# *Formation of GMCs*

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# Observational constraints

- All of contemporary SF is in GMCs
- Most of mass in GMCs is in $M>10^5\ M_\odot$ clouds
- Column density within a given GMC: $\Sigma_{cl}$~200 $M_\odot\ pc^{-2}$ , corresp. $N$~$10^{22} cm^{-2}$
- Lifetimes of GMCs ~ 20-30 Myr based on GMC/star cluster association stats
- Most GMCs of all masses contain stars $\Rightarrow$ SF is rapid once GMC forms

# How are GMCs formed?

- Bottom-up: pairwise coagulation starting from cold HI clouds (~ $10^3$ $M_\odot$ ) in region of size

$$R_{gather} = 190\mathrm{pc}\left(\frac{\mathrm{M}_6}{\bar{\mathrm{n}}_1}\right)^{1/3}$$

- Binary collision time:

$$t_{collis} = \frac{\sqrt{\pi}}{3}\left(\frac{\rho_{cl}}{\bar{\rho}}\right)^{2/3}\frac{R_{gather}}{\sigma} = \frac{\sqrt{\pi}}{4}\frac{\Sigma_{cl}}{\bar{\rho}\sigma} \approx 5\times 10^8\,\mathrm{yr}\,\frac{\Sigma_{\mathrm{cl},200}}{n_1}$$

- nb: gravitational focusing reduction factor

$$\left(1+\frac{\pi G R_{cl}\Sigma_{cl}}{\sigma^2}\right)^{-1}$$

is ~1 for M<$10^5$ $M_\odot$

# Bottom-up formation: slow!

- Total coagulation time = $\log_2(M_{final}/M_{init})$ $t_{collis}$ is >> $t_{GMC}$ unless ISM $\langle n \rangle \sim 100\ cm^{-3} \sim n_{GMC}$
- Slow bottom-up formation appears inconsistent with GMC lifetimes/ destruction by HII regions
- Possible exception: galactic center regions, with large $\langle n \rangle$

# Top-down: converging flow

- One-dimensional converging flow:

$$t_{accum} = \frac{\Sigma_{cl}}{\bar{\rho} v_{rel}} \approx 3\times10^{8}\,\mathrm{yr}\ \frac{\Sigma_{\mathrm{cl},200}}{n_1 v_{rel,20}}$$

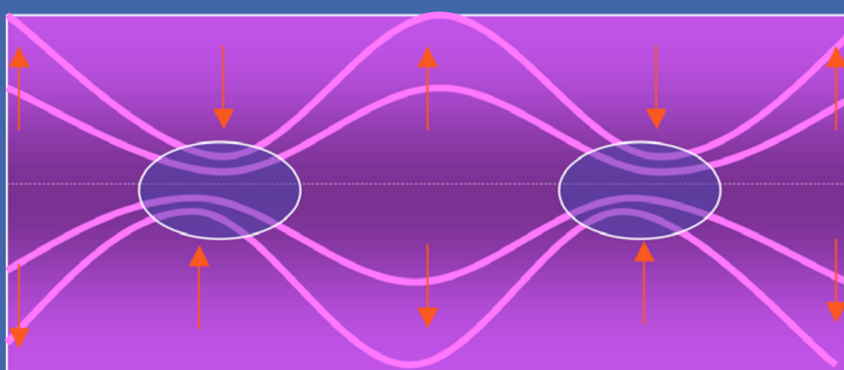
is time to accumulate total surface density $\Sigma_{cl}$ of shocked gas in stagnation region

- Problem: correlated flow cannot be maintained for long enough time to reach observed $\Sigma_{cl}$ unless background $\langle n \rangle$ is large

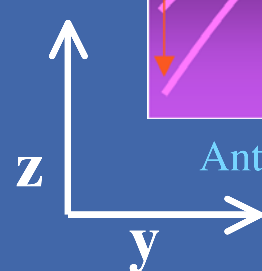
# Top-down: Parker Instability

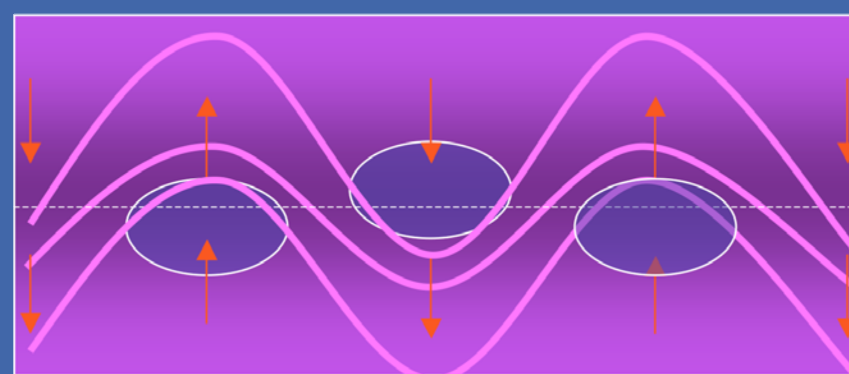
- Driven by magnetic buoyancy in background gravitational field from gas and stars; matter slides along field lines to collect in magnetic valleys
- Range of azimuthal wavelengths near $\lambda_y \sim 2\pi H \to 2$ kpc;
  initial growth rate $\sim v_A/H \Rightarrow t \sim 10^7$ yr
- Preference for long vertical wavelength (no nodes)

Refs:
Parker 1966, 1967
Shu 1974
Mouschovias et al 1974
Hanawa et al 1992
Giz & Shu 1993
J.Kim & Hong 1998
Chou et al 2000



