Interstellar Medium (ISM)

Lecutre given at the Summer School:
"Magnetic Fields: From Star-forming Regions to Galaxy Clusters and Beyond"

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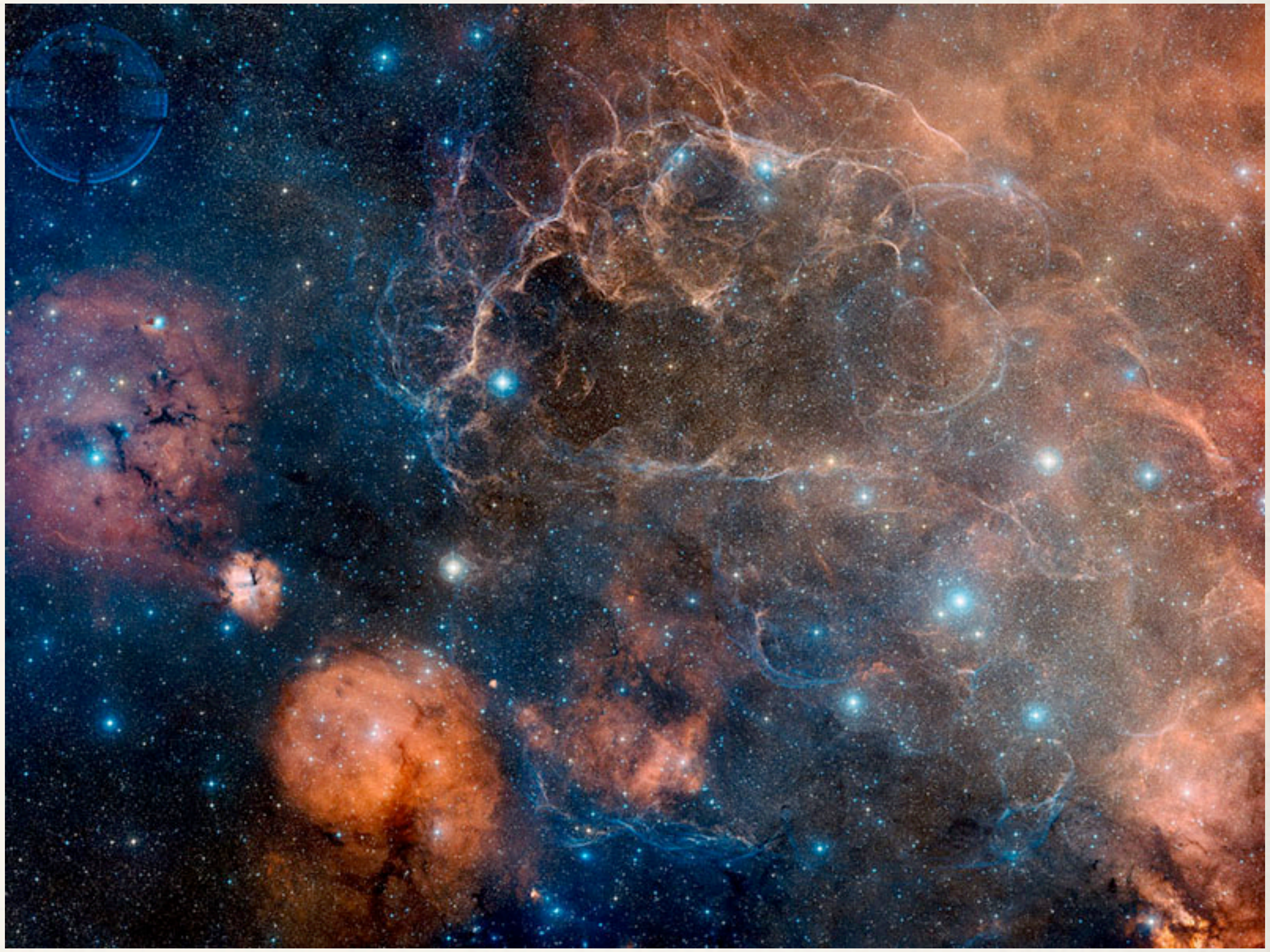
Lecture Overview

- Introduction
- Tools: Shocks, Instabilities, Turbulence
- Textbook ISM
- Complex ISM: Numerical Simulations
- Summary and Outlook


M51
HST / WFPC2

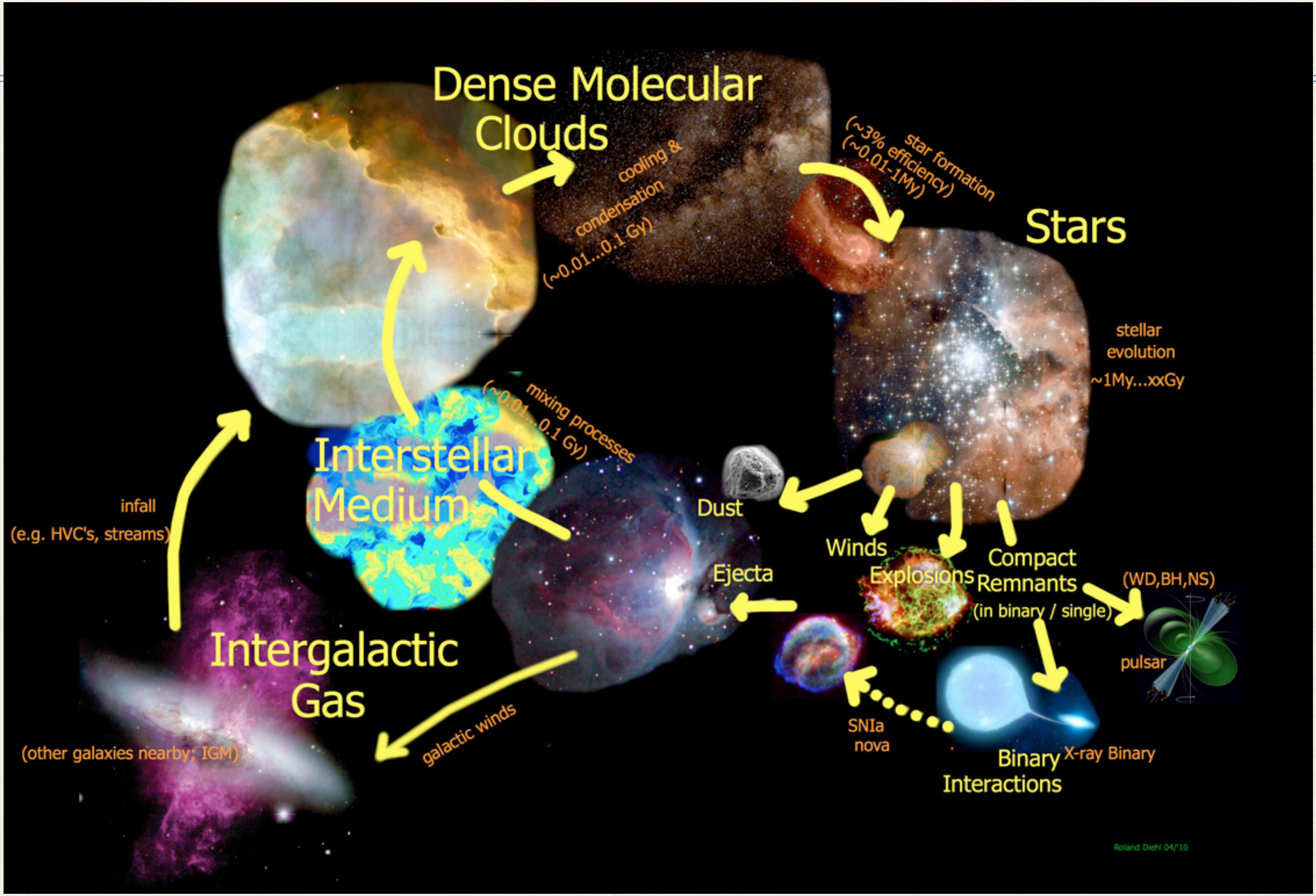
Introduction

- ISM is substrate from which stars form ➔ fundamental prerequisite of planetary systems and life
- Main components: **plasma**, **dust**, **magnetic fields, cosmic rays**
- ISM is immersed in galactic **gravitational potential** ➔ star formation can proceed
- ISM is a complex **nonlinear** system ➔ understanding of its structure and evolution is a major cornerstone of astrophysics



ISM region including Vela SNR in visible light: young stars, gas, dust, bubbles, shocks Credit: ESA/ESO/NASA Digitized sky

Galactic Matter Cycle



Tools: Hydrodynamic Equations

$$\frac{\partial\rho}{\partial t} + \vec{\nabla}(\rho\ \vec{v}) = Q \qquad (1) \quad Q\text{... Massenquellterm}$$

$$\rho\frac{\partial\vec{v}}{\partial t} + \rho\left(\vec{v}\vec{\nabla}\right)\vec{v} \equiv \rho\frac{d\vec{v}}{dt} = -\vec{\nabla}P + \vec{F}_{ext} \quad (2)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \left(\vec{v}\vec{\nabla}\right)(\rho\varepsilon) = \frac{d(\rho\varepsilon)}{dt} = \rho\Gamma - \rho^2\Lambda, \quad (3)$$

$$\frac{\partial}{\partial t}\left(\rho\varepsilon + \frac{1}{2}\rho u^2\right) = -\vec{\nabla}\left(\rho\vec{u}\left[\frac{1}{2}u^2 + \frac{\gamma}{\gamma-1}\frac{p}{\rho}\right]\right) + S, \quad (3')$$

$$\frac{d}{dt}\left(\frac{P}{\rho^\gamma}\right) = 0, \text{ (adiabatisch: } \delta Q = 0) \quad (4)$$

$$T = const. \quad \text{(isotherm)}$$

S … source of energy flux; Γ … heating function; Λ … cooling function

ε … energy per unit mass [J/kg]; F_{ext} … external body force

Solution of PDE's for given initial and boundary conditions

Tools: Shocks

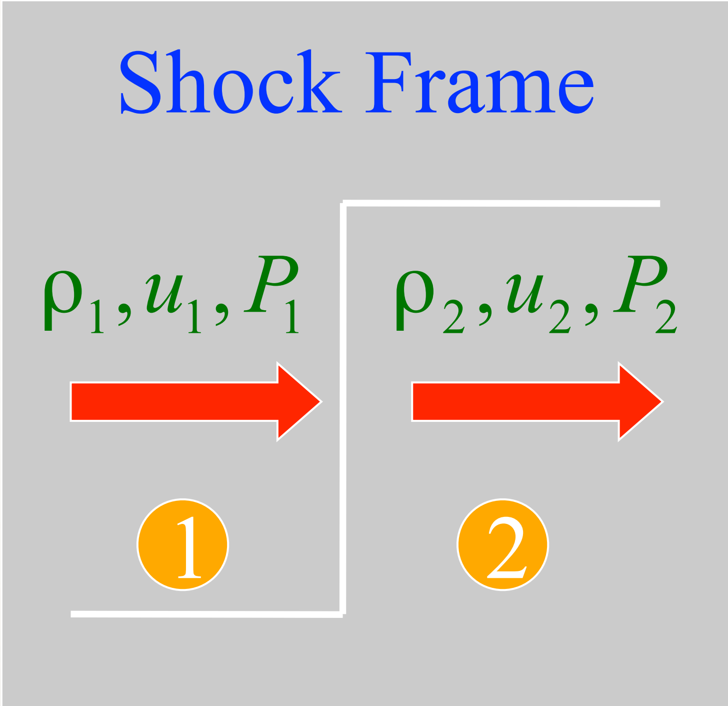
- Assumption: perfect gas, B=0
- ISM has low densities ➔ mean free path >> thickness: collisionless ➔ plasma instabilities and turbulent electromagnetic fields randomize incoming particle distribution
- treat shock as discontinuity and apply conservation laws (∂/∂t=0)

Rankine-Hugoniot Conditions

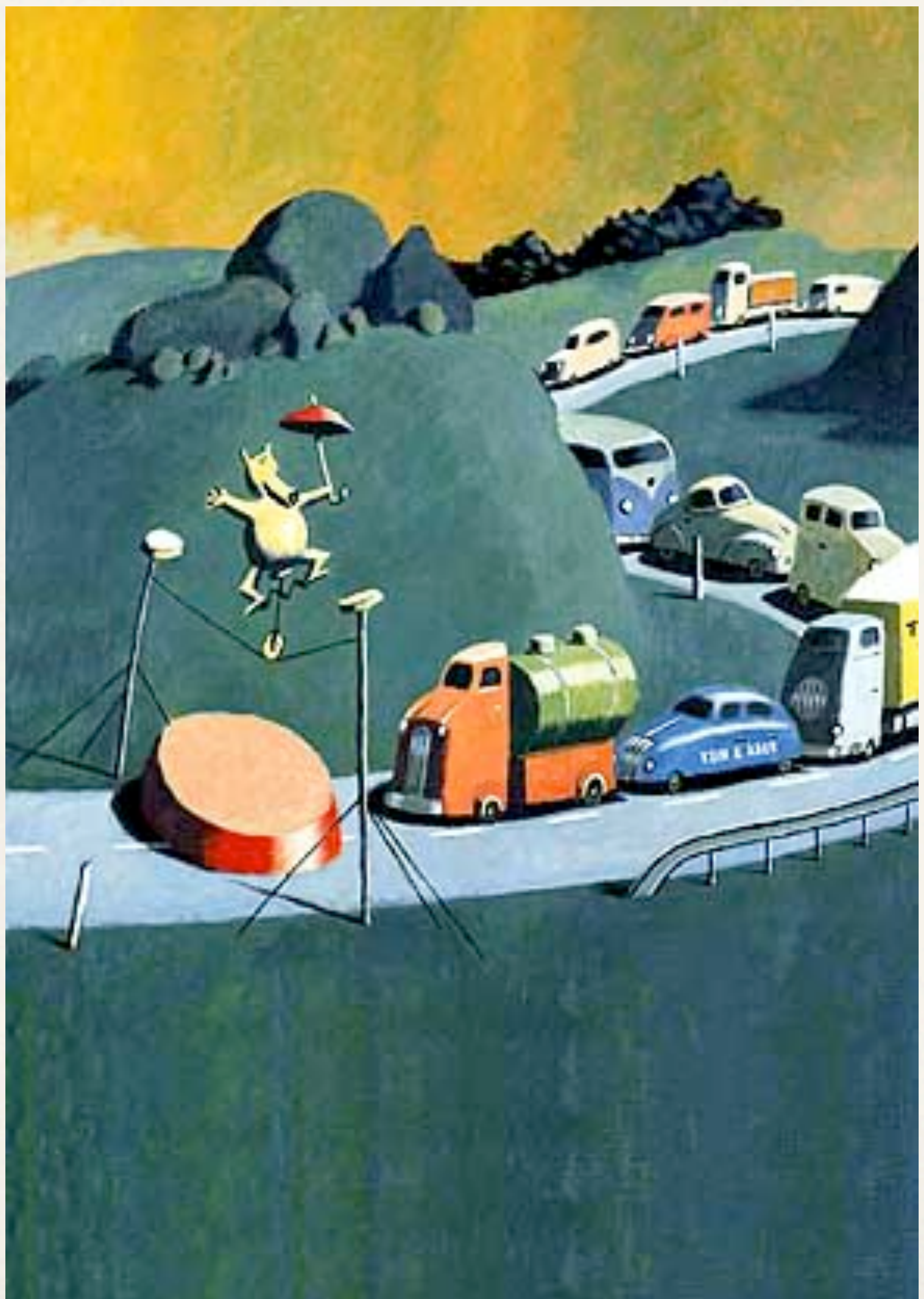
$$\rho_1 u_1 = \rho_2 u_2 \quad \text{(mass)}$$

$$P_1 + \rho_1 u_1^2 = P_2 + \rho_2 u_2^2 \quad \text{(momentum)}$$

$$\frac{1}{2}\rho_1 u_1^2 + \frac{\gamma}{\gamma - 1}\frac{P_1}{\rho_1} = \frac{1}{2}\rho_2 u_2^2 + \frac{\gamma}{\gamma - 1}\frac{P_2}{\rho_2} \quad \text{(energy)}$$



How does the famous traffic jam from "Nothing" originate?



Or is there a physical explanation?

Analoga: Traffic Jam

- „Speed of sound“ c_s= vehicle distance/reaction time=d/τ
- If car density is high and/or people are „sleeping“: c_s decreases
- If $v_{car} \geq c_s$ then a shock wave propagates backwards due to „supersonic“ driving
- Culprits for jams are people who drive too fast or too slow because they are creating constantly flow disturbances

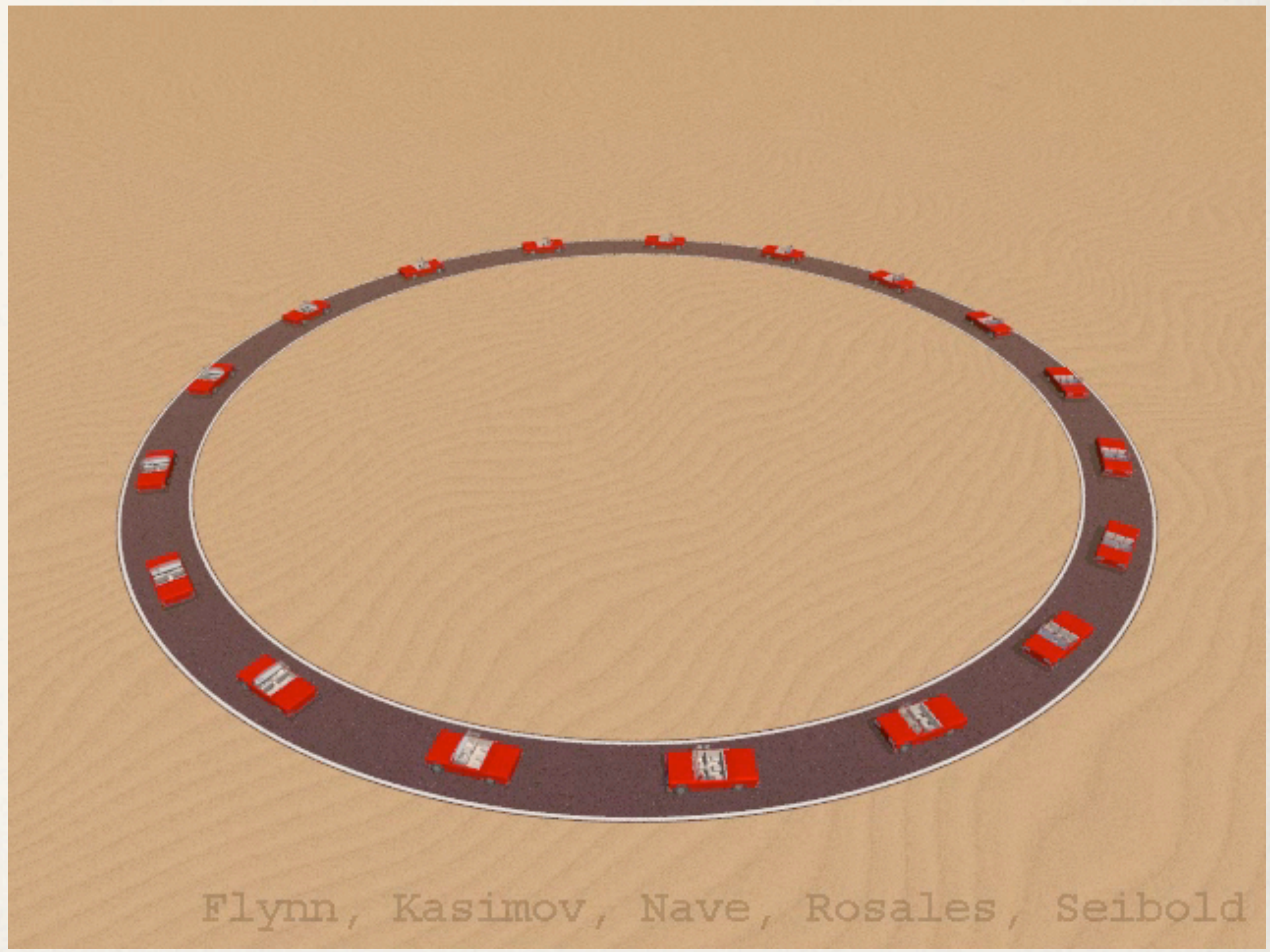
For each traffic density there is a maximum current density jmax and hence an optimum car speed to make $dj_{max}/d\varrho$ =0!

