# Numerical modeling of gravitational instability outcomes in multiphase circumstellar discs

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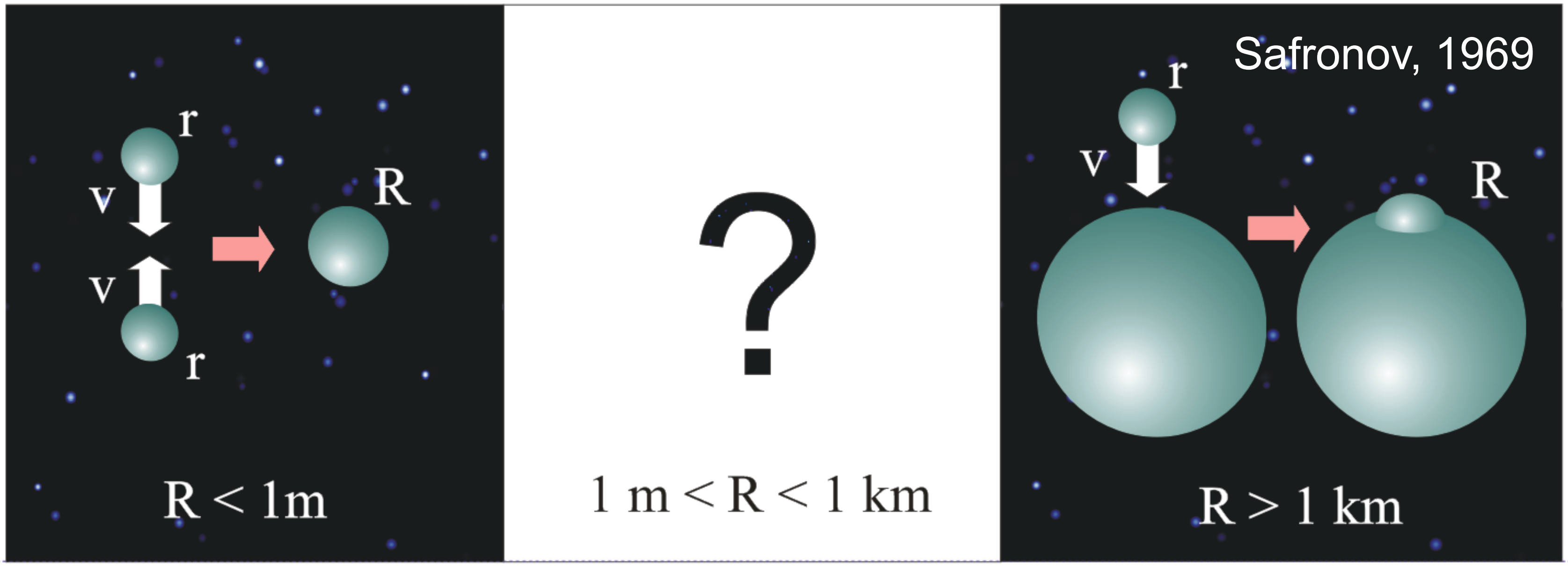
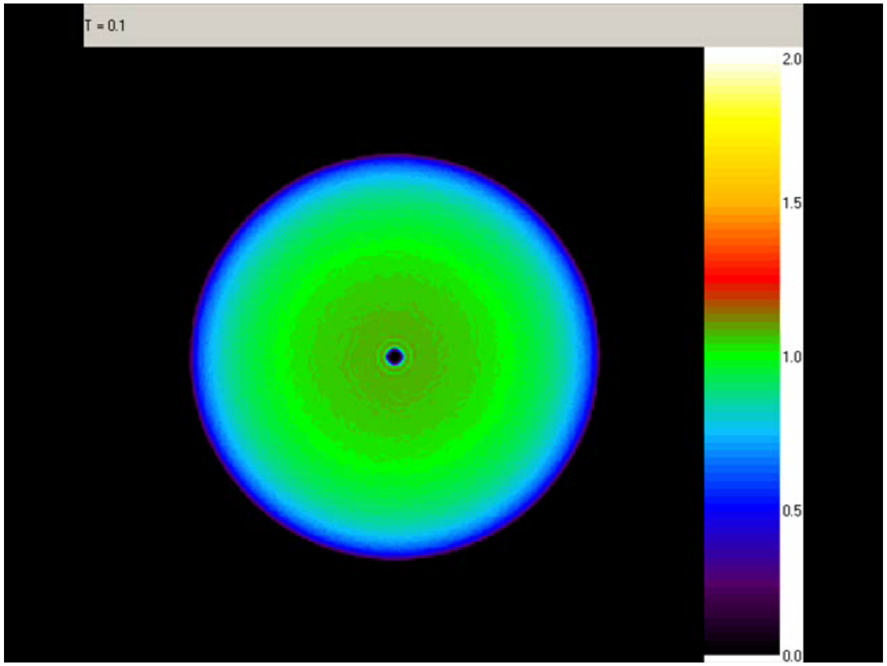
# Growth of solid bodies during formation and evolution of circumstellar disc

