The different spatio-temporal scales of the solar magnetism

Consorzio Interuniversitario per la Fisica Spaziale

International School of Space Science

L'AQUILA - ITALY

IL MIO VOLER CERCAR OLTRE LA META

SURFACE PROCESSES I

- Convection theory
  - Rayleigh Number
  - Schwarzschild-Ledoux Criterion
  - Rayleigh-Benard Convection
  - Mixing length
- Solar Convection:
  - Observations
  - Simulations

SOLAR PHYSICS UTOV

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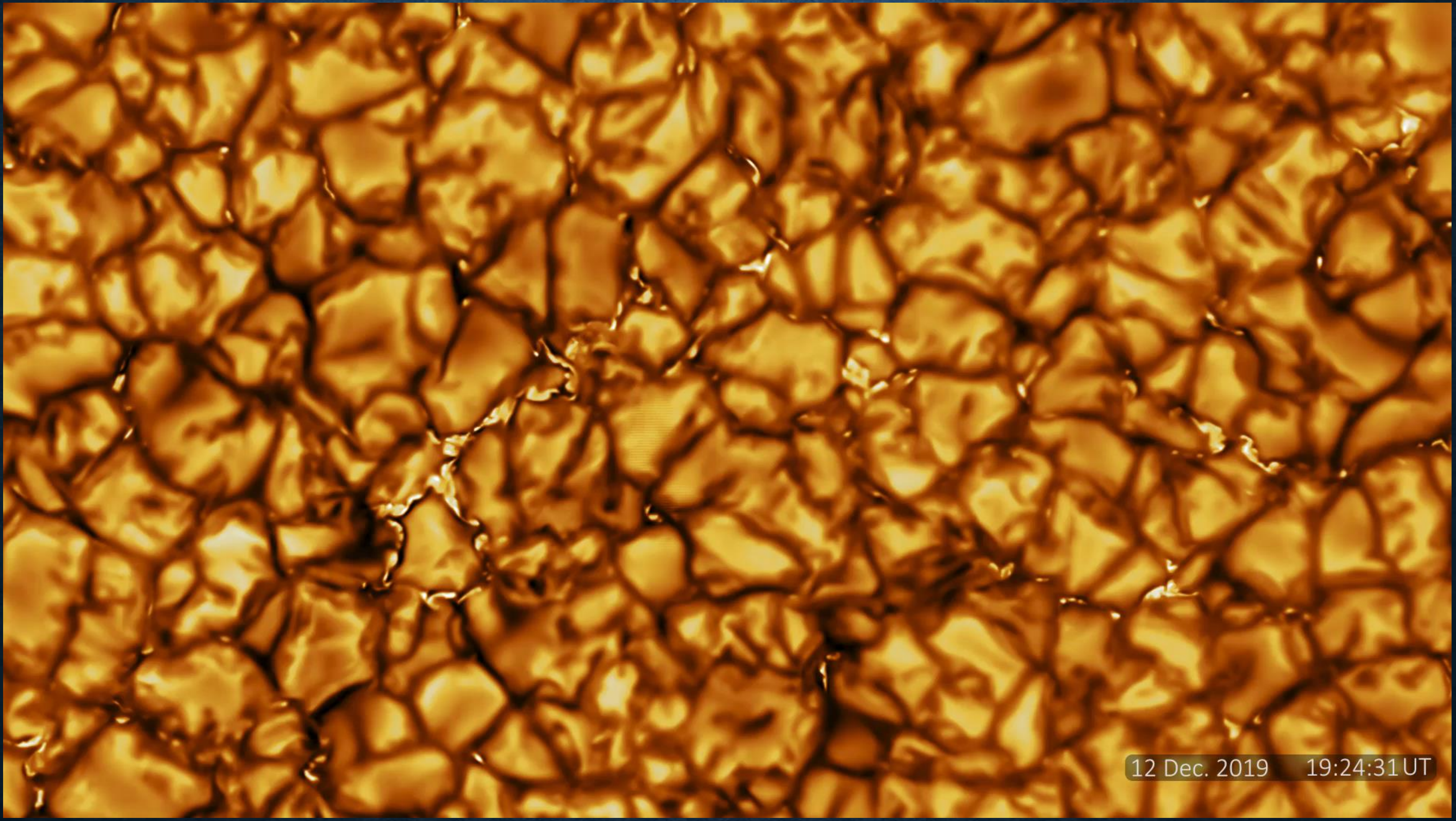
A LOOK AT THE SOLAR SURFACE



A&A 526, A60 (2011)

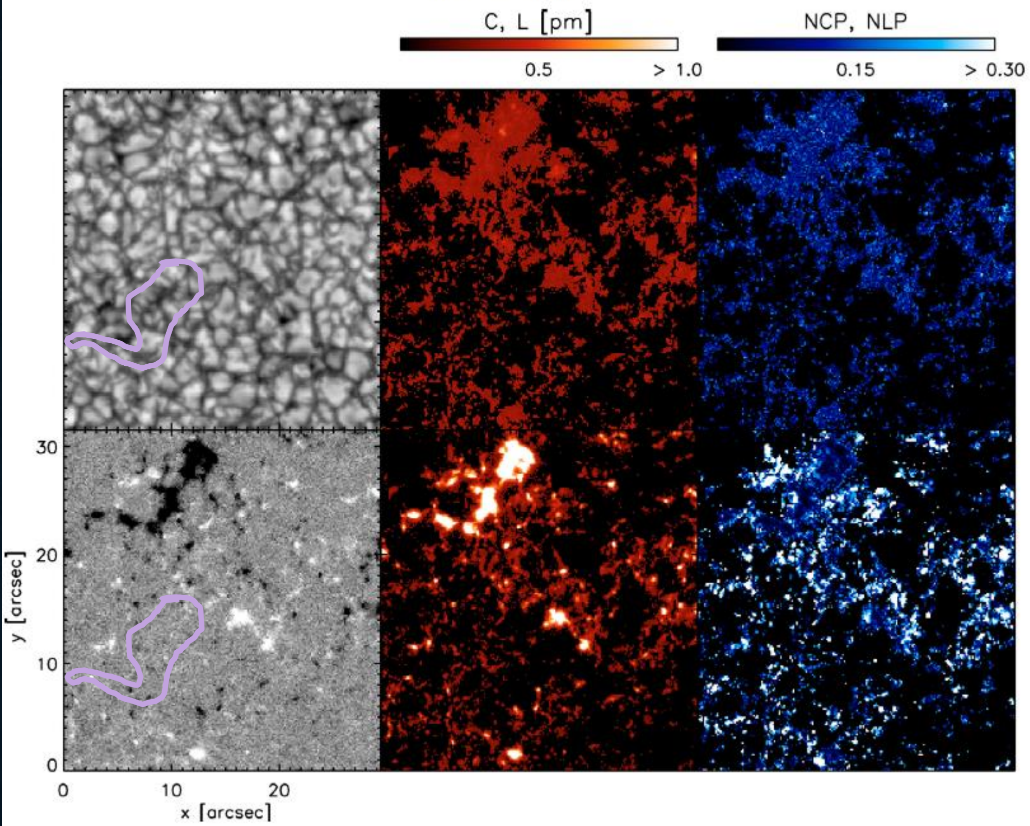


Fig. 2. Main observational properties of the representative 29.52″ × 31.70″ subfield selected for in-depth analysis. Continuum intensity (*upper-left panel*), total linear polarization (*L*, *upper-central panel*), net-linear polarization (*NLP*, *upper-right panel*), COG magnetogram saturated at ±200 G (*lower-left panel*), total circular polarization (*C*, *lower-central panel*), and net-circular polarization (*NCP*, *lower-right panel*). The total polarization maps are both saturated at 1 pm, while the net-circular and net-linear polarization maps are saturated at 0.3. Black pixels in *L*, *C*, *NLP*, and *NCP* maps represent regions with signals below the threshold for inversion. The bars on top represent the color palettes adopted for the two pairs of images below them.

Viticchié +, *Interpretation of HINODE SOT/SP asymmetric Stokes profiles observed in the quiet Sun network and internetwork*, A&A 526, A60 (2011)

"Our Sun, a fairly typical star in a fairly typical galaxy, is not a boring spherical static ball of gas but a complex evolving tangled medium of plasma and magnetic fields that produces structure in the form of convection cells, sunspots, and solar flares."

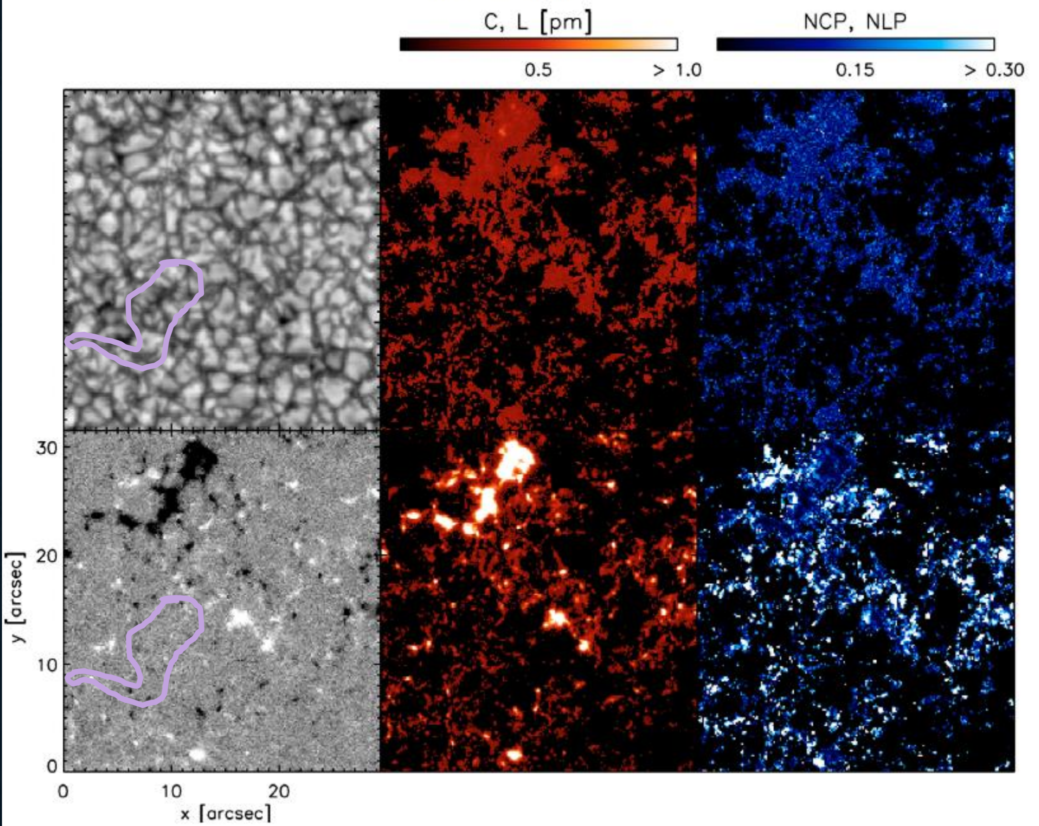
In PATTERN FORMATION AND DYNAMICS IN NONEQUILIBRIUM SYSTEMS, Michael Cross & Henry Greenside, Cambridge Univ. Press

One of the key questions we are addressing is **how does a simple physical system like the Sun produce such a complex dynamics?**

The inherent **nonequilibrium state** of the Sun is the answer.

Convection is a paradigm of a nonequilibrium system producing complexity at different solar scales.

A&A 526, A60 (2011)



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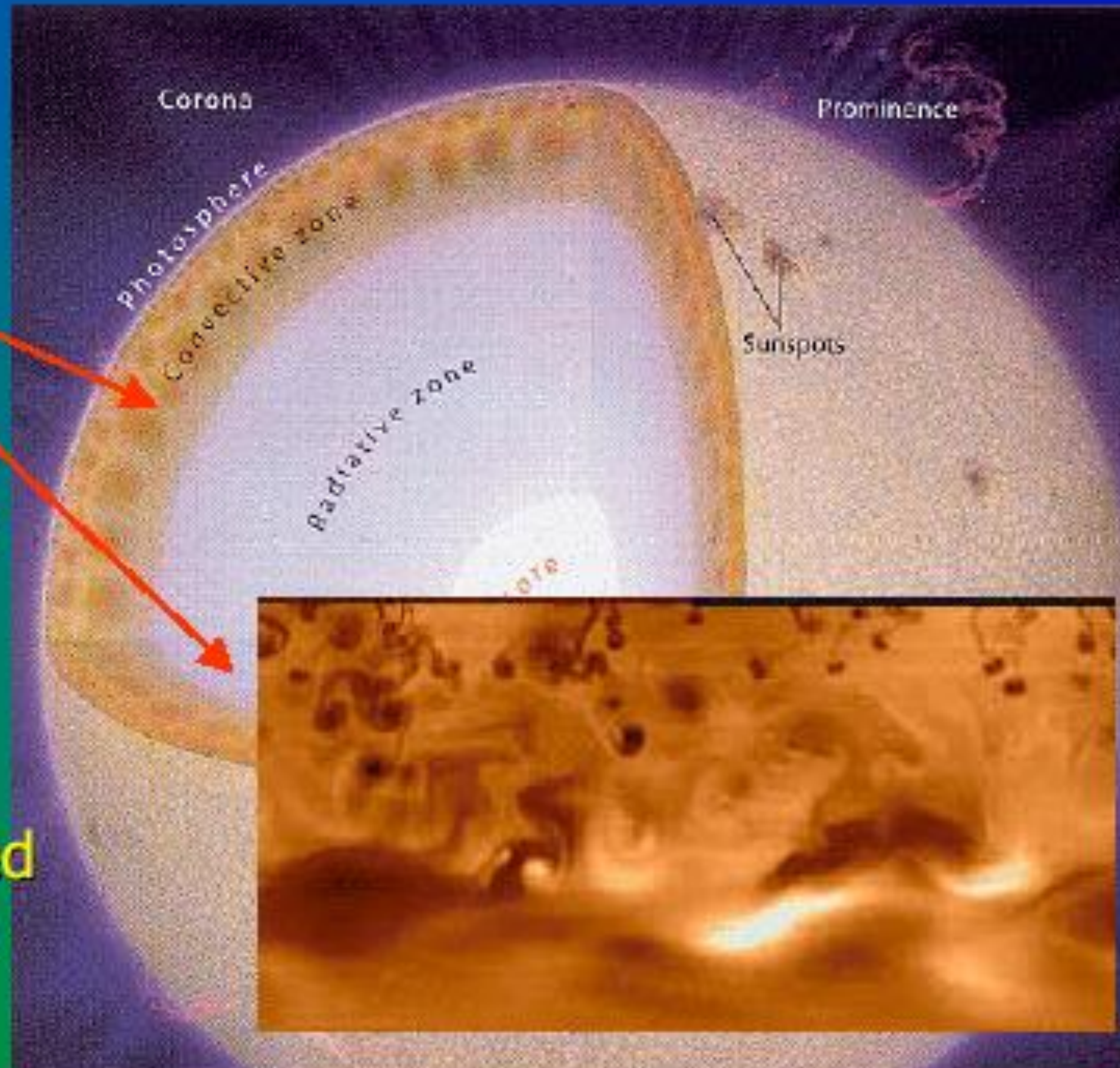
Driving a system away from equilibrium produces space-time symmetry breaking and consequent emergence of **structures** and **patterns**.

