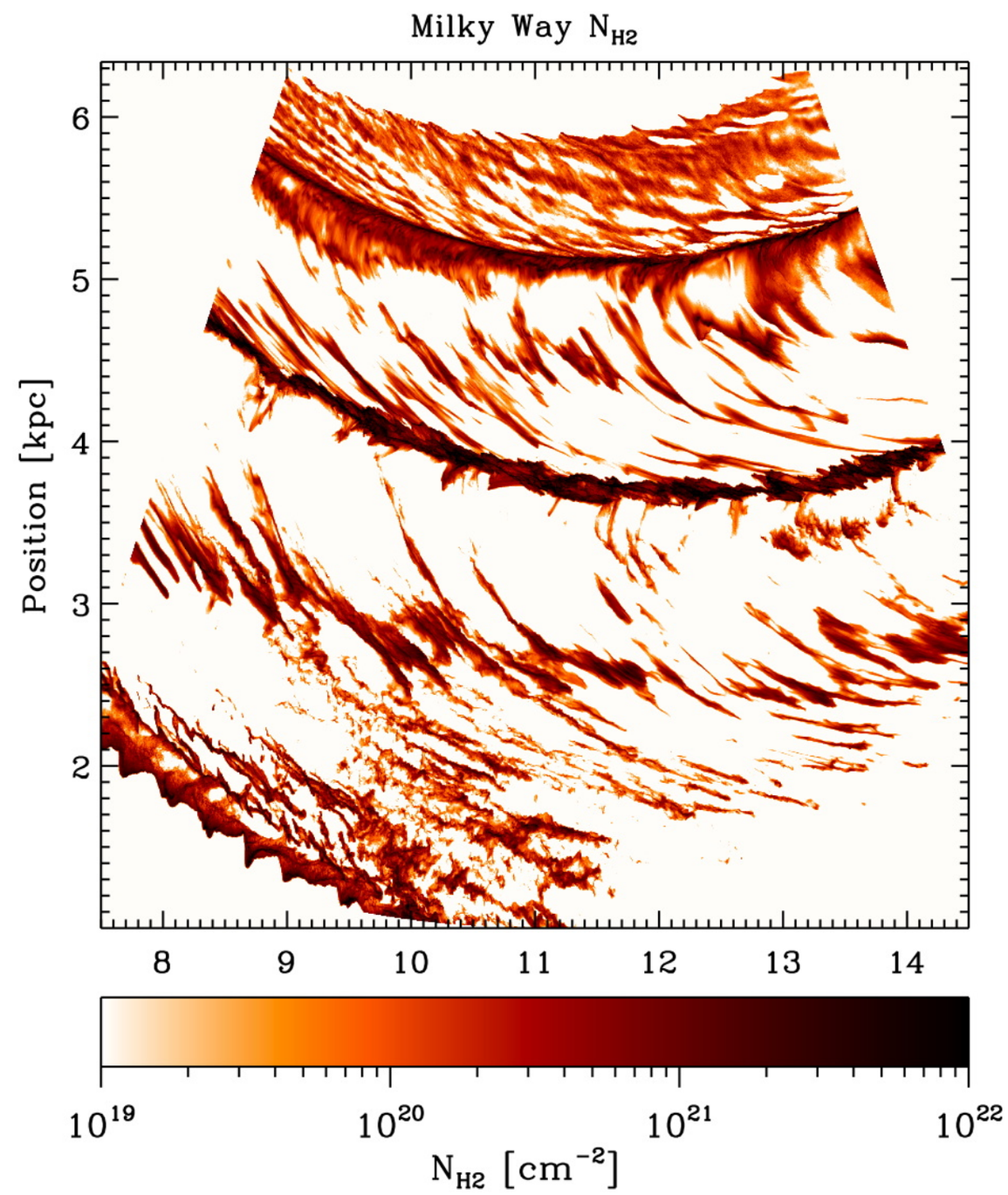
Gomez & Vazquez-Semadeni et al. (2014)