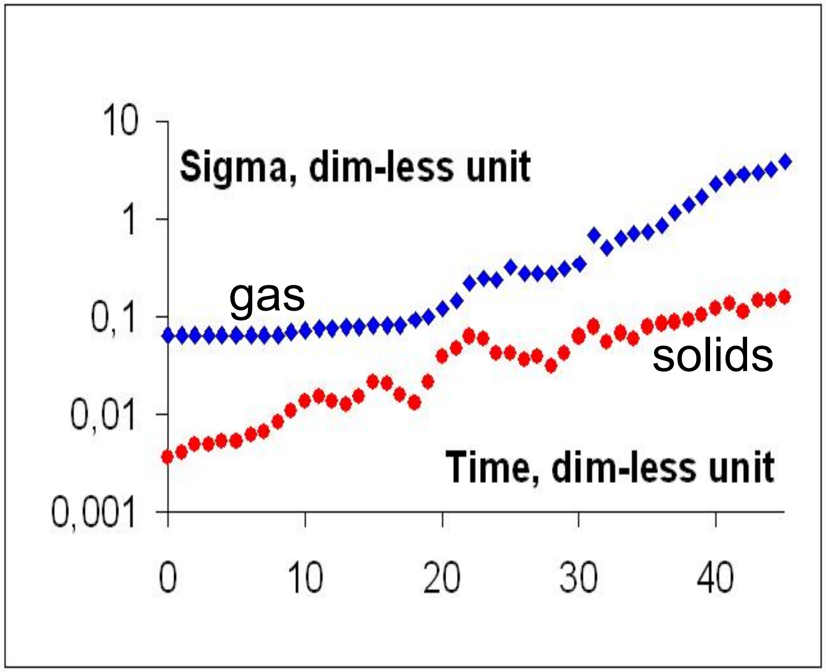


Safronov, 1969

# Self-gravitating clumps as zones of large bodies formation



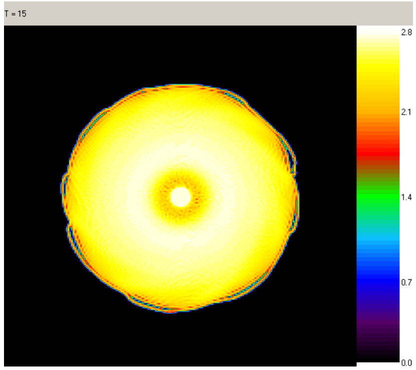
Logarithm of ‘boulders’
surface density



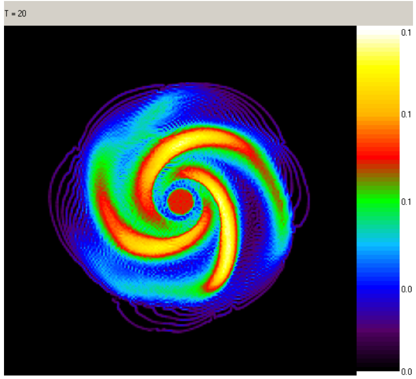
Growth of density in
self-gravitating clump

# Gaps in understanding of collapsing clumps formation in real protoplanetary disc

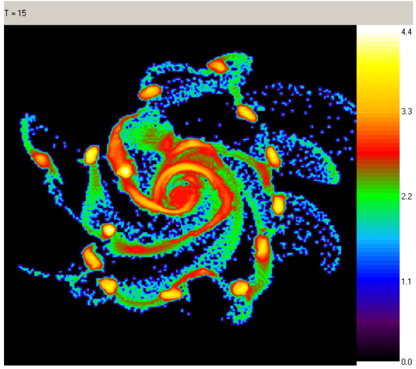
Temperature regulation of different structures formation



No structures



Spirals sleeves



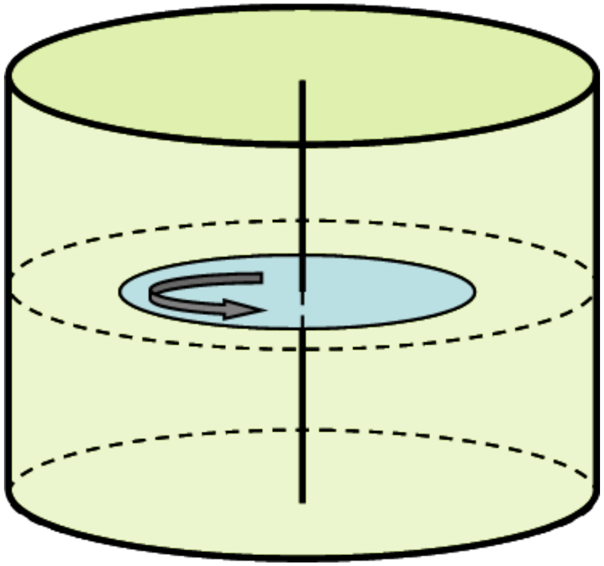
Collapsing clumps

Gas temperature decreasing

From quasi-stationary to unstable disc? How to skip intermediate temperature regime?

Fast cooling of stady-state massive disc is hardly ever possible due to increasing radiation of protosun.

# Quasi 3D-model of razor-thin disc on the stage of clumps formation



Gas dynamics

$$\frac{\partial\sigma}{\partial t} + div(\sigma\overrightarrow{v}) = 0,$$

$$\sigma\frac{\partial\overrightarrow{v}}{\partial t} + \sigma(\overrightarrow{v},\nabla)\overrightarrow{v} = -\nabla p^* - \sigma\nabla\Phi,$$

$$\frac{\partial S^*}{\partial t} + (\overrightarrow{v},\nabla)S^* = 0, \quad p^* = T^*\sigma.$$

$$\sigma_{par,gas} = \int_{-\infty}^{+\infty}\rho_{par,gas}dz;$$

Gravitational field

$$\Phi = \Phi_1 + \Phi_2, \Phi_1 = -\frac{M_c}{r},$$

$$\Delta\Phi_2 = 0, \quad \Phi_2 \longrightarrow_{r\to\infty} 0,$$

$$\frac{\partial\Phi_2}{\partial z}|_{z=0} = 2\pi(\sigma_{par} + \sigma_{gas}).$$

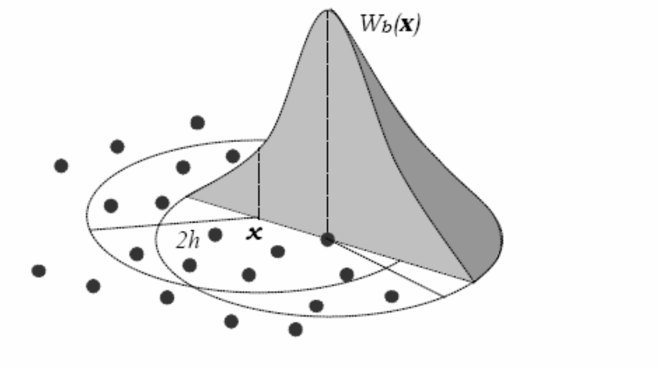
Solid dynamics

$$\frac{\partial f}{\partial t} + \overrightarrow{u}\frac{\partial f}{\partial\overrightarrow{r}} + \overrightarrow{a}\frac{\partial f}{\partial\overrightarrow{u}} = 0,$$

$$\overrightarrow{a} = -\nabla\Phi, \ \sigma_{par} = \int f d\overrightarrow{u}dz.$$

# Parallel code Sombrero

- Particle-in-Cell method for **Vlassov-Luiville equation**
- Iterative combined method which includes Fourier transformation and sweep to solve **Poisson equation**
- SPH to treat **gas dynamics**



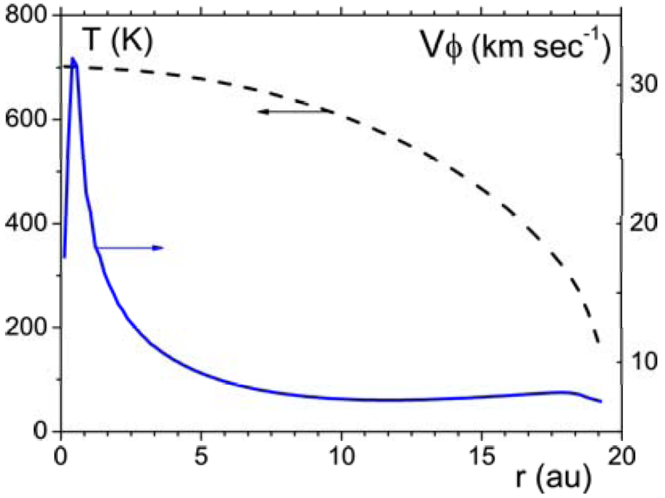
Nonlinear unstable dynamics - numerical results verification