The solar convection zone

- 200 Mm thick layer in turbulent motion
- Velocities range from 100 m/s (bottom) to 10 km/s (top)
- Energy flux nearly completely transported by convective motion



Credits: Manfred Schüssler (MPAE)

THE PROBLEM:

A fluid heated from below is pushed by buoyancy to rise

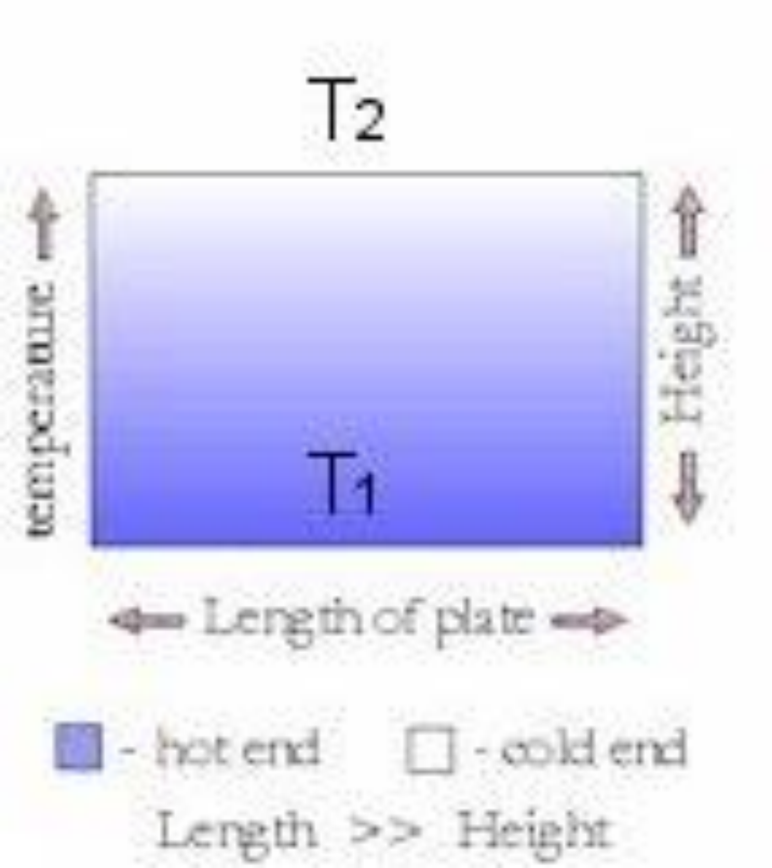
$F_{buoy.}$ ↑ when ΔT ↑

Convective Instability

The T distribution is modified by the convective flux.

The F_{buoy} (which is causing the flux) is affected by the modification of the flux itself!

RAYLEIGH-BÉNARD CONVECTION



$\Delta T = T_2 - T_1 > 0$

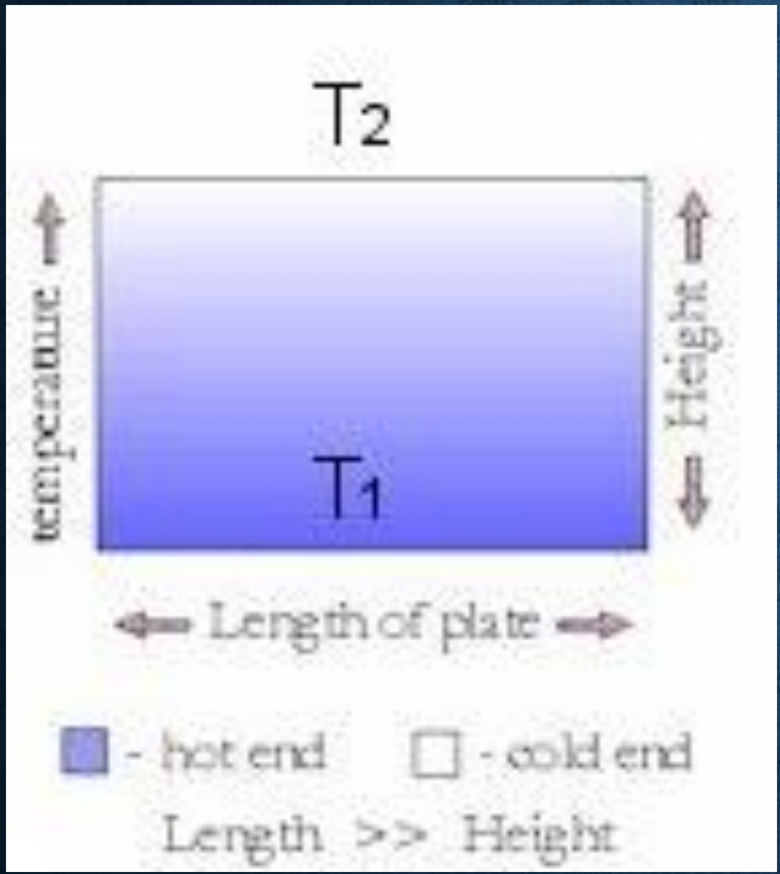
$\Delta T < \Delta T_c$

hydrostatic equilibrium, static fluid.

$\Delta T \geq \Delta T_c$

Instability, convective motion.

RAYLEIGH-BÉNARD CONVECTION



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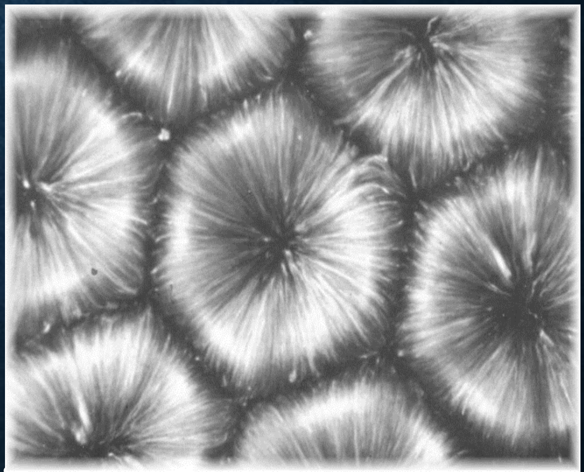


scales of the solar magnetism

RAYLEIGH-BÉNARD CONVECTION

The convection onset is inhibited by two dissipative effects:

1. Fluid viscosity: drag between the hotter parcel and the surrounding fluid
2. Heat diffusion: as soon as the hotter fluid parcel moves in a colder environment, it starts to diffuse its heat.

Convection will be important when the transport time across the bubble is smaller than or equal to the diffusion time to the surface.

$$\frac{2r}{v} \leq \frac{r^2}{4K}$$

$$v = \frac{1}{3}\frac{r^2 g\alpha\Delta T}{\nu}$$

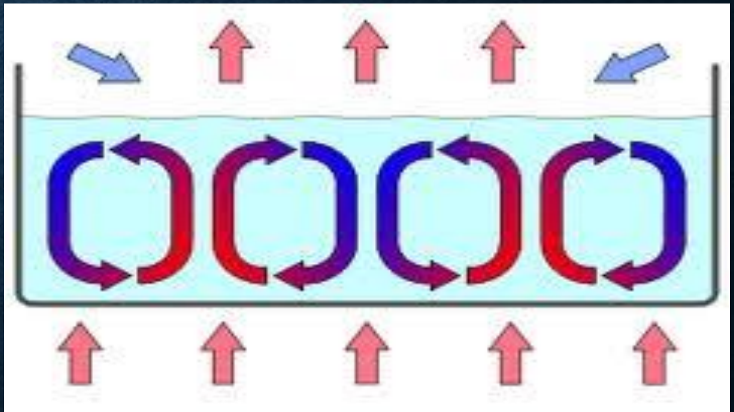
RAYLEIGH-BÉNARD CONVECTION

$$R \equiv \frac{g\alpha\Delta T r^3}{\nu\kappa}$$

R = Rayleigh number
g = gravity acceleration
α = thermal expansion coefficient
ΔT = temperature gradient
r = length scale
ν = kinematic viscosity
K = thermal diffusivity

When R exceeds the critical value R_C, convection occurs.
R tells us when the energy transport switches from radiative to convective.

The system reacts to the simultaneous attempts of hot layers to rise and cold layers to sink, by separating into **convective cells**.



The solar convection zone

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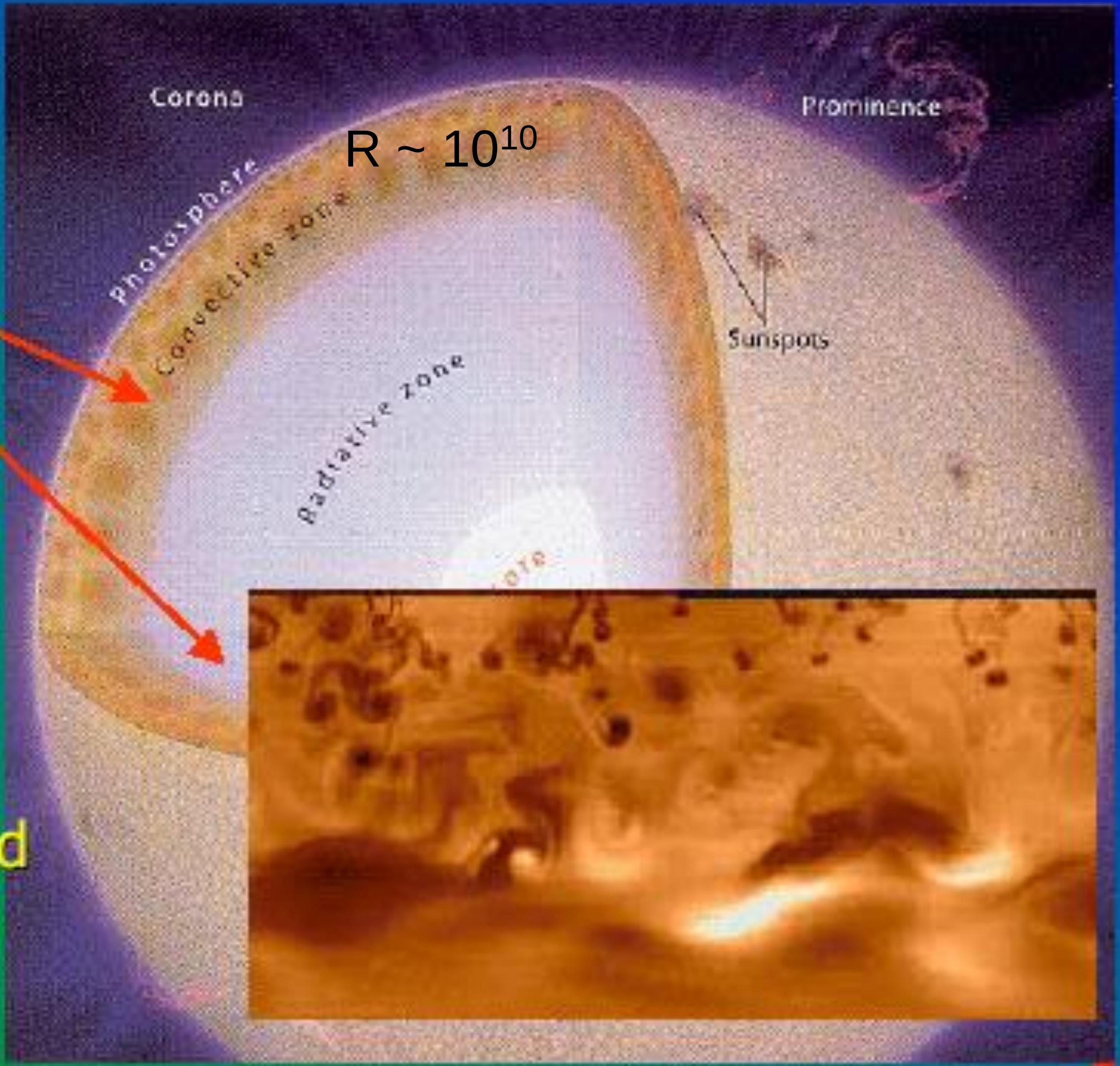


Credits: Manfred Schüssler (MPAE)

SCHWARZSCHILD CRITERION

A bubble in a fluid:

Hotter → Rising

Isolated → Adiabatic expansion

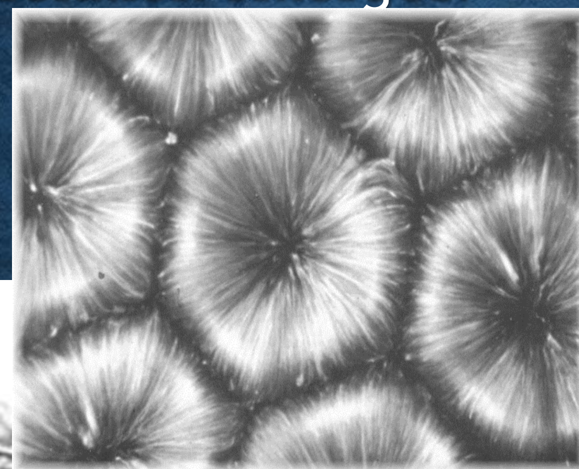
It keeps rising if:

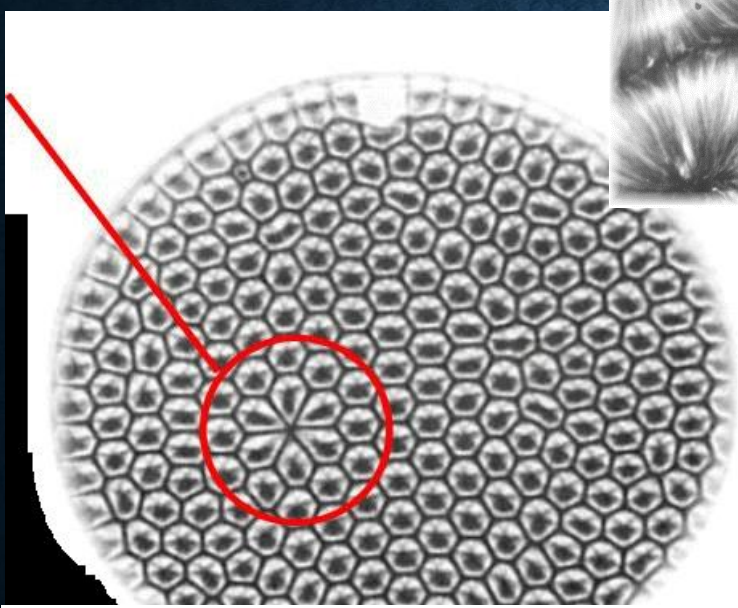
the Radiative Temperature Gradient is steeper than the Adiabatic Temperature Gradient

$$\nabla_{rad} < \nabla_{ad} (+k \nabla_{\mu})$$

RAYLEIGH-BÉNARD CONVECTION CELLS

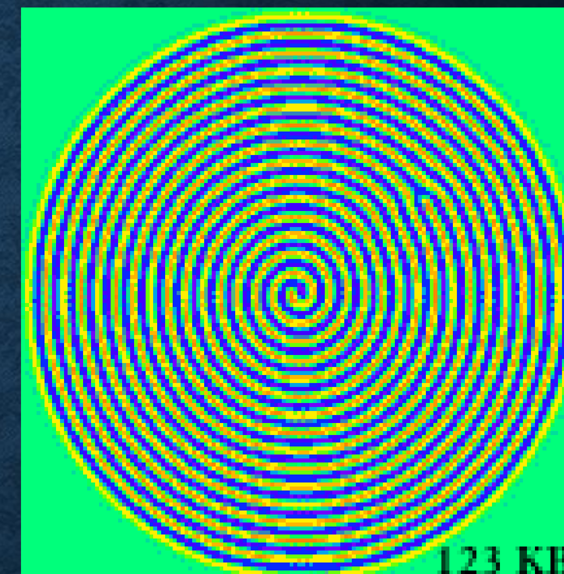
Spatio-temporal correlation emerges!





shallow layer - this could mean a layer of fluid 1 millimeter thick in a petri dish, or the first 2 kilometers of the Earth's atmosphere

$R \sim 10^3$-10^4



REYNOLDS NUMBER

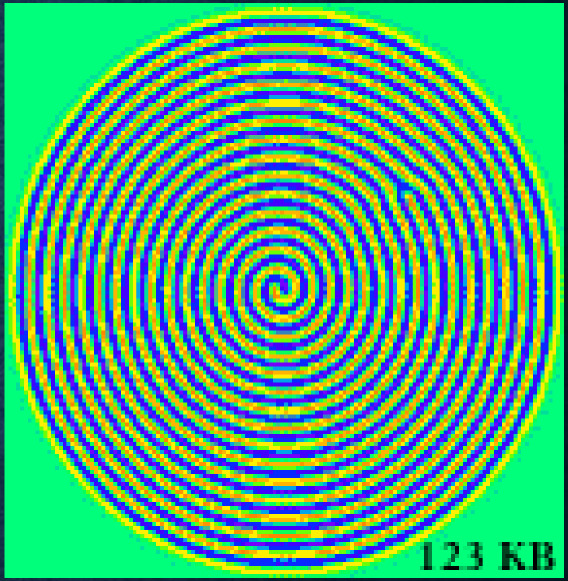
Spatio-temporal correlation emerges!

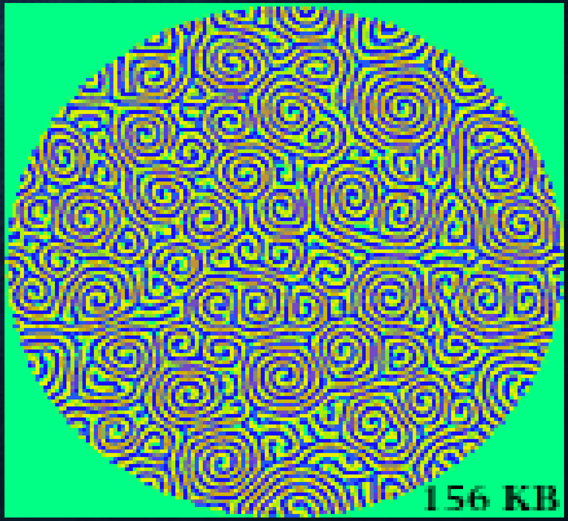
Then TURBULENCE comes….

$Re \equiv \upsilon L/\nu$

υ=velocity
ν=viscosity
L=length over which one can assume υ to be constant

$Re \sim 10^3$





HYDRO-DYNAMICS EQUATIONS

Mass Conservation Equation: Mass neither created nor destroyed

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

Energy Conservation Equation: Energy (Thermal+kinetic+gravitational) neither created nor destroyed

$$\frac{\partial E}{\partial t} + \nabla \cdot (v(E + p)) = 0$$

Momentum Equation: Change of the momentum of each plasma parcel determined by the forces acting on it

$$\frac{\partial \rho v}{\partial t} + \nabla \cdot \big(v \times (\rho v)\big) + \nabla p = 0$$

MLT

Old paradigm (mixing-length model):

- It exists a typical bubble **size**, a typical bubble **velocity** and a typical bubble **Mixing Length**

L is the distance a hot fluid parcel can move before dissolving

$$L=\alpha H_P$$

Where H_P is the pressure scale height and α is a factor between 0.5 and 2.5

With this assumption (and some *tedious* calculations), we can derive the convective heat flux as a function of local variables:

$$F_{conv} = -L\rho v T \frac{dS}{dr}$$

Neat: we can use this equation in our models of how a star works!

KOLMOGOROV VIEW AND MLT

Kolmogorov turbulence theory is the set of hypotheses that a small-scale structure is statistically homogeneous, isotropic, and independent of the large-scale structure .
The source of energy at large scales is the convection

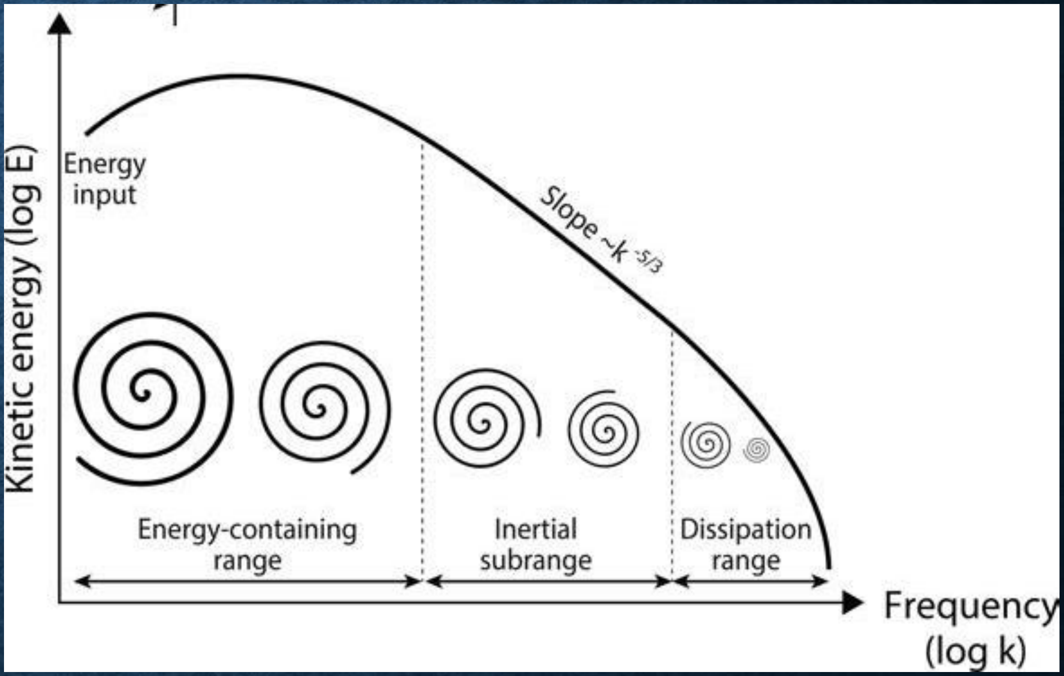
Energy cascade theory – unstable fluid masses under the influence of inertial forces, break up into smaller eddies to form a continuum self-similar of eddy size for the transfer of energy from a macroscale L_0 (outer scale of turbulence) to a microscale l_0 (inner scale of turbulence).

Dissipation range – scale sizes smaller than l_0 . The remaining energy in the fluid motion is dissipated as heat.

Power spectrum : Equivalent to the 2/3 power law of the structure function in the inertial range in three dimensions

$$\Phi_{RR}(\kappa) = 0.033 C^2_V \kappa^{-11/3} \quad \text{when} \quad 1/L_0 \ll \kappa \ll 1/l_0 .$$

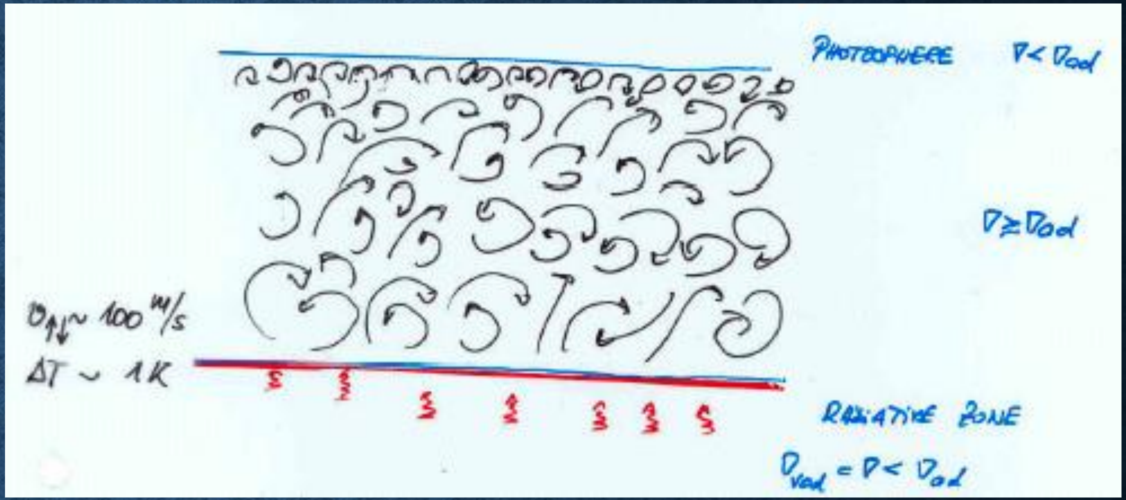
The power spectrum exhibits a 11/3 power law, which corresponds to a 1D spectrum with a 5/3 power law.



MLT + K41

Old paradigm (mixing-length model):

- fully developed turbulence with a hierarchy of "eddies"
- quasi-local, diffusion-like transport
- flows driven by local entropy gradient



L is the distance a hot fluid parcel can move before dissolving

$$\mathbf{L=\alpha H_P}$$

Where H_P is the pressure scale height and α is a factor between 0.5 and 2.5

With this assumption and using the Kolmogorov eddies spectrum (and some *more tedious* calculations), we can derive the convective temperature gradient as a function of local variables:

$$\frac{\partial T}{\partial m} = \frac{-T\left(\partial \ln T / \partial \ln P\right)}{4\pi\rho\, r^2 H_P}$$

NEW RESULTS

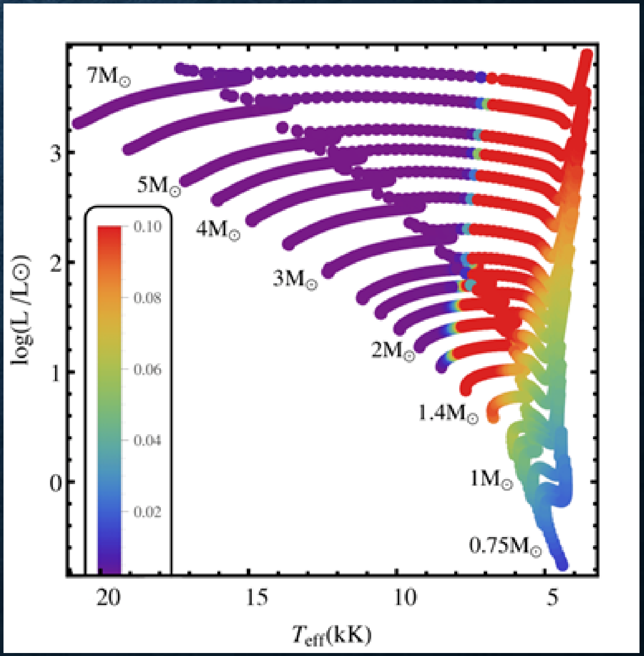
The new results of simulations, labs and observations tell us that the concept of Kolmogorov turbulent cascade to describe the solar convection is no longer viable

→ But let's not forget the success of the Mixing-Length Theory

→ Back to HD equations!

