Star formation laws and their role in models of the formation and evolution of galaxies

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Outline

1. SF thresholds

2. SF laws: KS versus Schmidt and implementation

3. SF laws in cosmological simulations of galaxy formation

Toomre (1964) criterion:

$$Q \equiv \frac{c_s \kappa}{\pi G \Sigma_g}$$

If Q < 1, neither pressure nor rotation can stabilize the disk.
But: wavelength dependent.

κ Epicycle frequency (from rotation curve)

c_s Sound speed (from velocity dispersion, or not!)

Σ_g Surface density (atomic plus molecular)

Can Toomre Q be used for *local* SF thresholds?

Assumption: disk is thin

- Disk scale height in outer disk ~ λ_{crit}
- Dwars/irregulars/tidal tails not very disky

Assumption: Axisymmetric perturbations

- SF is local → require truly local criterion

Can Toomre Q be used for SF thresholds in *outer* disks?

Assumption: $Q < 1$ triggers instability small scales

- $Q=1$ implies instability for $\lambda_{crit}/2 > 1$ kpc → spiral arms rather than molecular clouds
- $Q \ll 1$ required for instability on scales $\ll$ kpc
- $Q \ll 1$ implies $\sigma \ll 8$ km/s for observed Σ and κ
- For $\lambda \ll \lambda_{crit}$ Toomre becomes Jeans → rotation only important in center where λ_{crit} is small (but center is no disk…)