Resolution ~0.5 pc at GMC densities



Smith et al. (2014); AREPO code



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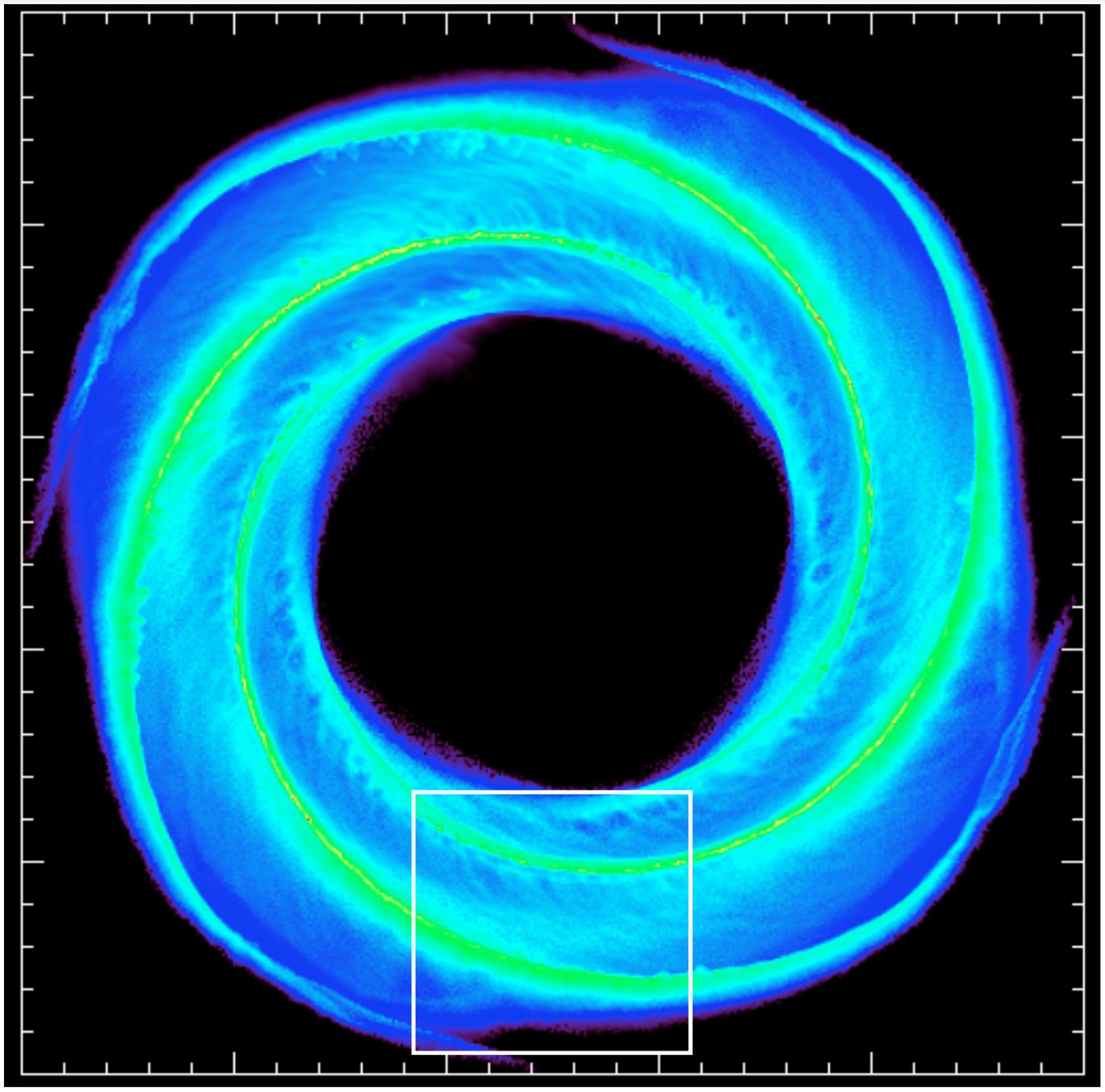

