Non-universal star formation in turbulent interstellar medium

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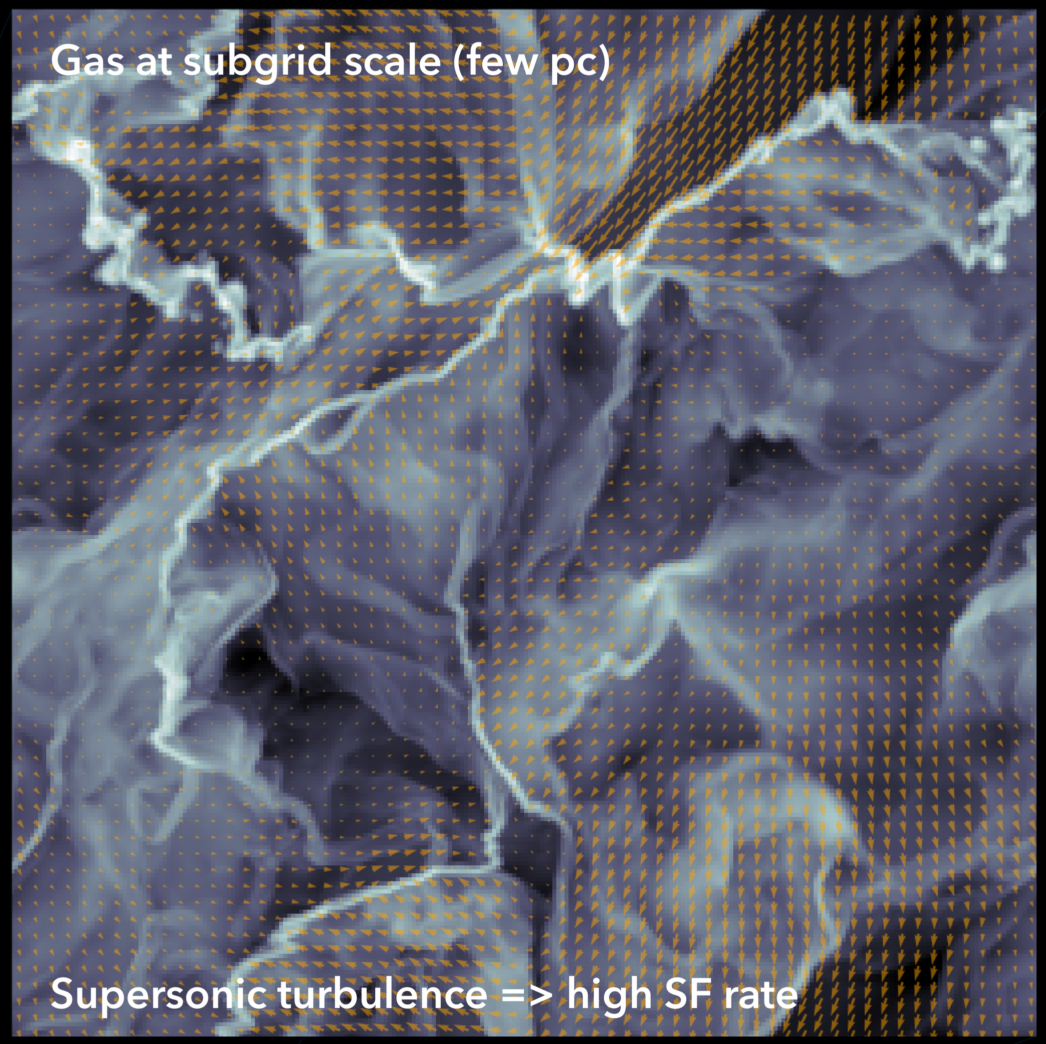
ABSTRACT. Recent observational evidence indicates variation of efficiencies at which giant molecular clouds (GMCs) convert their gas into stars. Consistent theory of galaxy formation must explain such variation. Common numerical models, in which star formation efficiency (SFE) is assumed constant (at the level of few %) above certain density threshold, by their design are not suitable for this purpose. Theoretically, variation of SFE is attributed to the turbulent nature of interstellar medium. Unfortunately, state-of-art galaxy formation models lack relevant small-scale motions due to limited resolution that hardly reaches typical scale of the largest GMCs (few 10 pc). However, with an appropriate subgrid model of turbulence star formation can be connected to resolved dynamics with the aid of theoretical and numerical models of star formation in turbulent medium. In this work we implement such model coupled with prescription for star formation in compressible MHD turbulence. We find that our model predicts distribution of r.m.s. turbulent velocities consistent with local and extragalactic observations (on average few km/s on 100 pc scale). In our model turbulence is produced in warm gas ($T \sim 10^4$ K) at level of few km/s and is amplified by compression in spiral arms up to few tens km/s. As far as star formation is concerned, in our simulation we observe distribution of rates that is in a good agreement with both local GMCs data and resolved extragalactic star formation maps. The resulting variation of efficiency is found to be due to scatter in turbulent properties. Our model predicts high abundance of molecular gas inefficiently forming stars along with existence of very efficient GMCs.



