Evolution of the Turbulent Interstellar Medium in Star Forming Galaxies

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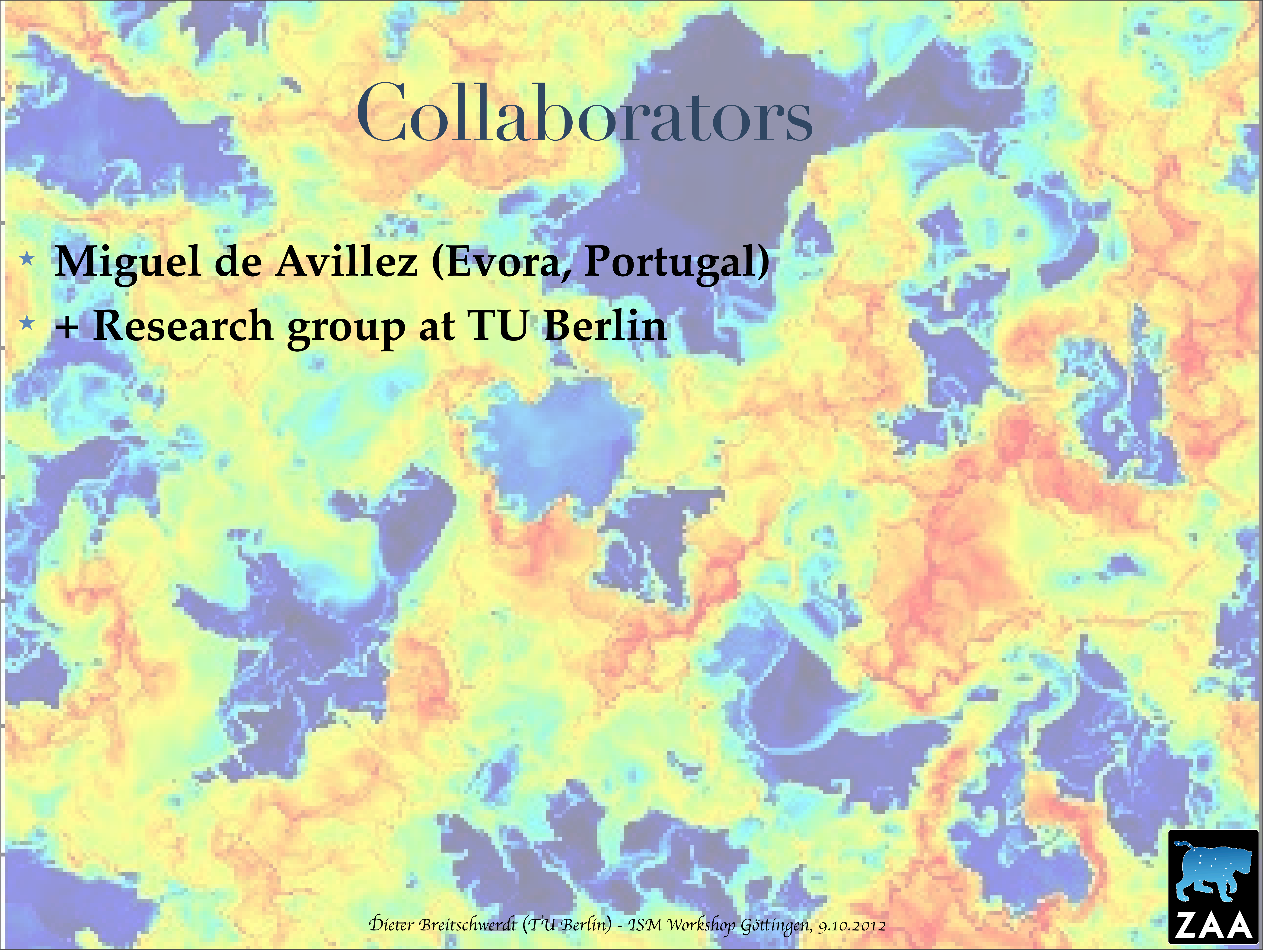
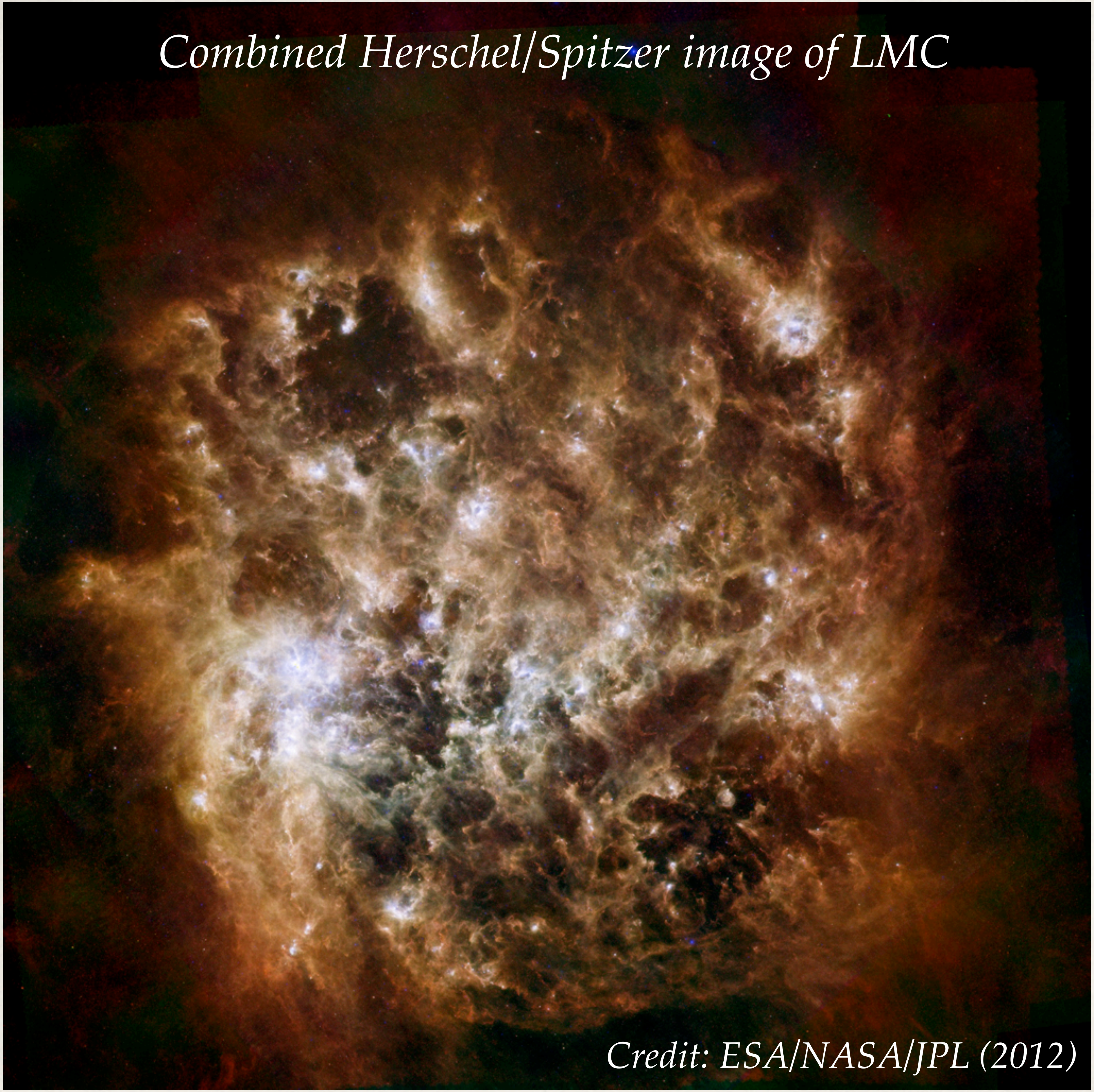
ZAA



Collaborators

- **Miguel de Avillez (Evora, Portugal)**
- **+ Research group at TU Berlin**

- Introduction
- Interstellar Turbulence
- 3D High Resolution Numerical ISM Simulations
- Non-Equilibrium Ionization Structure of the ISM
  - Time and Space dependent Cooling Function
- Comparison to Observations
  - OVI (FUSE data), n_e (Pulsar dispersion measures)
- Summary & Conclusions



Combined Herschel/Spitzer image of LMC

Credit: ESA/NASA/JPL (2012)

Textbook ISM:

- gas resides in distinct smooth *stable* phases
- hot phase has large volume filling factor ($f_{vh} > 50\%$)
- phase transitions in pressure equilibrium

Observations:

- filaments, frothy at high resolution; structure on all scales
→ **turbulence**
- wide range of temperatures, densities ($f_{vh} < 30\%$)
- gas, magnetic fields, cosmic rays, dust …
→ **multicomponent**

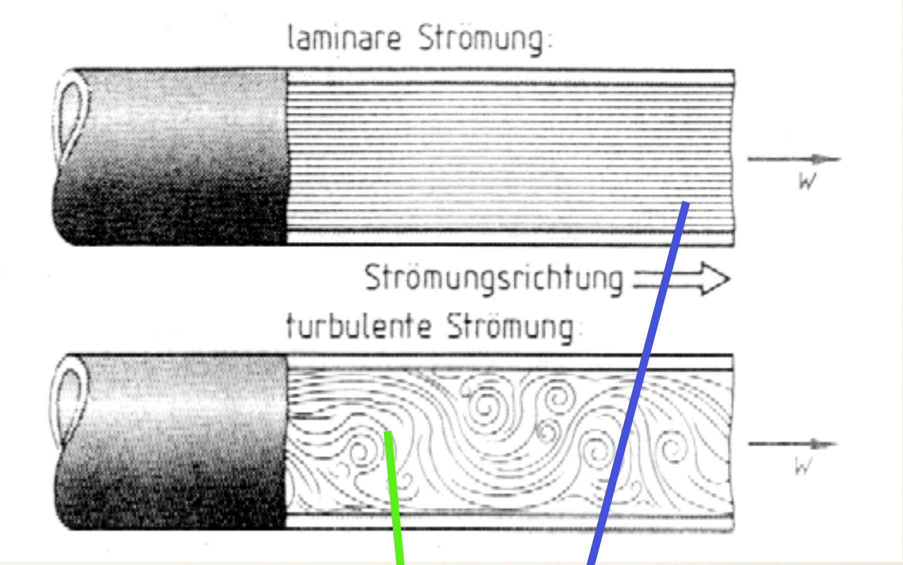
Interstellar Turbulence

- **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 differential rotation*
  - *self-gravity:* Jeans instability, thermal instability
  - *plasma instabilities*: Rayleigh-Taylor, Kelvin-Helmholtz, magnetorotational instability (MRI), cosmic ray streaming etc.
- **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 (u∇)u in Navier-Stokes-Eq.

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u}\nabla)\vec{u} = -\nabla\left(\frac{P}{\rho}\right) + \nu\nabla^2\vec{u},\ \vec{\omega} = \nabla\times\vec{u}$$

Incompressible Newtonian fluid

take curl and write as a function of vorticity ω:

"Eddies" are blobs of vorticity

$$\nabla(\frac{1}{2}u^2) = (\vec{u}\nabla)\vec{u} + \vec{u}\times\vec{\omega};\quad \frac{\partial\vec{\omega}}{\partial t} = \nabla\times[\vec{u}\times\vec{\omega}] + \nu\Delta\vec{\omega}$$

and since

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

we have

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

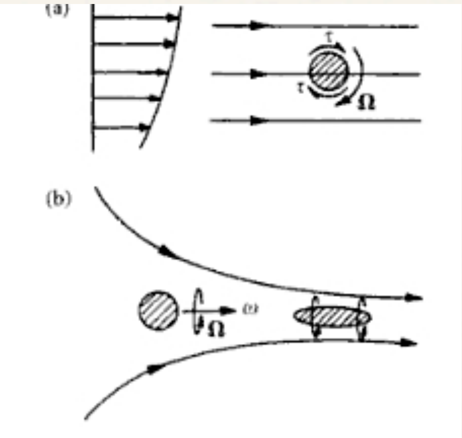


Figure 2.8 Vorticity can change because: (a) viscous forces spin up (or slow down) a fluid element or (b) because the moment of inertia of that element is changed.

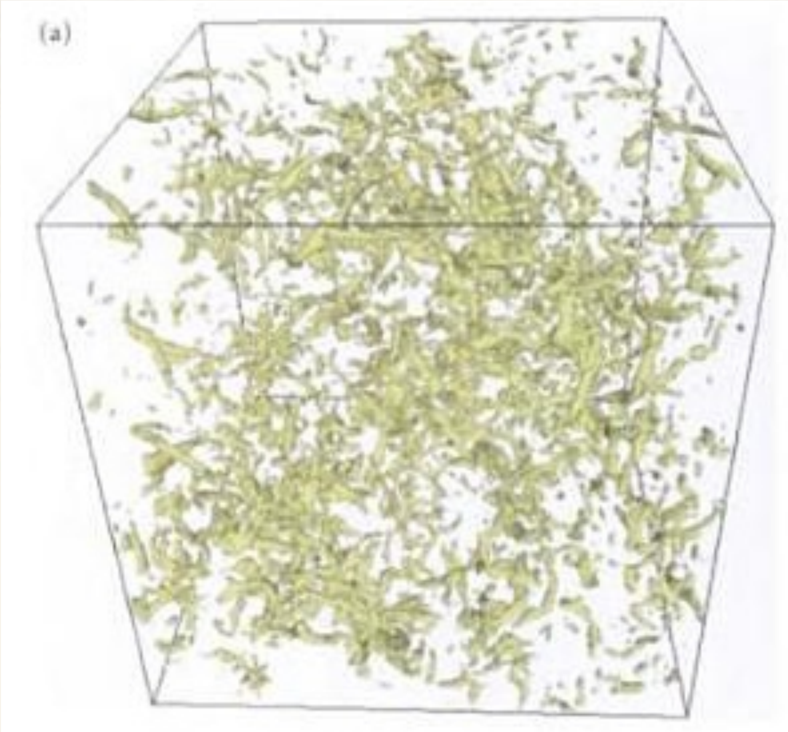
Change of vorticity:

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

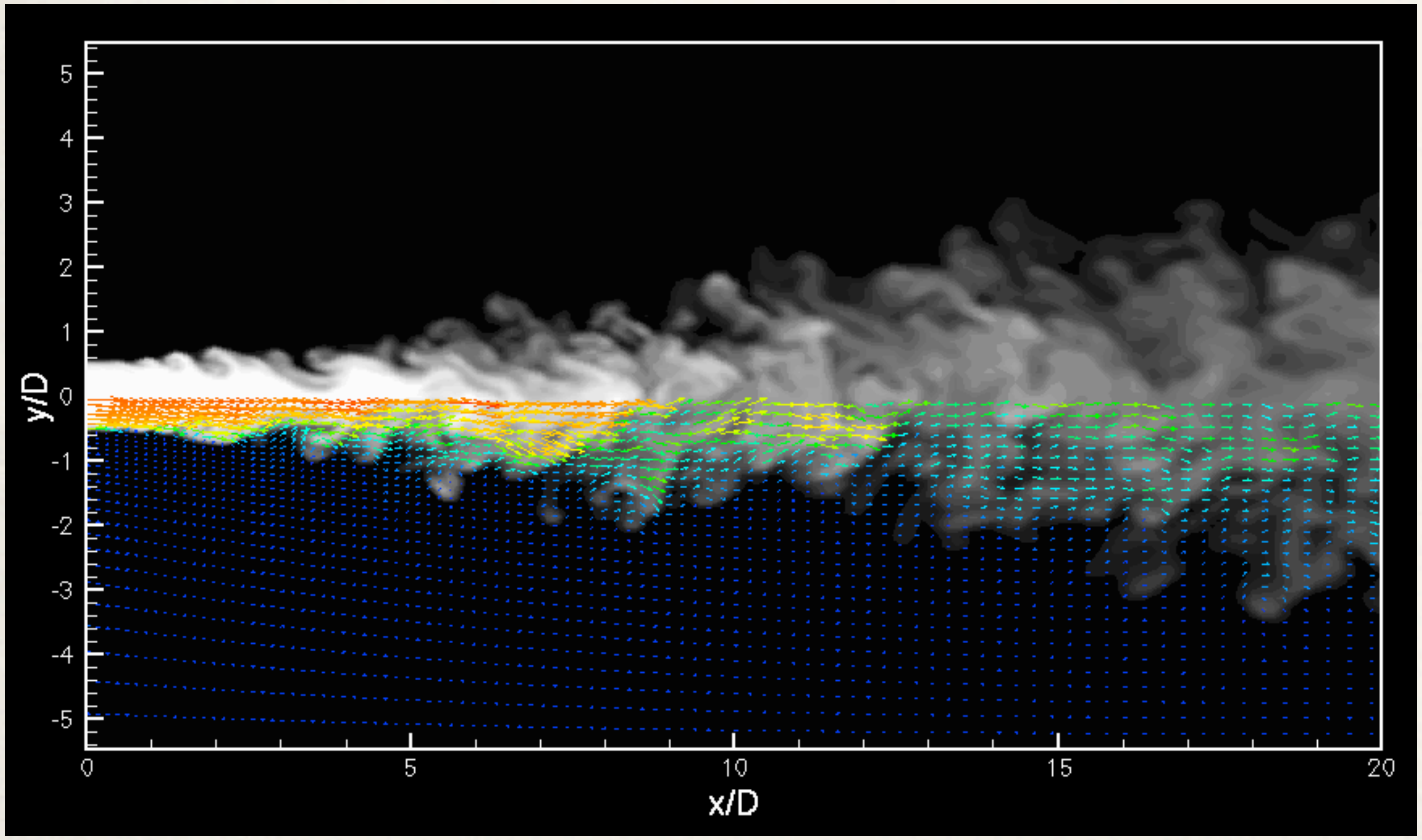
viscous torque due to applied viscous stresses (a))