Symmetric mode

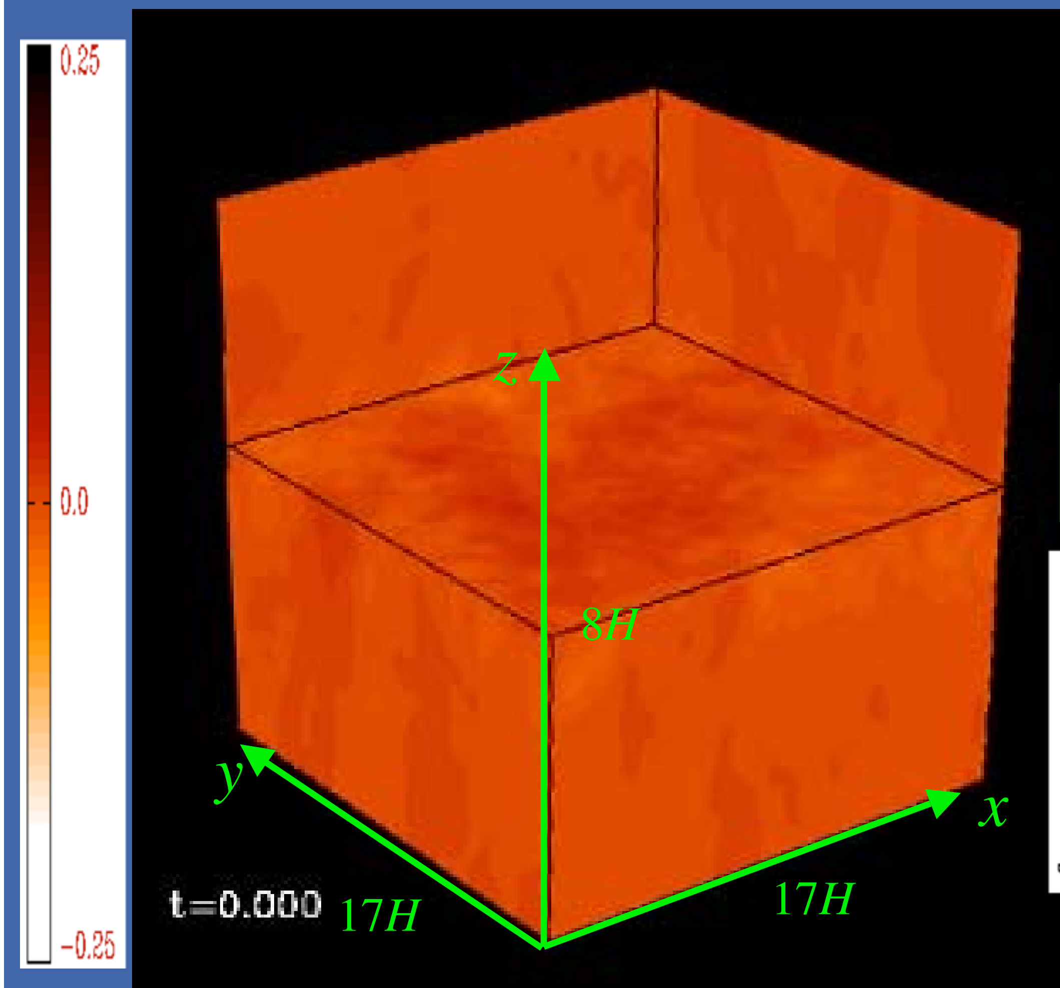


Antisymmetric (midplane-crossing) mode

# Nonlinear Parker mode with rotation and shear

- Only moderate density enhancement ($\rho_{max}$=1.75 $\rho_0$) at early times (self-limiting instability)
- Shear smears out density fluctuations at late times

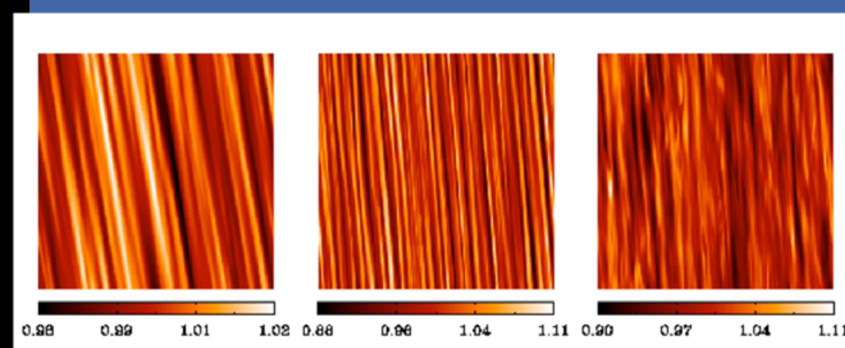



fractional density perturbation

Conclude: Parker instability does not by itself form GMCs

Kim, Ostriker, & Stone (2002)

See also: J. Kim et al 1998
J. Kim, Ryu & Jones 2001




Surface density: $t/t_{orb}$=1,2, 3

# Top-down: self-gravitating instability

- Key physical timescales:
  - Shear

$$t_{shear} = \frac{1}{q\Omega} = 0.5 \times 10^{8}\,\mathrm{yrs}\ \frac{1}{q}\left(\frac{R}{10\mathrm{kpc}}\right)\left(\frac{V_c}{200\mathrm{km\,s^{-1}}}\right)^{-1}$$

  - Epicyclic motion

$$t_{epi} = \frac{2\pi}{\kappa} = 2.2 \times 10^{8}\,\mathrm{yrs}\ \left(\frac{\mathrm{R}}{10\ \mathrm{kpc}}\right)\left(\frac{V_c}{200\mathrm{km\,s^{-1}}}\right)^{-1}$$

