March 14, 2006, lecture at Asian Winter School on Numerical Astrophysics

Global Structure of the ISM in galactic disks and in the central region of galaxies

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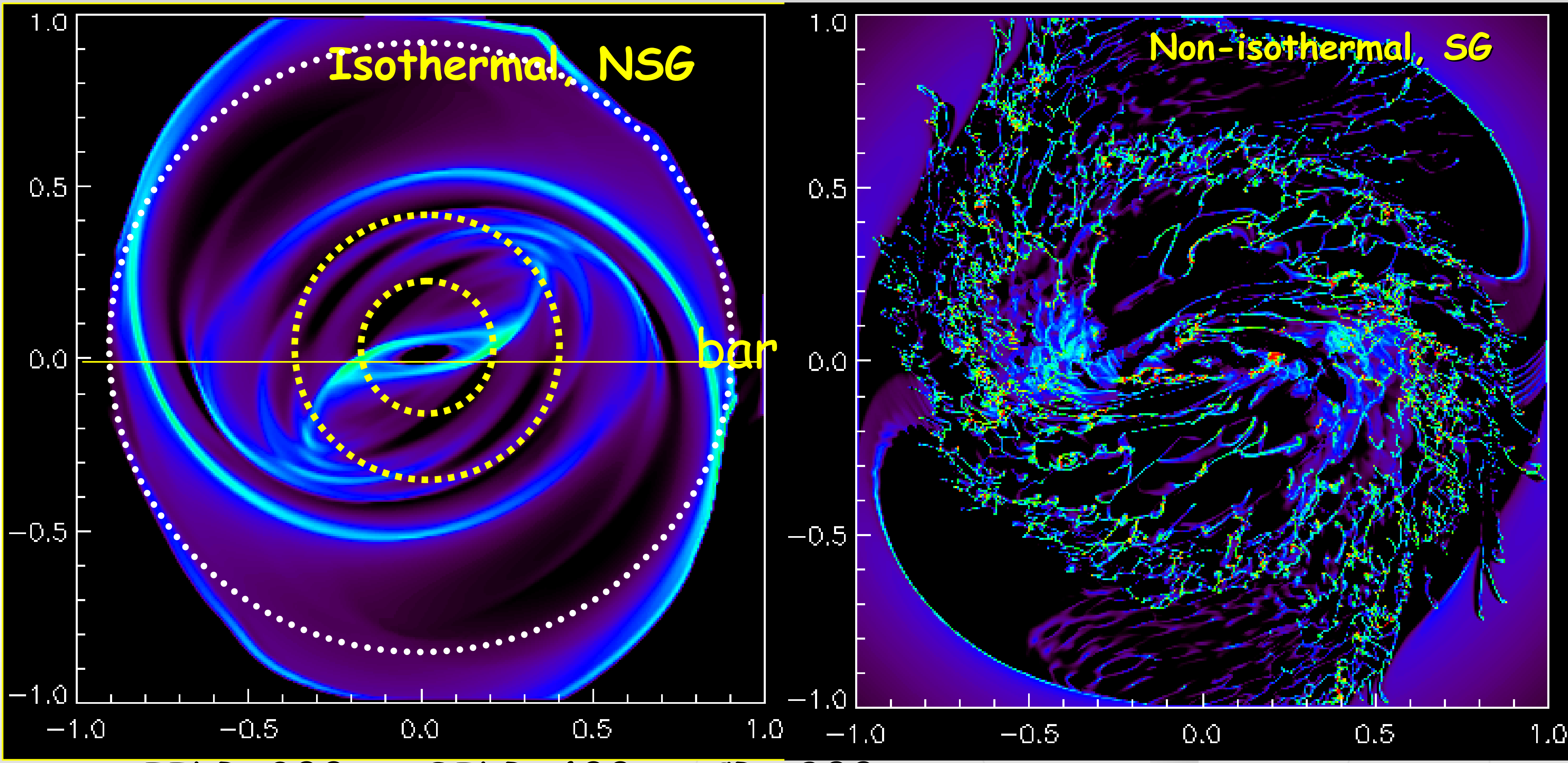
Methods & techniques

2D/3D Hydrodynamic Simulations,
Euler method with a uniform Cartesian grid

* Poisson equation for self-gravity
* Energy equation with heating/cooling processes
* Optimization for high-performance computers

Gas dynamics in a bar-potential



IILR=200pc, OILR=400pc, CR= 900pc

Taking into account relevant physics is essential, but….

Central region of M51(2kpc x 2kpc)

The ISM is very inhomogeneous on ~10 pc scale.

Many filaments, and "mesh" of the dust lanes

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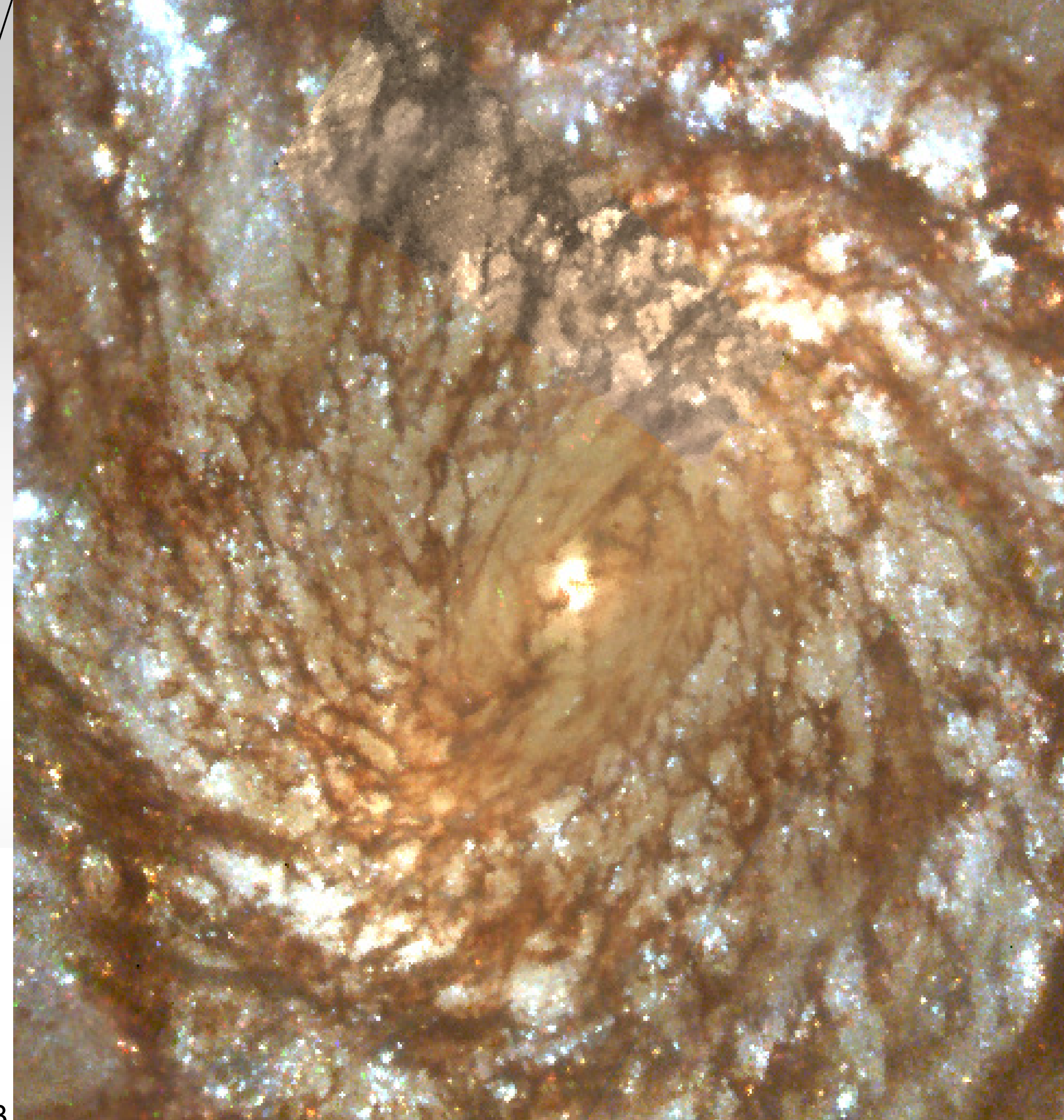
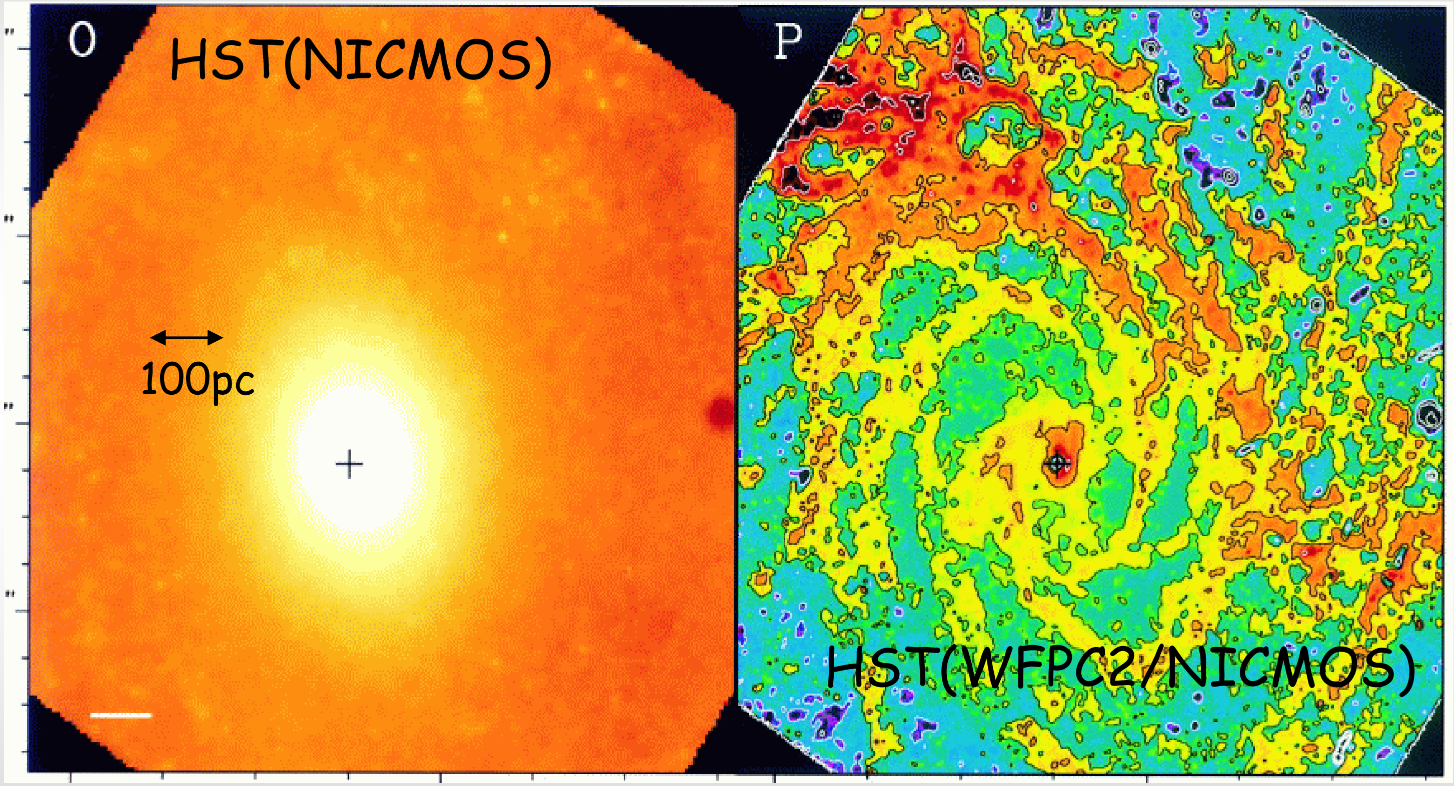


HST obs. *(Scoville et. al)*

Central region of Seyfert NGC 3982

multi-armed dust lanes



Regan & Mulchaney (1999)

Origin of the structures: Instabilities?

