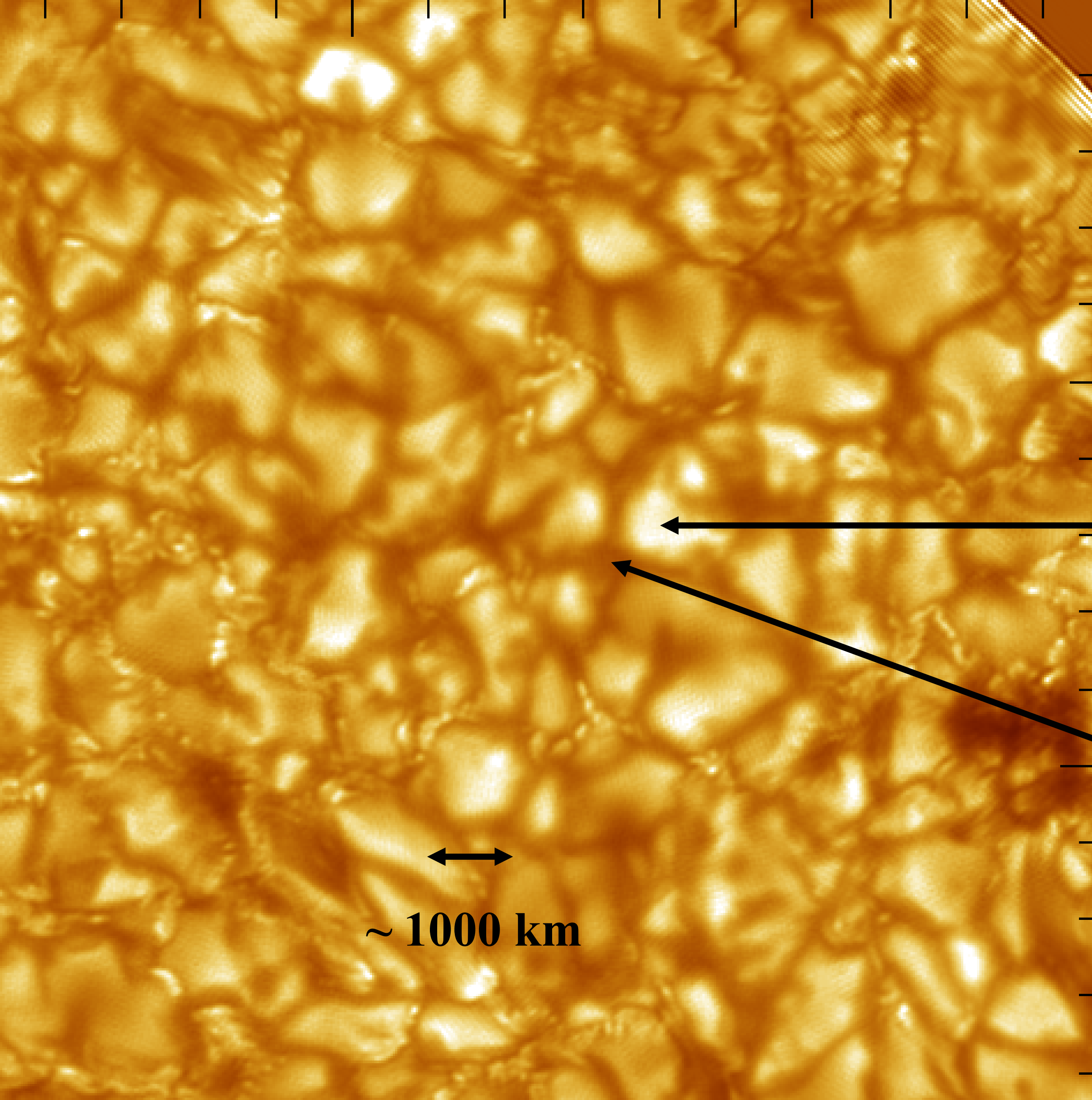
Solar Convection:
What it is &
How to Calculate it.

Bob Stein

The Sun is Dynamic, Convection is the Driver

- ➔ **Transports Energy**
- ➔ **Transports Angular Momentum**
- ➔ **Generates Magnetic Fields by Dynamo**
- ➔ **Excites Acoustic and Magnetic Waves**

The Solar Surface



Convection
(boiling water)

Hot gas rises
(floats up)
-> Brighter

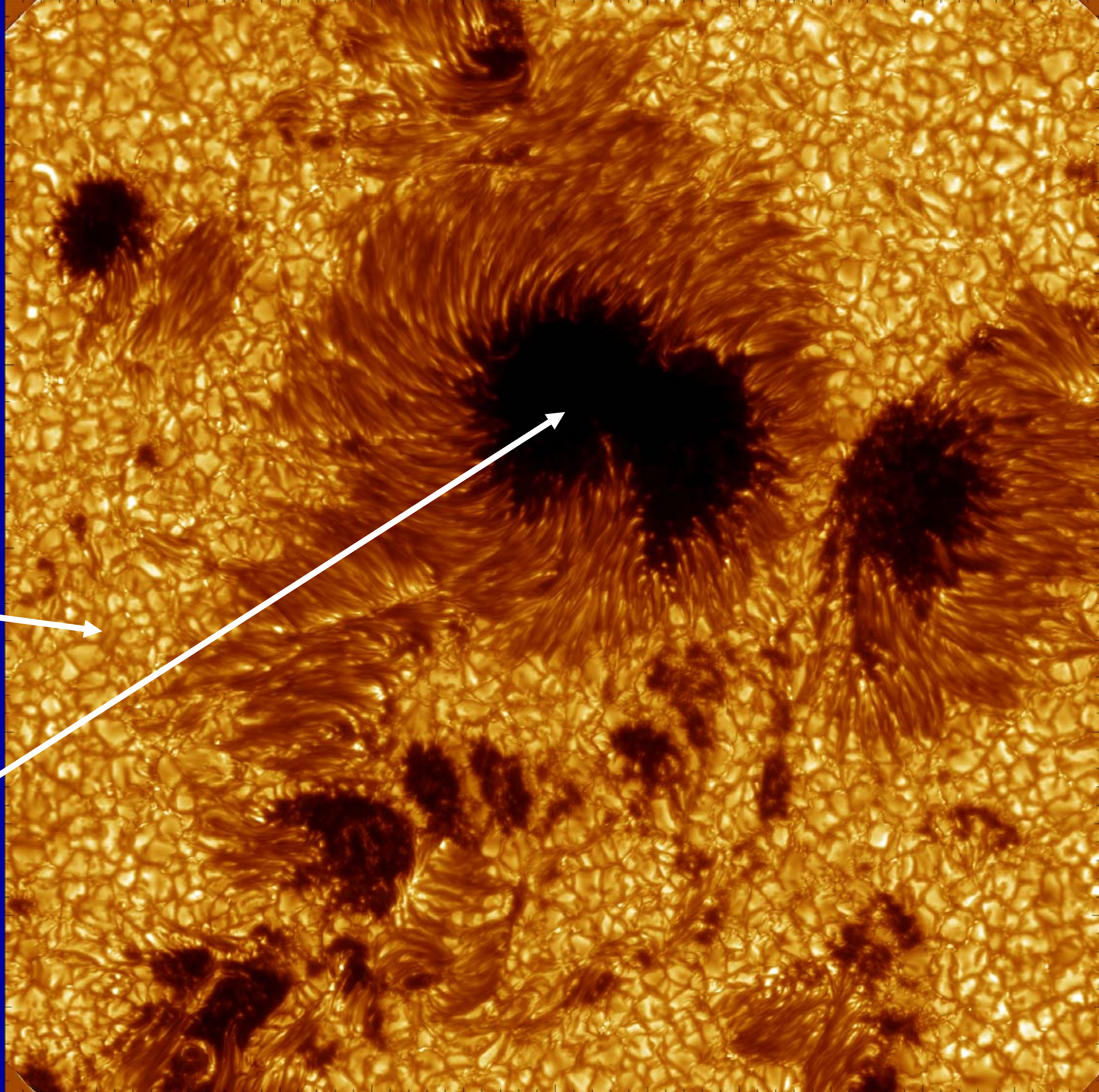
Cool gas sinks
(pulled down
by gravity)
-> Darker

The Solar Surface

10,000 km

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

The Solar Surface



Convection

Sunspots: Magnetic fields, Cooler -> Darker

Observed as Doppler Shift at the solar surface

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Magnetic Field

QuickTime™ and a
Motion JPEG A decompressor
are needed to see this picture.

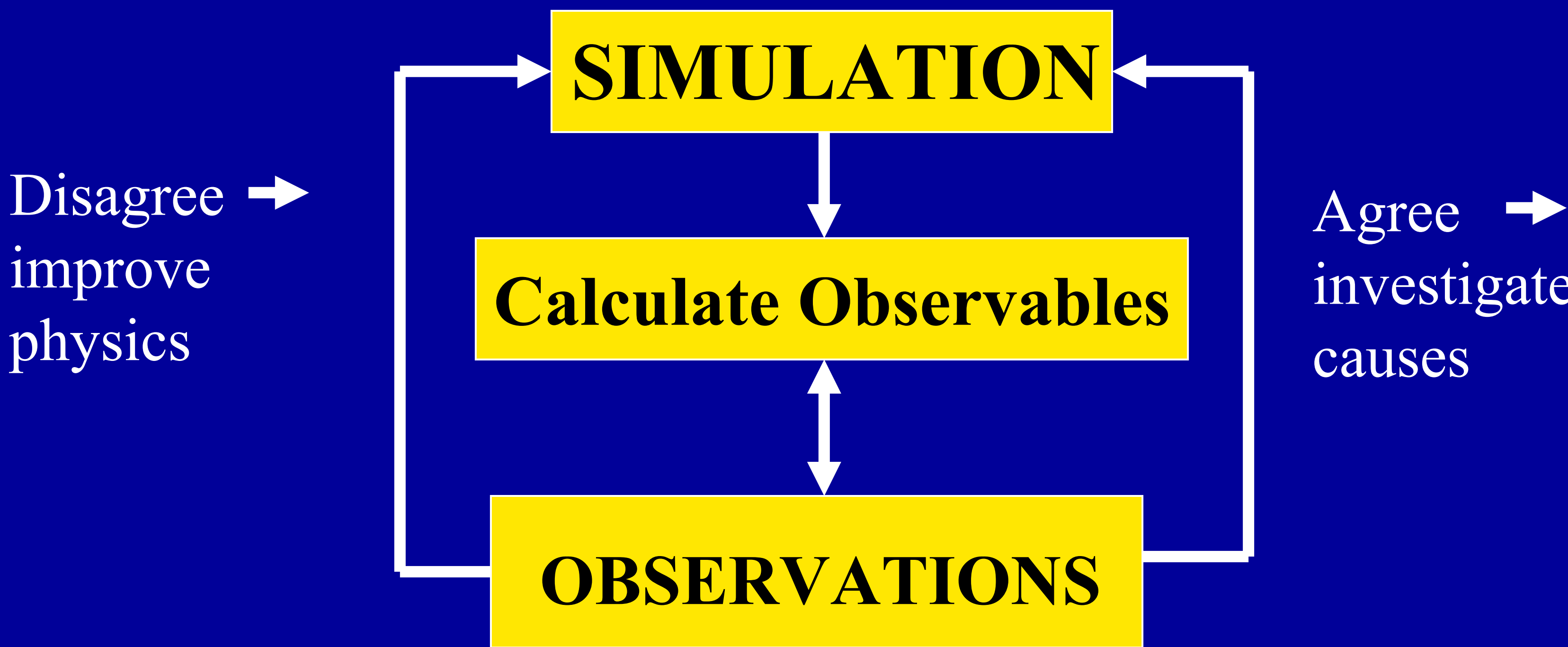
QuickTime™ and a
Video decompressor
are needed to see this picture.

