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Global SFR in Galactic Disks

WADA Keiichi
National Astronomical Observatory of Japan

Colin Norman
Johns Hopkins University

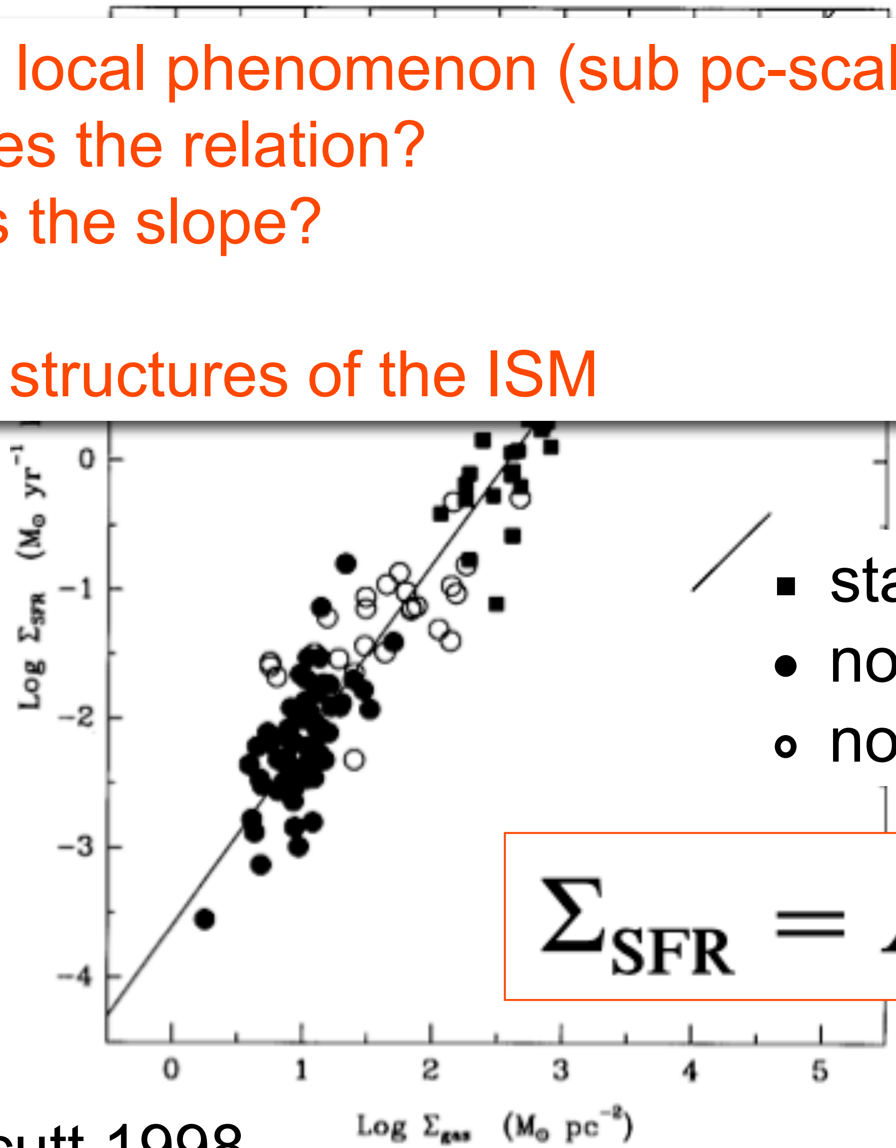
1. An intrinsic statistical structure of the ISM (looks universal) in the galactic ISM

2. The statistical feature is used to derive a *generalized* Schmidt-Kennicutt law.

Global star formation rate and surface density of the ISM in galaxies (Kennicutt law)

Star formation = local phenomenon (sub pc-scale), then what causes the relation?
what determines the slope?

==> global/local structures of the ISM



- starburst
- normal
- normal (center)

$$\Sigma_{SFR} = A\Sigma_{gas}^{N}$$

N=1.4

Kennicutt 1998

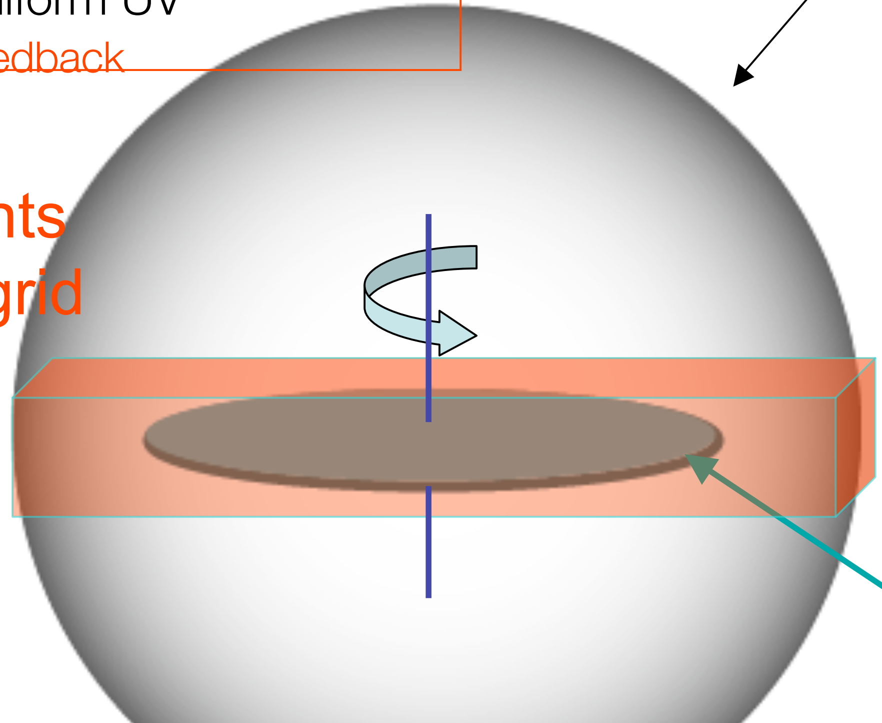
Intrinsic structure of the ISM?

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

- Self-gravity of the gas
- A cooling function ($10<T< 10^8$ K) is assumed (solar)
- Heating sources: uniform UV
  - No SNe energy feedback

Stellar/DM potential: fixed

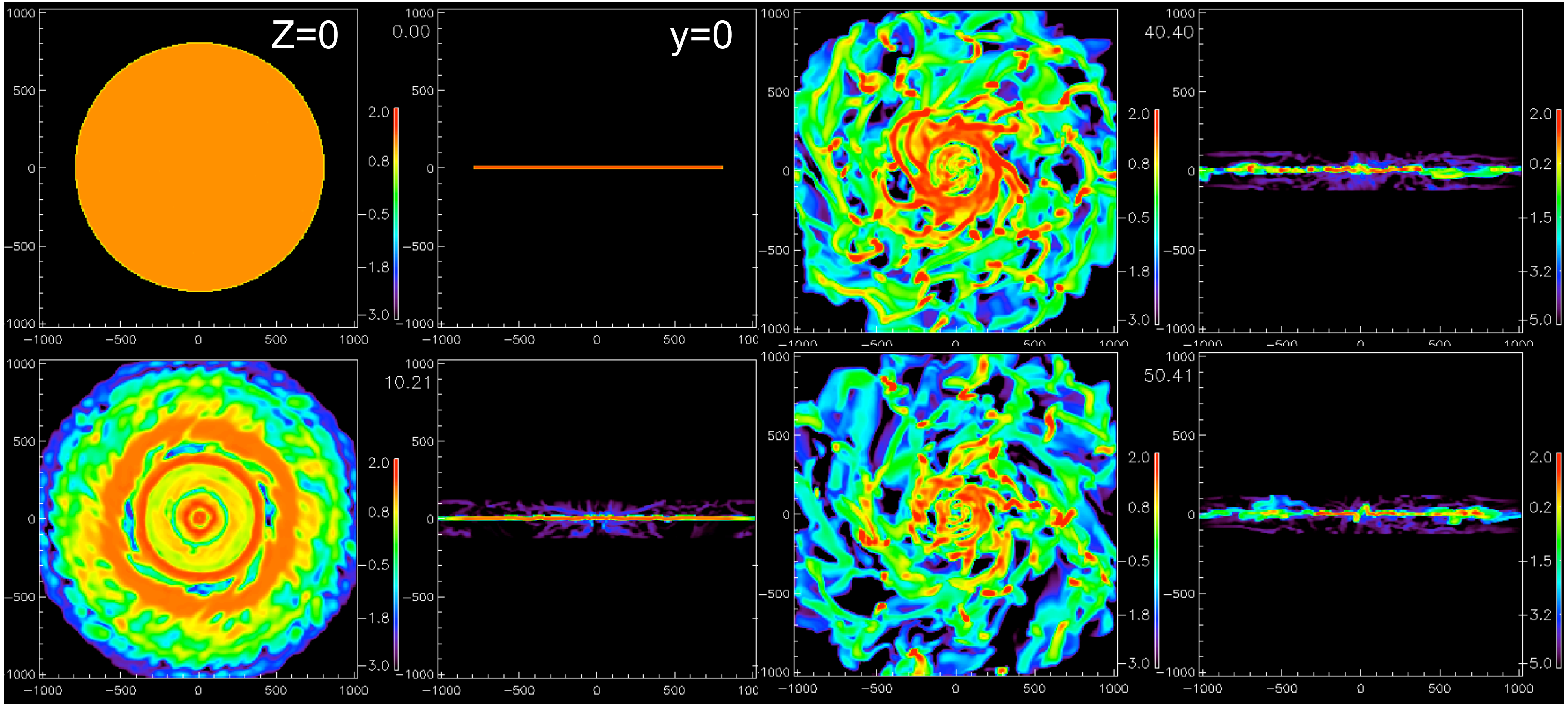
512^2x64 grid points
Resolution: 5pc/grid
(also 10pc/grid)

