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# Turbulent Mixing and Magnetic Field Amplification in the Galaxy

by

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# Plan of This Talk

1) Key Issues

2) Simulations and Movies

3) Bulk Turbulent Mixing

4) Diffusion Down to the Molecular Level

5) Magnetic Field Amplification

6) Conclusions

7) Additional Advantages of SN-Processing – Phases of the ISM

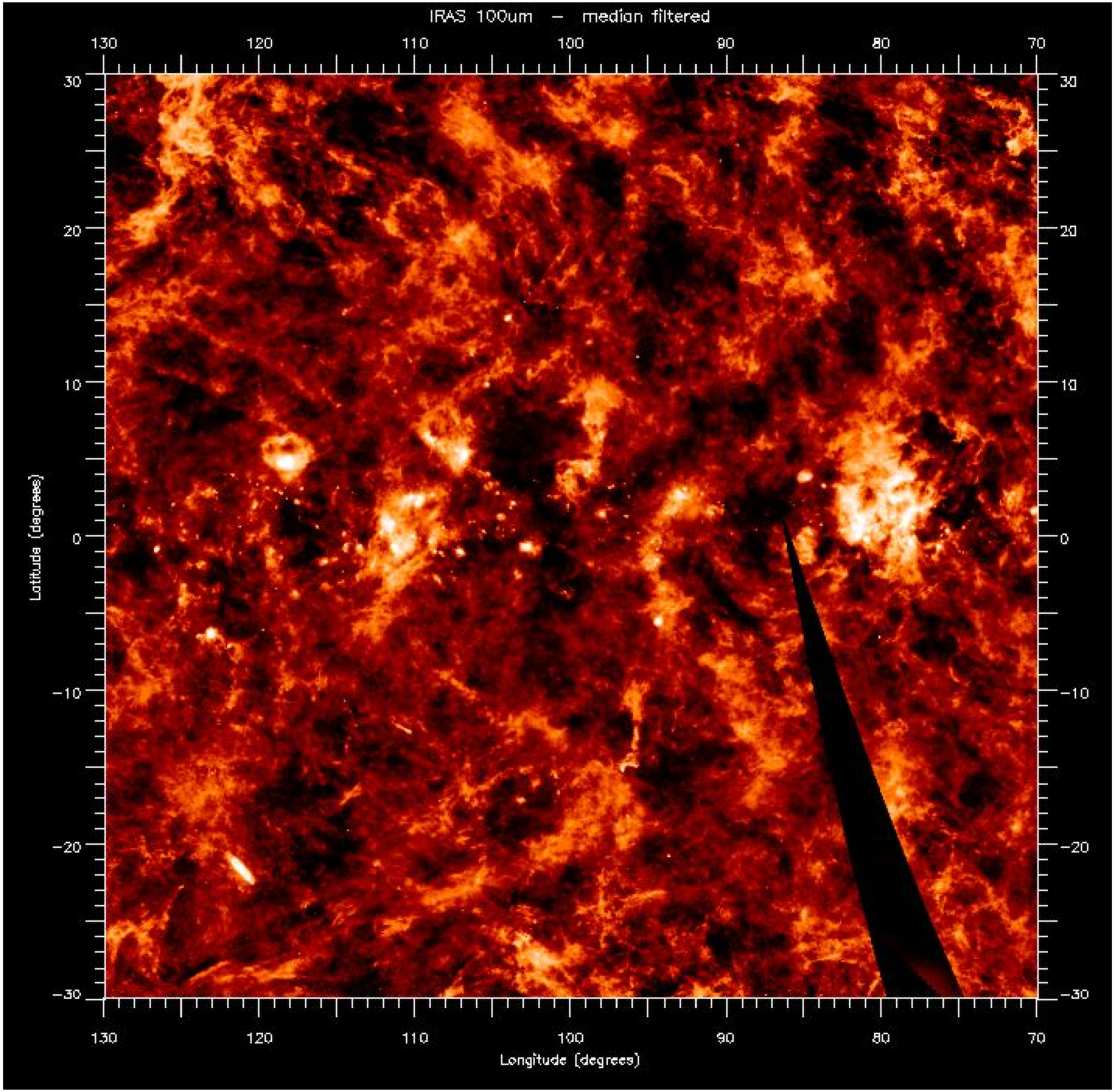
# 1) Key Issues for SNe-Driven Turbulence:
# Supernovae and their relation to the Interstellar Medium, Both Galactic & Proto-Galactic

**An Overview.**

Working Model : SNe put energy into ISM of Galaxy/Proto-Galaxy

- Making it turbulent
- Forming molecular clouds
- Triggering star formation

- Supernovae dominate the energy input in our Galactic ISM
  - More energetic than winds from massive stars by an order of magnitude!
- SN-driving establishes the turbulent velocity spectrum in the ISM.
- SN-driven turbulence determines the fractions of gas in hot, warm and cold phases.
  - Low mass stars only form in the cold phase.
- SN eject metals into the ISM and determine their mixing efficiency.
  - That in turn determines the cooling efficiency. Feeds back into low mass star formation
- SN drive magnetic field generation.
  - Low mass star formation requires magnetic fields to resolve the angular momentum problem.