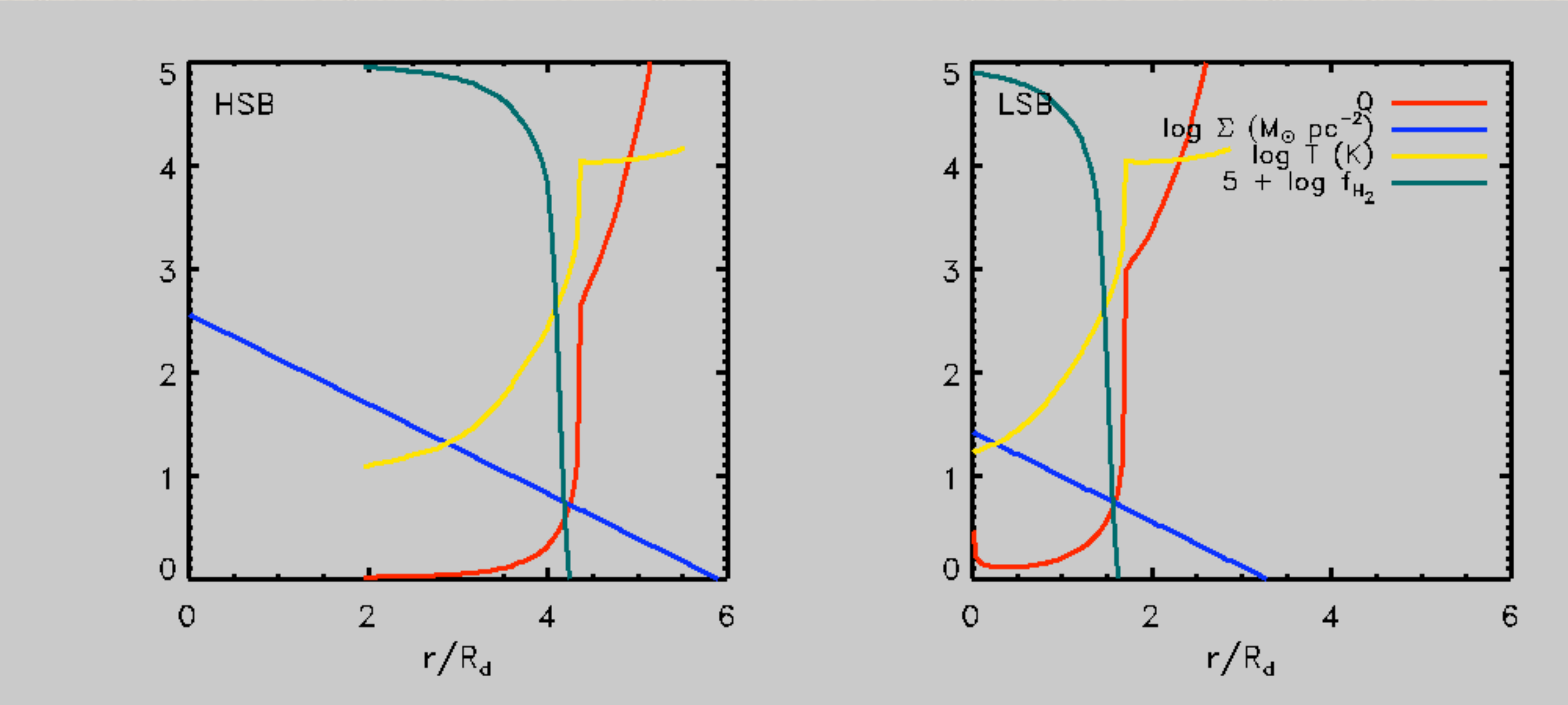
Thermogravitational Instability

- Outer disk physics simple:
  - Warm phase only (UV radation!)
  - No feedback from SF
- Cold phase is necessary for SF
- Phase transition is sharp
- $T_{cold} \sim T_{warm} / 100 \quad \Rightarrow \quad \sigma_{cold} \sim \sigma_{warm} / 10$

The transition to the cold phase triggers gravitational instability

JS (2004)

What Sets the SF Threshold?



$M_{200} = 10^{12} M_{\odot}, \quad \lambda = 0.05$

$M_{200} = 5 \times 10^{10} M_{\odot}, \quad \lambda = 0.1$

$c = 10, \quad j_d = m_d = 0.05$

JS (2004)

Thermogravitational instability explains

- SF threshold ~ HI to H2 transition
  - Metallicity-dependent saturation of HI surface density (see JS 2001; absorption line measurements)
  - Superiority of molecular SF laws on small scales
- Value and constancy (apart from weak metallicity dependence) of critical surface density (also for dwarfs/irregulars/tidal arms, etc)
- Need to rescale critical Q depending on assumed velocity dispersion
- “Subcritical” disks
- Value and constancy of velocity dispersion in outer disks

JS (2004)

SF thresholds in simulations: From surface to volume densities

$$\Sigma_g = \rho_g L_J \propto \left(\frac{f_g}{f_{th}}\right)^{1/2} \rho_g^{1/2} T^{1/2}$$

At the threshold:

$$T \sim 10^4 \text{ K}$$

$$f_g \sim 1$$

$$f_{th} \sim 1$$

$$\Rightarrow n_{\text{H,crit}} \sim 10^{-1} \text{ cm}^{-3}$$

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Star formation laws

Empirical Kennicutt-Schmidt law:

Theoretically motivated Schmidt law:

Buts:

- C may depend on density
-

Kennicutt-Schmidt and pressure laws

KS law $\dot{\Sigma}_* \propto \Sigma_g^n$

$$t_g = \frac{\Sigma_g}{\dot{\Sigma}_*}$$

$$t_g \propto \Sigma_g^{1-n}$$

Hydrostatic equilibrium $\Sigma_g \propto \tilde{n}_g L_J \propto (\tilde{n}_g T_{eff})^{1/2} \propto P_{tot}^{1/2}$

$$t_g \propto P_{tot}^{(1-n)/2}$$

KS and Schmidt law correspondence

KS law: $$\dot{\Sigma}_* = A\left(\frac{\Sigma_g}{1\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}}\right)^n$$

Corresponding Schmidt law:

$$\frac{\dot{\rho}_*}{\rho_g} = A\left(1\,\mathrm{M}_\odot\,\mathrm{pc}^{-2}\right)^{-n}\left(\frac{\gamma}{G} f_g P_{tot}\right)^{(n-1)/2} = \frac{\dot{m}_*}{m_g}$$

JS & Dalla Vecchia (2008)

KS and Schmidt law correspondence

For a polytropic equation of state:

$$P_{tot} \propto \rho^{\gamma_{eff}}$$

We have

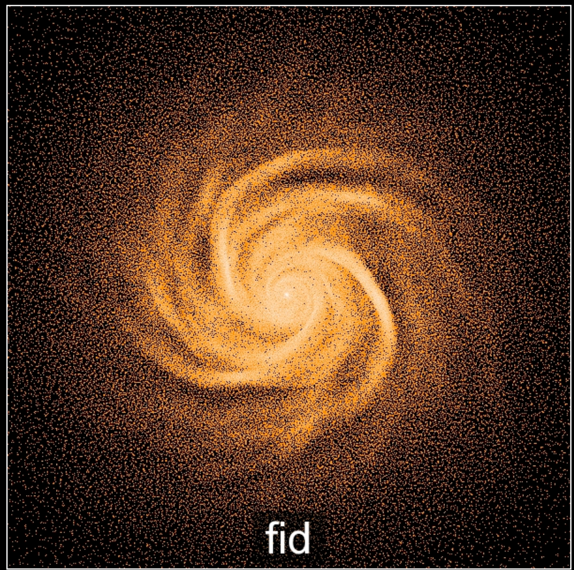
$$n_{KS} = \frac{2(n_{Schmidt} - 1)}{\gamma_{eff}} + 1$$

