Supernova-Induced Turbulent Mixing and the Broader Impact of SNe on Galactic & Proto-Galactic ISMs

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By

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Plan of This Talk

1) The Broader Impact of SNe: Supernovae and their relation to the Interstellar Medium, Both Galactic & Proto-Galactic, An Overview.

2) Simulations and Movies

3) A Very Brief Overview of Other SN-Driven Physics and its Relation to SEGUE

4) A Study of Bulk Turbulent Mixing

5) Diffusion Down to the Molecular Level

6) Conclusions

1) The Broader Impact of SNe: Supernovae and their relation to the Interstellar Medium, Both Galactic & Proto-Galactic, An Overview.

Let's adopt a Working Model : SNe put energy into ISM making it turbulent and triggering star formation.

1) Supernovae dominate the energy input in our Galactic ISM. More energetic than winds from massive stars by an order of magnitude!

2) Determine the pressure distribution in our Galaxy.

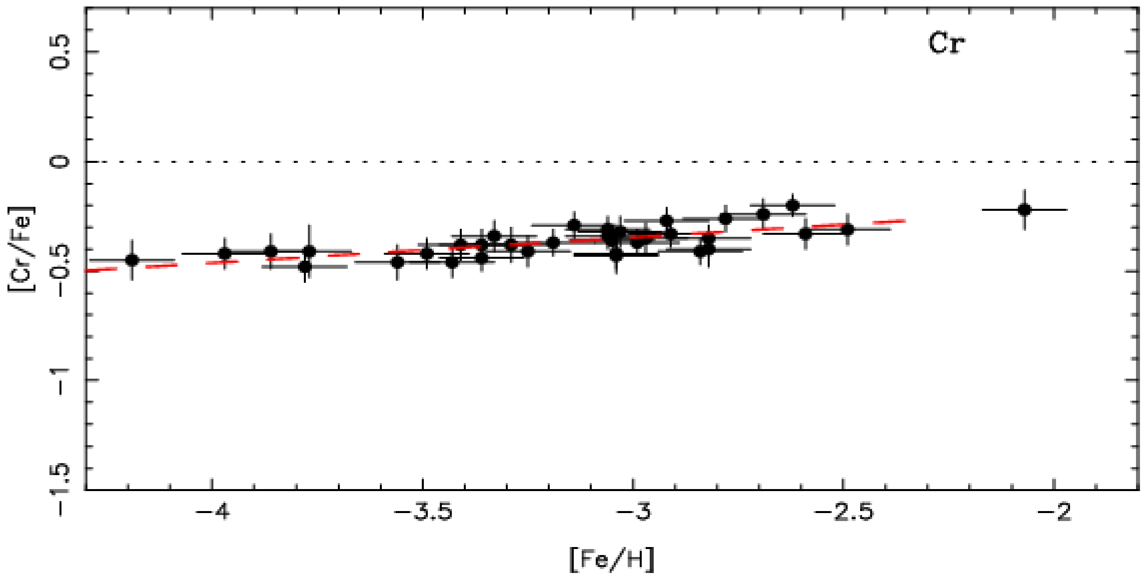
3) Determine the fractions of gas that resides in hot, warm and cold phases. – Low mass stars only form in the cold phase.

4) Establish the turbulent velocity spectrum in the ISM.

5) Drive magnetic field generation. – Low mass star formation requires magnetic fields to resolve the angular momentum problem.

6) Eject metals into the ISM. That in turn determines the cooling efficiency.

7) The turbulence in turn drives the mixing of supernova ejecta into the phases that form the next generation of low mass stars.



Cayrel et al (2004)

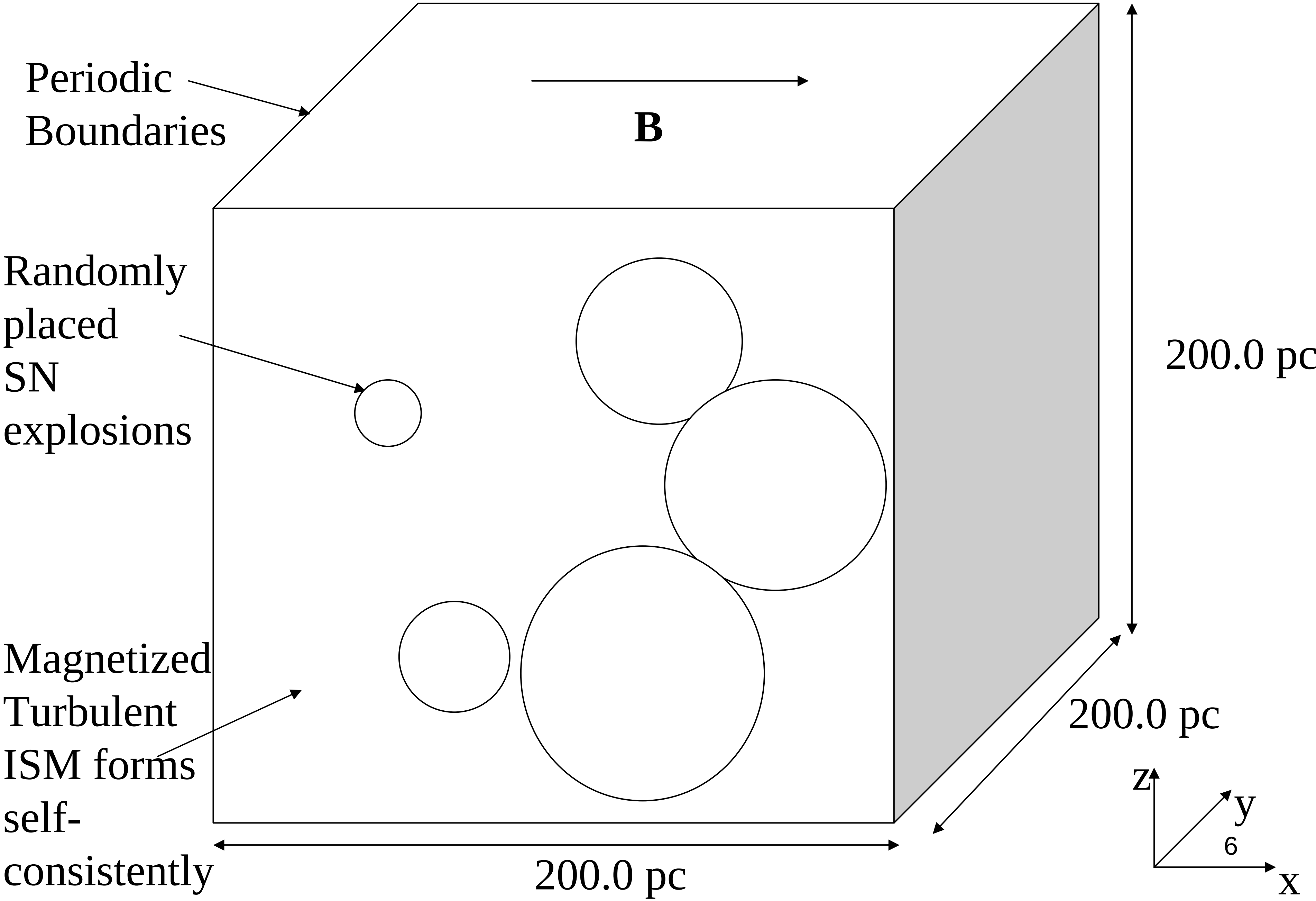
Data suggests that very metal poor, halo stars were formed in an environment that was chemically well-mixed.

