Turbulent Mixing in the Outer Solar Nebula

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1. Motivation

- Turbulence may regulate grain growth and settling and mix gas of different compositions.
- For example, comets contain HCN with deuterium abundance intermediate between molecular cloud and Solar values, but the nebula where comets formed was too cold for reprocessing.
- Interpretation of mm data on molecules in disks depends on the unknown vertical mixing rates.
- The outer Solar nebula was sufficiently ionized for turbulence driven by magneto-rotational instability.

Comet Ikeya-Zhang 2002

G. Rhemann & M. Jäger

Balbus & Hawley 1991:

Differential Rotation

+

Weak Magnetic Field

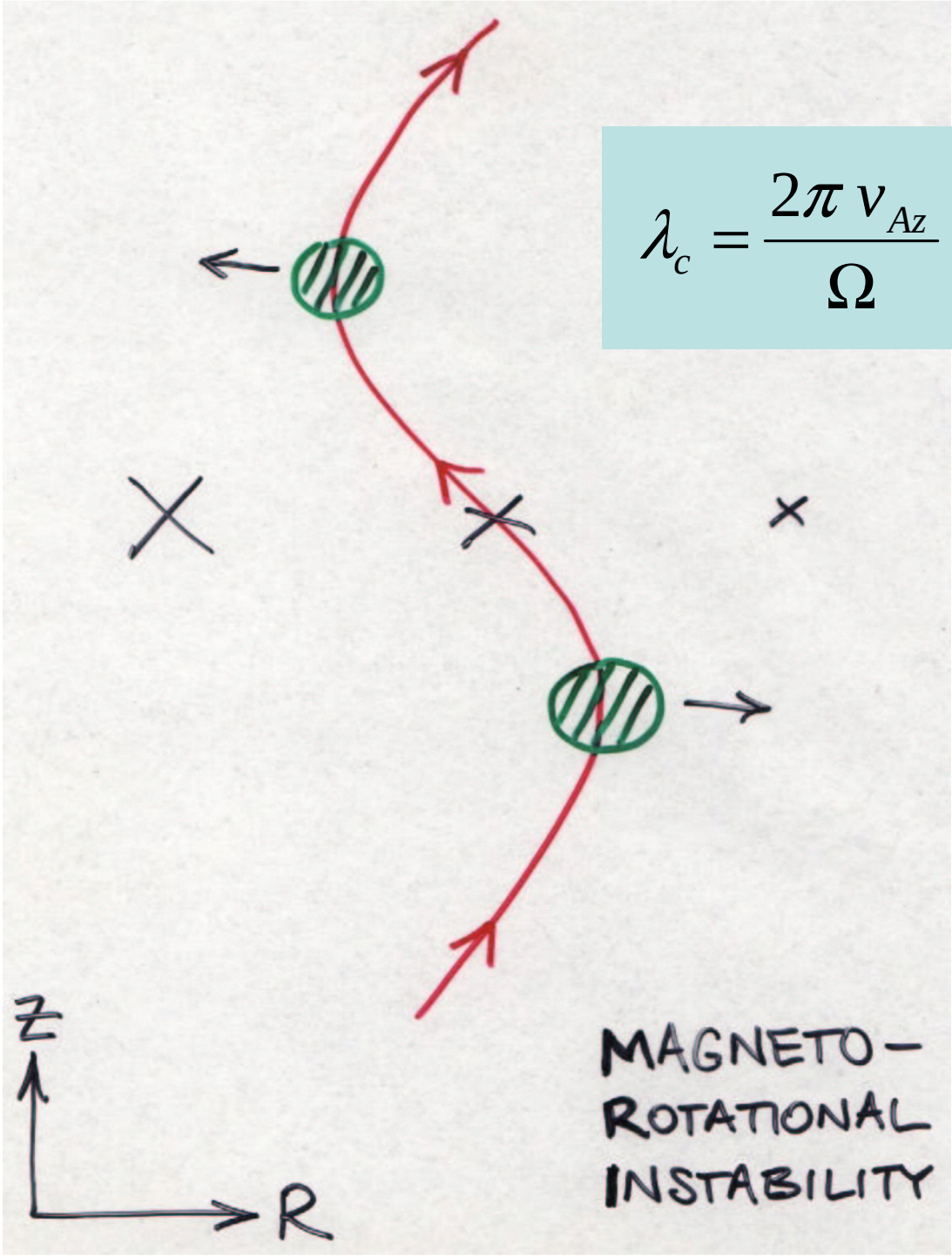
⬇

Local Dynamical Instability

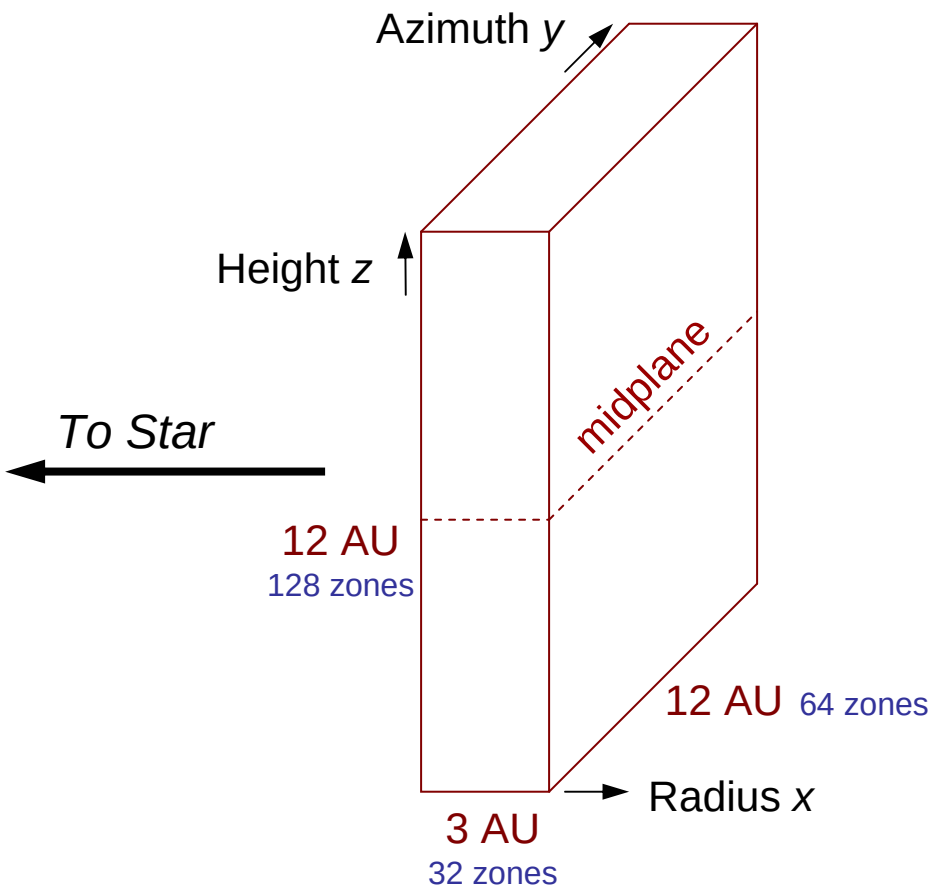
⬇

Turbulence

$$\lambda_c = \frac{2\pi v_{Az}}{\Omega}$$



2. Domain and Initial State



