

What regulates star formation?

A two-scale approach to explain the Schmidt-Kennicutt relation

**Noé Brucy, Patrick Hennebelle,
Frédéric Bournaud, Cédric Colling,
Tine Colman, Simon Iteanu**

Ramses User Meeting, 27th of September 2021

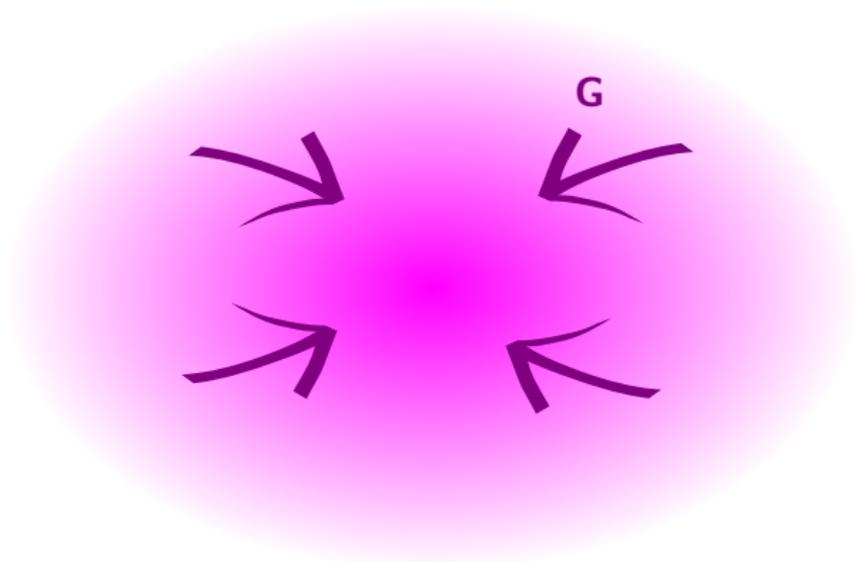
Star formation, a pure gravitational process?

Estimating the Star Formation Rate (SFR)



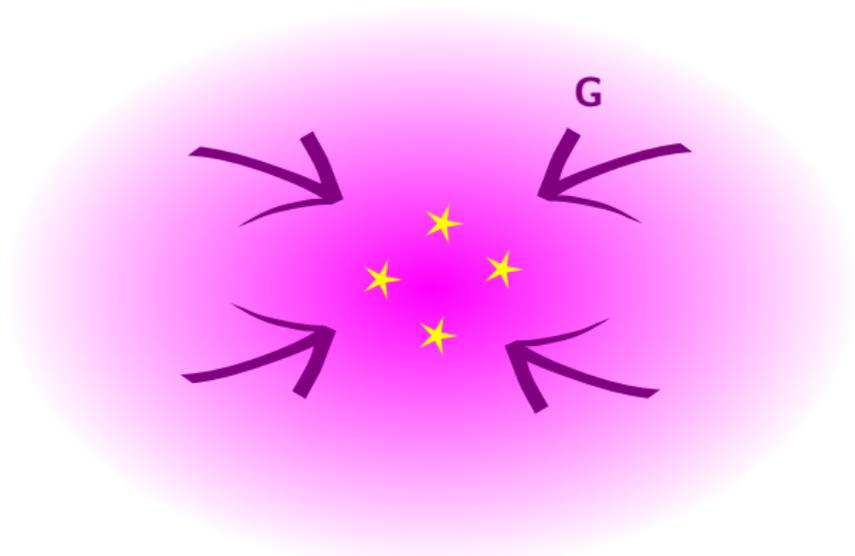
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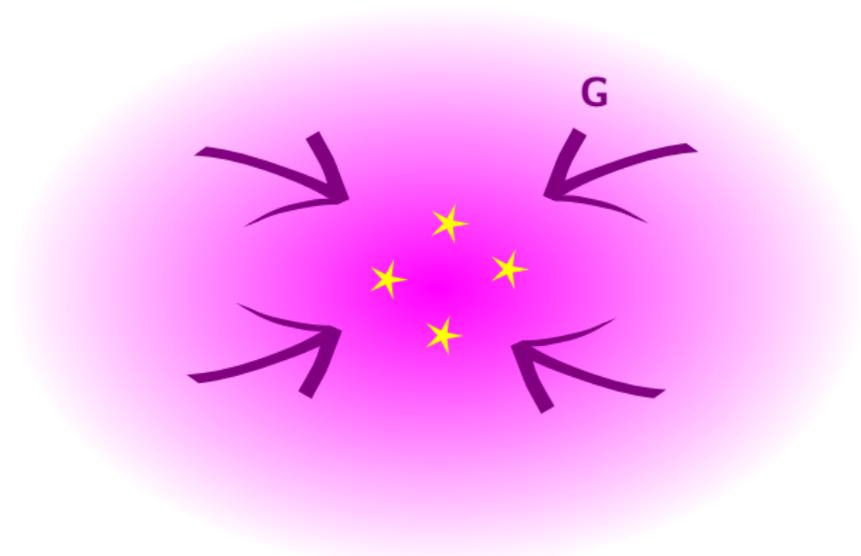
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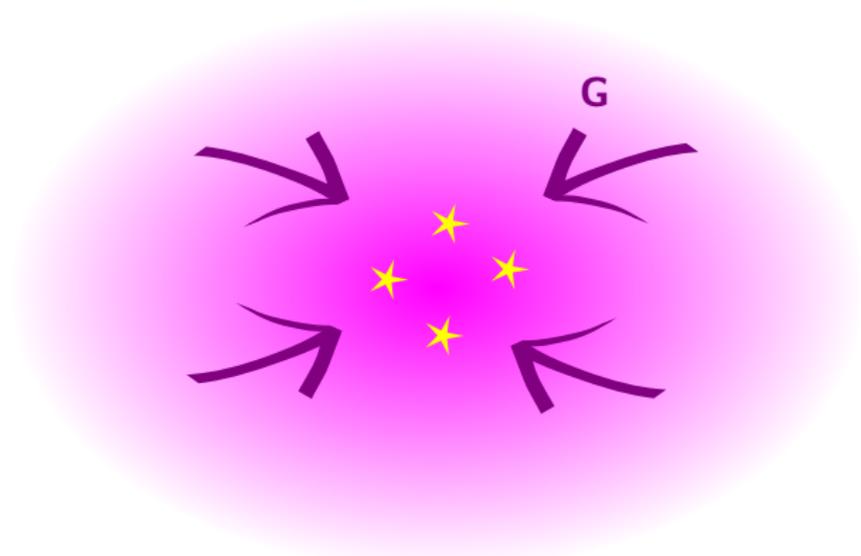
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$$SFR_{\text{grav}} \approx \frac{M_{\text{cloud}}}{t_{\text{free-fall}}} \approx 460 M_{\odot} \cdot \text{yr}^{-1}$$

