Galactic-Scale Dynamics and Turbulence

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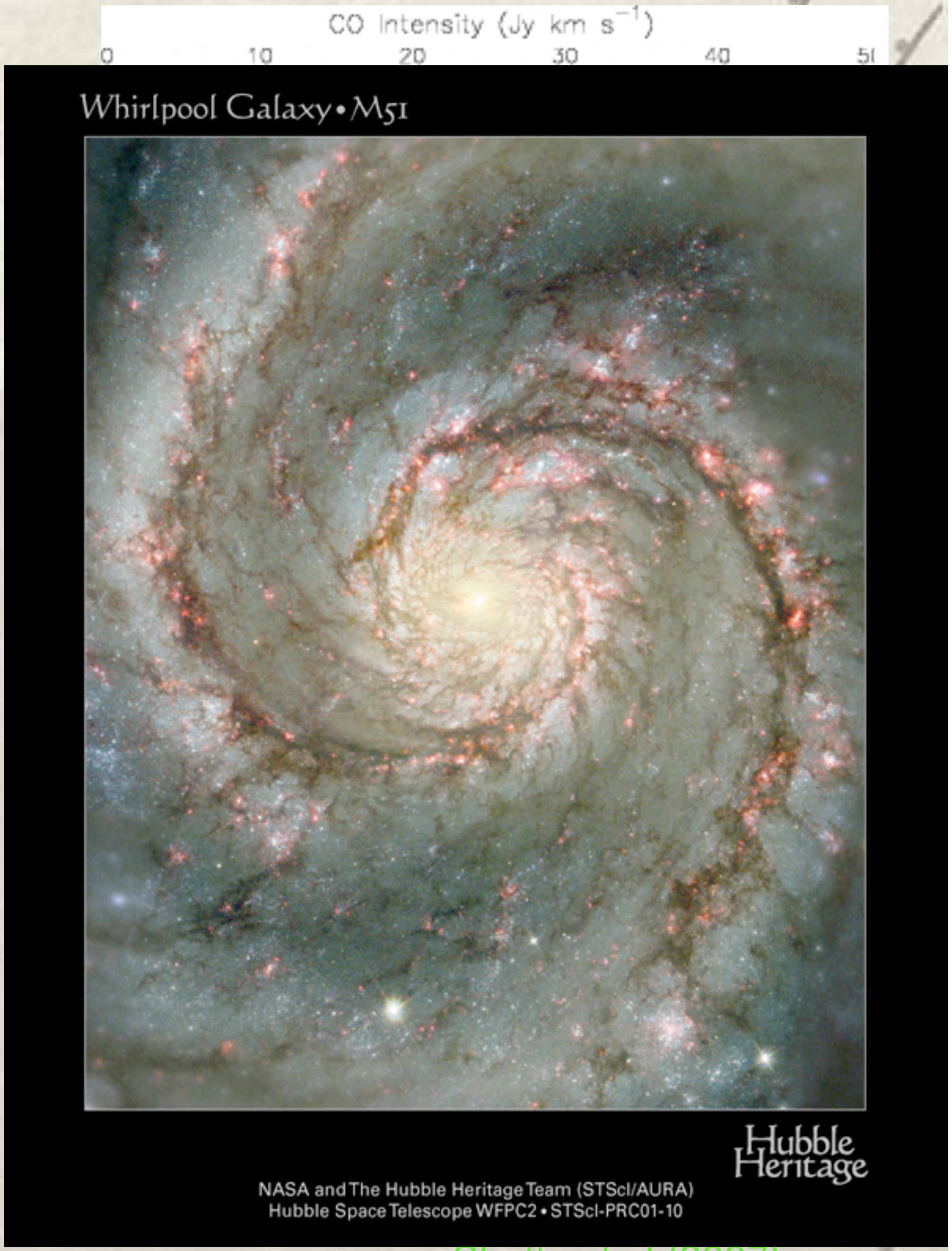
Outline

- Global-scale aspects of SF
  - Where/when does SF occur?
- Turbulence
  - Why should it be important for SF?
- What contributes to driving turbulence?
- Global models of SF with feedback
- Some open issues

Global Dynamics…

- Galaxies have prominent substructure:
  - Spiral arms + branches
  - Arm spurs/feathers
- Spiral arms:
  - Spacing scale determined by stellar component
  - Modal and/or tidally forced
  - Gaseous gravity contributes locally
  - Molecular gas is concentrated in arms
  - Star formation is concentrated in arms

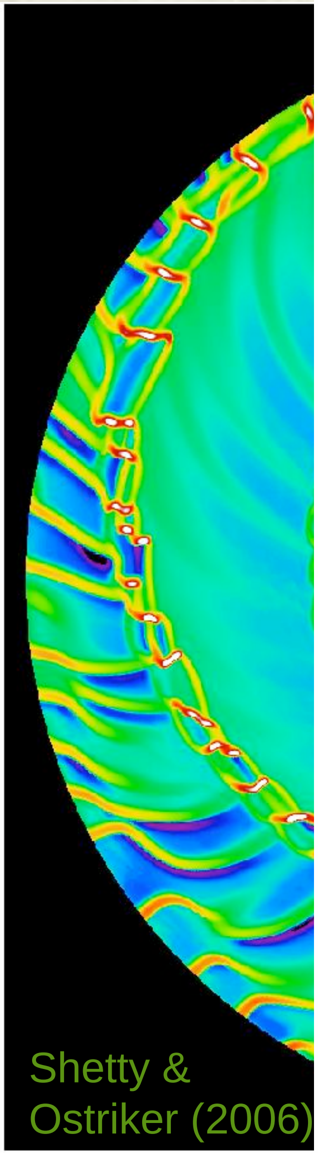


Shetty et al (2007)

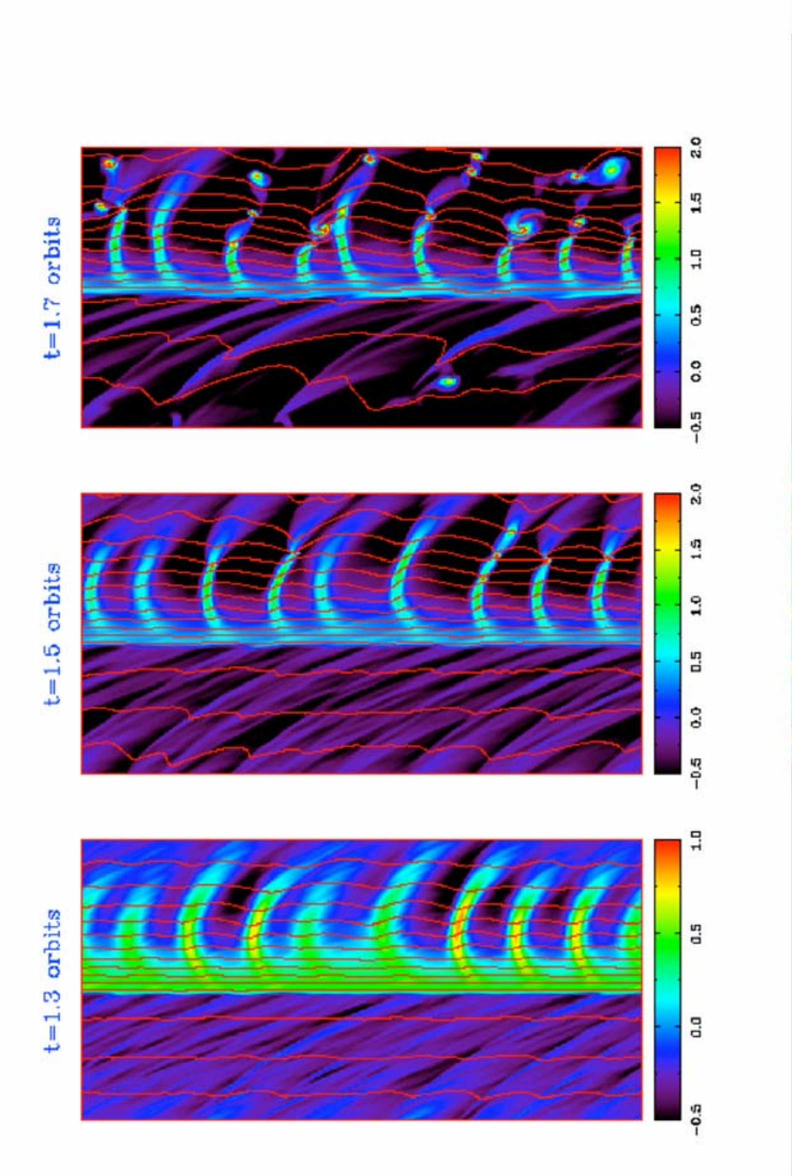
Shetty et al (2007)

Spiral-arm spurs & SF

- Spurs/feathers are evident in stellar emission, extinction, and dust IR (Elmegreen 1980, LaVigne et al 2006)
- Gas spurs form due to self-gravitating instability in arm (Kim & Ostriker 2002)
- Spur fragmentation yields “interarm” GMC and star formation if arm shock is moderate
- Strong shock/high arm surface density produces GMAs/GMCs in arm (Elmegreen 1994; Kim & Ostriker 2006; Shetty & Ostriker 2006)



Shetty & Ostriker (2006)



Kim & Ostriker (2002)

- Global galactic structure is essential to SF!
- SF “now”:

  spiral structure in stars→spiral structure in gas → spurs + GMCs

$$\Sigma_{SFR} = \frac{\varepsilon_{GMC}\Sigma_{gas}}{t_{lifecycle}} \approx \varepsilon_{GMC}\Sigma_{gas}\frac{m(\Omega - \Omega_p)}{2\pi}$$

- SF “then”?
  - Stronger spiral structure…
  - …but more gas overall ⇒ unstable in interarm regions
  - What sets $t_{lifecycle} = t_{diffuse} + t_{GMC}$ for gas “then”?

