Modelling star formation in galaxy formation simulations

```
double SFR(int cell) {
  double density = cell_gas_density(cell);
  double v_turb_2 = 2.*cell_gas_turbulent_energy(cell)/density;
  double c_s_2 = cell_gas_gamma(cell)*(cell_gas_gamma(cell)-1.0)*cell_gas_internal_energy(cell)/density;

  double t_ff_code = sfr.t_ff_factor/sqrt(density);
  double t_dyn_code = sfr.t_dyn_factor/sqrt( v_turb_2 + c_s_2 );

  return density/t_ff_code * sfr.efficiency*exp(-sfr.slope*t_ff_code/t_dyn_code);
}
```

Vadim Semenov (U.Chicago)

Andrey Kravtsov
University of Chicago

"Carving through the codes"
Davos, Switzerland
16 February, 2017

Nick Gnedin (Fermilab)

star formation in the real universe


```
double SFR(int cell) {
  double density = cell_gas_density(cell);
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  return density/t_ff_code * sfr.efficiency*exp(     r.slope*t_ff_code/t_dyn_code);
}
```
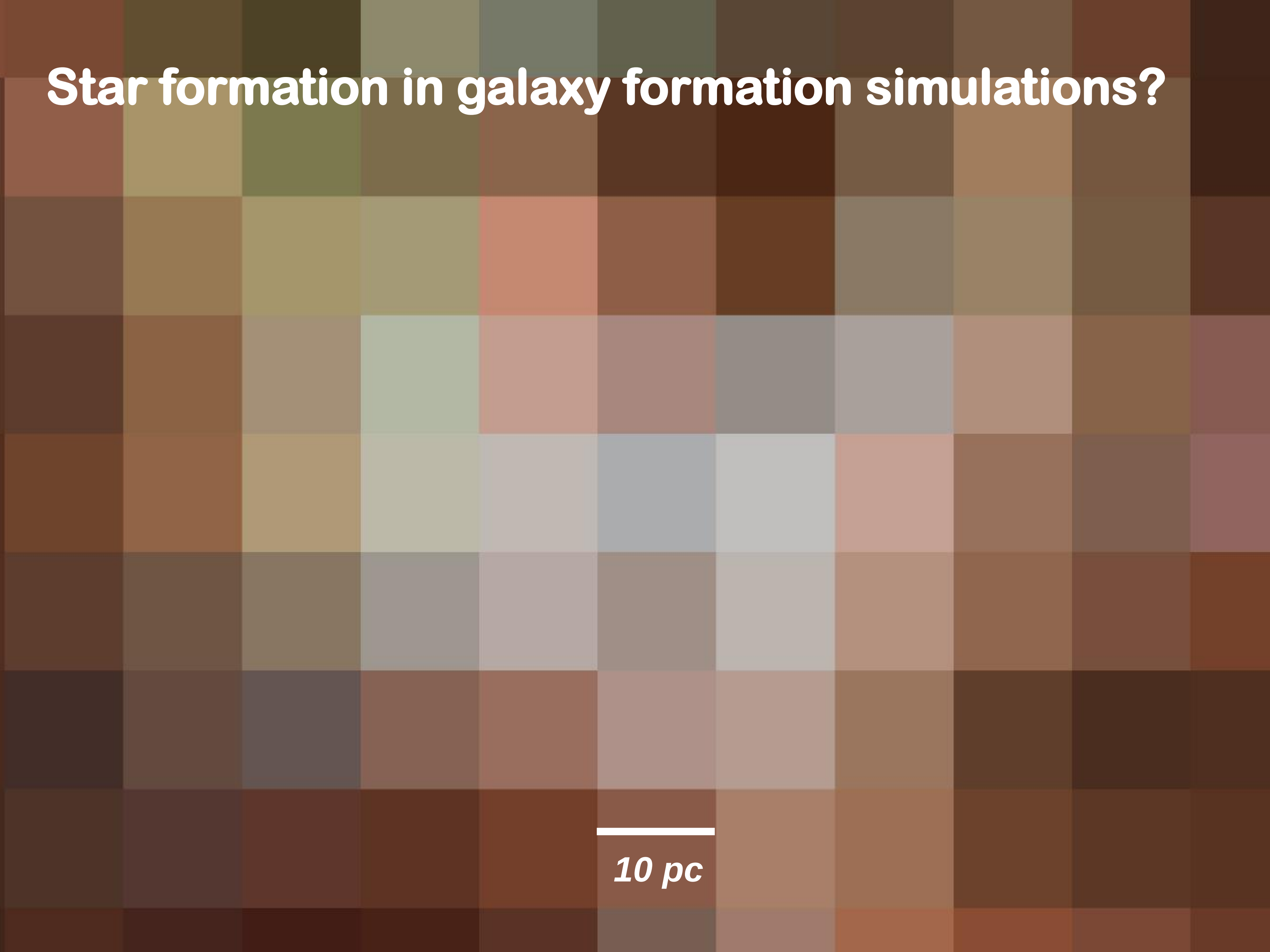

Star formation in galaxy formation simulations?



Star formation in the ART code

```
double SFR(int cell) {
  double density = cell_gas_density(cell);
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}
```

$$\dot{\rho}_\star = \frac{\rho_g}{t_{ff}} \epsilon_{ff} \qquad \epsilon_{ff} = \epsilon_w \exp(-s\, t_{ff}/t_{cross})$$

free-fall time: $t_{ff} = \sqrt{\frac{3\pi}{32 G \rho_g}}$

turbulent crossing time: $t_{cross} = \frac{\Delta_{cell}}{2\sigma_{turb}}$

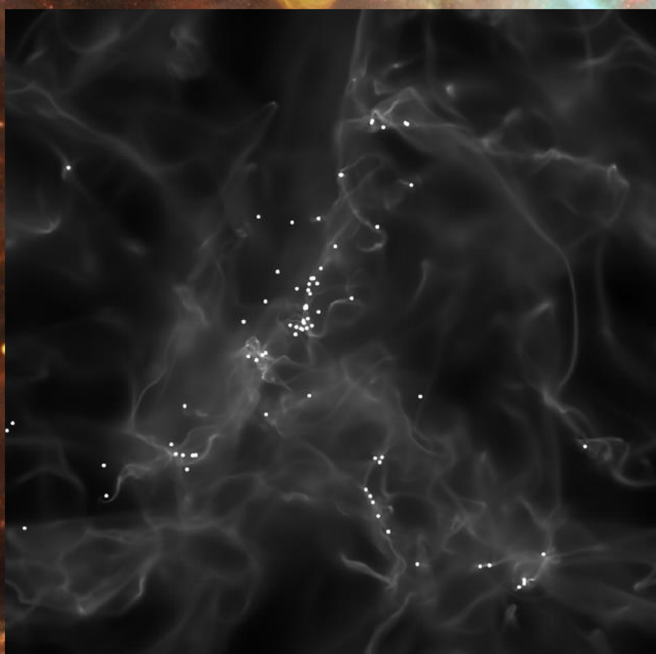
$\epsilon_w \approx 0.3 - 1.0$ = fraction of mass ejected by proto-stars in winds

$s = 1.6$ = constant derived from fit to simulation of supersonic turbulent boxes with star formation modelling by sink particles

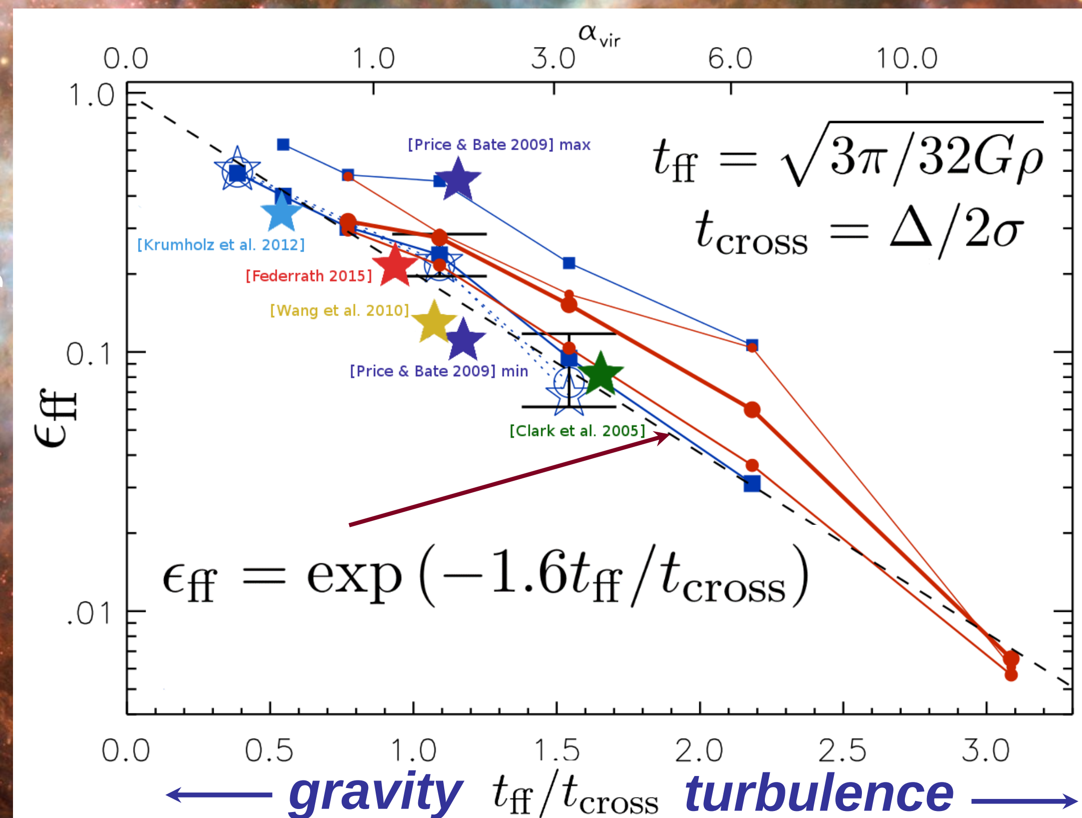
Results of recent simulations of star formation in turbulent medium