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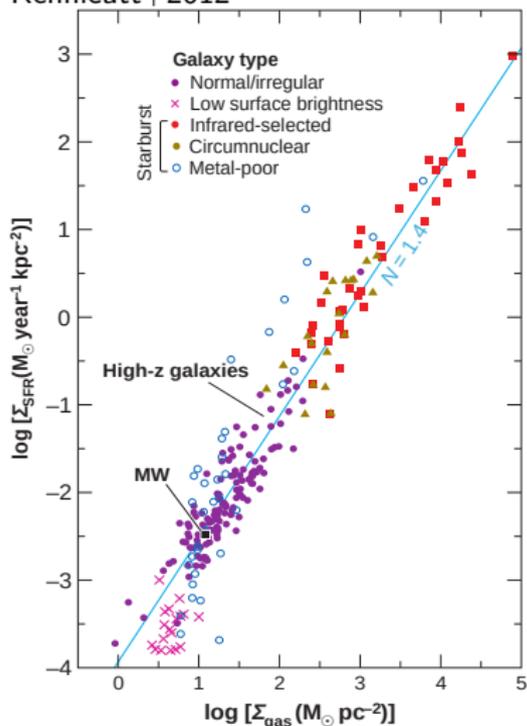
Estimating the Star Formation Rate (SFR)



$$SFR_{\text{grav}} \approx \frac{M_{\text{cloud}}}{t_{\text{free-fall}}} \approx 460 M_{\odot} \cdot \text{yr}^{-1} \gg SFR_{\text{obs}} \approx 2 M_{\odot} \cdot \text{yr}^{-1}$$

The Schmidt-Kennicutt law

Kennicutt+2012



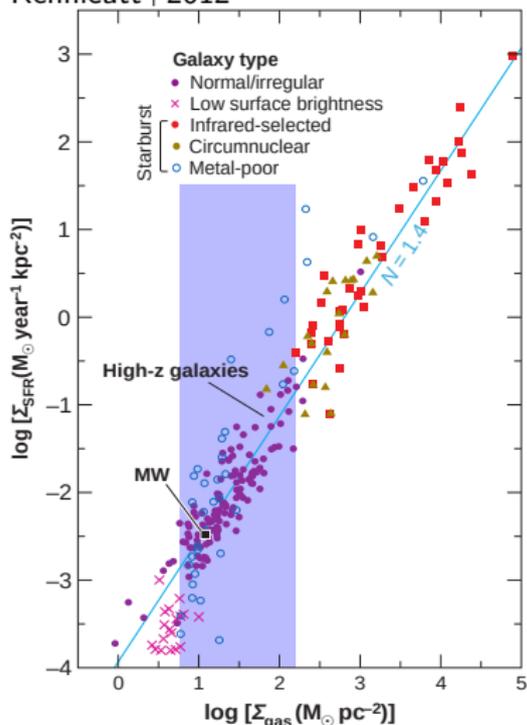
Relation between

Σ_{SFR} Surface density of SFR
 Σ_{gas} Surface density of gas

$$\Sigma_{\text{SFR}} \propto \Sigma_{\text{gas}}^{1.4}$$

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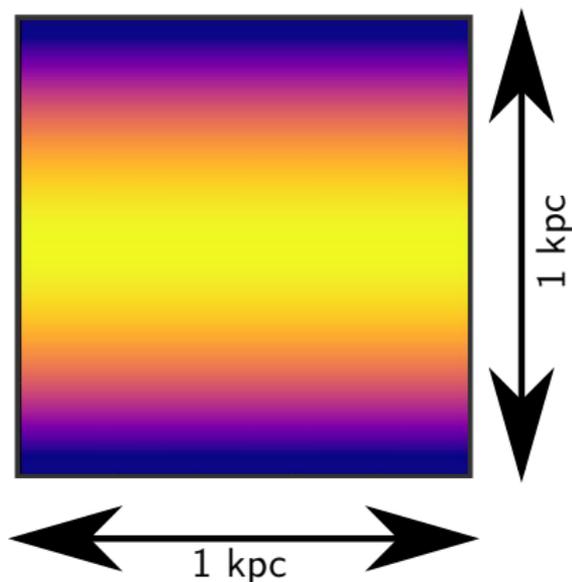
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Our study

- ▶ Dominating quenching processes explaining this law ?
- ▶ **Numerical investigation**

Putting a galaxy into a (numerical) box



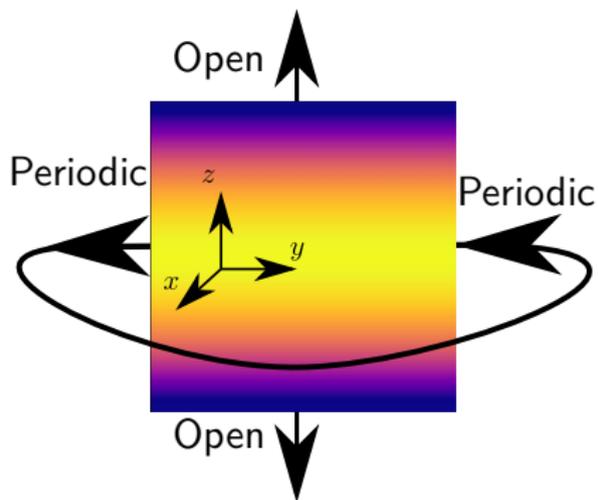
MHD simulations with RAMSES-ISM

- ▶ 1 kpc³ region of a galactic disk
- ▶ Resolution : uniform at ~ 4 pc
- ▶ MHD equations + cooling
- ▶ Star formation and feedback

Initial conditions

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

Putting a galaxy into a (numerical) box



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Star formation self-regulation

Description of the feedback models

HII regions



Expanding bubble of ionized hydrogen, with a shock.

