The Biggest Accretion Disks

Turbulence and Structure in the Diffuse ISM

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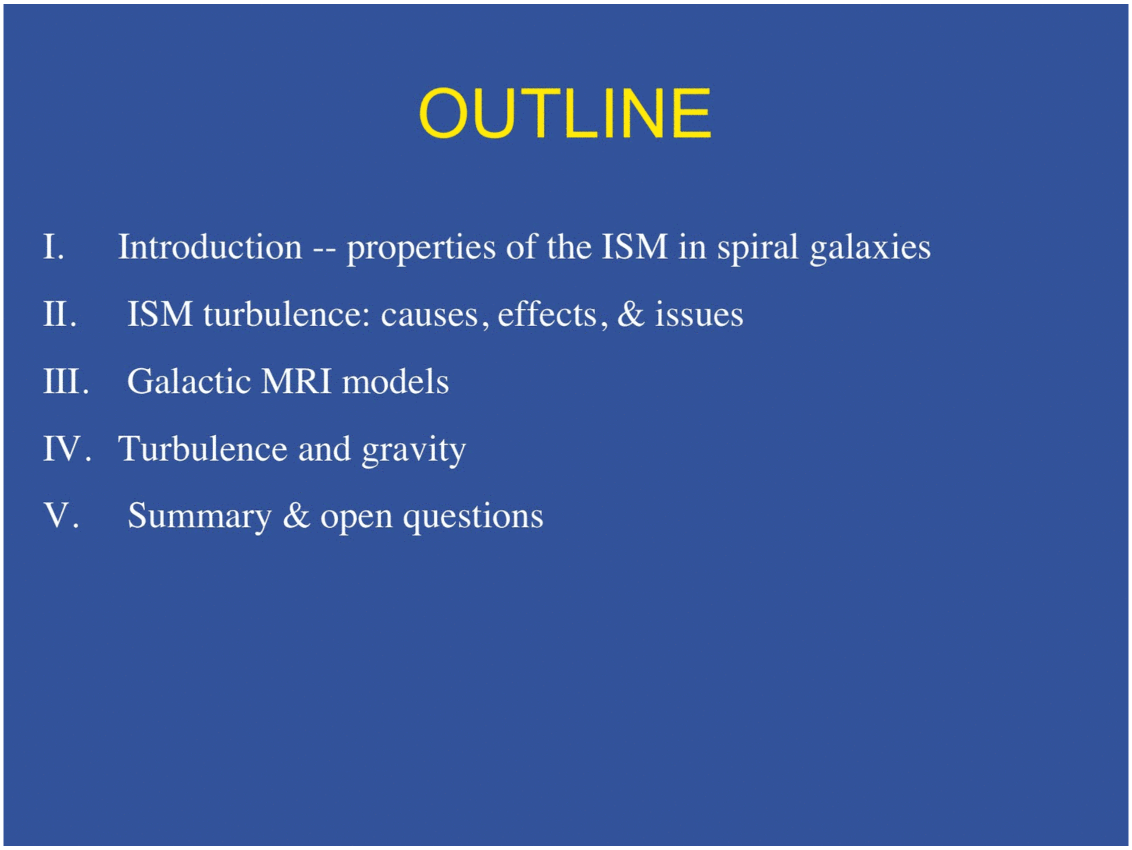


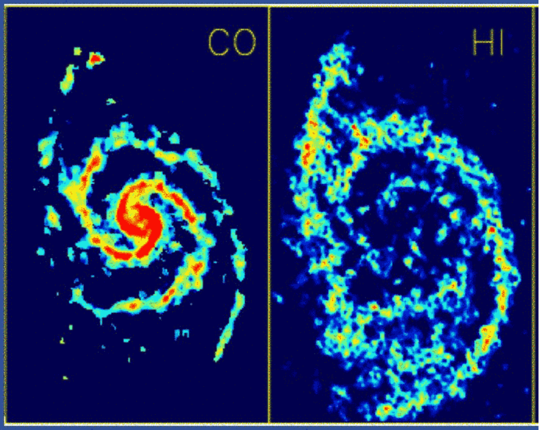
OUTLINE

I. Introduction -- properties of the ISM in spiral galaxies
II. ISM turbulence: causes, effects, & issues
III. Galactic MRI models
IV. Turbulence and gravity
V. Summary & open questions

I. Introduction

Orientation: global properties of the ISM in spiral galaxies

- Surface density:
  - Σ_{tot} = few -100 $M_\odot$ pc^{-2} ; exponential?
  - Σ_{HI} ≤10 $M_\odot$ pc^{-2} ; balance H_2
- Distribution:
  - H_2 is preferentially in arms; in grav. bound GMCs
  - HI is diffuse; non-SG clouds
- Scale height (MW; atomic):
  - H~150 pc inner (R< 8 kpc)
  - outer up to ~ 500pc
- Midplane density (MW):
  - n_{HI}=0.6 cm^{-3} inner galaxy; <0.3cm^{-3} outer (R>14 kpc)



M51 gas components
(Stuart Vogel/BIMA SONG)

- Other ISM components
  - warm ionized gas
  - hot gas

f_M small; f_V up to ~0.5

ISM structure

- Large scale
  - Concentration in spiral arms; due to external potential and SG
- Medium scale
  - Spurs trailing from arms into interarm regions
  - Superclouds ($M \sim 10^7\ M_\odot$) of H_2+HI in arms
  - Bubbles and chimneys of hot gas
- Small scale
  - H_2 GMCs ($M=10^5$-$10^6\ M_\odot$), and dark clouds ($M<10^4\ M_\odot$); $\langle n \rangle \sim 100\ cm^{-3}$; n to $10^5\ cm^{-3}$;$T \sim 10K$; $L \sim 20$ - 50pc
  - Cold atomic clouds ($n \sim 30 cm^{-3}$, $T \sim 100K$, $L \sim 1$-10pc)
  - Diffuse warm, atomic gas ($n \sim 0.3$; $T \sim 10^4 K$) + WIM and HIM ($T=10^5$-$10^6 K$) surrounds clouds

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ISM turbulence

- Milky Way:
  - Turbulent $\delta v \sim 7\ km\ s^{-1}$ for both warm, cold HI gas near Sun (Heiles & Troland 2003)
  - WIM $\delta v \sim 10$-$30\ km\ s^{-1}$ (Tufte, Reynolds, & Haffner 1999)
- External galaxies:
  - Measured for face-on galaxies; total HI $\delta v \sim 6$-$12\ km\ s^{-1}$
  - No secular trend of δv with galactic radius, even outside optical disk
  - Variations in δv uncorrelated with spiral arm phase/star formation

NGC 1058 -- Dickey et al 1990; Petric & Rupen 2001

NGC 1232 -- van Zee & Bryant 1999)

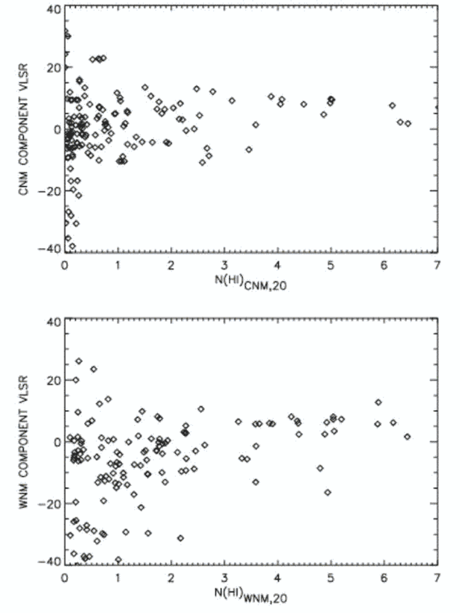
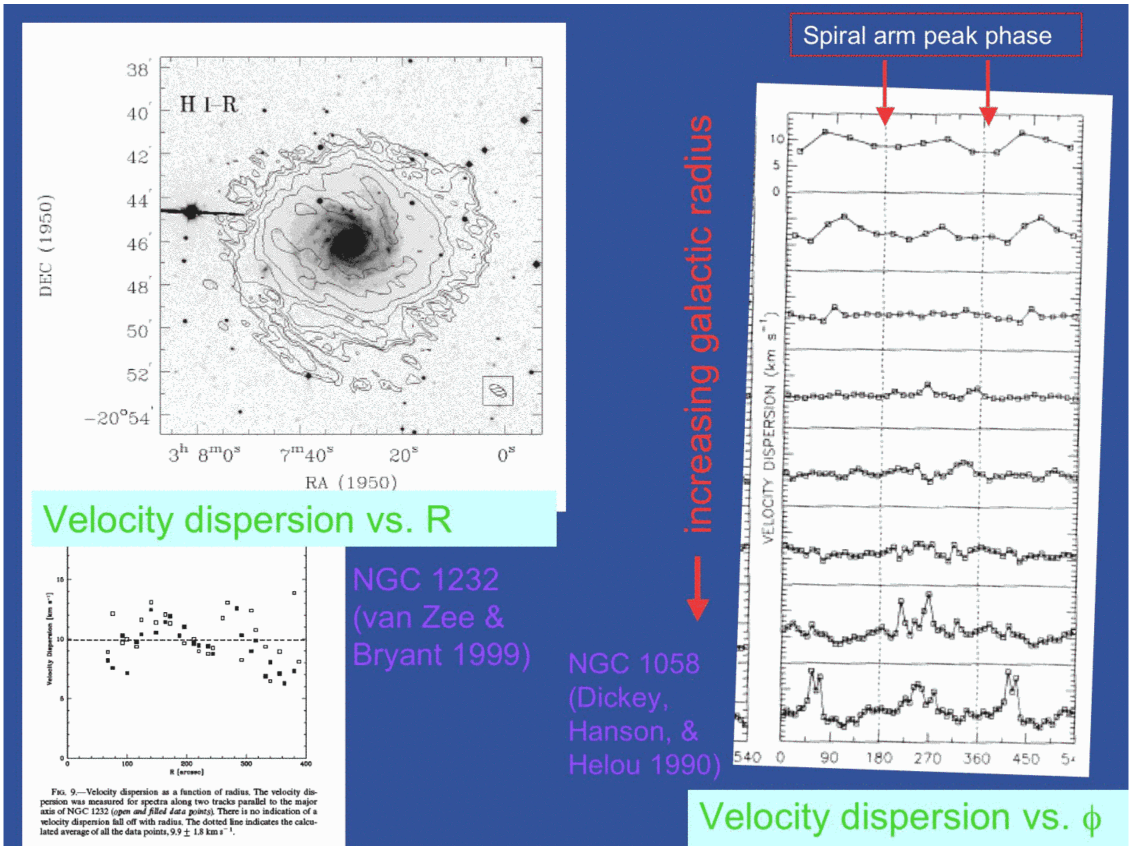