Boundaries

Radial: shearing-periodic

Azimuthal: periodic

Vertical: outflow, no inflow

Initial state from irradiated T Tauri disk model:

$$\mathbf{M} = \mathbf{M}_\odot$$

$$\mathbf{R} = \mathbf{30\ AU}$$

$$\mathbf{\Sigma} = \mathbf{25\ g\,cm^{-2}}$$

$$\mathbf{T} = \mathbf{25\ K}$$

Magnetic field has zero net flux.

Mass is added where needed so $\rho > \rho_{envelope} = 10^{-18}$ g cm^{-3}.

Isothermal MHD Equations Solved

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \mathbf{v} = 0$$

$$\frac{D\rho_c}{Dt} + \rho_c \nabla \cdot \mathbf{v} = 0$$

Follow the flow of a passive contaminant

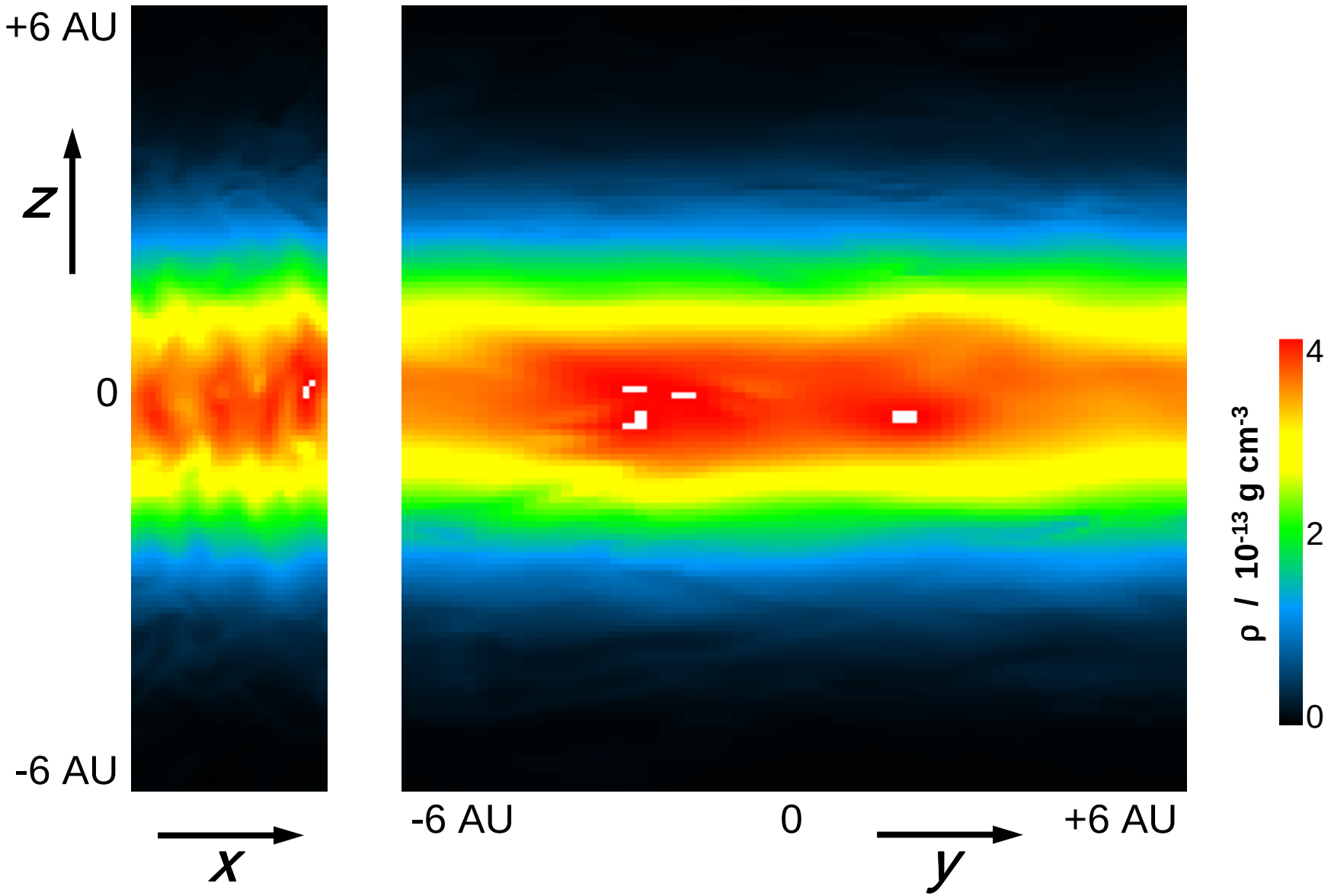
$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B} - 2\rho \mathbf{\Omega} \times \mathbf{v} + 3\rho \mathbf{\Omega}^2 \mathbf{x} - \rho \mathbf{\Omega}^2 \mathbf{z}$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B})$$

