De la dynamique galactique à la formation stellaire : comment est régulé le taux de formation d'étoiles ?

From galactic dynamics to star formation, what sets the star formation rate?

in collaboration with Patrick Hennebelle, Frédéric Bournaud, Tine Colman, Simon Iteanu et Corentin le Yhuellic

Journées du labex P2IO, 1/11/2022

Stars shape the universe.

- Stars represents only a few % of the mass of a galaxy
- But they play a key role in the galactic ecosystem
  - gravitational potential
  - injection of energy via feedback
  - metal enrichment

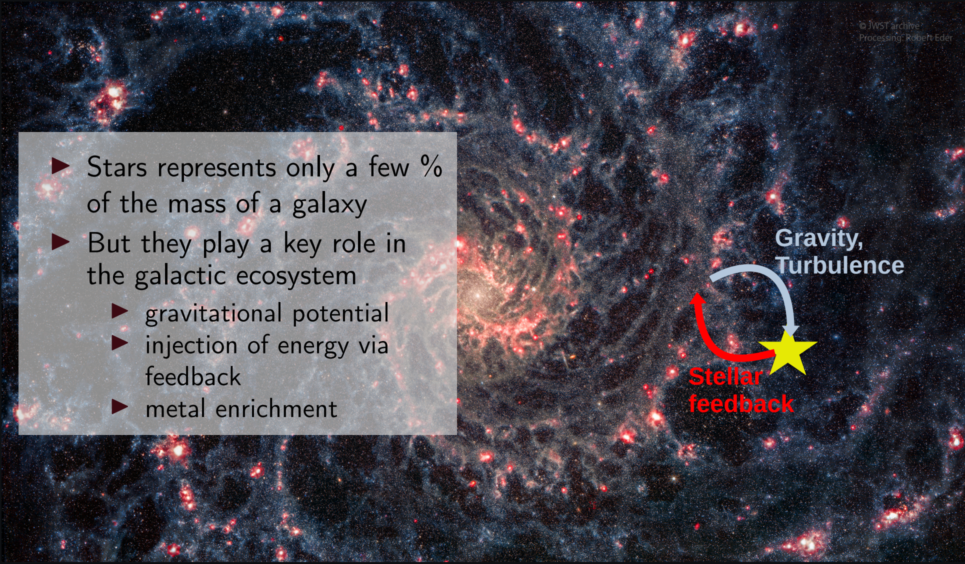

Image Credit: NASA, ESA, CSA, STScI; Processing Copyright: Robert Eder

Stars forms out of the dense gas of the InterStellar Medium

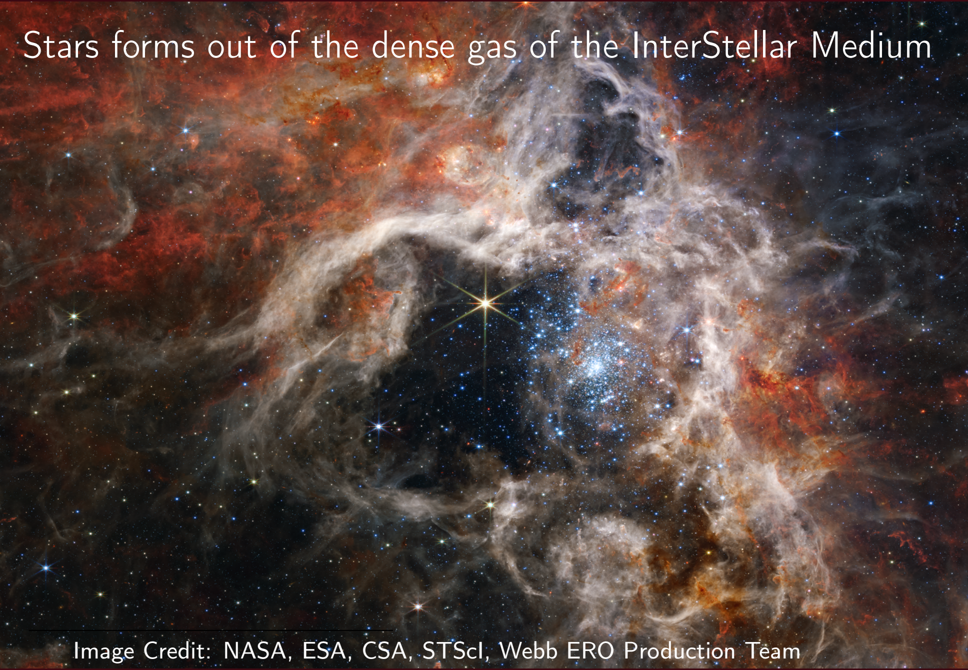

Image Credit: NASA, ESA, CSA, STScI, Webb ERO Production Team

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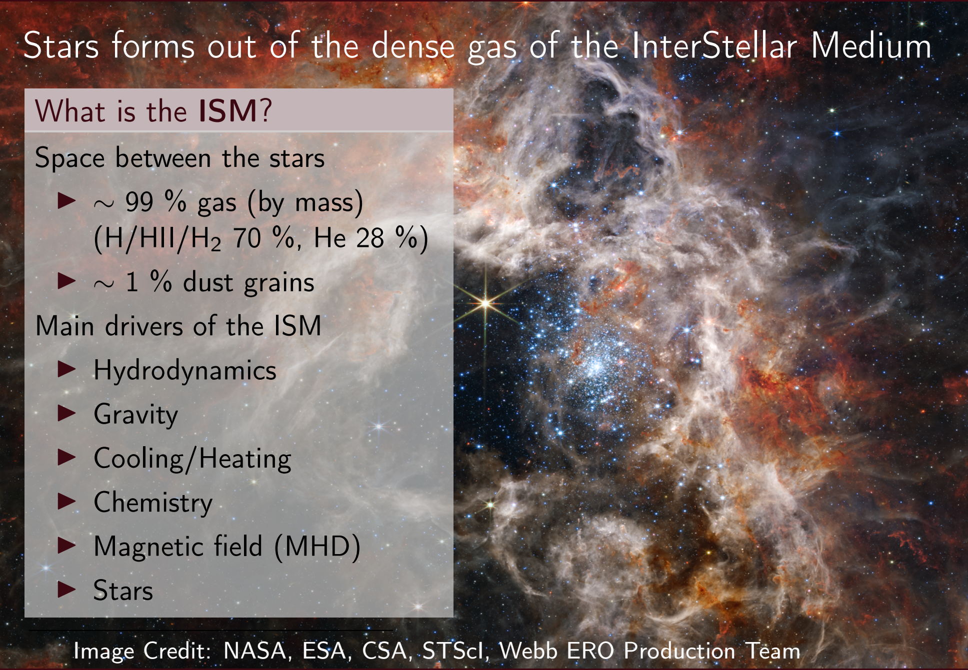


What is the **ISM**?

Space between the stars

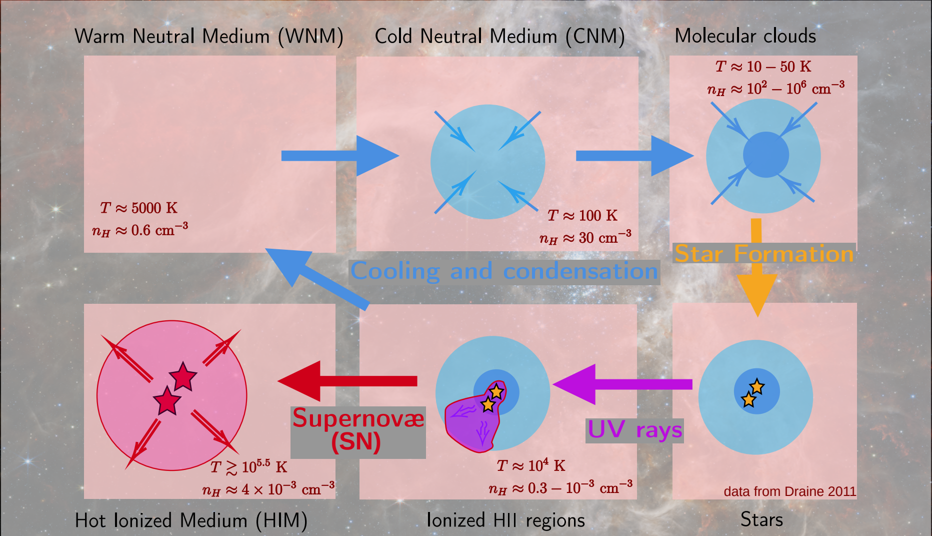
- $\sim$ 99 % gas (by mass) (H/HII/H_2 70 %, He 28 %)
- $\sim$ 1 % dust grains

Main drivers of the ISM

- Hydrodynamics
- Gravity
- Cooling/Heating
- Chemistry
- Magnetic field (MHD)
- Stars

Image Credit: NASA, ESA, CSA, STScI, Webb ERO Production Team

The matter cycle in the ISM



Warm Neutral Medium (WNM)

$T \approx 5000$ K

$n_H \approx 0.6$ cm^{-3}

Cold Neutral Medium (CNM)

$T \approx 100$ K

$n_H \approx 30$ cm^{-3}

Molecular clouds

$T \approx 10 - 50$ K

$n_H \approx 10^2 - 10^6$ cm^{-3}

Cooling and condensation

Star Formation

Stars

data from Draine 2011

UV rays

Ionized HII regions

$T \approx 10^4$ K

$n_H \approx 0.3 - 10^{-3}$ cm^{-3}

Supernovæ (SN)

Hot Ionized Medium (HIM)

$T \gtrsim 10^{5.5}$ K

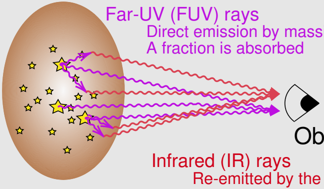
$n_H \approx 4 \times 10^{-3}$ cm^{-3}

The star formation rate (**SFR**)