Effects of turbulence on star formation

- Turbulent *small-scale* velocities and magnetic fields *discourage* SF, by contributing to effective pressure:
- In large-scale ISM for disk galaxies:
  - SF rate may depend on turbulent δv and $\delta v_A = \delta B/(4\pi\rho)^{1/2}$ through c_{eff} in Jeans time $t_J = c_{eff}/G\Sigma_g$
  - Masses of clouds that form may depend on turbulence through Jeans mass $M_J = c_{eff}^4/(G^2\Sigma_g)$
  - Whether active SF can occur at all may depend on turbulence through effective Toomre parameter $Q = \kappa c_{eff}/(\pi G \Sigma_g)$ ….
- *But also…*
- Turbulent *large-scale* velocities *encourage* SF by concentrating gas locally, from shocks
- Turbulent *large-scale* magnetic fields *encourage* SF by transferring angular momentum out of condensations

What is c_{eff} in Q?

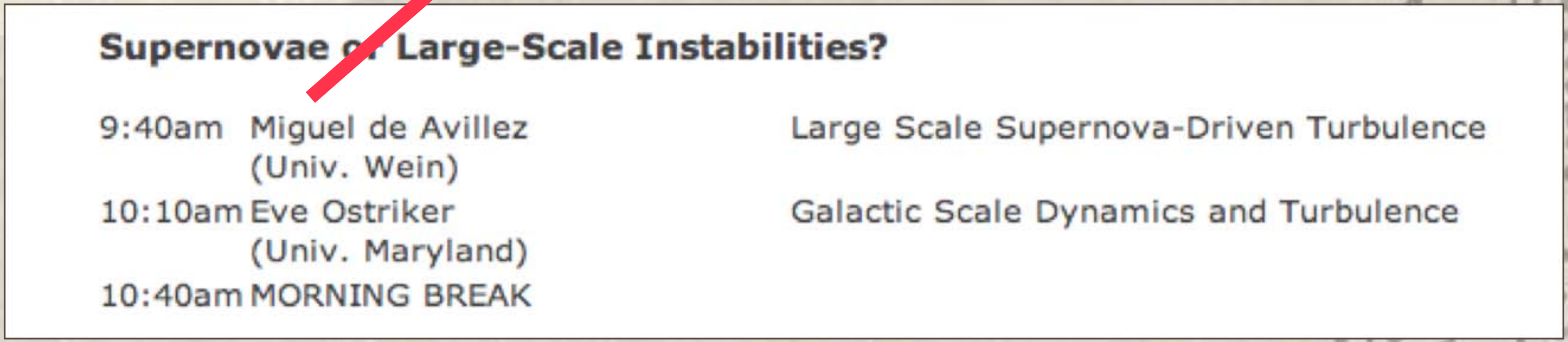
- If self-gravity regulates SF, then threshold surface density is sensitive to $c_{\rm eff}$

$$\Sigma_{crit} = 6 \mathrm{M}_\odot \mathrm{pc}^{-2} \left(\frac{c_{eff}}{6 \mathrm{km\,s}^{-1}} \right) \left(\frac{V_c}{200 \mathrm{km\,s}^{-1}} \right) \left(\frac{R}{15 \mathrm{kpc}} \right)^{-1} \left(\frac{Q_{crit}}{1.4} \right)^{-1}$$

- If $c_{\rm eff}$ includes *only thermal sound speed* c_s, then cold portion of disk with $c_s \sim 1$ kms^{-1} would essentially always be unstable
- Observations suggest that cold gas can be stable even if $\Sigma > \Sigma_{crit}(c_{\rm eff}=1 \text{ kms}^{-1})$ ⇒ $c_{\rm eff}$ includes non-thermal parts from δv and δv_A

Driving of ISM turbulence

- Traditional view: driving by supernovae
- Problems with driving *only* by SN (+ HII regions)
  - Intermittency of SF
  - No observed correlation of turbulence with SF (arm/interarm; inner/outer disk)
  - Outer disks lack SF but appear to contain cold gas that would be unstable without turbulence
- Contributing non-stellar sources:
  - Magnetorotational instability (sheared rotation +B)
  - Sub-threshold swing amplification (sheared rotation + G)
  - Non-steady spiral shocks
  - Other (thermal instability, Parker instability, CRs…)



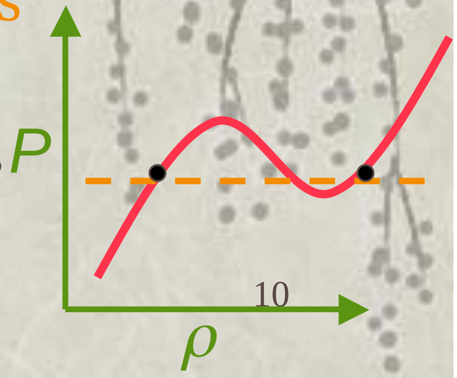
Supernovae ~~or~~ and Large-Scale Instabilities?

9:40am	Miguel de Avillez (Univ. Wein)	Large Scale Supernova-Driven Turbulence
10:10am	Eve Ostriker (Univ. Maryland)	Galactic Scale Dynamics and Turbulence
10:40am	MORNING BREAK	

Magnetorotational Instability

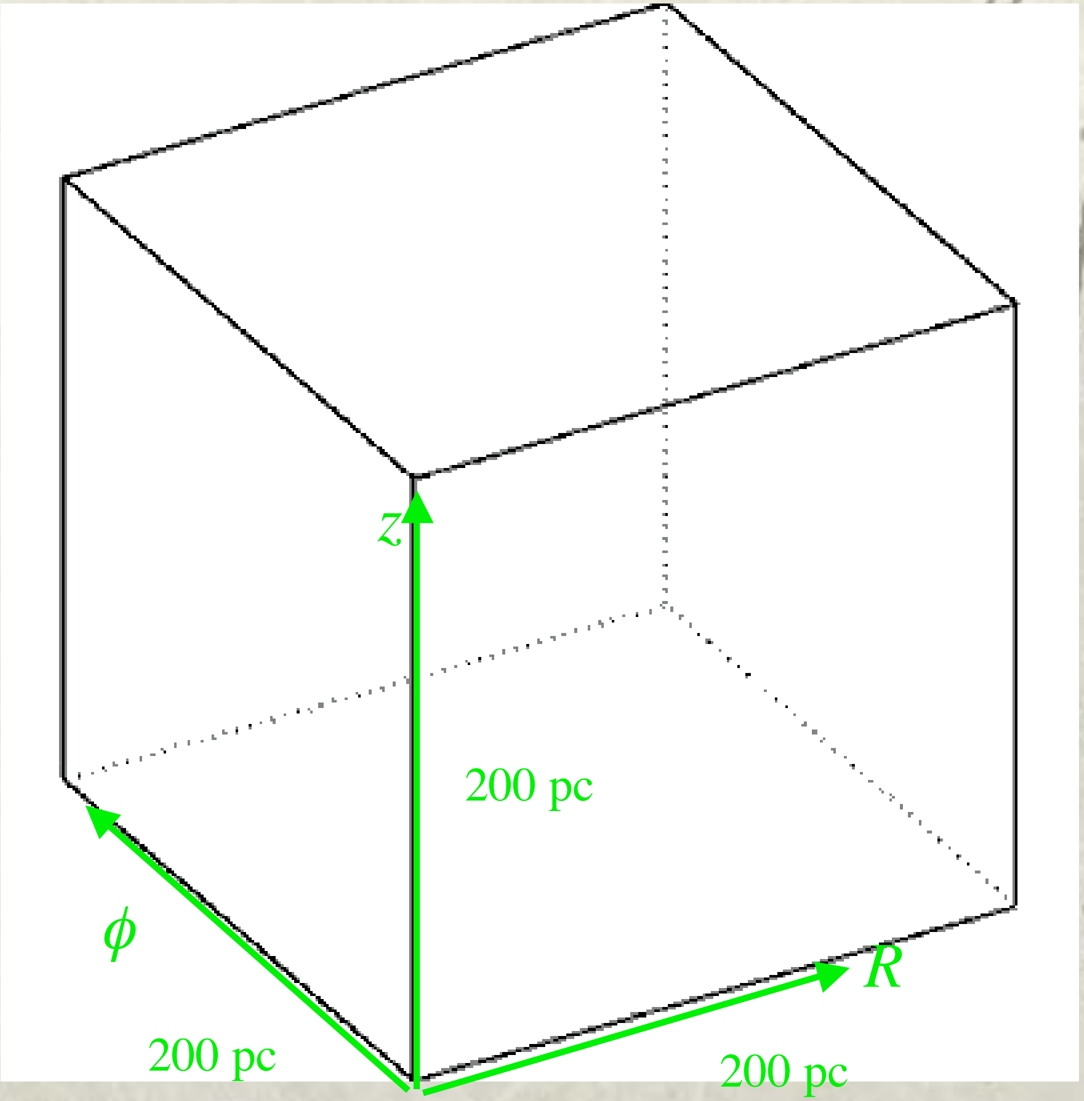
- Magnetorotational instability (MRI) is a generalization of Balbus-Hawley (1991) instability
- MRI requires angular velocity Ω to decrease outward
- Magnetic fields connect inward-displaced and outward-displaced fluid elements and transfer angular momentum from small *R* to large *R*
- Quasi-steady state turbulence develops for 3D models
- Sellwood & Balbus (1999) suggested MRI may be important in galaxies
- Differences in galaxies from MRI in accretion disks
  - ISM gas is cloudy/multi-phase
  - ISM gas has thermal pressure *P* set by heating & cooling
  - mean density is set by cold medium "loading":

$$\langle n \rangle = \frac{P}{kT_{warm}}\left(1 + \frac{M_{cold}}{M_{warm}}\right)$$



