On the feasibility of giant planet formation via disk gravitational fragmentation

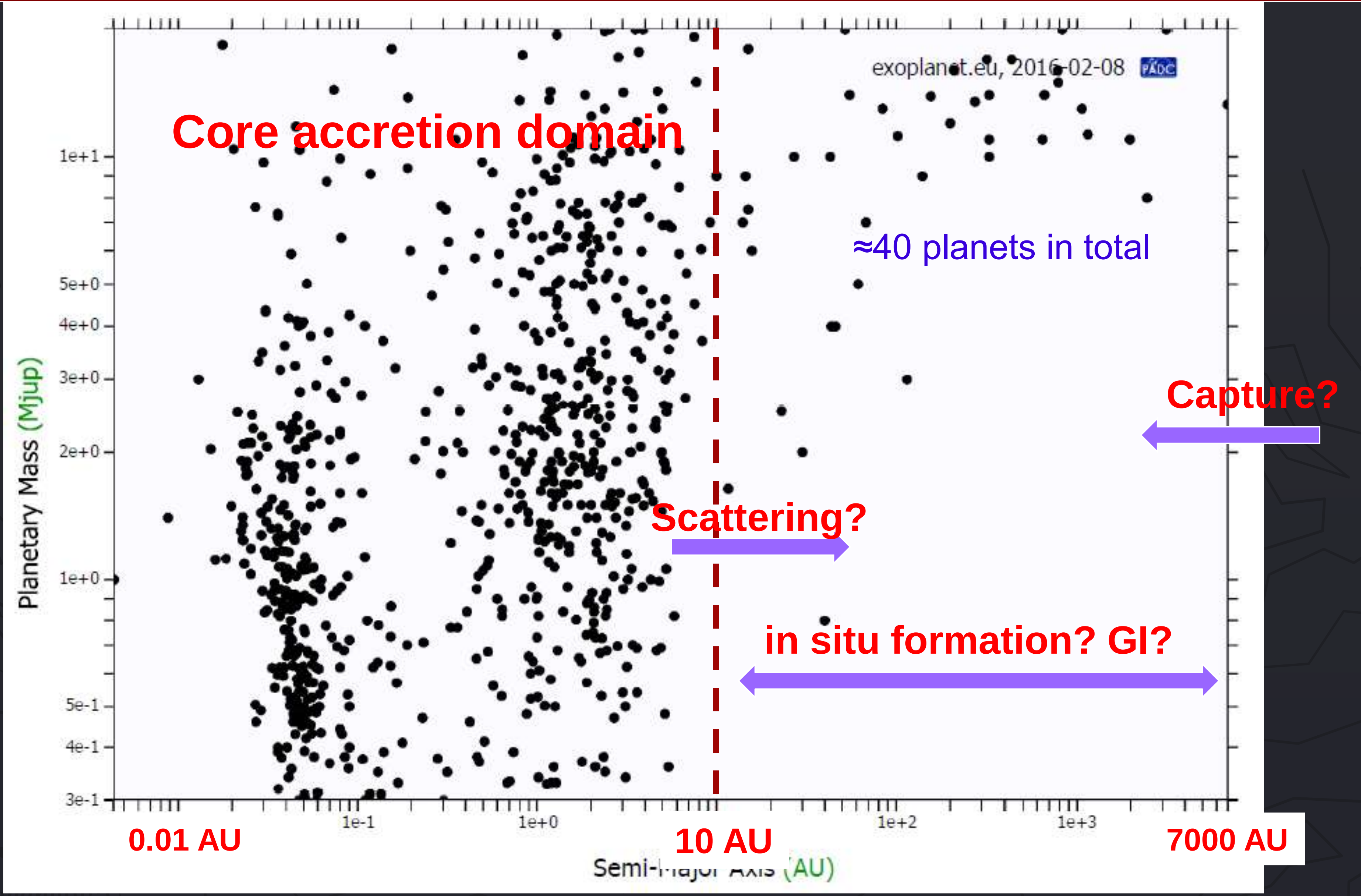
Eduard Vorobyov: The Institute of Astrophysics, The University of Vienna, Vienna, Austria

and

Research Institute of Physics, Southern Federal University, Rostov-on-Don, Russia

In collaboration with: Shantanu Basu, The University of Western Ontario, Canada

Giant planets: Mass vs. orbital distance



At r>10 AU, the growth time of a solid core with M>10 M_{earth} is greater than the mean gas disk lifetime, 2-3 Myr

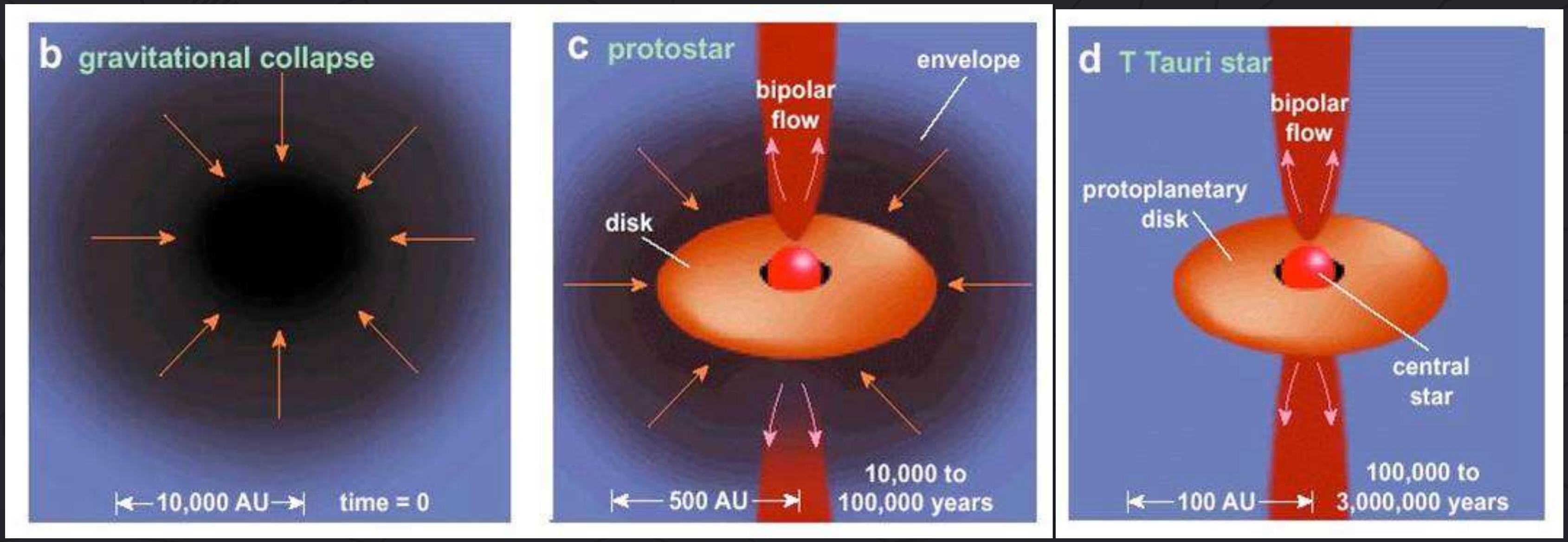
Isolated disk models are misleading when studying disk gravitational instability and fragmentation