The Sun in X-Rays

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

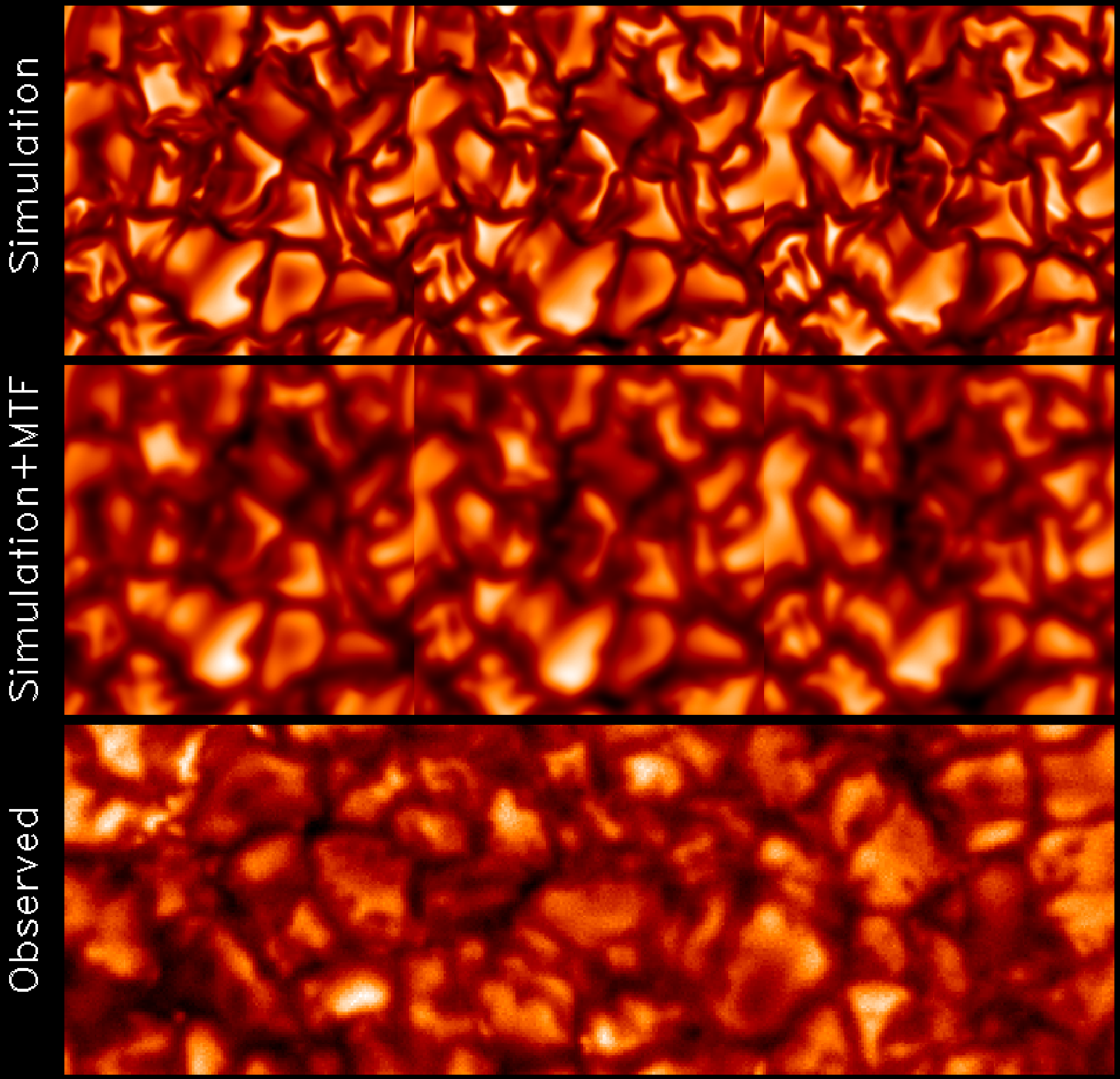
The Solar Wind

Models & Observations



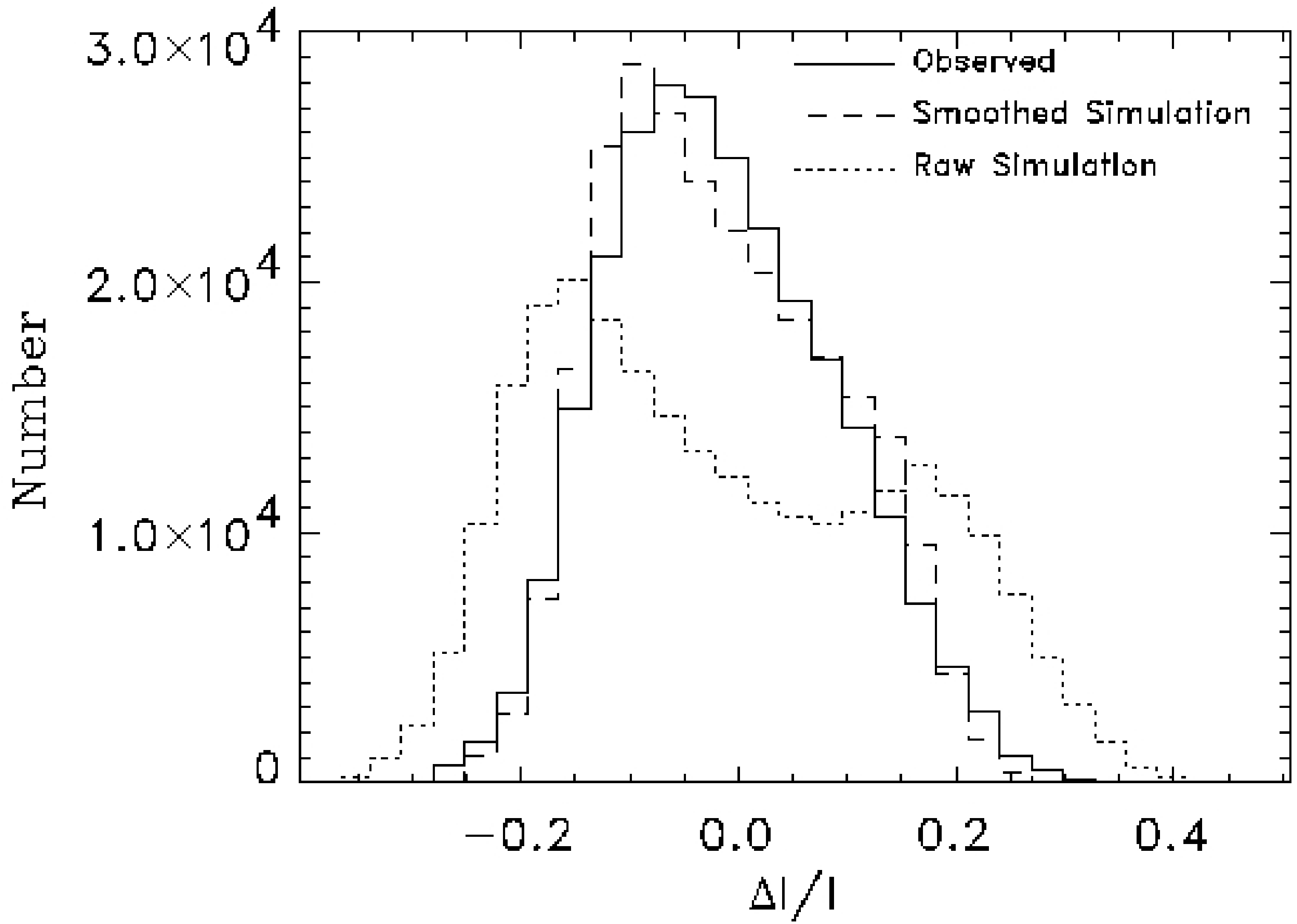
Comparison
Simulations vs. Observations

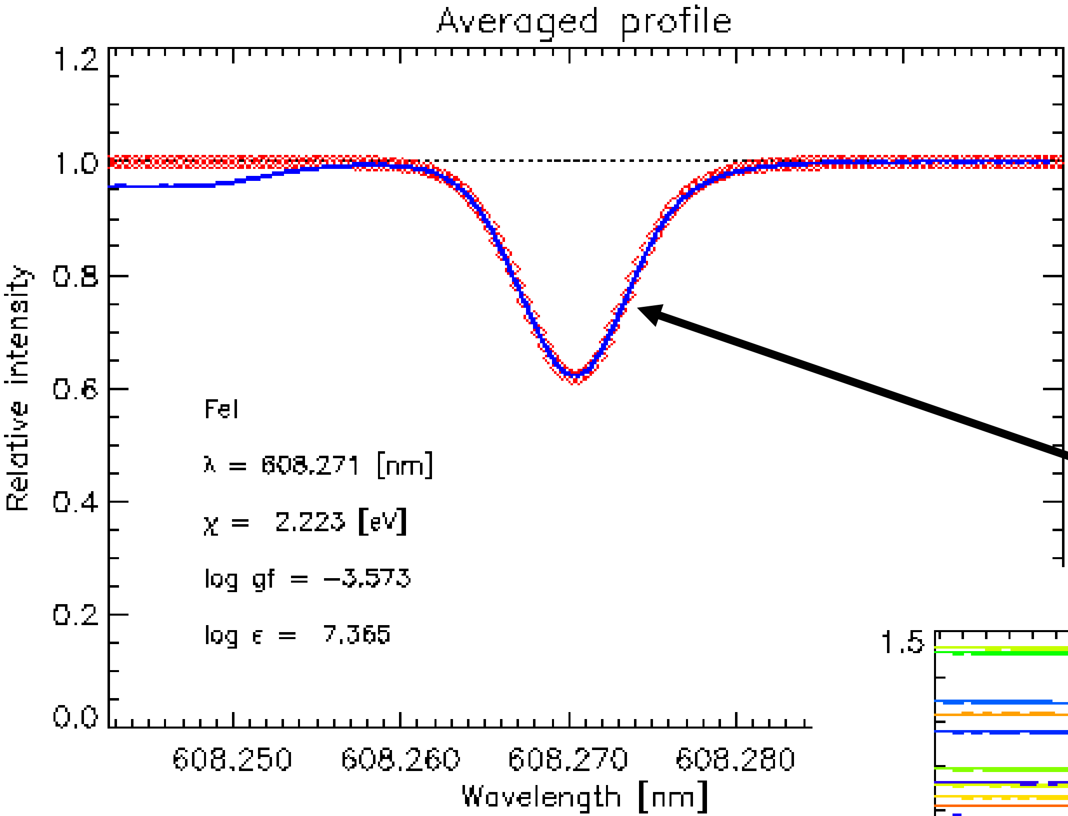
- Images
- Intensity distribution
- Spectrum
- Line profiles
- Magnetic Field distribution
- Resonant Oscillations



