Large Scale Interstellar Medium Simulations and their implications for the Radio Sky

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ZAA

Collaborators

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Overview

- High Resolution Numerical Simulations
- Hydro/MHD-Simulations
- Non-Equilibrium Ionization Structure (Electron Density Distribution)
- Radio Halos: Electron Transport
- Summary

M33: composite Chandra & HST

- filaments
- structure on scales

→ **turbulence**

- wide range of temperatures, densities

→ **multiphase**

- gas, magnetic fields, cosmic rays, dust …

→ **multicomponent**

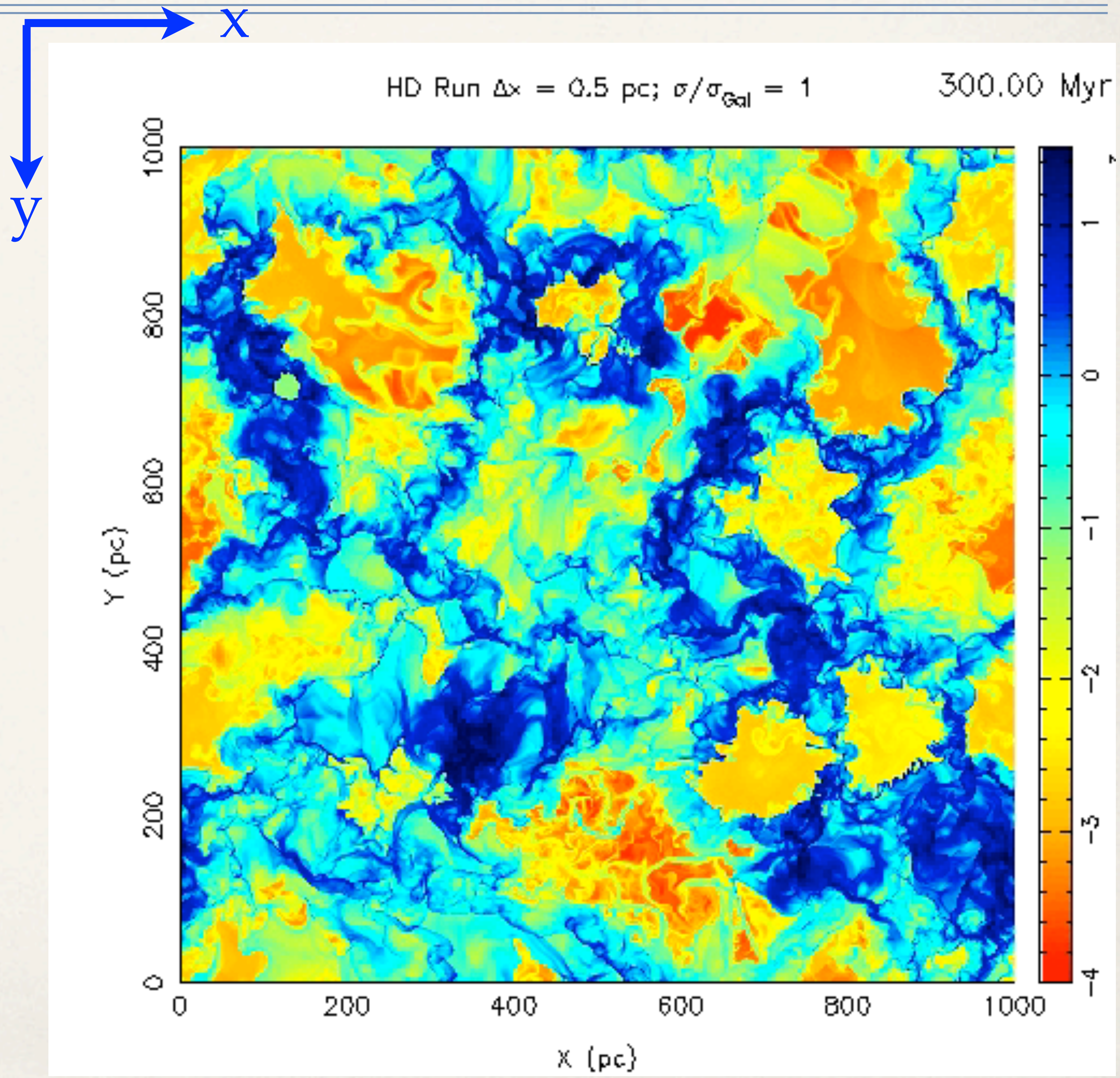
High Resolution ISM Simulations

- Solve full **HD/MHD equations** on a large grid: **1 kpc × 1kpc × ± 10 kpc** (Δx=0.5 pc or less)
- Fully time-dependent **non-equilibrium ionization (NEI) structure**
- 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)
- 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)**