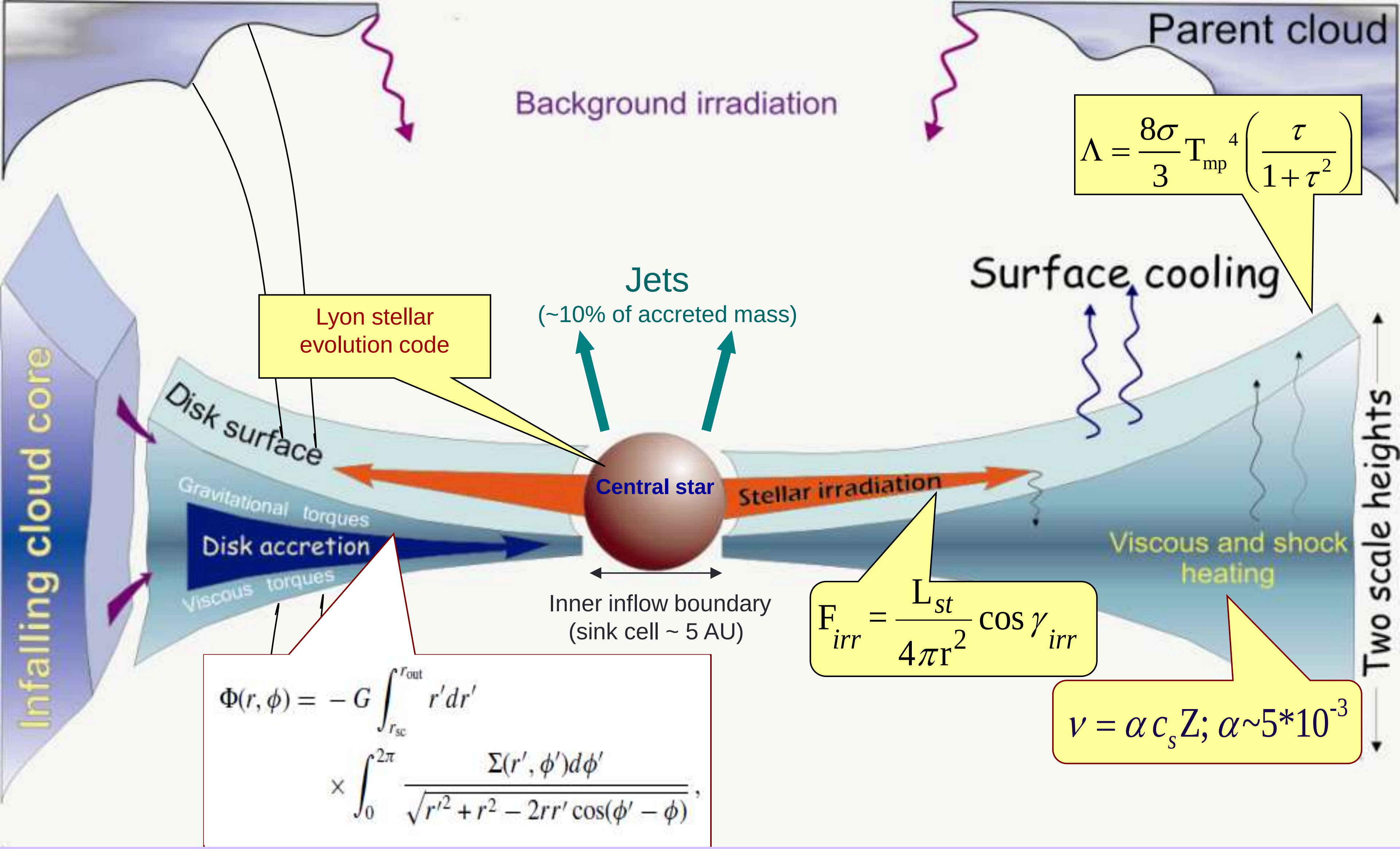
Mass loading from infalling envelope is the key factor causing the disk to fragment

(Vorobyov & Basu 2005, 2006)