Elmegreen '02; Krumholz & McKee '05; Hennebelle & Chabrier '11, Padoan & Nordlund '11, Salim et al. '16 – turbulence-based models of star formation and numerical simulations show that SF efficiency is a simple function of $\alpha_{\rm vir}$

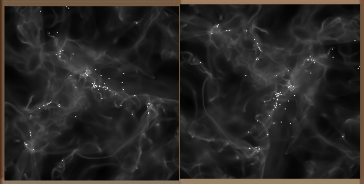
Padoan, Haugbolle, Nordlund '12 found that local efficiency of star formation per free fall time is a simple exponential function of the local ratio of free-fall and turbulent crossing time scales



SF efficiency



Star formation in the ART code



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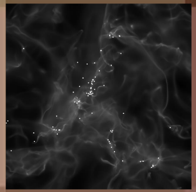

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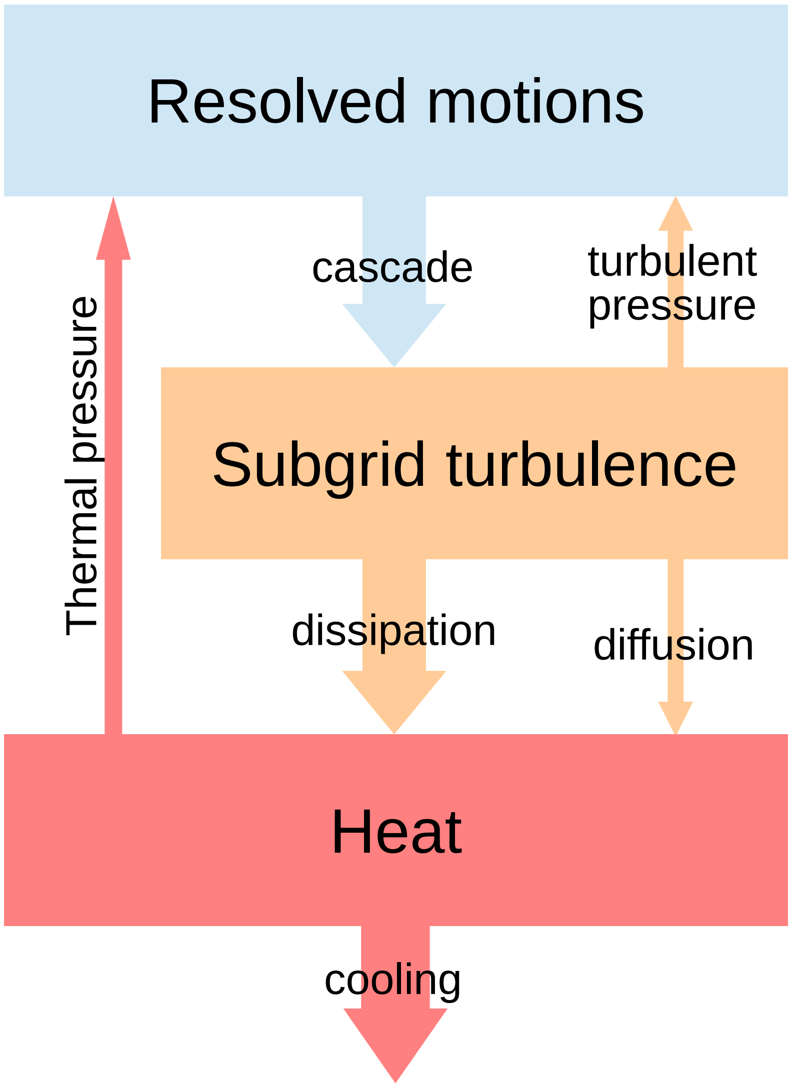
$s = 1.6$ = constant derived from fit to simulation of supersonic turbulent

introduce subgrid turbulence as a mediator between resolved motions and thermal energy



Semenov, Kravtsov & Gnedin 2016, ApJ 826, 200
using “shear-improved” sugrid turbulence model of
W. Schmidt et al. 2014

$$\frac{\partial}{\partial t}\rho + \nabla_k v_k \rho = 0$$

$$\frac{\partial}{\partial t}\rho v_i + \nabla_k v_k \rho v_i = -\rho\nabla_i\phi - \nabla_i\left(P + \frac{2}{3}K\right) + \nabla_k\tau_{ki}$$

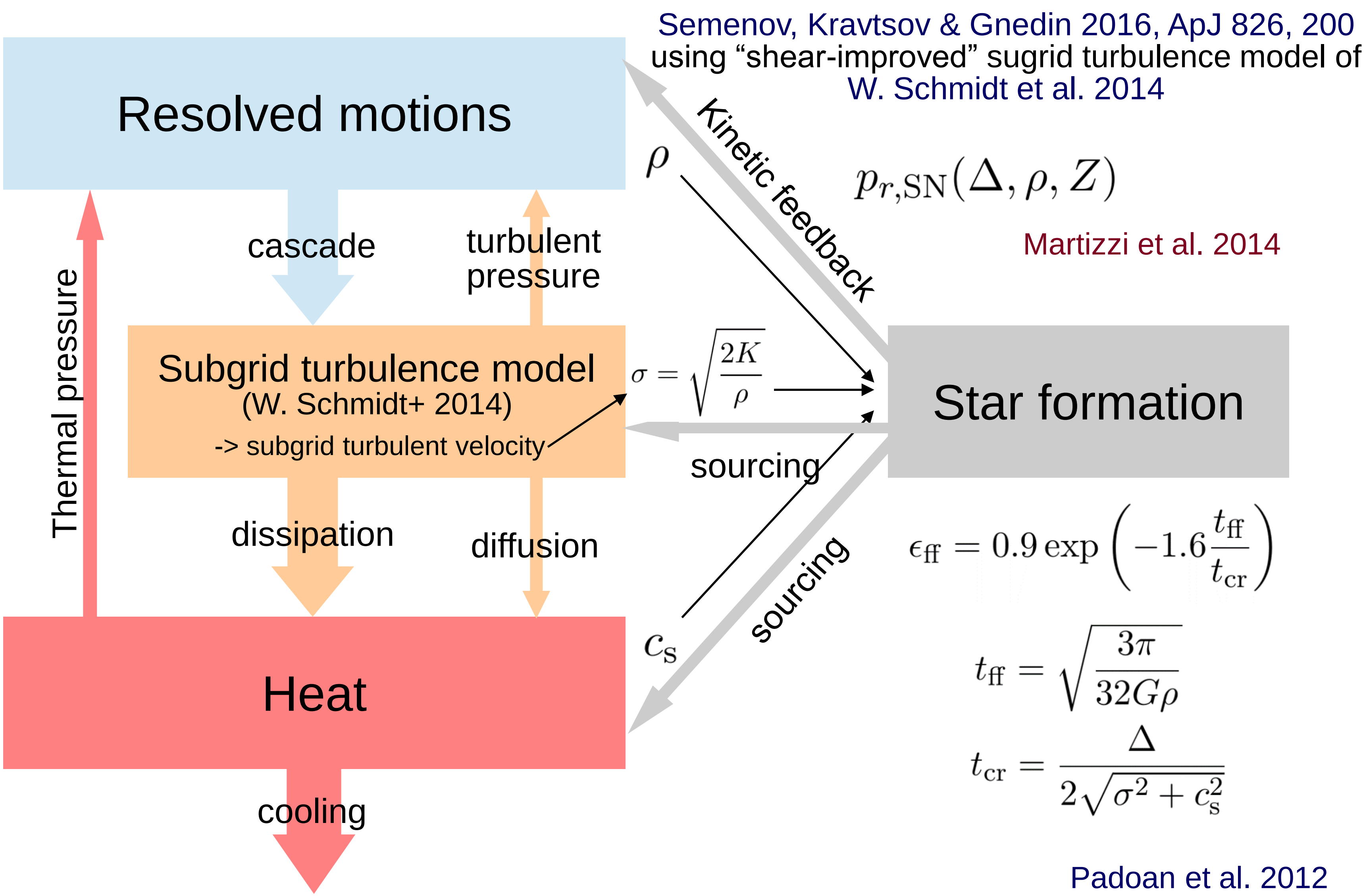
$$\frac{\partial}{\partial t}E + \nabla_k v_k E = -\rho v_k \nabla_k\phi - \nabla_k v_k\left(P + \frac{2}{3}K\right) - \\ - \Lambda_{\rm net} + \nabla_k v_i \tau_{ki} - \nabla_k\left(\mathfrak{F}_k^{(K)} + \mathfrak{F}_k^{(e)}\right)$$

$$\frac{\partial}{\partial t}K + \nabla_k v_k K = \tau_{ki}\nabla_k v_i - \epsilon - \frac{2}{3}K\nabla_k v_k + \nabla_k\mathfrak{F}_k^{(K)}$$

$$\sigma = \sqrt{\frac{2K}{\rho}}$$ - subgrid turbulent velocity

$$\frac{\partial}{\partial t}e + \nabla_k v_k e = \epsilon - \Lambda_{\rm net} - P\nabla_k v_k + \nabla_k\mathfrak{F}_k^{(e)}$$