Mass of star formed by unit of time

Observation of the SFR

① Measuring the light emission let us know the mass of young massive stars



Far-UV (FUV) rays

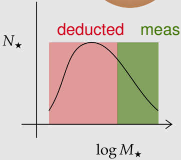
Direct emission by massive stars

A fraction is absorbed

Observer

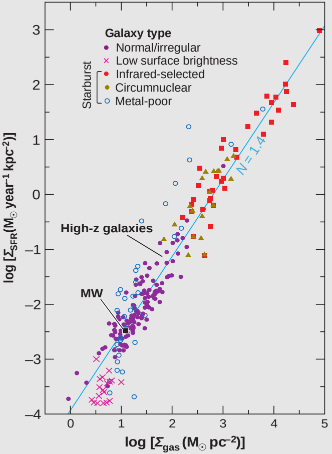
Infrared (IR) rays

Re-emitted by the dust



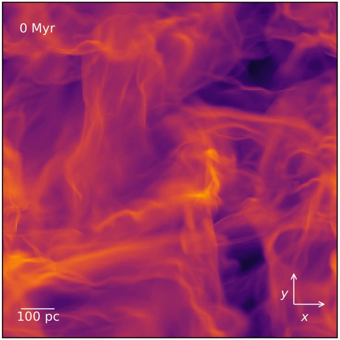
② The initial mass function enables to recover the total SFR

The Schmidt-Kennicutt ~~law~~ relation (**SK**)



What ~~triggers~~ stops star formation?

because gravity would consume all the gas quickly

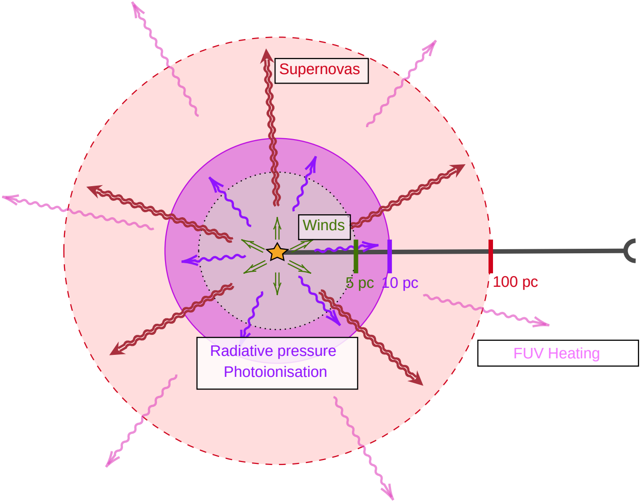


$$SFR_{\mathrm{grav}} \approx \frac{M_{\mathrm{dense}}}{t_{\mathrm{free-fall}}} \approx 460 \ \mathrm{M}_{\odot} \cdot \mathrm{yr}^{-1}$$

$$\gg SFR_{\mathrm{obs}} \approx 2 \ \mathrm{M}_{\odot} \cdot \mathrm{yr}^{-1}$$

What stops star formation?

A natural candidate: stars themselves! (via stellar feedback)



More stars → more feedback → less star formation. Self-regulation?

What stops star formation?

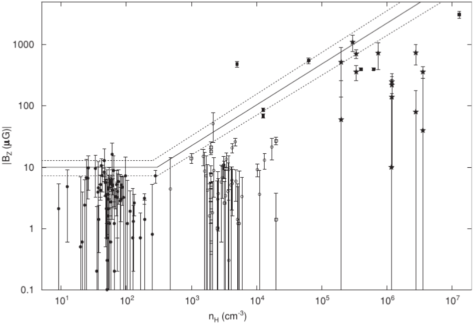
Magnetic field

- Magnetic pressure

$$P_{\mathrm{mag}} = \frac{B^2}{8\pi}$$

- Magnetic tension

$$\boldsymbol{T}_{\mathrm{mag}} = \frac{(\boldsymbol{B} \cdot \boldsymbol{\nabla})\,\boldsymbol{B}}{4\pi}$$

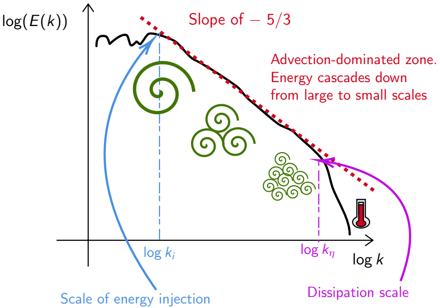


Crutcher et al.

Equipartition: $E_{\mathrm{magnetic}} \sim E_{\mathrm{turbulent}} \sim E_{\mathrm{thermal}} \sim E_{\mathrm{starlight}} \sim E_{\mathrm{dust\ emission}}$

What stops star formation?

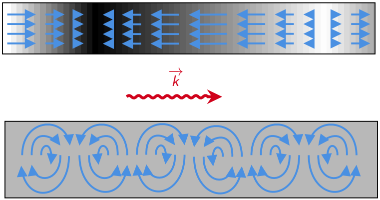
Turbulence



Richardson cascade for incompressible turbulence

Turbulence can be composed of

- compressive modes



- or solenoidal modes

Characterized by its strength σ and compressibility χ

Goals

- What is the more efficient process that quenches star formation?
- What regulates star formation?
- It is the same for all galaxies?

Outline

Physics

Hydrodynamics

Gas gravity

Stars and dark matter gravity

Star formation

Stellar feedback SN HII FUV

Magnetic field

Turbulence σ χ

Scale

Small: < 10 pc

- $\cdot$ Atoms: 10^{-25} pc
- $\star$ Stars: 10^{-8} to 10^{-5} pc
- $\bowtie$ Protoplanetary disks: 10^{-4} pc
- • Star clusters: 1 pc

Medium: 1 pc to 1 kpc

- $\otimes$ HII regions: 10 pc
- $\circledast$ SN shells: 100 pc
- ☁ Molecular clouds: 100 pc

Large: 100 pc to 20 kpc

- $\oint$ Galaxy : 10 kpc

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Focus Included ~~Not included~~

Scale

~~Small: < 10 pc~~

Medium: 1 pc to 1 kpc

~~Large: 100 pc to 20 kpc~~

Outline

I - Introduction
II - Kiloparsec simulations
III - Disk simulations
IV - Conclusions

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Outline

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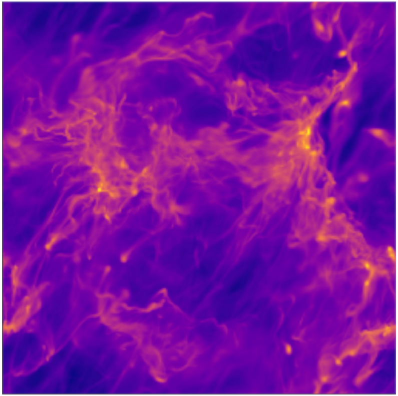
II - Kiloparsec simulations



Brucy+ 2020,
Brucy+ 2022 (subm), with a glimpse of Brucy & Hennebelle, 2023 (in prep.)

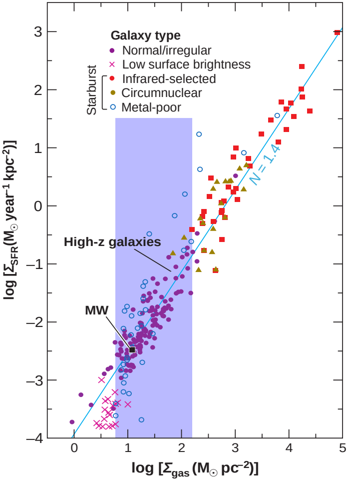
Outline

Kiloparsec simulations

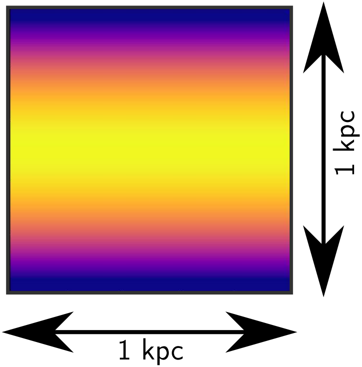
Goals We focus what quenches the SFR in dense environments, and in particular

- ⋆ **Role of stellar feedback**
- ↻ **Role of large scale turbulence**
- ∪ **Role of magnetic field**

Can these processes explain the observed SFR from the Schmidt-Kennicutt (SK) relation?



Main simulation setup



Roughly similar setup:
FRIGG, TIGRESS, SILCC.

MHD simulations with Ramses

- MHD equations + cooling
- Star formation and feedback
- **No** very hot gas ($> 10^6$ K)

Initial conditions

- $\rho(z) = n_0 \exp\left(-\frac{1}{2}\left(\frac{z}{z_0}\right)^2\right)$
- Stellar and dark matter potential
- $B_x(z) = B_0 \exp\left(-\frac{1}{2}\left(\frac{z}{z_0}\right)^2\right)$

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Outline

II - Kiloparsec simulations
  A - Stellar feedback
  B - Large scale turbulence

Focus Included ~~Not included~~

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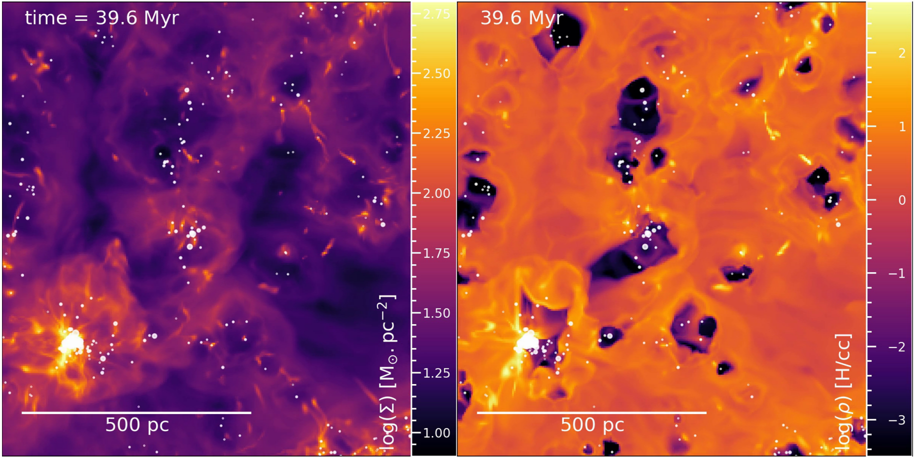
Outline

