What regulates the star formation rate in galaxies?

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Plan of the talk

Star formation rate in kpc box simulations

- -is stellar feedback sufficient?
- -the probable role of turbulence (and magnetic field)

A multi-scale analytical model of turbulence regulated SFR

- -the « classical » SFR models
- -the need for more physically motivated models
- -new model and its prediction
- -comparison with a set of idealised simulations

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What regulates star formation in the Galaxy / galaxies?

-low (few percent) efficiency of star formation
-Schmidt-Kennicutt relation: $d\Sigma/dt \propto \Sigma^{1-1.4}$

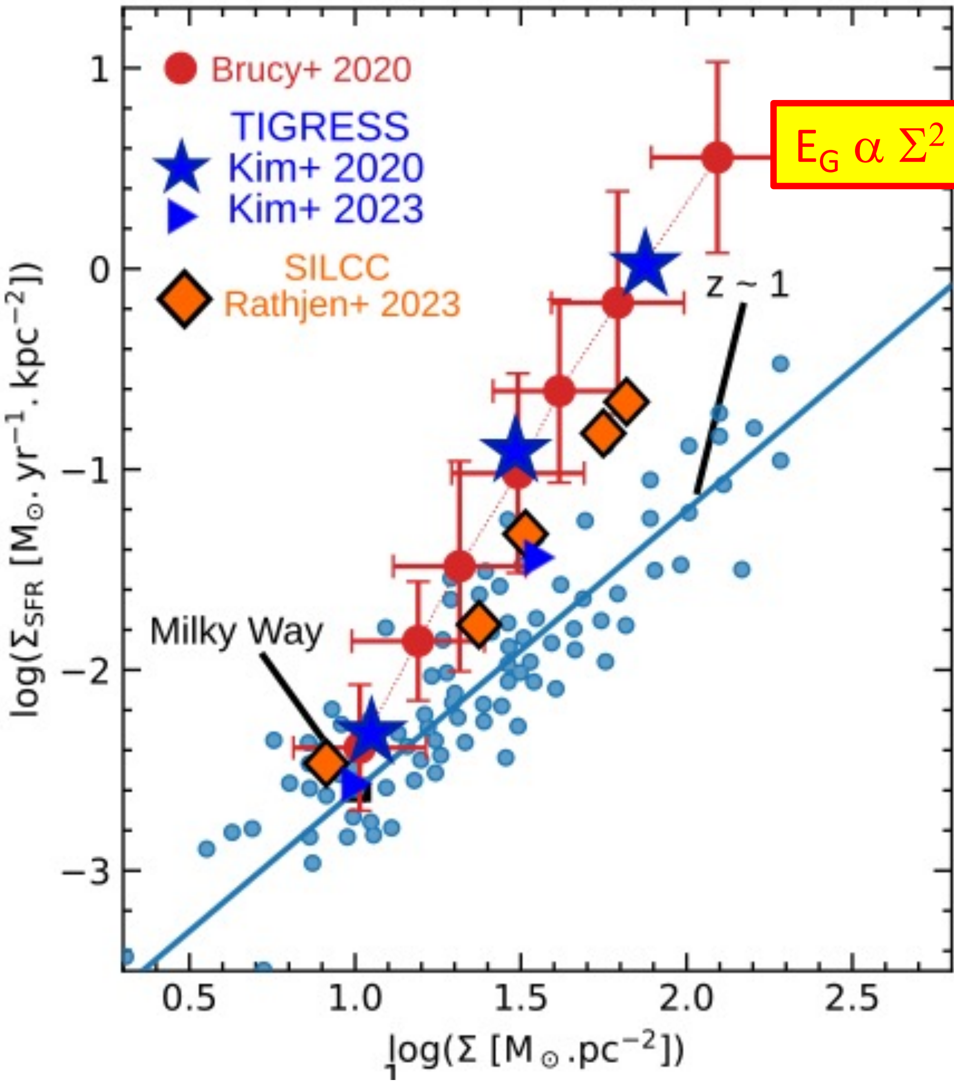
-Magnetic field
If strong enough, magnetic field counteract efficiently gravity, it then diffuses through ambipolar diffusion – Problem: field may not be strong enough
e.g. Mouschovias 1977, Shu+ 1987

-Turbulence
Dual role of turbulence which both compresses the gas through shocks and disperse the gas. Problem: turbulence decays in one freefall time
e.g. MacLow & Klessen 2004, H&Falgarone 2012