MRI in ISM gas

- *g=0* ⇒ no vertical stratification

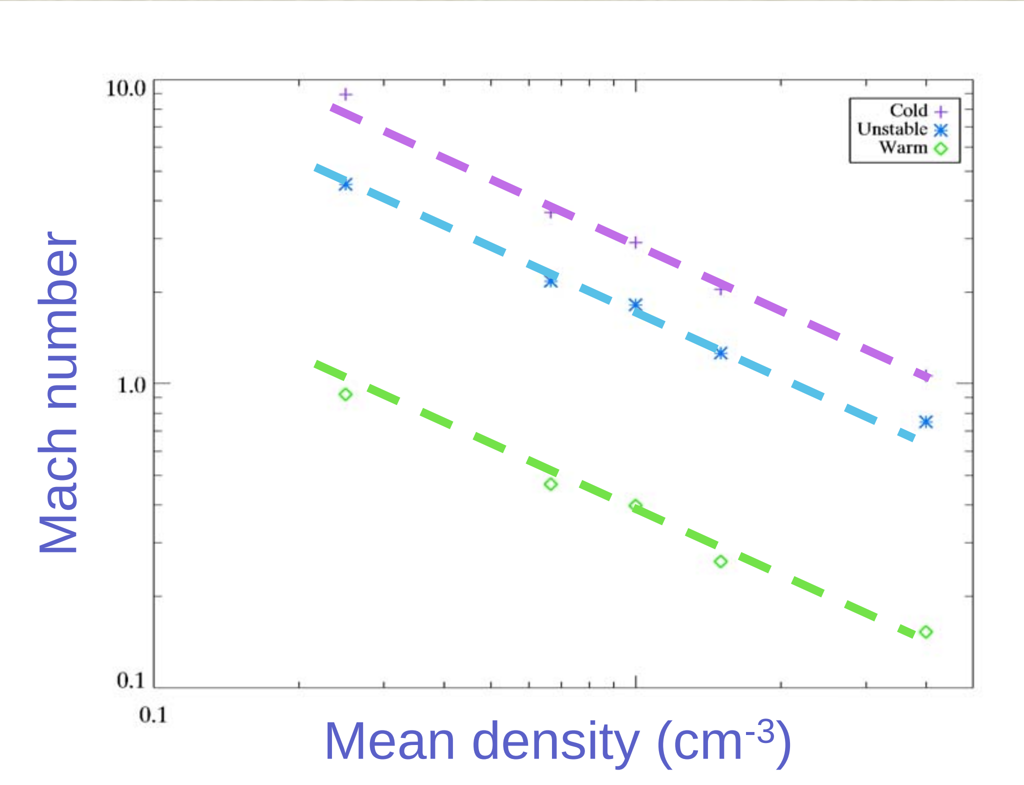


Two-phase turbulent ISM model

Piontek & Ostriker (2005)

Saturation scalings of MRI in ISM

- $\langle \delta v^2 \rangle^{1/2} = 3\ \mathrm{km\ s^{-1}} \times \langle n \rangle^{-0.77}$
- At low $\langle n \rangle$, cold cloudlets are trans-sonic with respect to warm medium (up to 8 km $\mathrm{s^{-1}}$)
- $\langle B^2 \rangle$ ~ independent of $\langle n \rangle$
- In saturated state, $\beta = P_{th}/P_B \sim 0.5$



Piontek & Ostriker (2005)

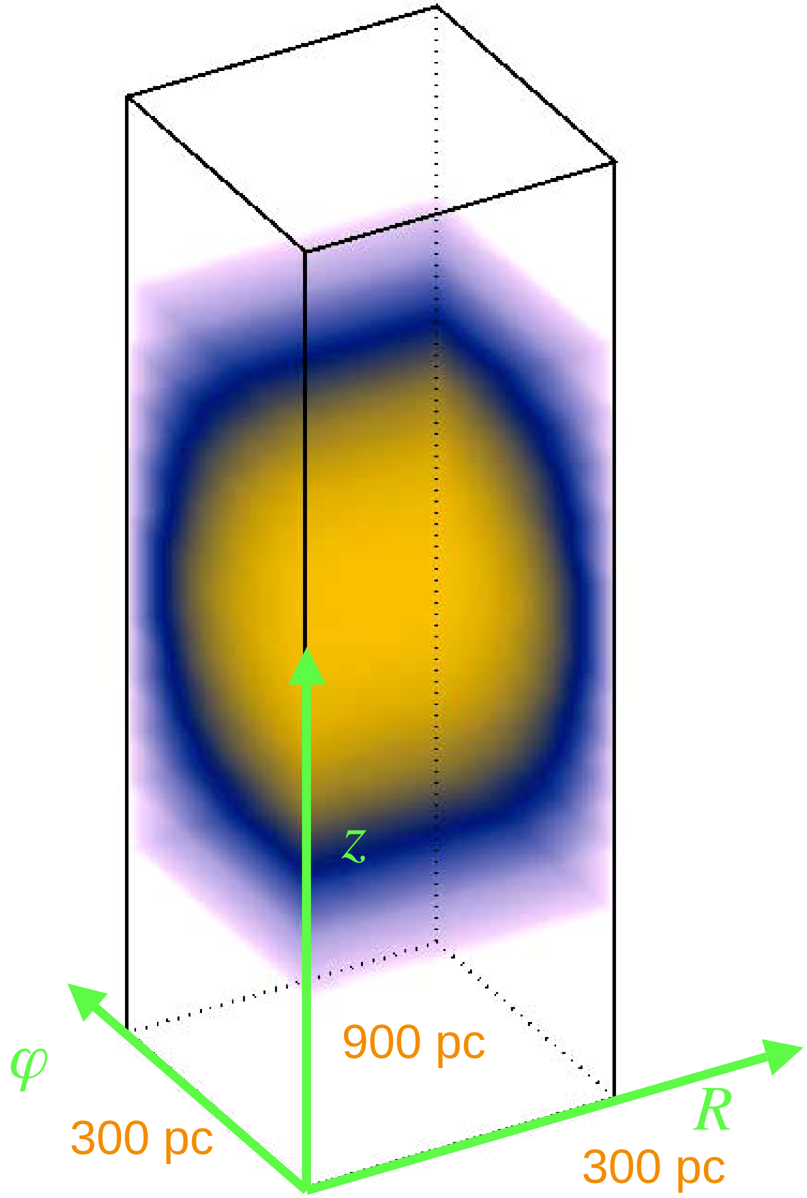
Cloudy gas + MRI+g_z

- *Cold gas preferentially settles in midplane*

Solar neighborhood model:

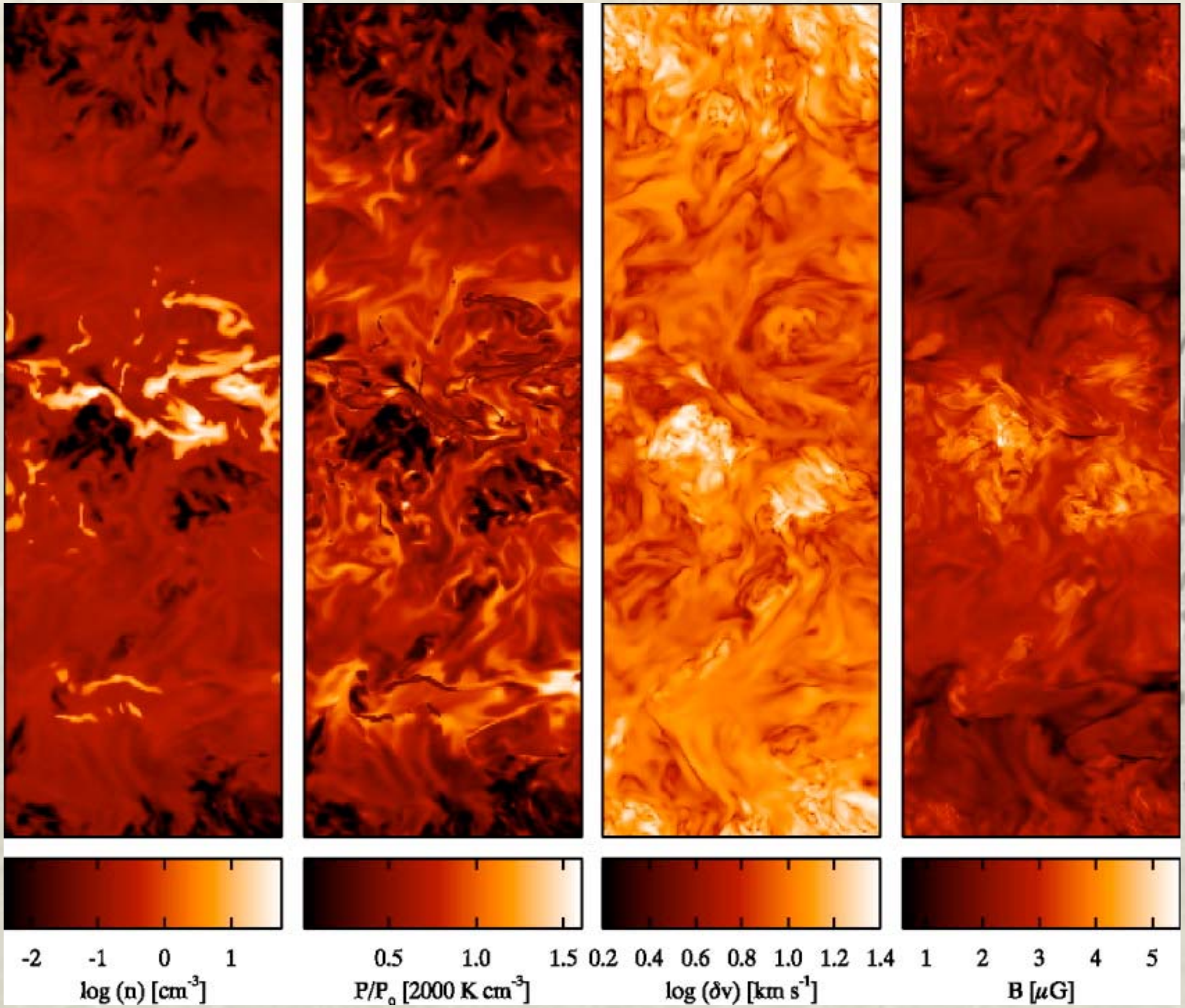
- 128x128x384 box
- t_{max}= 10 orbits
  $=2.5 \times 10^9$ yrs
- $n_{init}(z=0)$ =1 cm^{-3}
- Σ_{tot}=10 $M_\odot$ pc^{-2}