II - Kiloparsec simulations
- A - Stellar feedback
- B - Large scale turbulence

Focus Included ~~Not included~~

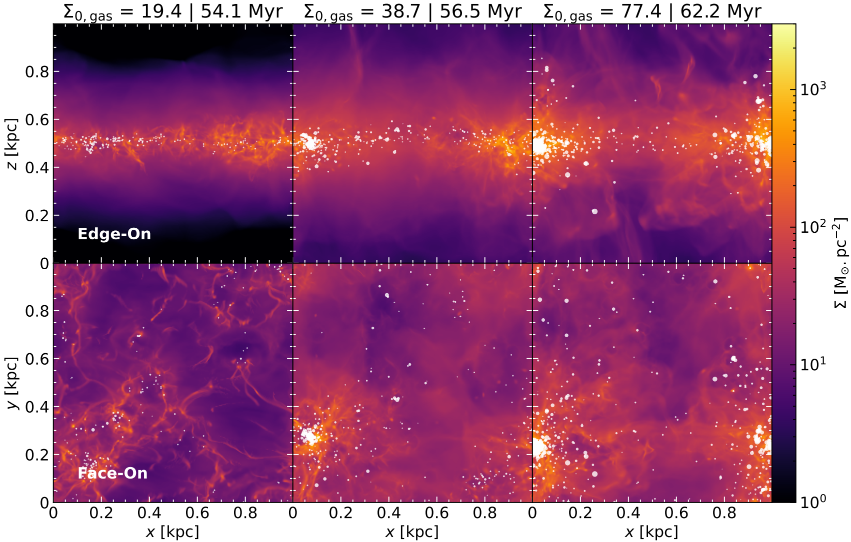
A - With only stellar feedbacks

$\Sigma = 38.7\ \mathrm{M}_\odot \cdot \mathrm{pc}^{-2}$. Face on views of column density (left) and midplane density (right).

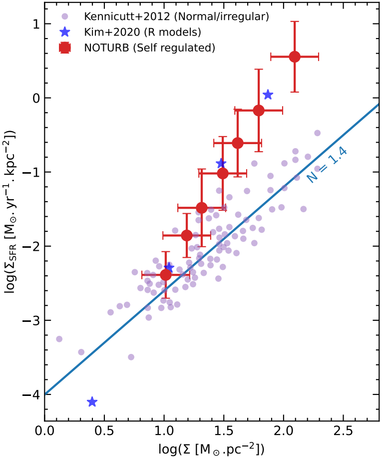


A - With only stellar feedbacks

Column density maps



A - With only stellar feedbacks



Stellar feedback is sufficient in Milky-Way like galaxies ... BUT is too weak in high-*z* galaxies.

B - The influence of larger-scale dynamics: turbulent driving

Turbulence from galactic dynamics

- Spirals, mass transfert → turbulence (eg. Krumholz+ 2018)

B - The influence of larger-scale dynamics: turbulent driving

$$\boldsymbol{f}(\boldsymbol{x},t) = \color{red}{f_{\mathrm{rms}}}\color{black}\times \int \hat{\boldsymbol{f}}(\boldsymbol{k},t) e^{i\boldsymbol{k}\cdot x} d^3\boldsymbol{k}$$

Turbulence from galactic dynamics

- Spirals, mass transfert → turbulence (eg. Krumholz+ 2018)
- Expected injected power: $P_{\mathrm{LS}} \propto \Sigma_g^4$ or $P_{\mathrm{LS}} \propto \Sigma_g^{2.5}$

Model

An extra 2D force is added to generate random motion at scales between 300 and 1000 pc.

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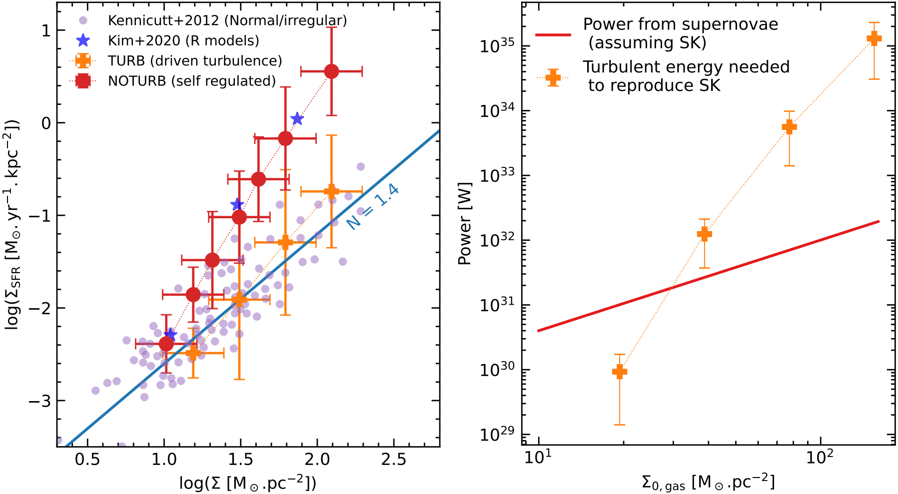
Focus Included ~~Not included~~

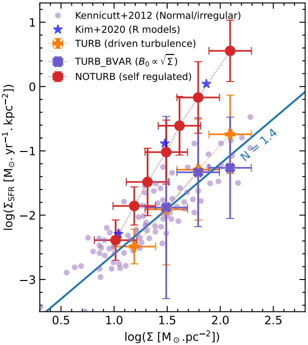
Power needed to retrieve the Schmidt-Kennicut relation



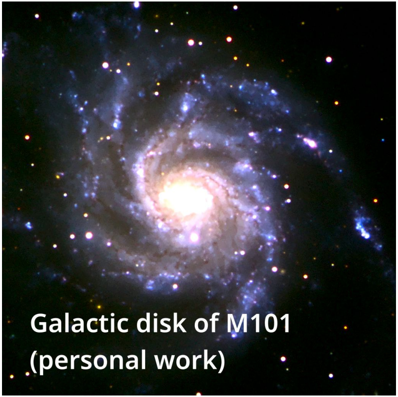
Stellar feedback is not powerful enough to quench star formation.

Conclusion of part II

- Role of stellar feedback.
    - Not **powerful** enough to quench star formation in gas-rich galaxies
- Role of large scale turbulence.
    - A suitable candidate for gas-rich galaxies
    - Increase **speed dispersion** and **anisotropy**
    - **Solenoidal** driving 10x more **efficient**



IV - Full galactic simulations



Outline

Constraining the turbulent driving

Is the turbulence we inject realistic ?

What would be a realistic turbulent driving at these scales for gas-rich galaxies?

- analytical models (gravoturbulence (Nusser+2022), radials motions (Krumholtz+2018), accretion from outside the galaxy (Forbes+2022))
- observational constraints (PHANGS, Sun+2022),
- galactic scale simulations.

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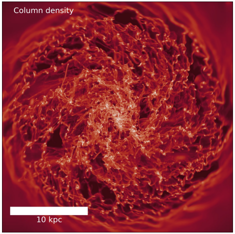
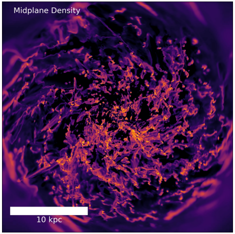
Work in progress: galactic scale simulations and measure turbulence





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Small: $<$ 10 pc

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III - Full galactic simulations

Focus Included ~~Not included~~

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III - Full galactic simulations

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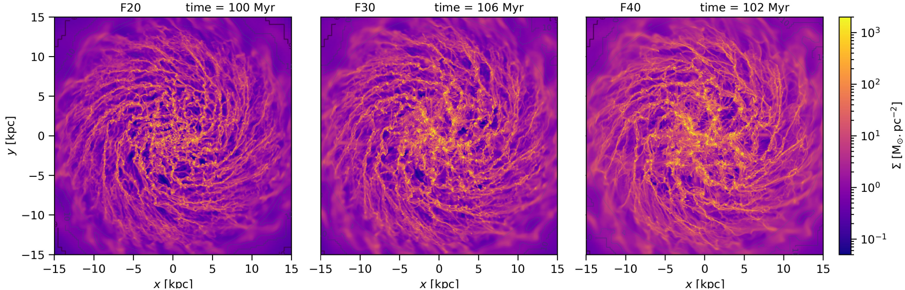
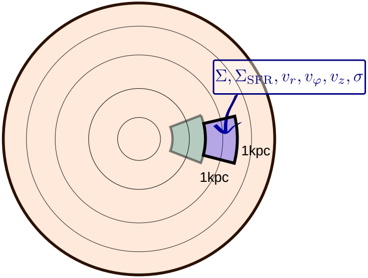
Column density maps