If $v_{car} \geq c_s = d/\tau$: Shock wave propagates backwards

Why?

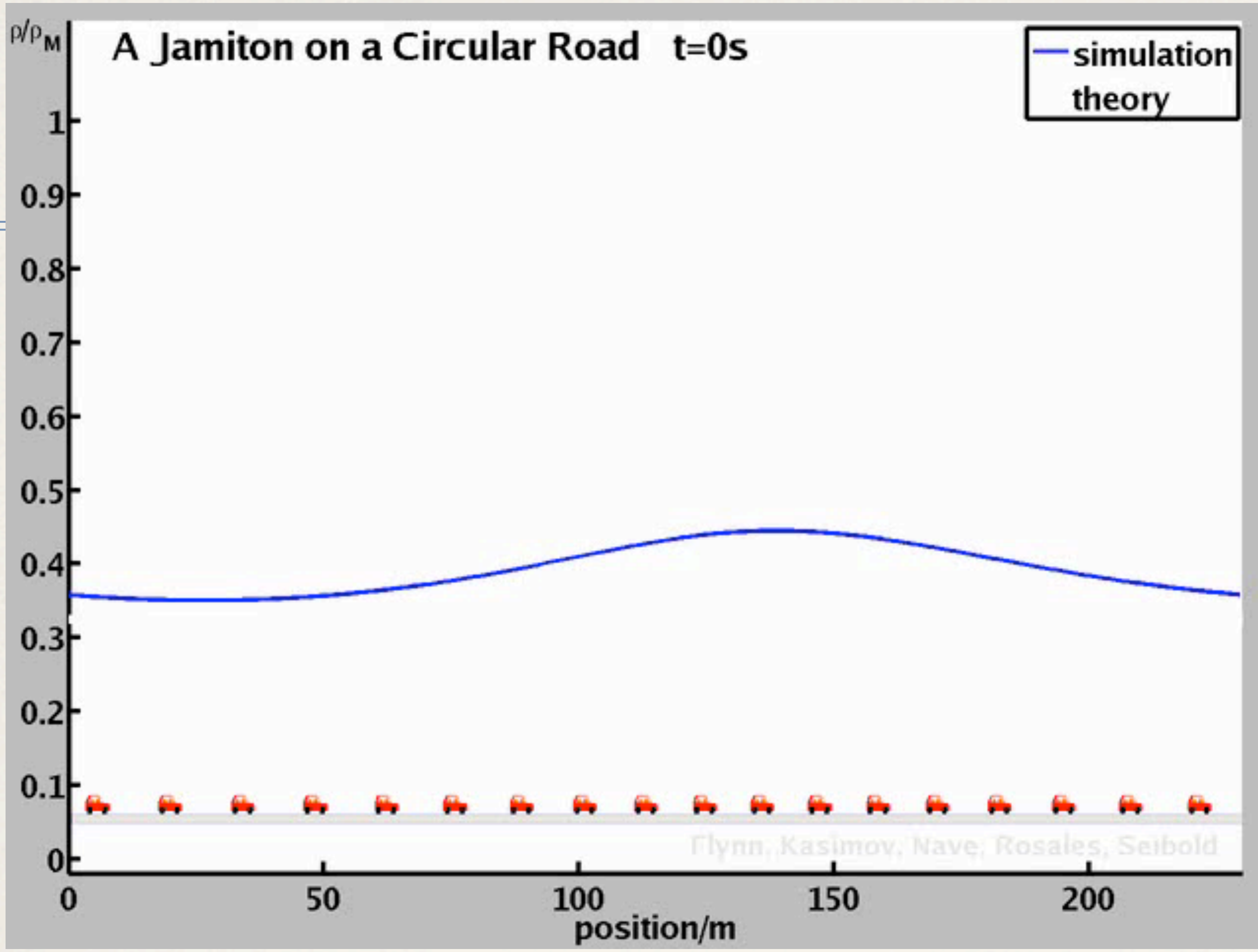
Obstacles, “extreme” driving ➔ drivers have to break ➔ Generation of perturbations in traffic flow

➔ “steepening” of perturbation into a into backwards travelling shock wave



Credit: Traffic Jam Modelling, MIT, USA

Numerical Simulation



Credit: Traffic Jam Modelling, MIT, USA

For each traffic density ρ exists a maximum flow density $j_{max} = \rho\, v_{car}$ and thus an optimal car speed, so that: $dj_{max}/d\rho = 0$, i.e. the traffic flux has a maximum!

Hydraulic Jump

„sound speed": $c_s = \sqrt{gh}$ (Theory of Shallow Water)

Kitchen Sink Experiment

total pressure:

$P_{tot} = P_{ram} + P_{hyd}$

$$P_{tot} = \rho v^2 + \rho gh$$

At the bottom: $v > c_s$

➔jump in water heigh

Behind the jump:

$h_2 > h_1$

$V_2 < V_1$

$V_1 > c_1$ „ supersonic"

$V_2 < c_2$ „ subsonic"

Tools: Fluid instabilities

- Equilibrium configurations (especially in plasma physics) are often subject to instabilities
- **Boundary surfaces**, separating two fluids are susceptible to become unstable (e.g. contact discontinuity, stratified fluid)

- Simple test: **linear perturbation analysis**
  - Assume a **static background** medium at rest
  - Subject the system to **small amplitude disturbances: $X \sim e^{i(kx+\omega t)}$**
  - If $\mathrm{Im}(\omega) < 0$: **exponential growth** with time
  - However: no guarantee, system can be 1st order stable and 2nd or higher order unstable

Rayleigh-Taylor & Kelvin-Helmholtz instability

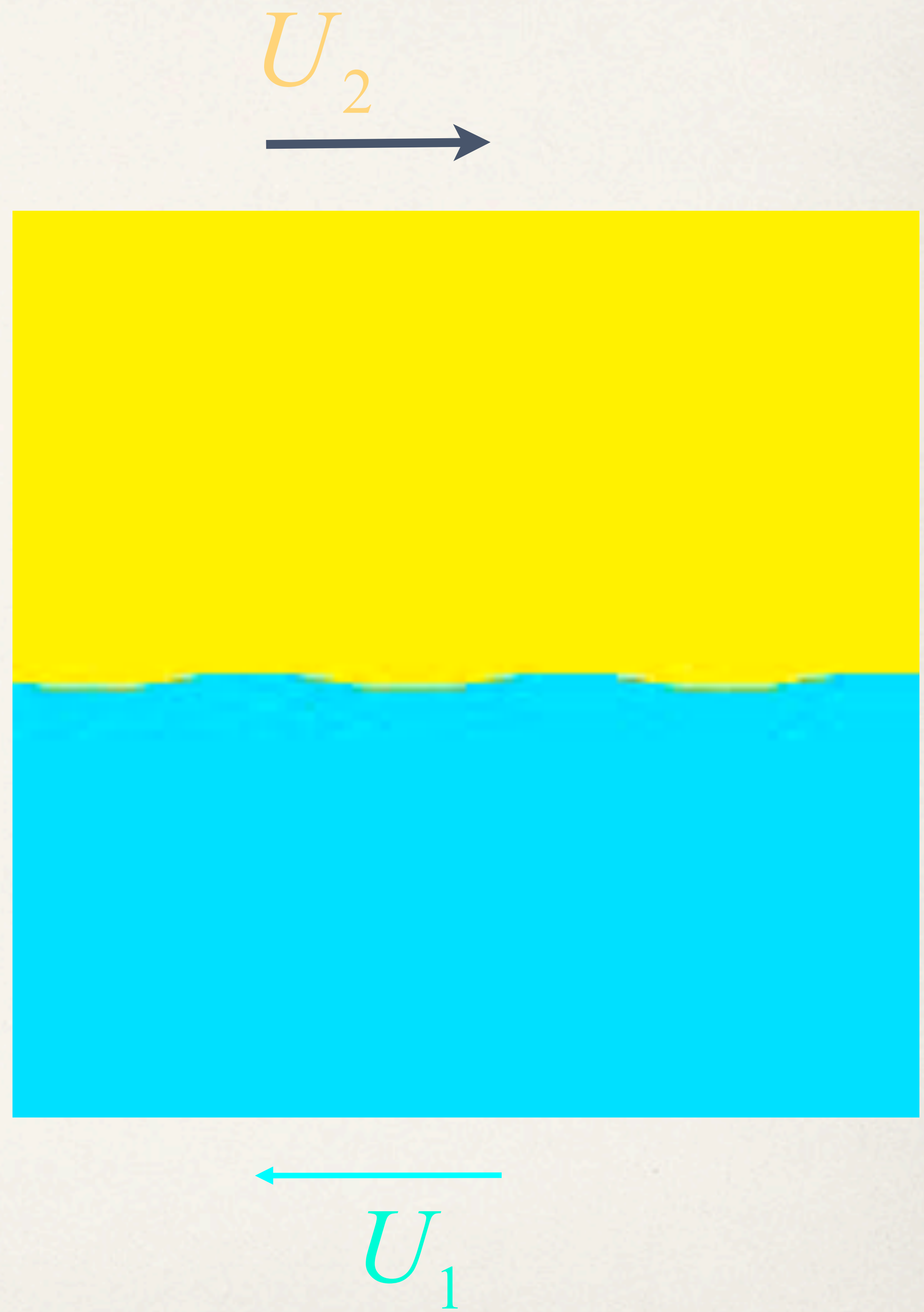
Gravity waves: fluid with different density at interface ➔ gravity acts as restoring force to fluid element displaced from equilibrium (e.g. water waves, clouds); $c=(g/k)^{1/2}$

- Why does the surface on a lake have ripples?

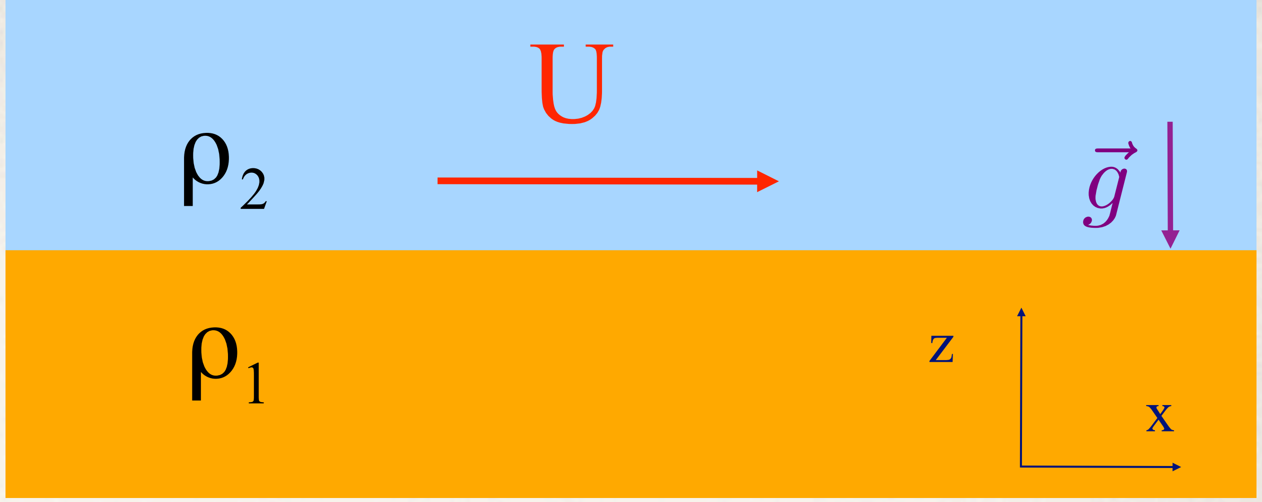
Rayleigh-Taylor & Kelvin-Helmholtz instability

Cloud – wind interface:
 Shear flow generates ripples and kinks in the cloud surface due to Kelvin-Helm-holtz instability: „Cat's eye" pattern

2D Simulation of Shear Flow



Fluid instabilities



z=zs: surface where ϱ changes discontinously

$$\rho\frac{\partial u}{\partial t}+\rho\,U\frac{\partial u}{\partial x}+\rho\,w\frac{dU}{dz}=-\frac{\partial}{\partial x}\delta P$$

$$\rho\frac{\partial v}{\partial t}+\rho\,U\frac{\partial v}{\partial x}=-\frac{\partial}{\partial y}\delta P$$

$$\rho\frac{\partial w}{\partial t}+\rho\,U\frac{\partial w}{\partial x}=-\frac{\partial}{\partial z}\delta P-g\delta\rho$$

$$\rho\frac{\partial\delta\rho}{\partial t}+U\frac{\partial\delta\rho}{\partial x}=-w\frac{d\rho}{dz}$$

$$\frac{\partial\delta z_s}{\partial t}+U_s\frac{\partial\delta z_s}{\partial x}=w(z_s)$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

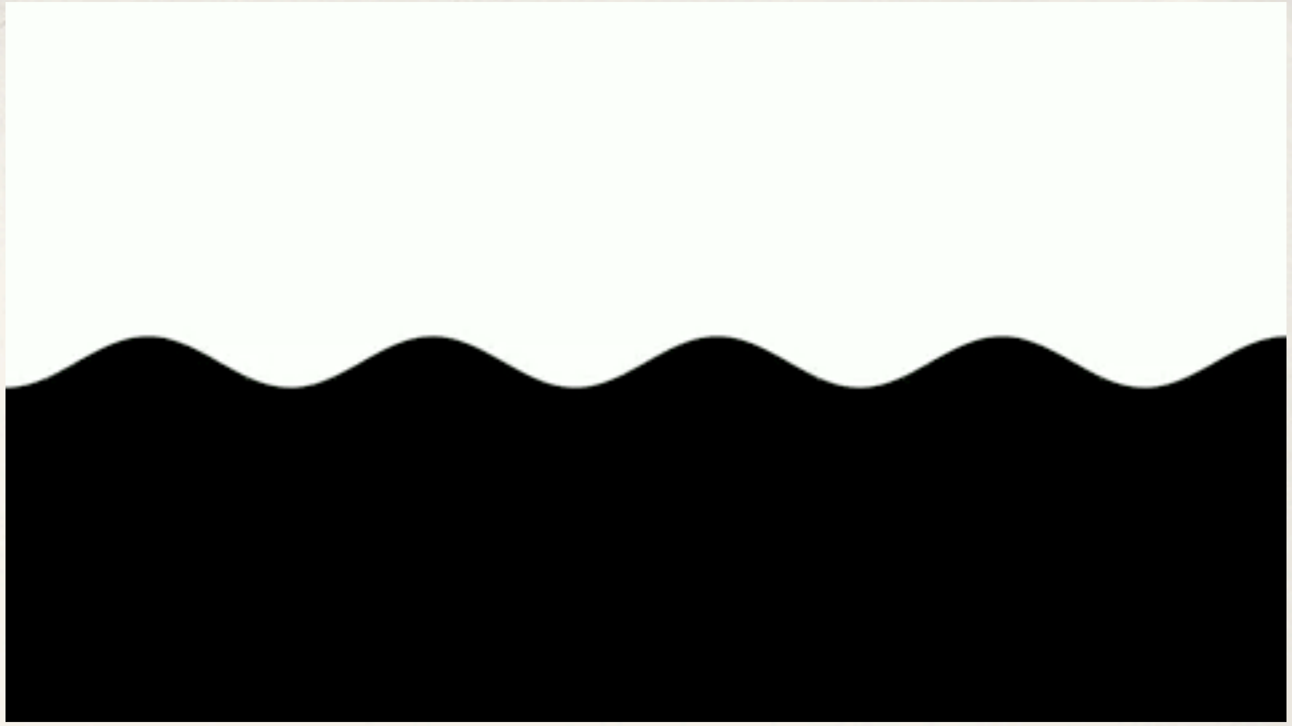
- inserting normal modes into perturbed equations yields a dispersion relation ($\nabla\rightarrow i\,\mathbf{k}$, $\partial/\partial t\rightarrow i\,\omega$)
- growth rate: $\omega\equiv\sigma$,

$$\sigma=-k_x\frac{\rho_1U_1+\rho_2U_2}{\rho_1+\rho_2}\pm\left[gk\frac{\rho_1-\rho_2}{\rho_1+\rho_2}-k_x^2\frac{\rho_1\rho_2(U_1-U_2)^2}{(\rho_1+\rho_2)^2}\right]^{1/2}$$