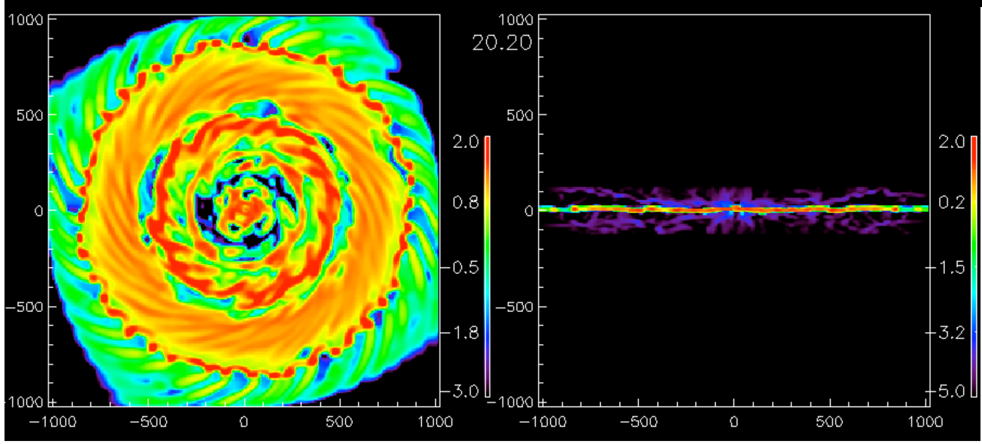


Thin gas disk
$\sim 10^{8\text{-}9}$ M_{sun}
R= 1.28 kpc

Methods: AUSM w/ uniform grid+ Poisson eq. Solver(FFT)

CPU time: ~ 10-200 hours/run
on Fujitsu VPP5000 32 PEs (0.3 TF) in NAOJ



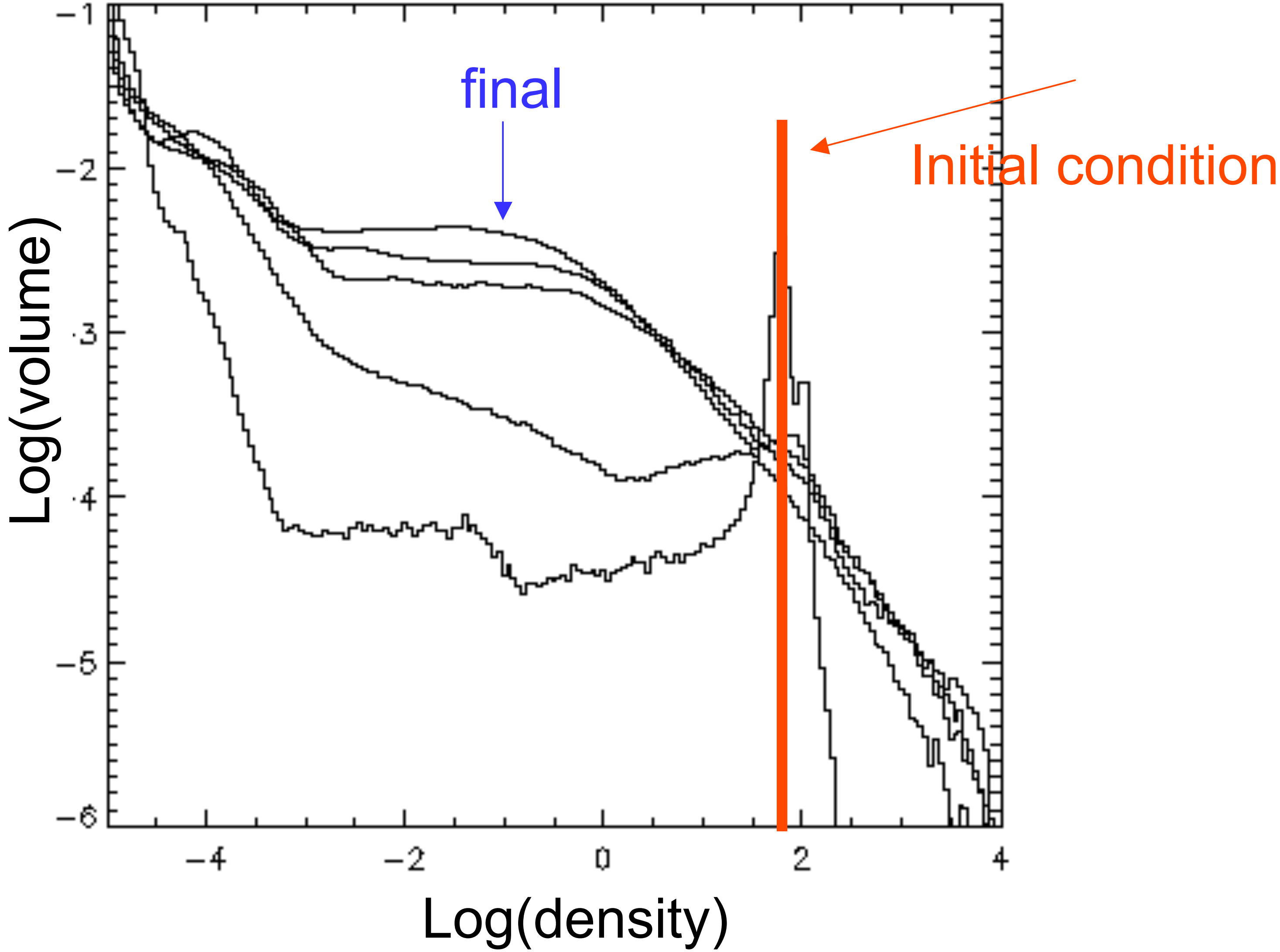


3-D evolution of a galactic disk

2.56kpc x 2.56kpc x 0.32kpc

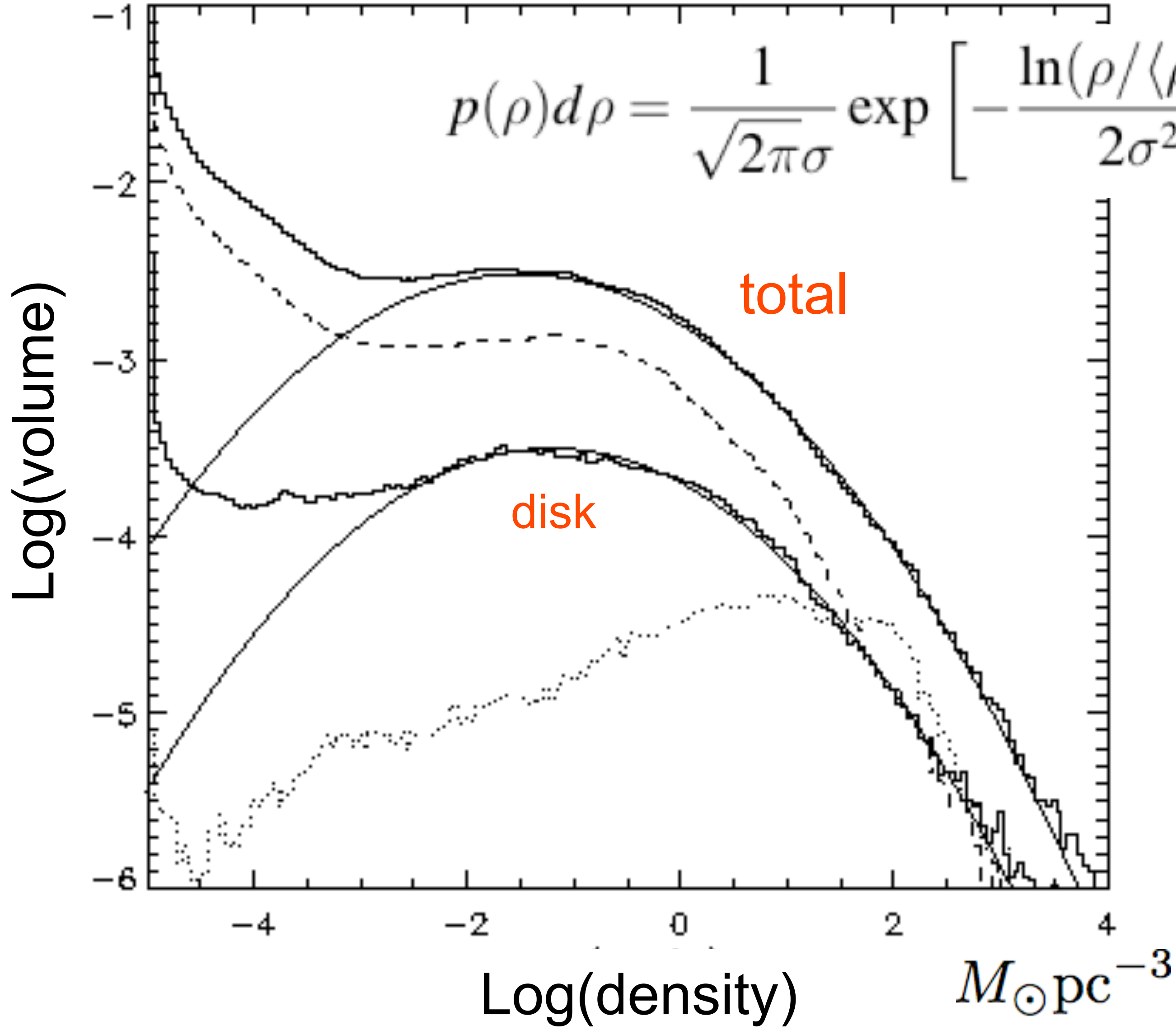
Resolution: 10 pc~ $L_{jeans,\,min}$

Evolution of density PDF (Probability Distribution Function) in a 3-D galactic disk