Emergent Intensity

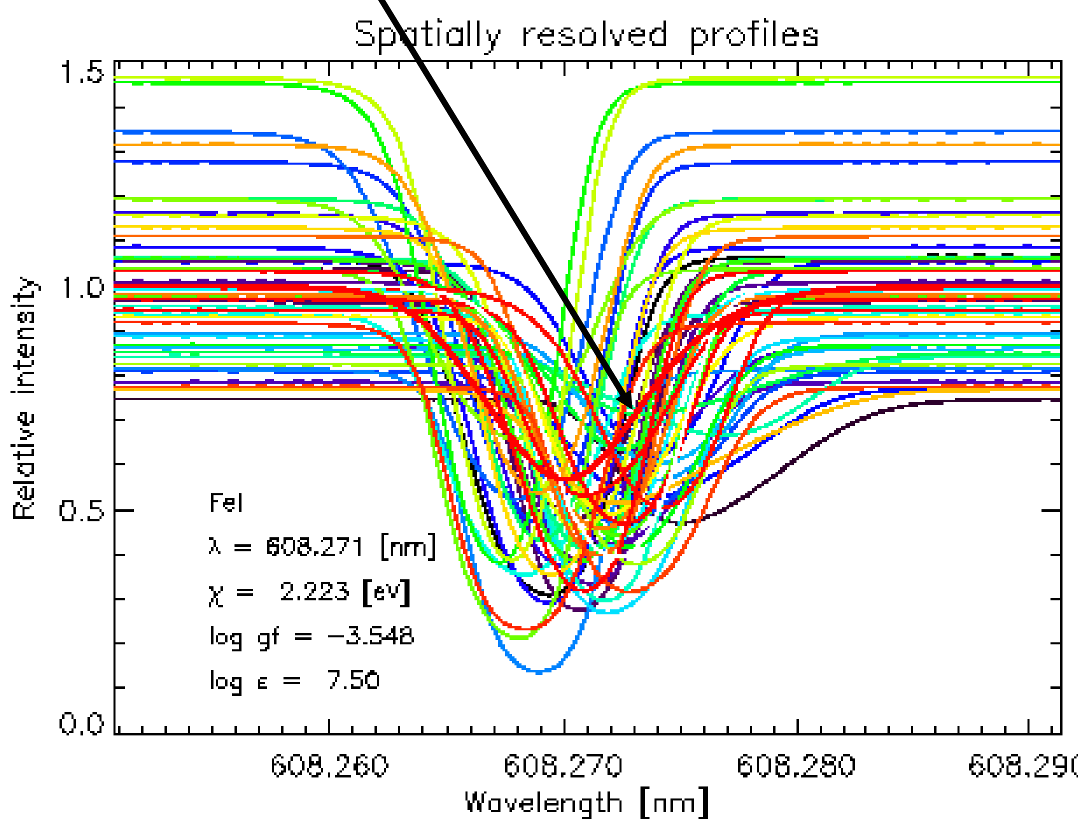
Intensity Histogram





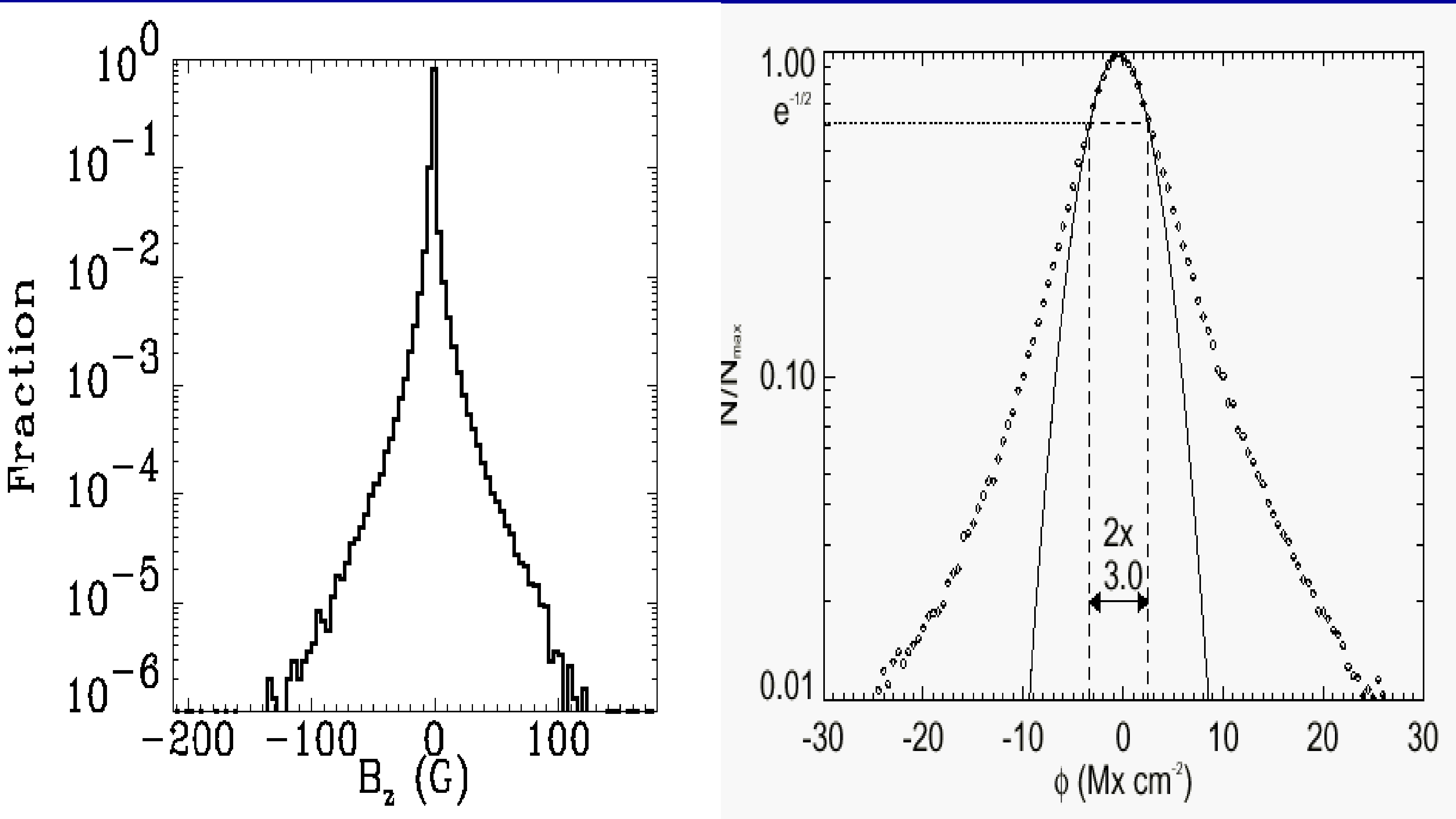
Line Profiles

Average Profile



Iron:
Majority species
Equilibrium populations
Heavy-> small Doppler width
Weak lines

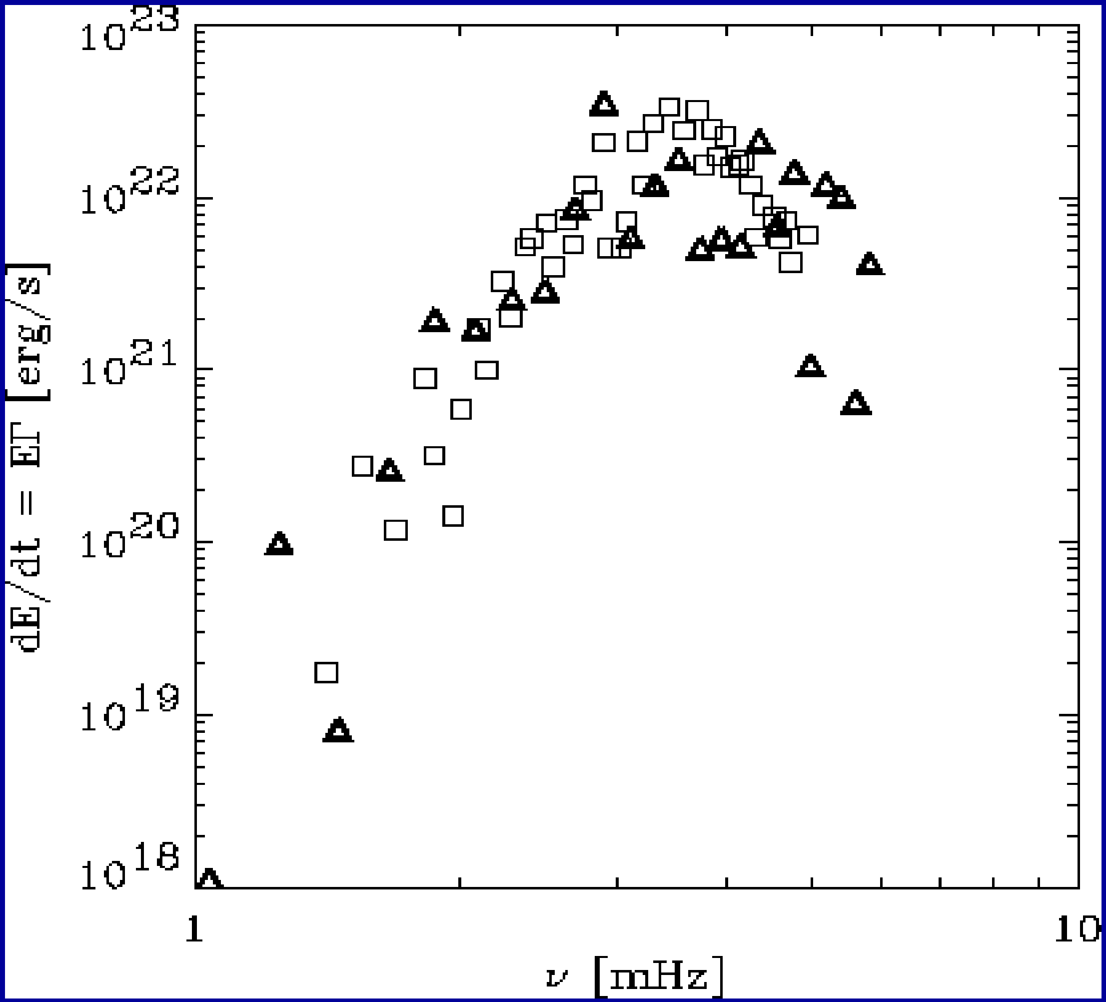
Field Distribution



simulation observed

Both simulated and observed distributions are stretched exponentials.

P-Mode Excitation



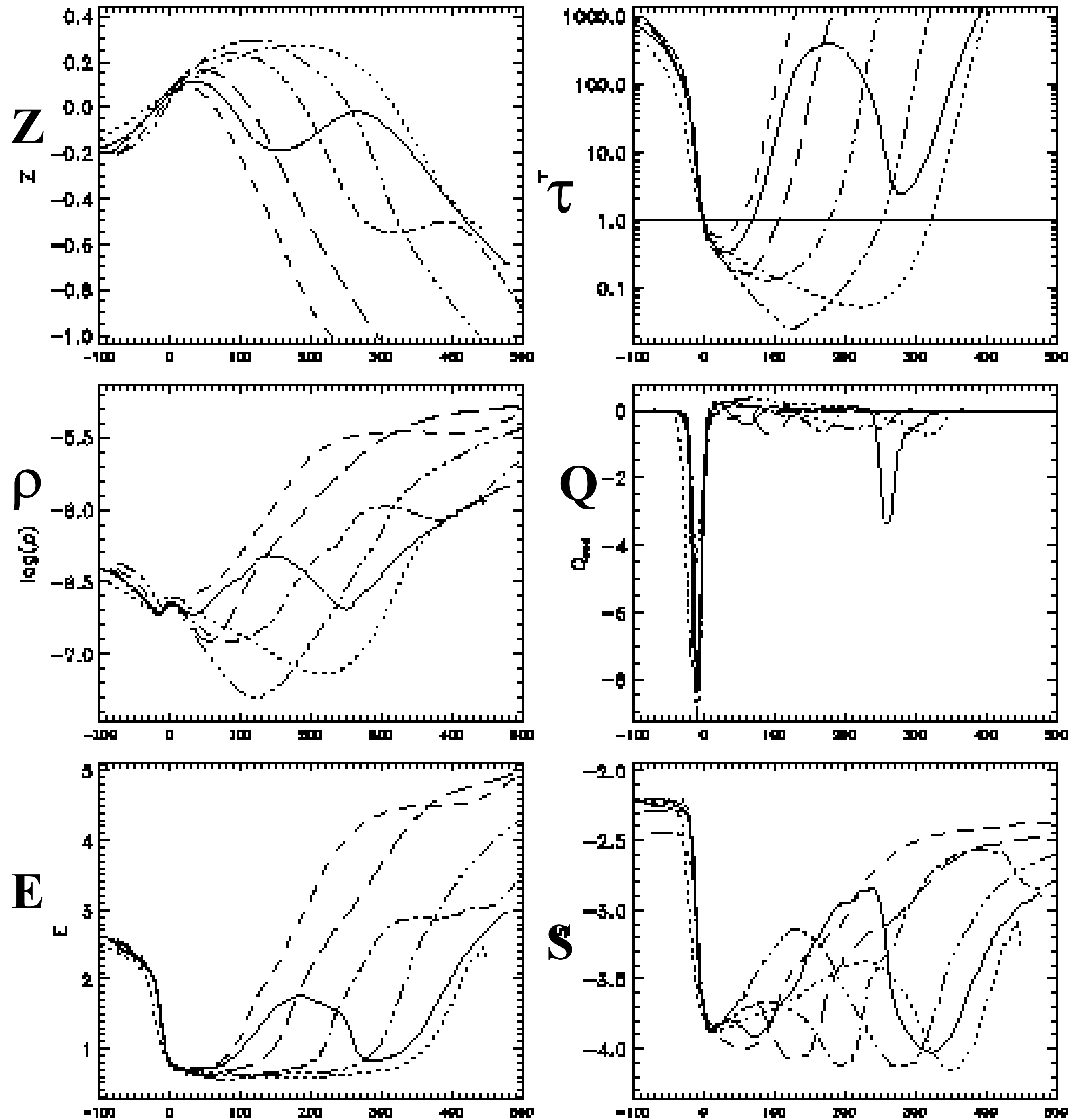
Triangles = simulation, Squares = observations (l=0-3)
Excitation decreases both at low and high frequencies

Causes:

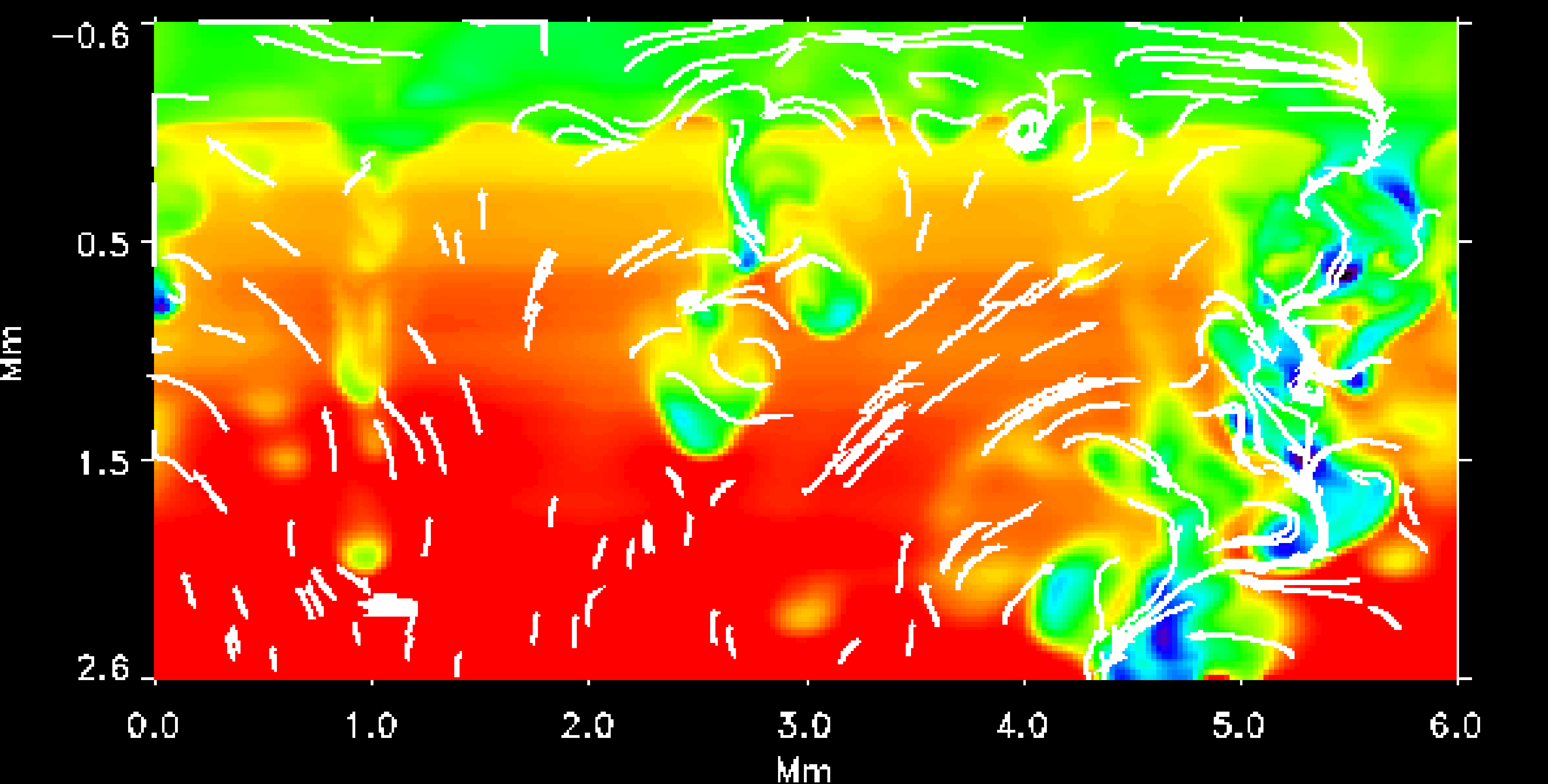
convection

Convection is Driven by Radiative Cooling at Surface:

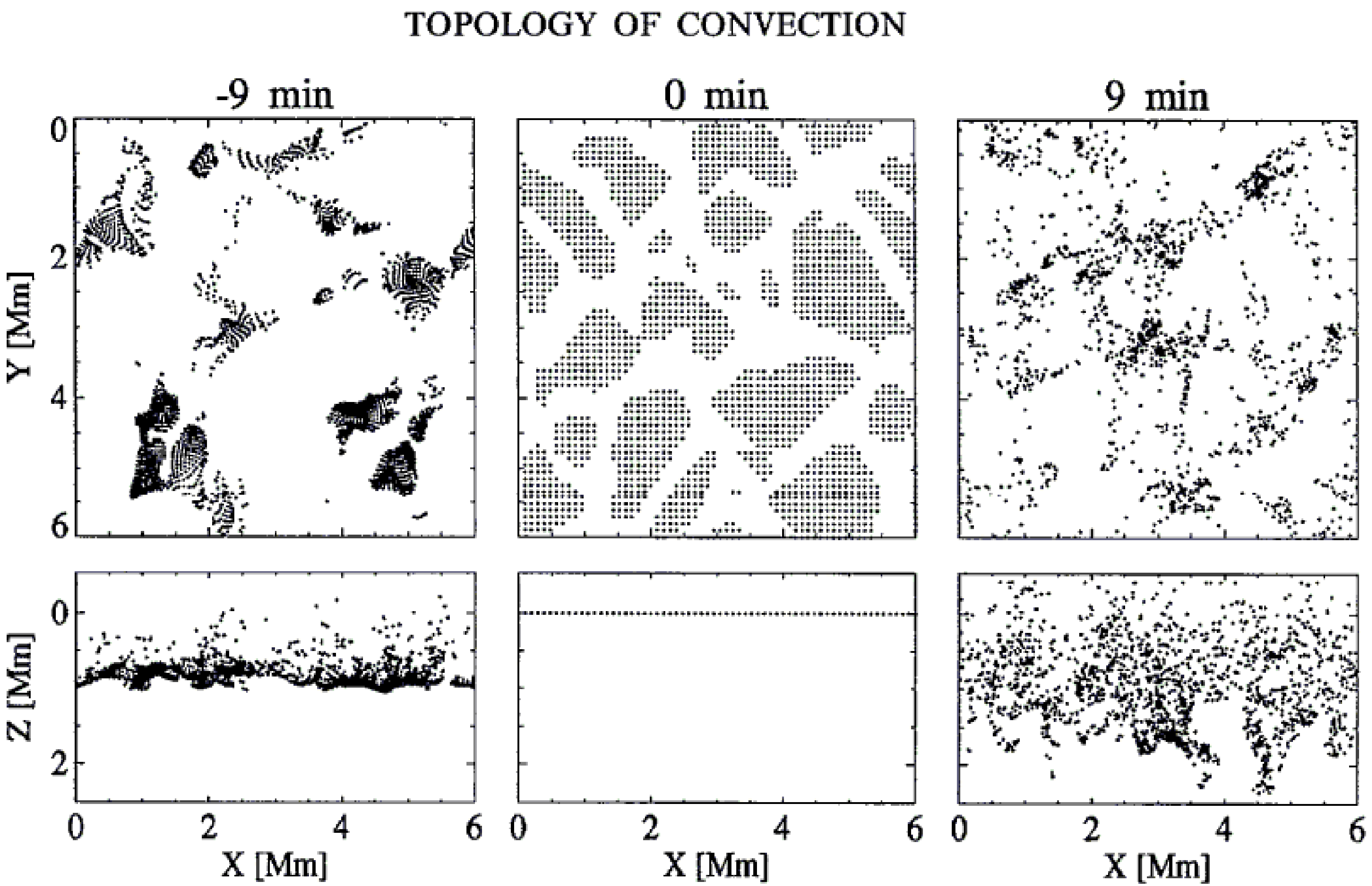
Fluid Radiates away its Energy & Entropy -> Denser -> pulled down by Gravity



Stratified convective flow: diverging upflows, turbulent downflows

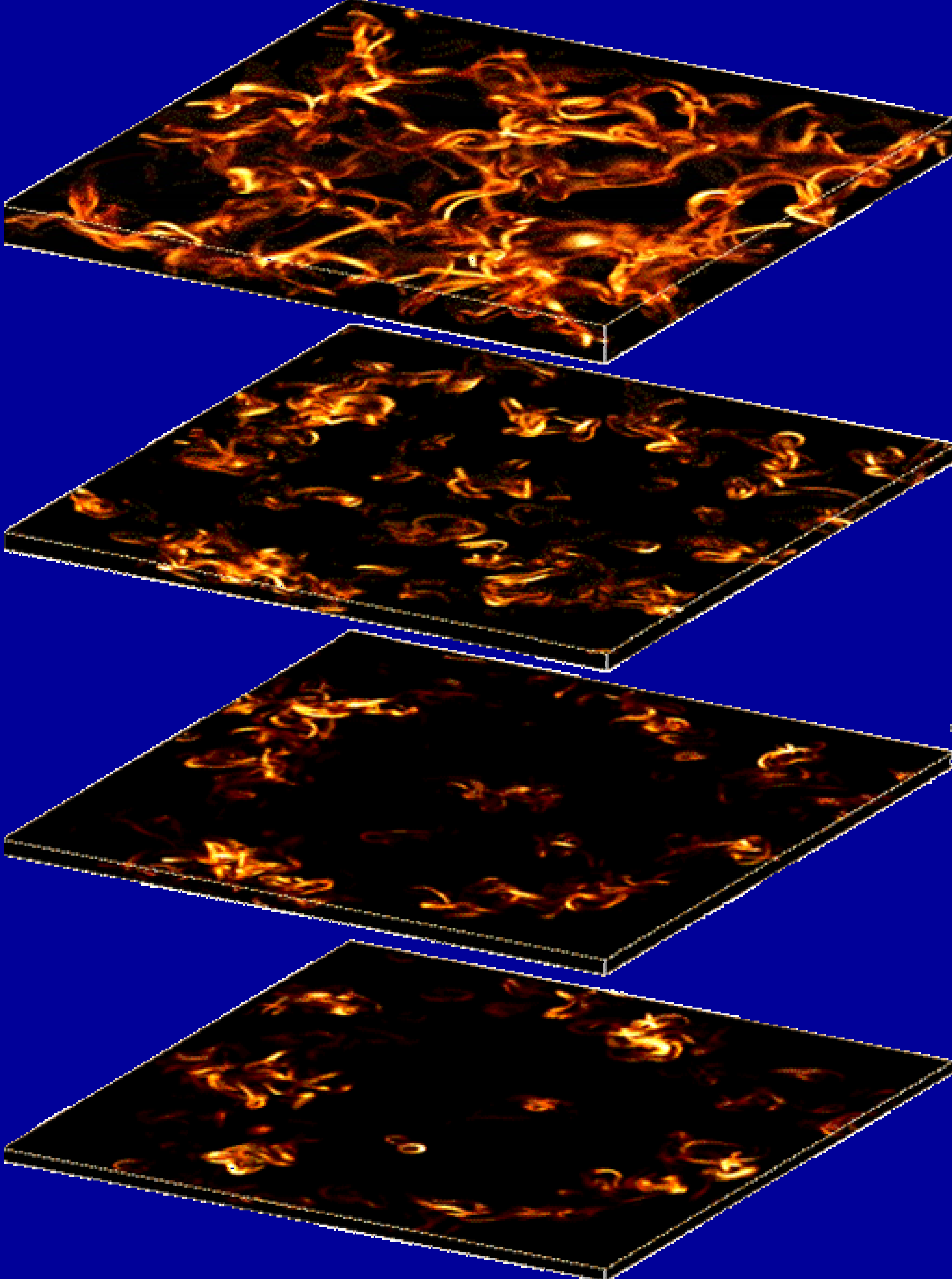


Velocity arrows, temperature fluctuation image (red hot, blue cool)