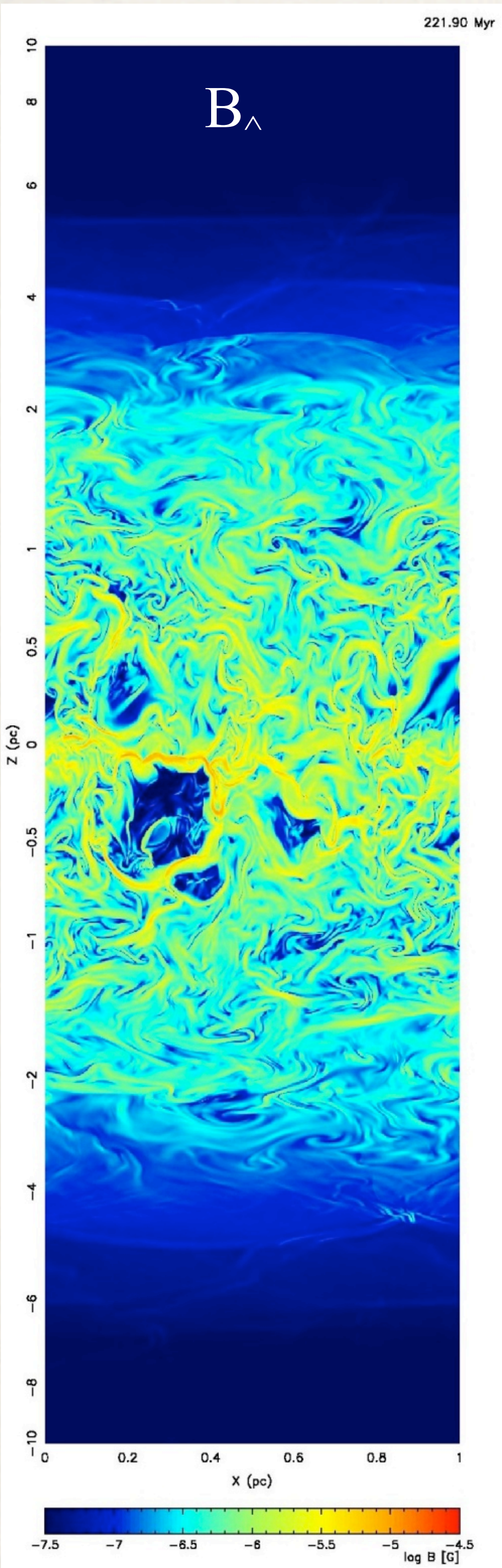
HD-Evolution of ISM

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) ➔ **turbulence**
- large amount of gas in **thermally unstable** phases
- **electron density** distribution determined by turbulence and **non-equilibrium ionization (NEI)**

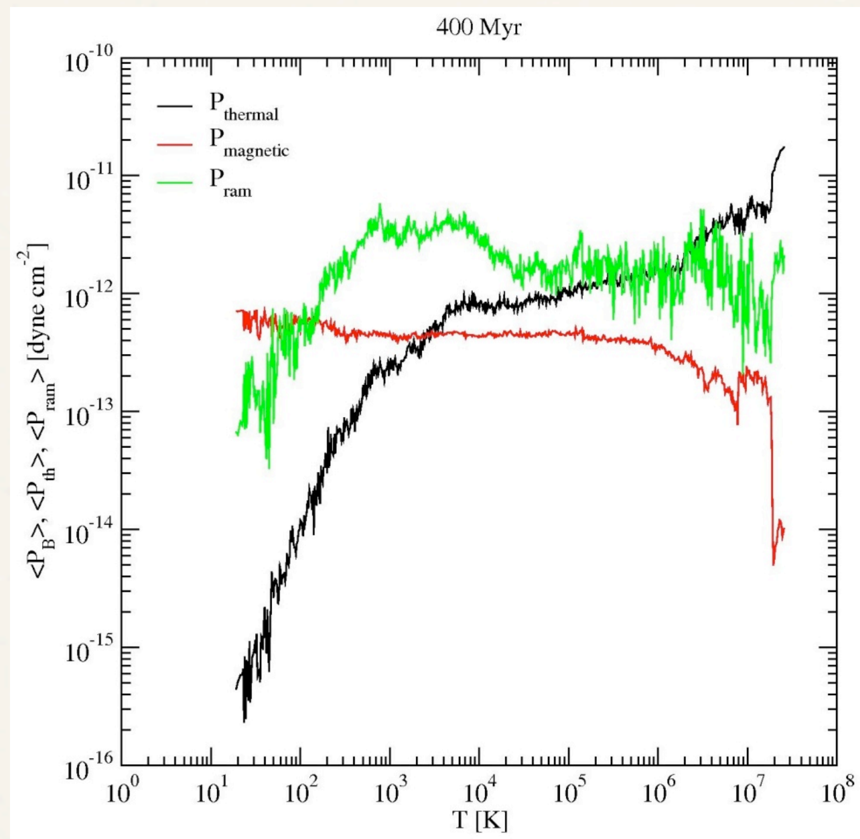


MHD-Evolution of ISM



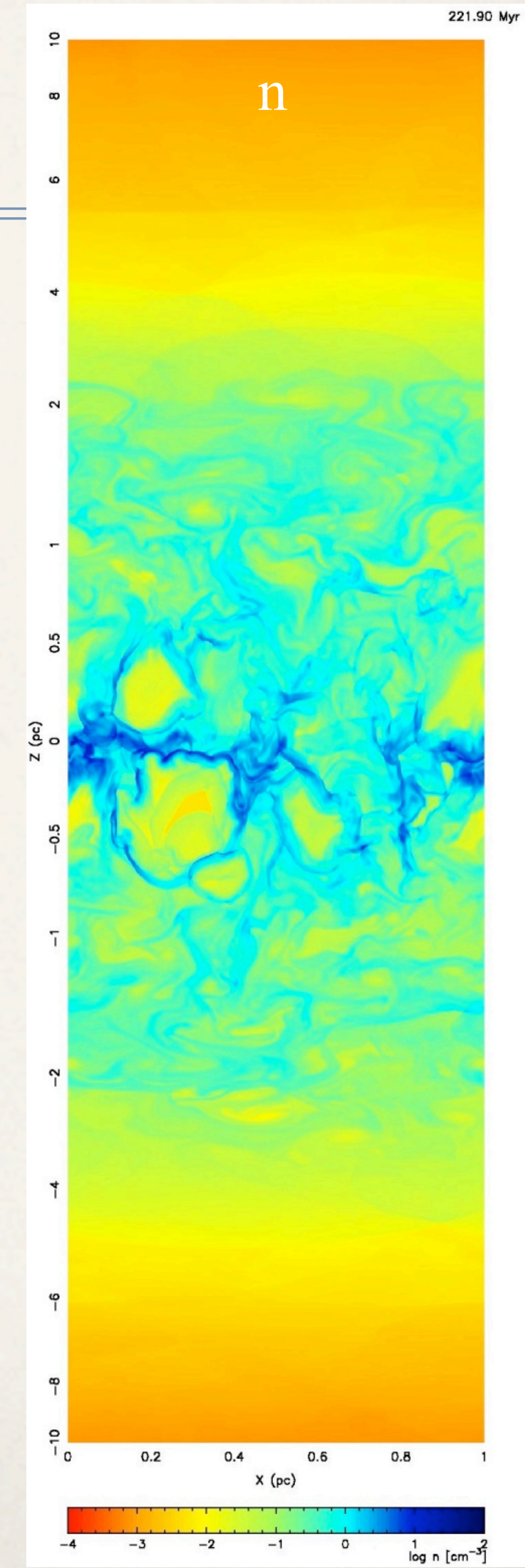
Avillez & Breitschwerdt, 2005

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



Which pressure determines ISM dynamics?