Varying numerical resolution
Results of different codes comparation

# Disc parameters

- Disc radius 20 AU
- Mass of gas $0.52M_o$
- Mass of solids $0.03\ M_o$
- Mass of central body $0.45M_o$

Initially unstable discs with Q<1



V.Snytnikov talk, Snytnikov, Stoyanovskaya, MNRAS 2012, accepted

| Experiment No | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Initial gas temperature at $R = 10$ au (K) | 610 | 610 | 234 | 610 |
| Initial velocity dispersion of solids (m s$^{-1}$) | 1900 | 95 | 1900 | 1900 |
| Initial Jeans length in gas | 0.42 | 0.42 | 0.26 | 0.27 |
| Initial Jeans length in solids at $R = 1$ au | 6.45 | 0.016 | 6.45 | 6.45 |
| Effective adiabatic exponent $\gamma^*$ | 1.66 | 1.66 | 1.66 | 1.1 |
| Outcome of instability development | 3 spiral arms in gas and solids | Gas-solid clumps in the inflection points of 5 spiral arms | Gas-solid clumps at 3 different radii | Gas-solid clumps at 1 radius |

# Toomre and Jeans gravitational instability for multi-phase system.

# Analytical expectations or what we look for.

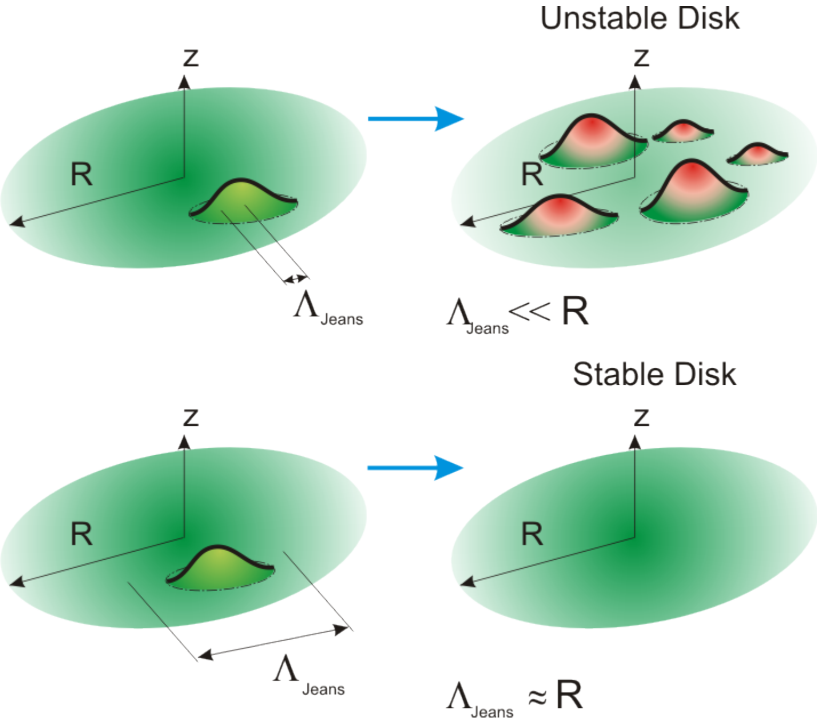
Jeans length for continuum and collision-less medium in “plane” assumption

$$\Lambda_{gas} = \frac{c_s^2}{G\sigma_{gas}},$$

$$\Lambda_{par} = \frac{v_d^2}{G\sigma_{par}}.$$

Jeans length for hybrid system – nonlinear combination

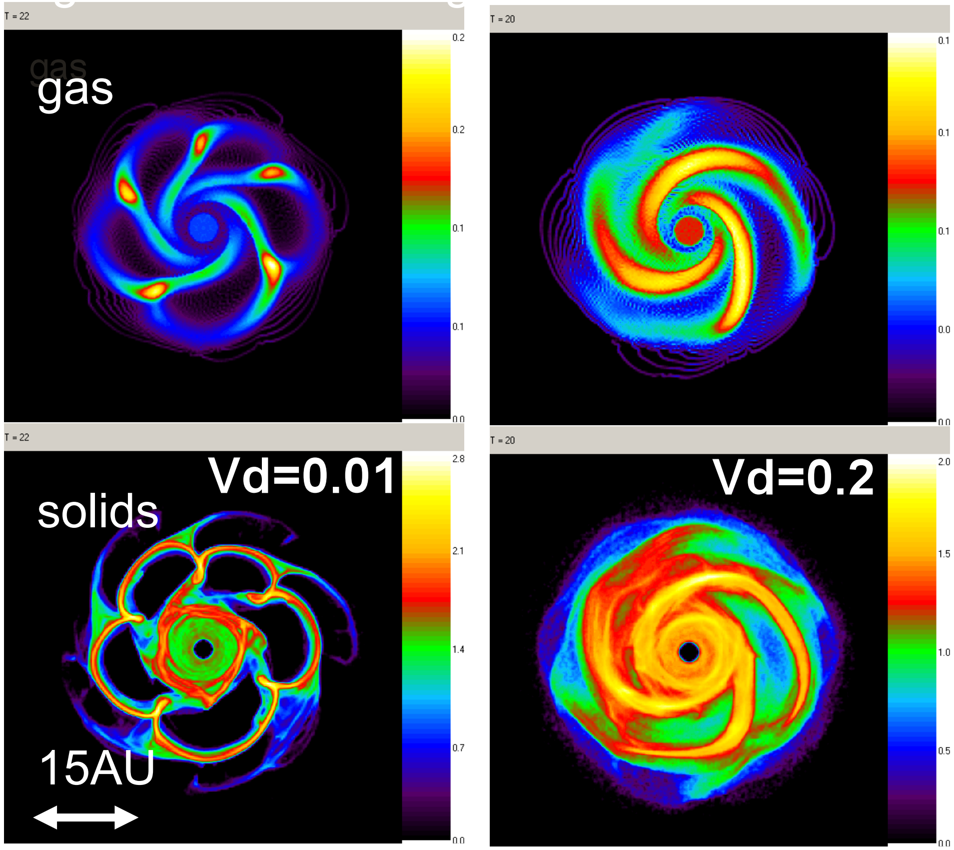
$$\frac{1}{\Lambda} = \frac{1}{\Lambda_{gas}} + \frac{1}{\Lambda_{par}}.$$