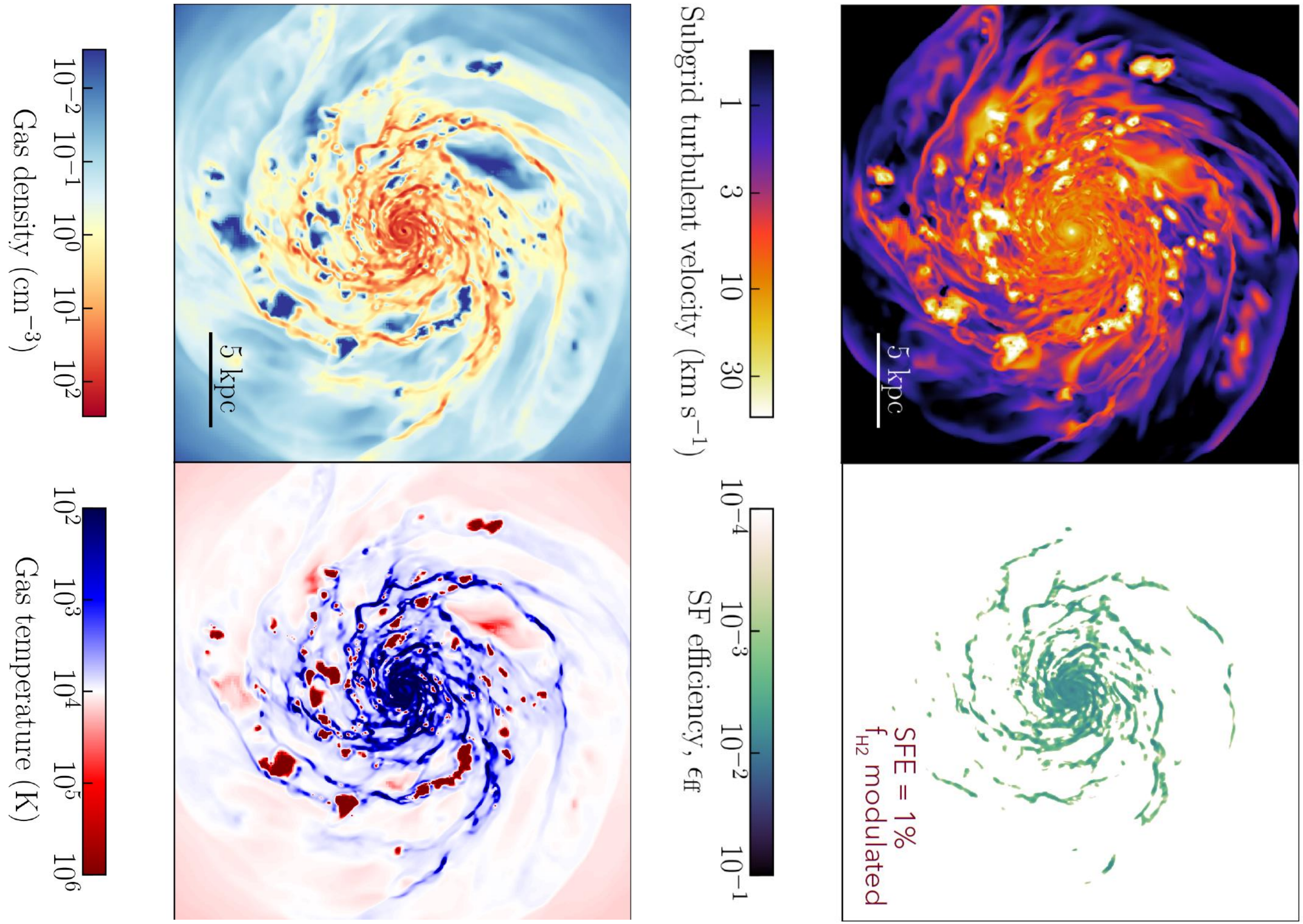
turbulence-based star formation model +
SN remnant simulation calibrated feedback



testing star formation prescription in a controlled galaxy simulation

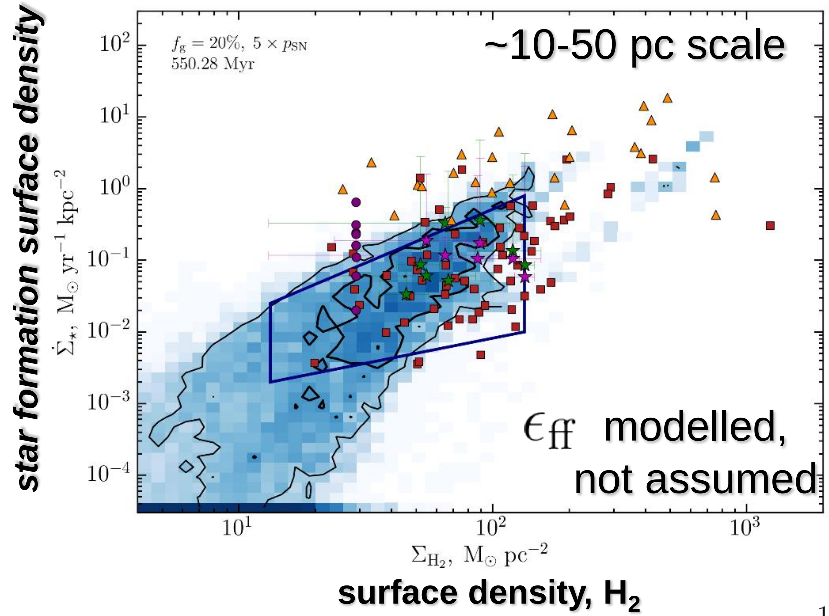
- *Simulations of an ~L* sized isolated galaxy embedded in an NFW halo = AGORA initial conditions*
  $M_{disk} \sim 4.3\text{x}10^{10}\ M_{sun,}\ R_{disk} = 3.5$ kpc, $f_{gas} = 0.2$;
- *N-body+hydrodynamics with Adaptive Mesh Refinement ART code*
  Resolution within the disk: $\Delta = 40$ pc (also checked $\Delta = 20$, 10 pc)
- *Z-dependent heating + cooling and FUV self-shielding calibrated on RT simulations (Safranek-Schneider et al. '17)*
- *Supernovae feedback injecting momentum and energy as predicted by SN bubble simulations with a boost factor of ~1-10 to account for multiple subsequent SNe affecting environment*
- *+ shear-improved subgrid turbulence model* (Schmidt+ '14; Semenov, Kravtsov & Gnedin '16) allows to follow turbulent velocity dispersion on a subrid level and compute local effective temperature and "virial parameter"