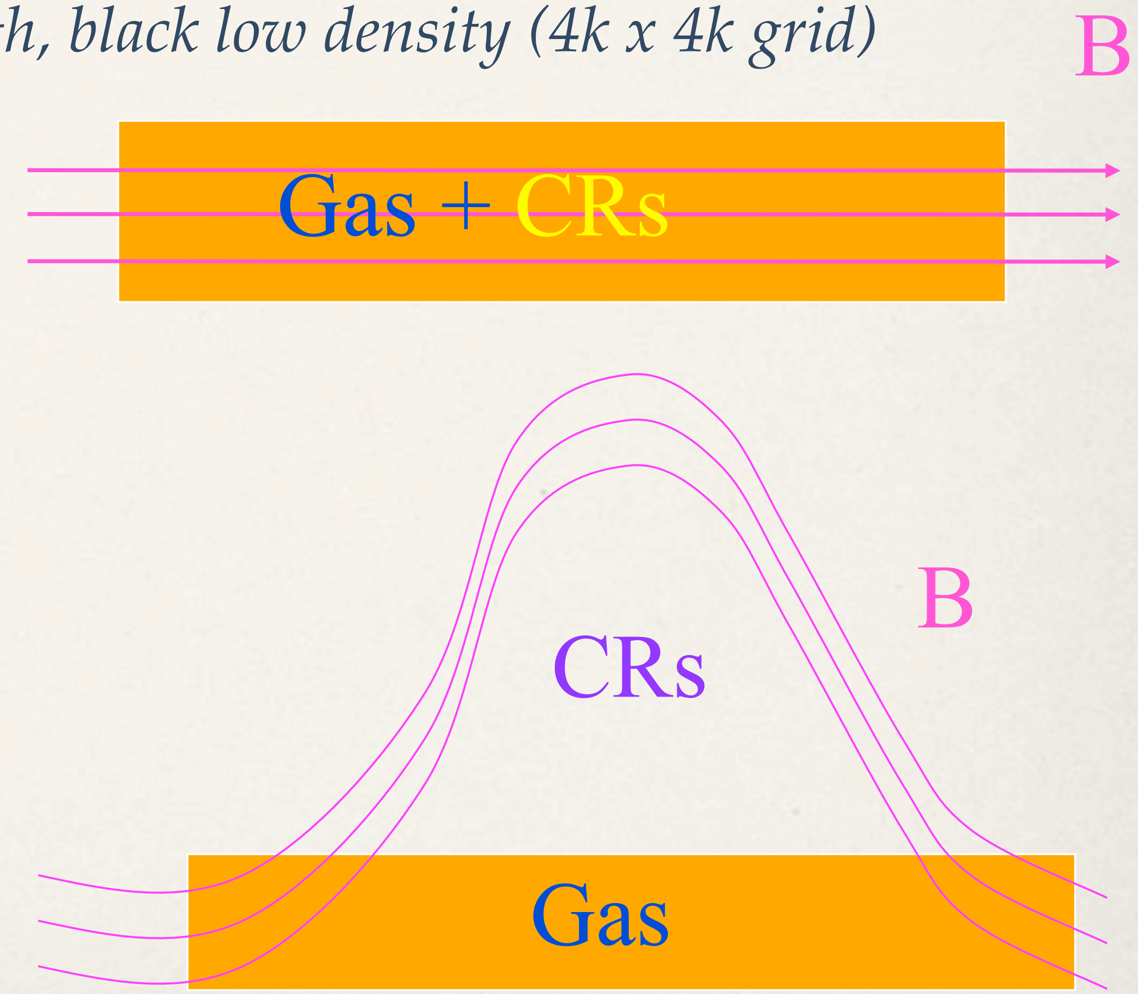
- If $k_x=0$: $\sigma=\pm\sqrt{gk\frac{\rho_1-\rho_2}{\rho_1+\rho_2}}$ $\quad k_x=k\cos\vartheta$
- Rayleigh-Taylor instability
- $k_x\neq0$: $k>\frac{g(\rho_1^2-\rho_2^2)}{\rho_1\rho_2(U_1-U_2)^2\cos^2\vartheta}$
- Kelvin-Helmholtz instability

Fluid instabilities

- Rayleigh-Taylor instability (**RTI**): $\varrho_1 < \varrho_2$ (depending on direction of acceleration!)
- Kelvin-Helmholtz instability (**KHI**): for $U_1 - U_2 \neq 0$ always; large velocity difference leads to long wavelength instability
- **Parker instability**: cosmic rays (CRs) coupled to B-field, which is frozen into plasma and held down to disk by gas
- CRs exert buoyancy forces ➔ gas slides down field lines to minimi-ze potential energy ➔ "Parker loops"



Rayleigh-Taylor instability (2D Sim): white is high, black low density (4k x 4k grid)



Parker instability (qualitative picture)

Thermal Instability

Classical Theory due to Field (1965)

- criterion can be directly derived from 2nd law of thermodynamics

$$T\frac{dS}{dt} = -(\gamma - 1)L$$

L…net energy loss function (L=0 thermal equ.)

- perturb the entropy S→S+δS and linearize: $$\frac{d\ln|\delta S|}{dt} = -(\gamma-1)\left[\frac{\partial(L/T)}{\partial S}\right]_A$$

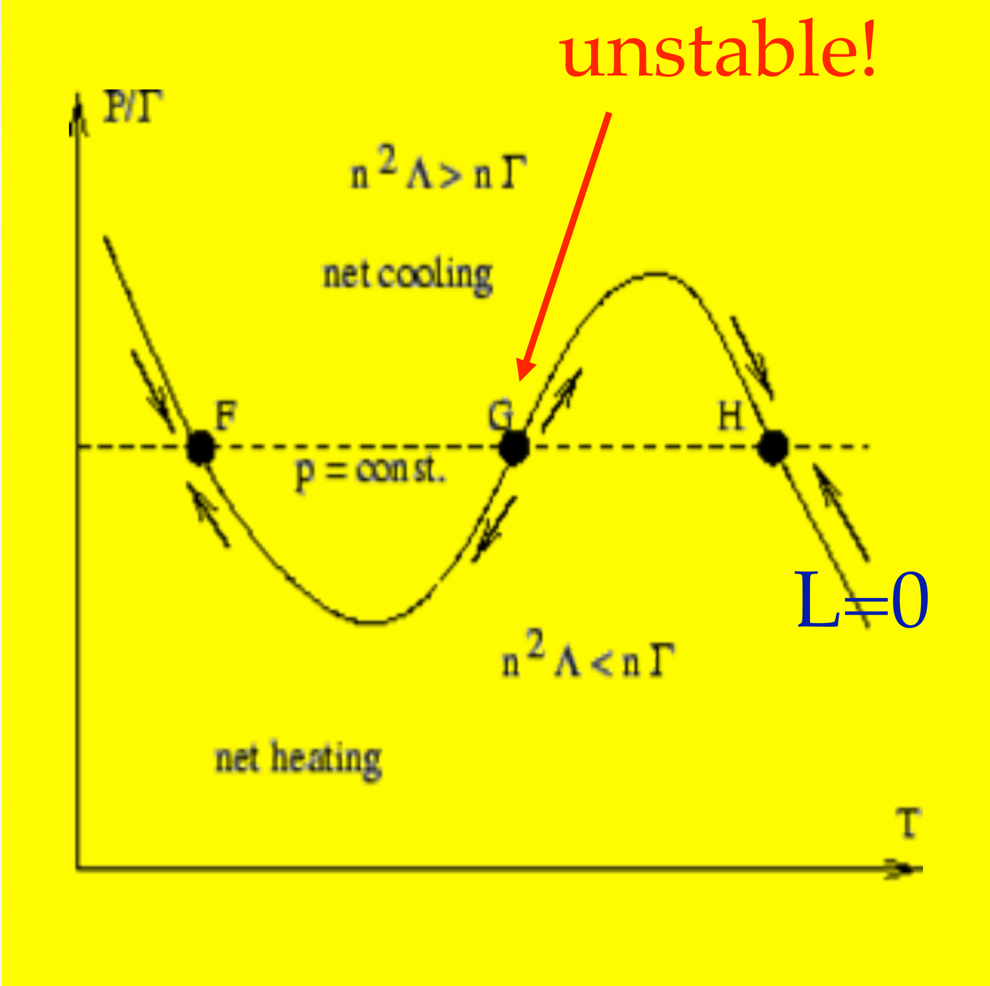
- Stability, if δS decreases with time, i.e. $$\left[\frac{\partial(L/T)}{\partial S}\right]_A > 0$$

- Perturb around equilibrium at constant pressure, i.e mechanical equilibrium ($dS=C_p\,dT$) for local condensational modes ($C_p>0$):

$$\left(\frac{\partial L}{\partial T}\right)_P > 0$$

easily violated for standard interstellar cooling functions

- Field criterion does not take into account dynamical processes, e.g. turbulence
- Turbulent diffusion can stabilize, inhibiting local condensation modes (cf. solar chromosphere): $\nu_{turb} \sim Re\, \nu_{mol}$
- Thermal instability inhibited, if fluctuations occur on time scales less than the cooling time: $\boldsymbol{\tau_{eddy} << \tau_{cool}}$



$$\frac{\lambda}{\Delta u} \sim \left(\frac{\rho}{\varepsilon}\right)^{1/3} \lambda^{2/3} < \frac{k_B T}{n\Lambda(T)} \quad (Kolmogorov)$$

$$\Rightarrow \lambda < \left(\frac{k_B \bar{m}}{\Lambda_0}\right)^{3/2} \frac{\varepsilon^{1/2}}{\rho^2} T^{3/4}, \quad \Lambda(T) \sim \Lambda_0 T^{1/2}$$

Points F and H are stable

Stability if:

$$\left(\frac{\partial L}{\partial T}\right)_P > 0$$

$$L = n^2 \Lambda(T) - n\Gamma$$

- incompressible turbulence strictly not true
- for WNM, $\varepsilon \sim 10^{-26}$ erg cm^{-3} s^{-1}, n~0.3cm^{-3}, T~1000 K: $\lambda < 10^{19}$ cm

ISM in Star Forming Galaxies

- Morphology of Galaxies: **Bulge**, **Disk**, **Halo**
- Active star formation in disk galaxies ➔ gas and dust
- Important components to consider: **Magnetic fields, cosmic rays**

	Gas Phase	T [K]	n[cm^{-3}]	f_V	f_M
I	MM[1)] = Molecular Medium (H_2)	~ 20	~ 10^3	0.01	0.3-0.6
II	CNM = cold neutral medium	~ 100	20 – 60	0.05	
III	WNM = warm neutral medium	~ 6000	~ 0.05 – 0.3	0.3 – 0.4	
IV	WIM = warm ionized medium	~ 8000	~ 0.1 – 0.5	0.1 – 0.2	
V	HIM[2)] = hot ionized medium	~ 10^6	~ 10^{-3}	0.5	~ 0.01

1) not in pressure equilibrium (gravitationally bound)
2) no phase transition, heated by SNRs and superbubbles

- According to classical theory gas exists in various stable **phases** in the p-V-diagramm
- Transitions possible by **heating** and **cooling**
- **star formation** drives matter cycle

➔ **how does the interstellar gas evolve?**

Textbook ISM

- **3-Phase ISM** (McKee & Ostriker 1977):
- overall pervasive HIM:
- (n,T) = ($10^{-2.5}$ cm^{-3}, $10^{5.7}$ K)
- regulated by SNe: f_V ~ 0.5-0.7
- HIM interspersed with clouds
- clouds consist of core of CNM and envelopes of WNM, WIM
- smooth distribution in stable phases
- global pressure equilibrium ➔ static view
- **Problems**:
- f_V ~ 0.2 - 0.3
- DIG not predicted
- CNM mostly in filaments not in clouds
- no global pressure equil.: 500 < P/k < 5000 K cm^{-3}
- ~ 50% of WNM in thermally unstable regions (Heiles & Troland 2003)

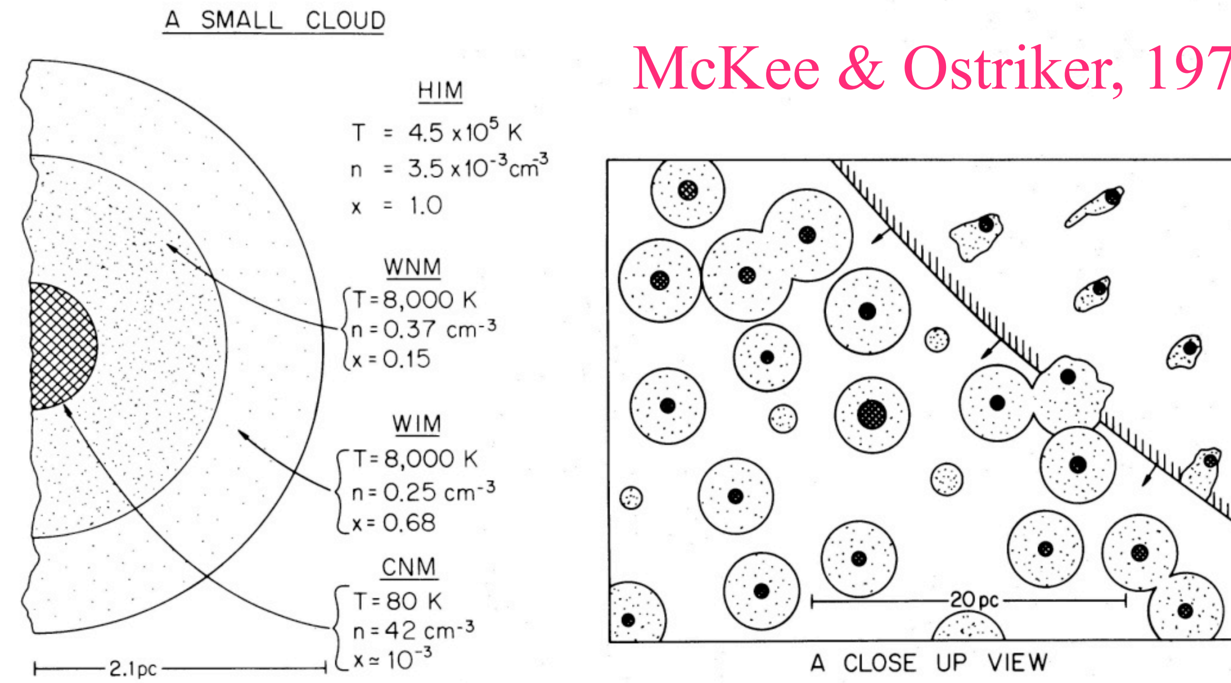


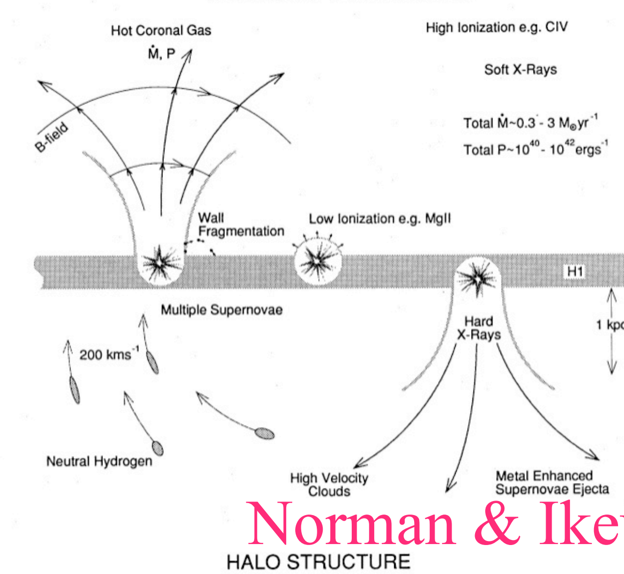
FIG. 1 FIG. 2

McKee & Ostriker, 1977

FIG. 1.—Cross section of a characteristic small cloud. The crosshatched region shows the cold core, which gives the usual optical absorption lines. Next is the warm neutral medium (WNM) with ionization produced by soft X-ray background. The outer layer (WIM) is gas largely ionized by stellar UV background. Typical values of hydrogen density n, temperature T, and ionization $x = n_e/n$ are shown for each component, except that a higher than average value of the soft X-ray flux has been assumed in order to produce a significant amount of WNM at this pressure.

FIG. 2.—Small-scale structure of the interstellar medium. A cross section of a representative region 30 pc × 40 pc in extent is shown, with the area of the features being approximately proportional to their filling factors. A supernova blast wave is expanding into the region from the upper right. The radius of the neutral cores of the clouds (represented by crosshatching) ranges from about 0.4 to 1 pc in this small region; all the clouds with cores have warm envelopes (*dotted regions*) of radius a_w ~ 2.1 pc. A few clouds are too small to have cores. The envelopes of clouds inside the SNR are compressed and distorted.

No. 1, 1989 DISK-HALO INTERACTION 381



Norman & Ikeuchi, 1989

HALO STRUCTURE

FIG. 5.—A sketch of some of the obvious qualitative aspects of the halo structure in the chimney model. The observational characteristics and effects on galaxy evolution of these disk-halo connections are discussed in §§ IV and V.

- **chimney model** (Norman & Ikeuchi, 1989): SNe correlated in space and time ➔ "fountain flow" ➔ reduces f_V
- **but**: is essential physics included?