Model

Expansion computed via radiative transfert.

(Geen+, (2016))

Far Ultra Violet



Energetic UV photons can go trough the gas and heat it.

Model

Uniform heating of the gas, proportional to the SFR.

(Ostriker+ 2010)

Supernovae



End of life of massive stars, injects 10^{51} erg in the ISM.

Model

Stellar object with random motion that eventually inject momentum. (Iffrig+ 2017)

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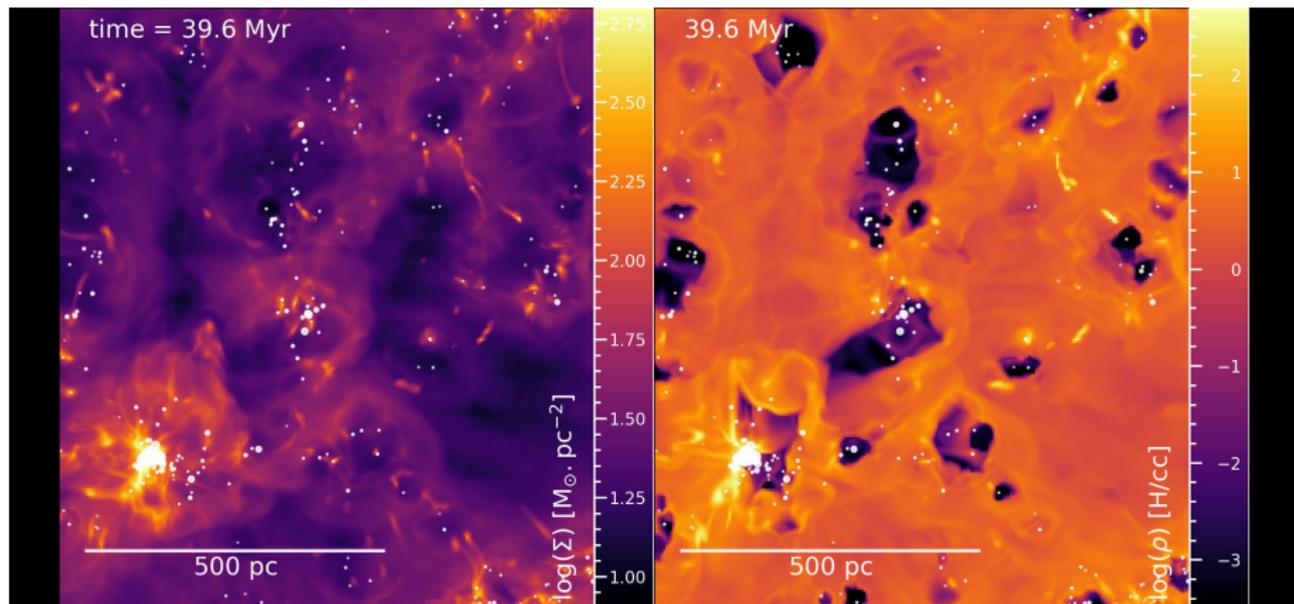
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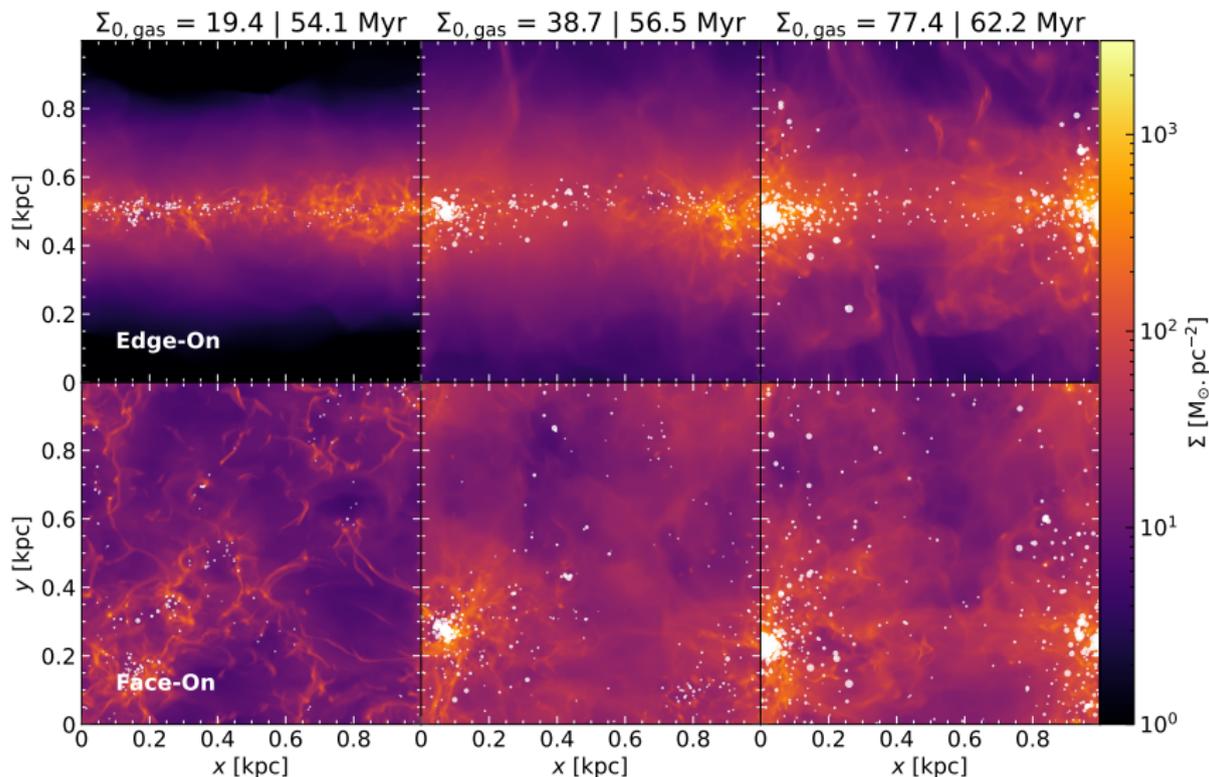
With only stellar feedbacks