But with numerical codes &

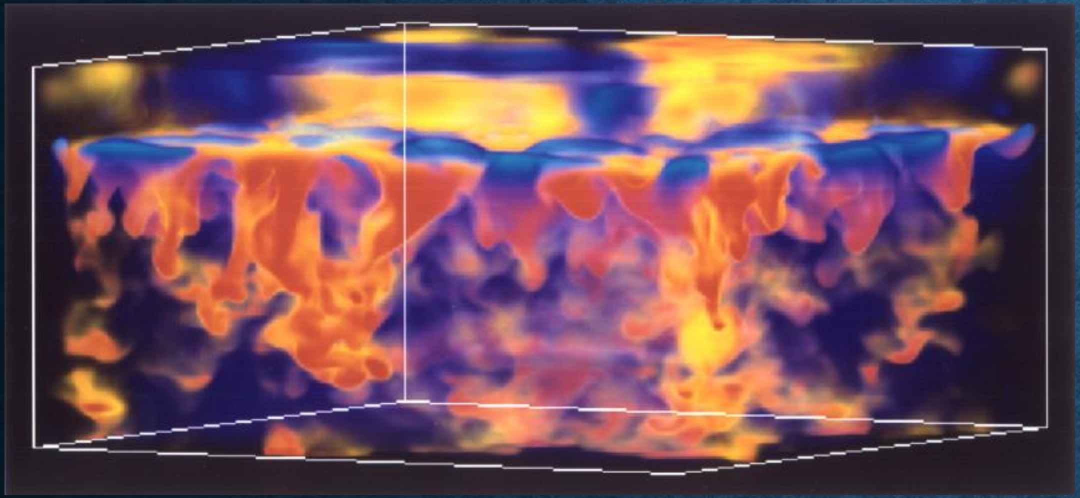
high performance computing

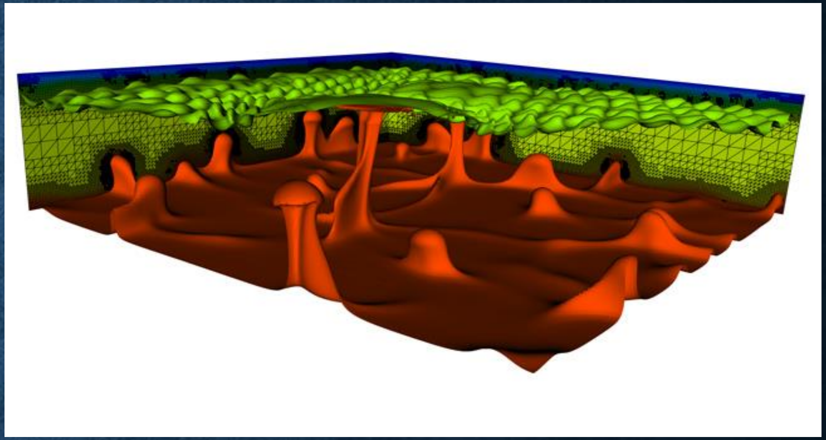


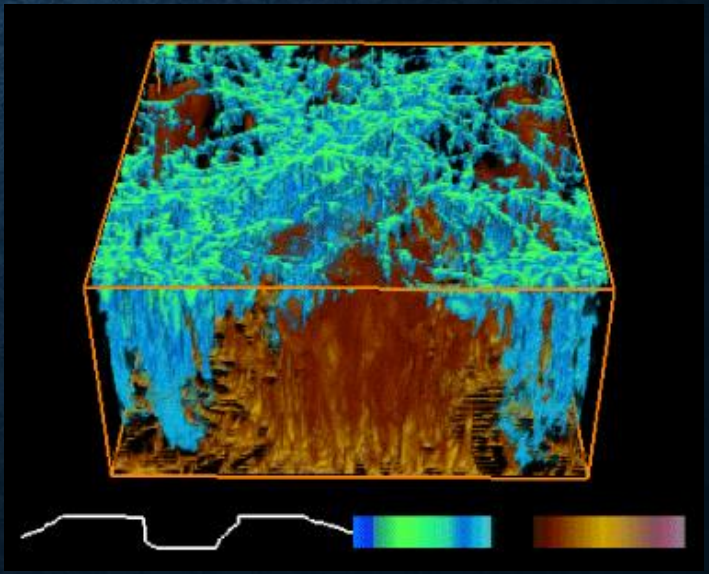
CONVECTION CELLS?

Re ~ 10^4 - 10^8

CONVECTION CELLS







Re > 10^8

Spatio-temporal correlation survives!

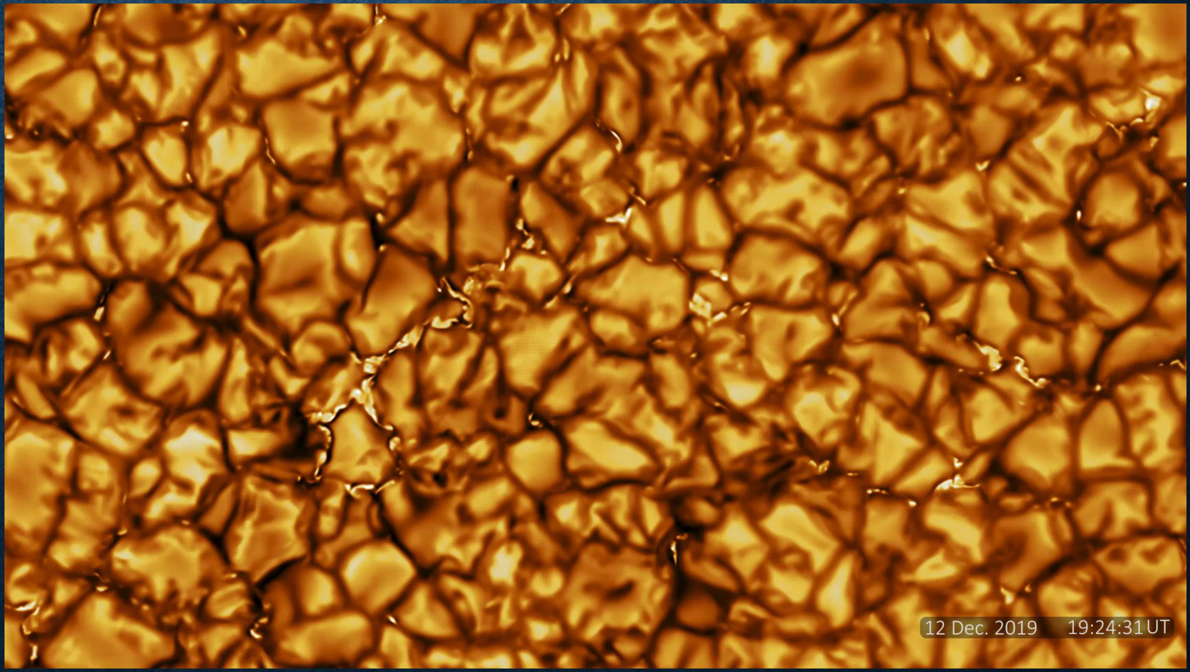
ACTUAL SOLAR CONVECTION

- **Numerical Simulations**
  - Effects of T, P and ρ stratification, non-linearity, non-stationarity, compressibility, shocks, challenge the application of linear mode superpositions (as in the MLT).

- **Observations**
  - **Continuum imaging** (***granulation***)
    - Spatial structuring : distribution functions, statistics, correlations, internal structure (~ 0.05'' / pixel)
    - Temporal evolution: formation, fragmentation, average lifetime
  - **Spectral imaging**
    - Doppler Imaging (***granulation, super-granulation***)
    - Velocity structures (internal structure of granules and inter-granular down-flows)
    - Velocity and gradients distributions
  - **Trackers motion**
    - Horizontal velocities (***granulation, super-granulation***)
    - Local Correlation Tracking (***meso-granulation***)

ACTUAL SOLAR CONVECTION: GRANULATION

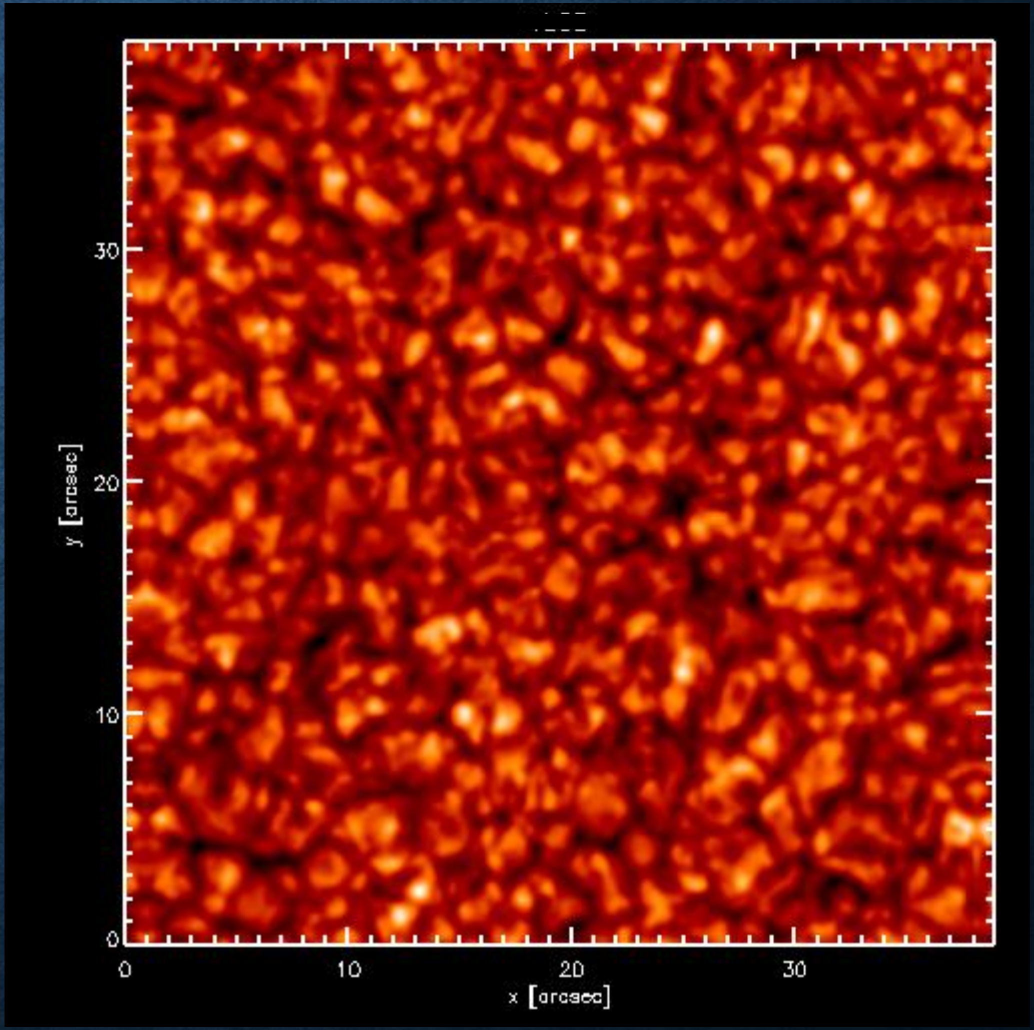
- Continuum imaging
- Doppler imaging



ACTUAL SOLAR CONVECTION: GRANULATION

Continuum imaging

Doppler imaging



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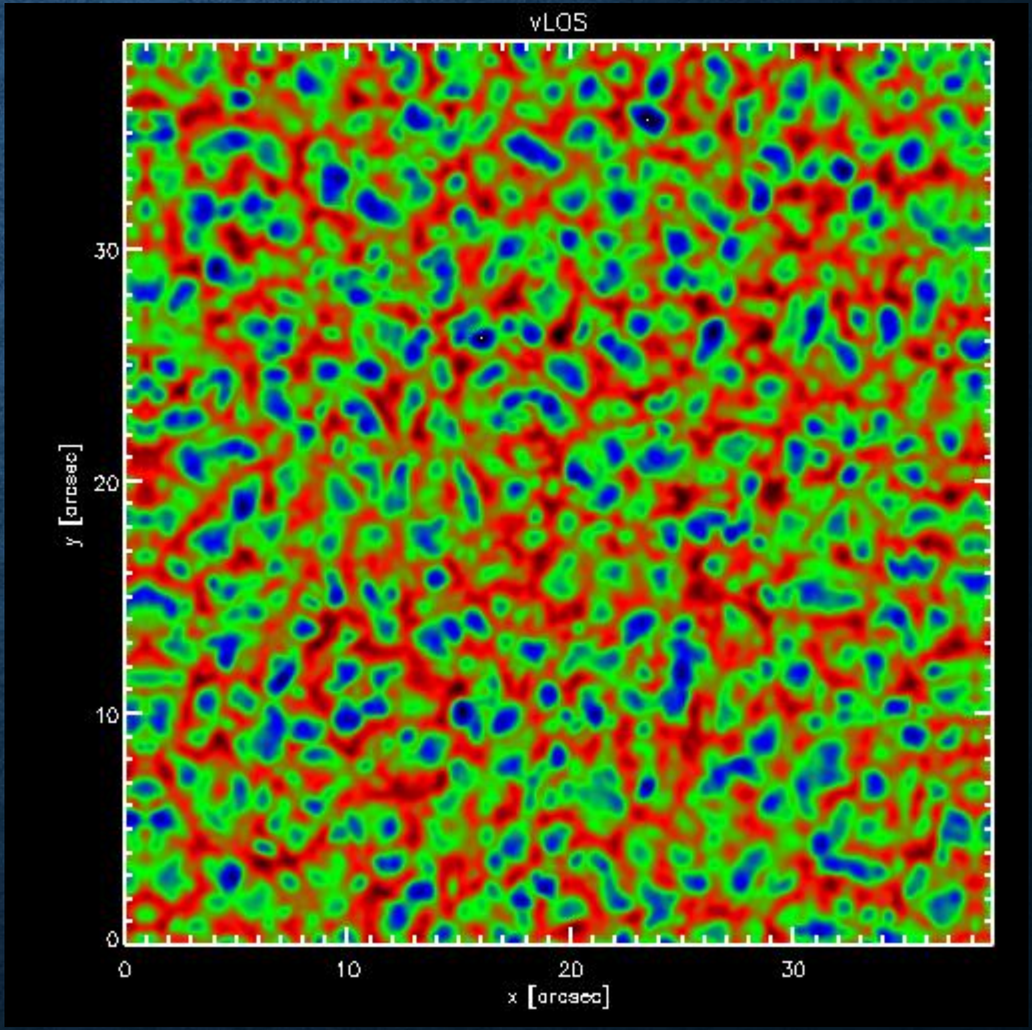

