Self-regulated star formation: concepts and computations

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Outline

- Self-regulated SF in turbulence-dominated systems: concept and formulation
- Computational results: starbursts and outer disks
- Self-regulation: radiation effects
- Computational results: star-forming clouds with IR radiation

I. Self-regulation: the concept
II. Starburst and outer-disk simulations
III. Continuum radiation effects
IV. RHD simulations of SF clouds

Turbulent driving and dissipation

Consider system of mass M, size L^3, turbulence v

- Assume SF feedback momentum/mass is p_*/m_*
- Momentum input rate is $$\dot{p}_{driv} = \frac{p_*}{m_*}\dot{M}_*$$
- Momentum dissipation rate is $$\dot{p}_{diss} \sim \frac{vM}{t_{dyn}} \sim \frac{v^2 M}{L}$$
- Balancing, $$\dot{M}_* \sim \frac{v^2 M}{L p_*/m_*}$$
- For system in dynamical equilibrium $v^2 \sim GM_{tot}/L$

$$\Rightarrow \quad \dot{M}_* \sim \frac{G M_{tot} M}{L^2 p_*/m_*}$$

Self-regulated star formation

Star-forming equilibrium gaseous system supported by driven turbulence

- $M_{tot} \sim M \Rightarrow \quad \dot{M}_* \sim \frac{v^2 M}{L p_* / m_*} \rightarrow \frac{G M^2}{L^2 p_* / m_*}$

- Can also define: $\dot{M}_* \equiv \varepsilon_{ff} \frac{M}{t_{ff}} \sim \varepsilon_{ff} \frac{v M}{L}$

Krumholz et al; Padoan et al; Federrath et al

ε_{ff} depends in principle on $\alpha_{vir} \sim (t_{ff}/t_{dyn})^2$, v/c_s, v/v_A; small if turbulence can disperse structures before they collapse

$$v \sim \varepsilon_{ff} \frac{p_*}{m*}$$

dynam. equil.
driving=dissipation
SF efficiency definition

$$L \sim \frac{G M}{v^2}$$

dynam. equil.

$$\dot{M}_* \sim \frac{G M^2}{L^2 p_* / m_*}$$

dynam. equil.
driving=dissipation

Gas-dominated starburst disk

Ostriker & Shetty (2011)

$$\dot{M}_* \sim \frac{GM^2}{L^2 p_*/m_*} \longrightarrow \frac{\dot{M}_*}{L^2} \sim \frac{GM^2}{L^4 (p_*/m_*)}$$

$$\Rightarrow \quad \Sigma_{\rm SFR} \sim \frac{G\Sigma^2}{p_*/m_*}$$

- Star formation rate per unit area in disk is
  - *independent* of details of turbulence
  - *independent* of $\varepsilon_{\rm ff}$ on small scales
- Disk thickness and internal dynamical time must adjust until momentum feedback rate matches vertical weight of ISM

Gas-dominated starburst disk

Ostriker & Shetty (2011)

$$\dot{M}_* \sim \frac{GM^2}{L^2 p_*/m_*} \longrightarrow \frac{\dot{M}_*}{L^2} \sim \frac{GM^2}{L^4 (p_*/m_*)}$$

$$\Rightarrow \quad \Sigma_{\rm SFR} \sim \frac{G\Sigma^2}{p_*/m_*}$$

- As for other strongly turbulent systems, expect low ε_{ff}, with self-consistent v related to feedback momentum by:

$$v \sim \varepsilon_{ff} \frac{p_*}{m*}$$

- L is disk thickness H:

$$H \sim \frac{GM}{v^2} \sim \frac{GH^2\Sigma}{v^2} \Rightarrow H \sim \frac{v^2}{G\Sigma}$$

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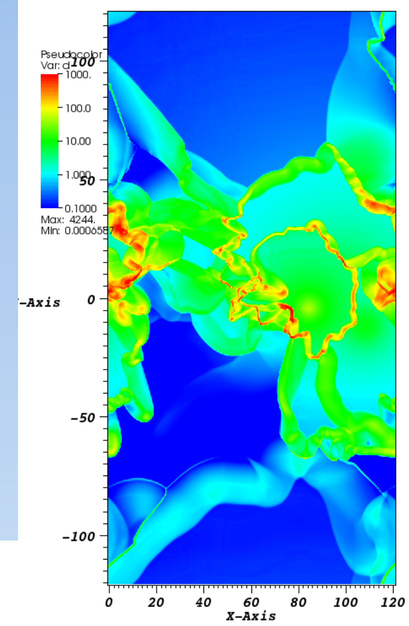
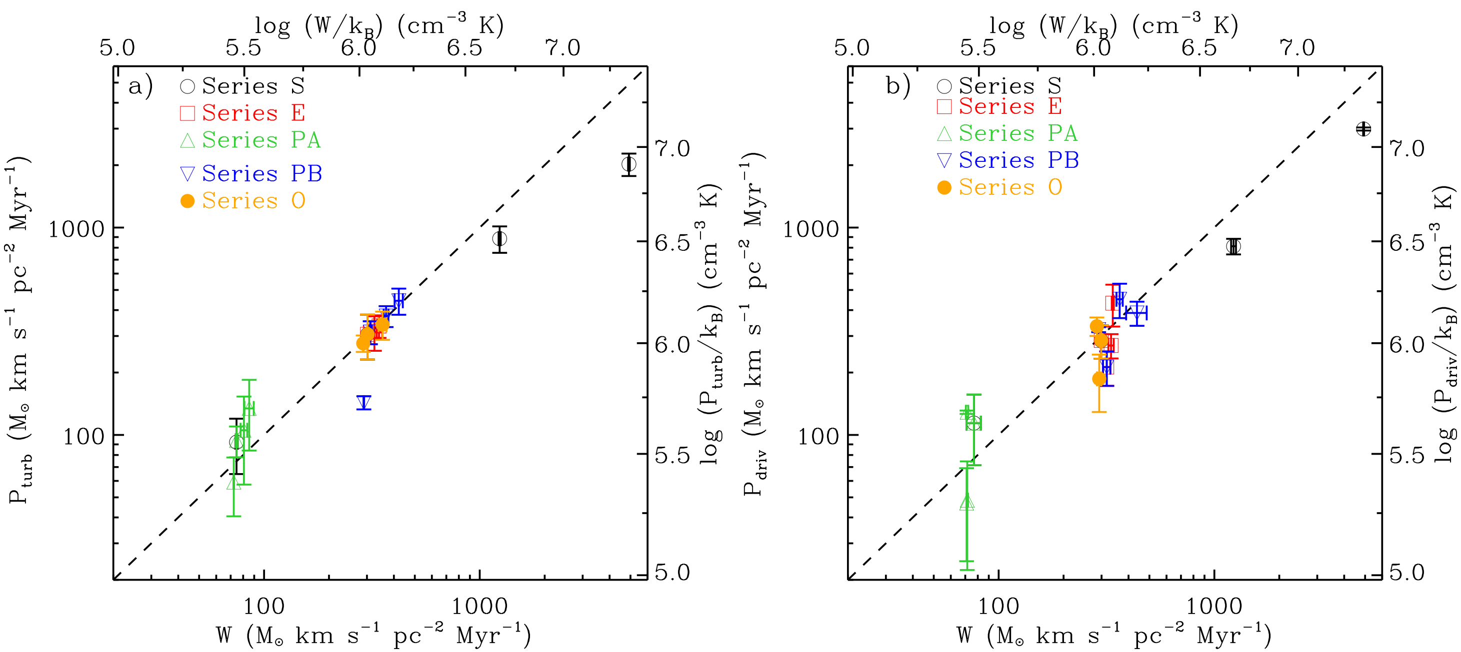
Starburst regime simulations

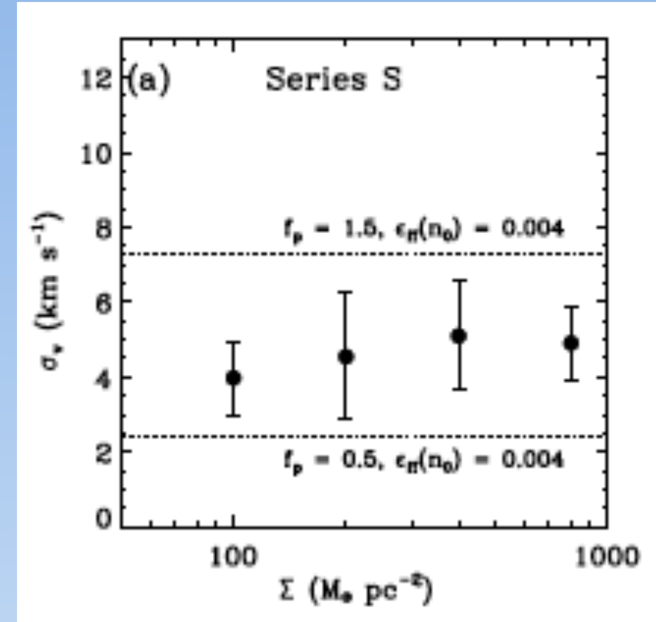
Shetty & Ostriker (2012)

- Feedback-driven, turbulence-dominated equilibrium:
  - $P_{turb} \approx W \approx \pi G \Sigma^2/2 \approx (1/4)(p_*/m_*)\Sigma_{SFR}$
  - Simulation yields $\varepsilon_{ff}(\rho_0)$~0.005-0.01 insensitive to other conditions
  - Simulation yields v_z~ 5-10 km/s $\propto p_*/m_*$



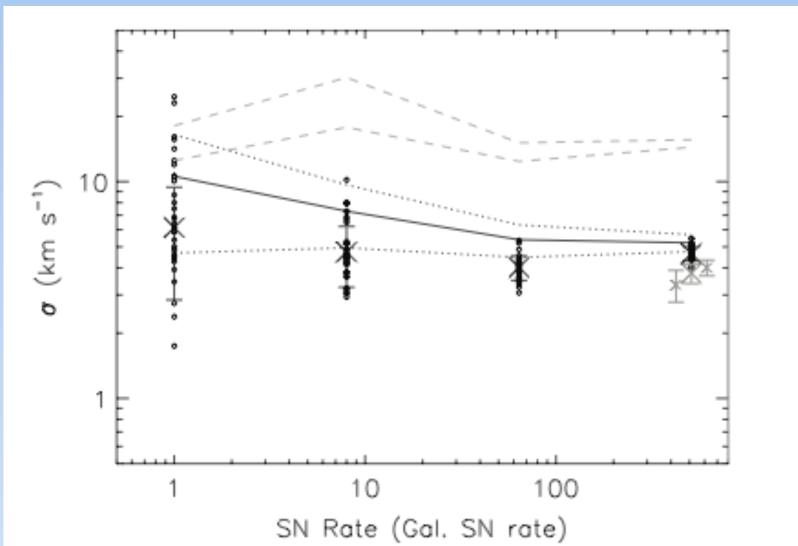


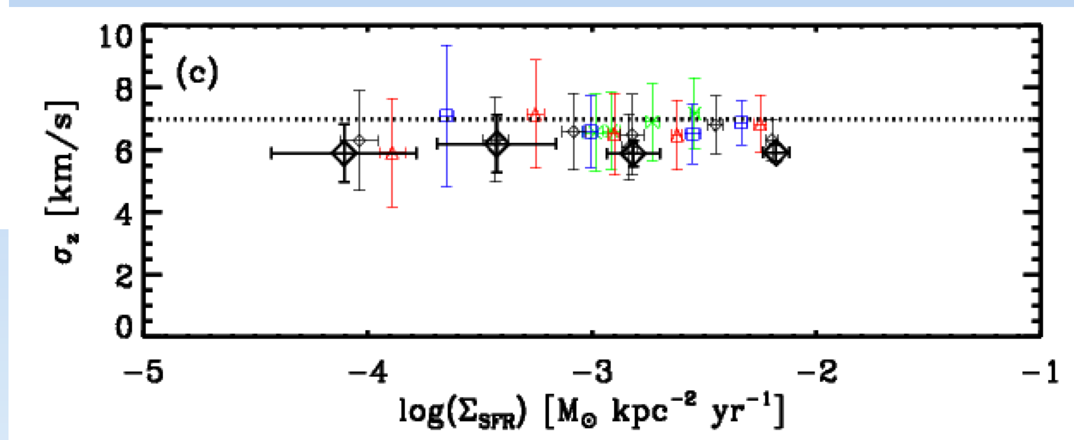
Supernova-driven turbulence



Shetty & Ostriker (2012)