  - Self-gravity

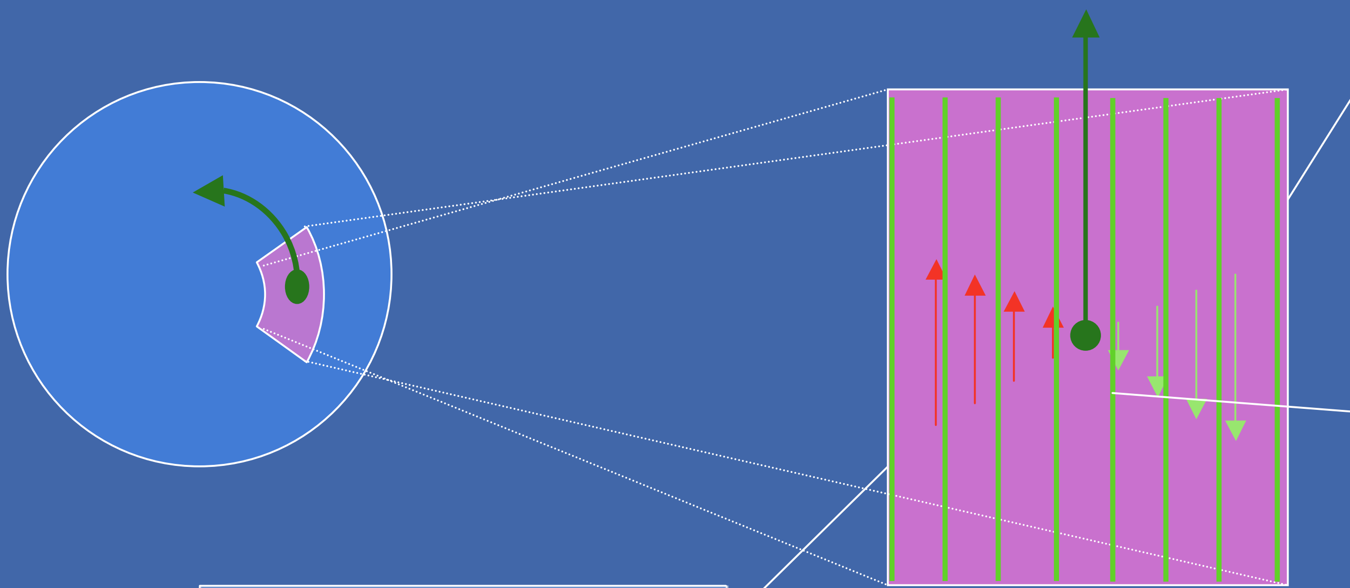
$$t_{grav} = \left(\frac{\lambda}{G\Sigma}\right)^{1/2} = 1.5 \times 10^{8}\,\mathrm{yrs}\ \left(\frac{\lambda}{\mathrm{kpc}}\right)^{1/2}\left(\frac{\Sigma}{10\mathrm{M}_{\Theta}\,pc^{-2}}\right)^{-1/2}$$

  - Thermal pressure

$$t_s = \frac{\lambda}{c_s} = 1.4 \times 10^{8}\,\mathrm{yrs}\ \left(\frac{\lambda}{\mathrm{kpc}}\right)\left(\frac{c_s}{7\mathrm{km\,s^{-1}}}\right)^{-1}$$

# Large-scale dynamics with shear

For moderate-scale ISM dynamics (L>H), must include background sheared rotation. May consider a local patch of the disk:

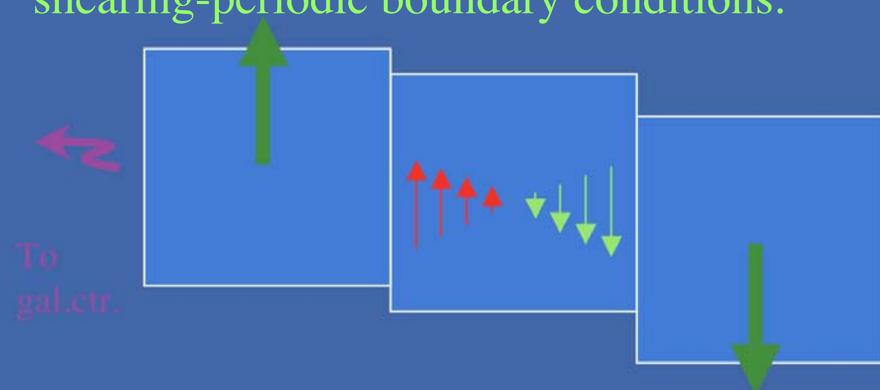


Exterior rotation is slower for “normal” shear

Mean magnetic fields are predominantly toroidal

Interior rotation is faster for “normal” outer-disk shear

For simulations with local model, apply shearing-periodic boundary conditions:




Similar approach may also be used when spiral arms are present (Roberts 1969)

