SCIENTIFIC CONFERENCE
Russian Supercomputing Days

September 27-28, 2021, Moscow

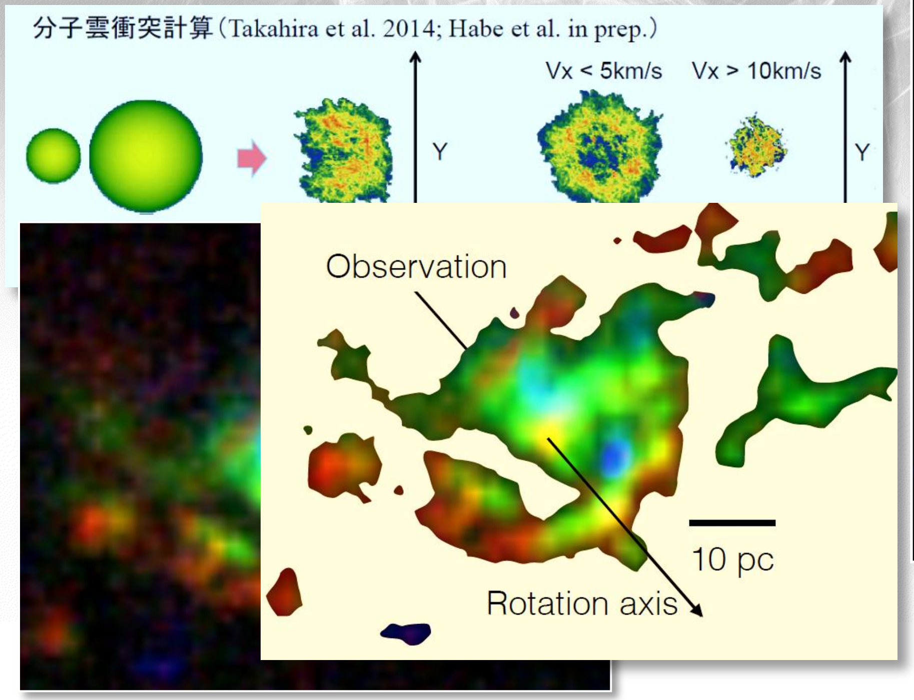
# Clumps and filaments generated by collisions between rotating and non-rotating molecular clouds

**Boris Rybakin***, **Valery Goryachev****

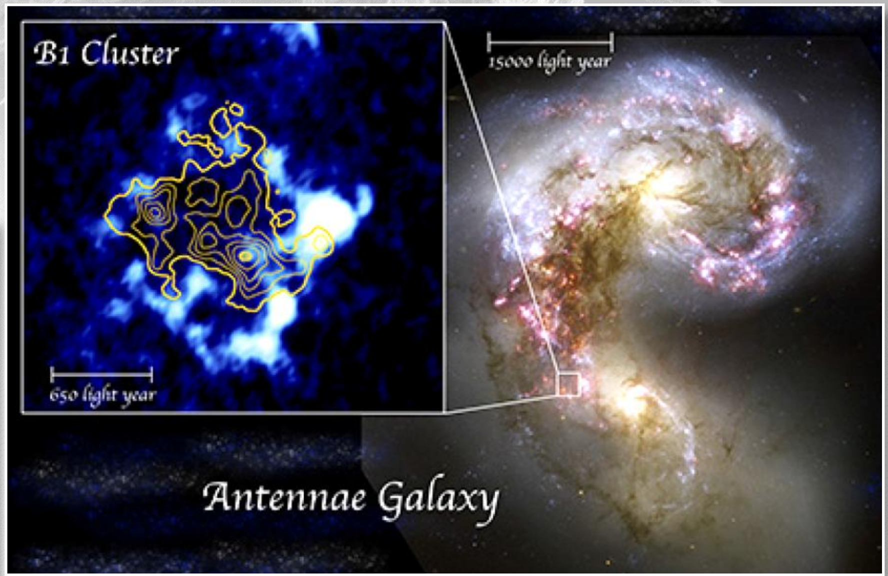
* Dep. of Gas and Wave Dynamics, MSU, ** Dep. of Mathematics, TvSTU

# Collisions between molecular clouds and star origination

The aim of our work is to analyze the results of parallel numerical simulation of collisions between molecular clouds during a head-on impact-penetration, with some displacement cases, and taking into account rotations of nebulae.

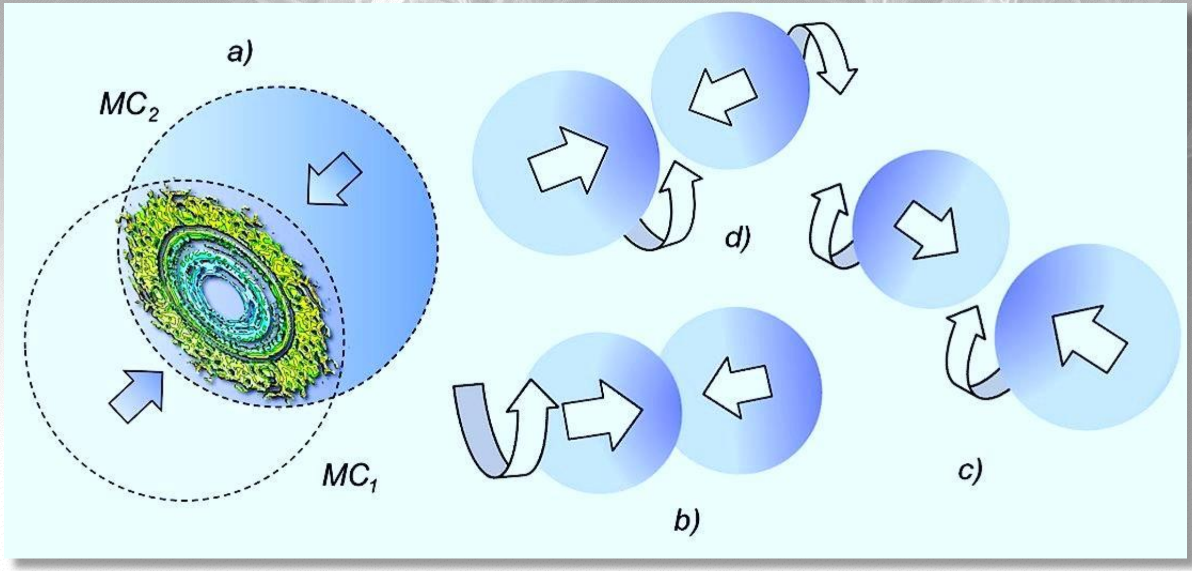



**The dynamic processes in molecular clouds with rotation are just beginning to be studied, the question of what role rotation plays in the evolution of molecular clouds and the creation of pre-stellar zones remains open**. One a recent study of rotation and structure of the spiral molecular cloud G052.24 + 00.74 is presented in [Guang-Xing Li, F. Wyrowski, K Menten. Revealing a spiral-shaped molecular cloud in our galaxy: Cloud fragmentation under rotation and gravity. *A&A*, 598, A96, 1-15, (2017)]