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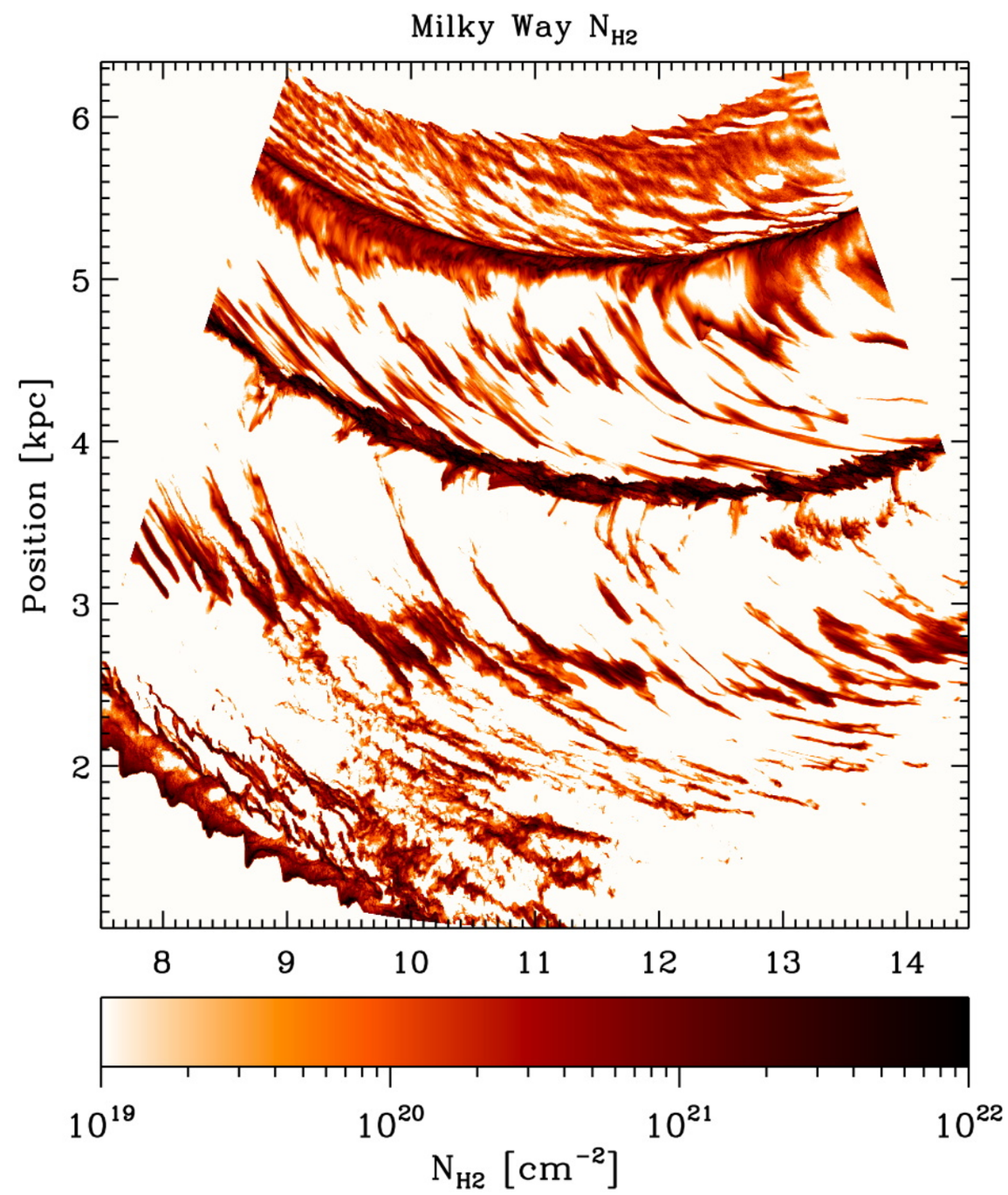
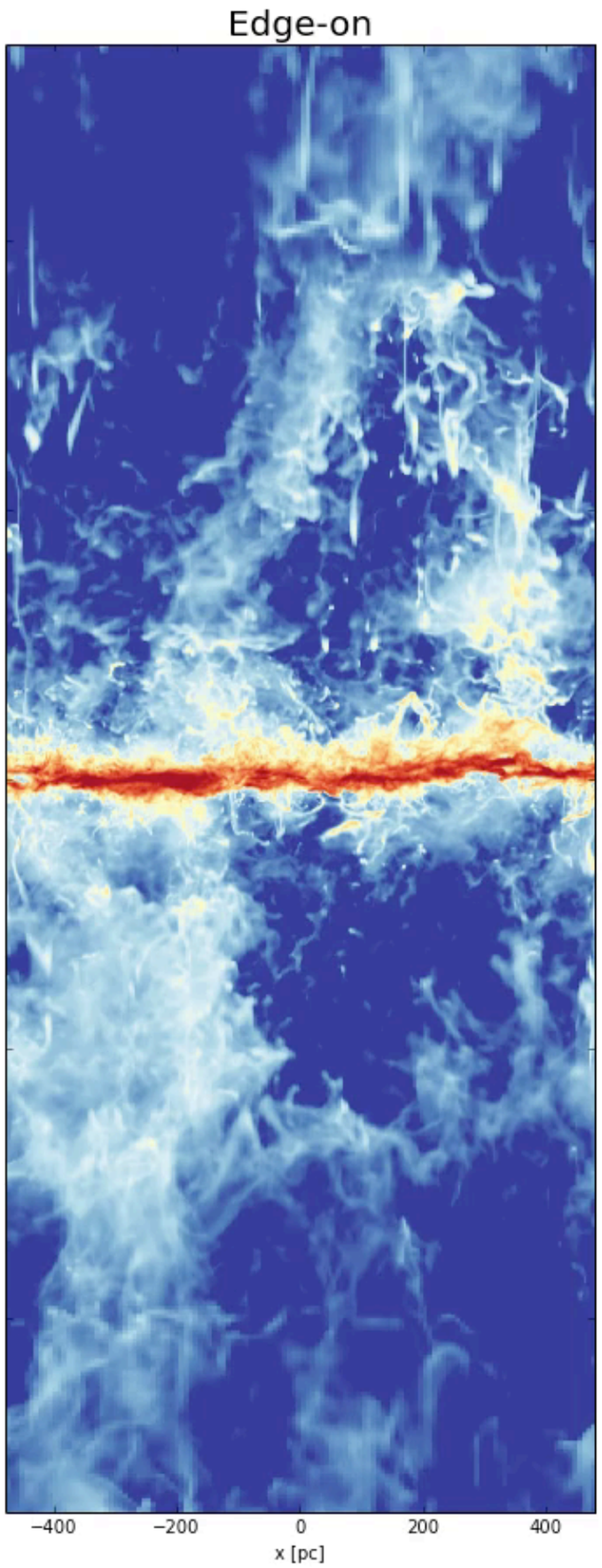
