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The influence of the Kelvin-Helmholtz instability on the shape and decay of molecular clouds remnants moving behind the shock wave after a supernova explosion

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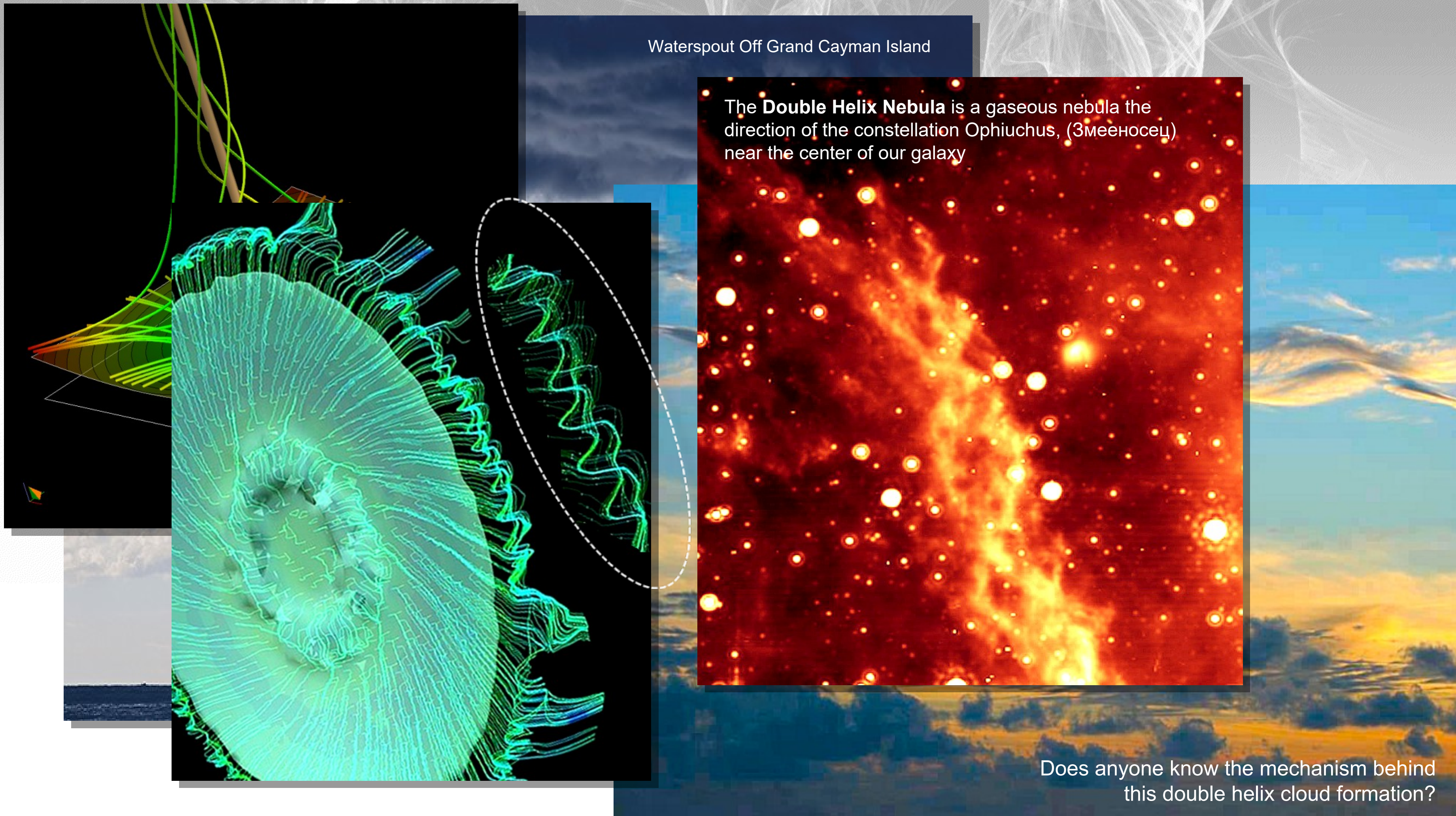
Vortex nature of the environment



Waterspout Off Grand Cayman Island

The **Double Helix Nebula** is a gaseous nebula the direction of the constellation Ophiuchus, (Змееносец) near the center of our galaxy

Does anyone know the mechanism behind this double helix cloud formation?

Collision of molecular clouds MCs and SW/SNR

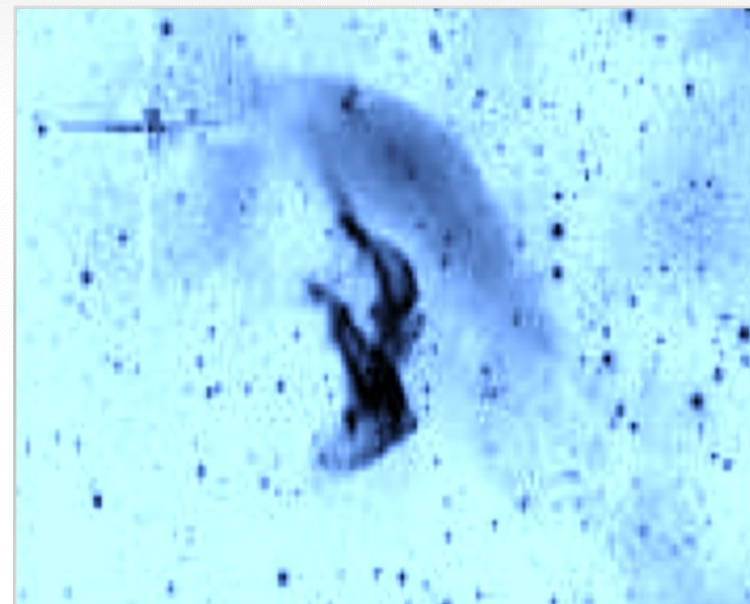
S. Temporin, R. Weinberger and B. Stecklum,
A photo-ionized canopy for the shock-excited Criss-Cross Nebula, A&A, Vol. 467, 1, 2007

In 1997, a new optical nebula with a filamentary morphology was discovered. A photoionized, dome-shaped appearance of the Criss-Cross Nebula, formed by a strong shock wave (presumably following a supernova explosion), has been recorded. Because of its unique shape, it is called as nebula “крест-накрест”.

The researchers noticed a distinct arc of optically observable nebula near Criss-Cross, which was interpreted as a SW/SNR interaction.