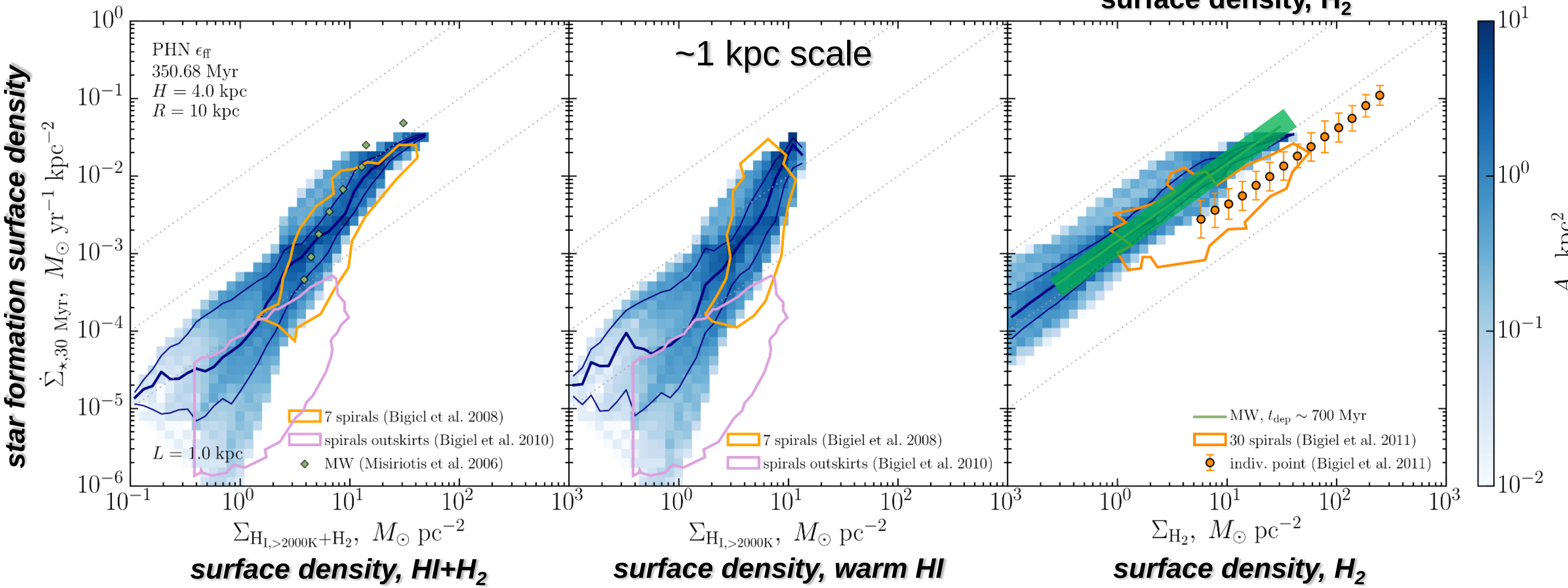
Simulated disk after 2 rotation periods



Test against observations: Kennicutt-Schmidt relation on 1 kpc and ~40 pc

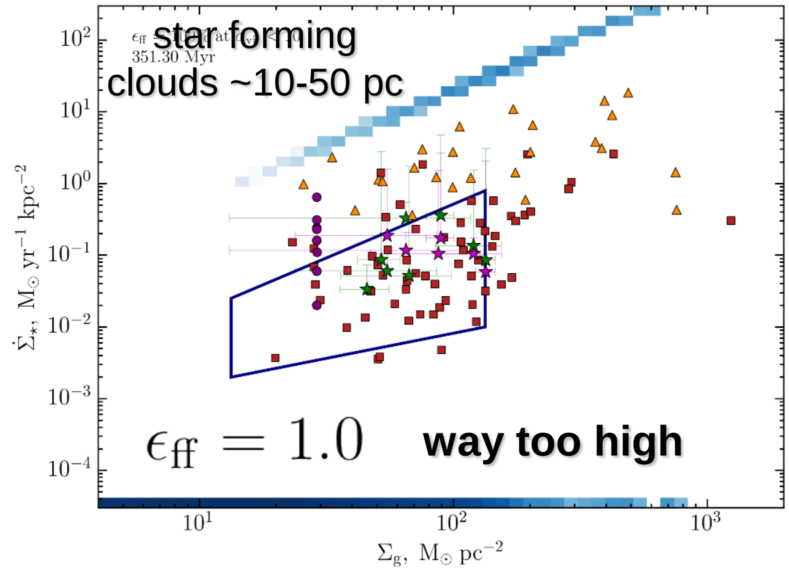
model of star formation based on subgrid turbulence model and efficiencies predicted by high-resolution GMC simulations
Semenov, Kravtsov & Gnedin, 2016, ApJ 826, 200
consistent with observations on small and large scales

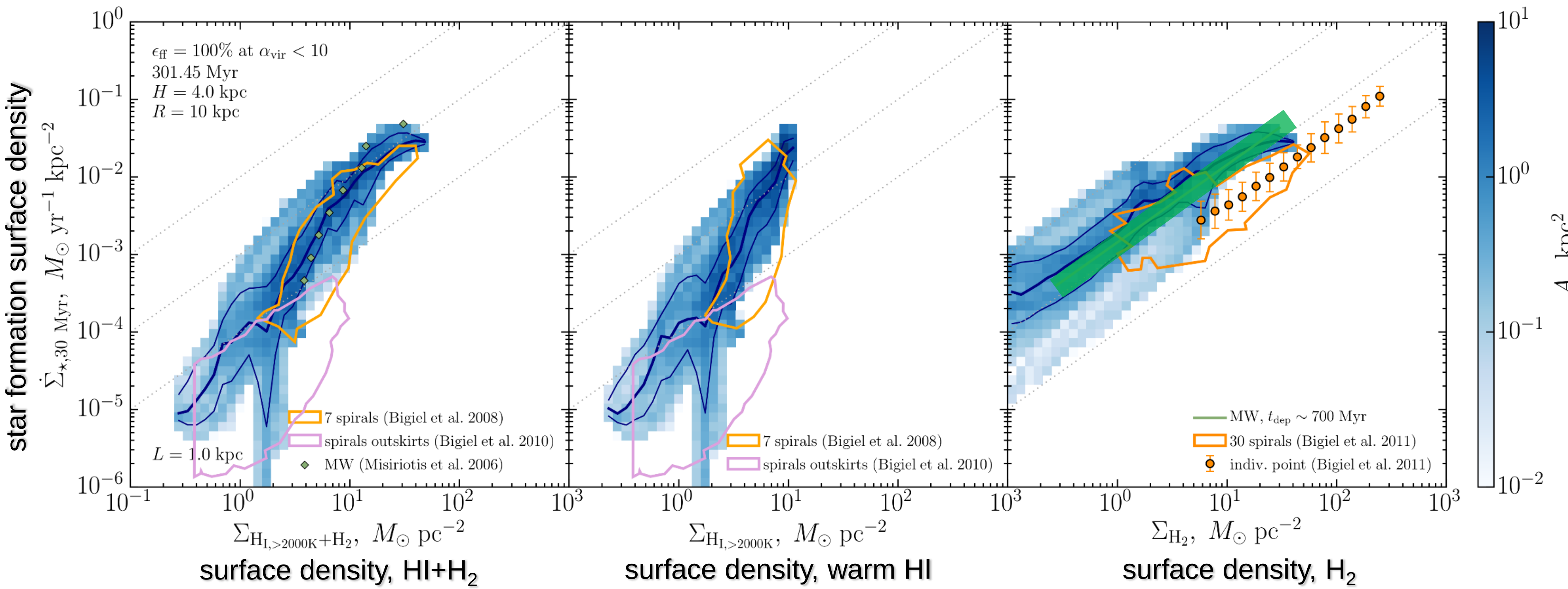




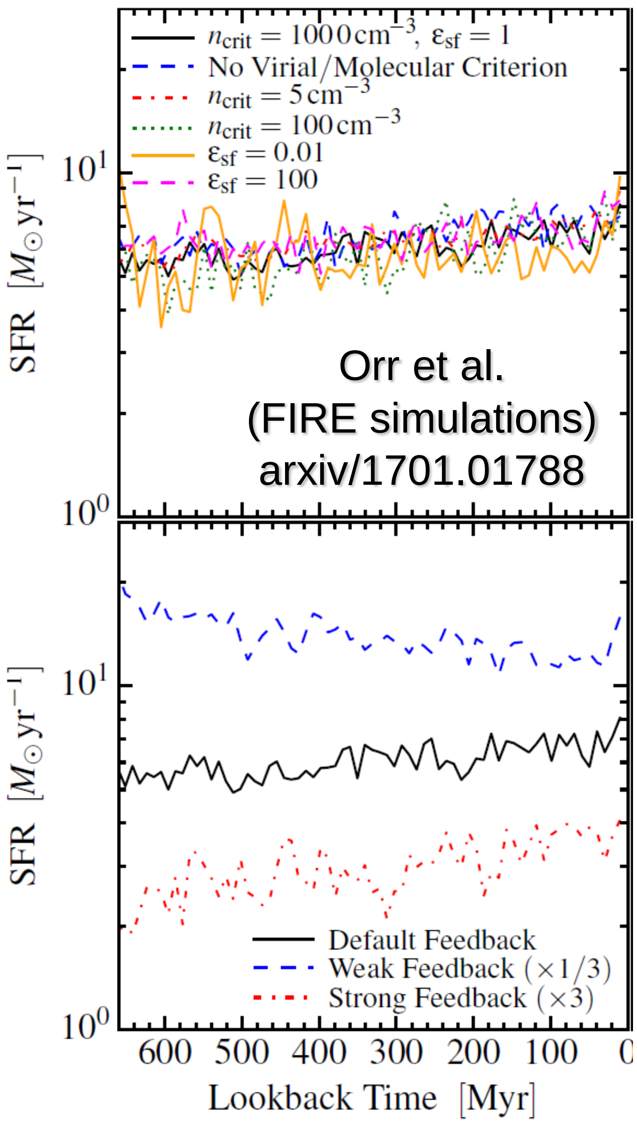
Kennicutt-Schmidt relation on 1 kpc and ~40 pc scale

star formation assuming ϵ_{ff} = const = 1.0
consistent with observations on ~kpc scales
(cf also Hopkins+ '13, Orr+ '17),
but not on ~10-50 pc scales