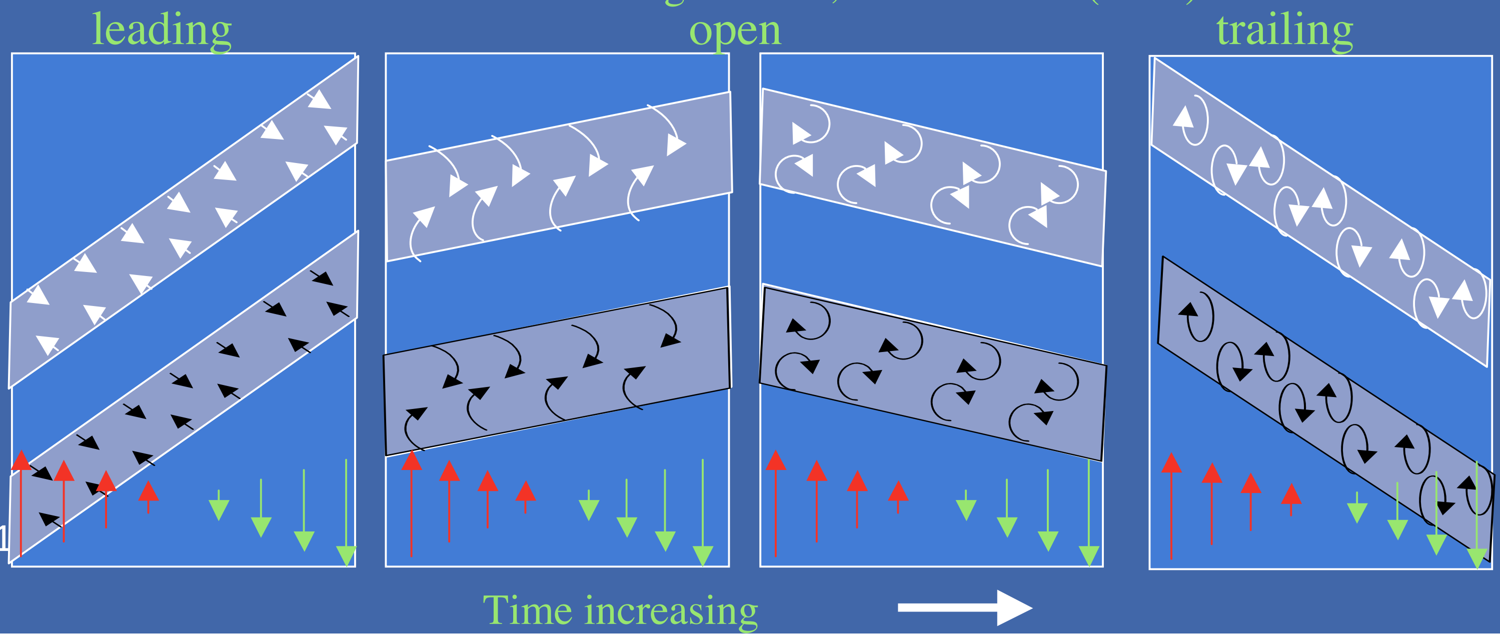
# Swing amplifier

– Growth occurs due to cooperation of epicyclic motion, shear, self-gravity

– Need low $Q \equiv \kappa c_s/\pi G\Sigma$ for significant growth

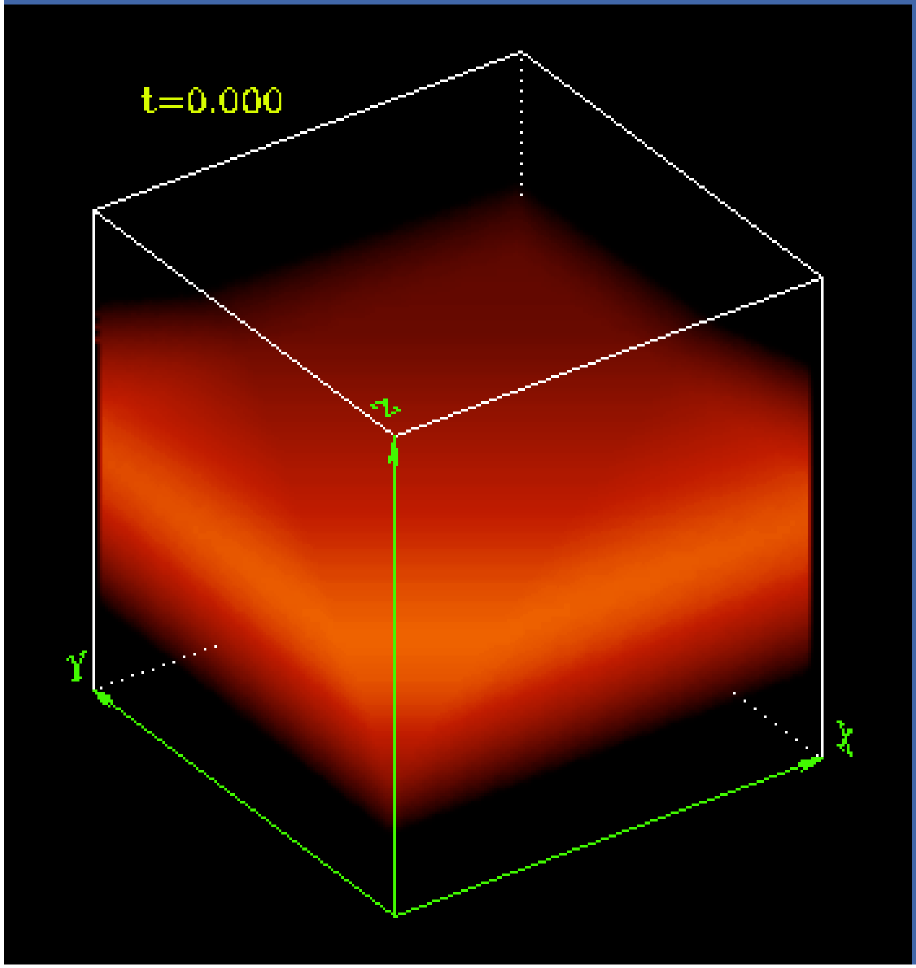
$$Q = 1.5\left(\frac{c_S}{7\,km s^{-1}}\right)\left(\frac{V_c}{200\,km s^{-1}}\right)\left(\frac{R}{10\,kpc}\right)^{-1}\left(\frac{\Sigma_{gal}}{10\,M_\Theta pc^{-2}}\right)^{-1}$$

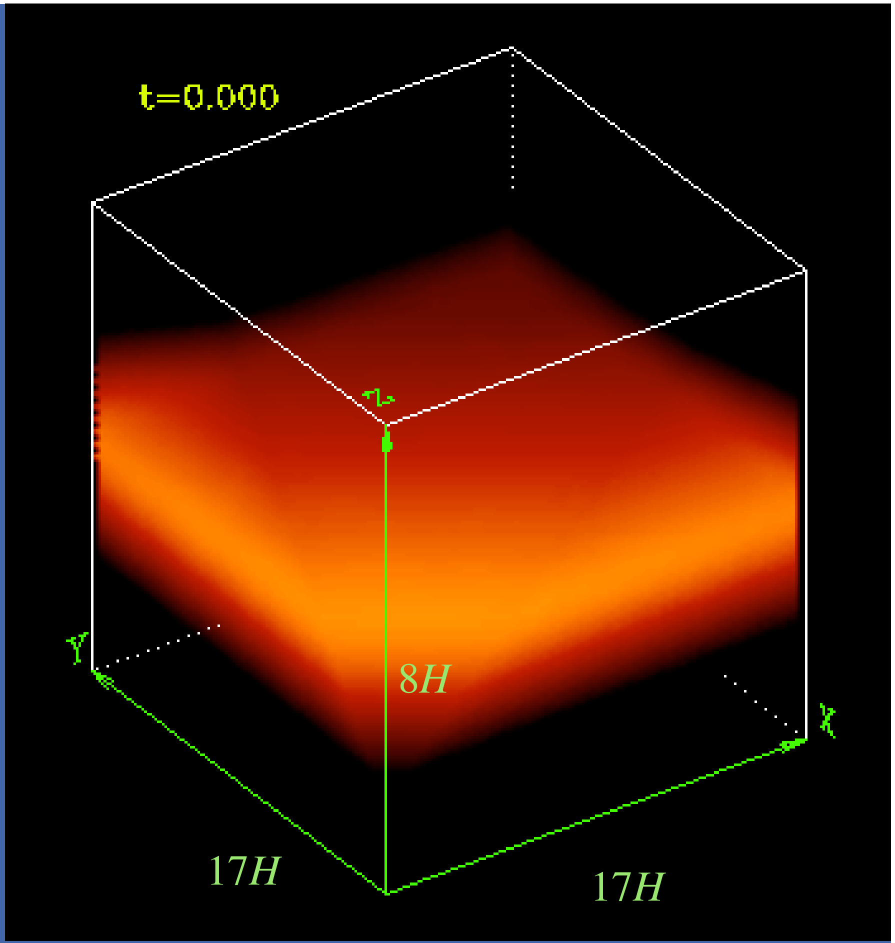
Schematic of shearing wavelet, after Toomre (1981)