**Examples of two colliding molecular clouds (represented by the blue color and yellow contours) forming star clusters discovered by radio observations.** Images of the Antennae Galaxies and fragment with CCC are shown. Japanese researchers have found that collisions of gas clouds floating in space precipitate the birth of star clusters. [Star Formation Triggered by Cloud–Cloud Collisions, May 10, 2021, Science]. *Nobeyama Radio Observatory, Nagoya University, National Astronomical Observatory of Japan, NASA, JPL-Caltech, R. Hurt (SSC/Caltech), Robert Gendler, Subaru Telescope, ESA, The Hubble Heritage Team (STScI /AURA), Hubble Collaboration, and 2MASS.*

# Initial Conditions in Simulation of ♋ CCC




Scenarios of clouds collision implemented in the study

MC1 Johansson, E. & Ziegler, U., 2011.

MC2 Pittard, J.M. at al. 2009.

Four interaction options were used in numerical experiment:

a) head-on collision without rotation;
b) the impact of the non-rotated cloud with a rotating one;
c) clouds colliding with rotation in the same direction;
d) clouds mutual penetration with a counter rotation.

In some cases, the simulation of CCC with a shift of moving direction was added.

The axes of the rotation of clouds coincided with the impact direction.

# Numerical Realization and Parallelization

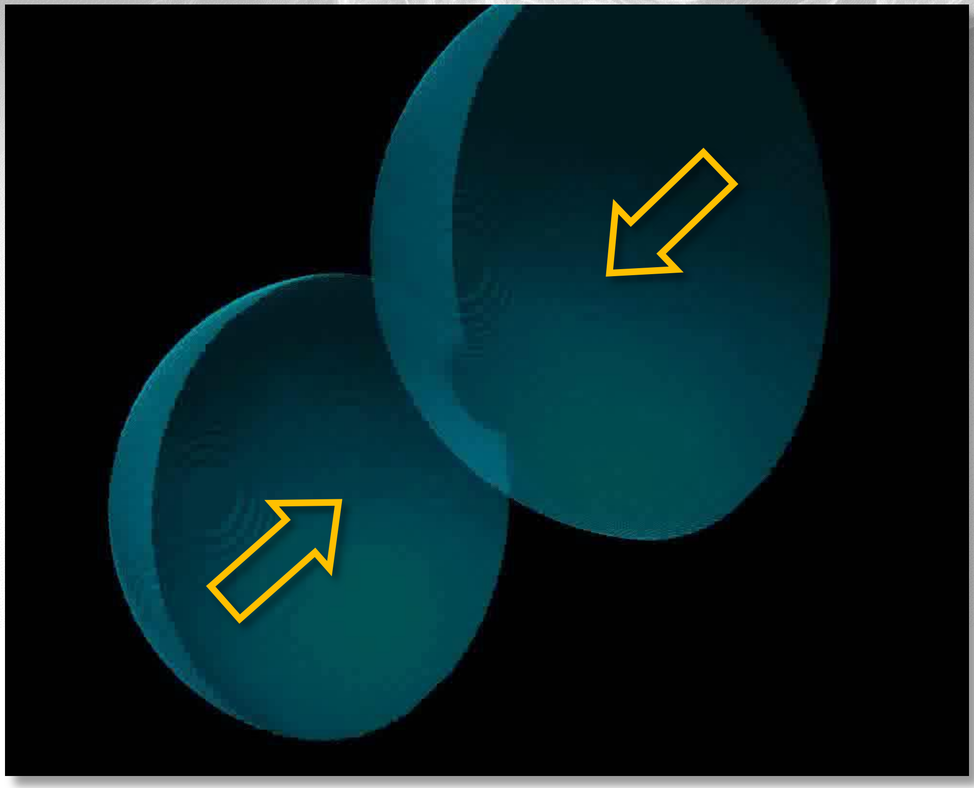
To solve the equations a numerical simulation with difference scheme of high resolution like TVD is used. The code employs conservative shock-capturing scheme. The difference scheme has second-order accuracy and allows high-accuracy computations to be done for the zones close to shock waves and contact discontinuities, and nonphysical oscillations to be prevented.

There are TVD - Total Variation Diminishing scheme with second order of accuracy for border cell fluxes and modification of TVD scheme giving a limited number of oscillations. They are deduced from an expression for first order of accuracy formula using linear correction. The $1^{st}$ order fluxes are specified as average on boundaries. Correction of $2^{st}$ order of accuracy is used for false oscillations restriction. VanLeer's limiters are used for this operation.

Computations were conducted on one (and more in another case) core of the Intel Xeon E2630 processor and on one, two and four graphic accelerators. Intel Vtune Amplifier XE was used to profile the code using CPU. Operating quality of in-house code is perfectly tolerable. The computation of four sub-procedures has 80% of CPU time. After optimization a parallelization possibilities of mentioned subroutines become sufficiently more high.

In numerical experiment we use a parallel version of Coarray Fortran (CAF). In the previous version, the OpenMP parallel programming technology was used to speed up calculations. It allowed performing calculations on 40 cores of one server node were done in an acceptable time. The addition of the rotation influence of clouds in calculations with more than one billion nodes significantly increased the time of calculation. In this regard, a modification of the program using CAF technology was realized. The Fortran 2018 programming language and the Intel Parallel Studio XE 2019 compiler were probated. Comparative calculations were performed on one node of the cluster with two 12-core processors. Calculations showed an almost equal acceleration in parallel operations with a small but quite tangible advantage of Coarray Fortran with accompanying operation and activities.