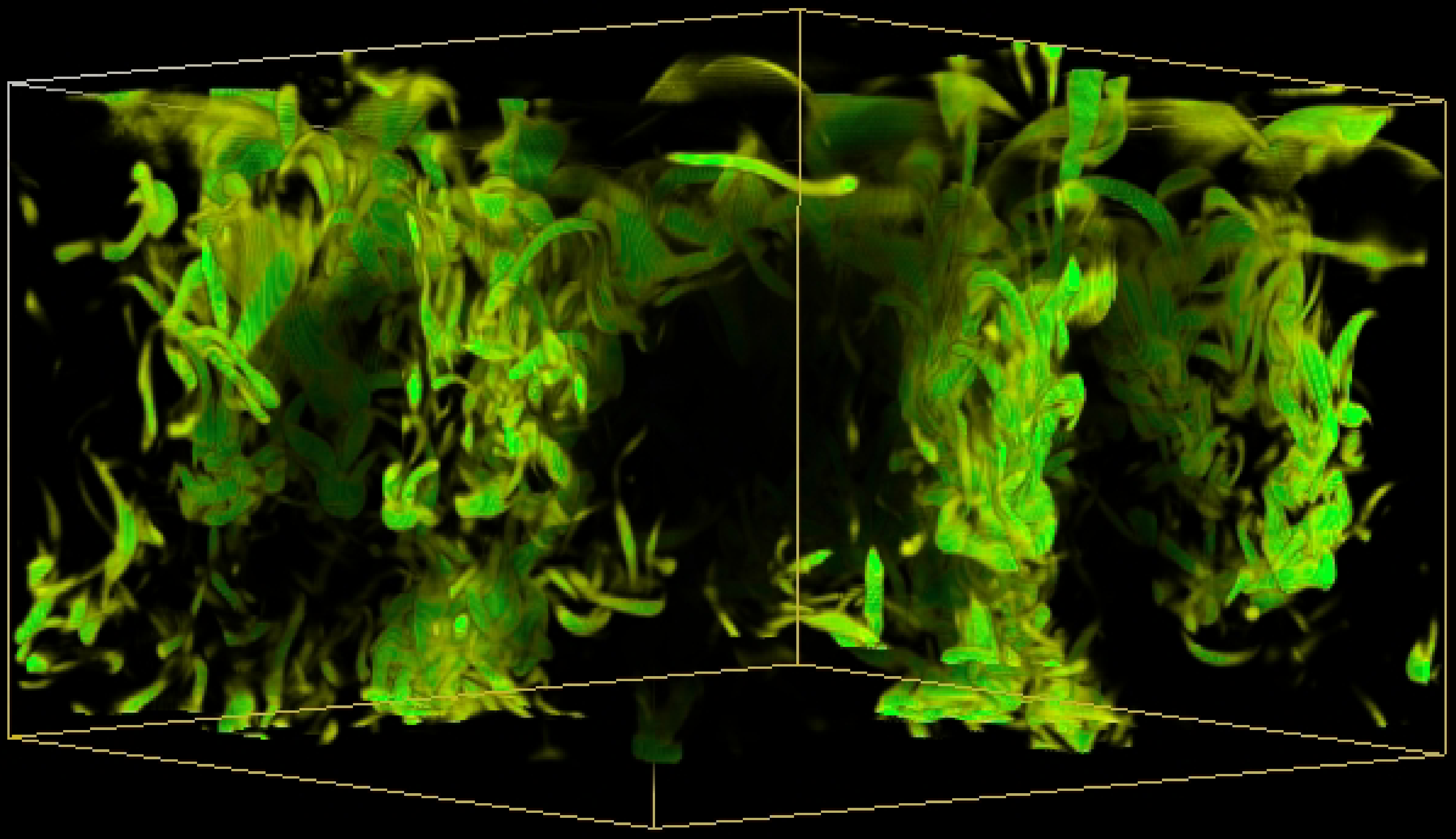


Stein & Nordlund, ApJL 1989

Downflows:
cell size
increases
with depth



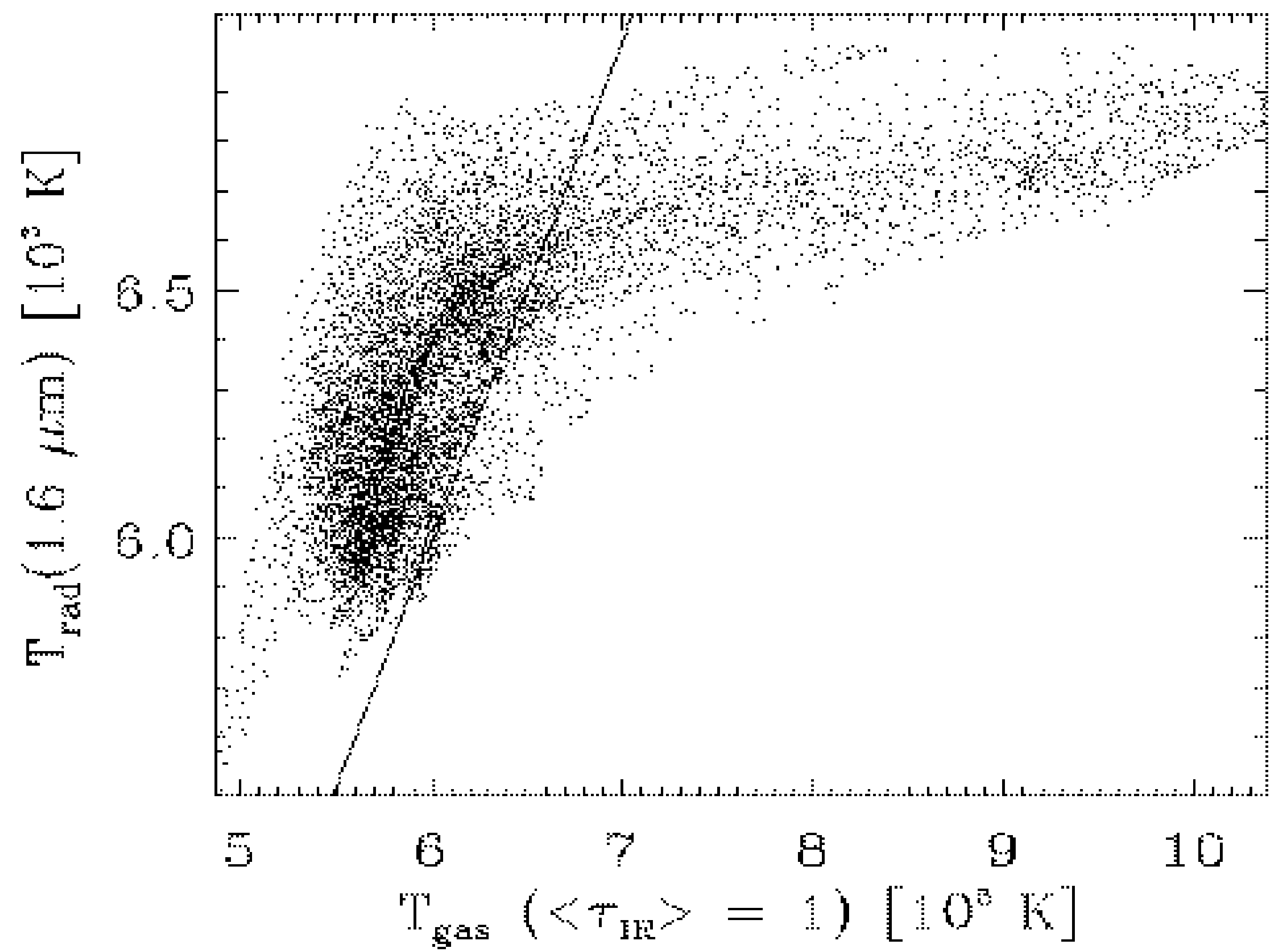
Vorticity: Downdrafts are Turbulent



Turbulent downdraft

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

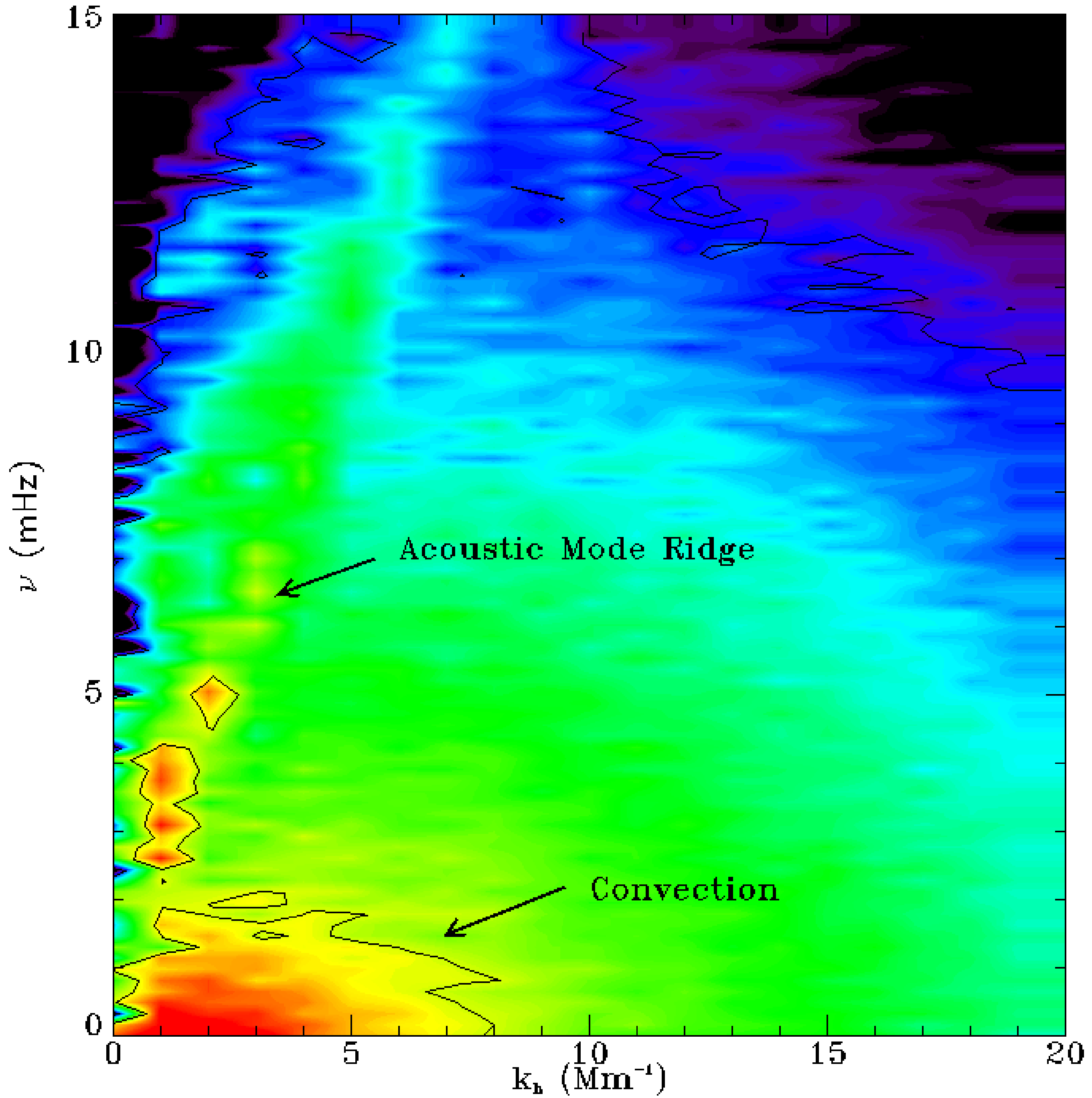
Never See Hot Gas



Causes:

Oscillations

Simulation Modes

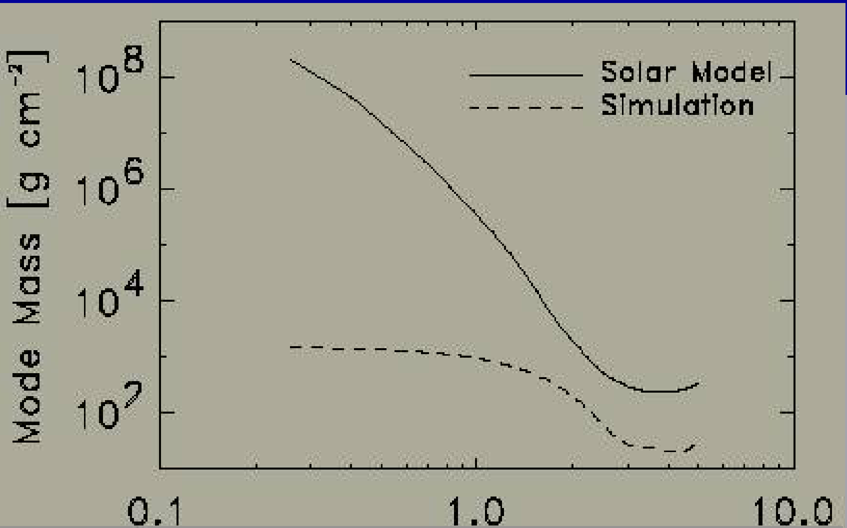


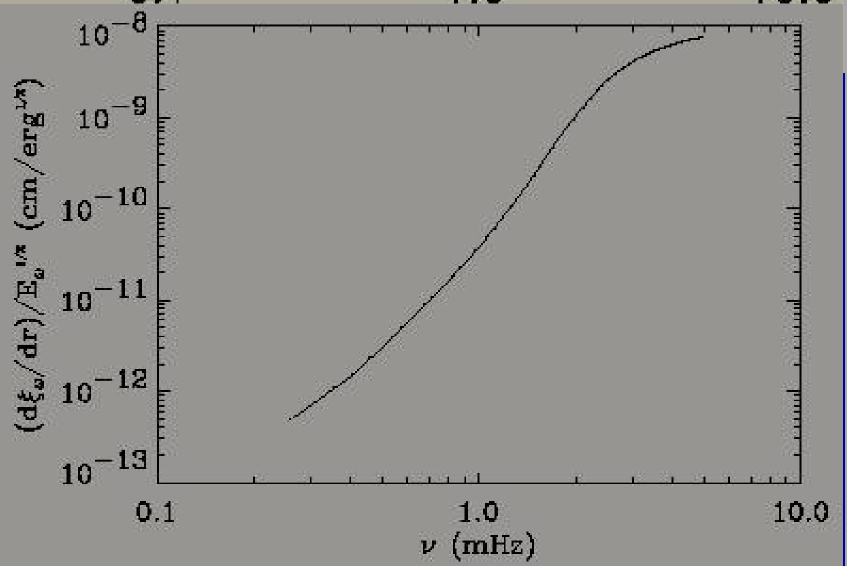
Oscillations Excited by Turbulent Pressure & Entropy Fluctuations

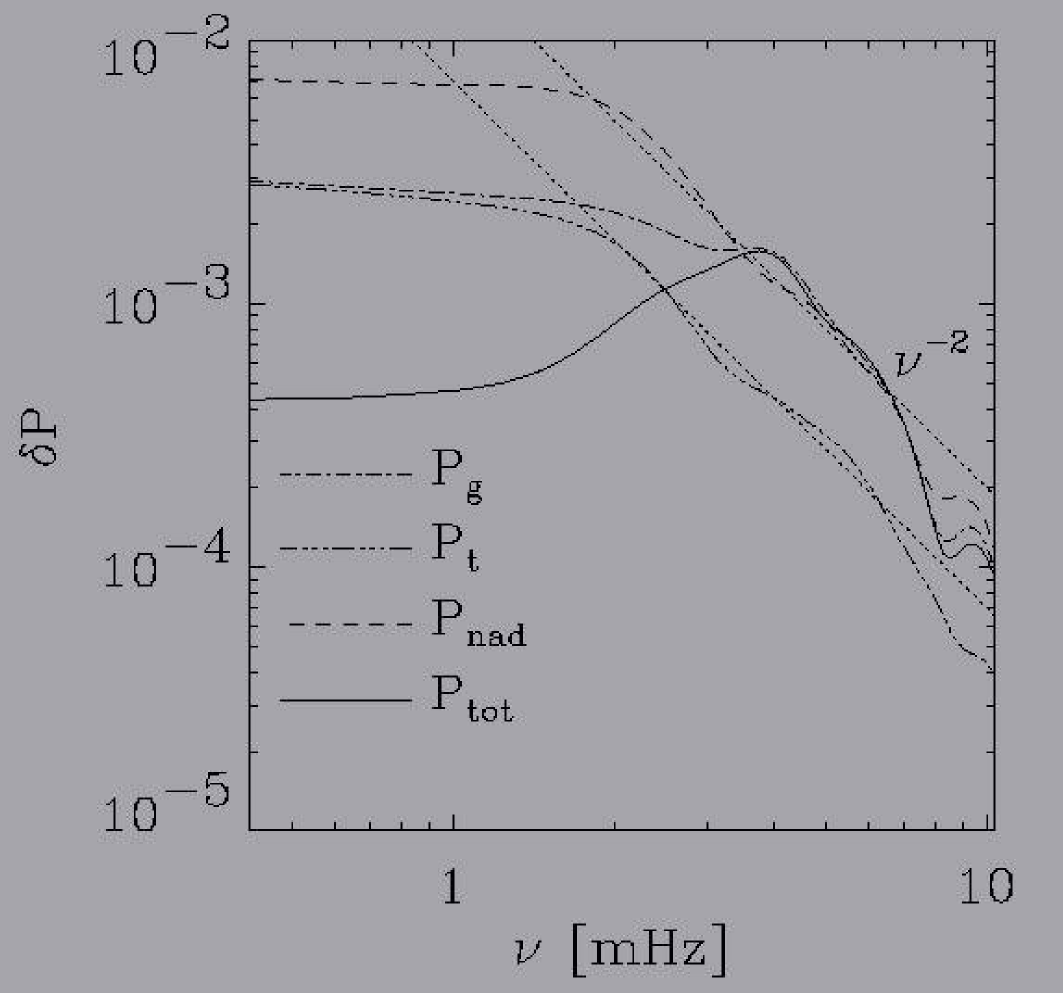
$$\frac{\Delta\langle E_\omega\rangle}{\Delta t} = \frac{\omega^2 \left| \int_r dr\, \delta P_\omega^* \frac{\partial \xi}{\partial r}\right|^2}{8 \Delta \nu E_\omega}$$