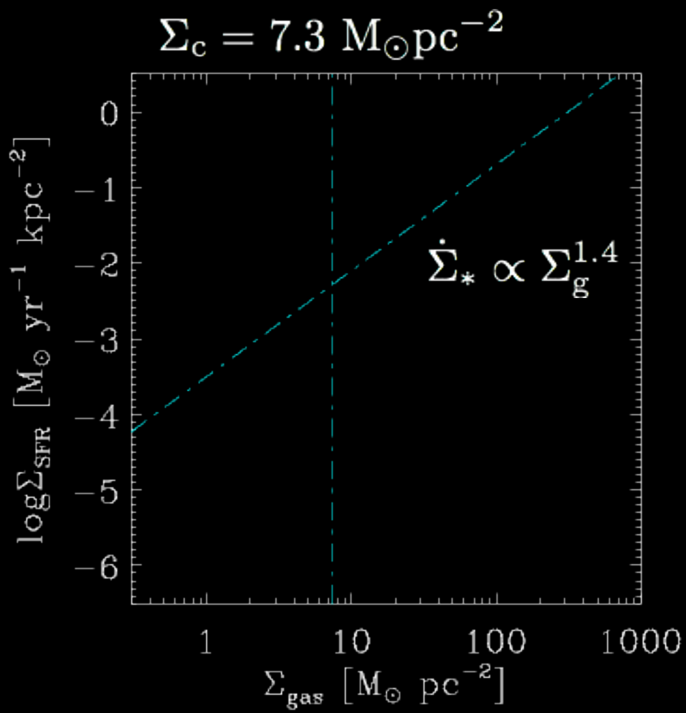
The two power-law indices differ unless

$$n = 1 \quad \vee \quad \gamma_{eff} = 2$$

JS & Dalla Vecchia (2008)

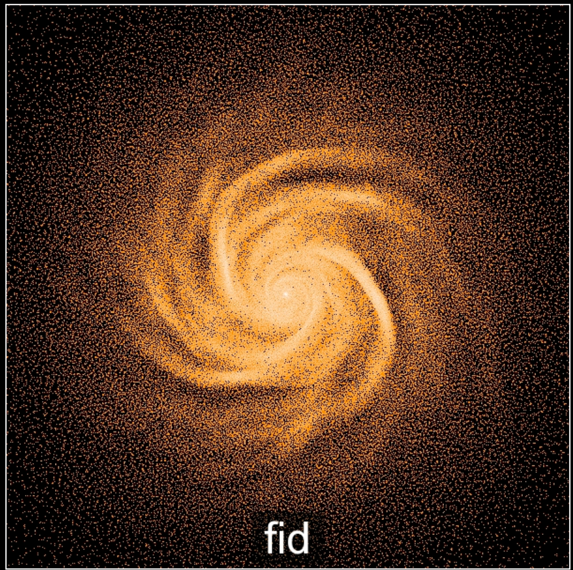
Kennicutt-Schmidt law

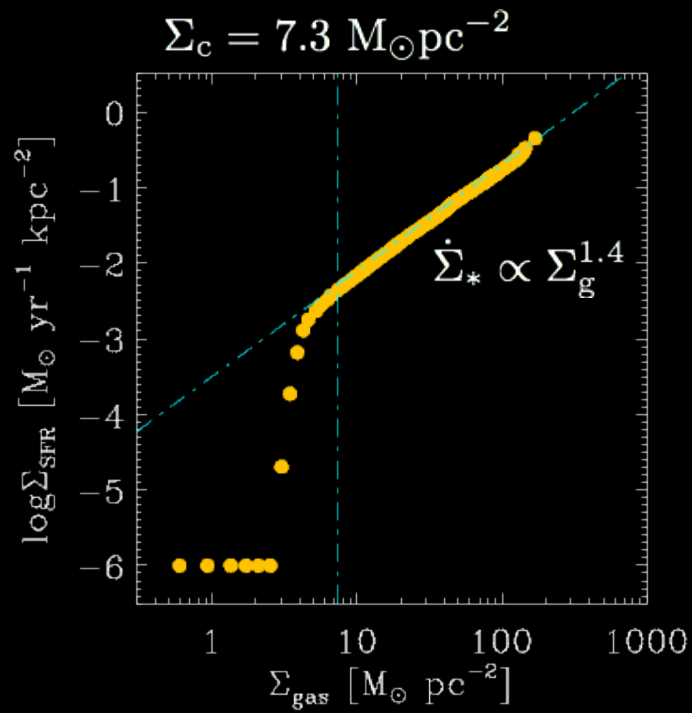




JS & Dalla Vecchia (2008)