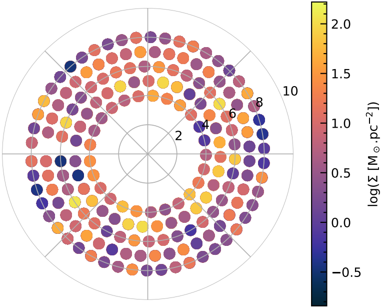
Gas Fraction: 20 % 30% 40%

First insights

Sectors extraction

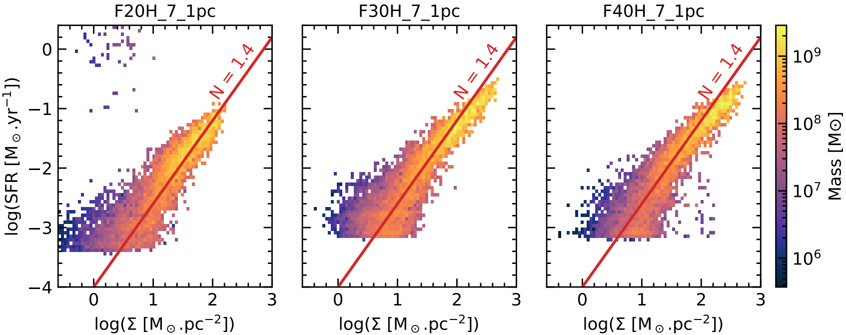


Sector extraction



Position of the extracted sectors

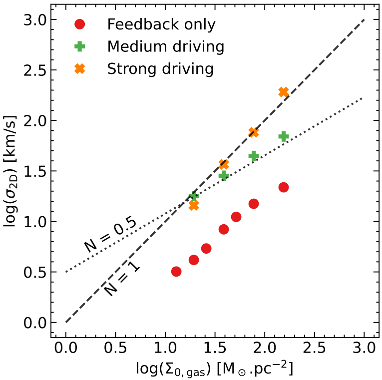
SFR and Schmidt-Kennicutt law



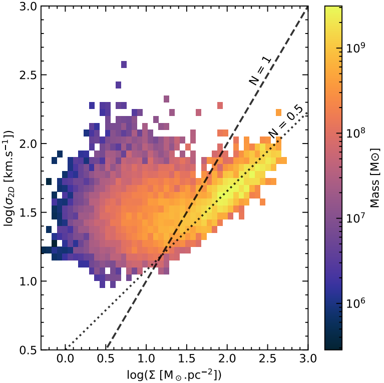
Gas Fraction: 20 % 30% 40%

Comparison between kpc boxes and full galaxy simulations

Preliminary results on velocity dispersion for a galaxy with 30 % gas fraction



Box simulations



Galactic simulation

Comparison between kpc boxes and full galaxy simulations

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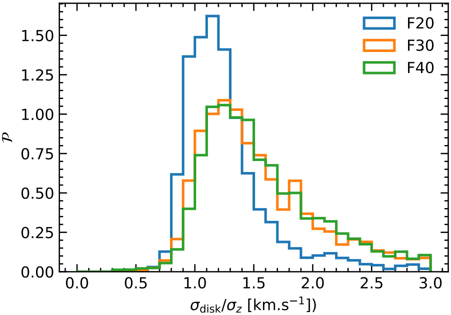
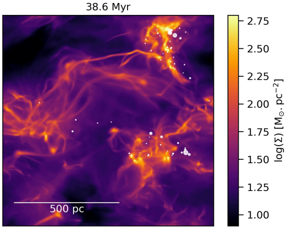
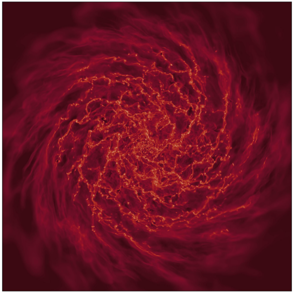


Turbulence is less strong and anisotropic than our requirements in kpc simulations

Summary



- Feedback regulation is suitable in Milkay-way like galaxies but not in higher column density environnments,
- The turbulence from large scale motions in the galaxy interacts
- Galactic simulations can be used to constrain turbulent driving at the kiloparsec scale.



Perspective

- Completion of the parameter study at the kiloparsec scale
- **Better understanding of the turbulence injection**
  - Fourier analysis of the galactic scale simulation
  - Tracking where the turbulent energy come from
  - Add magnetic field
- How much the SFR is quenched? (this work) → How?
  - Work on the link between SFR and turbulence
  - Similar work on feedback

Physics

- Hydrodynamics
- Gas gravity
- Stars and dark matter gravity
- Star formation
- Stellar feedback SN HII FUV
- Magnetic field
- Turbulence σ χ

Scale

- Small: $<$ 10 pc
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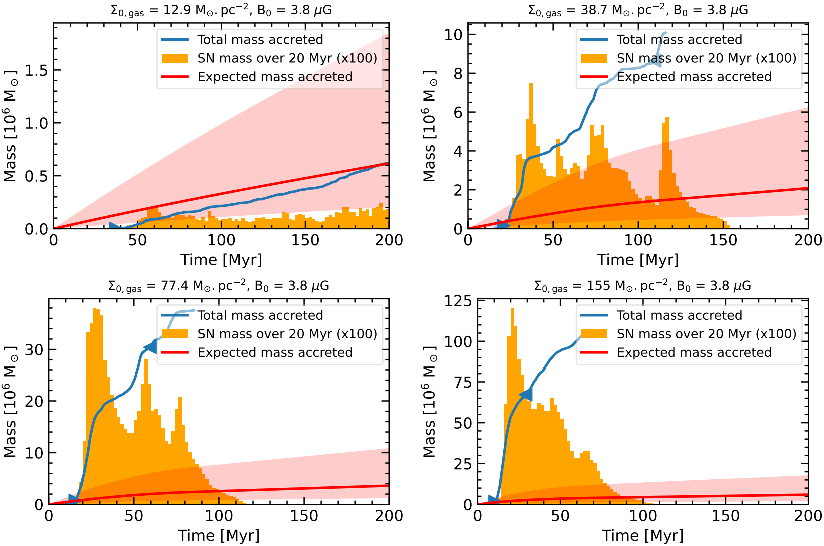
Appendix

With only stellar feedbacks



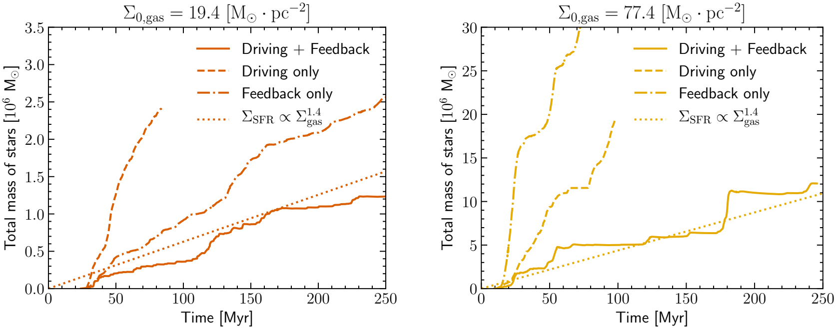
$\Sigma_{0,\mathrm{gas}}$ = 12.9 $\mathrm{M}_\odot.\mathrm{pc}^{-2}$, B_0 = 3.8 μG

$\Sigma_{0,\mathrm{gas}}$ = 38.7 $\mathrm{M}_\odot.\mathrm{pc}^{-2}$, B_0 = 3.8 μG

$\Sigma_{0,\mathrm{gas}}$ = 77.4 $\mathrm{M}_\odot.\mathrm{pc}^{-2}$, B_0 = 3.8 μG

$\Sigma_{0,\mathrm{gas}}$ = 155 $\mathrm{M}_\odot.\mathrm{pc}^{-2}$, B_0 = 3.8 μG

Is stellar feedback needed ?



Stellar feedback is necessary, but its importance decreases as the gas column density increases.

The influence of larger-scale dynamics: turbulent driving

Turbulence from galactic dynamics

- Spirals, mass transfert → turbulence (eg. Krumholz+ 2018)

The influence of larger-scale dynamics: turbulent driving

ϵ specific power injected
v_l typical speed at a scale l
σ_g speed dispersion of the gas

$$\epsilon \sim \frac{v_l^3}{l} \quad , \tag{1}$$

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The influence of larger-scale dynamics: turbulent driving

$$\epsilon \sim \frac{v_l^3}{l} \propto \sigma_g^3, \qquad (1)$$

Q Toomre parameter
κ epicyclic frequency
Σ_g gas column density
G gravitational constant

$$Q = \frac{\sigma_g \kappa}{\pi \Sigma_g G} \propto \frac{\sigma_g \kappa}{\Sigma_g} \sim 1, \qquad (2)$$

Turbulence from galactic dynamics

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$$Q = \frac{\sigma_g \kappa}{\pi \Sigma_g G} \propto \frac{\sigma_g \kappa}{\Sigma_g} \sim 1, \qquad (2)$$

2 cases: $\kappa \propto \sigma_g$ or constant κ

$$\sigma_g \propto \Sigma_g^{0.5} \text{ or } \sigma_g \propto \Sigma_g, \qquad (3)$$

$$\epsilon \propto \Sigma_g^{1.5} \text{ or } \epsilon \propto \Sigma_g^3, \qquad (4)$$

Turbulence from galactic dynamics

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The influence of larger-scale dynamics: turbulent driving

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2 cases: $\kappa \propto \sigma_g$ or constant κ

$$\sigma_g \propto \Sigma_g^{0.5} \text{ or } \sigma_g \propto \Sigma_g, \qquad (3)$$

$$\epsilon \propto \Sigma_g^{1.5} \text{ or } \epsilon \propto \Sigma_g^3, \qquad (4)$$

$$P_{\mathrm{LS}} \propto \Sigma_g^{2.5} \text{ or } P_{\mathrm{LS}} \propto \Sigma_g^4. \qquad (5)$$

with P_{LS} the total power injected.

Turbulence from galactic dynamics

- Spirals, mass transfert → turbulence (eg. Krumholz+ 2018)
- Expected injected power: $P_{\mathrm{LS}} \propto \Sigma_g^4$ or $P_{\mathrm{LS}} \propto \Sigma_g^{2.5}$

The influence of larger-scale dynamics: turbulent driving

$$\boldsymbol{f}(\boldsymbol{x}, t) = f_{\mathrm{rms}} \times \int \hat{\boldsymbol{f}}(\boldsymbol{k}, t) e^{i\boldsymbol{k}\cdot x} d^3\boldsymbol{k}$$

Turbulence from galactic dynamics

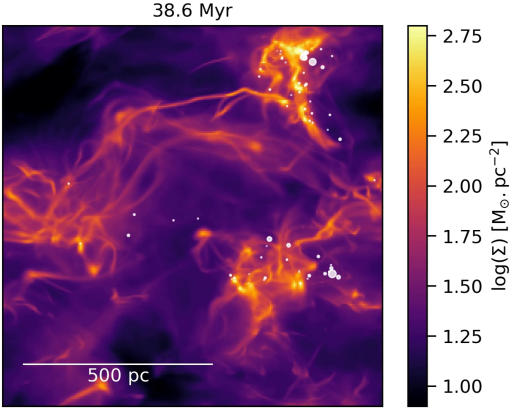
- Spirals, mass transfert → turbulence (eg. Krumholz+ 2018)
- Expected injected power: $P_{\mathrm{LS}} \propto \Sigma_g^4$ or $P_{\mathrm{LS}} \propto \Sigma_g^{2.5}$

Model

An extra 2D force is added to generate random motion at scales between 300 and 1000 pc.