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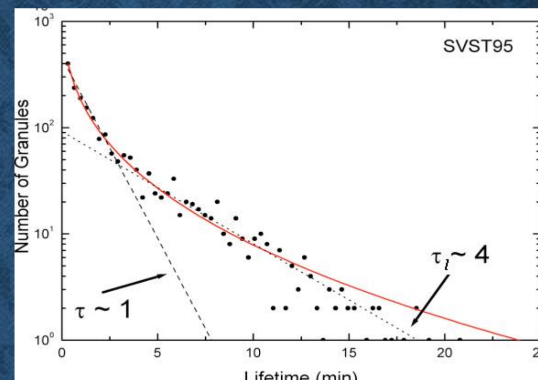
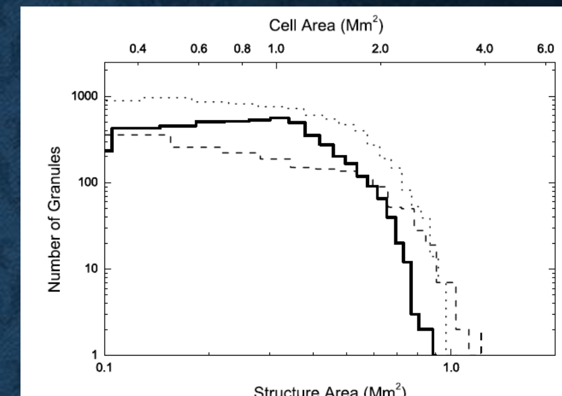
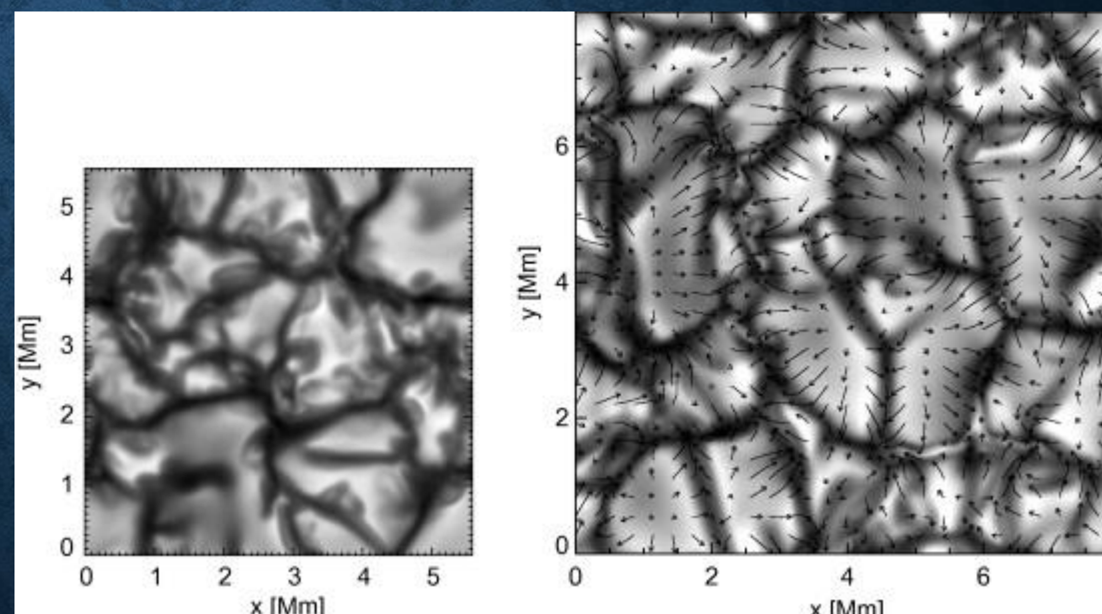






Granulation **FACT SHEET**:

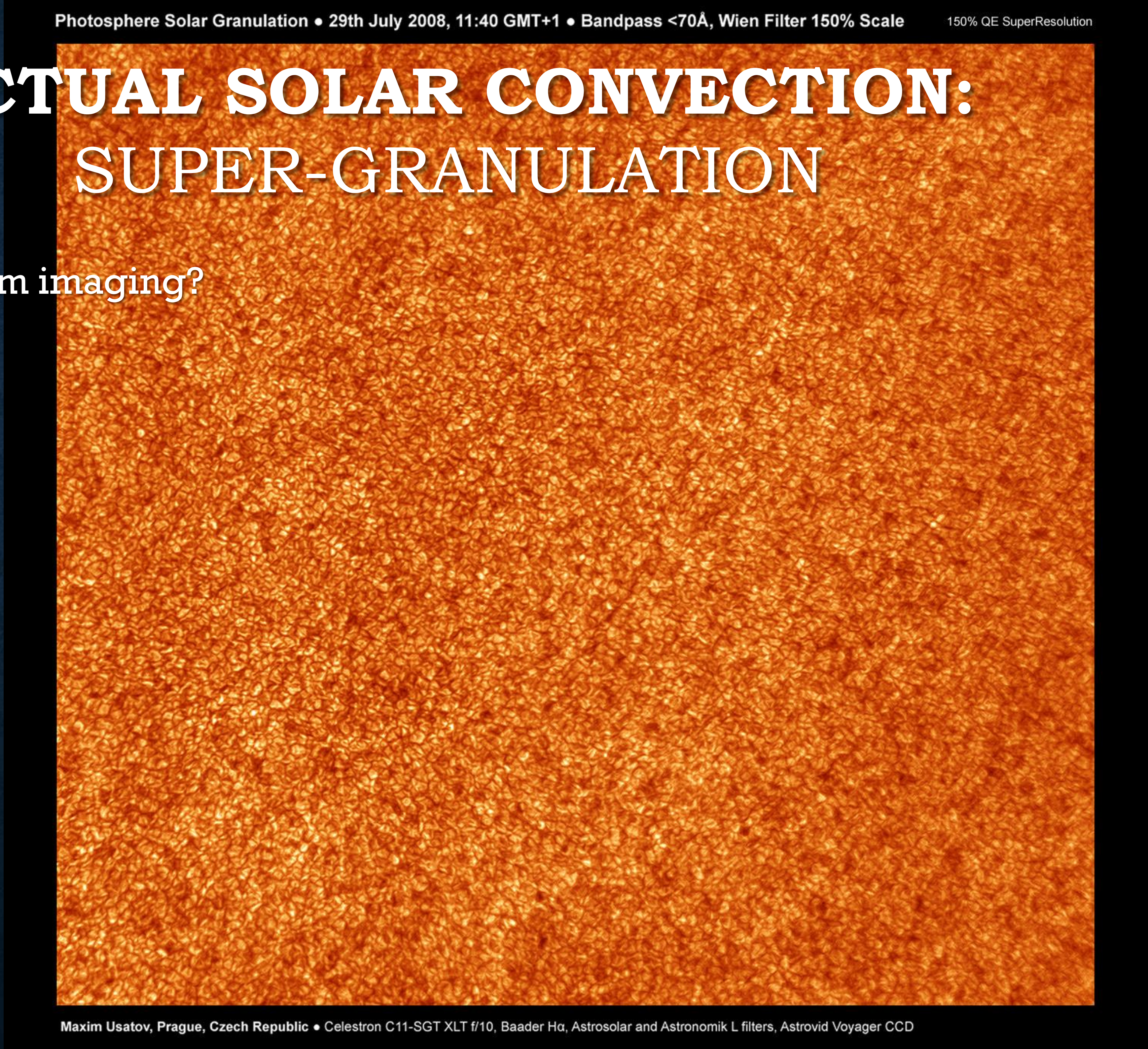
Size:	~1 Mm
Timescale:	~5 min
V_{LOS}-T correlation:	VStrong
V_{LOS}-V_{HOR} correlation:	Strong
T-V_{HOR} correlation:	Strong

ACTUAL SOLAR CONVECTION: SUPER-GRANULATION

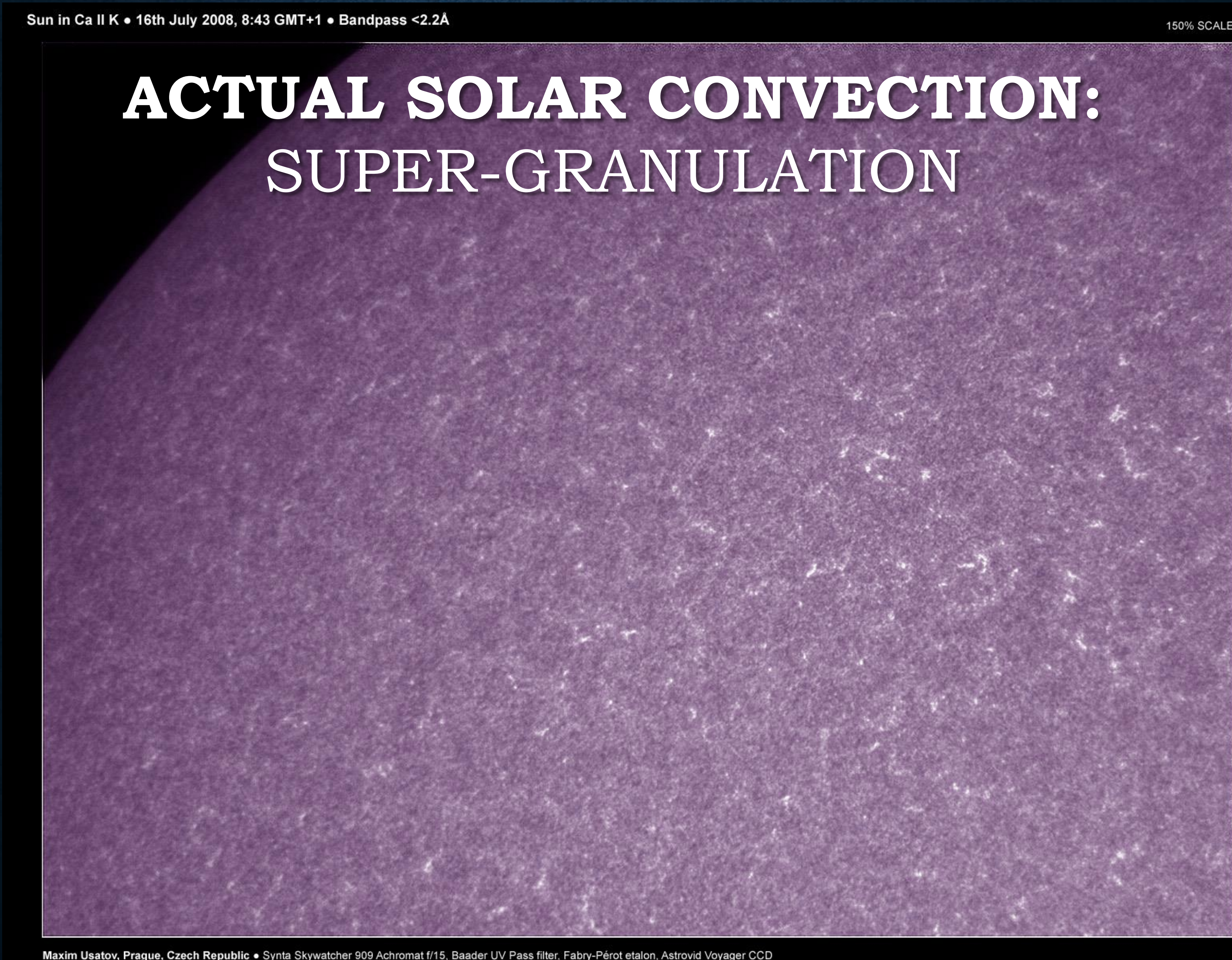
Continuum imaging?

ACTUAL SOLAR CONVECTION:
SUPER-GRANULATION

Continuum imaging?