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

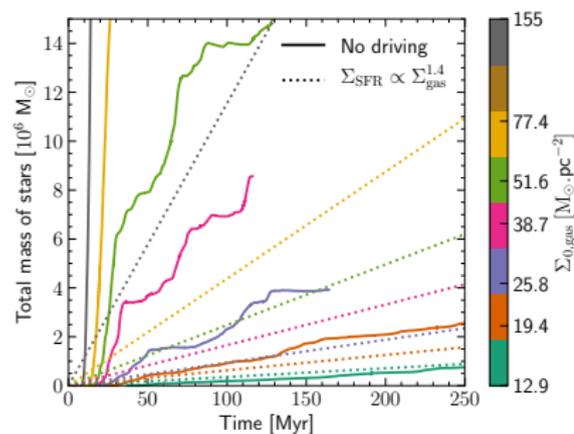


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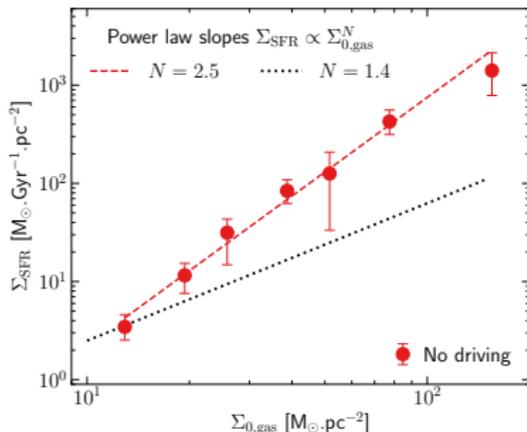
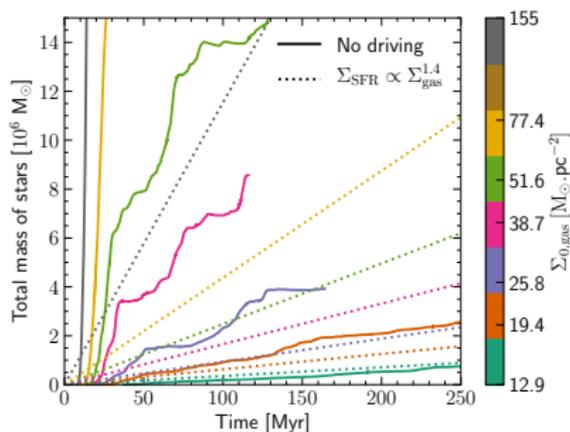
Column density maps



With only stellar feedbacks

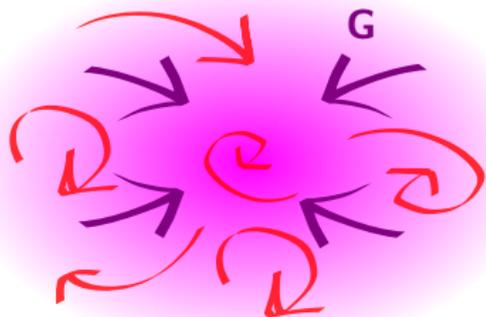


With only stellar feedbacks



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

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

$$\epsilon \sim \frac{v_l^3}{l} \quad (1)$$

Turbulence from galactic dynamics

- ▶ Spirals, mass transfert → turbulence (eg. Krumholz+ 2018)
- ▶ Expected injected power:
 $P_{\text{LS}} \propto \Sigma_{\text{g}}^4$

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Q Toomre parameter

κ epicyclic frequency

Σ_g gas column density

G gravitational constant

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

Turbulence from galactic dynamics

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$$\epsilon \propto \Sigma_g^3. \quad (3)$$

P_{LS} the total power injected.

$$P_{\text{LS}} \propto \Sigma_g^4. \quad (4)$$

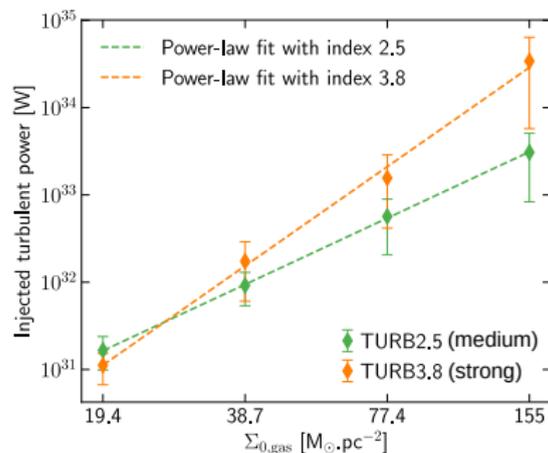
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The influence of larger-scale dynamics: turbulent driving

2 sets of simulations :

$$P_{\text{LS}} \propto \Sigma_{\text{g}}^{2.5} \text{ and } P_{\text{LS}} \propto \Sigma_{\text{g}}^{3.8}$$



Turbulence from galactic dynamics

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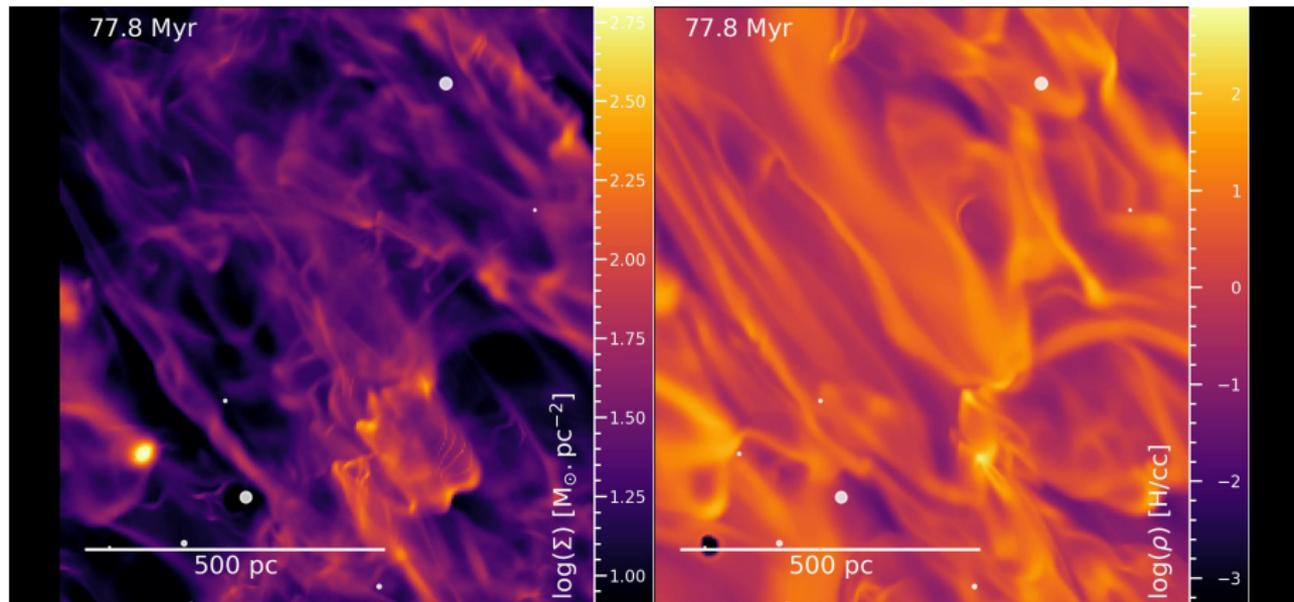
Model