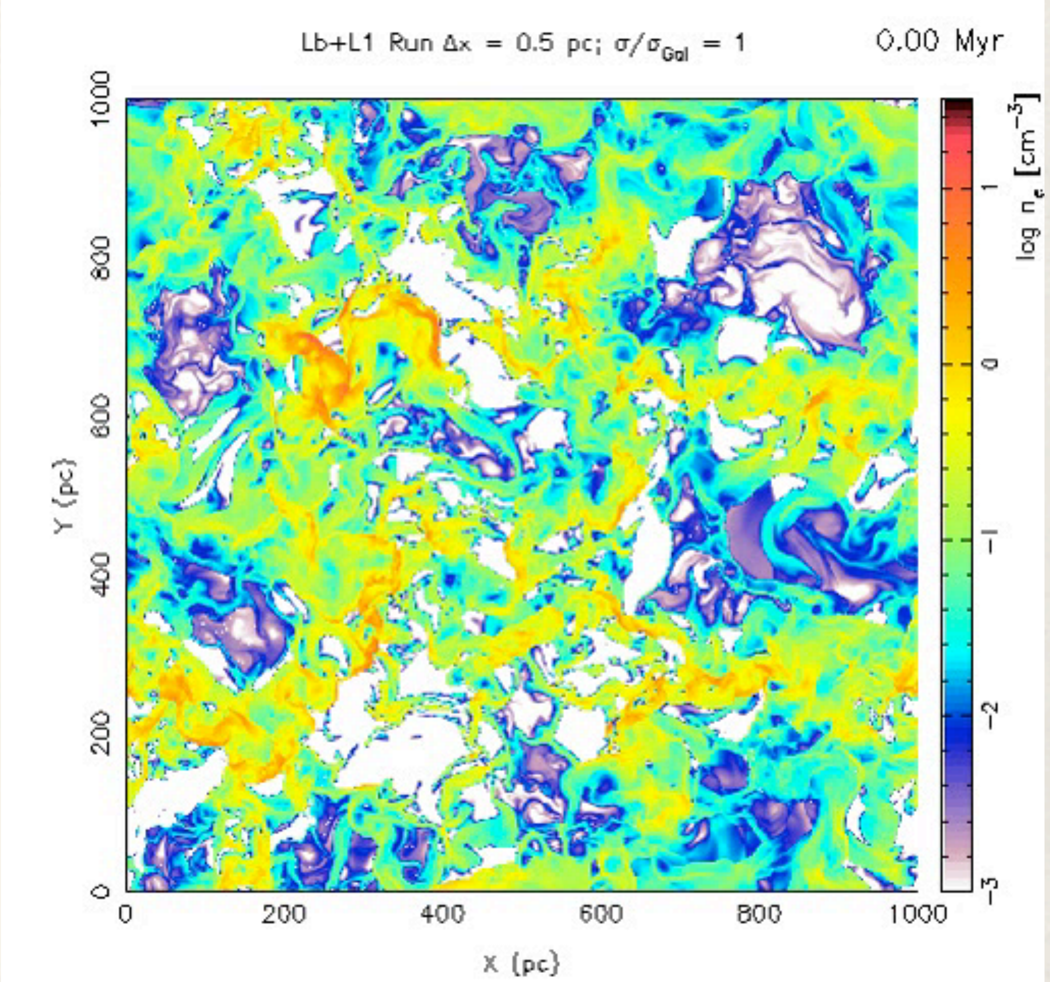
- For $T < 200$ K: **magnetic** pressure dominates,
- for $200\ K < T < 10^6$ K **ram pressure** dominates,
- for $T>10^6$ K **thermal pressure** dominates