- Filaments/clumps/clouds, holes, voids/holes
- Multi-phase: Cold gas, Warm gas, Hot gas
- Turbulent + rotation

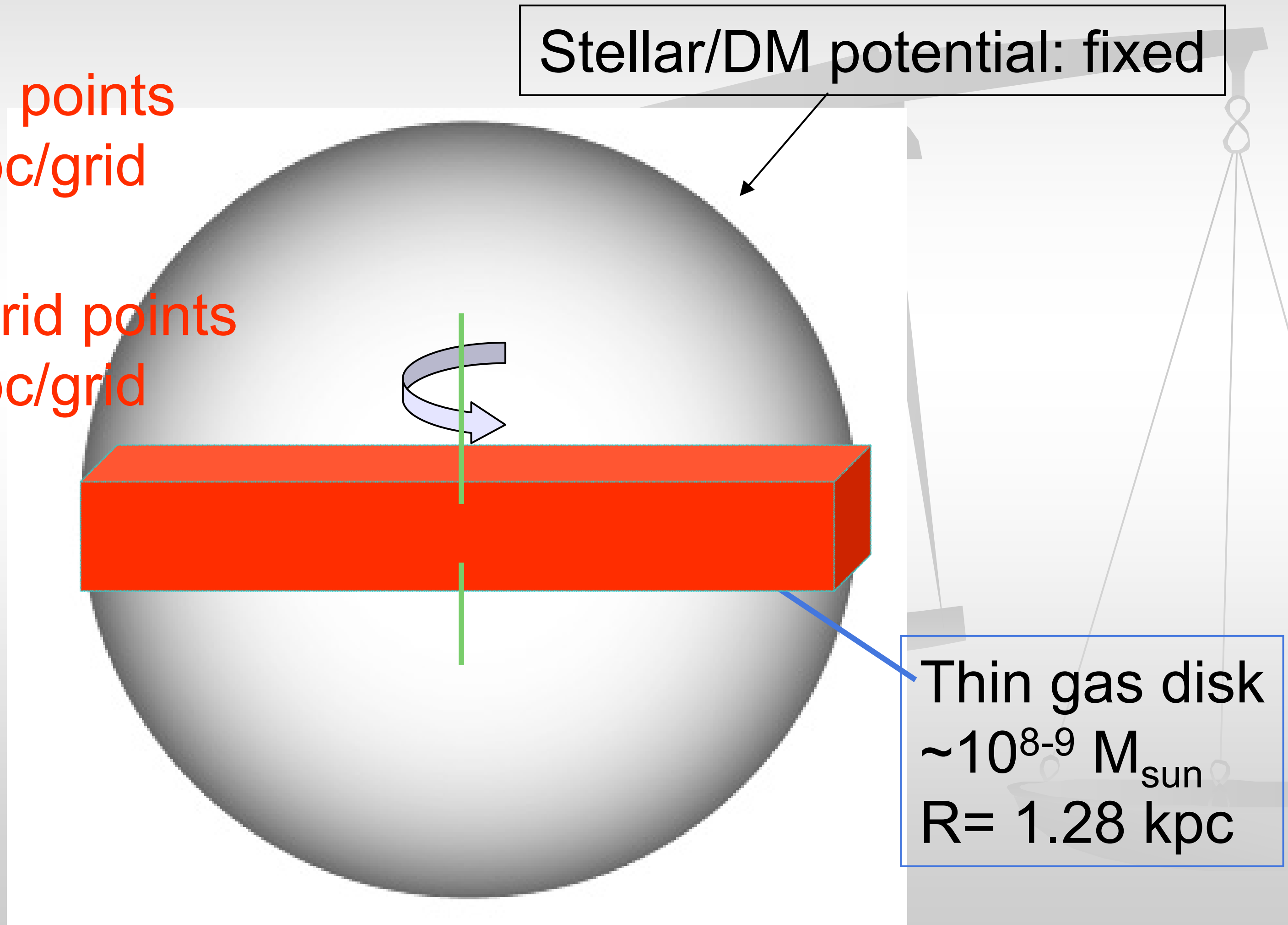
- Is it possible to be quasi-stable on a galactic scale, but unstable on a local scale?

- Can we reproduce these features by numerical simulations from the first principle (with minimal assumptions)?

2D/3-D Hydrodynamics of a gas disk in a spherical galactic potential

2D: 2048^2 grid points
Resolution: 1pc/grid

3D: 512^2x64 grid points
Resolution: 5pc/grid



Evolution/Structure of the massive gas disk
-- 2-D/3-D Hydrodynamic **Global** Modeling --

Initial conditions and input physics:

- Rotationally supported, uniform disk in a fixed spherical potential (stars +DM)
- Self-gravity of the gas
- A cooling function ($10<T< 10^8$ K) is assumed.
- Heating sources: uniform UV & supernova explosions
  - Evolution of SNR is directly followed w/ sub-pc resolution

Wada & Norman (2001,2003), Wada (2001), Wada, Meurer, Norman(2002)

Basic Equations

Conservation of mass, momentum, & energy, Poisson eq.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0, \quad (1)$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla)\boldsymbol{v} + \frac{\nabla p}{\rho} + \nabla \Phi_{\mathrm{ext}} + \nabla \Phi_{\mathrm{sg}} = 0, \quad (2)$$

$$\frac{\partial E}{\partial t} + \frac{1}{\rho} \nabla \cdot [(\rho E + p)\boldsymbol{v}] = \Gamma_{\mathrm{UV}} - \rho \Lambda(T_g), \quad (3)$$

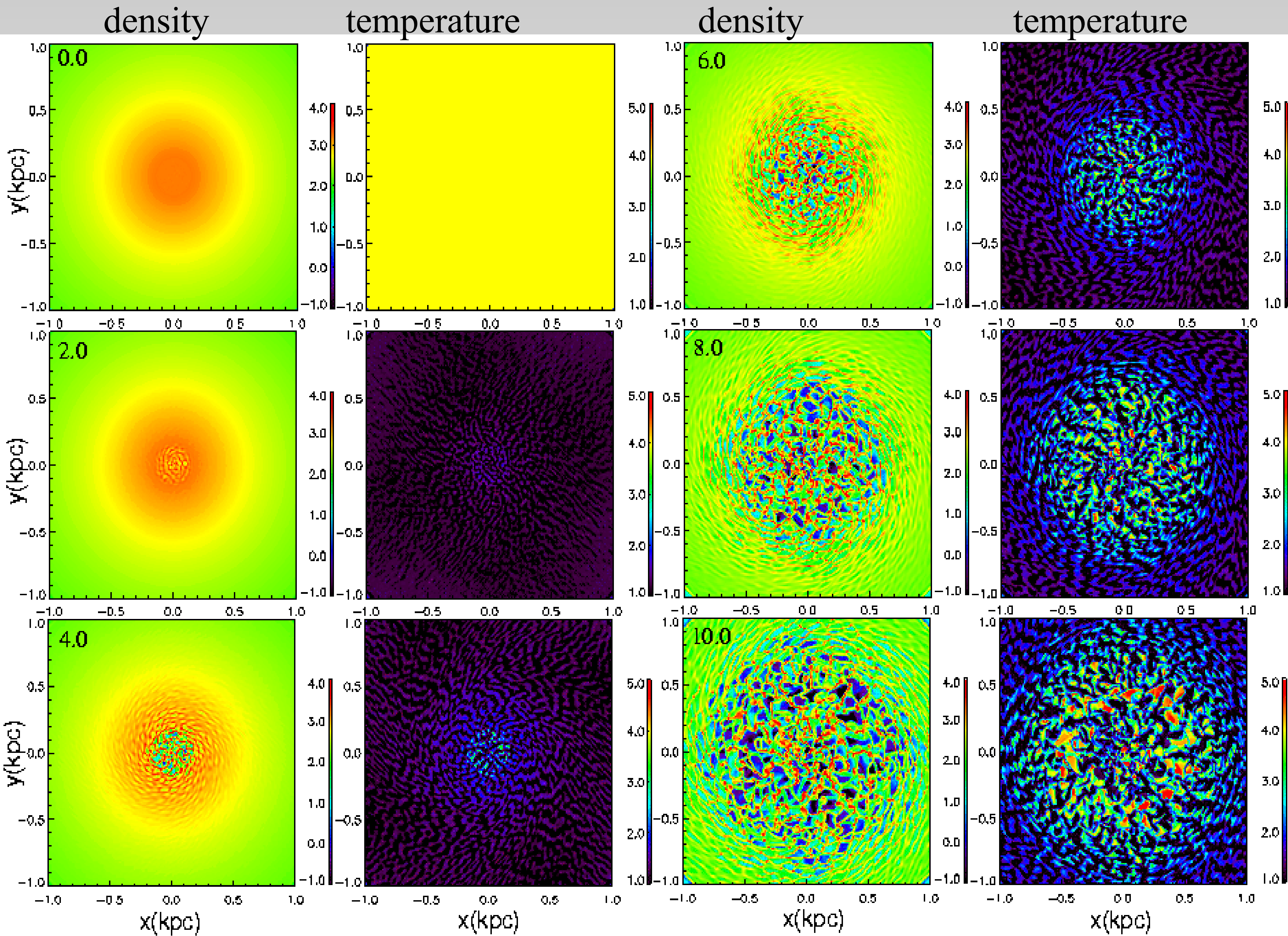
$$\nabla^2 \Phi_{\mathrm{sg}} = 4\pi G \rho, \quad (4)$$

Methods: AUSM w/ uniform grid: 256^3, 256^3x 128, 512^2x32;
2048^2 - 4096^2)
+ Poisson eq. Solver(FFT)