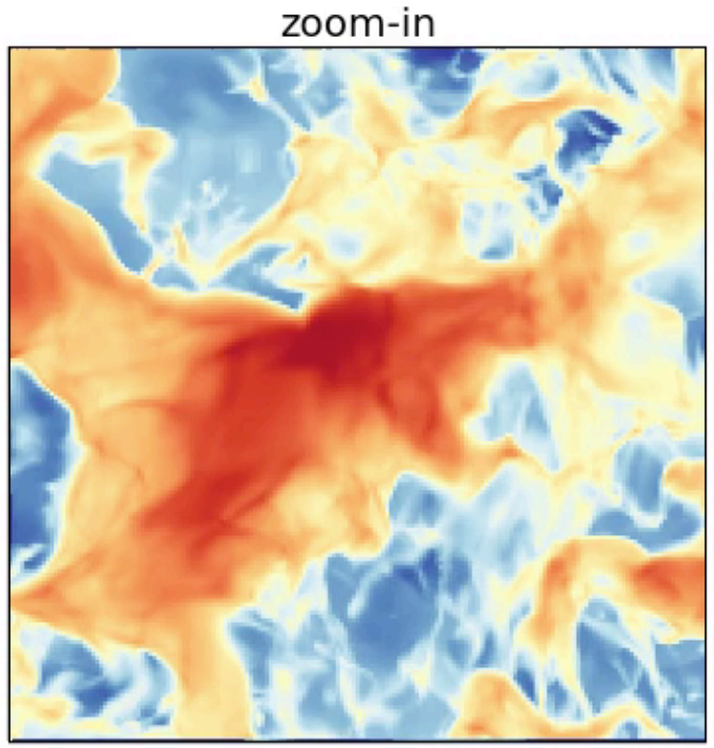
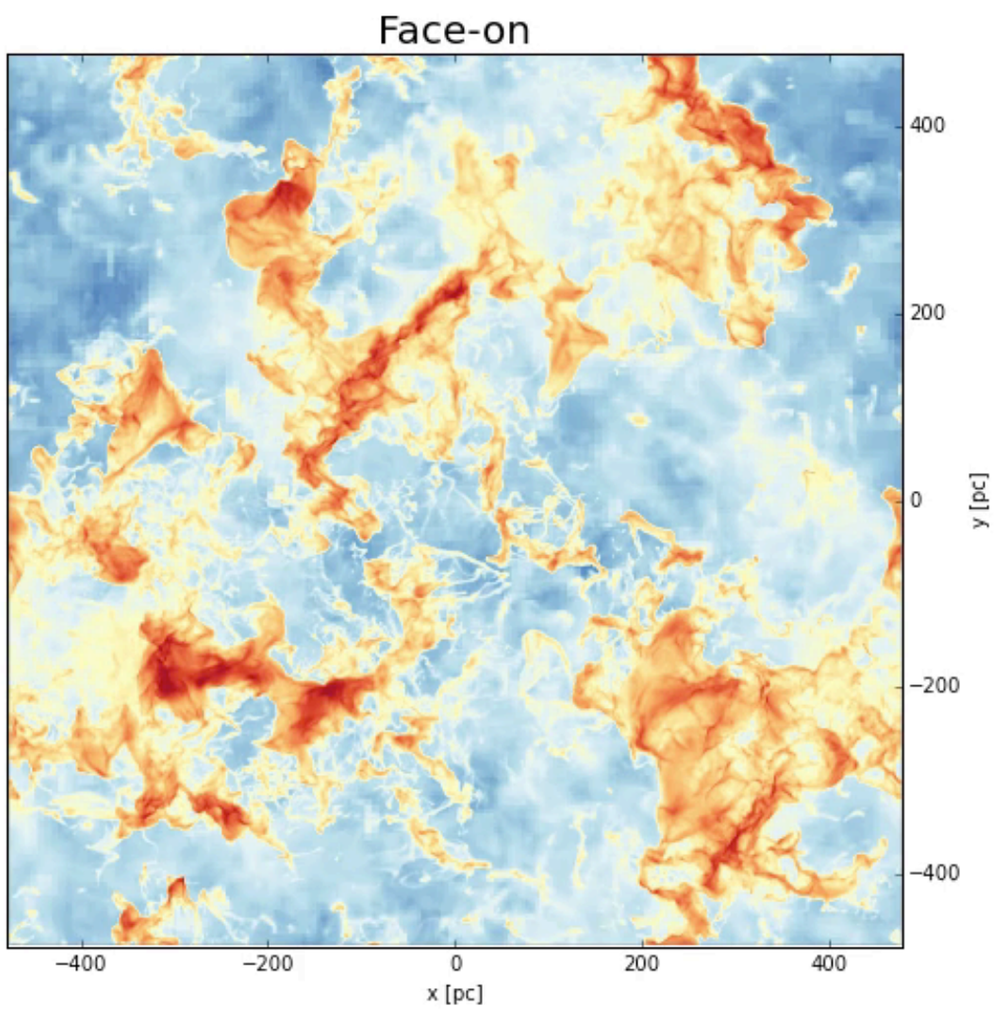