Entropy Fluctuations

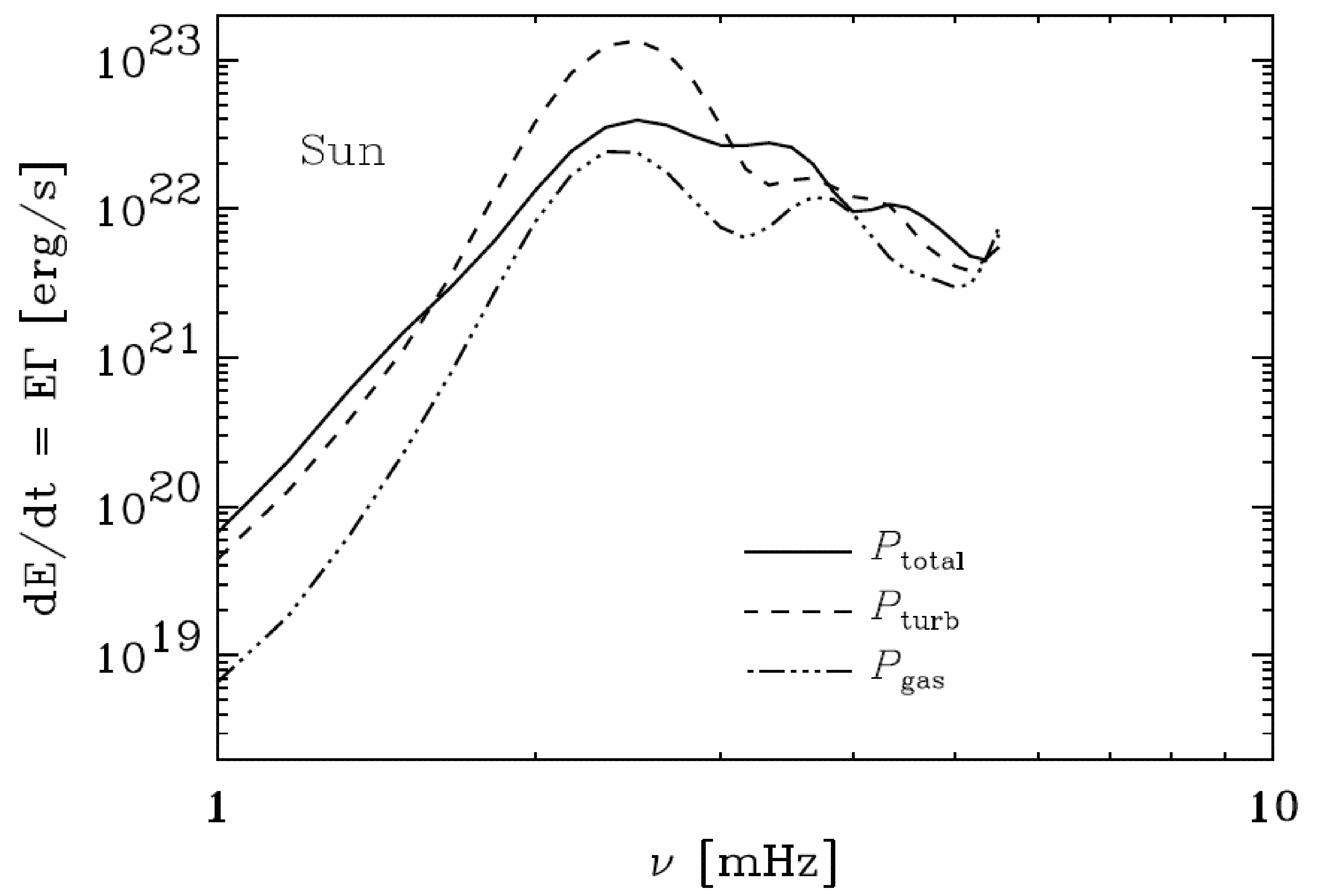
Peak Excitation ~ 5 minutes



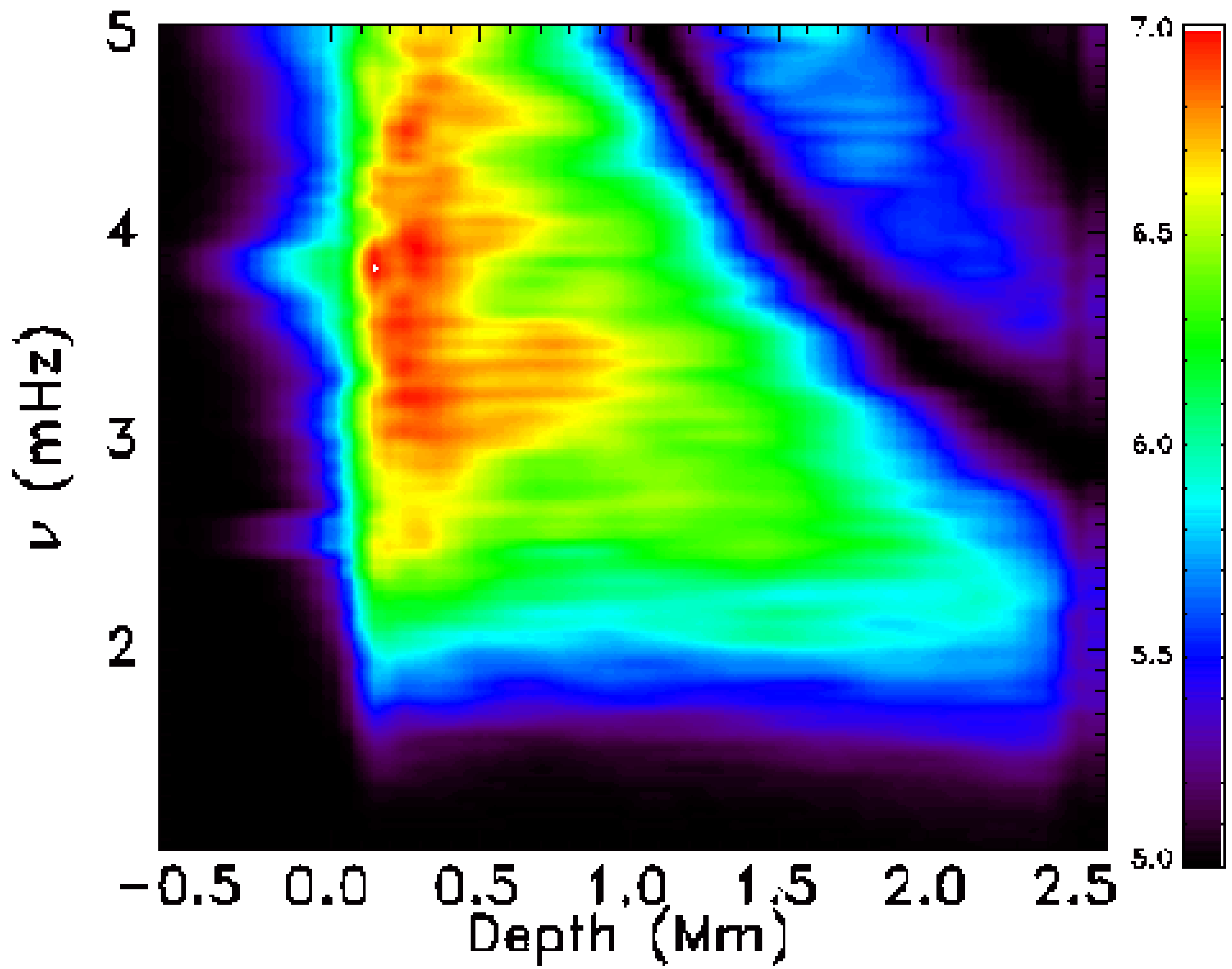




Turbulent Pressure > Entropy Fluctuations



Oscillations Excited close to Surface



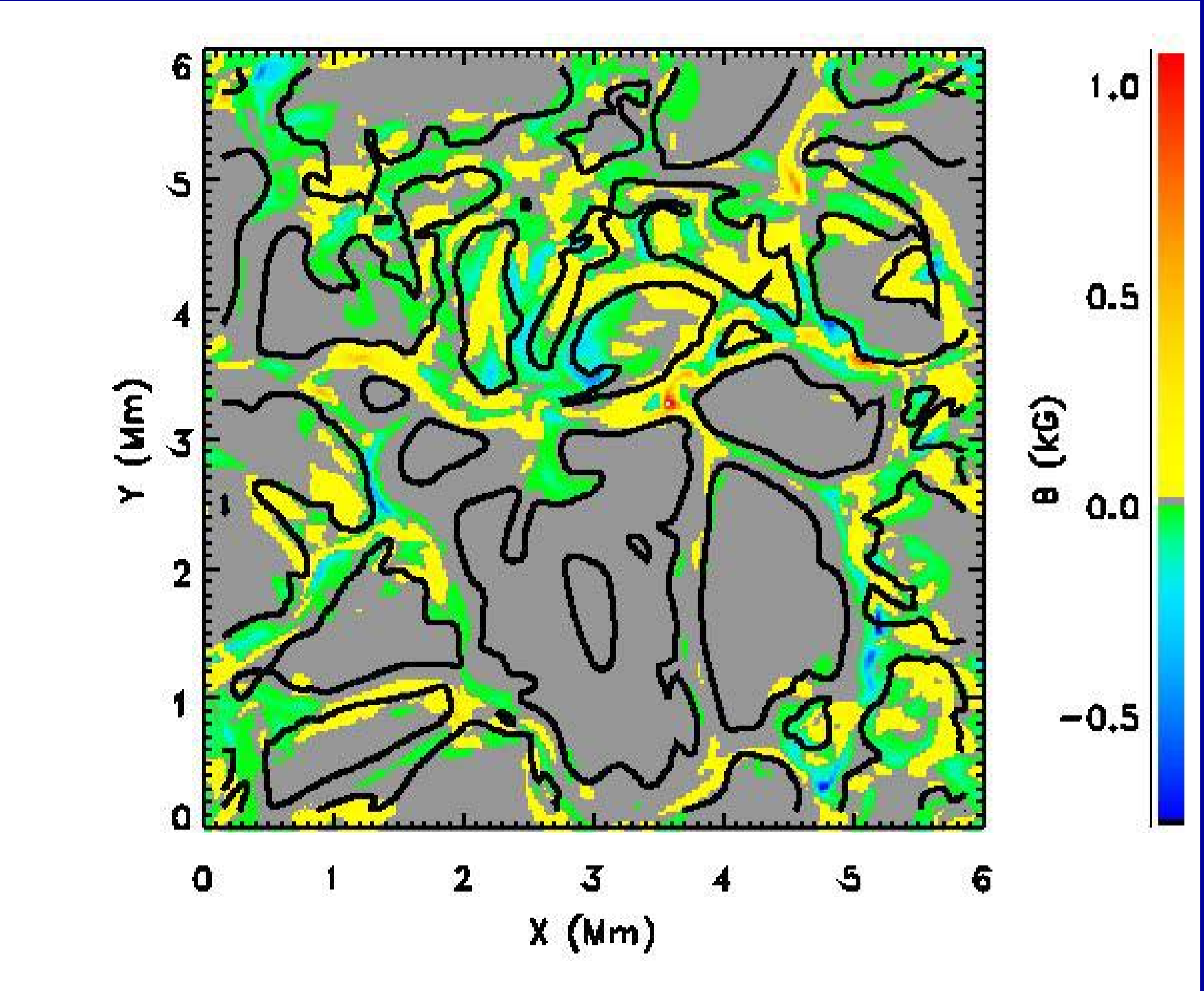
Causes:

Magnetic Field

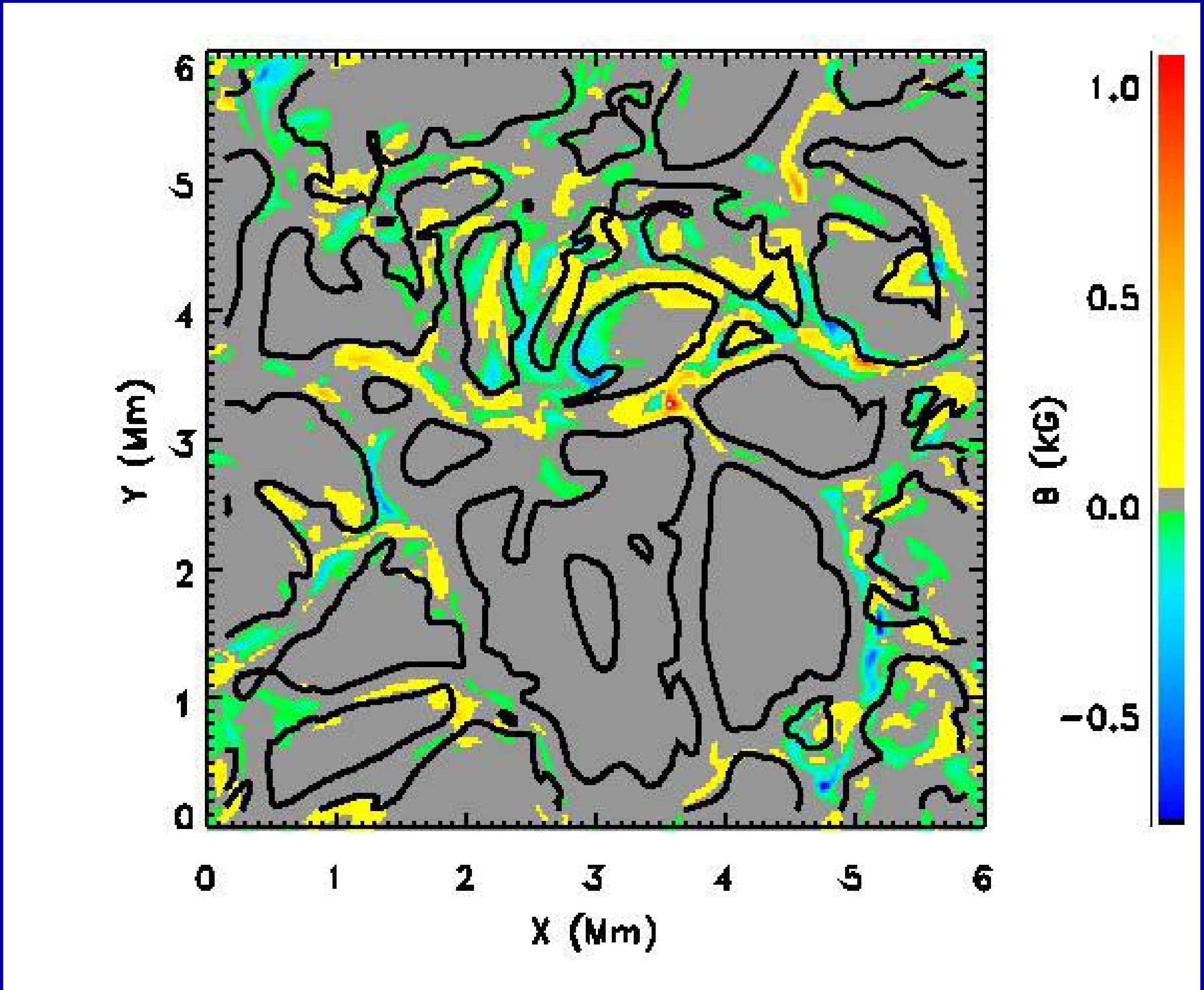
Magnetic Field Reorganization

QuickTime™ and a
decompressor
are needed to see this picture.