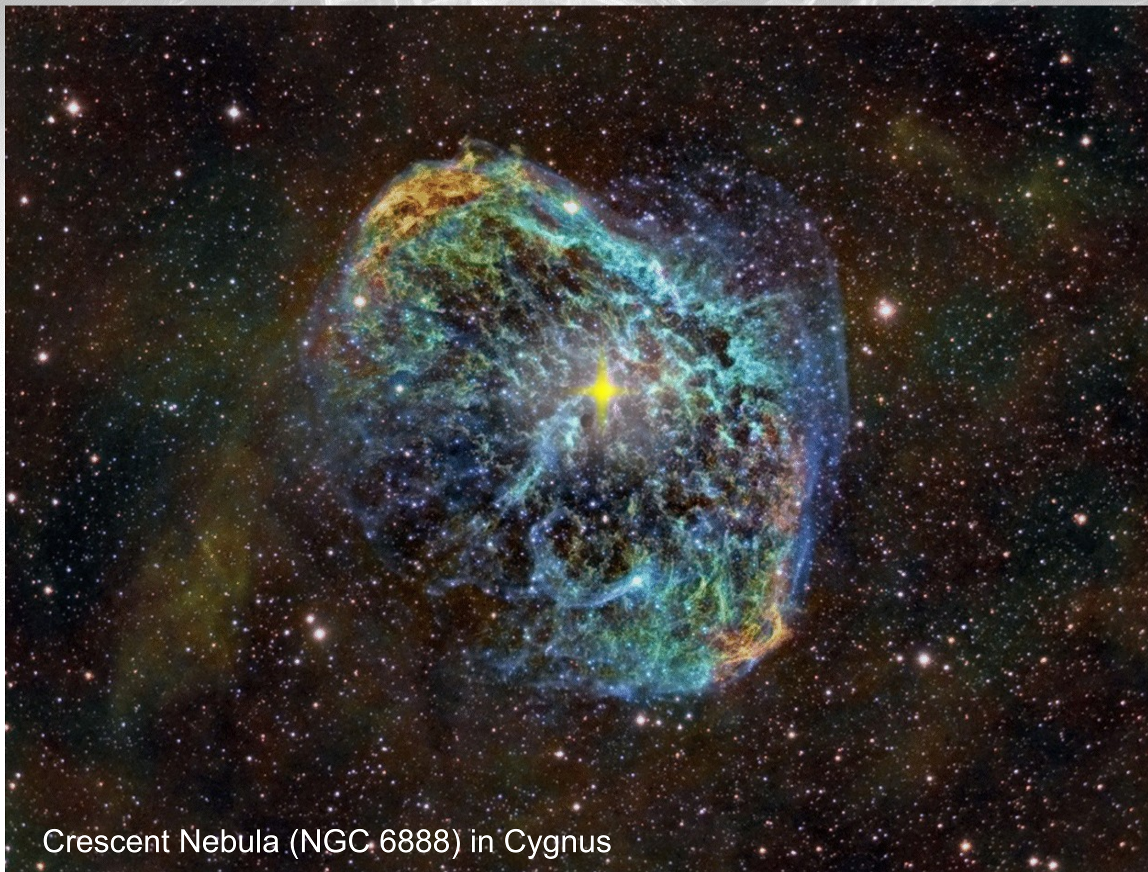
The Criss-Cross was formed by slow action from an expanding relic cold spot or Eridani supervoid, but the observed broad arc is definitely photoionized and may be a residual trace of the SNR.

Long-ago supernova remnants (SNRs) fill large volumes of space in the universe. They contain giant regions of condensed gas and dust (clumps, molecular clouds) created by the SN explosion or formed by the stellar winds of their predecessors. During evolution, a certain number of clouds will be destroyed and scattered in the shock SW/MC/MC interaction.



Stellar Wind (SNE)/MCs interplay

Another possible scenario is: |●- SN remnants and Star Wind /MCs.



Crescent Nebula (NGC 6888) in Cygnus

NGC 6888 - Crescent Nebula (Полумесяц), is a cosmic bubble about 25 light-year across, blown by winds from its central, bright, massive star, classified as a Wolf-Rayet star (WR 136). NGC 6888 is about 5000 ly away in the constellation Cygnus (Созвездие Лебедя).

D = 25 ly (7,66 ps).

Hubble palette:
RGB: SII-sulfur, Hu-hydrogen, OIII-oxygen.

Wolf-Rayet star ejects substance order one $M_\odot$ per 10000 years.

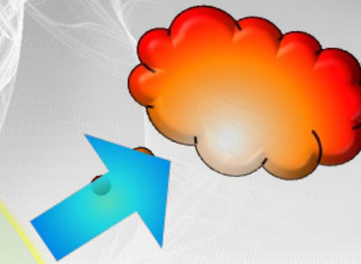
Nebula structure is a result of interplay between powerful stellar wind with remnants after supernova blast (or possible MC's collision). Prospective explosion of supernova can trigger a new giant formation.

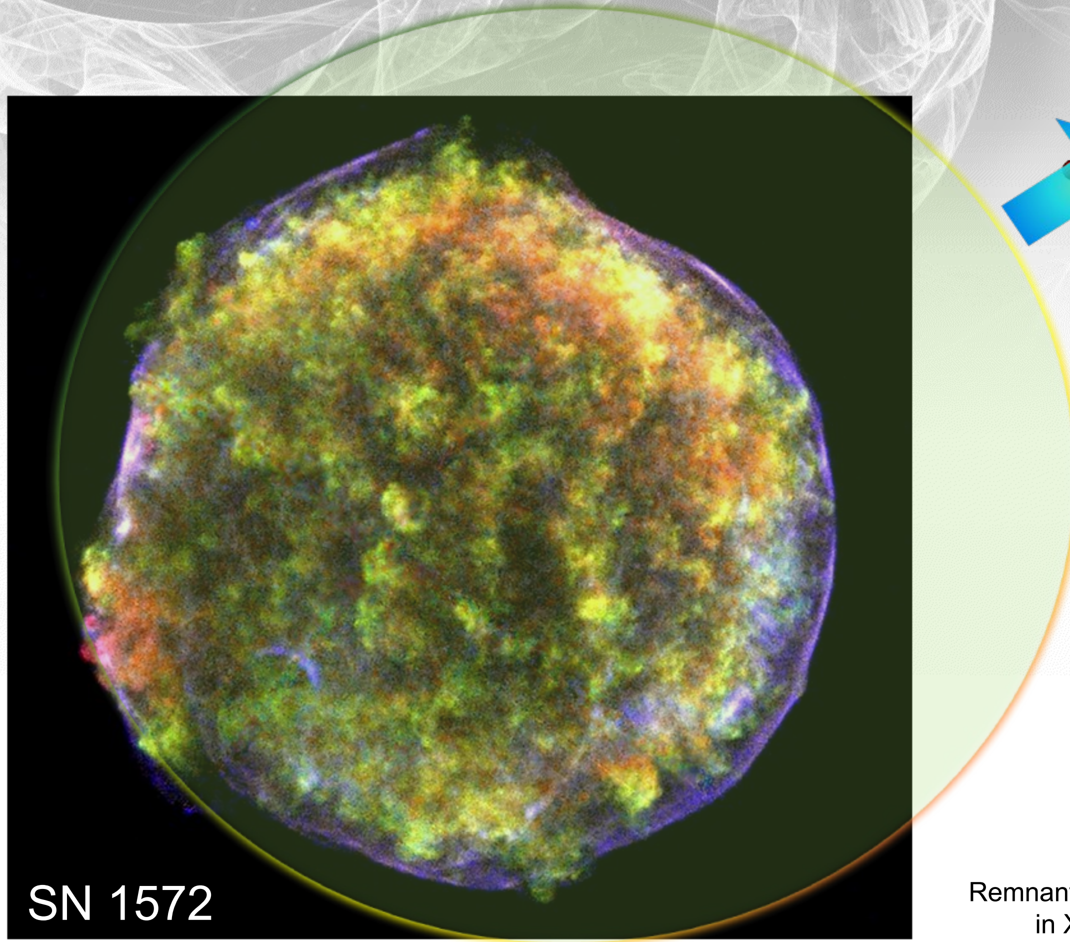
Motivation

SN 1572 (*Tycho's Supernova*), or B Cassiopeiae, was a supernova of Type 1a in the constellation Cassiopeia, one of eight supernovae visible to the naked eye in historical records. It appeared in early November 1572 and was independently discovered by many individuals.

A **Type Ia supernova** is a type of SN that occurs in binary systems (two stars orbiting one another) in which one of the stars is a white dwarf.

Its SNR has been observed optically but was first detected at radio wavelengths. It is often known as 3C 10, a radio-source designation, although increasingly as Tycho's supernova remnant (Ticho Brahe's – 1572 - extensive work *De nova et nullius aevi memoria prius visa stella* ("Concerning the Star, new and never before seen in the life or memory of anyone"), published in 1573 with reprints overseen by Johannes Kepler in 1602 and 1610.