Turbulence II

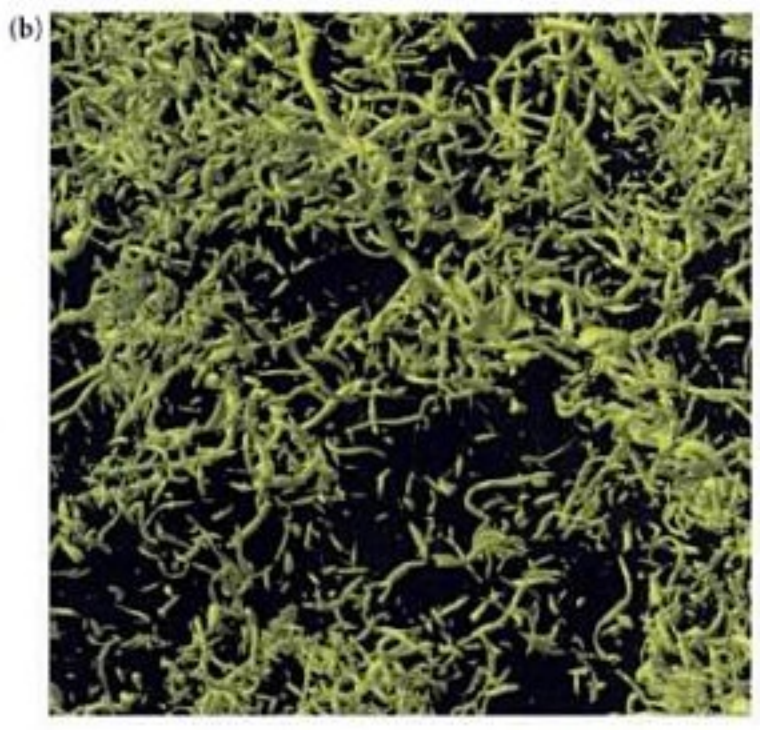
- **Turbulence**: essentially a 3D chaotic solution of NS-Eq., but has large number of degrees of freedom
- Stretching of fluid elements causes increase in vorticity ➔ **“vortex tubes”**



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



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

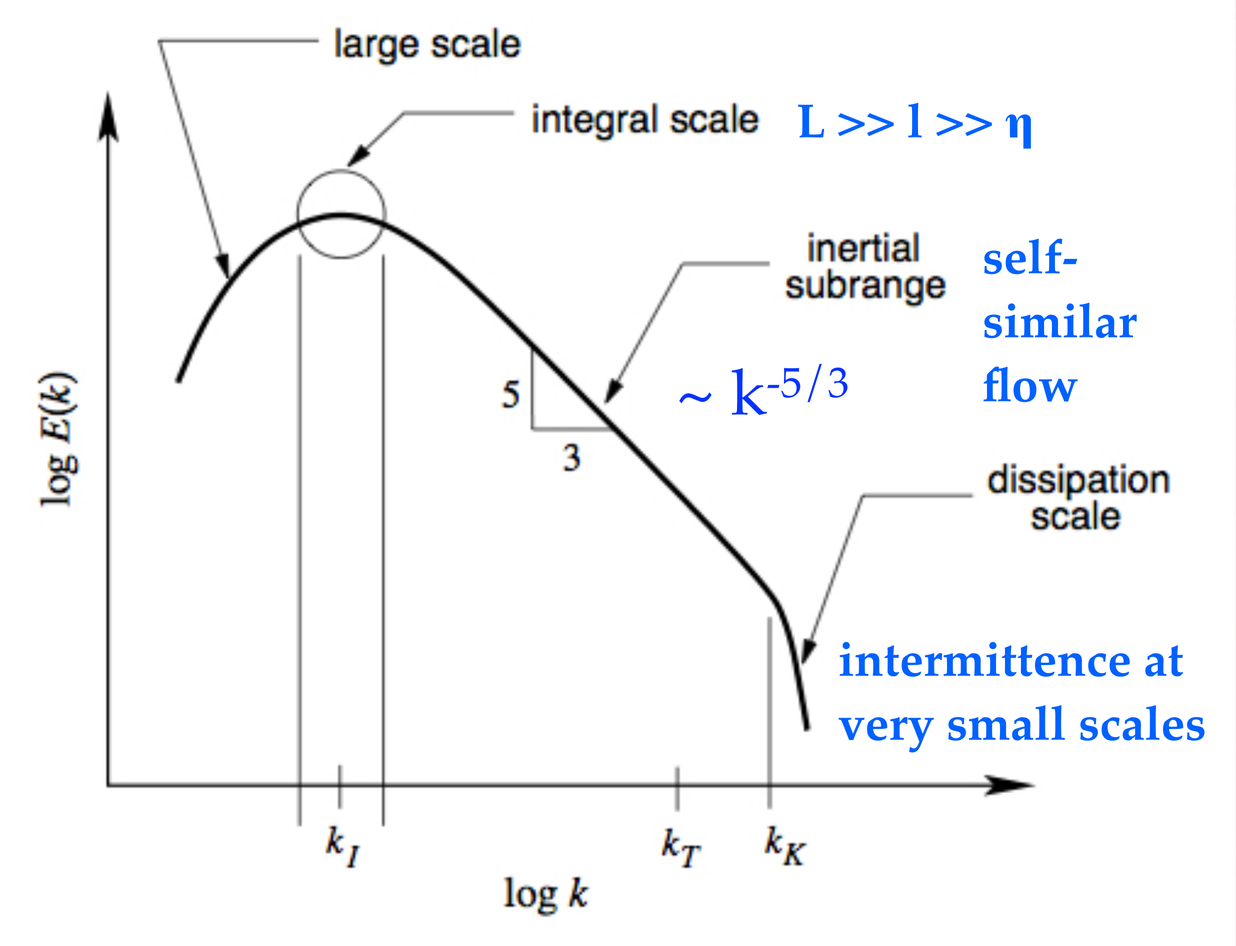


Direct Numerical Simulation of isotropic turbulence (s.a.); Re ~1200 (cf. Davidson)

Turbulence III

- Turbulence model: **Kolmogorov** (1941, K41), for *incompressible* turbulence ($\nabla u=0$)
- **Assumptions** for large Re:
- (i) turbulence on small scales is *statistically isotropic* ➔ **universal**

- (ii) statistics on small scales is exclusively determined by ν and $\varepsilon_D=\varrho u^2/\tau$ (**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.)
- ➔ observed in clouds: $\boldsymbol{\sigma\sim L^{0.38}}$ (Larson, 1981)
- 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: $Re=u\eta/\nu \sim$ $\sim(\varepsilon_K/\varrho)^{1/3}\,\eta^{4/3}/\nu \sim 1$ ➔ $\eta \sim (\nu^3/\varepsilon_K)^{1/4}$
- $u \equiv v \sim \nu/\eta = (\nu\varepsilon_K)^{1/4}$
- **Energy dissipation rate** $\varepsilon_D = \varepsilon_K$, independent of Re and l! $\mathbf{1/2 \langle u_i\, u_i\rangle = \int E(k)\, dk}$
- **Dimensiononal analysis**:
- $[k]=1/L$, $[E(k)]=L^3\,T^{-2}$, $[\varepsilon_D]=L^2\,T^{-3}$ (iii) $\mathbf{E(k) = f(k,\varepsilon_D)} = C\,\varepsilon_D^{2/3}\,k^{-5/3}$
- C is a universal constant!
- structure function (of order n):

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

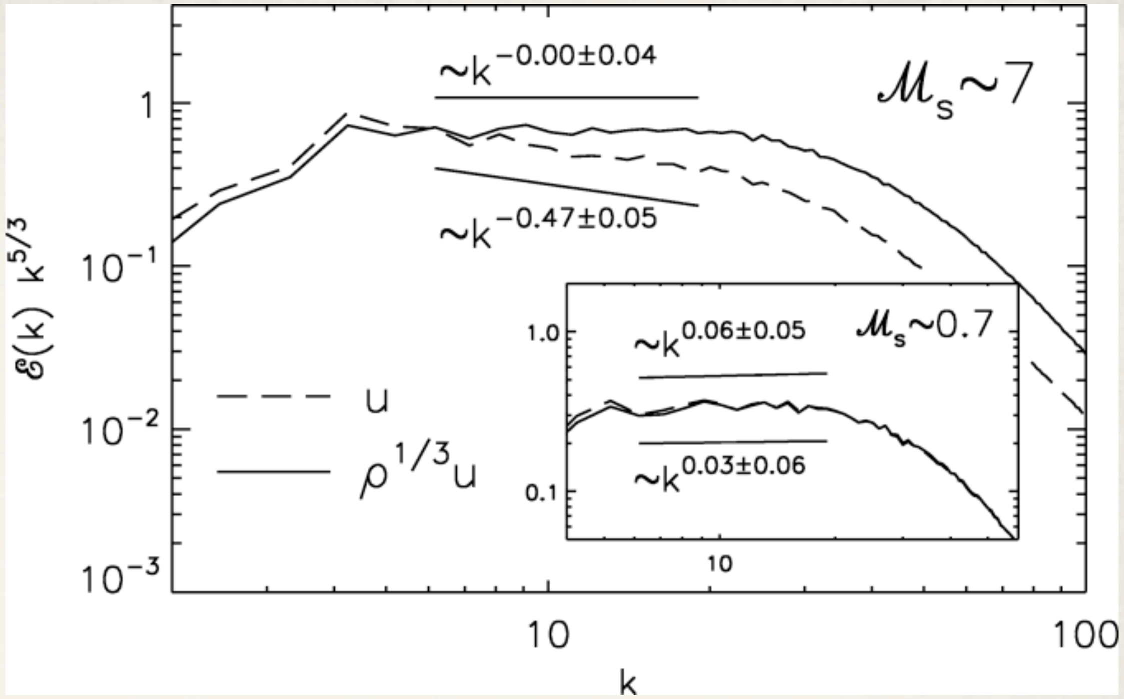
Turbulence IV

- **Compressible** Turbulence model: *v.Weizsäcker (1951), Fleck (1996)*
- **Assumptions**:
- (i) no magnetic field
- (ii) no self-gravity

- (iii) scale-invariant density fluctuations (“clouds”) obey a hierarchy of scales on subsequent levels ν:

$$\frac{\rho_\nu}{\rho_{\nu-1}} = \left(\frac{l_\nu}{l_{\nu-1}}\right)^{-3\alpha}, \; 0 \le \alpha \le 1$$

  $0 \le \alpha \le 1$: compressibility, ϱ_ν … average density, 3α … number of dimensions for compression
- (iv) α essentially the **same** on all levels
- energy transfer in a statistical steady state in terms of <u>*energy density*</u> *(Lighthill 1955)*, i.e. $\varrho\varepsilon_K = \varrho\, u^3/l = \text{const.}$ ➔ $u \sim (l/\varrho)^{1/3}$
- ➔ $\varrho^{1/3}\, u \sim l^{1/3} \equiv v$



Spectra of v and u for compressible and incompressible (MHD) turbulence (Kowal & Lazarian 2007); α=0.23 ➔ $k^{5/3}\,E(k) \sim k^{-2\alpha} \sim k^{-0.46}$

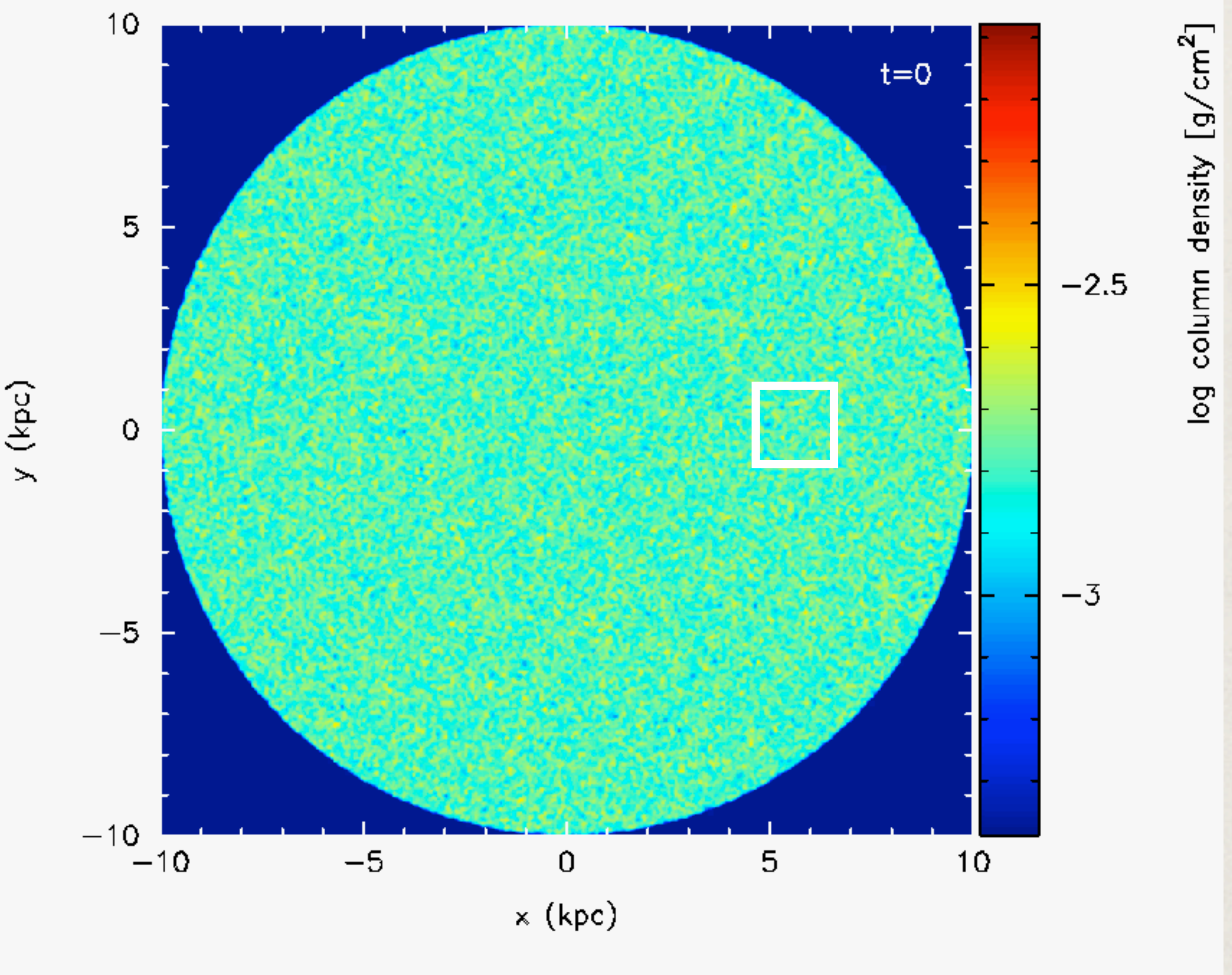
- Set of scaling relations:

$$\begin{aligned} \rho &\sim l^{-3\alpha},\; N \sim l^{1-3\alpha} \\ M &\sim l^{3-3\alpha},\; u \sim l^{1/3+\alpha} \\ E(k) &= \frac{1}{2}\frac{dv^2}{dk} \sim k^{-5/3-2\alpha} \end{aligned}$$

- fractal dimension: D=3-3α
- **transformation** to K41 (**$v \sim l^{1/3}$**) by **$v \equiv \varrho^{1/3}\, u$** (density weighted velocity, *Kritsuk et al. 2007*) ➔ restoring the 2nd order velocity structure function
- α=0.15 (*Kritsuk et al. 2007*)

ISM Simulations I: Large Scales

- Goal: simulate **whole galaxies**
- **3D SPH** (Dobbs et al. 2011)
- fixed gravitational potential, including spiral arms
- heating & cooling, self-gravity
- no magnetic fields
- energy source due to star formation (SF), efficiency 5 - 40%
- UV photon background field
- maximum mass resolution: **2500 M_{sol}** (larger than Jeans length)
- focus on clouds, cold gas
- for T>5000 K, $n \sim 10^{-3}$ cm^{-3}: $\Delta l \sim 300$ pc: too large for studying turbulence and gas phase transitions



Evolution of column density (Dobbs et al. 2011, MNRAS; courtesy Claire Dobbs)