Global models that self-consistently follow Cloud → Disk transition

Pre-stellar phase | Class 0 and I phases | T Tauri phase

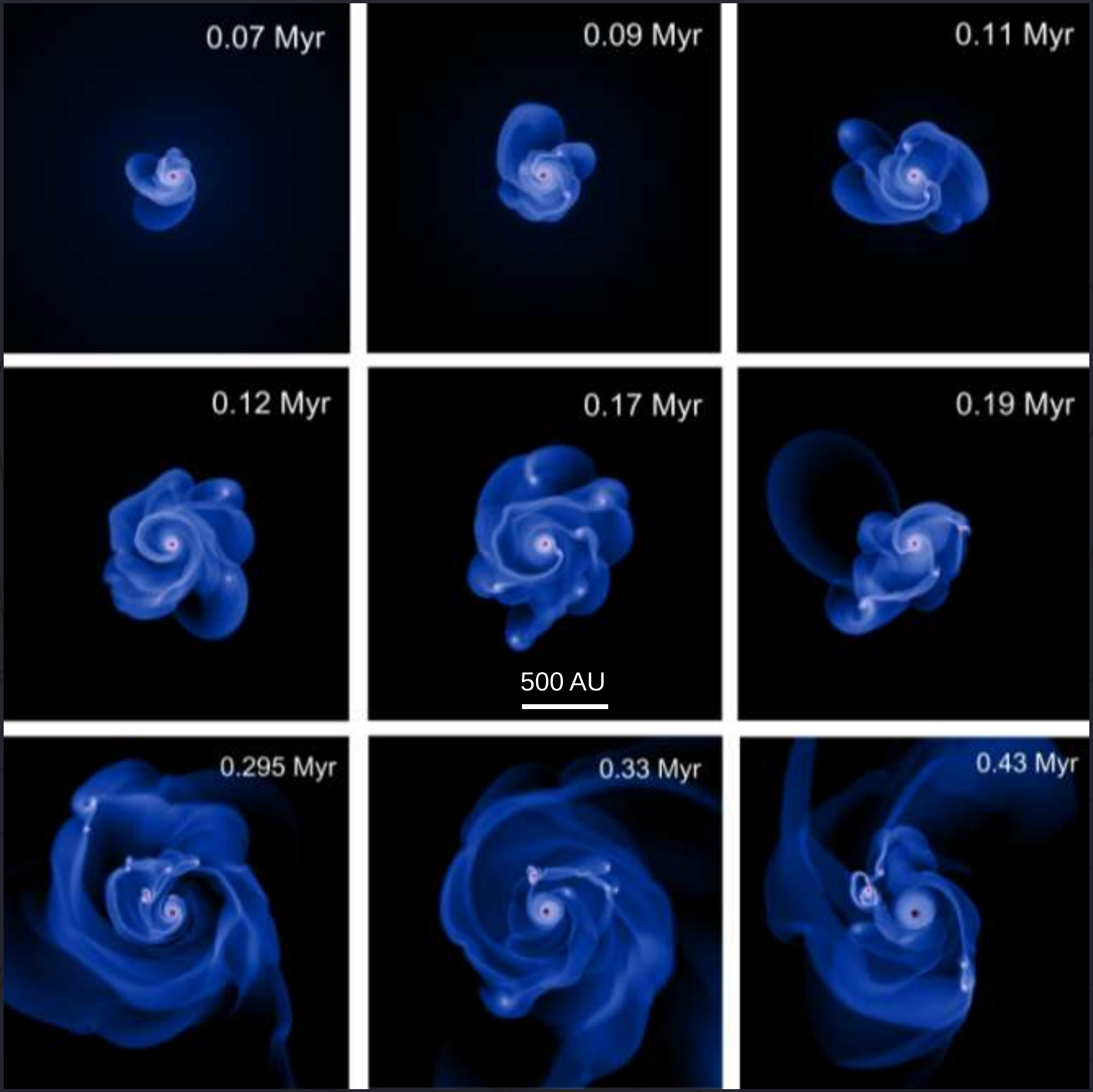




Cons: Not full 3D. Two-dimensional thin-disk with approximate reconstruction of the vertical structure (not razor-thin!)

Pros: 1) Self-consistently follows cloud → disk formation
2) Long integration times (~ Myr)
3) High resolution (<1 AU at r<100 AU)

Long-term evolution of self-gravitating circumstellar disks



Initial conditions:

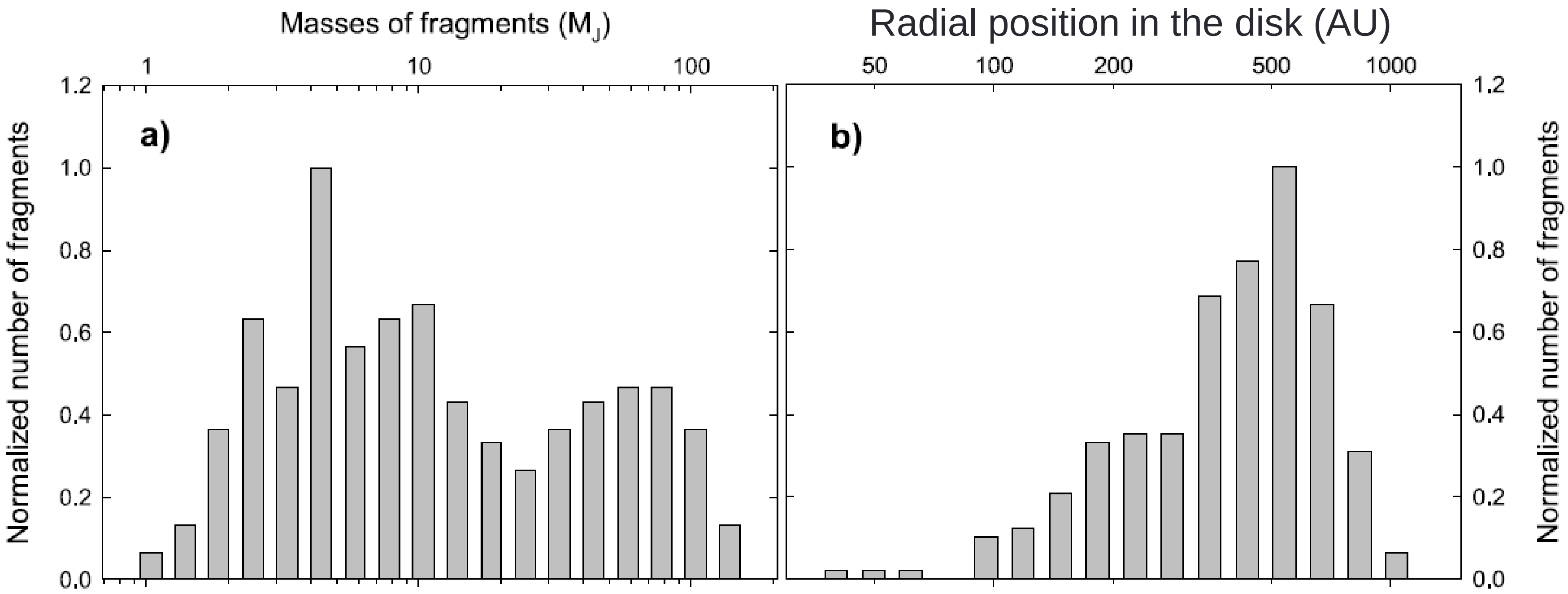
Collapsing cloud core with

$M_{core} = 1.07\ M_{\odot}$

$\beta = 0.7\%$

β is the ratio of rotational to gravitational energy in the core

Properties of fragments



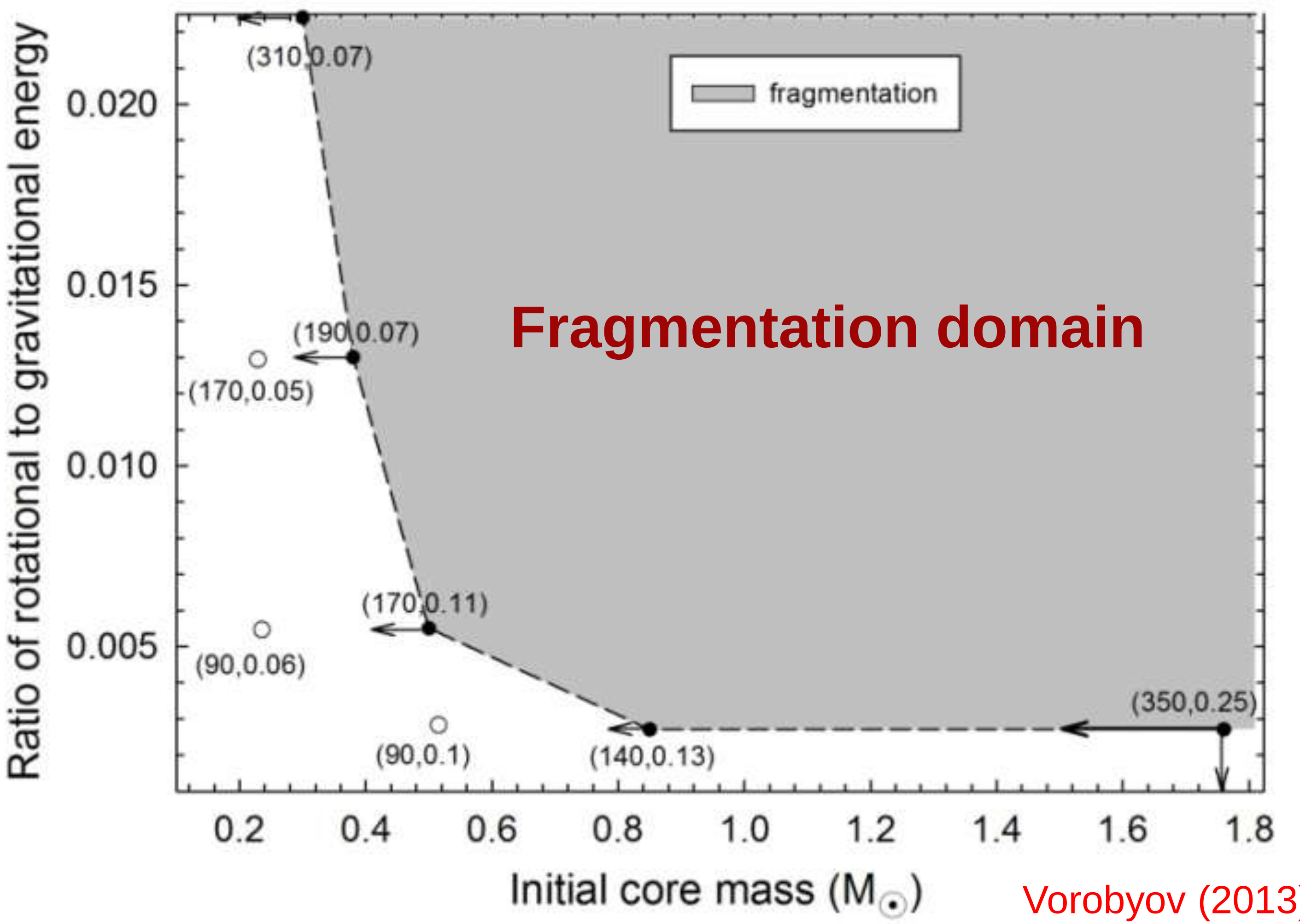
Clump masses: 1 --100 M_{Jup} Clump radii: a few AU – a few tens of AU.

Adiabatic cores with rotation and pressure balancing self-gravity.

Number of fragments: up to 10, depending on the initial cloud mass and angular momentum

Disk fragmentation domain in the beta – M_{core} phase space

Numbers in parentheses are disk radius [AU] and disk mass [$M_\odot$]



