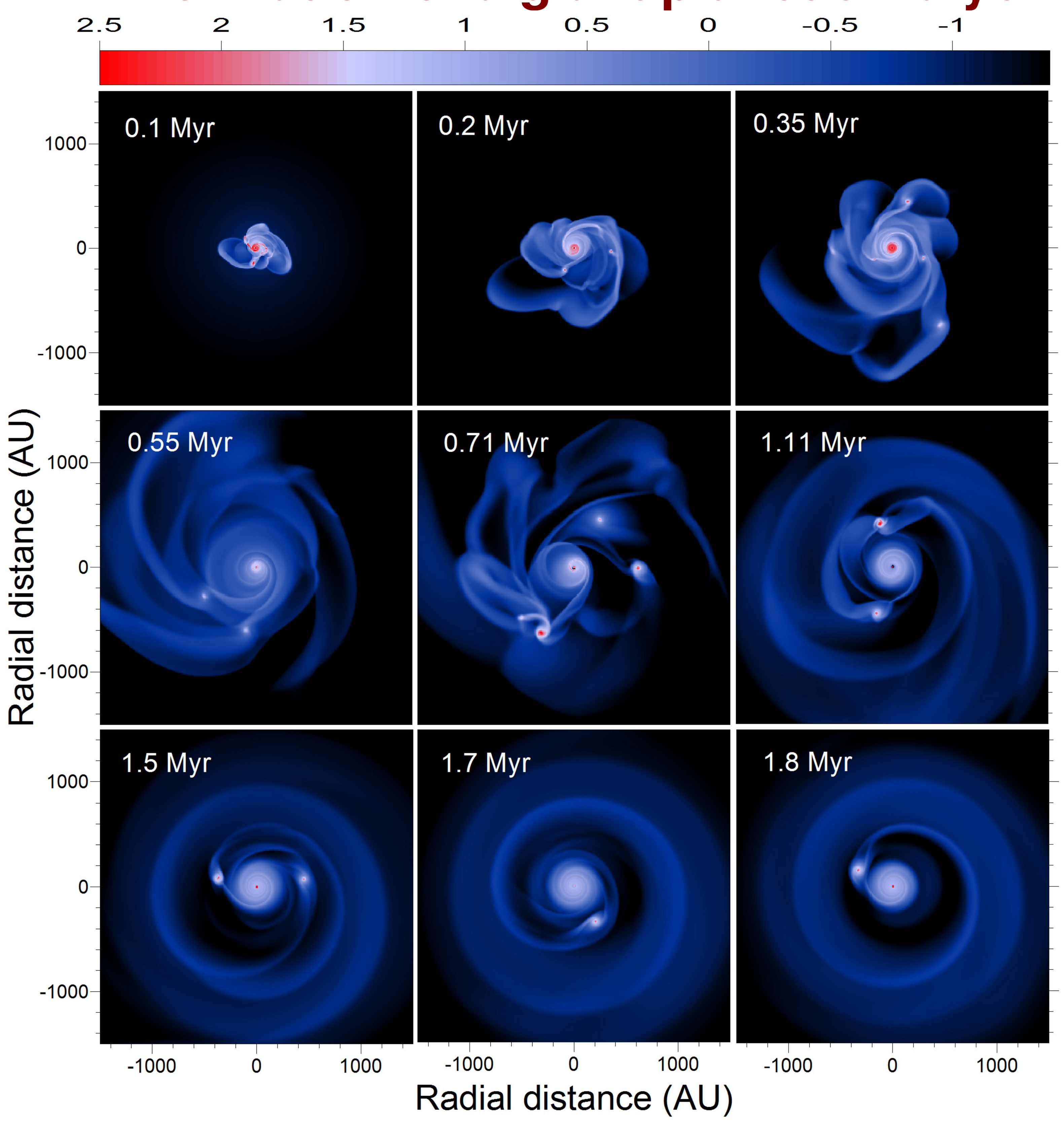
Formation and detection of giant planets and brown dwarfs on wide orbits

Eduard Vorobyov[1,2], Michael Dunham[3], and Olga Zakhozhay[4]