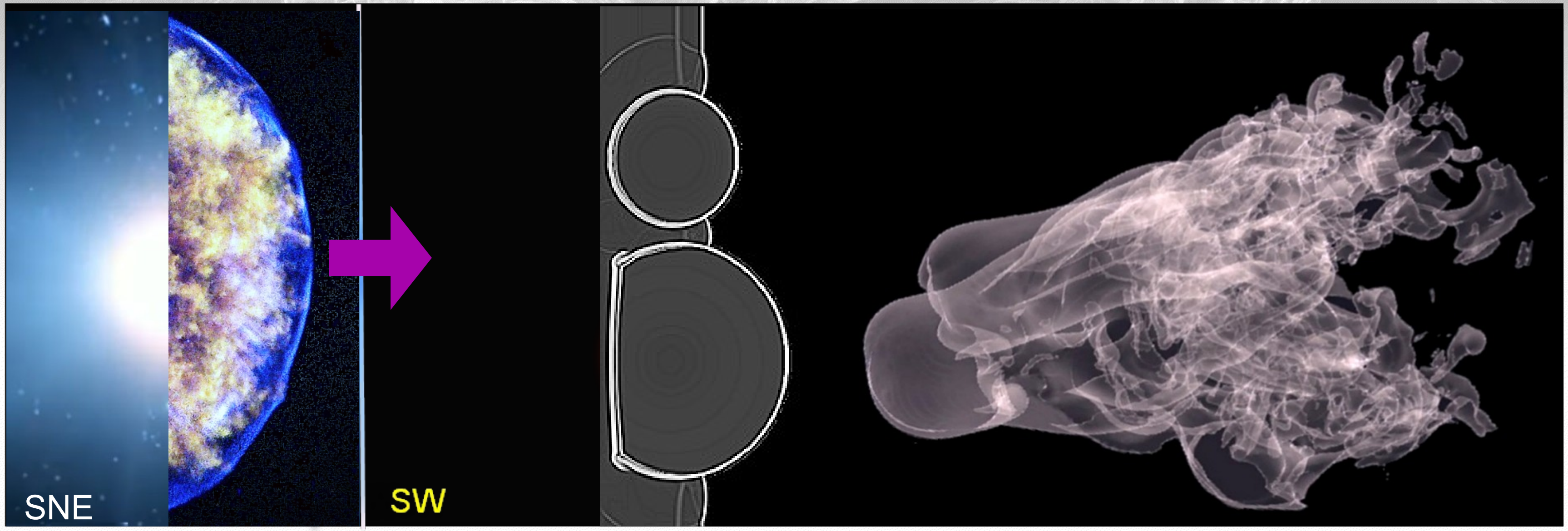
Remnant SN 1572 as seen in X-ray light from the Chandra X-ray Observatory

In-house software is used in simulation. The code to solve Eulerian equations (authorized "Black Matter") is intended for the numerical solution of problems of high-speed gas dynamics on high-performance clusters of hybrid architecture with a high degree of parallelization of calculations.

High-order difference schemes used in code have guaranteed monotonicity preservation of conservation laws. The second-order accurate total variation diminishing (TVD) approach used provides high resolution capturing of shocks and prevents unphysical oscillations, therefore it describes the local discontinuity preserving hyperbolic conservation laws.

The developed program uses heterogeneous parallelization of calculations on the CPU and GPU. When performing calculations on GPU, OpenACC technology is used, and on IntelXeon processors, Coarray Fortran technology is used. A number of tests have shown that parallelization with this approach significantly reduces command execution time.
In the latest program version, AMR (Advanced Mesh Refinement) grids began to be used to improve the accuracy of calculations in high-gradient and sharply intermittent flow areas. To aim of validation of AMR addition in code some tests were performed. One of them was the numerical calculation of the gravitational potential of collapsing sphere, with five AMR levels of refinement.
In test we numerically simulated the gravitational collapse of a gas spherical volume, repeating the initial data on the distribution of the matter density of a centrally condensed sphere. The obtained simulation results were quite satisfactory in terms of matching accuracy. The Intel Cluster Edition 2018 compiler was used to implement the code. PGI Fortran was used for GPU computing.
Additional verification of the computational code using AMR was carried out in [*Rybakin B. Dynamic evolution and morphological analysis of supersonic turbulence arising during the collision of prolate and spherical clouds. Acta Astronautica, 215, 325-332, (2023)*], where the simulation results for MC of prolate and spherical form were compared with solution of Chandrasekhar. The agreement between the numerical and analytical solutions was obtained within the specified accuracy.
In order to increase computational performance, a parallelization algorithm on GPUs was used additionally. Data management in code with CUF kernels was done explicitly. Device-side arrays are declared with the device and pinned attribute, and data is explicitly passed from host to device and back. For not very large grid sizes (up to three hundred million grid points), GPU parallelization gave better results than OpenMP, but as the grid size increases, GPU performance some decreases. It was checked on slightly outdated processors. On the new ones, taking into account tensor cores on the GPU, everything changes.

One of the goals of the numerical modeling was to study the shape change and evolution of emerging coherent structures in cloud formations (MCs) imbalanced after collisions with a strong shock wave (SW) from a supernova explosion.



B. Rybakin, V. Goryachev. Coherent instabilities leading to fragmentation of molecular clouds interacted with shock wave of supernova blast remnants. In Turbulence, Waves and Mixing: In Honor of Lord Julian Hunt's 75th Birthday, Ed. S.G. Sajjadi and H.J.S. Fernando, IMA, King's College, Cambridge, 2016

The masses of each cloud were specified accordingly 0.005 $M_\odot$ and 0.007 $M_\odot$.

MC$_s$: T_{cl} = 100 K, $\rho_{cl} = 1.075\times10^{-22}$ g sm^{-3} **ISM**: $\rho_{ism} = 2.15\times10^{-25}$ g sm^{-3} $T_{ism} = 10^4$ K

$\chi = \rho_{cl} / \rho_{ism} = 500$ M = 7, u_{sh}= 104 km/s, $\rho_{sh} = 8.6\times10^{-25}$ g sm^{-3}, $T_{sh} = 1.5\times10^5$ K

Post-shock front space ~ 2-5 pc. t_{swoc} : 2000 years.

Computational area dimensions: 3.2×1.6×1.6 pc. Computational grid: 2×1024^3 nodes.

SW/MCs – evolution of remnants and eddy formation shown by numerical schlierens for the central section of cloud remnants for the time interval t = 20000 - 1200000 years.

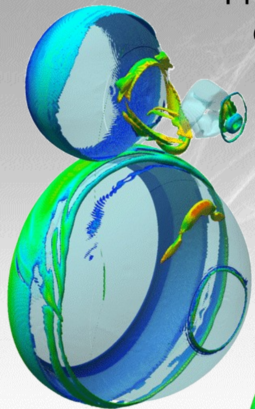
MCs morphing: from ring vortices to elongated filaments, horseshoes and hairpins

From the moment the shock wave begins to penetrate into molecular clouds, the reflected shock waves push apart closed folds of matter of different densities, forming KH vortices. Reflected secondary shock waves pass through layers of matter and consolidate volumetric condensations into thread-like structures.

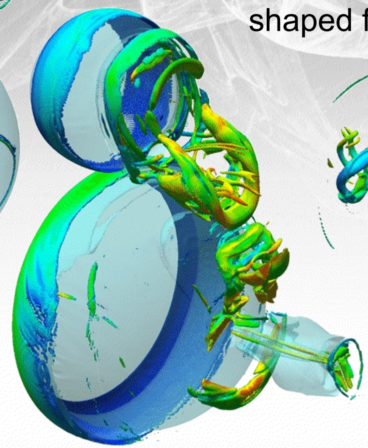
Vortex rings are continuously formed, they are transformed into a horseshoe-shaped form, stalk-shaped formations and arc-shaped closed gas condensations are created, which are reformatted with an increase in the local gas density in the concentrations.

The vortex rings behind the main shock wave (the advancing SW wave is indicated in outline) form connected vortex filaments (trefoil-shaped structures).