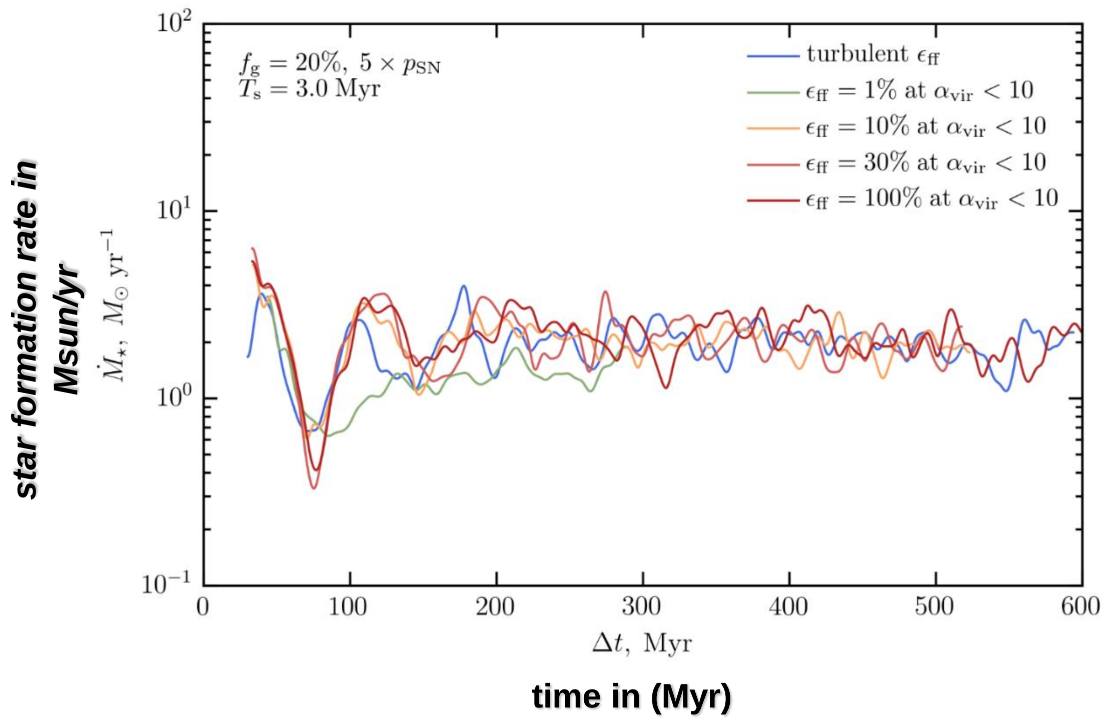
Implications for modelling star formation in galaxy formation simulations



Global galactic SFR insensitive to local sf efficiency. Some nonlinear self-regulation?

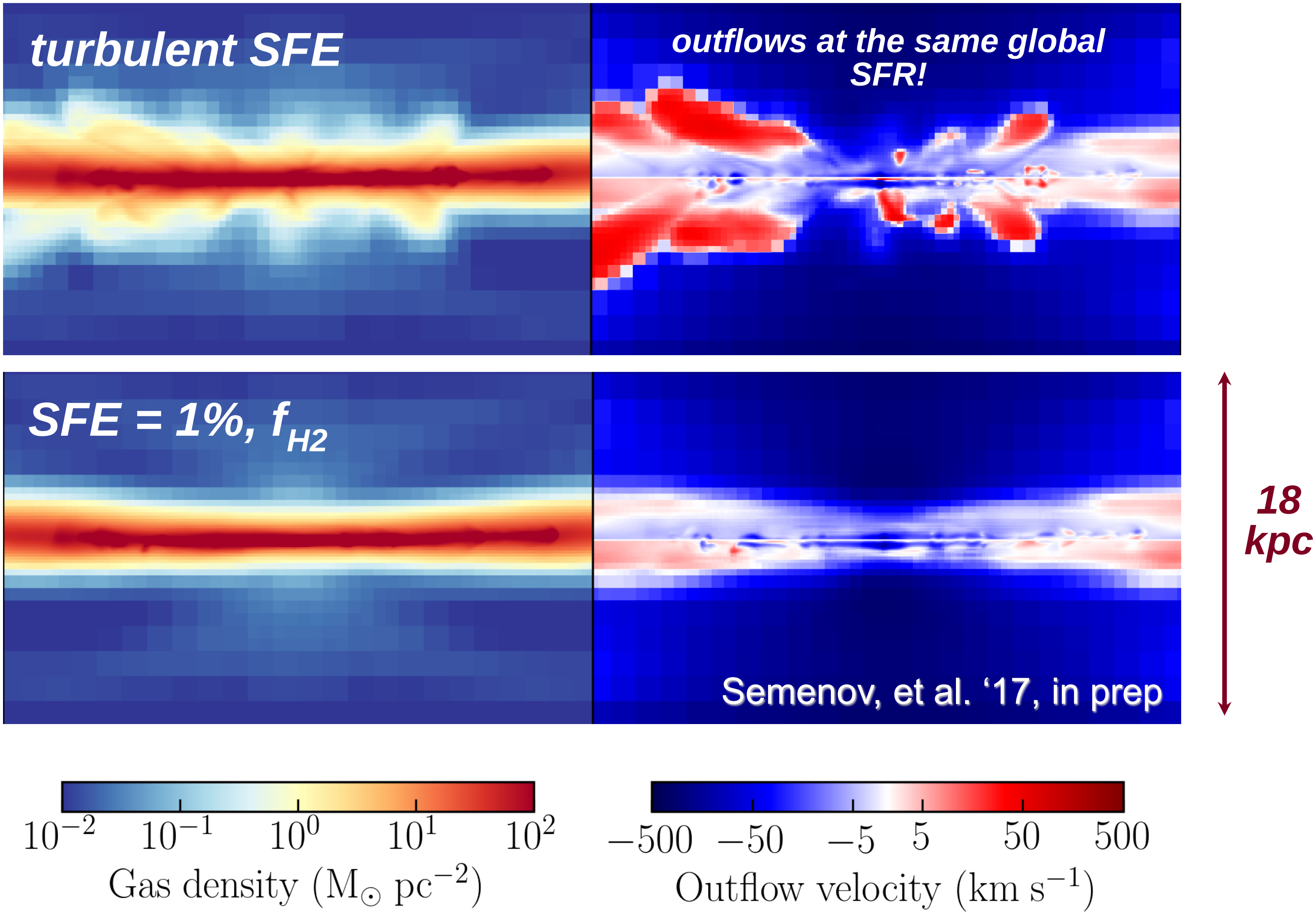
<u>No</u>.

Note that SFR scales linearly with the strength of feedback



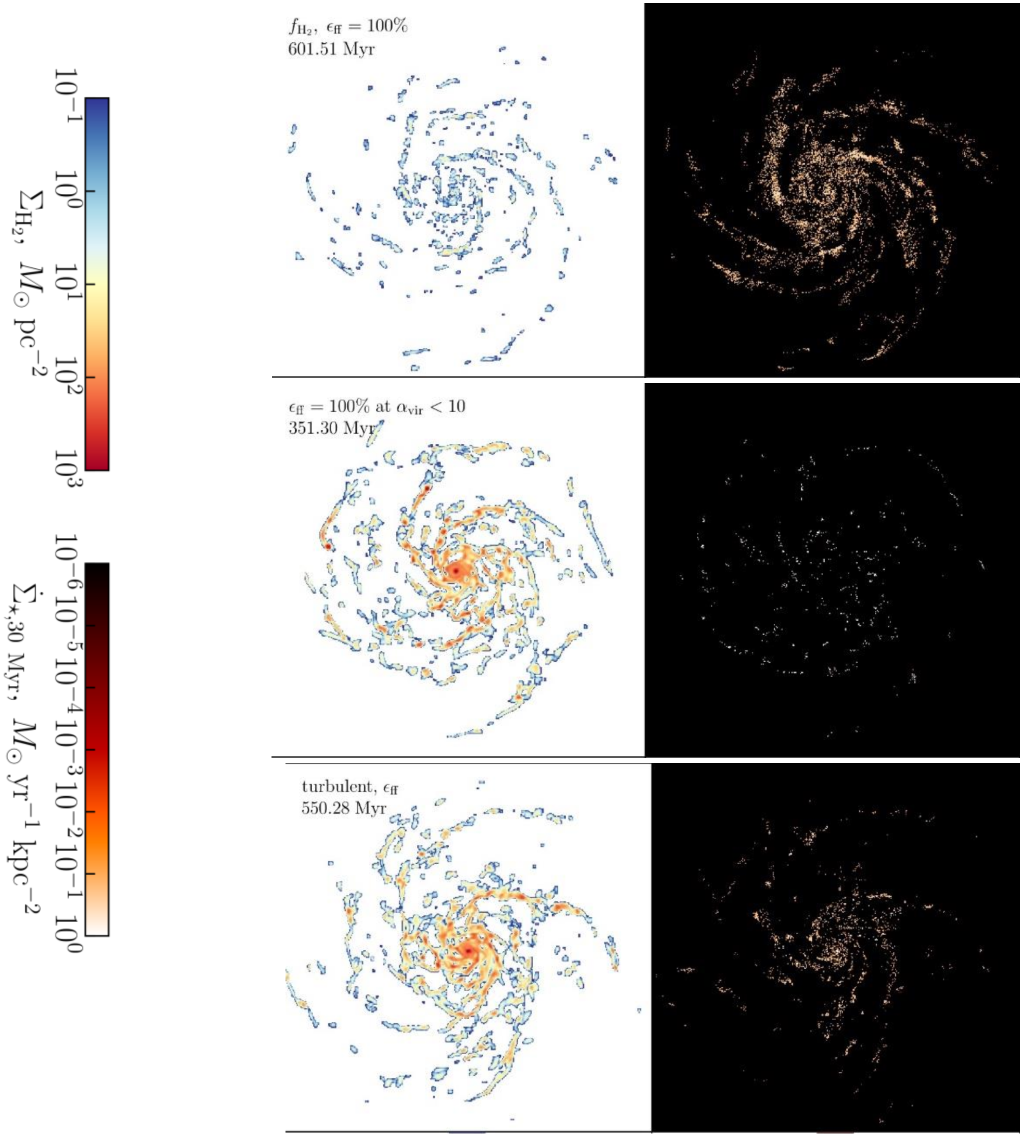
Do value and variation of ε really matter then?