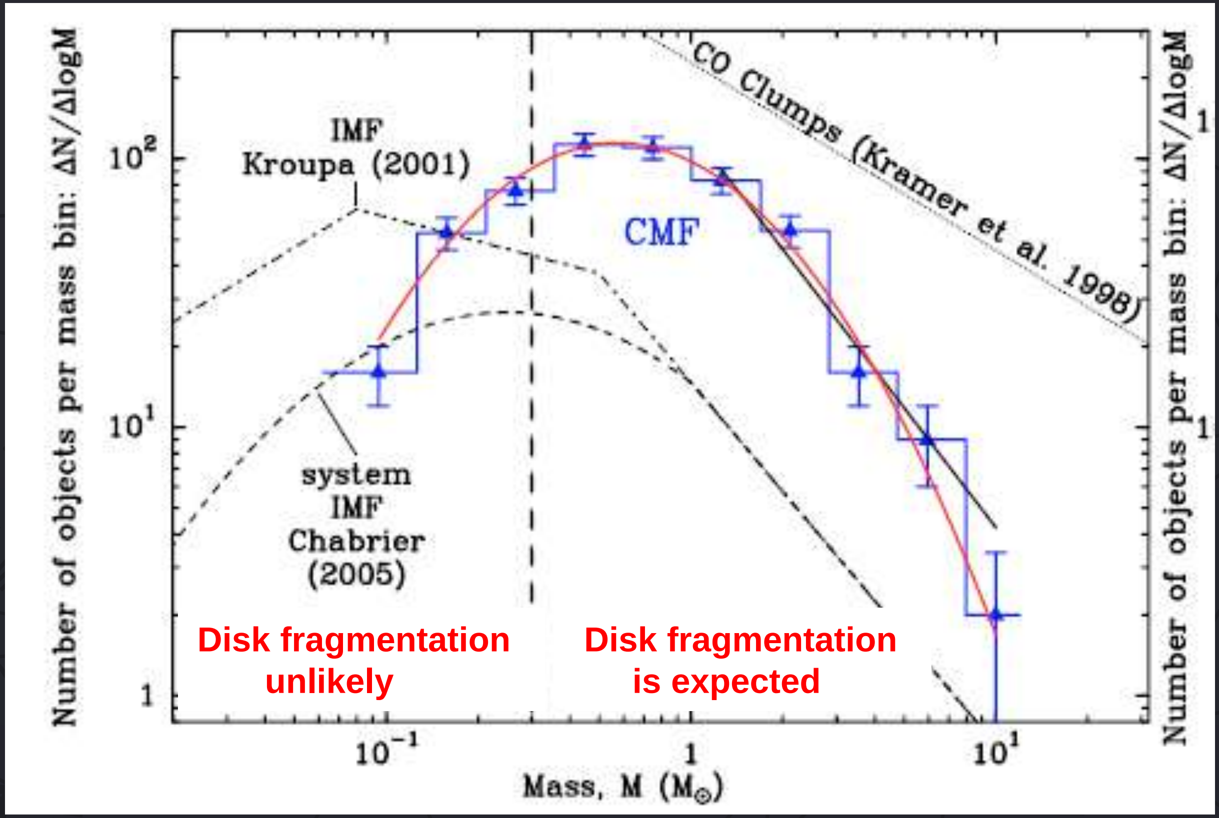
Vorobyov (2013)

$M_{core} > 0.3\ M_\odot$; $\beta > 0.3\%$, $M_{disk} > 0.07\ M_{sun}$

Initial core mass function in the Aquila region (Andre et al. 2010)

Critical core mass

$0.3\ M_{sun}$



Depending on the distribution of β-parameter (from 0.01% to 7%, Caselli et al. 2002),

40% - 70% of collapsing cores are supposed to form fragmenting disks

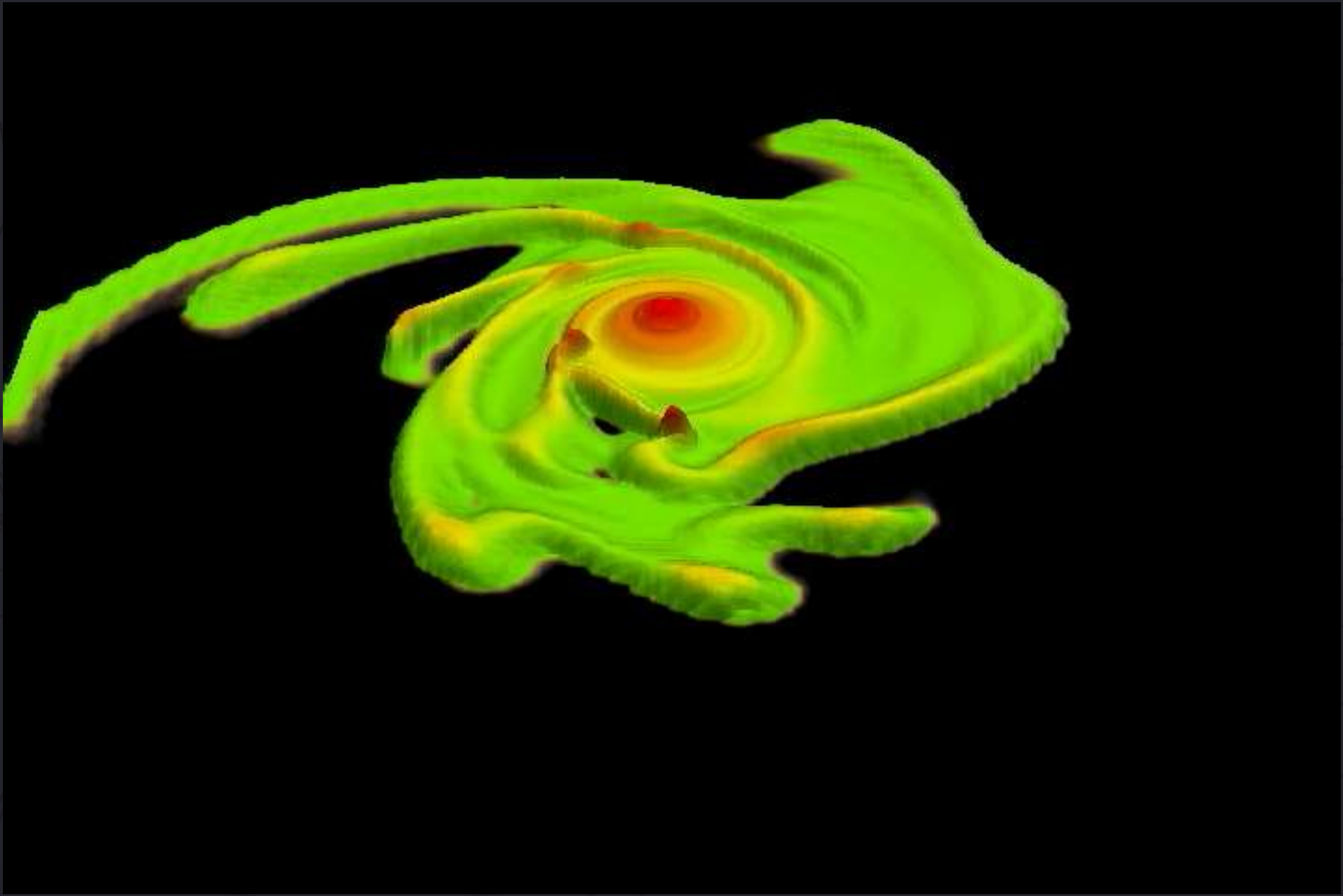
(Vorobyov & Basu 2015)

Survival of fragments. Runaway inward migration.