M33: composite Chandra & HST

- filaments, frothy at high resolution
- structure on scales $\rightarrow$ **turbulence**
- wide range of temperatures, densities $\rightarrow$ **multiphase**
- gas, magnetic fields, cosmic rays, dust … $\rightarrow$ **multicomponent**

Interstellar Turbulence

- **Reynolds Number** is high: $Re = u\,L/\nu \sim 3\ 10^3\ M\ L\ [pc]\ n\ [cm^{-3}]$, i.e. 10^5 - 10^7 (Elemegreen & Scalo, 2004); $M=u/c$ … Mach number
- ISM is highly **turbulent** and **compressible**! (v. Weizsäcker 1951)

- **Possible driving sources**:
  - stellar: HII regions, stellar winds, supernovae (SNe), superbubbles
  - galactic rotation
  - self-gravity
  - plasma instabilities: Rayleigh-Taylor, Kelvin-Helmholtz, magnetorotational instability (MRI), cosmic ray streaming
- **SNe** dominate energy input in spirals (MacLow & Klessen 2004):

$$\epsilon \approx 3 \times 10^{-26} \left(\frac{\eta_{SN}}{0.1}\right) \left(\frac{\sigma_{SN}}{1SNu}\right) \left(\frac{H_D}{100pc}\right)^{-1} \left(\frac{R_{SF}}{15kpc}\right)^{-2} \left(\frac{E_{SN}}{10^{51}erg}\right) \mathrm{erg\,cm^{-3}\,s^{-1}}$$

Turbulence I

- Reynolds-number: **Re**=u L/ν ~**10^5 - 10^7**
- **Nonlinearity due to** term (u∇)u
- Since $\nabla \left(\frac{u^2}{2} \right) = (\vec{u}\nabla)\vec{u} + \vec{u} \times \vec{\omega}, \; \vec{\omega} = \nabla \times \vec{u}$

  take curl of **Navier-Stokes-Eq.** and write it as a function of **vorticity** ω:

$$\frac{\partial \vec{\omega}}{\partial t} = \nabla \times [\vec{u} \times \vec{\omega}] + \nu \Delta \vec{\omega}$$

and since

$$\nabla \times [\vec{u} \times \vec{\omega}] = (\vec{\omega} \cdot \nabla)\vec{u} - (\vec{u} \cdot \nabla)\vec{\omega}$$

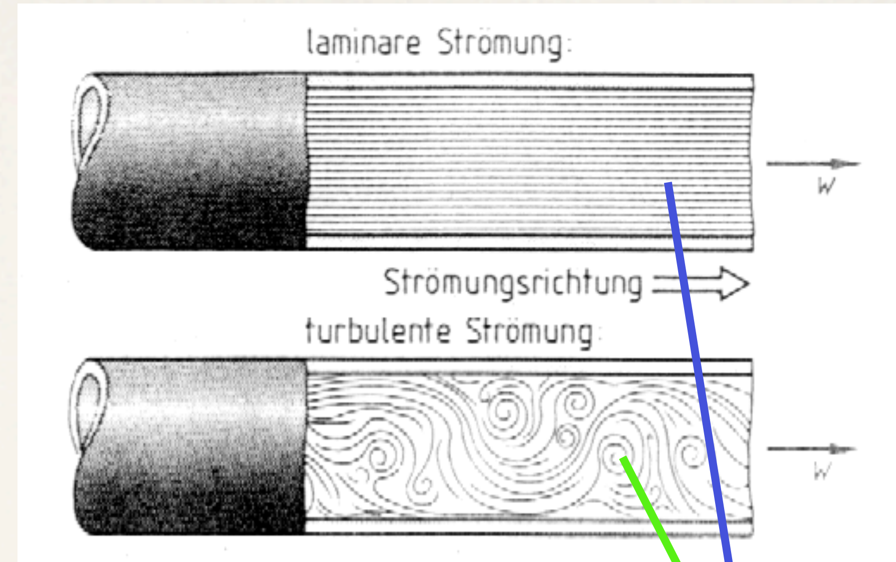
we have

$$\frac{D\vec{\omega}}{Dt} \equiv \frac{\partial \vec{\omega}}{\partial t} + (\vec{u} \cdot \nabla)\vec{u} = (\vec{\omega} \cdot \nabla)\vec{u} + \nu \Delta \vec{\omega}$$

Change of vorticity:

change of moment of inertia by stretching of fluid element (b)

viscous torque due to applied viscous stresses (a))



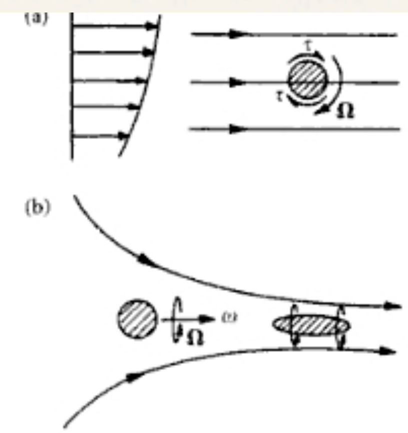
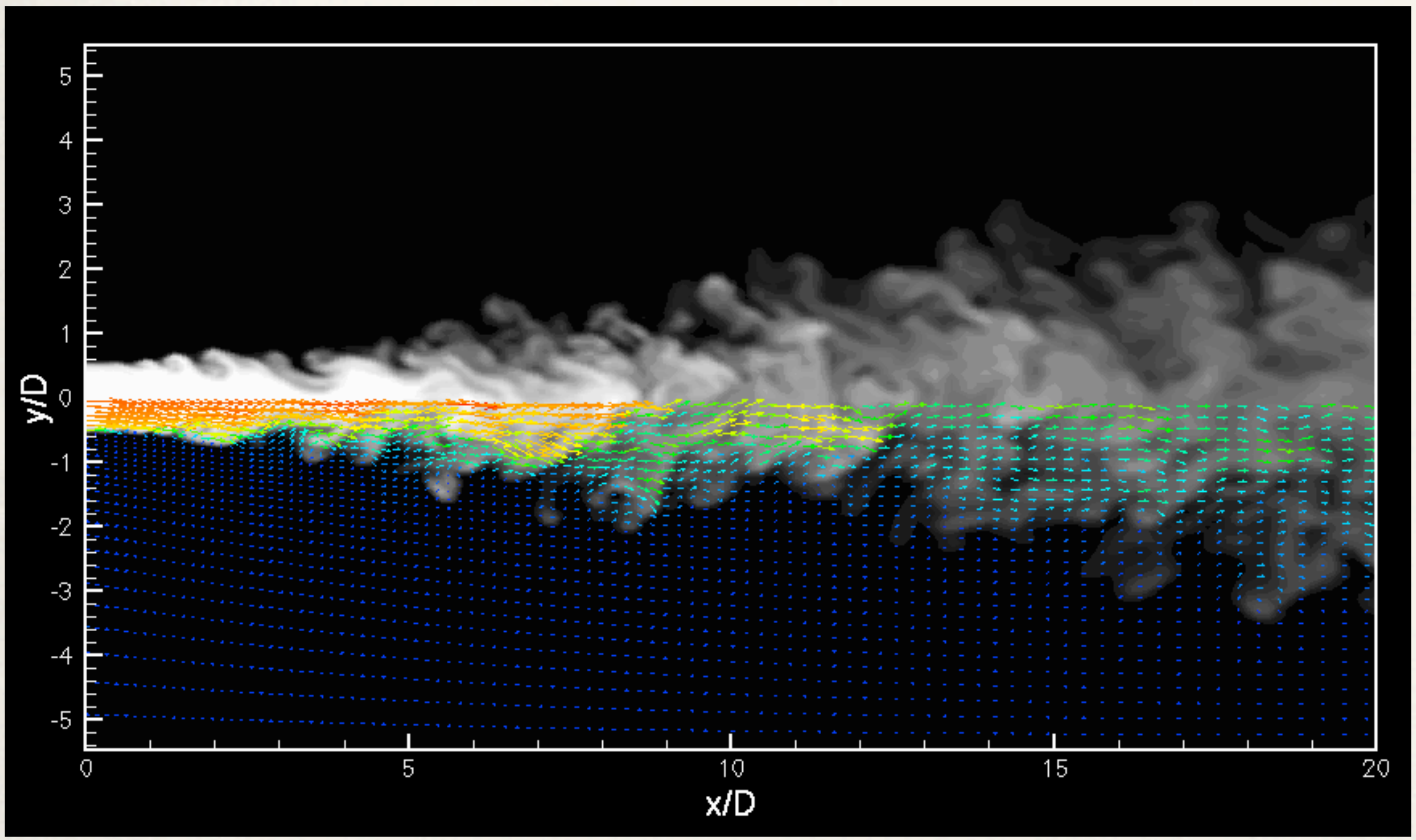


Figure 2.8 Vorticity can change because: (a) viscous forces spin up (or slow down) a fluid element or (b) because the moment of inertia of that element is changed.

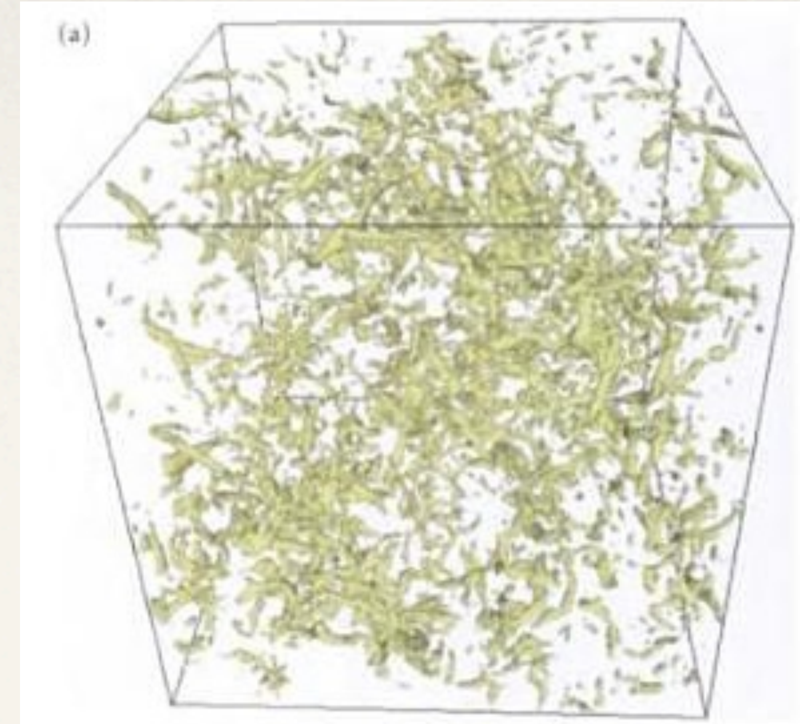
Turbulence II

- **Turbulence**: essentially a 3D chaotic solution of NS-Eq.
- Stretching of fluid elements causes increase in vorticity

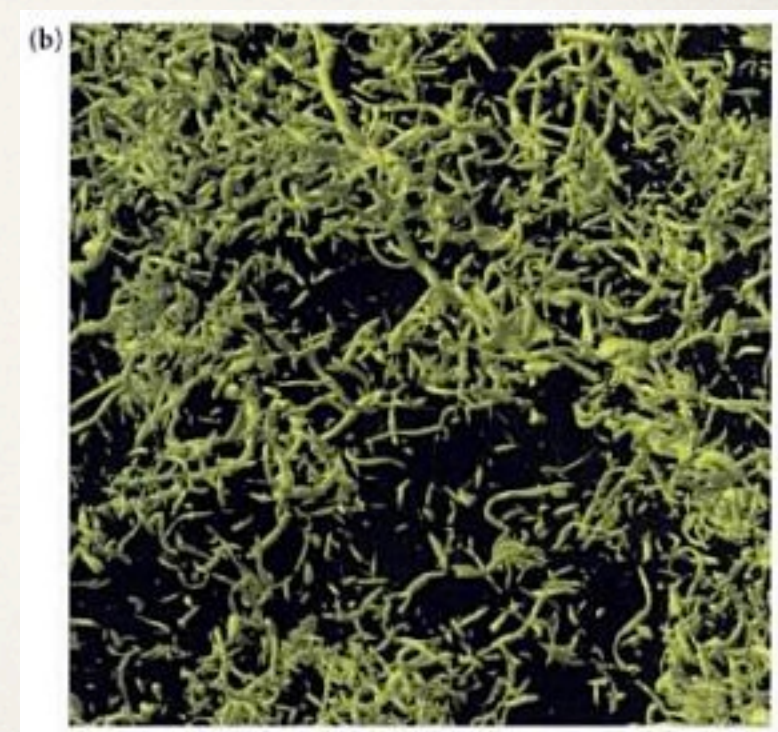
➔ **"vortex tubes"**



3D-Simuation of a laborator jet in non-reactive gas, Re ~21000 (2D projection)
Credit: D. Glaze (Purdue University); arrows: velocity field



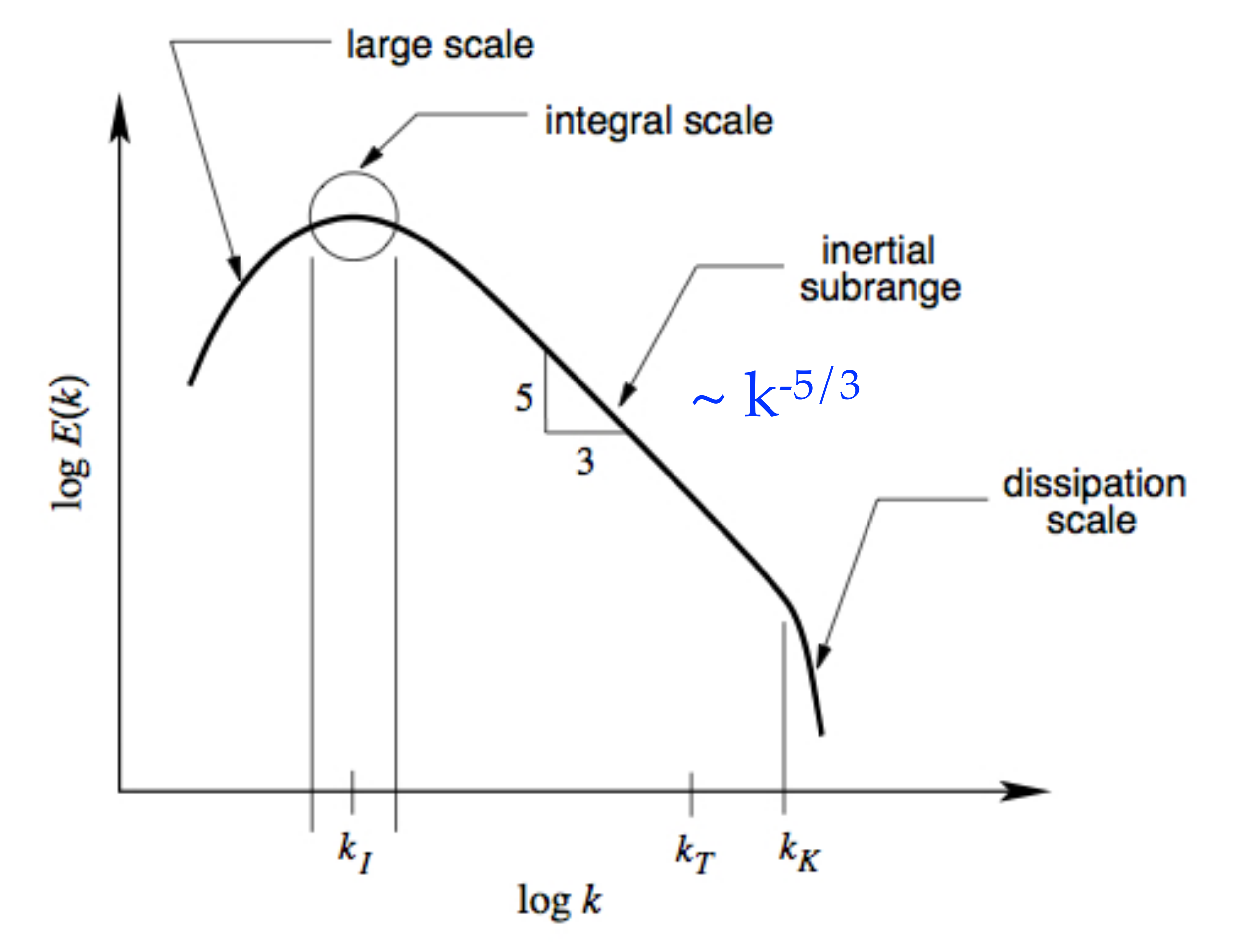
Large Eddy Simulation of isotropic turbulence in a periodic box; shown are contours of vorticity



Direct Numerical Simulation of isotropic turbulence (s.a.); Re ~1200 (cf. Davidson)

Turbulence III

- Turbulence model: **Kolmogorov** (1941), for *incompressible* turbulence ($\nabla u=0$)
- **Assumptions** for large Re:
- (i) turbulence on small scales is *statistically isotropic* ➔ universal character
- (ii) statistics on small scales is exclusively determined by ν and $E_D=\varrho\varepsilon_D=\varrho u^2/\tau$ (**dissipation**)
- Richardson: **energy cascade** from large to small eddies
- Large eddies generated by **instability** ➔ break-up into smaller eddies ➔ kin. energy rate per unit mass $\varepsilon_K=u^2/\tau= u^3/l=\text{const.}$ ("turn-over time": $\tau=l/u$) ➔ $u \sim l^{1/3}$ ($\varrho\sim$const.)
- Energy input on large scales; cascade driven by inertial forces, viscous stresses negligible for large eddies ("**inertial range**")



Spectral energy density E(k) in Kolmogorov turbulence

- Energy dissipation on **micro-scale η** ➔ viscous forces dominate: $Re=u\eta/\nu \sim$ $\sim(\varepsilon_K/\varrho)^{1/3}\,\eta^{4/3} \sim 1$ ➔ $\eta \sim (\nu^3/\varepsilon_K)^{1/4}$
- **Energy dissipation rate** $\varepsilon_D = \varepsilon_K$, independent of Re and l!
- **Dimensiononal analysis**:
- $[k]=1/L$, $[E(k)]=L^3\,T^{-2}$, $[\varepsilon_D]=L^2\,T^{-3}$ ➔ $E(k) = f(k,\varepsilon_D) = C\,\varepsilon_D^{2/3}\,k^{-5/3}$
- C is a universal constant!
- is real turbulence statistically **selfsimilar**?

ISM: Numerical Simulations I

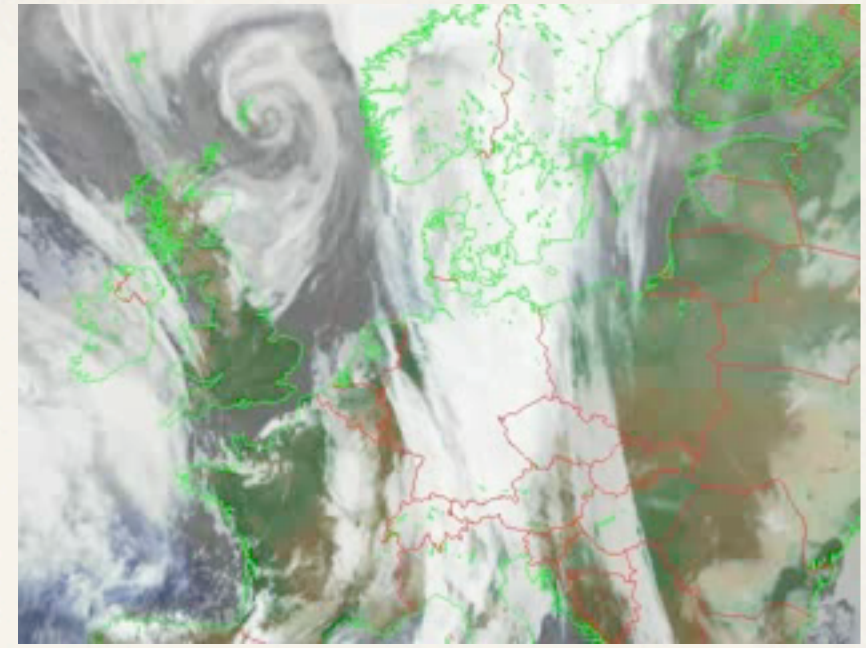
- **ISM** is a highly **nonlinear** system
- described by HD/MHD equations with source terms (mass, momentum, energy)
- comparable to meteorology, but compressible
- **Navier-Stokes-Gleichung(NS)**:

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \nabla\cdot\mathbb{T} + \mathbf{f},$$

- T (τ_{ij}) … stress tensor; μ=ϱν; for **Newtonian fluides** (linear viscosity model, e.g. valid for gases):

$$\tau_{ij} = \mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

$$\overbrace{\rho\Big(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\text{Unsteady acceleration}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\text{Convective acceleration}}\Big)}^{\text{Inertia (per volume)}} = \overbrace{\underbrace{-\nabla p}_{\text{Pressure gradient}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}}}^{\text{Divergence of stress}} + \underbrace{\mathbf{f}}_{\text{Other body forces}}.$$



Top: *weather evolution (permanent rain in East Germany 2.-3.11.2009)*
Bottom: *Hurrican Kathrina (development and evolution 24.-30.8.2005)*