CPU time: ~ 10-200 hours/run

w/ Fujitsu VPP5000, 32 PEs (0.3 TF), in NAOJ

Time evolution of the disk

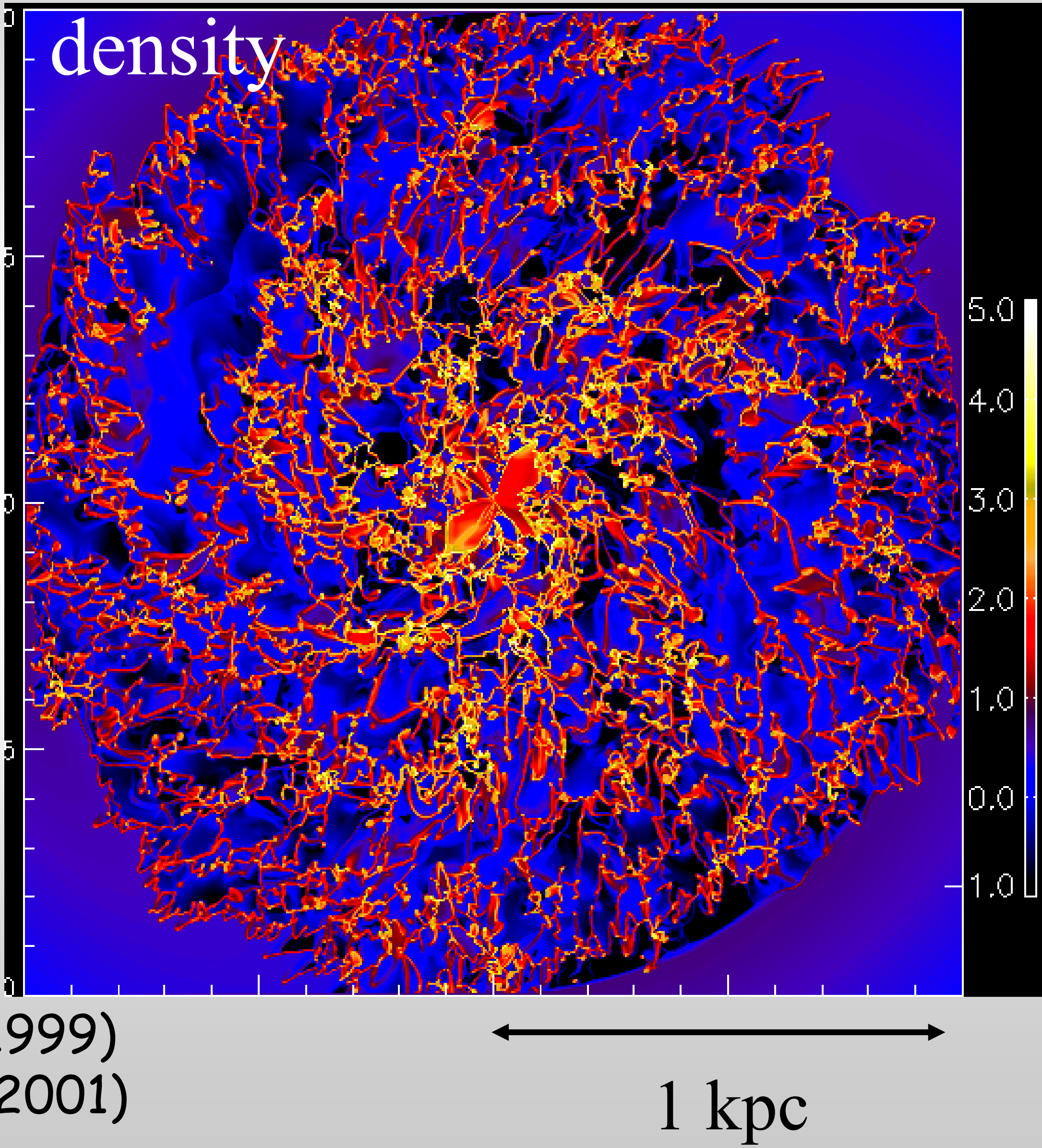


"tangled-web" structure of the ISM in a galaxy

No energy input from supernovae

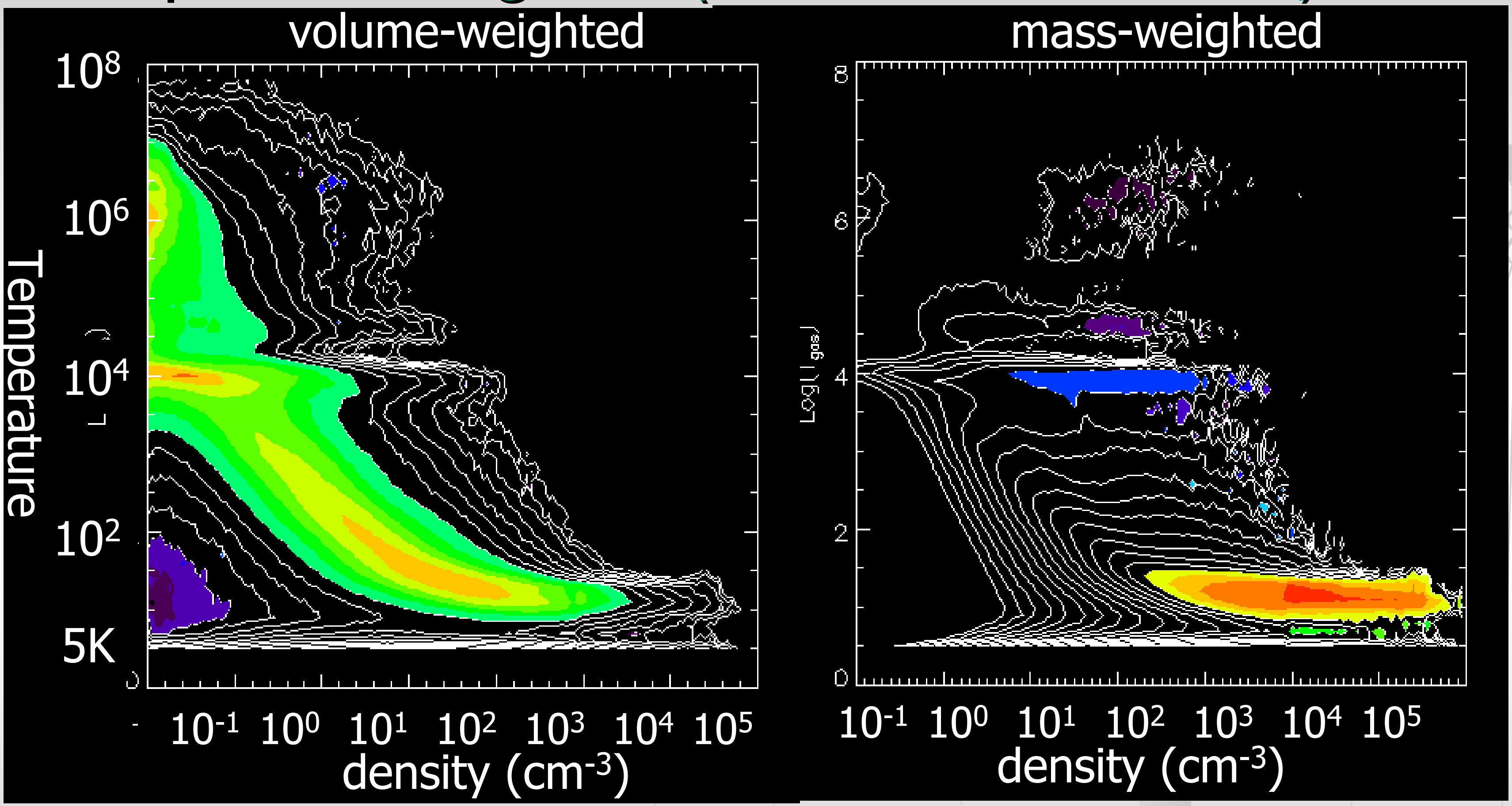
2048^2 grids, 0.98pc/grid

- *Clumps/filaments*
  - *high density, low T(<100K)*
  - *"GMC" = complex of clouds & filaments*
- *Cavities/Holes*
  - *low density, high T*
  - *Shock heated gas (~10^5 K)*



Wada & Norman, ApJ 516, L13 (1999)
ApJ 546, 172 (2001)

physical condition of the ISM phase-diagram (with SN feedback)



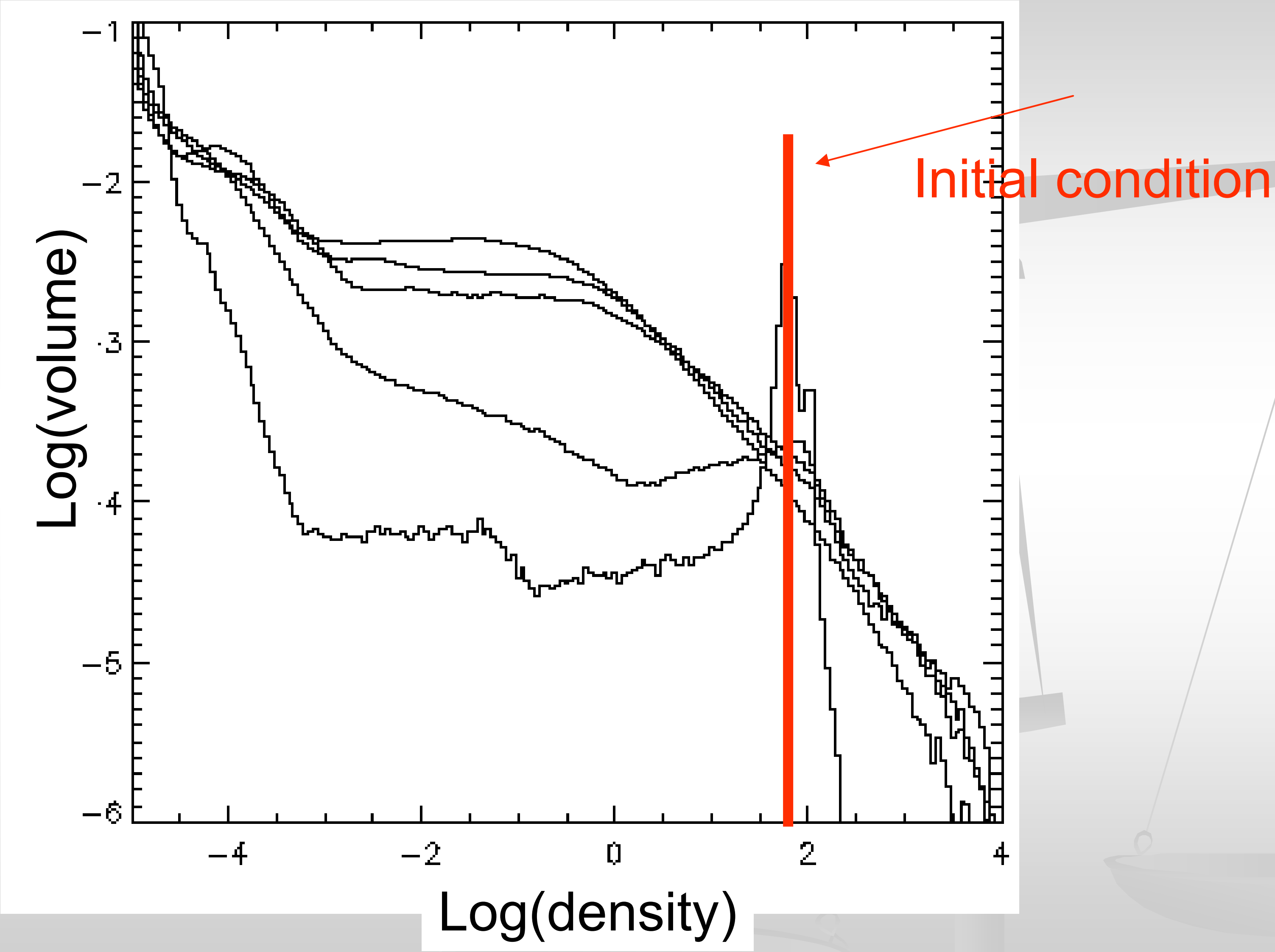
Density ranges over four orders of magnitude for a given T_{gas}.