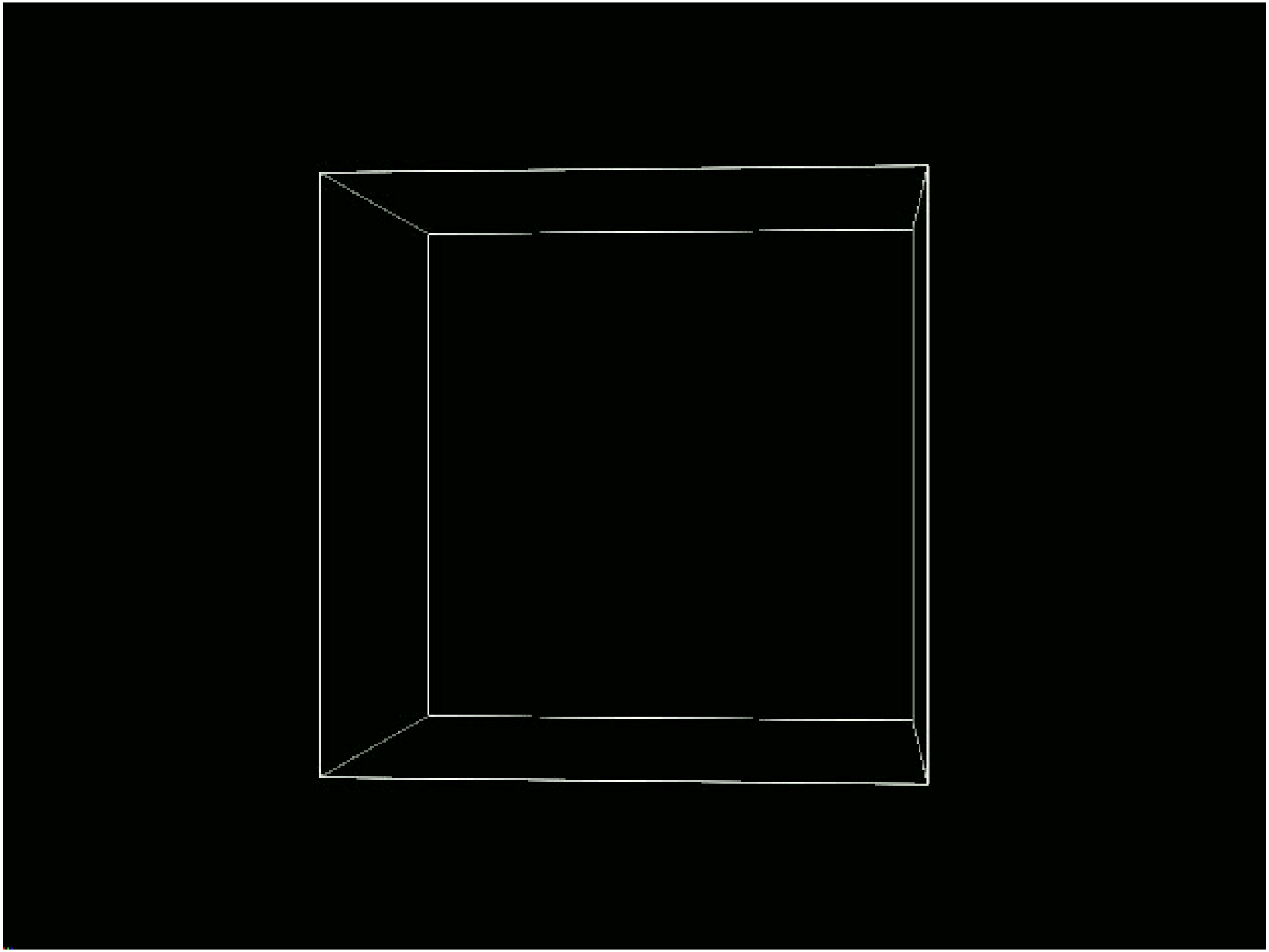
Various tracers of SN-progenitors in various mass ranges show differing degrees of mixing. (this conf.)

<u>Goal</u> : Find a dynamical testbed for exploring such processes.