Include Coriolis, tidal and vertical gravity forces in a frame rotating at orbital speed

$$p = c_s^2 \rho$$

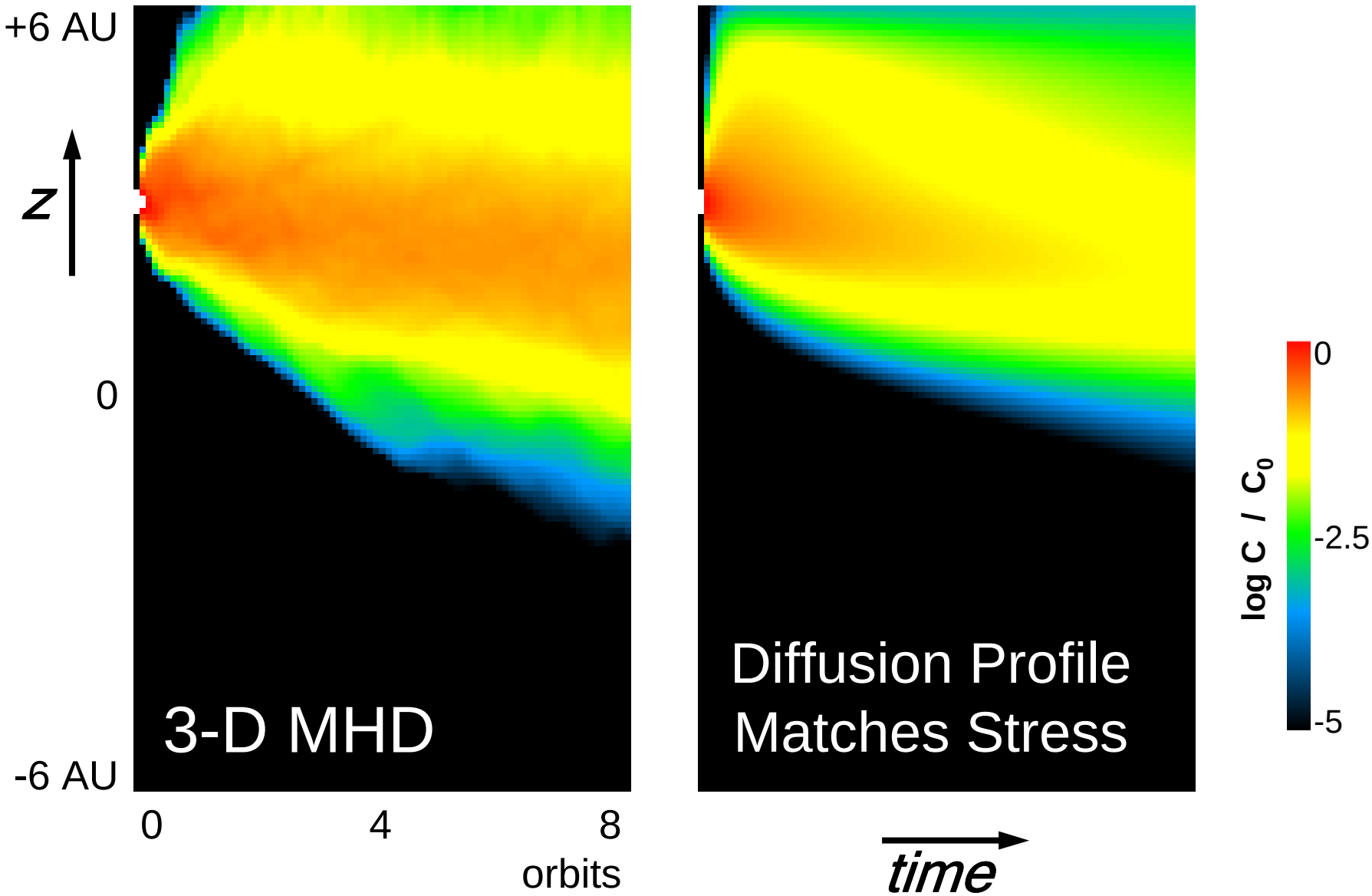
Typical Density Distribution



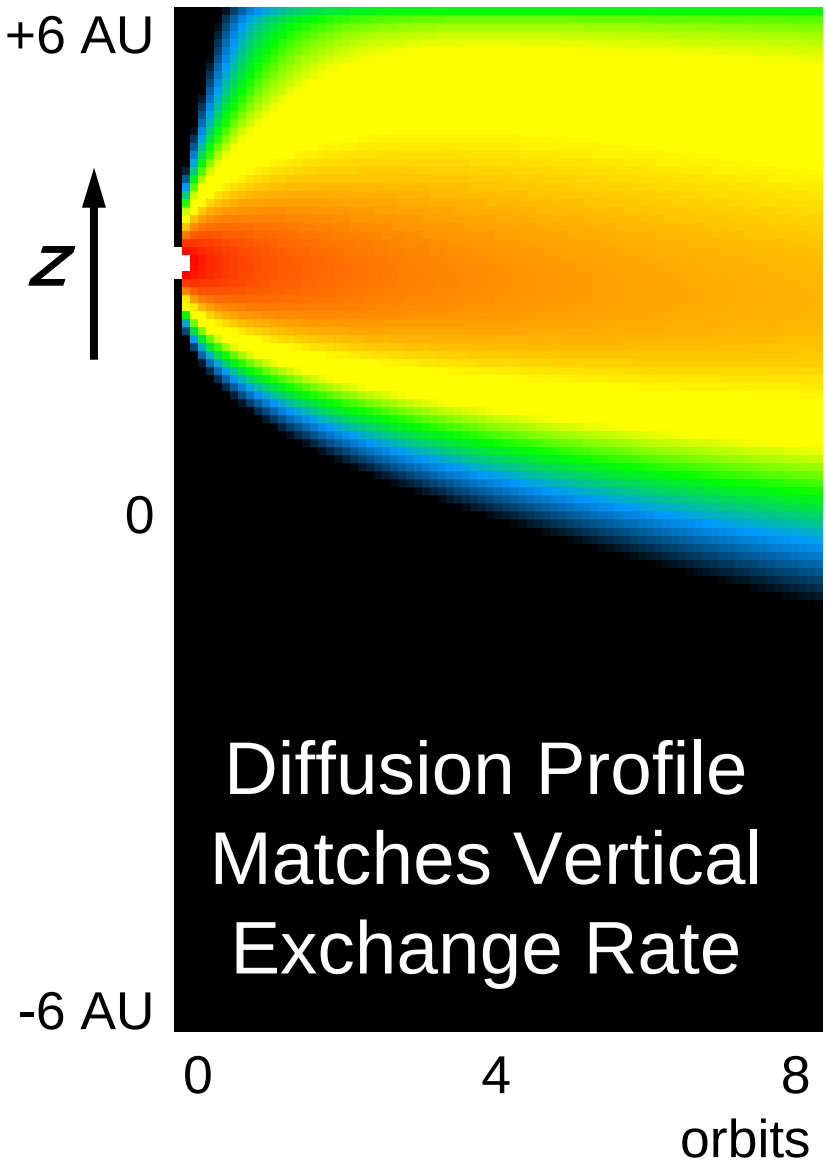
3. Mixing Rates

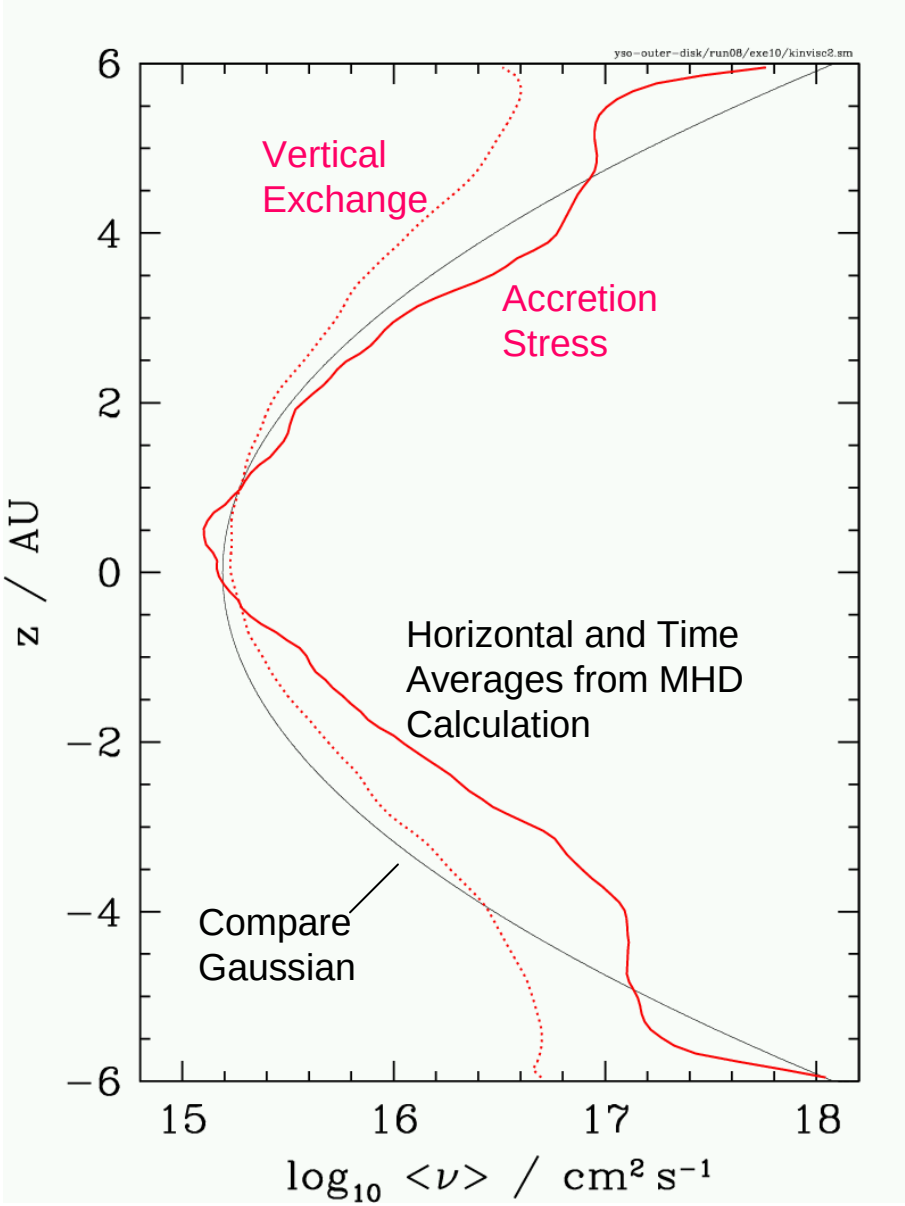
- Once turbulence is well-established, a passive tracer species is added in a thin horizontal layer.
- As the tracer spreads, its horizontally- or *x,y*-averaged density is plotted against height *z* and time.
- Results are compared with 1-D diffusion calculations in which the diffusion coefficients vary with height. Best agreement occurs for diffusion coefficient proportional to the mean rate of vertical exchange of vertical linear momentum in the MHD calculation.
- Mixing is fastest in the surface layers, where it is a few times slower than radial angular momentum transfer. Near the midplane the two occur at about equal rates.