8/20/07



Piontek & Ostriker (2007)

R-z slices at t=8 orbits



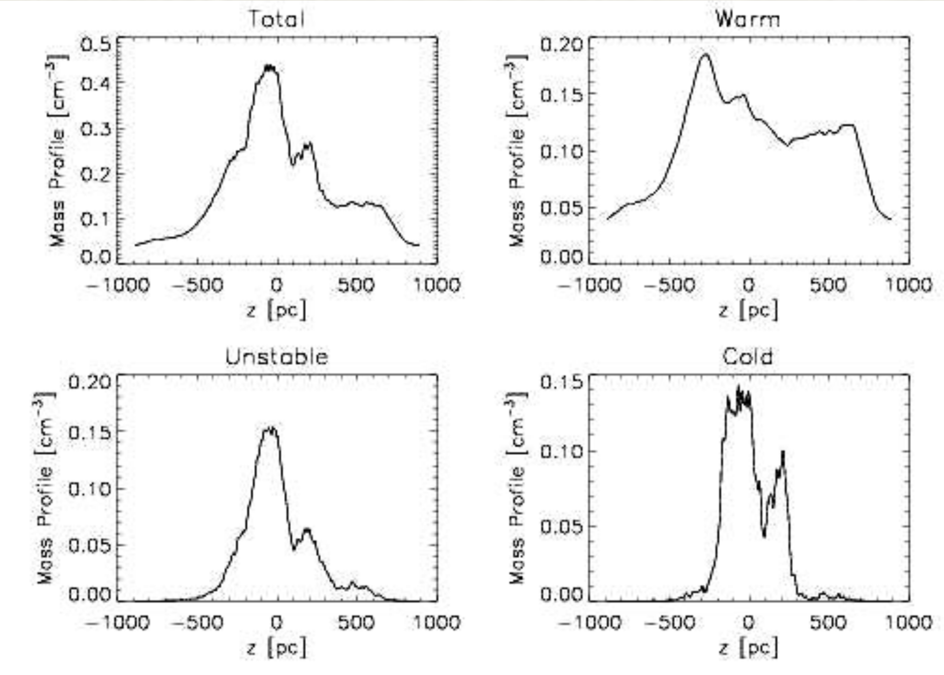
Piontek & Ostriker (2007)

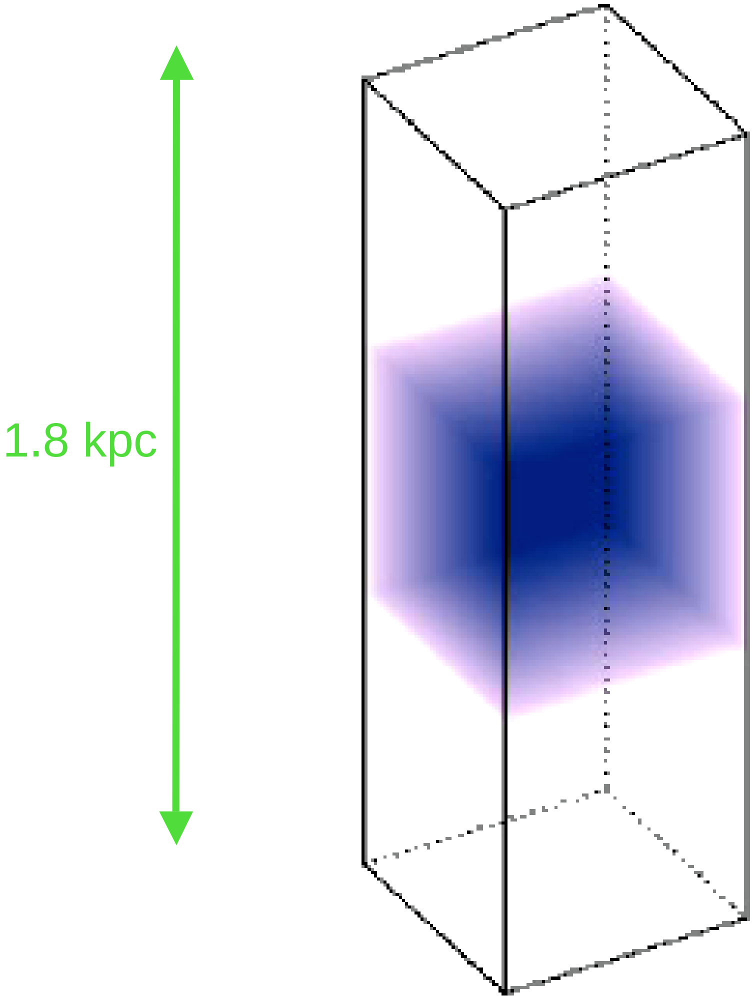
Outer disk model

- Low surface density $\Sigma_{tot}=6\ M_{\odot}\ pc^{-2}$
- Low gravity $\rho_{eff}=0.003 M_{\odot}\ pc^{-3}$
- Results:

Compared to inner-disk,

- Lower fraction of cold gas (20%)
- Larger $\delta v \sim 5$ km/s
- Larger cold gas scale height ⇒ $\langle v_A \rangle > 8$ km/s



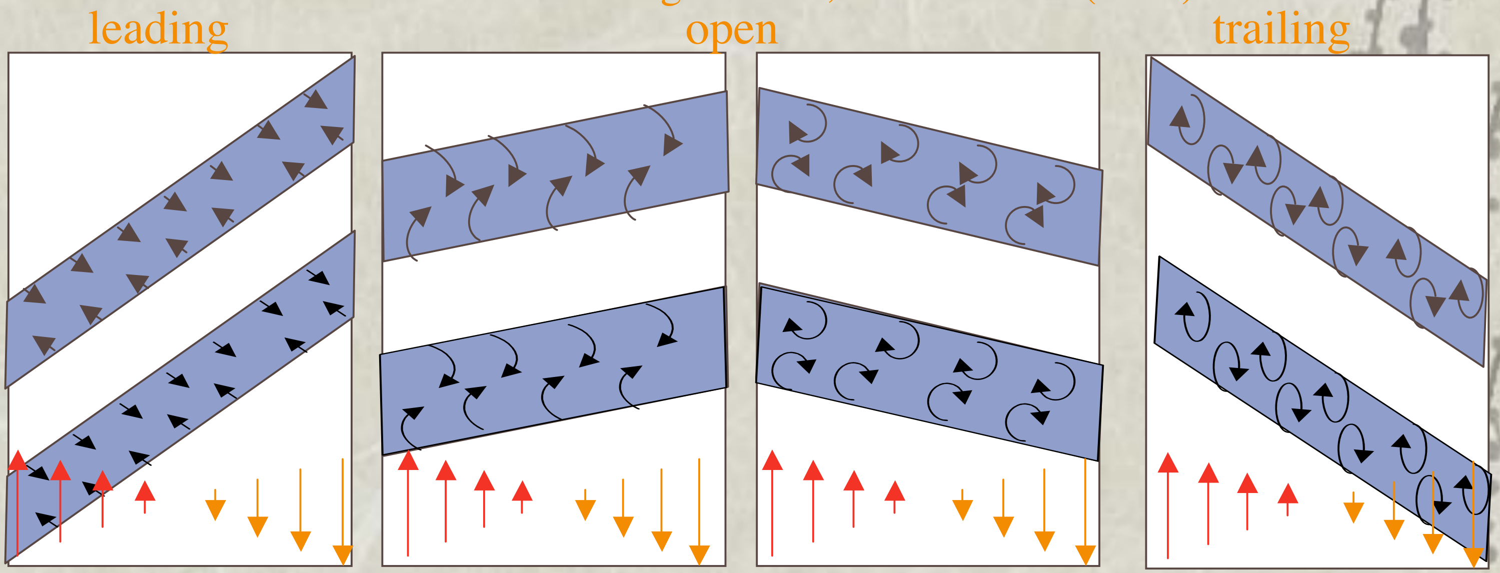


Piontek & Ostriker (2007)