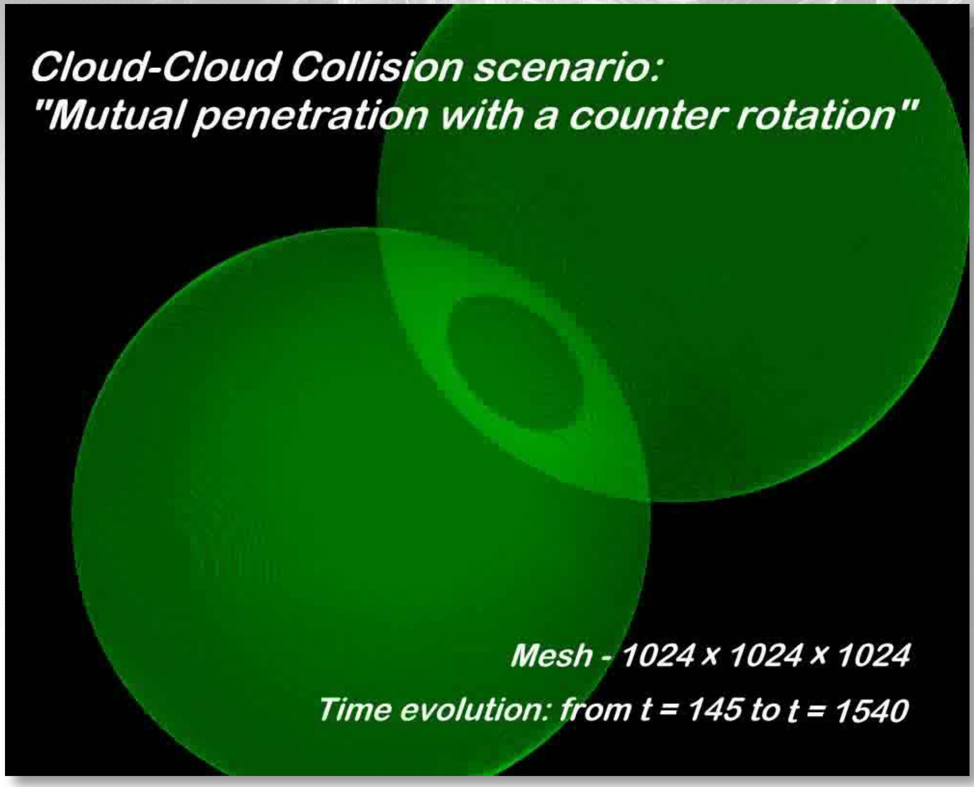
# Head-on MCs collision – case a)



a) CCC without rotation

In this case, we simulate the collision of molecular clouds that are performed without rotation. A cluster of clumps is originating during the process of cloud remnants fragmentation.

- Initial penetration of left cloud $MC_1$ into right $MC_2$ is accompanied by a rapid change of pressure in a contact shock layer. At first stages, energy/density spatial reallocation occurs with slightly radial redistribution of gas matter to the boundaries with ISM. At the same time, the size of the clouds (measured at the outer edge) decreases. The matter of the clouds passes into the core.
- The formation of a bow-shock over-compressed gas layer with waved conditional boundaries starts at the end of this stage. The intensity of this reformation depends on counter gas streams force and shock pulsations. The process is accompanied by the clump number growth with fragments breakup and spread-out of filaments.
- It is accompanied by a stretch of filaments in a post-collision area and gas turbulization in outer shells, a continuation of clump shaping due to strengthening of Kelvin-Helmholtz (KH) and Nonlinear Twin Shell Instability (NTSI), spatial growth of finger structures, acceleration of clumps ablation into outer ISM and subsequent theirs collapse
- At the stage of the final penetration of left cloud into right and rupturing the shell of last one, new dense forms locally bundled in this area of originated pre-stellar formation, transforms into more compressed clumps with maximum possible density, being reached in CCC evolution.

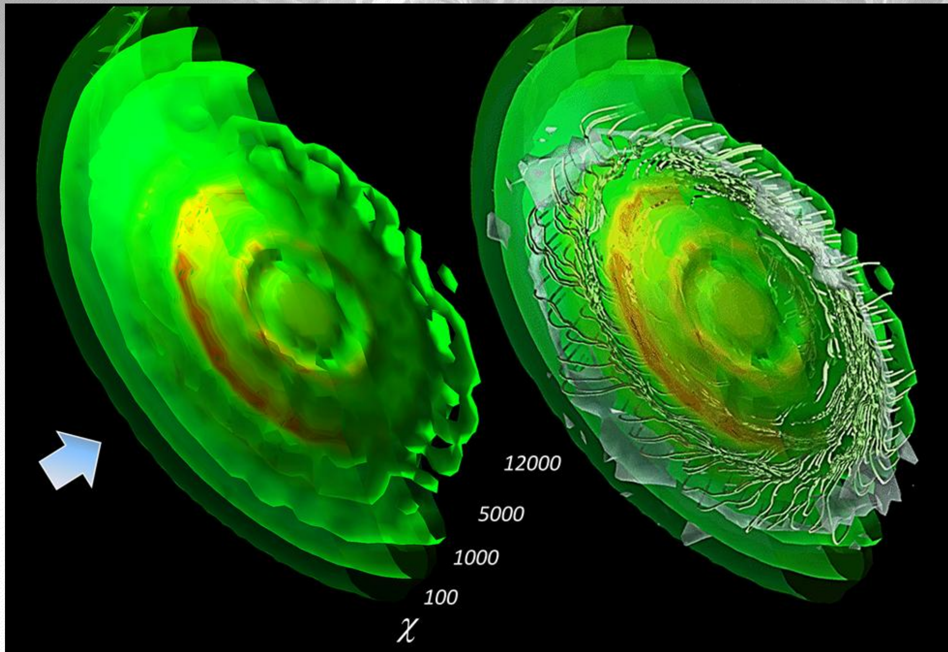



a) CCC with a counter rotation

In this case, we simulate the collision of molecular clouds in a situation with rotation of clouds, with the slightly rotated structure in a high compression zone. Filaments and clumps are originating near stagnation surface.