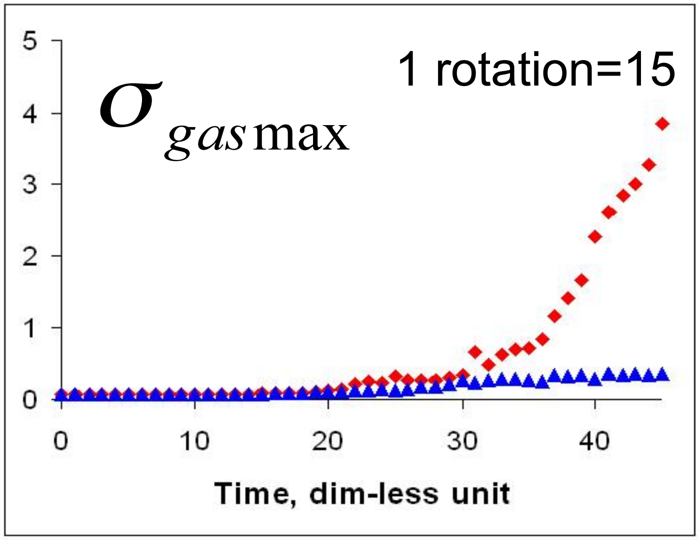
$$Q = \sqrt{\frac{\Lambda_{par}\Lambda_{gas}}{\Lambda_{gas}+\Lambda_{par}} \frac{\Omega^2}{G(\sigma_{gas}+\sigma_{par})}}.$$

Snytnikov, Stoyanovskaya, MNRAS 2012 ,accepted

# ‘Butterfly effect’ or influence of solid bodies on gas dynamics



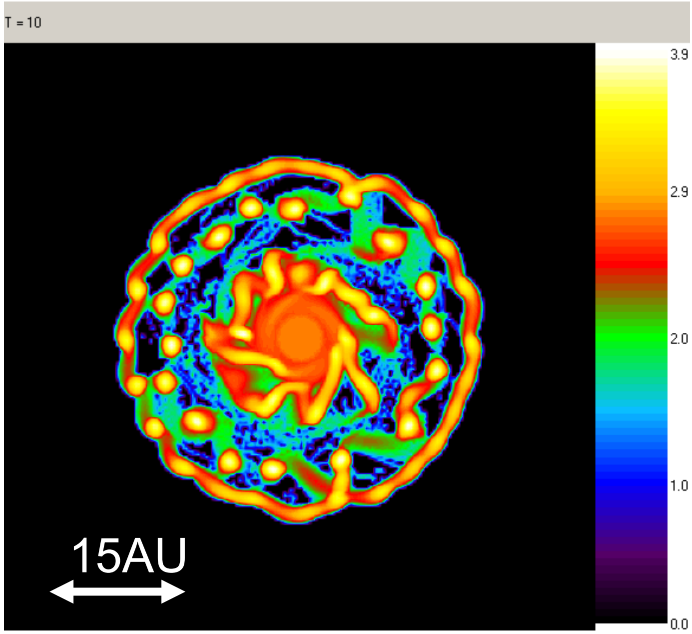
Sensitivity of structure formation to initial parameters of low-massive solids subsystem – analogue to ‘butterfly effect’ in chaotic system dynamics.

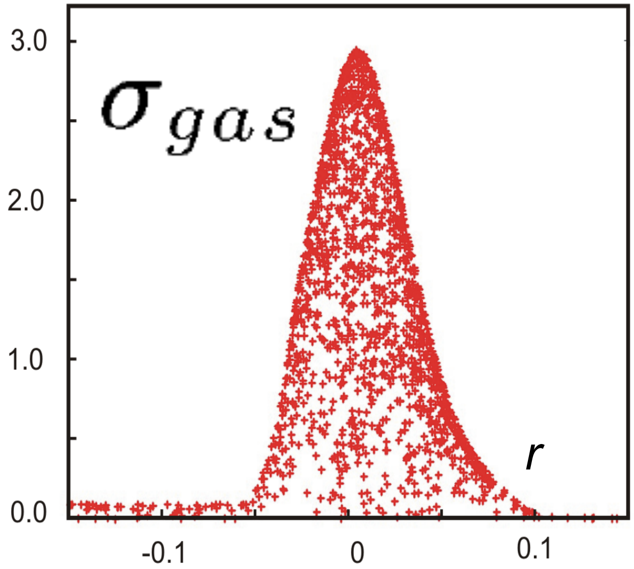


Growth of maximum density in structures

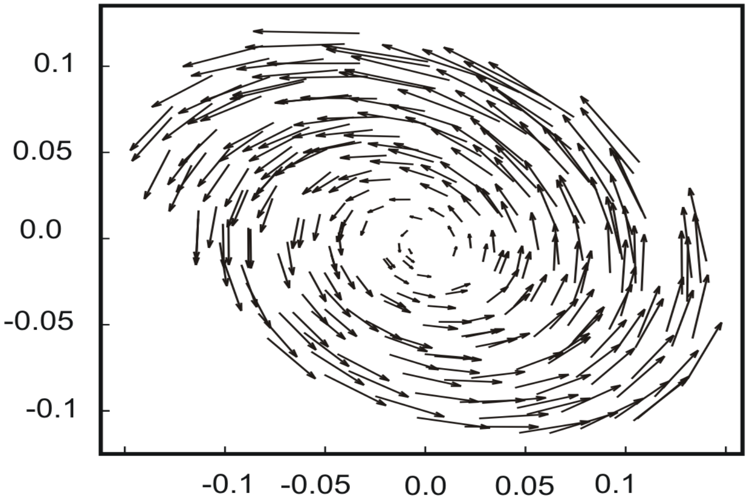
$$\frac{M_{subdisc}}{M_{star}} = 1 \qquad \frac{\sigma_{par}}{\sigma_{gas}} = \frac{1}{20} \qquad c_s \sim 0.1$$