-Stellar Feedback
Likely important to inject turbulence in the ISM and to disrupt molecular clouds
Difficulty: A broad diversity of feedback and environments – hard to assess
e.g. Krumholz+2015, Girichidis+2020

Perhaps more fundamentally:
$E_G \propto \Sigma^2$ but $E_{feed} \propto \Sigma^{1-1.4}$

Trying to reproduce Schmidt-Kennicutt relation in kpc galactic boxes self-regulated ISM (see Naab's talk)



$E_G \ \alpha \ \Sigma^2$ but $E_{feed} \ \alpha \ \Sigma^{1-1.4}$

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Why is feedback regulated ISM failing to reproduce SK relation? The role of externally driven turbulence?

What sources of turbulence do we foresee?

The gas orbital energy of the galaxy which is tapped by gravitational instabilities (Bournaud et al. 2010, Krumholz et al. 2018)

Maximum ε ? $\varepsilon \sim V_{rot}^3/R$ => enormous source of free energy

How do we drive?

$$d\hat{\boldsymbol{f}}(\boldsymbol{k},t) = -\hat{\boldsymbol{f}}(\boldsymbol{k},t)\frac{dt}{T} + F_0(\boldsymbol{k})\boldsymbol{P}_\zeta\left(\begin{pmatrix} k_x \\ k_y \\ 0 \end{pmatrix}\right)\cdot d\boldsymbol{W}_t$$

(Schmidt+2006,2009)

Bidimensional driving

75% solenoidal modes – compressible forcing change our conclusion quantitatively

How intensively do we drive?

$$\epsilon \sim \frac{v_l^3}{l} \propto \sigma^3 \qquad Q = \frac{c_s\kappa}{\pi\Sigma G} \propto \frac{\sigma\kappa}{\Sigma} \qquad \epsilon \propto \Sigma^3. \qquad P_{\rm inj} \propto \Sigma^4.$$

(incidently note that feedback provides "only" $P_{inj} \propto \Sigma^{1.4}$)

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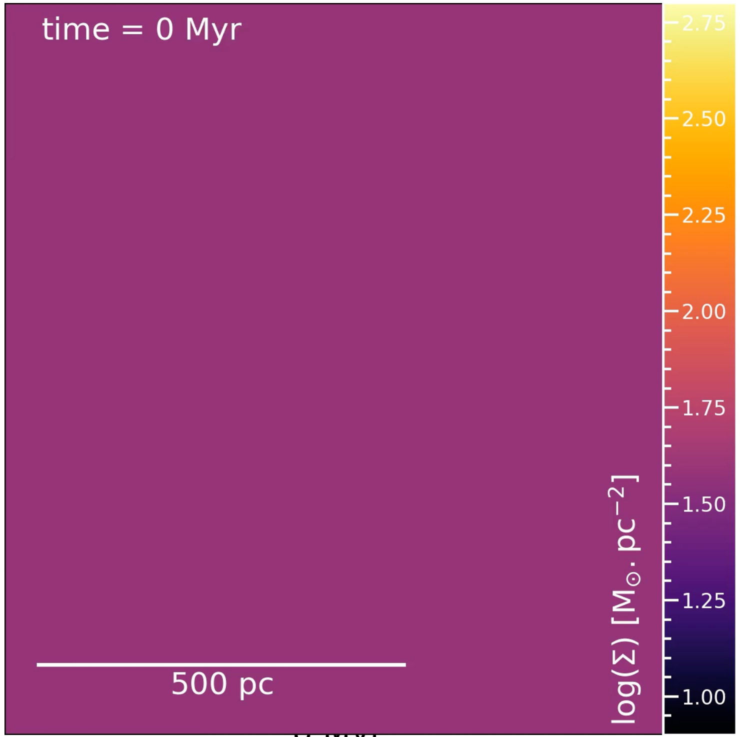
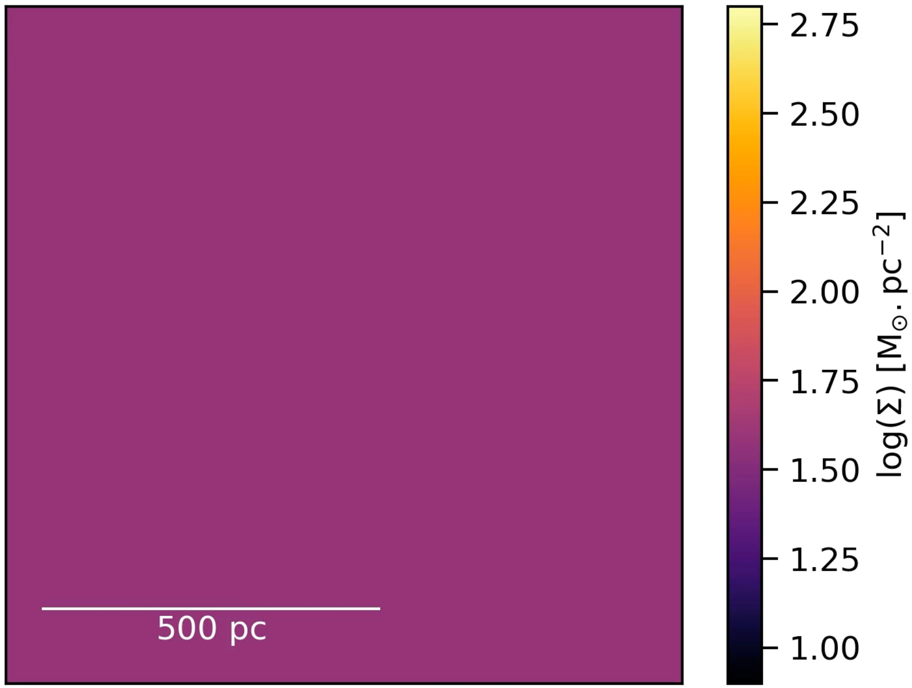
Without driving