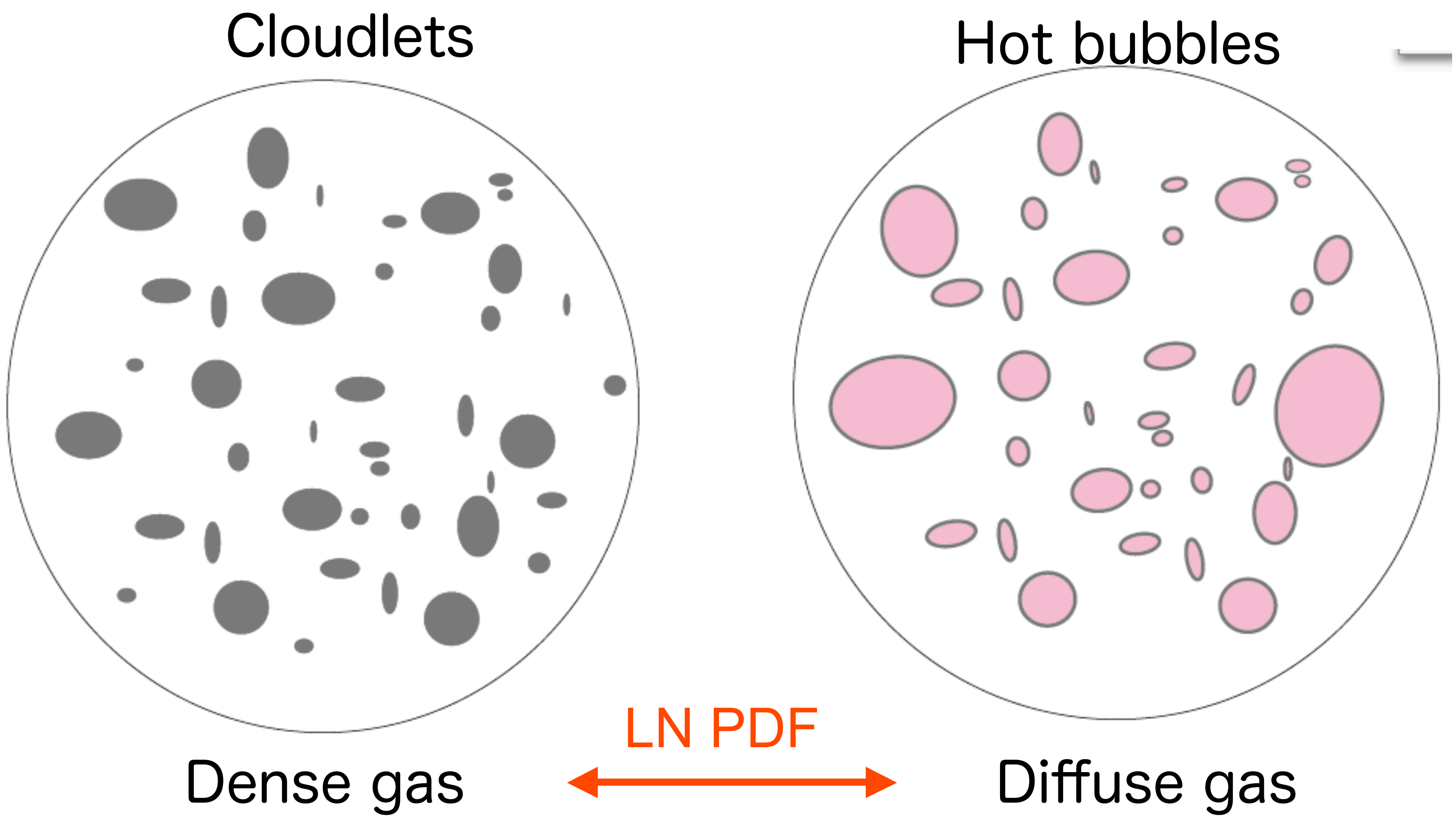


Volume-weighted density PDF in a steady-state

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



Different phases (e.g. high density regions and low density voids) are related through LN-PDF.



Origin of Log-normal PDF

If the inhomogeneous structure is caused by highly non-linear, random processes,
and the system is globally stable during long enough time,
the density PDF should be Log-Normal.

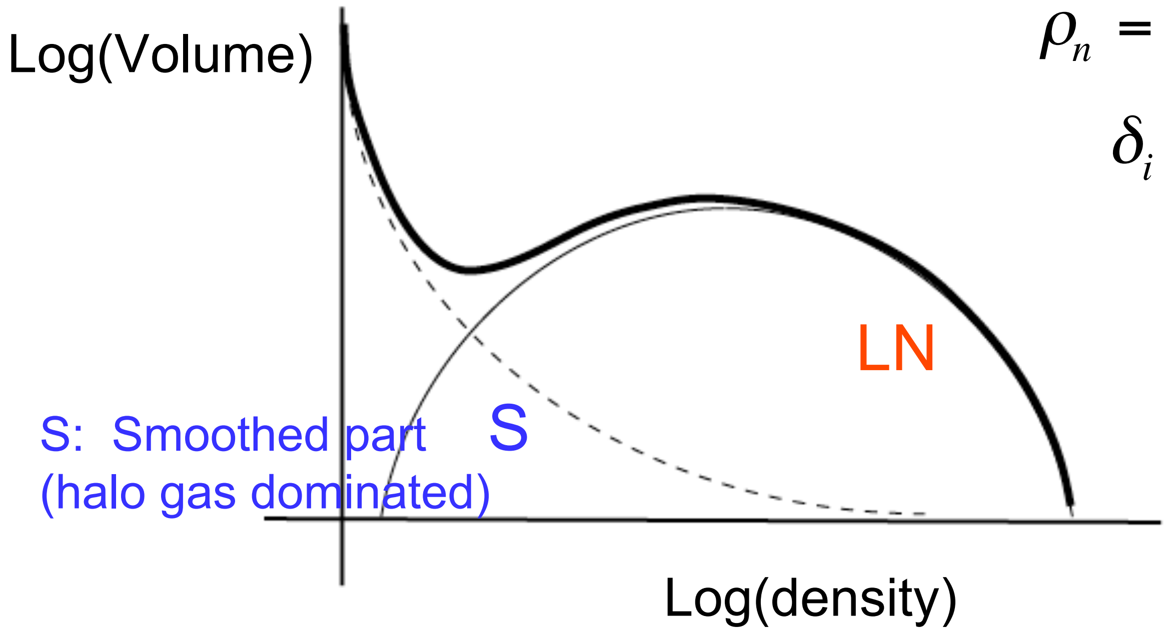
$$\rho_i = \delta_{i-1}\rho_{i-1}$$

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

δ_i :independent events

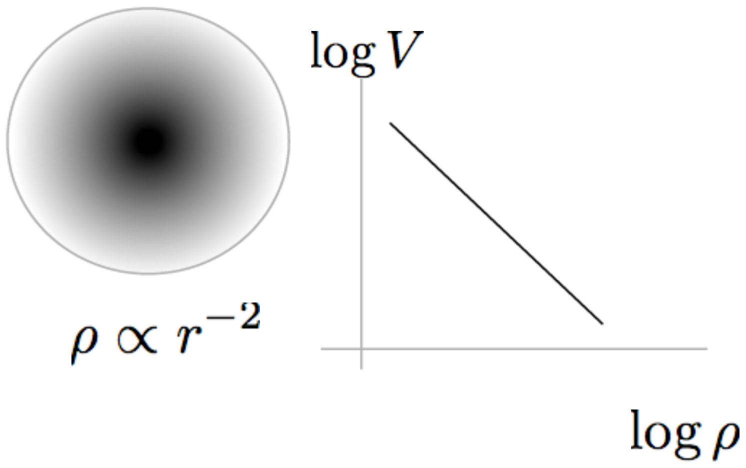
$$\ln(\rho_n) \rightarrow N(\mu, \sigma^2)$$
$$n \rightarrow \infty$$

Central limit theorem

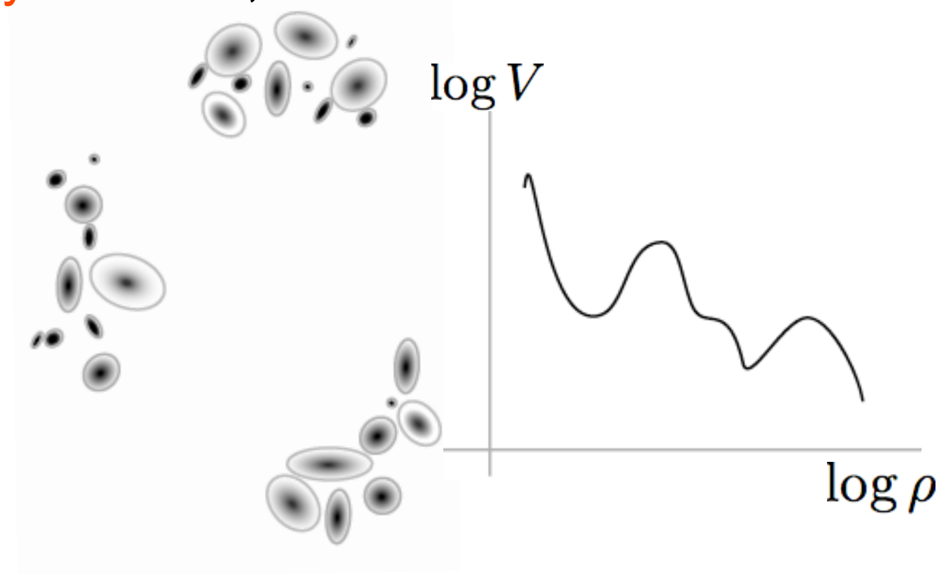


Globally stable galactic disk ➡ Mathematical conditions are satisfied.