Momentum-driven





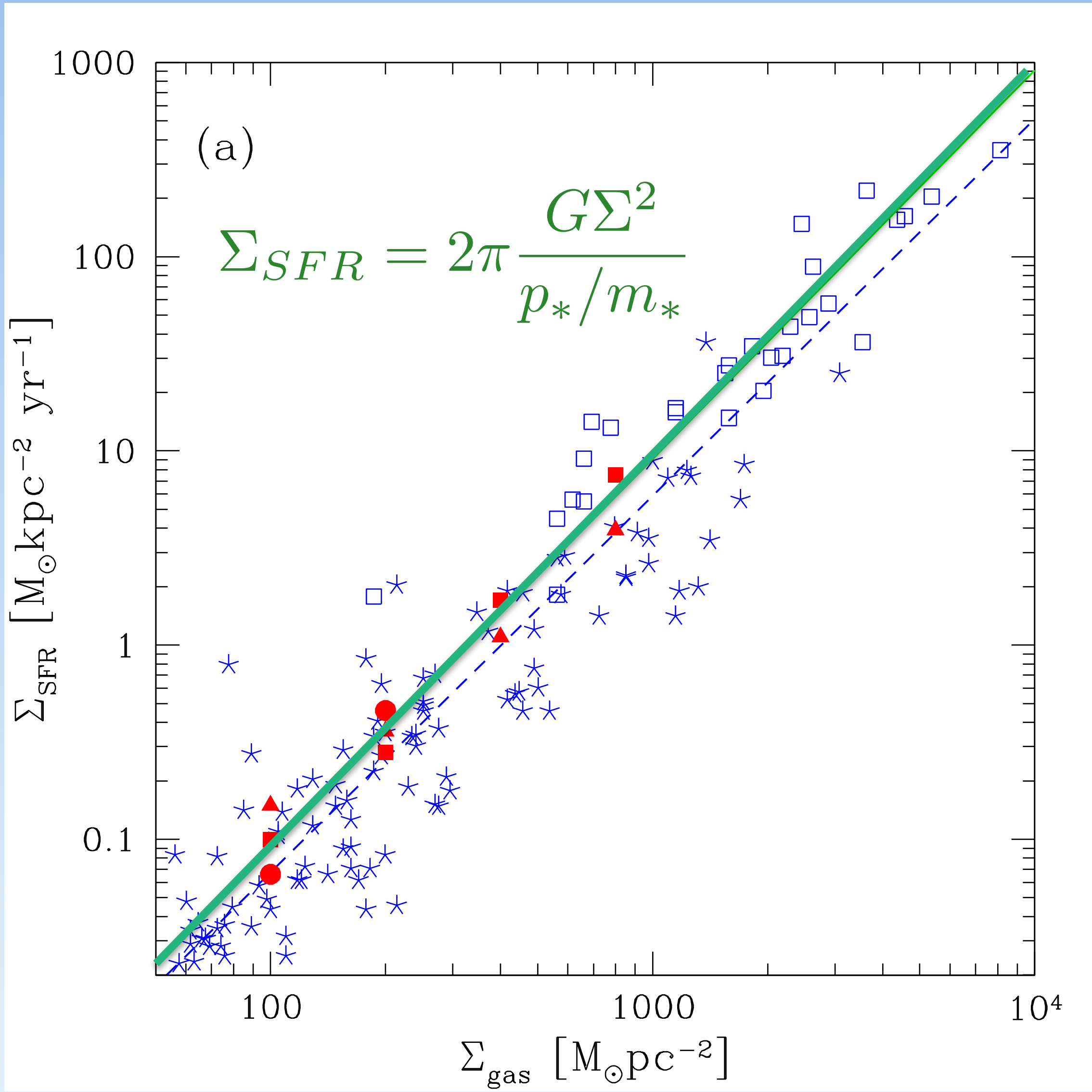
Energy-driven Joung et al (2009)

Kim et al (2011, 2013)

Radiative SN remnants (Cioffi et al 1988; Blondin et al 1998, Thornton et al 1998):

$$\frac{p_*}{m_*} \approx 3000\mathrm{km\,s^{-1}} \left(\frac{E_{\rm SN}}{10^{51}\mathrm{erg}}\right)^{0.94} \left(\frac{n_0}{1\mathrm{cm}^{-3}}\right)^{-0.12} \left(\frac{m_*}{100M_\odot}\right)^{-1}$$

Starburst regime



Ostriker & Shetty (2011)

Data from Genzel et al (2010) sample

for p_*/m_*=3000 km/s

Self-regulation in externally-confined disks

Atomic-dominated regions of galactic disks are confined by the vertical *stellar* rather than vertical *gas* potential:

- Gravitational free-fall time (gas):

$$t_{\rm ff} = \left(\frac{3\pi}{32G\rho}\right)^{1/2} = 43{\rm Myr}\left(\frac{n_H}{1\ {\rm cm}^{-3}}\right)^{-1/2}$$

- Dynamical crossing time:

$$t_{\rm dyn} = \frac{1}{(4\pi G\rho_*)^{1/2}} = 13{\rm Myr}\left(\rho_*/0.1M_\odot\ {\rm pc}^{-3}\right)^{-1/2}$$

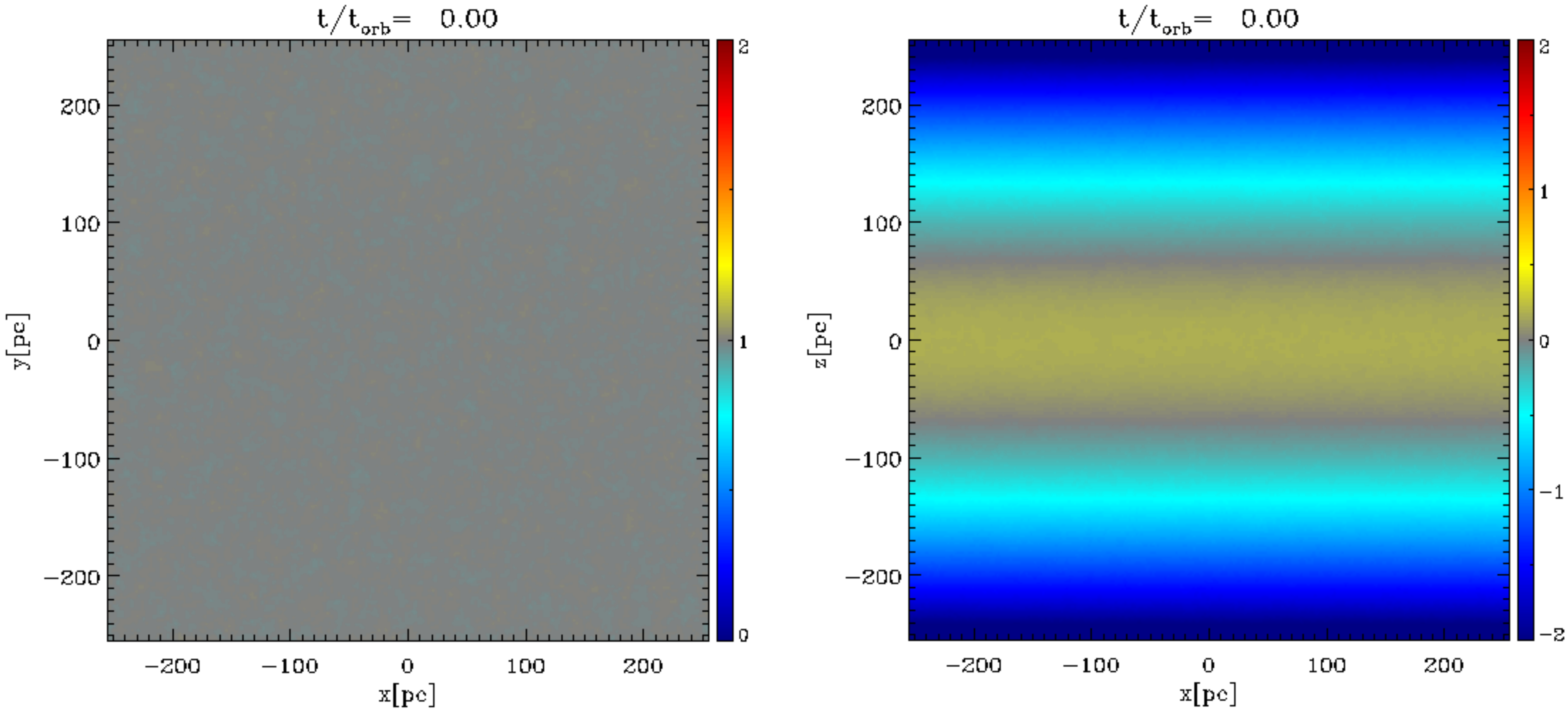
- Self-regulation via turbulent driving when $t_{ff} >> t_{dyn}$:

$$\dot{M}_* \sim \frac{GM_{tot}M}{L^2 p_*/m_*} \longrightarrow \Sigma_{SFR} \sim \frac{G\Sigma_{gas}\rho_{star}H_{gas}}{p_*/m_*}$$

$$H_{\rm gas} \sim v(G\rho_{star})^{-1/2} \qquad \boxed{\Sigma_{SFR} \sim \frac{\Sigma(G\rho_{star})^{1/2}v}{p_*/m_*}}$$

Simulations with turbulent feedback and radiative heating and for outer-disk regime

- Kim, Kim, & Ostriker (2011); Kim, Ostriker, & Kim (2013)
  - include turbulent driving from SN (momentum injection)
  - include dependence of heating rate on star formation rate ($\Gamma \propto J_{FUV} \propto \Sigma_{SFR}$)



Self-regulation in externally-confined disks

Allowing for thermal as well as turbulent feedback to atomic gas, $P_{th} = \eta_{th} \Sigma_{SFR}$ and $P_{turb} = \eta_{turb} \Sigma_{SFR}$, with

$P_{th} + P_{turb} = (\eta_{th} + \eta_{turb})\Sigma_{SFR} = P_{DE}$ for

$$P_{DE} = \frac{\Sigma}{2} g_z \approx \frac{\pi G \Sigma^2}{2} + \Sigma (2G\rho_*)^{1/2} \sigma_z$$

depending only on the gravity and total gas surface density of the disk form vertical dynamical equilibrium

- General result is

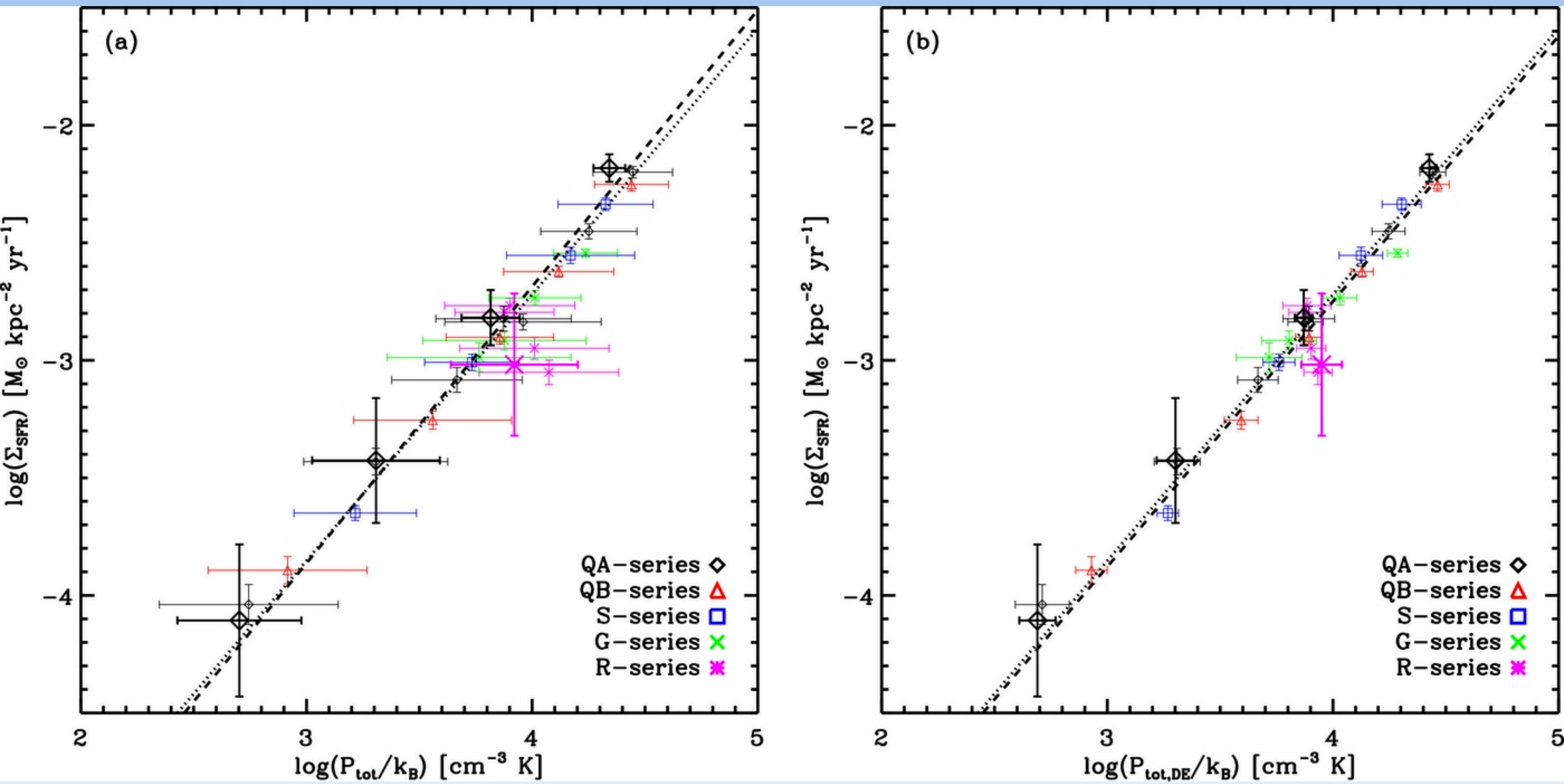
$$\Sigma_{SFR} = 2 \times 10^{-3} M_\odot \text{ kpc}^{-2} \text{yr}^{-1} \left(\frac{P/k}{10^4 \text{cm}^{-3} \text{K}} \right)$$

and for outer disk regions:

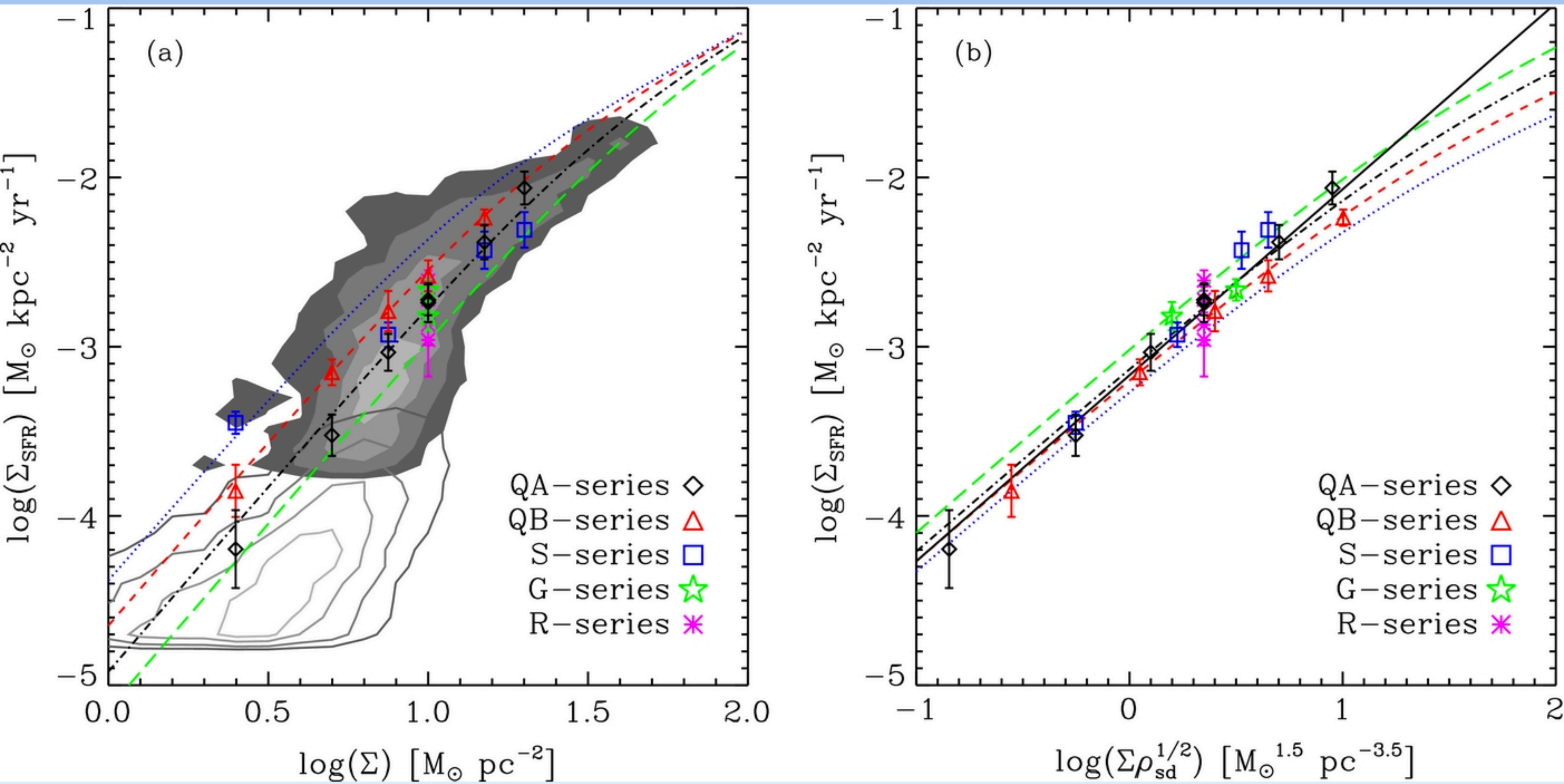
$$\Sigma_{SFR} = 2 \times 10^{-3} M_\odot \text{kpc}^{-2} \text{yr}^{-1} \left(\frac{\Sigma}{10 M_\odot \text{pc}^{-2}} \right) \left(\frac{\rho_*}{0.1 M_\odot \text{pc}^{-3}} \right)^{1/2}$$

Ostriker, McKee, & Leroy (2010); Kim, Kim, & Ostriker (2011), Kim, Ostriker, Kim (2013)

$$P_{DE} = \frac{\Sigma}{2} g_z \approx \frac{\pi G \Sigma^2}{2} + \Sigma (2G\rho_*)^{1/2} \sigma_z$$

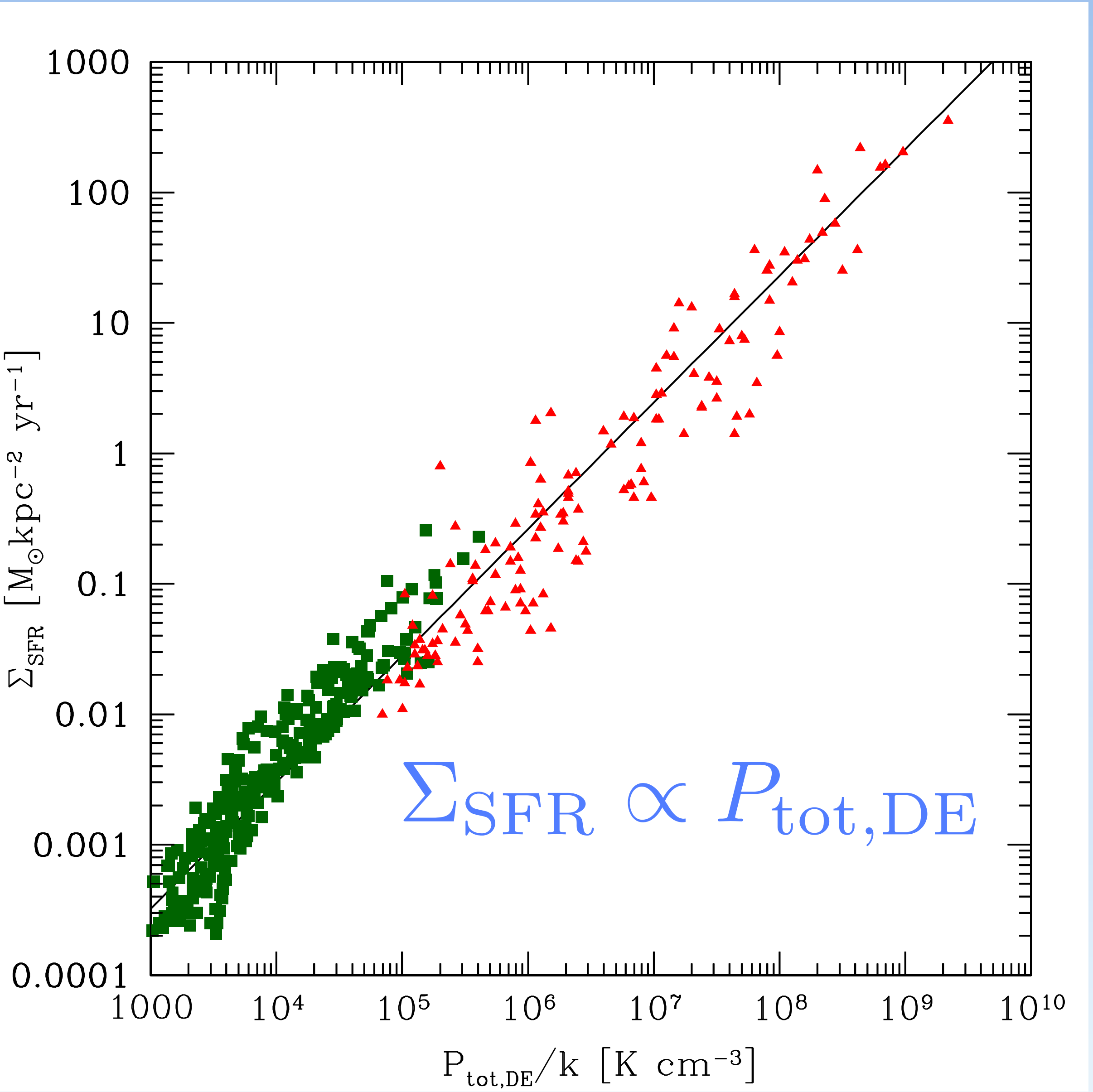


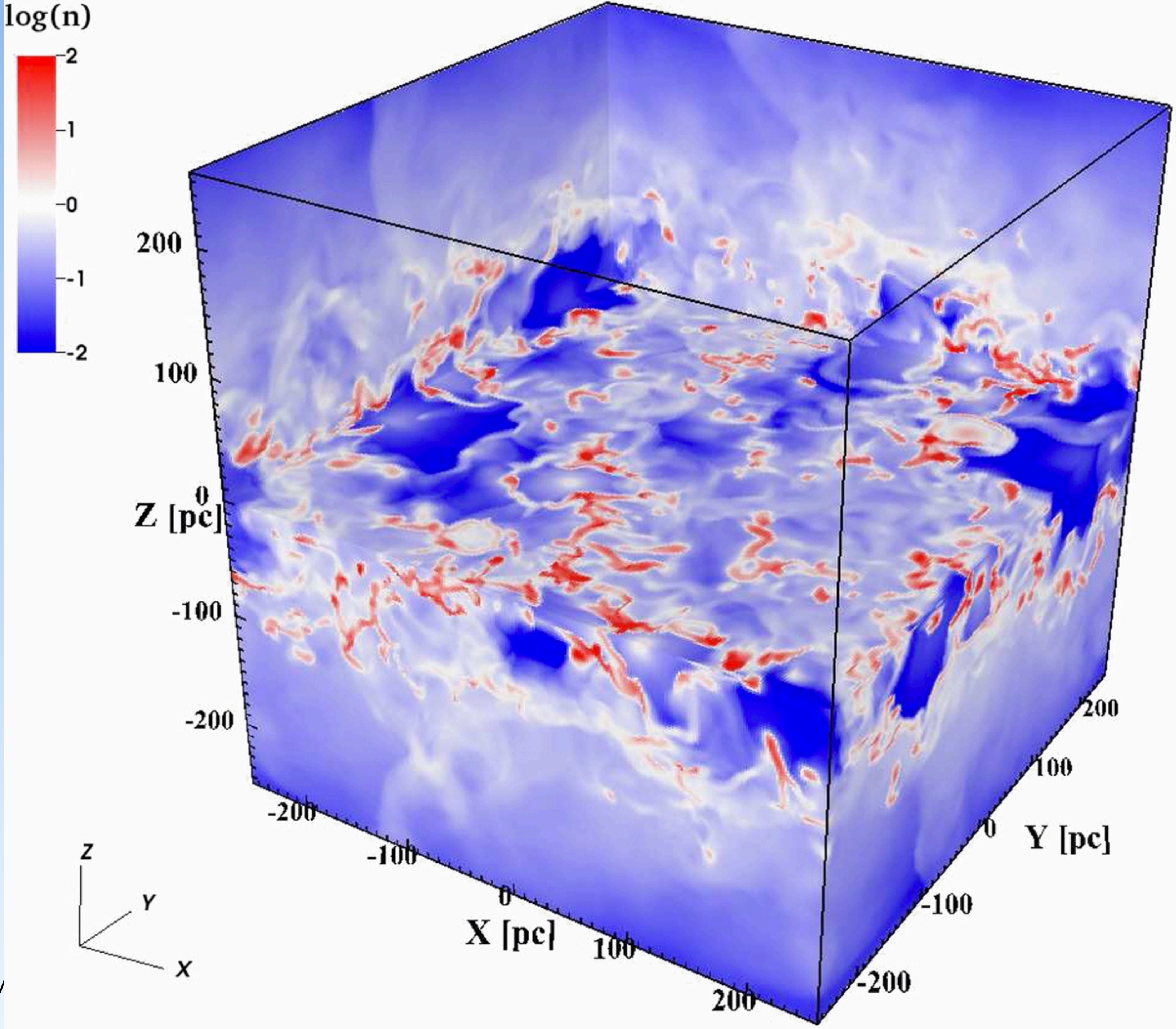
Kim, Ostriker, & Kim (2013)

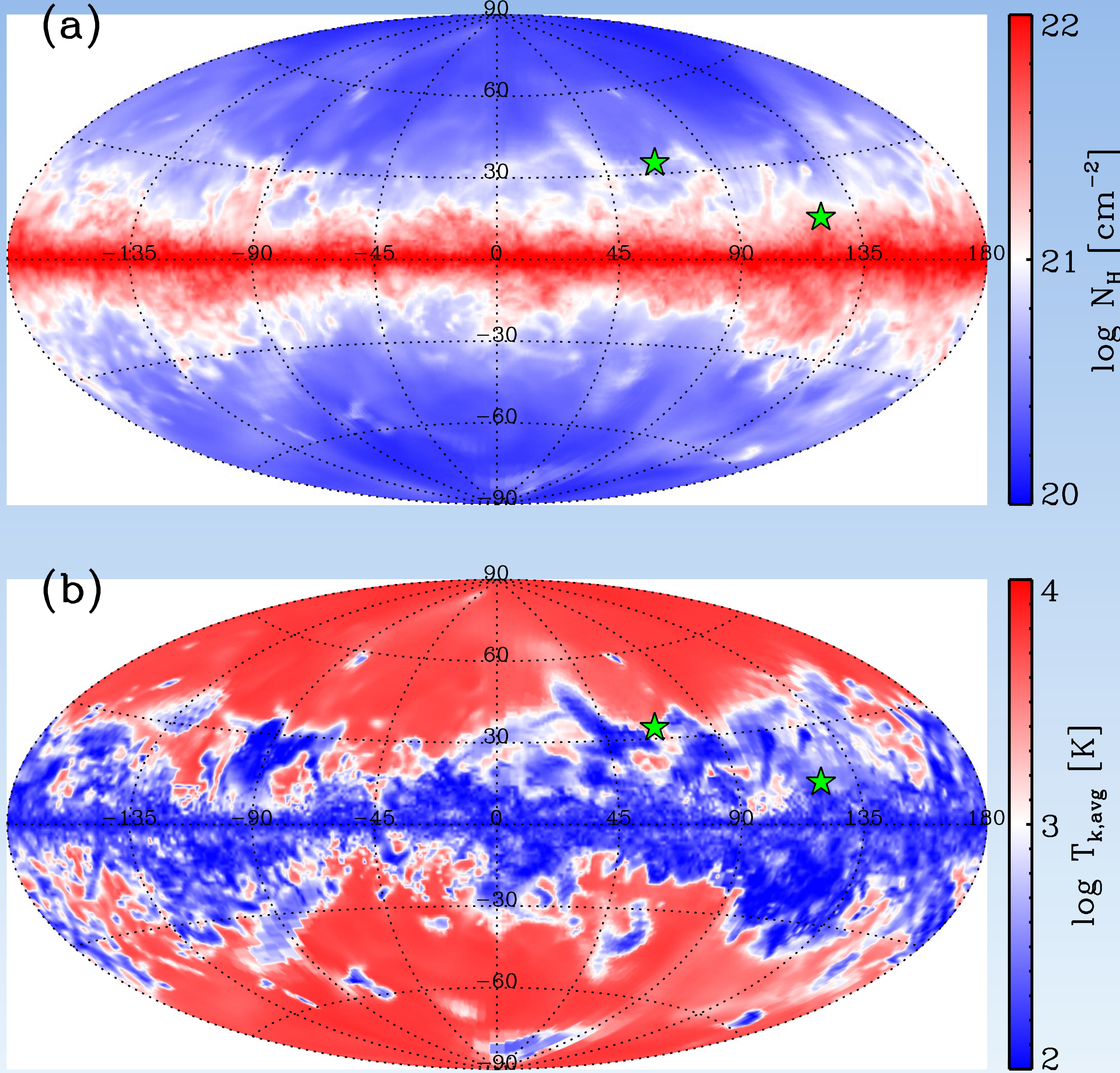


Kim, Kim, & Ostriker (2011)