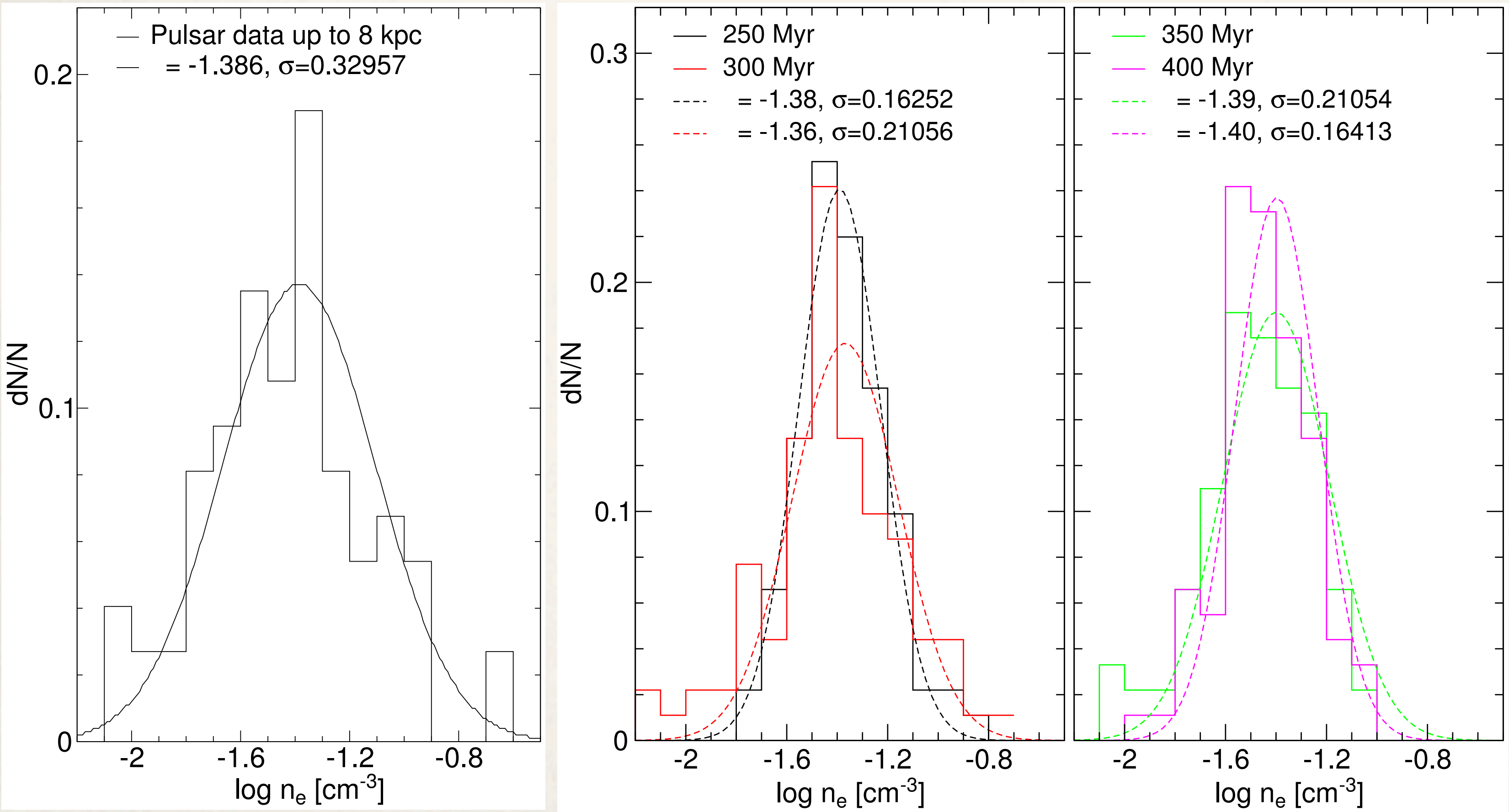


NEI structure of ISM: n_e distribution

Avillez, Asgekar, Breitschwerdt, Spitoni (2011)

- study **electron density distribution n_e** in solar neighbourhood in **NEI**
- simulations in good agreement with pulsar dispersion measures for $|b| < 5^o$; $<n_e> = DM/d$
- n_e distribution is lognormal: $<n_e> = 0.04 \pm 0.01$ cm^{-3}