A homogeneous system

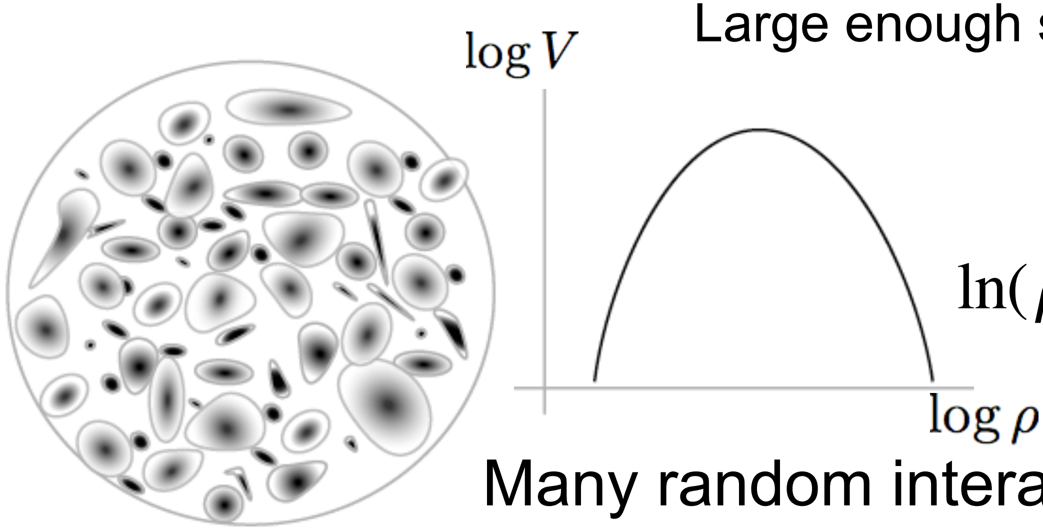


If the system has many sub-subsystems but globally unstable, its PDF is not LN.



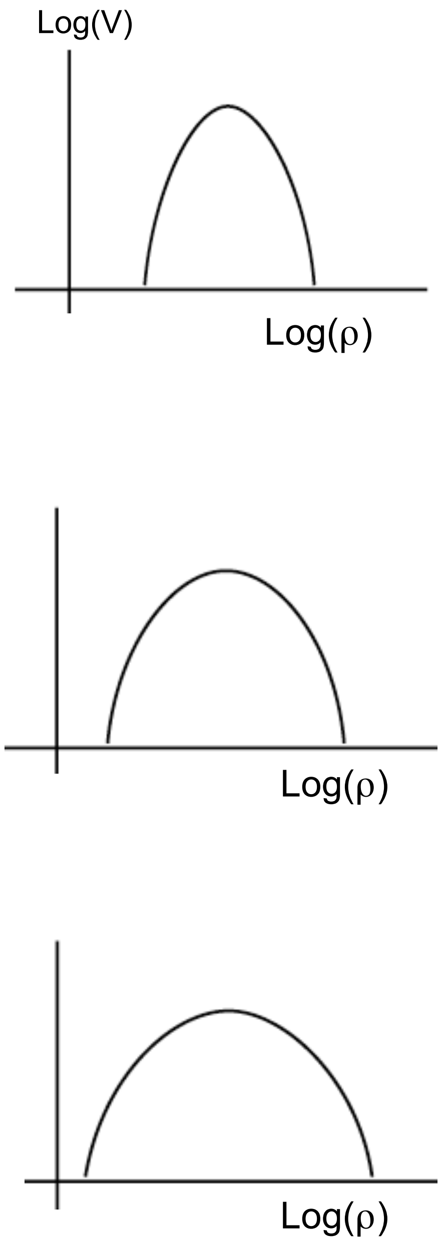
Inhomogeneous, globally stable system (e.g. galactic disk)