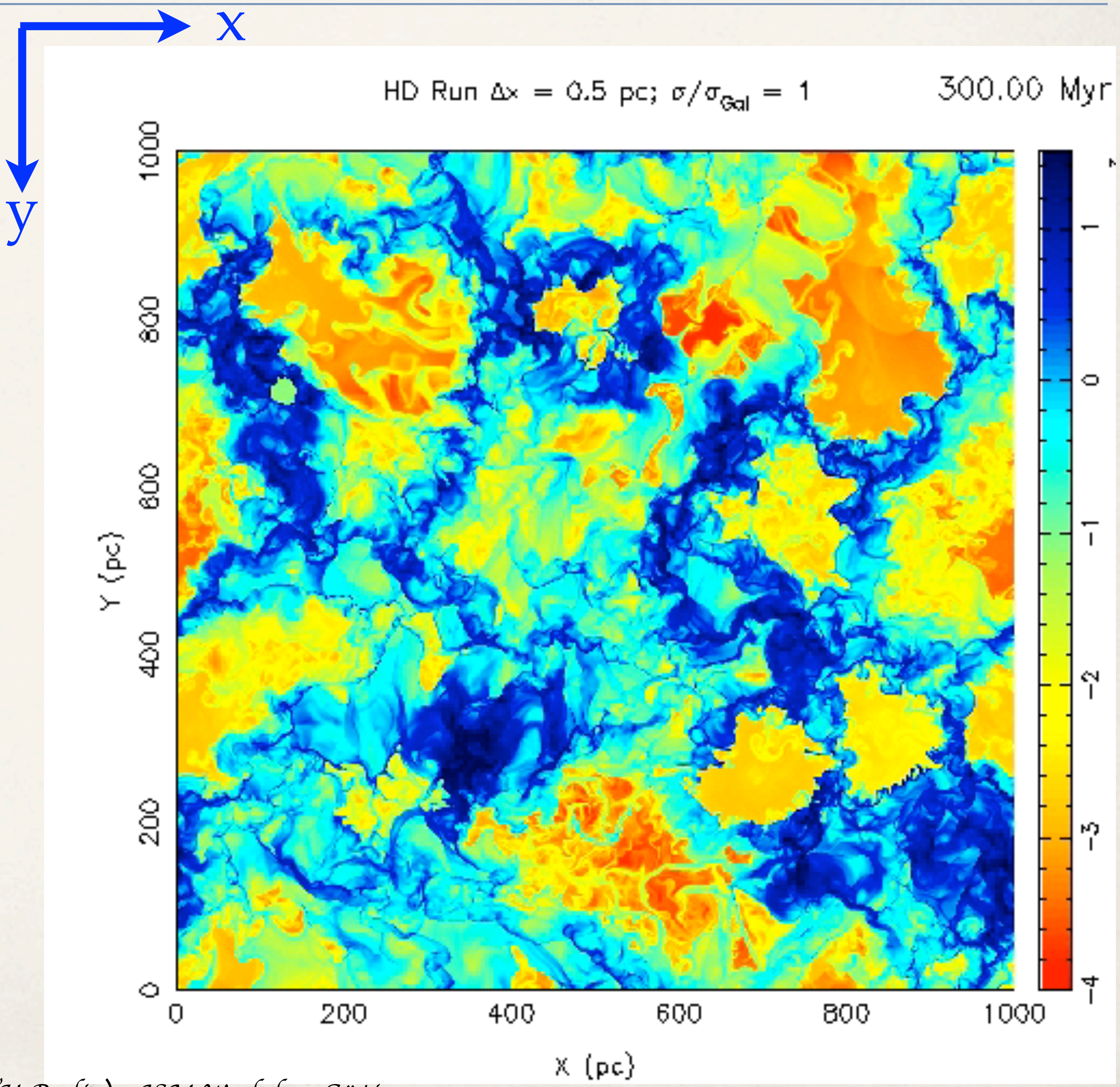
ISM: Numerical Simulations II

- **Mesoscale ISM simulations**: sufficiently large to cover integral scale, sufficiently small to resolve gas phases distributions (Δx=0.5 pc or less)
- Solve full 3D **HD/MHD equations** on a large grid: **1 kpc × 1 kpc × ± 10 kpc**
- Type Ia,b,c/II Supernovae random + clustered in disk
- Background heating due to diffuse UV photon field (Wolfire et al. 1995)
- Thermal conduction including saturation (Dalton & Balbus 1993)
- Gravitational field by stars + self-gravity
- SFR $\propto$ 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 $\tau \sim 400$ My
- ➔ sufficiently long to erase memory of initial conditions!
- 3D calculations on parallel processors with adaptive mesh refinement (**AMR**) grid code

HD-Evolution of ISM

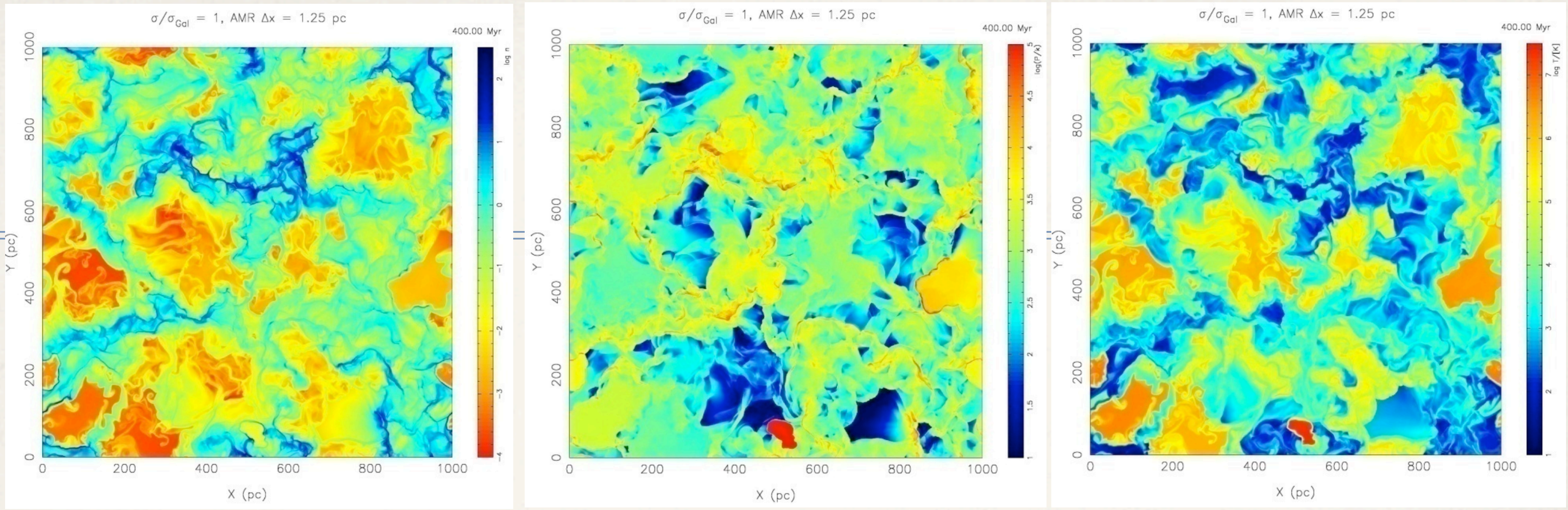
Avillez & Breitschwerdt, 2010

- **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 generates 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)

σ=1

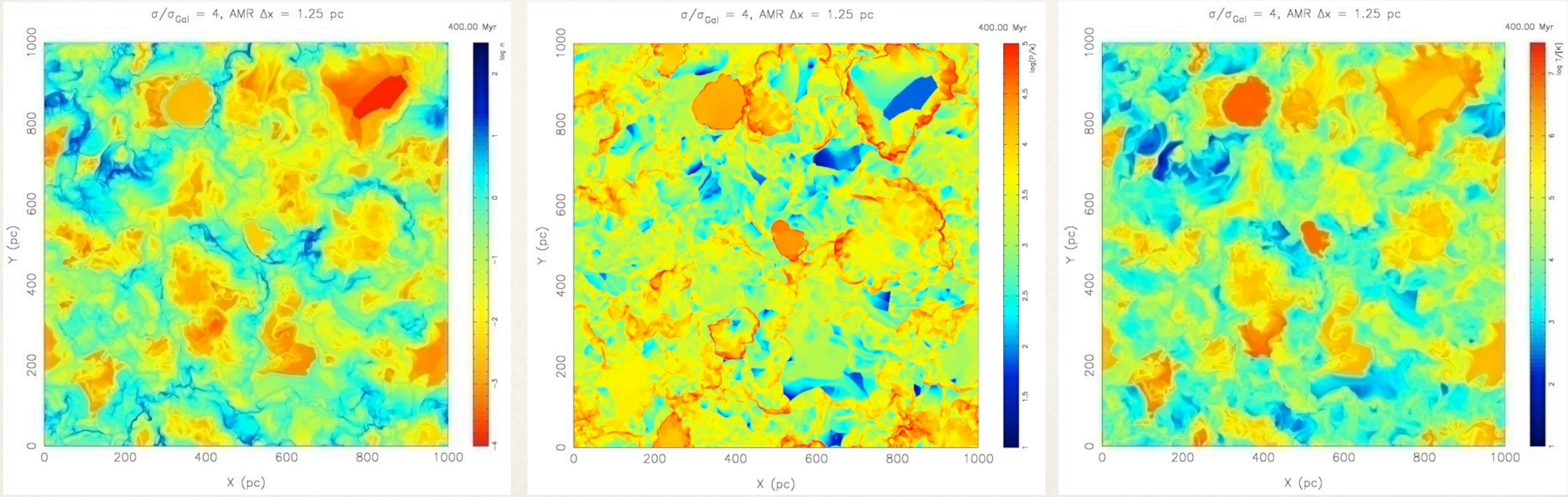


n

P/k

T

σ



σ=4

σ … SN rate

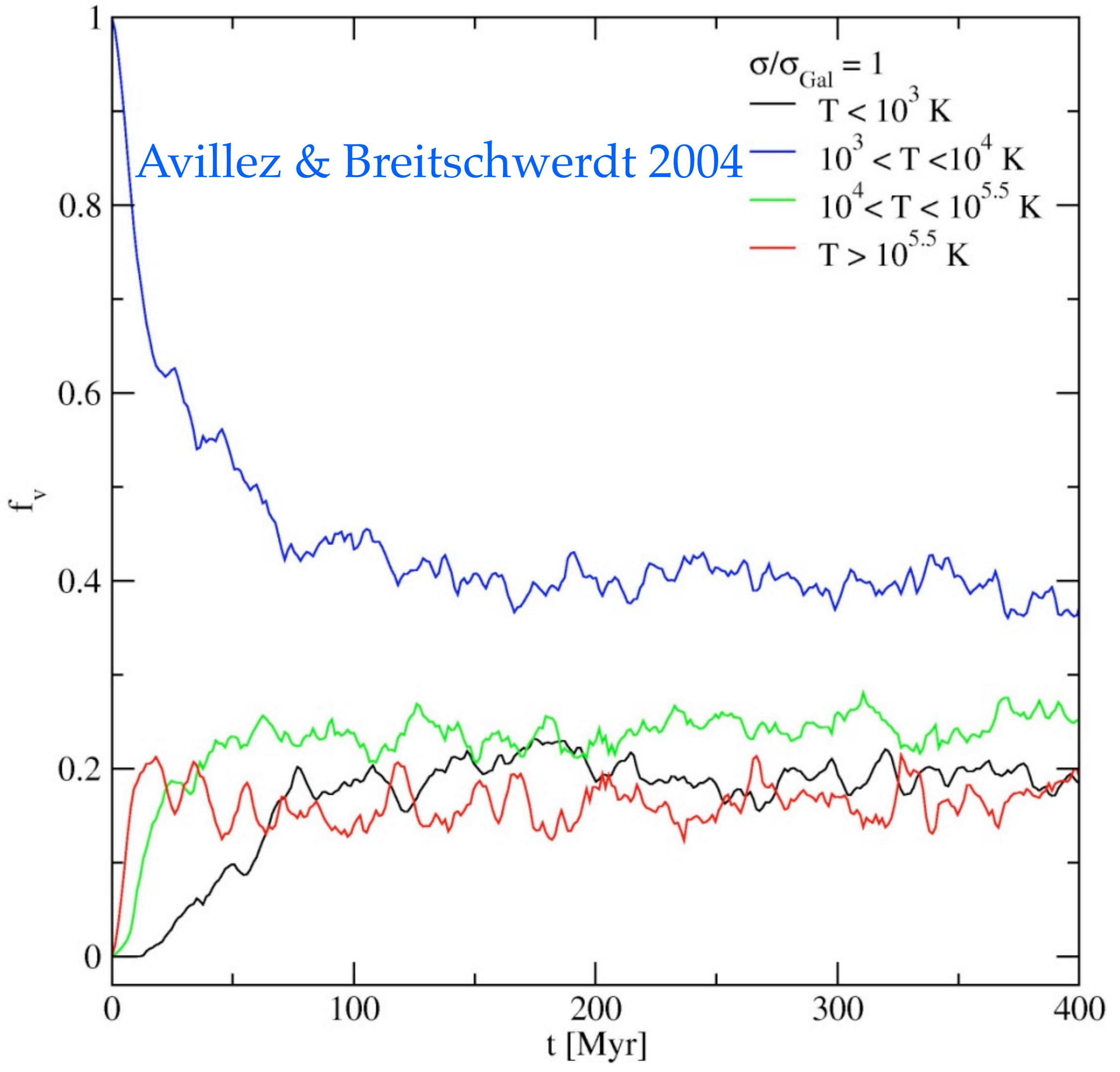
Results

- Pressure far from uniform: spatial variation even for high SN rate ($\sigma/\sigma_{gal} = 4$)
- $\langle P/k \rangle \sim 3000$ for Milky Way, i.e. 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: $f_V \sim 0.2$
- lots of gas in thermally unstable regions

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



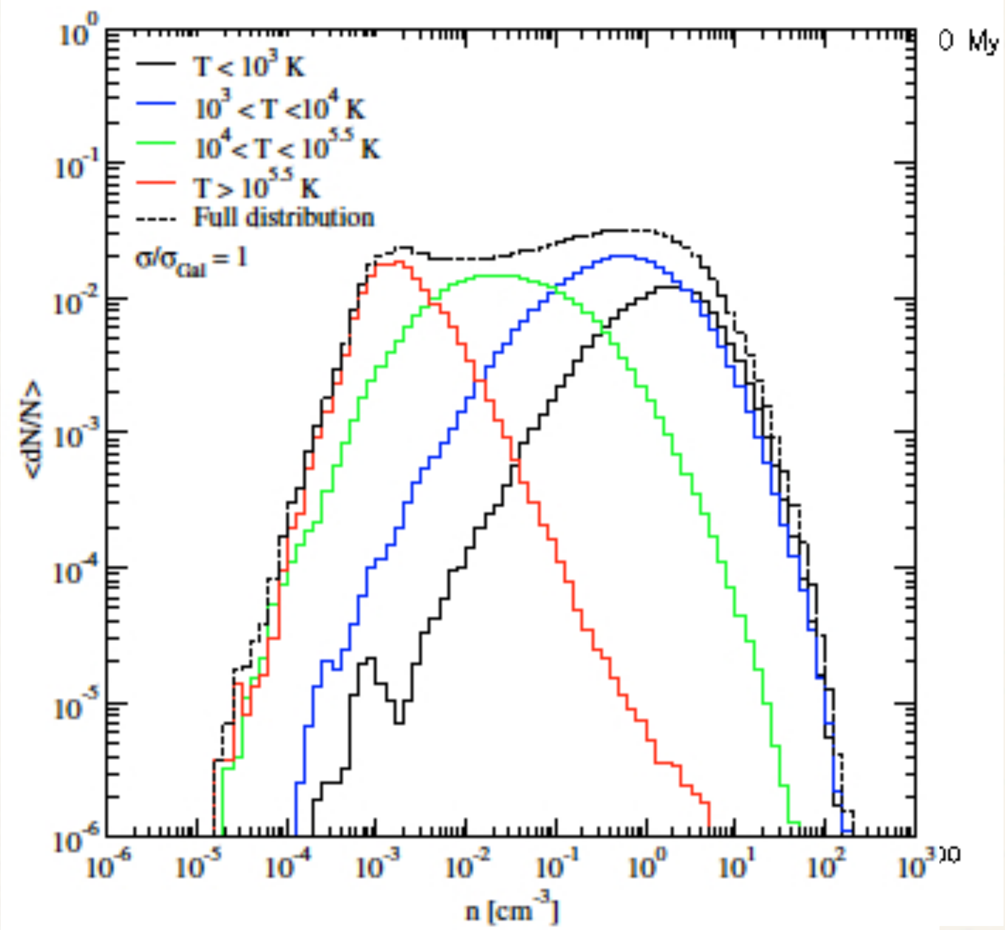
Avillez & Breitschwerdt 2004

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

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

Results III: Probability Density Functions (PDFs)

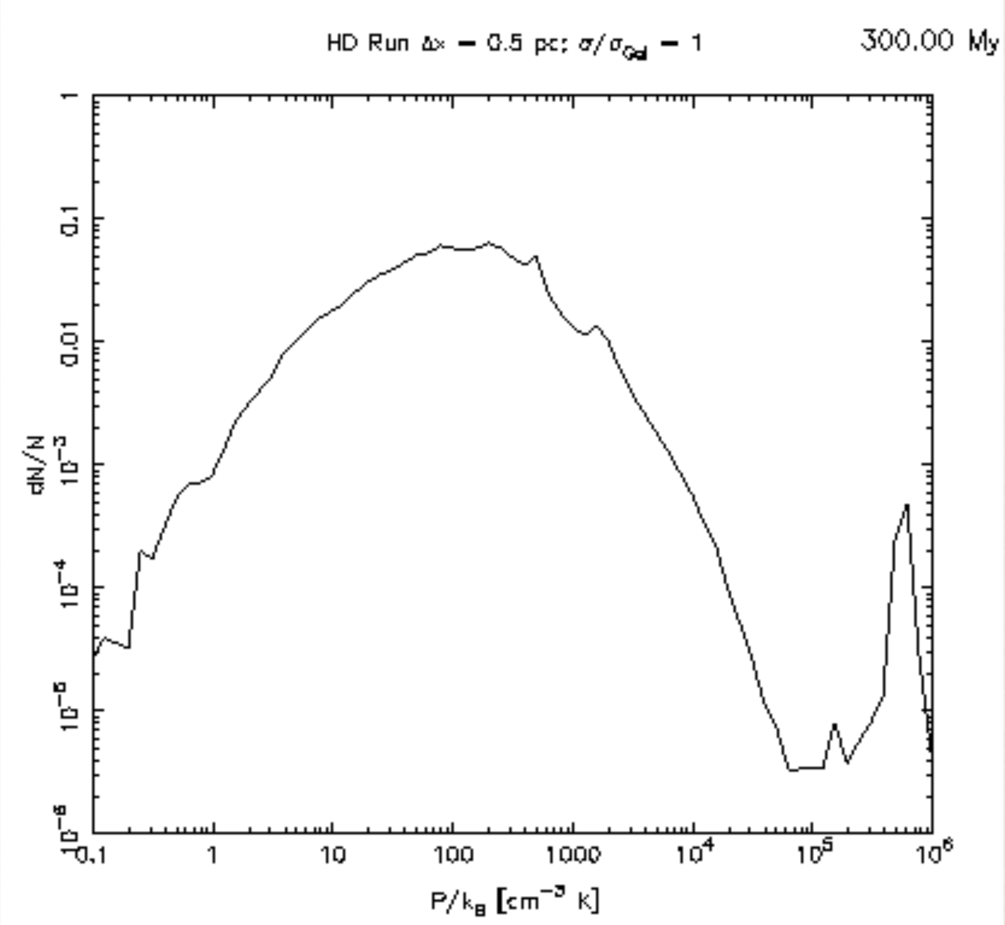
Avillez & Breitschwerdt, 2009



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;