Comparing Mixing Processes 1



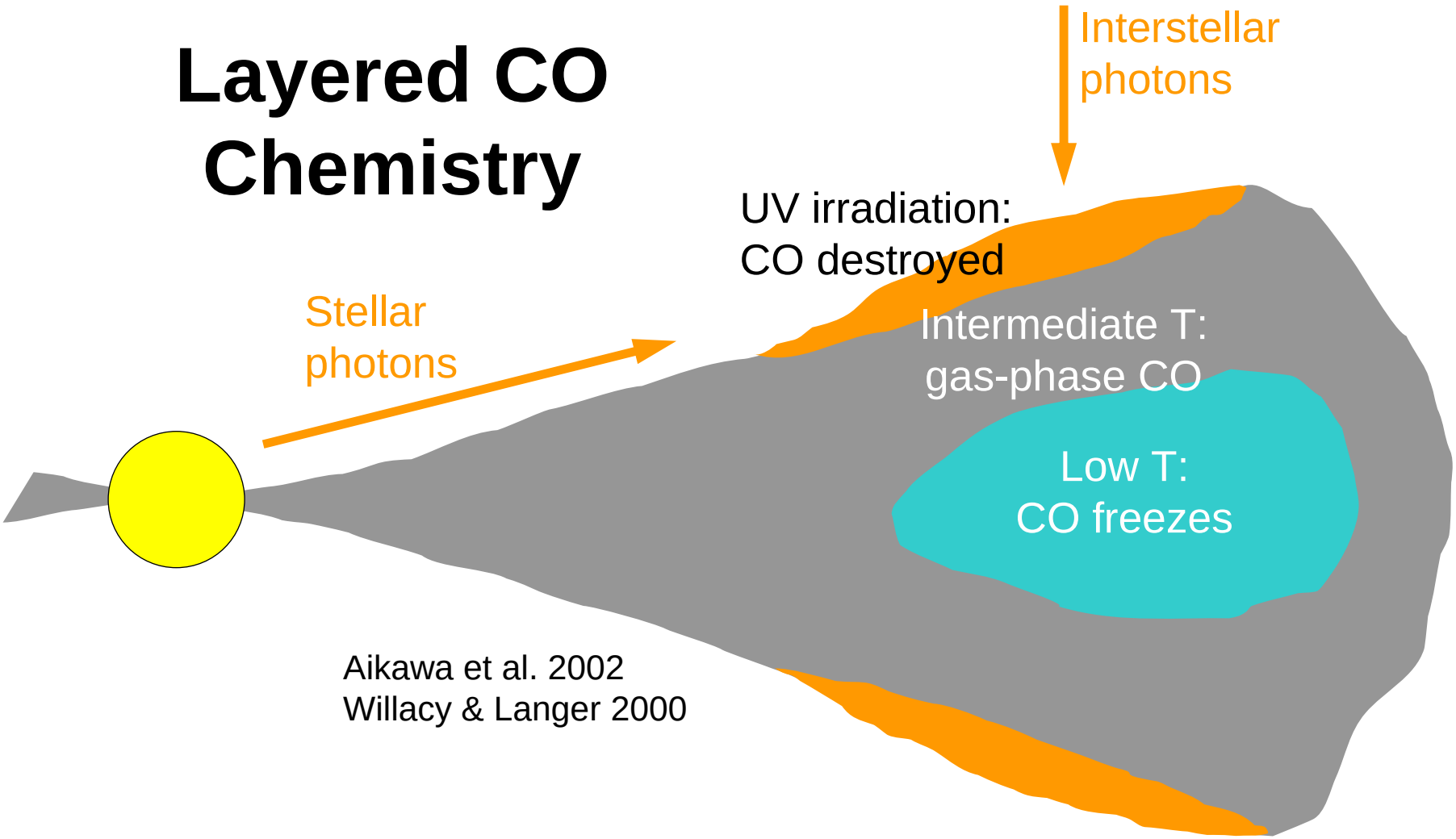
Comparing Mixing Processes 2