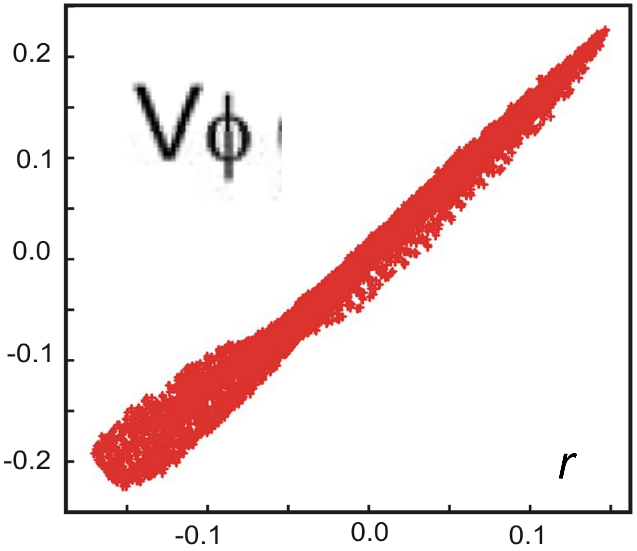
# Individual clump of gas



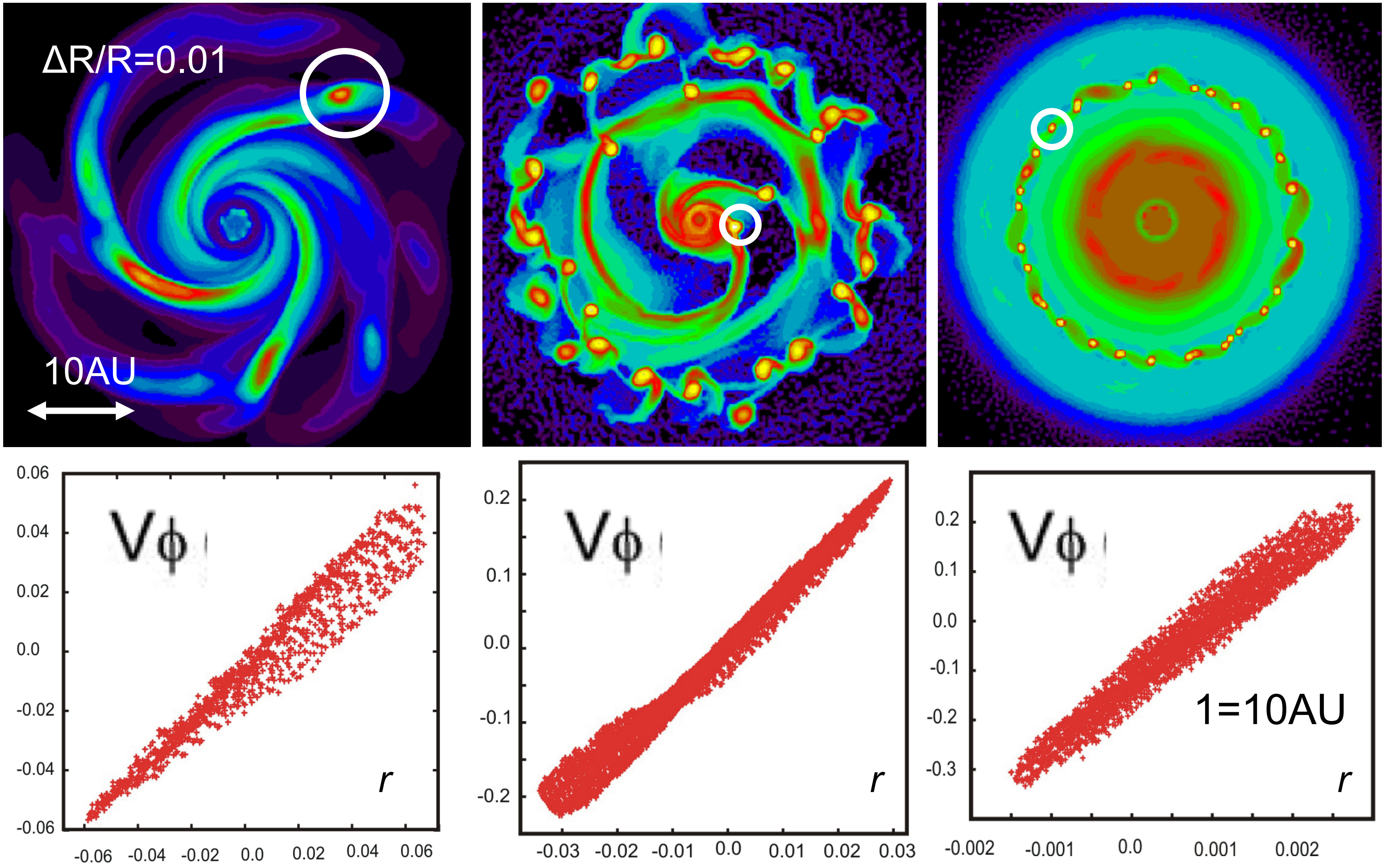


1=10AU

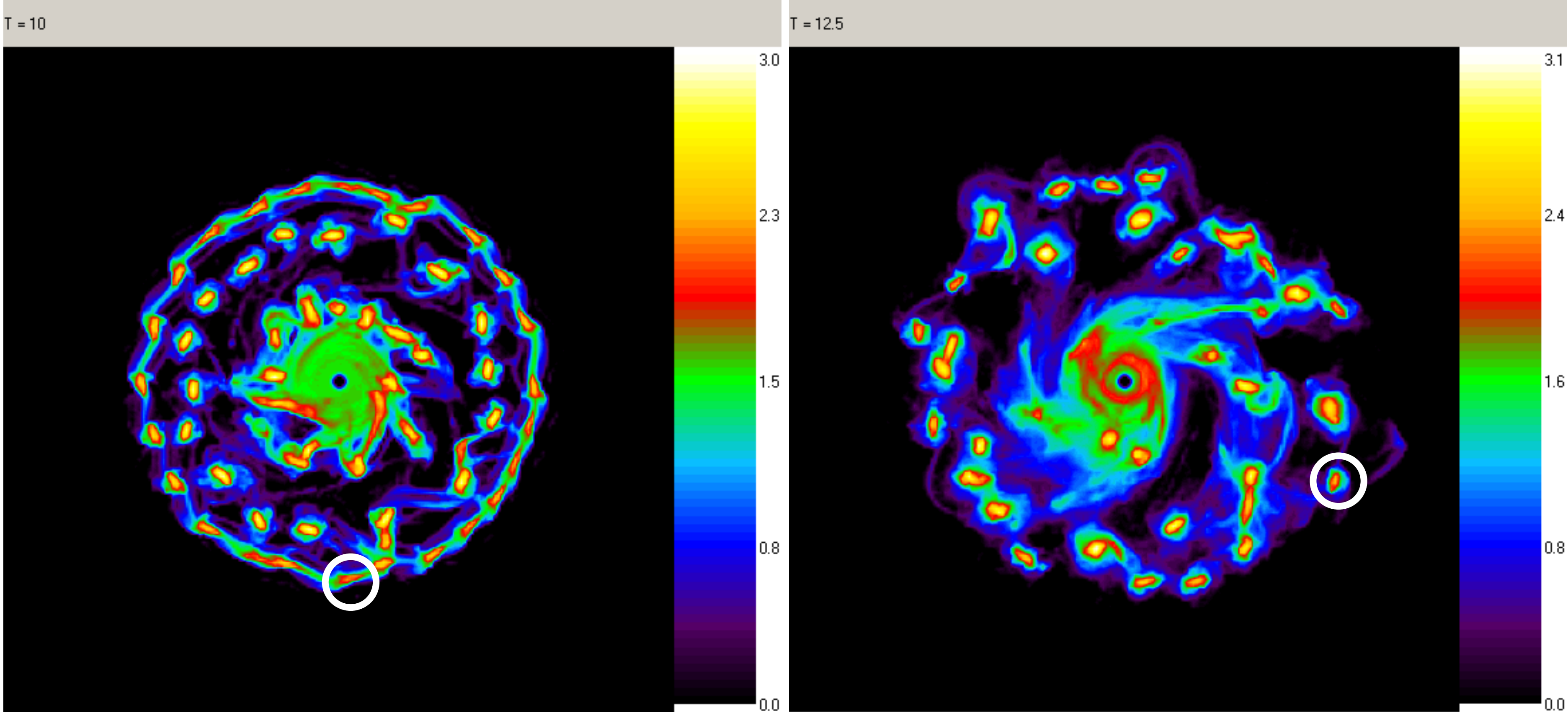




# Gaseous clumps rotating like solids around their density maximum



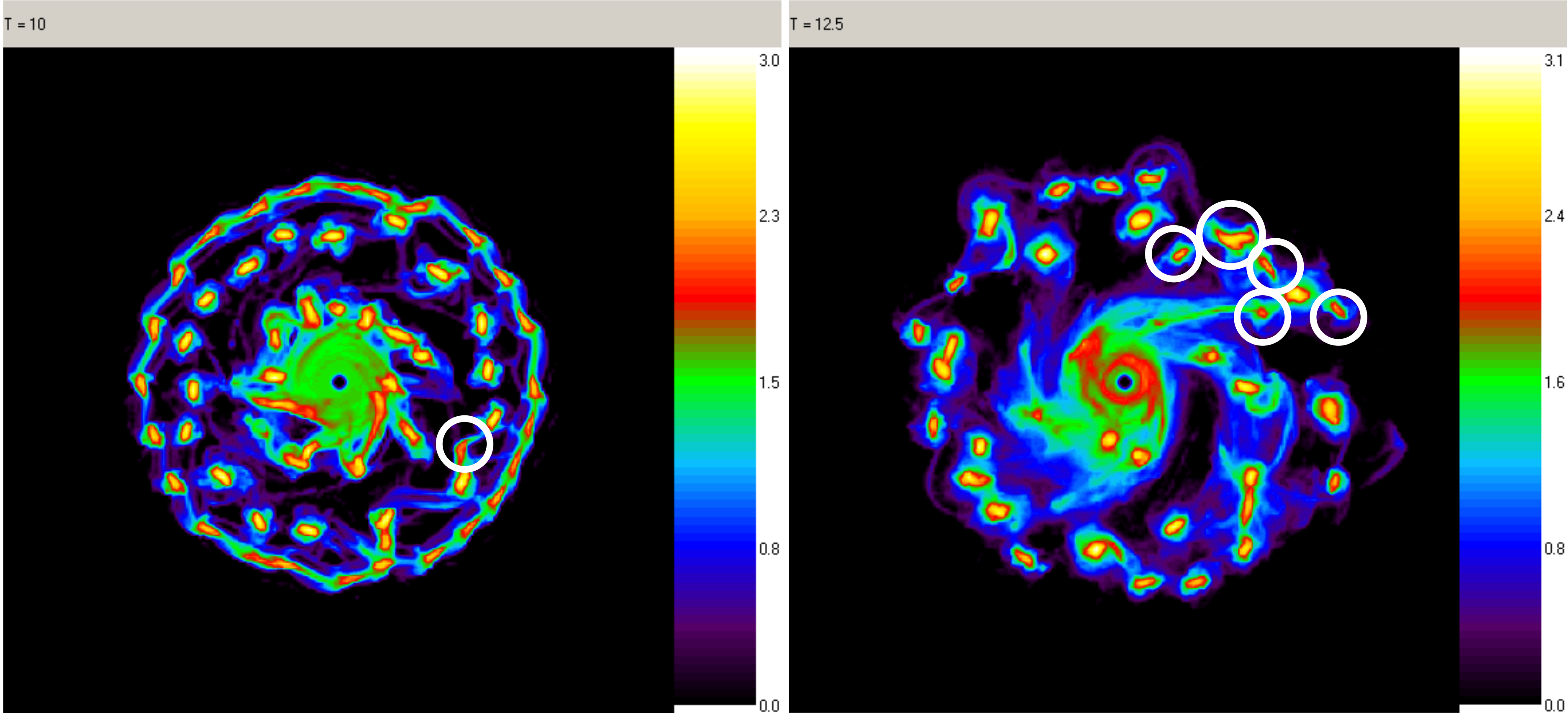