evolution with self-gravity $t_{SG} = 0.0$ Myr







Ibanez-Mejia et al. (in prep.)

Emerging picture:

N-PDFs of most molecular clouds are **heavily affected** by gravity

… *i.e., turbulence plays a less significant role.*

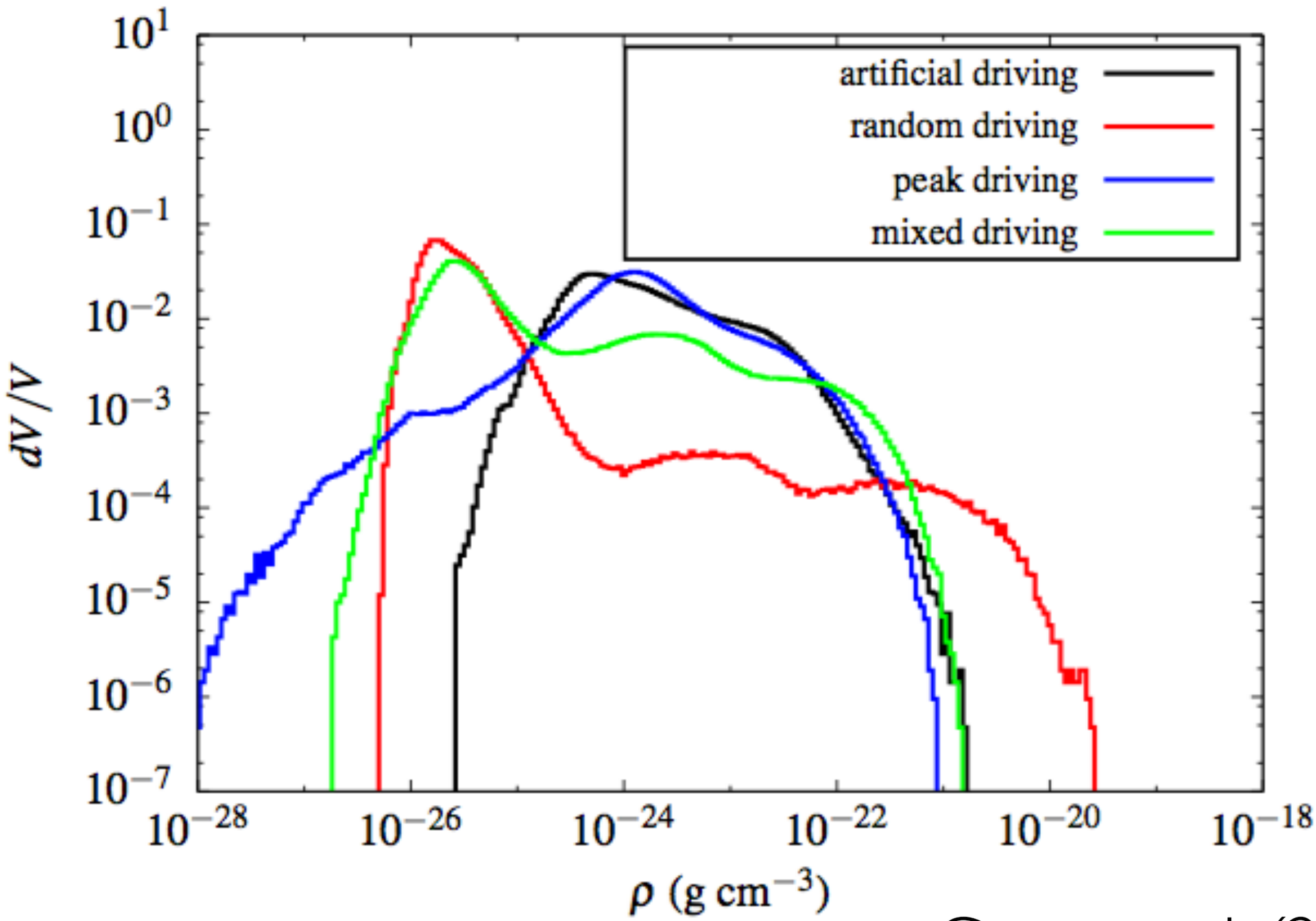
N-PDFs **quite possibly evolve** in time-scales relevant for star formation

… *but simulations of where clouds form* in situ *are needed.*

Galactic-scale understanding of the PDFs is crucially missing

… *but on its way as we speak.*

Feedback?



Gatto et al. (2015)

Relative density structure affects analytic SF laws

$s = \ln(\rho/\rho_0)$

$$\mathrm{SFR}_{\mathrm{ff}} \propto \int_{s_{\mathrm{crit}}}^{\infty} \frac{t_{\mathrm{ff}}(\rho_0)}{t_{\mathrm{ff}}(\rho)} \frac{\rho}{\rho_0} p(s)\, ds\,.$$

Krumholz & McKee (2005)
Padoan & Nordlund (2011)
Hennebelle & Chabrier (2011, 2013)
Zamora-Avile et al. (2012)
Krumholz et al. (2012)
Federrath & Klessen (2013),
…

Probability density function
of gas density (ρ-PDF)