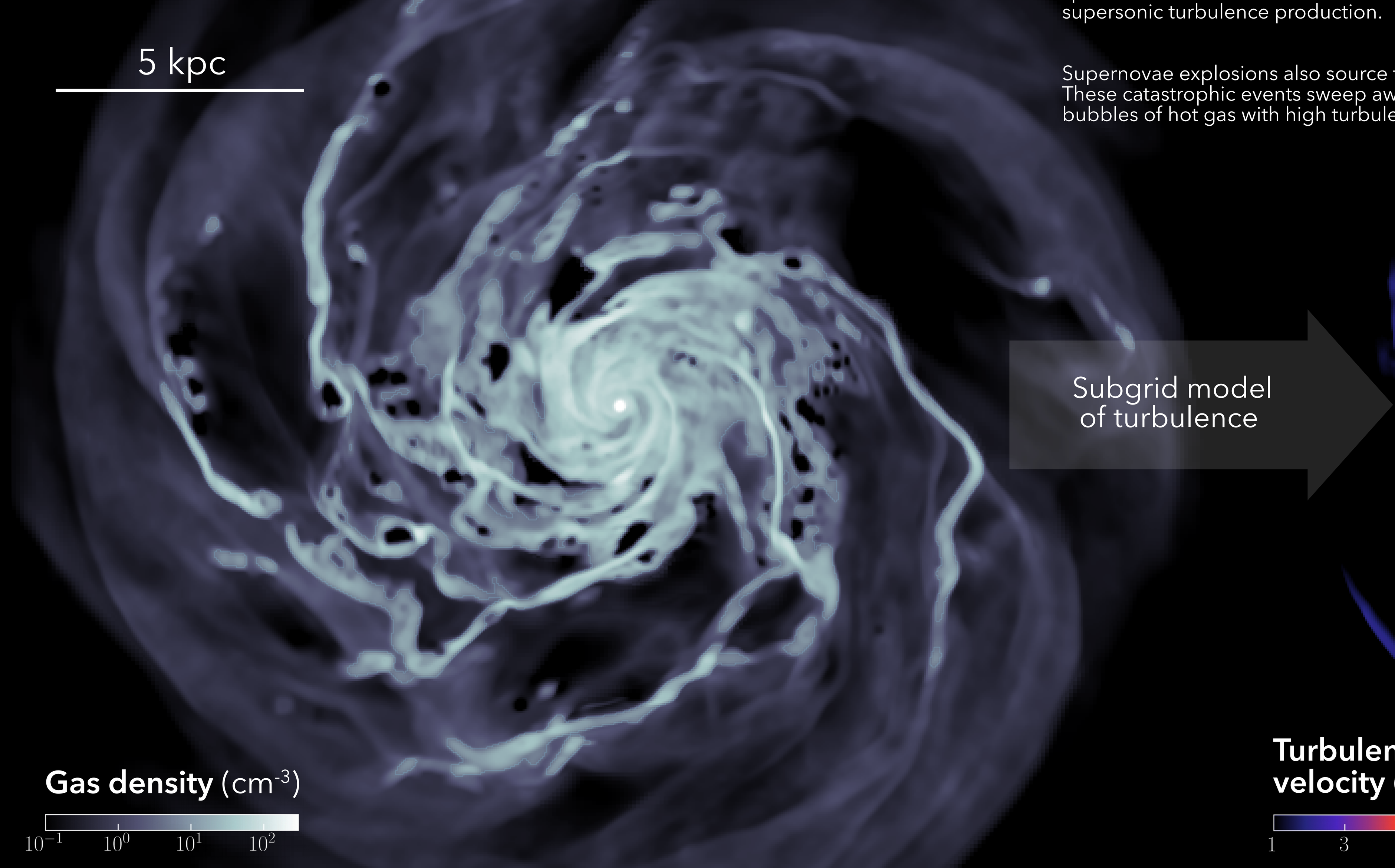
CONNECTION BETWEEN TURBULENCE AND STAR FORMATION. Stars are formed in turbulent dense regions of interstellar medium (ISM) called giant molecular clouds. Typical size of these clouds varies from few pc up to about hundred pc. These clouds are relatively cold ($T \sim 10 - 100$ K) and typical turbulent velocities of their gas (~10 km/s) are **supersonic**. In this regime turbulence becomes compressible. Supersonic random motions produce shock waves. Overlapping shocks create density caustics where gas may become gravitationally unstable. Further collapse results in formation of stars. Therefore, overall rate at which gas is converted into stars in GMCs is a result of interplay between gravity and MHD turbulence.
In the **trans-** and **subsonic** regime outside GMCs hot gas is well supported against gravity by thermal motions. Turbulence is weakly compressible and velocity field is solenoidal. Therefore, this gas does not produce stars. Turbulence in hot gas (~10^4 K) in between spiral arms is well in subsonic regime.