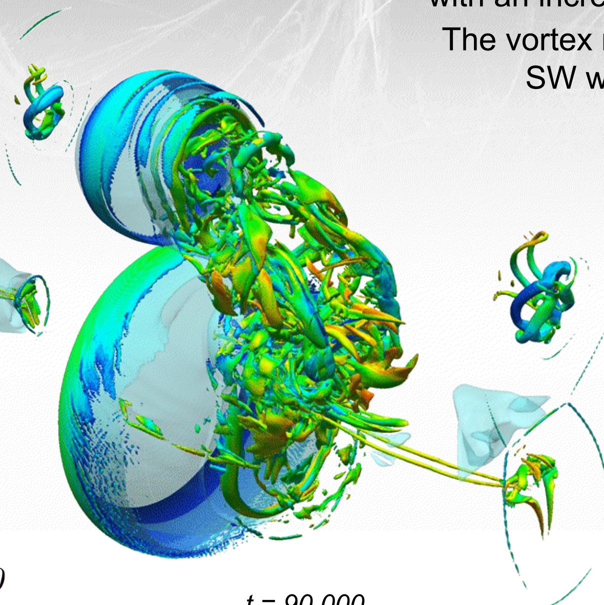
$$\Omega = \nabla \times \boldsymbol{V}$$



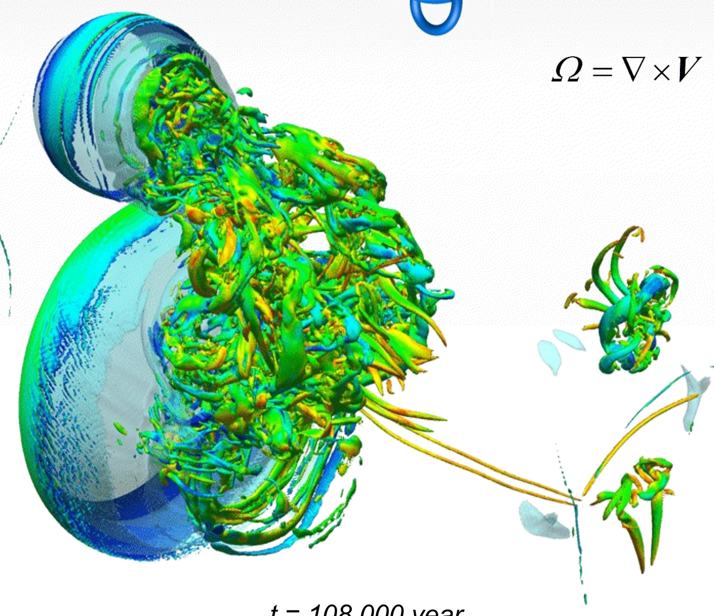
t = 50,000



t = 70,000



t = 90,000

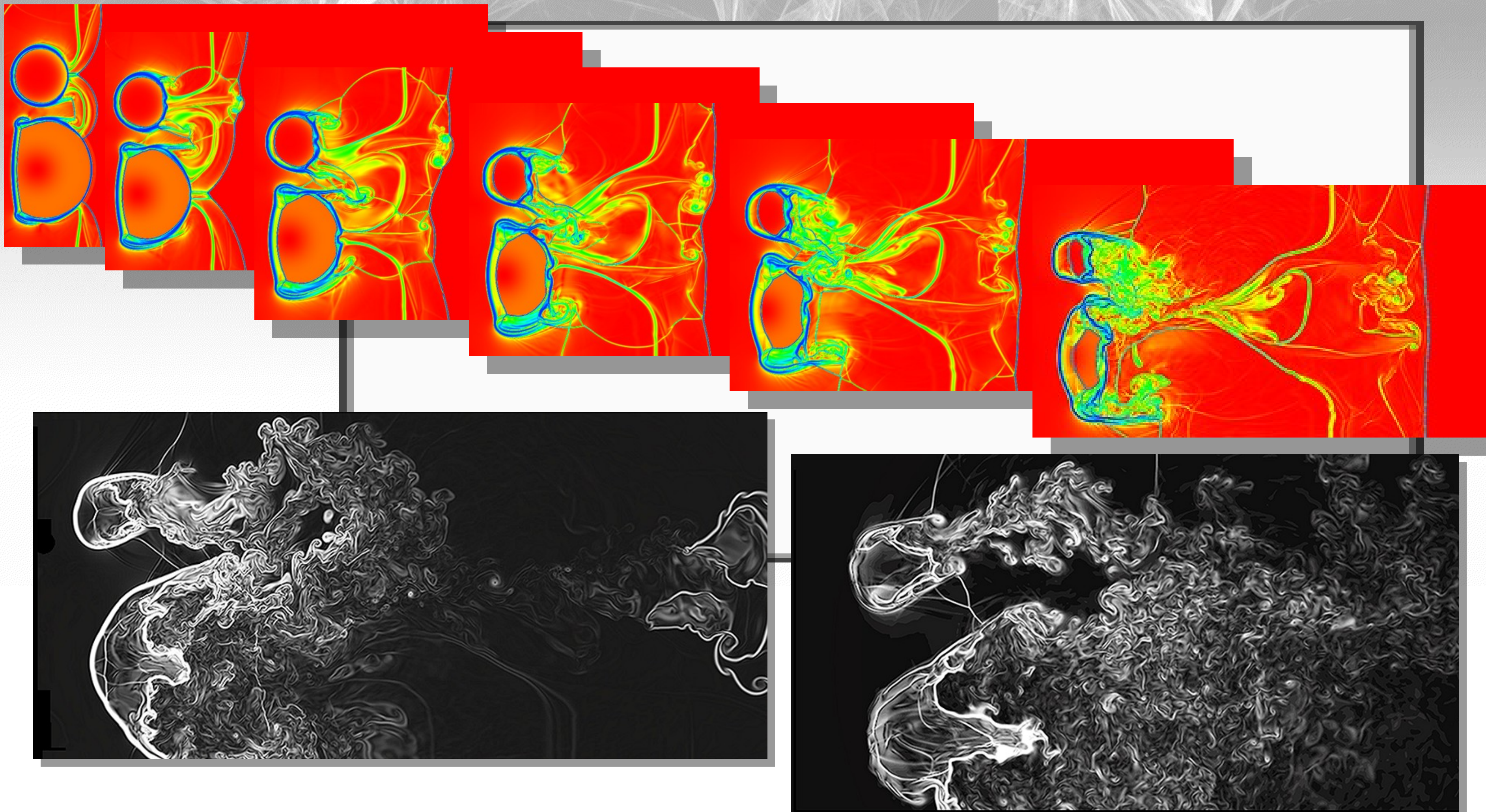


t = 108,000 year

$$Q = \frac{1}{2}\left(u_{i,i}{}^{2} - u_{i,j}u_{j,i}\right) = \frac{1}{2}\left(\|\boldsymbol{\Omega}\|^{2} - \|\boldsymbol{S}\|^{2}\right) > 0$$

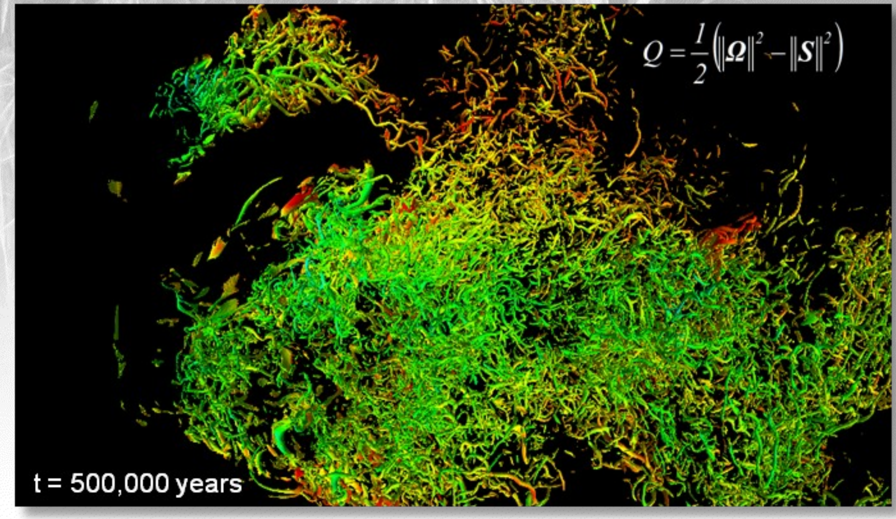
The interference of reflected density waves and the gradient change in supersonic velocities lead to deep differentiation of gas density, the value of which increases to χ ~ 20,000. Layers of condensed matter are concentrated inside gas shells of cylindrical-conical shape, elongated in the direction of propagation of the main shock wave.