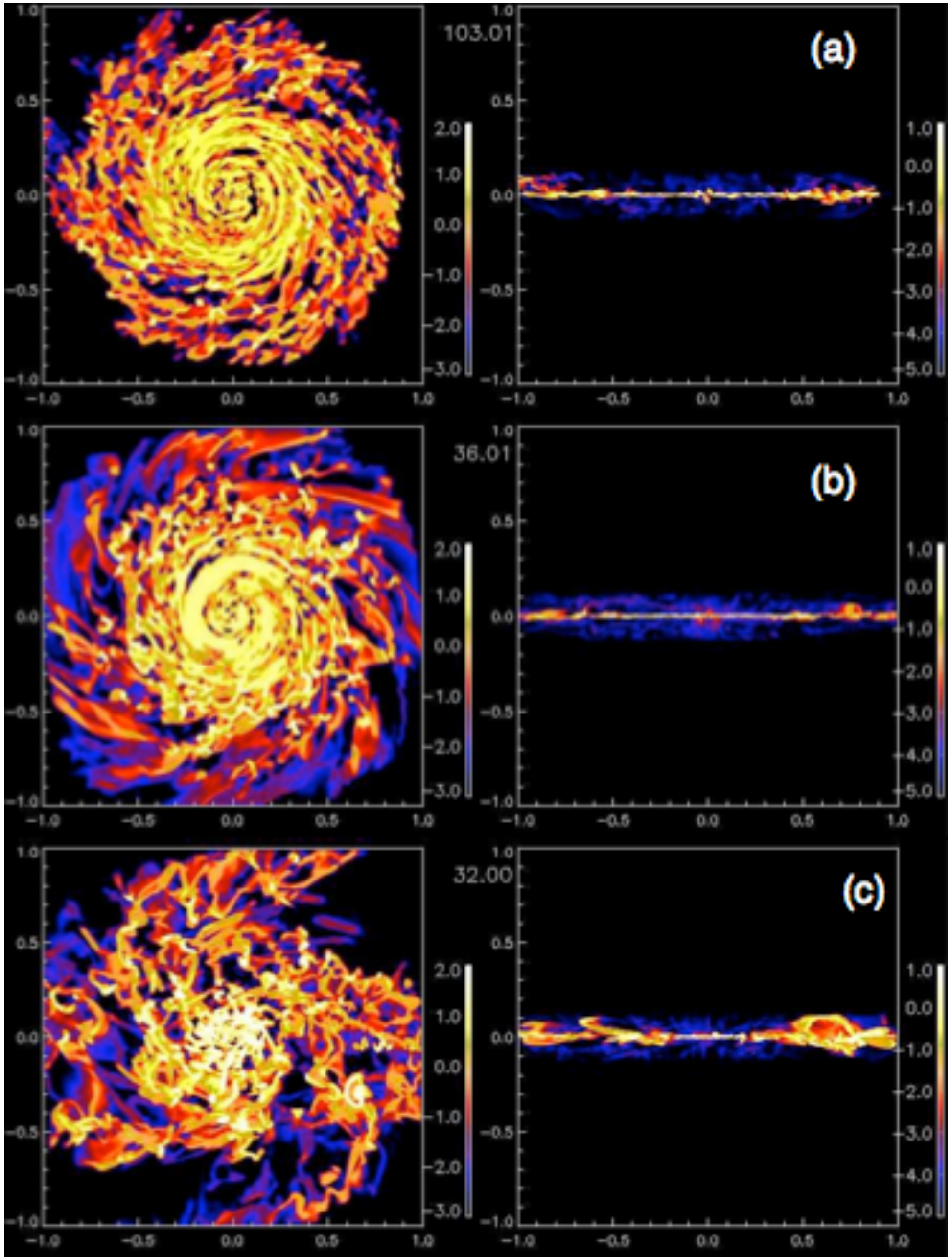
Large enough statistical samples



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

Many random interactions that change density





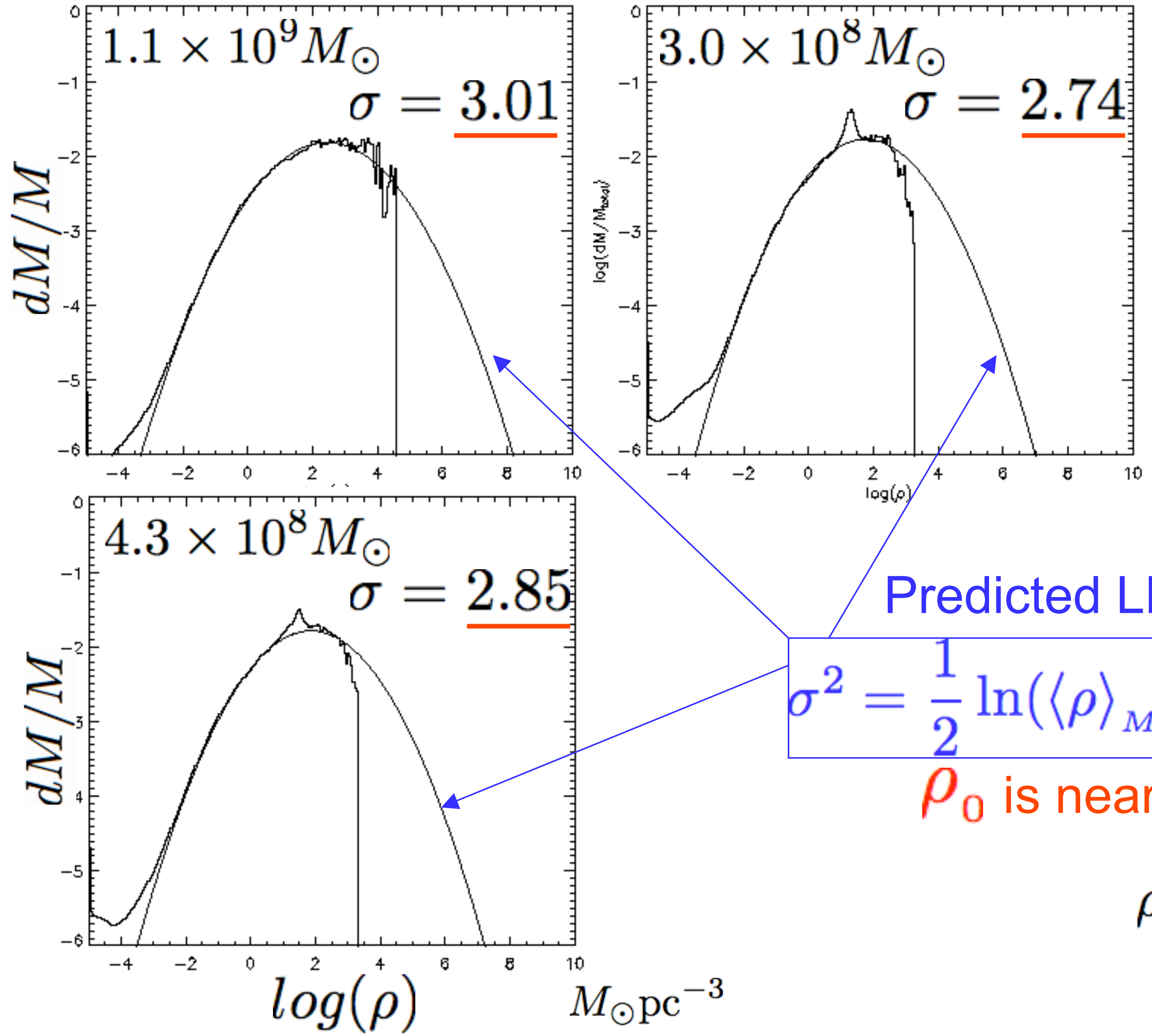
Less massive

massive

$$\langle \rho \rangle_V = \rho_0 e^{\sigma^2/2}$$

Larger dispersion in more massive system

Mass-weighted density PDF



In more massive disks, the LN-dispersion is larger.

Predicted LN-PDF

$$\sigma^2 = \frac{1}{2}\ln(\langle\rho\rangle_M/\rho_0)$$

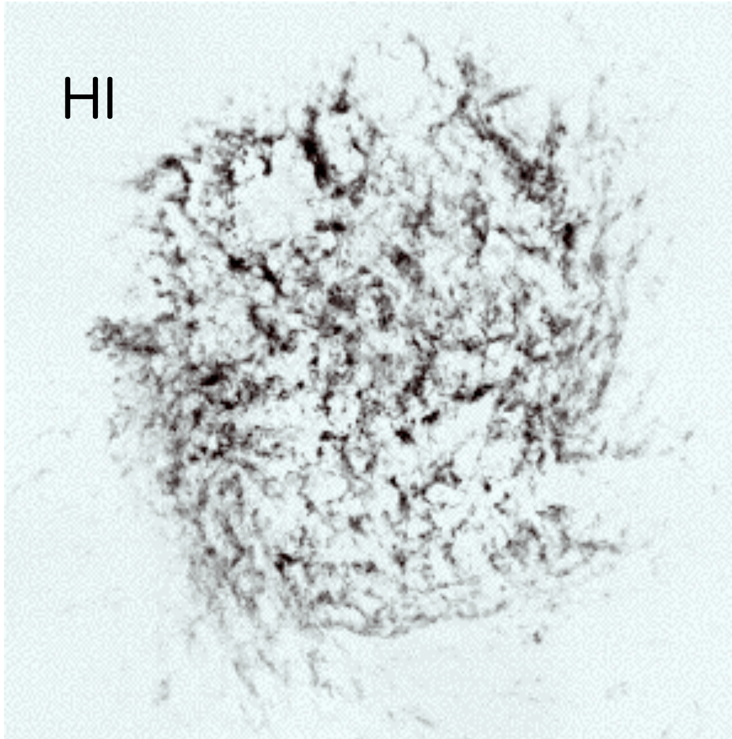
ρ_0 is nearly constant.

$$\rho_{0,M} = \rho_{0,V}\, e^{\sigma^2}$$

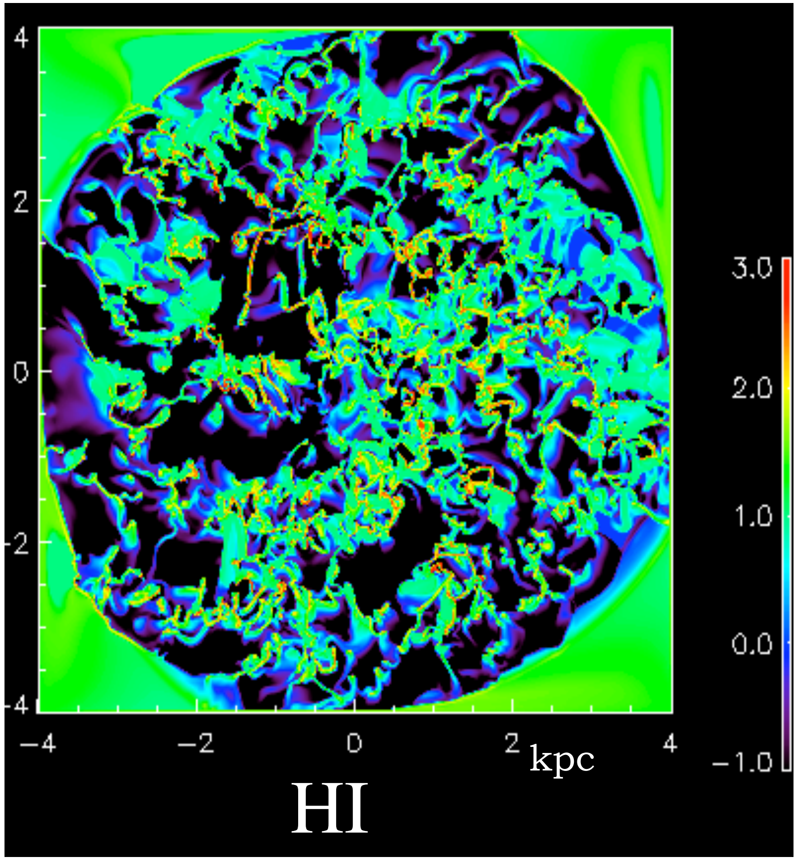
For LN-PDF

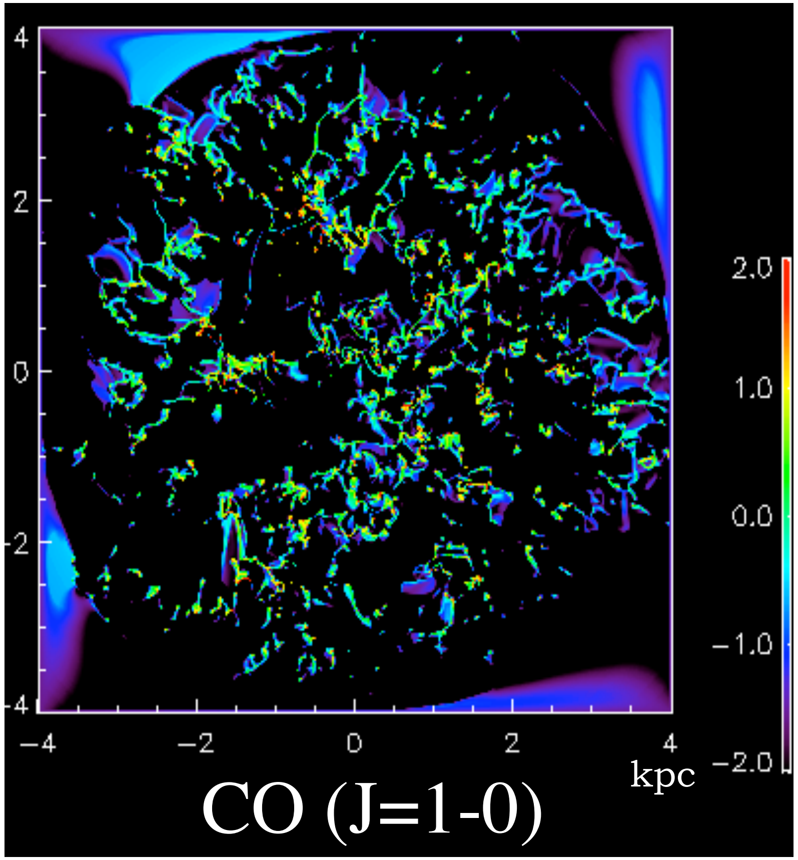
Is the numerical model realistic? Modeling LMC