An extra 2D force is added to generate random motion at scales between 300 and 1000 pc (with the turbulence module in Ramses)

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

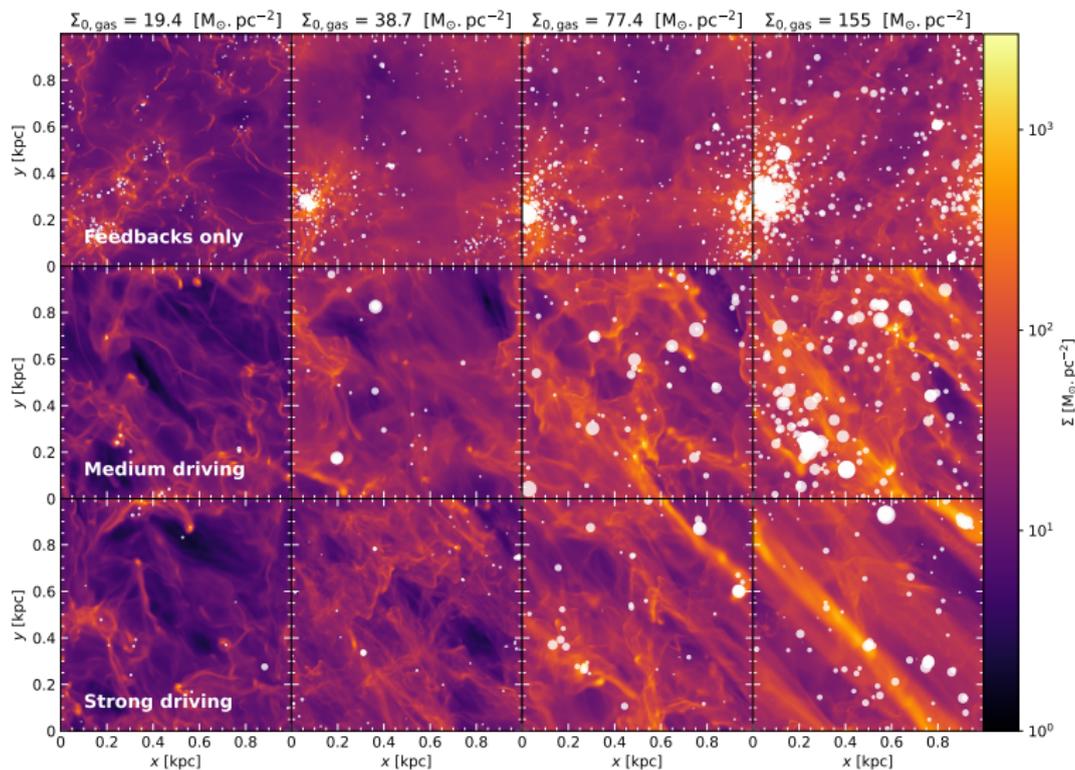
With large-scale turbulence driving

$\Sigma = 38.7 M_{\odot} \cdot \text{pc}^{-2}$, strong driving. Face on views of column density (left) and midplane density (right).

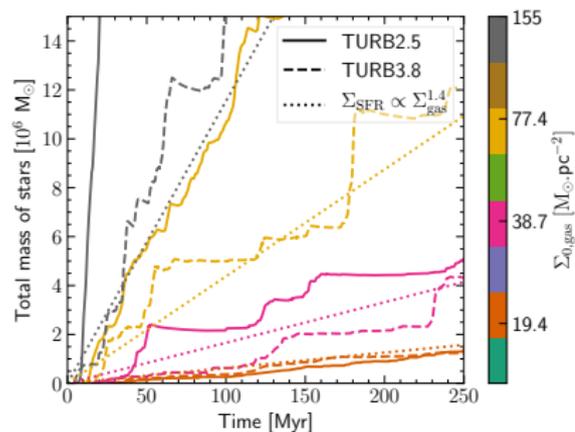


With large-scale turbulence driving

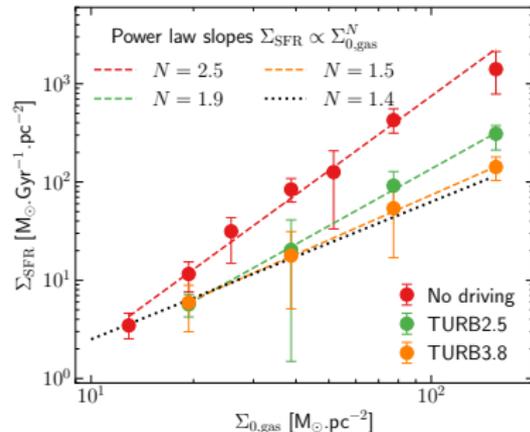
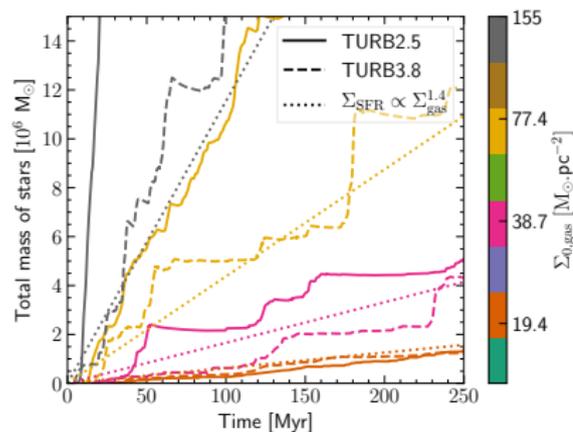
Column density maps - Comparison



With large-scale turbulence driving



With large-scale turbulence driving



With turbulent driving, the SFR closely follows the SK law

Constraining the turbulent driving

Is the turbulence we inject realistic 🤖 ?