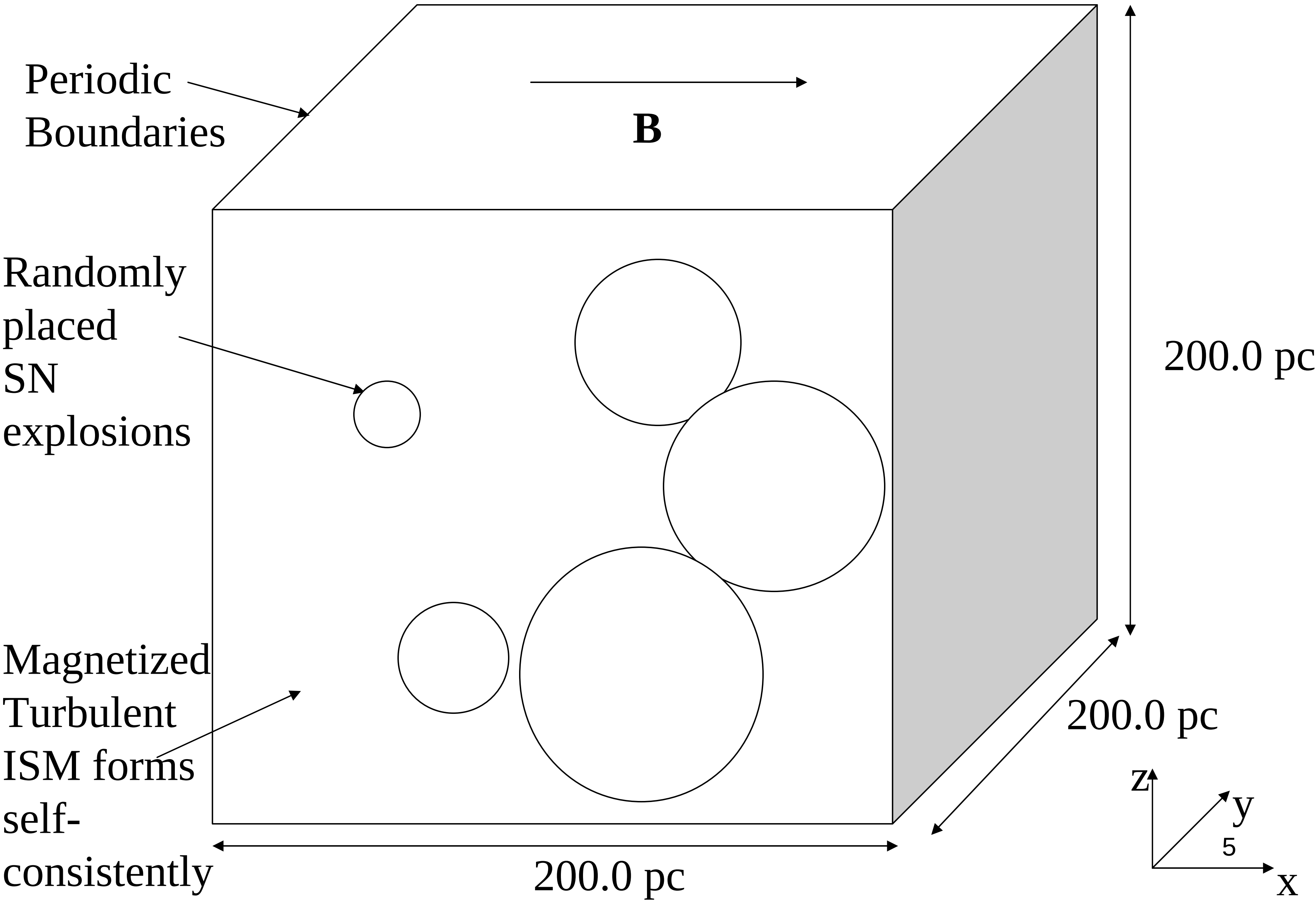

IRAS 100μ map of a patch of the ISM.

Patchy, "porous" structure.

Fluctuations on a range of scales – hallmark of turbulence.

## 2) Simulations and Movies

Vary SN rate, ISM parameters, Ejecta, Metallicity

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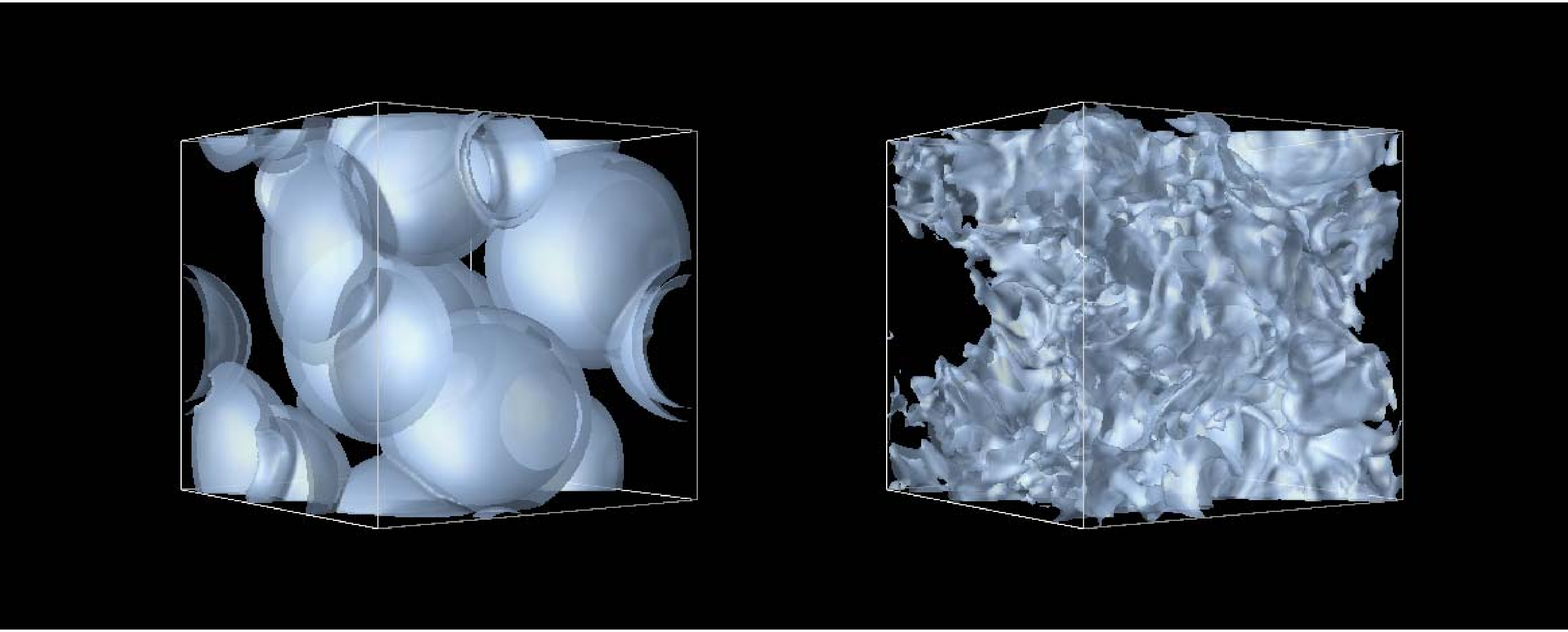
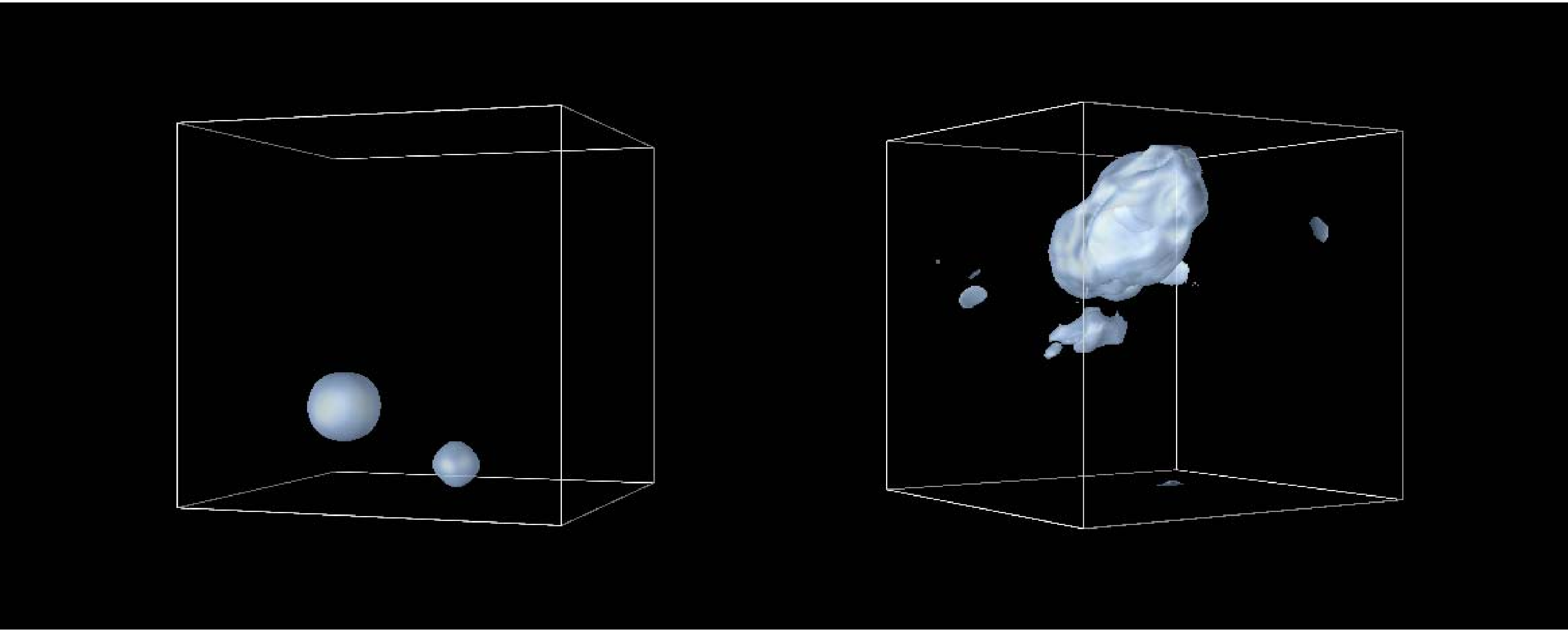