# Solid dynamics in solitary clumps – waves or moving volumes



94% of solid’s mass were kept in clump.

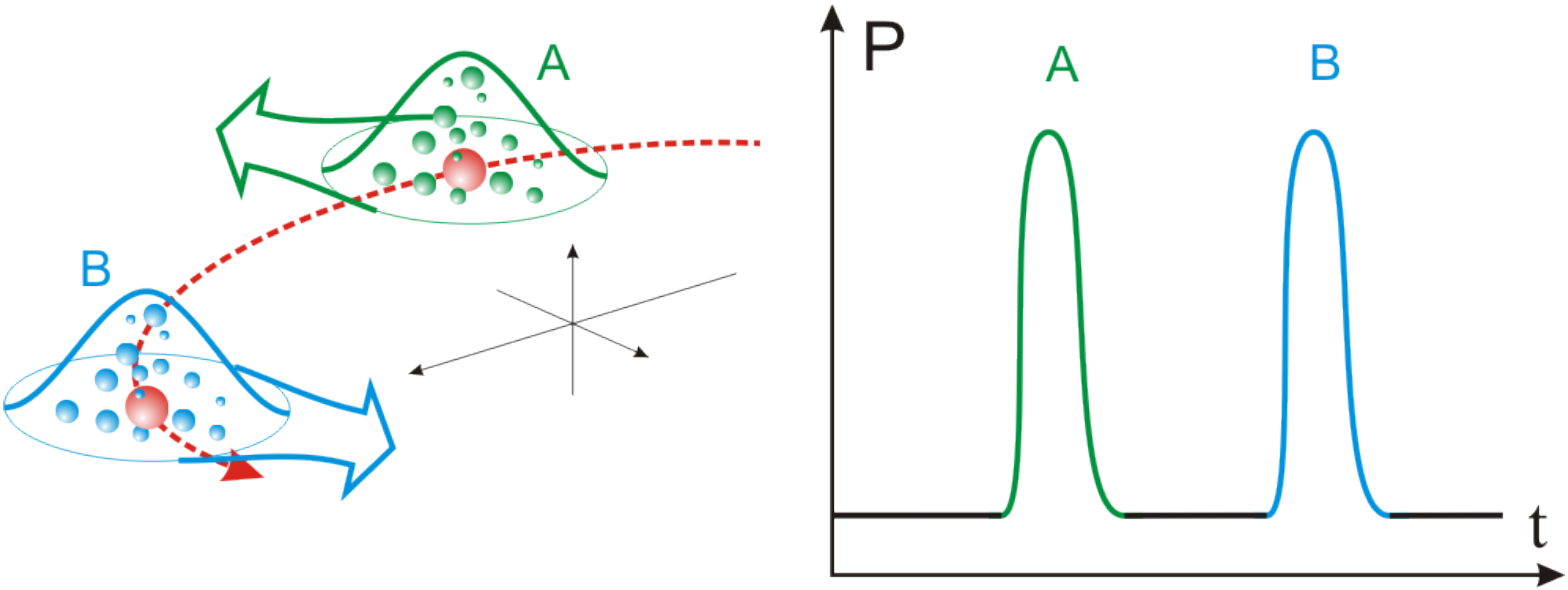
It means that gravitational potential of clumps can capture solid bodies and produce epicyclical trajectories.