# Results from **3D** simulations

– Thresholds for nonlinear instability:
  - $Q_{th}$ <1 unmagnetized case
  - $Q_{th}$~1 strongly magnetized case
  - $Q_{th}$~1.6 for weakly magnetized cases (MRI unstable)
– Characteristic $M \sim M_J \Rightarrow \sim 10^7\ M_\odot$




Unmagnetized model: $Q$=0.7

*MRI decreases surface density required for gravitational instability by >50%*

Weakly-magnetized (MRI) model: Q=1.5, $\beta_0$=100

Kim, Ostriker, & Stone (2002, 2003)

# Jeans scales in disk

- 2D Jeans length in gas is

  $L_J = c_s^2/G\Sigma_g = 1.1\ \mathrm{kpc}\ (c_s/7\ \mathrm{km\ s^{-1}})^2\ (10\ M_\odot\ \mathrm{pc}^{-2}/\Sigma_g)$
- 2D Jeans time is

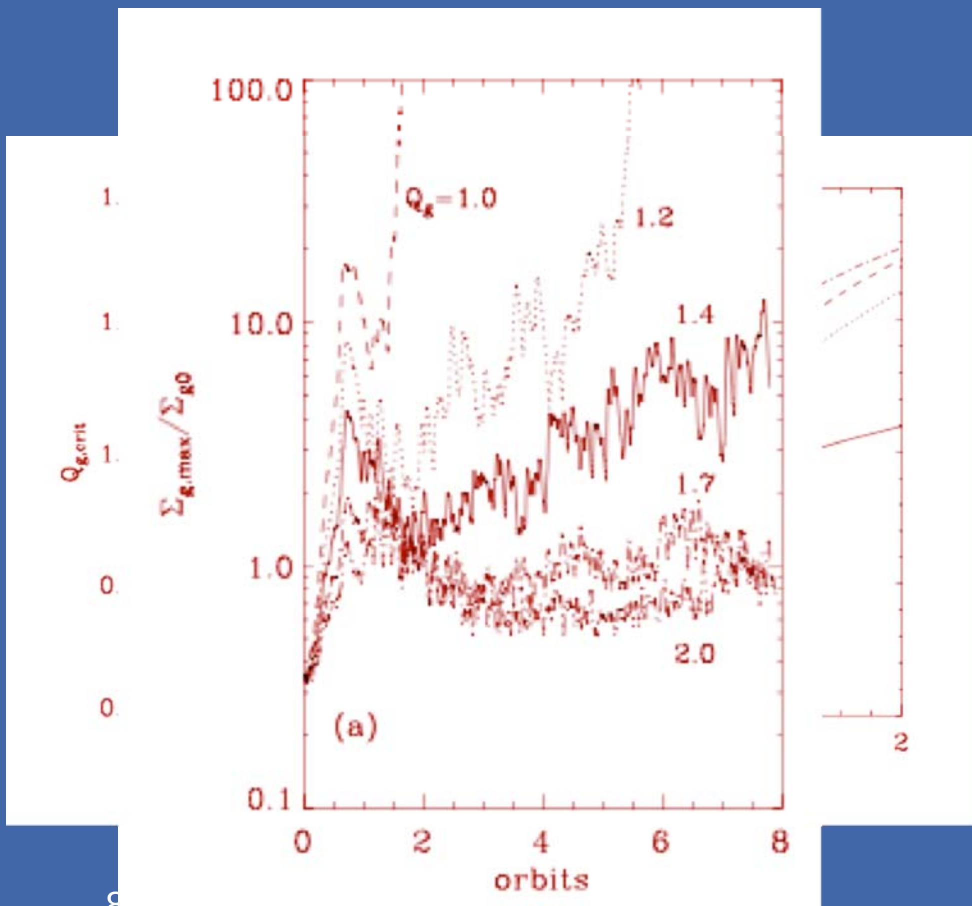
  $t_J = c_s/G\Sigma_g = 1.6 \times 10^8\ \mathrm{yrs}\ (c_s/7\ \mathrm{km\ s^{-1}})\ (10\ M_\odot\ \mathrm{pc}^{-2}/\Sigma_g)$
- 2D Jeans mass is