Evolution of SW/MCs post collision formation – numerical shliriences of MCs meridional section

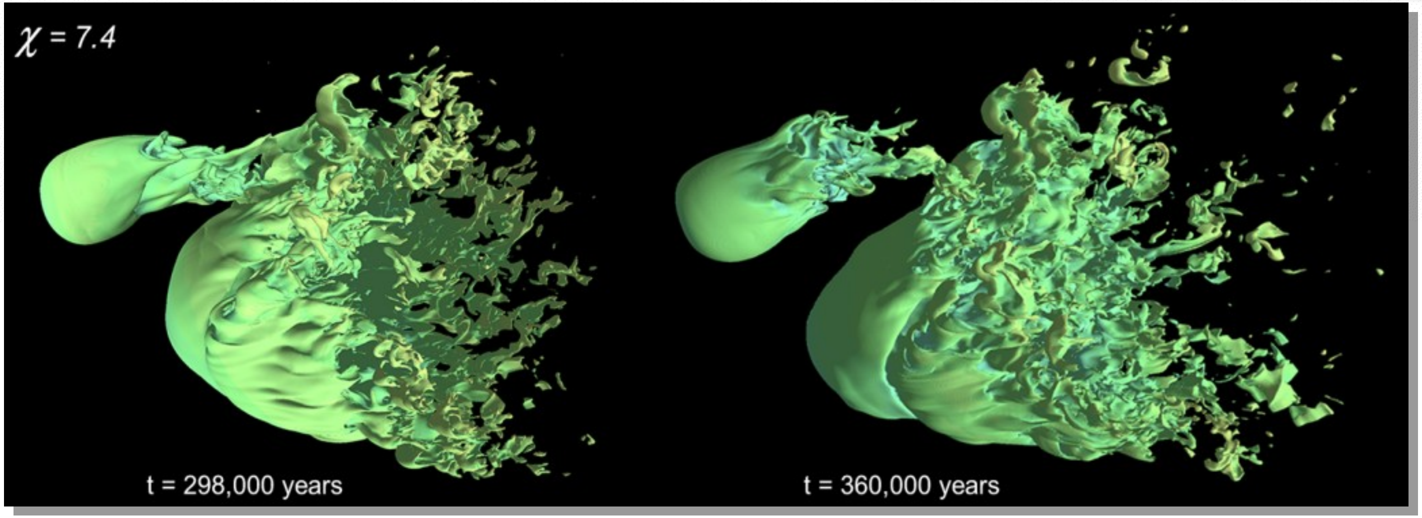


Evolution of MCs remnants after passing SW

$$Q = \frac{1}{2}\left(u_{i,i}^{\ 2} - u_{i,j}u_{j,i}\right) = \frac{1}{2}\left(\|\boldsymbol{\Omega}\|^2 - \|\boldsymbol{S}\|^2\right) > 0$$

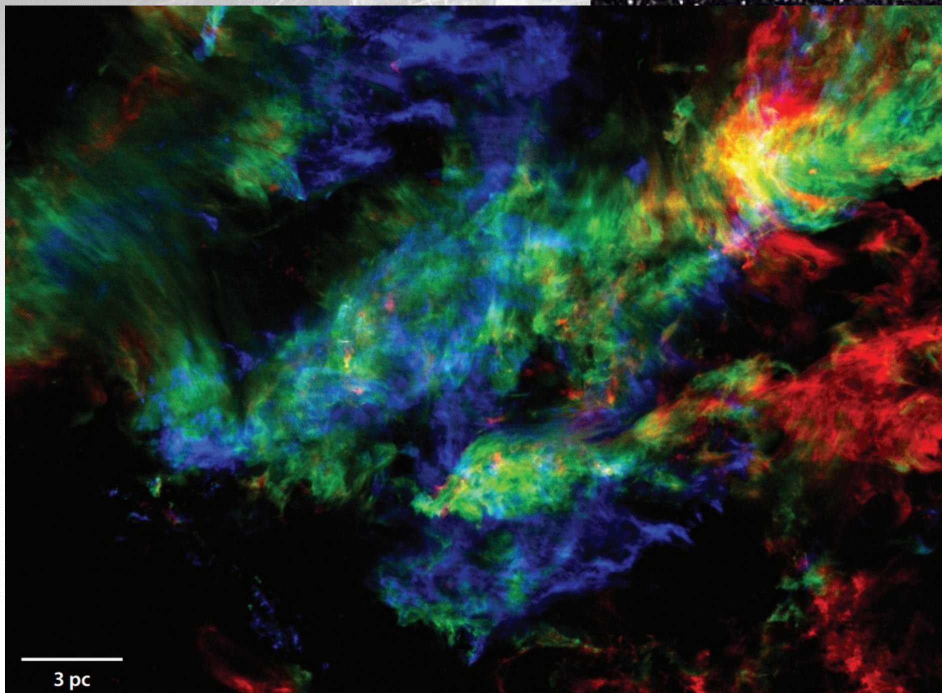


The eddy identification method using the Q-criterion was one of the first Eulerian local approaches (Hunt et al.). Vortex regions are identified where Q, the second invariant of the velocity gradient, is positive. The method is convenient and often used due to its simplicity and ability to effectively display vortex structures.



Samples of some MCs and their conical deformation under influence of changes in velocity