FACE-ON MILKY WAY LIKE GALAXY (simulation results):

The Adaptive Mesh Refinement (ART) code

disk mass = 4.3×10^{10} M_{sun}
gas fraction = 0.2

minimal cell size = 40 pc

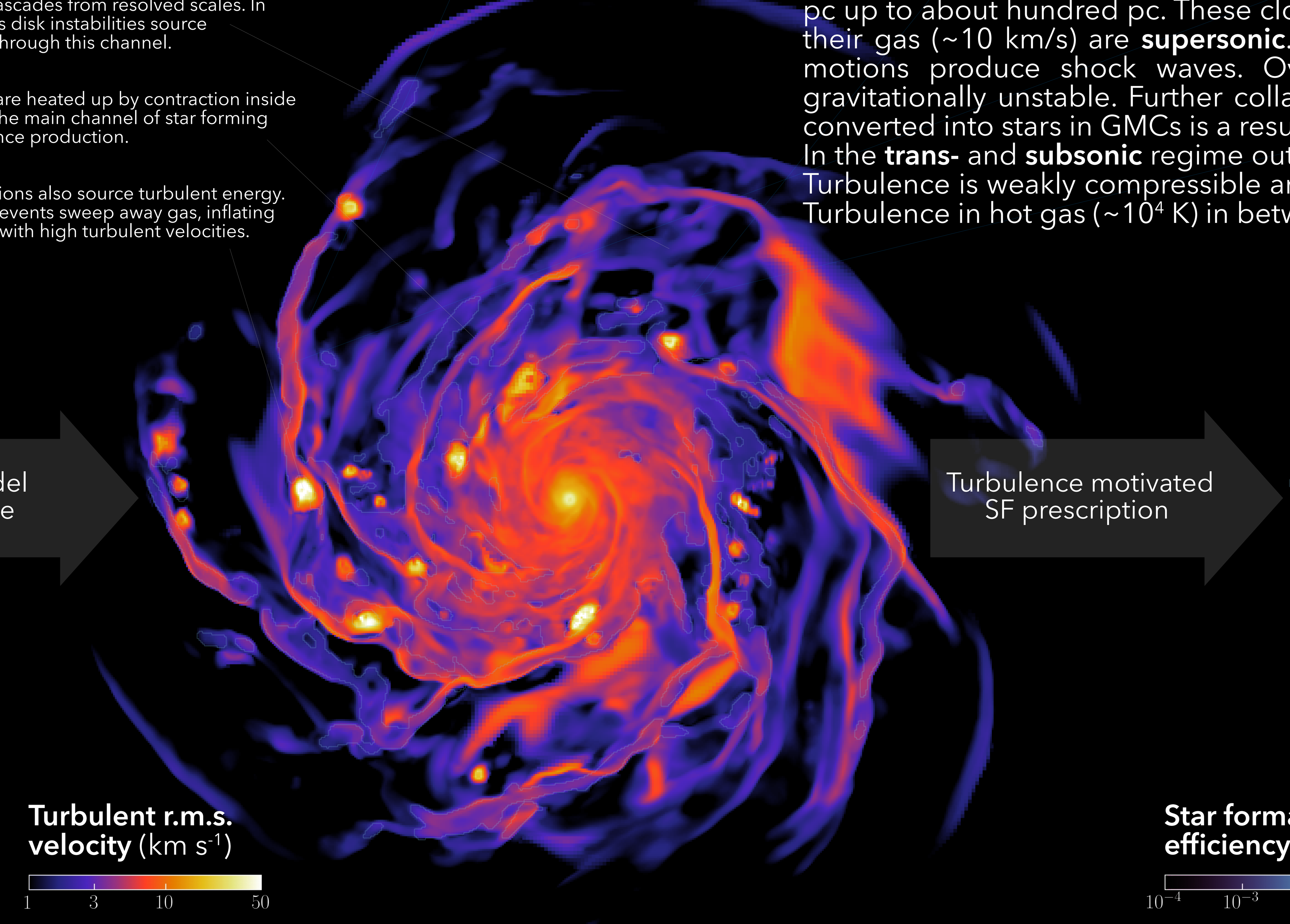