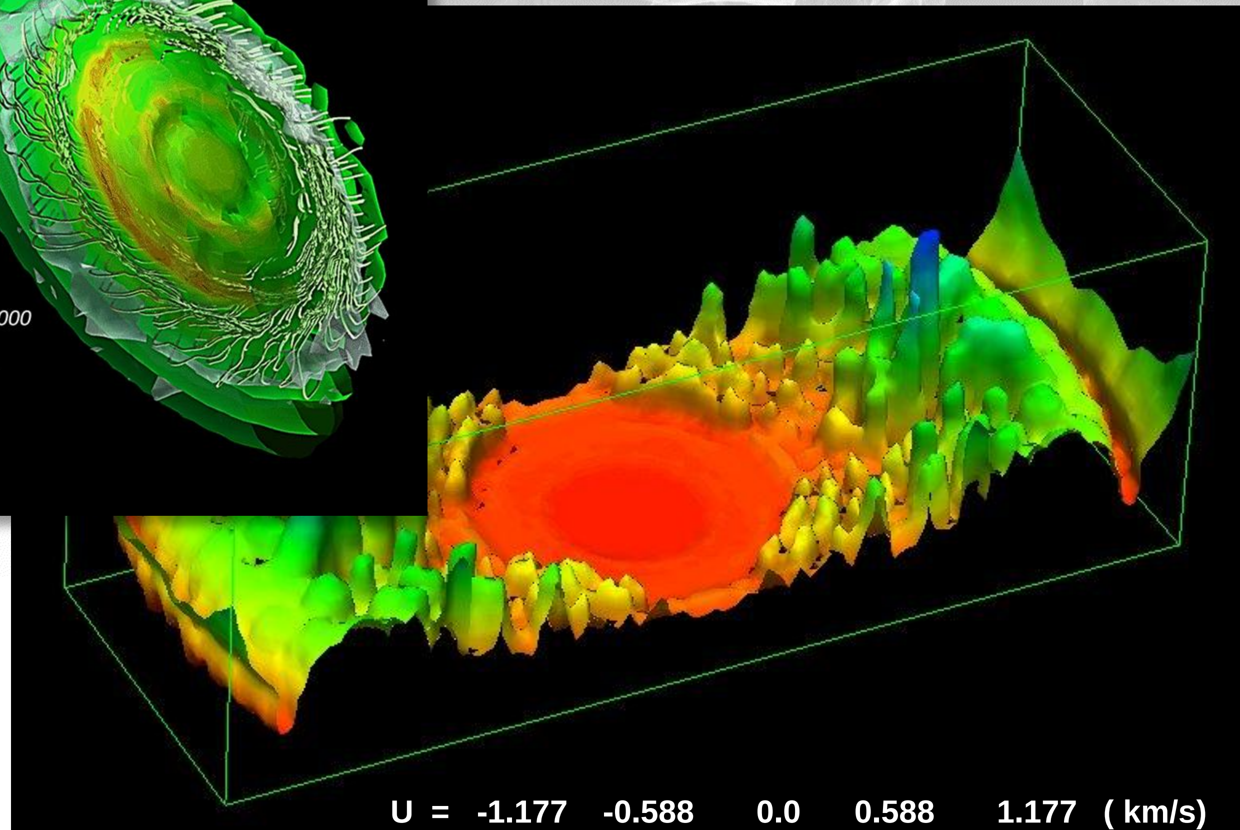
- The initial penetration of the left cloud MC1 into the right MC2 is accompanied by a rapid change in pressure in the contact shock layer, with a faster radial redistribution of gas masses in the core, and mass transfer to the boundary with ISM.
- At the end of this stage, the formation of a compressed gas layer of the bow shock zone with oscillated perturbations on peripheral boundaries of the core begins. The radius of the outer zone of the new formation sharply increases. The intensity of this transformation depends on the centrifugal strength of the opposing gas stream and shock pulsations in the emerging filaments. The process is accompanied by stretching of the helical filaments with the formation of annular structures at the periphery.
- The third phase is characterized by a stretching and crossing of filaments in a collision area and periphery of it with intensive turbulization behind cloud remnants, with a continuation of their reshaping due to the strengthening of Kelvin-Helmholtz and Nonlinear Twin Shell Instability.
- At the stage of the final penetration of left cloud into right and rupturing the shell of last one, new dense forms locally bundled in this area of originated pre-stellar formation, transforms into more compressed clump cluster with maximum possible density, being reached in CCC evolution.

# Velocity Perturbations in Compressed Layer and Isodensity

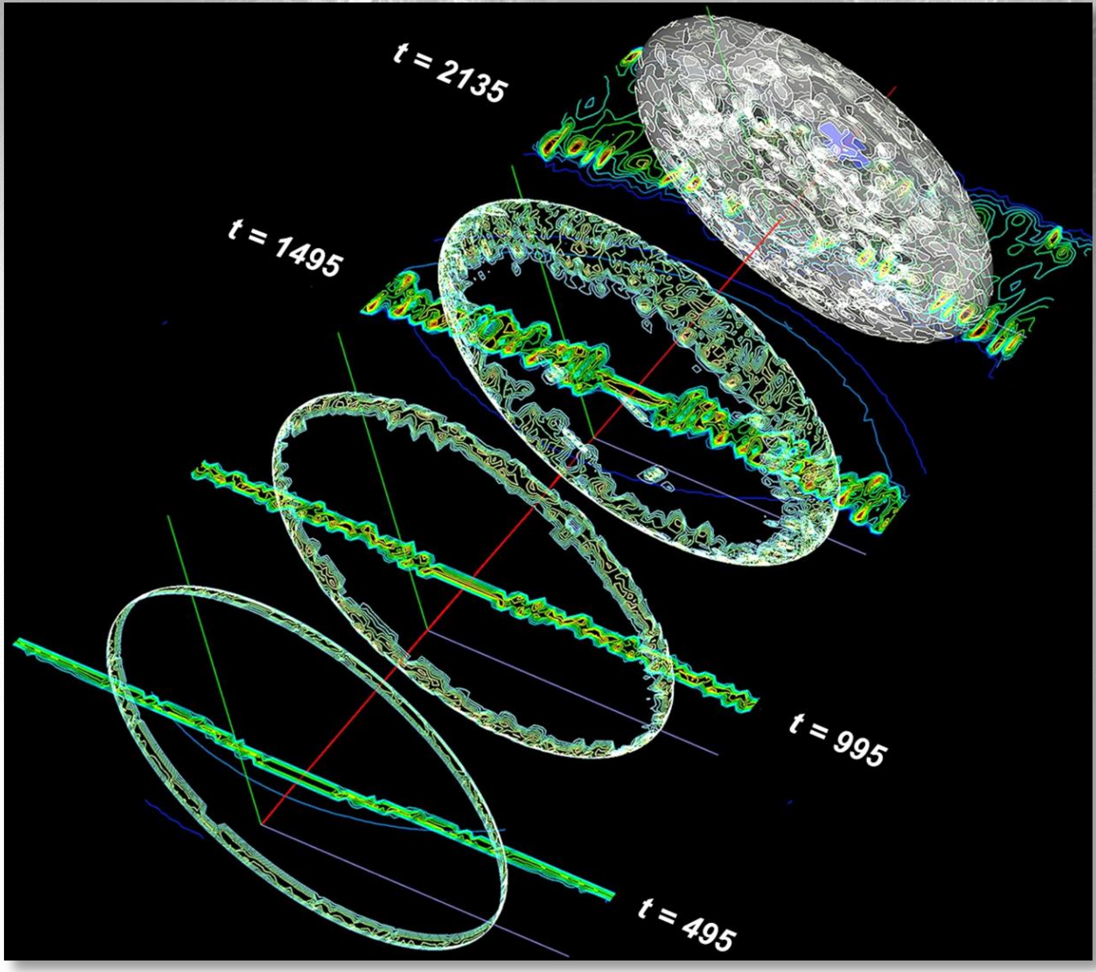



Instantaneous isodensities layers for case (b) - impact of the non-rotated cloud with rotating one. Unstable growth of “finger” structures for inner density layers with $\chi$ = 12000. Manifestation of Kelvin - Helmholtz instability