FIG. 11.—V_{LSR} vs. $N(H\ I)_{20}$ for CNM (*top*) and WNM components (*bottom*), for sources with $|b| > 10°$. $N(H\ I)$ is in units of $10^{20}\ cm^{-2}$.

Heiles & Troland (2003)



Velocity dispersion vs. R

NGC 1232 (van Zee & Bryant 1999)

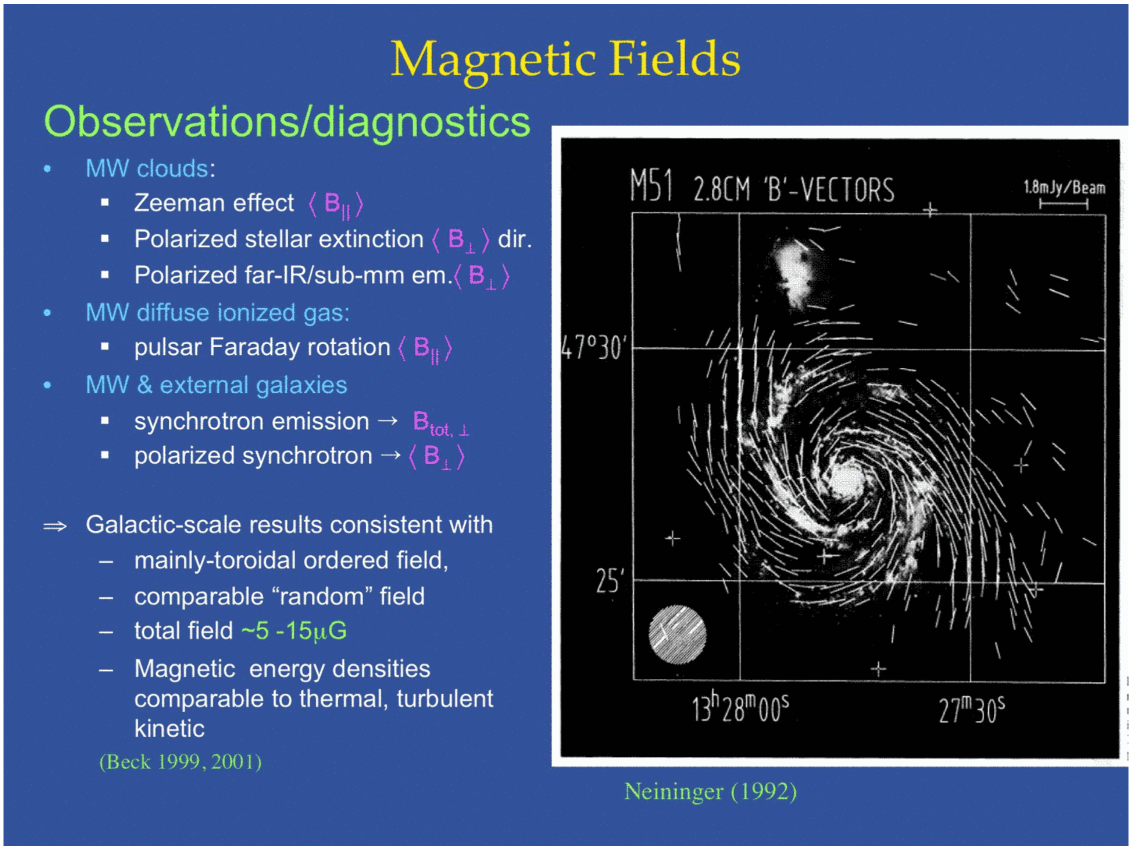
FIG. 9.—Velocity dispersion as a function of radius. The velocity dispersion was measured for spectra along two tracks parallel to the major axis of NGC 1232 (*open and filled data points*). There is no indication of a velocity dispersion fall off with radius. The dotted line indicates the calculated average of all the data points, 9.9 ± 1.8 km s^{-1}.

Spiral arm peak phase

increasing galactic radius

NGC 1058 (Dickey, Hanson, & Helou 1990)

Velocity dispersion vs. ϕ



Magnetic Fields

Observations/diagnostics

- MW clouds:
  - Zeeman effect $\langle B_{||} \rangle$
  - Polarized stellar extinction $\langle B_{\perp} \rangle$ dir.
  - Polarized far-IR/sub-mm em.$\langle B_{\perp} \rangle$
- MW diffuse ionized gas:
  - pulsar Faraday rotation $\langle B_{||} \rangle$
- MW & external galaxies
  - synchrotron emission → $B_{tot, \perp}$
  - polarized synchrotron → $\langle B_{\perp} \rangle$

⇒ Galactic-scale results consistent with

- mainly-toroidal ordered field,
- comparable "random" field
- total field ~5 -15μG
- Magnetic energy densities comparable to thermal, turbulent kinetic

(Beck 1999, 2001)

Neininger (1992)

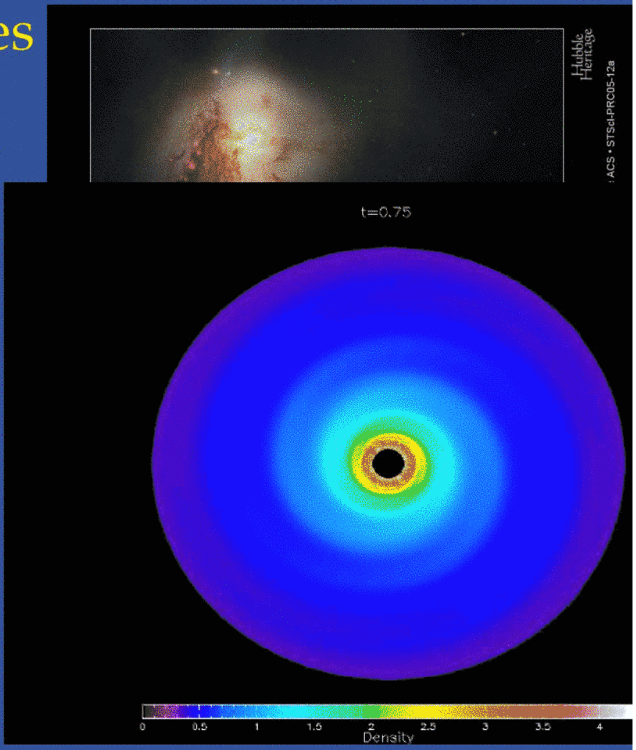
II. Turbulence Issues

``Astrophysics'' questions

- What generates turbulent *v, B* ?
- How does turbulence affect physical structure? e.g.
  - Cloud mass spectrum?
  - Vertical distribution of gas?
  - Density profiles across spiral arms?
- How does physical structure affect turbulence? e.g.
  - Effect of cloudy/multiphase structure on turbulent driving and dissipation?
  - Effect of cloudy structure on turbulent power spectrum?
- How are turbulence and thermal ISM properties related?
  - Is turbulent heating/cooling important?

``Astronomy" issues

- *How do turbulence & structure in the ISM affect star formation?*
- Star formation takes place in massive GMCs, likely formed via gravitational instabilities
  - How do GMC formation rates depend on ISM turbulence?
  - How do cloud properties (masses, internal turbulent states,…) depend on diffuse ISM tubulence?
  - How is the galactic GMC distribution affected by turbulence & structure in the diffuse ISM?