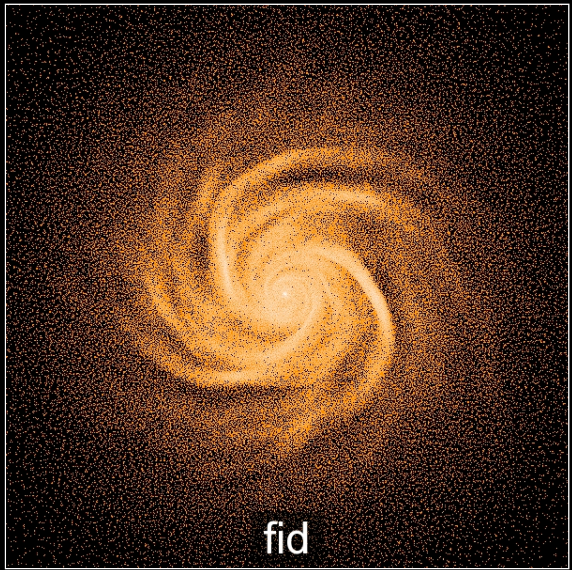
Kennicutt-Schmidt law



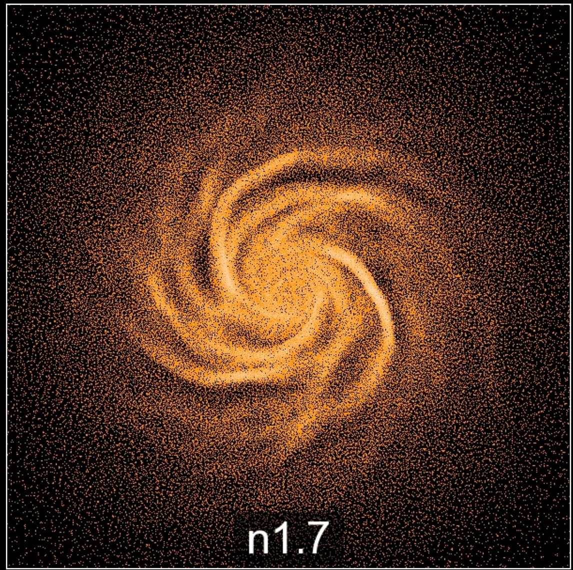


JS & Dalla Vecchia (2008)