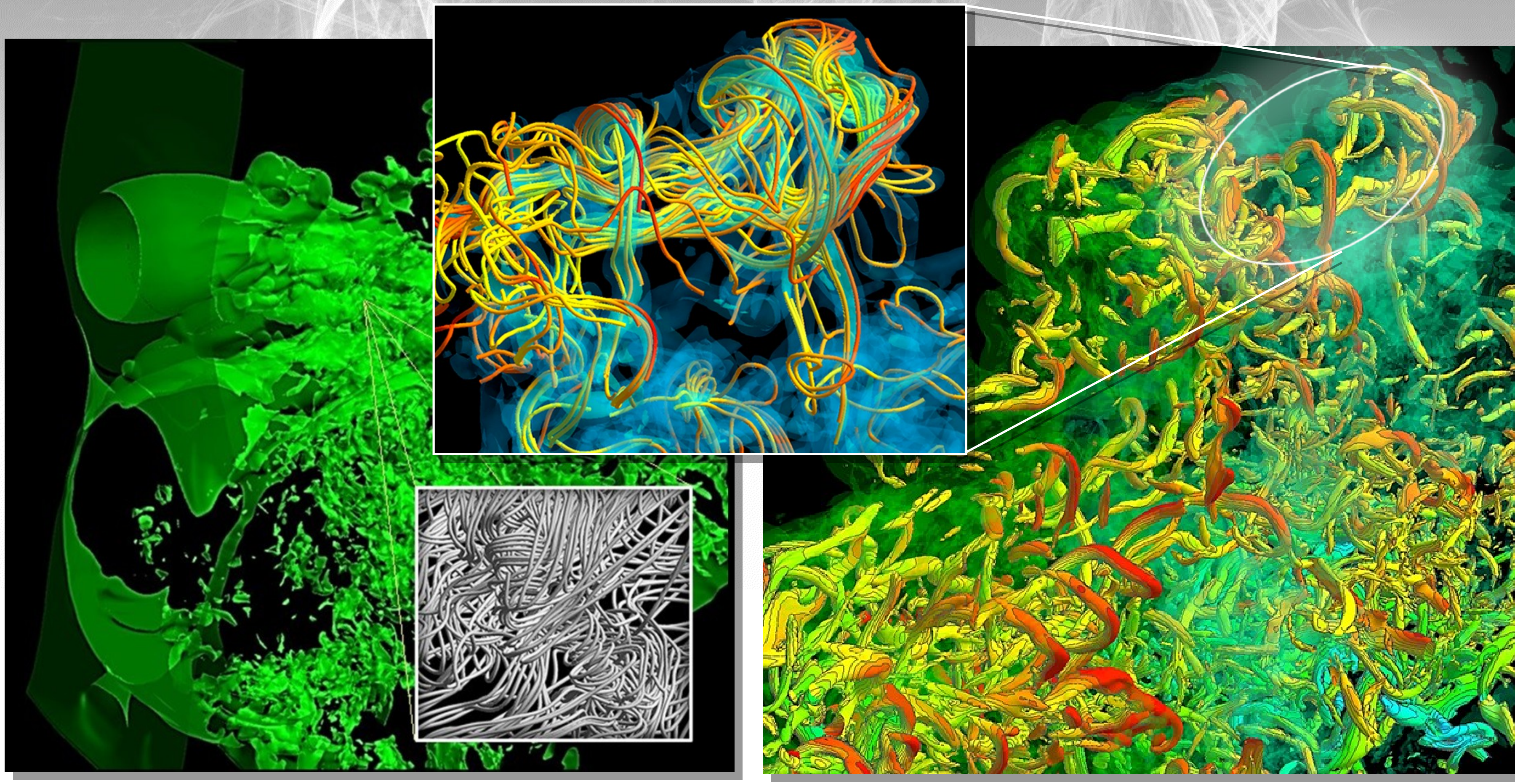
The Smith Cloud, discovered in the 1960s, is travelling at over 310 kilometers per second, and if it were visible in the sky it would be 30 times larger than the full Moon.



The figure illustrates the intricate gas distribution and velocity structure of molecular clouds that is revealed by high spatial dynamic range imaging of CO emission from nearby clouds. An image of CO emission from the Taurus molecular cloud integrated over velocities intervals 0–5 km s−1 (blue), 5–7.5 km s−1 (green), and 7.5–12 km s−1 (red), illustrating the complex velocity field of the Taurus cloud. The data are from Narayanan et al. (2008).

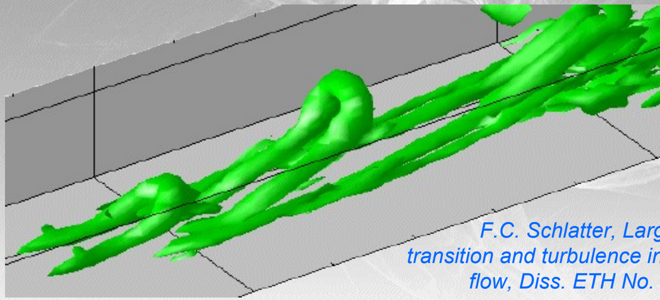
M. Heyer1 and T.M. Dame, Molecular Clouds in the Milky Way, Annu. Rev. Astron. Astrophys., 53: 583–629, (2015)

Shear instability KHI and hairpin vortices during transformation of MCs

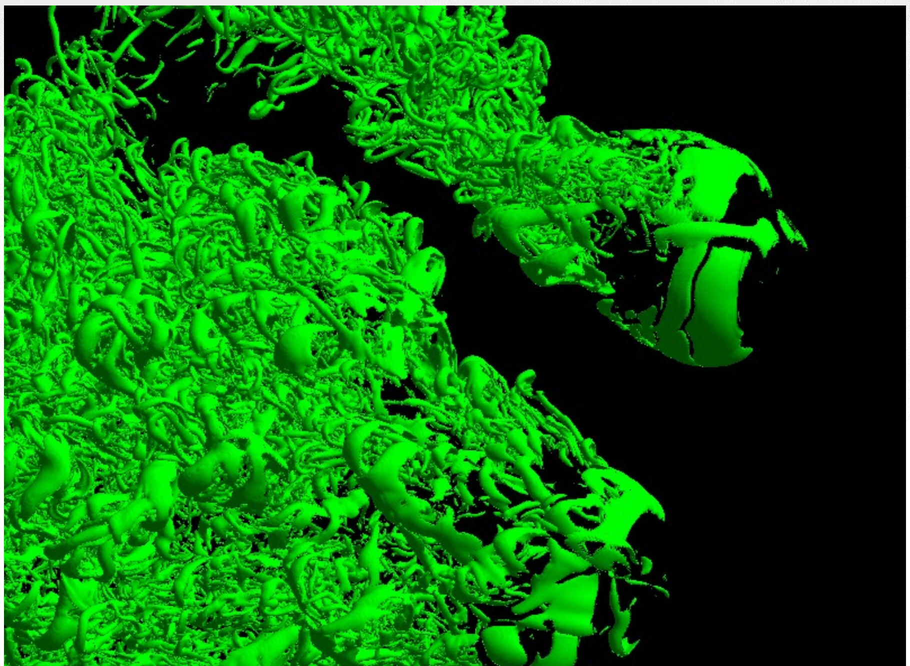


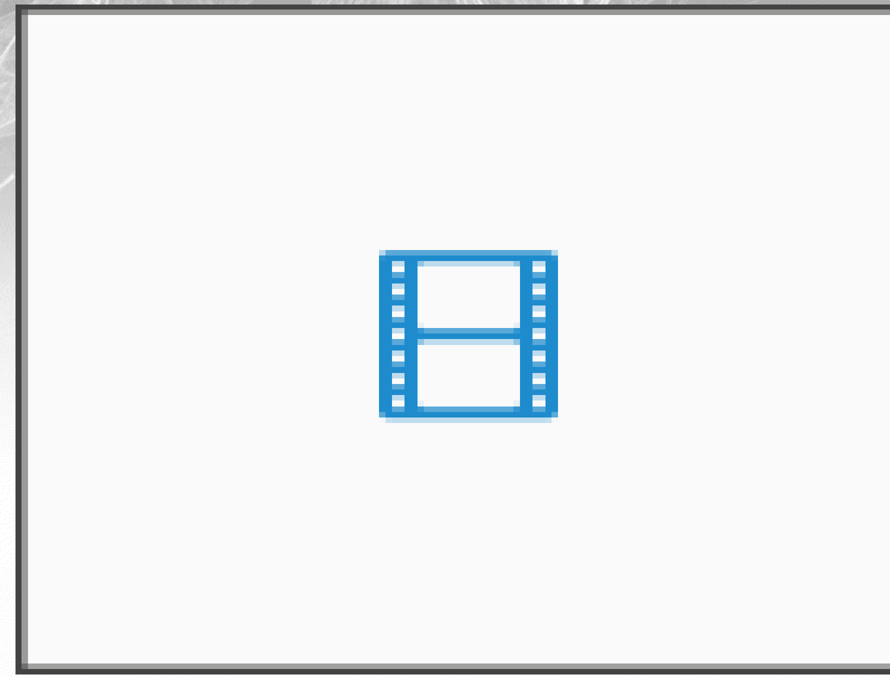
Formation of vortex formations inside and on the surface of MCs residues: KH instability - elongation of loops - hairpin vortices

Vorticity distribution shown by Q-vortices



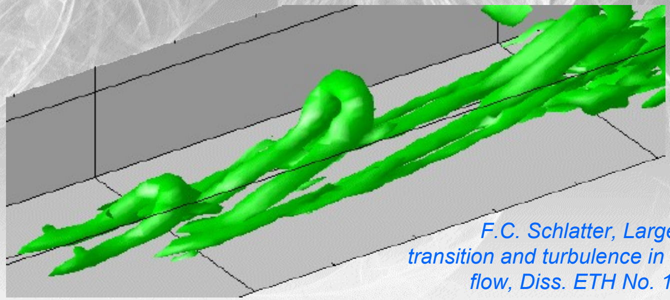
F.C. Schlatter, Large-eddy simulation of transition and turbulence in wall-bounded shear flow, Diss. ETH No. 16000, Zurich, 1975.