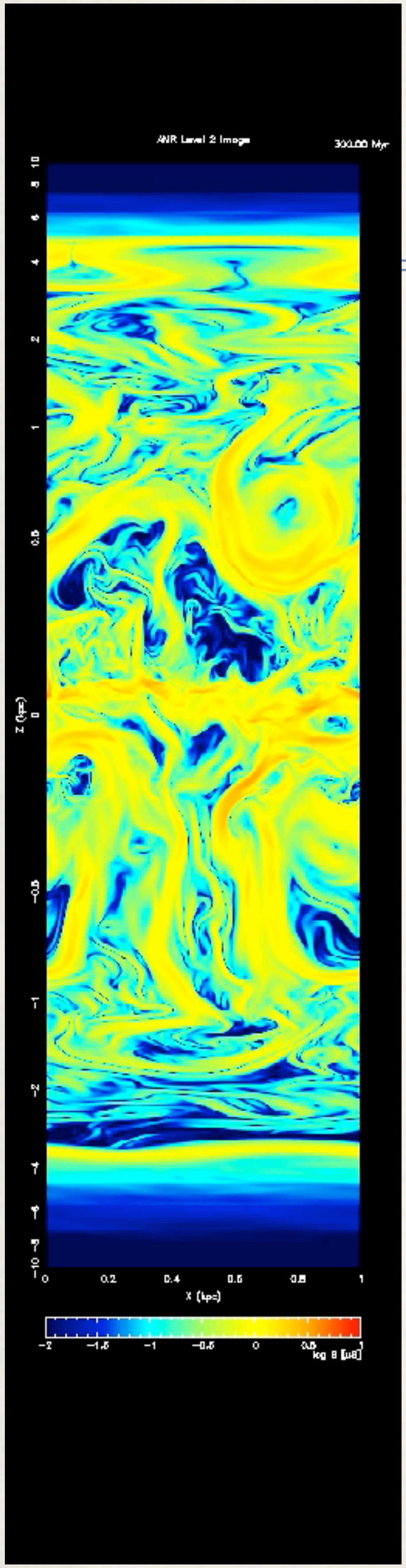
broad pressure distribution

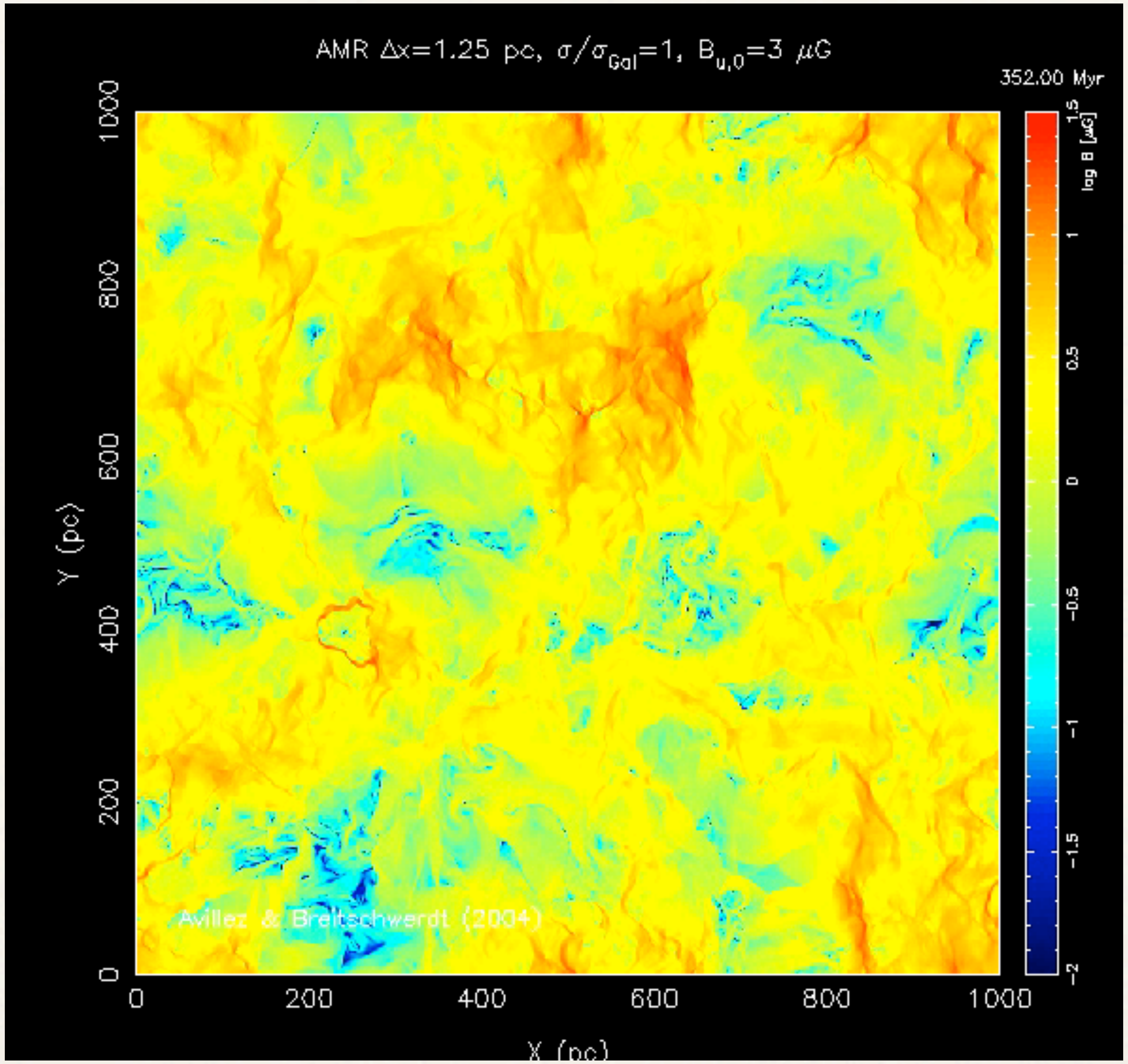


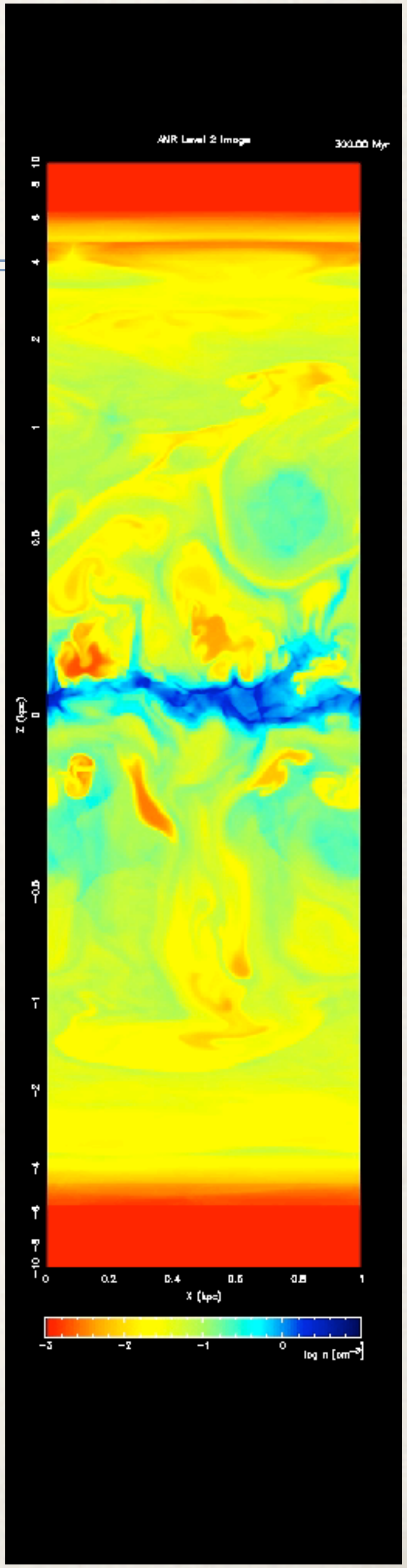
- PDF gives probability to find a fraction f(x) of gas in given density/pressure regime
- For $X \in \{\varrho,P\}$) we have: $$P(a \leq X \leq b) = \int_a^b f(x)dx$$
- In a SN driven ISM the distribution is very broad ➔ substantial fraction of gas exists outside "phases", i.e. in **thermally unstable**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

MHD-Evolution of ISM I

Avillez & Breitschwerdt, 2005a

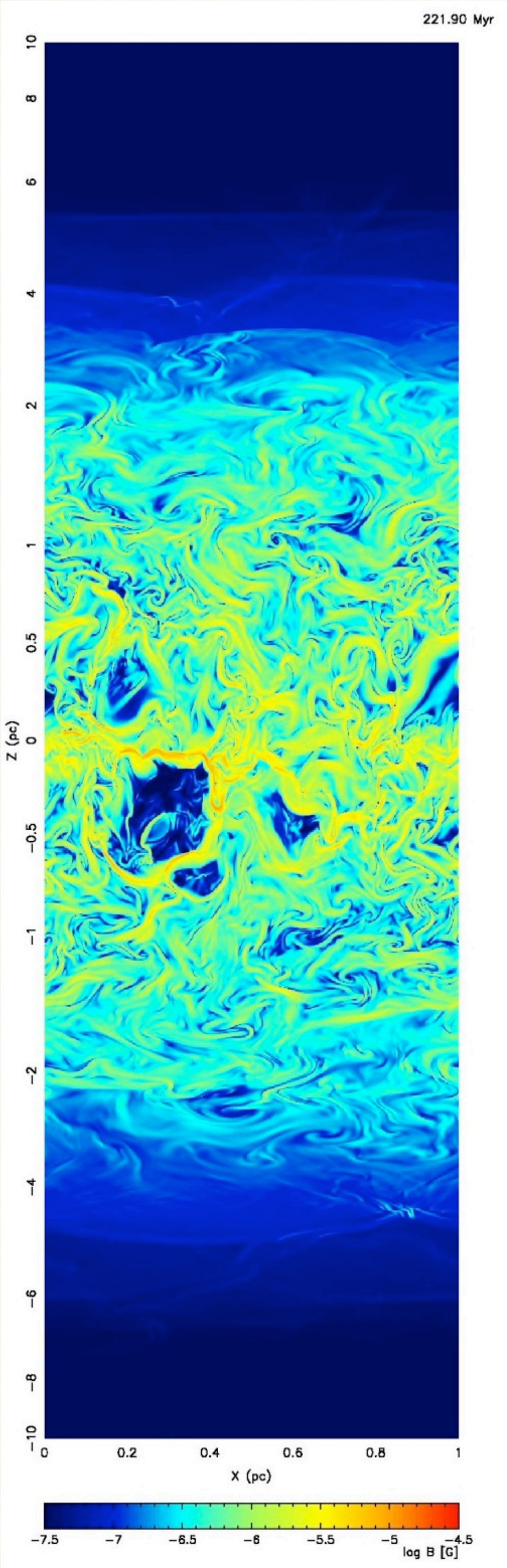






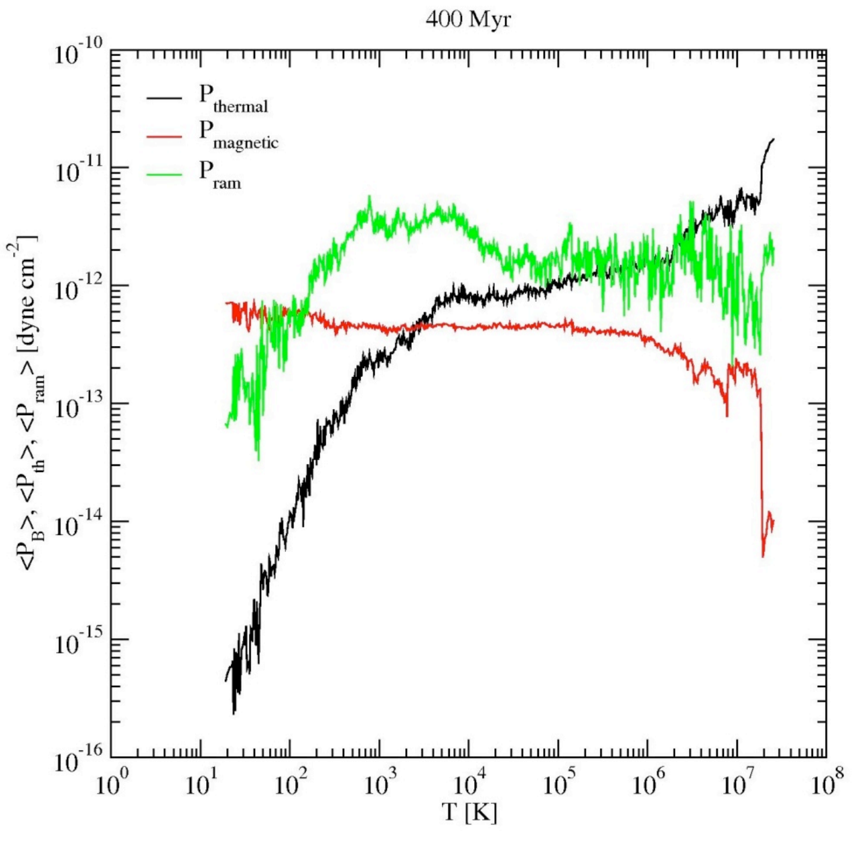
Outflow not inhibited by B-Field; lines of force drawn out by disk-halo flow ➔ loop structure

MHD-Evolution of ISM II



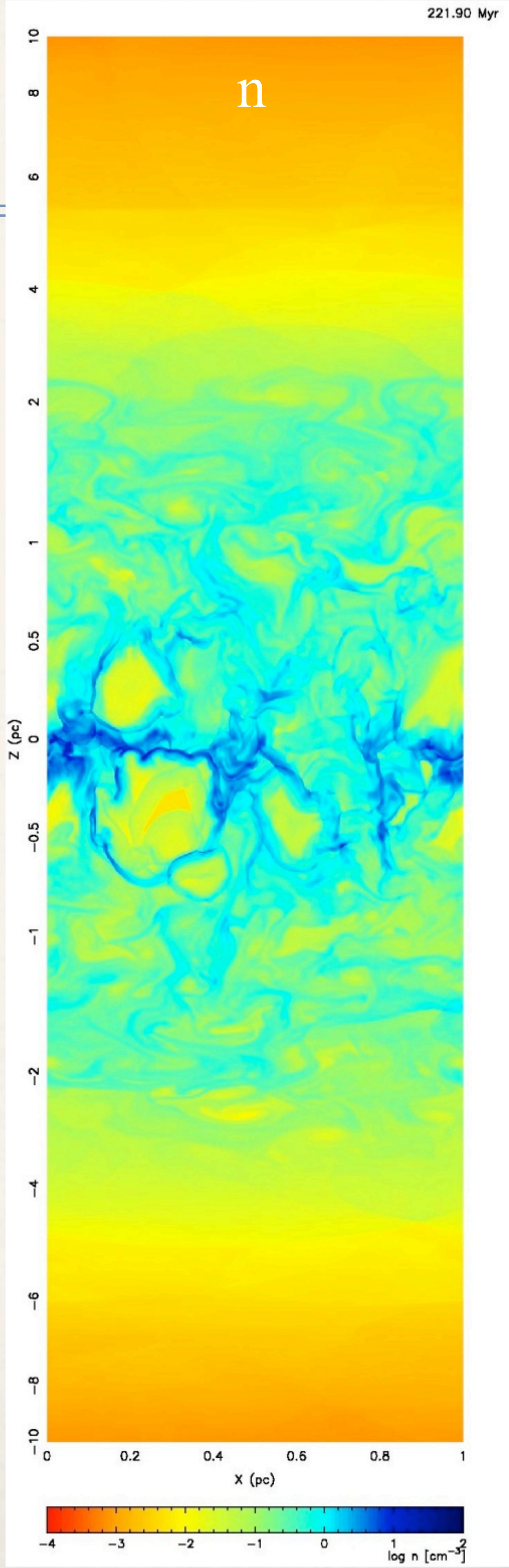
Avillez & Breitschwerdt, 2005a

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



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)
  - SN increased **turbulence** can work against condensation ➔ turbulent transport of energy (cf. heat conduction in the solar chromosphere)
  - **eddy crossing time << cooling time**

Stability of "Phases" II

- Field criterion does not take into account turbulent dynamics
- **Turbulent diffusion** can stabilize, inhibiting local condensation modes (cf. solar chromosphere), transporting energy to cooling regions: $\nu_{\mathrm{turb}} \sim \mathrm{Re}\ \nu_{\mathrm{mol}}$
- Thermal instability inhibited, if fluctuations occur on time scales less than the cooling time: $\boldsymbol{\tau_{\mathrm{eddy}} << \tau_{\mathrm{cool}}}$

$$\tau_{\mathrm{eddy}} \sim \frac{\lambda}{\Delta u} \sim \left(\frac{\rho}{\epsilon}\right)^{1/3} \lambda^{2/3} < \frac{k_B T}{n \Lambda(T)}$$