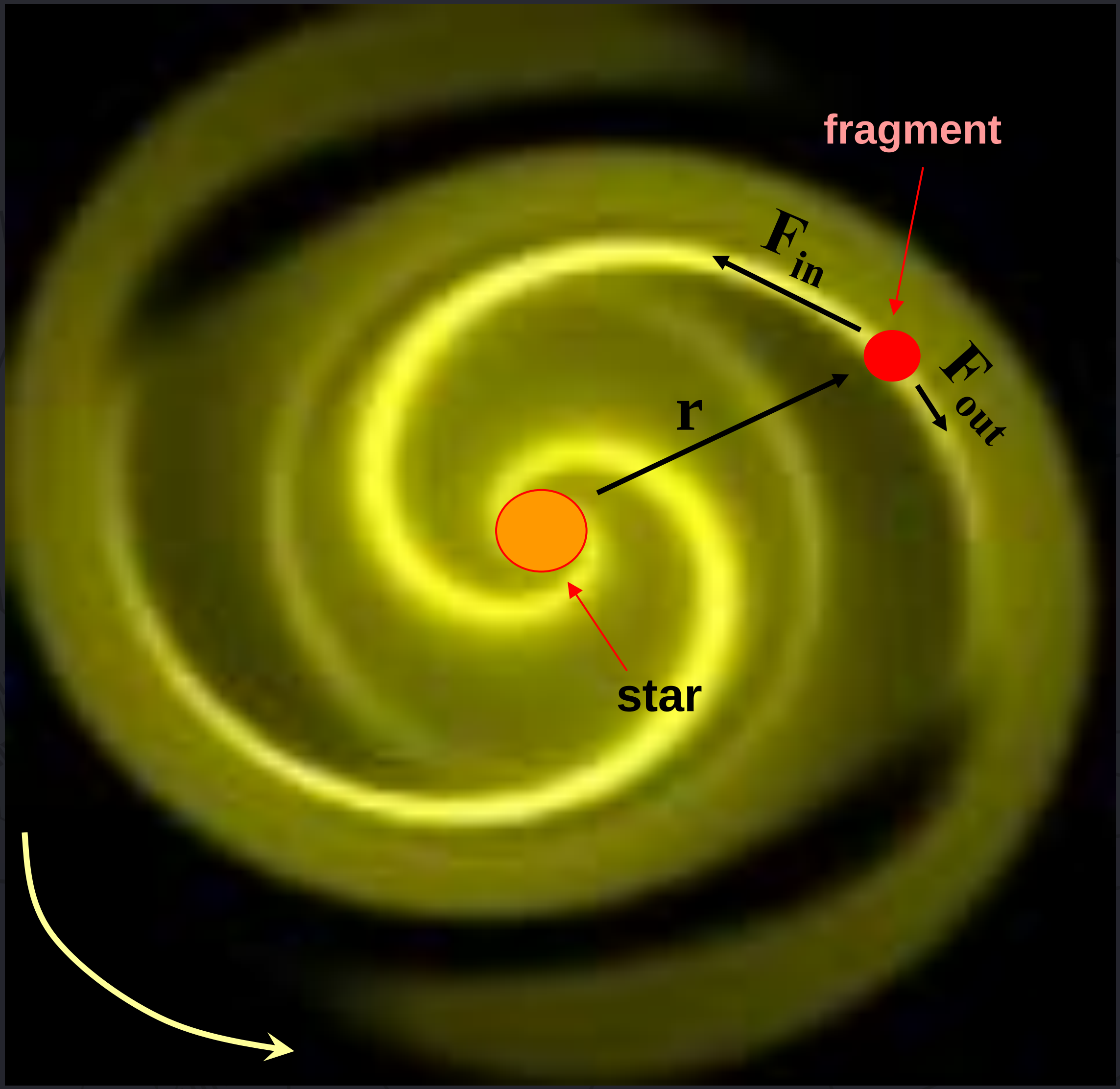
(Vorobyov & Basu 2005, ApJL; Vorobyov & Basu 2006, 2010, 2015 ApJ)