Constraining the turbulent driving

Is the turbulence we inject realistic 🤔 ? we need to check ... 😞

Constraining the turbulent driving

Is the turbulence we inject realistic 😊 ? we need to check ... 😞

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

- ▶ 🕸 observational constraints: inputs welcome!
- ▶ 📄 compute it from galactic scale simulations.

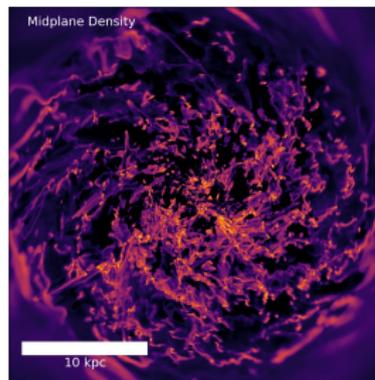
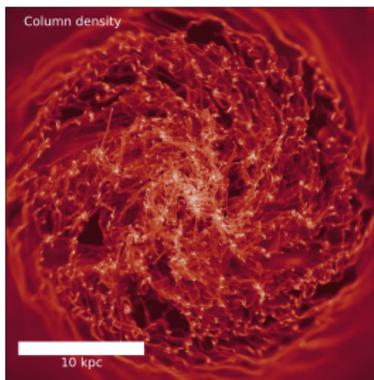
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Work in progress: setting up galactic scale simulations and measure turbulence



The plan

We model

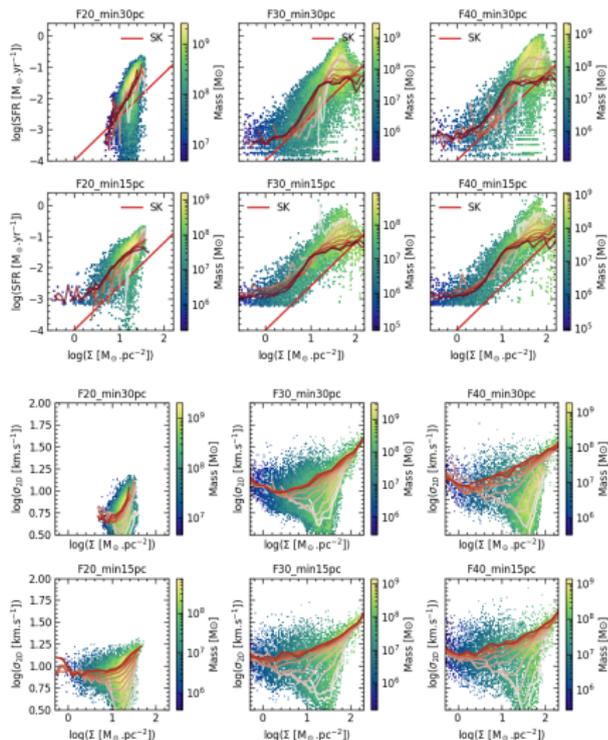
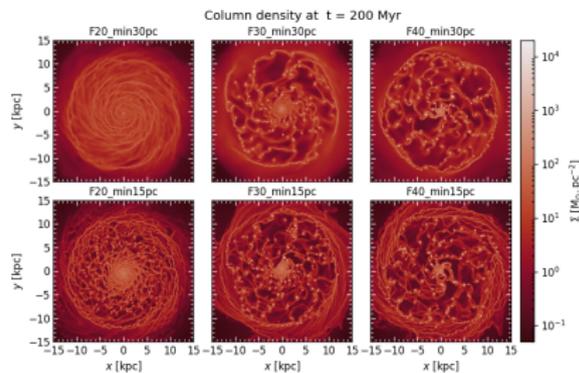
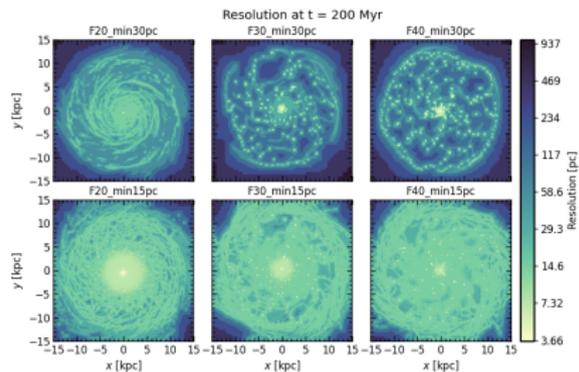
- ▶ Small (12 kpc radius) disk galaxies with gas fraction from 10 to 50 %.
- ▶ with high minimal resolution within the disk (7 pc)
- ▶ as a first step, no magnetic field

We look at

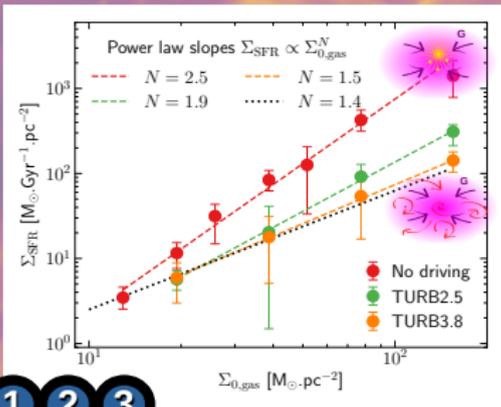
- ▶ the star formation rate
- ▶ the velocity dispersion at the kpc scale
- ▶ power spectrums, energy evolution, ...