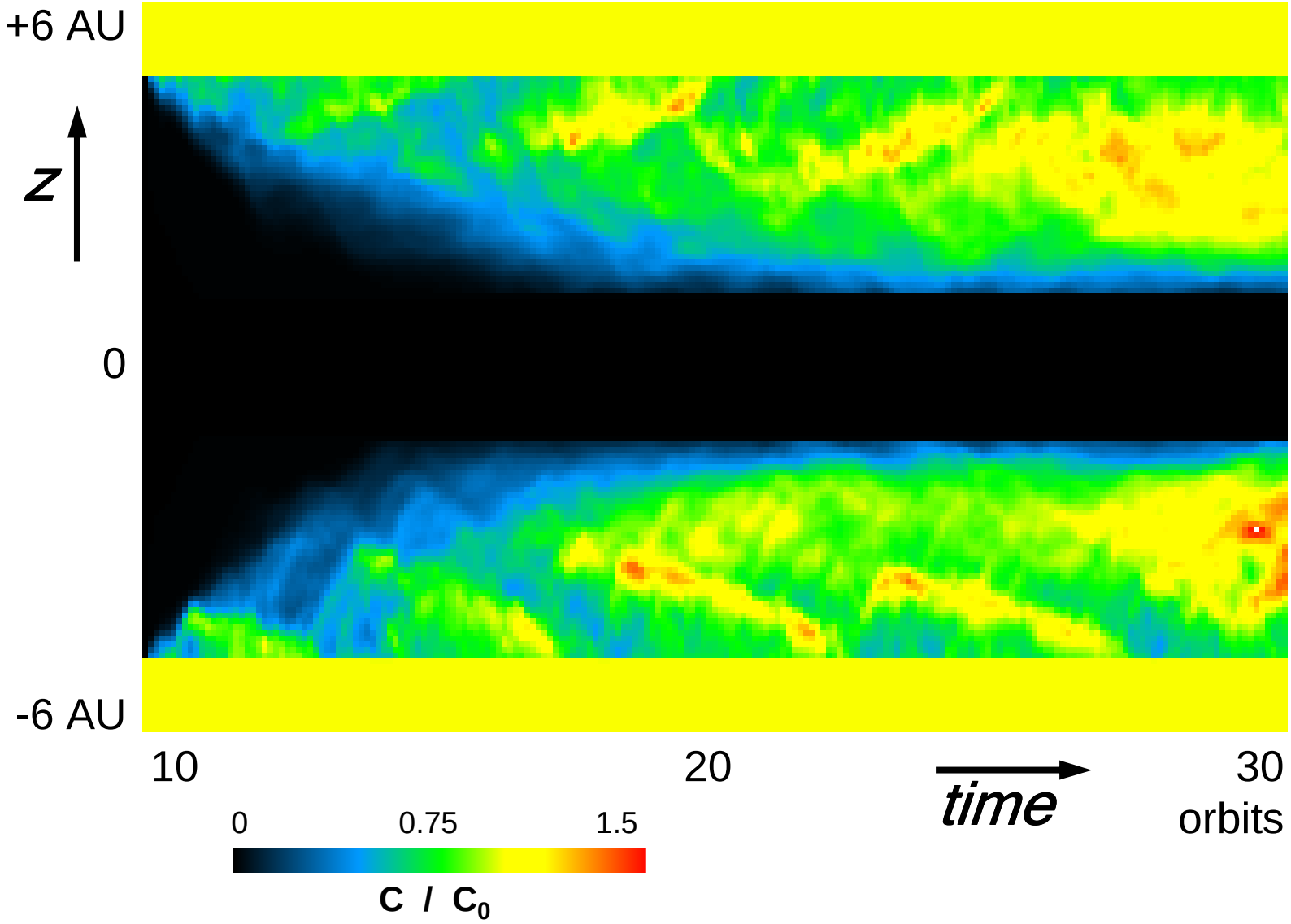
4. Steady State & Fluctuations

Layered CO Chemistry

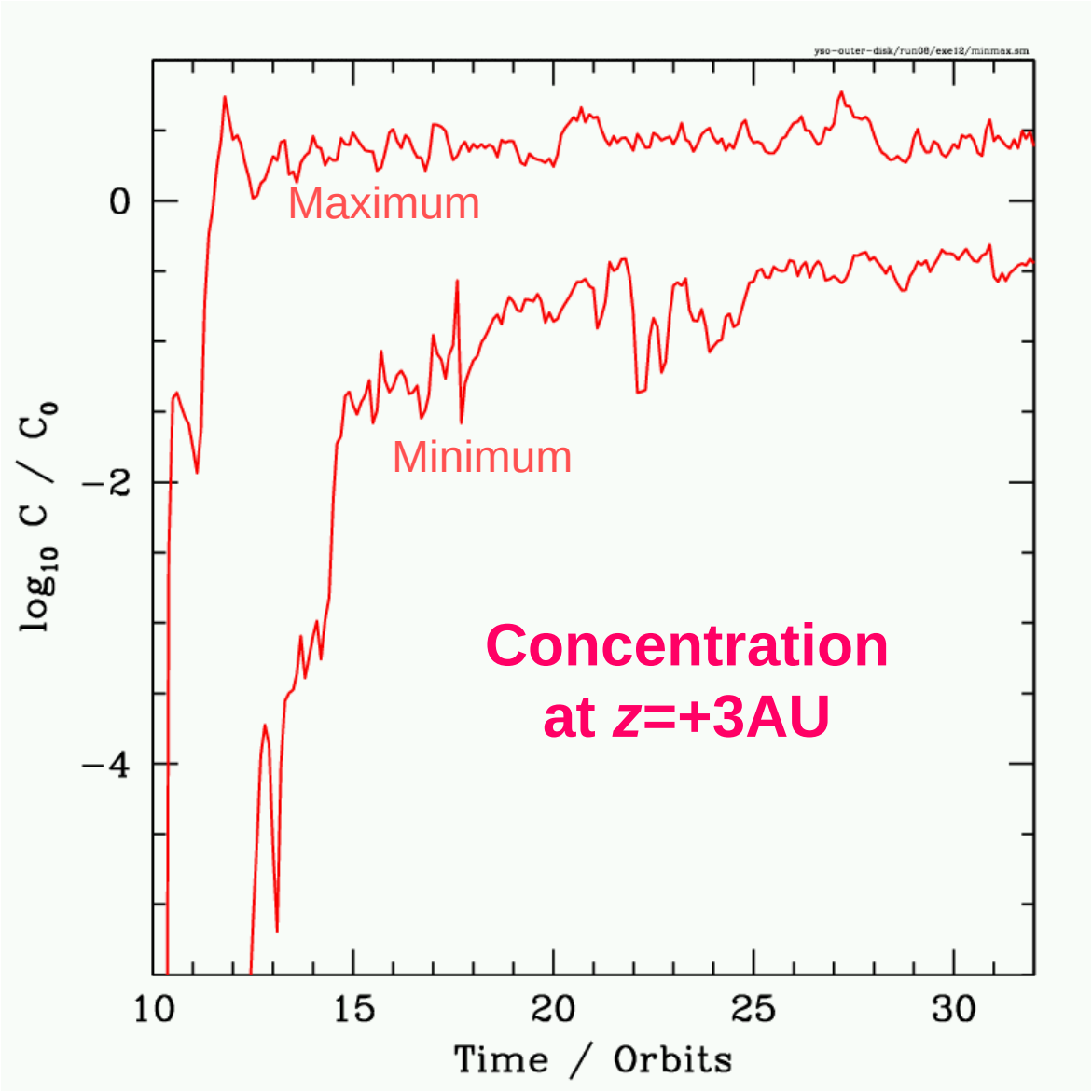