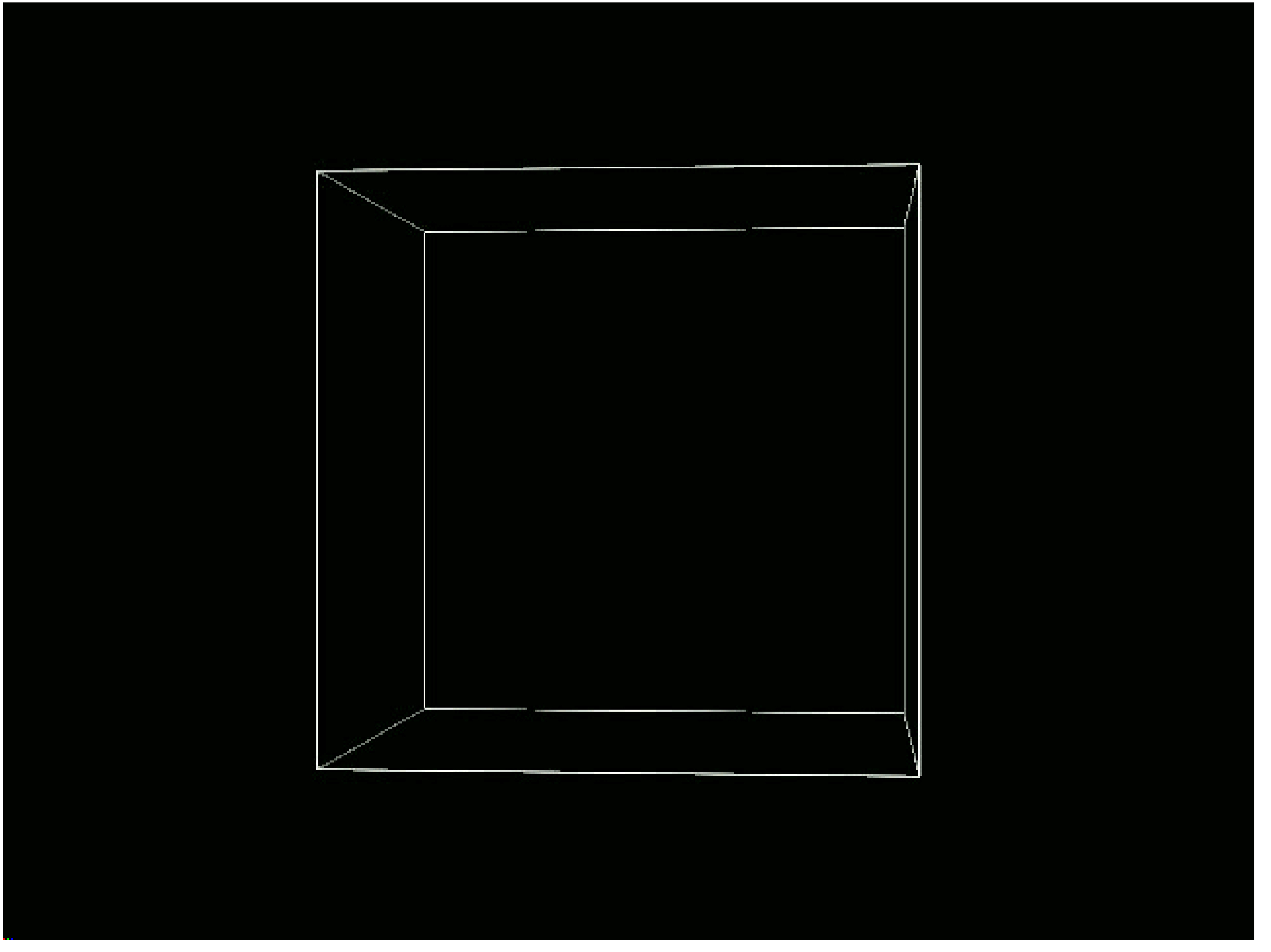
2) Simulations and Movies

Vary SN rate, ISM parameters, Ejecta, Metallicity

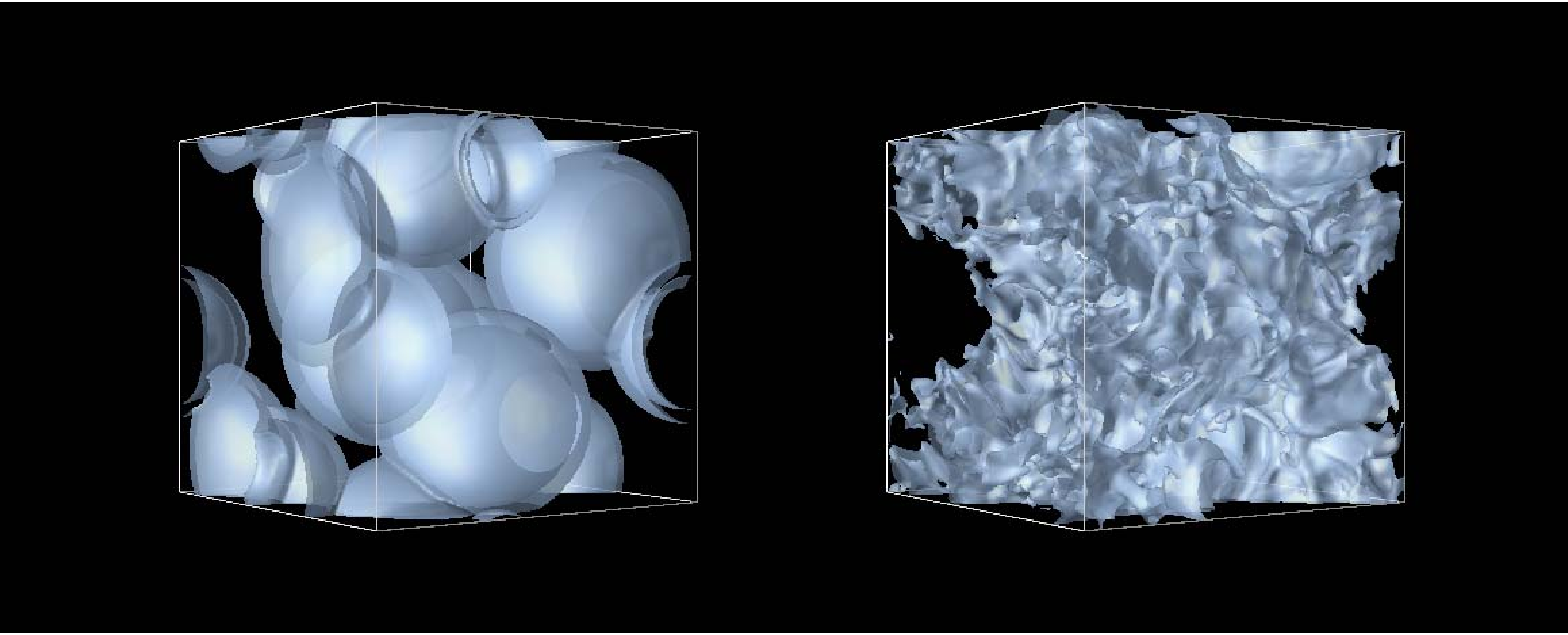




Movie showing isosurface rendering of the density. The porosity of the ISM is clearly visible.