⇒Pressure is distributed in a wide range

⇒Different phases are not necessary in a pressure equilibrium

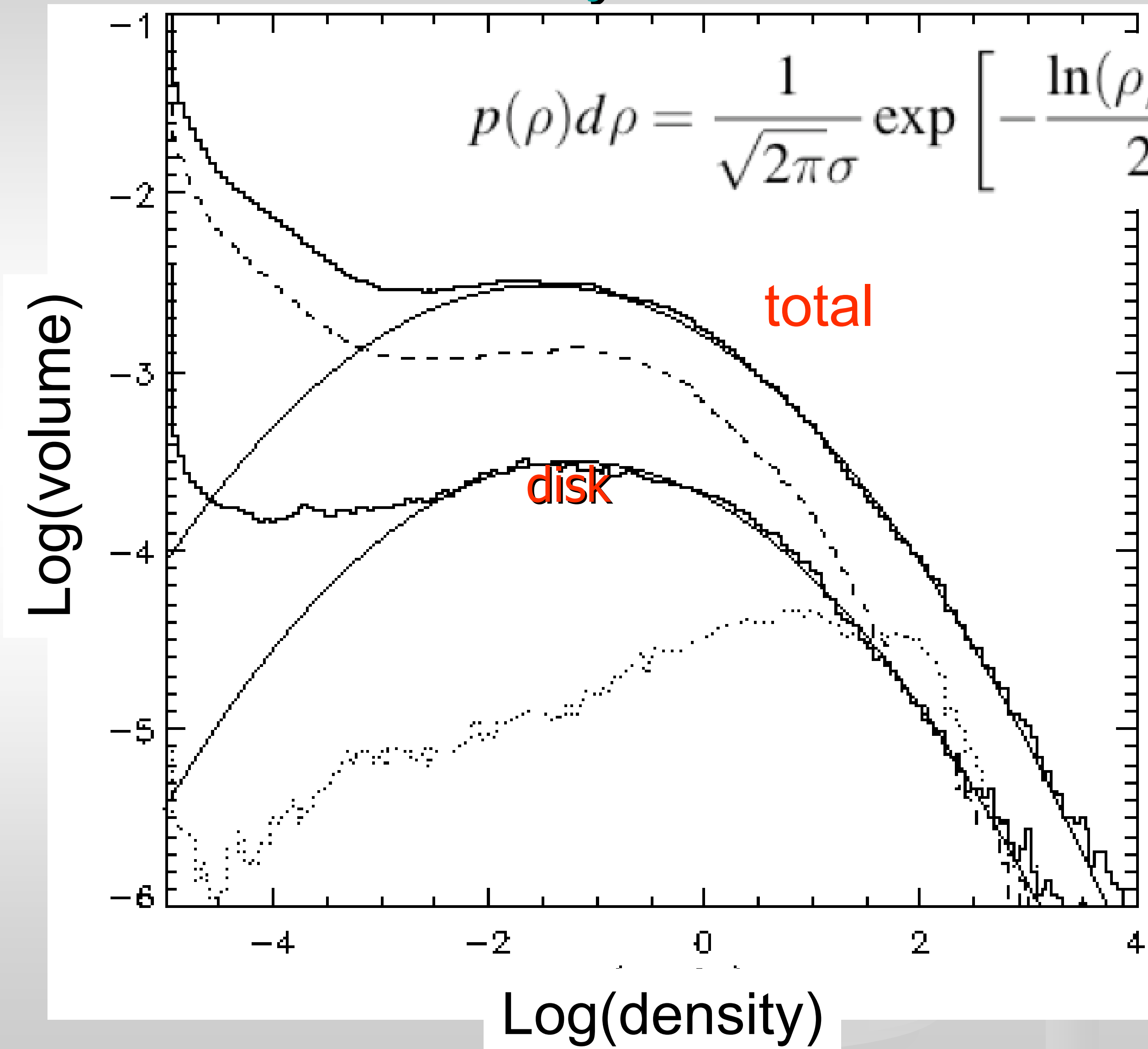
Evolution of PDF in 3-D galactic disk

Initial condition is lost within a few dynamical times.

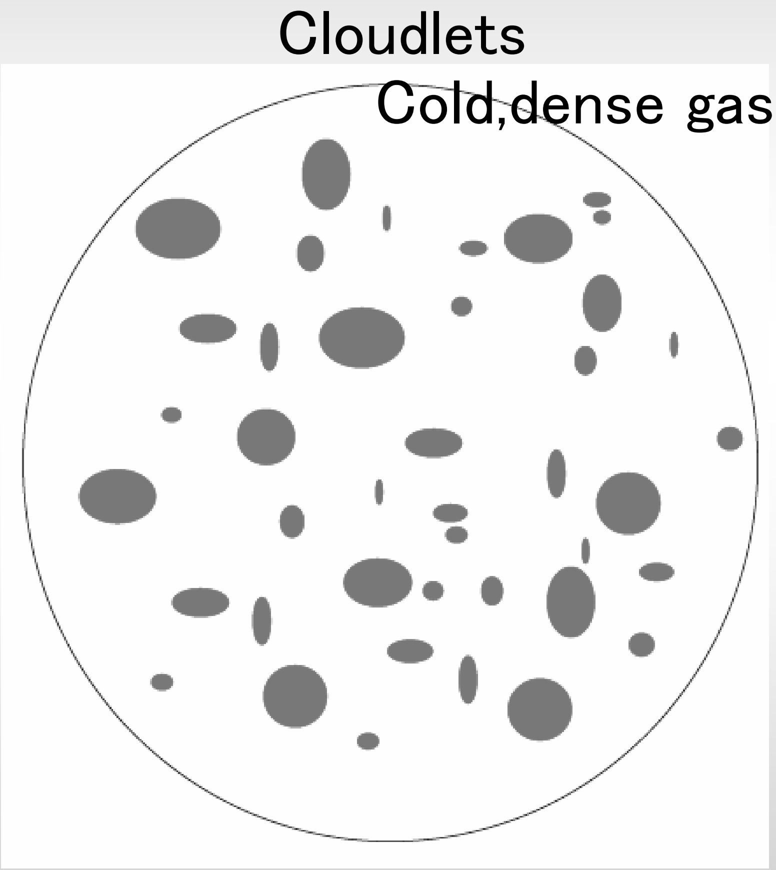


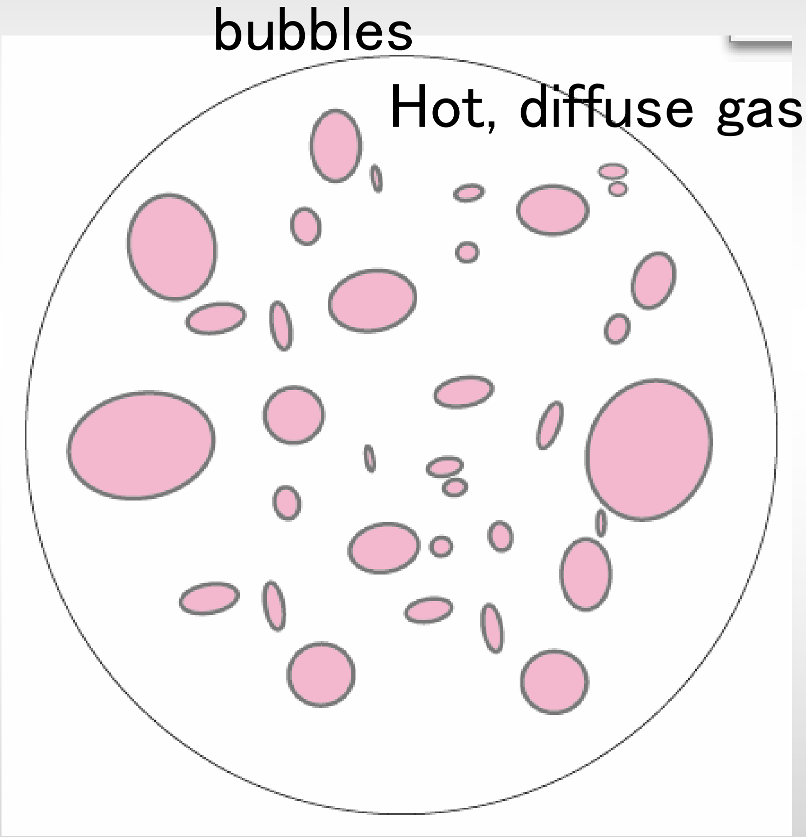
Volume-weighted density PDF in a steady-state

$$p(\rho)d\rho = \frac{1}{\sqrt{2\pi\sigma}} \exp\left[-\frac{\ln(\rho/\langle\rho\rangle)^2}{2\sigma^2}\right] d\ln\rho$$



ISM in a galactic disk is NOT discrete phases.





High density gas is not independent of lower density gases.

Universal PDF of the ISM in galaxies

Log-Normal part: Highly inhomogeneous.

Higher density gases occupy smaller volumes.

Structures of dense gases are not independent of lower density gases.

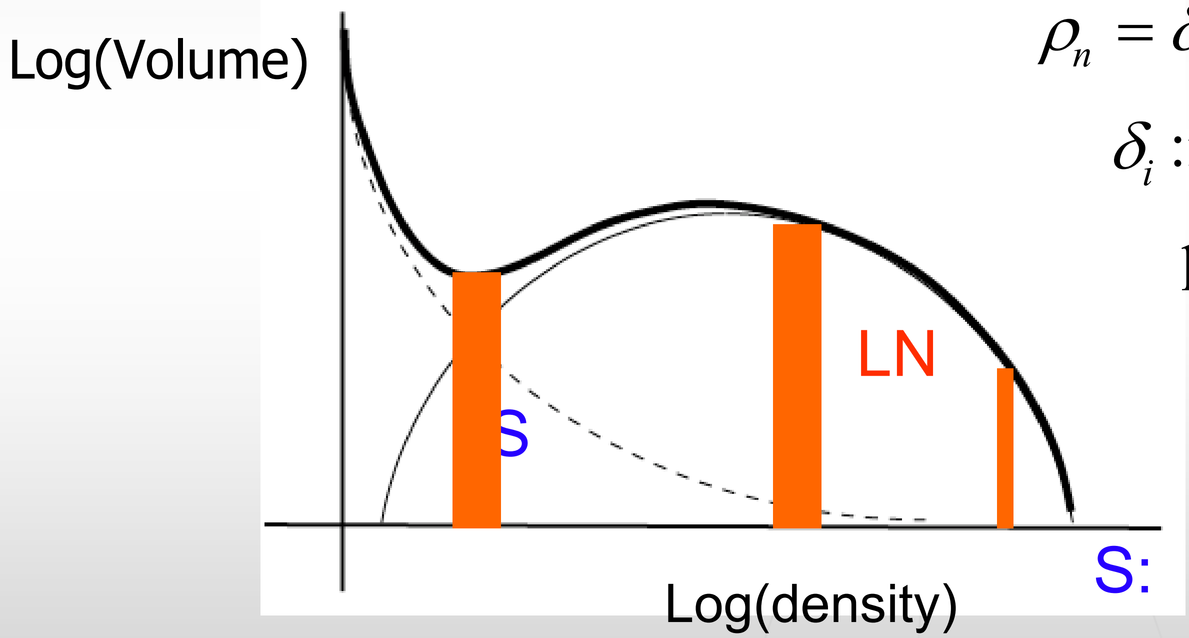
Shock, collapse,etc ->. $\rho_i = \delta_{i-1}\rho_{i-1}$

$$\rho_n = \delta_n \delta_{n-1} \ldots \delta_0 \rho_0$$

δ_i :independent events

$$\ln(\rho_n) \to N(\mu, \sigma^2)$$
$$n \to \infty$$

Central limit theorem



S: Smoothed part

Globally stable disk ⟶ PDF does not evolve

A 2-D model with energy feedback from supernovae

1 kpc

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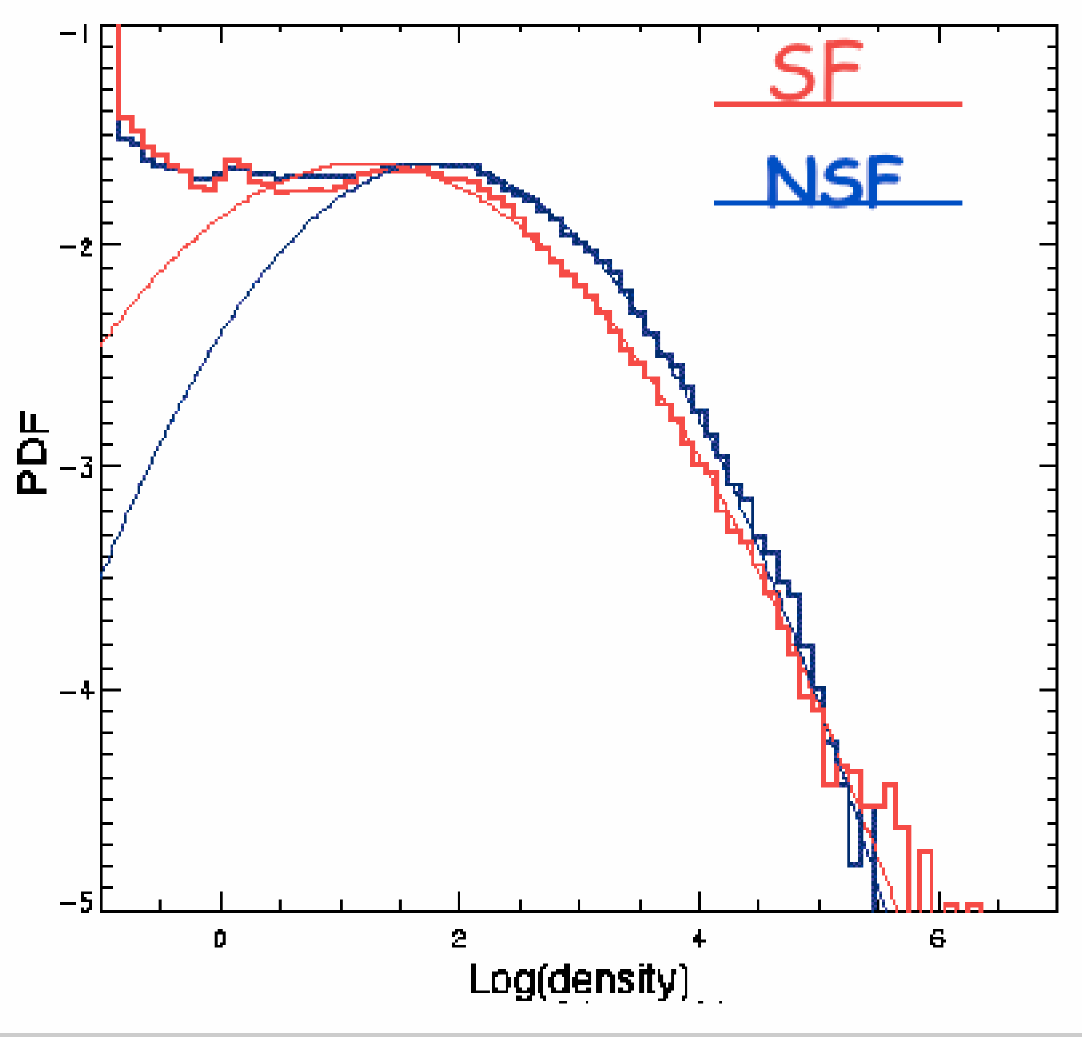
density