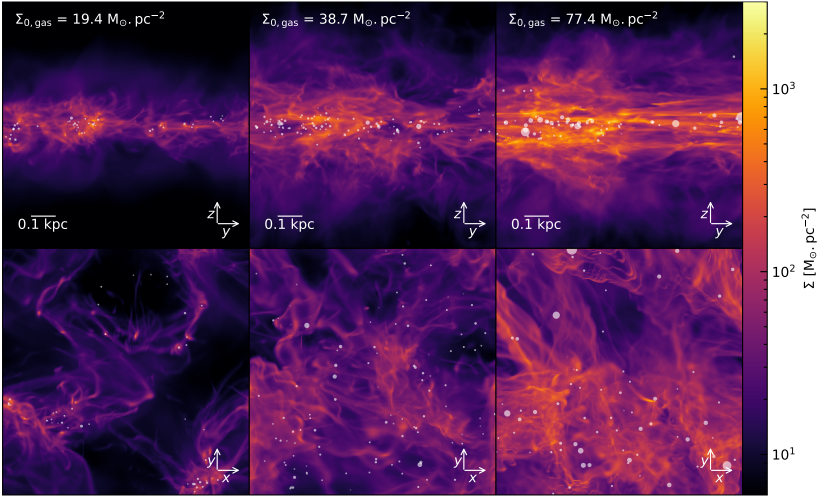
With large-scale turbulence driving

$\Sigma = 38.7\ \mathrm{M}_{\odot} \cdot \mathrm{pc}^{-2}$, strong driving. Face on views of column density

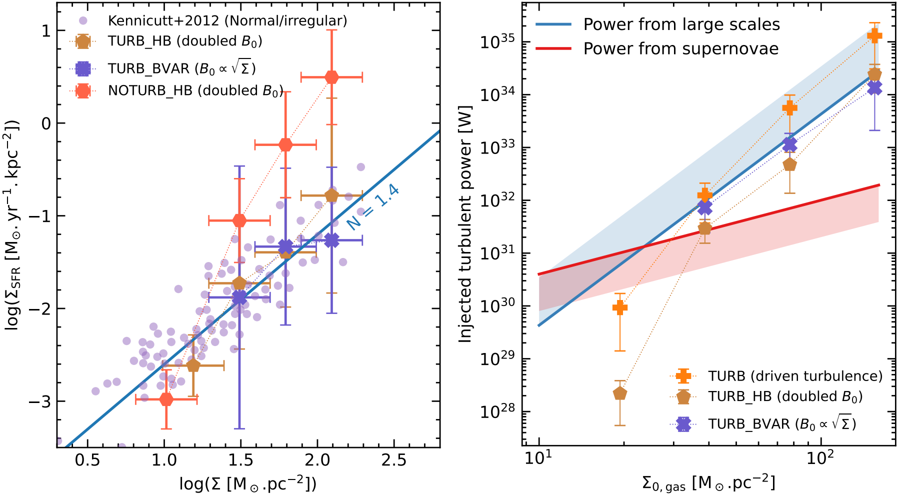


Can we reproduce Schmidt-Kennicutt with turbulence driving?

Column density maps

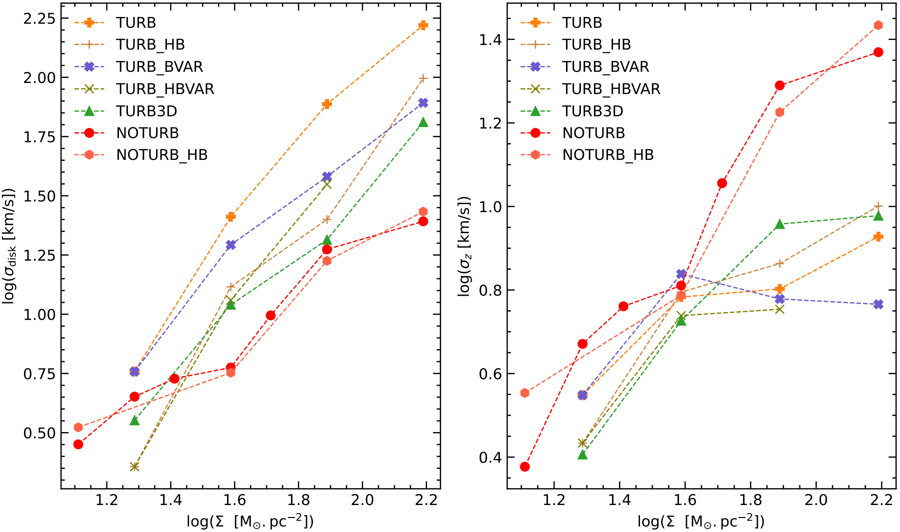


High magnetic field

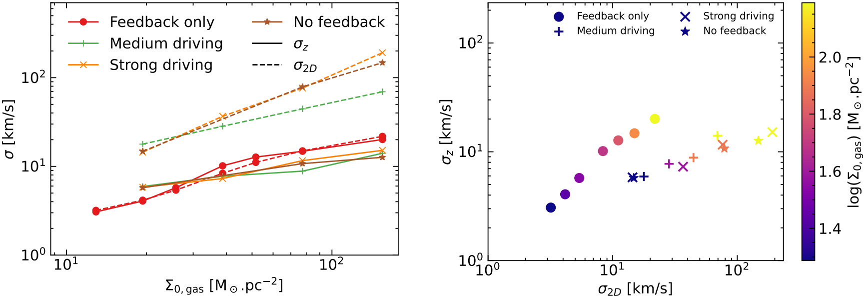


Even with higher B field, we cannot reproduce SK without injecting turbulence

Velocity dispersion



A word about velocity dispersion

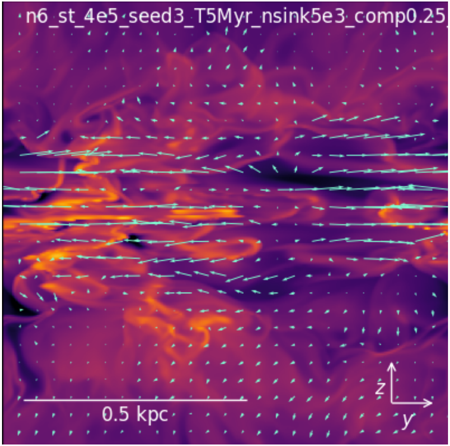


Velocity dispersion measured in the simulations, where

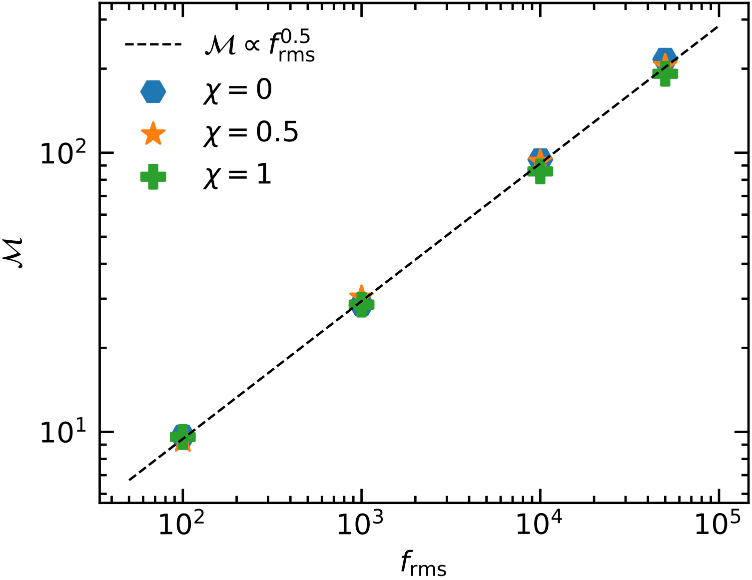
$$\sigma_{2D} = \sqrt{\sigma_x^2 + \sigma_y^2}/\sqrt{2}.$$

The simulations with high 2D turbulent driving show a high anisotropy, while simulations without driving are almost isotropic.

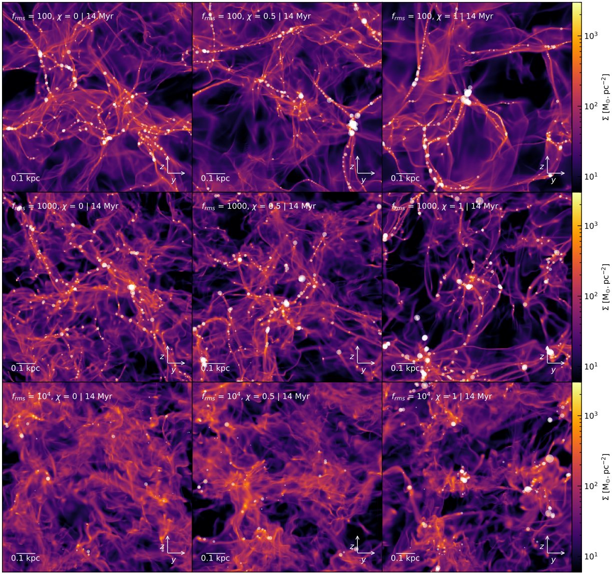
Apodized Driving



Further study (WIP): Link between SFR and turbulence

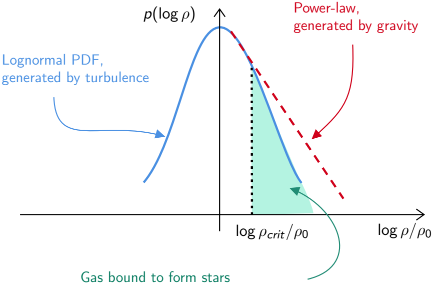


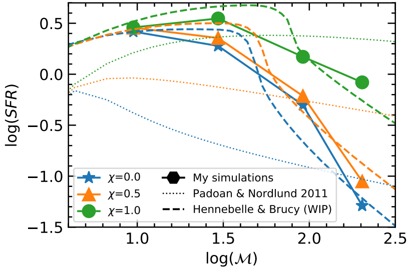
Further study (WIP): Link between SFR and turbulence



Further study (WIP): Link between SFR and turbulence

Using an idealized turbulent box



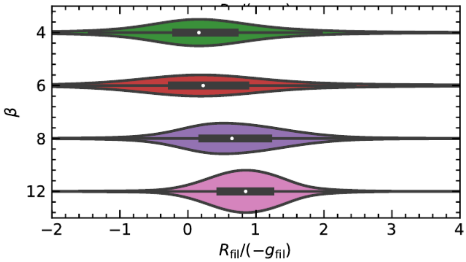


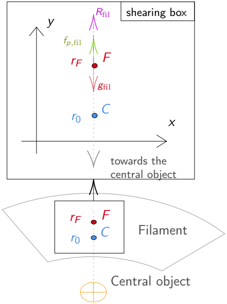
- Goal: improve existing analytical SFR models for higher Mach number.