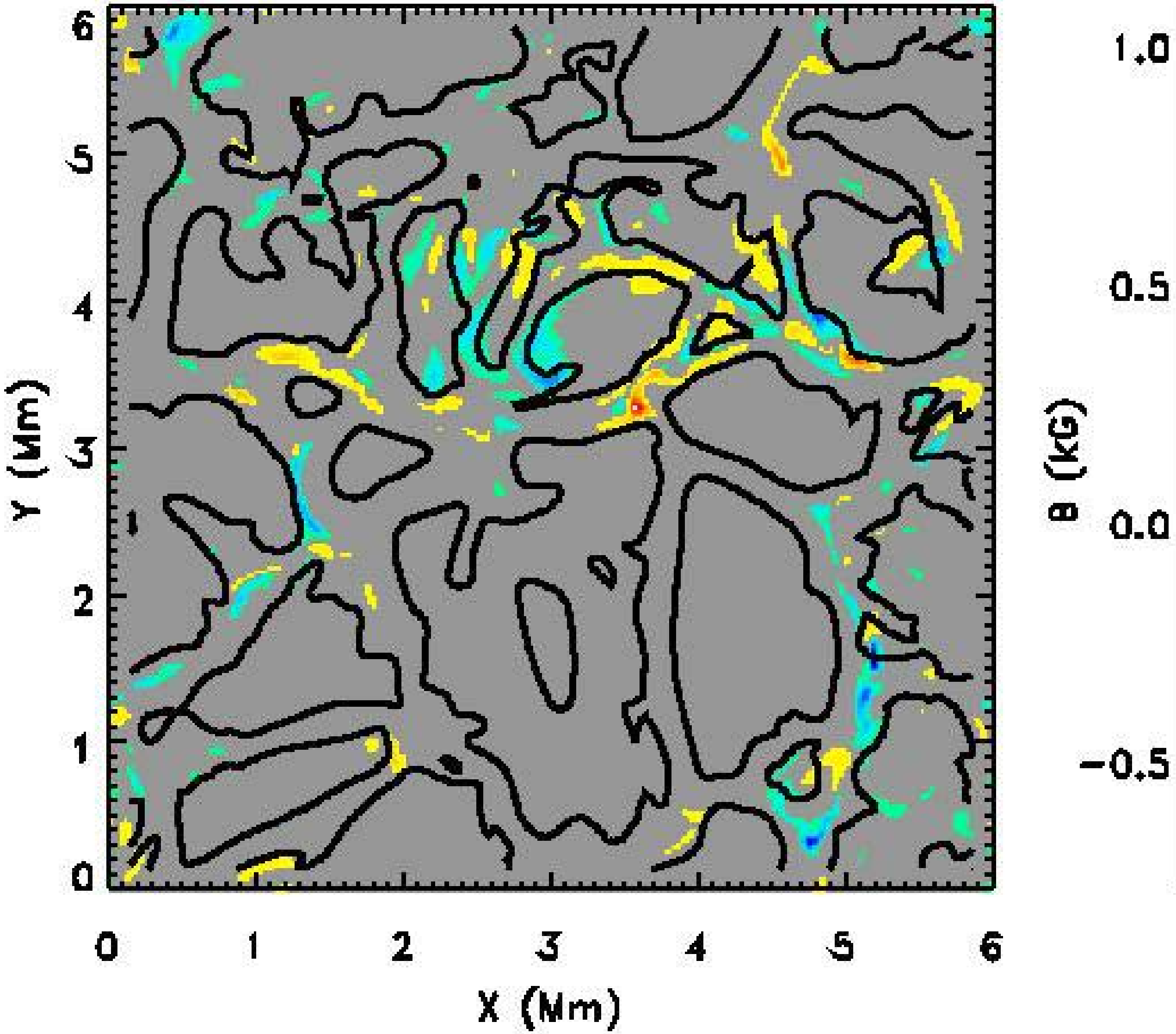
Exponential Distribution



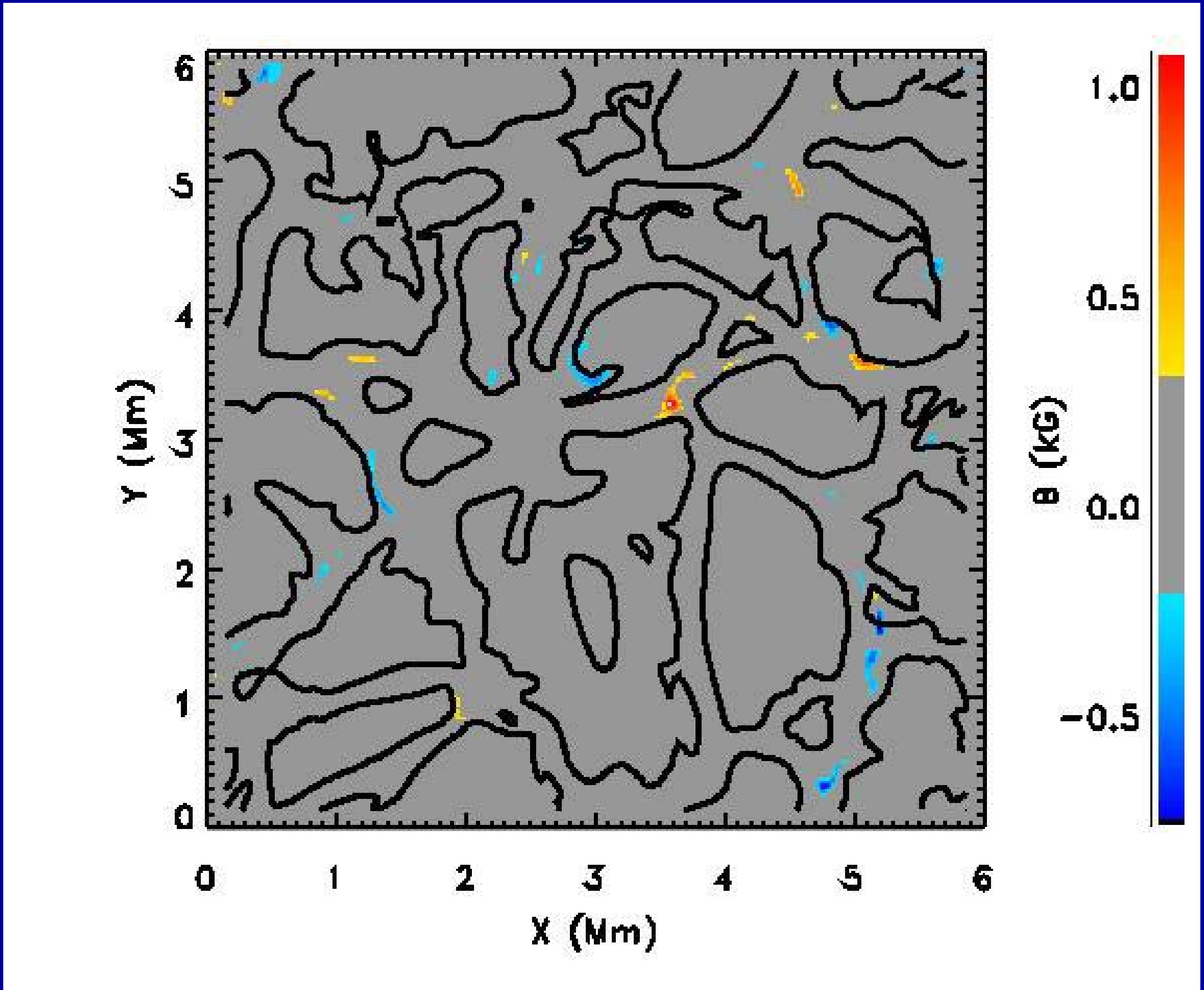
Exponential Distribution



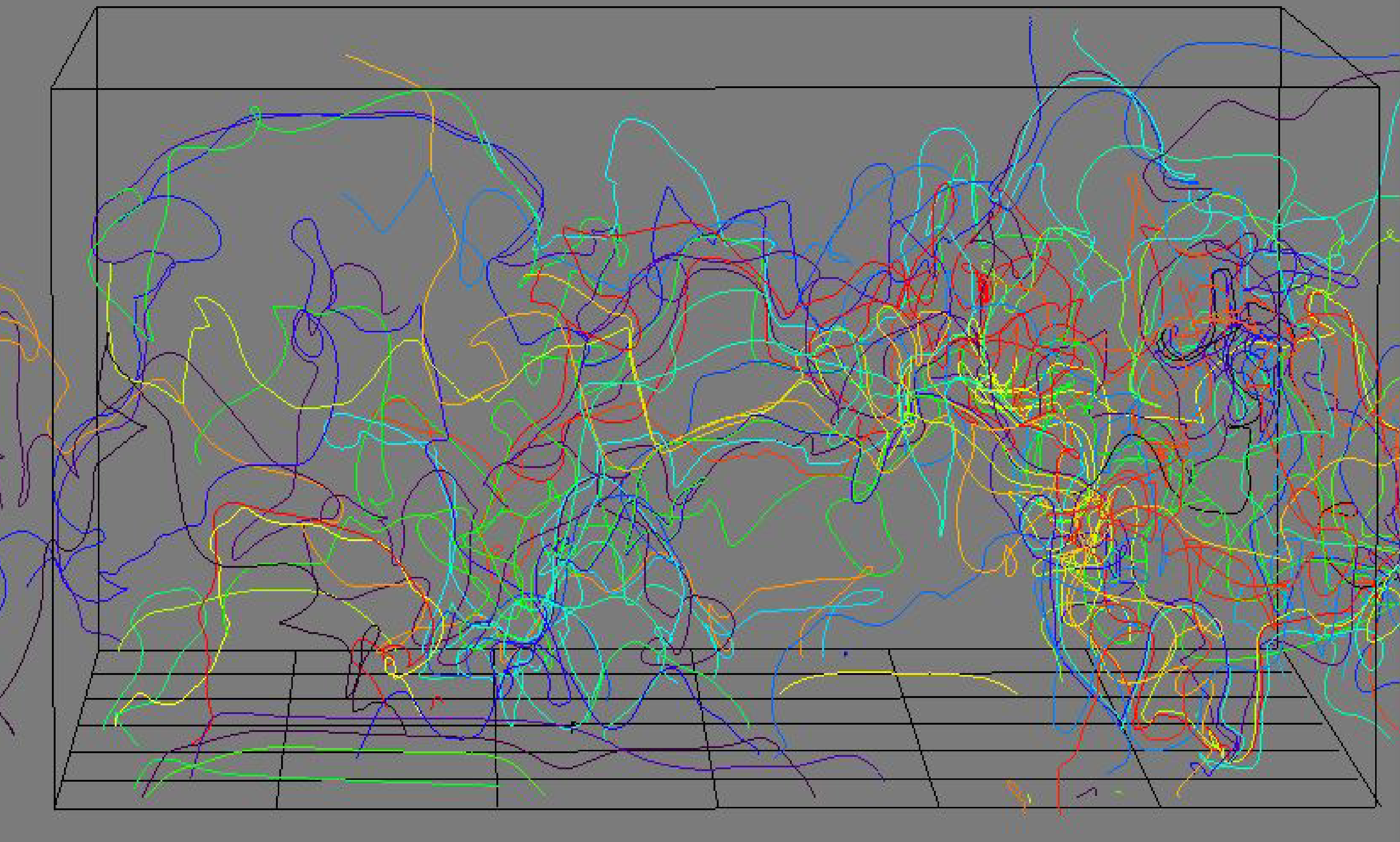
Exponential Distribution



Exponential Distribution



Magnetic Field Lines



Methodology

Equations:

Conservation of Mass

$$\frac{\partial \rho}{\partial t} = \nabla \bullet (\rho \vec{u})$$

Conservation of Momentum

$$\frac{\partial \rho \vec{u}}{\partial t} = \nabla \bullet \vec{\vec{T}} + \rho \vec{g} + \vec{J} \times \vec{B}$$

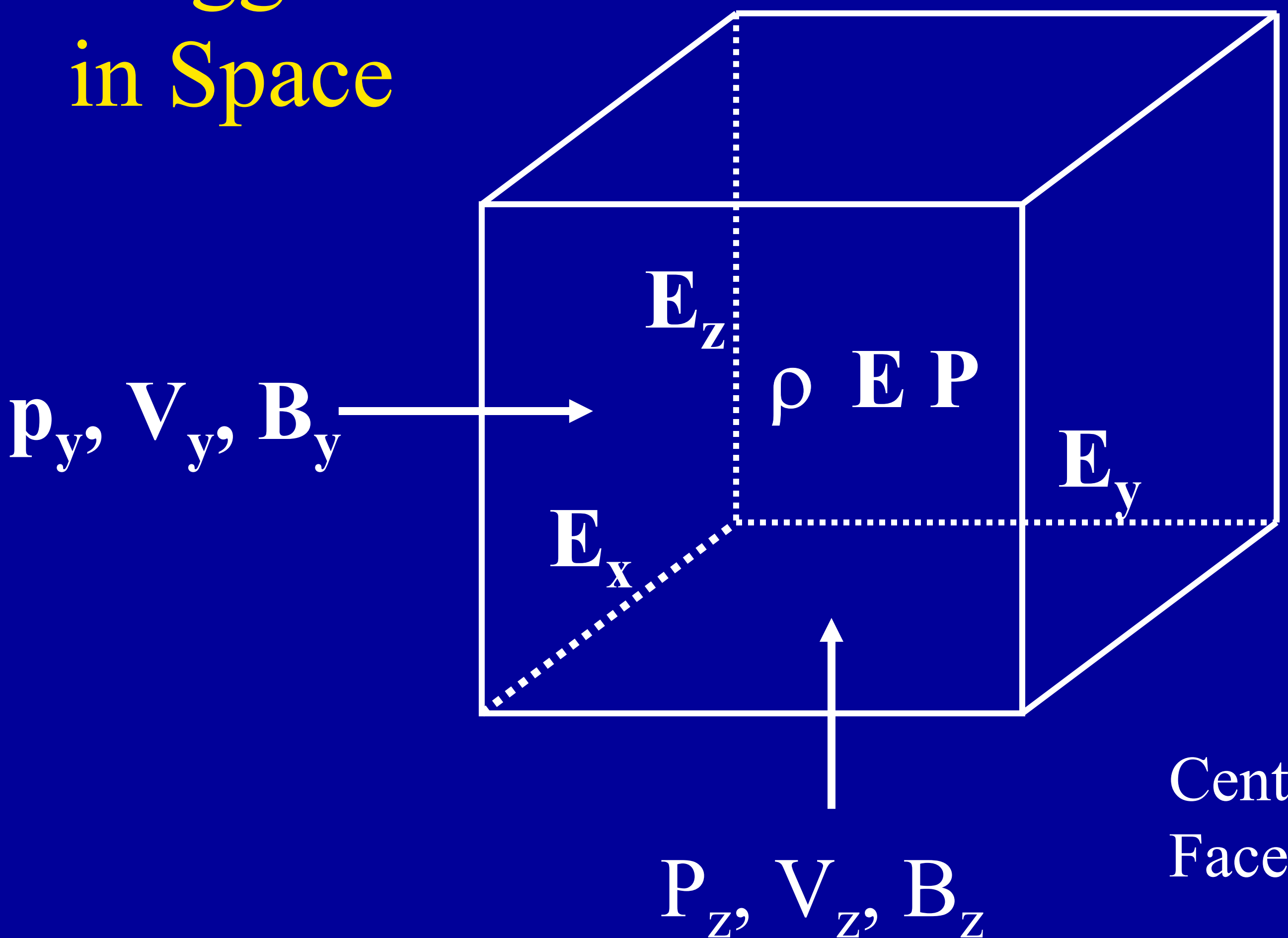
Conservation of Energy

$$\frac{\partial e}{\partial t} = \nabla \bullet (\rho \vec{u} e) - \vec{\vec{T}} \bullet \vec{\vec{S}} + Q_{rad}$$

Induction

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} = \nabla \times (\vec{u} \times \vec{B} - \eta \vec{J})$$

Variables Staggered in Space



Center: i,j,k
Faces: i-1/2,j-1/2,k-1/2

Spatial Derivatives: 6^th order Finite Difference

$$\left(\frac{\partial f}{\partial x}\right)_{j-1/2} = a\left(f - f_{j-1}\right) + b\left(f_{j+1} - f_{j-2}\right) + c\left(f_{j+2} - f_{j-3}\right)$$

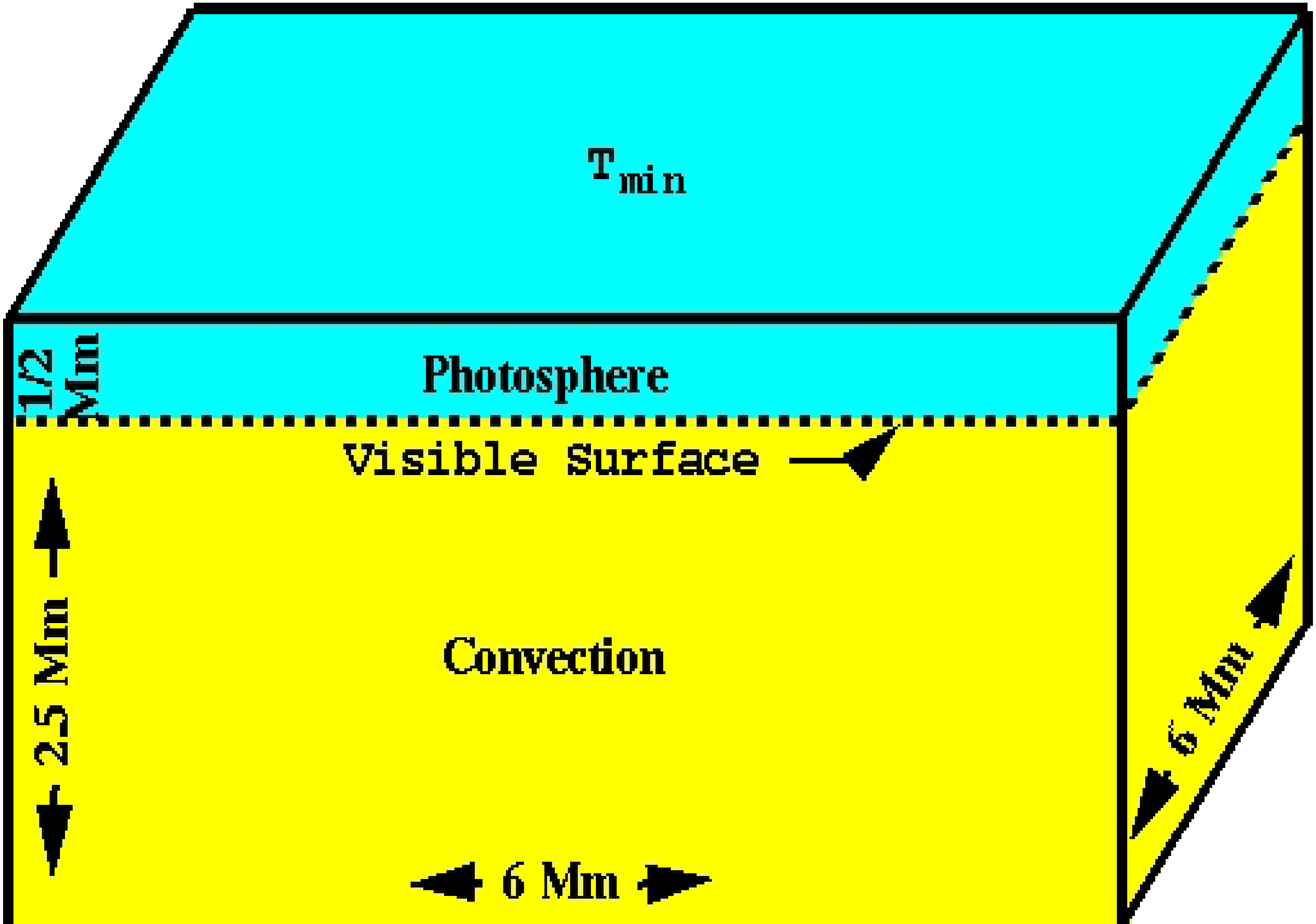
Time Advance: 3rd order Runge-Kutta

$$\left(\frac{\partial f}{\partial t}\right)^{n} = \alpha_n \left(\frac{\partial f}{\partial t}\right)^{n-1} + \left(\frac{\partial f}{\partial t}\right)^{n}$$

$$f^{n} = f^{n-1} + \beta_n \Delta t \left(\frac{\partial f}{\partial t}\right)^{n}$$

n=1-3

Computational Domain



Characteristic Boundary Conditions

Unique Conservative Equations

$$\frac{\partial \overrightarrow{U'}}{\partial t} + \sum_{k=1}^{m} \frac{\partial \overrightarrow{F^k}}{\partial x^k} = \overrightarrow{D'}$$

Non-unique Wave-like Equations

$$\frac{\partial \overrightarrow{U}}{\partial t} + \sum_{k=1}^{m} \overrightarrow{A^k} \frac{\partial \overrightarrow{U}}{\partial x_k} = \overrightarrow{D}$$

Characteristic Equations

$$\vec{\ell}_i^{\,T} \bullet \left(\frac{\partial}{\partial t} + \lambda_i \frac{\partial}{\partial x_1} \right) \vec{U} = \vec{\ell}_i^{\,T} \left(-\sum_{k=2}^{m} \vec{A}^k \frac{\partial \vec{U}}{\partial x_k} + \vec{D} \right)$$

Characteristic Boundary Conditions

Boundary Conditions on OUTGOING characteristics is the Characteristic Equations evaluated using one-sided derivatives

$$\vec{\ell}_i^{\,T} \frac{\partial \vec{U}}{\partial t} = \vec{\ell}_i^{\,T} \bullet \left(-\lambda_i \frac{\partial \vec{U}}{\partial x_1} - \sum_{k=2}^{m} \vec{A}^k \frac{\partial \vec{U}}{\partial x_k} + \vec{D} \right)$$

For INCOMING characteristics the normal derivatives in the characteristic directions must be evaluated using the physics boundary conditions.

$$d_i = \lambda_i \vec{\ell}_i^{\,T} \frac{\partial \vec{U}}{\partial x_1}$$

For (non-magnetic) Gas

$$d_{1,5} = (u_x \mp c)\left(\frac{\partial P}{\partial x} \mp \rho c \frac{\partial u_x}{\partial x}\right)$$

$$d_2 = u_x\left(c^2 \frac{\partial \rho}{\partial x} - \frac{\partial P}{\partial x}\right)$$

$$d_{3,4} = u_x \frac{\partial \overrightarrow{u_H}}{\partial x}$$

The End