Aikawa et al. 2002
Willacy & Langer 2000

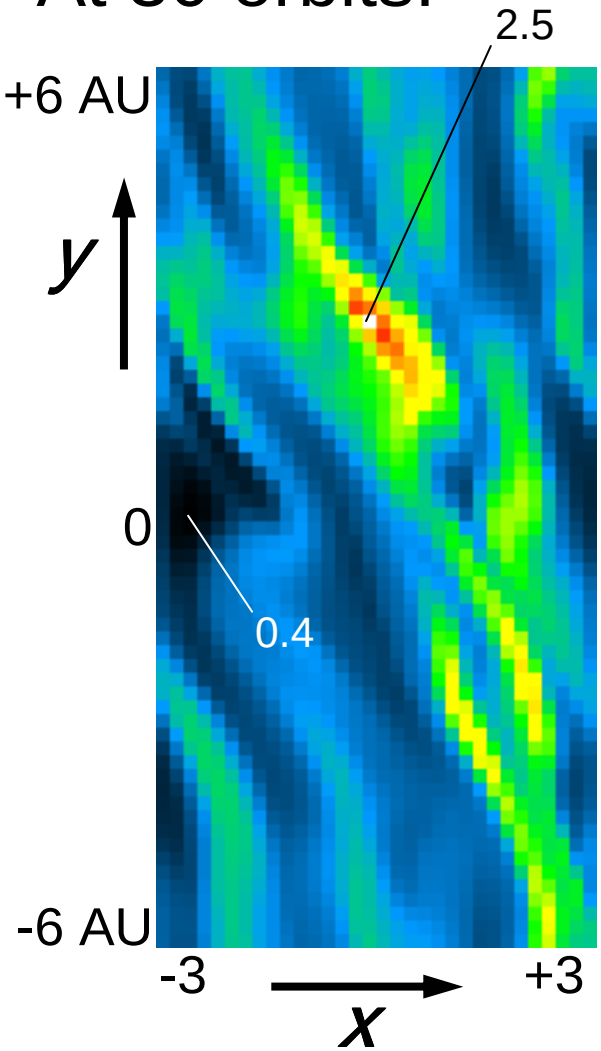
Turbulent Mixing Between Source and Sink