Σ_{SFR} vs. equilibrium pressure

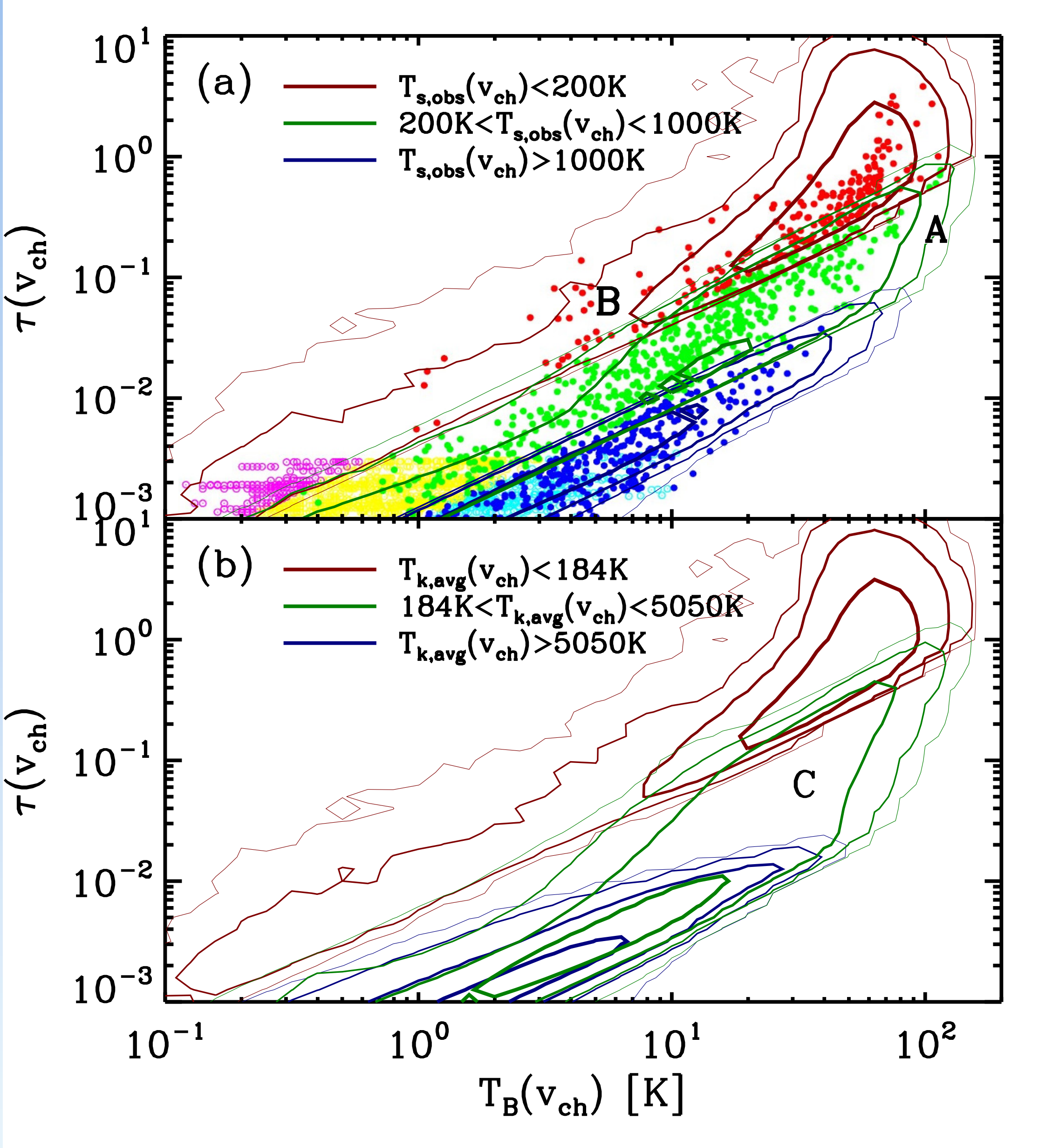



log(n)
2
1
0
-1
-2
200
100
0
Z [pc]
-100
-200
-200
-100
0
X [pc]
100
200
200
100
0
Y [pc]
-100
-200
Z
Y
X



Kim, Ostriker, Kim (2014)

21 cm T_B, T_s, τ



Kim, Ostriker, Kim (2014)

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Radiation force

- Direct radiation

$$\dot{p} = \frac{\mathcal{L}_*}{c} \to \frac{\varepsilon_{nuc} c^2 \dot{M}_*}{c} \quad \Rightarrow \frac{p_*}{m_*} = \frac{\dot{p}}{\dot{M}_*} = \varepsilon_{nuc} c \sim 180\mathrm{km/s}$$

- Reprocessed radiation

Overall ISM: $$\frac{p_*}{m_*} = \varepsilon_{nuc} c \kappa_{IR} \Sigma \sim 180\mathrm{km/s} \times \tau_{IR}$$

$$\tau_{IR} = 2\kappa_{IR} \frac{\Sigma}{10^4 M_\odot \ \mathrm{pc}^{-2}}$$

Individual cluster-forming cloud: $$\dot{p} \sim \frac{\mathcal{L}_* \tau_{IR}}{c} \to \frac{\Psi M_* \tau_{IR}}{c}$$

$$\frac{p_*}{m_*} \sim \frac{\Psi \tau_{IR} t_{embed}}{c} \sim 20\mathrm{km/s} \frac{t_{embed}}{\mathrm{Myr}} \tau_{IR}$$

or $$\frac{p_*}{m_*} \sim v \frac{\Psi \kappa_{IR}}{Gc} \frac{t_{embed}}{t_{dyn}} \sim v$$

Turbulent, cluster-forming cloud with IR radiation

- Starting with $\varepsilon_{ff} \sim \frac{v}{p_*/m*}$, efficiency over cloud lifetime is

$$\varepsilon \sim \varepsilon_{ff} \frac{t_{life}}{t_{ff}} \sim \frac{v}{L} \frac{v}{p_*/m_*} t_{life} \sim \frac{v^2 M_*}{L\dot{p}} \sim \frac{GM}{L^2} \frac{M_*}{\dot{p}} \sim \frac{G\Sigma M_*}{\dot{p}}$$

- Momentum input rate from reprocessed IR is

$$\dot{p} \sim \frac{\mathcal{L}_* \tau}{c} \sim \frac{M_* \Psi \kappa_{IR} \Sigma}{c}$$

$$\Rightarrow \boxed{\varepsilon \sim \frac{Gc}{\Psi \kappa_{IR}}}$$

cf. Murray et al (2010)

NB: for cluster with radiation-driven shell, exact result is:

$$\varepsilon_{min} = \left[\frac{\Psi \kappa_{IR}}{2\pi G c} - 1 \right]^{-1}$$

Ostriker & Shetty (2011)

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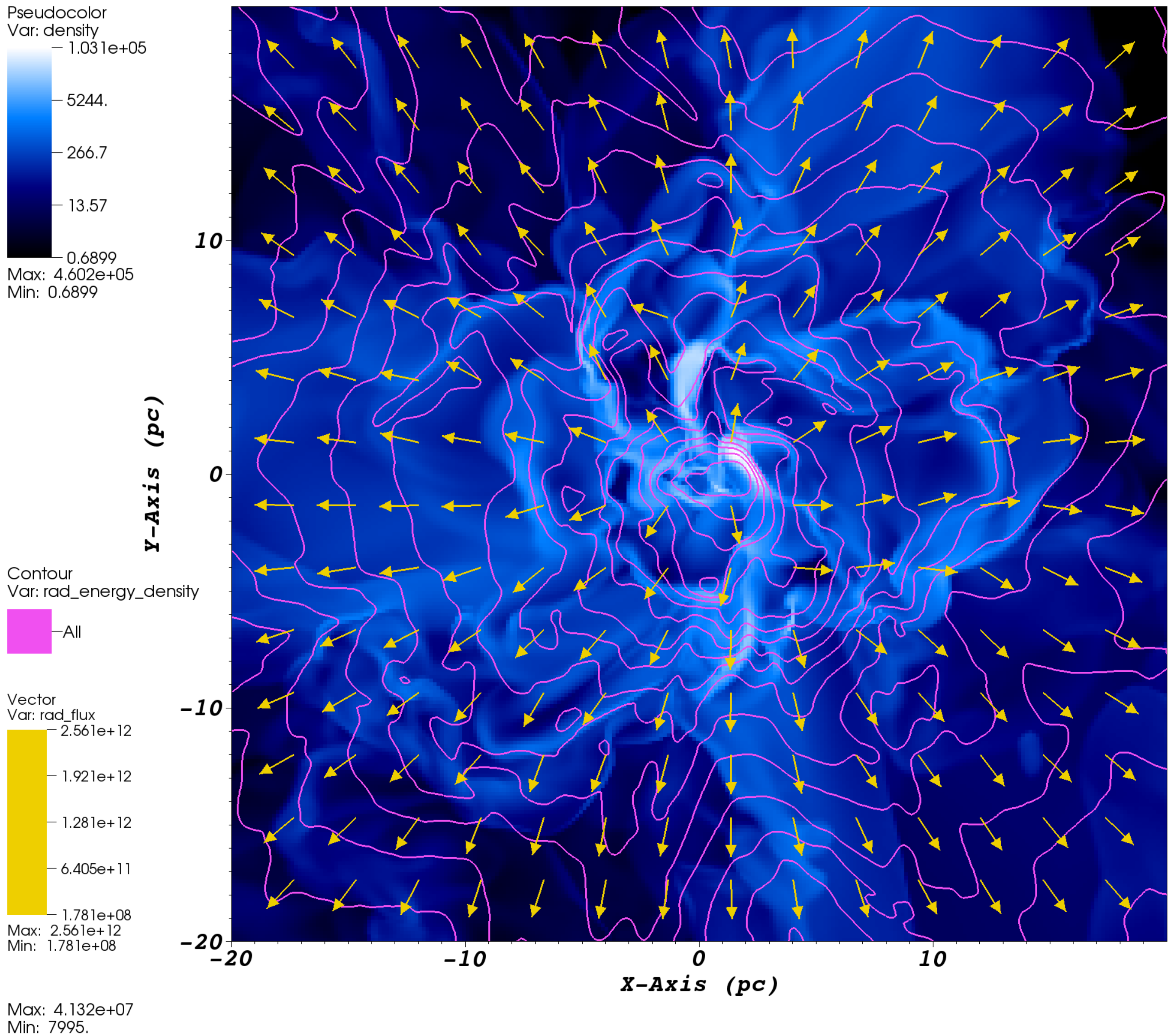
Cluster-forming cloud with IR radiation: numerical simulation

Skinner & Ostriker (2014)

- Consider evolution of a turbulent, star-forming GMC, including effects of reprocessed radiation
- Solve evolution equations for first two radiation moments (energy and flux) using RSL method with M1 closure (Skinner & Ostriker 2013), combined with gas integration of *Athena*
- Sink particles (Gong & Ostriker 2013) model star (sub) clusters with luminosity $\mathcal{L}_* = \Psi M_*$
- Consider a range of κ, initial cloud mass M_{GMC} and radius R_{GMC}

R=10 pc, M=1e6 Msun, kappa=20 cm^2 g^-1, N=256, t/t_ff=3



Cluster-forming cloud with IR radiation: numerical simulation

Skinner & Ostriker (2014)

- Measure gas mass converted to stars vs ejected
  - efficiency $\varepsilon_* = M_*/M_{GMC}$ and $\varepsilon_{wind} = M_{ejected}/M_{GMC}$
- Measure gas momentum ejected p_{ej}
  - compute $p_*/m_* = p_{ej}/M_*$ compared to $v=(GM/R)^{1/2}$
- Explore gas and radiation structure in cloud:

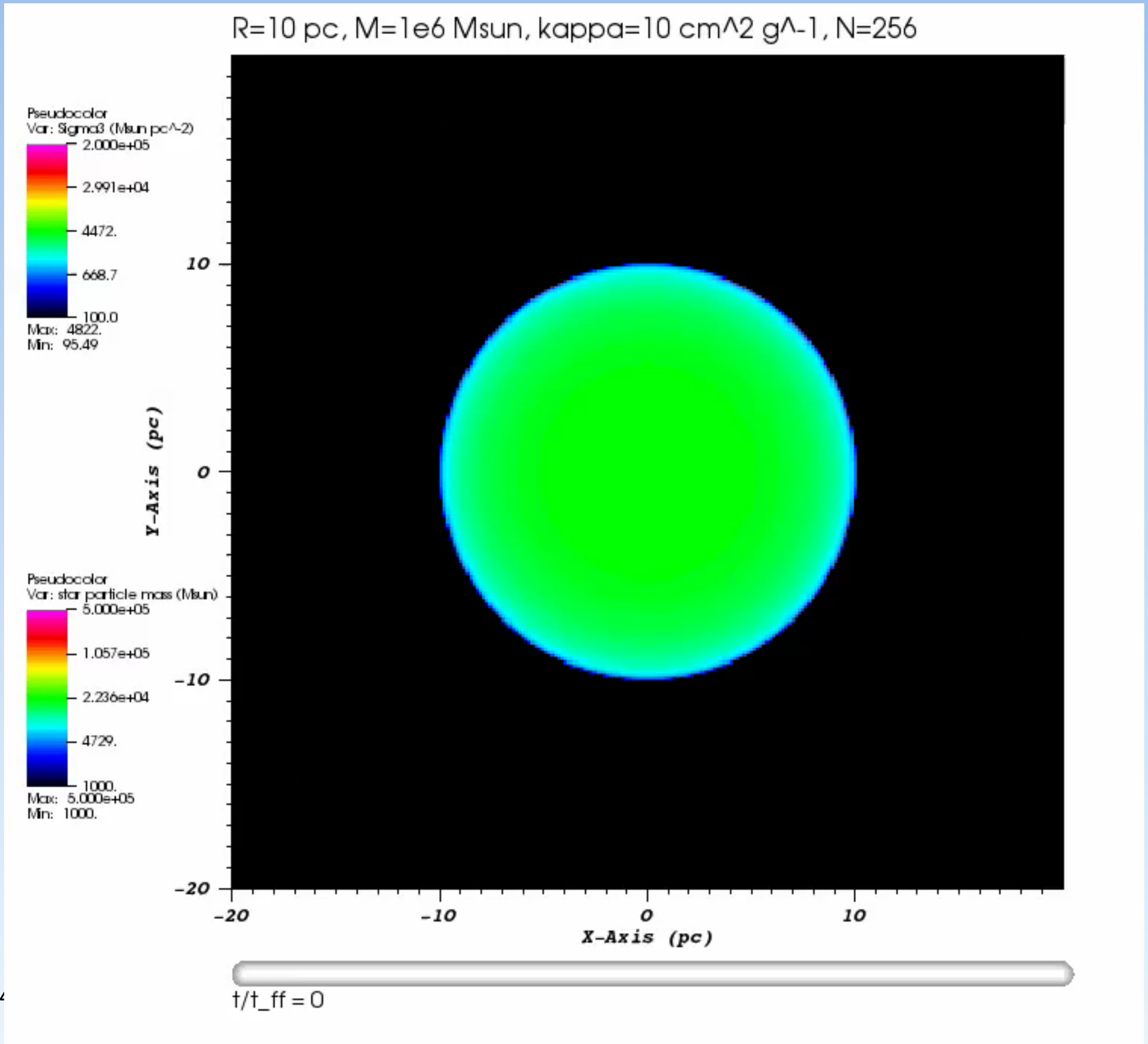
$$f_{Edd}(r) = \frac{\langle F_r \rho \kappa / c \rangle}{\langle g_r \rho \rangle}; \quad f_{Edd} = \frac{\int \langle F_r \rho \kappa / c \rangle r^2 dr}{\int \langle g_r \rho \rangle r^2 dr} \quad versus \quad \frac{\Psi \kappa}{4\pi G c}$$

$$f_{trap} = \frac{\int \langle F_r \rho \kappa / c \rangle 4\pi r^2 dr}{\mathcal{L}/c} \qquad versus \qquad \tau = \int \rho \kappa dr$$

cf. Krumholz & Thompson; Davis et al

Star-forming cloud with RHD

Skinner & Ostriker (2014)



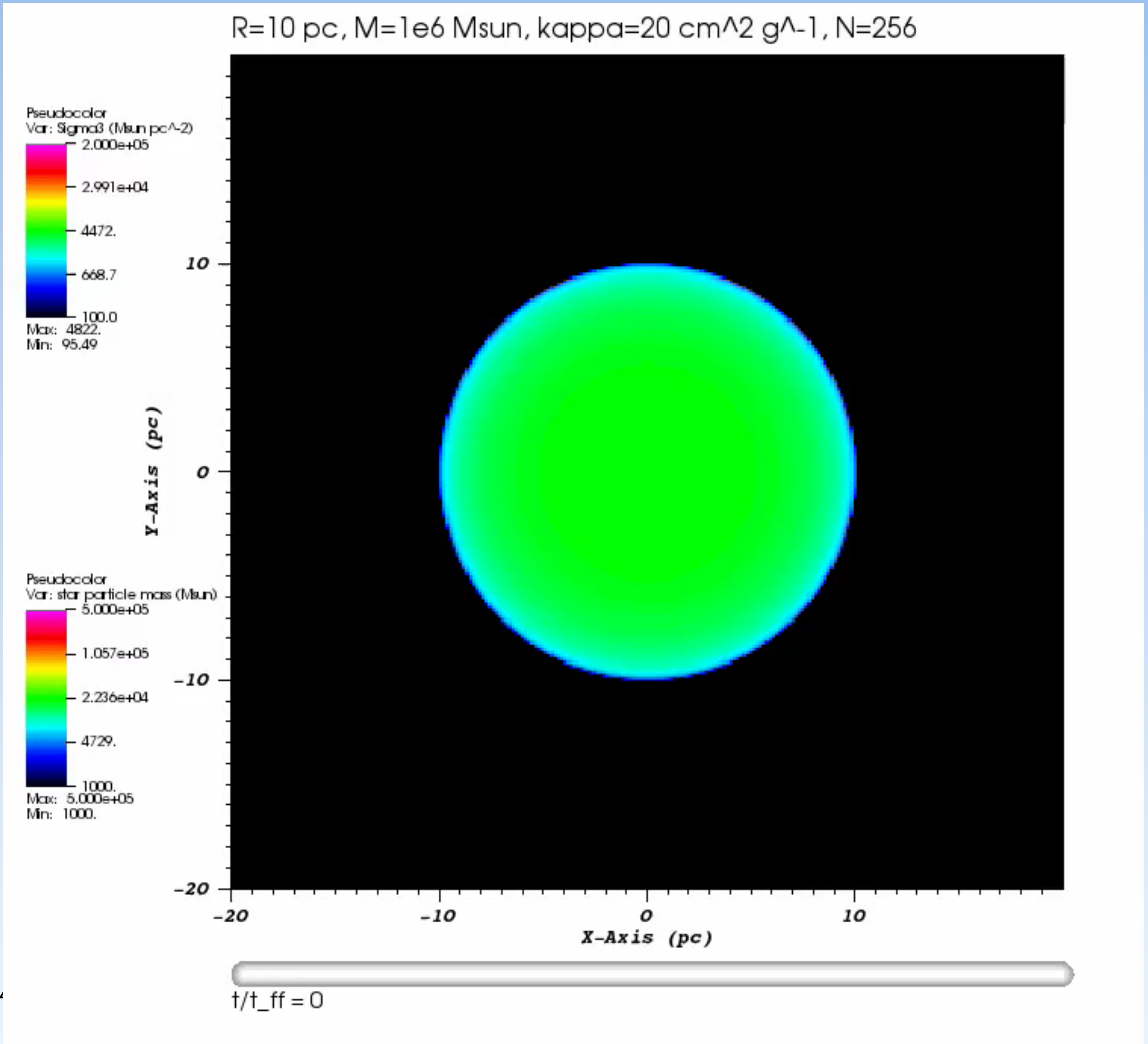
$10^6\ M_\odot$ initial cloud with sink particles and RHD

κ=10 g/cm^2

$L_* = \Psi M_*$ for subclusters; Ψ=1700 erg/s/g

t_{ff}=0.52 Myr

Star-forming cloud with RHD



Skinner & Ostriker (2014)

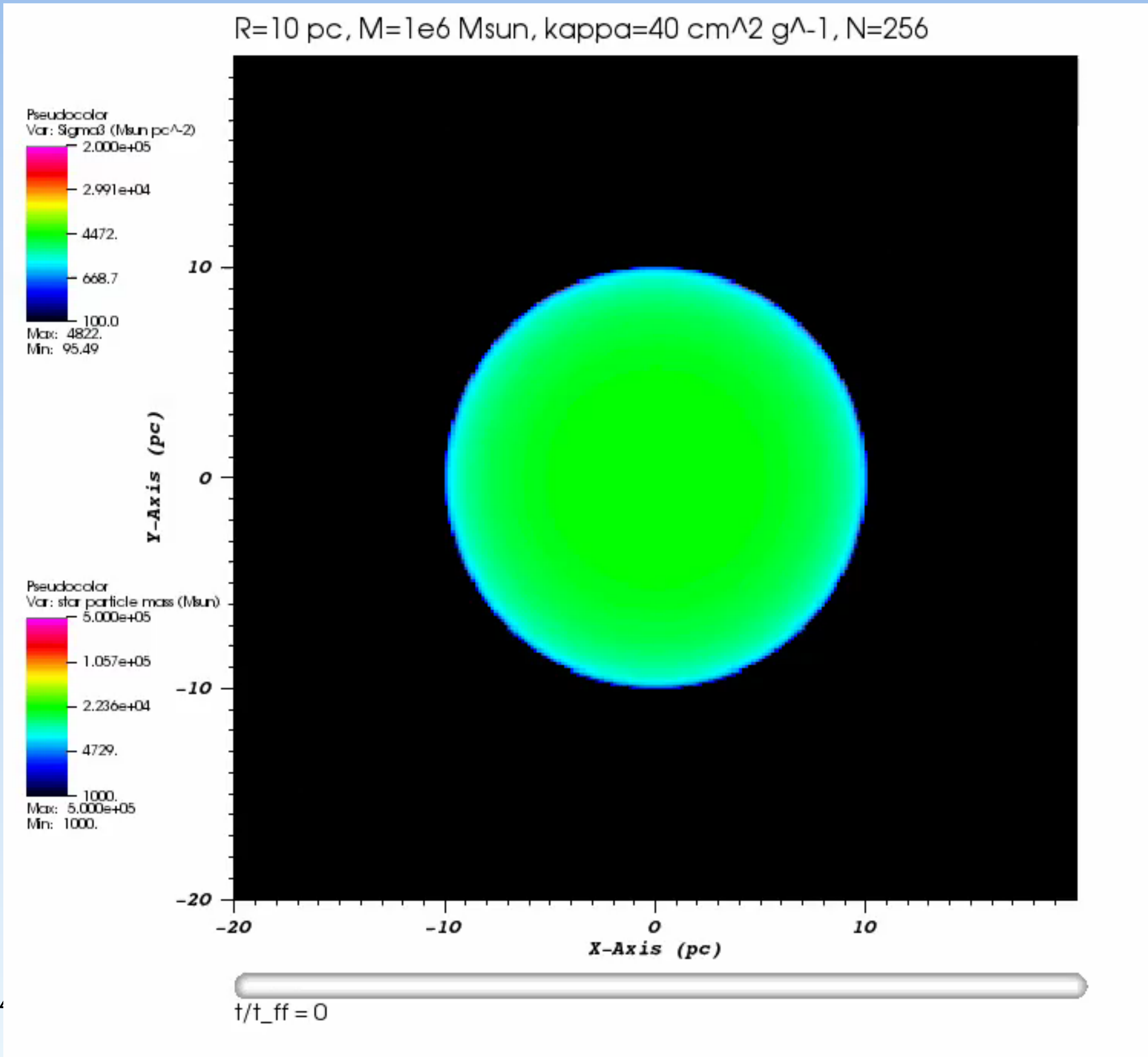
10^6 $M_\odot$ initial cloud with sink particles and RHD

κ=20 g/cm²

$L_* = \Psi M_*$ for subclusters; Ψ=1700 erg/s/g

t_{ff}=0.52 Myr

Star-forming cloud with RHD



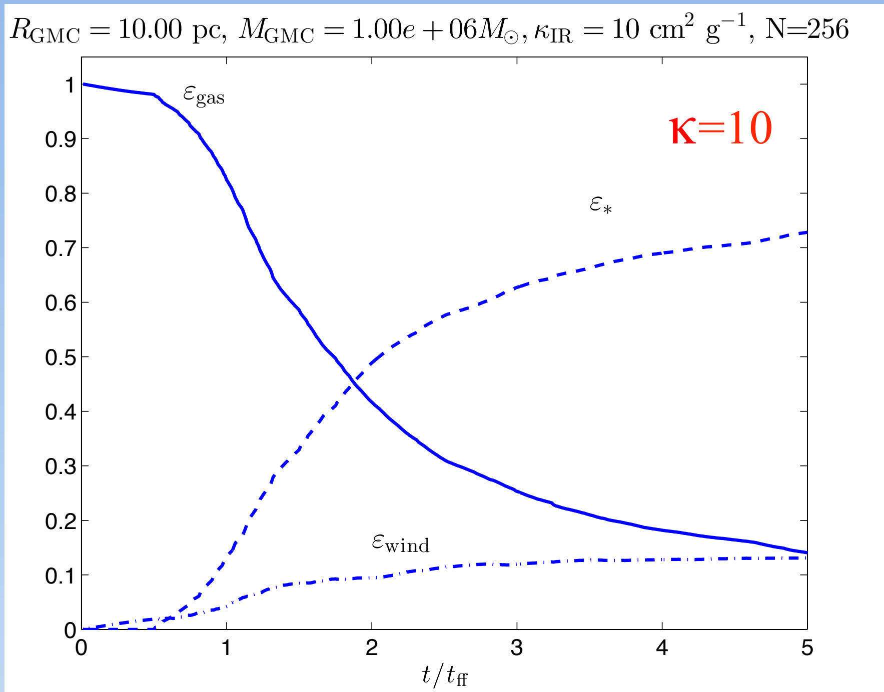
Skinner & Ostriker (2014)

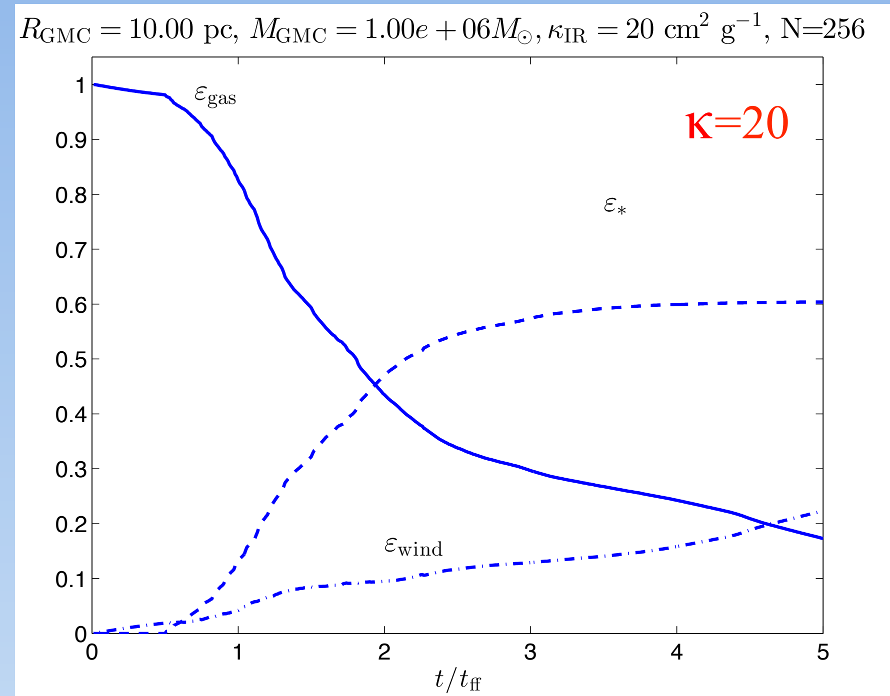
$10^6 M_\odot$ initial cloud with sink particles and RHD