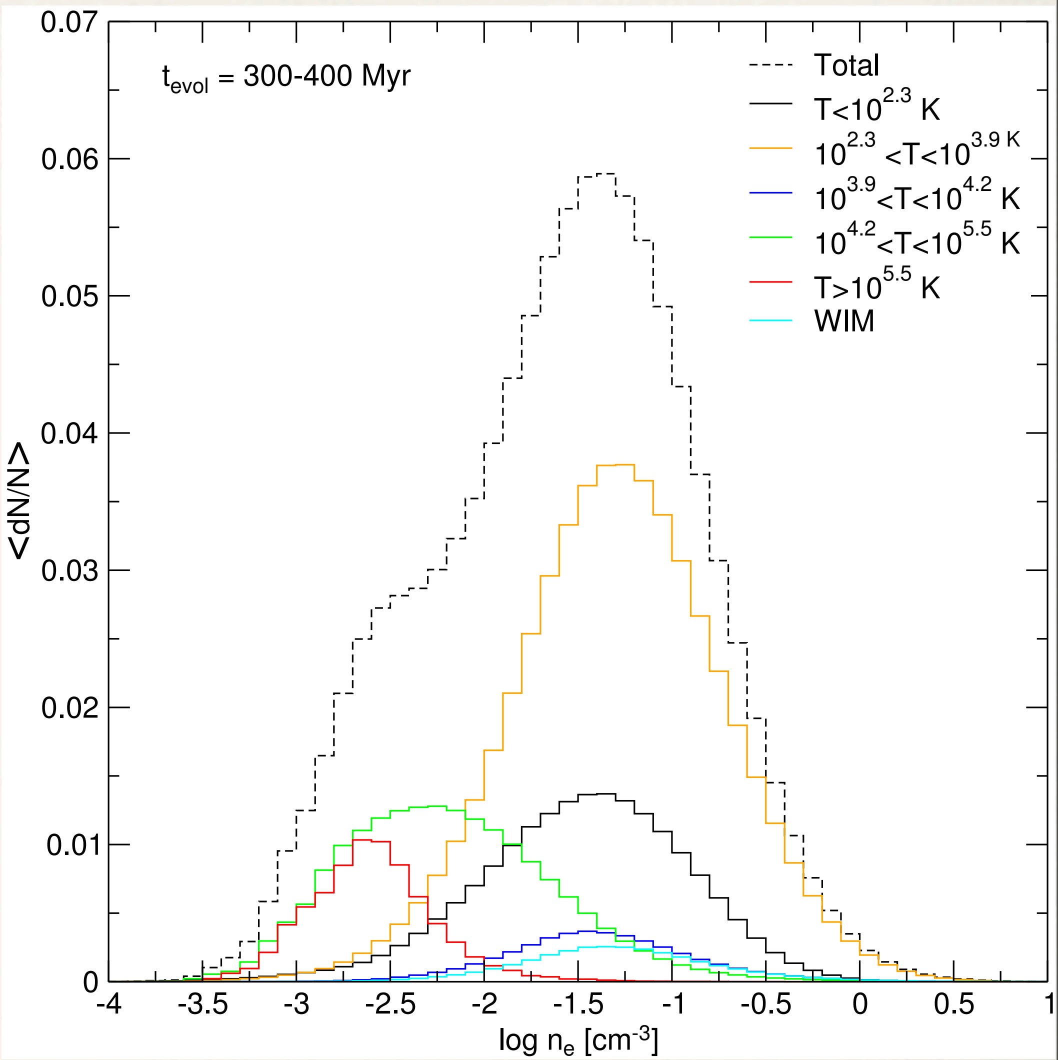




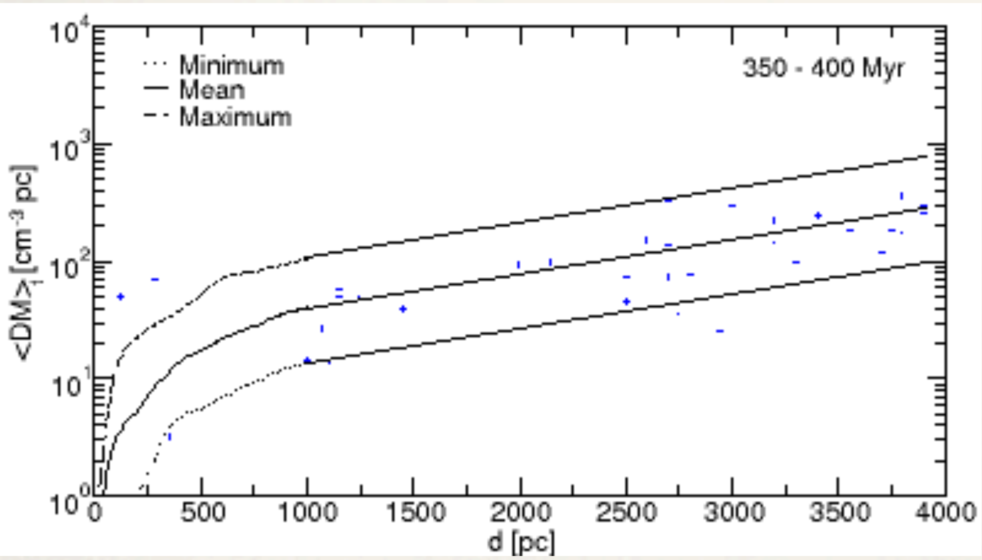
Top: *NEI simulation of electron density*
Left: *Electron density derived from measurements of 75 pulsars for $|b| < 5^o$; Result: $\log(n_e) = -1.386$, $\sigma = 0.33$*
Middle & Right: *Histograms (solid lines) and Gaussian fits (dashed lines) from dispersion measures of* <u>*NEI simulations*</u> *taken at different times; $\log(n_e) = -1.4$ to -1.38, $\sigma = 0.16 - 0.21$*

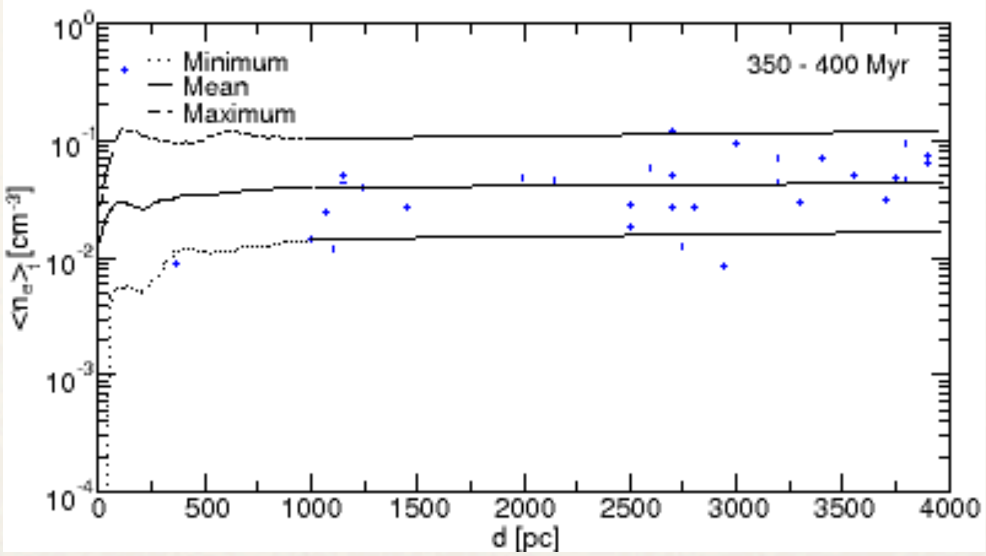
NEI structure of ISM (VI): n_e distribution

Avillez, Asgekar, Breitschwerdt, Spitoni (2011)



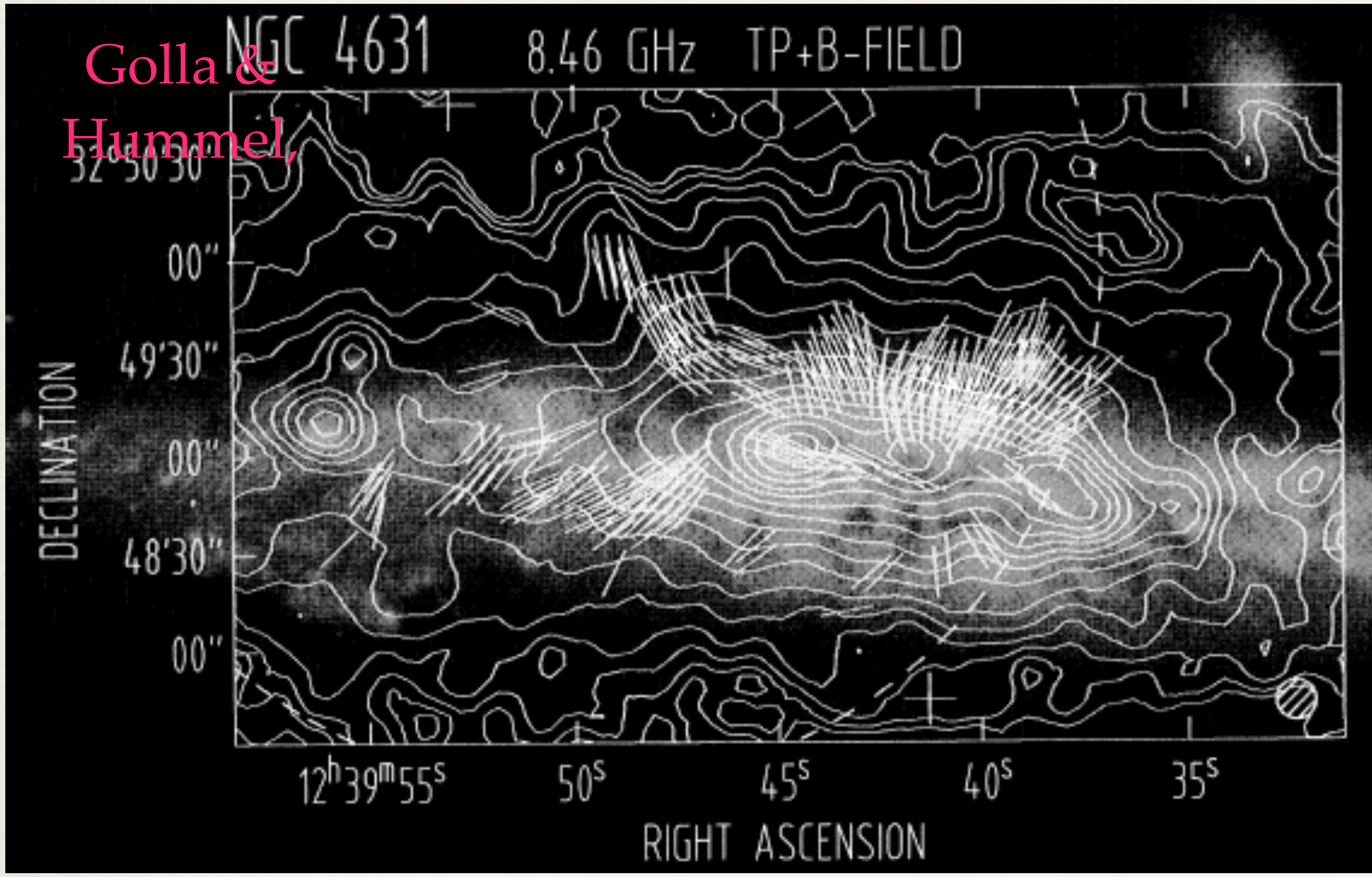
- electron distribution n_e different for NEI ➔ ionization structure and number of free electrons is different
- pulsar dispersion measures (mean, minimum and maximum) are in very good agreement with observations (from ATNF catalogue with distance measurements)
- <n_e> remains almost constant with distance