Dendritic U-components of contrary gas flow velocities in highly compressed MCs layer near stagnation point-flow surface corresponding to the case of CCC with $\chi$ relation 500 and cross-cloud velocity 5.885 $km \cdot s^{-1}$. |U|=0.0 is a stagnation point-flow set.



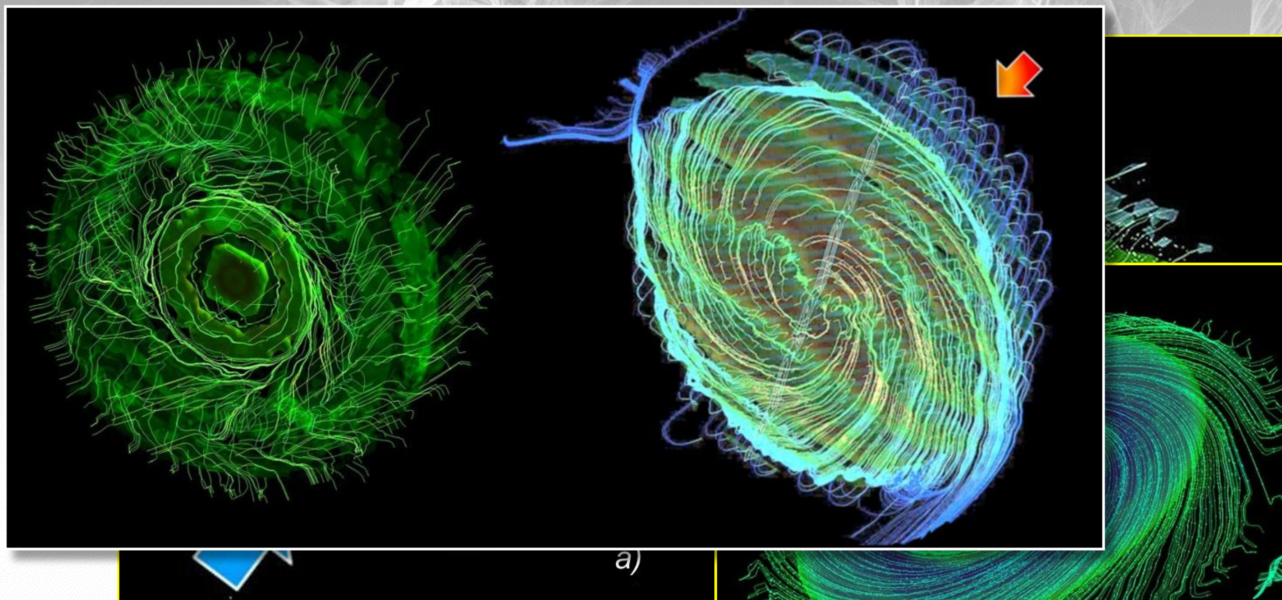
# Velocity Perturbations and Non Linear Thin Shell Instability




**NTSI - Non-Linear Thin Shell Instability** (Vishniac,1994) play a crucial role in triggering perturbation and oscillated spatial deformation of the compressed core.

NTSI leads to formation of bending shell structure and deformation of MCs at the initial distortion phase of their shaping. The misalignment of ram flow and thermal gradient direction causes shear in the layer, leading to local gas density enhancements or a decline over compressed blobs in the core. Observable dynamic can be illustrated in left figure, which presents log-density contours - log $\chi$ for some stages of evolution of impact area in core initiated by ram gas pressure on both sides of the stagnation zone. One can see how core layers of different densities change and expand like a corrugate shell. Any imbalance in the directions of stream jets penetrating via stagnation surface and temperature gradient vectors direction can enhance perturbation of the stream interface and allow this instability to grow. The pattern of deformations observed in recent simulation largely coincides with the results from (McLeod A, Whitworth A 2013 Simulations of the non-linear thin shell instability *Monthly Notices of the Royal Astronomical Society,* **431**).

# Head-on CCC: Non-rotated Clouds (a) and Collision with Rotation(d)




$MC_1$♋$MC_2$: Spatial reshaping of two colliding MCs is illustrated in figure, where originated clump formations and filament embryos are shown during the collision follow two scenarios of non-rotated clouds (a) and clouds rotated in a contrary direction (d).

Wisps of originated clumps from colliding streams are redistributed across the rings around the impact axis. Gas streams move from the central stagnant spot to the periphery, starting from both sides of the formed core (in front and behind it), doing oscillation in density zones in the ring-shaped formations.