- High resolution mapping
  - HI (Kim et al. 1998)
    - Δ~15pc
  - CO(Fukui et al. 1999)
    - Δ~40pc
- Simulation: Δ= 8pc for the whole disk
  - Wada , Spaans, Kim (2000)
  - 2D, 2048^2



2-D simulation + radiative transfer model





Wada , Spaans, Kim (2000)

CO 'clouds'
in the LMC model

- w/o SN feedback

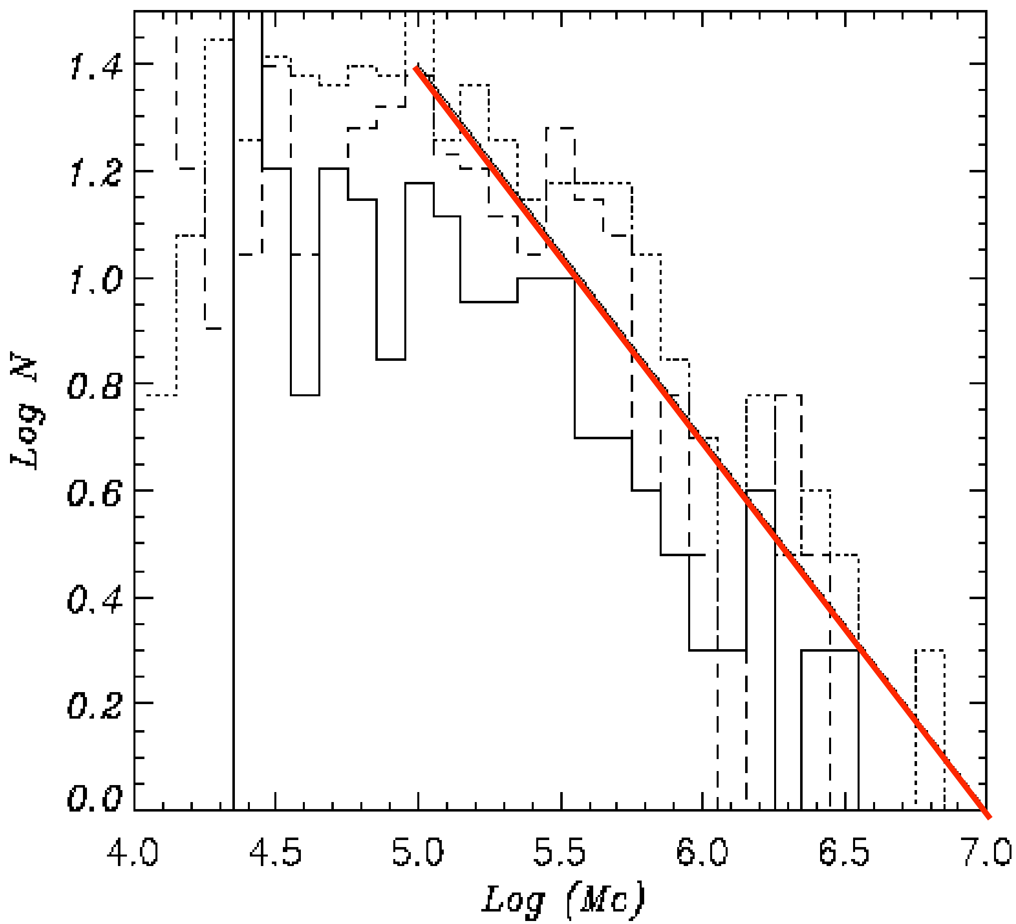
$dN/dM_c \sim M_c^{-1.8}$

- w SN feedback

$dN/dM_c \sim M_c^{-2}$

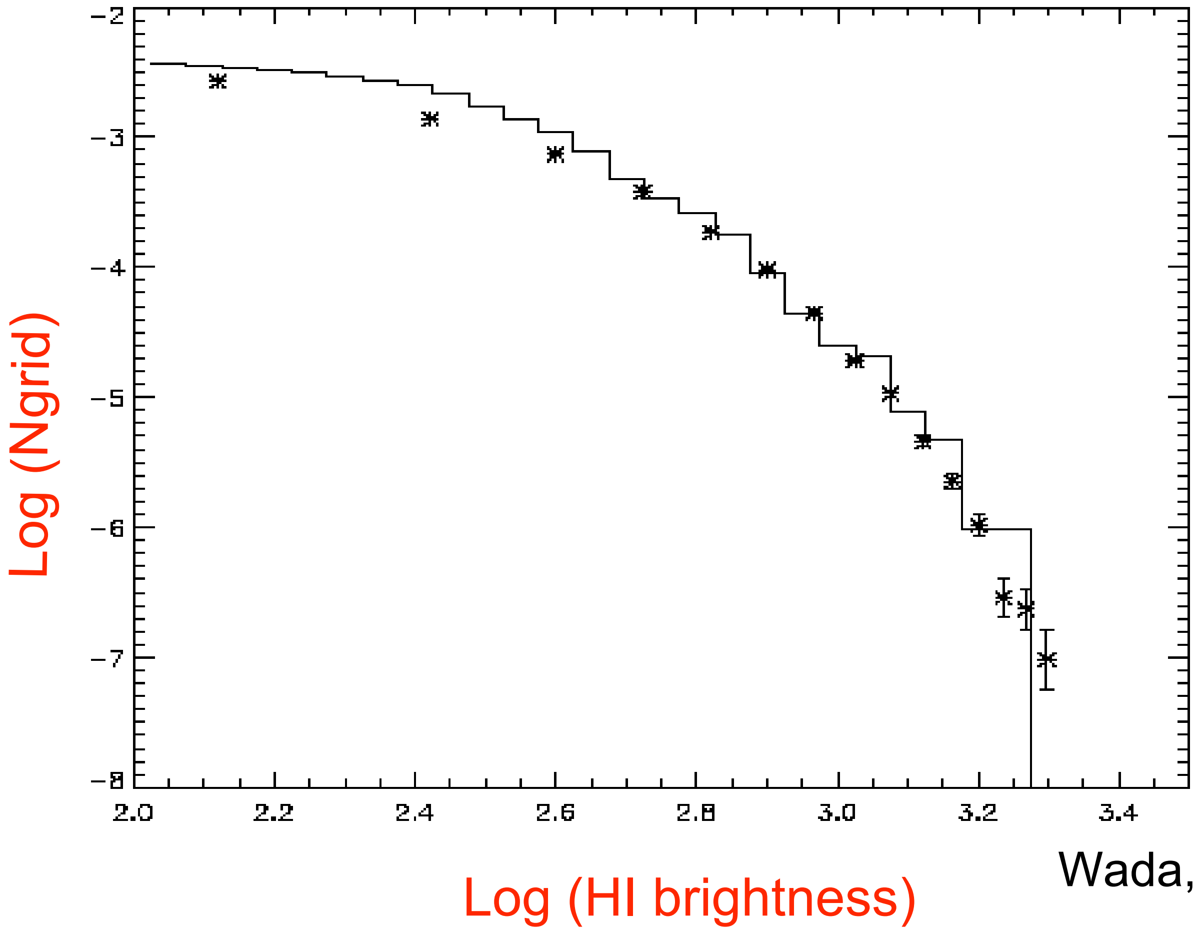
- NANTEN Survey

$dN/dM_c \sim M_c^{-1.7}$
(Fukui et al. 1999)



Histogram of HI intensity

(model vs. observations)

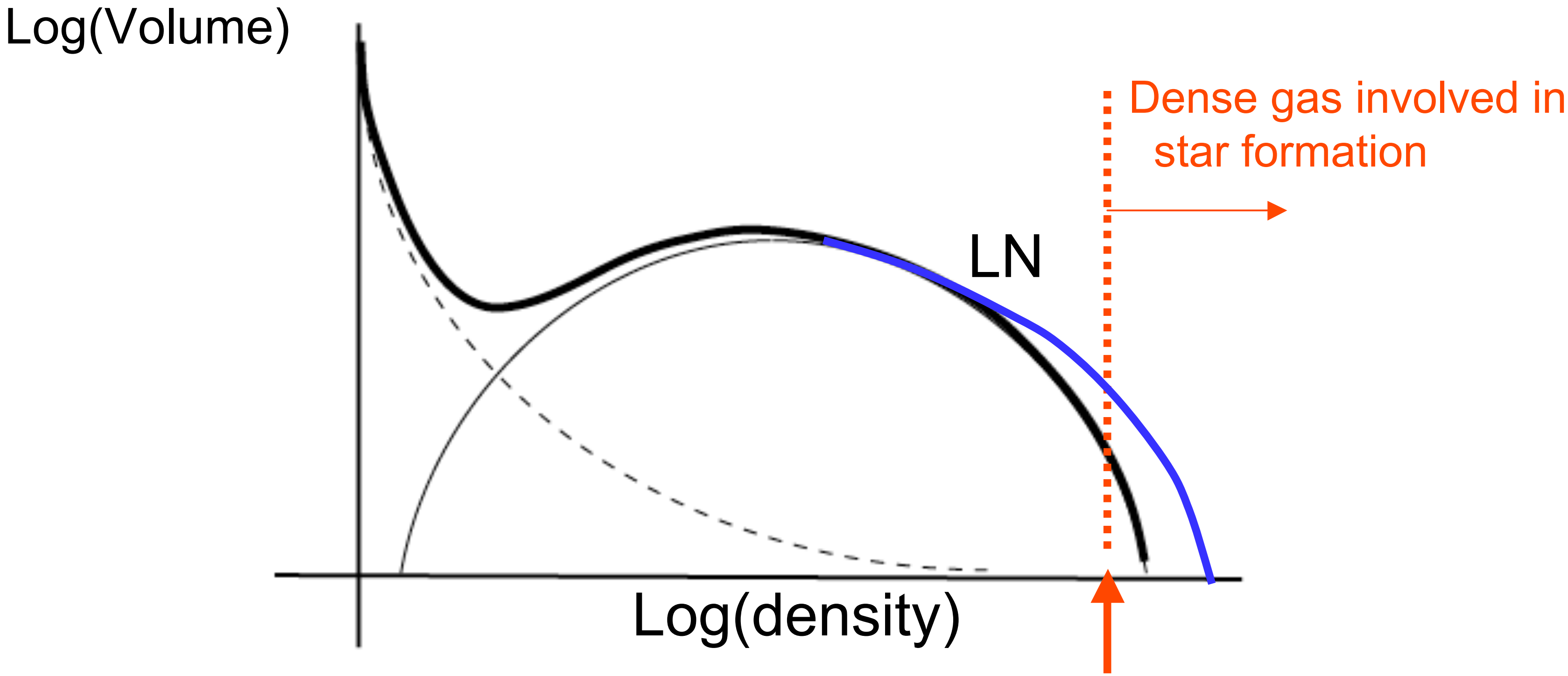


Wada, Spaans, Kim (2000)