Early time | Late time

Density IsoSurfaces -- SNe-Induced ISM Turbulence



Early time Late time

Pressure IsoSurfaces -- SNe-Induced ISM Turbulence

# 3) Bulk Turbulent Mixing - A Study

1) SN-ejecta enrich the ISM with metals.

2) Astro-archeology:
   r-process ejecta (e.g. Ba) in EMP stars ➔ SN-progenitor stars in precise mass ranges
   Turbulent mixing provides a dynamical basis for the stochasticity required in GCE models

3) The ejecta can even change the metallicity of the ISM
   ➔ changing the cooling rate and the formation of molecular gas
   ➔ The amount of molecular gas, via cooling processes, regulates low mass star formation.

4) In the Galactic Chemical Evolution literature, mixing times that range from instantaneous to 100 Myr have been used. It helps to quantify this via simulations.



5) Current observations favor efficient mixing.

# Bulk Turbulent Mixing (continued)

6) Since motion in a turbulent fluid, just like Brownian Motion, is a random walk process we make the hypothesis that: SN-ejecta in a turbulent ISM follow a diffusion equation (think of smoke in wind):

$$\frac{\partial Y_i}{\partial t} + \mathbf{v} \bullet \nabla Y_i = \nabla \bullet \left( \eta_{\text{turb}} \nabla Y_i \right)$$

← Put in Large-Scale Sims.

↑ Obtained from Mid-Scale Sims.

This governs the bulk transport of ejecta.

The turbulent diffusivity, $\eta_{turb}$ , is the parameter of interest.

7) Time "*T*" for a system of length "*L*" to be homogenized by turbulence :

$$T = \frac{L^2}{\eta_{\text{turb}}}$$

8) To measure the above transport process we set up a cloud of Lagrangian marker particles and follow their evolution and spread in the turbulent flow as a function of time. The turbulent diffusivity $\eta_{turb}$ is then given by:

$$\eta_{turb} = \frac{1}{3}\,\frac{d}{dt}\left\langle \left[ \left\{ \mathbf{r}(t) - \langle \mathbf{r}(t) \rangle \right\} - \left\{ \mathbf{r}(t_0) - \langle \mathbf{r}(t_0) \rangle \right\} \right]^2 \right\rangle$$

$$\approx \frac{1}{3}\,\frac{1}{(t - t_0)}\left\langle \left[ \left\{ \mathbf{r}(t) - \langle \mathbf{r}(t) \rangle \right\} - \left\{ \mathbf{r}(t_0) - \langle \mathbf{r}(t_0) \rangle \right\} \right]^2 \right\rangle$$

9) The turbulent eddies forget their structure and start over in a coherence time. Thus after the passage of each unit of coherence time the particles randomly change their velocity. This is a random walk process.