# Solid's dynamics in solitary clumps – if solid bodies migration from one clump to another is possible



Solid bodies from one clump were found in 5 different clumps, which confirms that migration of solids from one clump to another takes place.

# Unique physical conditions for boulders moving through clumps

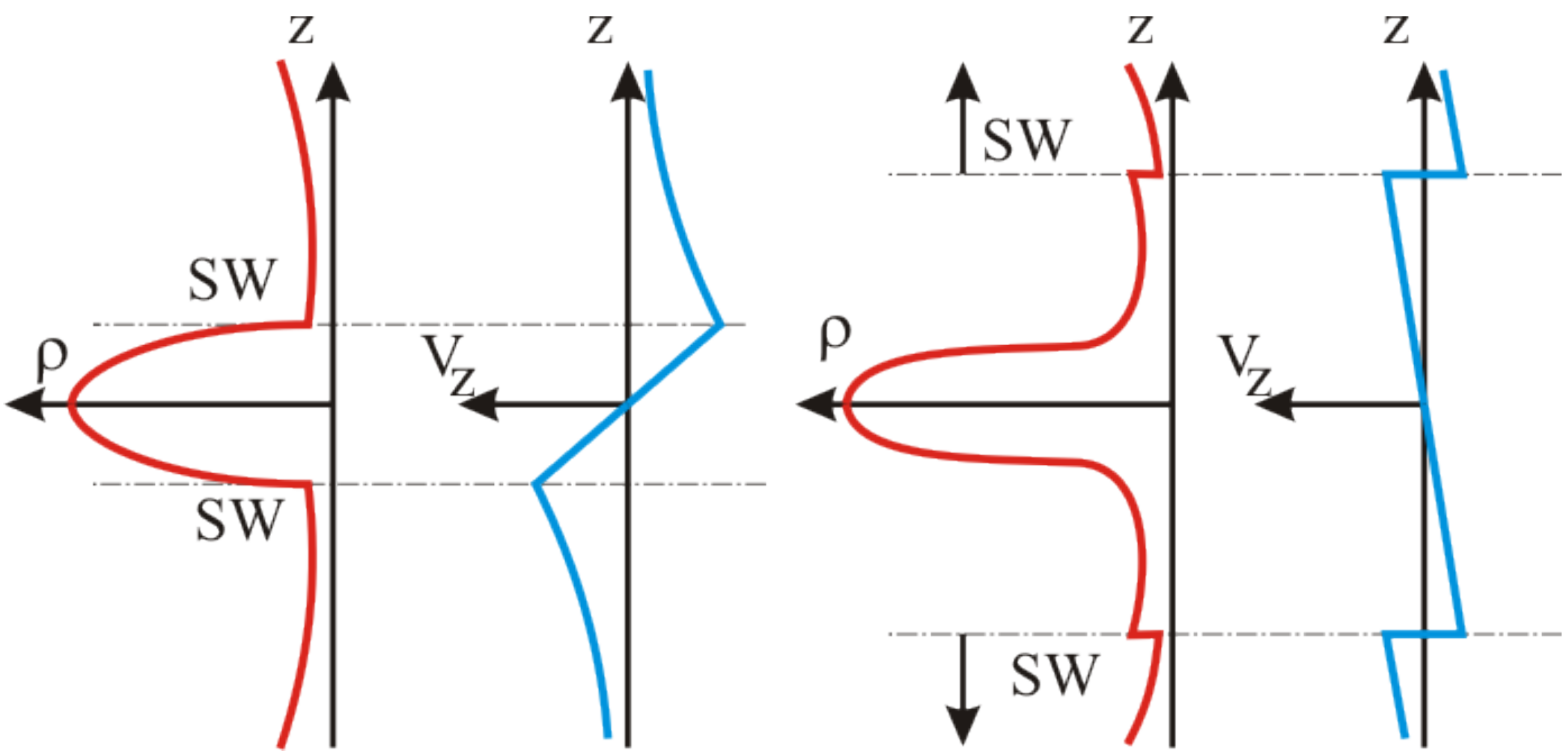


Astrobiology application. Periodically changing pressure for boulders can provide conducive environment for RNA-colonies evolution

# Conclusion

- Self-gravitating clumps can be formed in massive discs due to **gravitational instability of multiphase medium** produced by interaction of massive gas and low-massive solids.
- All individual clumps on the stage of its formation rotate around the density maximum as solid bodies independently of their size and formation time.
- Gravitational potential of gaseous clumps capture solid bodies and produce their epicyclical trajectories. About 0.1% of solids can be transferred from one clump to another.