ISM: Numerical Simulations II

- Solve full 3D **HD/MHD equations** on a large grid: **1 kpc × 1kpc × ± 10 kpc** (Δx=0.5 pc or less)
- Type Ia,b,c/II SNe random + clustered in disk
- Background heating due to diffuse UV photon field
- Gravitational field by stars + self-gravity
- SFR ∝ local density/temp.: **n >10 cm^{-3}/T<100 K**
- Generate stars according to an IMF
- Formation and motion of OB associations (➔ random velocity of stars)
- Fully time-dependent **non-equilibrium ionization (NEI) structure**
- Evolution of computational volume for τ ~ 400 My
- ➔ sufficiently long to erase memory of initial conditions!
- 3D calculations on parallel processors with adaptive mesh refinement **(AMR)**

ISM: High Resolution numerical Simulations III

- Numerical Solution of HD/MHD-Eqs.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \vec{u} = q$$

$$\frac{\partial \rho \vec{u}}{\partial t} + \nabla \cdot \underline{\mathrm{T}} = \rho \vec{f} + \vec{m}$$

$$\frac{\partial W}{\partial t} + \nabla \cdot \vec{S} = \rho \vec{u}(\vec{f} + \vec{m}) + W_0$$

$$\vec{E} = -\frac{1}{c}\left[\vec{u} \times \vec{B}\right]$$

$$\frac{\partial \vec{B}}{\partial t} = -c\left[\nabla \times \vec{E}\right]$$

$$\nabla \cdot \vec{B} = 0 \,(\text{as initial condition})$$

- ideal MHD ($\sigma \to 0$)

- with

$$\underline{\mathrm{T}} = \rho \vec{u} \otimes \vec{u} + \left[P + \frac{B^2}{8\pi}\right] \cdot \underline{\mathrm{I}} - \frac{\vec{B} \otimes \vec{B}}{4\pi}$$

$$W = \frac{1}{2}\rho u^2 + \frac{P}{\gamma - 1} + \frac{B^2}{8\pi}$$

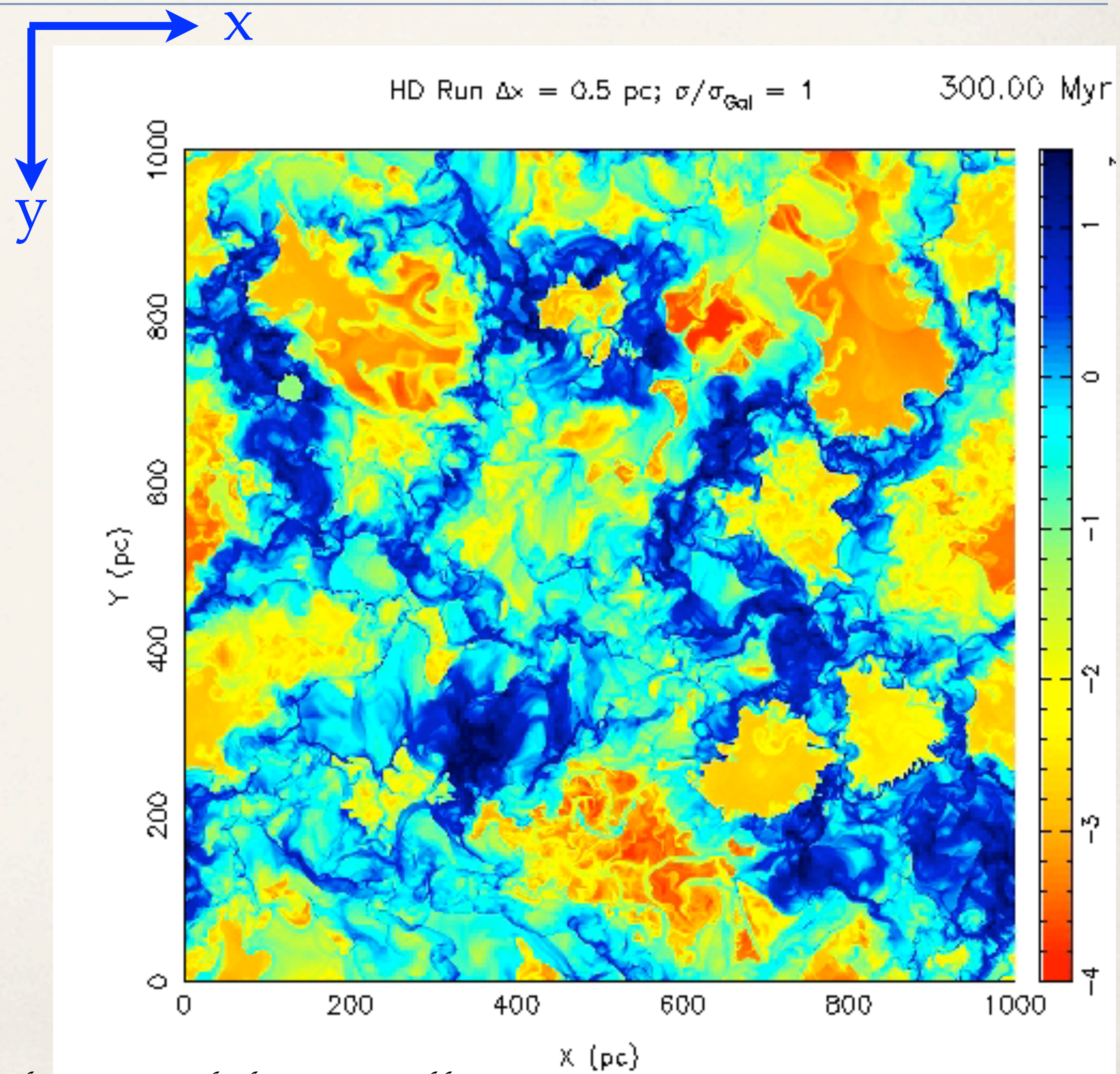
$$\vec{S} = \left(\frac{1}{2}u^2 + \frac{\gamma}{\gamma - 1}\frac{P}{\rho}\right)\rho \vec{u} + \frac{\vec{E} \times \vec{B}}{4\pi}$$

- Realistic **Boundary Conditions**: mass, momentum, energy input by SNe and stellar winds
- **Source terms**: $q=M_{ej}/(V_{ej}\, t_0)$, $m=q\, V_{ej}$, $dW_0/dt=(W_{k0}+W_{th})/t_0$
- galactic gavitational field, diffuse photon field (UV background heating)

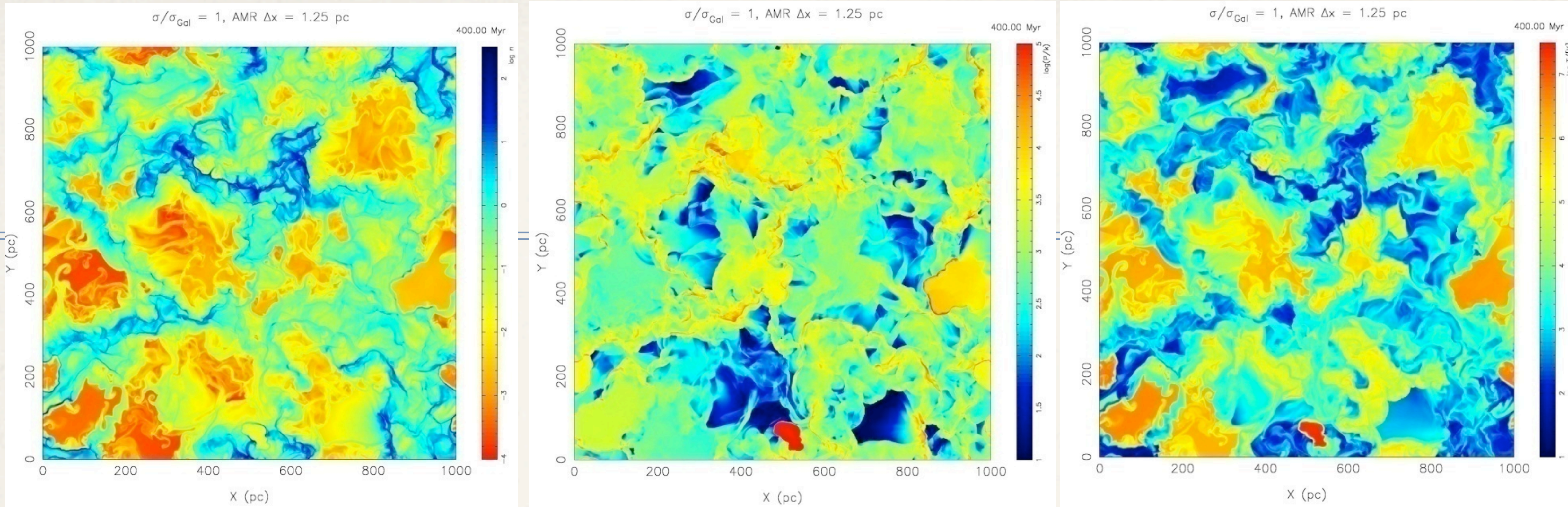
HD-Evolution of ISM

Avillez & Breitschwerdt, 2010

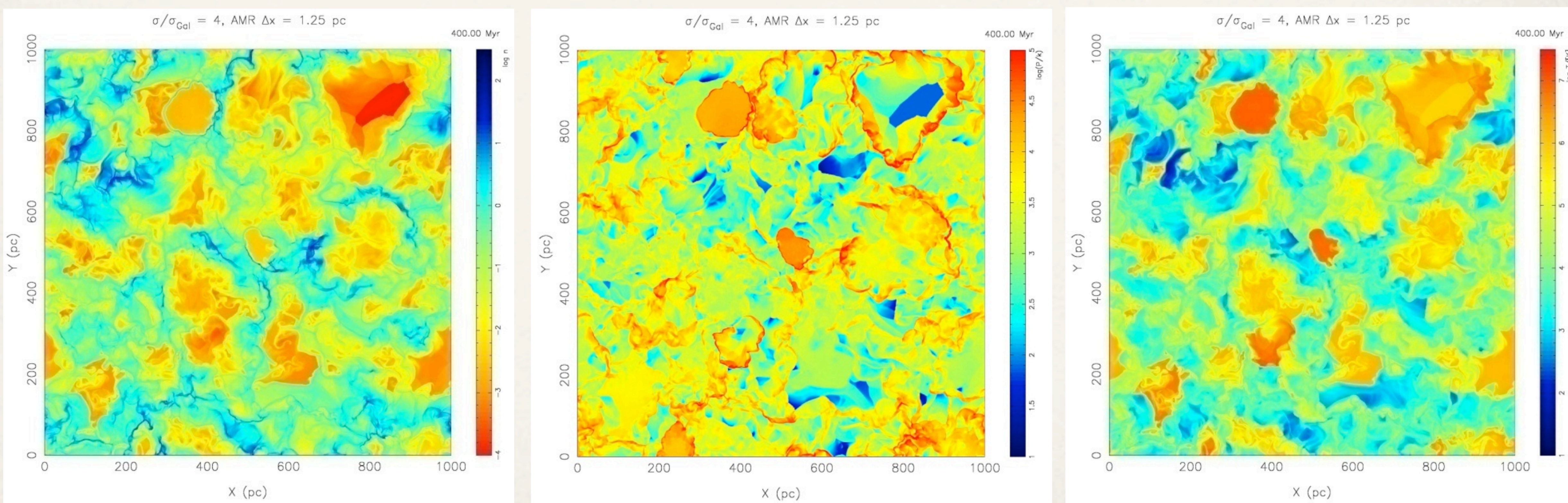
- **Collective** effect of SNe induces **break-out** of ISM disk gas ➔ “**galactic fountain**” (cf. intermediate velocity clouds) ➔ reduce disk pressure
- Density and temperature distribution shows **structures on all scales** (cf. observation of filaments)
- **shear flow** due to expanding SNRs generate high level of **turbulence ➔ coupling of scales**
- Cloud formation by **shock compressed layers ➔** clouds are **transient** features ➔ generation of new stars
- large amount of gas in **thermally unstable** phases
- **volume filling factor** of HIM ~ 20%
- **no pressure equilibrium!**



2D cuts through 3d data cube (disk cut)



n P/k T



σ

σ … SN rate

Results I

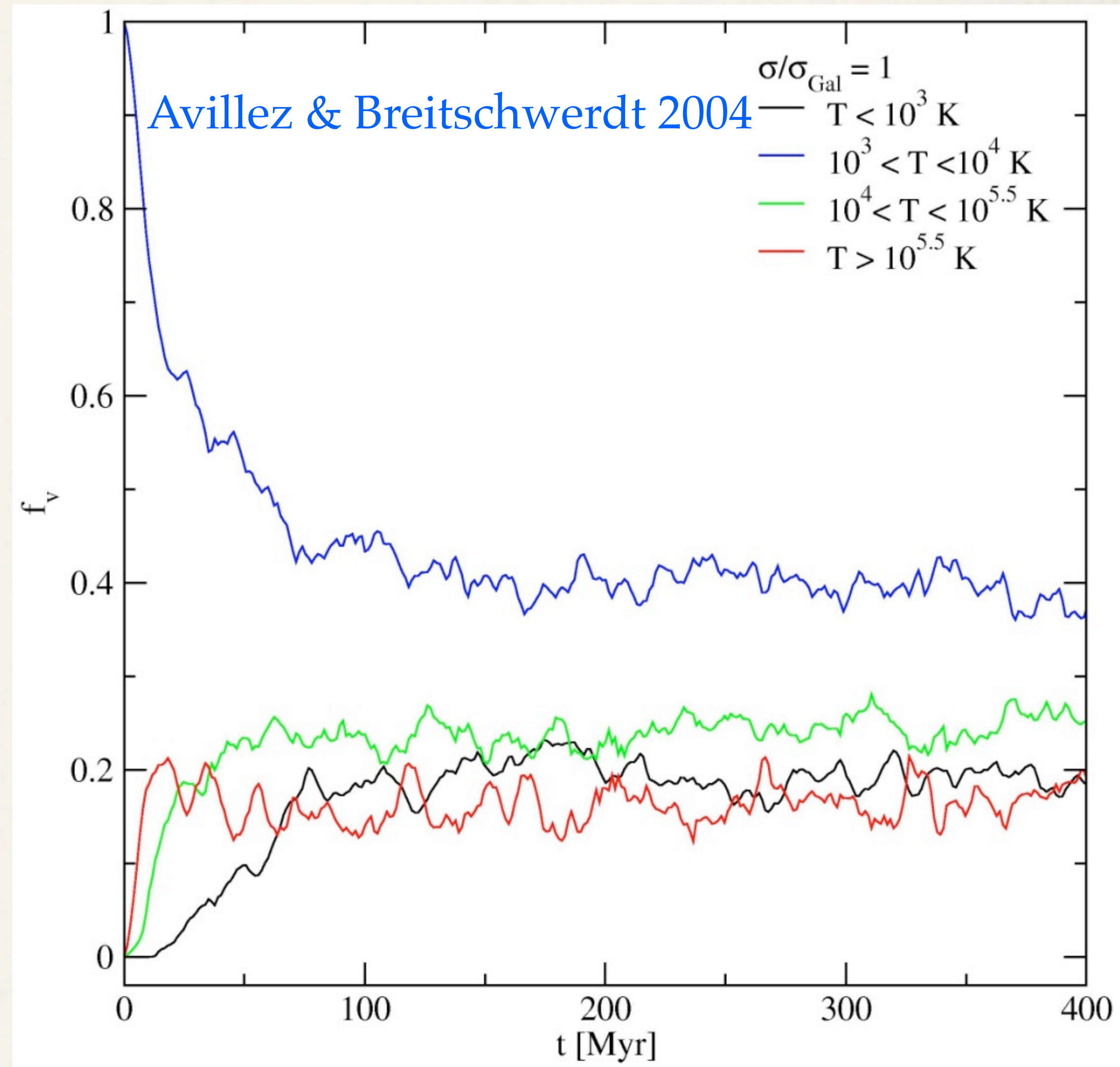
- P/k far from uniform: spatial structure even for high SN rate ($\sigma/\sigma_{gal} = 4$)
- <P/k> ~ 3000 for Milky Way, i.e. much less than canonical values of $> 10{,}000$
- **Reason**: due to fountain flow, average disk pressure can be lowered
- lots of small scale structure: filaments
- shock compressed layers ➔ cloud formation
- lower volume filling factor for HIM: $f_V \sim 0.2$

Results II: Volume filling factors

σ/σ_g	f_{cold}	f_{cool}	f_{warm}	f_{hot}
1	0.19	0.39	0.25	0.17
2	0.16	0.34	0.31	0.19
4	0.05	0.3	0.37	0.28
8	0.01	0.12	0.52	0.35
16	0	0.02	0.54	0.44

cold: $T<10^3$ K; cool: $10^3 < T < 10^4$ K
warm: $10^4 < T < 10^{5.5}$ K; hot: $T>10^{5.5}$ K

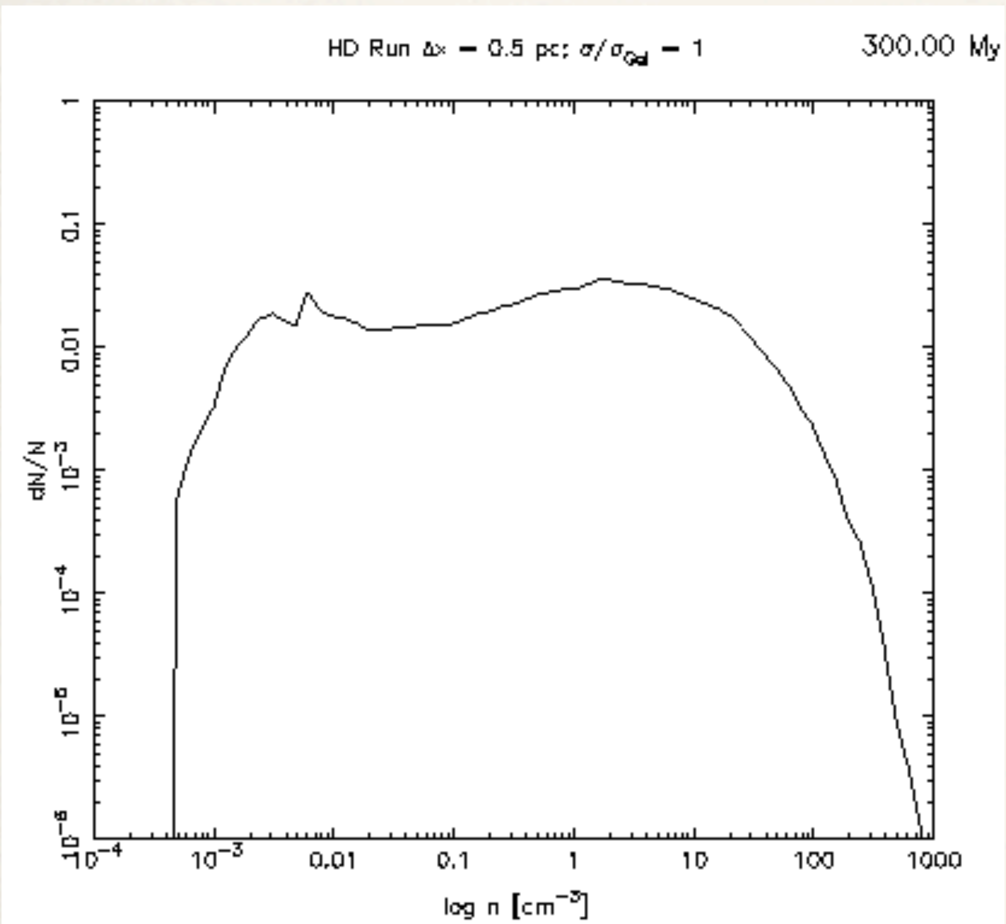
- **increase in SN rate:**
- f_V of hot gas still not dominating!
- f_V of cold gas decreases substantially



- f_V fairly const. with time for t > 200 Myr
- Reason: break-out of SBs and fountain flow acts as pressure release valve!
- f_V of hot gas is fairly low!
- (in agreement with HI holes in ext. gal.)