$E_G \propto \Sigma^2$ but $E_{feed} \propto \Sigma^{1-1.4}$

With “sufficient” driving



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Externally driven turbulence is able to explain Schmidt-Kennicutt (if sufficiently strong driving is applied…)

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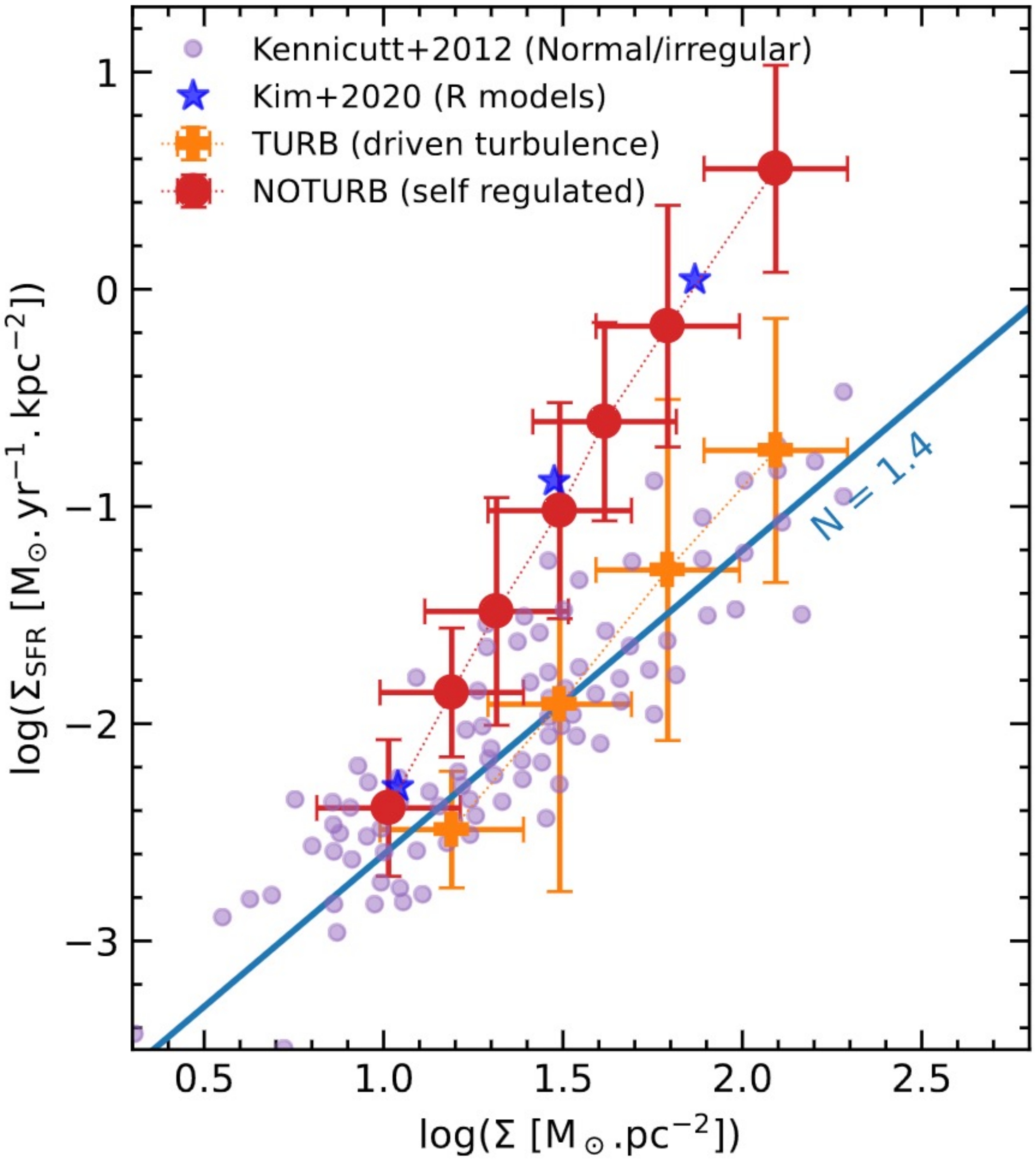