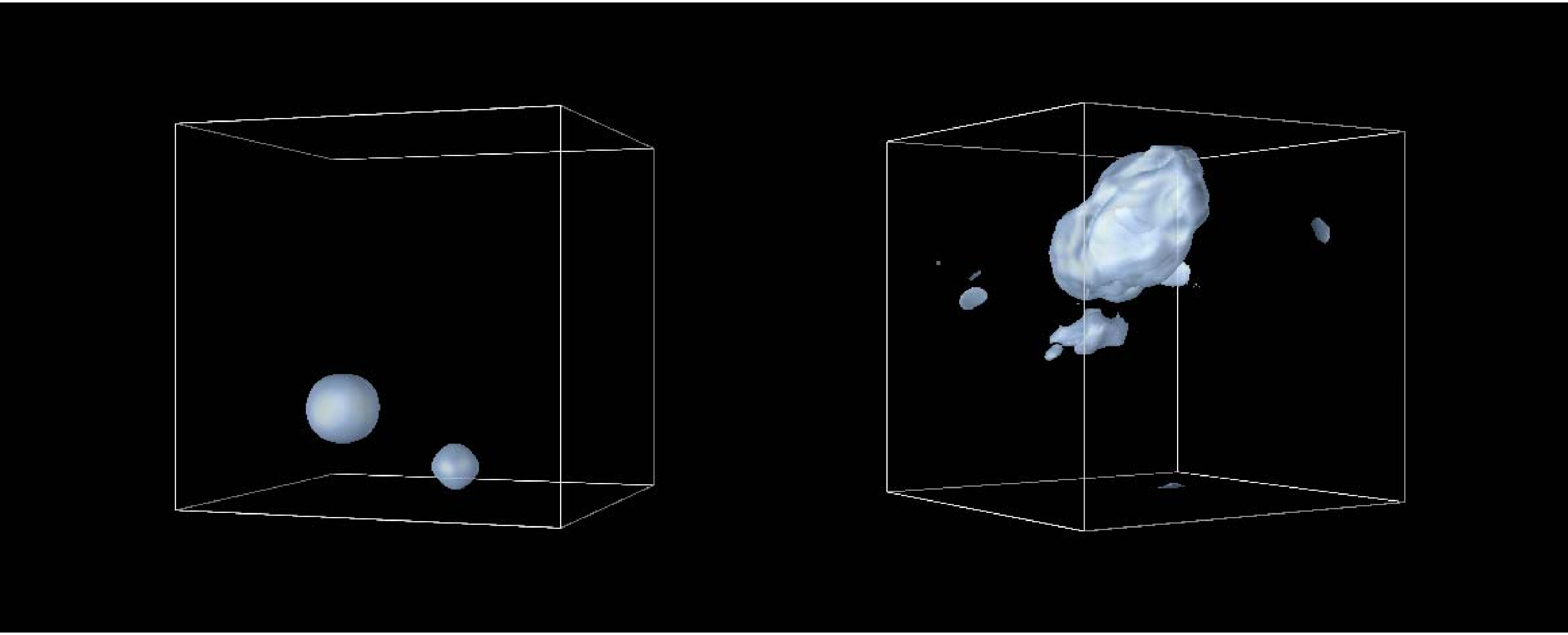
Movie showing isosurface rendering of the pressure. SNRs are spherical initially but become progressively non-spherical as the level of self-consistently generated turbulence rises.



Early time

Late time

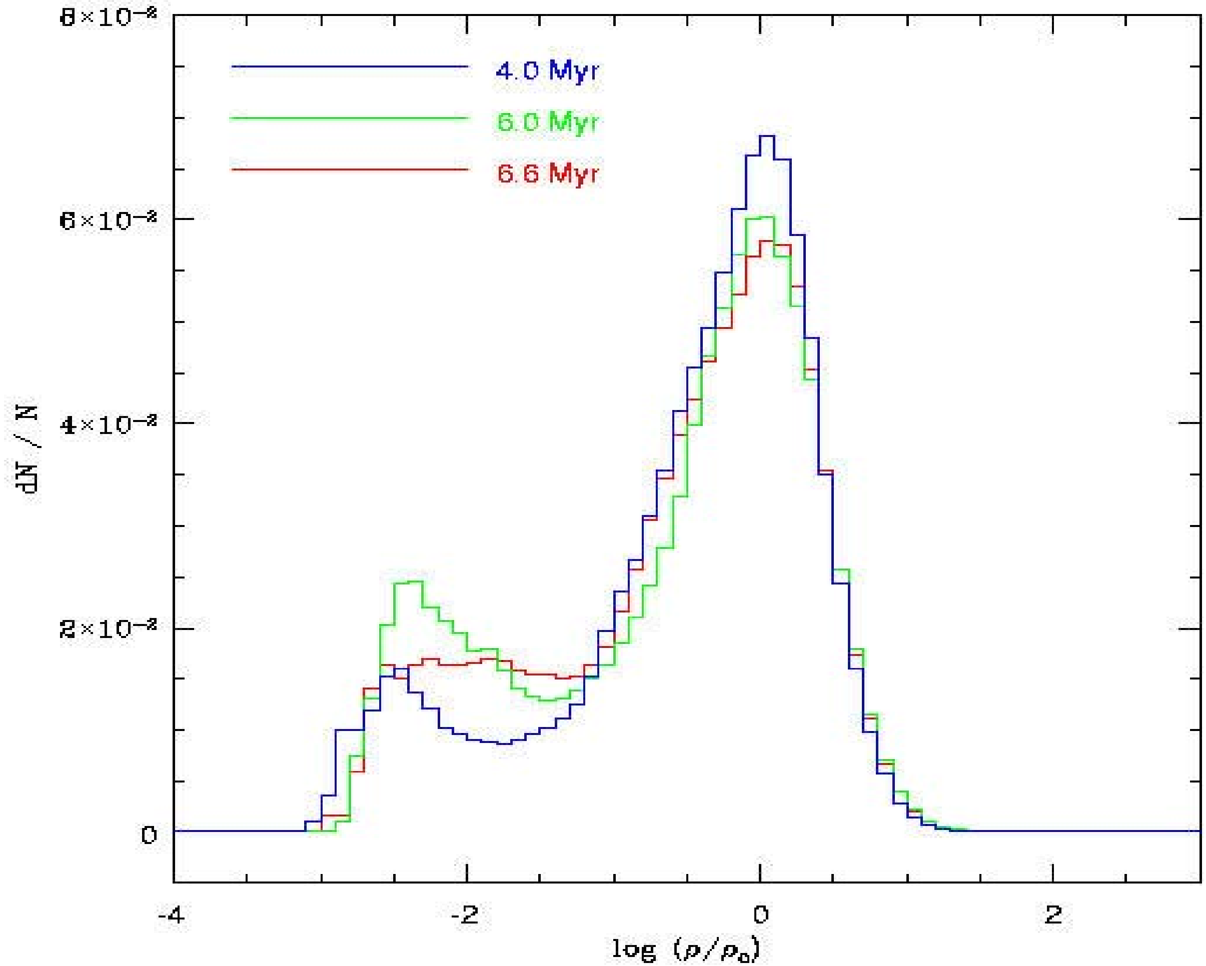
Density IsoSurfaces -- SNe-Induced ISM Turbulence