(incompressible turbulence)

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

- values for **WNM**: $\varepsilon \sim 10^{-26}$ erg cm^{-3} s^{-1}, n~0.3 cm^{-3}, T~1000 K, $\Lambda_0 \approx 1.9\ 10^{-27}$ erg cm^3 s^{-1} K$^{-1/2}$: **$\lambda < 10^{19}$ cm ➔** thermal instability inhibited on parsec scales
- compressible turbulence: strong dependence on α in "Fleck-model":

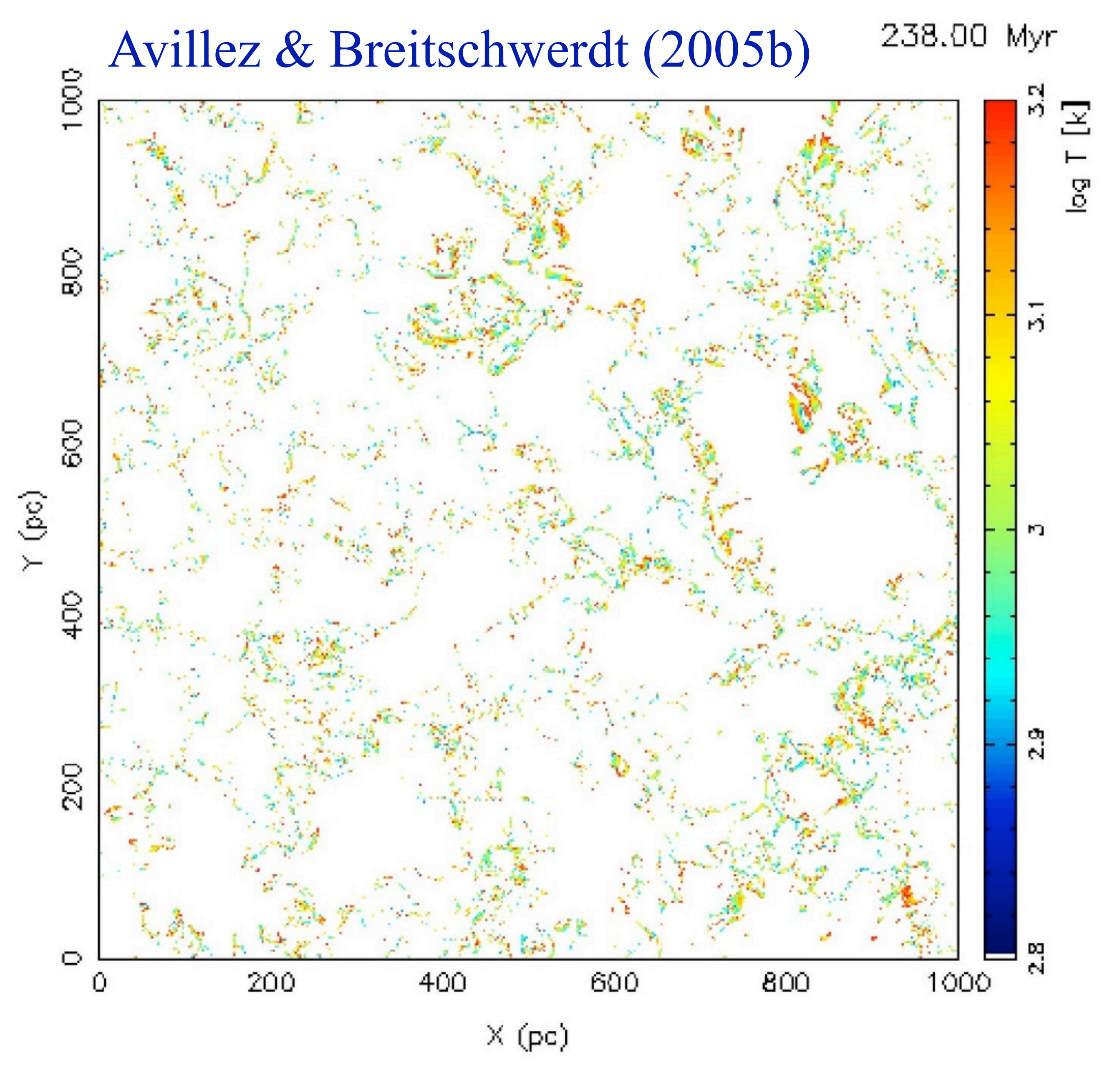
$$\lambda < \left[\frac{3}{2}\left(\frac{\epsilon_V}{\rho_0^4}\right)^{1/3} \frac{\bar{m} k_B T^{1/2}}{\Lambda_0} l_0^{-4\alpha}\right]^{3/(2-12\alpha)}$$

(compressible turbulence)

- compressibility decreases critical length, because cooling time decreases faster than turn-over time; **$\alpha \sim 0.1$: $\lambda \sim l_0^{-0.4}\ T^{1.75}$; $\alpha = 0$: $\lambda \sim T^{0.75}$**

Stability of "Phases" III

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

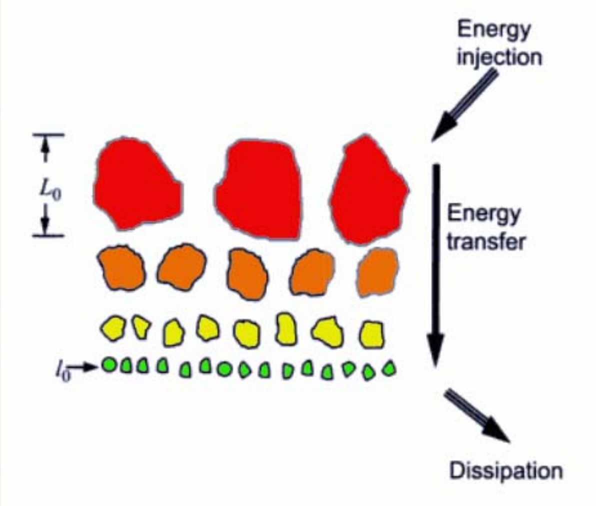

Avillez & Breitschwerdt (2005b)

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):

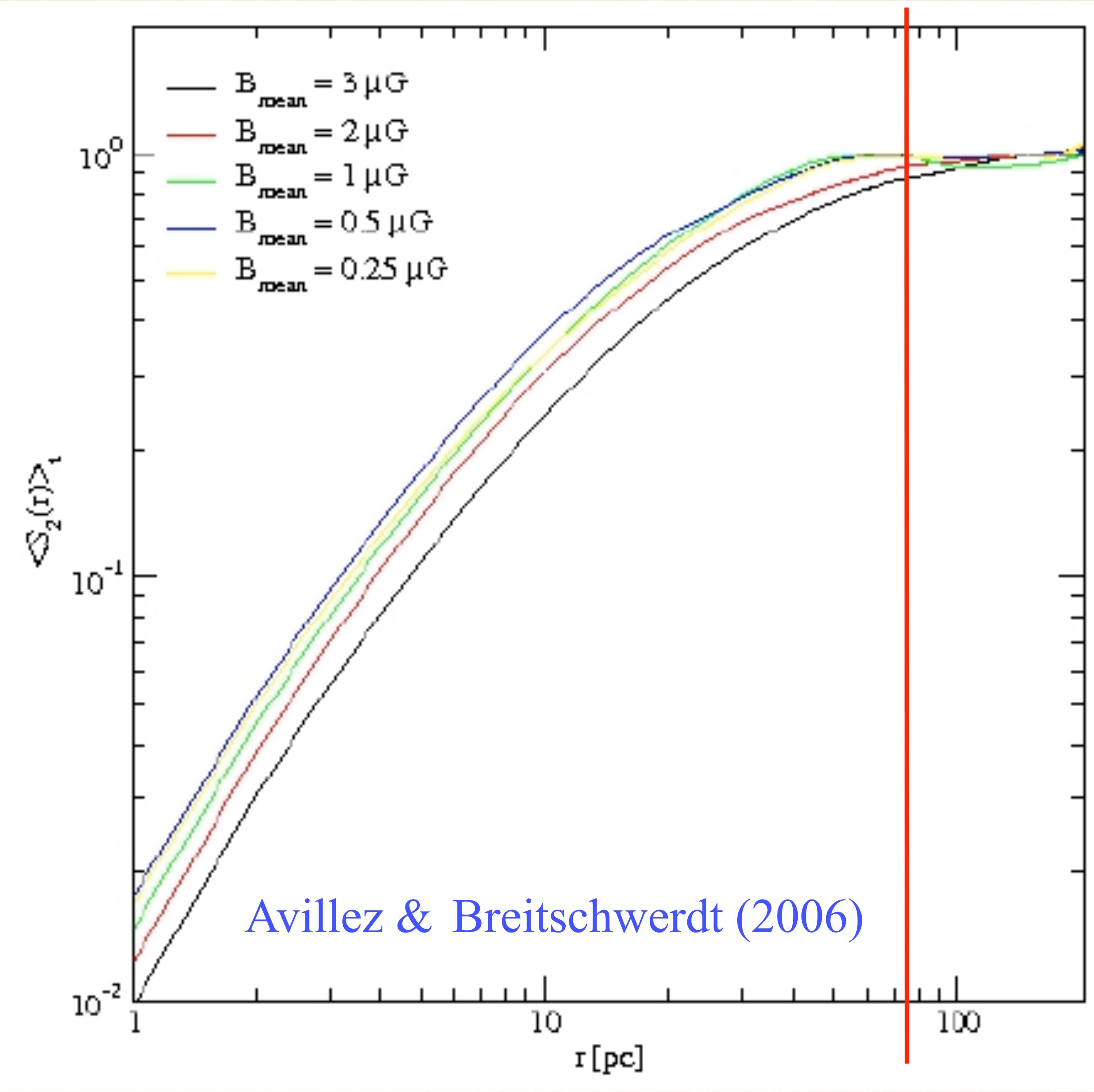
"Big whorls have little whorls that feed on their velocity, and little whorls have lesser whorls and so on to viscosity"



- 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



Avillez & Breitschwerdt (2006)

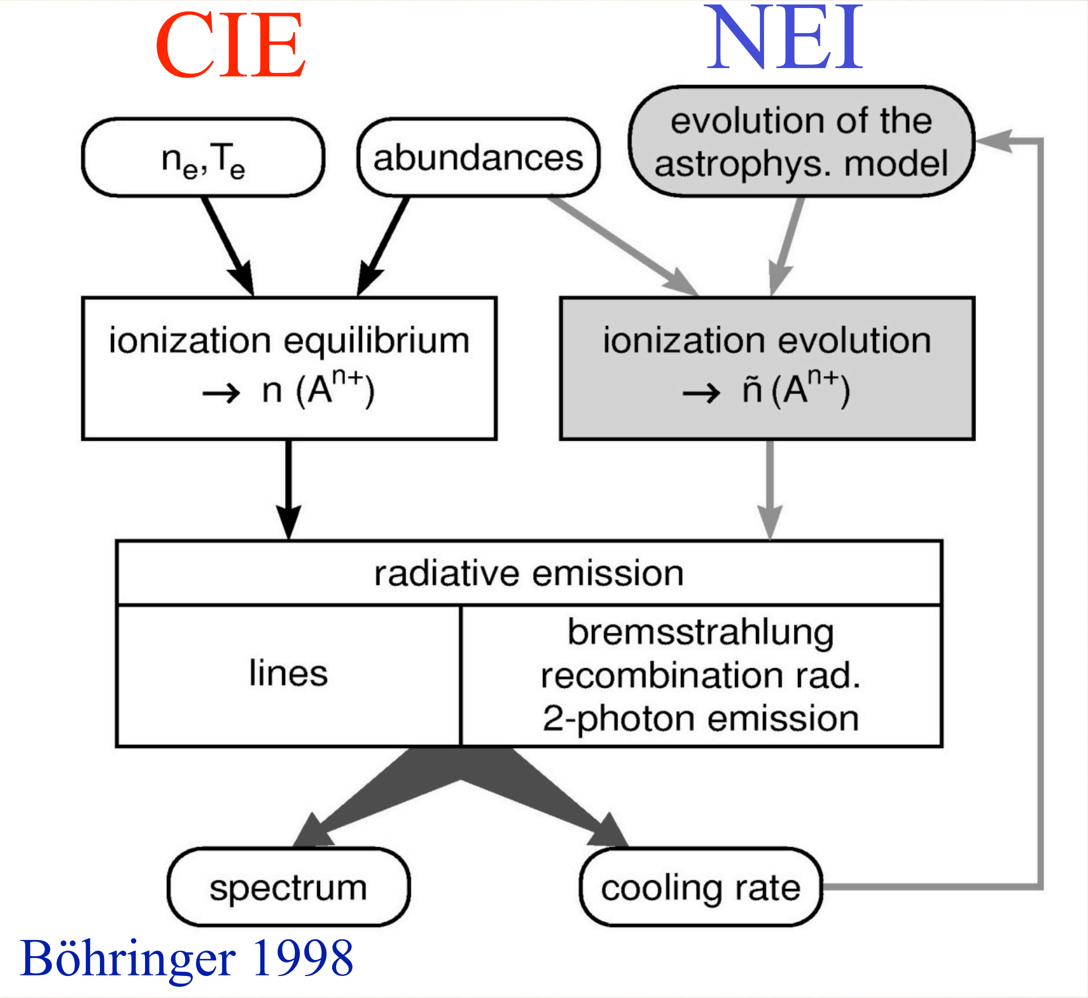
$<S_2(r)>$ flattens at r ~ 75 pc: **integral scale**

Fleck (1996): $S_p(r) \sim v^p \sim l^{p/3}$ ➔ $S_2(r) \sim l^{2/3}$

$$\frac{1}{2}\langle \vec{u}^2 \rangle = \int_0^\infty E(k)dk\,,\ \frac{1}{2}\langle \vec{\omega}^2 \rangle = \int_0^\infty k^2 E(k)dk$$

Non-equilibrium ionization (NEI) structure of ISM (I)

- **optically thin hot plasmas**: continuum + line spectrum ($n_e < 10^4$ K: coronal approx.)
- **collisional ionization equilibrium (CIE)**: ionization by collisions (3-body process) is balanced by **radiative recombination ➔** no detailed balancing, because atomic time scales are different
- plasma is driven out of CIE ➔ **non-equilibium ionization (NEI)** structure, e.g. Kafatos (1973), Shapiro & Moore (1976), Stone & Norman (1993) etc.
- particularly striking effect: **fast adiabatic cooling** like in a galactic fountain or wind (Breitschwerdt & Schmutzler, 1994)


CIE

NEI

n_e, T_e

abundances

evolution of the astrophys. model

ionization equilibrium → n (A^{n+})

ionization evolution → ñ (A^{n+})

radiative emission

lines

bremsstrahlung

recombination rad.

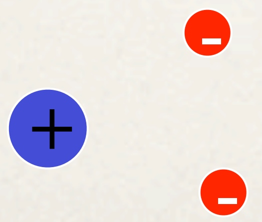
2-photon emission

spectrum

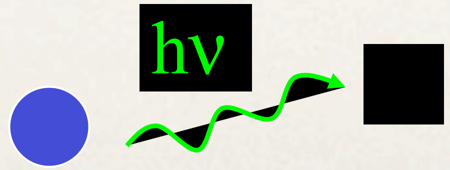
cooling rate

Böhringer 1998

Top: *CIE vs. NEI plasma emission codes; in* ***CIE****, plasma emission can be calculated (in coronal approx., i.e.* $n_e < 10^4$ *cm*$^{-3}$*) once and for all if* n_e*,* T_e *and Z are given; in* ***NEI*** *Z + astrophysical model for dynamical evolution is required!*
Left: *Animation of collisional ionization by electrons*