Kennicutt & Evans 2012

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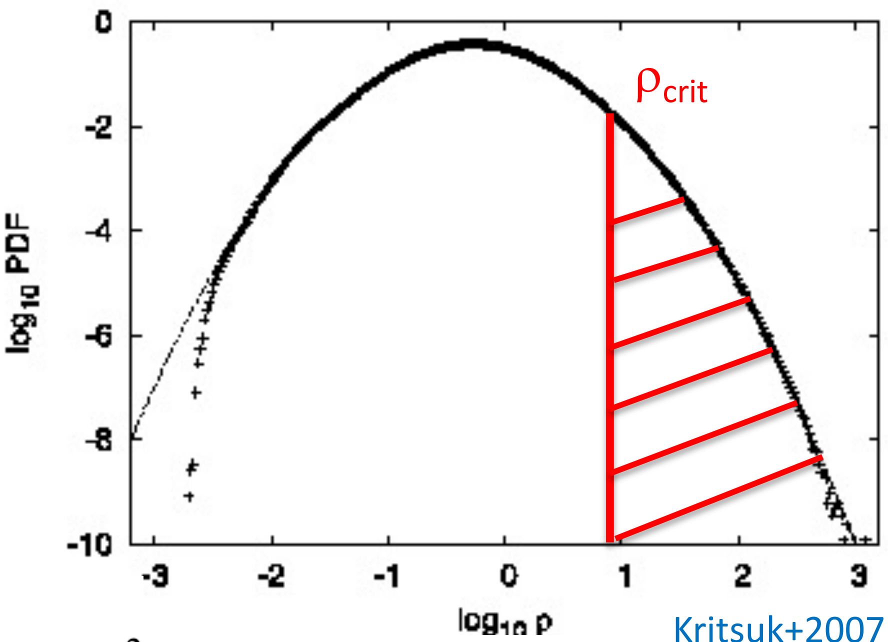
Classical analytical models for the Star formation rate

Krumholz&McKee 2005, Padoan&Nordlund 2011, H&Chabrier 2011, 2013, Renaud+2012

Log-normal PDF : turbulence and no gravity

$$\mathcal{P}(\delta) = \frac{1}{\sqrt{2\pi\sigma_0^2}} \exp\left(-\frac{(\delta-\bar{\delta})^2}{2\sigma_0^2}\right), \quad \delta = \ln(\rho/\rho_0)$$

$$\bar{\delta} = -\sigma_0^2/2\,, \quad \sigma_0^2 = \ln(1+b^2\mathcal{M}^2),$$



Kritsuk+2007

Critical density from sonic length

$$\lambda_s = R_0\left(\frac{c_s}{\sigma_0}\right)^2 = R_0\mathcal{M}^{-2}, \qquad \rho_{\rm crit,KM} = \pi\frac{c_s^2\mathcal{M}^4}{G R_0^2} = \frac{4}{5}\pi\rho_0\alpha_{\rm vir}\mathcal{M}^2$$