Inward migration of fragments

Initial core mass = 1.0 Msun



Survival of fragments



$$\Gamma_{in} = \mathbf{r} \quad \mathbf{F}_{in} > 0$$

$$\Gamma_{out} = \mathbf{r} \quad \mathbf{F}_{out} < 0$$

$$\frac{dL_{fr}}{dt} = \Gamma_{in} + \Gamma_{out}$$

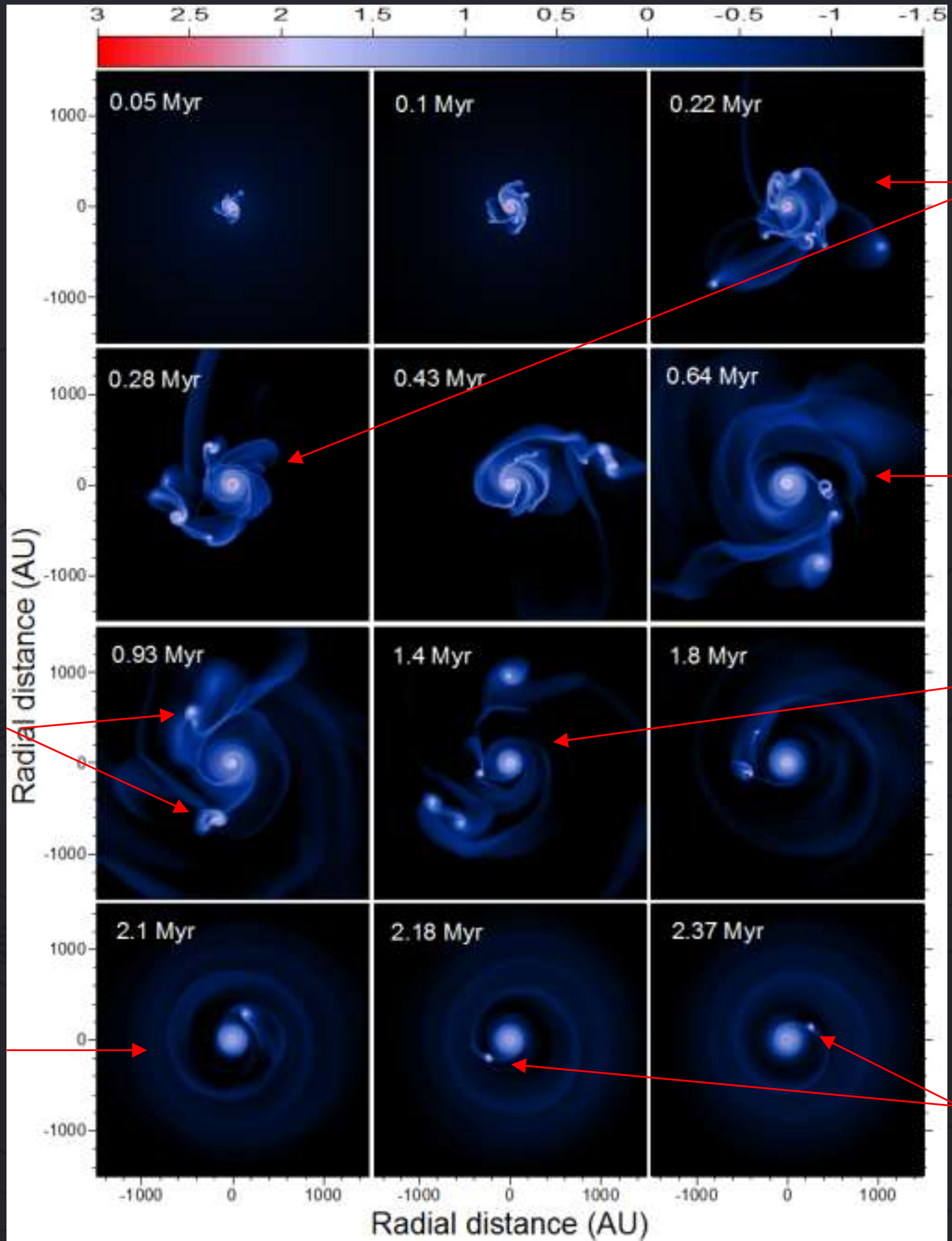
Fragments may stay at quasi-stable orbits for as long as $\Gamma_{in} > \mathrm{abs}(\Gamma_{out})$

In the early phase this inequality almost always breaks due to

1) continuing disk growth via accretion from the infalling envelope.
2) sub-Keplerian velocity of the accreted material

Fragments need to form in the T Tauri phase to avoid fast migration (Vorobyov & Basu 2010; Kratter et al. 2010, Vorobyov 2013)

Formation and evolution of a fragmenting disk ($M_{core} = 1.7\ M_\odot$; $\beta = 0.56\%$)



Disk experiences vigorous fragmentation, but most fragment migrate onto the star

The embedded phase ends at 0.65 Myr

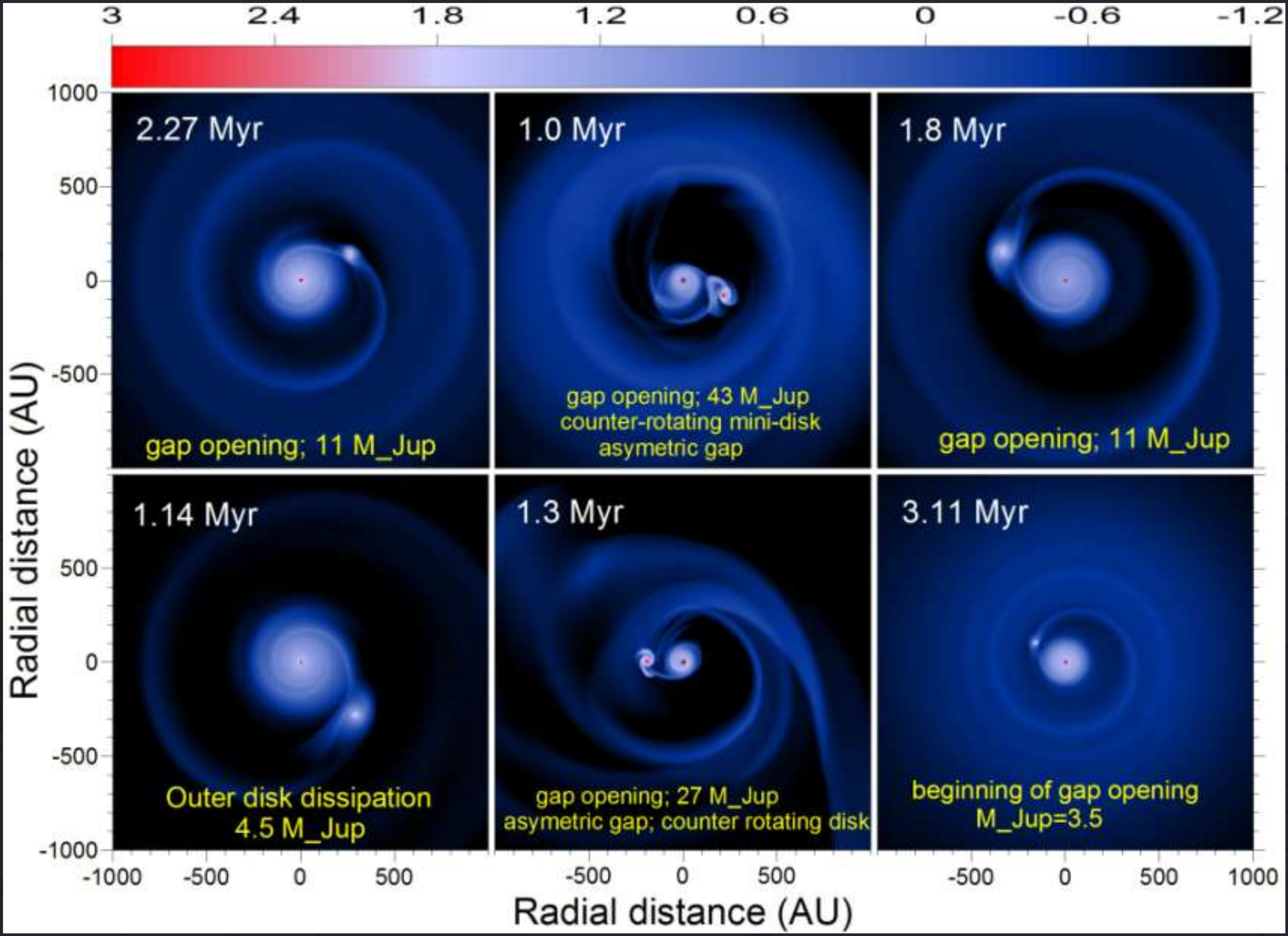
Two fragments survived through the embedded phase