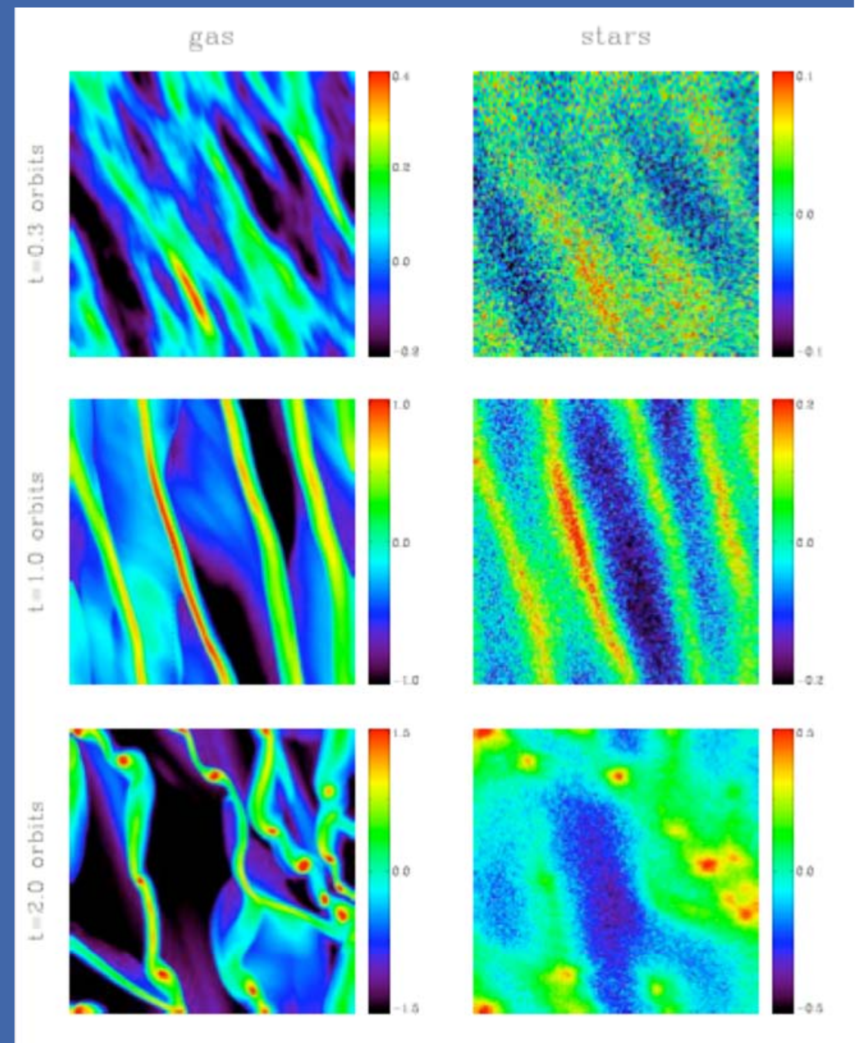
  $M_J = L_J^2\,\Sigma_g = 1.3 \times 10^7\ M_\odot\ (c_s/7\ \mathrm{km\ s^{-1}})^4\ (10\ M_\odot\ \mathrm{pc}^{-2}/\Sigma_g)$

# “Swing” in thick disk including stars

- Nozero disk thickness stabilizes
- Stellar disk destabilizes
- Critical Q ≈1.4 for clump formation