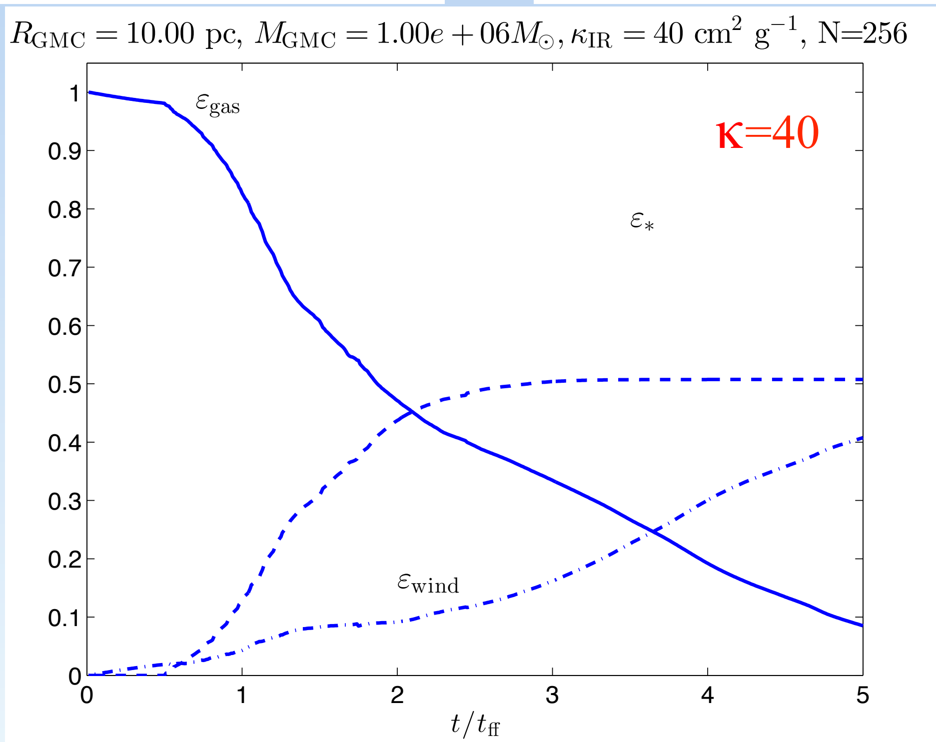
κ=40 g/cm^2

$L_* = \Psi M_*$ for subclusters; Ψ=1700 erg/s/g

t_{ff}=0.52 Myr

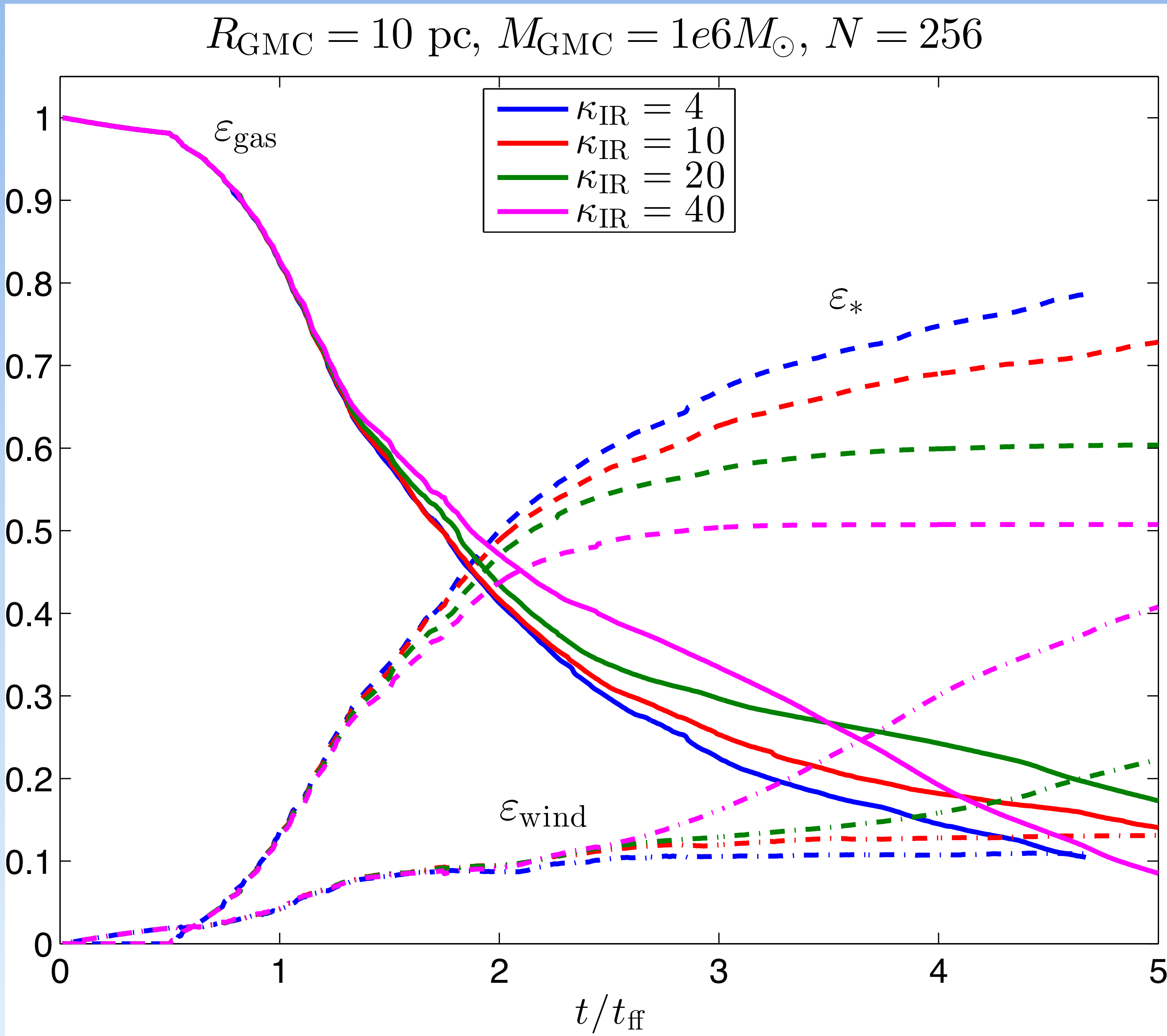






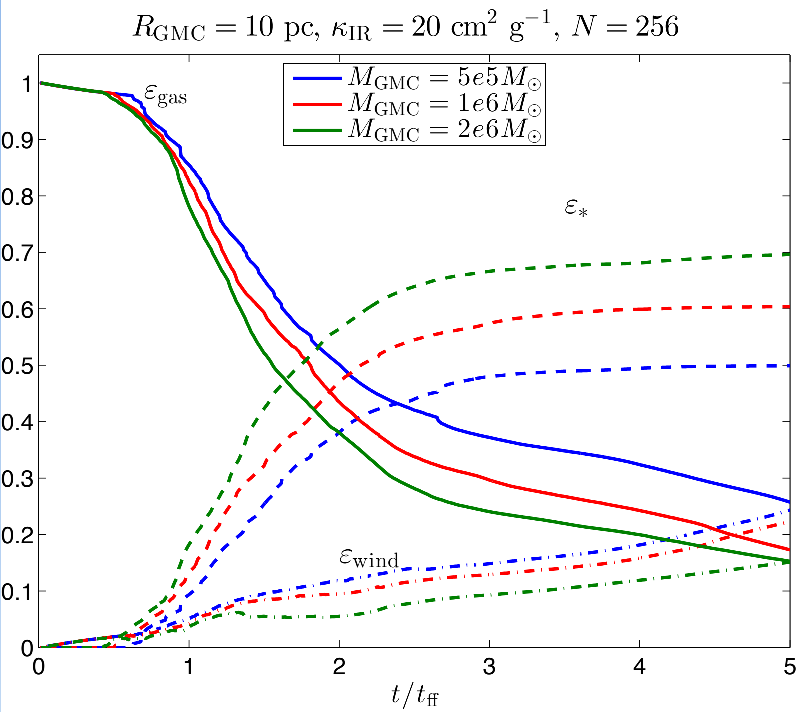
Skinner & Ostriker (2014)

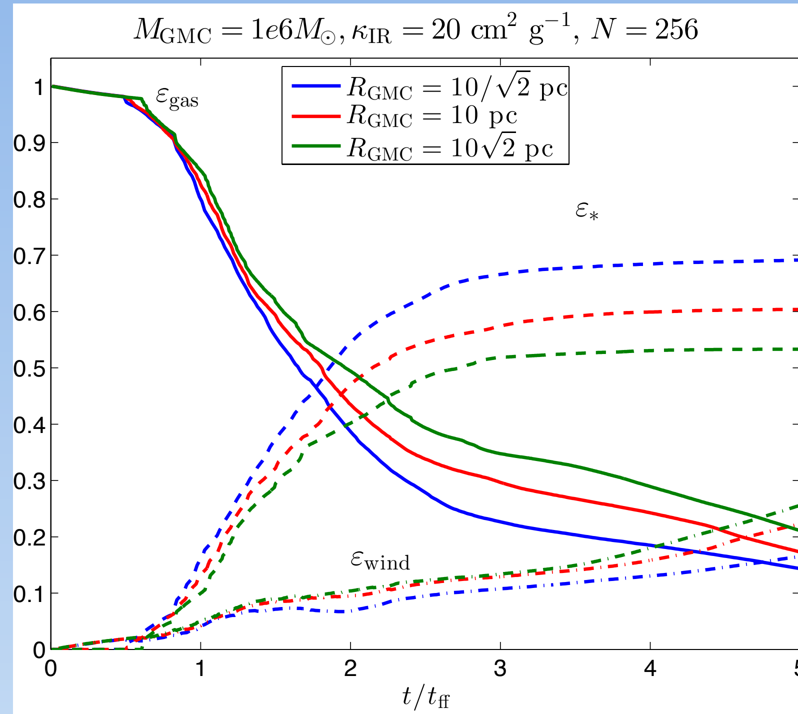
$t_{\rm ff}$=0.52 Myr



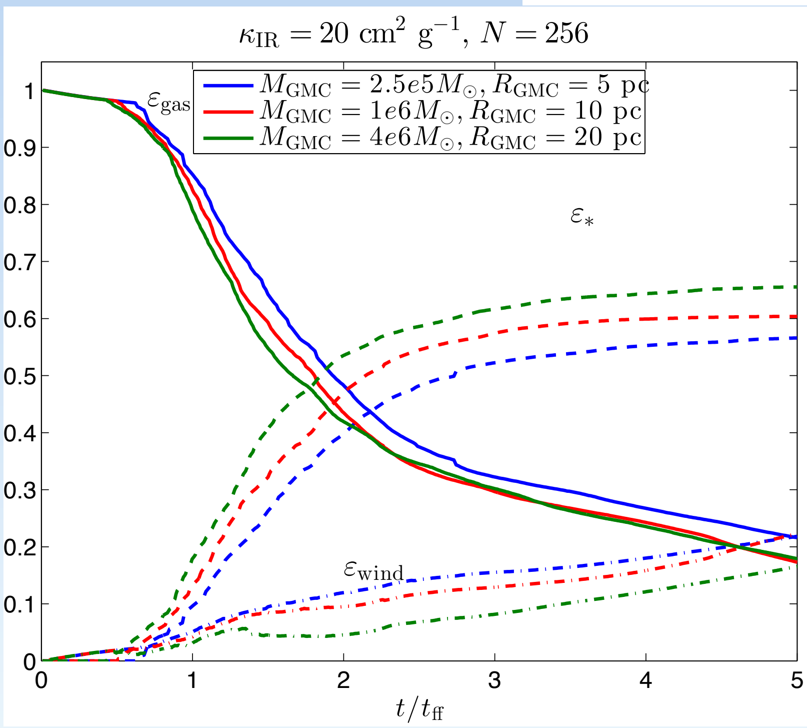
Skinner & Ostriker (2014)

t_{ff}=0.52 Myr





Skinner & Ostriker (2014)



Fractional mass loss and net SF efficiency relatively insensitive to cloud mass and size