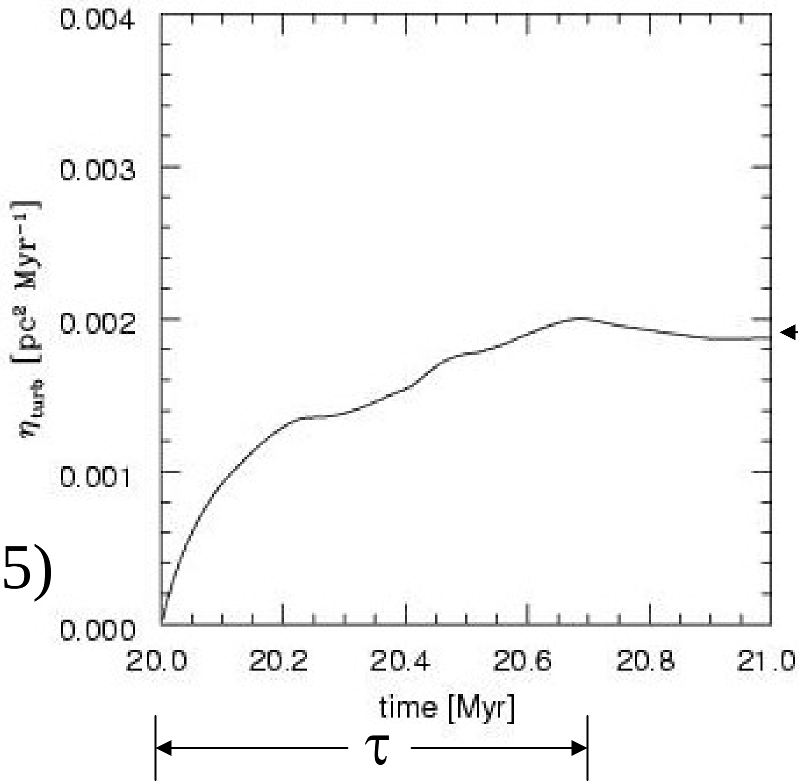
10) For times shorter than a coherence time, each particle moves ballistically with the velocity "**v**" of the eddy it is on:

$$\left( \mathbf{r}(t) - \langle \mathbf{r}(t) \rangle \right) \propto \mathbf{v}\ t$$

11) For times longer than a coherence time the particle moves randomly:

$$\left( \mathbf{r}(t) - \langle \mathbf{r}(t) \rangle \right)^2 \propto t$$

D.B. & Kim (2005)




← $\eta_{turb}$=5.7×10$^{26}$ cm$^2$sec$^{-1}$

12) Simulations have gotten to the point where we can read off $\eta_{turb}$ from the simulations. This can be done for entire ranges of ISM parameters.

13) A mixing length type of argument says that $\eta_{turb} = \left\langle v_{rms}^2 \right\rangle \tau$ ; where $\tau$ is the coherence time of the turbulence; $\sqrt{\left\langle v_{rms}^2 \right\rangle}$ is the rms velocity.

14) The coherence time and rms velocity can also be read off from the simulations. (These are v.v. long running – resolve 100's of turn over times)

# 4) Diffusion Down to the Molecular Level

1) While the bulk transport of SN-ejecta is given by the above diffusion equation, we also seek a mechanism to mix the metals down to the molecular level. This is needed for the metal-seeded gas to cool uniformly to form the next generation of stars.

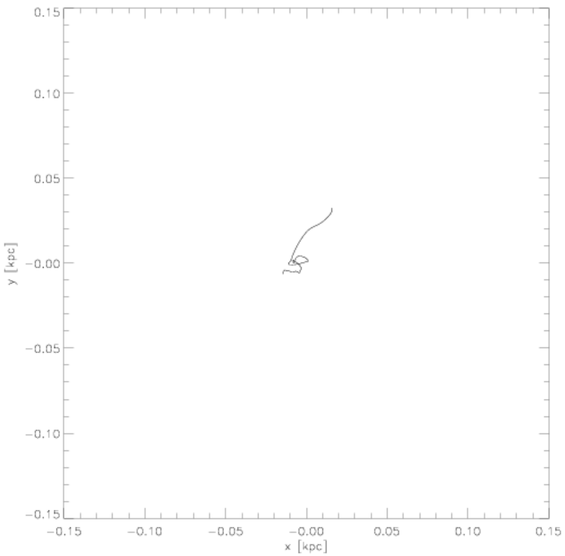
2) This is important because the molecular diffusivity in the ISM and proto-galactic ISM is almost 5 orders of magnitude smaller than the turbulent diffusivity.

3) The molecular diffusion obeys :

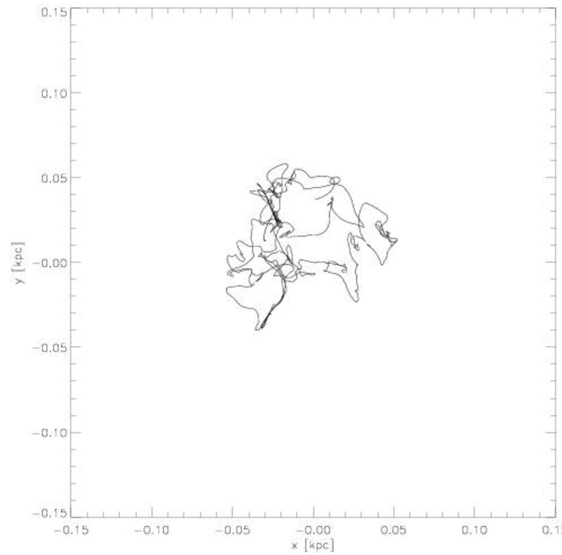
$$\frac{\partial Y_i}{\partial t} + \mathbf{v} \bullet \nabla Y_i = \nabla \bullet \left( \eta_{\text{mol}} \nabla Y_i \right)$$

4) Think of cream mixing into coffee: The only way to make the process efficient is to draw the cream out into thin, narrow structures at which point the diffusion of those structures (by the molecular diffusion operator) becomes very efficient.