Turbulization of cloud remnants with representation of hairpin vortices by isosurfaces of the Q-criterion (50000).
The value of the velocity Ux in the range -3 < Ux < 10 at the stage of evolution MCs - t = 600,000 years is highlighted in color.

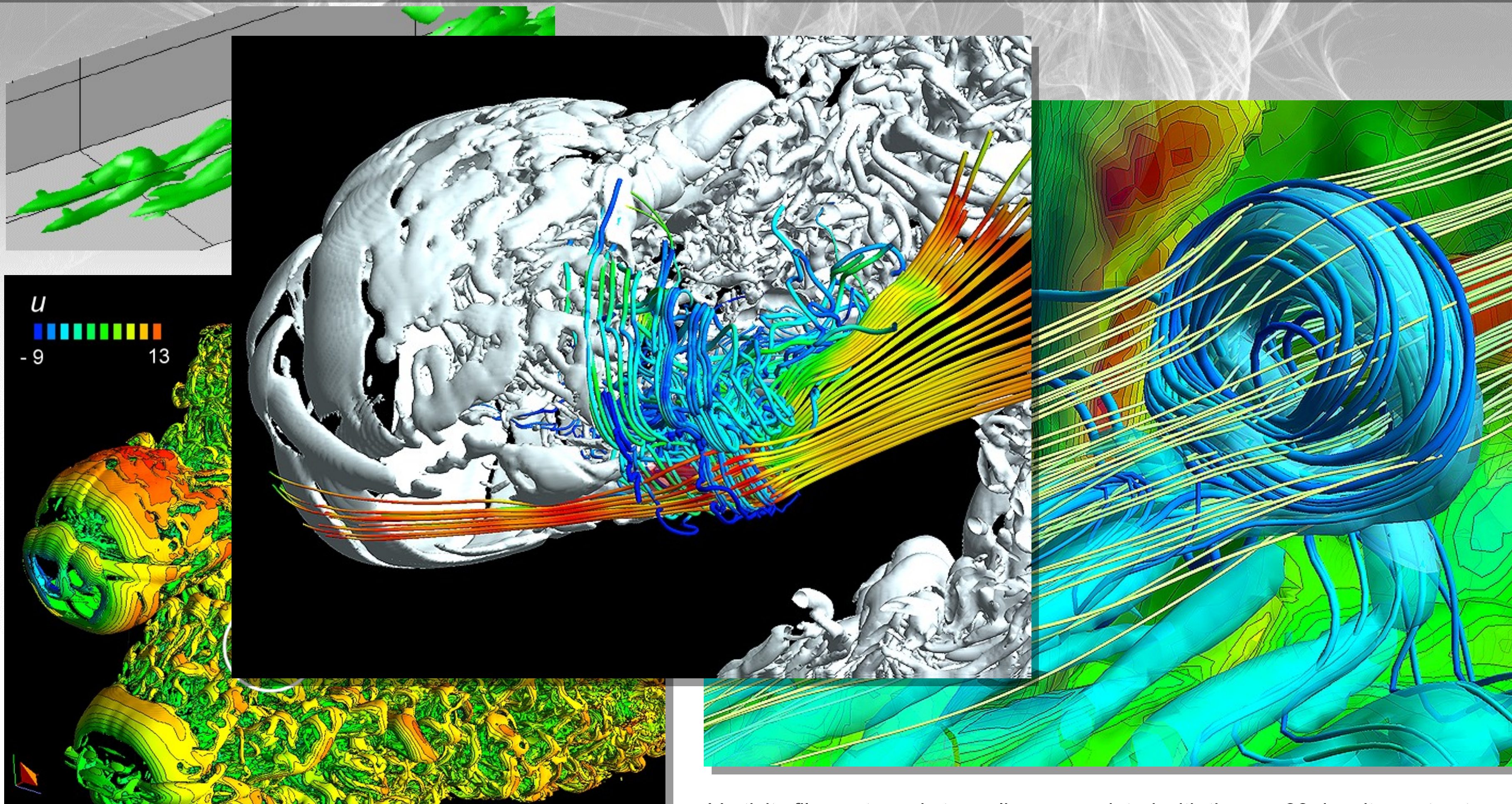
Vorticity distribution in different scale



F.C. Schlatter, Large-eddy simulation of transition and turbulence in wall-bounded shear flow, Diss. ETH No. 16000, Zurich, 1975.

$$Q = \frac{1}{2}\left(u_{i,i}{}^{2} - u_{i,j}u_{j,i}\right) = \frac{1}{2}\left(\left\|\boldsymbol{\Omega}\right\|^{2} - \left\|\boldsymbol{S}\right\|^{2}\right) > 0$$

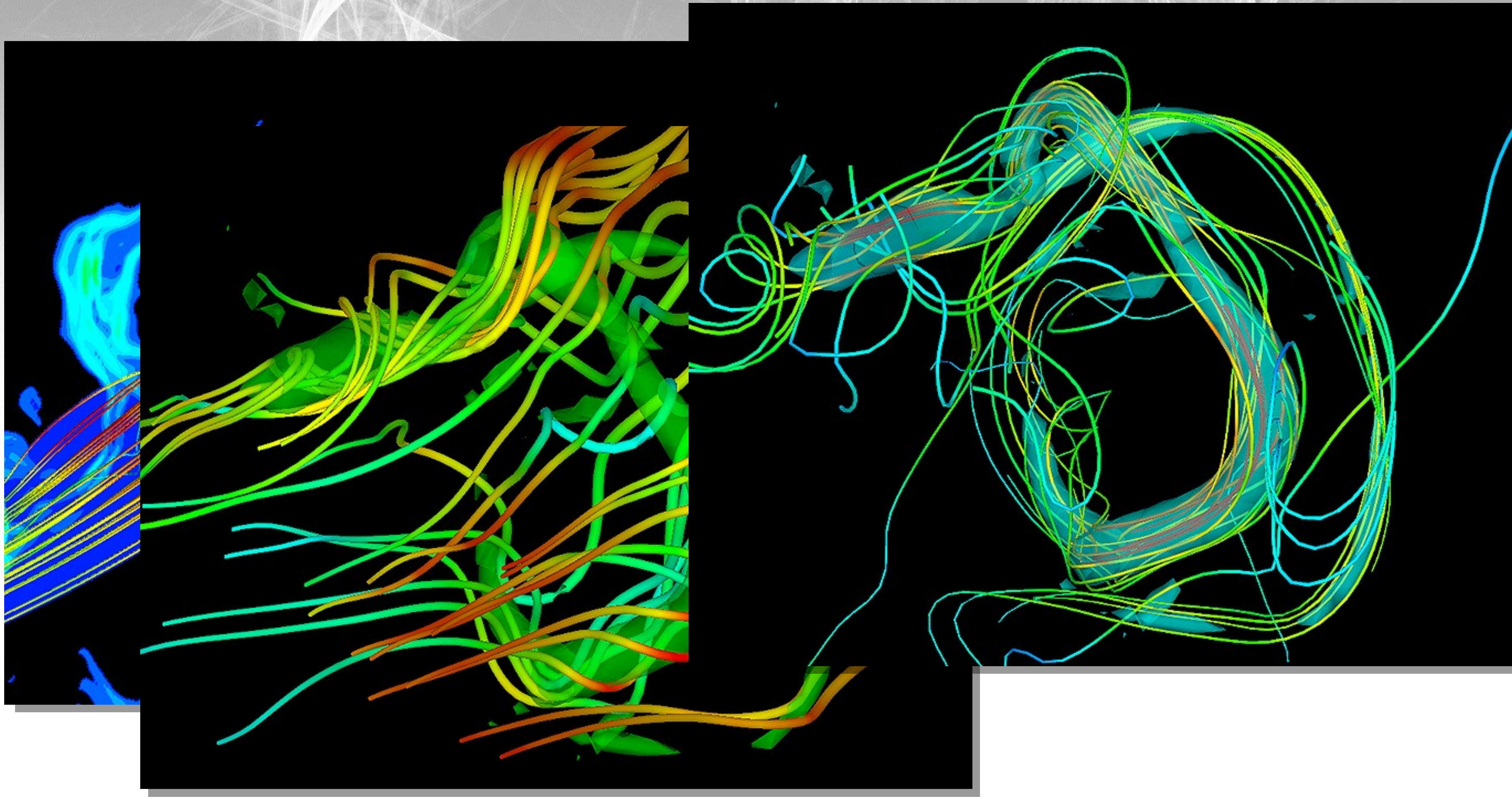
Q - vortices arising when cloud remnants dissipate