Main sources of turbulence:

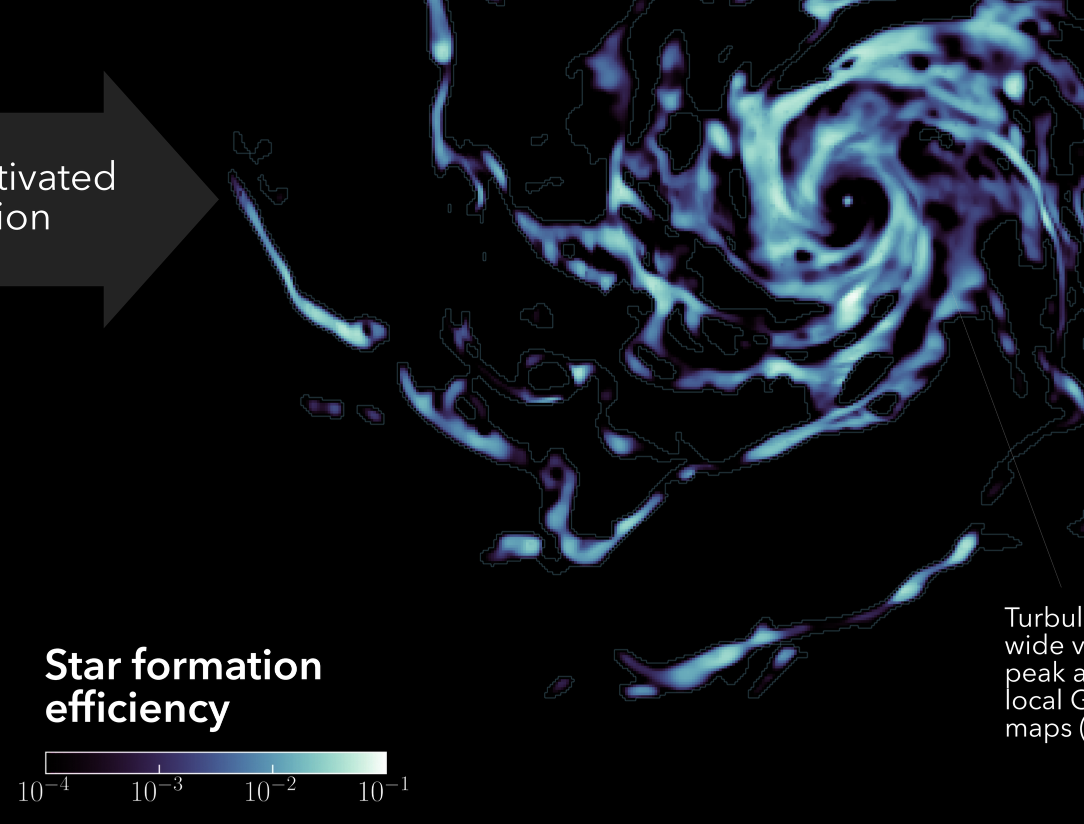
Turbulent energy cascades from resolved scales. In between spiral arms disk instabilities source turbulence mainly through this channel.