Results III: Probability Density Functions (PDFs)

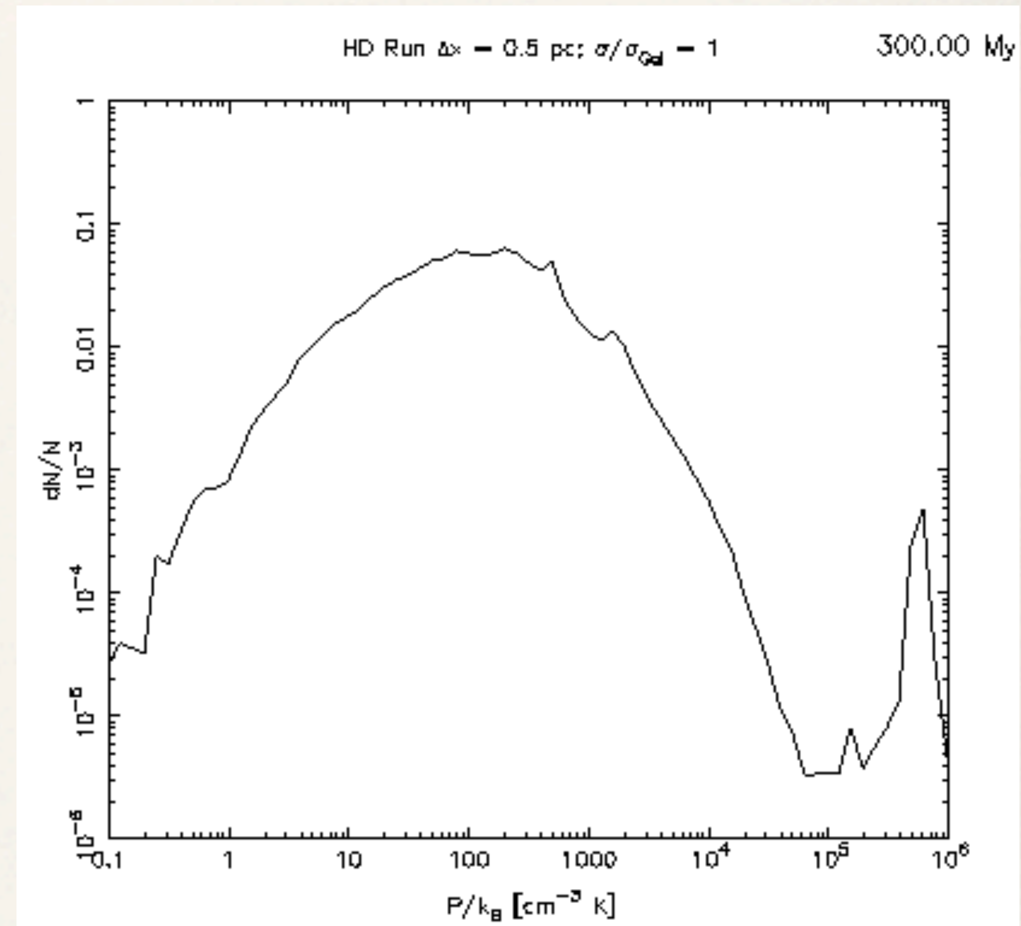
Avillez & Breitschwerdt, 2009



Time-dependent evolution of the averaged volume weighted density and pressure PDFs in the ISM over 4 x 10^8 yr

Note: shock waves propagating through gas;

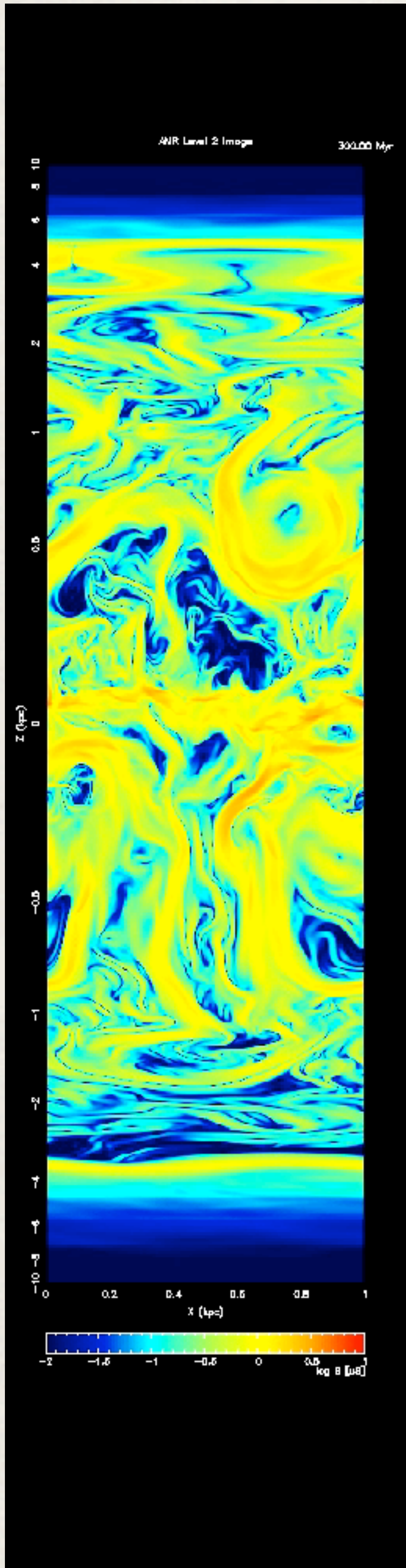
broad pressure distribution

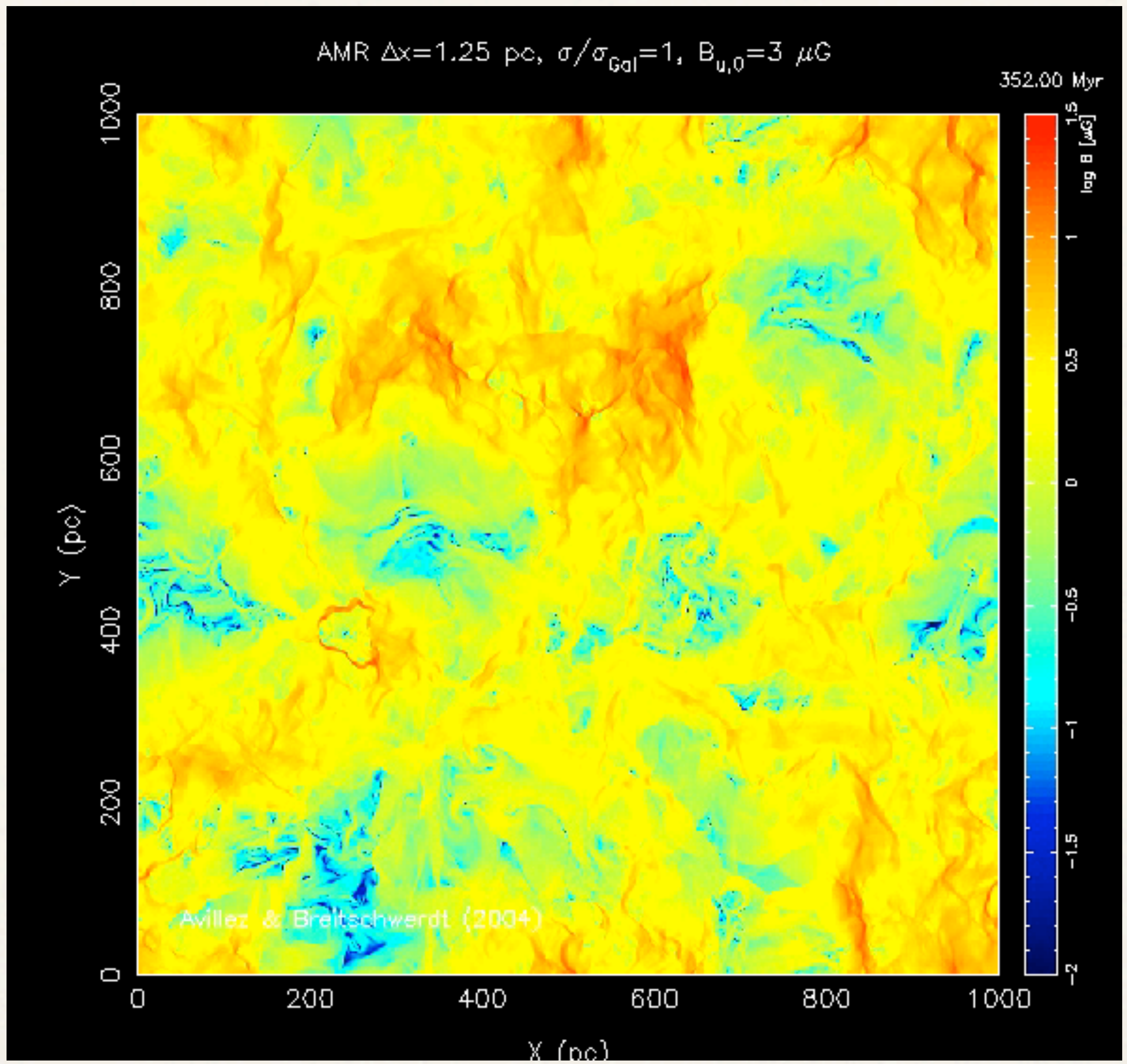


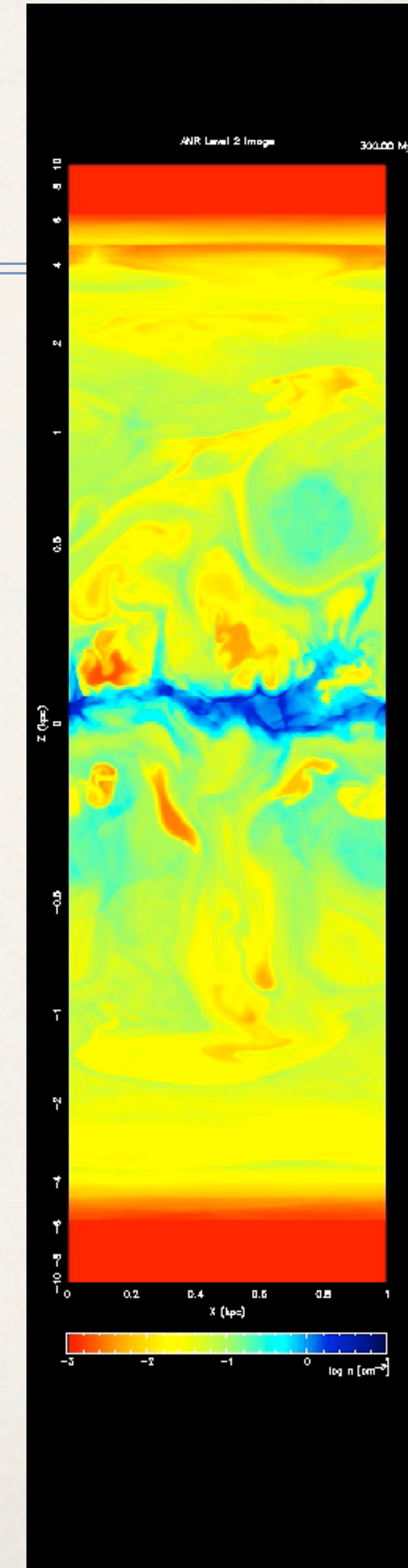
- PDF gives probability to find a certain fraction f(x) of gas in a particular density/pressure regime
- For X∈ {ϱ,P}) we have: $$P(a \leq X \leq b) = \int_a^b f(x)dx$$
- In SN driven ISM the distribution is very broad ➔ substantial fraction of gas exists outside "phases", i.e. in **thermally unstable** regions!

MHD-Evolution of ISM I

Avillez & Breitschwerdt, 2005a

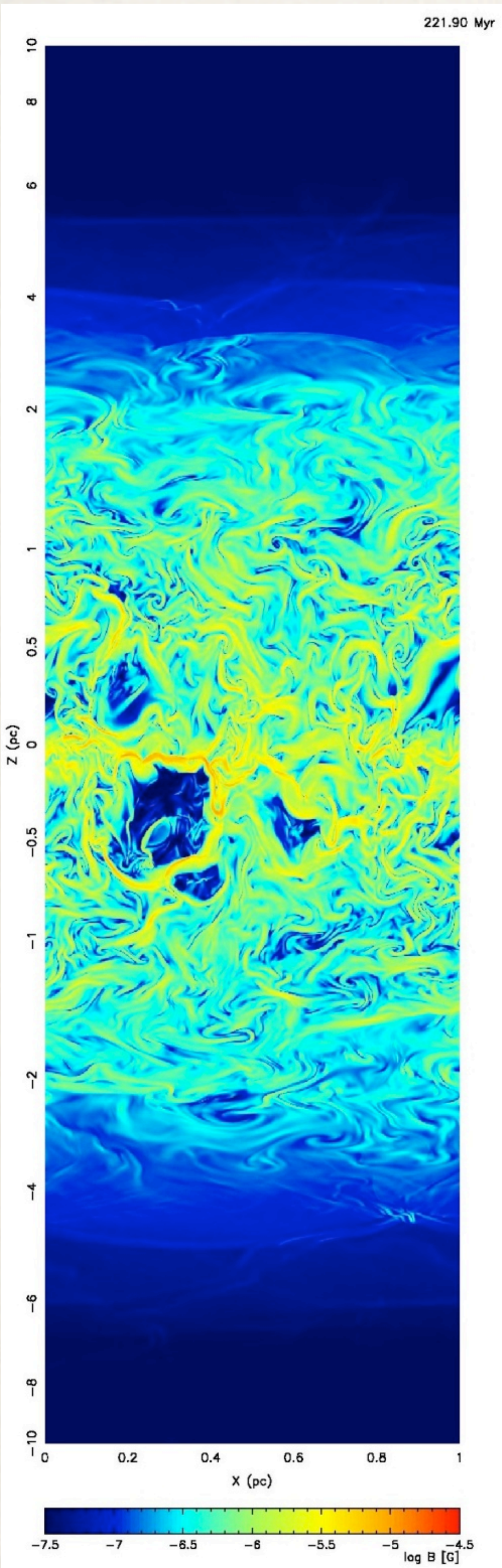






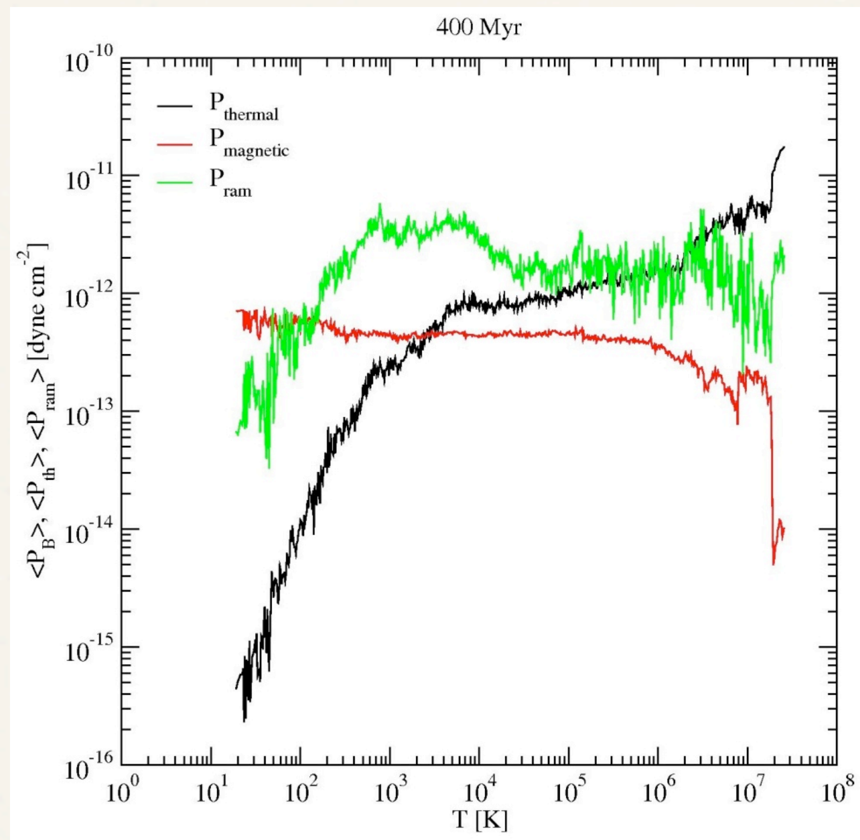
Outflow not inhibited by B-Field; lines of force drawn out by disk-halo flow ➔ loop structure

MHD-Evolution of ISM II



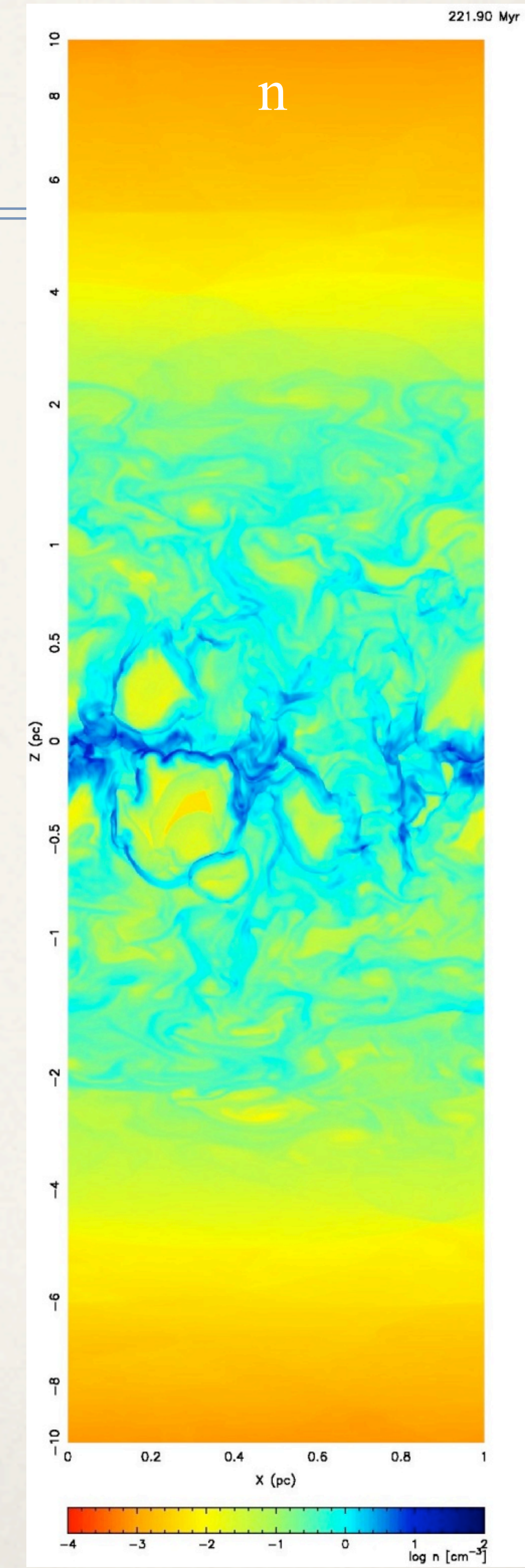
Avillez & Breitschwerdt, 2005a

B-field // to disk cannot prevent outflow into halo; Halo density is **inhomogeneous (Fountain)**



Which pressure determines ISM dynamics?