1) Institute of Astrophysics, University of Vienna, Vienna 1170, Austria
2) Research Institute of Physics, Southern Federal University, Rostov-on-Don, 344090, Russia
3) Department of Astronomy, Yale University, New Haven, CT 06520, USA
4) Main Astronomical Observatory, National Academy of Sciences of Ukraine, Kyiv, Ukraine

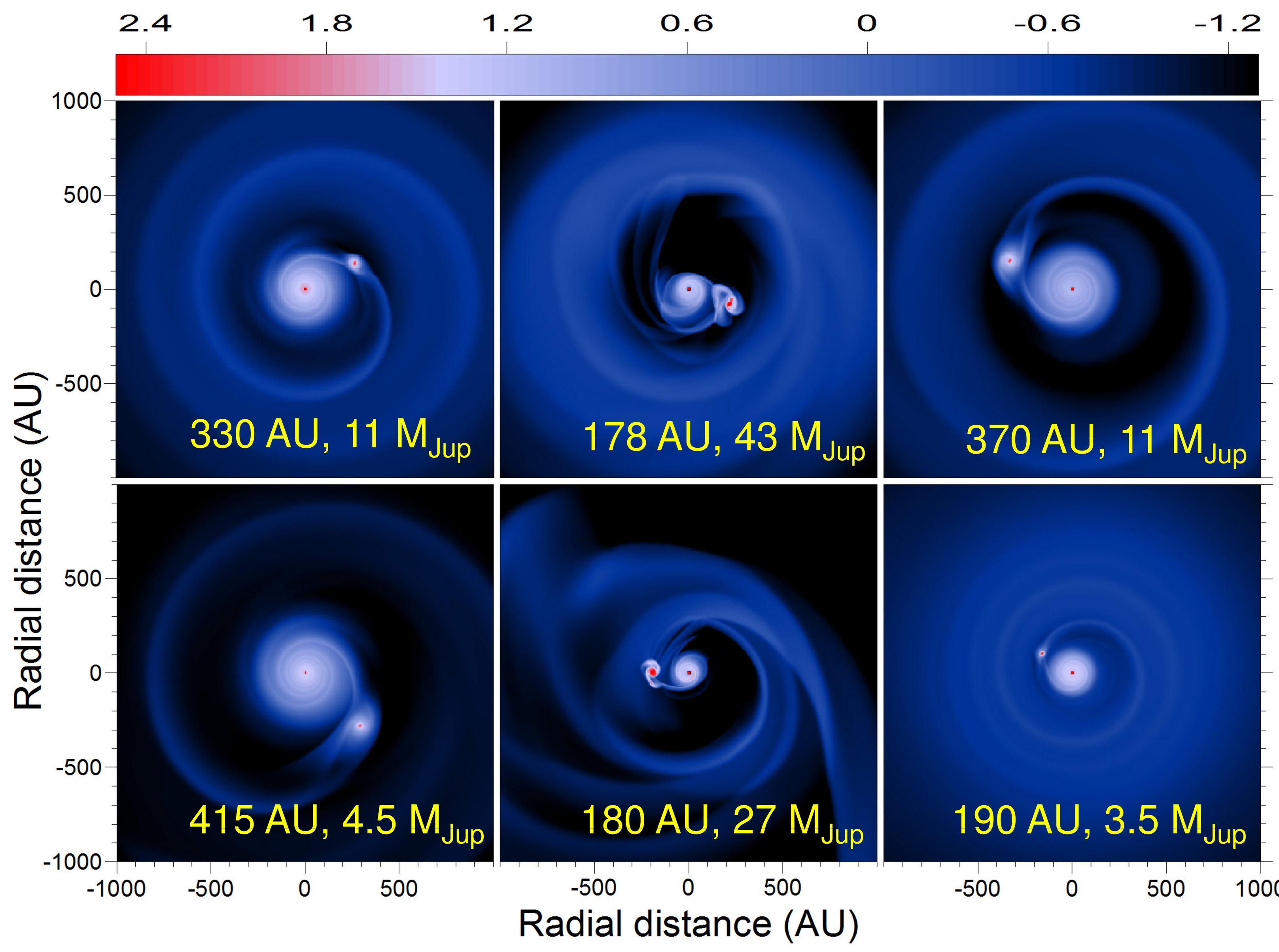
Using numerical hydrodynamics simulations of protostellar disks, we investigate the formation likelihood of massive gas giants (GPs) and brown dwarfs (BDs) on wide orbits via disk fragmentation.The fragments span a mass range from about a Jupiter mass to very-low-mass protostars and are located at distances from a few tens to a thousand AU, with a dearth of objects at ≤100 AU. The number of fragments can range from a few to more than 10 at a time. However, most fragments are driven onto the star due to the loss of angular momentum via gravitational interaction with spiral arms, dispersed via tidal interactions, or ejected into the intracluster medium. We found that fragments can survive and mature into GP/BD companions on wide orbits only in massive and extended protostellar disks ($M_{disk} \geq 0.2\ M_\odot$), experiencing gravitational fragmentation not only in the embedded but also in the early T Tauri phases of star formation. Disk fragmentation produced GP/BD embryos with masses in the 3.5 - 43 M_{Jup} range, covering the whole mass spectrum of directly-imaged, wide-orbit companions to (sub-)solar mass stars. On the other hand, it fails to produce embryos on orbital distances ≤170 AU, whereas several directly-imaged companions were found at smaller orbits down to a few AU. Disk fragmentation also failed to produce wide-orbit companions around low-mass stars $M_{st} \leq 0.7\ M_\odot$ and multicomponent systems, in disagreement with observations. We conclude that disk fragmentation is unlikely to explain the whole observed spectrum of wide-orbit companions to (sub-)solar-mass stars [1]. We also explore the possibility of observational detection of the fragments in disks viewed through the outflow cavity at a distance of 250 pc and demonstrate that one hour of integration time with the ALMA is sufficient to detect GP/BD embryos with masses as low as 1.5 M_{Jup} at orbital distances up to 800 AU from the protostar. For the adopted resolution of our simulated ALMA images of 0.1” the fragments can be detected at distances down to 50 AU. At smaller distances, the fragments usually merge with the central density peak [2].