Non-axisymmetric

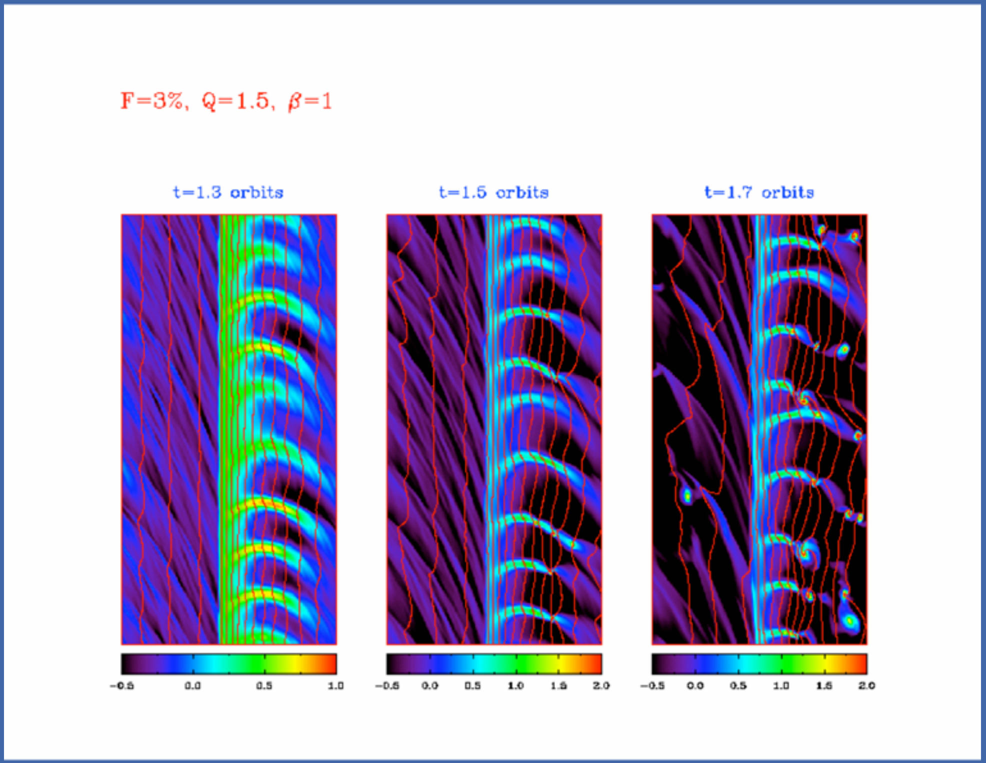


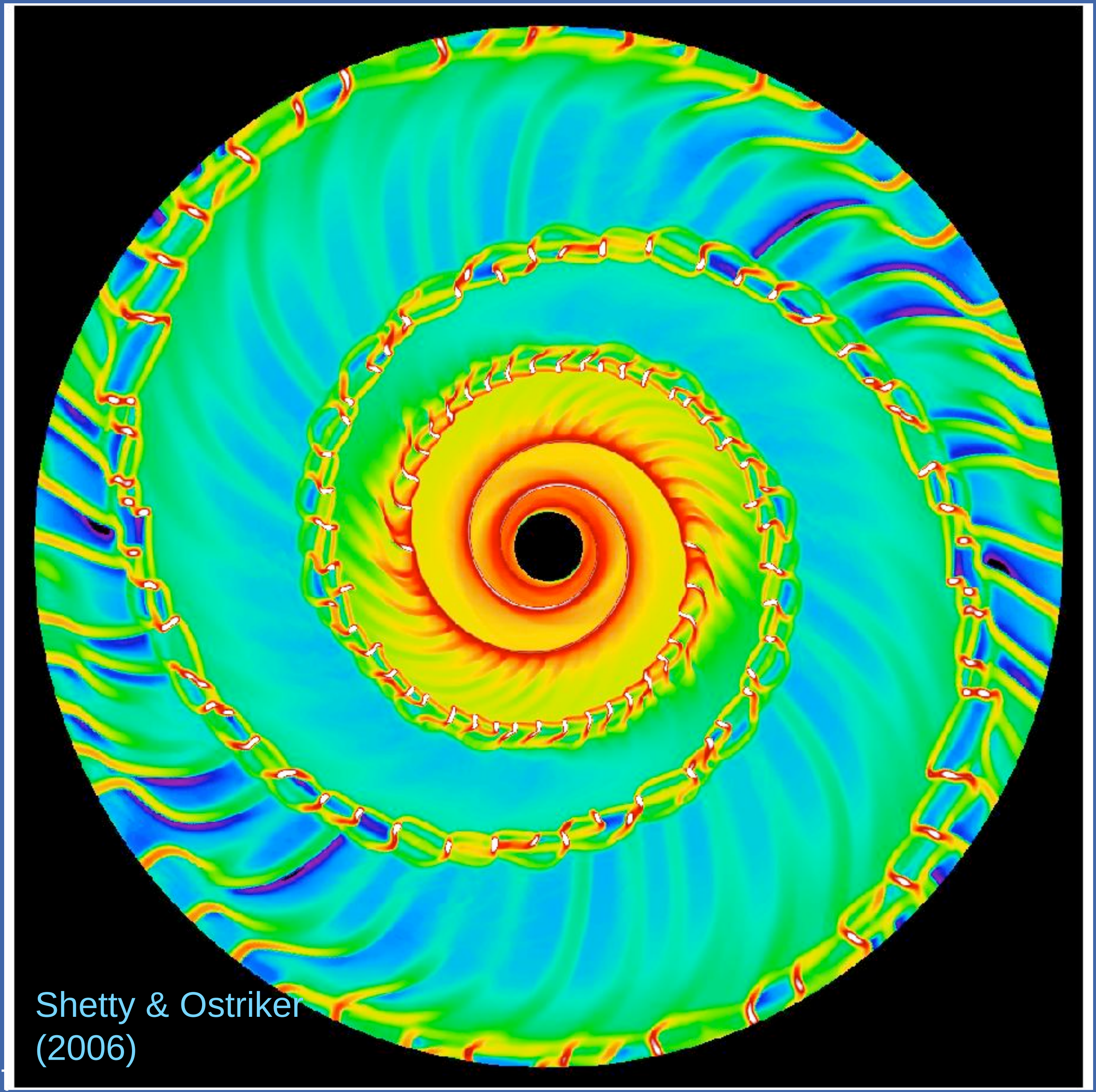

Kim & Ostriker (2007)