Analytical model for filaments

- First try : pure hydrostatic model
- only self-gravity and pressure.
- We solved the Lame-Emden equations for a cylindrical distribution.
- Does not convincingly match the simulations

Analytical model for filaments



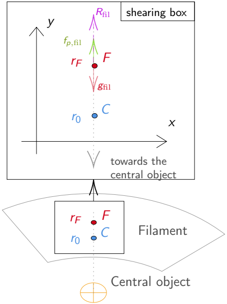


Support due to differential rotation plays a role !

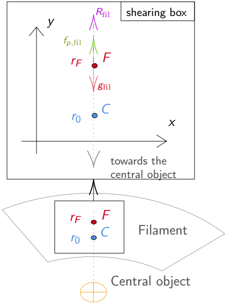
Analytical model for filaments

Simplifying assumptions:

1. shearing box approximation,
2. mechanical equilibrium,
3. gas is locally isothermal,
4. filaments are thin.



Analytical model for filaments



Simplifying assumptions:

1. shearing box approximation,
2. mechanical equilibrium,
3. gas is locally isothermal,
4. filaments are thin.

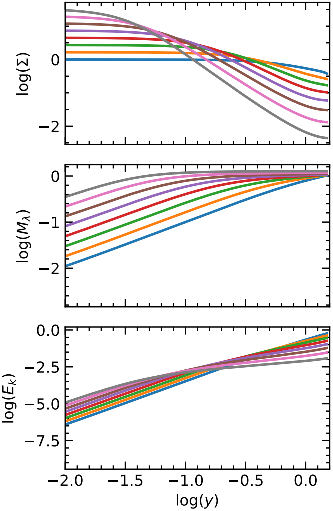
We end up with a integro-differential equation for the normalized column density $\widetilde{\Sigma}$ in the filament.

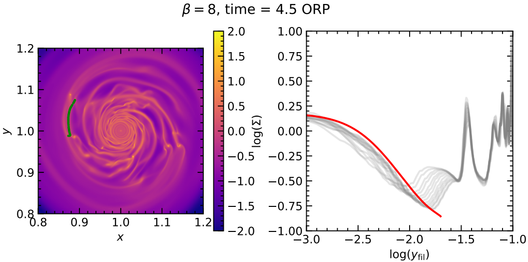
$$\frac{\partial_{\widetilde{y}}\widetilde{\Sigma}}{\widetilde{\Sigma}} = \int_0^{\widetilde{\Lambda}} \widetilde{\Sigma}(0, y') D(y', \widetilde{y}, \varepsilon)\, \mathrm{d}y' + \widetilde{y}. \tag{1}$$

where

$$D(y, y', \varepsilon) = \frac{y' - y}{(y - y')^2 + \varepsilon^2} - \frac{y' + y}{(y' + y)^2 + \varepsilon^2} \tag{2}$$

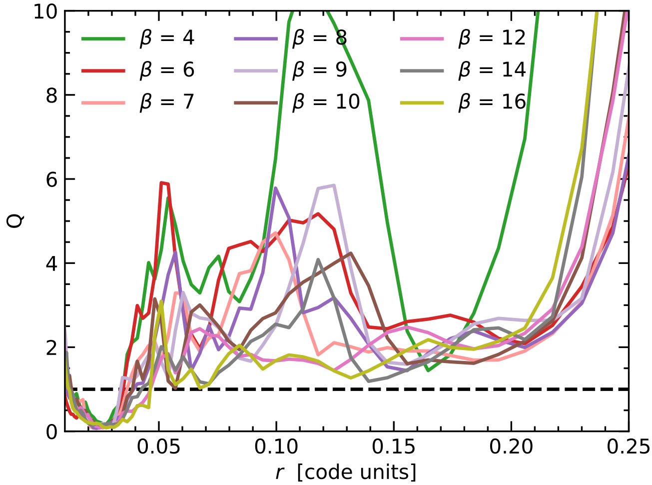
Analytical model for filaments



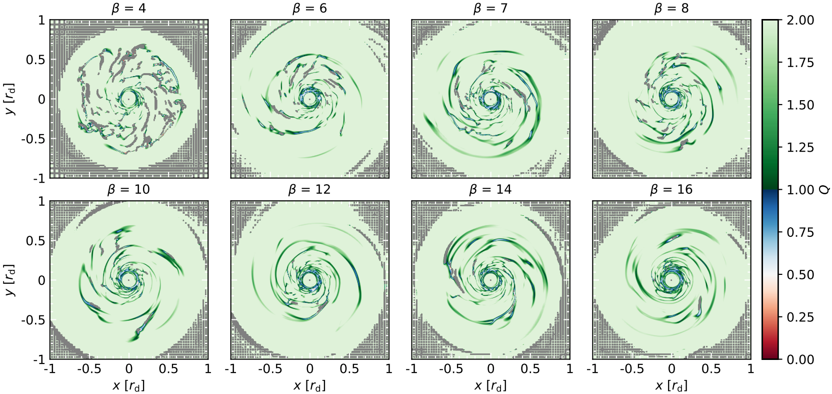


- The model enables to build a sequence of equilibrium (left)
- The model can be fitted to actual filaments in the simulation (top)
- BUT the model cannot explain the slope of the Σ-PDF (profile too stiff, PDF too flat).

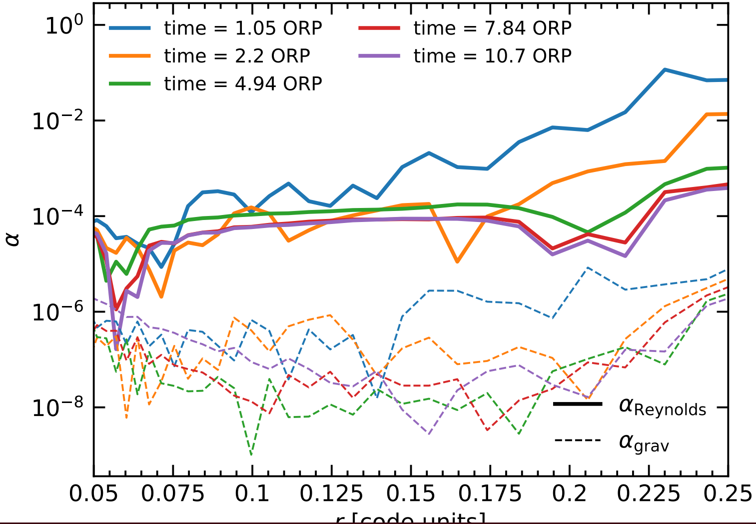
Q


10
8
6
4
2
0
Q
0.05
0.10
0.15
0.20
0.25
r [code units]
β = 4
β = 6
β = 7
β = 8
β = 9
β = 10
β = 12
β = 14
β = 16

Q


β = 4
β = 6
β = 7
β = 8
β = 10
β = 12
β = 14
β = 16
1
0.5
0
-0.5
-1
y [r_d]
x [r_d]
-1
-0.5
0
0.5
1
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Q

Alpha - Q = 3


time = 1.05 ORP
time = 2.2 ORP
time = 4.94 ORP
time = 7.84 ORP
time = 10.7 ORP
α_{Reynolds}
α_{grav}
α
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
0.05
0.075
0.1
0.125
0.15
0.175
0.2
0.225
0.25
r [code units]

HD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0, \quad (3)$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + \frac{1}{\rho} \nabla P = -\frac{GM}{r^2 + z^2} (\cos(\theta) \boldsymbol{e_r} + \sin(\theta) \boldsymbol{e_z}) \quad (4)$$

$$\frac{\partial E}{\partial t} + \nabla \left((E + P) \boldsymbol{u} \right) = 0 \quad (5)$$

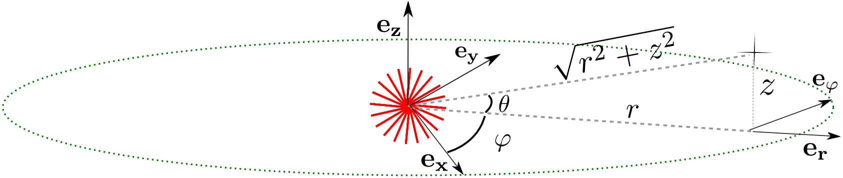


Figure: Coordinate system.

Self-gravity

New source term in Euler equation. Poisson potential:

$$\Delta\phi = -4\pi G\rho$$

Cooling

New source term in energy equation:

$$\frac{\partial E}{\partial t} + \nabla\left((E + P)\,\boldsymbol{u}\right) = -\frac{E_{int}}{t_{cool}}$$

where $E_{int} = E - E_c$ is the internal energy and $E_c = \frac{1}{2}\rho\boldsymbol{u}^2$ is the kinetic energy.