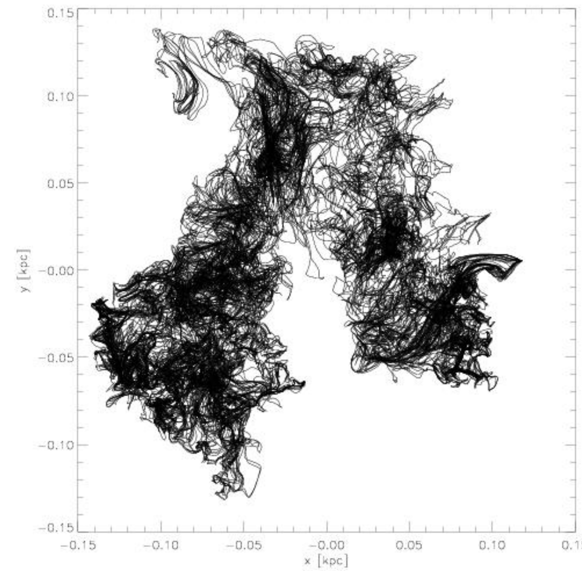
In the same spirit as mixing cream in a coffee cup, let us take a line segment and trace its evolution. Notice that the segment grows exponentially in time. (0.8Myrs of simulation time are shown)
In 0.8 Myrs it almost becomes volume-filling.



t=0.1 Myr

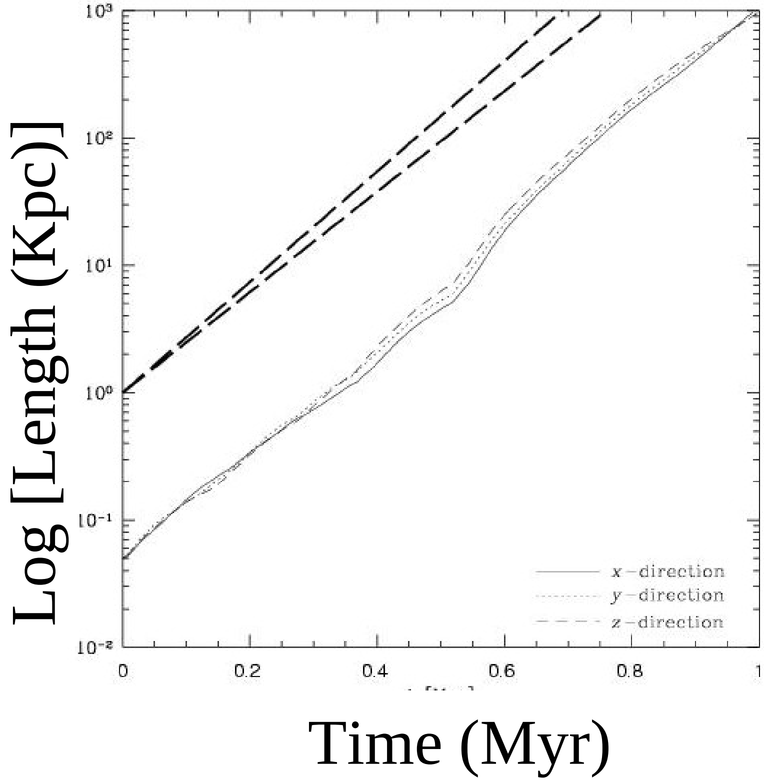


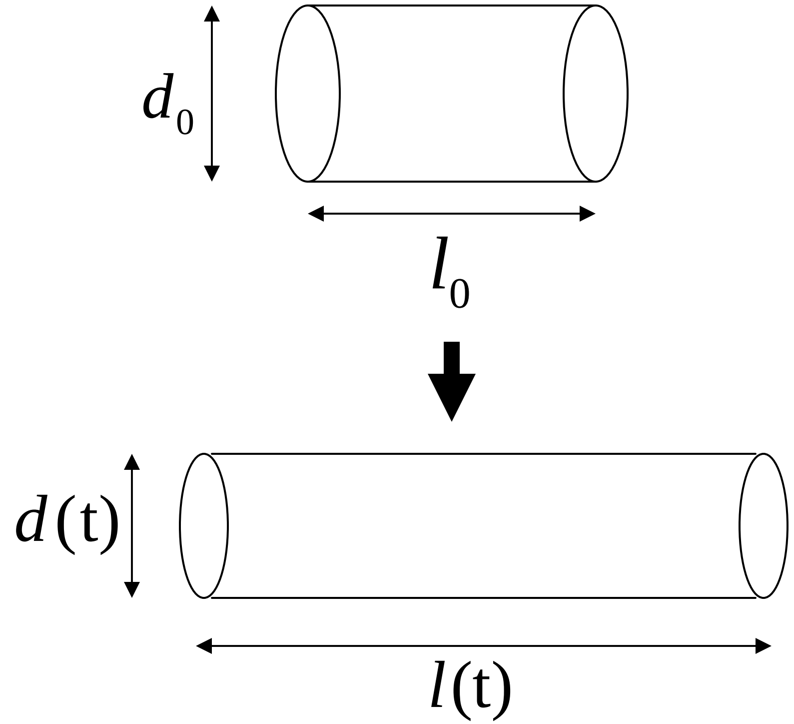
t=0.4 Myr



t=0.8 Myr

D.B. & Kim (2005)




5) The above plot shows the exponential growth of the length of the line segment. The growth time is $\tau_{\mathrm{line}}$ = 0.1Myr so that: $l = l_0 \; \exp\left[\, \mathrm{t}/\tau_{\mathrm{line}} \right]$

6) It can be shown that thin, narrow structures form very fast, i.e. in a time given by 2 $\tau_{\mathrm{line}}$ ! $l(\mathrm{t})\, d^2(\mathrm{t}) = l_0 \; d_0^2 \quad \Rightarrow \quad d(\mathrm{t}) = d_0 \; \mathrm{e}^{-\mathrm{t}/(2\tau_{line})}$

7) As a result, mixing down to the molecular level is extremely efficient in a SN-driven turbulence.

## 5) Magnetic Field Amplification

High Redshift Systems:-

1) Rotation measures in high-redshift quasars indicates the presence of magnetic fields in them, Perry, Watson and Kronberg (1993).

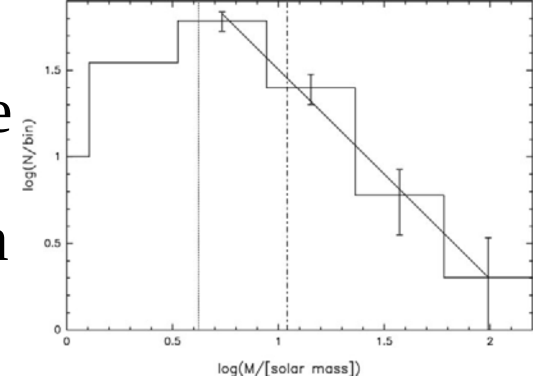
2) Fields of few μG in damped Ly-α systems at z=2, Wolfe, Lanzetta and Oren (1992). ➔ Magnetic fields form and grow to full strength on at least some scales pretty fast. Important for galaxy-building.