Shetty & Ostriker (2005)

Turbulent driving

- Traditional view: driving by supernovae (cf. Spitzer)
  - $(dE_{turb}/dt)_{in} = \varepsilon_{SN}\, \varepsilon_{SF}\, E_{SN}/(m_{SN}\, t_{cloud\ form})$
  - $(dE_{turb}/dt)_{out} \sim (\delta v)^2/t_{cloud\ collis} \sim (\delta v)^3/H$

  Using $t_{cloud\ form} \sim t_{orb} = 2.5\times 10^8$ yrs, $t_{cloud\ collis} \sim H/\delta v$ with H=150 pc, $\varepsilon_{SF} \sim 0.1$, $\varepsilon_{SN} \sim \delta v/(4 v_{SN,cool})$ with $v_{SN,cool} \sim 85$ kms^{-1} , $m_{SN} \sim 250\ M_\odot$, this yields

  $\delta v \sim 6$ kms^{-1} …..consistent with observations, but is it a coincidence??
- Problems with SN driving
  - Intermittency of SF
  - No observed correlation of turbulence with SF
  - Outer disks lack SF but are (likely) turbulent
- Another potential source of turbulence: tap galactic rotation with MRI (cf. Sellwood & Balbus 1999)
  - Principal difference from MRI in previous (accretion disk) models is that ISM gas is cloudy/multi-phase

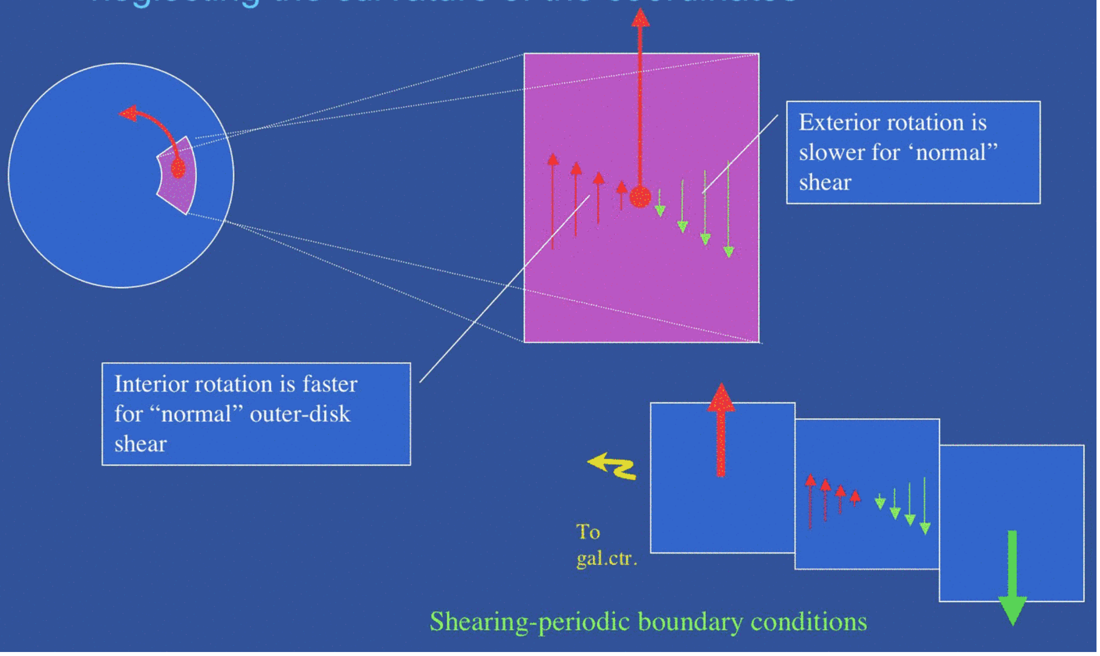
III. Galactic MRI models

Numerics / model specifications

- Time-dependent integration of MHD variables using version of ZEUS code (Stone & Norman 1992a,b)
- Simple atomic cooling+diffuse heating fit (cf Wolfire et al 2003); energy update via implicit solver
- Conduction implemented to spatially resolve thermally-unstable wavelengths on computational grid
- Local Cartesian model with shearing-periodic boundary conditions (Hawley, Gammie, & Balbus 1995; Stone et al 1996)
- 2D poloidal-plane “XZ” models in $(100\text{pc})^2$ box (Piontek & Ostriker 2004)
- 3D models in $(200\text{pc})^3$ box (Piontek & Ostriker 2005a)
- 3D stratified models in 600pc×300pc×900pc box (Piontek & Ostriker 2005b)
- Initial $P_0/k=2000$ K cm^{-3}; initial $n=0.25\text{-}4$ cm^{-3} ; initial $\beta=100$

Shearing periodic box

For local models , consider a small patch of the disk, neglecting the curvature of the coordinates



Exterior rotation is slower for 'normal" shear

Interior rotation is faster for "normal" outer-disk shear

To gal.ctr.

Shearing-periodic boundary conditions

Magnetohydrodynamic equations in the local frame

- Continuity equation: $\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \mathrm{v}) = 0$
- Momentum equation:

$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v} = -\frac{\nabla P}{\rho} + \frac{(\nabla\times\mathbf{B})\times\mathbf{B}}{4\pi\rho} + 2q\Omega^2\mathbf{x} - 2\Omega\times\mathbf{v} - \nabla\Phi_s + \mathbf{g}_{ext}$$

Dimensionless shear parameter q=-dlnΩ/dlnR;

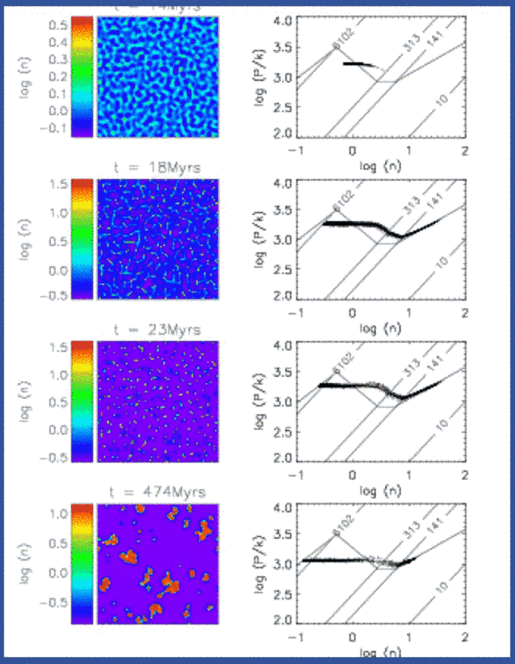
epicyclic frequency $\kappa^2=2(2-q)\Omega^2$; background $v_0=-q\Omega x\,\hat{y}$

- Energy equation:

$$\frac{\partial \mathcal{E}}{\partial t} + \mathbf{v}\cdot\nabla\mathcal{E} = -(\mathcal{E}+P)\nabla\cdot\mathbf{v} - \rho(\rho\Lambda-\Gamma) + \nabla\cdot(\mathcal{K}\nabla T)$$

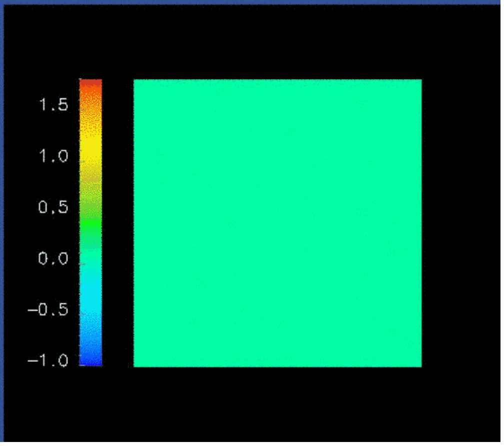
- Induction equation: $\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B})$
- Poisson equation: $\nabla^2\Phi_s = 4\pi G\rho$

Thermal Instability and HI structure



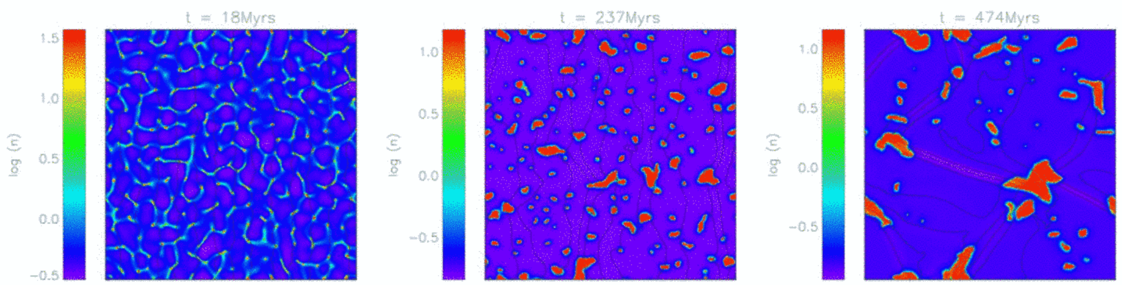
Piontek & Ostriker (2004)

- Thermal instability develops due to bistable heating/cooling equilibrium curve
- Medium becomes segregated into cold clouds/warm intercloud gas within ~20 Myr
- TI produces turbulence, but amplitude is very low (<0.4 kms^{-1})