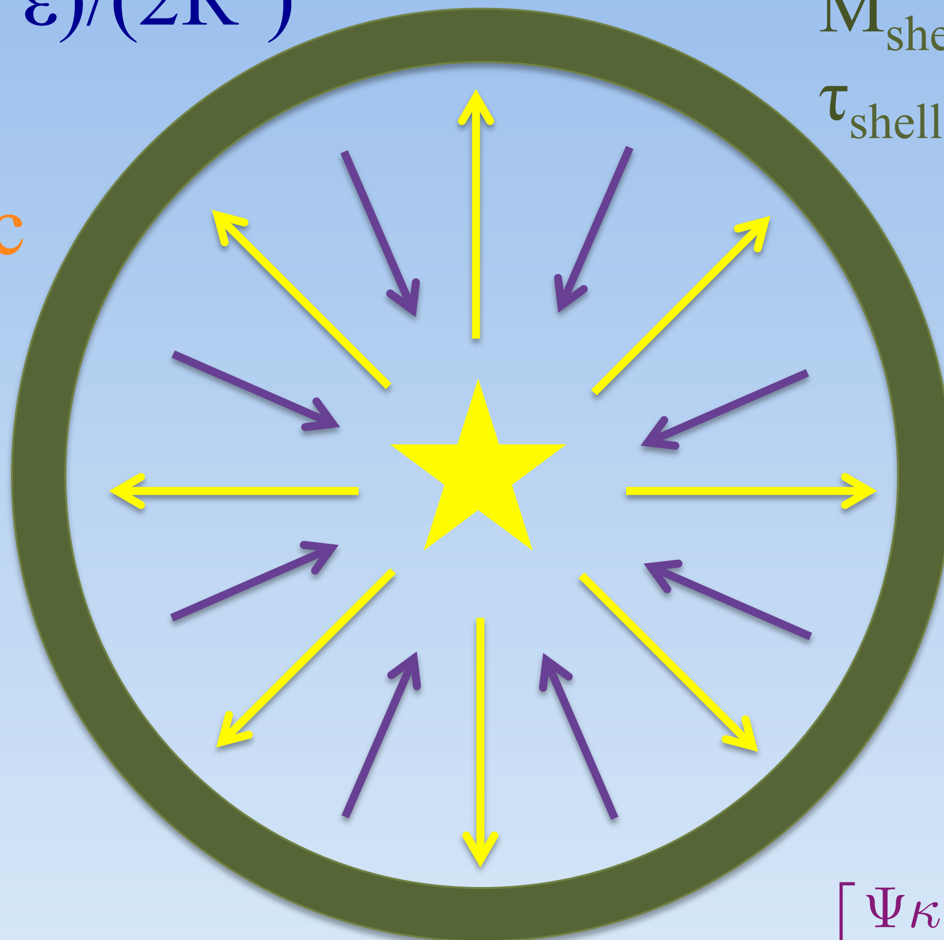
$t_{\rm ff}$=0.52 Myr

$F_{grav} = GM(1+\varepsilon)/(2R^2)$

$M_{shell} = (1-\varepsilon)\, M$

$\tau_{shell} = \kappa M_{shell}/(4\pi R^2)$

$F_{rad} = \mathcal{L}_* \tau_{shell}/c$



$M_* = \varepsilon M$

$\mathcal{L}_* = \Psi M_*$

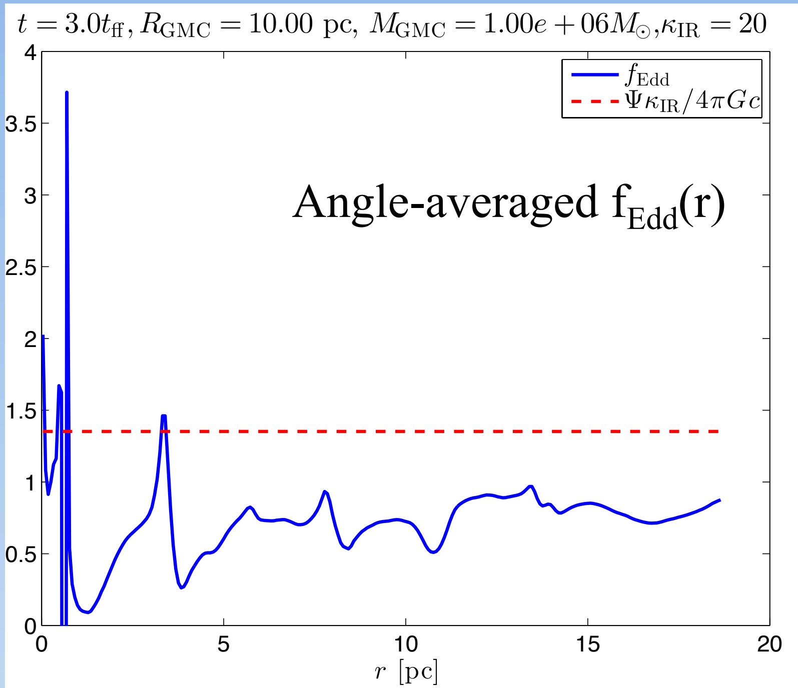
Ostriker & Shetty (2011)

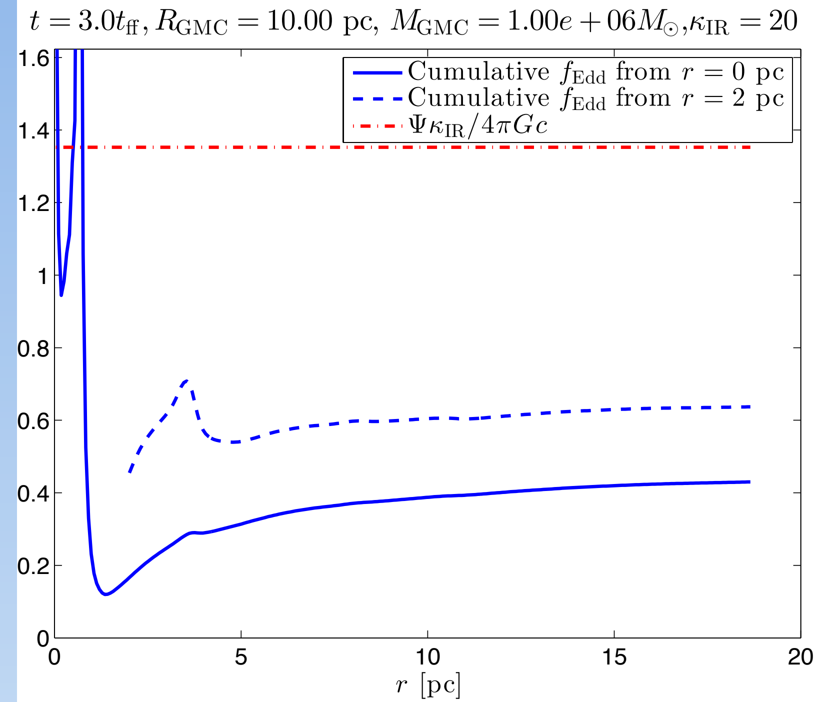
$$\varepsilon_{min} = \left[\frac{\Psi \kappa_{IR}}{2\pi G c} - 1\right]^{-1}$$

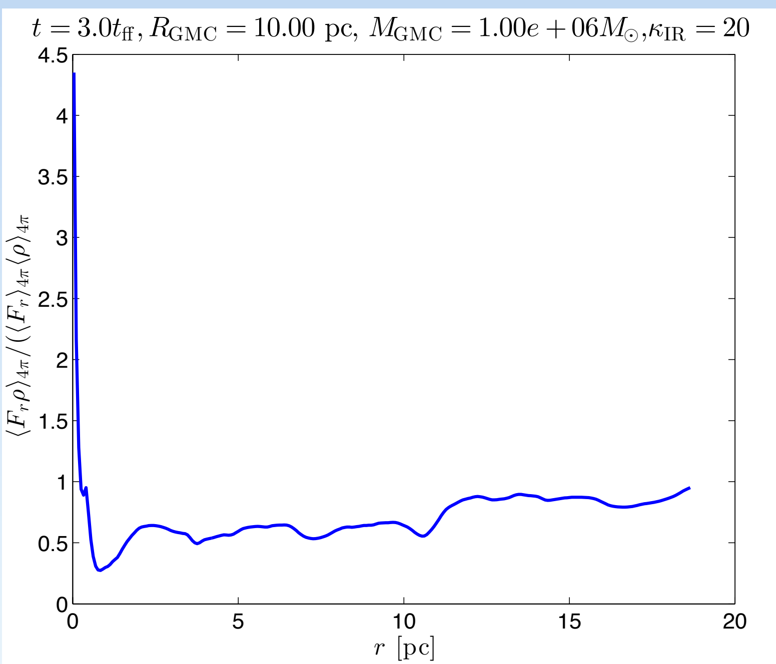
$\rightarrow 2$ for $\kappa = 10$ $(BOUND)$

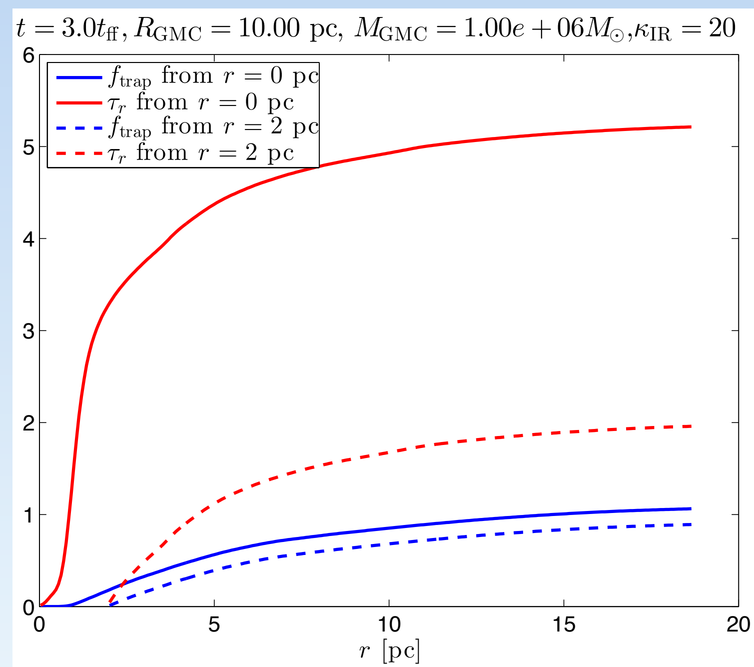
$\rightarrow 0.5$ for $\kappa = 20$

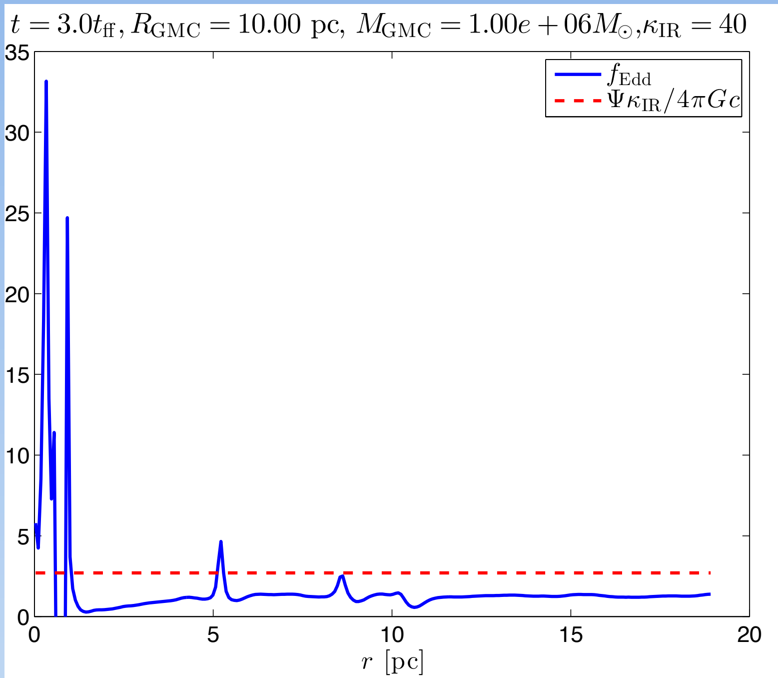
$\rightarrow 0.2$ for $\kappa = 40$

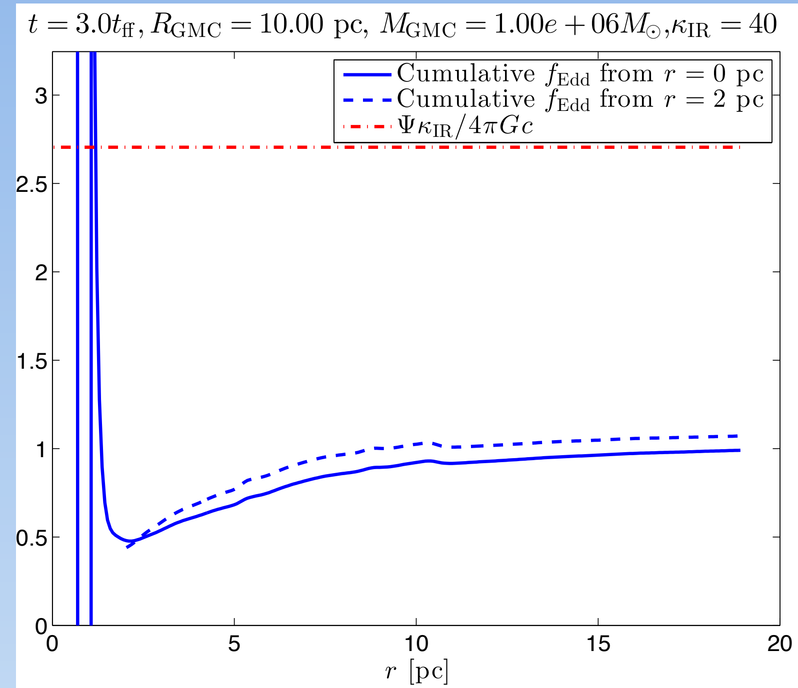

$t = 3.0 t_{\rm ff}, R_{\rm GMC} = 10.00$ pc, $M_{\rm GMC} = 1.00e + 06 M_\odot, \kappa_{\rm IR} = 20$
$f_{\rm Edd}$
$\Psi \kappa_{\rm IR} / 4\pi G c$
Angle-averaged $f_{\rm Edd}(r)$
r [pc]