First insights

 Preliminary 



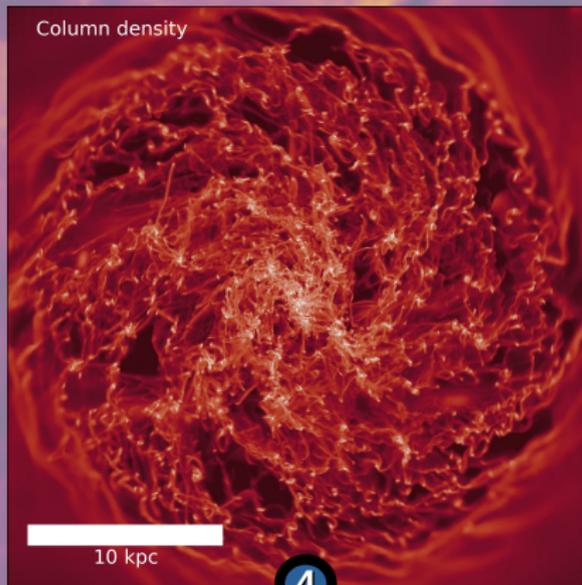
- 1 **Stellar feedback alone can explain the Schmidt-Kennicutt Law in MW-like galaxies.**
- 2 **But it is too weak in gas-rich galaxies (and by far !)**
- 3 **2D turbulent driving can reduce the SFR enough.**



1 2 3

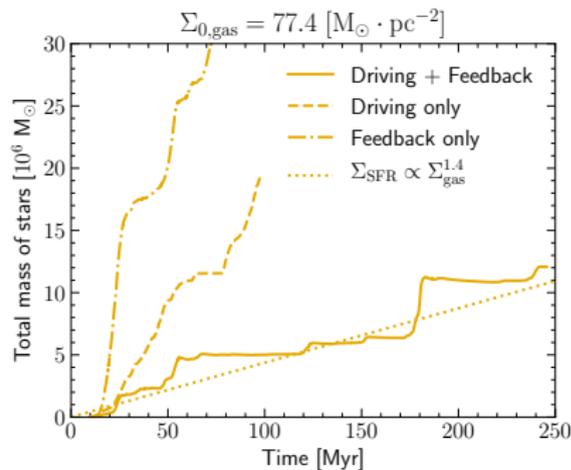
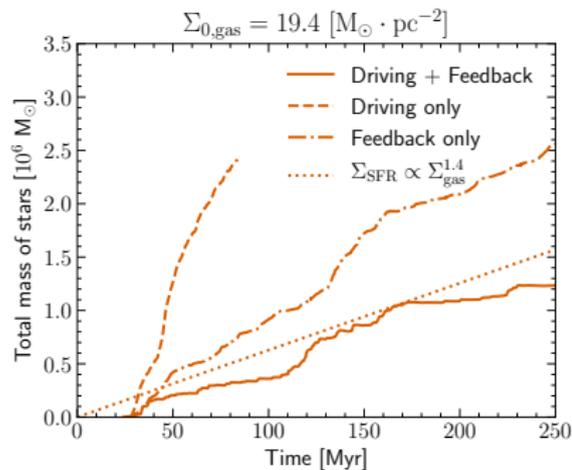
Box Simulations – Ramses-ISM

- 4 **The way forward: constrain kpc-scale turbulence via galactic disk simulations**



Galactic Simulations – Ramses

Is stellar feedback needed ?

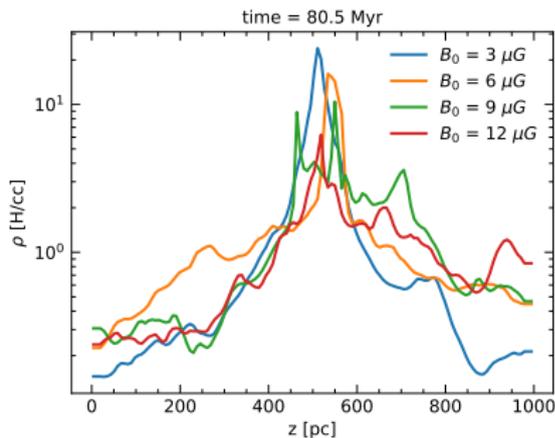
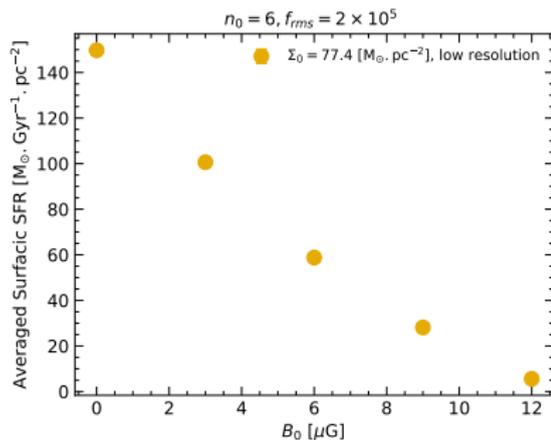


Stellar feedback remains necessary, but its importance decreases as the gas column density increases.

Follow-up: Influence of the magnetic field

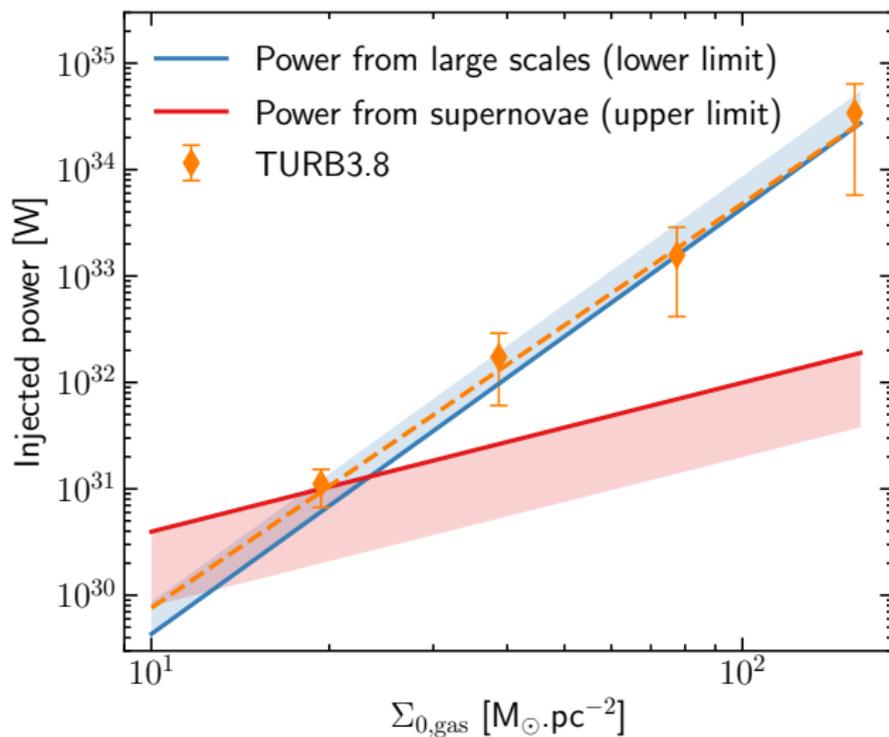
Internship of Simon Iteanu - preliminary work at low resolution

$$\text{Initial magnetic field } B_x(z) = B_0 \exp\left(-\frac{1}{2} \left(\frac{z}{z_0}\right)^2\right)$$