They do (Agertz & Kravtsov '16; cf. also Romain Teyssier's talk on Monday)



Distribution of young stars in different sf recipes

α_{vir} threshold confines star formation to isolated, compact regions compared to more diffuse star formation in H_2 with constant ε_{ff}, which enhances efficacy of feedback (Hopkins, Narayanan & Murray 2013; cf. similar effect was seen by Governato+'10, Guedes+ '11)



H_2 based sf

α_{vir} threshold sf

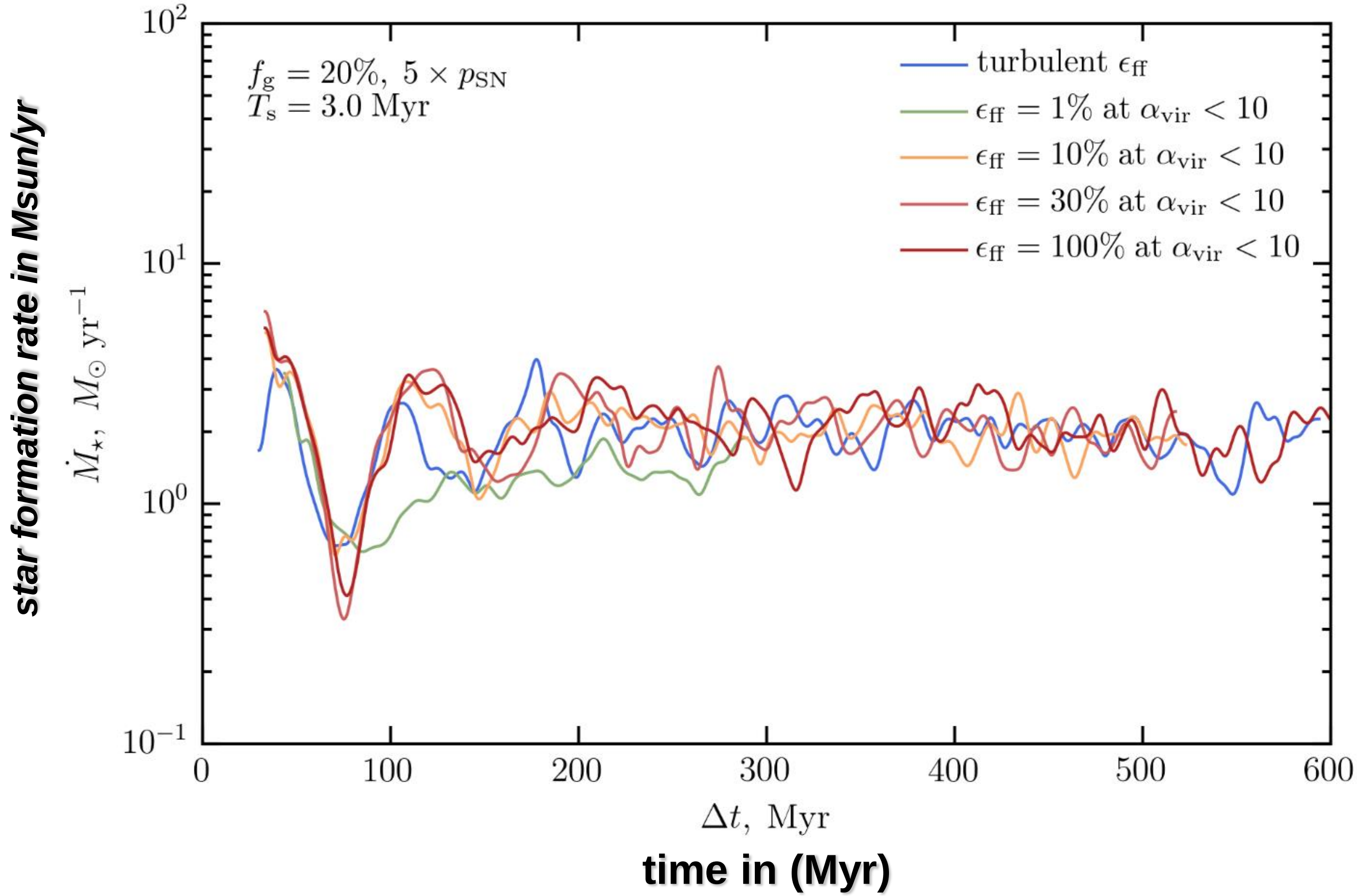
turbulence-based sf
ε_{ff} locally is estimated using calibration of GMC simulations + subgrid turbulence modelling

Global star formation rate independent of ε_{ff} : what's going on?

global gas depletion time: $\tau_{\rm dep} = M_{\rm g}/\dot{M}_\star \sim 2 - 10 \text{ Gyr}$

gas depletion time in star forming regions : $\tau_\star = M_{\rm sf}/M_{\star,\rm sf} \sim 5 - 500 \text{ Myr}$

$$\tau_\star = \left\langle \frac{\epsilon_{\rm ff}}{t_{\rm ff}} \right\rangle^{-1}$$



slow global depletion is a result of rapid gas cycling

Number of cycles, N_c

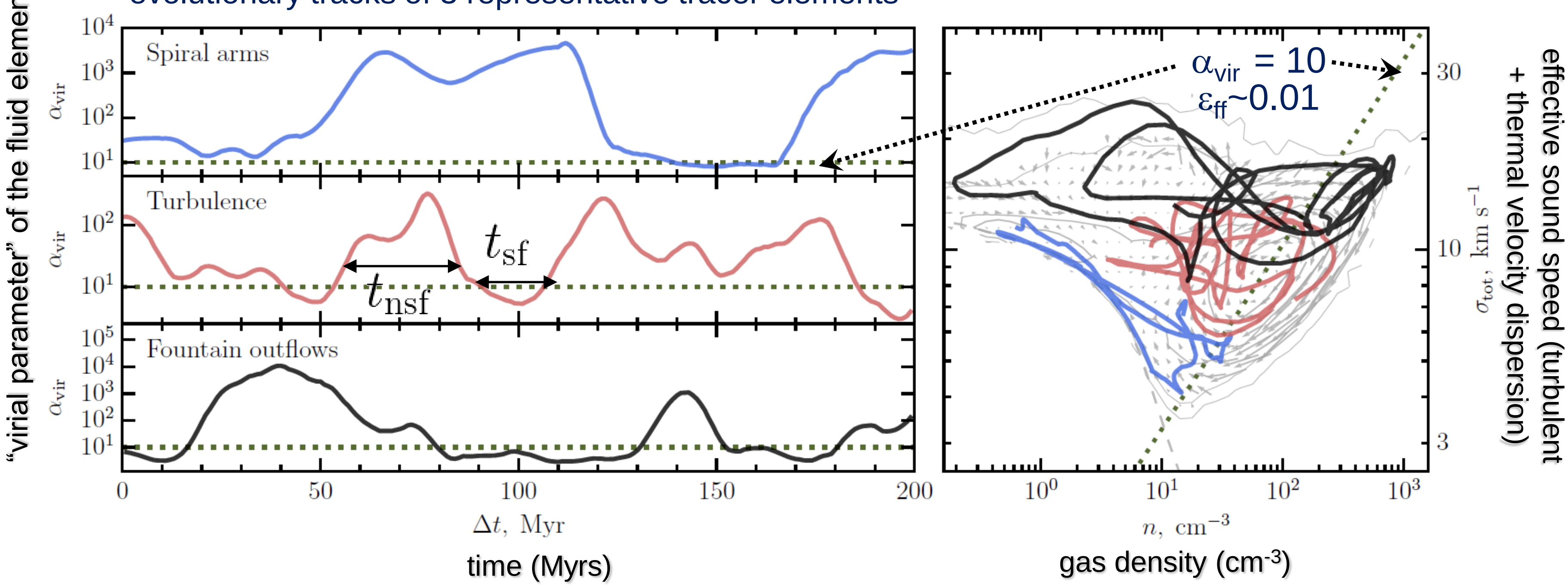
$$f_{\rm sf} \equiv \frac{M_{\rm sf}}{M_{\rm g}} \approx \frac{t_{\rm sf}}{t_{\rm nsf} + t_{\rm sf}} \longrightarrow \tau_{\rm dep} = \frac{\tau_\star}{f_{\rm sf}} = \frac{\tau_\star}{t_{\rm sf}}(t_{\rm nsf} + t_{\rm sf})$$