ACTUAL SOLAR CONVECTION:
SUPER-GRANULATION



ACTUAL SOLAR CONVECTION: SUPER-GRANULATION

Full-disk Dopplergram → Fulldisk Dopplergram.mp4

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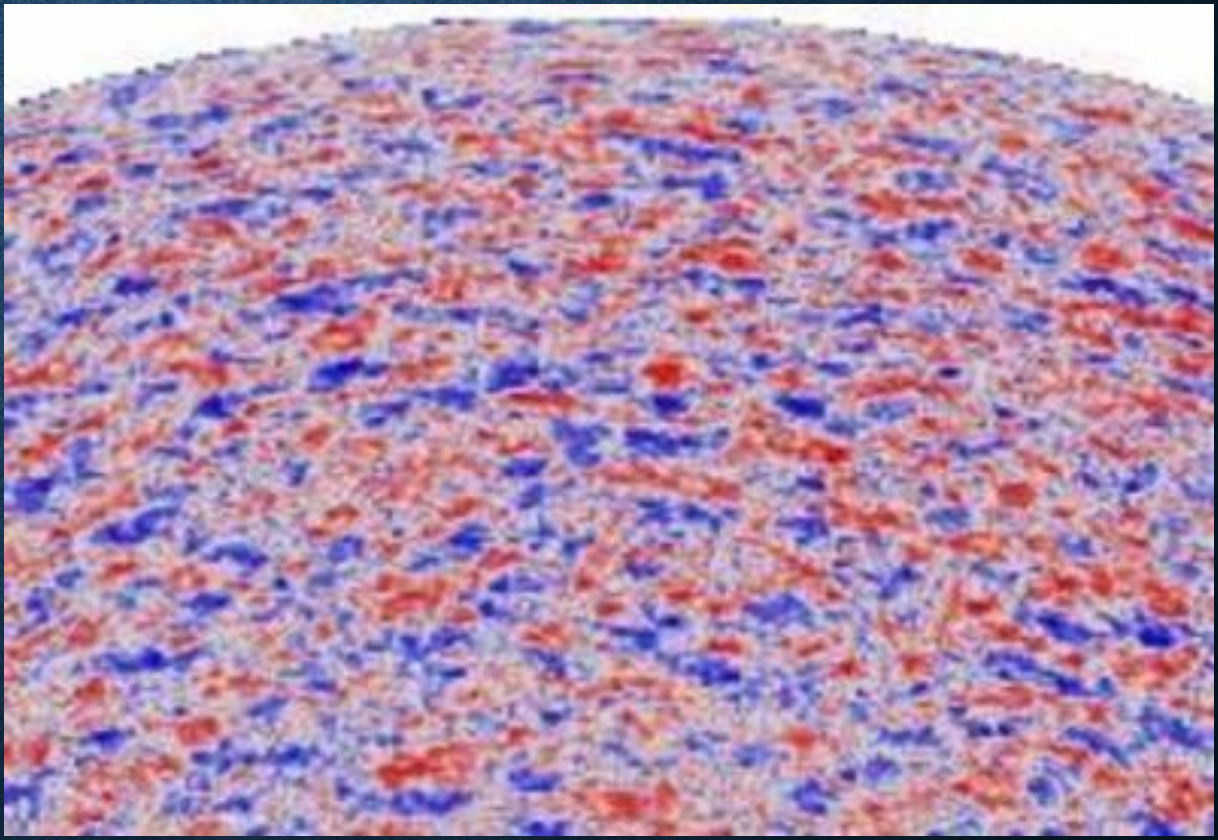

ACTUAL SOLAR CONVECTION: SUPER-GRANULATION

Helioseismology → Local Helioseismology.mp4

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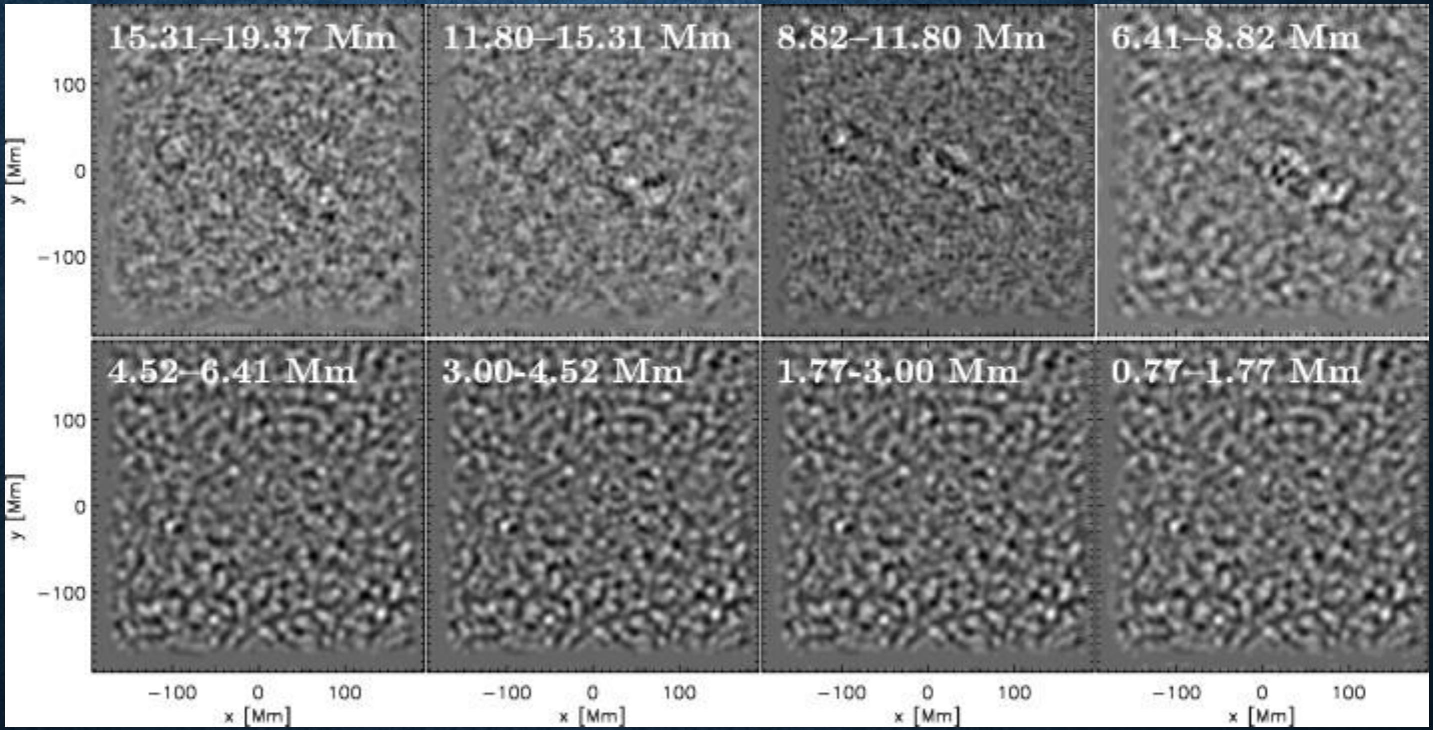
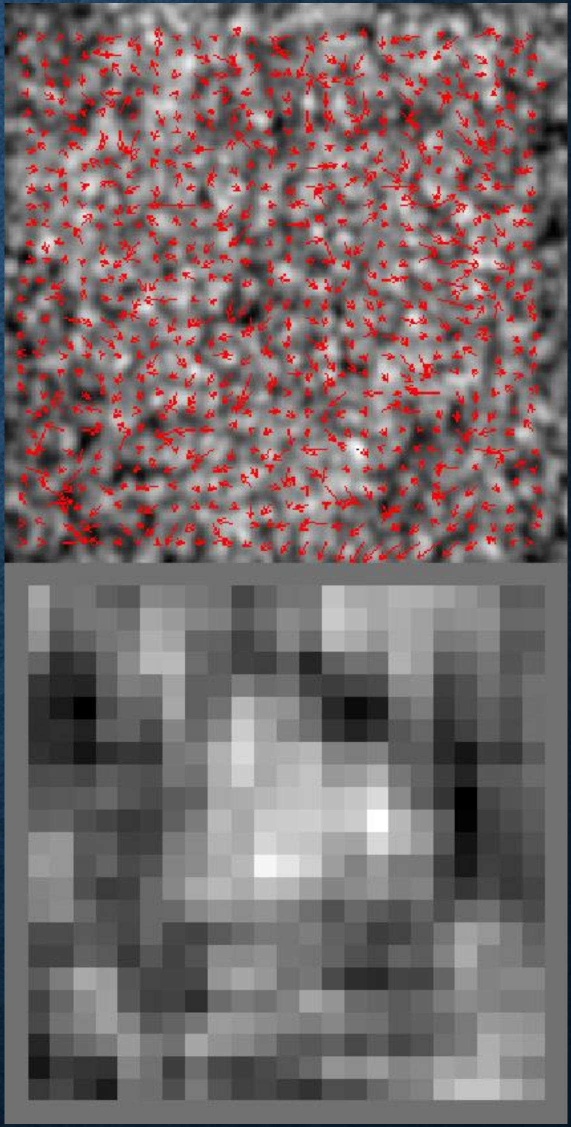


ACTUAL SOLAR CONVECTION: SUPER-GRANULATION

Horizontal flow field

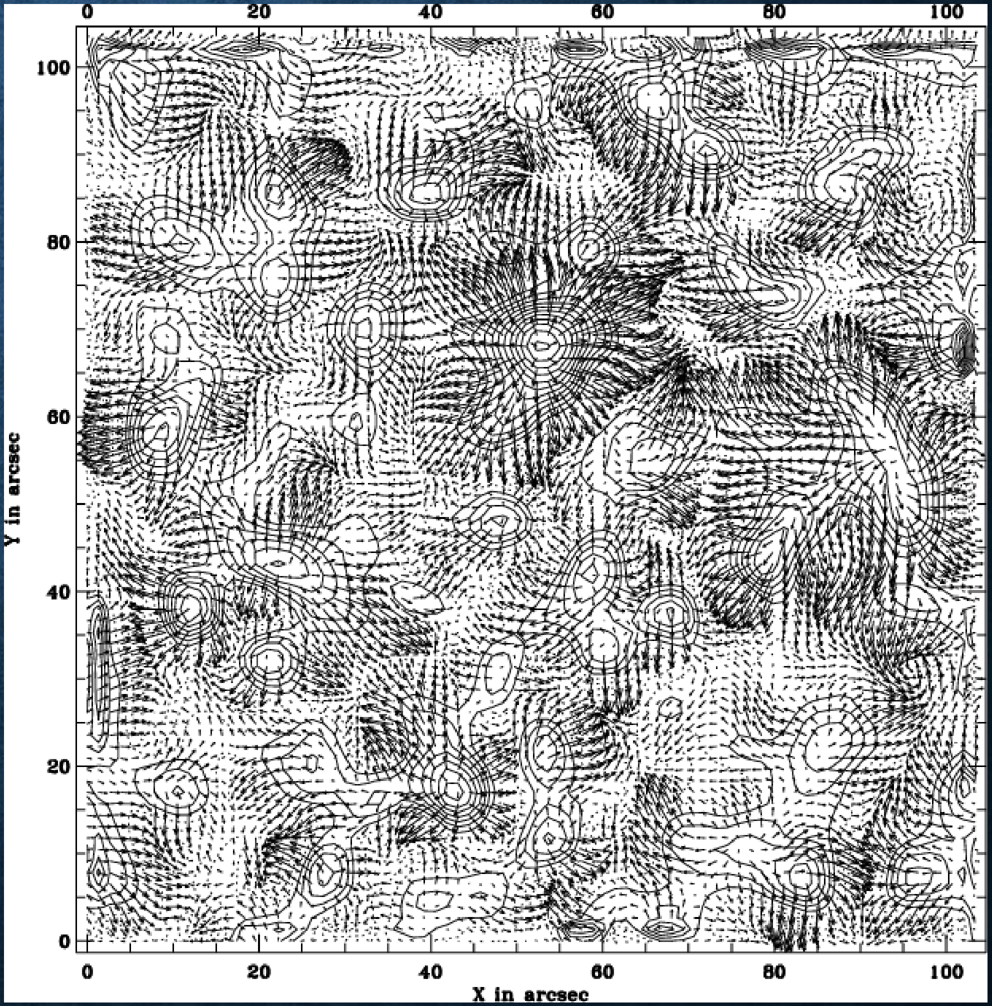


Super-Granulation **FACT SHEET**:

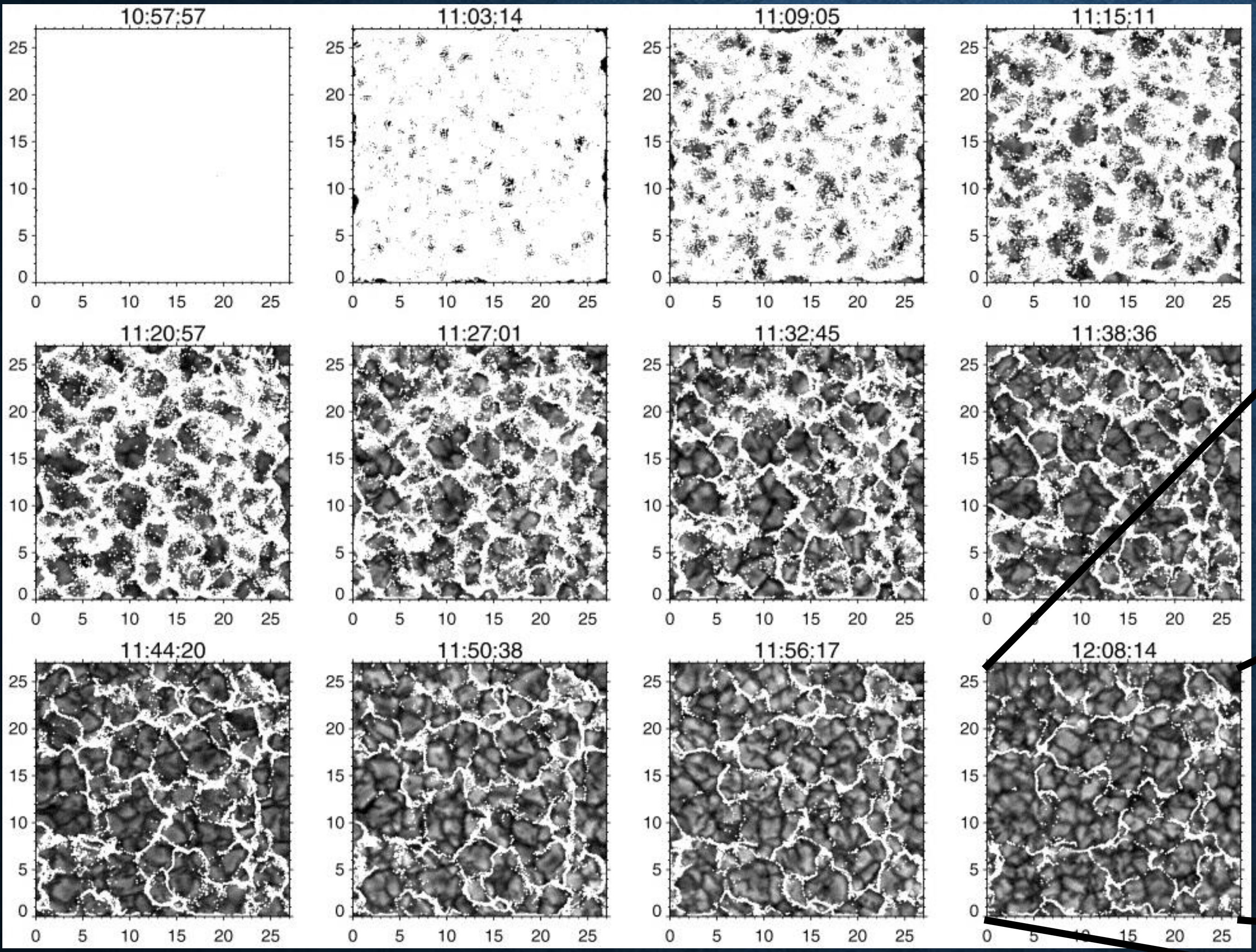
Size: ~30 Mm
Timescale: ~24 h
V_{LOS}-T correlation: Feeble
V_{LOS}-V_{HOR} correlation: Feeble
T-V_{HOR} correlation: Perhaps