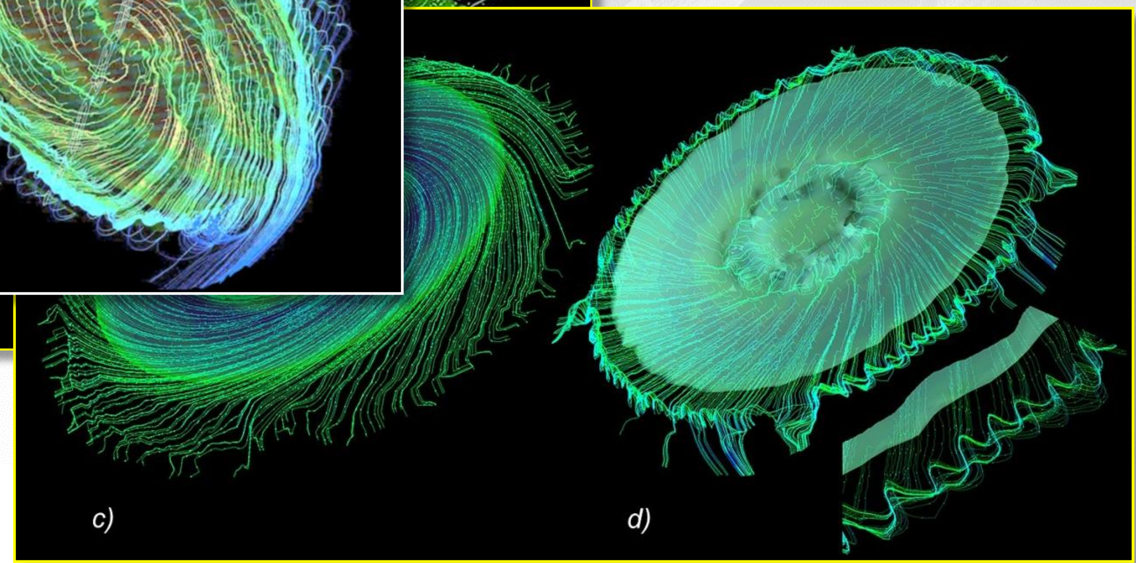
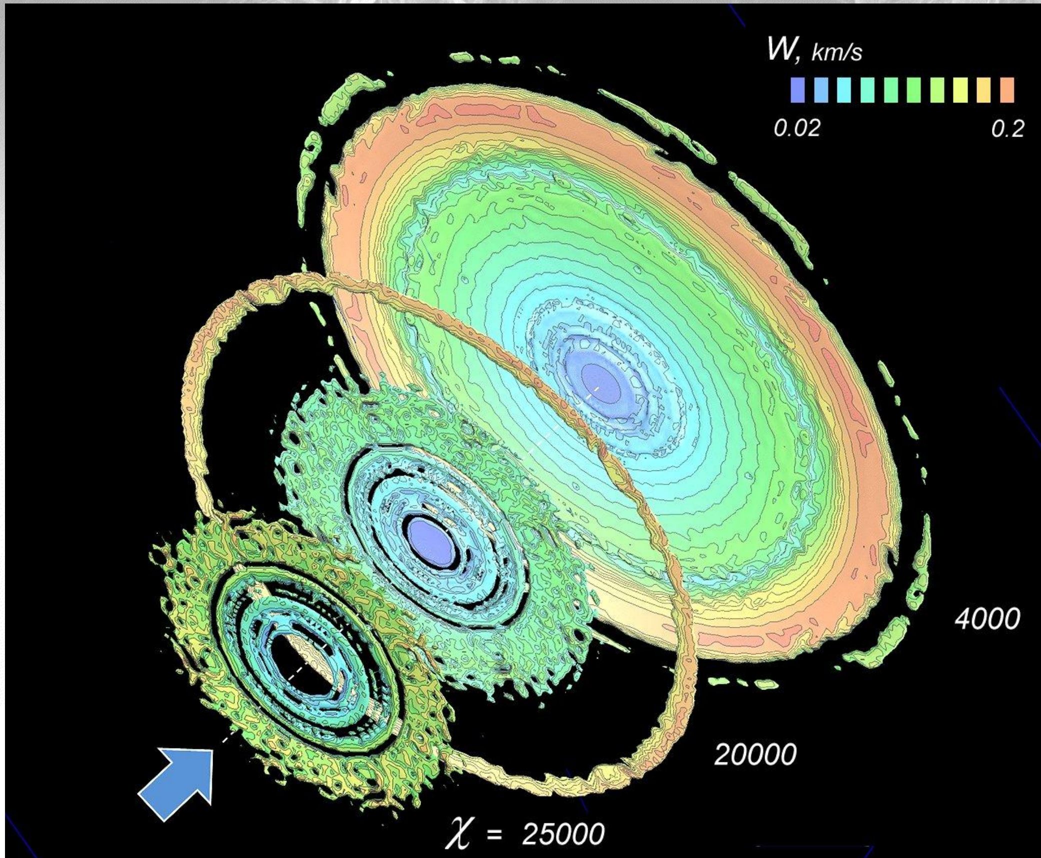



Illustration of stream pathlines beginning from the collision zone of core ($\chi$ = 10000) for cases of oncoming rotated clouds collision by scenarios (c) and (d).
In case d), one can see double-helical trajectories of counter streams interacting at the periphery of the core.

# Evolution of Density Contrast Fields in CCC with Counter Rotation



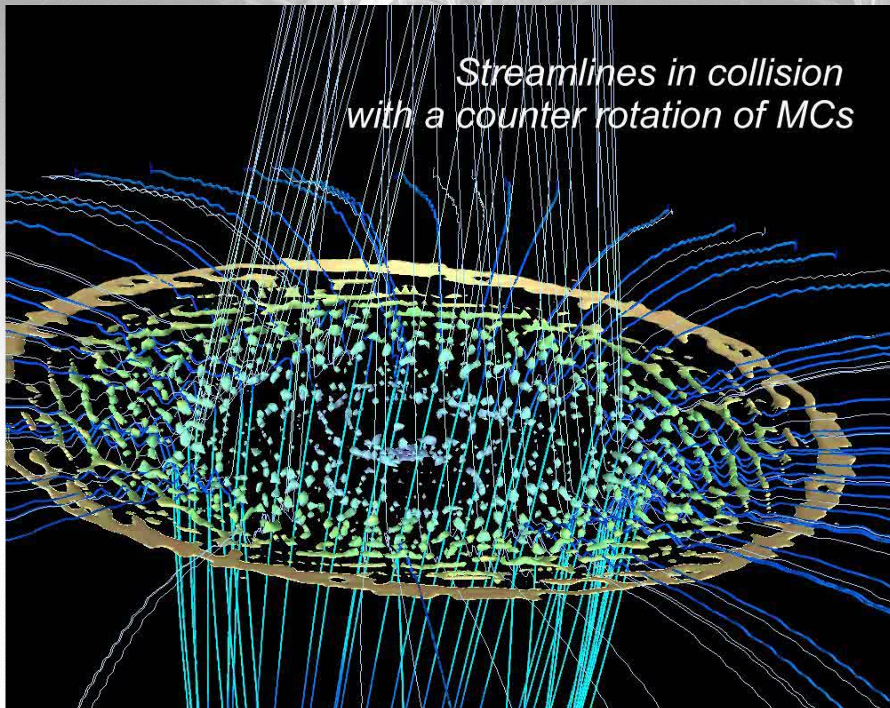

MC1♋MC2 : Isodensities $\chi$ = *4000, 20000, 25000* and contours of tangential velocity in the impact zone of MC's for head-on CCC by scenario d) at first stage of evolution.