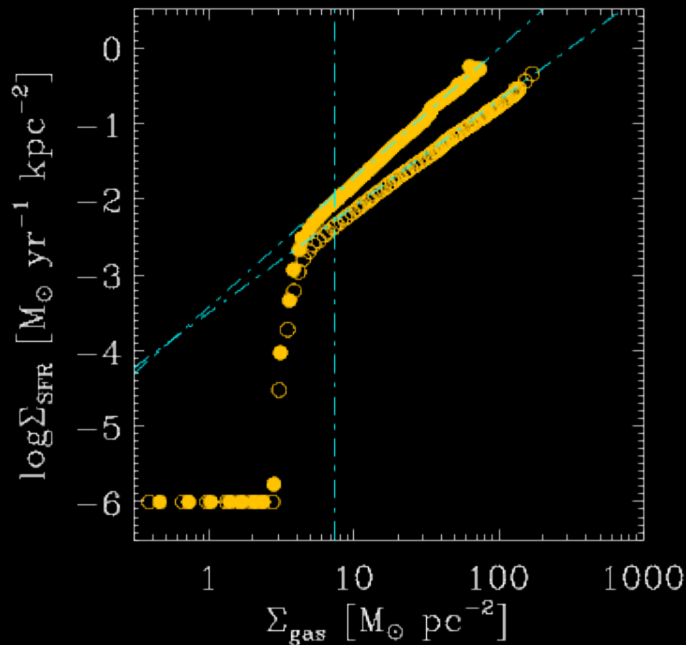
Kennicutt-Schmidt law



$\dot{\Sigma}_* \propto \Sigma_g^{1.4}$

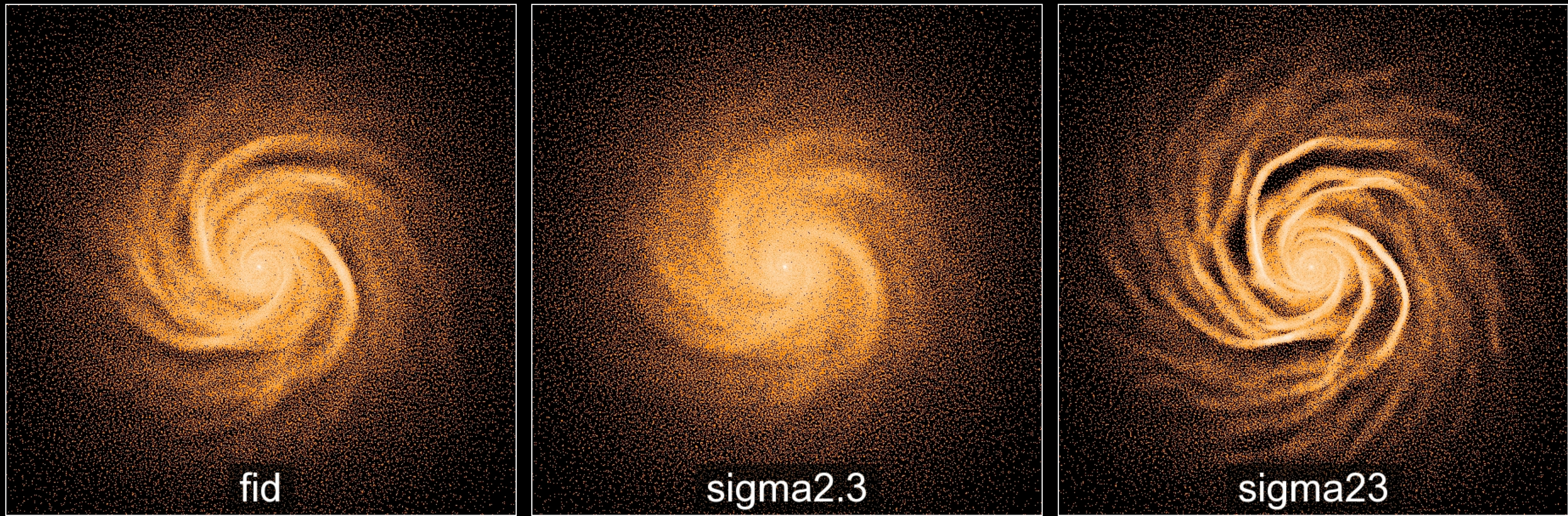


$\dot{\Sigma}_* \propto \Sigma_g^{1.7}$



JS & Dalla Vecchia (2008)