$$\boxed{\tau_{\rm dep} = N_{\rm c} t_{\rm nsf} + \tau_\star}$$

$\tau_{\rm dep} \gg t_{\rm nsf}$ — time scale of gas evolution

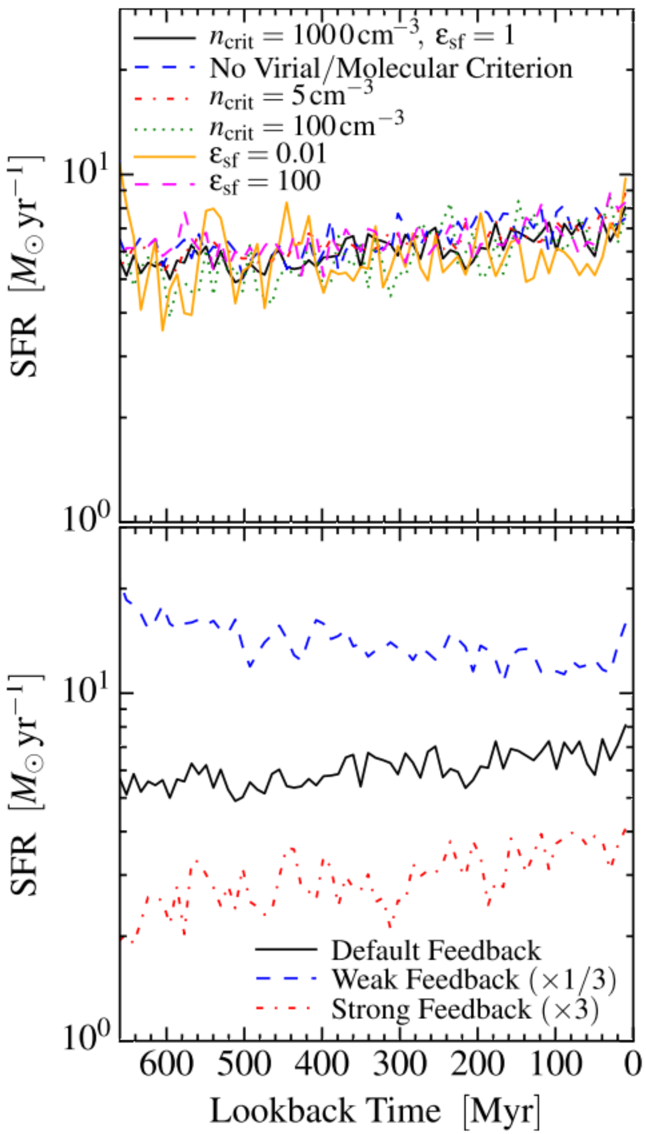
$\tau_{\rm dep} > \tau_\star$ — depletion time in GMCs

evolutionary tracks of 3 representative tracer elements



Insensitivity of global star formation rate (i.e. gas depletion time) from ε_{ff} explained

Orr et al (2017)



$$\tau_{\rm dep} = N_{\rm c} t_{\rm nsf} + \tau_\star \qquad N_{\rm c} = \frac{\tau_\star}{t_{\rm sf}}$$

for $\epsilon_{\rm ff} \gtrsim 0.01 \qquad \tau_\star \ll N_{\rm c} t_{\rm nsf}$

*N*c is insensitive to local ε_{ff}: as efficiency increases, both $\tau_\star$ and tsf decrease proportionally (the latter due to feedback) because for a given feedback implementation, to terminate sf phase a given fixed fraction of gas needs to be turned into stars:

$$\epsilon_\star = \frac{m_\star}{m_{\rm g}} = \frac{t_{\rm sf}}{\tau_\star} = \frac{1}{N_{\rm c}}$$

Hence, global depletion time is insensitive to the depletion time of star forming regions (set by local ε_{ff})

At the same time, feedback makes tnsf longer increasing depletion time, thereby decreasing SFR

Semenov, Kravtsov & Gnedin 2017 to be submitted

summary

➢ Modern simulations and analytical models of turbulent star forming regions provide an interesting and useful way to model local star formation efficiency

➢ Implementation of such model based on the shear-improved subgrid turbulence model of Schmidt et al. 2013 results in realistic global Kennicutt-Schmidt relation on kpc scale and consistent gas depletion time in star forming regions at ~10-50 pc scale.

➢ Simulations provide an insight into why global SFR is insensitive to local star formation efficiency and why global gas depletion time to star formation is so long in galaxies

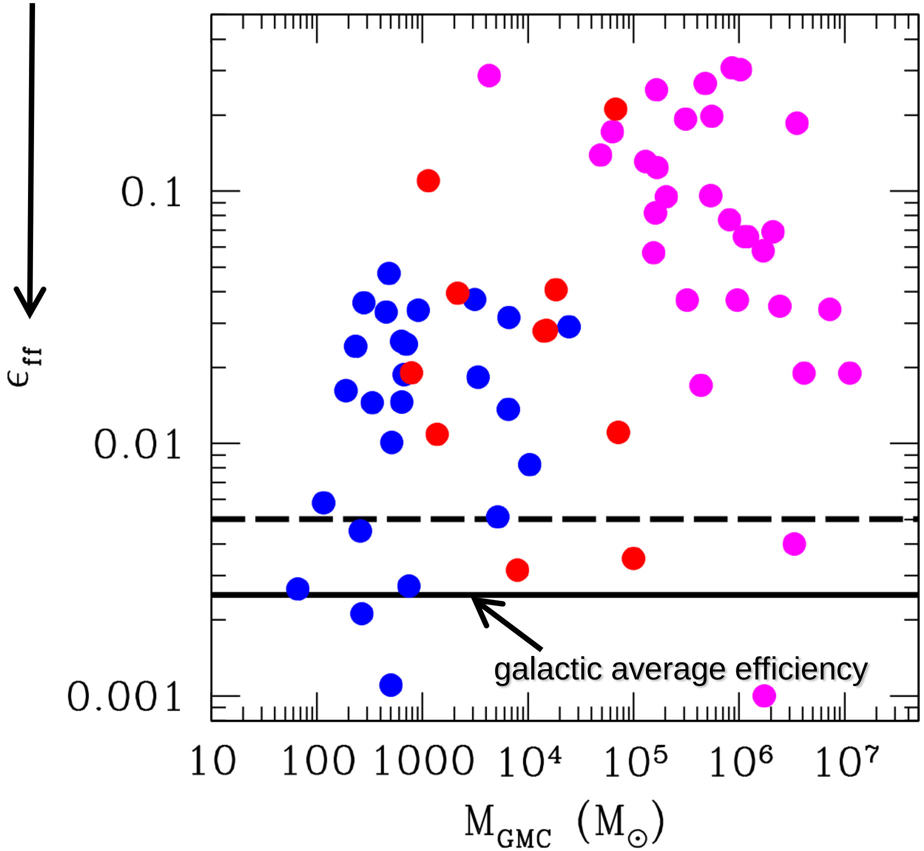
Gas evolves fast and spends only a small time in actively-star-forming phase (i.e. lifetime of star-forming clouds are short) due to dynamical disruption and dispersal by feedback. Gas has to go through many cycles of evolution to star-forming phase with significant fraction of each cycle spent without forming stars.

New simulation-calibrated implementations of star formation and stellar feedback and study of the physical origin of long depletion time: *Semenov, Kravtsov & Gnedin 2016, ApJ 826, 200;*
Semenov, Kravtsov & Gnedin 2017, to be submitted