Swing amplifier: turbulence driven by self-gravity and shear

- Growth occurs due to cooperation of epicyclic motion, shear, self-gravity
- Need low $Q \equiv \kappa c_{\mathrm{eff}}/\pi G\Sigma$ for significant growth
- Low enough $Q \Rightarrow$ disk fragments into massive clumps with $M \sim M_J$ → *see W.-T. Kim poster*

Schematic of shearing wavelet, after Toomre (1981)

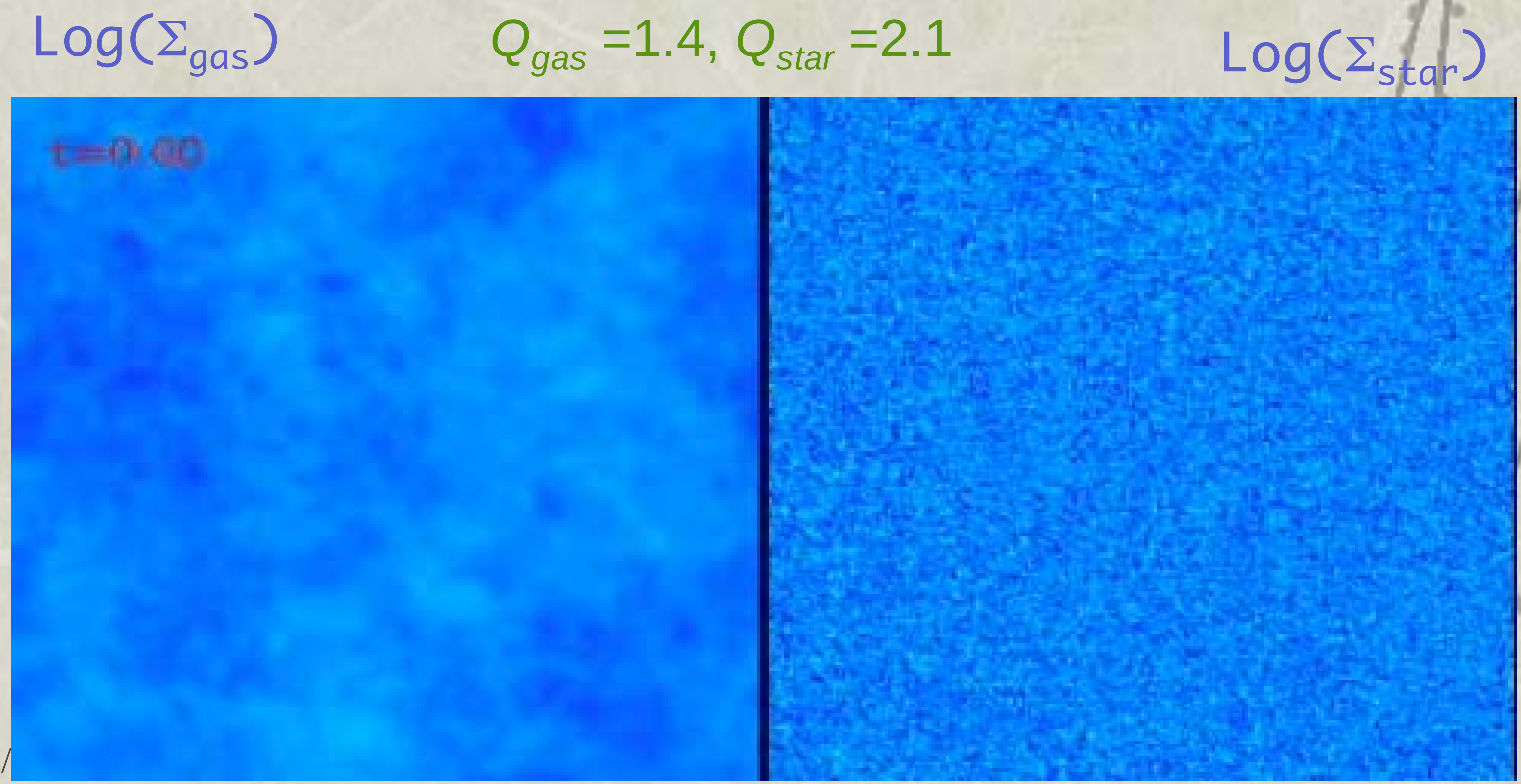


Time increasing →

Because epicyclic motion is in the same direction as shear, matter lingers in overdense regions and wavelet is amplified by self-gravity

"Swing" in disk with $Q > Q_{crit}$

- If $Q > Q_{crit}$, fragmentation does not occur but nonlinear density and velocity fluctuations can be driven
- Velocity dispersion is very sensitive to Q ; $\delta v \approx 4$ km s^{-1} when $Q \approx Q_{crit}$



$\mathrm{Log}(\Sigma_{gas})$

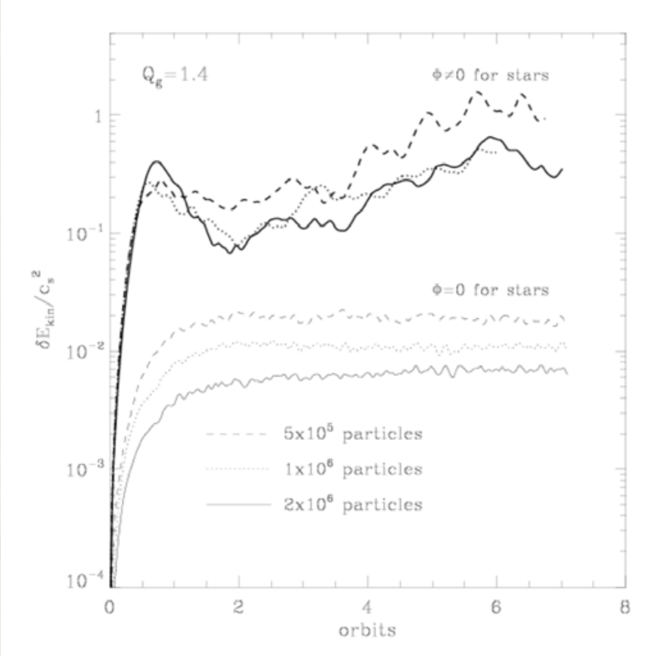
$Q_{gas} = 1.4$, $Q_{star} = 2.1$

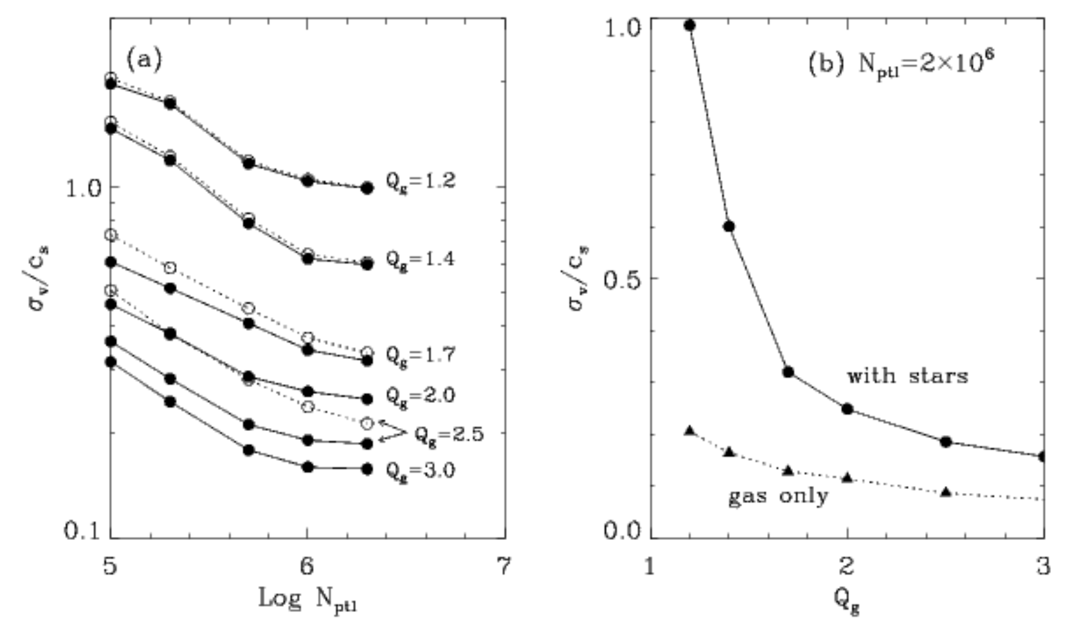
$\mathrm{Log}(\Sigma_{star})$

Kim & Ostriker (2007)

Effect of stellar potential on turbulence

- Sufficient particle number is required so that Poisson noise effects do not contaminate results
- Turbulence increases by at least a factor two when stellar contribution is included