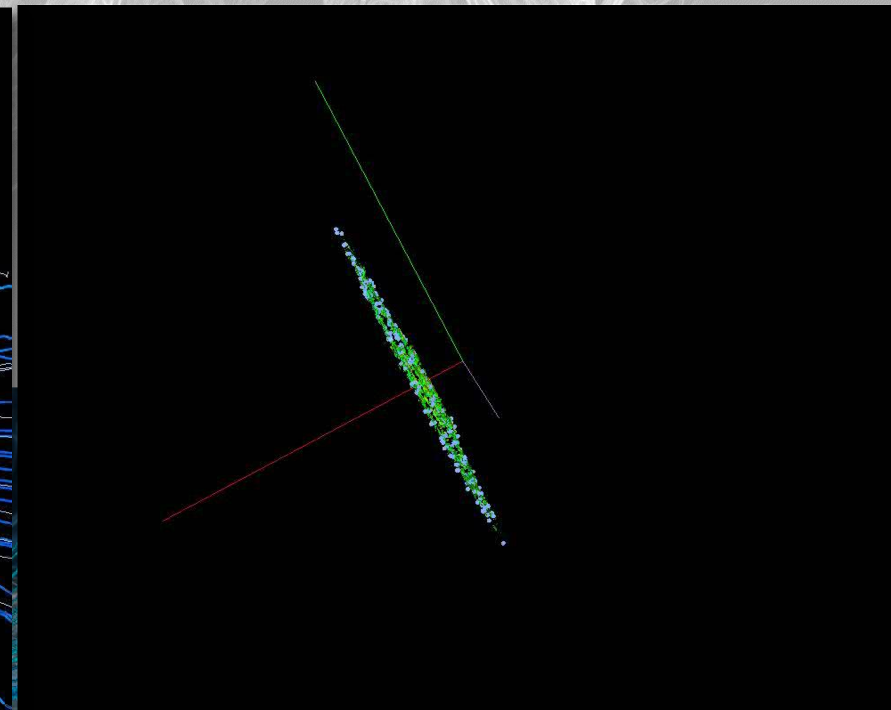
Change in the angular momentum of clouds rotating in the opposite direction leads to the emergence of peripheral filaments in the outer layers at the first stage of collision. As the process of mutual penetration of clouds develops, the distribution of the tangential velocity in front and behind of the stagnation surface of the gas streams undergoes a complex transformation in the radial and axial directions.

Sharp spatial changes in the velocity and density fields lead to a helical change in the gas transport with the release of toroidal zones with the over compression of matter inclusions in the collision core.

Different level of Iso-densities (separately highlighted in the figure) and tangential velocity contours on them are shown.

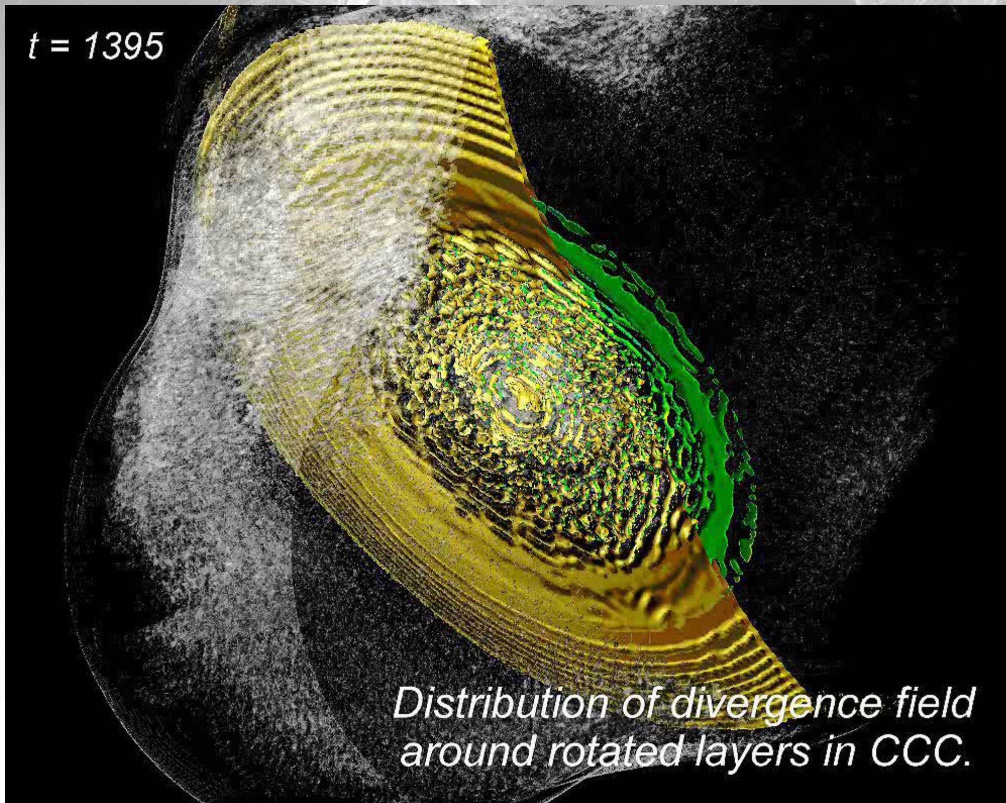
# Pathlines in Head-on CCC with Counter Rotation - d)



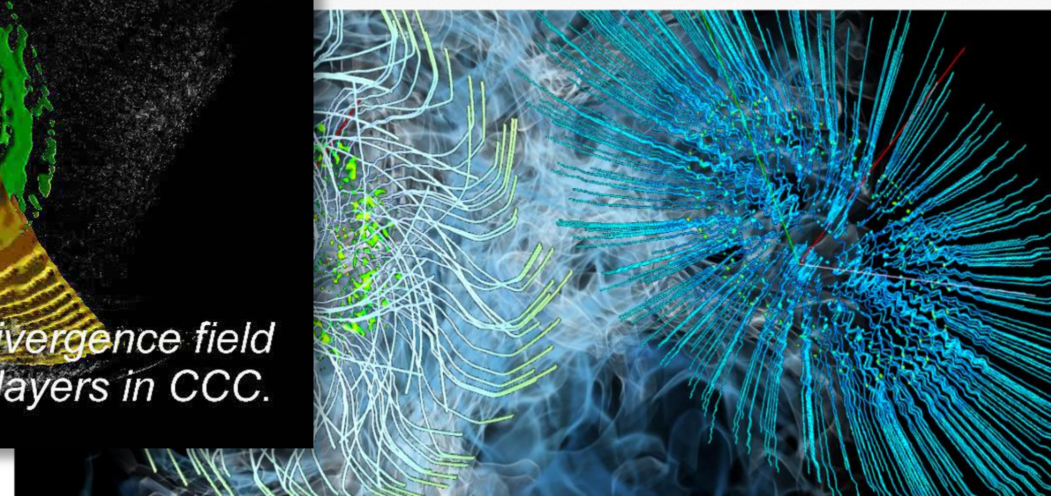



Spatial reshaping is illustrated in movie, where originated clump formations and filament embryos are shown during CCC with clouds rotated in a contrary direction (d).