Early time   Late time

Pressure IsoSurfaces -- SNe-Induced ISM Turbulence

3)A Very Brief Overview of Other SN-Driven Physics and its Relation to SEGUE

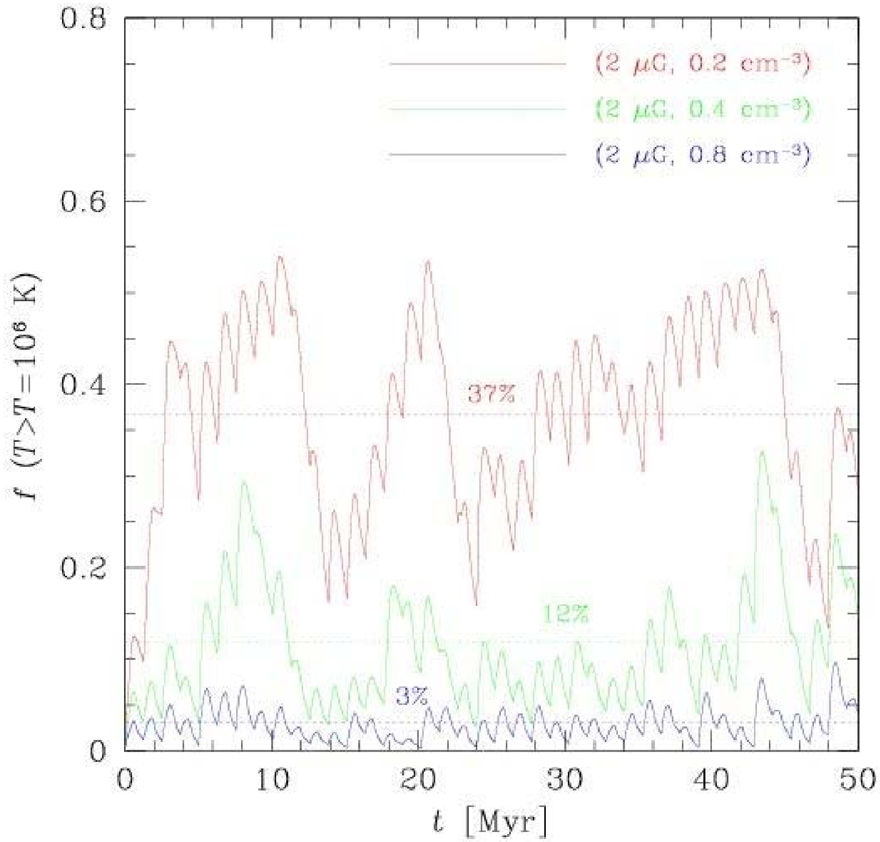


1) Density histogram showing multiphase ISM

2) Both the warm and hot phases occupy a wide range of densities!

3) There is a substantial amount of intermediate temp. gas, in keeping with observations.

We can trace out the filling factor of hot gas, which is measured by FUSE to be 20%.



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!

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

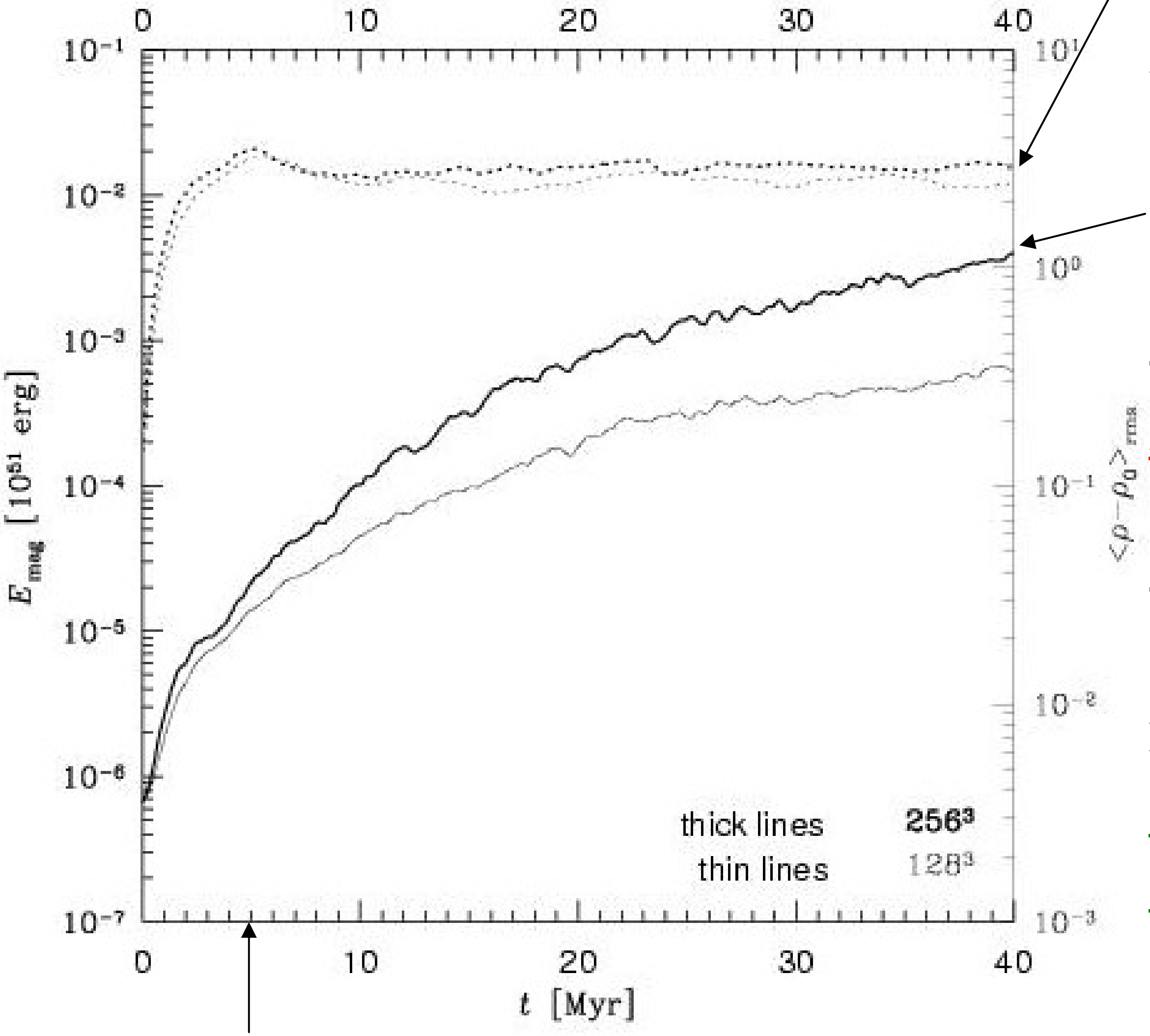
Thus use the simulations to put bounds on the parameters.