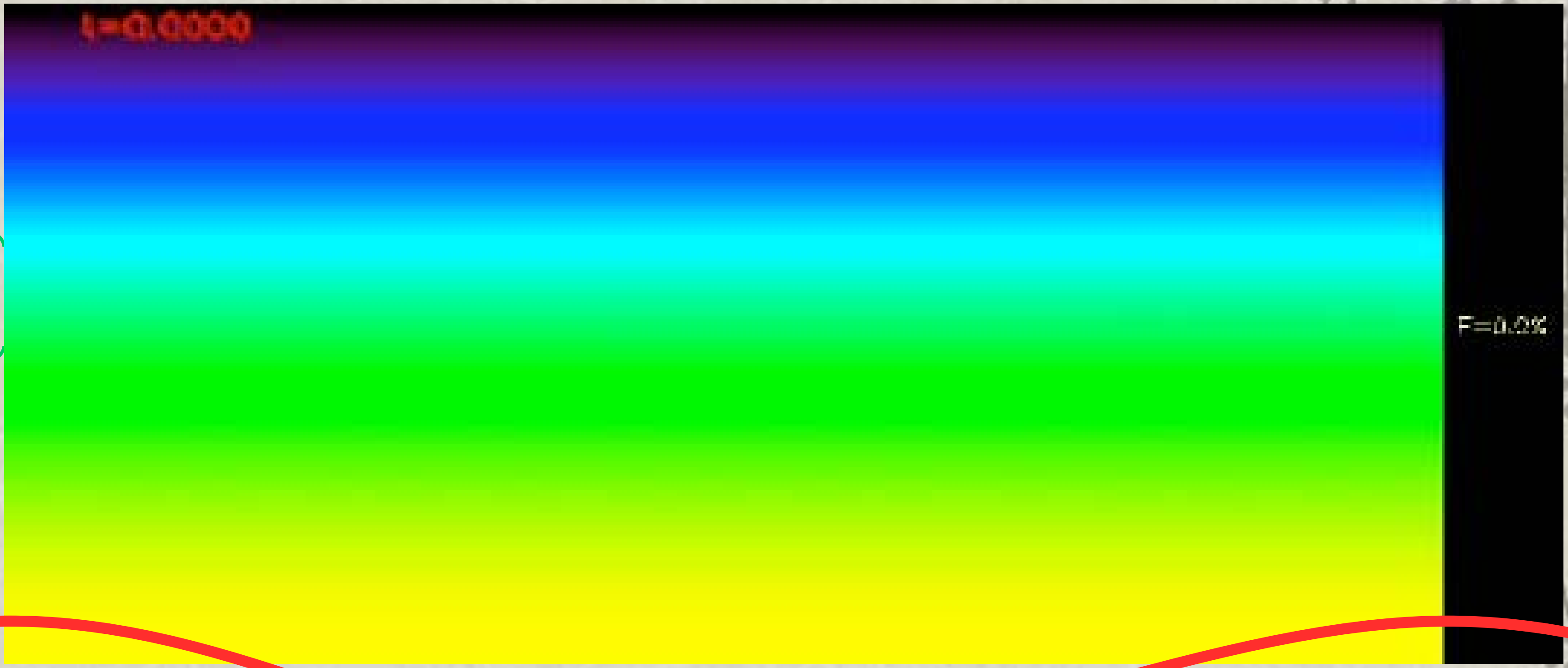




Kim & Ostriker (2007)

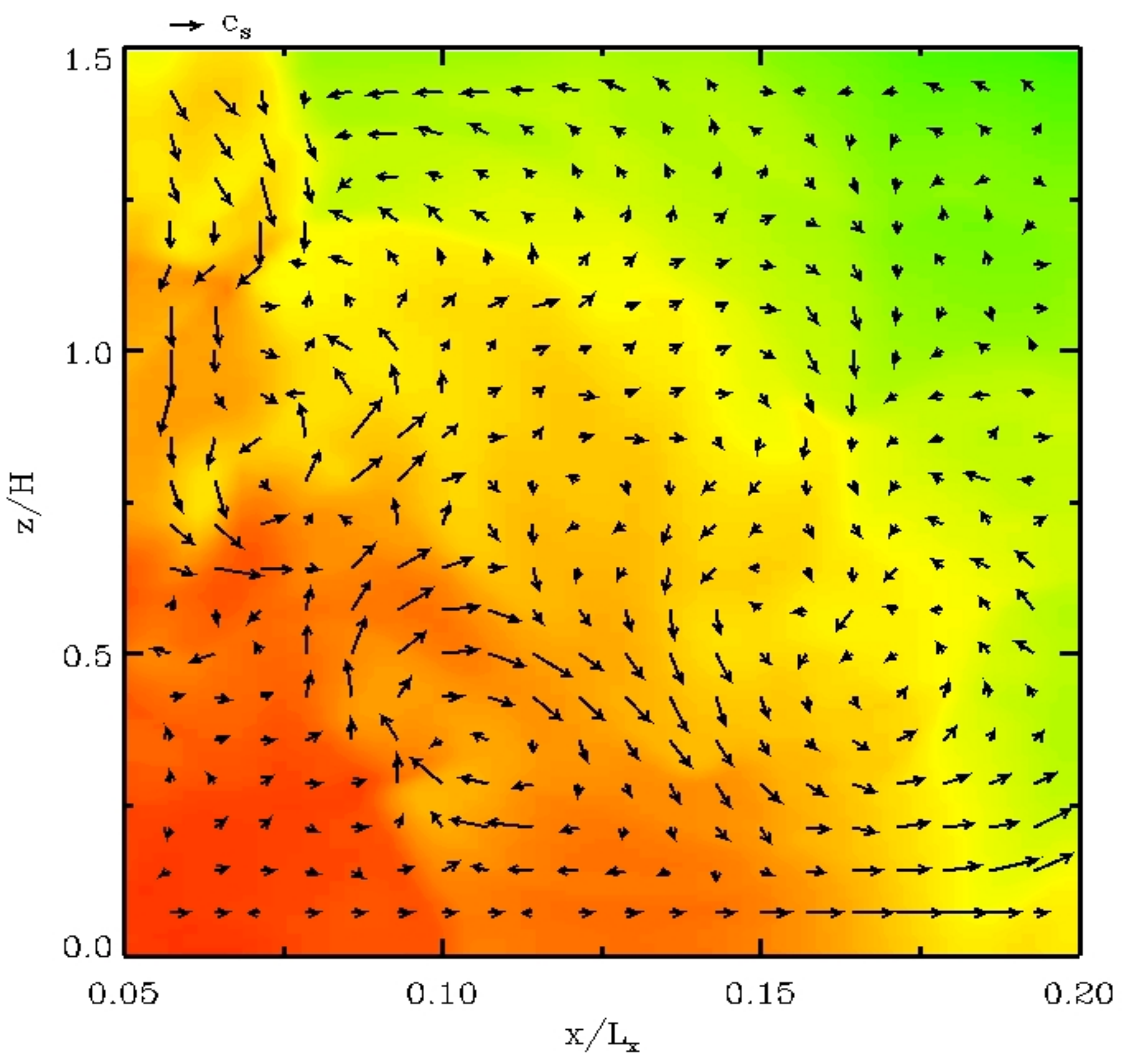
Turbulence driving by spiral shock

- Spiral shock front cannot be steady in radial-vertical plane
- Shock flaps horizontally relative to potential minimum
- Curved shock drives vertical motions
- Large-scale vertical and horizontal motions cascade into turbulence



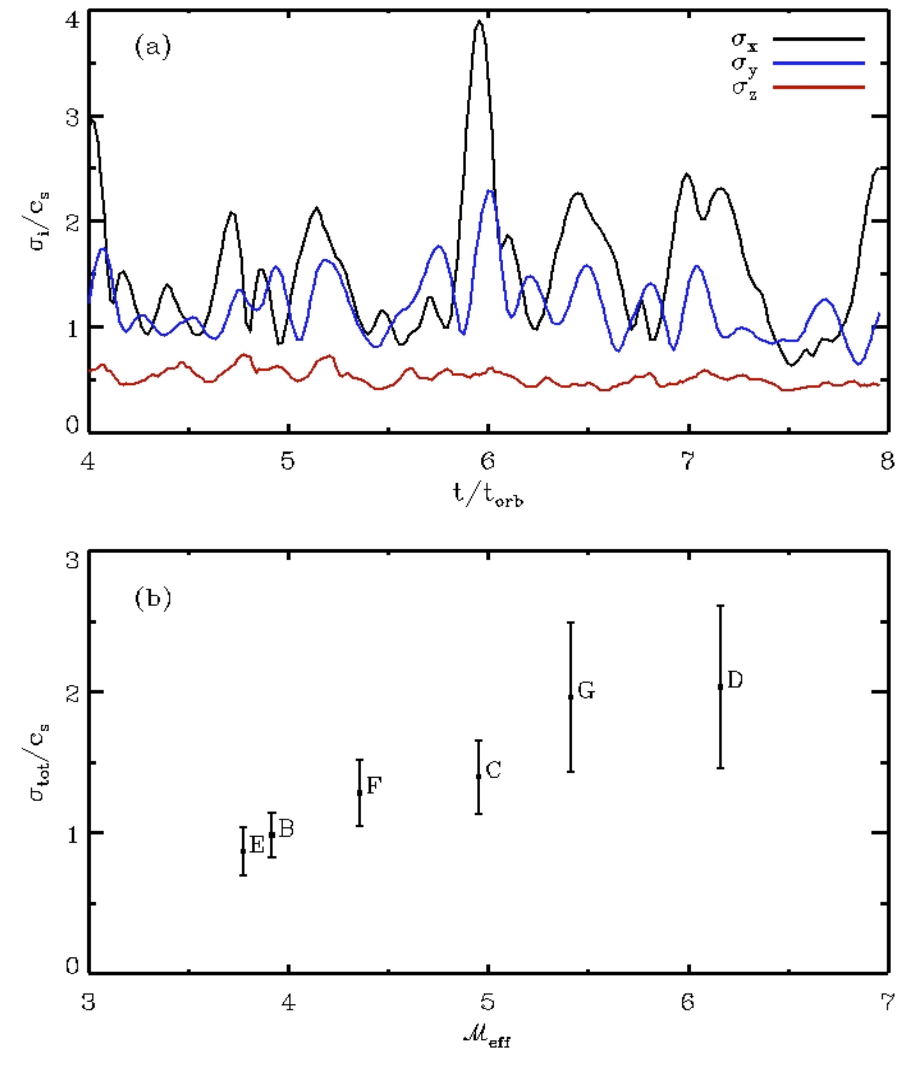
Kim, Kim, &
Ostriker (2006)

Turbulence downstream from shock



Turbulent amplitudes from spiral shock

- Quasi-steady state develops
- Horizontal velocities exceed vertical velocities: $\delta v_R \sim \delta v_\phi \sim 2\ \delta v_z$
- Velocity dispersion is 2× lower in interarm region than arm region
- Velocity dispersion increases with strength of shock
- $\delta v_{tot} > c_s$ when $\mathcal{M}_{eff} > 4$



`Kim, Kim, & Ostriker (2006)`

Turbulence is present…what does it do?