Even if the spatial structure is complicated, DF is very smooth

star formation model in LN-PDF

Average density ↑ ⇒ dispersion of PDF ↑ ⇒
fraction of high density clumps ↑ ⇒ SFR ↑

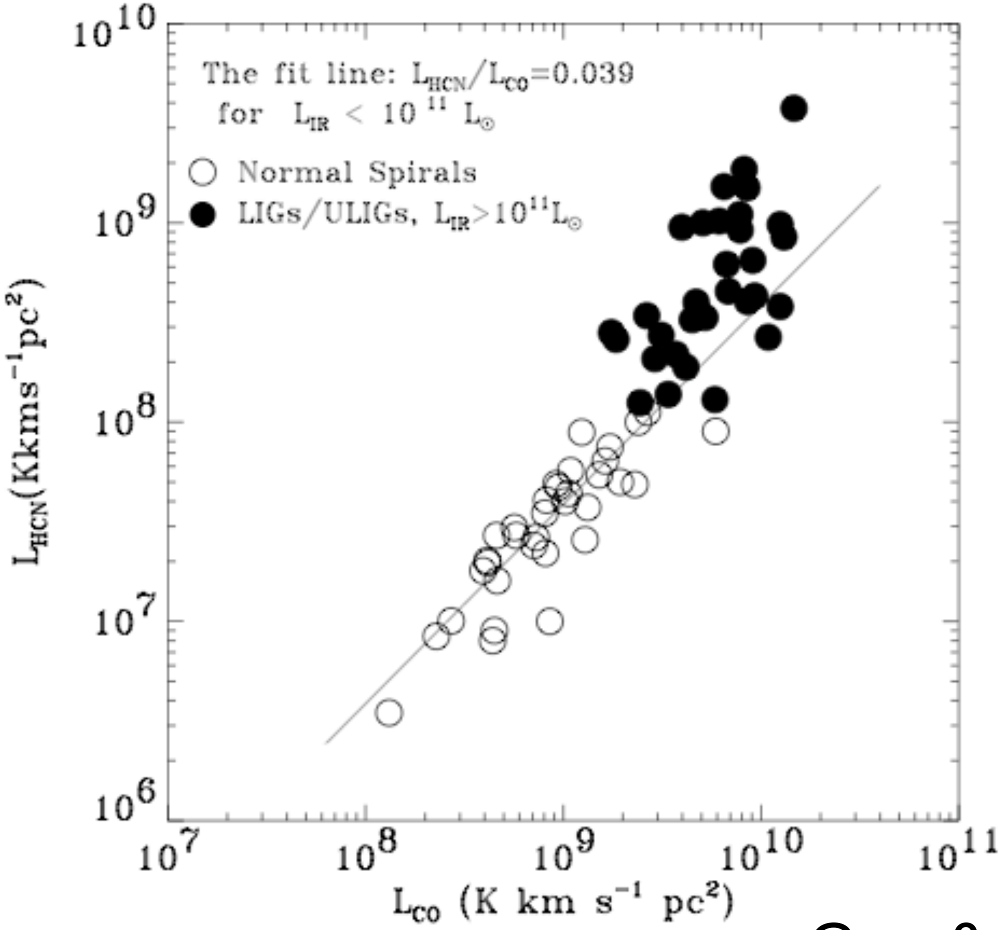


critical density
necessary for local SF
e.g. $n=10^{3\text{-}5}$ cm^{-3}

$$\langle \rho \rangle_V = \rho_0 e^{\sigma^2/2}$$

Star forming galaxies show larger fraction of high density gas

L_{HCN} (dense gas tracer $n>10^4$ cm^{-3}) vs. L_{CO}



65 galaxies

Gao & Solomon (2004)

SFR in the ISM characterized by LN-PDF

$$\dot{\rho}_\star = \epsilon_c (G\rho_c)^{1/2} f_c \bar{\rho}$$

efficiency

Gas mass involving LN pdf

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

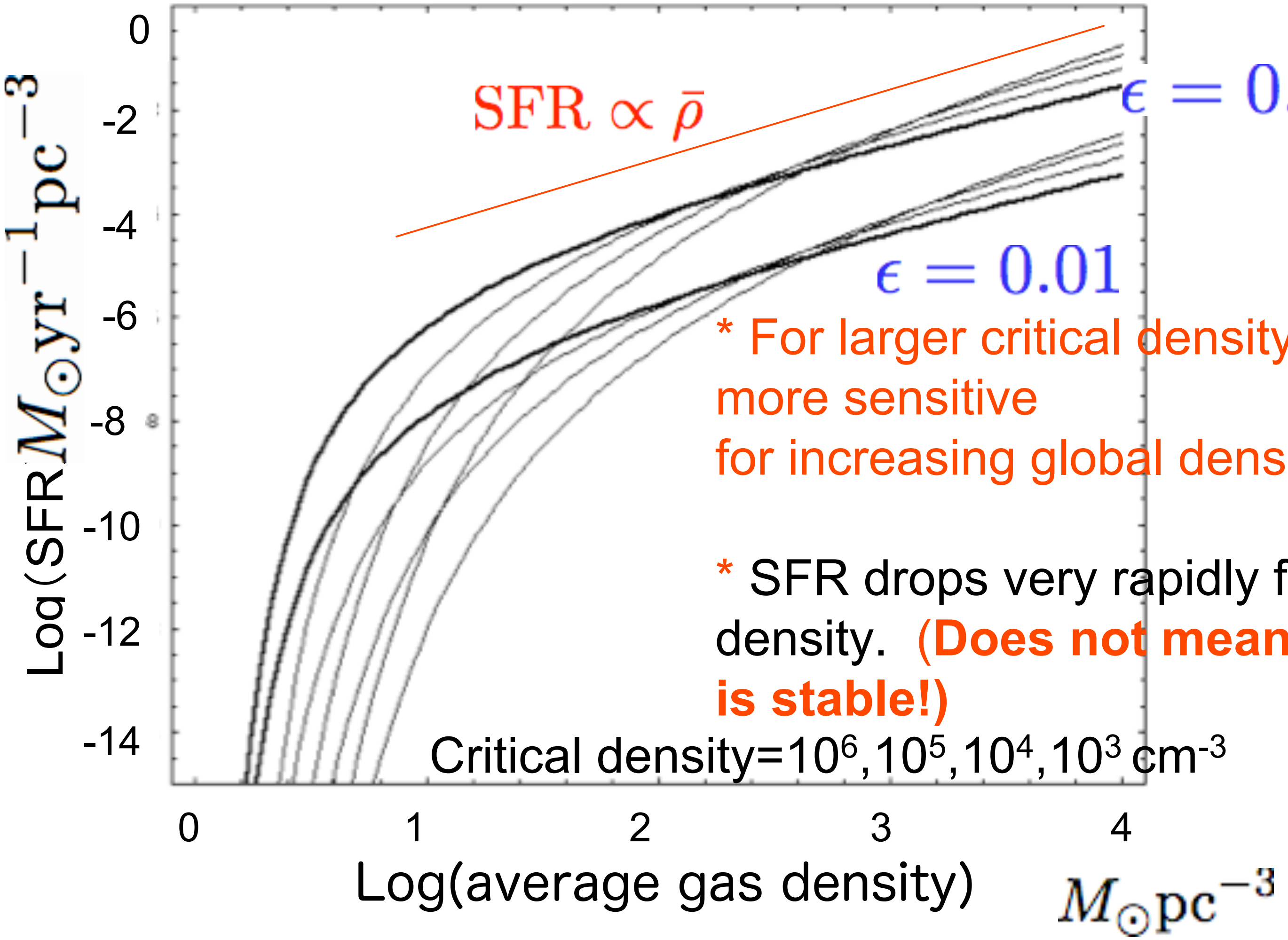
Fraction of gas denser than a critical density:

$$f_c(\delta_c) = \frac{\int_{\ln\delta_c}^{\infty} \delta \exp\left[-\frac{(\ln\delta)^2}{2\sigma^2}\right] d(\ln\delta)}{\int_{-\infty}^{\infty} \delta \exp\left[-\frac{(\ln\delta)^2}{2\sigma^2}\right] d(\ln\delta)}, \qquad \delta_c \equiv \rho_c/\rho_0$$

$$= \frac{1}{2}[1 - \mathrm{Erf}[z(\delta_c)]] \qquad z(\delta_c) \equiv \frac{\ln\delta_c - \sigma^2/2}{\sqrt{2}\sigma}$$