Our Galaxy:-

3) Evidence for density fluctuations spanning over 10 orders of magnitude! Spectral index suggestive of turbulence. Armstrong, Rickett and Spangler (1995).

4) Evidence that there is a mean magnetic field of 1.8 mG with a fluctuating magnetic field component of 5 mG, Beck et al (1996). Shows even in spectra, albeit over a more limited range, Minter and Spangler (1996), Fosalba et al (2002), Han Ferriere and Manchester (2004).

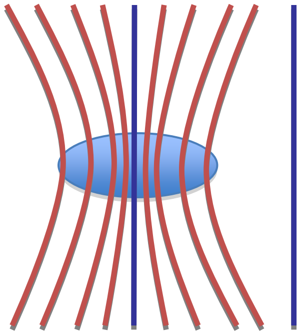
**Why are magnetic fields needed?** – Answer: Low mass star formation. Imprint of IMF set by turbulence




Olmi et al. 2009
Mass spectrum
in Vela D

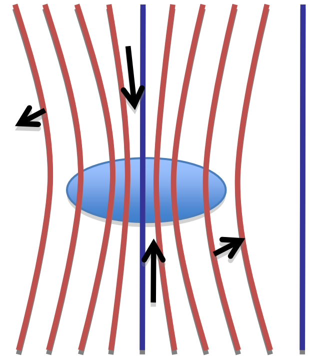
Present low mass star formation occurs exclusively in cold molecular clouds – Jeans argument. Same holds for early epochs of low mass stars.

Unlike hi mass star formation, there is an angular momentum problem in low mass star formation.



Magnetic fields help get rid of that angular momentum.

SNe → drive turbulence → forms field on ***smaller*** scales.

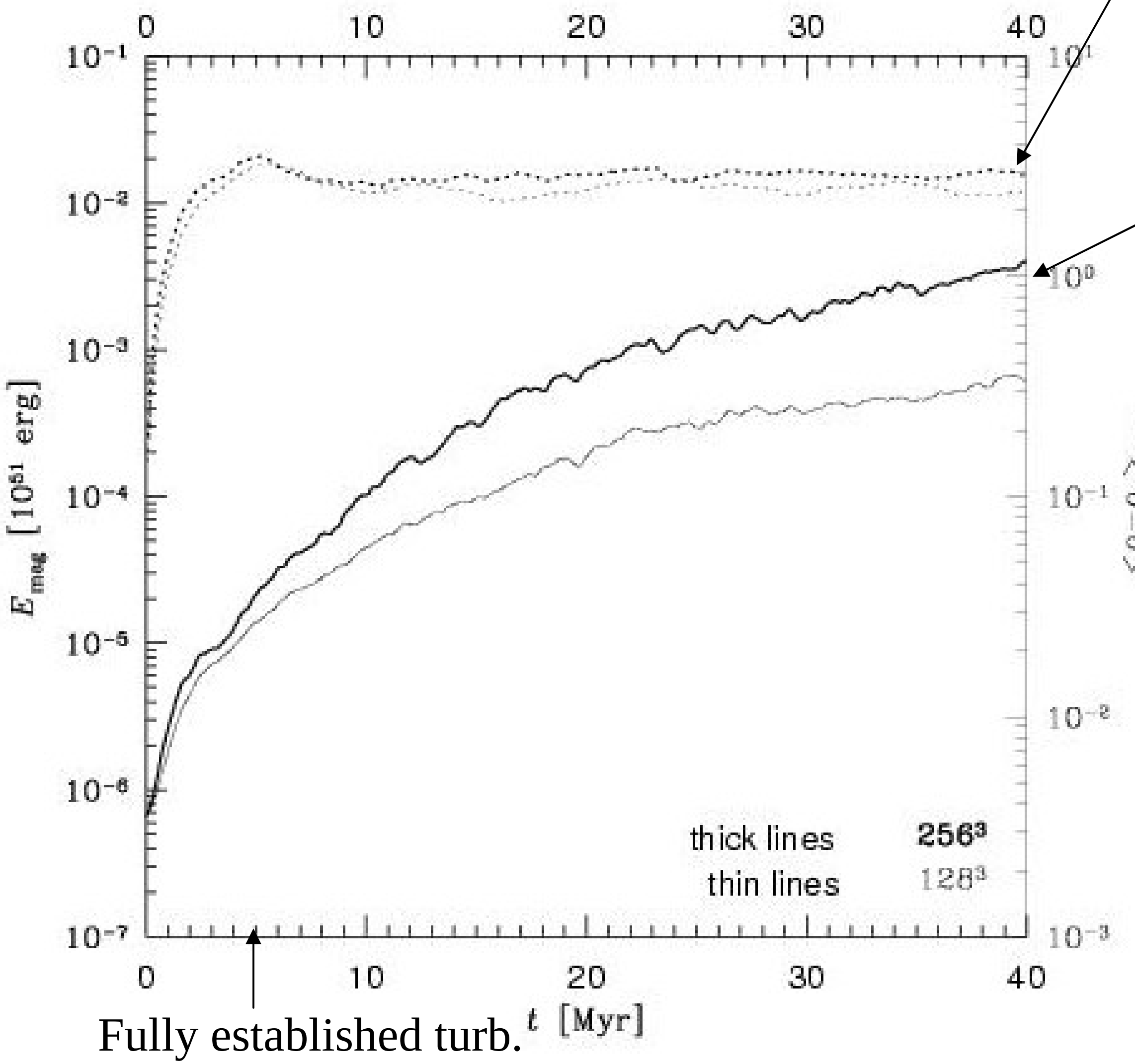


Later stages of low mass star formation – Field stops/regulates the collapse.

High Mass Stars → UV + Cosmic Rays → partially ionized medium → permits field to escape.

1) Fully developed, steady state turbulence after 5 Myr. (Every point has been processed by SNR.)

**Mag. Energy**; r.m.s. density v/s time




Fully established turb.