Cooling time $t_{cool} = \beta\Omega^{-1}$

Initial conditions

Vertical equilibrium

$$\frac{1}{\rho}\frac{\partial P}{\partial z} + \frac{GM\sin(\theta)}{r^2 + z^2} = 0$$

$$\rho(r, z) = \rho_c(r)\exp\left(\frac{GM}{c_s^2}\left(\frac{1}{\sqrt{r^2 + z^2}}\right) - \frac{1}{r}\right)$$

where $\rho_c(r)$ is a free parameter chosen so that $\Sigma \propto r^{-1}$

Initial conditions

Radial equilibrium

$$\frac{u_\varphi^2}{r} = \frac{1}{\rho}\frac{\partial(c_s^2\rho)}{\partial r} + r\frac{GM}{\left(r^2+z^2\right)^{3/2}}$$

$$\Omega^2 = \frac{1}{\rho r}\frac{\partial(c_s^2\rho)}{\partial r} + \frac{GM}{\left(r^2+z^2\right)^{3/2}}$$

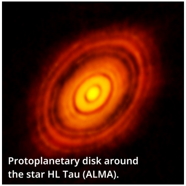
$$\Omega^2(r \leq r_{in}) = \frac{GM}{r^3} - \frac{5}{2}\frac{c_s^2}{r^2}$$

$$\Omega^2(r > r_{in}) = \frac{GM}{r^2\sqrt{r^2+z^2}} - \frac{7}{2}\frac{c_s^2}{r^2}$$

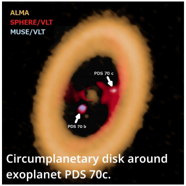
Fragmentation of self-gravitating disks

- Self-gravitating disks: disks massive enough so that their own gravity plays an significant role.
- Can be found around black holes (galaxies), stars (protoplanetary disks) or planets (circumplanetary disks).
- Fragmentation, when the gas collapse under is own gravity is important for star, planet and moon formation.

Galactic disk of M101 (personal work)

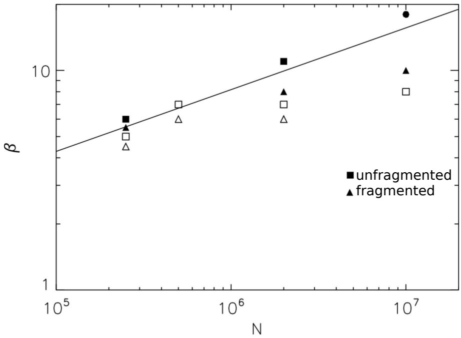


Protoplanetary disk around the star HL Tau (ALMA).



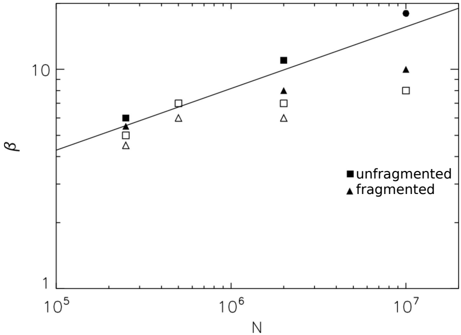
Circumplanetary disk around exoplanet PDS 70c.

Non-convergence of the stability limit



Critical value for β as a function of resolution, Meru & Bate 2012 and Rice et al. 2014.

Non-convergence of the stability limit



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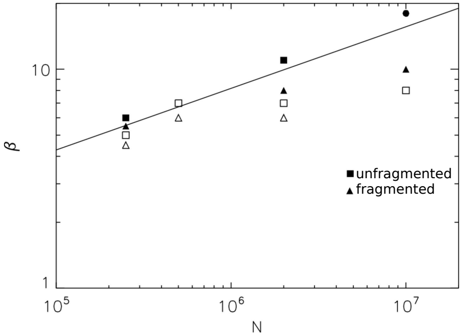
Paardekooper 2012, Hopkins 2013: Stochastic aspects

Non-convergence of the stability limit



Critical value for β as a function of resolution, Meru & Bate 2012 and Rice et al. 2014.

Paardekooper 2012, Hopkins 2013: Stochastic aspects

The simulations are mainly SPH or on 2D fixed-size grid.

"It would be interesting to try to understand the convergence problem with a Godunov scheme"
Meru & Bate 2012

Description of the simulations

Code: Ramses

- Finite volumes over a 3D grid.
- Conservative scheme (Godunov).
- Adaptive Mesh refinement.

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- $M_{\text{disk}} = M_{\star}/10$.
- Equilibrium: $Q(t = 0) \geq 2$.
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- TIC : pre-run to have turbulent initial conditions.

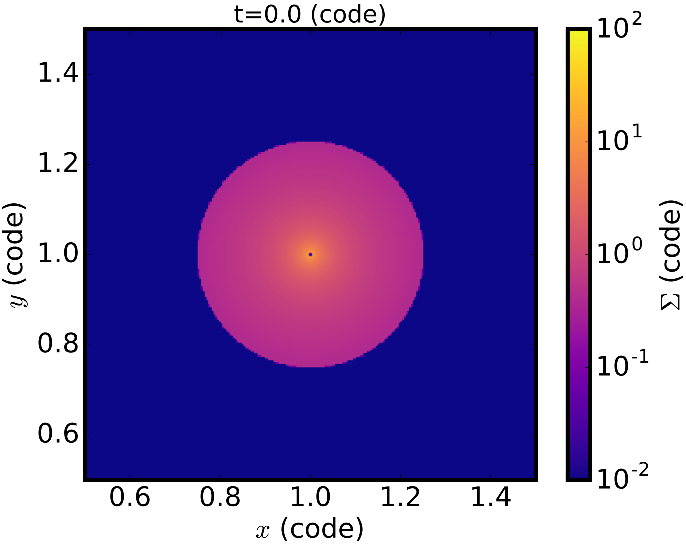
Resolution

Size of a cell $dx = 2^{-l}$ where l is the level of refinement.

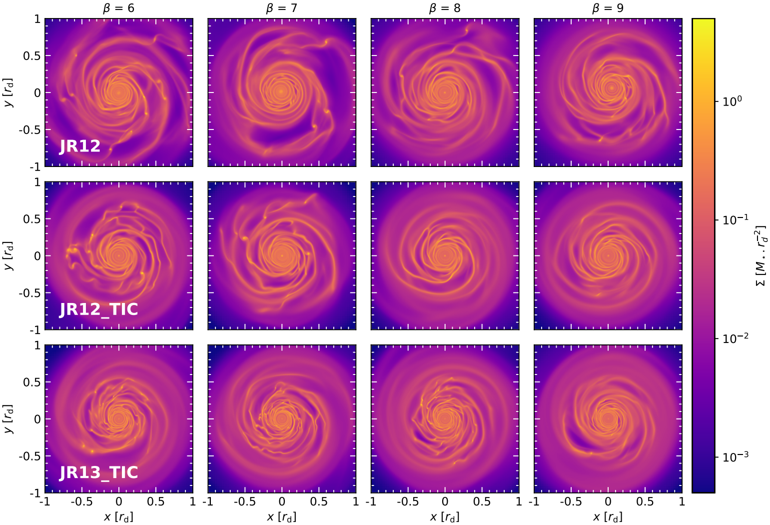
Grid at $l = 6$ (box) and $l = 10$ (disk, on 256^3 cells) + extra refinement based on jeans length λ_J. Cell refined if $l < l_{\text{max}}$ and $dx > 20\lambda_J$.

Group	l_{max}	Initial cond.
JR11	11	smooth
JR12	12	smooth
JR12_TIC	12	turbulent
JR13_TIC	13	turbulent

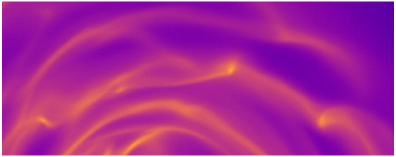
Results: movie for $\beta = 7$ (group JR12)



Results: Column density maps



What shapes the PDF ?



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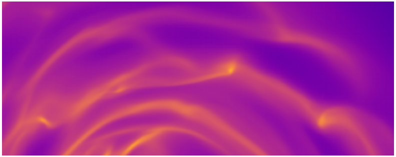

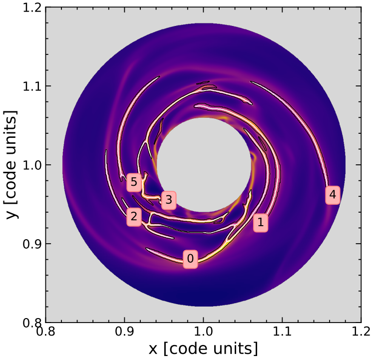

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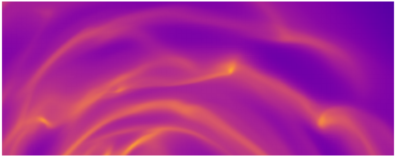
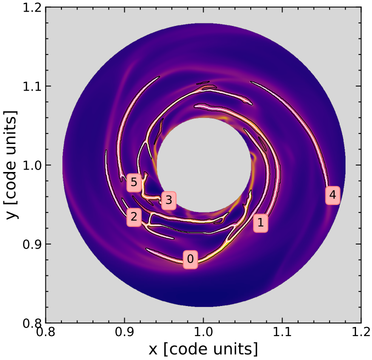
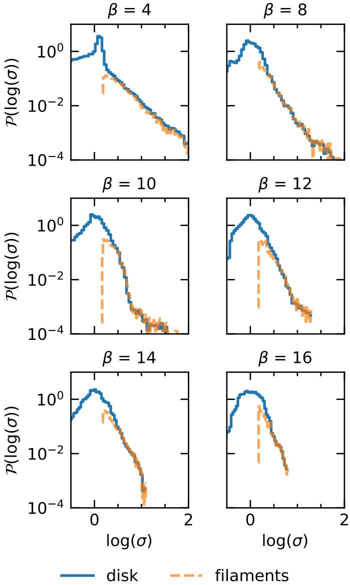
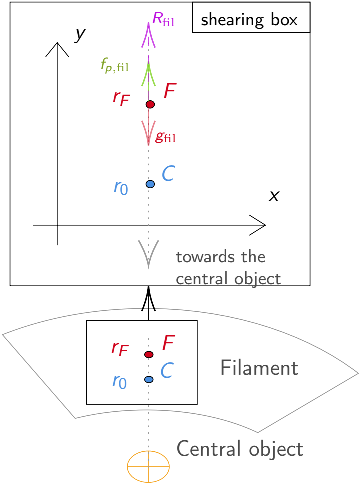
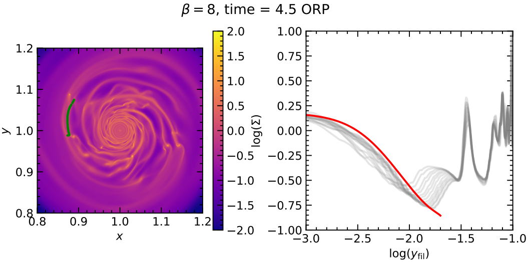