temperature
Red: $T > 10^6$ K

Effect of stellar energy feedback on the PDF

Log-Normal PDF is robust

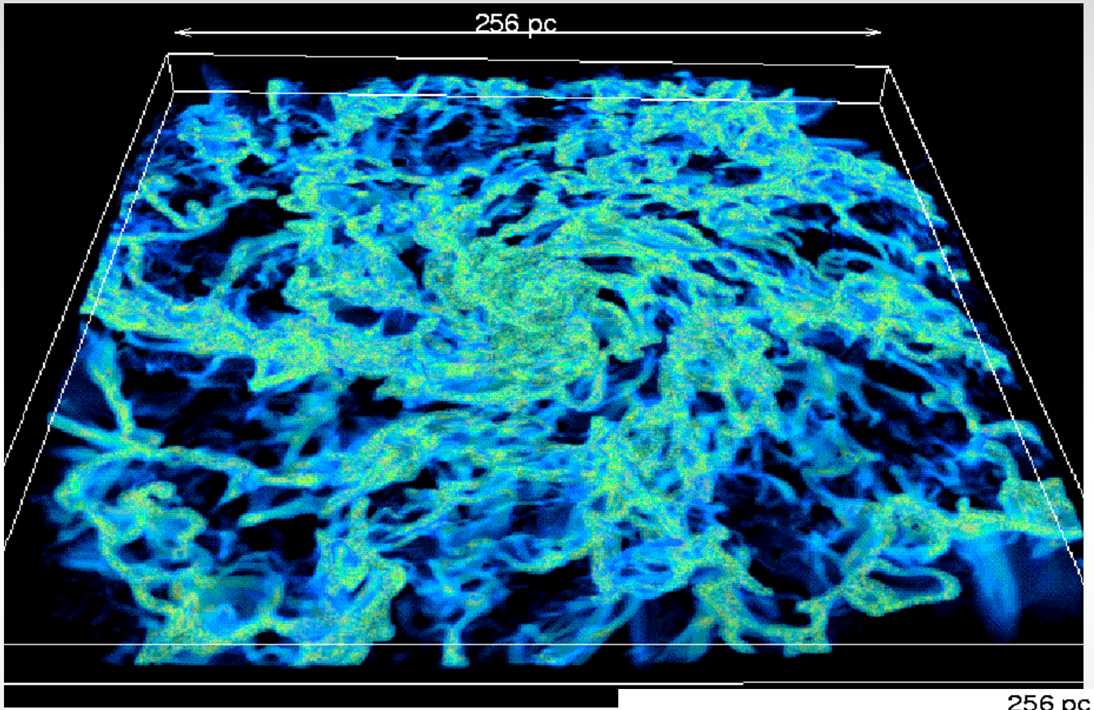
$$PDF(\rho) \propto Exp\left[\frac{-(\ln(\rho)-\ln(\rho_0))^2}{2\sigma^2}\right]$$

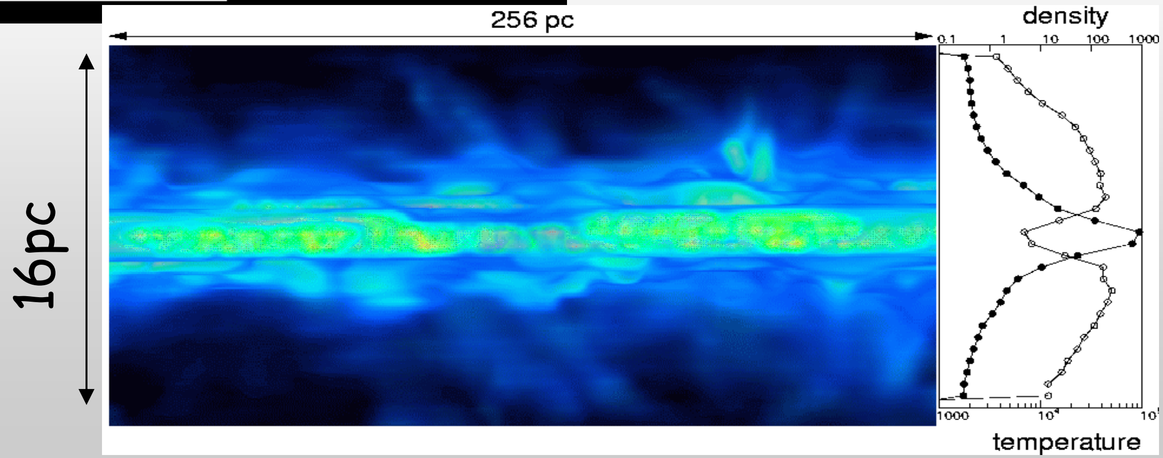


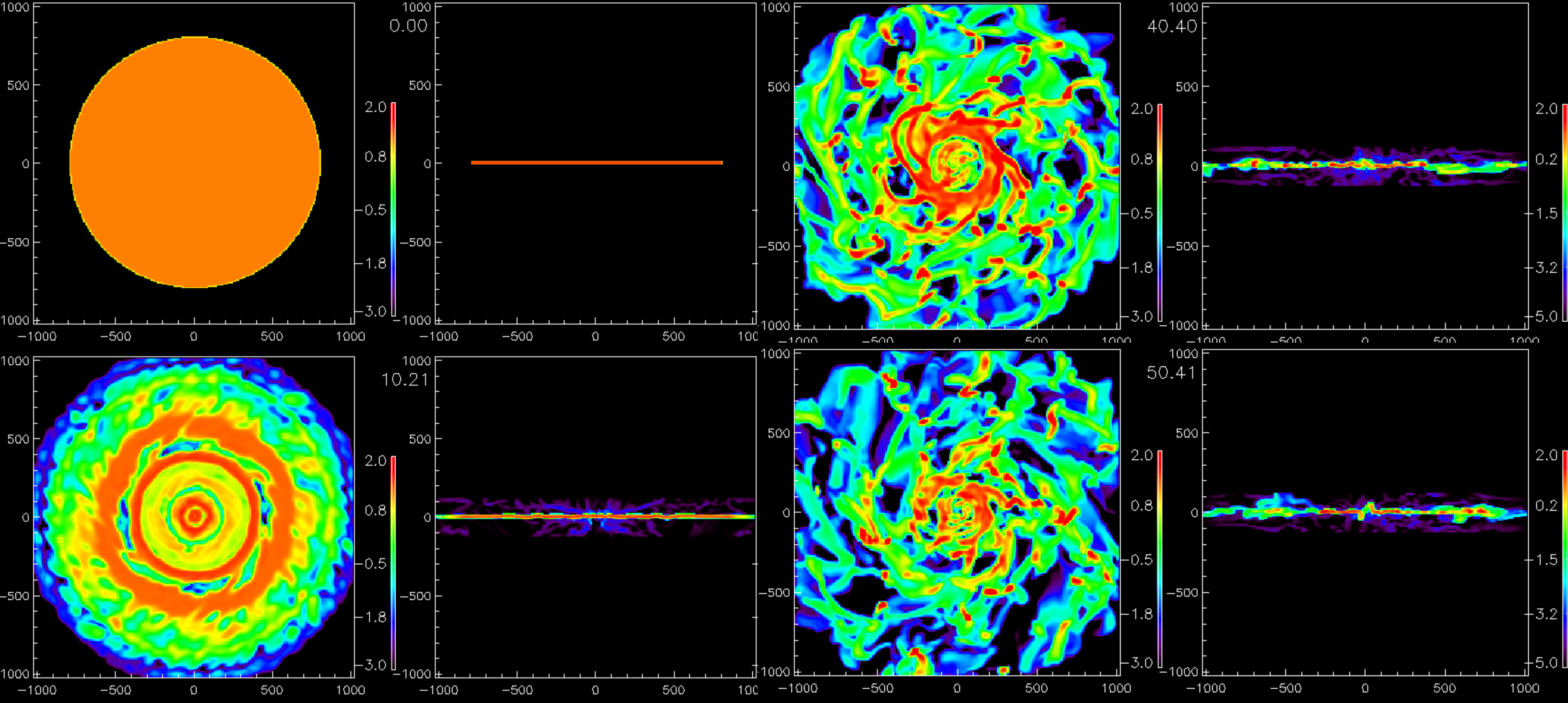
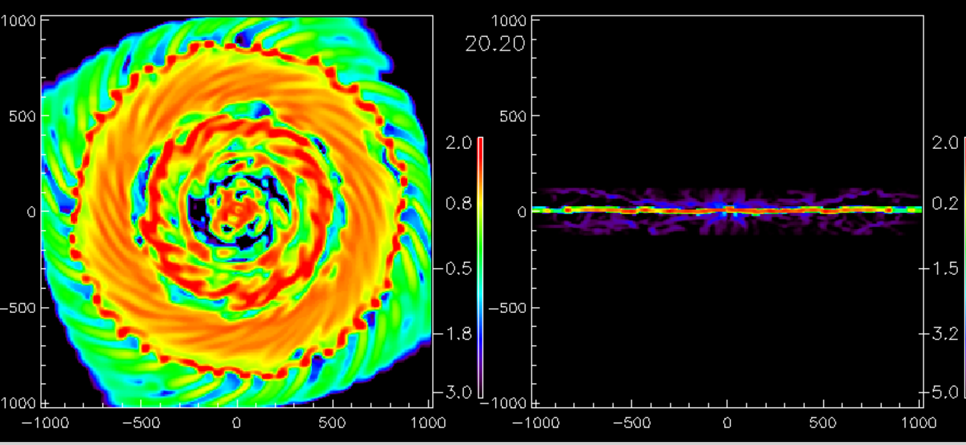
3D structure of a nuclear massive disk

512^2 x 32 grid points (0.5 pc/grid)