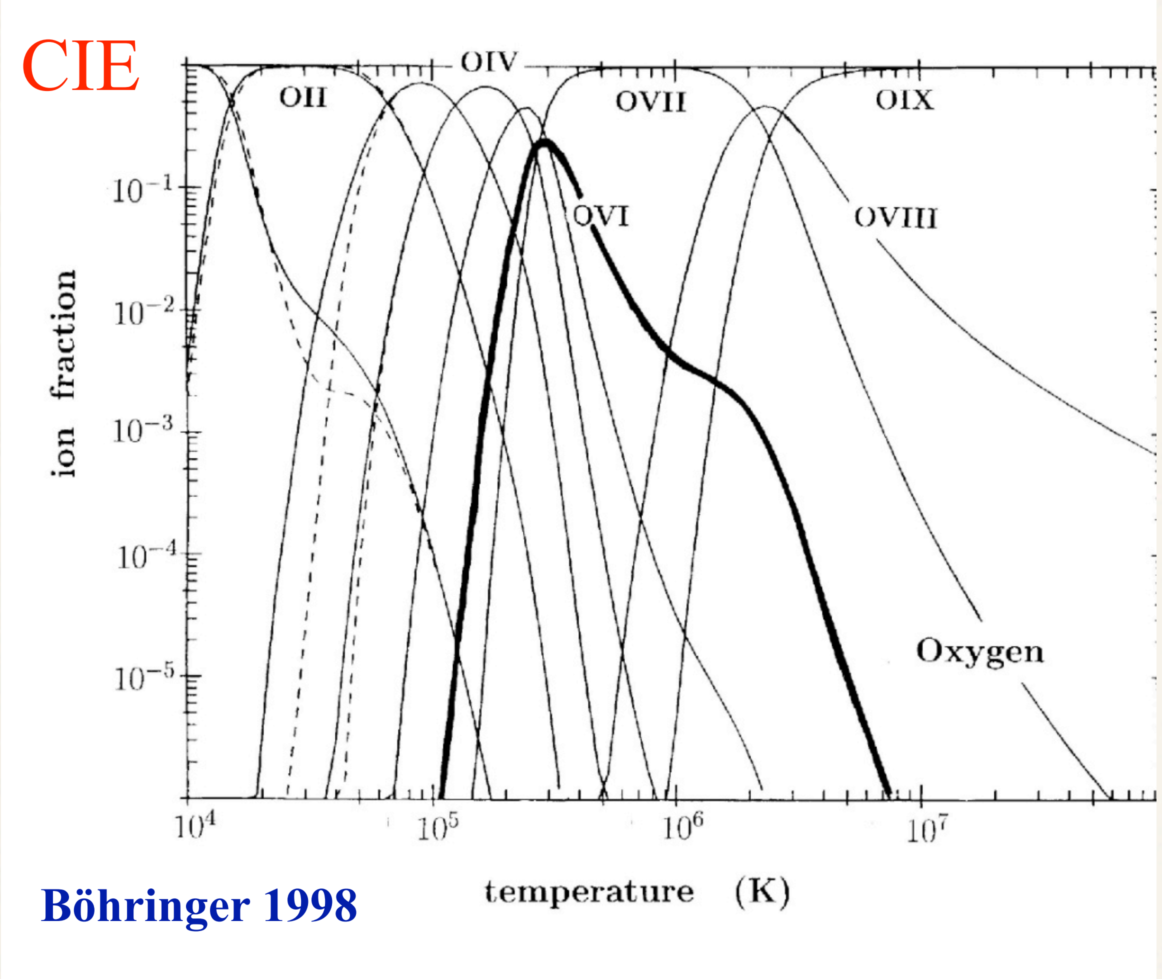


collisional ionization

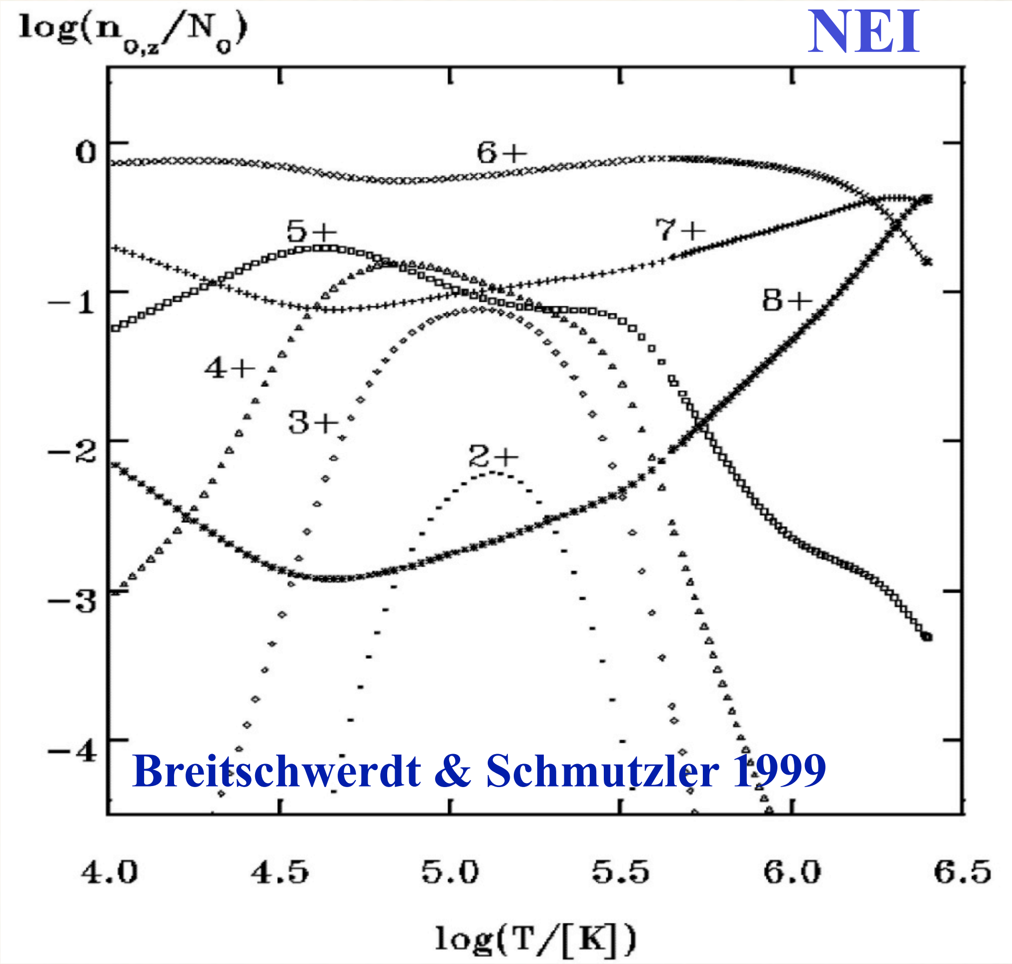


radiative recombination

Example: ionization structure of oxygen in CIE and NEI



Böhringer 1998



Breitschwerdt & Schmutzler 1999

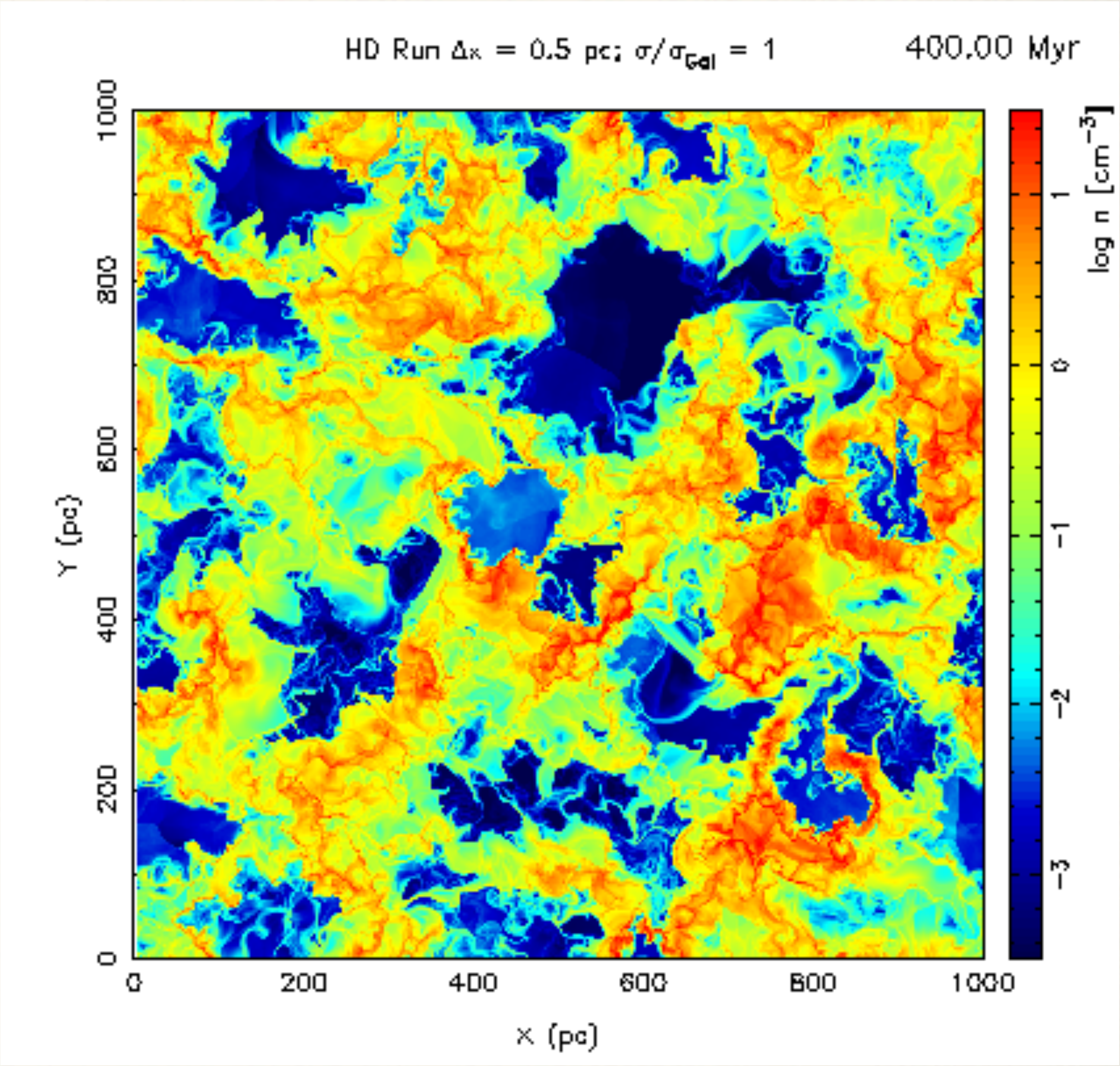
- **CIE:** ionization fractions *x* of O depend only on temperature T (for given Z) ➔ sharply peaked ➔ convenient diagnostic tool for determining T
- **NEI**: *x* depends on dynamical and thermal history of plasma ➔ more difficult to fit spectrum, but: **evolution of plasma can (in principle) be inferred!**

NEI structure of ISM (II)

Avillez, Breitschwerdt, Manuel (2011)

- Flow changes ϱ and **T**
- this modifies **ionization structure**
- which in turn modifies **cooling function** $\Lambda(T,Z)$
- which changes outflow
- ➔ **Time-dependent Cooling Function**

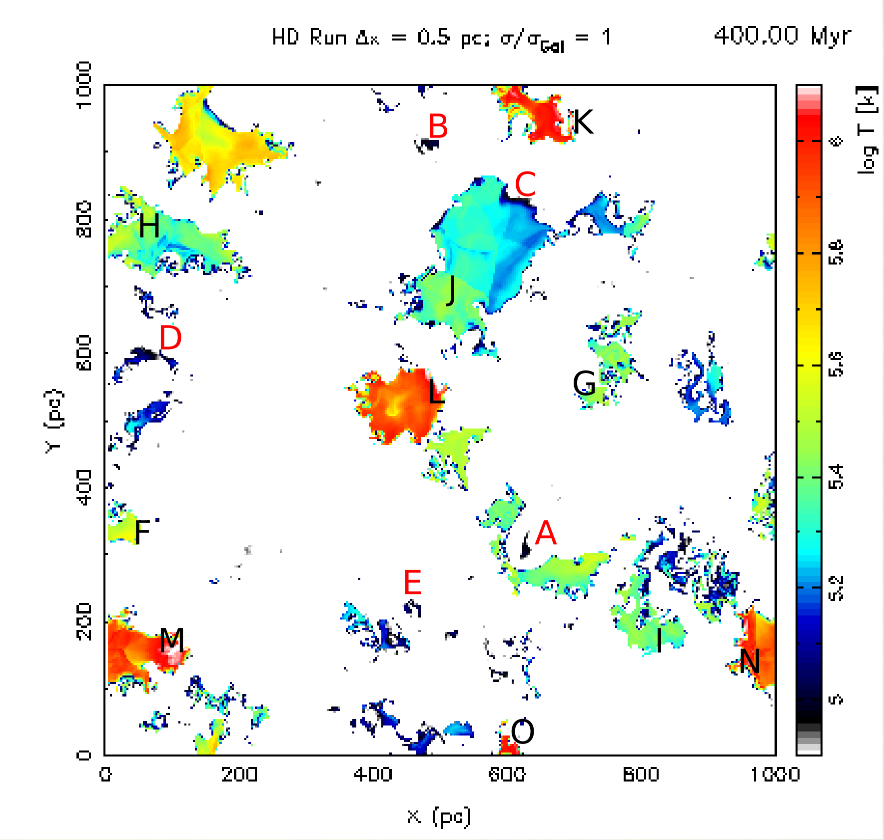
- **Modelling**: use 10 most abundant elements
- 3D hydrodynamics (parallelized with AMR) with a highest resolution of 0.5 pc
- include most important processes: electron impact ionization, excitation auto-ionization, radiative and dielectronic recombination, charge exchange reactions, continuum (bremsstrahlung, free-bound, 2-photon) and line emission

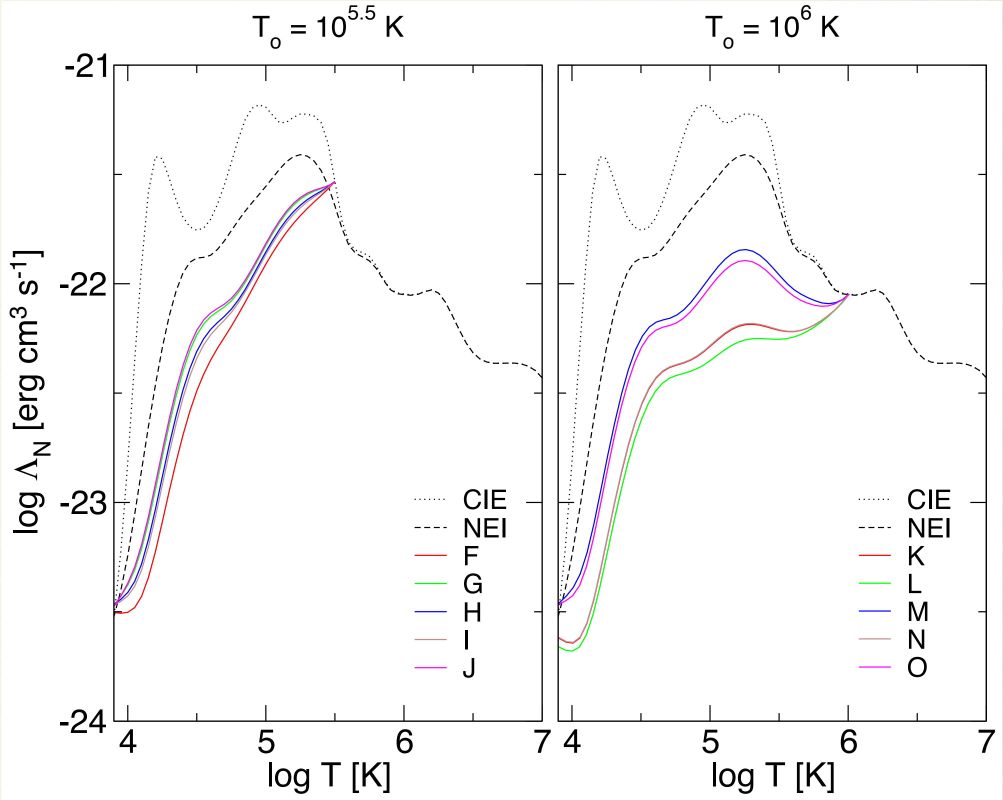


__Top__: 3D high resolution NEI simulation, cut through galactic midplane (at solar circle), after evolution time t= 400 Myr

NEI structure of ISM (III)

- **CIE cooling curves** are no longer valid → cooling depends on the **thermal** and **dynamical history** of the plasma, i.e. distribution of ionization stages
- Ionization structure varies from place to place and with time → multitude of different cooling functions: $\mathbf{\Lambda = \Lambda(r,t; T, Z)}$
- **delayed ionization**: plasma is *underionized* due to slow ionization of neutral plasma → typical for cold plasmas collisionally ionized by shocks
- **delayed recombination**: plasma is *overionized* due to slow recomb. of high ionization stages → typical for very hot cooling plasmas
- NEI cooling curves of cooling down plasma below CIE since deficiency of outer electrons for line emission
- X-ray observations of diffuse hot plasma show signs of delayed recombination

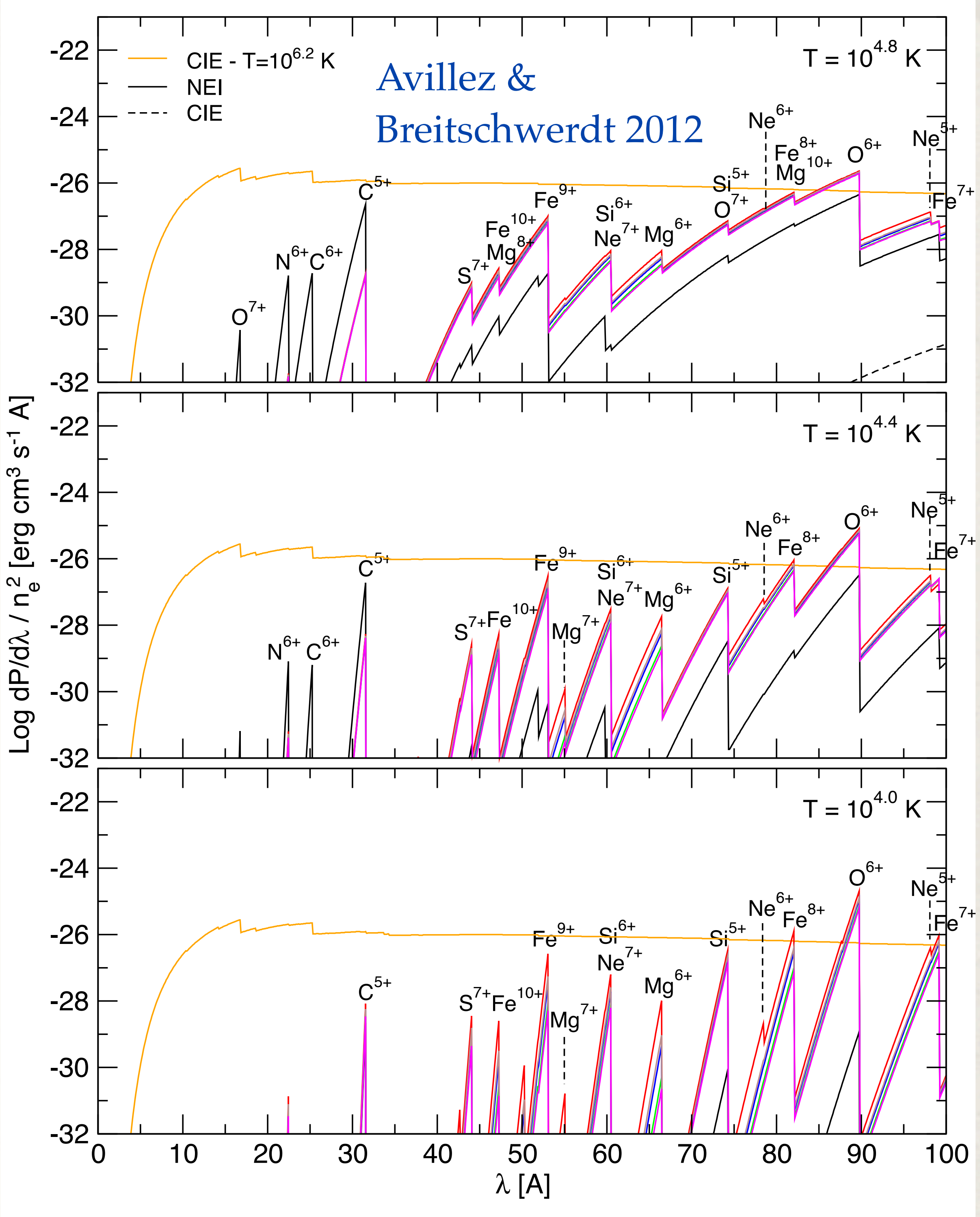




__Top__: Midplane cut of NEI simulations marking regions of different temperatures: $10^{5.5}$ K (F-J), 10^{6} K (K-O)
__Bottom__: Cooling curves of different places with different initial temperatures; dotted line is CIE and and dashed line is NEI of an initially completely ionized plasma