Formation of a giant planet embryo

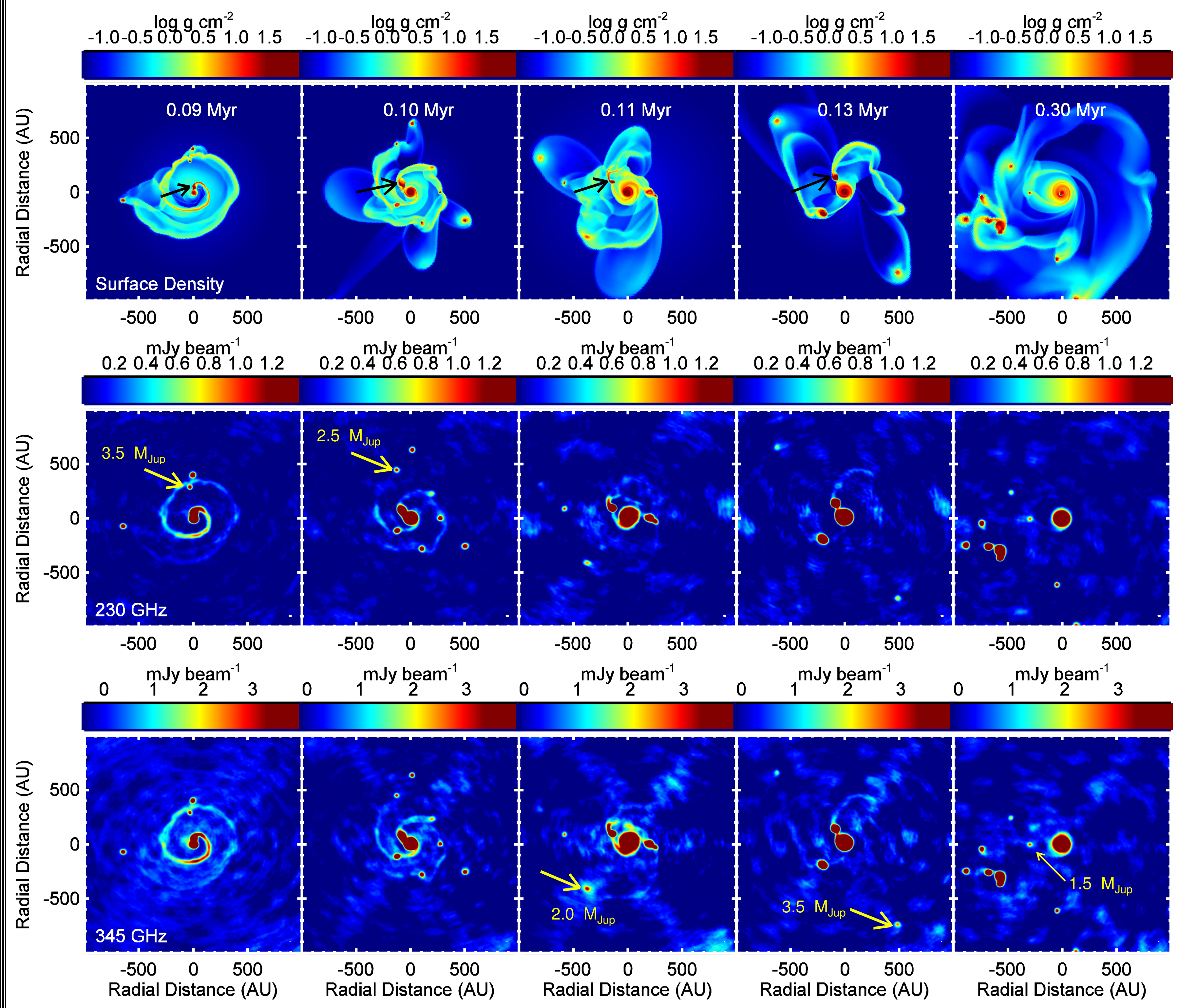


Top figure presents the gas surface density maps at various times since the formation of the central protostar (located in the center). Only the inner 3000 x 3000 AU box is shown. The scale bar is in log *g cm*$^{-2}$. Note two fragments on quasi-stable orbits at 1.11 Myr. One of the fragments disperses at 1.55 Myr and the other survives to the end of numerical simulations (1.8 Myr), turning into an 11 M_{Jup} giant planet on a quasi-stable orbit at 370 AU from a 1.1 $M_\odot$ star [1].

Bottom figure presents six models that revealed the formation GP/BD embryos on quasi-stable, wide orbits with distance in the 170 – 415 AU range and masses in the 3.5-43 M_{Jup} limit (indicated in each panel). The scale bar is in log *g cm*$^{-2}$. In other 54 considered models fragments have not survived, implying a low probability of GP/BD formation via disk fragmentation [1].



Detection of fragments in protostellar disks



Top figure. *Top row*: Gas surface density maps of the inner 2000 x 2000 AU obtained in numerical hydrodynamics simulations at five times since the formation of the central protostar [2]. The black arrows point to the most massive fragments in the disk. *Middle and bottom rows*: The corresponding synthetic ALMA images at 230 GHz (middle) and 345 GHz (bottom). The beam size is indicated in white in