# Rotation and Divergent Fields in CCC with Counter Rotation - d)



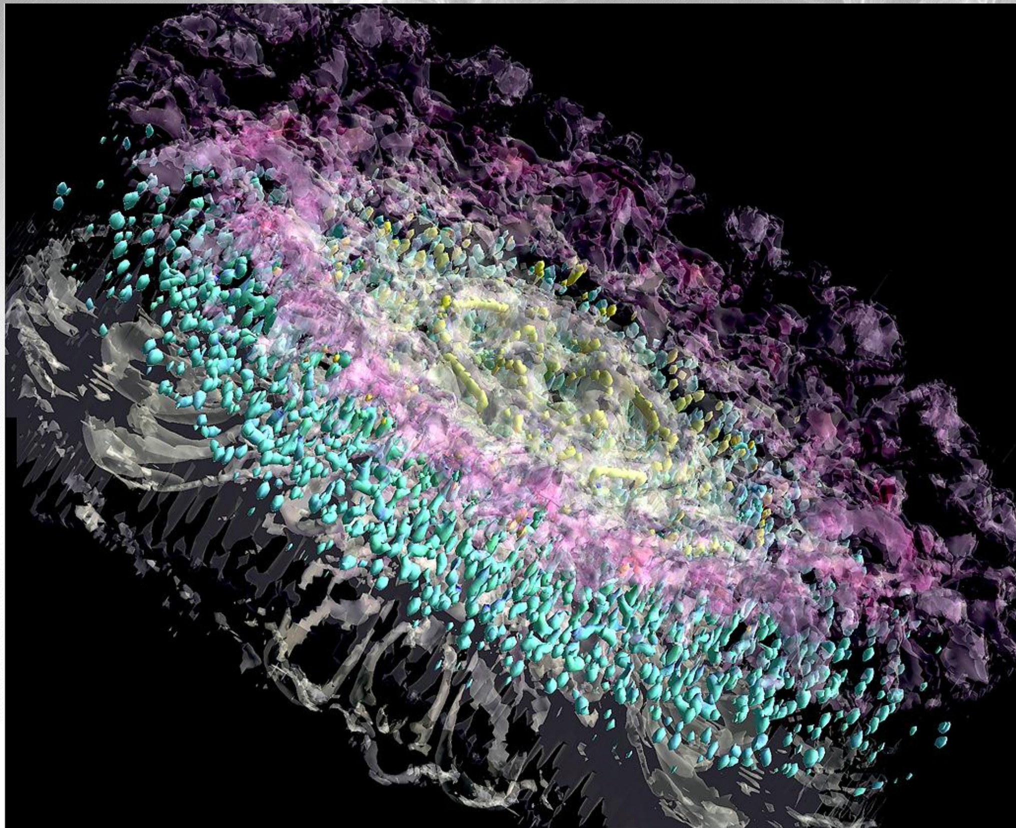
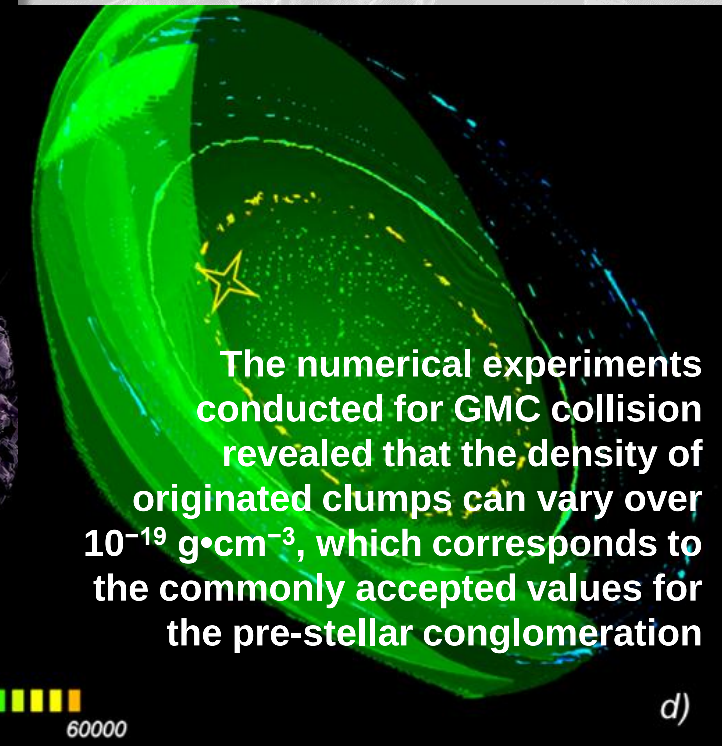

The prediction of the formation of possible pre-stellar nucleation zones was carried out on the basis of a search of spatially limited over-compressed clumps where conditions for gas matter consolidation in small volumes are satisfied for gas sinks into overcompressed blobs. This approach is used in more complicated simulations (turbulence + gravitation) [Hubber D. at al., Astronomy & Astrophysics, 529 ]. Maximally reached compressibility of clumps and negative velocity divergence zones were investigated. Such bounded places are favorable to condensing flow and are perspective to star origination.



Fields of velocity divergence *div (**U**)* = -1 and -5 and iso-surfaces of density contrast ($\chi$ > 30000 at t = 1395)

# Clustering of Clumps at Different Stages of CCC Evolution

Spatial vortex streams at the moment of complete passage of clouds, piercing separated clump formations (density contrast over 30000, maximal value – over 600000) with concentric distribution in possible pre-stellar zones after a collision of giant molecular clouds.


Fields of negative divergence sink areas (green color coded) in collision of contrary rotated nebulae at the beginning stage and at the final stage of mutual penetration of non-rotated and rotated molecular clouds with clump claster.


Thank you !