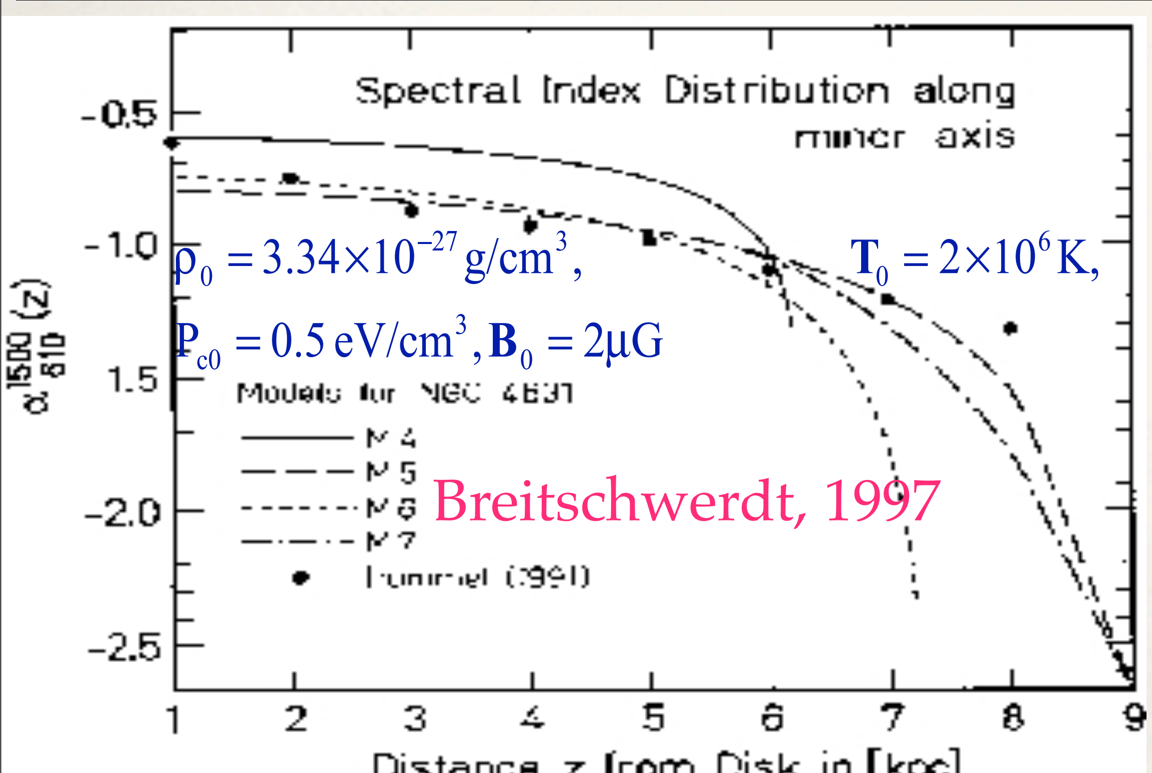


Top: *Time averaged histogram of electron densities for different ISM regimes in Galactic disk*
Left: *time averaged dispersion measures (mean, minimum and maximum) over a period of 50 Myr, 501 snapshots taken at 0.1 Myr intervals*
Right: *electron density as a function of distance (blue crosses: pulsar observations)*

Radio Continuum Halo Emission (I)



- Nonthermal radio emission of NGC4631
- Significant linear polarization to z ~5 kpc
- Solving diffusion-advection equation for rel. electrons with synchrotron and IC loss