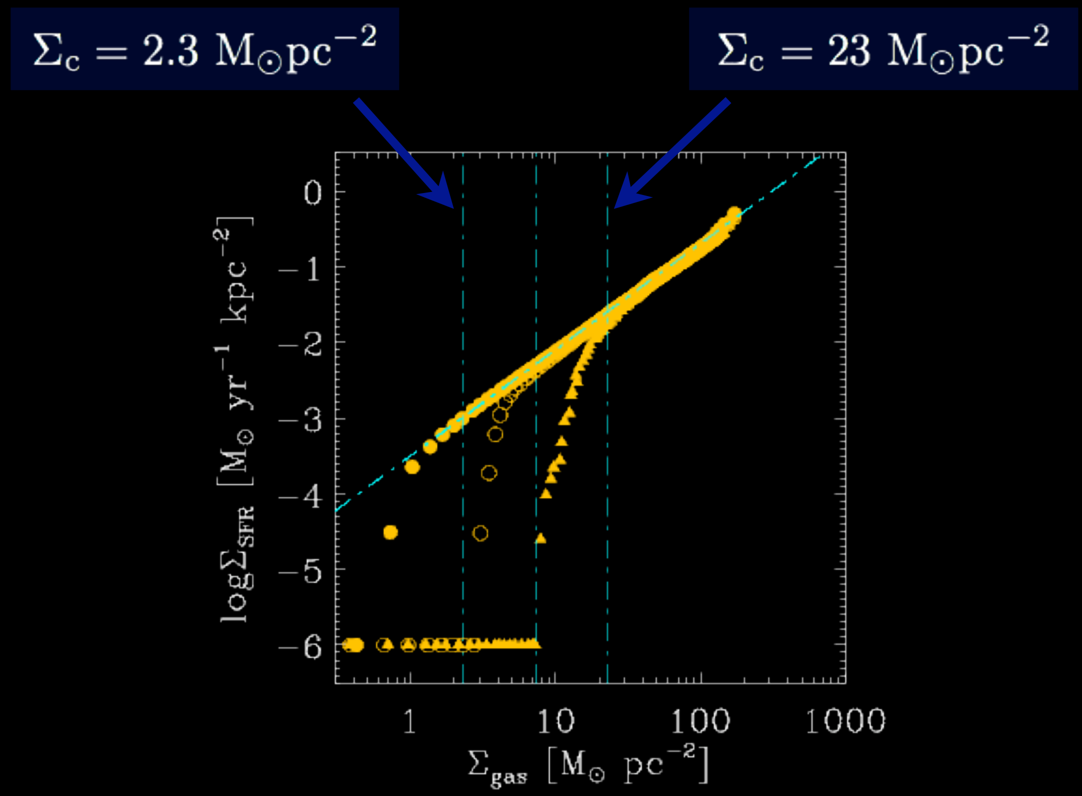
Kennicutt-Schmidt law - SF threshold



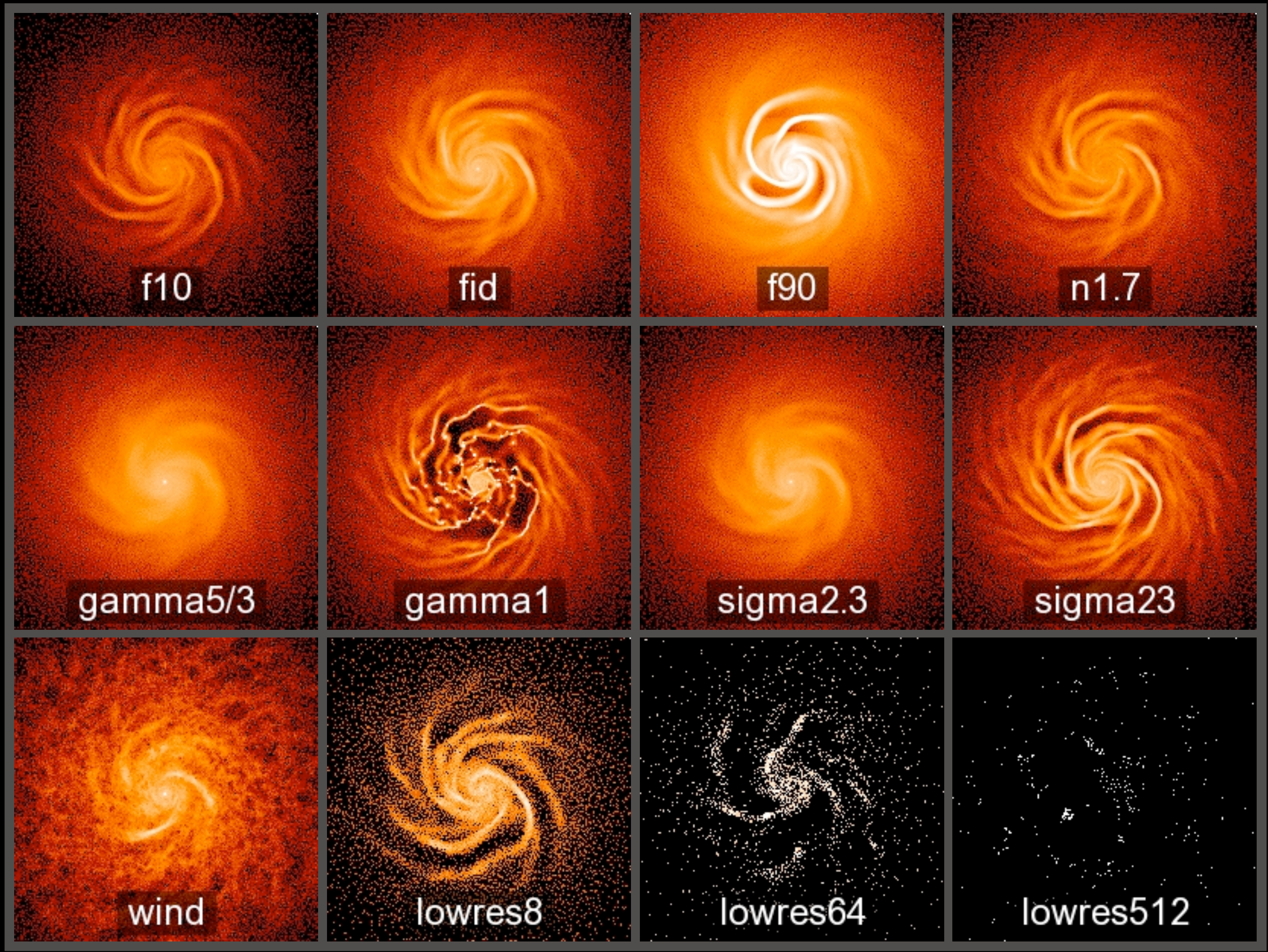
$\Sigma_c = 7.3\ M_{\odot}pc^{-2}$ $\Sigma_c = 2.3\ M_{\odot}pc^{-2}$ $\Sigma_c = 23\ M_{\odot}pc^{-2}$