ACTUAL SOLAR CONVECTION: MESO-GRANULATION

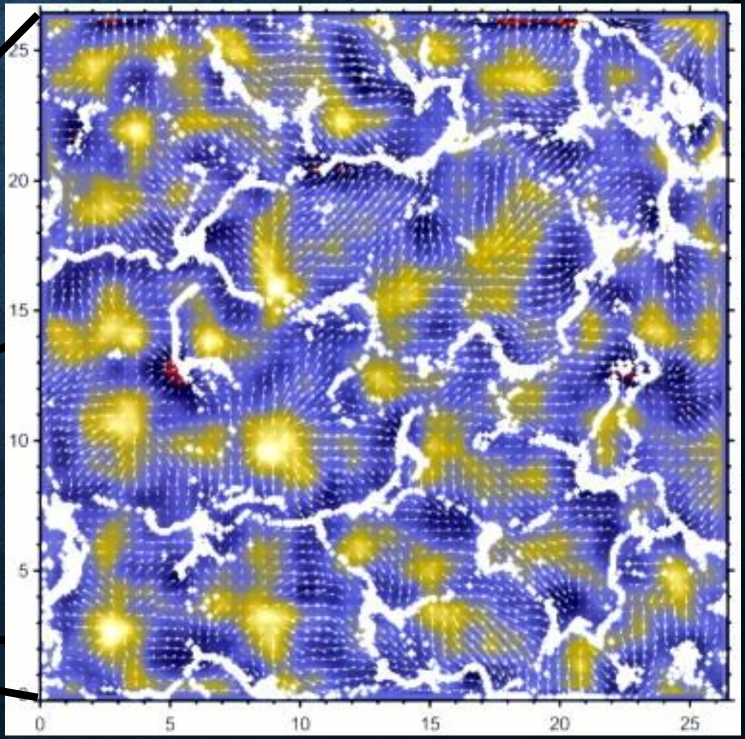
Local Correlation Tracking



ACTUAL SOLAR CONVECTION: MESO-GRANULATION



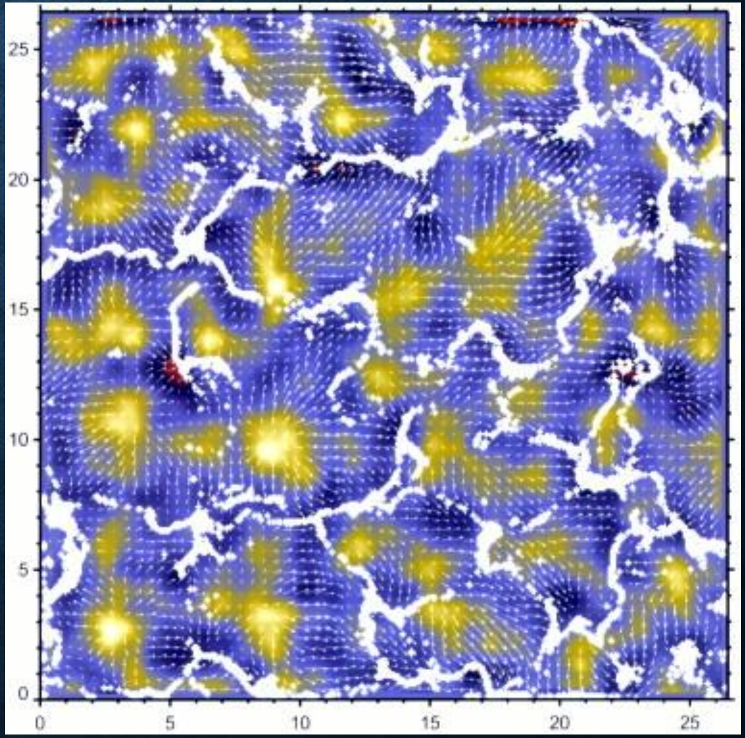
Passive Tracers (Corks)
+
Local Correlation Tracking



ACTUAL SOLAR CONVECTION: MESO-GRANULATION

Meso-Granulation **FACT SHEET**:

Size: 5-10 Mm
Timescale: 0.5-2 h
V_{LOS}-T correlation: ?
V_{LOS}-V_{HOR} correlation: ?
T-V_{HOR} correlation: Feeble



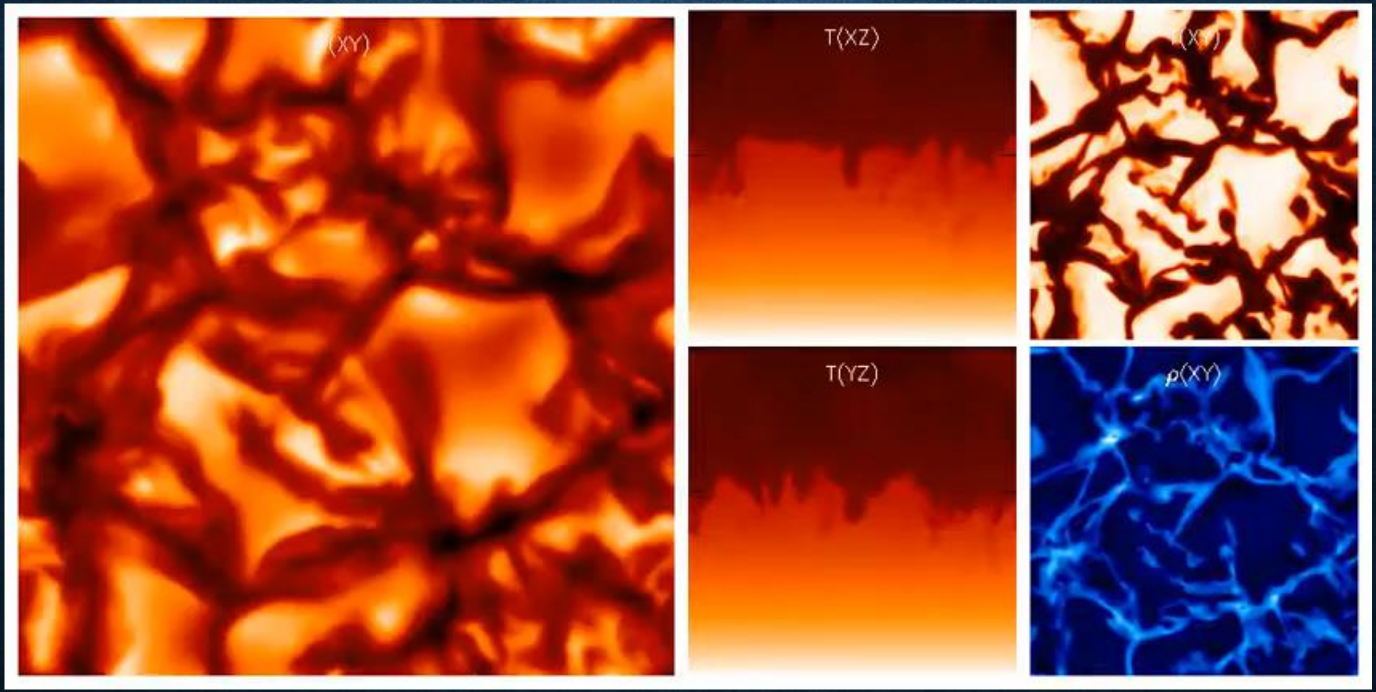
SOLAR CONVECTION SIMULATIONS

Limits of the simulations:

Computational box size

Numerical diffusion

→ NEED MORE COMPUTER POWER!!!



The Stagger-Grid group

SOLAR CONVECTION SIMULATIONS

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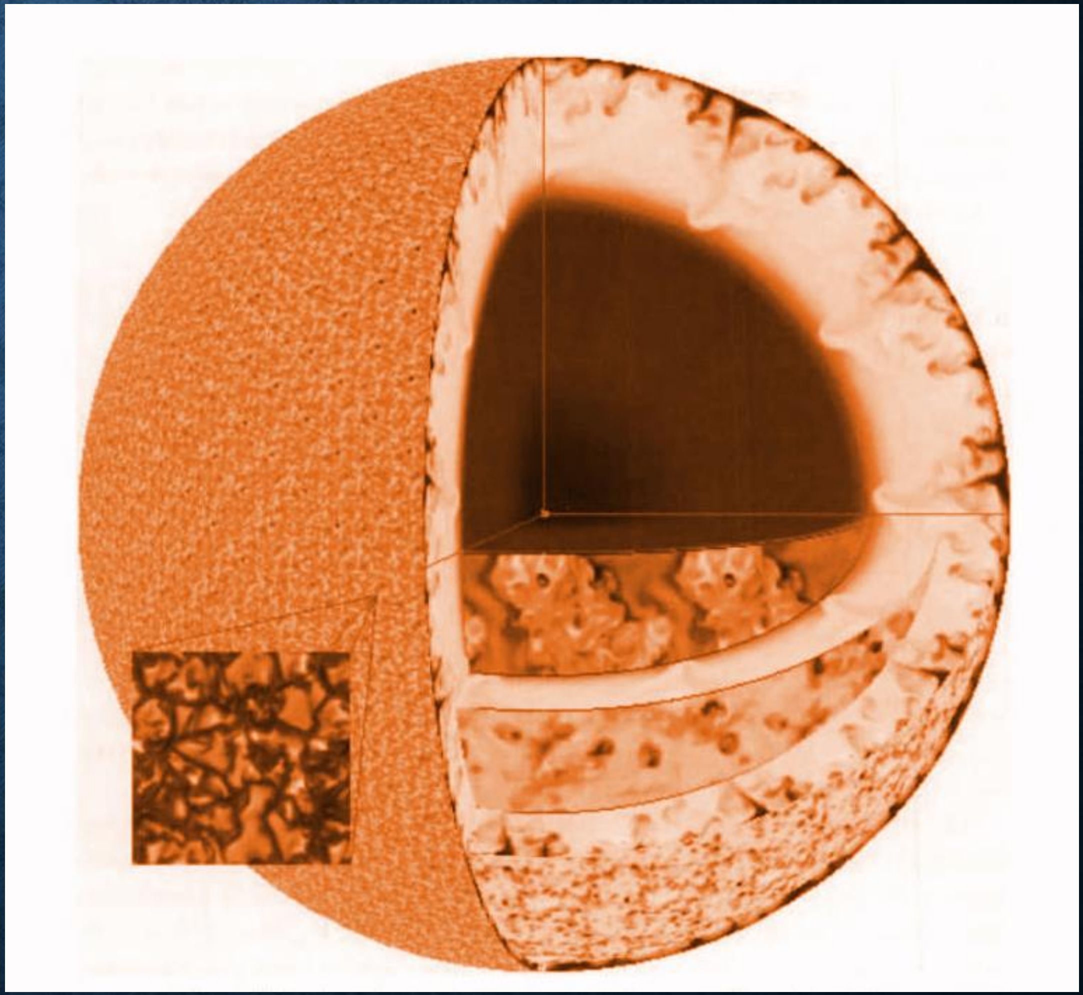
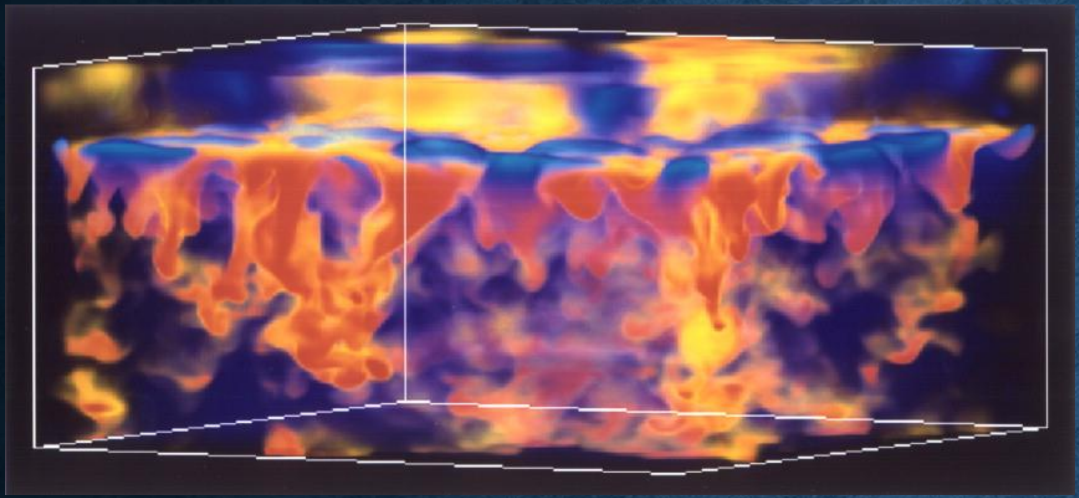


SOLAR CONVECTION SIMULATIONS

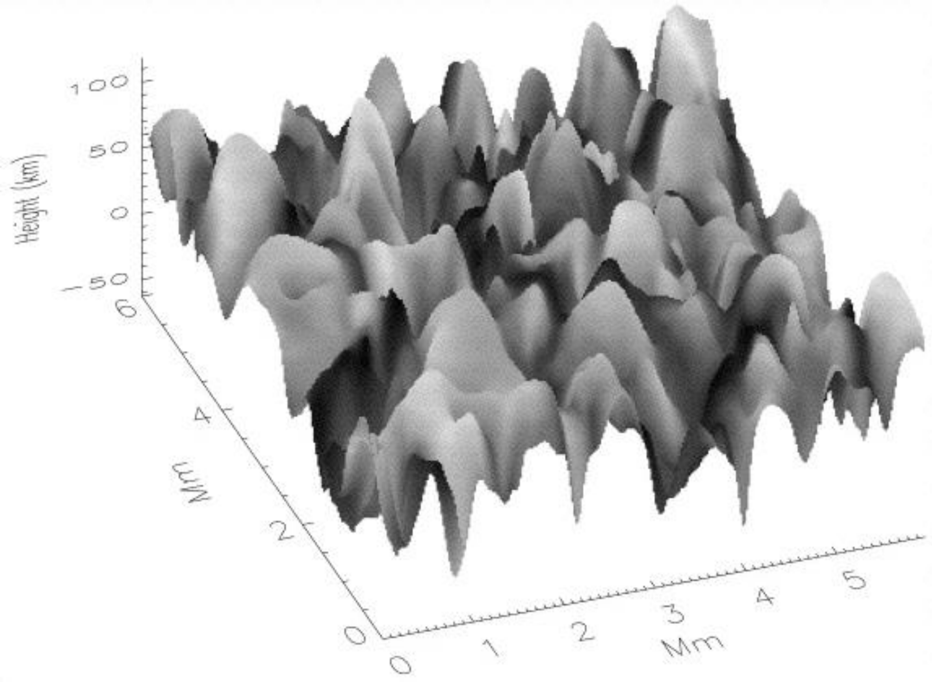


Entropy fluctuation seen from below the solar surface. Blue: high-entropy up-flows. Yellow and red: low-entropy down-flows.