Wada (2001) ApJ 559, L41





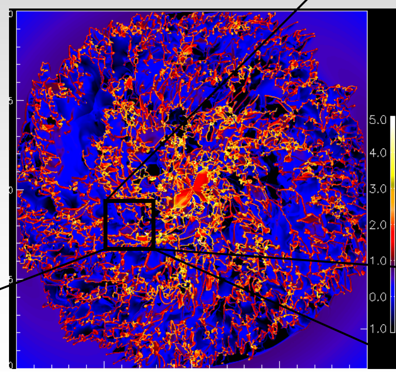
3-D evolution of a galactic disk

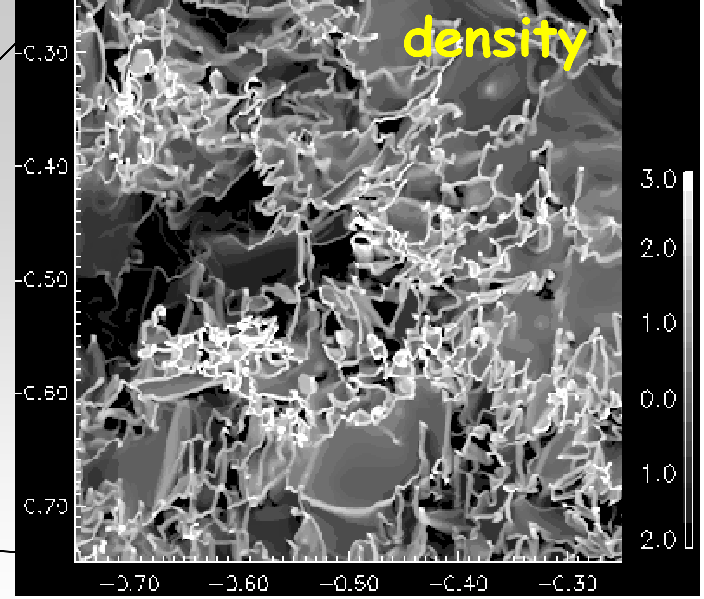
2.56kpc x 2.56kpc x 0.32kpc

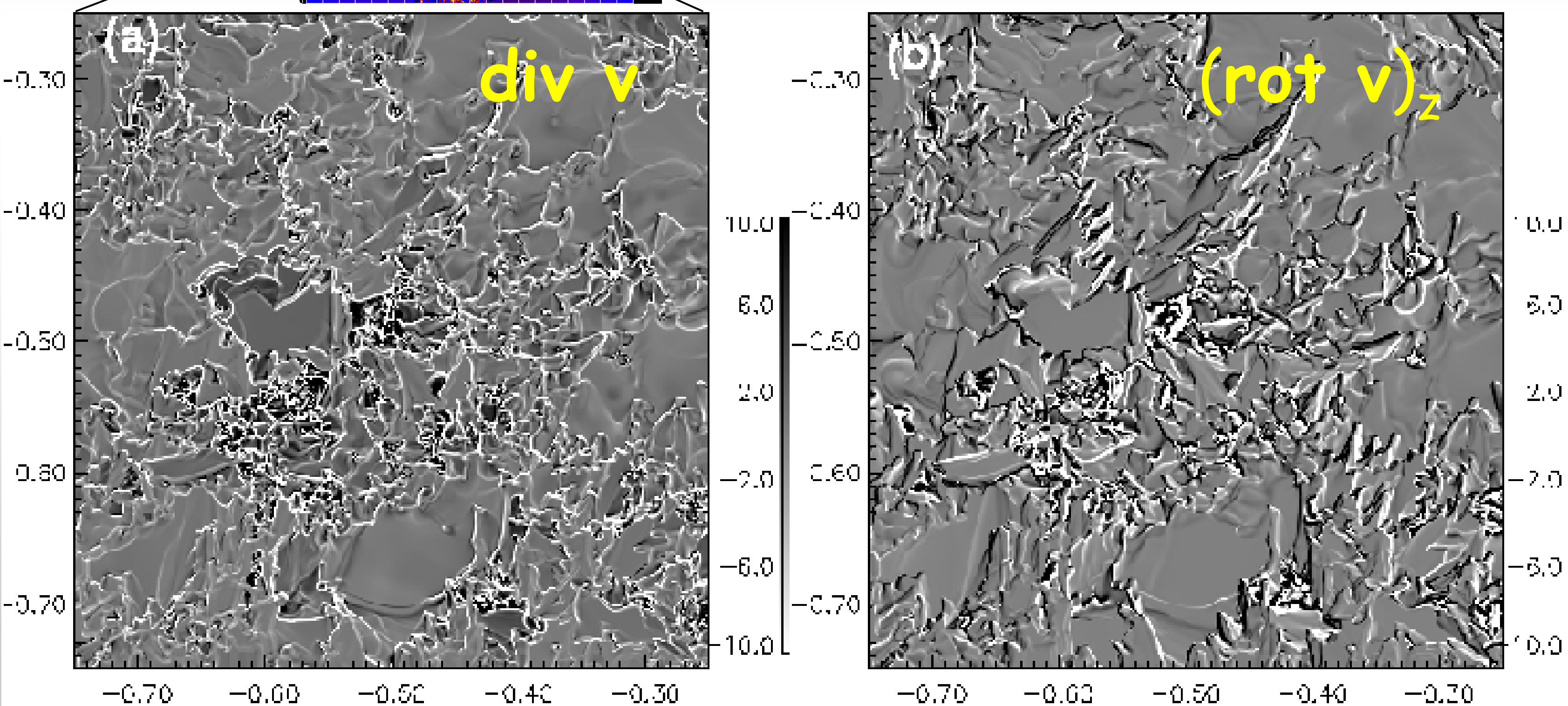
Resolution: 10 pc~ $L_{jeans,\ min}$

Turbulent structure of the 'tangled web'

No supernovae



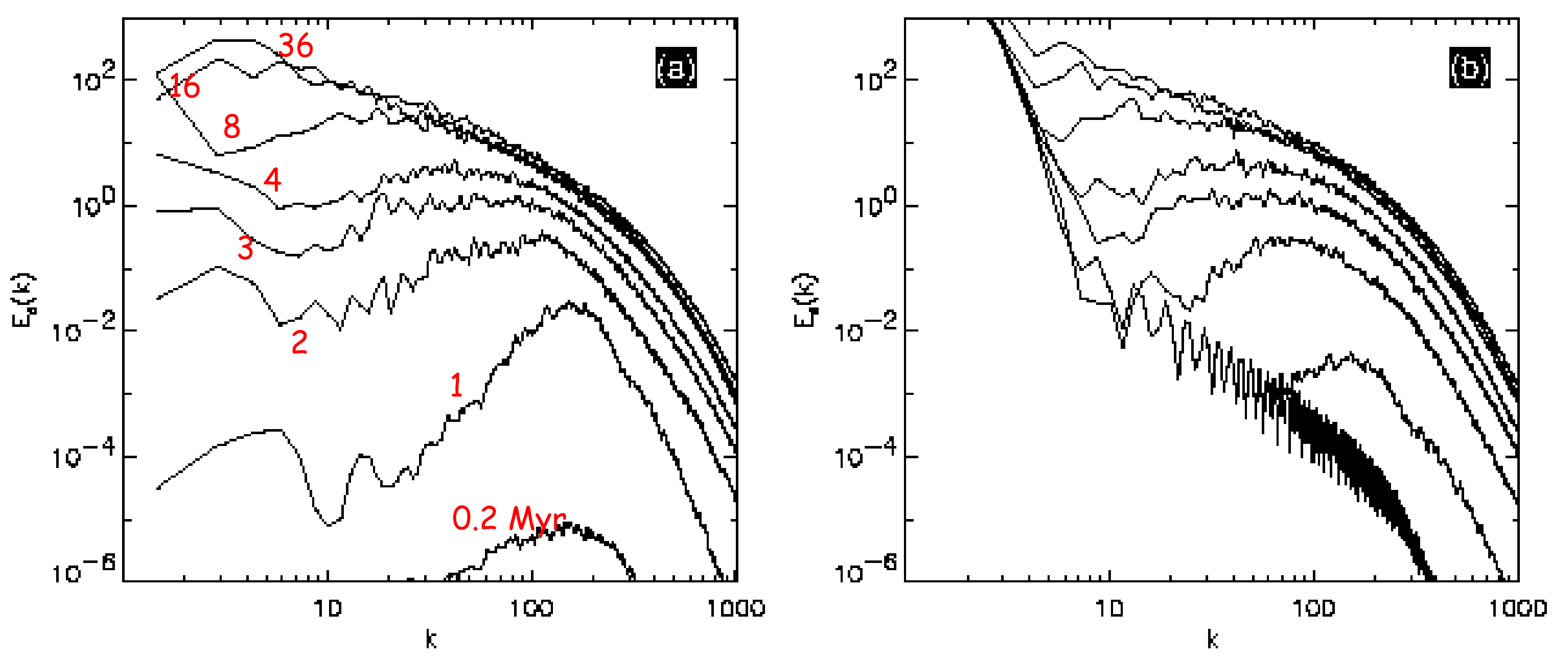




Evolution of Energy spectrum (no SN, 2-D model)

The spectrum attains a power-law in ~20Myr

Compressible (rotational free) Incompressible (divergence free)

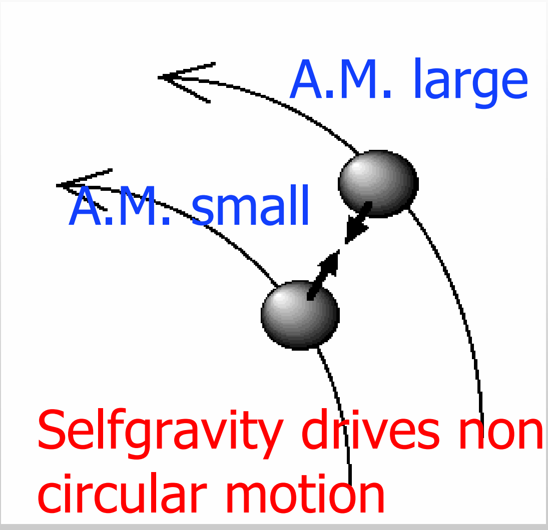


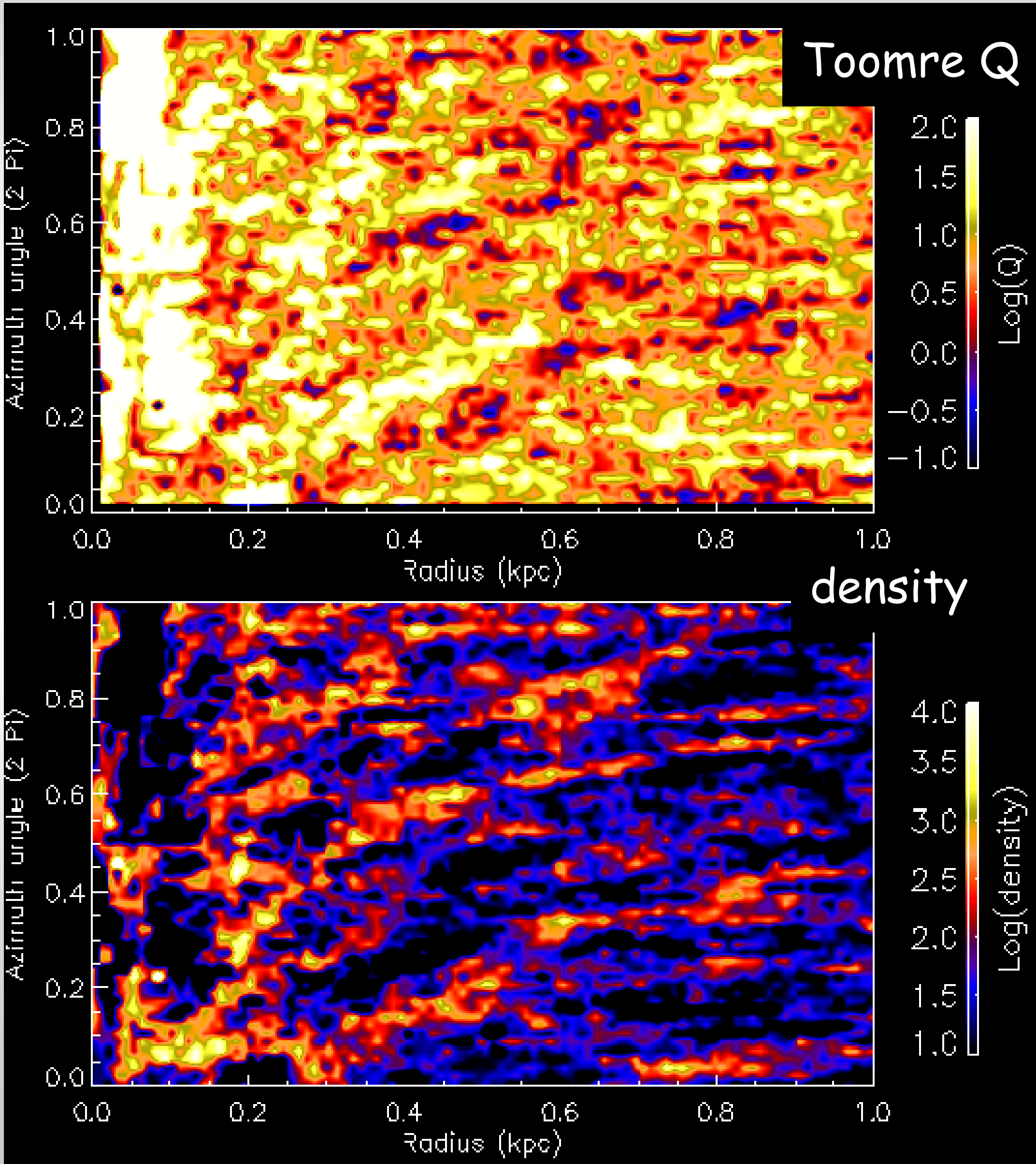
There is no explicit energy input.
Turbulence on a galactic scale is self-regulated without supernovae.