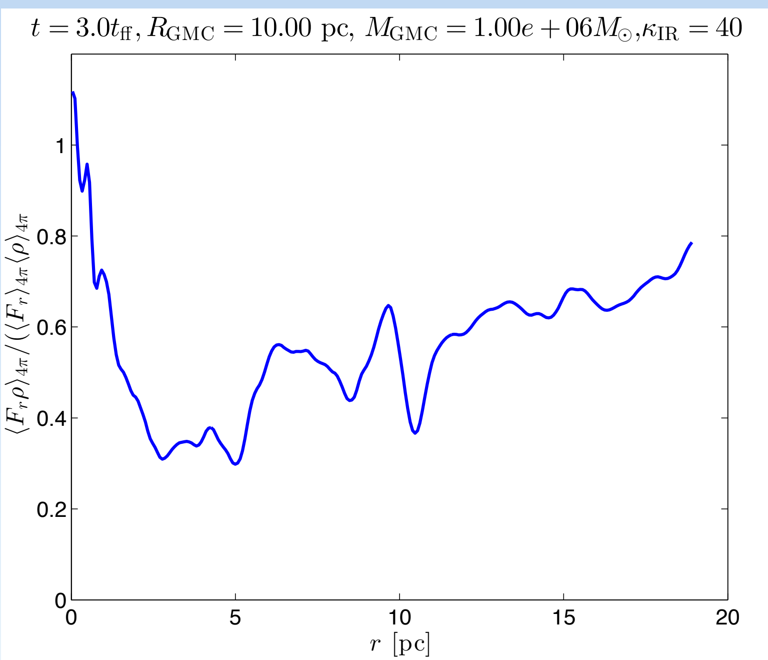

$t = 3.0 t_{\rm ff}, R_{\rm GMC} = 10.00$ pc, $M_{\rm GMC} = 1.00e + 06 M_\odot, \kappa_{\rm IR} = 20$
Cumulative $f_{\rm Edd}$ from $r = 0$ pc
Cumulative $f_{\rm Edd}$ from $r = 2$ pc
$\Psi \kappa_{\rm IR} / 4\pi G c$
r [pc]

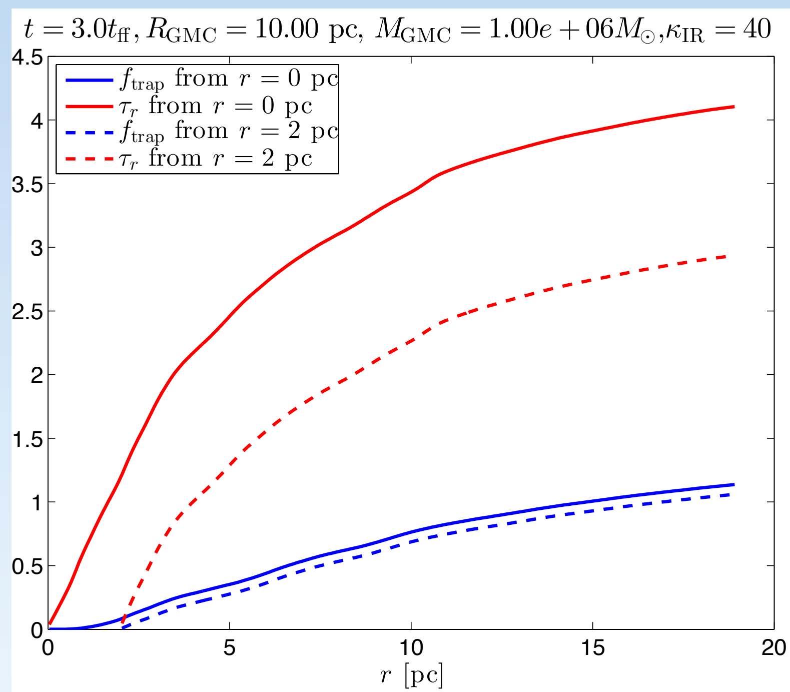

$t = 3.0 t_{\rm ff}, R_{\rm GMC} = 10.00$ pc, $M_{\rm GMC} = 1.00e + 06 M_\odot, \kappa_{\rm IR} = 20$
$\langle F_r \rho \rangle_{4\pi} / (\langle F_r \rangle_{4\pi} \langle \rho \rangle_{4\pi})$
r [pc]


$t = 3.0 t_{\rm ff}, R_{\rm GMC} = 10.00$ pc, $M_{\rm GMC} = 1.00e + 06 M_\odot, \kappa_{\rm IR} = 20$
$f_{\rm trap}$ from $r = 0$ pc
τ_r from $r = 0$ pc
$f_{\rm trap}$ from $r = 2$ pc
τ_r from $r = 2$ pc
r [pc]

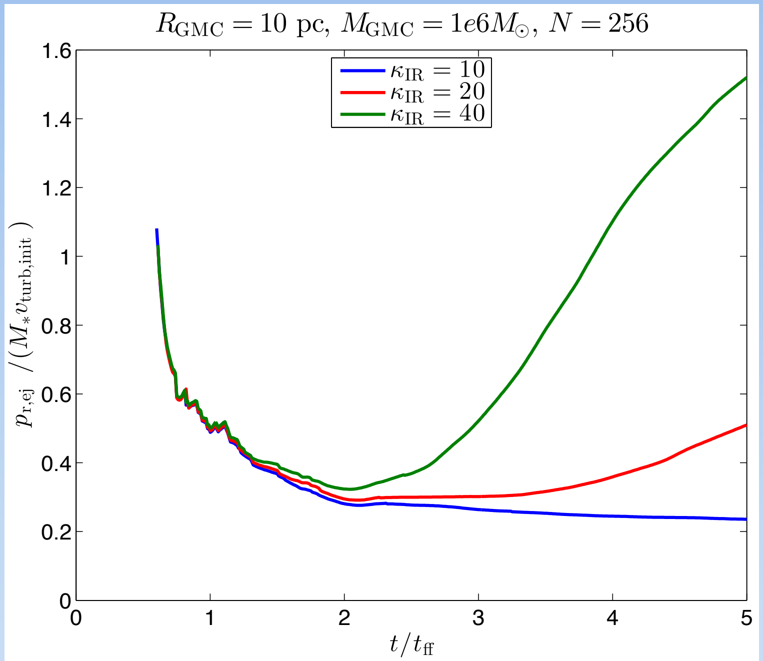

$t = 3.0t_{\rm ff}, R_{\rm GMC} = 10.00$ pc, $M_{\rm GMC} = 1.00e+06 M_\odot, \kappa_{\rm IR} = 40$
$f_{\rm Edd}$
$\Psi\kappa_{\rm IR}/4\pi Gc$
r [pc]

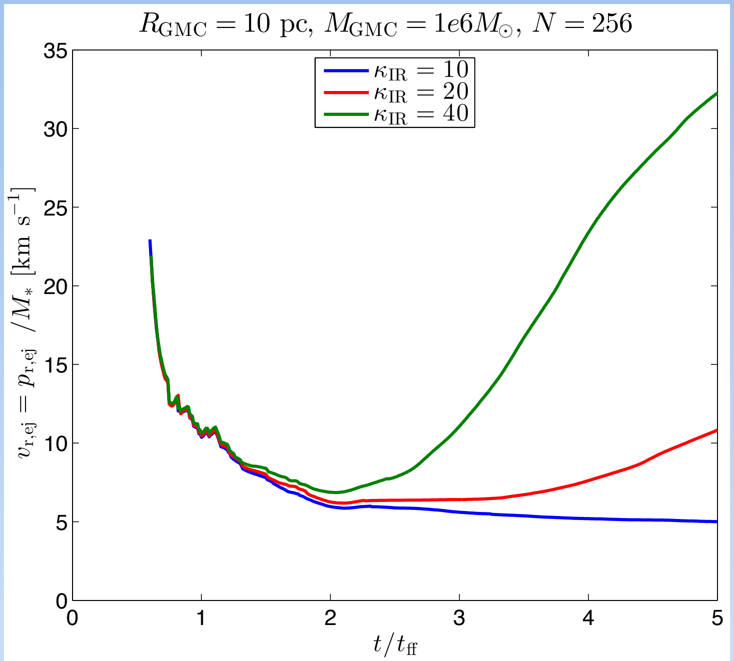

$t = 3.0t_{\rm ff}, R_{\rm GMC} = 10.00$ pc, $M_{\rm GMC} = 1.00e+06 M_\odot, \kappa_{\rm IR} = 40$
Cumulative $f_{\rm Edd}$ from $r = 0$ pc
Cumulative $f_{\rm Edd}$ from $r = 2$ pc
$\Psi\kappa_{\rm IR}/4\pi Gc$
r [pc]


$t = 3.0t_{\rm ff}, R_{\rm GMC} = 10.00$ pc, $M_{\rm GMC} = 1.00e+06 M_\odot, \kappa_{\rm IR} = 40$
$\langle F_r \rho \rangle_{4\pi} / (\langle F_r \rangle_{4\pi} \langle \rho \rangle_{4\pi}$
r [pc]


$t = 3.0t_{\rm ff}, R_{\rm GMC} = 10.00$ pc, $M_{\rm GMC} = 1.00e+06 M_\odot, \kappa_{\rm IR} = 40$
$f_{\rm trap}$ from $r = 0$ pc
τ_r from $r = 0$ pc
$f_{\rm trap}$ from $r = 2$ pc
τ_r from $r = 2$ pc
r [pc]

Momentum injection to ISM

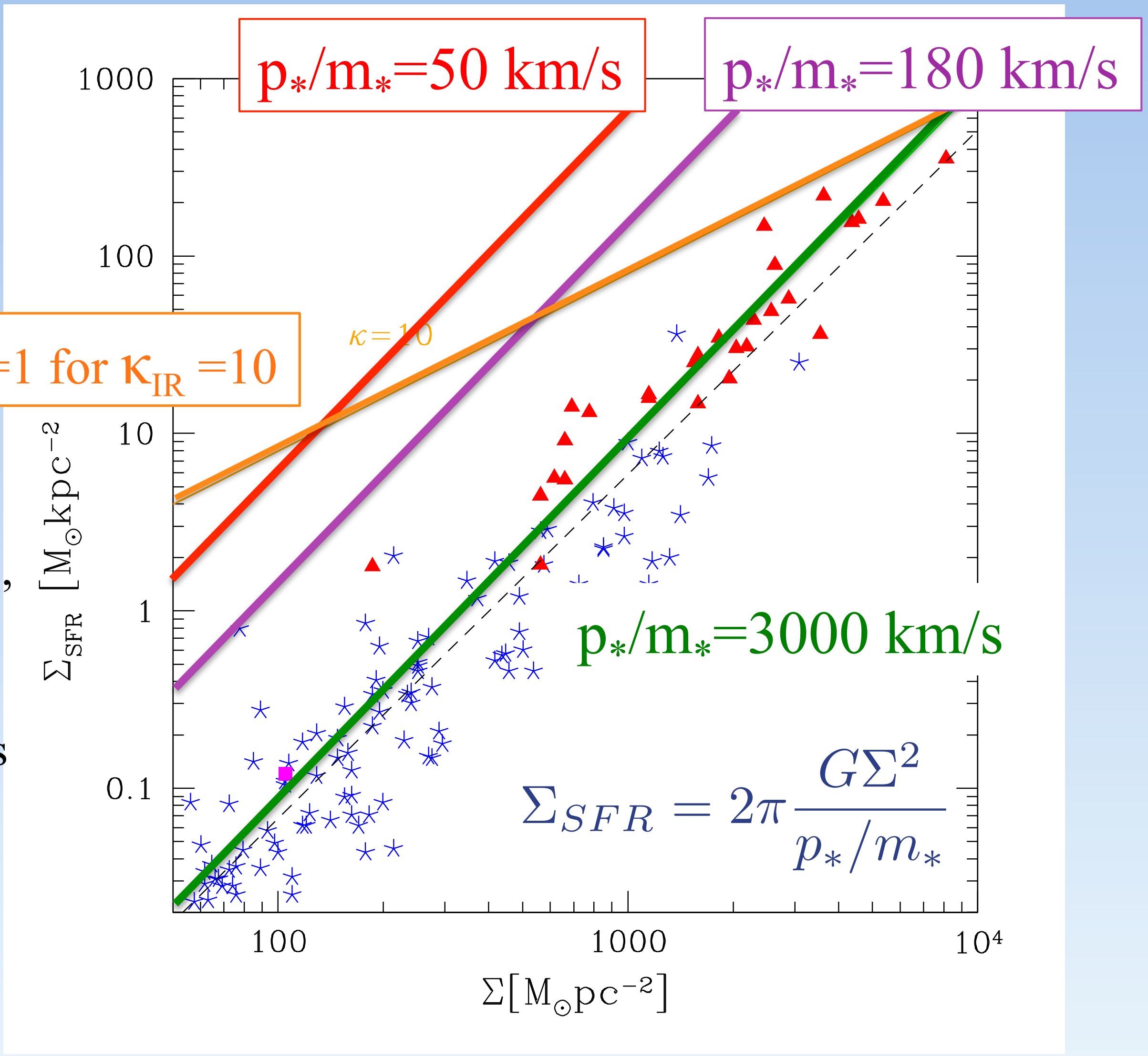




Momentum/mass given to the ISM:

$p_*/m_* = p_{ej}/M_* \sim v_{cloud} < 100$ km/s

Radiation momentum feedback and large-scale SFRs



f_{Edd}=1:
$\Sigma_{SFR}=2\pi G\Sigma/(\varepsilon_{nuc}c\kappa)$,
corresponding to
$p_*/m_* = \varepsilon_{nuc}c\kappa\Sigma$
$= \tau_{IR}\times 180$km/s

Summary

- System in force balance and driving/dissipation balance for turbulence driven by feedback has

$$v \sim \varepsilon_{ff} \frac{p_*}{m*} \qquad L \sim \frac{GM_{tot}}{v^2} \qquad \dot{M}_* \sim \frac{GM_{tot}M}{L^2 p_*/m_*}$$

- For gas-dominated disk system (starburst)

$$\Sigma_{\rm SFR} \sim \frac{G\Sigma^2}{p_*/m_*}$$, or more generally: $$\Sigma_{SFR} \sim \frac{\Sigma g_z}{p_*/m_*}$$

- Numerical simulations agree with simple theory and match observations of galactic $\Sigma_{\rm SFR}$ *provided p_*/m_* is large*
- Simulations of turbulent, star-forming clouds with IR radiation show that $\varepsilon = M_*/M_{\rm cloud}$ is large (order-unity) and p_*/m_* is small (< 100 km/s) for realistic κ and $v_{\rm cloud}$
- Further detailed studies are needed to quantify p_*/m_* from other sources (SNe with realistic ISM model, CR with realistic coupling,…) and connect to galactic winds