The vertical vorticity forces the filamentary down-flows to twist, while they cross the entire computational domain.

The local plasma temperature deforms the τ=1 surface.
The RMS variation on the solar surface is ~30 km.

The hot rising plasma reaches τ=1 higher than the cold down-drafts.

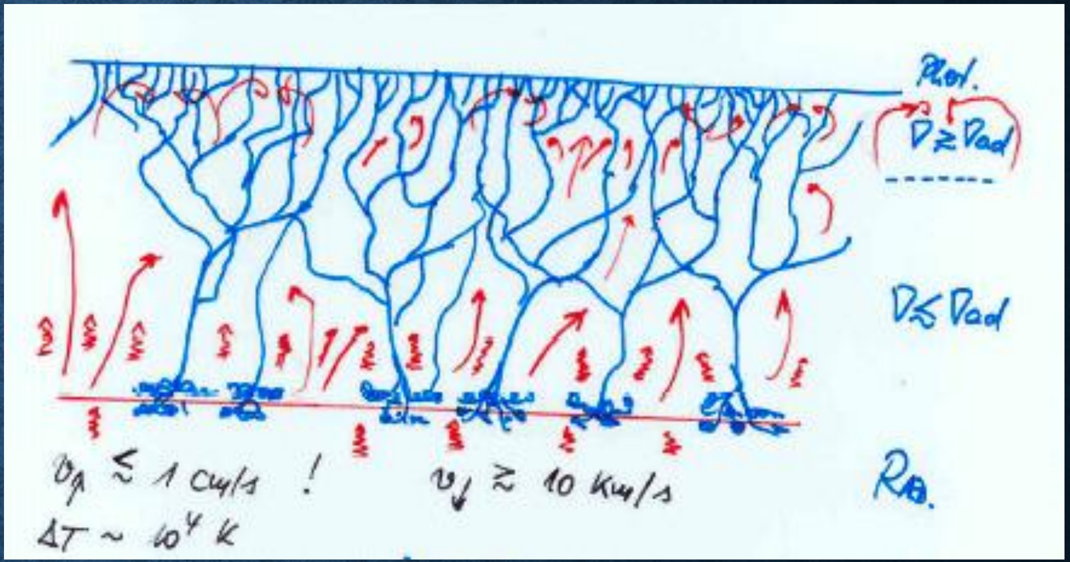


Simulations of Solar Granulation. I. General Properties
R. F. STEIN & Å. NORDLUND
ApJ, 499:914 933, 1998 June 1

SOME RESULTS FROM THE SIMULATIONS

- Strong inhomogeneities (i.e. steep T and v variations)
- High P fluctuations (buoyancy braking)
- Supersonic velocities → Shocks
- Up- vs Down-flows asymmetry, non-local dynamics
- Strong, narrow down-flows vs large -almost laminar- up-flows
- Correlated down-flows and less organized up-flows
- Topology varying with depth
- Granulation is a shallow phenomenon. The down-drafts may cross the entire convection zone!
- The simulations reproduce the main features of the solar granulation
- Hot fragmenting up-flows , cold down-flows in a network
- Timescales, spatial scale, “exploding granules”
- Average spectral line profiles!

COHERENT PLASMA STRUCTURES



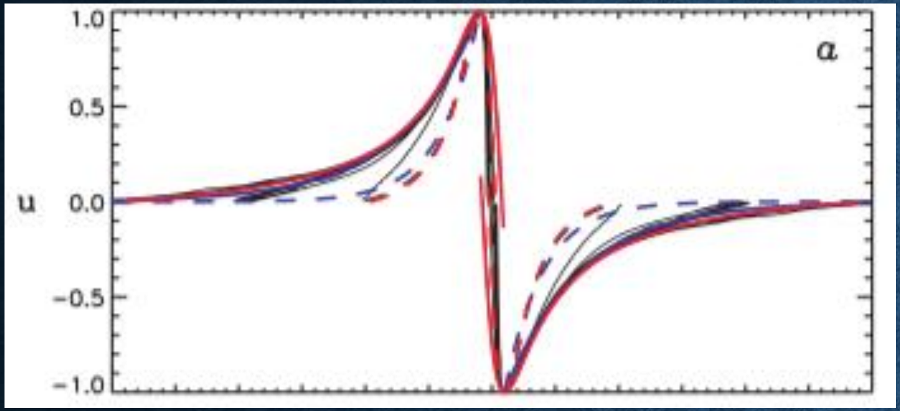
New interpretation
(of lab & numerical experiments):

- turbulent down-drafts, quasi-laminar iso-entropic up-flows
- flows driven by surface entropy sink (radiative cooling)
- non-diffusive transport
- larger scales (meso/super-granulation) driven by compressing and merging

Spruit, H.C., 1997, MemSAIt, **68**, 397

- Bulk of the fluid almost passive
- Plumes and thermals crossing all the convective zone
- Connection between topmost and bottommost layers
- Strong overshooting
- Plume formation at 'typical' distance
- Pattern formation

n-body advection model 1/3



[Rast 2003]

Downflow driven convection

- The down-flow creates an advection field:

  $V\, exp(-d/\sigma)$

- Down-flow intensity decays exponentially with time:

  $V(t+\tau) = V\, exp(-\Delta t/\tau)$

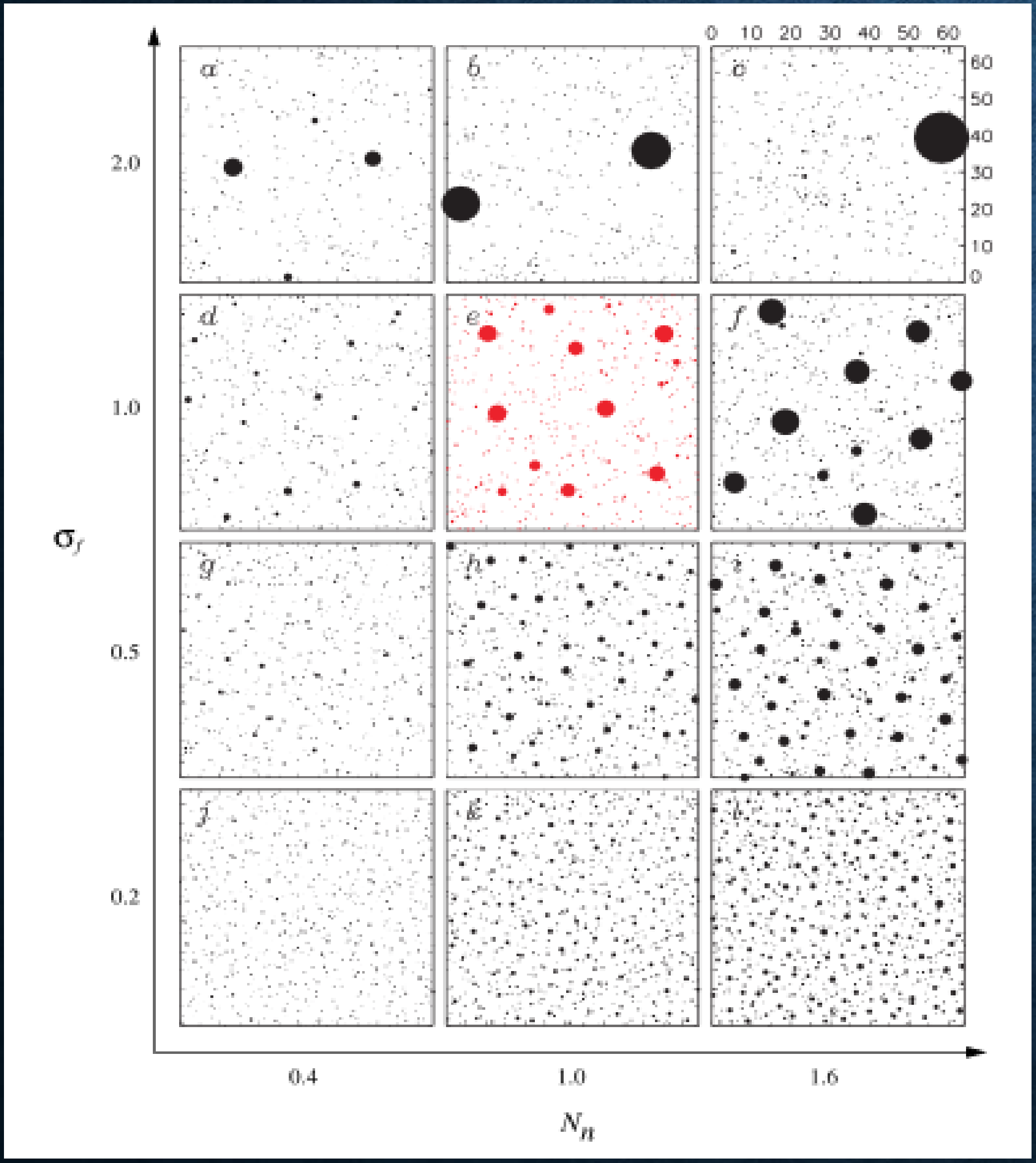
The rules:

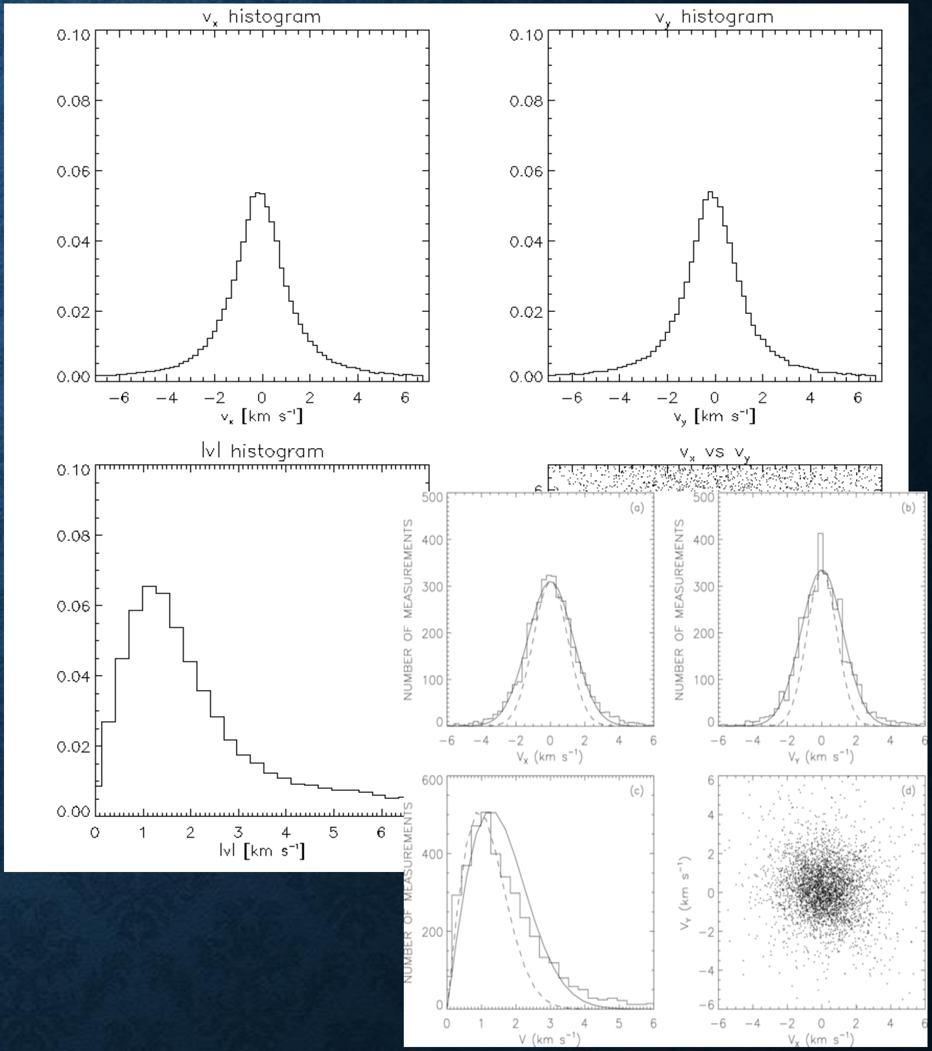
- Periodic toroidal domain
- N down-flows in random initial positions with Gaussian V distribution
- The down-flow motion is due to the combined effect of all the other down-flows
- Down-flows merge if distance < 1 px
- Adaptive time step:

  Δt = min(distance) / max(velocity)

- Total flux is conserved by introducing new down-flows in random positions

n-body advection model 2/3





Chitta et al., 2012

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