JS & Dalla Vecchia (2008)

Kennicutt-Schmidt law - SF threshold



JS & Dalla Vecchia (2008)



JS & Dalla Vecchia (2008)

Star formation laws

- Surface density, pressure and volume density SF laws can be related analytically
- Any input SF law can be implemented in simulations without tuning parameters, independent of the effective equation of state
  - → Bypass ignorance of SF, ideal for simulations that do not resolve the ISM
  - → Cannot learn about the physics behind the SF laws picked out by nature

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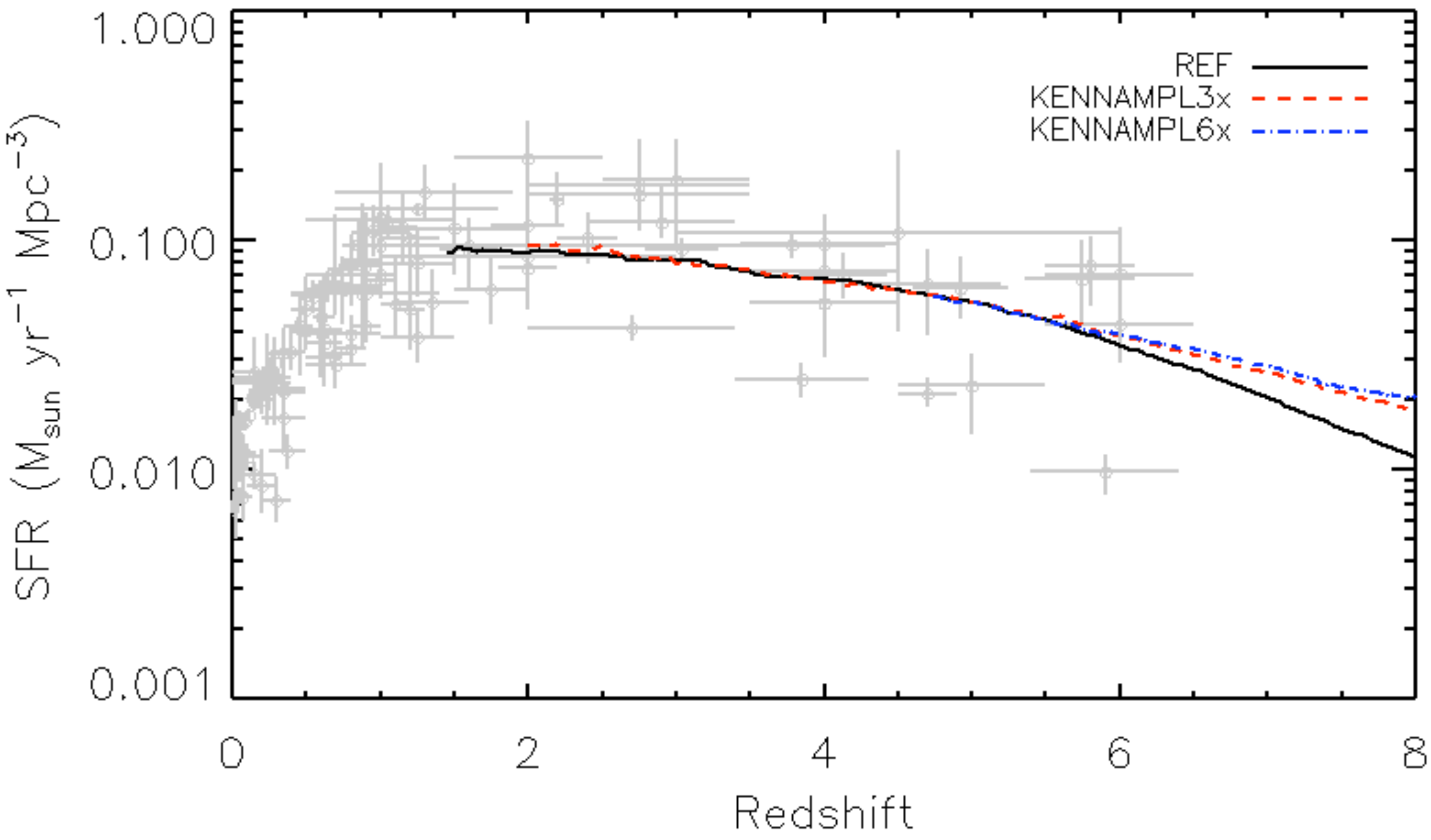