Rotational component: galactic rotation dominates turbulent energy on large-scale

Distribution of stable/unstable regions

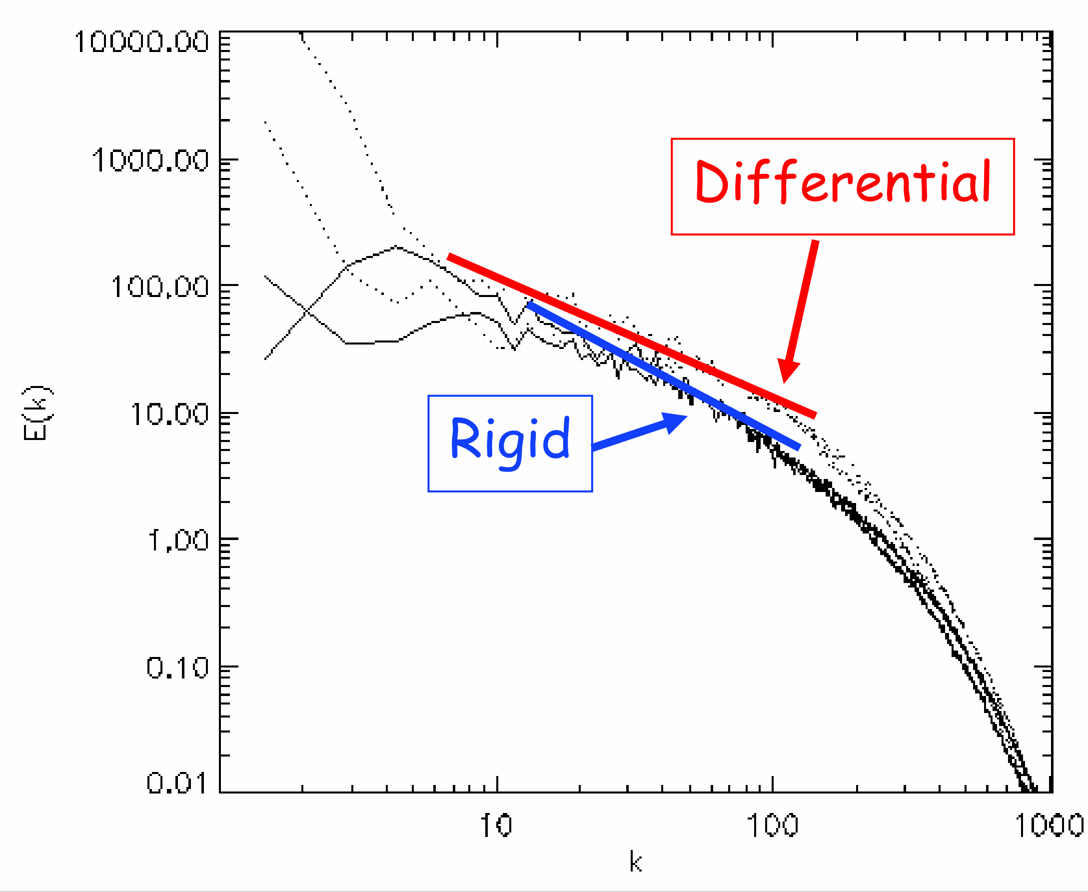
- Stable and unstable regions patchily exist.
- median Q ~ 5, but large dispersion
- Energy source of the turbulence = local gravitational instability + galactic rotation





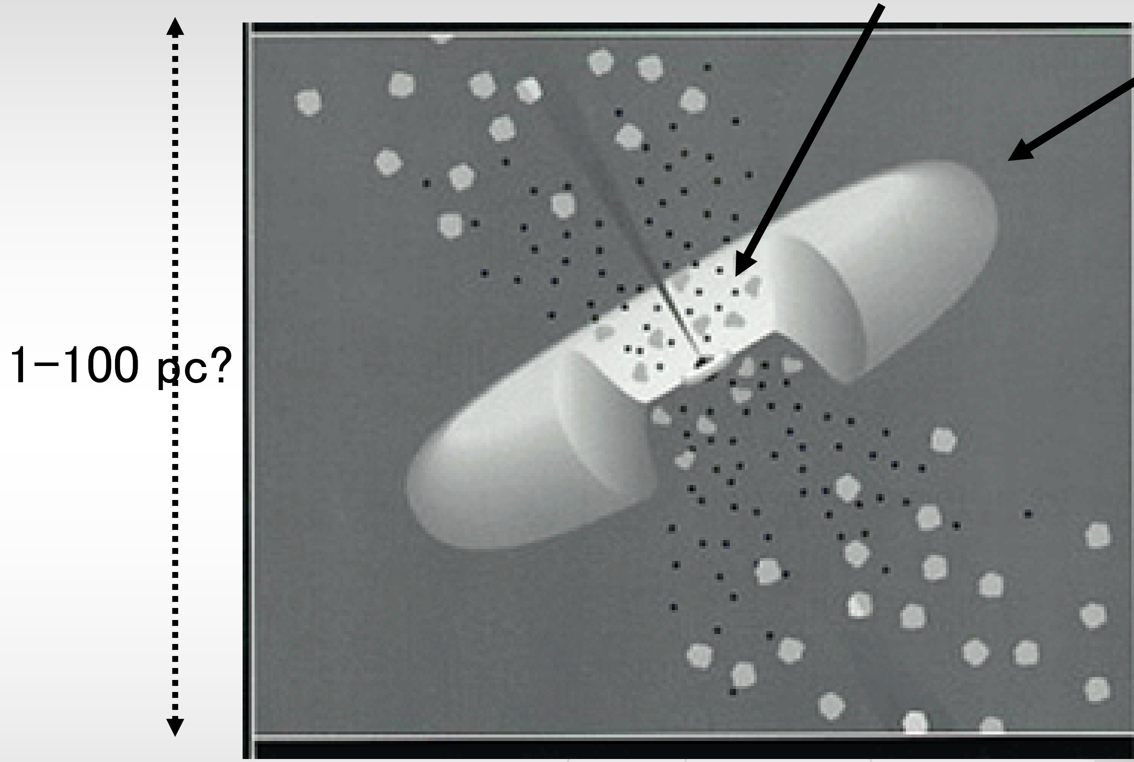
Note: differential rotation is not essential to maintain the turbulence

- Turbulence is also developed in a rigid rotation disk.
- Energy spectrum is slightly steeper in rigid rotation.



KW, Meurer, Norman (2002)

Structure of AGNs



Super massive BH (10^{6-8} M_{sun}) ＋ accretion disk (AU scale)＋ BLR + NRL + Obscuring molecular torus (1–100 pc) + Jet + ENLR

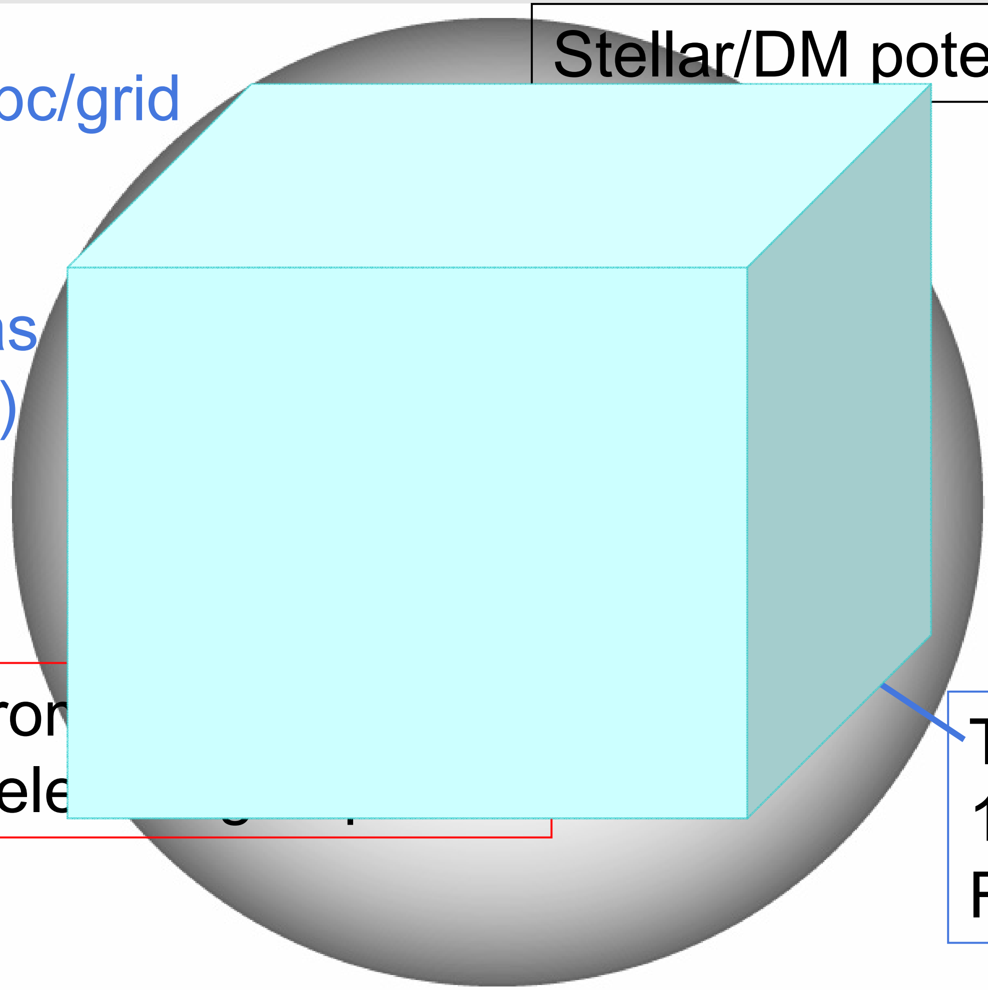
Energy source： mass accretion (0.01– 1 Msun yr^{-1})

3-D Hydrodynamics of a massive gas disk around a SMBH (KW & Norman 02; KW & Tomisaka 05)

256^3 grid points
Resolution: 0.25pc/grid

Self-gravity of gas
Cooling(10-10^8K)