Summing-up over the PDF weighted by mass and freefall

$$\mathrm{SFR}_{ff}^{\rm simp} = \epsilon\int_{\delta_{\rm crit}}^{\infty}\frac{\tau_{ff}^0}{\tau_{ff}(\rho)\phi_t}\widetilde{\rho}\mathcal{P}(\delta)d\delta = \frac{\epsilon}{\phi_t}\int_{\delta_{\rm crit}}^{\infty}\widetilde{\rho}^{3/2}\mathcal{P}(\delta)d\delta$$

$$= \frac{\epsilon}{2\phi_t}\exp\left(3\sigma_0^2/8\right)\left[1+\mathrm{erf}\left(\frac{\sigma_0^2-\ln(\widetilde{\rho}_{\rm crit})}{2^{1/2}\sigma_0}\right)\right]. \quad (8)$$

H&Chabrier 2011

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Why a freefall time rather than a replenishement time?

The density PDF over which we integrate, is set by turbulence
The question is then over which timescale dense gas is being replenished
There is no reason that the dense gas is replenished in a local freefall time

Why a density threshold?

A piece of fluid can collapse at any density if big enough

Why no turbulent support?

Turbulence can disperse a piece of fluid if strong enough

Why spatial distribution of mass not accounted for?

Flows with very different powerspectra can have same PDF
Flows broken in small entities may be stable against gravity

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An analytical model to predict the star formation rate

(Press & Schecter 1974, H&Chabrier 2008)

Unstable mass at scale R from density PDF

$$M_{\rm tot}(R) = M_0 \int_{\delta_{\rm crit}(R)}^{\infty} e^{\delta} \mathcal{P}_R(\delta) {\rm d}\delta.$$

Unstable mass at scale R from cloud spectrum

$$M_{\rm tot}(R) = \int_0^{M_{\rm crit}(R)} M \mathcal{N}(M)\, {\rm d}M.$$

M_{crit}, ρ_{crit} from virial analysis:

$$M_{\rm crit}(R) = \frac{a_v}{G} R \left(3c_s^2 + \sigma_0 \left(\frac{R}{R_0} \right)^{2\eta_v} \right).$$

Taking the derivative with respect to R:

$$\mathcal{N}(M_{\rm crit}) = \mathcal{N}_1 + \mathcal{N}_2 = \qquad (26)$$

$$\frac{\rho_0}{M_{\rm crit}} \frac{{\rm d}R}{{\rm d}M_{\rm crit}} \times \left(-\frac{{\rm d}\delta_{\rm crit}}{{\rm d}R} \exp(\delta_{\rm crit}) \mathcal{P}_R(\delta_{\rm crit}) + \int_{\delta_{\rm crit}}^{\infty} \exp(\delta) \frac{{\rm d}\mathcal{P}_R}{{\rm d}R} {\rm d}\delta \right),$$

Summing over the unstable cores divided by the replenishment time

$$\mathrm{SFR}_{\rm ff} = \mathrm{SFR} \frac{\tau_{\rm ff,0}}{\rho_0 L_0^3} = \int_0^{\tilde{M}_{\rm sup}} \frac{\tilde{\mathcal{N}}(\tilde{M}) \tilde{M}}{\tilde{\tau}_{\rm cont}(R)} {\rm d}\tilde{M},$$

We get the SFR as a function of Mach number, density PDF, density variance.

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An estimate of the replenishment time
« PDF » weigthed turbulent scale dependent crossing time

$$\tau_{\rm cross}(R') = \frac{R'}{\sigma(R')}, \qquad \sigma(R') = \sigma_0 \left(\frac{R'}{L_i}\right)^{\eta_v} \qquad R'/R = \rho/\rho'.$$