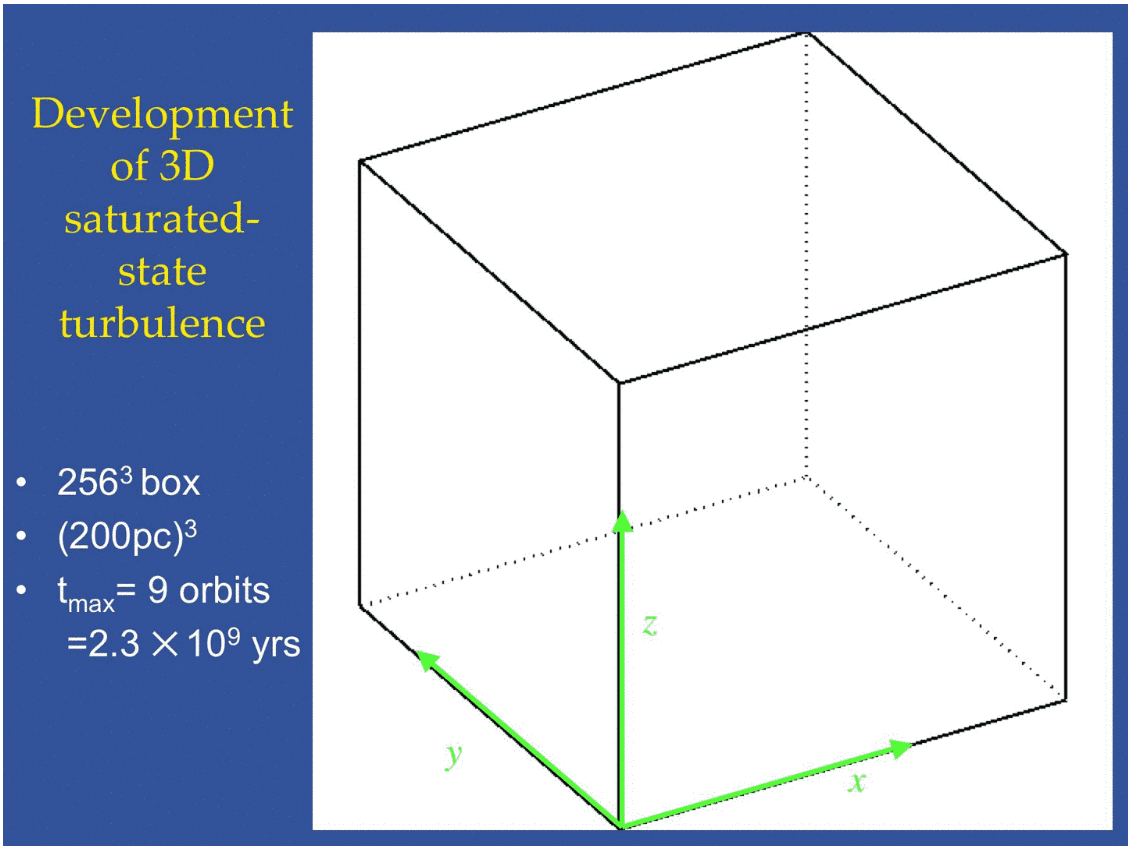


Growth of MRI in cloudy medium

- Growth rates ~ same as in single-phase medium at same $\langle\rho\rangle$, provided intercloud separation $< \lambda/2$
- Clouds grow by agglomeration; strong bends in *B*-field are in clouds
- Channel flow dominates late stages of 2D models

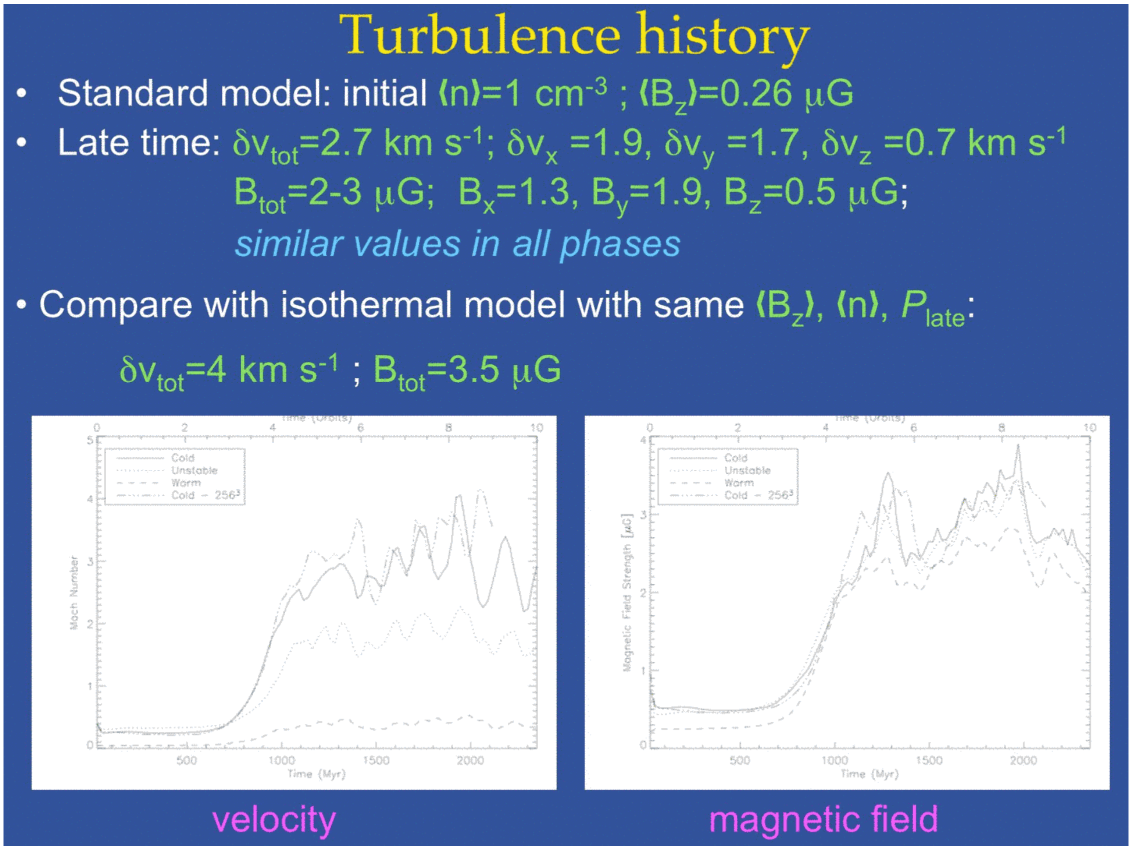


Piontek & Ostriker (2004)



Development of 3D saturated-state turbulence

- 256^3 box
- $(200\mathrm{pc})^3$
- t_{max}= 9 orbits =2.3 × 10^9 yrs



Turbulence history

- Standard model: initial $\langle n\rangle$=1 cm^{-3} ; $\langle B_z\rangle$=0.26 μG
- Late time: δv_{tot}=2.7 km s^{-1}; δv_x =1.9, δv_y =1.7, δv_z =0.7 km s^{-1}
  B_{tot}=2-3 μG; B_x=1.3, B_y=1.9, B_z=0.5 μG;
  similar values in all phases
- Compare with isothermal model with same $\langle B_z\rangle$, $\langle n\rangle$, P_{late}:

  δv_{tot}=4 km s^{-1} ; B_{tot}=3.5 μG

velocity

magnetic field

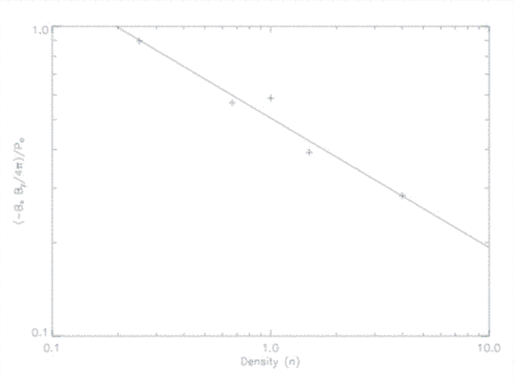
Scalings of saturated-state turbulent stresses

- Vary mean density in the box; other parameters fixed
- $\langle -B_x B_y \rangle / P_0 \propto \langle n \rangle^{-0.4}$
- $\langle \rho v_x v_y \rangle / P_0 \propto \langle n \rangle^{-1.1}$

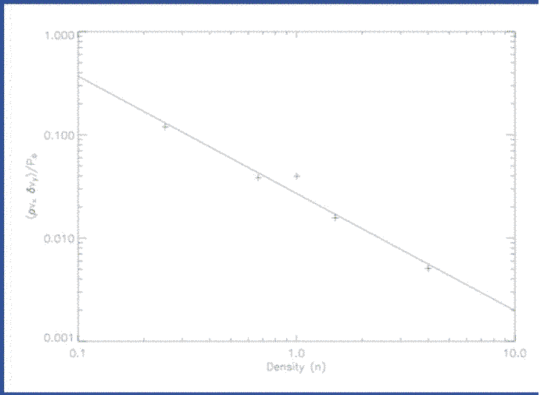
Compare:

HGB(95) stresses $\propto L_z \Omega v_{A,z} / c_s^2 \propto \langle n \rangle^{-0.5}$

Sano et al (2004) stresses $\propto v_{Az}^{3/2} \propto \langle n \rangle^{-0.75}$



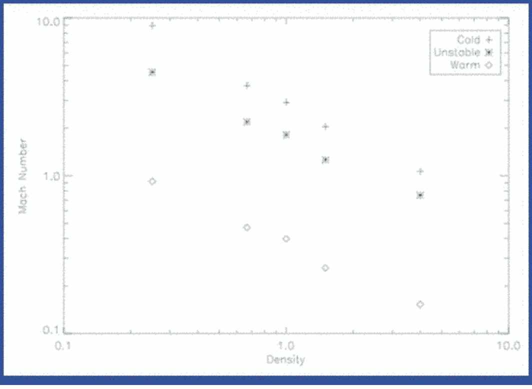
Maxwell stress



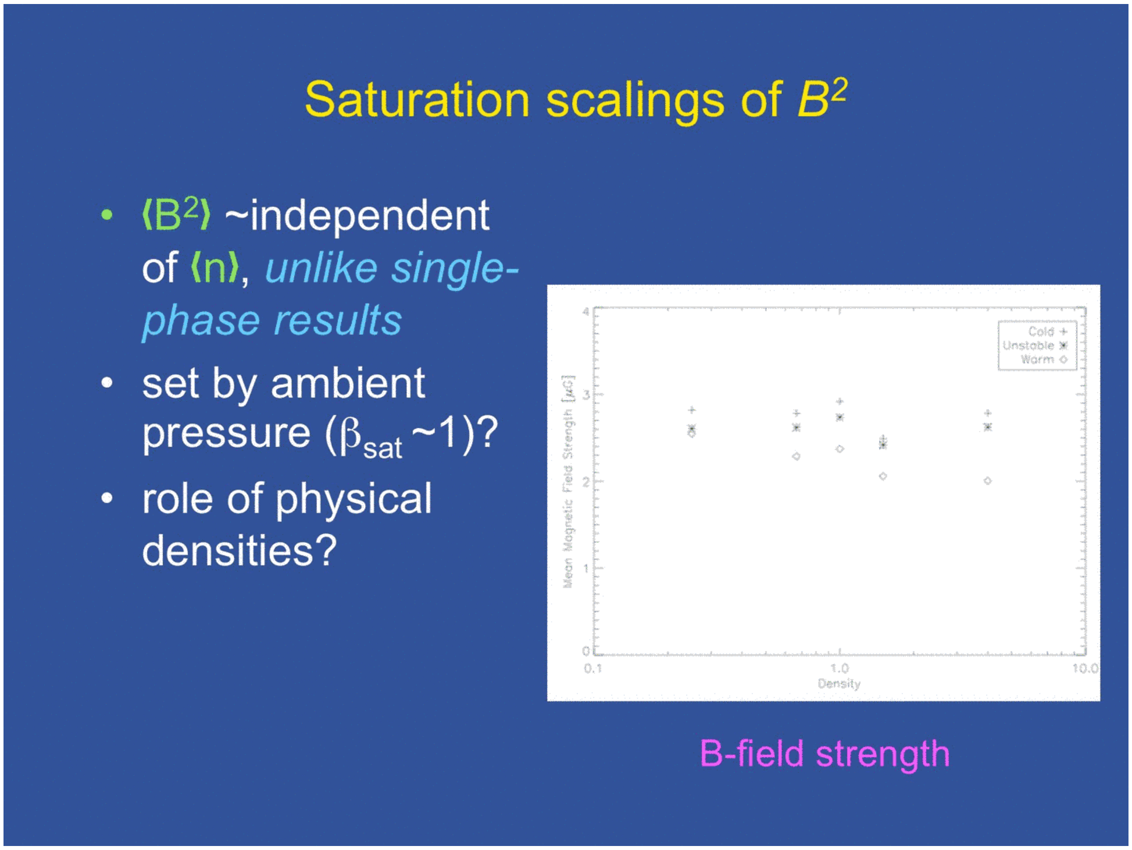
Reynolds stress

Saturation scalings of δv

- $\langle \delta v^2 \rangle^{1/2} \propto \langle n \rangle^{-0.77}$ (or $\langle n \rangle^{-0.7}$ for warm-only);
- this agrees with scaling prediction from equating
  $dE/dt_{\text{MRI input}} \sim \Omega \langle -B_x B_y \rangle / (4\pi \langle \rho \rangle) \propto \langle n \rangle^{-1.4}$ with
  $dE/dt_{\text{collis diss}} \sim (\delta v)^3 \langle \rho \rangle / (r_{cl} \rho_{cl}) \propto \langle n \rangle$
- At low $\langle n \rangle$, cold cloudlets are trans-sonic with respect to warm medium (up to 8 km s^{-1})
- Low- $\langle n \rangle$ velocity dispersions are large enough to provide large outer-galaxy turbulence



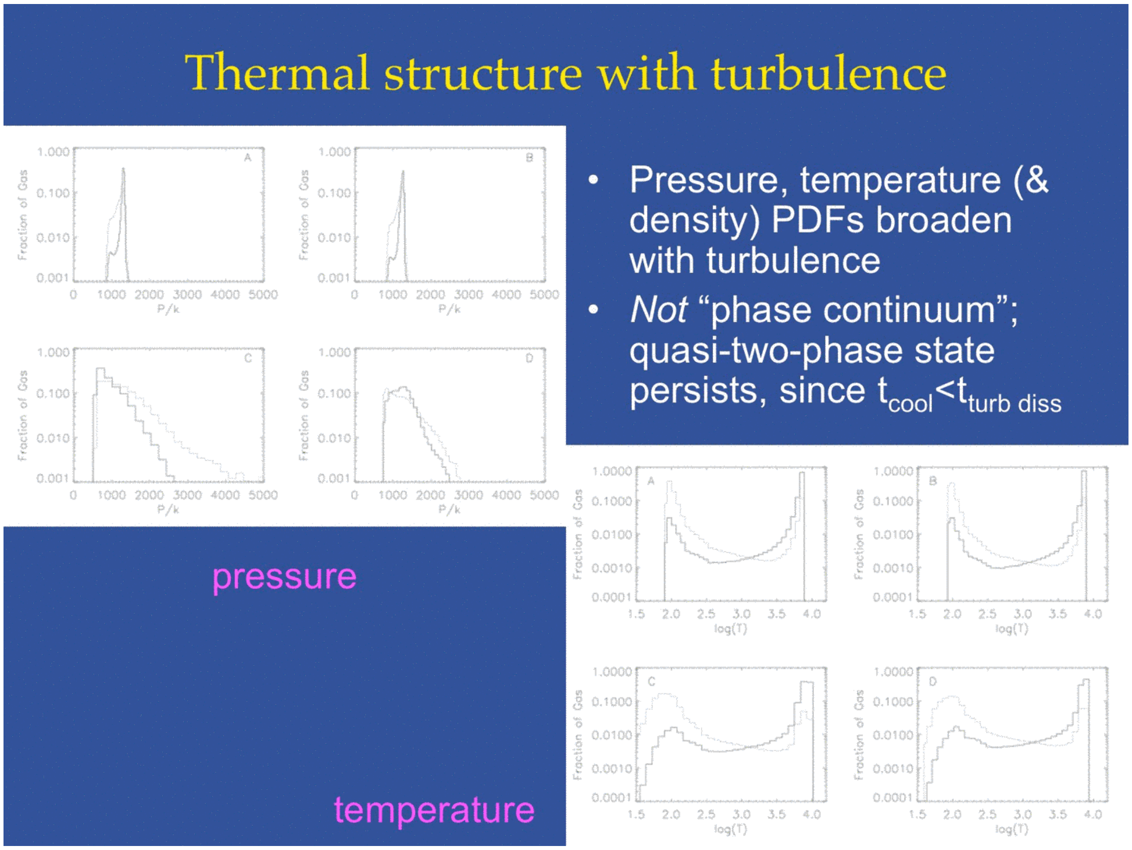
Mach number



Saturation scalings of B^2

- $\langle B^2 \rangle$ ~independent of $\langle n \rangle$, *unlike single-phase results*
- set by ambient pressure (β_{sat} ~1)?
- role of physical densities?