Remnants of MCs (Q = 10,000) at stage t = 600,000 years.

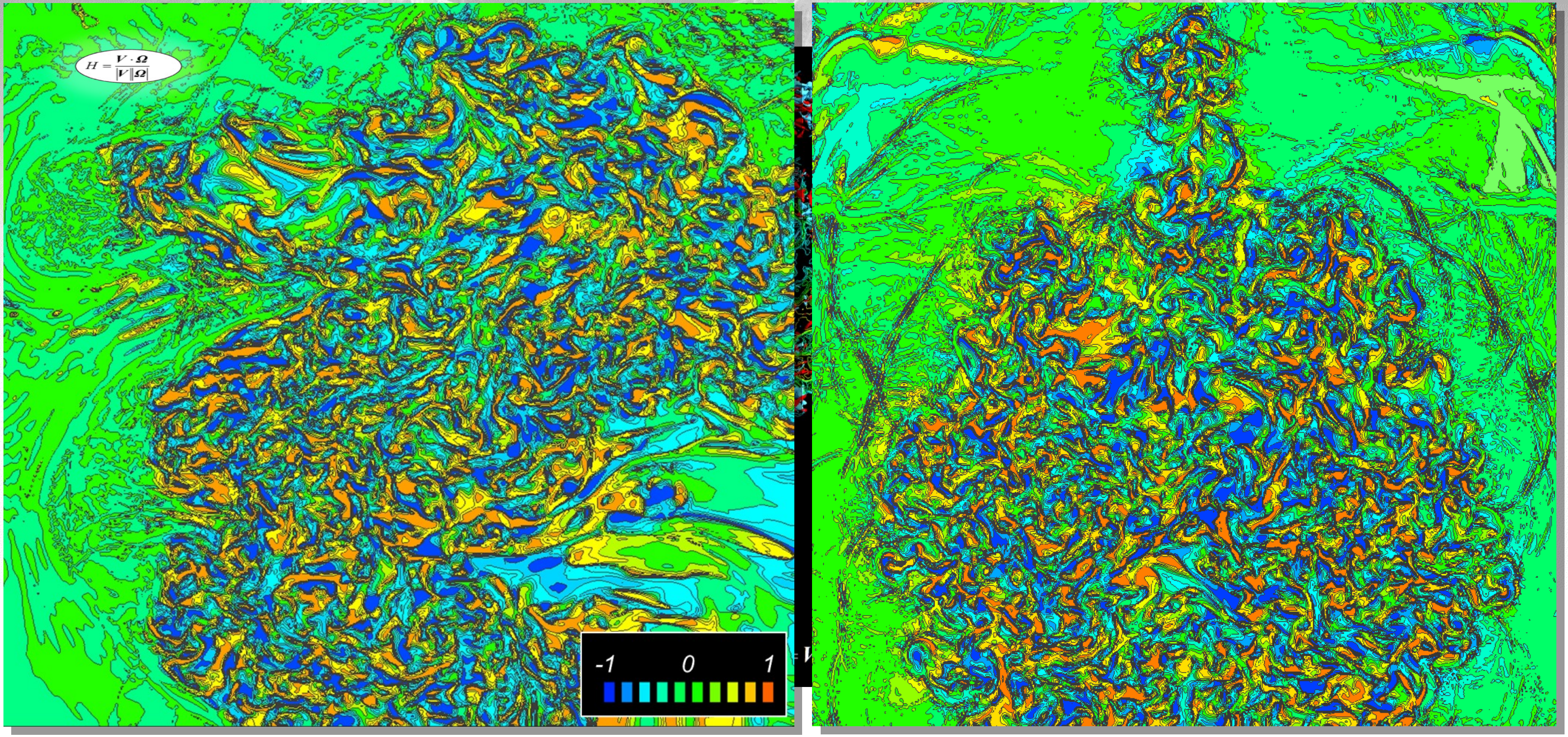
Vorticity filaments and streamlines associated with the χ = 30 density contrast isosurface of the cloud top remnant.

The screw lines formation in some remnants place

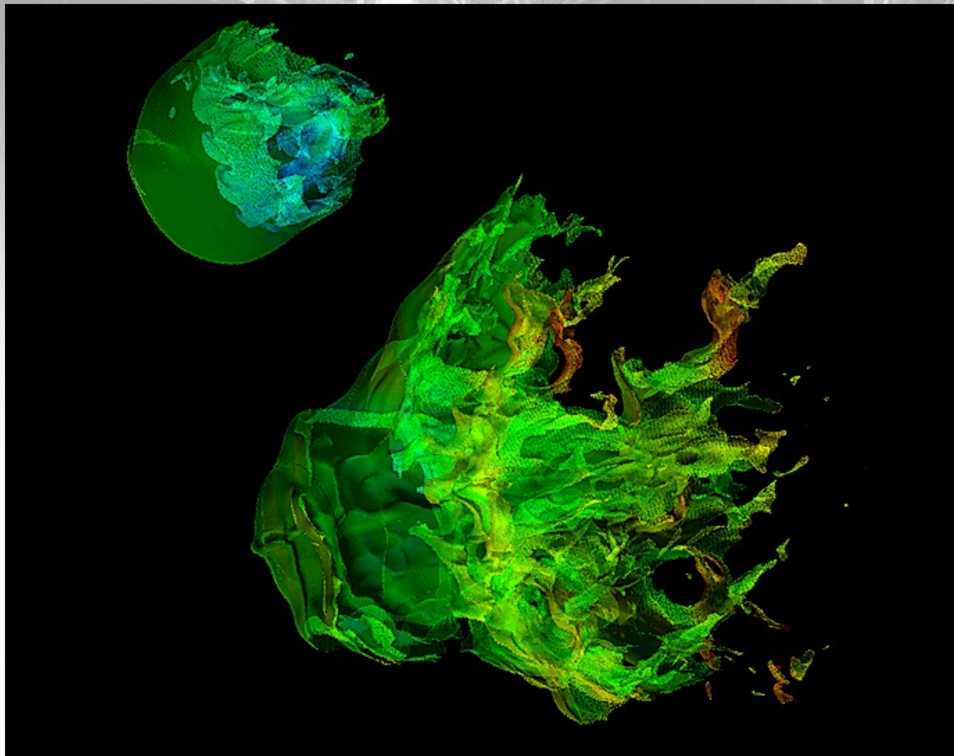


Q – criterion structure: the relationship of fluid stream lines and vortex filaments inside and outside Q - isosurface.

Helicity (normalized) can improve our imagination of vortex MCs remnants



Normalized helicity isoclines H shown in meridional and orthogonal cuttings of MCs at evolution stage t = 300 000 years



Thank You!