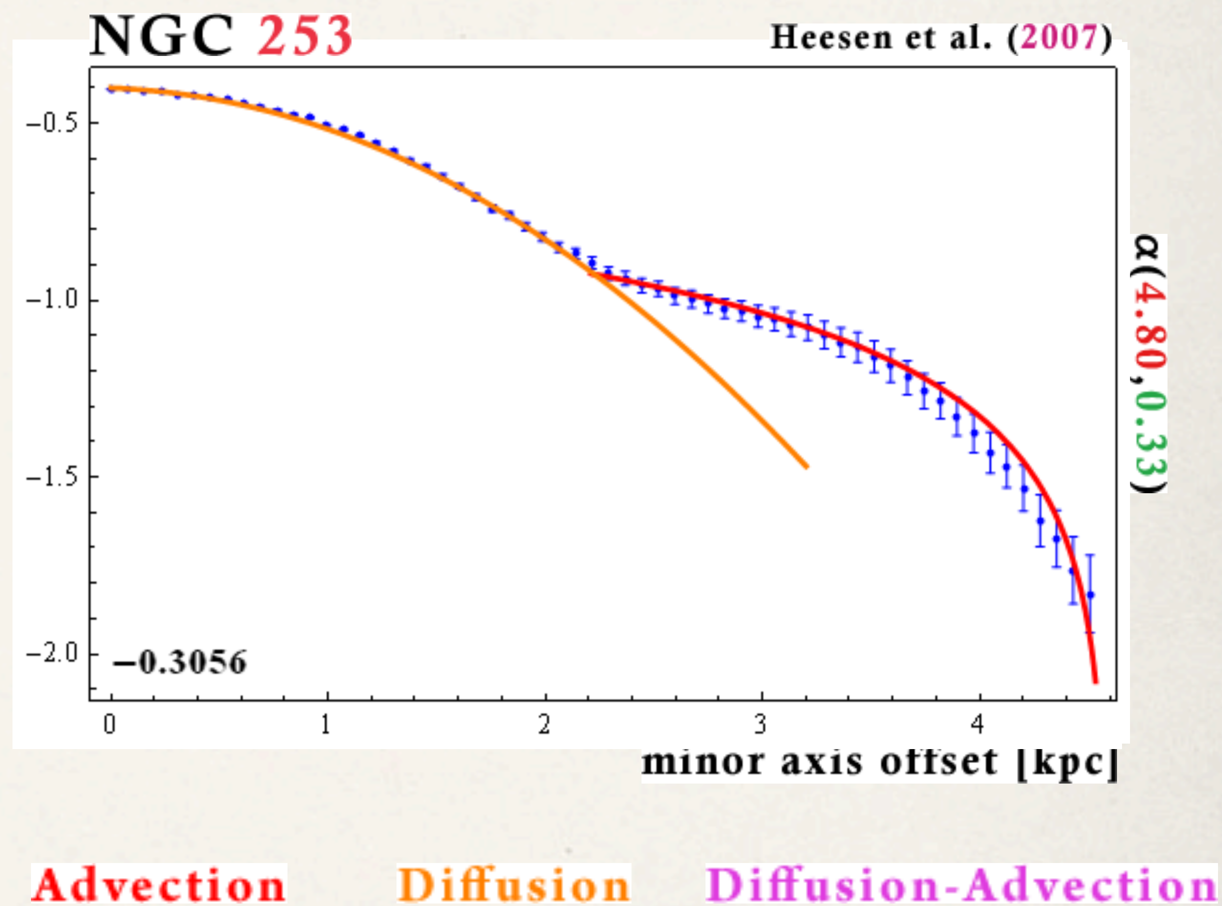


$$
\begin{aligned}
&- \frac{\partial}{\partial z}\left(D(E,z)\frac{\partial N(E,z)}{\partial z} - u(z)N(E,z)\right) \\
&- \frac{\partial}{\partial E}\left(\frac{1}{3}\frac{du}{dz} E N(E,z) - \frac{dE}{dt} N(E,z)\right) = Q(E,z) \\
Q(E,z) &= K_0 E^{-\gamma_0} h_g \delta(z)
\end{aligned}
$$

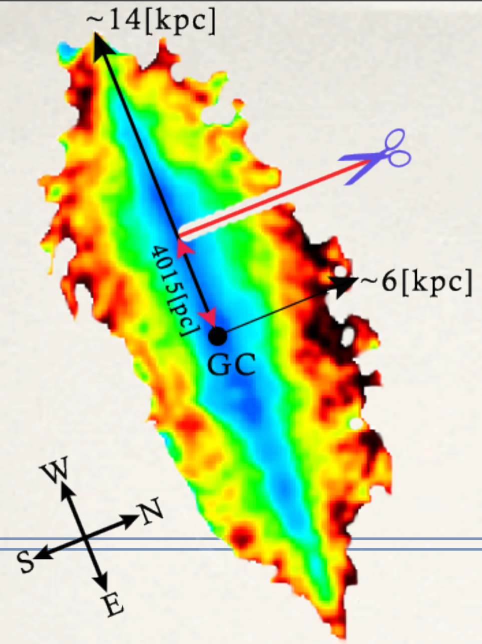
Spectral index variation along minor axis explained by accelerating wind!

Radio Continuum Halo Emission (II)

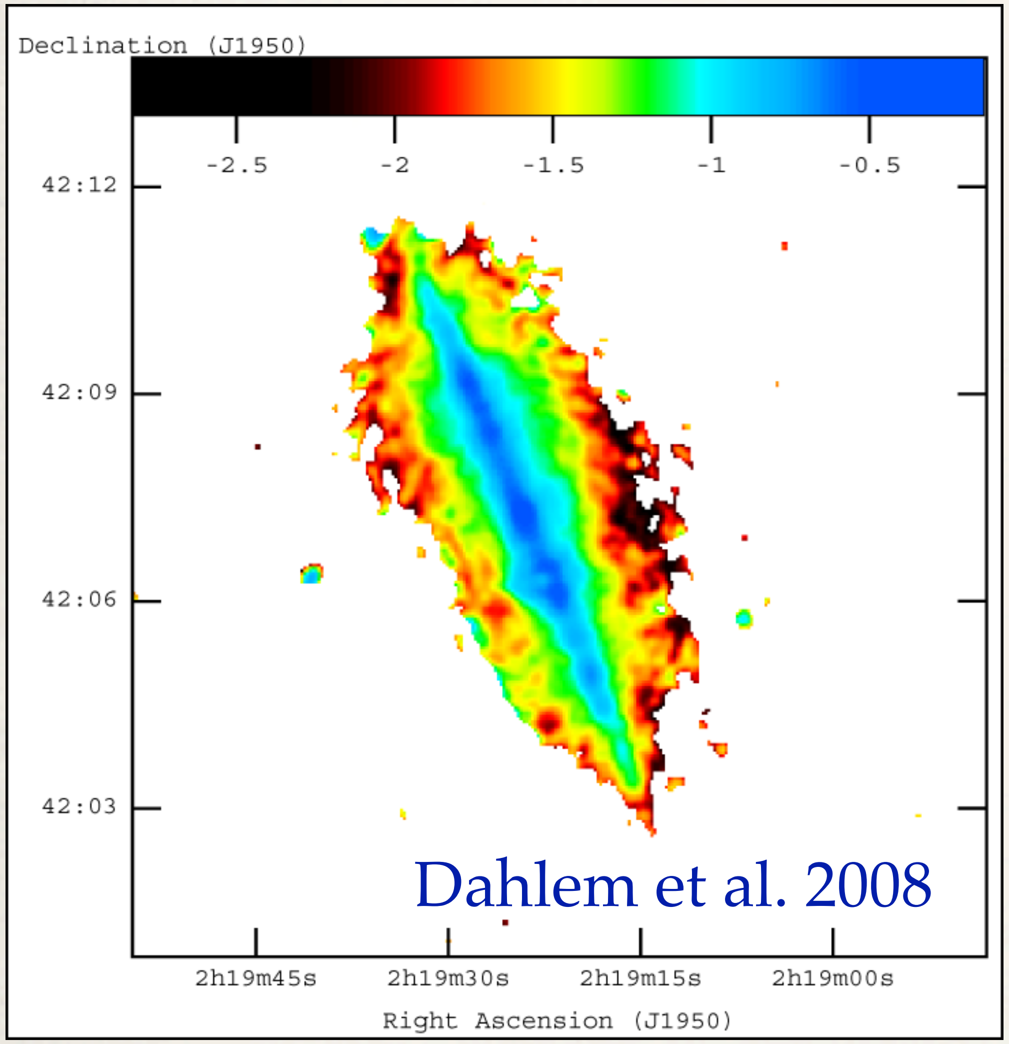
- **Non-thermal radio emission of NGC 253:**
- spectral index close to sources up to vertical distances from disk of z ~ 1-2 kpc dominated by **diffusion**
- for z ≥ 1-2 kpc transport dominated by **advection** due to **galactic wind**
- transport mechanism varies locally in agreement with local superbubble break-out from galactic disk