B-field strength



Thermal structure with turbulence

- Pressure, temperature (& density) PDFs broaden with turbulence
- *Not* “phase continuum”; quasi-two-phase state persists, since $t_{cool} < t_{turb\ diss}$

pressure

temperature

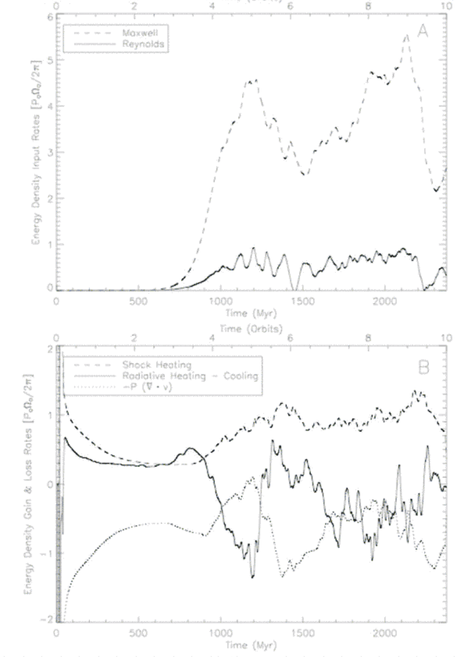
Energetics

- ~1/4 of MRI input energy is captured (in shock heating)
- PdV work provides net cooling (expansion), 30% of shock heating
- Radiative processes provide net cooling, 70% of shock heating
- $\mathcal{E}_{th}/(dE/dt)_{MRI}$ =60Myr
- $\mathcal{E}_{th}/(dE/dt)_{shocks}$ =100Myr

Compare to:

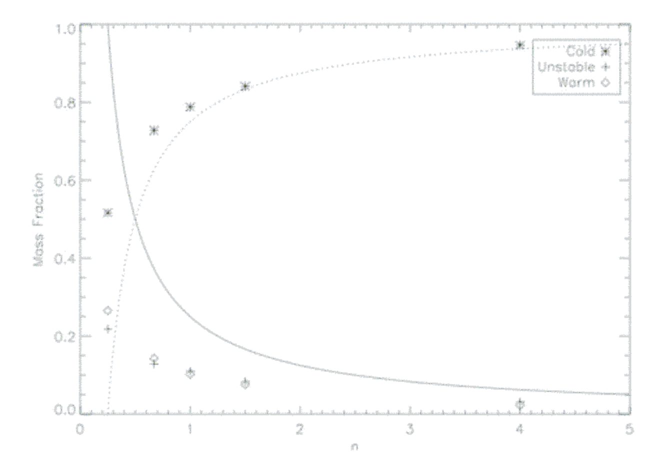
t_{cool}~few Myr in warm/diffuse gas;

t_{cool}~few 10^4yr in cold/dense gas



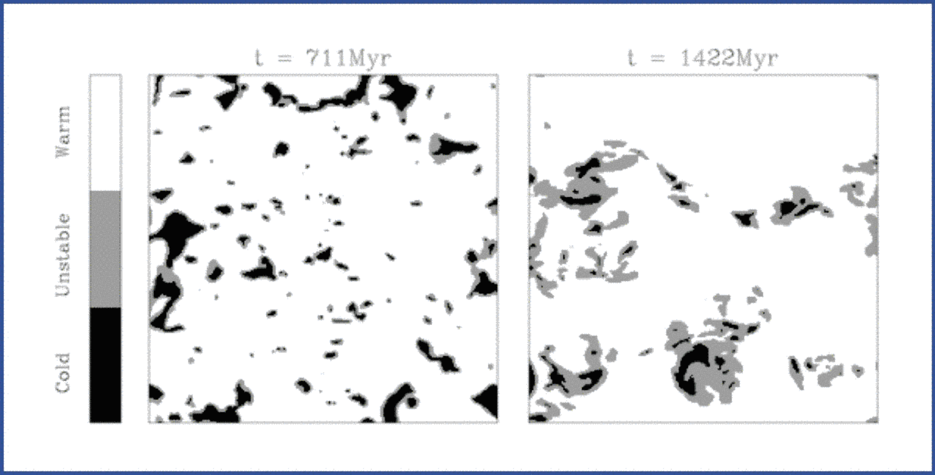
Total mass fractions

- Mass fraction in cold component increases with ⟨n⟩ ; exceeds static prediction at low ⟨n⟩ due to turbulent compression
- Thermally-unstable and warm components have comparable mass at all ⟨n⟩



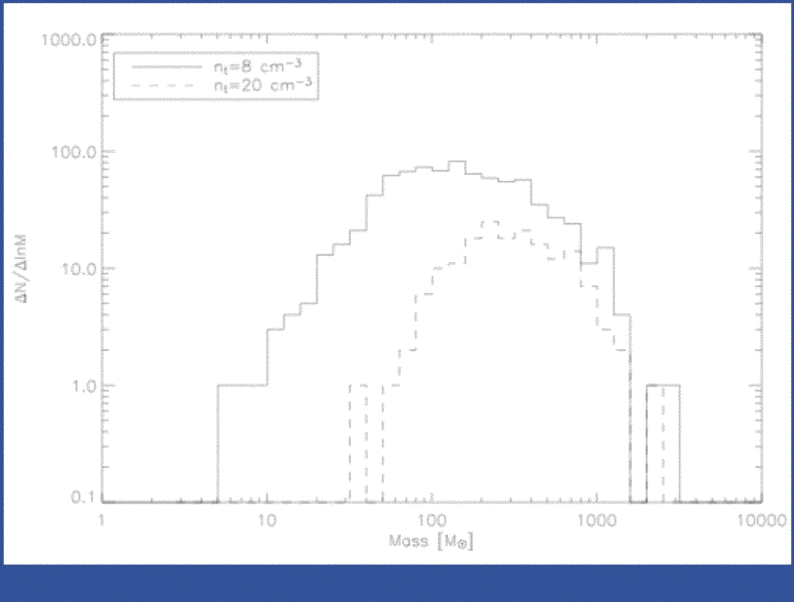
Spatial distribution of thermal phases

- Thermally-unstable gas is in envelopes surrounding cold gas

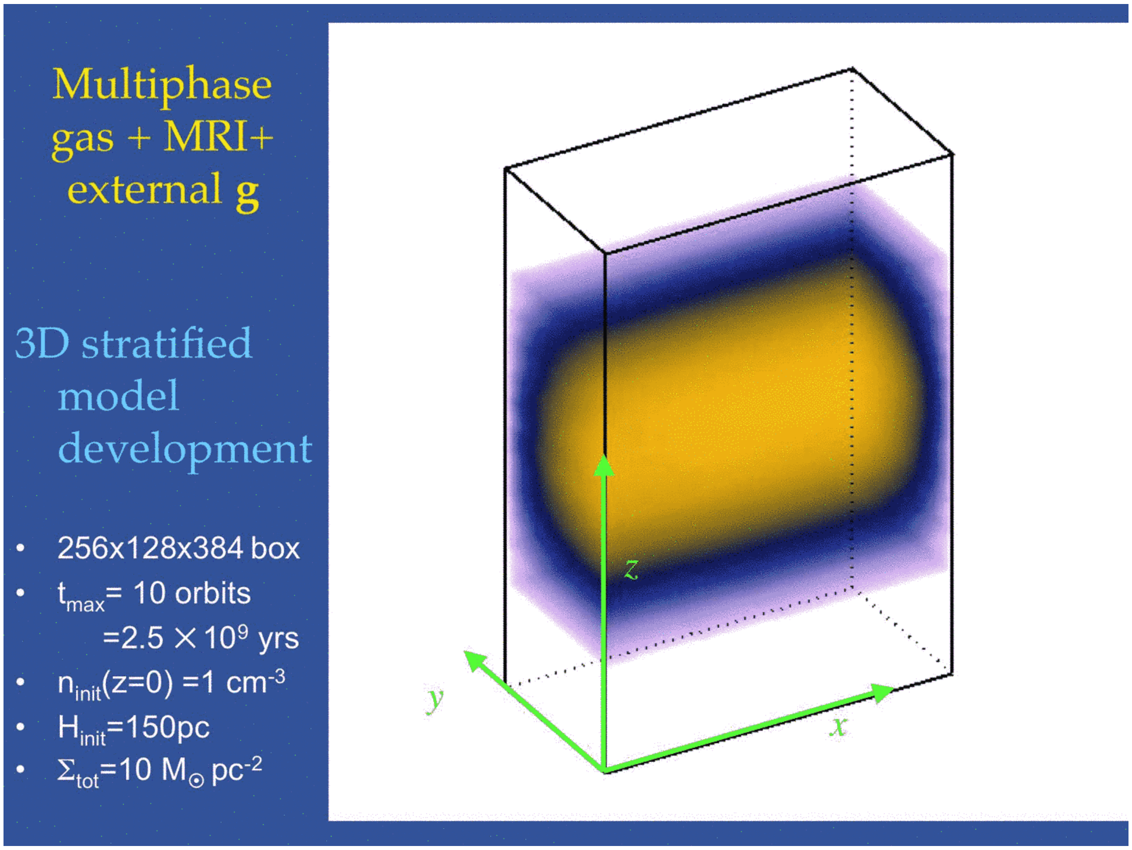


Cloud mass function

- Characteristic scale M~100 $M_\odot$ ⇒ L~ 7 pc
- Consistent with equating t_{shear}~t_{collis}