- For $T < 200$ K: **magnetic** pressure dominates,
- for $200\ \mathrm{K} < T < 10^6$ K **ram pressure** dominates,
- for $T > 10^6$ K **thermal pressure** dominates



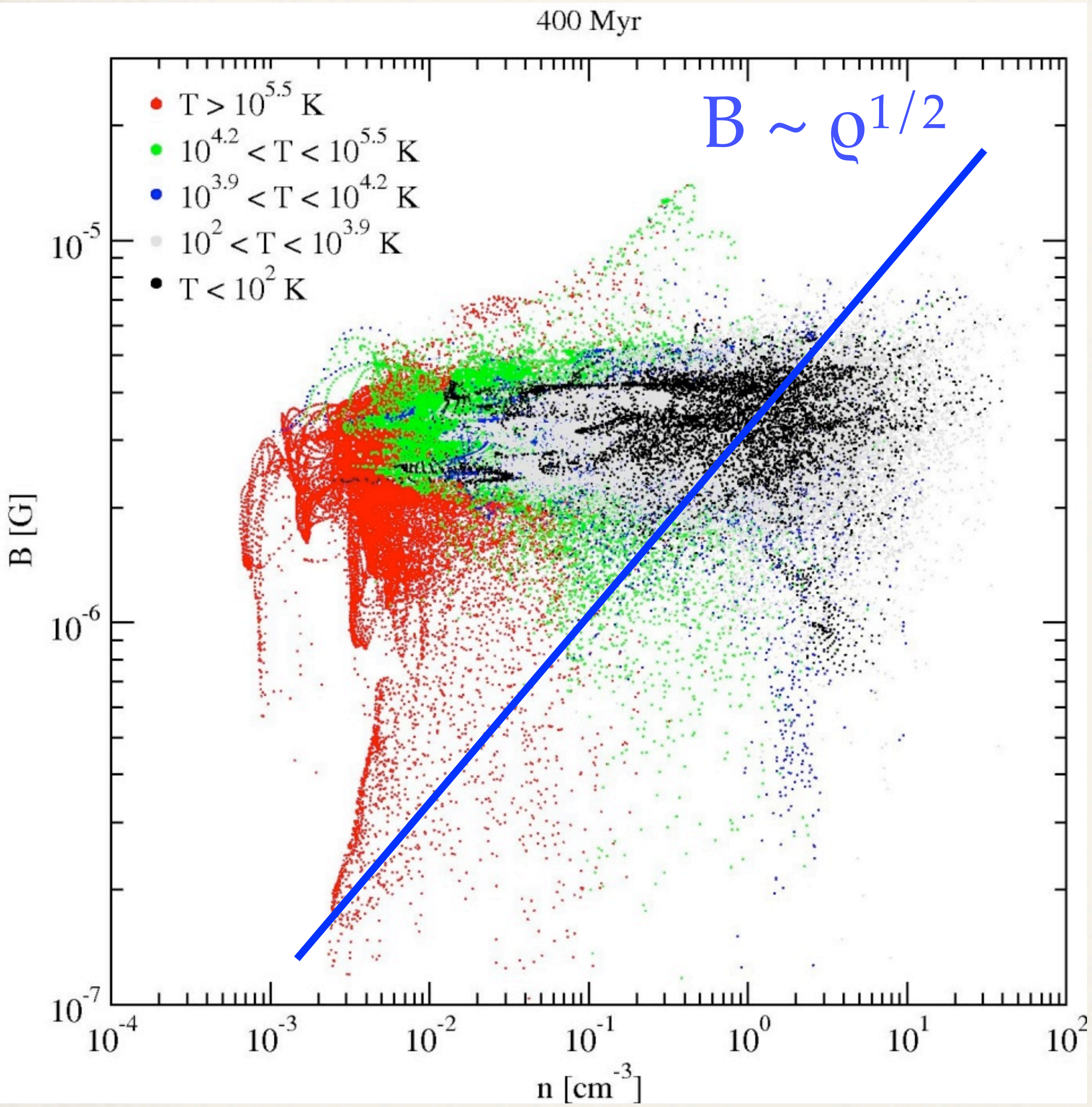
Does the field follow the Chandrasekhar-Fermi law?

Chandrasekhar & Fermi (1953) derived a relation between B and ϱ

Idea:

Deviation a of plane of polarization of star-light from spiral arm direction due to ran-dom
motions of B-field induced by gas turbulence

$$\Rightarrow B = \sqrt{(4/3)\pi\rho}\,\frac{v_{turb}}{a} \Rightarrow V_A = \frac{v_{turb}}{\sqrt{3}a}$$



Result: CF law meaningless: in ISM very broad distribution for all temperatures in the (B-n) scatter plot

Why?

- flow is ram pressure dominated
- supersonic/superalfvenic turbulence

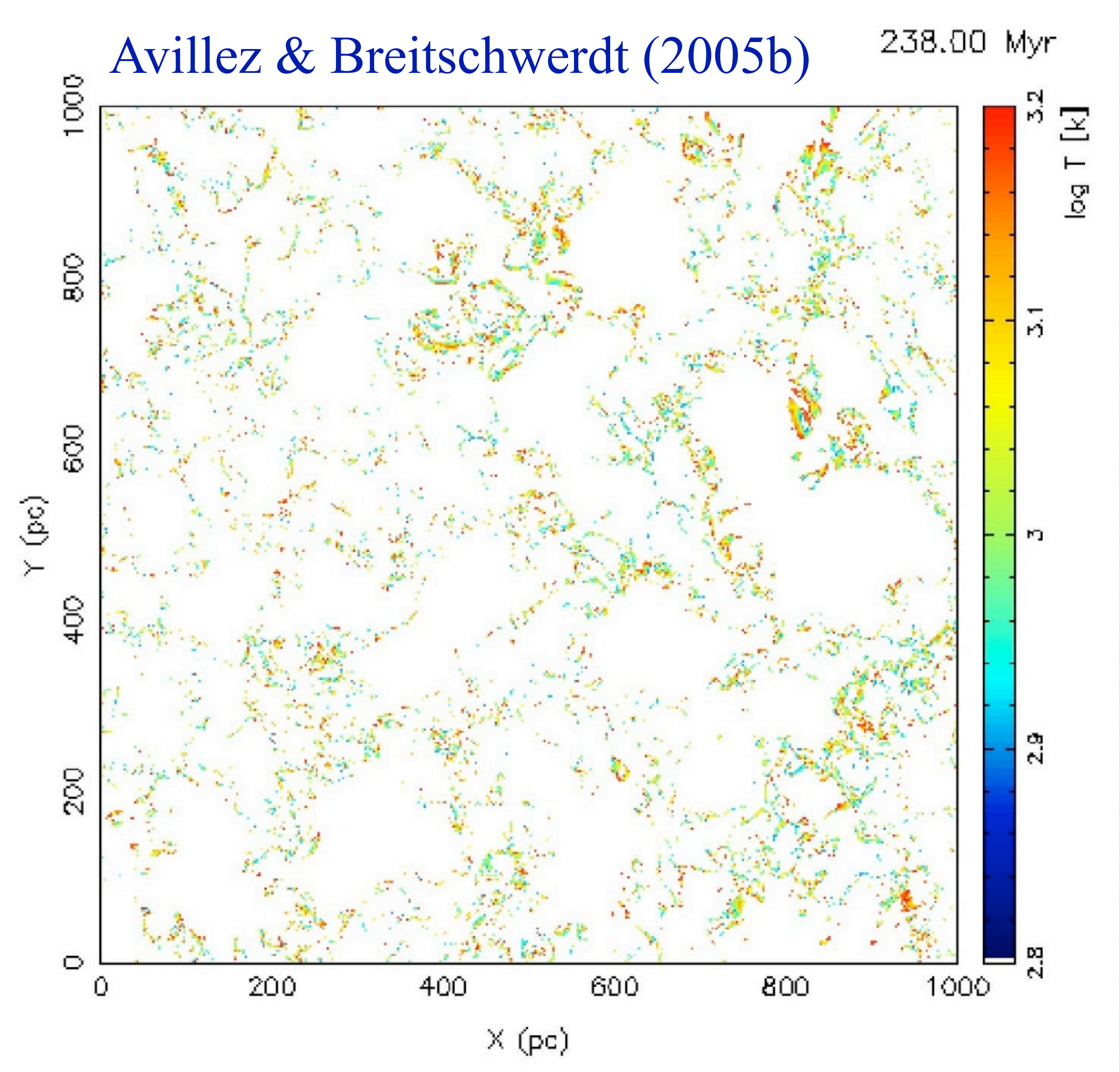
07/18/11

Stability of "Phases" I

- Heiles (2001) reports that > 47% of WNM is in a classically unstable phase between 500 – 5000 K
- Our simulations show that in total 40% of ISM mass is unstable
  - 500 < T < 5000 K: ~ 55% of the gas is unstable
  - $T > 10^{5.5}$ K: ~10% is unstable
- Does this contradict classical thermal stability theory (Field, 1965)?
- Not necessarily, because
  - stability of "phases" was derived in a time-asymptotic limit:
  - instability means that **cooling time** << **dynamical time scale**
  - stable points determined by properties of interstellar cooling curve
- However, in a time-dependent dynamical picture things can be different (e.g. Kritsuk & Norman 2002, Gazol et al. 2001)
  - shock waves can induce strong heating
  - SN increased **turbulence** can work against condensation
  - **eddy crossing time << cooling time**

Stability of "Phases" II

- WNM in the thermally unstable temperature regime (500 - 1500 K) shows filamentary structure
- classically there should be no gas observable
- distribution on small scales (~ pc)
- ➔ agreement with HI observations by Heiles (2001), Heiles & Troland (2003)

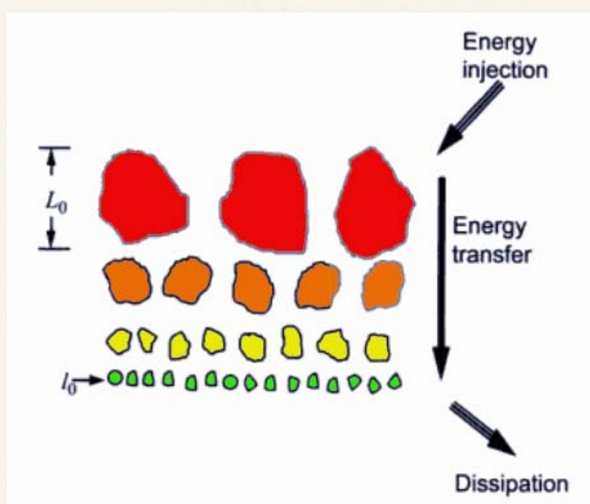


WNM in the thermally unstable regime:
631 K ≤ T ≤ 1585 K

At which scale is turbulence generated?

- ISM turbulence is generated by shear flows ➔ increases vorticity
- largest eddies break up at a turn-over time $\tau \sim l/\Delta v$ ➔ energy fed in at large scale
- Richardson (1922):

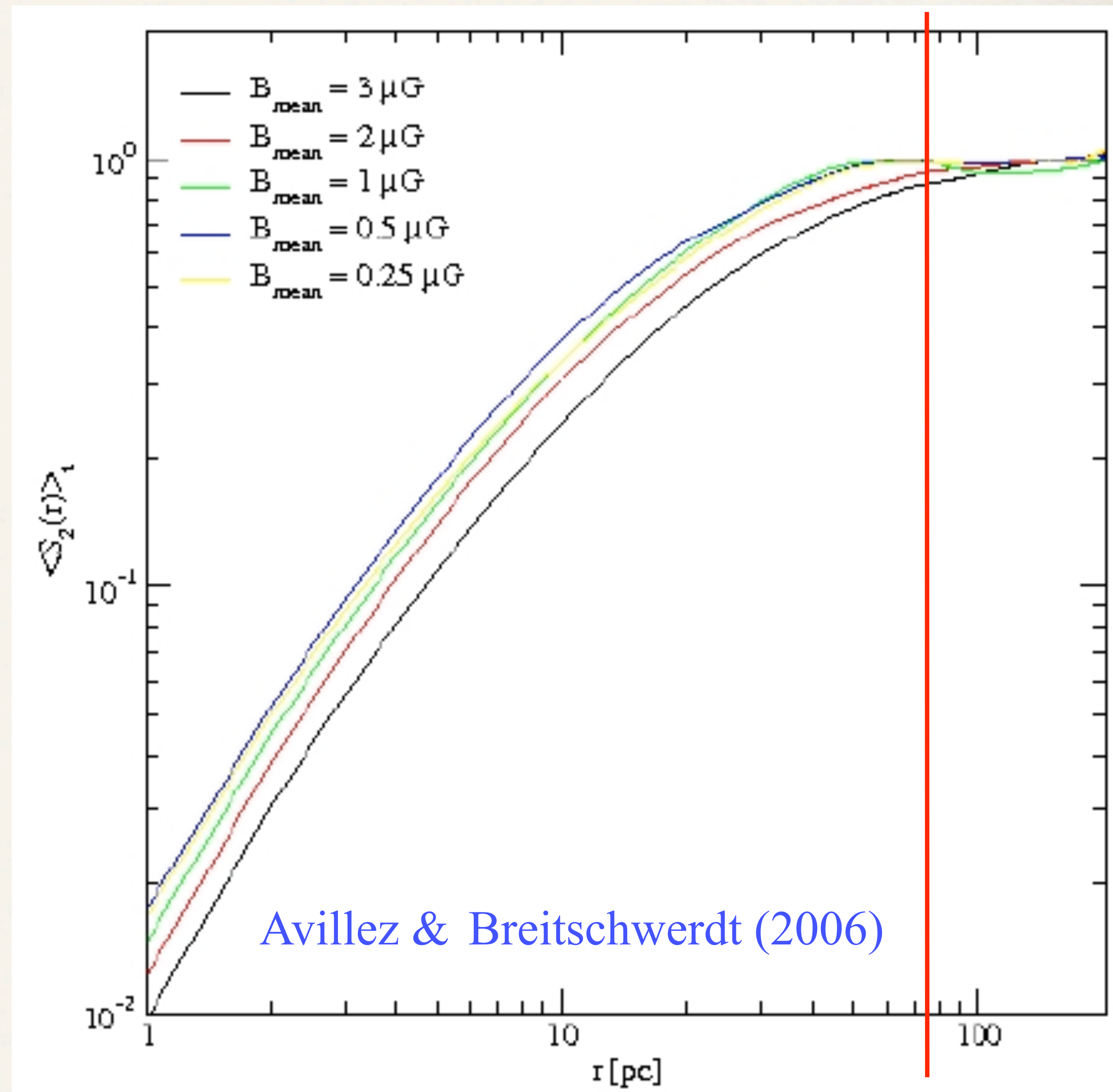
"Big whorls have little whorls that feed on their velocity, and little whorls have lesser whorls and so on to viscosity"



- 2nd order structure function (measure for E_{kin} contained in eddie of size r)

$$S_2(r) = \left\langle (\Delta v)^2 \right\rangle = \left\langle [u_x(\vec{x} + r\vec{e}_x) - u_x(\vec{x})]^2 \right\rangle$$

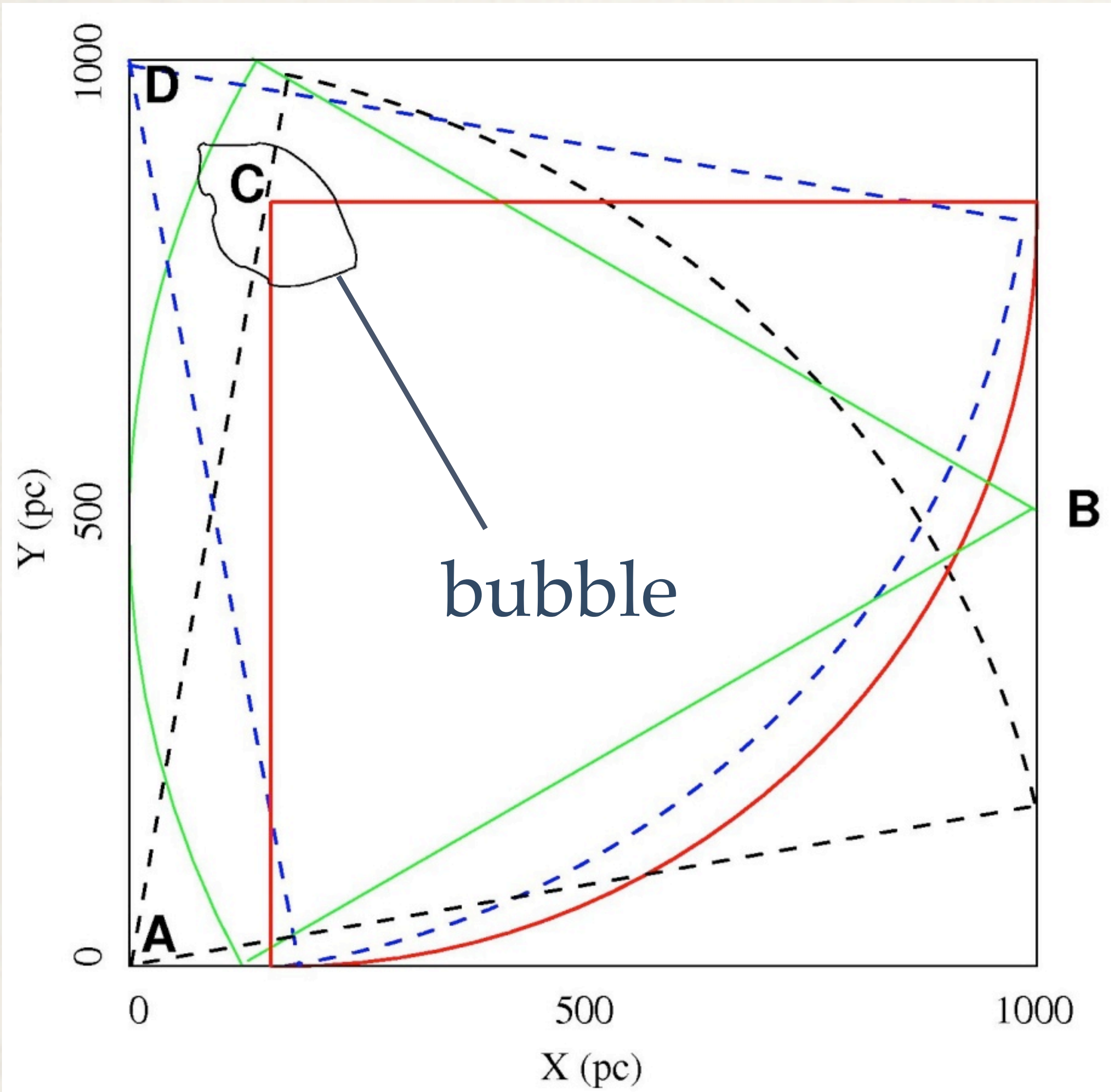
- integral scale ~ break-up scale of superbubbles