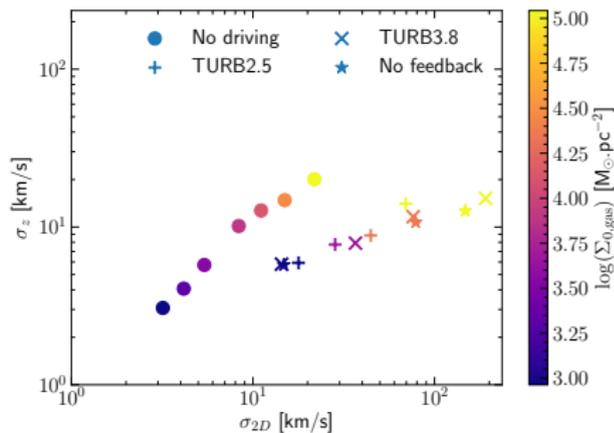
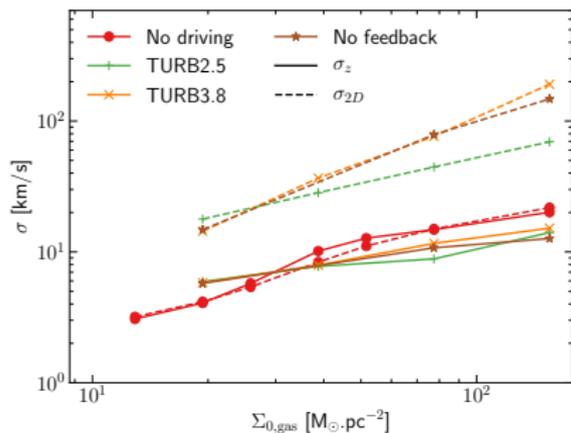


Stronger magnetic field increases disk height (via magnetic pressure) and reduce star formation.

Needed and available energy



A word about velocity dispersion



Velocity dispersion measured in the simulations, where

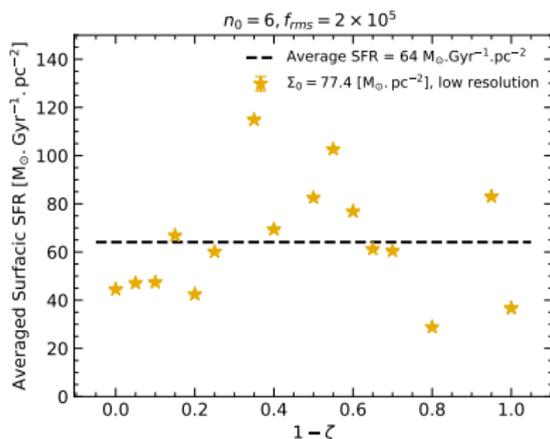
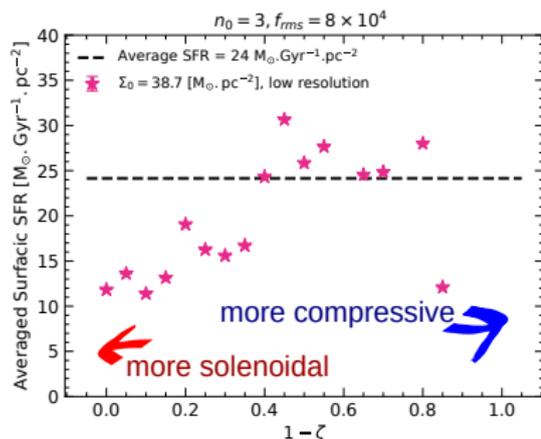
$$\sigma_{2D} = \sqrt{\sigma_x^2 + \sigma_y^2} / \sqrt{2}.$$

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

Follow-up: Influence of the compressibility

Internship of Simon Iteanu - preliminary work at low resolution

Study of the influence of the solenoidal forcing fraction ζ . $1 - \zeta$ is the compressive forcing fraction.

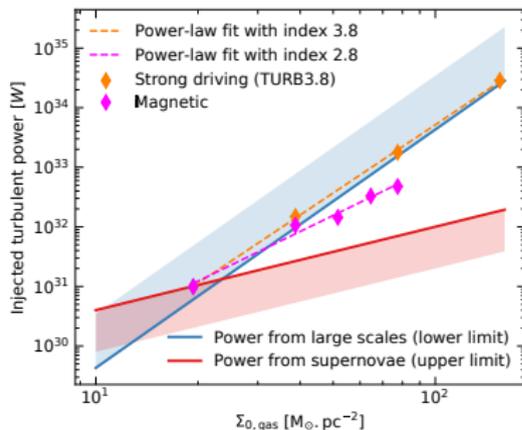
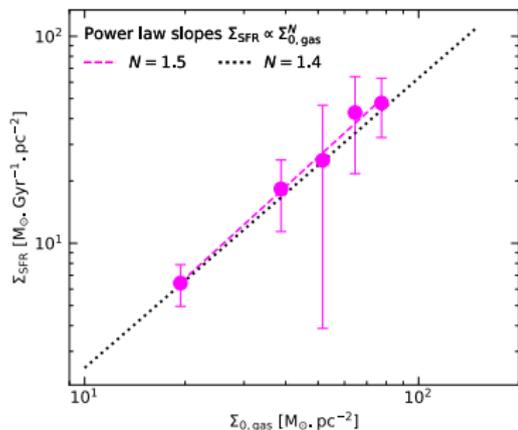


Solenoidal driving seems to quench star formation more efficiently.

Follow-up: Influence of the magnetic field

preliminary work

If the magnetic field scales with the column density (here $B_0 \propto \Sigma^{1/2}$), we can reproduce the SK law with less power injected from the turbulent driving).



With large-scale turbulence driving

Column density maps for the strongest driving