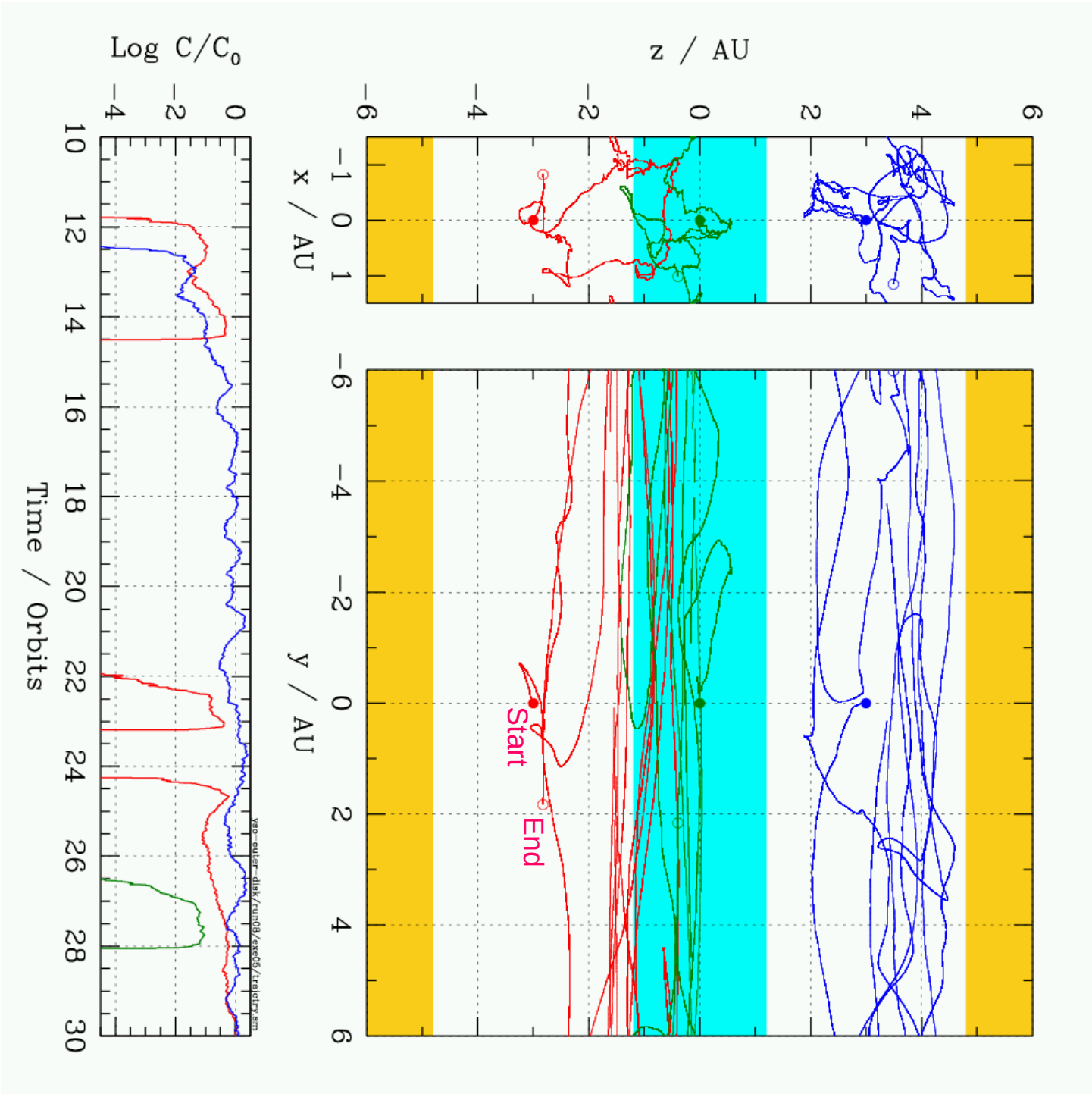
Effects of Turbulent Fluctuations



At 30 orbits:



5. Dust Grain Orbits



Conclusions

1. The gas mixes vertically at about the rate that angular momentum is transferred radially.
2. Mixing is faster in the surface layers than at the midplane, due to larger Alfven speeds.
3. The horizontally-averaged abundance profile is roughly fit by 1-D vertical diffusion.
4. Individual fluid elements have erratic abundance histories that are not well described by diffusion.