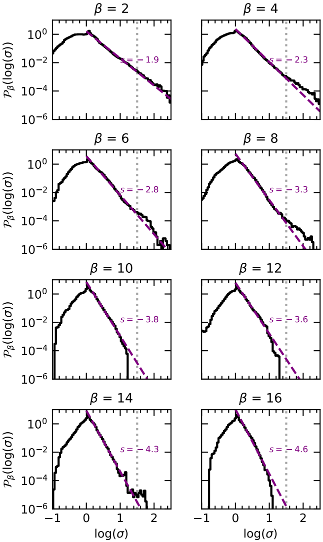
Analytical model for the radial profile of filaments

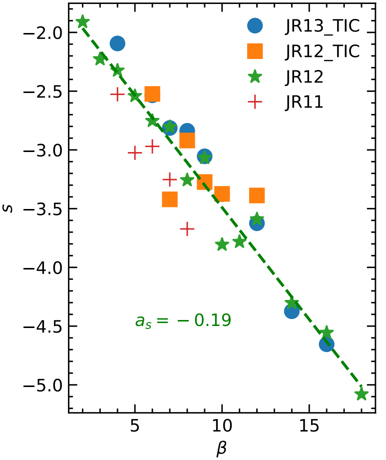




- Model of a infinite filament undergoing pressure, tidal forces and self gravity.
- The model can be fitted to actual filaments in the simulation (top)
- But the radial profile of filaments is not enough to understand the PDF

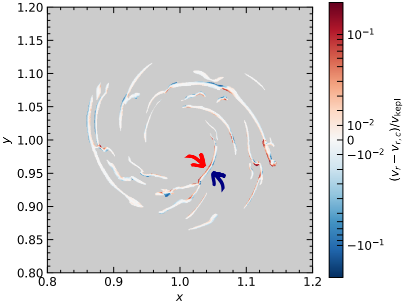
How to explain the $s - \beta$ correlation ?



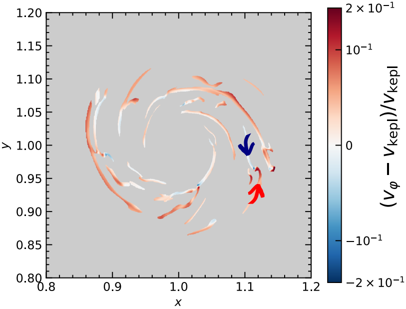


$$s = -0.2\beta - 1.6, \;\; R^2 = 0.97$$

The PDF is not built radially but alongside filaments



Radial collapse



Azimuthal collapse

Filaments are collapsing in the azimuthal direction.

How to explain the $s - \beta$ correlation ?

Heating by gravitational instabilities in ring of mean column density $\overline{\Sigma}$, height h, and volume V.

$$\alpha_{\mathrm{grav}} = \frac{2}{3}\frac{1}{4\pi G}\frac{2h}{\overline{\Sigma} c_s^2 V}\int_V g_r g_\varphi \,\mathrm{d}V. \tag{6}$$

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Since

$$\mathrm{PDF}(\Sigma) = \frac{P_0}{\sigma_0 \overline{\overline{\Sigma}}}\left(\frac{\Sigma}{\sigma_0 \overline{\overline{\Sigma}}}\right)^{s-1}. \quad (7)$$

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we can write

$$\alpha_{\mathrm{grav}} = \frac{2}{3}\frac{h}{2\pi G c_s^2}\int_{\sigma_0 \overline{\Sigma}}^{\infty} \frac{P_0}{\sigma_0}\frac{g_r g_\varphi}{\overline{\overline{\Sigma}}^2}\left(\frac{\Sigma}{\sigma_0 \overline{\overline{\Sigma}}}\right)^{s-1} \mathrm{d}\Sigma \tag{8}$$

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How to explain the $s - \beta$ correlation ?

If self-gravity dominates, we can approximate

$$g_r \simeq \varepsilon_r 2\pi G\Sigma \text{ and } g_\varphi \simeq \varepsilon_\varphi 2\pi G\Sigma \tag{9}$$

where ε_r and ε_φ are unknown efficiencies.

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where ε_r and ε_φ are unknown efficiencies. Injecting back into (8),

$$\alpha_{\mathrm{grav}} = -\frac{2}{3}\frac{2\pi G\overline{\Sigma} h\varepsilon_r\varepsilon_\varphi}{c_s^2}\frac{\sigma_0^2 P_0}{s+2}. \tag{10}$$

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$$g_r \simeq \varepsilon_r 2\pi G\Sigma \text{ and } g_\varphi \simeq \varepsilon_\varphi 2\pi G\Sigma \tag{9}$$

where ε_r and ε_φ are unknown efficiencies. Injecting back into (8),

$$\alpha_{\mathrm{grav}} = -\frac{2}{3}\frac{2\pi G\overline{\Sigma} h\varepsilon_r\varepsilon_\varphi}{c_s^2}\frac{\sigma_0^2 P_0}{s+2}. \tag{10}$$

From the energy balance (cooling = heating),

$$\alpha = \frac{2}{5}\frac{1}{\beta}. \tag{11}$$

How to explain the $s - \beta$ correlation ?

If self-gravity dominates, we can approximate

$$g_r \simeq \varepsilon_r 2\pi G\Sigma \text{ and } g_\varphi \simeq \varepsilon_\varphi 2\pi G\Sigma \tag{9}$$

where ε_r and ε_φ are unknown efficiencies. Injecting back into (8),

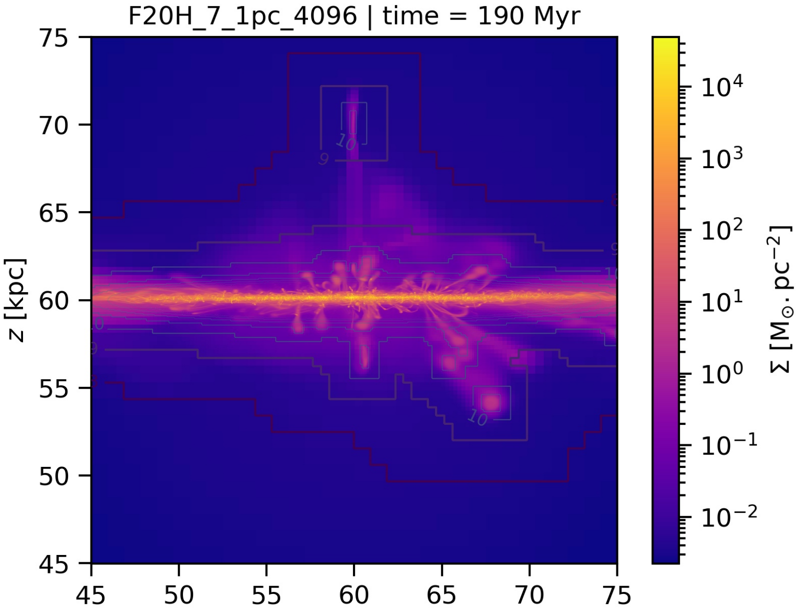
$$\alpha_{\mathrm{grav}} = -\frac{2}{3}\frac{2\pi G\overline{\Sigma} h \varepsilon_r \varepsilon_\varphi}{c_s^2}\frac{\sigma_0^2 P_0}{s+2}. \tag{10}$$

From the energy balance (cooling = heating),

$$\alpha = \frac{2}{5}\frac{1}{\beta}. \tag{11}$$

Finally, we retrieve a linear relationship between s and β:

$$s = -\frac{10}{3}\varepsilon_r \varepsilon_\varphi \sigma_0^2 P_0 \ \beta - 2. \tag{12}$$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75
70
65
60
55
50
45
z [kpc]
45
50
55
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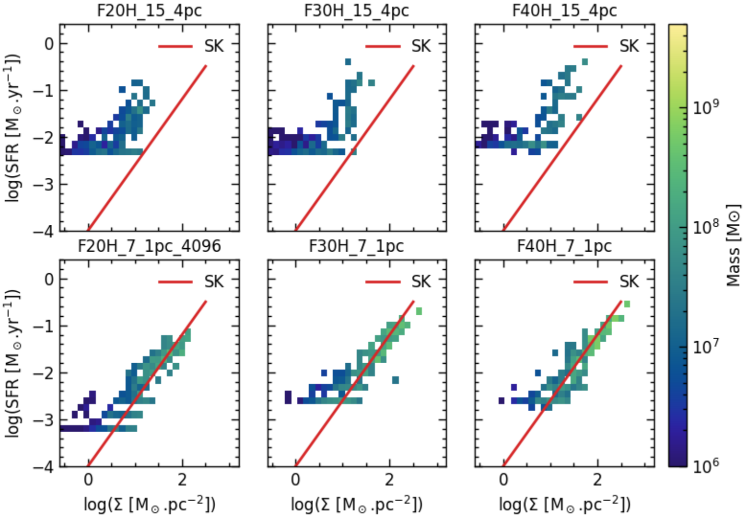
10
9
10
8
9
10
10
9
8
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
$\Sigma\ [\mathrm{M}_\odot.\mathrm{pc}^{-2}]$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F30H_15_4pc
F40H_15_4pc
F20H_7_1pc_4096
F30H_7_1pc
F40H_7_1pc
SK
log(SFR [M⊙.yr−1])
log(Σ [M⊙.pc−2])
0
−1
−2
−3
−4
0
2
Mass [M⊙]
10^9
10^8
10^7
10^6