Stellar/DM potential: fixed



Energy input fro
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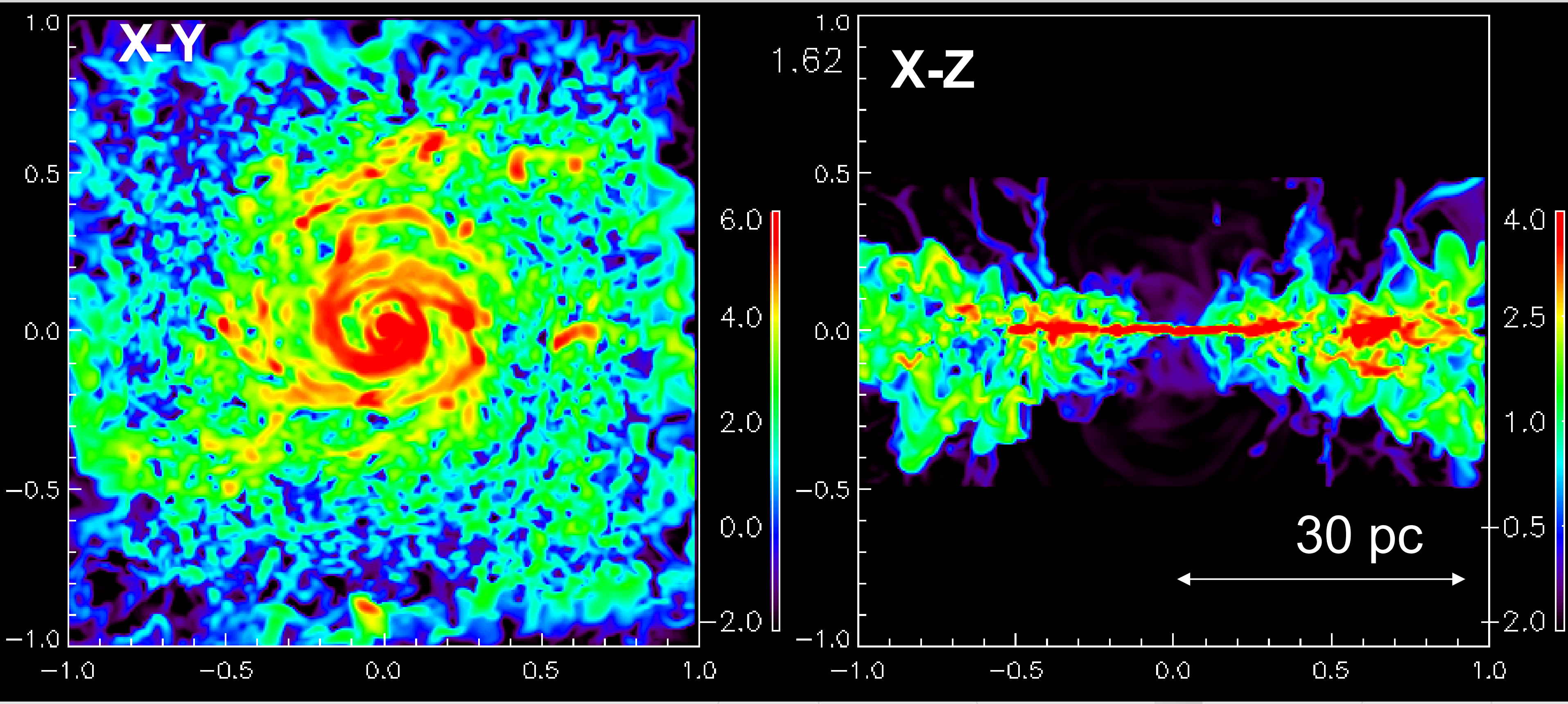
Thin gas disk
10^7 M_{sun}
R=30pc

Starburst driven "torus" around SMBH

density

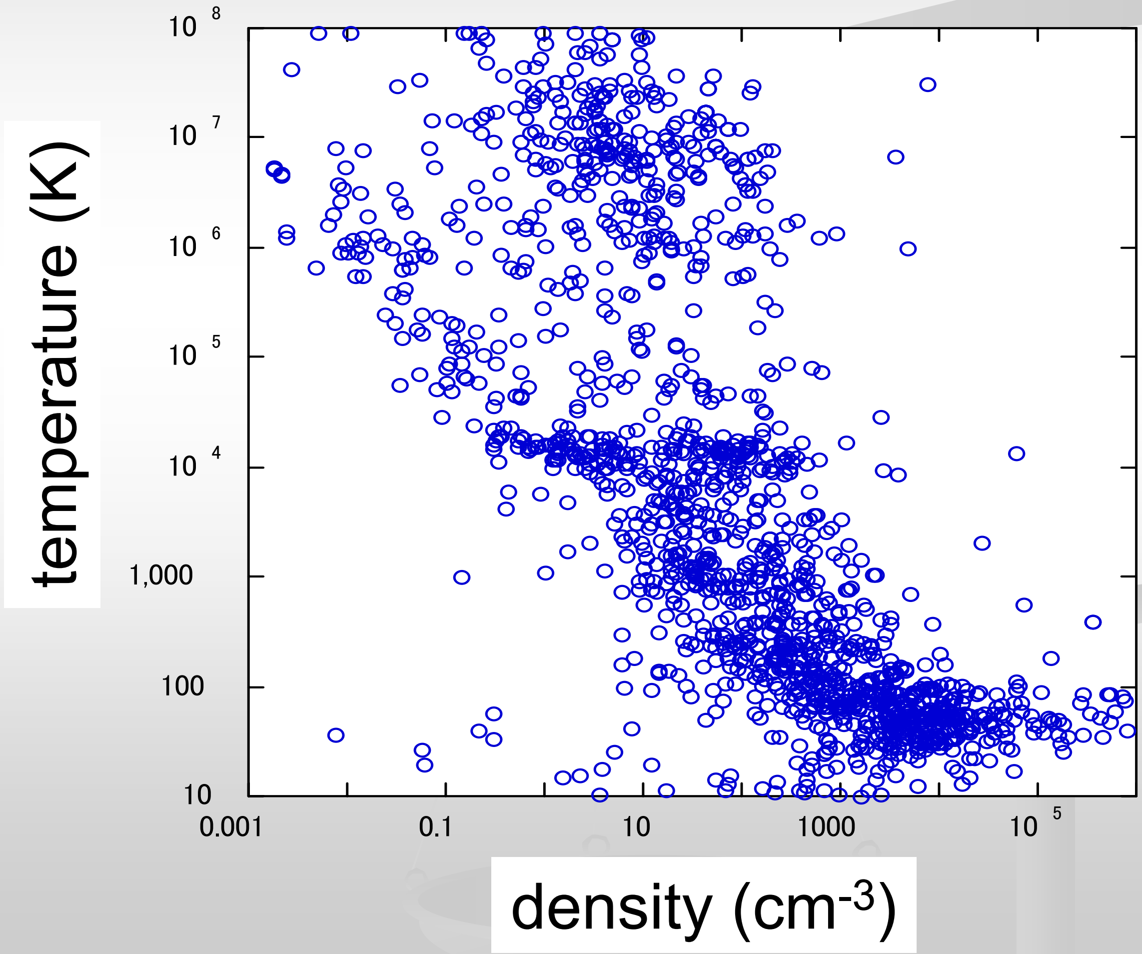
KW & Norman '02



- ISM is a flared disk with clumps and filaments.
- Scale height is determined by energy balance between turbulent dissipation and SN heating in a gravitational potential.

Density,temperature in the "torus"

T~ 50-10^7 K, n ~ 0.1-10^5 cm^{-3}



KW & Norman (2002) ApJ 566, L21

Obscuring "torus" around a supermassive BH with nuclear starburst

256^2 x 128, uniform grid, 0.25pc/grid
Radiative cooling (5–10^8 K), SN feedback, selfgravity
$M_{BH} = 10^8\ M_{sun}$, $M_{gas} = 10^7\ M_{sun}$,

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64 pc

Geometry of SNe-driven torus

If we assume:

- Internal motion of the torus is turbulent
- turbulent energy dissipation =heating by SNe

$$\frac{\rho_g v_t^2}{\tau_d} = \eta s_\star E_s,$$

Hydrostatic equilibrium

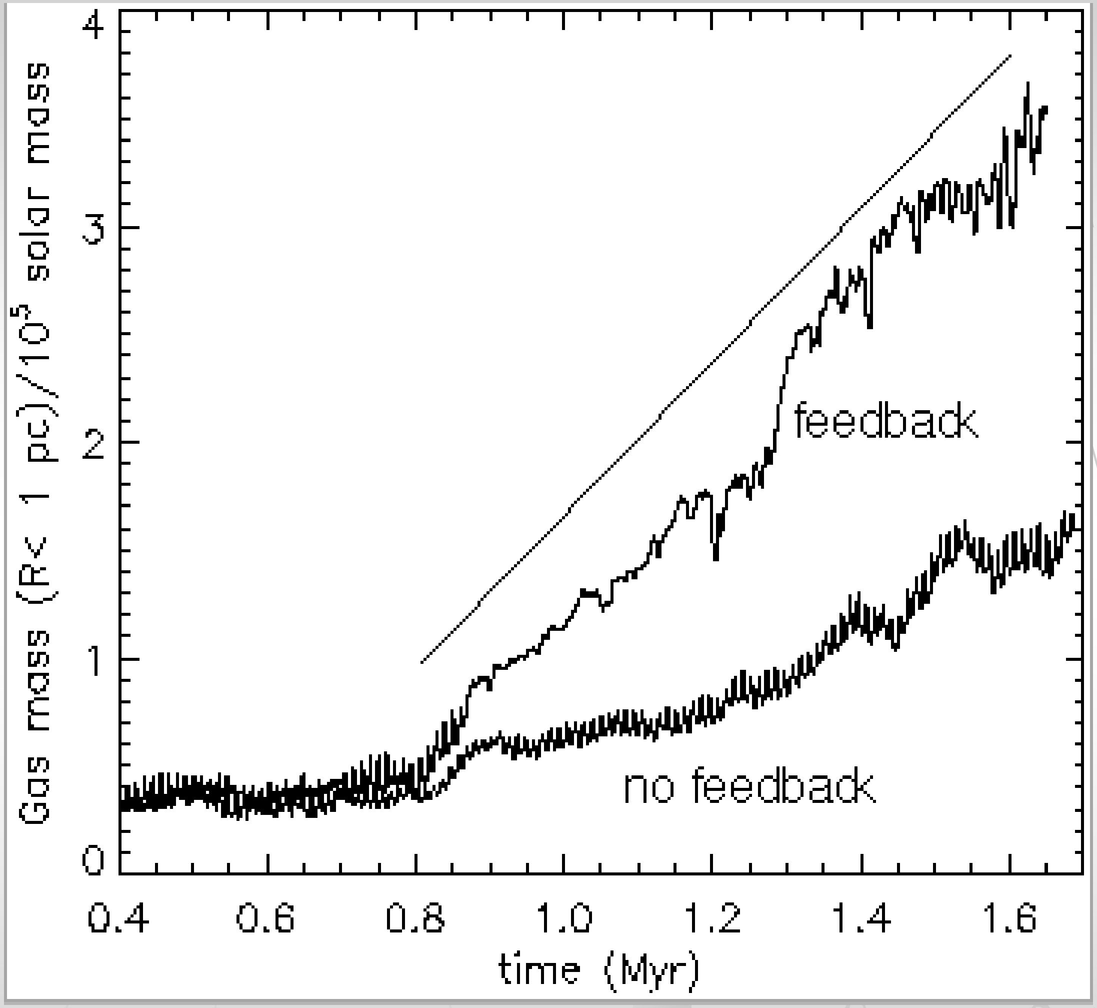
Scale height h(r)

$$h_1(r) = (\xi \eta \alpha E_s)^{1/2} G^{-1/2} M_{\mathrm{BH}}^{-1/2} r^{3/2},$$ (BH dominant region)

Scale height of the torus is proportional to $(\mathrm{SFR}/M_{BH})^{1/2}$

Gas accretion to the nucleus (R<1pc)

I. average accretion rate ~ 0.3 Msun/yr
II. accretion rate is enhanced by the starburst.
III. Angular momentum transport by turbulent viscosity



※ **accretion rate is time-dependent ($\tau \sim 10^{4-5}$ yr)**

Summary: Origins of the inhomogeneity of the ISM in galactic disks and in AGNs

1. Gravitational and Thermal instabilities coupled with the galactic rotation
   - Fully developed turbulence is naturally generated in galactic disks.
   - The turbulent motion is maintained by the galactic rotation, and local shear motion.

2. Supernova explosions in a dense gas.
   - SNRs interact with the inhomogeneous ISM, and it causes turbulent motion in the torus.
   - The accretion rate toward the central BH is time dependent.