IV. Turbulence and gravity

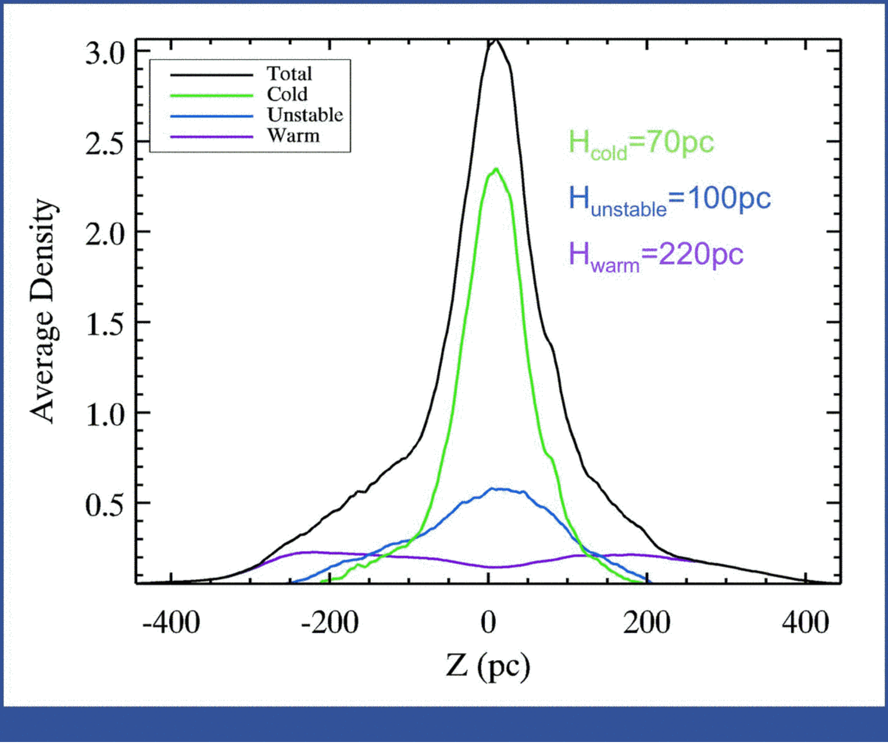


Multiphase gas + MRI+ external **g**

3D stratified model development

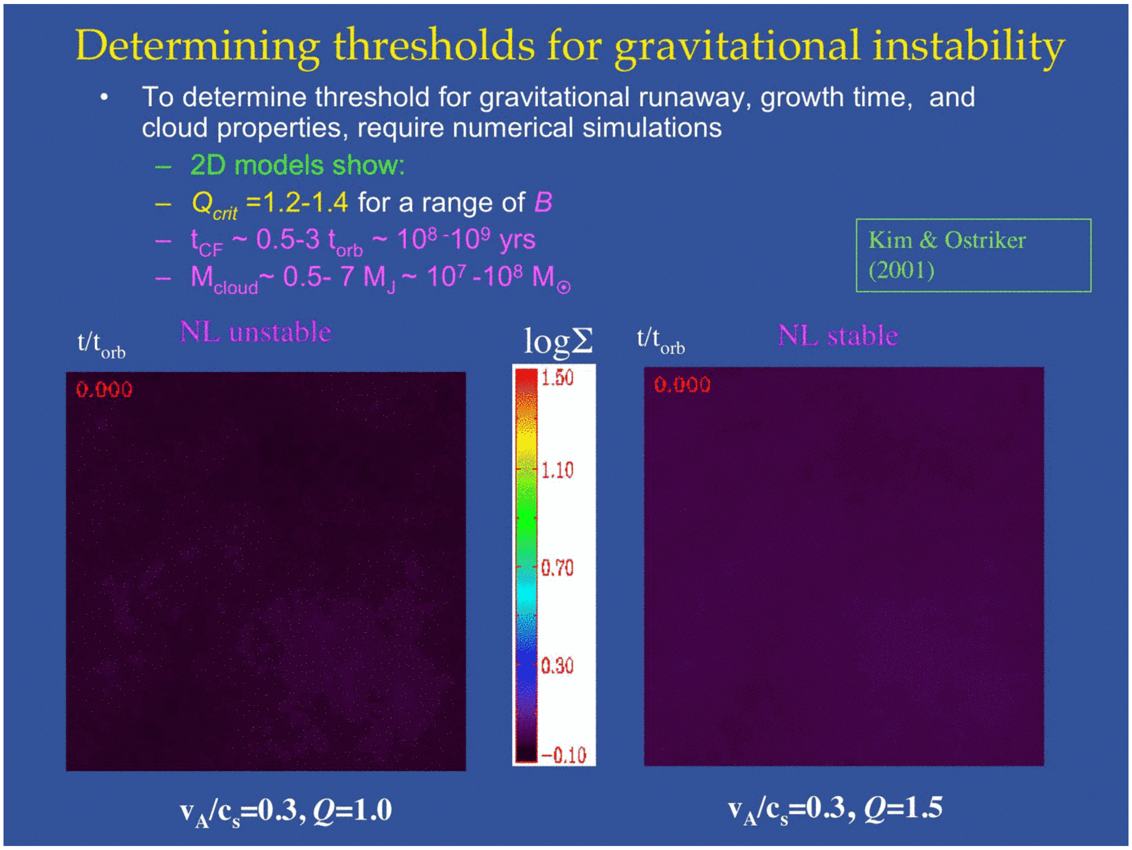
- 256x128x384 box
- t_{max}= 10 orbits
  =2.5 × 10^9 yrs
- $n_{init}(z=0)$ =1 cm^{-3}
- H_{init}=150pc
- Σ_{tot}=10 $M_\odot$ pc^{-2}

Vertical profile in saturated state



Comparison of turbulent and quiescent states

	Cold mass fraction	Warm mass fraction	Unstable mass fraction	Cold scale height	Warm scale height
quiescent	0.76	0.24	0.01	7pc	240pc
turbulent	0.50	0.25	0.25	70pc	220pc



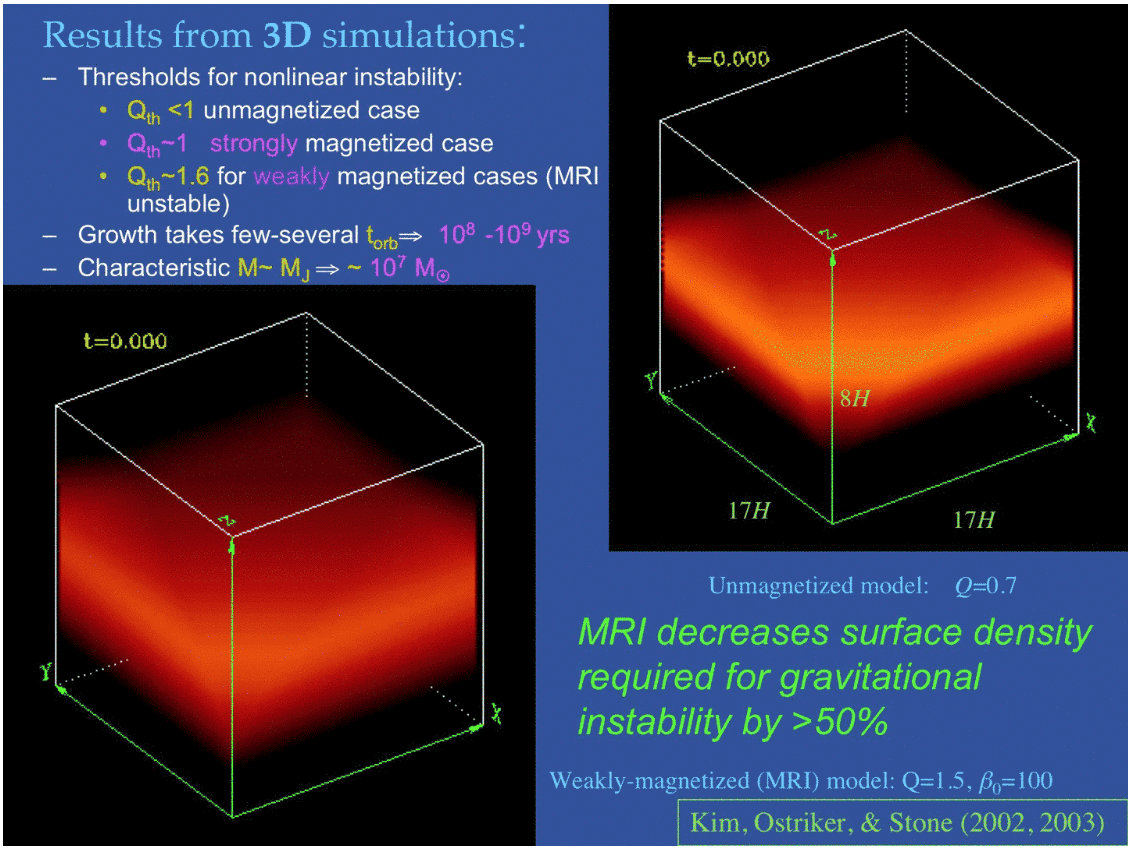
Determining thresholds for gravitational instability

- To determine threshold for gravitational runaway, growth time, and cloud properties, require numerical simulations
  - 2D models show:
  - Q_{crit} =1.2-1.4 for a range of B
  - $t_{CF} \sim 0.5\text{-}3\ t_{orb} \sim 10^8\text{-}10^9$ yrs
  - $M_{cloud} \sim 0.5\text{-}7\ M_J \sim 10^7\text{-}10^8\ M_\odot$