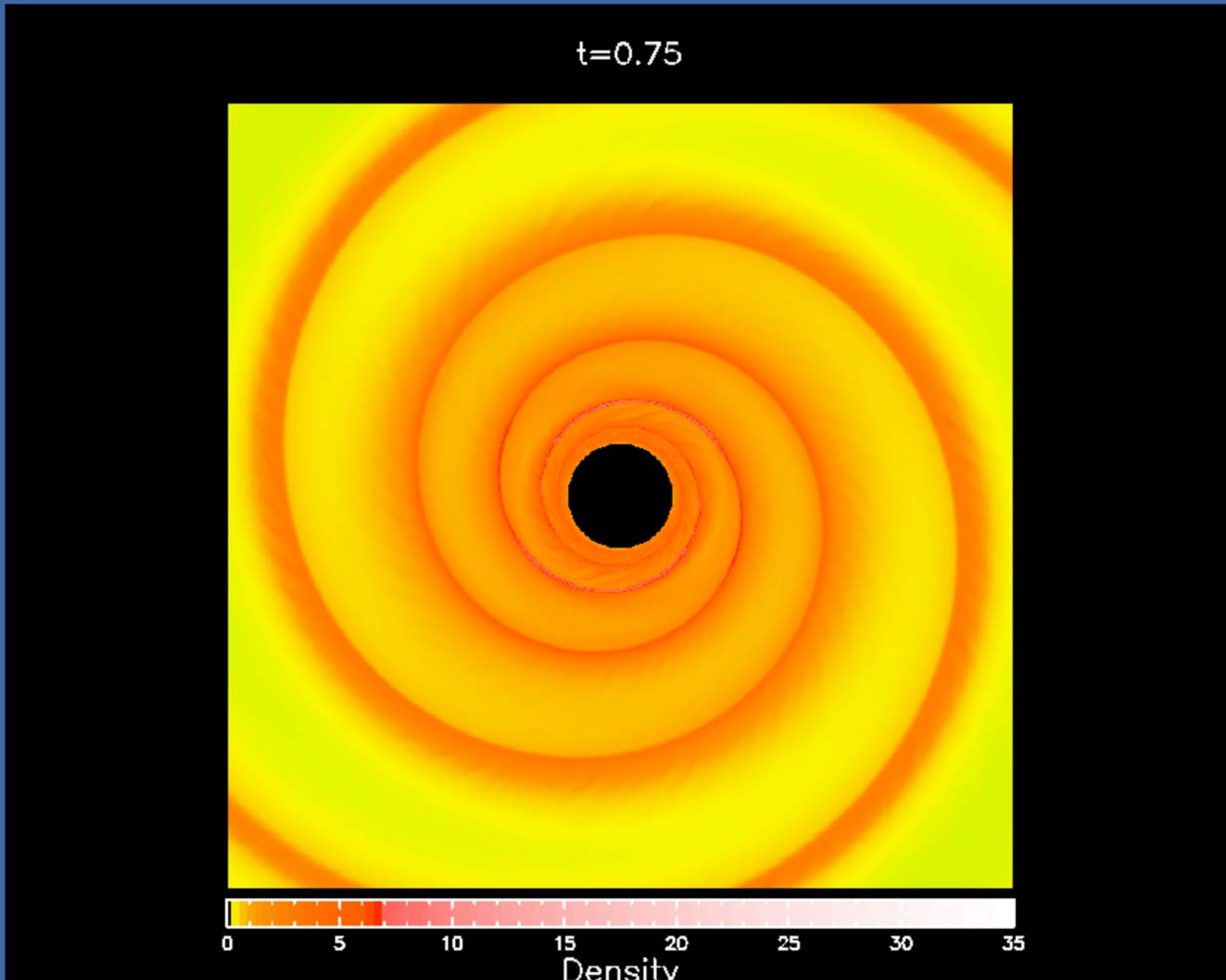
# With spiral structure…

- Jeans mass and Jeans time lower in spiral arms, due to galactic shock
- Self-gravity leads to growth of spiral-arm spurs
- GMCs form in arm if shock is strong
- GMCs form downstream if shock is weaker
- Clump masses in the range $10^6$-$10^7$ $M_\odot$

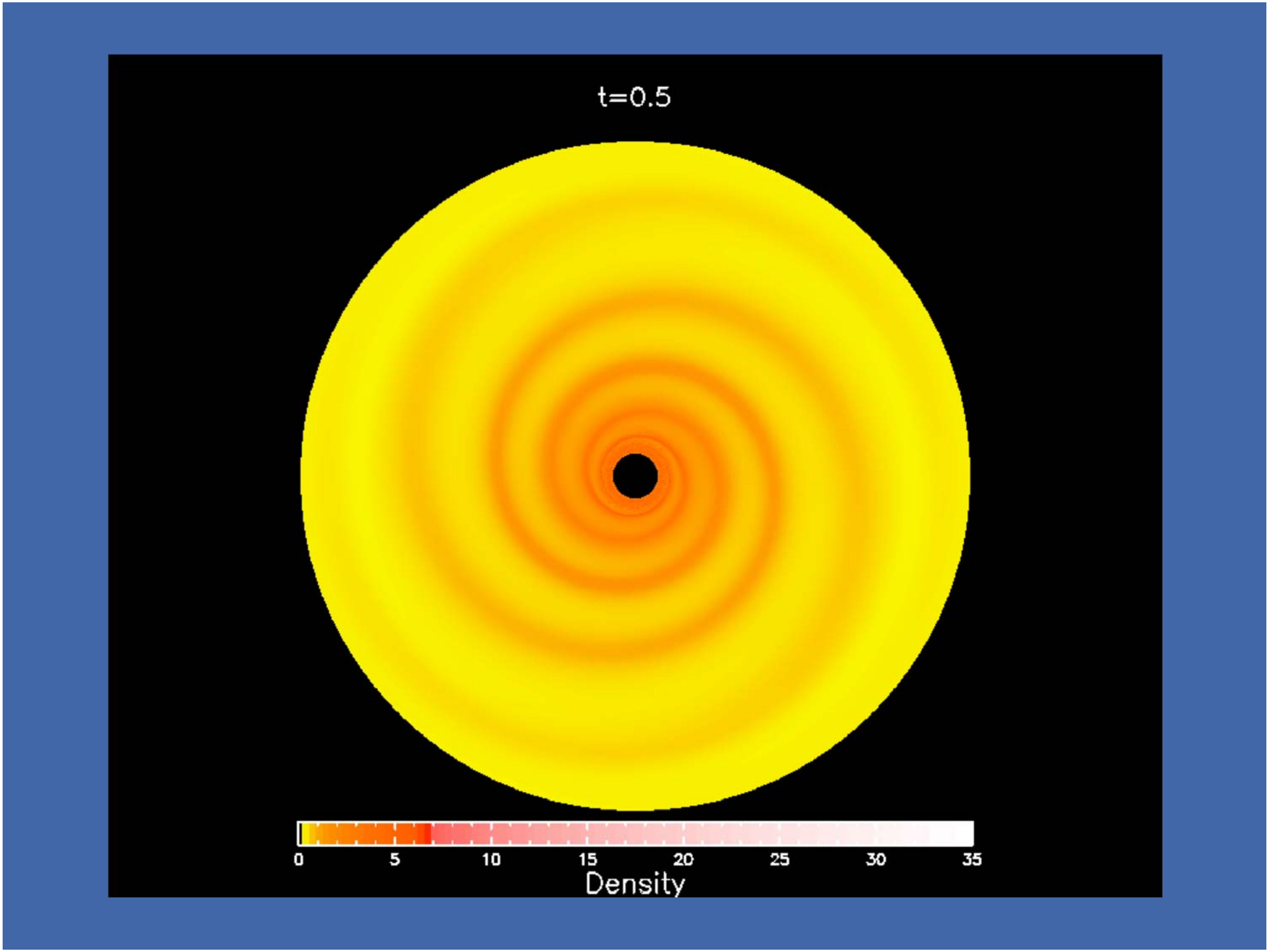



Kim & Ostriker (2002)


Shetty & Ostriker
(2006)




Shetty & Ostriker (2006)


t=0.5
0
5
10
15
20
25
30
35
Density

# Open questions…

- How does gravitational instability develop in multiphase medium?
- Can a single (meaningful) $c_{eff}$ be defined that incorporates turbulence ($\delta v$, $\delta B$) to yield $t_J = c_{eff}/(G\Sigma)$ and $L_J = c_{eff}^2/(G\Sigma)$ ?
- Are magnetic fields stabilizing or destabilizing in net?
- How do massive clouds (GMAs) fragment into GMCs as they form?
- Does pre-existing cloudy structure matter?
- How does feedback affect the range of masses that result, and net SF efficiencies?
  - e.g. if $t_{destroy} > t_{form,}$ is this a starburst?
- ……