Turbulent motions are heated up by contraction inside spiral arms. This is the main channel of star forming supersonic turbulence production.

Supernovae explosions also source turbulent energy. These catastrophic events sweep away gas, inflating bubbles of hot gas with high turbulent velocities.



Usual star formation prescription based on density and temperature thresholds would result in constant efficiency within this contour. This approach neglects observed wide variation of star formation efficiencies.



Turbulent model of star formation does predict wide variation of SFE (up to ~10% with the main peak at ~0.1%) consistent with observations of local GMCs and extragalactic star formation maps (Semenov, Kravtsov & Gnedin, in prep.).

The state-of-art galaxy formation simulations have limited resolution and do not resolve scales of typical GMCs (few to hundred pc). Therefore, these simulations lack information on turbulent motions relevant for star formation. However, as well as other important but computationally intractable processes (cooling, supernova feedback, etc.) this unresolved turbulence can be treated with an appropriate subgrid model. In our AMR simulation of isolated Milky Way like disk we implement the model described by Schmidt et al. (2014). This subgrid model connects unresolved turbulence to resolved dynamics of hydrodynamical flows and predicts how much turbulent energy is contained in each computational cell.

REFERENCES:
Padoan, P., Haugbølle, T., & Nordlund, Å. 2012, ApJ, 759, L27
Robertson, B., & Goldreich, P. 2012, ApJ, 750, L31
Schmidt, W., et al. 2014, MNRAS, 440, 3051

The implemented subgrid model treats turbulence as an additional energy field. This field is self-consistently evolved by a separate hydrodynamical equation similarly to thermal energy. Subgrid turbulence is coupled to resolved dynamics via turbulent cascade and non-thermal component of pressure. As well as thermal pressure this turbulent component does work during volume change. Thus, turbulence heats up (cools down) during adiabatic contraction (expansion) of gas (Robertson & Goldreich, 2012). In our simulations this proved to be the main source of supersonic turbulence production in the regions of high star formation rate. The model also includes sourcing by supernovae, turbulent diffusion and dissipation into heat on physically motivated timescale. This model successfully predicts observed average turbulent velocity in Milky Way like galaxies (few km/s on 100 pc scale).

In numerical simulations star formation is usually parametrized by the efficiency at which gas is converted into stars per free-fall time:

$$\dot{\rho}_\star = \epsilon_{\rm ff} \rho / t_{\rm ff}$$

The star formation efficiency (SFE) is typically assumed to be universal (few %) with some artificial thresholds in density and temperature ($T < T_{cr}$ and $\rho > \rho_{cr}$). However, numerical simulations of self-gravitating supersonic MHD turbulence show that star formation efficiency does vary depending on turbulent properties of GMCs. Padoan et al. (2012) found that SFE exponentially decreases with increasing ratio of the free-fall time to the turbulent crossing time. Free-fall time depends only on gas density and therefore is easily accessible in simulations. Turbulent crossing time on the other hand can be derived from the output of the subgrid turbulence model.