observed sf efficiency in star-forming clouds

star formation efficiency per free-fall time

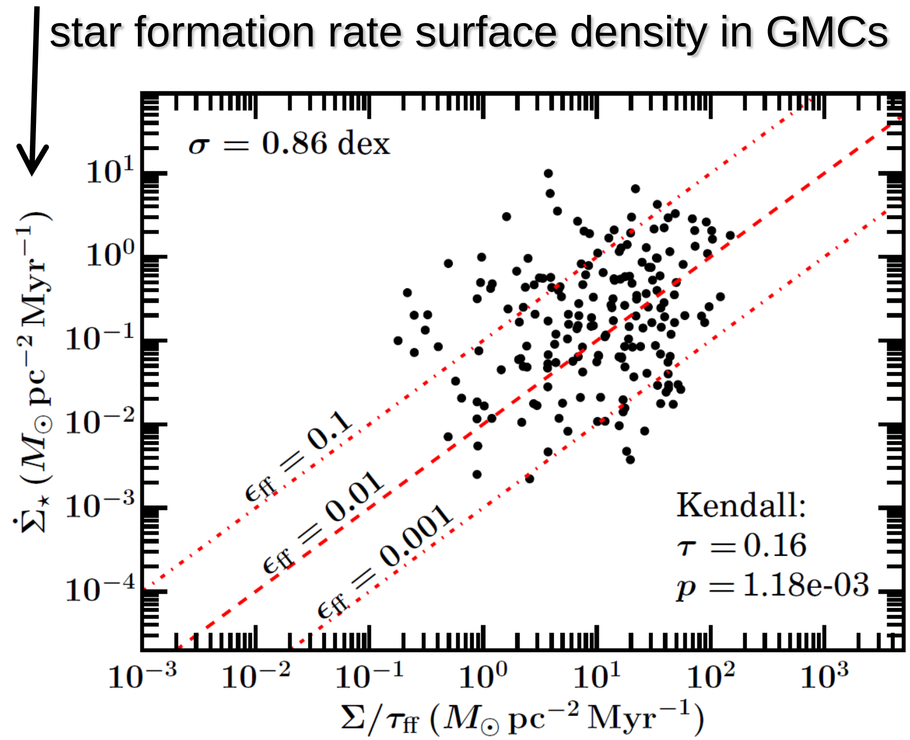
Lee et al. arxiv/1608.05415



GMC gas mass

Agertz & Kravtsov 2015

star formation rate surface density in GMCs



gas surface density/free fall time

also Krumholz & Tan 2007

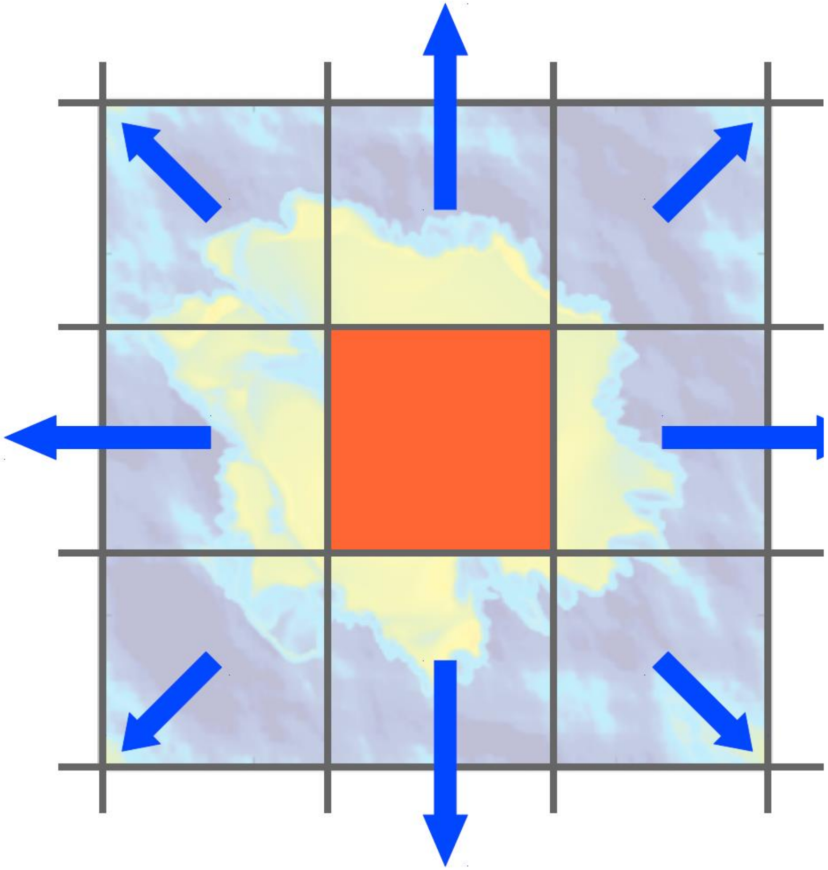
Krumholz, Dekel & McKee 2012, ApJ 745, 69

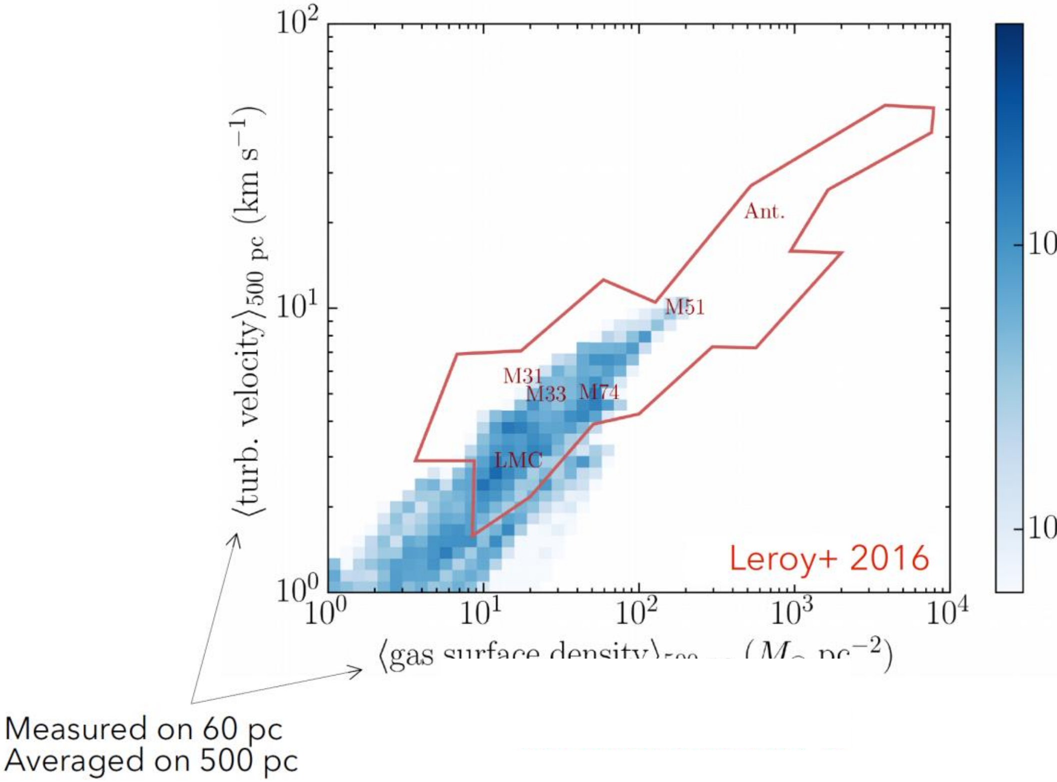
Vutisalchavakul et al. 2016, ApJ (arXiv/1607.06518)

Local supernova feedback implementation

model based on detailed simulations calibrating thermal energy and kinetic momentum injection by supernova remnants , as a function of gas density and metallicity [Kim & Ostriker ‘14; Martizzi et al. ’15]

Implementation checked and calibrated against observations of resolved gas velocity dispersion measurements in nearby galaxies [Leroy+ ‘16]





Non-universal star formation efficiency

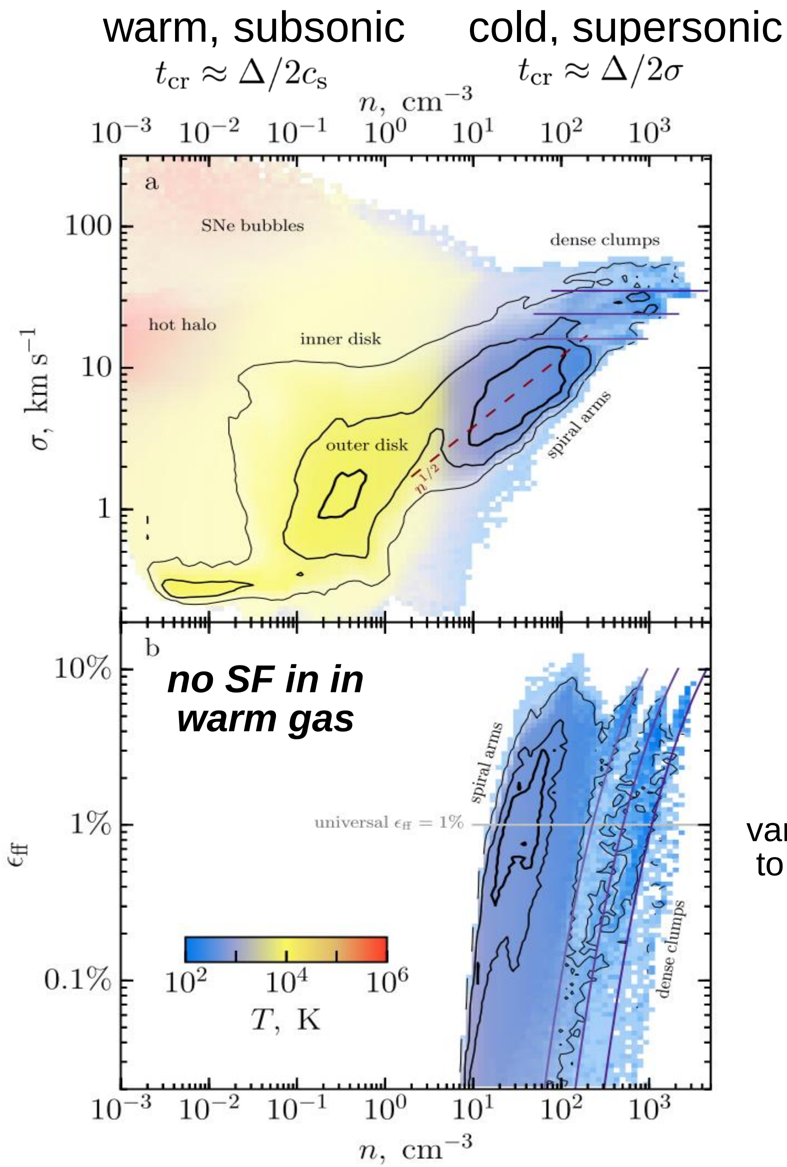
$$\epsilon_{\rm ff} = 0.9 \exp\left(-1.6 \frac{t_{\rm ff}}{t_{\rm cr}}\right)$$

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32 G\rho}}$$

$$t_{\rm cr} = \frac{\Delta}{2\sqrt{\sigma^2 + c_{\rm s}^2}}$$

- Density threshold
- Average $\varepsilon_{ff} \sim 1\%$
- Wide variation of ε_{ff}

contours in the model pdf: 5, 15, 30%



Wide variation due to scatter in σ