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

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

Low mass star formation requires magnetic fields to resolve the angular momentum problem.

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



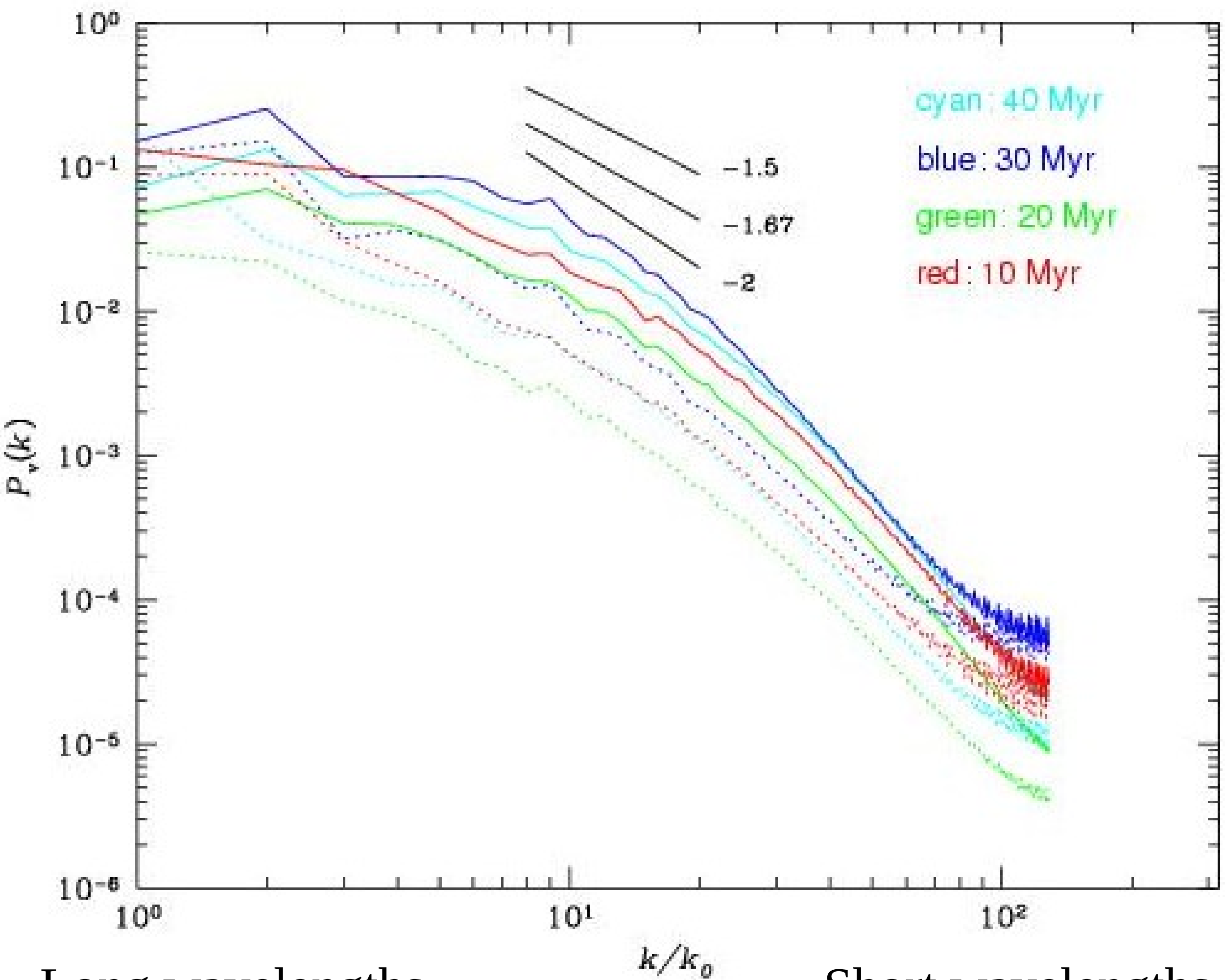
2) Density remains constant ➔ field growth takes place in steady state turbulence.

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.

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

Spectra of compressive (dashed) and solenoidal (solid) velocities.



Long wavelengths   Short wavelengths

1) The problem has strong shocks ➔ compressive motions expected to dominate. Expectation not realized.

2) Dominant motion is vortical – recall shock-density interaction!

3) Vorticity helps build helicity ➔ helps make magnetic fields! Thus we have a dynamical explanation for field growth.

4) A Study of Bulk Turbulent Mixing

1) SN-ejecta enrich the ISM with metals.

2) Astro-archeology: Certain r-process ejecta, such as Eu, can even be tracers of SN-progenitor stars in precise mass ranges, Mathews & Cowan (1990).

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) Current observations favor efficient mixing.

5) SN-ejecta in a turbulent ISM follow a diffusion equn:

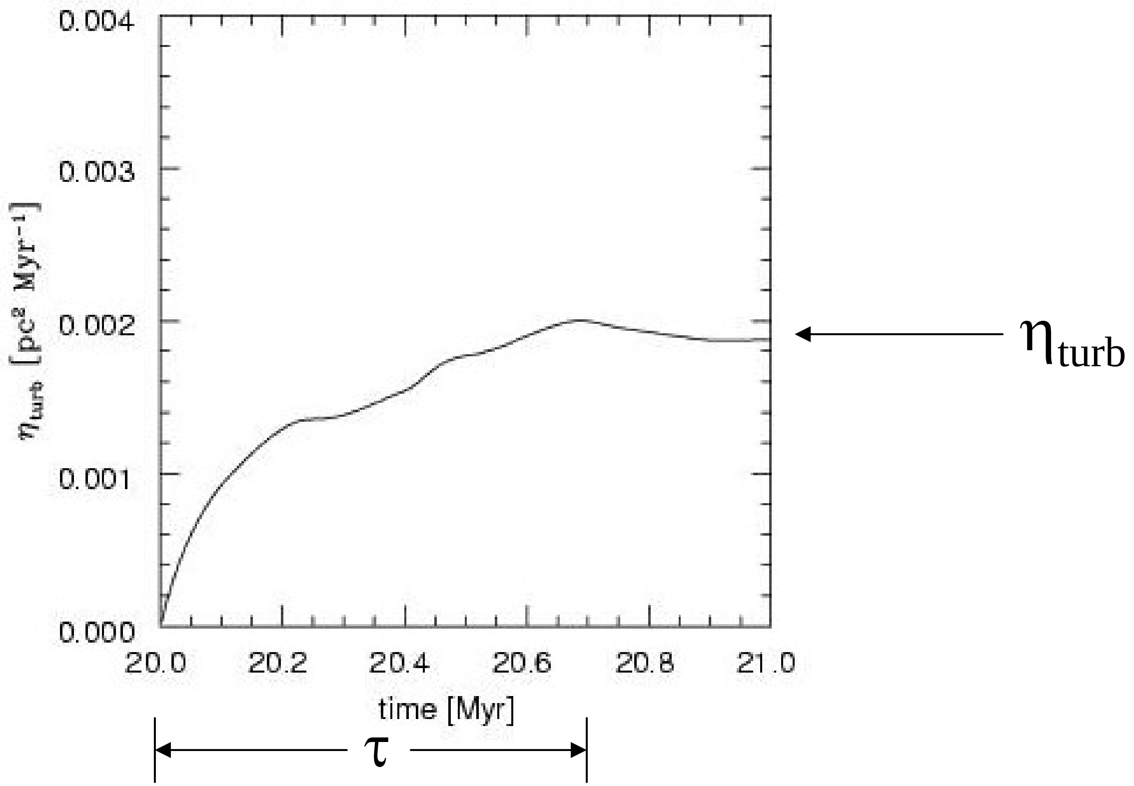
$$\frac{\partial \theta}{\partial t} + v \bullet \nabla \theta = \nabla \bullet \left(\eta_{turb} \nabla \theta \right)$$

This governs the bulk transport of ejecta.

6) The turbulent diffusivity, η_{turb} , is the parameter of interest.

7)The diffusion is then given by:

$$\theta(x,t) = \frac{1}{2\sqrt{\pi \; \eta_{turb} \; t}} \int_{-\infty}^{+\infty} \theta(x^{\prime}, t{=}0) \exp \left[(x - x^{\prime}) / 4 \; \eta_{turb} t \right] dx^{\prime}$$



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

9) A mixing length theory can also be constructed so that $\eta_{turb} = \langle v_{rms}^2 \rangle \, \tau$
τ is the coherence time of the turbulence; $\sqrt{\langle v_{rms}^2 \rangle}$ is the rms velocity.

10) The coherence time and rms velocity can also be read off from the simulations.

5) 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.

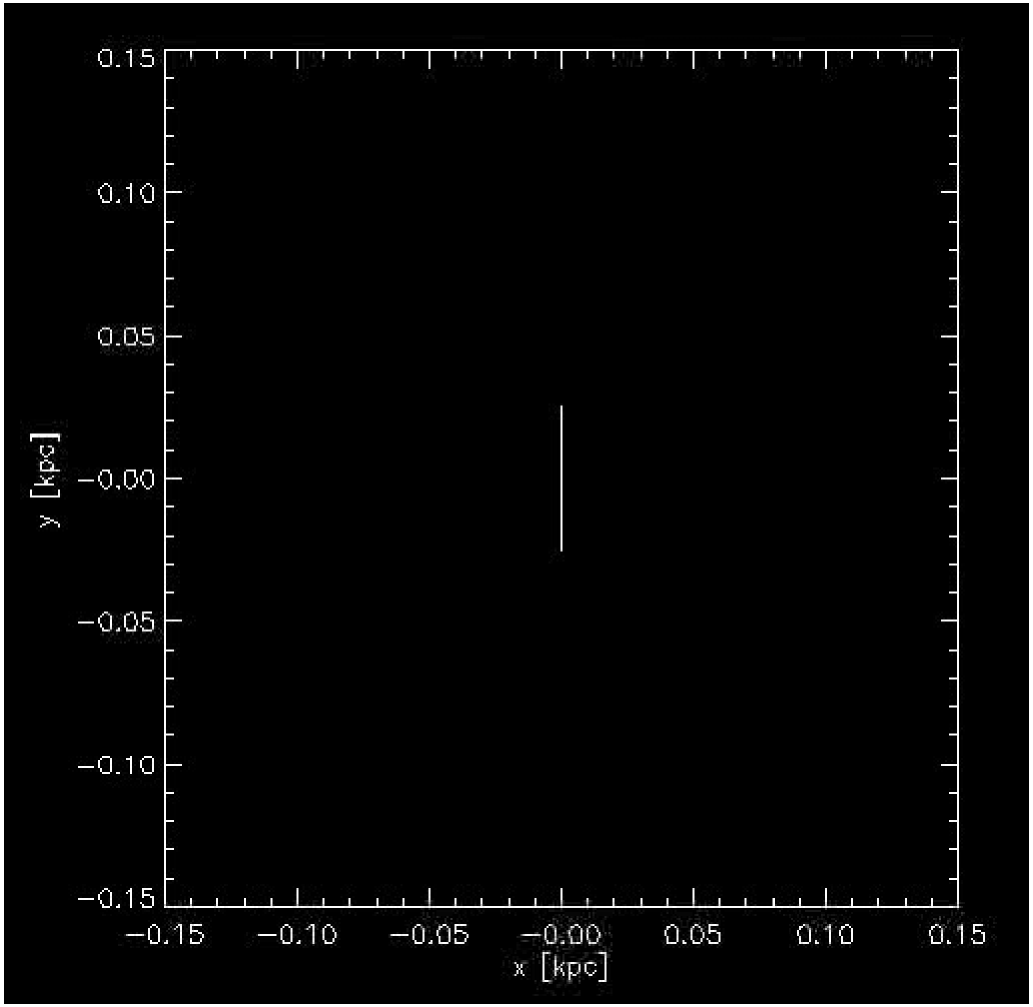
2) This is important because the molecular diffusivity in the ISM and proto-galactic ISM is almost 10 orders of magnitude smaller than the turbulent diffusivity.