the bottom right of each panel. The images are displayed on a logarithmic scaling to capture the full dynamic range of the central density peaks, surrounding fragments, and spiral disk structure. The least massive detectable fragments are indicated with yellow arrows.

Bottom table provides a comparison of GP/BD characteristics obtained using numerical modeling with those derived from direct imaging of wide-orbit companions (The Extrasolar Planets Encyclopedia, http://exoplanet.eu).

Comparison of models with observations

	Modeling	Observations	Conclusions
Mass of companion	3.5 – 43 M_{Jup}	3 – 40 M_{Jup}	Disks may not grow massive enough to form upper-mass BD companions.
Orbital distance	178 – 415 AU	15 – 1170 AU	• GPs at r<170 AU are likely to form via gravitational scattering. •The lack of BDs at r<170 AU is in agreement with the BD desert. • BDs at r>500 AU are likely to form via core fragmentation. Formation gateway of GPs at such wide orbits is uncertain.
Mass of the host star	0.75 – 1.2 $M_\odot$	0.16 – 2.1 $M_\odot$	• Formation of GPs/BDs companions around low-mass stars (<0.7 $M_\odot$) via disk fragmentation is unlikely because their disks are stable against fragmentation.

[1] Vorobyov, E. I. 2013, A&A, 552, 129; [2] Vorobyov, E. I., Zakhozhay, O., Dunham, M. 2013, MNRAS, 1629, in press

Numerical simulations were performed on the VSC-2, SHARCnet, and ACEnet computer clusters