NEI structure of ISM (IV)

- **NEI spectrum:**
- saw-tooth emission line structure
- soft X-ray emission at kinetic temperatures as low as 25,000 K!!!
- NEI emission at 0.3 keV higher at T=10^4 K than CIE emission at 10^6 K
- CIE emission at 0.3 keV for T=10^4 K negligible
- NEI spectrum unique, as it reflects the **thermal and dynamical history** of the plasma



***Top**: NEI simulation of free-bound emission of a plasma initially at temperature 10^6 K located at sites K-O*

Modeling soft X-ray emission from the ISM

Procedure:

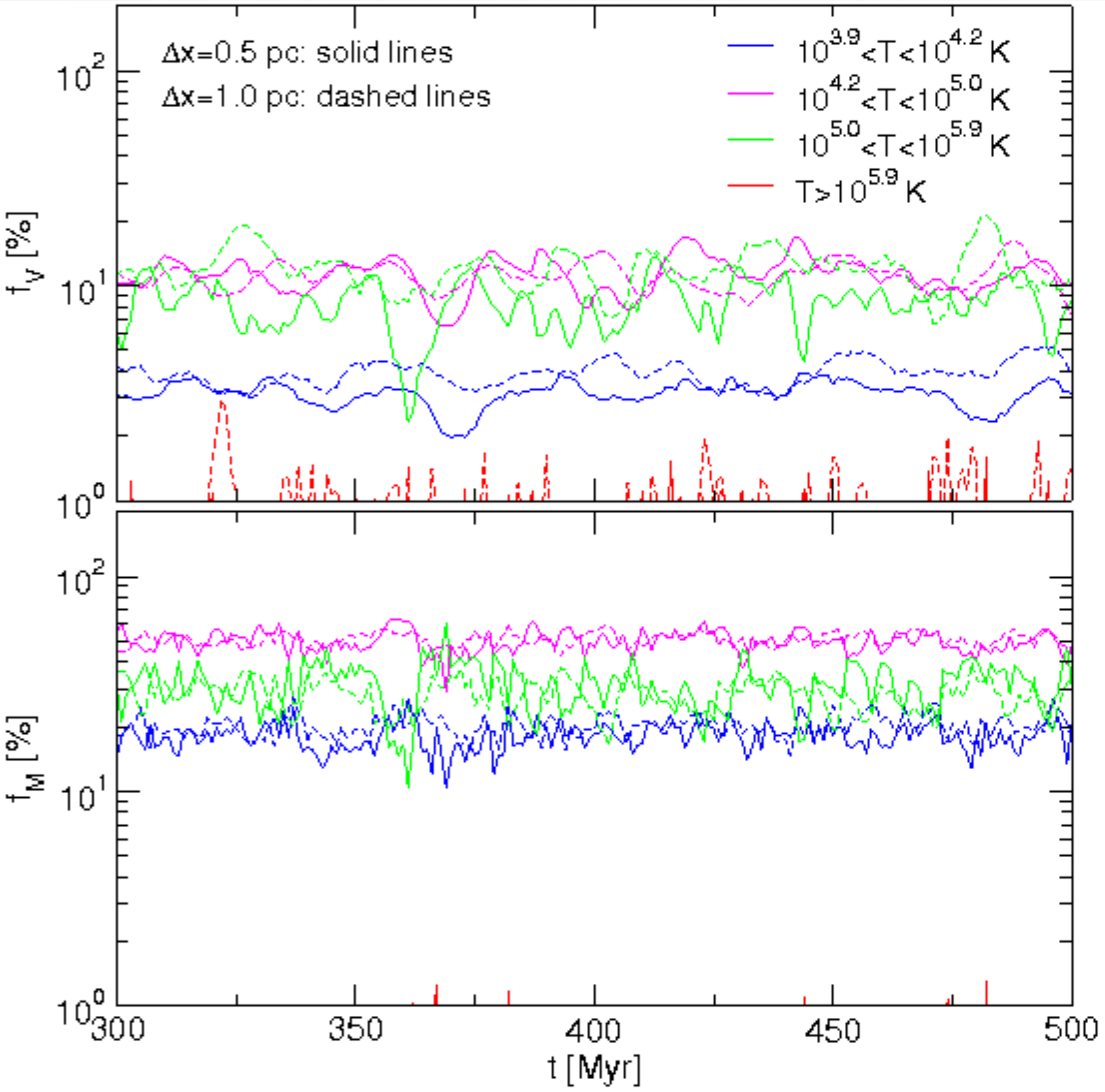
- **Generating** an ISM model and follow time-dependent evolution of ions (NEI) ➔ integrate spectrum along line of sight
- **Binning** of high-resolution unabsorbed synthetic (model) spectrum into e.g. EPIC pn channels (for XMM-Newton)
- **Folding** spectrum through detector response matrix

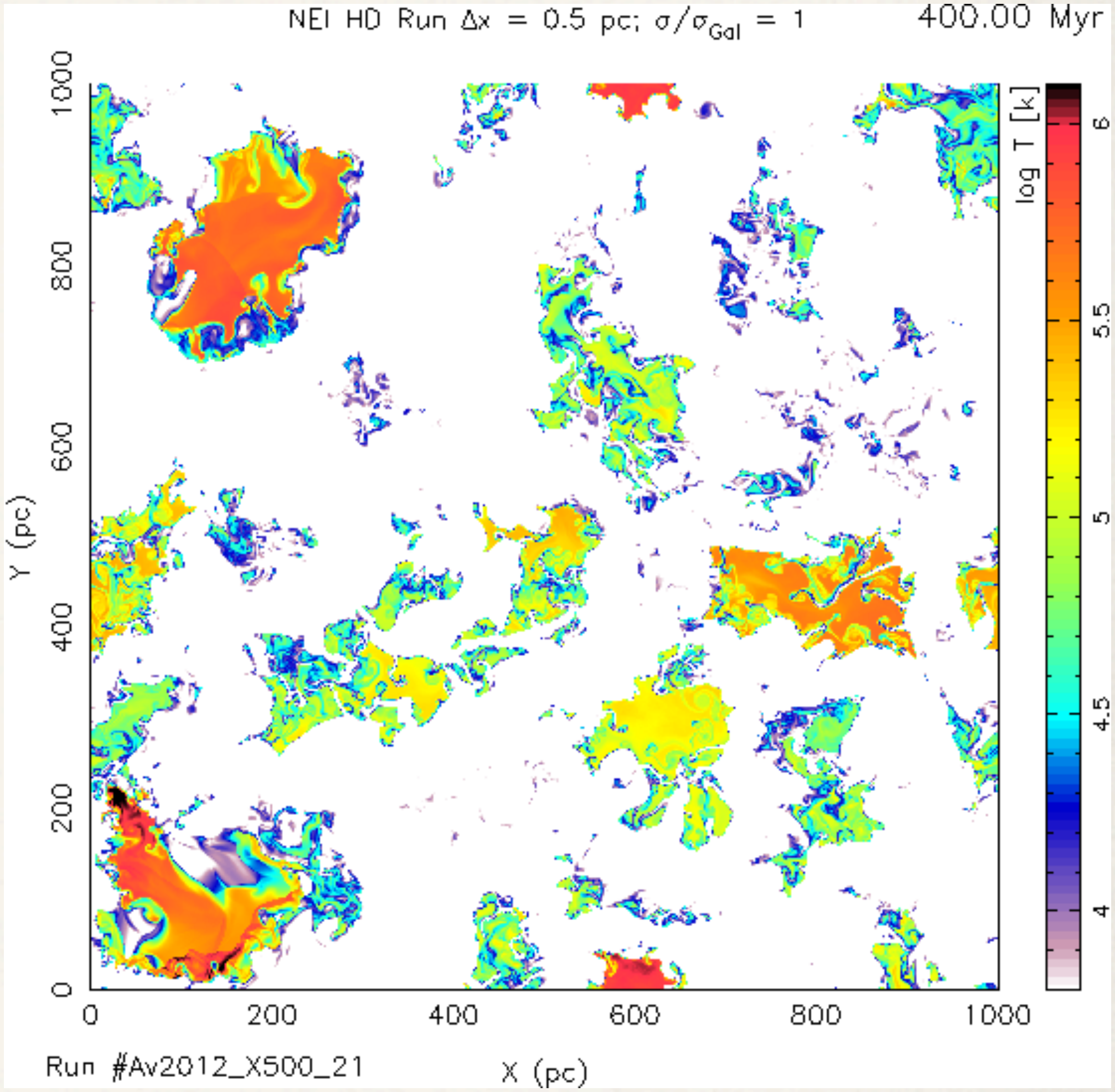
➡ Treating observed and synthetic spectrum equally! (Breitschwerdt 2003)

- **Fitting** synthetic spectrum in XSPEC (X-ray spectral fitting routine) to observational data
- **Comparing** with observed spectrum and iterate outflow model if necessary until convergence

Comparison to Observations I: OVI

Avillez & Breitschwerdt (2012)



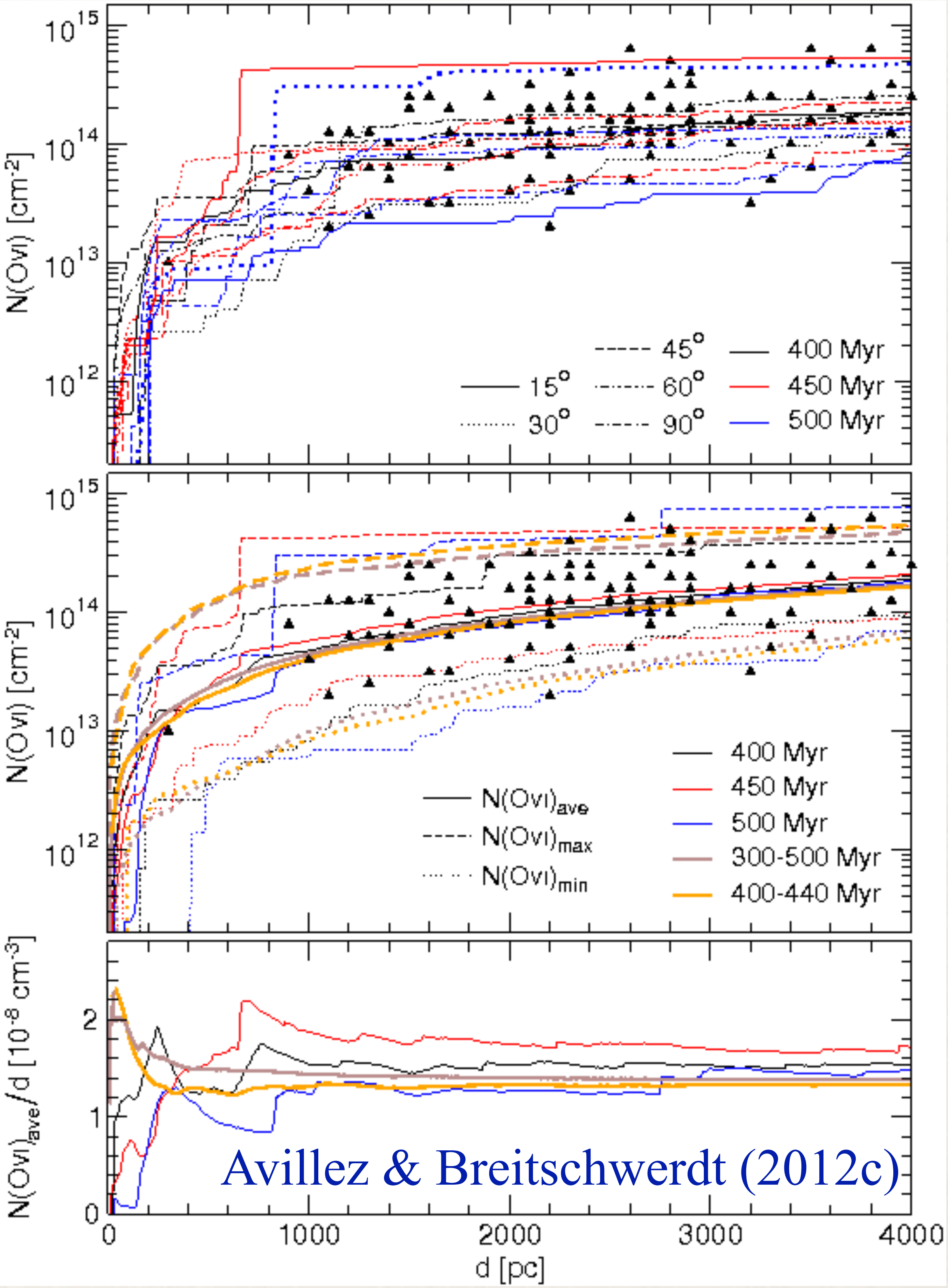


- OVI traces cooling down HIM
- OVI produced in **turbulent mixing layers**!
- **70%** of OVI in **NEI** below 10^5 K, i.e. well below the CIE value!!!

- OVI temperature distribution in the ISM; shown are values $10^{3.8} < T(\mathrm{OVI}) < 10^{6.1}$ K highest n(OVI) densities in cool clumpy regions
- Zoom into bubble shows turbulent mixing

Comparison to Observations II: OVI

- FUSE & Copernicus data of **OVI absorption lines** towards background stars
- Comparison with **NEI** simulations: spatially averaged (red and blue curves) and single LOS of N(OVI) at different angles and at different times
- N(OVI) converges to an average value of 1.3 - 1.4 10^{-8} cm^{-2}
- FUSE observations for |z| ≤ 150 pc: N(OVI) ~ 1.3 10^{-8} cm^{-2} (Bowen et al. 2008)
- dispersion of N(OVI) ~ const. ➔ clumpy distribution along LOS

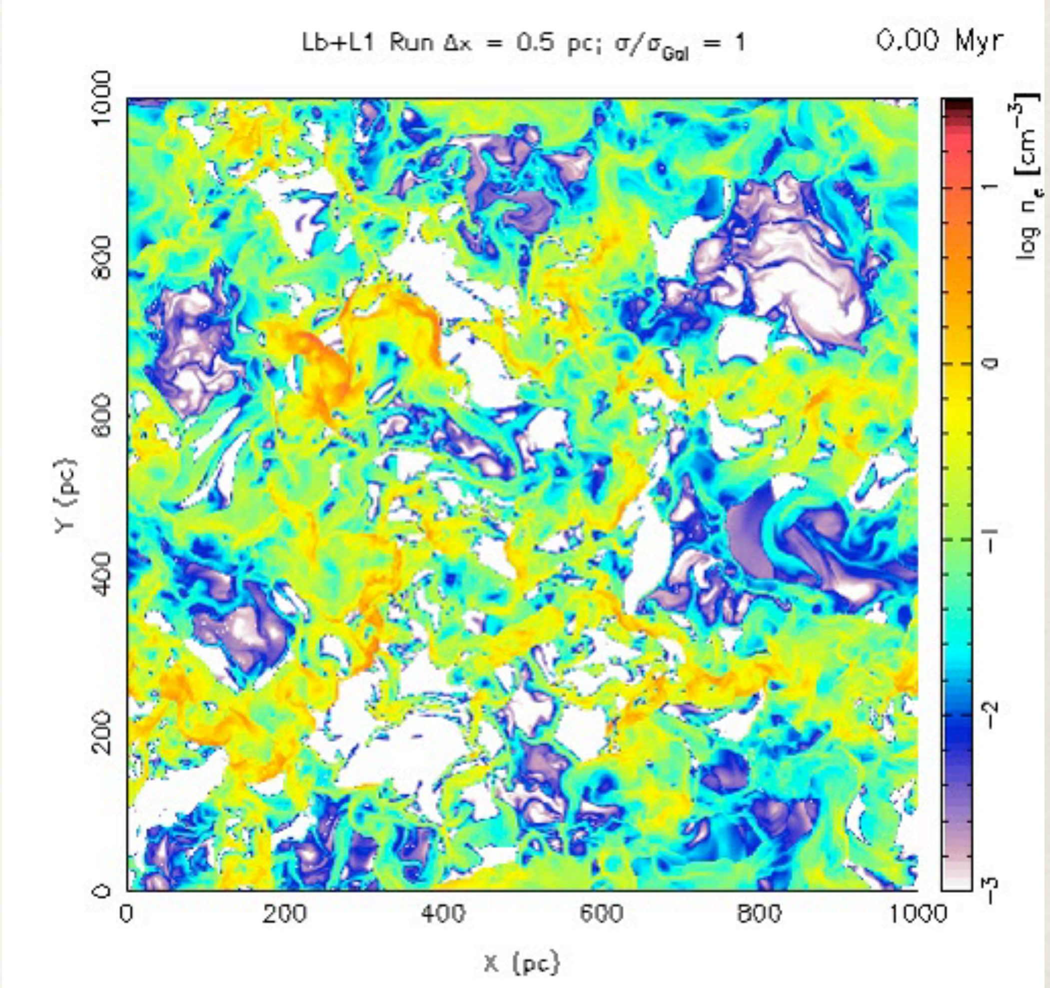


Avillez & Breitschwerdt (2012c)