- Stellar sources do not appear sufficient to power all turbulence in the ISM
- Important non-stellar sources of kinetic and magnetic turbulence include MRI, “swing”, spiral shocks
- Non-stellar sources combine with each other and stellar sources
- Next step: need direct investigation to test exactly how [whether? when?] turbulence counteracts gravity
  - Can we define a c_{eff} based on δv, δv_A and $\langle c_s \rangle$ such that SF is regulated by Q, t_J, L_J?

→ *Need to measure Σ_{SFR} directly, self-consistently including different forms of turbulence*

Global model with “SN” feedback

- Isothermal EOS, $V_c/c_s=30$
- External spiral potential
- “thick disk” gravity; $H/R=0.01$
- Feedback threshold at $\Sigma=320\ M_\odot\ \mathrm{pc}^{-2}$
- Probability of cloud destruction in time δt

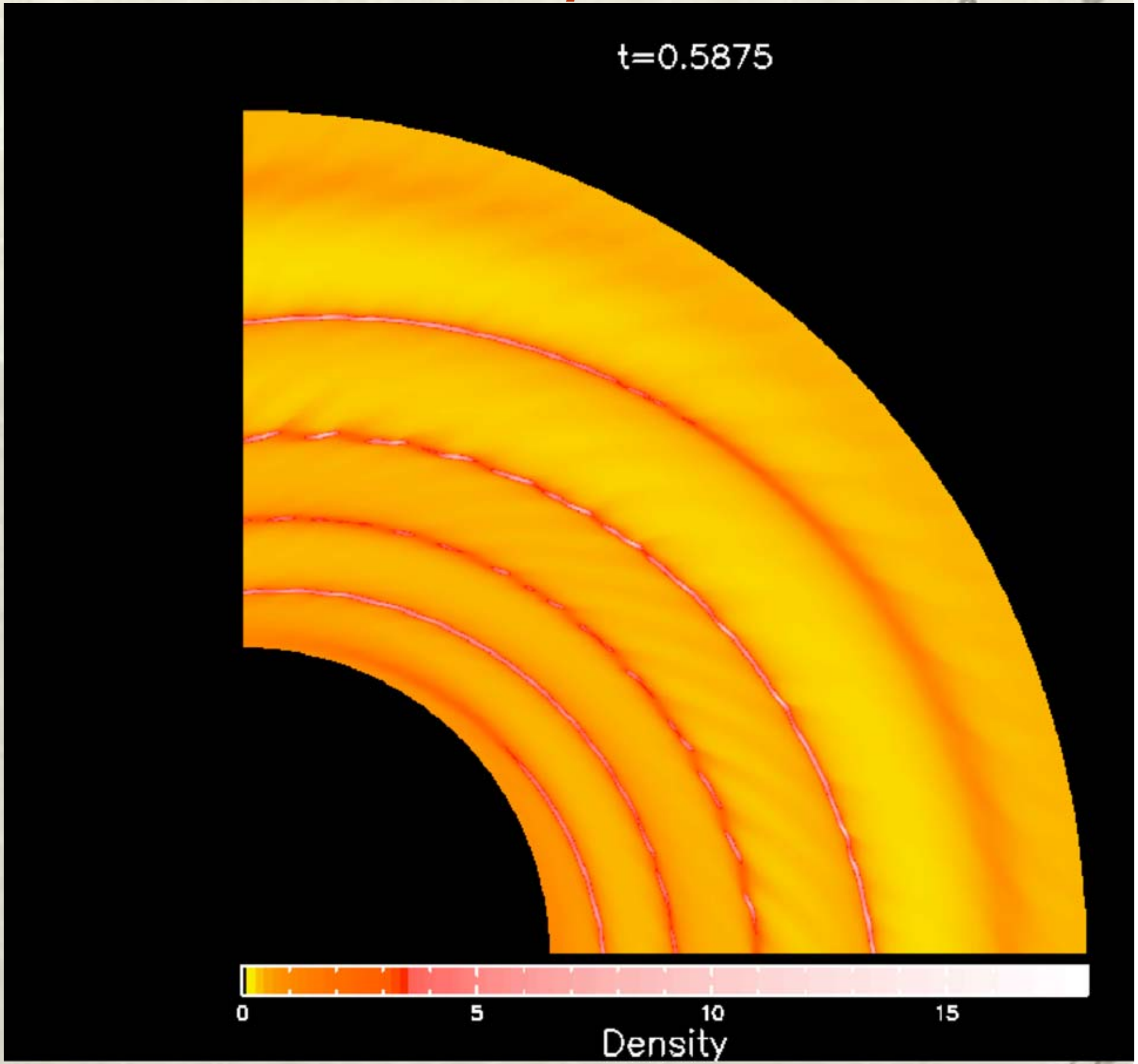
  $= \delta t / t_{GMC}$

  $= \delta t\, R_{SN}\, M_{cloud}/N_{SN}$

  $= \delta t\, R_{SN}\, M_{SN}/\varepsilon_{SF}$
- “SN” event momentum input:

$$p_{SN} = \varepsilon_{SF} \frac{M_{cloud}}{M_{SN}} M_{shell} v_{shell}$$

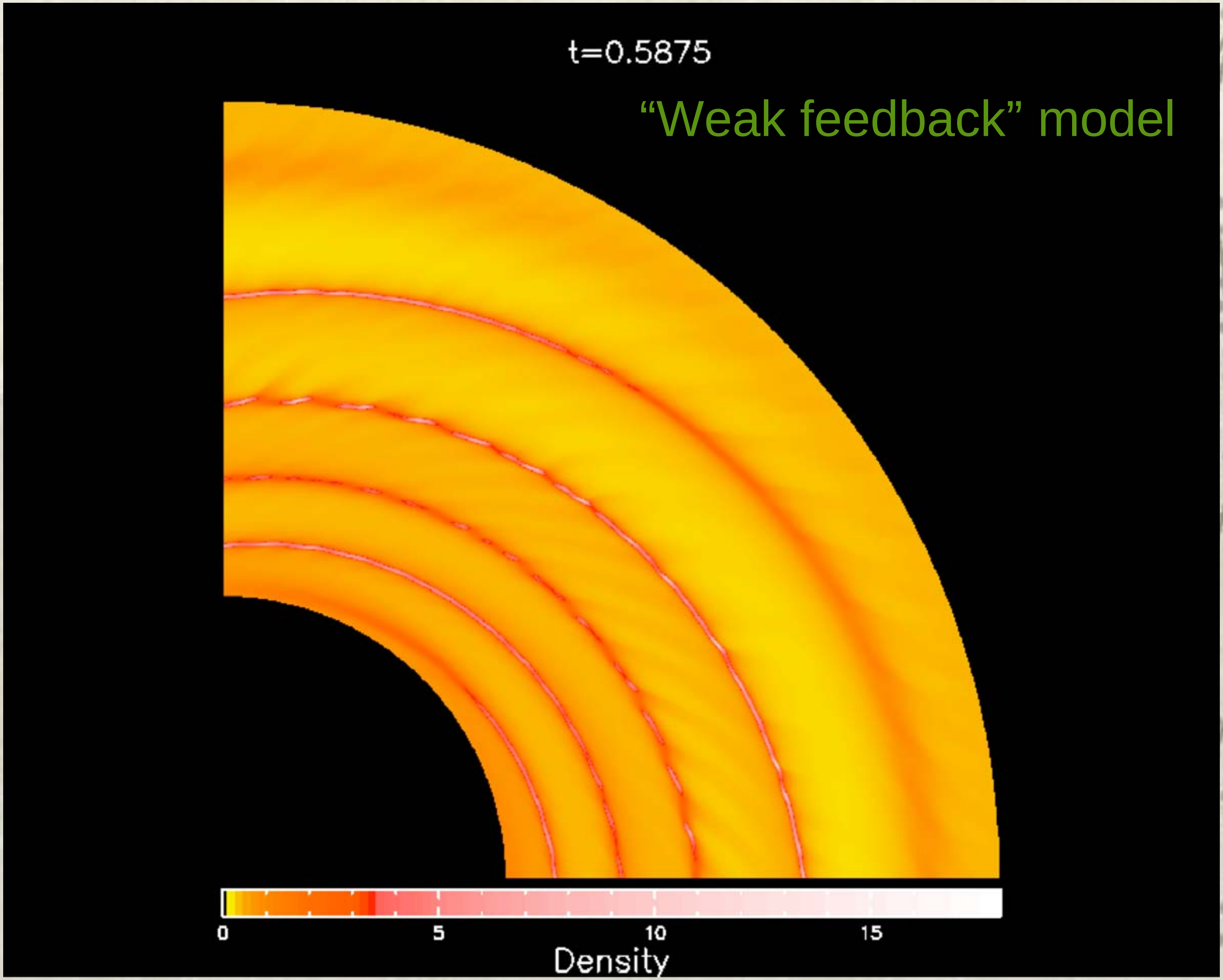
- Expanding shell is created



Shetty & Ostriker (2007)