Another episode of disk fragmentation in the T Tauri stage

Only one fragment finally survives

the survived fragment opens a gap and settles on a quasi-stable orbit

Six models (out of >60) showing the formation of brown dwarfs and giant planets



Maximum eccentricity of the orbits is 0.07

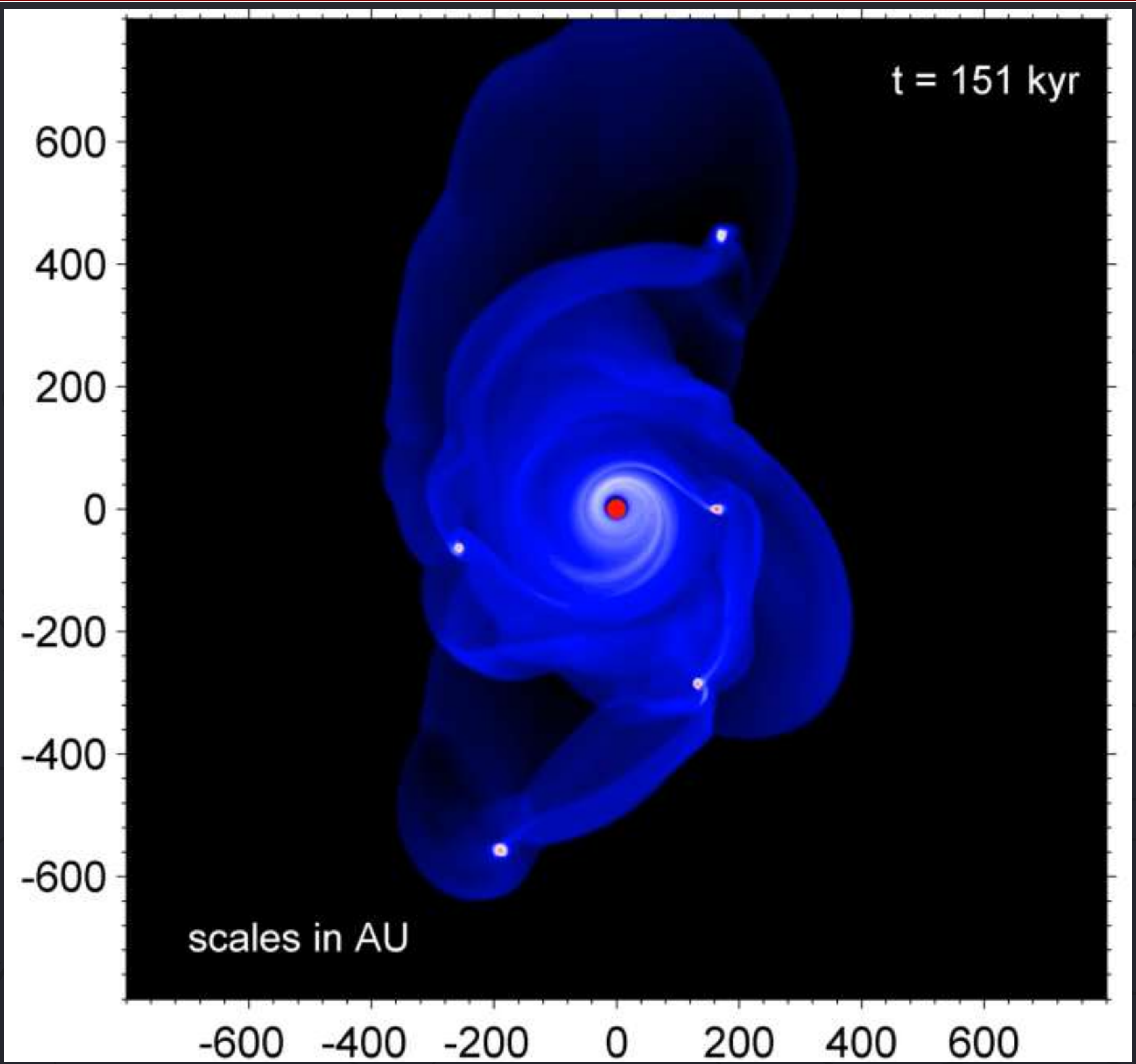
Comparison of models with observations

	modeling	observations	Conclusions and reasons for mismatch
Object mass	3.5 – 43 M_{Jup}	1.7 – 40 M_{Jup}	
Orbital distance	178 – 415 AU	10 – 7000 AU	• very wide separation planets (>500 AU) fail to form because disks do not grow to radii >> 500 AU. • runaway inward migration of fragments hinders planet formation at radii <150 AU
Mass of the host star	0.75 – 1.2 $M_{\odot}$	0.16 – 2.1 $M_{\odot}$	• Low-mass stars (<0.7 $M_{\odot}$) have also low-mass disks – insufficient for gravitational fragmentation.

Disk fragmentation cannot explain the whole spectrum of observed wide-orbit planets!

(Vorobyov A&A, 2013, 552, 129)

Inward migration and tidal downsizing



High resolution

0.1— 0.7 AU
in the inner 100 AU

Formation of giant planets revisited