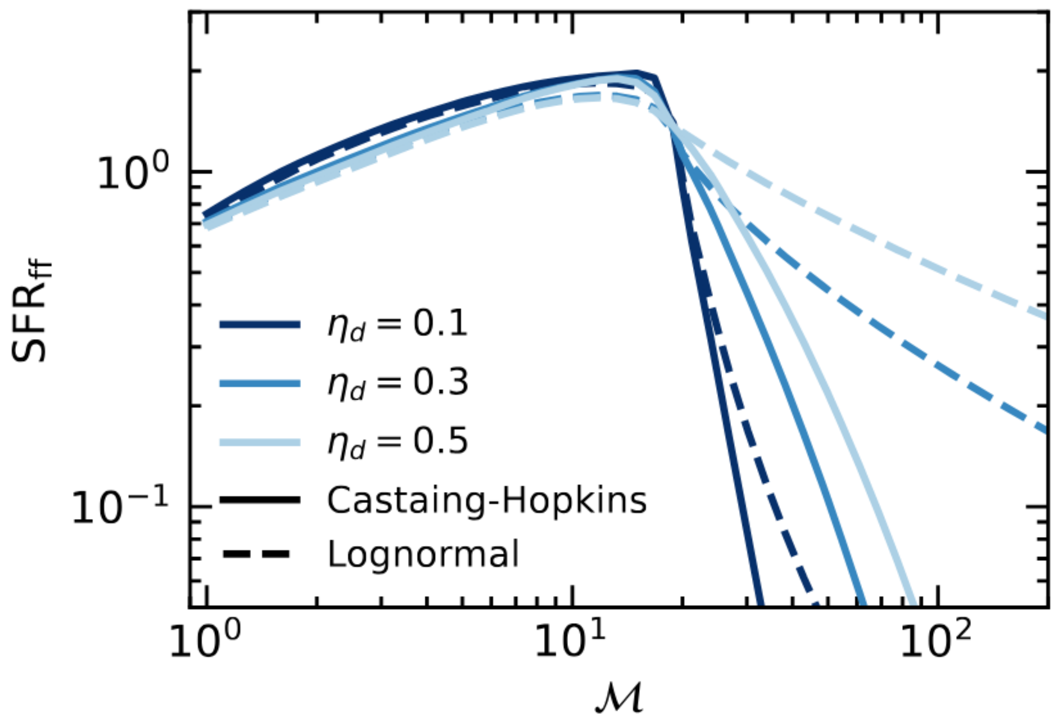
$$\tau_{R,R'} = \frac{\tau_{\rm cross}(R')}{\epsilon(R,R')} = \frac{L_i^{\eta_v}}{\epsilon(R,R')\sigma_0} R^{1-\eta_v} \left(\frac{\rho}{\rho'}\right)^{1-\eta_v}$$

$$\tau_{\rm rep}(R) = \frac{\int_{-\infty}^{\ln(\rho)} \tau_{R,R'} \rho' \mathcal{P}(\rho')\, {\rm d}\ln(\rho')}{\int_{-\infty}^{\ln(\rho)} \rho' \mathcal{P}(\rho')\, {\rm d}\ln(\rho')},$$

$$= \frac{L_i^{\eta_v}}{\sigma_0} R^{1-\eta_v} \rho^{1-\eta_v} \frac{\int_{-\infty}^{\ln(\rho)} \epsilon(R,R')^{-1} (\rho')^{\eta_v} \mathcal{P}(\rho')\, {\rm d}\ln(\rho')}{\int_{-\infty}^{\ln(\rho)} \rho' \mathcal{P}(\rho')\, {\rm d}\ln(\rho')},$$

Predicted SFR as a function of Mach number for different log ρ powerspectra

Most important feature: at high Mach, the SFR drops steeply.



6 cases corresponding to

-2 different PDF
-3 different powerspectrum of log ρ

This happens when:
the turbulent injection length / the size of the system is comparable to the *turbulent Jeans length*