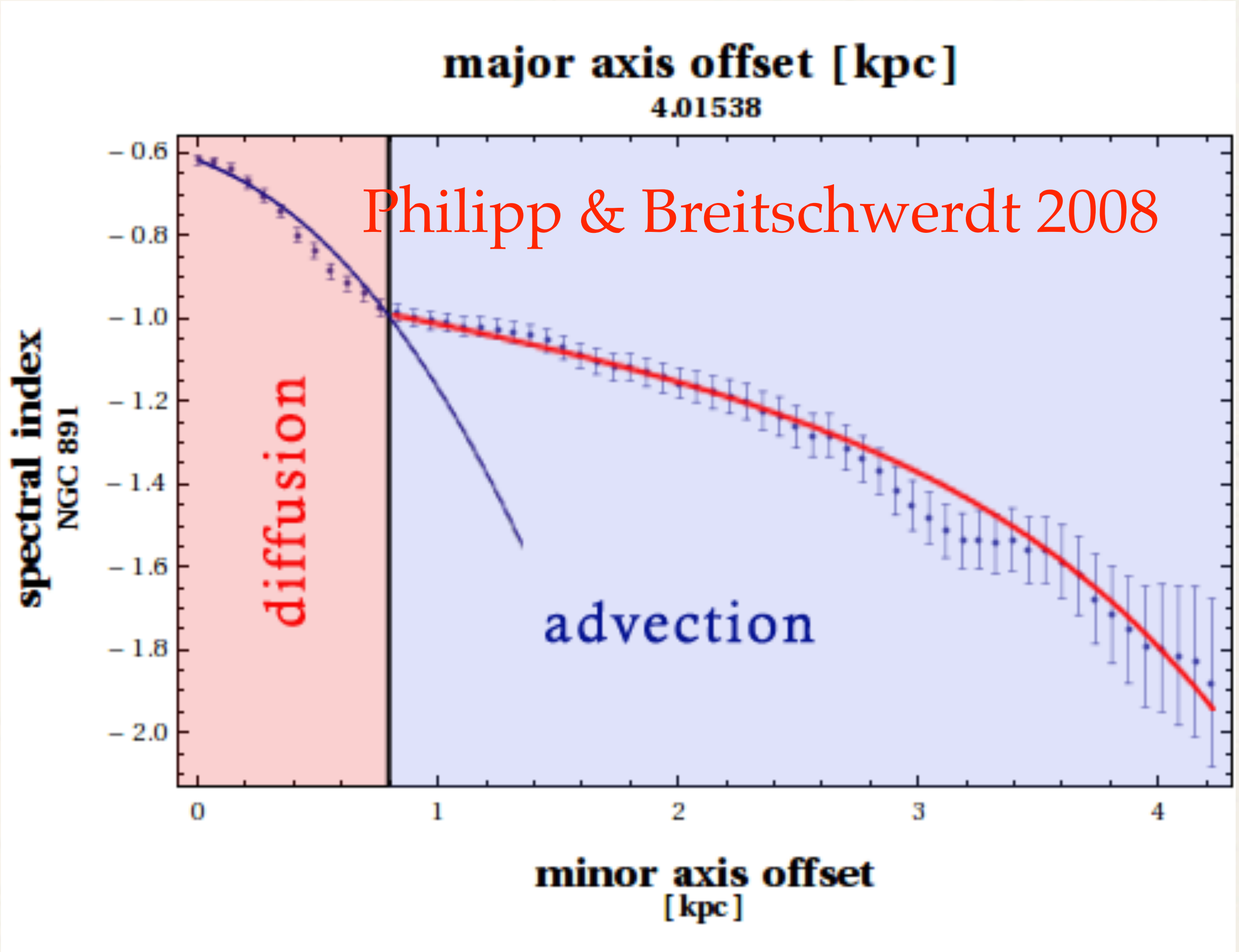
Top: Comparison between the model (including a galactic wind) and observations (blue dots with error bars) of the starburst galaxy NGC 253; data from Heesen et al.



Radio observations of NGC 891



Radio continuum observations of NGC 891 halo at different radio frequencies



Lower halo: transport is diffusive

Upper halo: transport is advective

Summary & Conclusions

- ISM radio observations (e.g. cold, warm and ionized galactic medium) can constrain **high resolution ISM simulations**
- Compare MHD simulations of galactic magnetic fields on small and large scales with SKA observations
- Study ISM and magnetic fields in young (high redshift galaxies)
- **Galactic winds** driven by CRs and/or thermal gas modify structure of galactic halos (best observed edge-on)
- ➔ steady-state models & full blown high resolution AMR simulations
- ➔ study transport of CR electrons in galactic outflows
- ➔ spectral index variations along minor axis
- ➔ study magnetic fields in galactic halos
- CR acceleration beyond the “knee” in galactic halos?

Suggestions & Collaborations on Topics of Common Interest Welcome