See R. Shetty poster

Q=1 “strong feedback” model

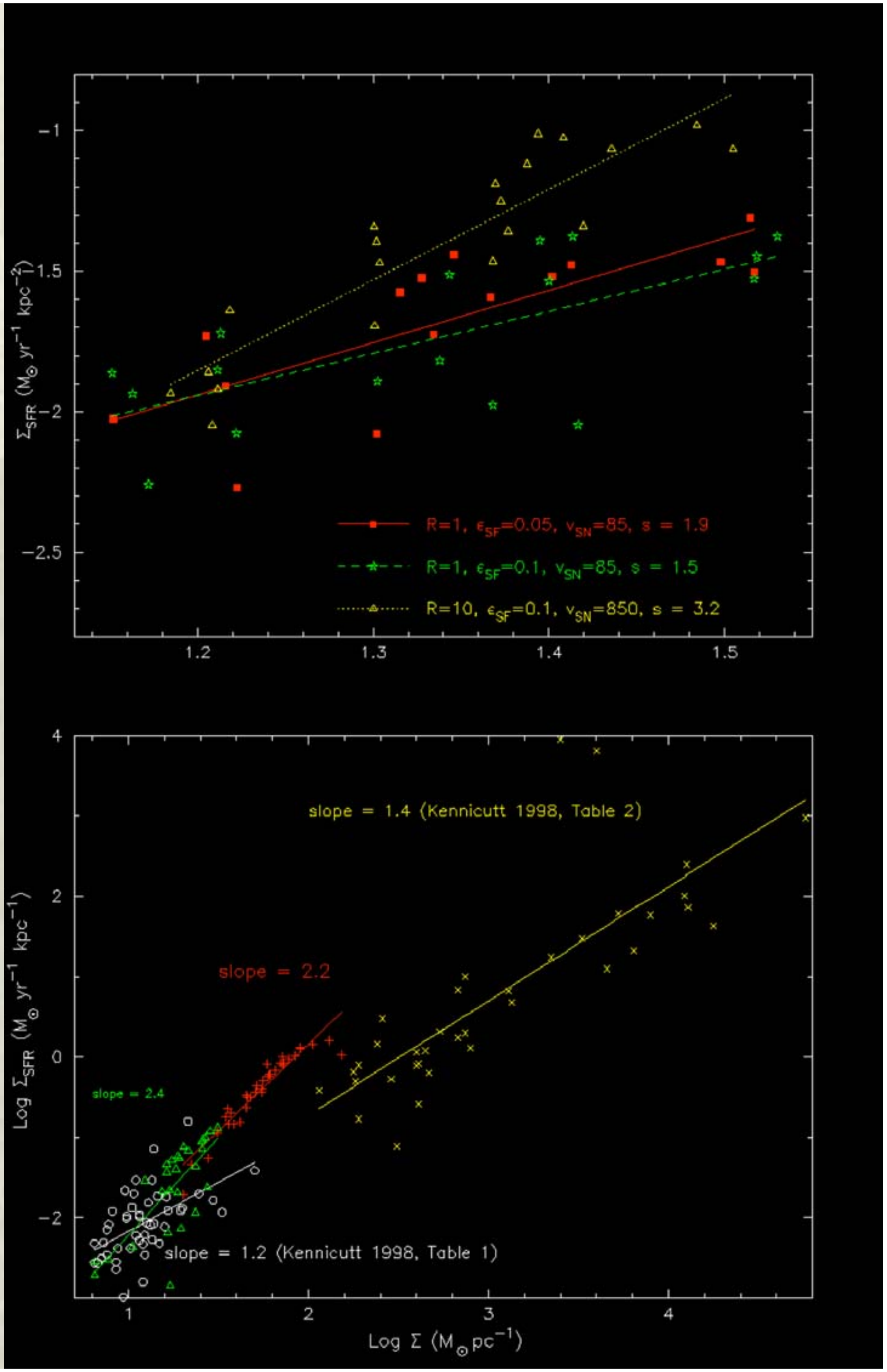


“Weak feedback” model

Shetty & Ostriker (2007)

"Kennicutt-Schmidt" behavior

- SFR increases with surface density
- Large scatter!
- Similar Σ_{SFR} to observations at low Σ
- Steeper slope than in observations, other simulations
- disk thickness effect…?



Shetty & Ostriker (2007)

Disk thickness effects in t_{grav}

- Thick disk has fastest-growing Jeans mode growth rate

$$\gamma^2 = \frac{2\pi G\Sigma}{H}\left(\frac{x}{1+x} - \frac{x^2}{2h}\right) \quad \text{where} \quad x(1+x)^2 = \frac{H\pi G\Sigma}{c_s^{\,2}} \equiv h$$

- In terms of h and Q, $\quad \frac{H}{R} = \frac{h}{\sqrt{2}}\frac{c_s}{V_c}Q$

- Self-gravitating disk has $h=1 \Rightarrow x=0.47 \Rightarrow$

  $t_{grav}=1/\gamma \approx c_s/2G\Sigma = t_{J,2D}/2$

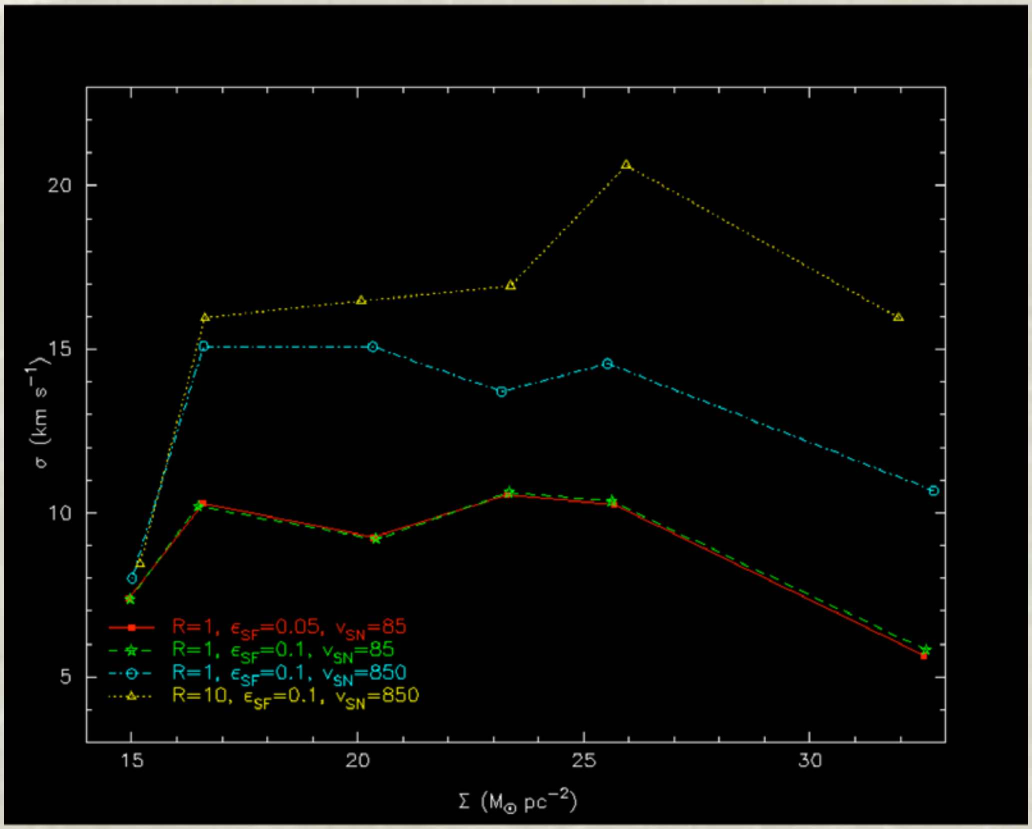
- If vertical direction has fixed numerical thickness large compared to natural thickness (e.g. numerically unresolved), $\quad h = H_{numer}\frac{\pi G\Sigma}{c_s^{\,2}} >> 1$

  then $x \approx h^{1/3} \Rightarrow t_{grav}=1/\gamma \approx \sqrt{\frac{H_{numer}}{2\pi G\Sigma}}$ independent of c_s

- *Notice difference in scalings:* $\Sigma/t_{grav} \propto G\Sigma^2/c_s$ versus $\Sigma/t_{grav} \propto \Sigma^{1.5}\,(G/H_{numer})^{1/2}$

Velocity dispersion in feedback models

- Large-scale velocity dispersion increases with strength of feedback
- Velocity dispersion is relatively independent of Σ (and R) in each model
- Increase in large-scale velocity dispersion does not suppress SF
- Simple replacement of $c_s \rightarrow c_{eff} = (c_s^{\ 2} + \sigma^2)^{1/2}$ is too naive; i.e. $t_{grav} \neq \sigma/G\Sigma$
- Scale of turbulence is important!



Shetty & Ostriker (2007)

Open issues

- Disk scale heights in ISM
  - Observations (cold phase?); simulations (resolution)
- Multi-scale turbulence:
  - Composite spectrum, including all sources?
  - Variations with location/environment?
  - Variations with thermal ISM phase? Effects on *H*?
- Positive and negative effects of turbulence on SF
  - Direct demonstration of negative effect!
  - Is there a clean separation by scale?
- Can SF be self-regulated?
  - Can negative effects (small-scale) exceed positive effects (large-scale) of turbulence driven by SF?
  - Or is gas depleted until SFR drops?