Kim & Ostriker (2001)

v_A/c_s=0.3, Q=1.0

v_A/c_s=0.3, Q=1.5



Results from 3D simulations:

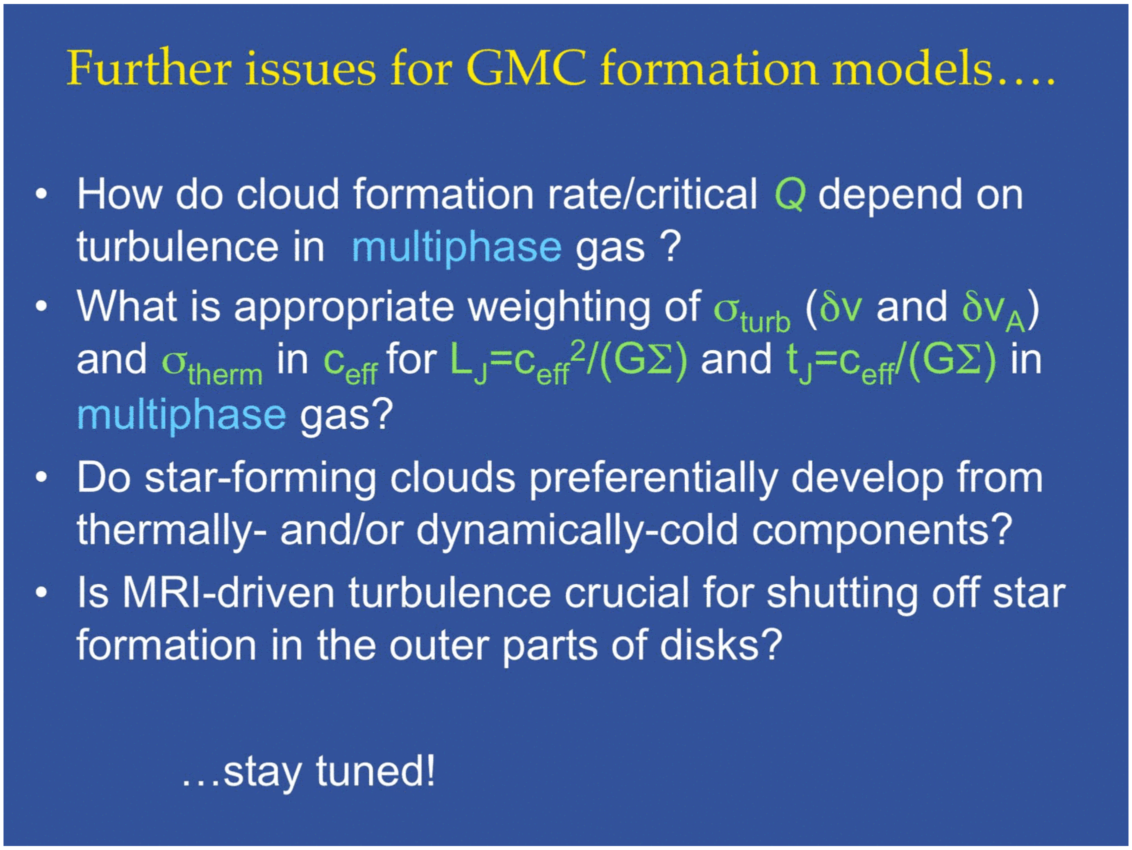
- Thresholds for nonlinear instability:
  - Q_{th} <1 unmagnetized case
  - Q_{th}~1 strongly magnetized case
  - Q_{th}~1.6 for weakly magnetized cases (MRI unstable)
- Growth takes few-several $t_{orb} \Rightarrow 10^8\text{-}10^9$ yrs
- Characteristic $M \sim M_J \Rightarrow \sim 10^7\ M_\odot$

Unmagnetized model: Q=0.7

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

Weakly-magnetized (MRI) model: Q=1.5, β_0=100

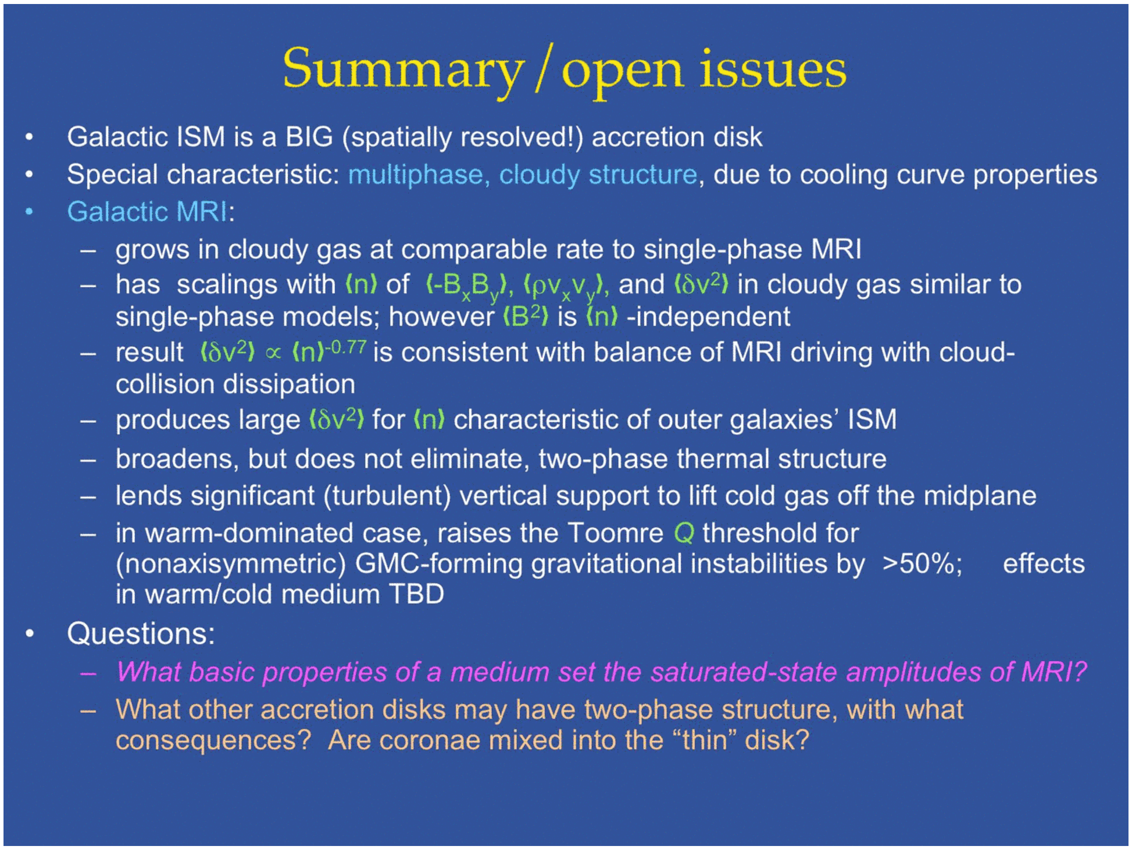
Kim, Ostriker, & Stone (2002, 2003)



Further issues for GMC formation models….

- How do cloud formation rate/critical Q depend on turbulence in multiphase gas ?
- What is appropriate weighting of σ_{turb} (δv and δv_A) and σ_{therm} in c_{eff} for $L_J=c_{eff}^2/(G\Sigma)$ and $t_J=c_{eff}/(G\Sigma)$ in multiphase gas?
- Do star-forming clouds preferentially develop from thermally- and/or dynamically-cold components?
- Is MRI-driven turbulence crucial for shutting off star formation in the outer parts of disks?

…stay tuned!



Summary / open issues

- Galactic ISM is a BIG (spatially resolved!) accretion disk
- Special characteristic: multiphase, cloudy structure, due to cooling curve properties
- Galactic MRI:
  - grows in cloudy gas at comparable rate to single-phase MRI
  - has scalings with $\langle n \rangle$ of $\langle -B_xB_y \rangle$, $\langle \rho v_x v_y \rangle$, and $\langle \delta v^2 \rangle$ in cloudy gas similar to single-phase models; however $\langle B^2 \rangle$ is $\langle n \rangle$ -independent
  - result $\langle \delta v^2 \rangle \propto \langle n \rangle^{-0.77}$ is consistent with balance of MRI driving with cloud-collision dissipation
  - produces large $\langle \delta v^2 \rangle$ for $\langle n \rangle$ characteristic of outer galaxies' ISM
  - broadens, but does not eliminate, two-phase thermal structure
  - lends significant (turbulent) vertical support to lift cold gas off the midplane
  - in warm-dominated case, raises the Toomre Q threshold for (nonaxisymmetric) GMC-forming gravitational instabilities by >50%; effects in warm/cold medium TBD
- Questions:
  - *What basic properties of a medium set the saturated-state amplitudes of MRI?*
  - What other accretion disks may have two-phase structure, with what consequences? Are coronae mixed into the "thin" disk?