SFR depends on average gas density on a kpc-scale

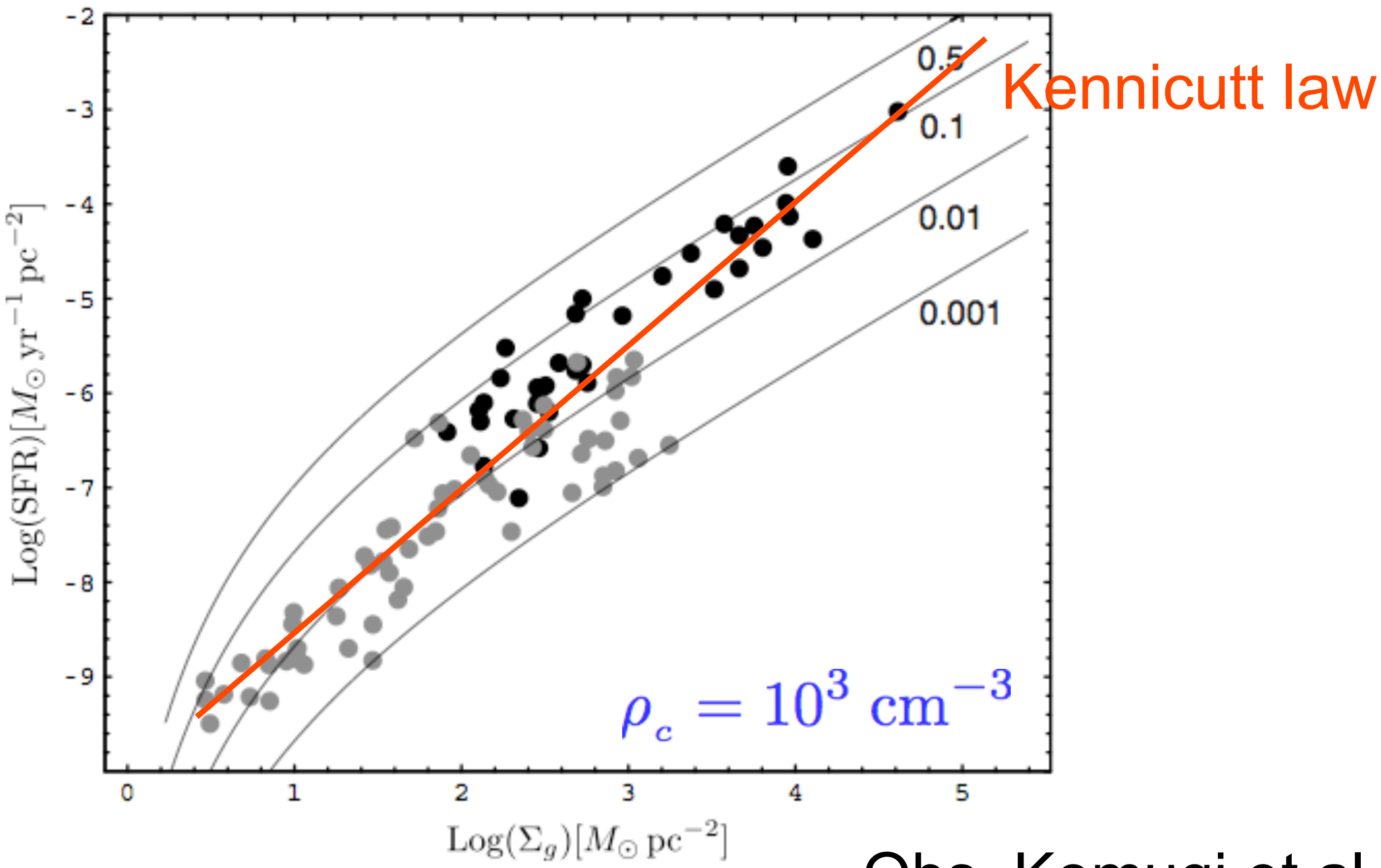
$$\dot{\rho}_\star = \epsilon_c (G\delta_c)^{1/2} f_c \rho_0^{3/2} e^{\sigma^2/2}$$



* For larger critical density, SFR is more sensitive for increasing global density.
* SFR drops very rapidly for lower density. **(Does not mean the disk is stable!)**

Comparison with observed SFR

Normal galaxies SF Efficiency =0.001~0.01
Starburst Efficiency=0.01~0.1



Obs. Komugi et al.

What is the characteristic density ρ_0?

Effective sound velocity takes the minimum around ρ_0

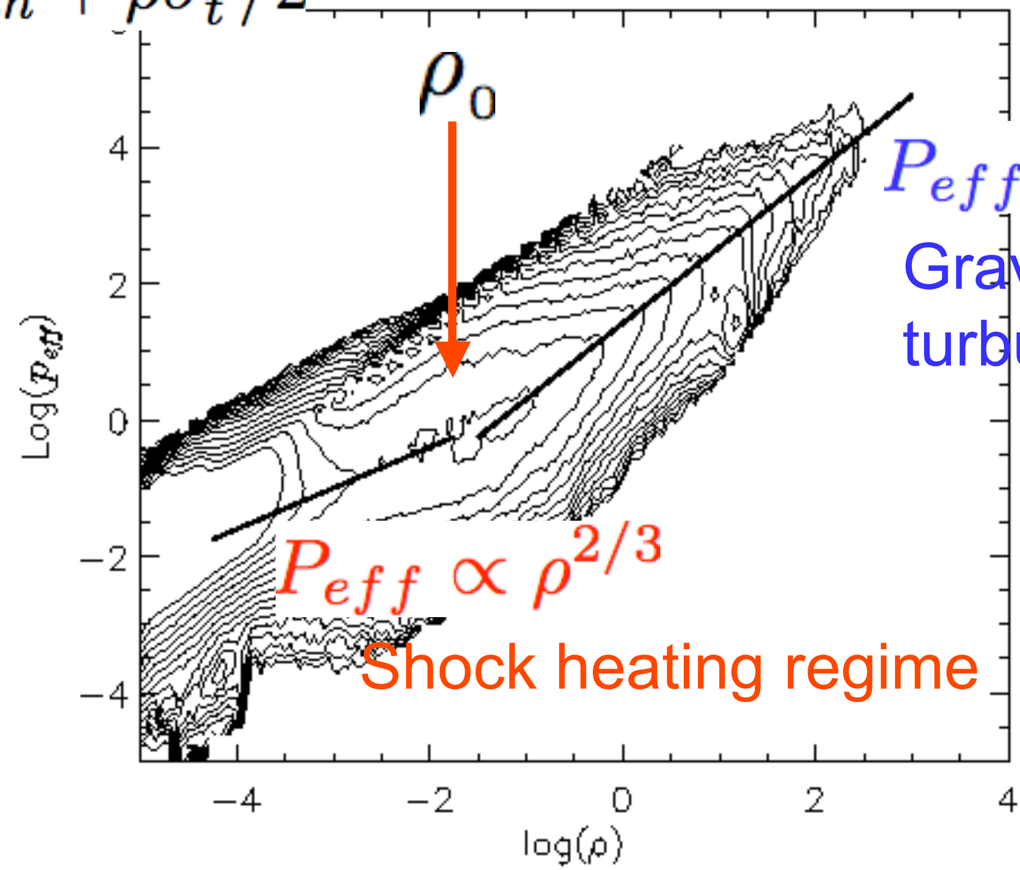
$$c_{eff}^2 \equiv dP_{eff}/d\rho$$

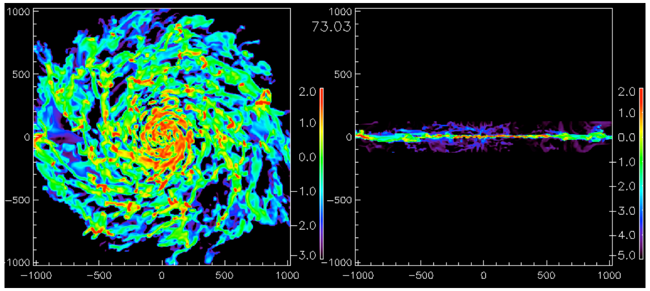
$$P_{eff} \equiv P_{th} + \rho\sigma_t^2/2$$

→ " turbulent flow is *stagnated* around ρ_0"

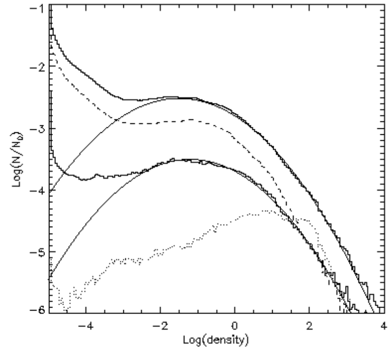
c_{eff} is minimum

ρ_0 is nearly constant $\sim 1\mathrm{cm}^{-3}$





Summary



- Density structure of the ISM in galactic disks revealed by 3-D simulations
  - It is characterized by a Log-Normal PDF
  - This is a feature of globally stable, inhomogeneous system produced by non-linear development of instabilities.
  - Dispersion of LN-PDF is a function of the average density (total gas mass)
- If this is universal, then
  - SFR in galaxies can be described as a function of average gas density, and critical density for local SF (generalized Schmidt-Kennicutt law).
  - High SFR is due to large fraction of high density gas (consistent with observations) and high efficiency.

- There would be a mechanism to enhance SF efficiency in dense clouds in starbursts. -> positive feedback?