N(OVI) density in the ISM as a function of LOS

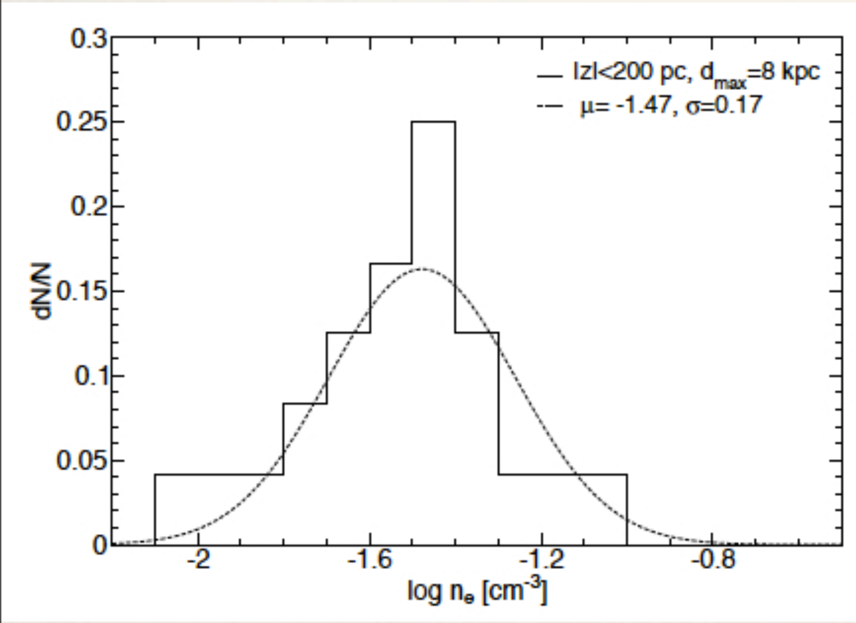
Comparison to Observations III: Electron distribution

- Study **electron density distribution n_e** in solar neighbourhood in **NEI**
- Simulations in good agreement with **pulsar dispersion measures** (DM=$\int n_e \, dl$) for $|b| < 5^o$; $<n_e>$=DM/d
- n_e distribution is **lognormal**: $<n_e> = 0.04 \pm 0.01$ cm^{-3}
- Reason: Maximum entropy principle, central limit theorem

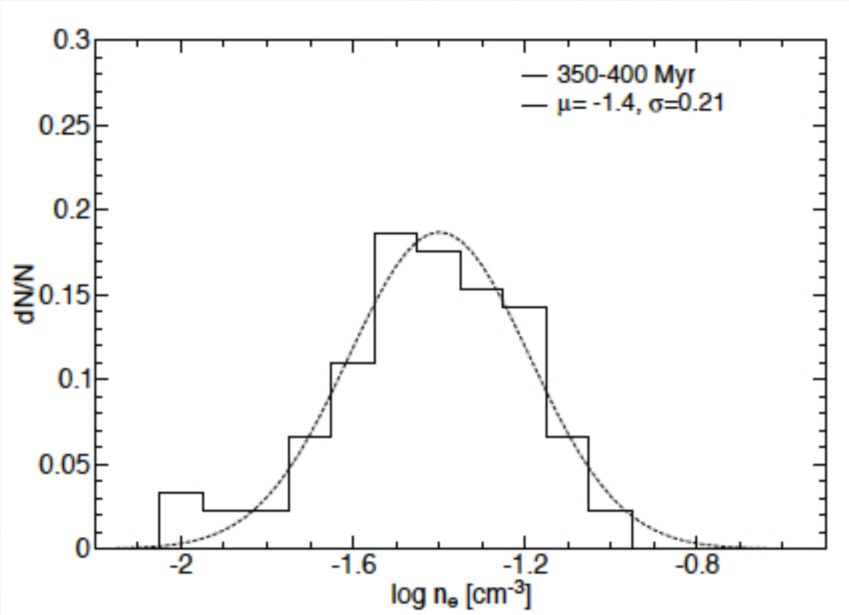


Avillez, Asgekar, Breitschwerdt, Spitoni (2012)

Observations

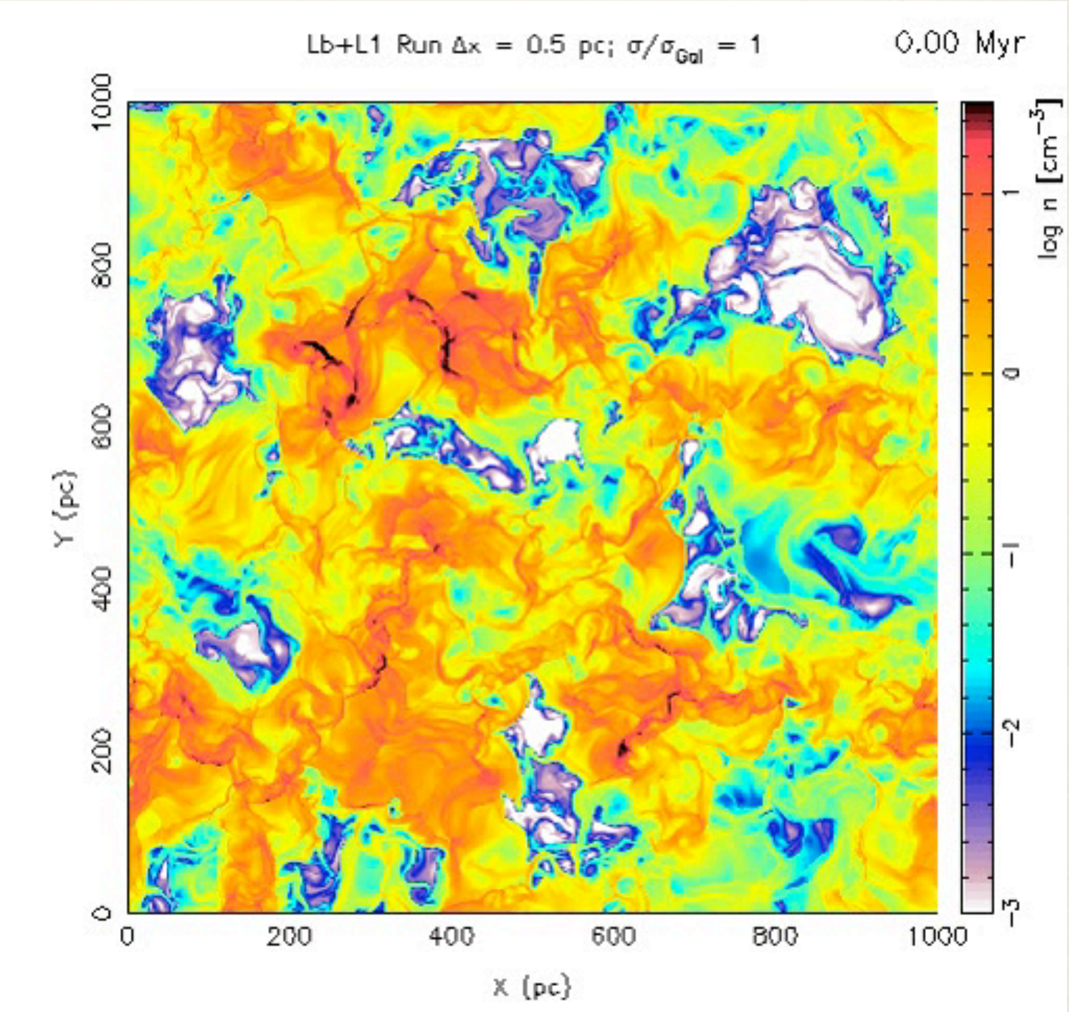


NEI-Model



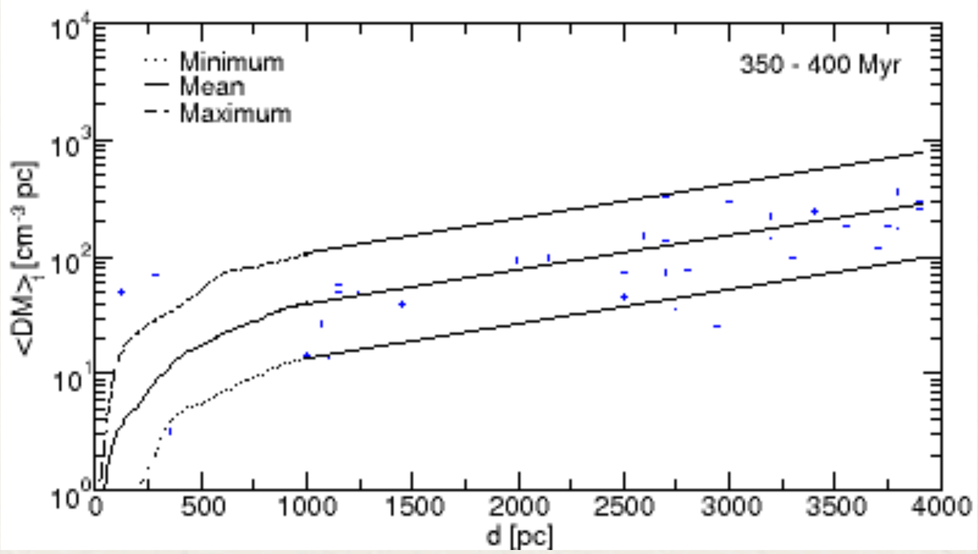
Top: *NEI simulation of electron density*
Left: *Electron density derived from measurements of 75 pulsars for* $|z| < 200$ *pc, with* $200 \text{ pc} < d < 8 \text{ kpc}$*; Result:* $\log(n_e) = -1.47 \pm 0.02$, $\sigma = 0.17 \pm 0.02$
Right: *Histograms (solid line) and Gaussian fits (dashed line) from dispersion measures of* ***NEI simulations*** *taken at different times from 350 - 400 Myr;* $\log(n_e) = -1.4$ *to* -1.38, $\sigma = 0.16 - 0.21$

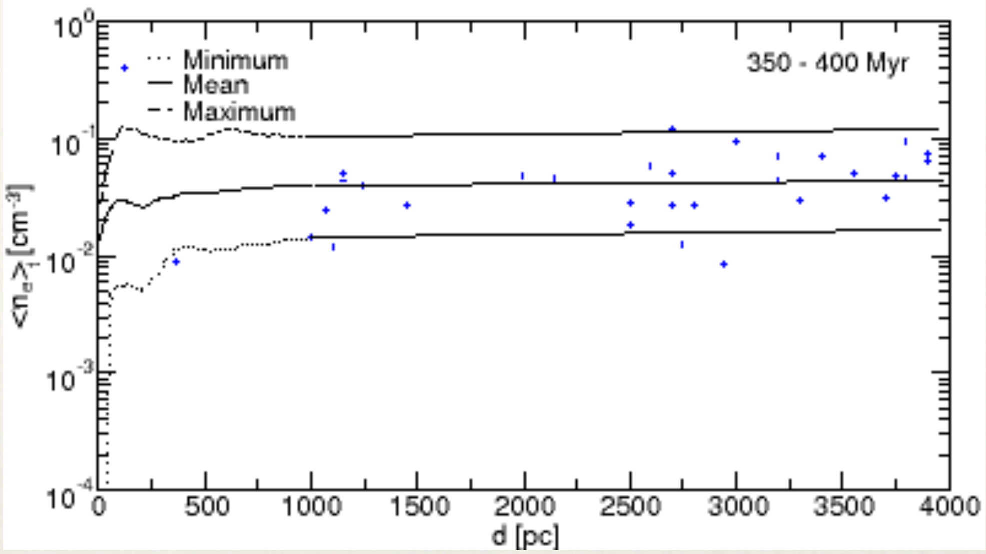
Comparison to Observations IV: Electron distribution



- Electron distribution n_e is different for **NEI**, as the ionization structure, and hence the number of free electrons is different
- **Pulsar dispersion measures** (mean, minimum and maximum) are in good agreement with observations (from ATNF catalogue with distance measurements)
- n_e remains almost constant with distance
- 80% of n_e by mass in thermally unstable region ($200 < T < 10^{3.9}$); WNM filling factor 4-5% (Gaensler et al. 2008)

Avillez, Asgekar, Breitschwerdt, Spitoni (2012)





Top: *NEI simulation of gas density (including Local Bubble and Loop I)*

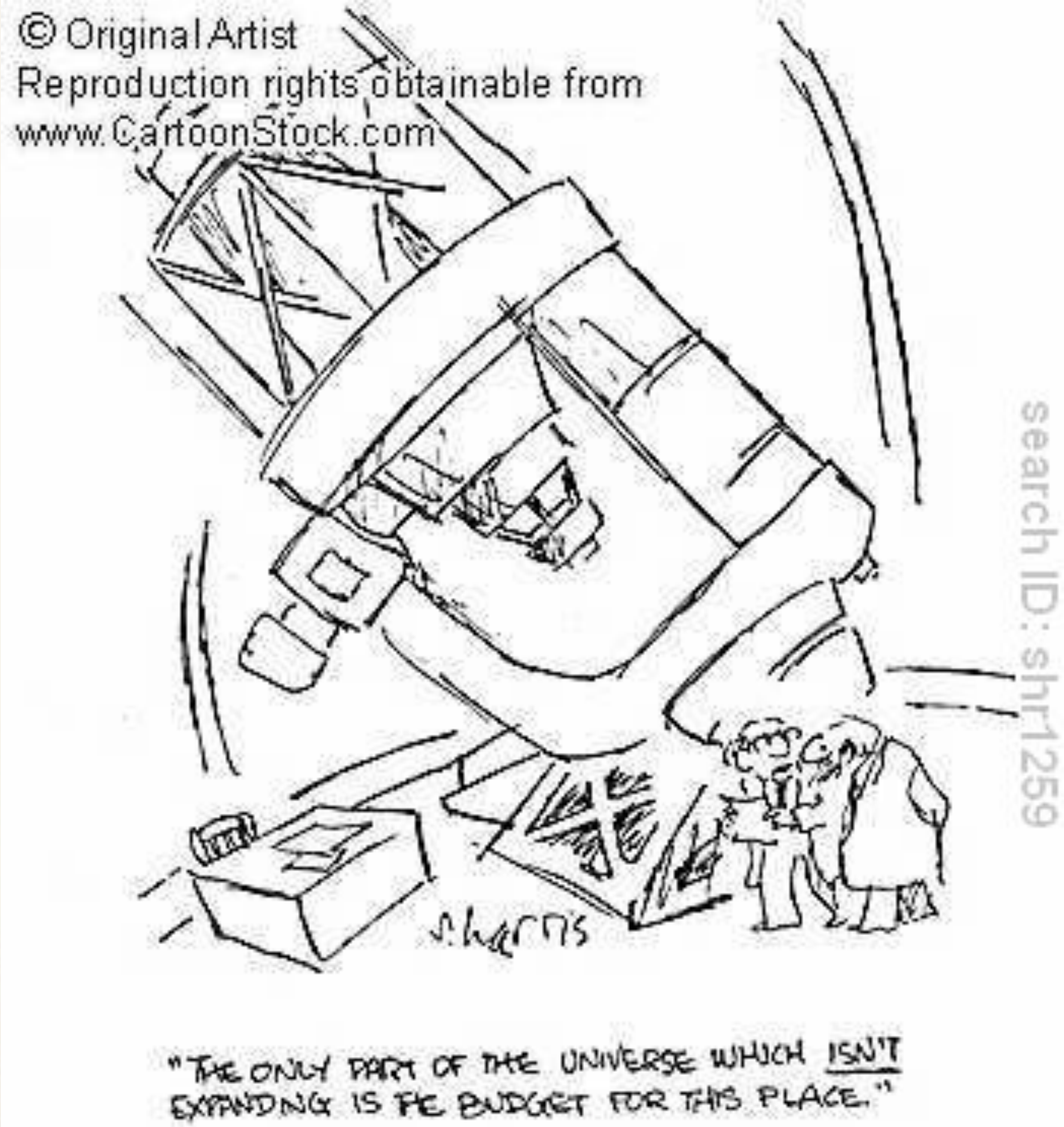
Left: *time averaged dispersion measures (mean, minimum and maximum) over a period of 50 Myr, 501 snapshots taken at 0.1 Myr intervals*

Right: *electron density as a function of distance (blue crosses: pulsar observations)*

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; **still missing**: detailed chemistry, radiation transport, cosmic rays, differential rotation, galactic dynamo ...
  - (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 observation)
- "**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 good agreement with FUSE- and Copernicus data
- Dynamical and turbulent ISM drives plasma **out of ionization equilibrium** (NEI) ➔ interstellar **cooling function** depends on **plasma history** and hence **varies in space and time**
- **Electron density distribution lognormal** (n_e=0.04±0.01 cm^{-3}) consistent with pulsar obs.
- **Closest to Earth SN: ~ 2.2 Myr.** at ~ **85 pc** distance (derived from fit to ^{60}Fe data)

Thank you for your attention!



"The only part of the Universe which isn't expanding is the budget for this place."