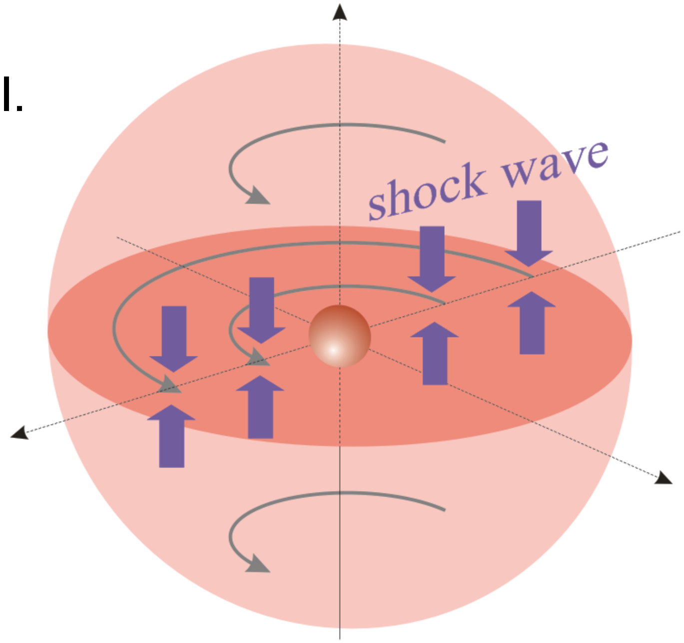
# Formation of massive gas-dust disc by the collision of the opposing streams during the molecular cloud collapse



# Possible mechanisms to “trigger” clumps formation

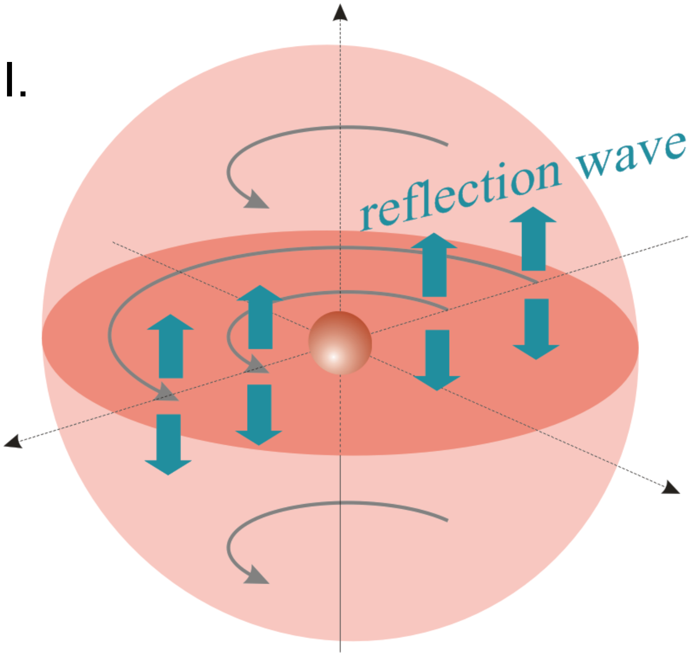
## Rapid formation of unstable multiphase subdisc

I.



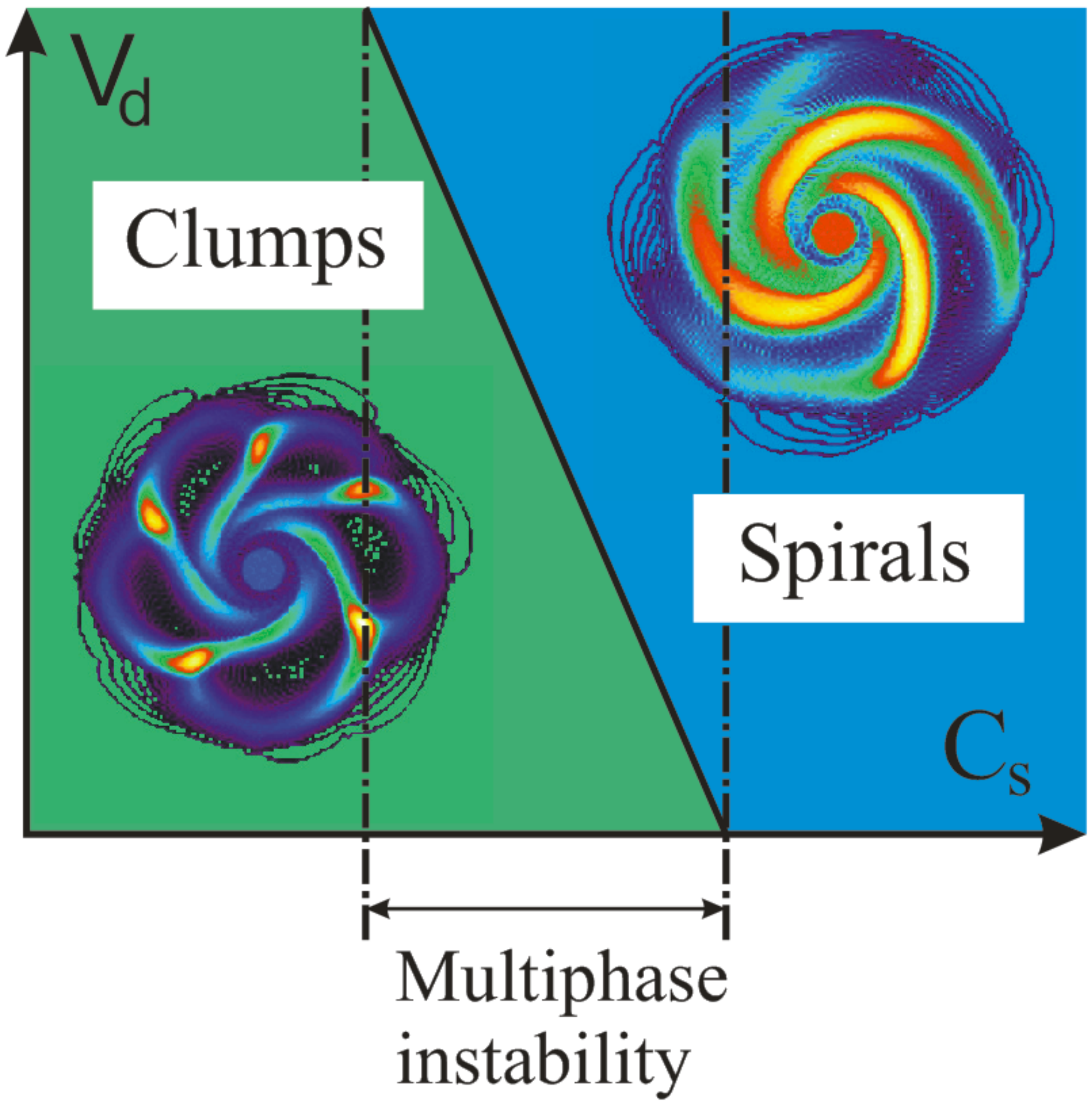
Shock wave **concentrates gas and solids** inside the equatorial plane. **Velocity dispersion of solids decreases** due to collisions with counter-flow wave.

II.



Reflection wave **spreads gas** and causes **gas cooling**. Solids leave in equatorial plane.

# When we can meet ‘butterfly effect’



# Toomre parameter (initial value) for the calculations