3) The molecular diffusion obeys : $\frac{\partial \theta}{\partial t} + \mathrm{v} \bullet \nabla \theta = \nabla \bullet \left(\eta_{\mathrm{mol}} \nabla \theta \right)$

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.



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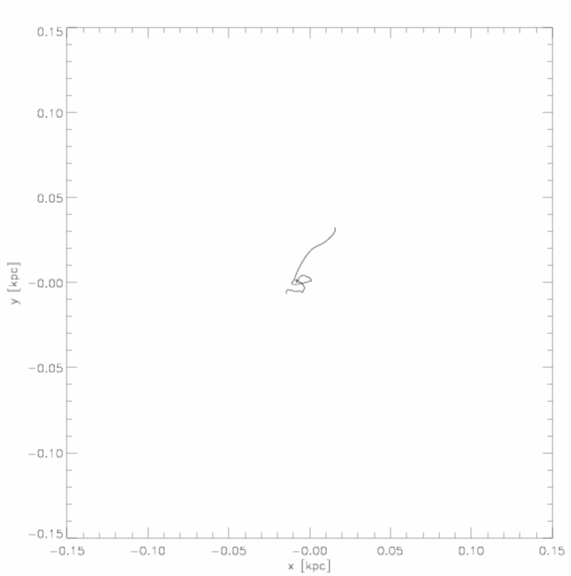
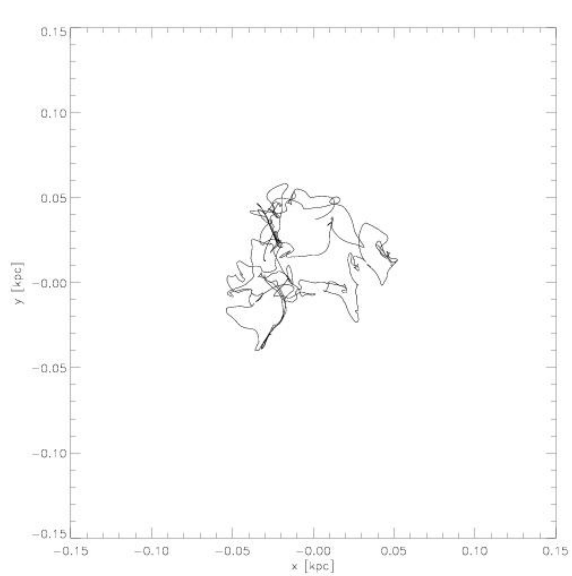
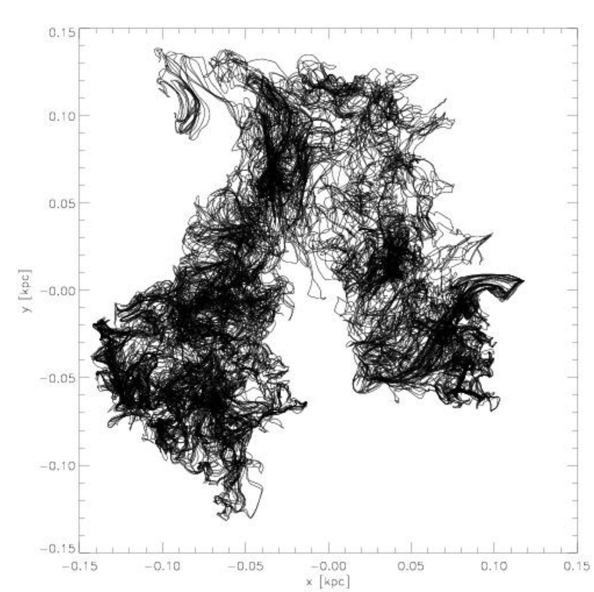


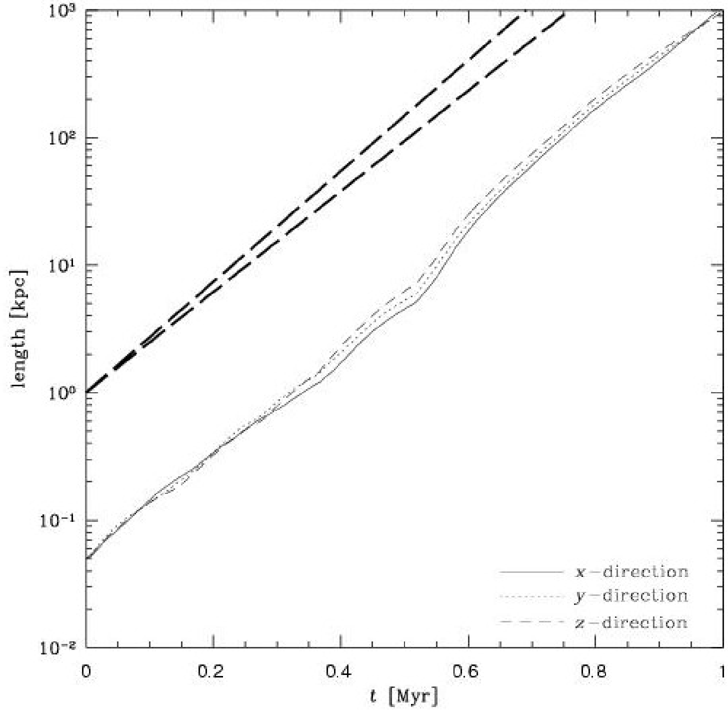
t=0.1 Myr



t=0.4 Myr



t=0.8 Myr



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

6) It can be shown that thin, narrow structures form very fast, i.e. in a time given by 2 $\tau_{\rm line}$!

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

6) Conclusions

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

2) Coupled with HST and FUSE data such studies enable us to understand the Galactic ISM and even constrain its values.

3) Coupled with SEGUE data such studies will also enable us to understand proto-Galactic ISMs.

4) We have shown how SNe regulate various aspects of the multiphase ISM and the processes that catalyze low mass star formation in such an ISM.

5) The turbulence in the current Galactic ISM and the proto-Galactic ISM is also regulated by SNe.

6) The studies have already shown that too high a rate of SNe → cold phase is destroyed → no low mass star formation.
Too low a rate of SNe → turbulent mixing is not efficient enough to be consistent with data.

7) The bulk turbulent mixing can now be quantified as a function of SN-rate, ISM parameters etc.

8) 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.

9) The next frontier would be to design even more precise numerical experiments that retain information about SN-progenitor masses and yields and use them to arrive at testable predictions that can be compared to even more detailed observations that are coming on line (see next talk).