=> No available gravitationally unstable density fluctuations

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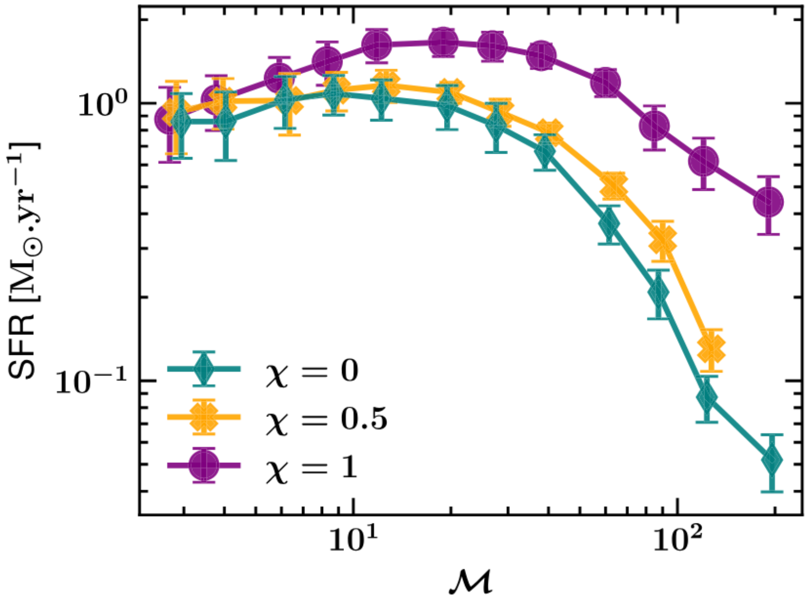
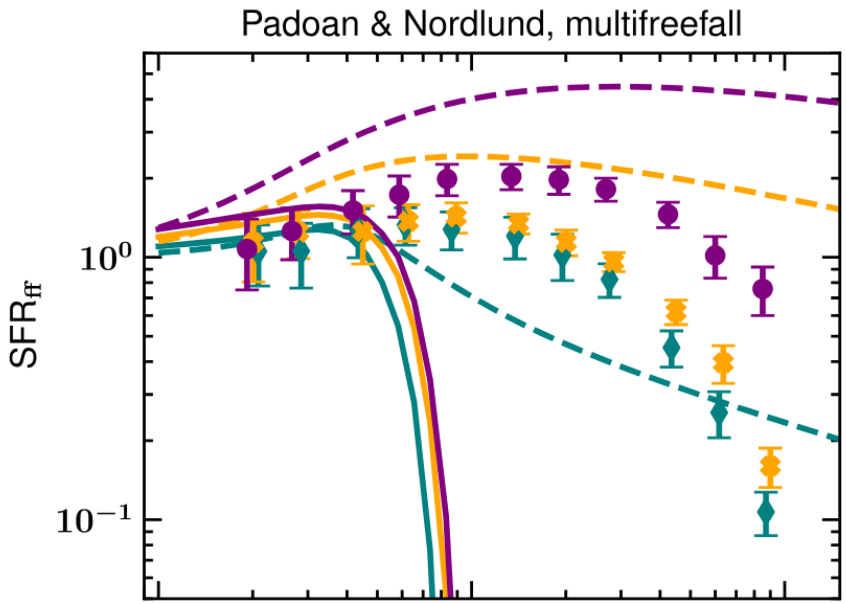
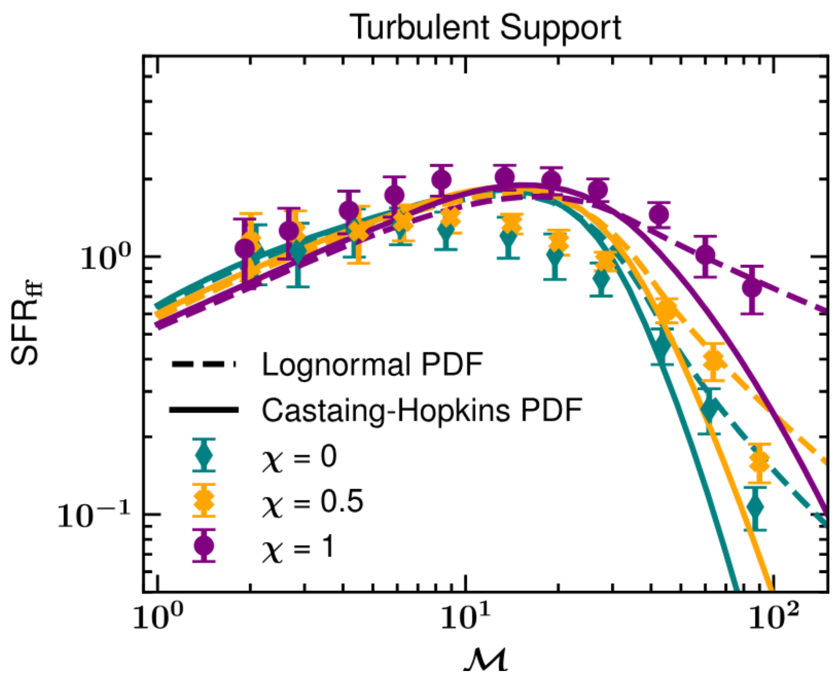
SFR from idealised (isothermal/no feedback) simulations
Comparison with analytical models







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Conclusions

-Galactic box simulations seem to require external driving and/or strong magnetization
Stellar feedback is not enough

-Classical SFR models suffer strong inconsistencies and fail to reproduce high Mach simulations

-Turbulent support model seems to be doing a reasonable job but several properties such as density pdf, density powerspectrum are needed

-the SK relation is likely a consequence of turbulence+magnetic field+stellar feedback