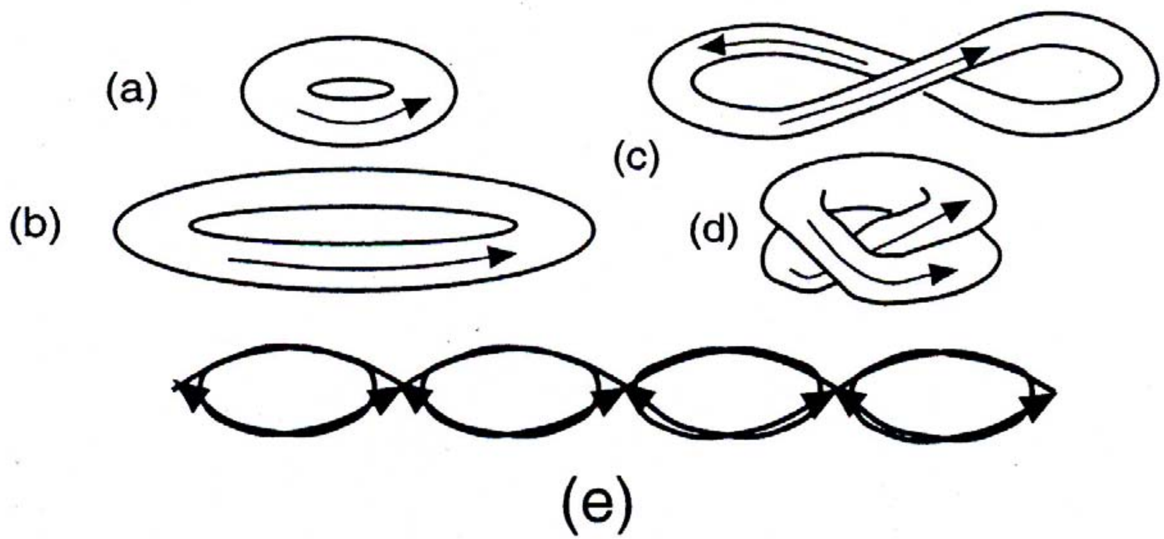
2) Density remains constant ➔ field growth takes place in steady state turbulence.

3) Field grows by > $10^2$ orders of magnitude in 40Myr! Fast growth of field is a robust conclusion.

4) $128^3$ and $256^3$ zone simulations both show robust growth. Numerical $Re_m$ does not affect qualitative results.

D.B. *et al.* (2004)

5) By a sequence of Stretch, Twist and Fold operations we can grow **B**. Known as the STF dynamo. Note: These are vigorous motions that scramble the mean field!




6) STF dynamo is kinematical. Small-scale dynamo theories that include dynamics have also been constructed.

7) Both the above predict growth times that can be as fast as eddy turnover times.

## 6) Conclusions

1) The present study and its possible extensions enable us to explore the additional advantages of SNe and their role in processing the current Galactic ISM and proto-Galactic ISM.

2) The bulk turbulent mixing can now be quantified as a function of SN-rate, ISM parameters etc. The turbulent diffusivity for mixing SN-ejecta can be catalogued for different ISMs/SN-rate/metallicity.

3) The diffusion down to the molecular level by the formation of thin, narrow structures has been shown to be very efficient in SN-driven turbulence.

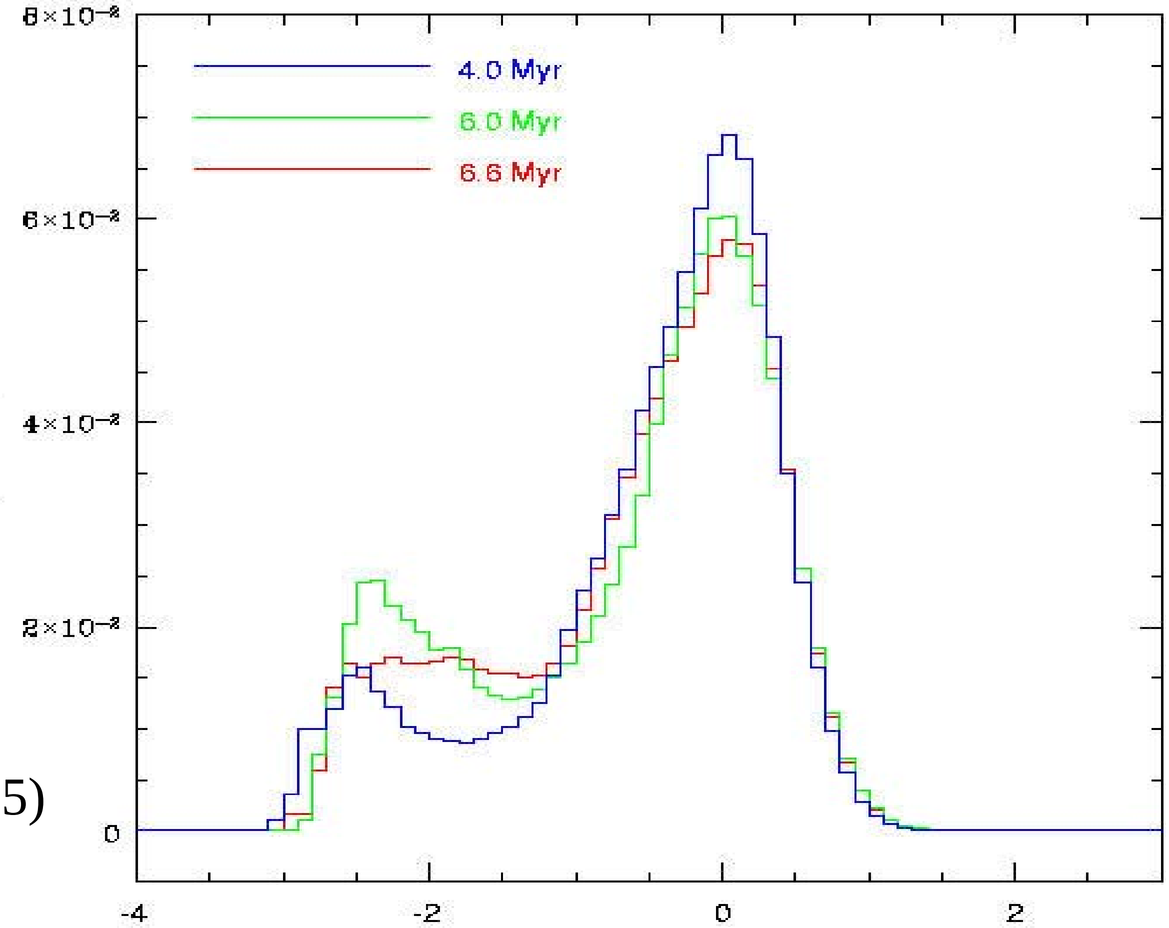
4) Magnetic fields, needed for catalyzing low mass star formation, can also be grown rapidly on small scales in Galactic and proto-galactic environments.