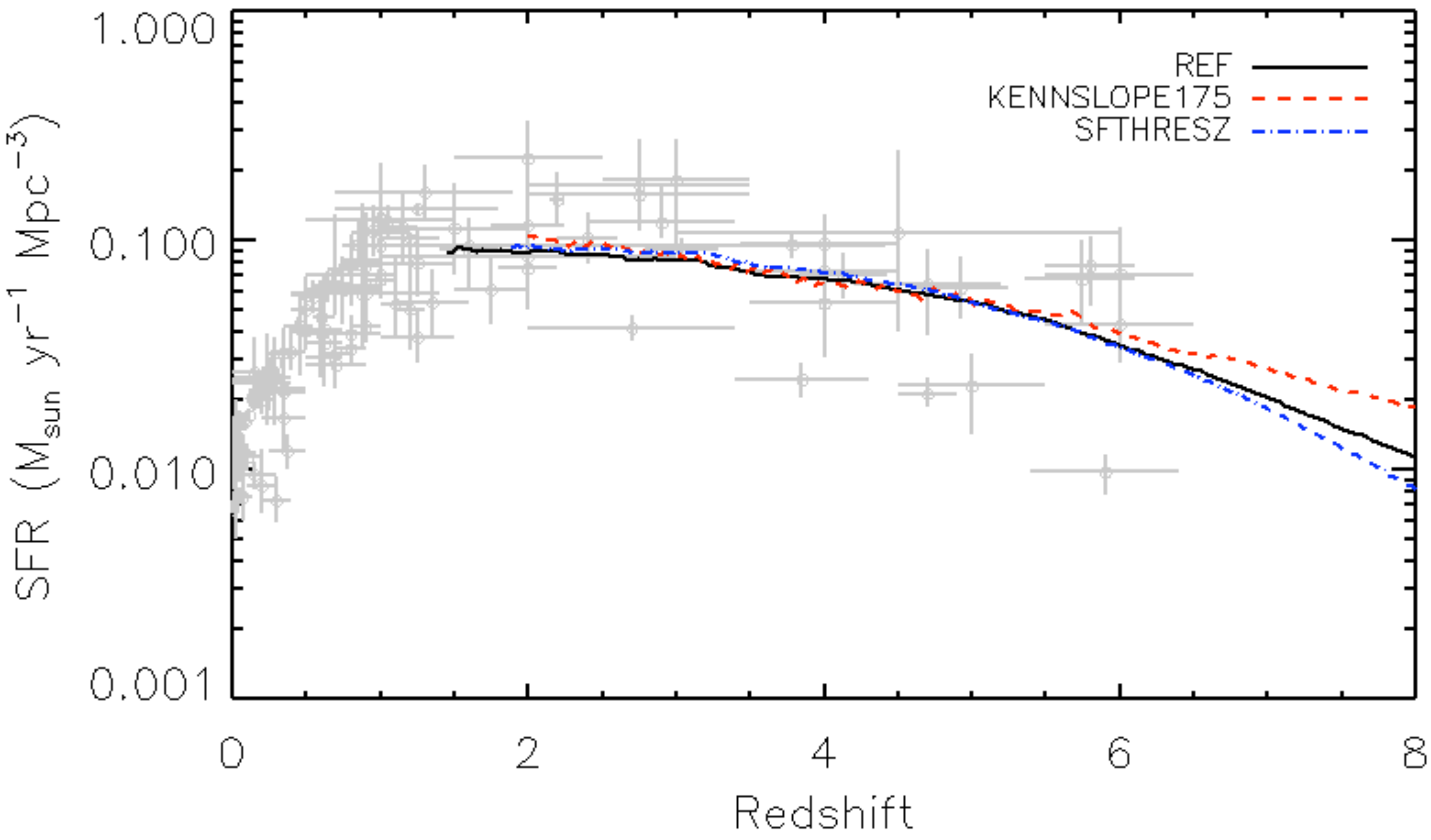
Cosmological simulations: Varying the SF efficiency



Cosmological simulations: Varying the SF law



Can we understand galaxy formation without understanding SF?

- No, because galaxies consist of stars

But:

- To first approximation galaxy star formation rates determined by inflow and outflow rates (self-regulation)
- Cannot understand galaxy formation without strong outflows that eject most of the baryons

  → need more than cold flows and gravitational instability

  → need monster in the bath tub/swimming pool