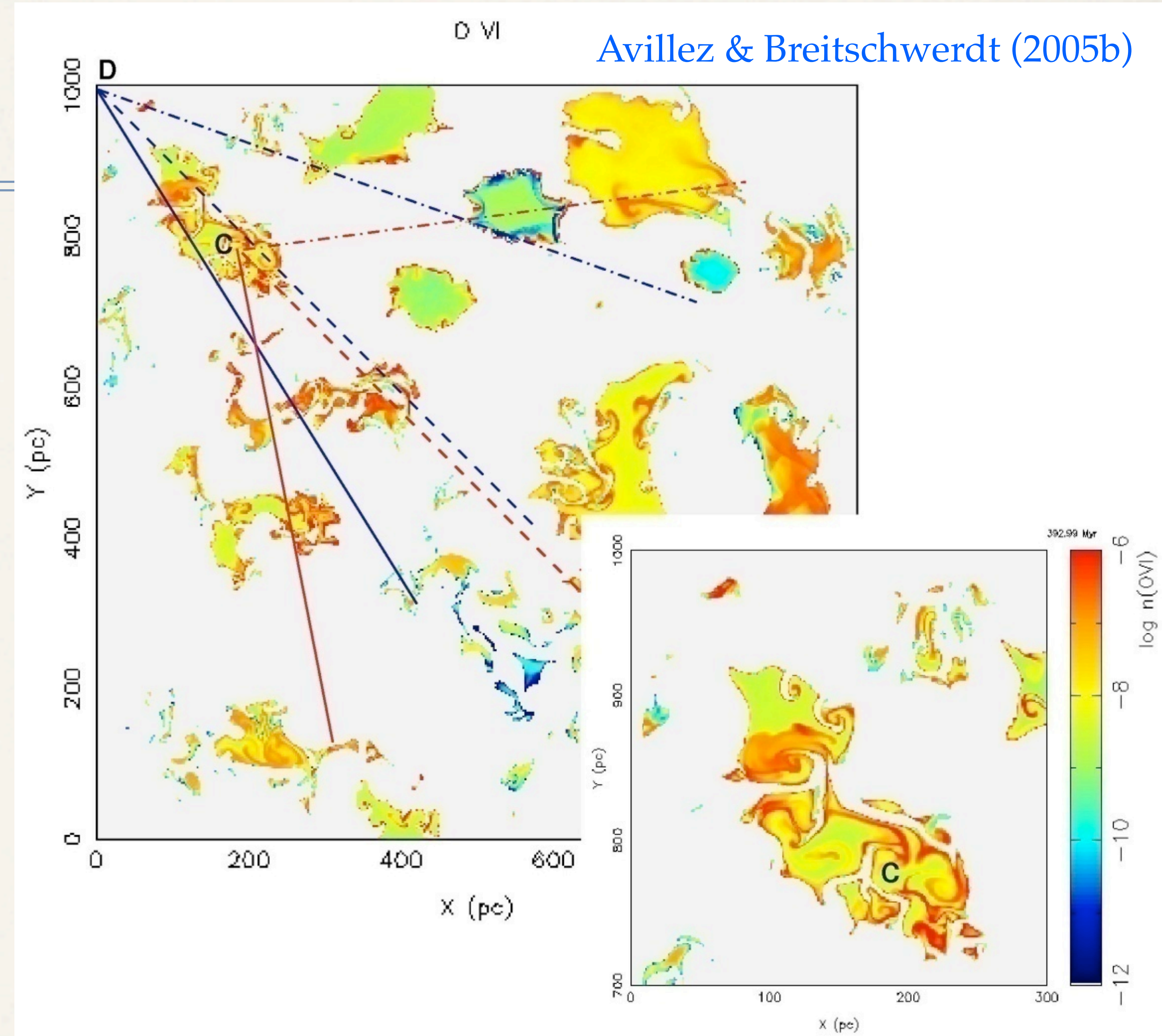


<S_2(r)> flattens at r ~ 75 pc: **integral scale**

Kolmogorov: $\langle [\delta \mathbf{u}(r)]^n \rangle = C_n \varepsilon^{n/3} r^{n/3}$

Comparison with Observations I



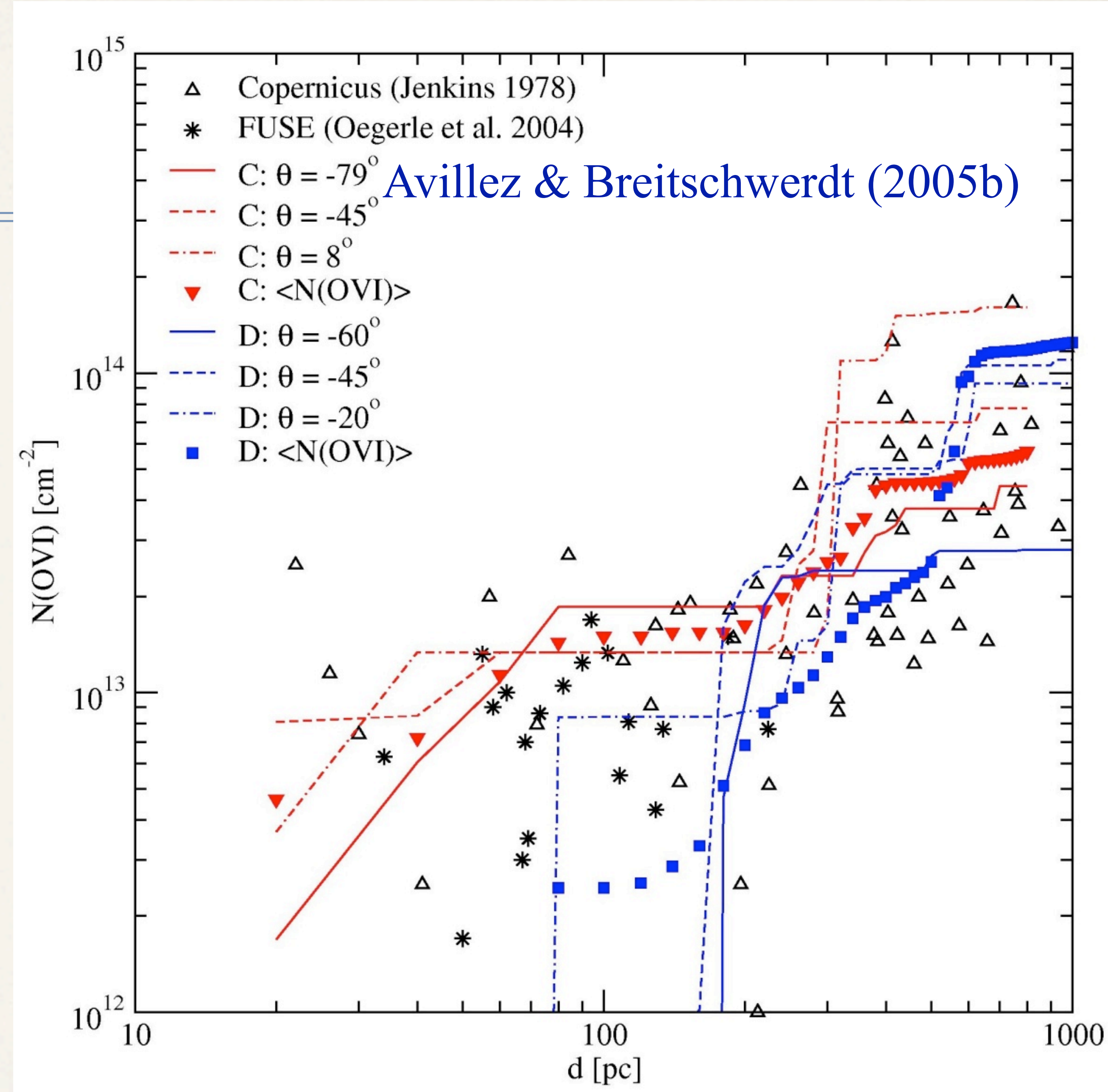


- OVI traces cooling down HIM
- OVI produced in conduction fronts? Efficieny too high
- our simulations: OVI generated in **turbulent mixing layers**!

OVI density distribution in the ISM; shown are values $10^{-12} < n(OVI) < 10^{-6}$ cm^{-3}
Zoom into bubble shows turbulent mixing

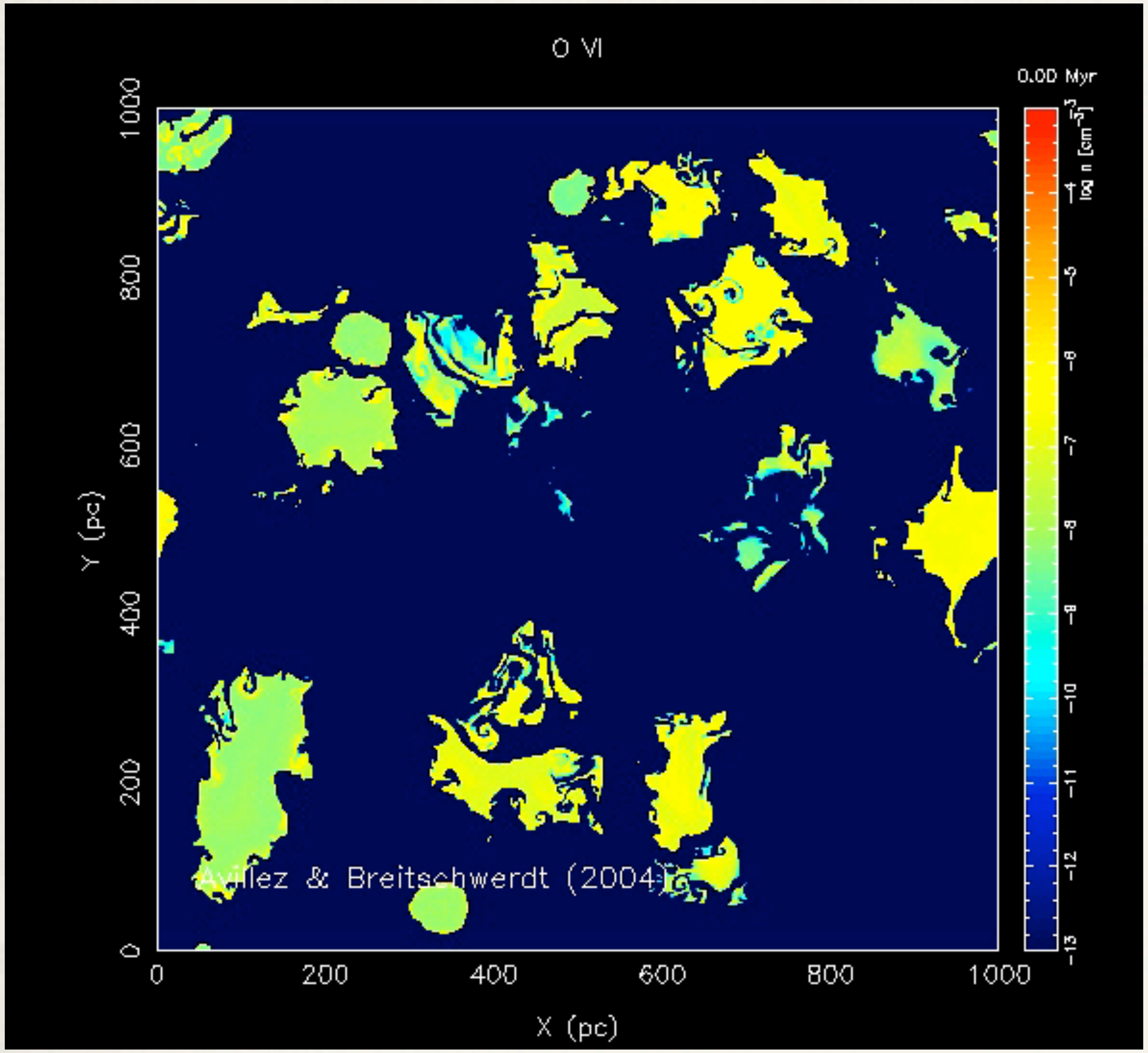
Comparison with Observations II

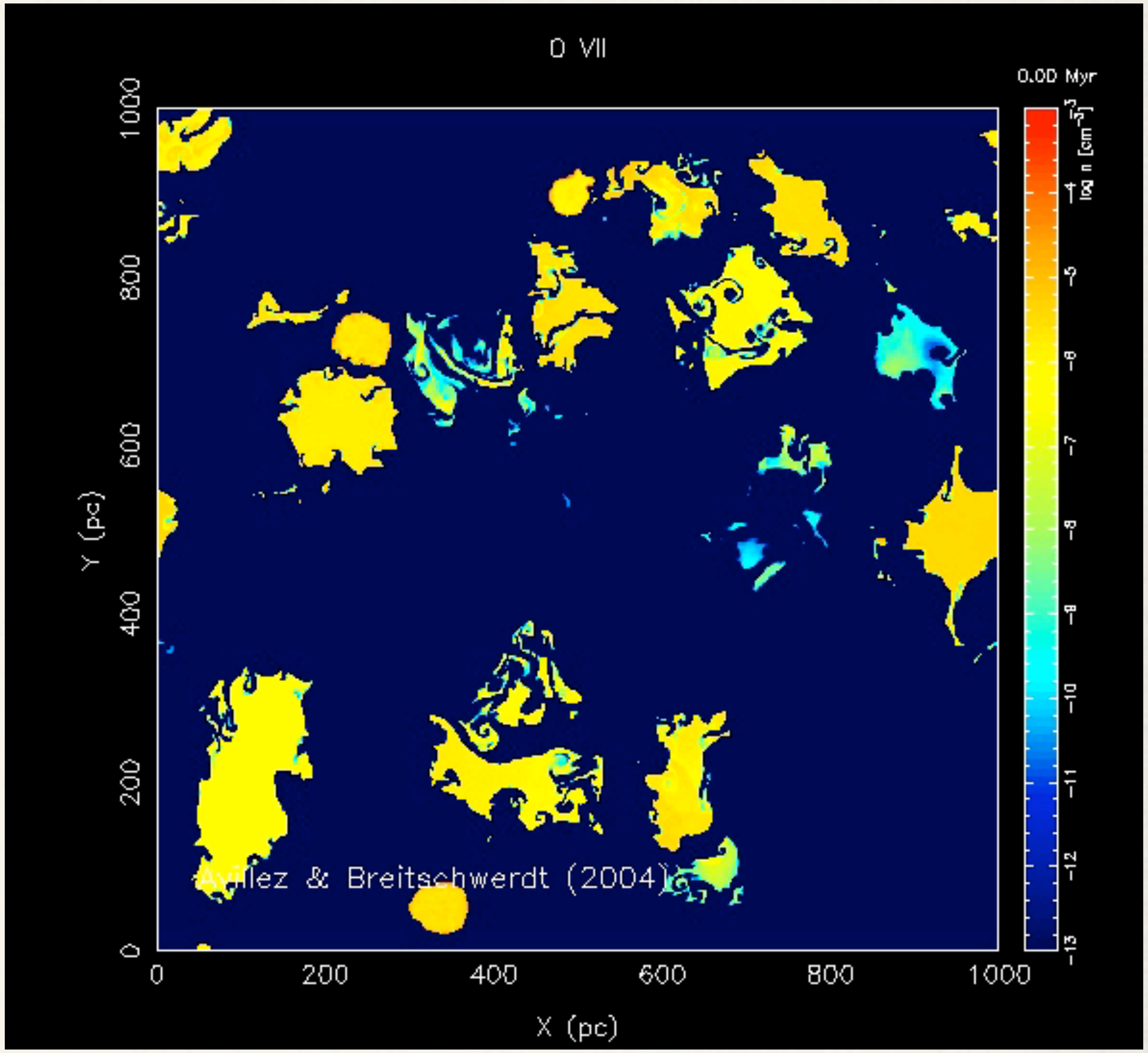
- FUSE & Copernicus data of OVI absorption lines towards back-ground stars
- comparison with simulations (at t = 393 Myr): spatially averaged (red triangles, blue squares) and single LOS N(OVI)
- ISM has a pattern, repeating on scales of a few 100 pc!
- Note: simulations carried out before observations of Oegerle et al. (2004)



N(OVI) density in the ISM as a function line of sight length; labels A - D correspond to different vantage points, curves to different angles

OVI and OVII distribution in ISM





- OVI traces HIM gas cooling down; in collisional ionization equilibrium (CIE) this corresponds to T ~ 3 10^5 K
- OVII traces hot gas during ongoing SN activity; in CIE OVII traces gas of T ~ 10^6 K

But how realistic is CIE?

Summary

- ISM is a highly **turbulent**, compressible medium ➔ **nonlinear dynamics** requires high resolution **numerical simulations**

- Simulations require:
  - (i) sufficiently long evolution time to erase "memory" effects of initial conditions
  - (ii) inclusion of essential physical processes
  - (iii) observables should be independent of resolution
- SN-driven ISM shows structures on **all scales** (coupling by **turbulence**)
- High level of turbulence maintained by on-going star formation
- "**Galactic Fountain**" acts as pressure release valve in the disk ➔ reduces volume filling factor of hot "phase"
- ISM **not** in pressure equilibrium (average pressure lower in agreement with obs.)
- "**Clouds**" are shock compressed layers, in which new stars are born
- large mass fraction in **thermally unstable** regime
- **OVI-distribution** due to turbulent mixing ➔ in very good agreement with FUSE- and Copernicus data
- dynamical and turbulent ISM drives plasma **out of ionization equilibrium** ➔ interstellar **cooling function** depends on **plasma history** and hence **varies in space and time**
- **Closest to Earth SN: ~ 2.2 Myr.** at ~ **65 pc** distance (derived from fit to ^{60}Fe data)

Thank you for your attention!