5) They also set the multiphase structure of the ISM, providing the cold phase needed for forming the low mass stars.

# 7) Additional Advantages of SN-Processing – Phases of the ISM

## Simulations of Multiphase ISM

dN / N

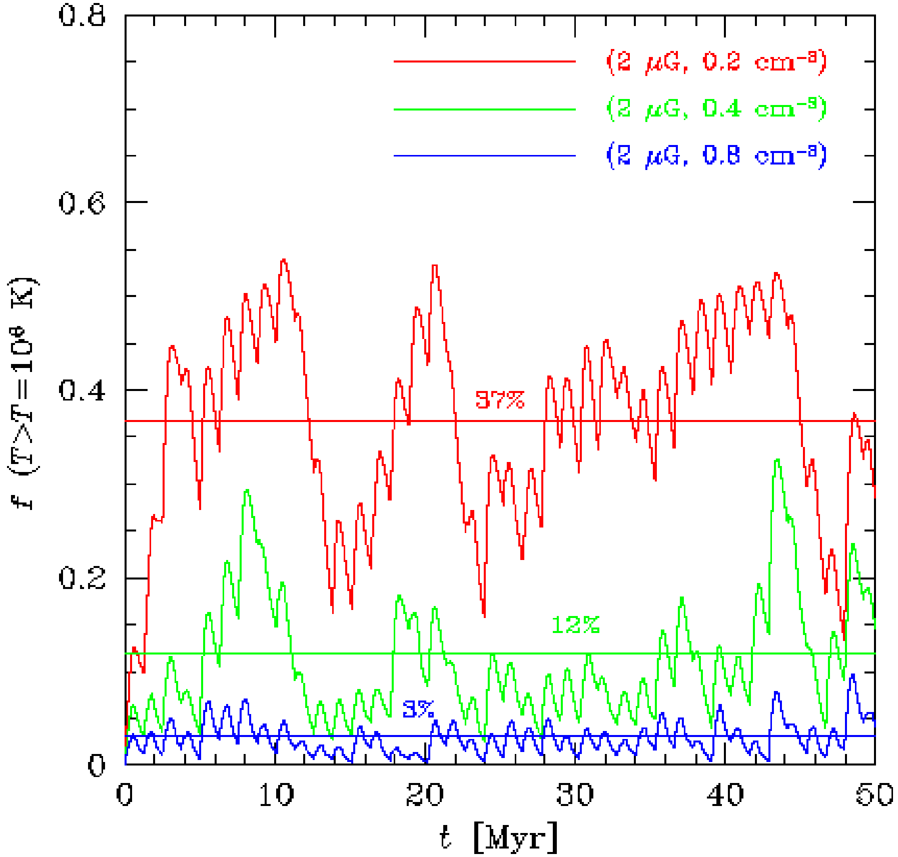


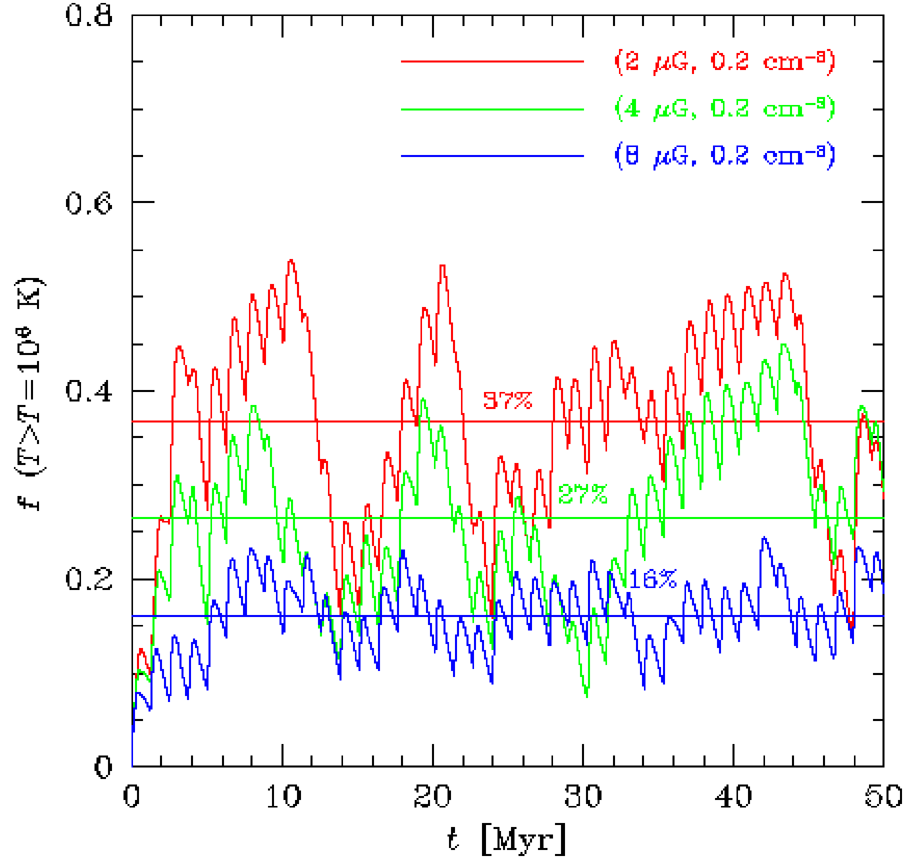

Log ( $\rho / \rho_0$ )

Mac Low, D.B. *et al.* (2005)

- Density histogram ➔ multiphase ISM
- Both the warm and hot phases occupy a wide range of densities!
- Substantial amount of intermediate temperature gas
    - ✓ consistent with observations.

# Filling Factors for Hot Gas (Relevance to Chandra)




1) Too high a rate of SNe or too under-dense an ISM ➔ practically all the gas is turned into the hot phase ➔ Star Formation comes to a halt!

2) Too low a rate of SNe ➔ Turbulent mixing becomes inefficient!

3) Thus use the simulations to put bounds on the parameters.

4)For the ISM, the filling factors constrain the range of ISM parameters.



5) Do same for proto-Galaxy with the help of SEGUE data.