How do wide-orbit planets form?

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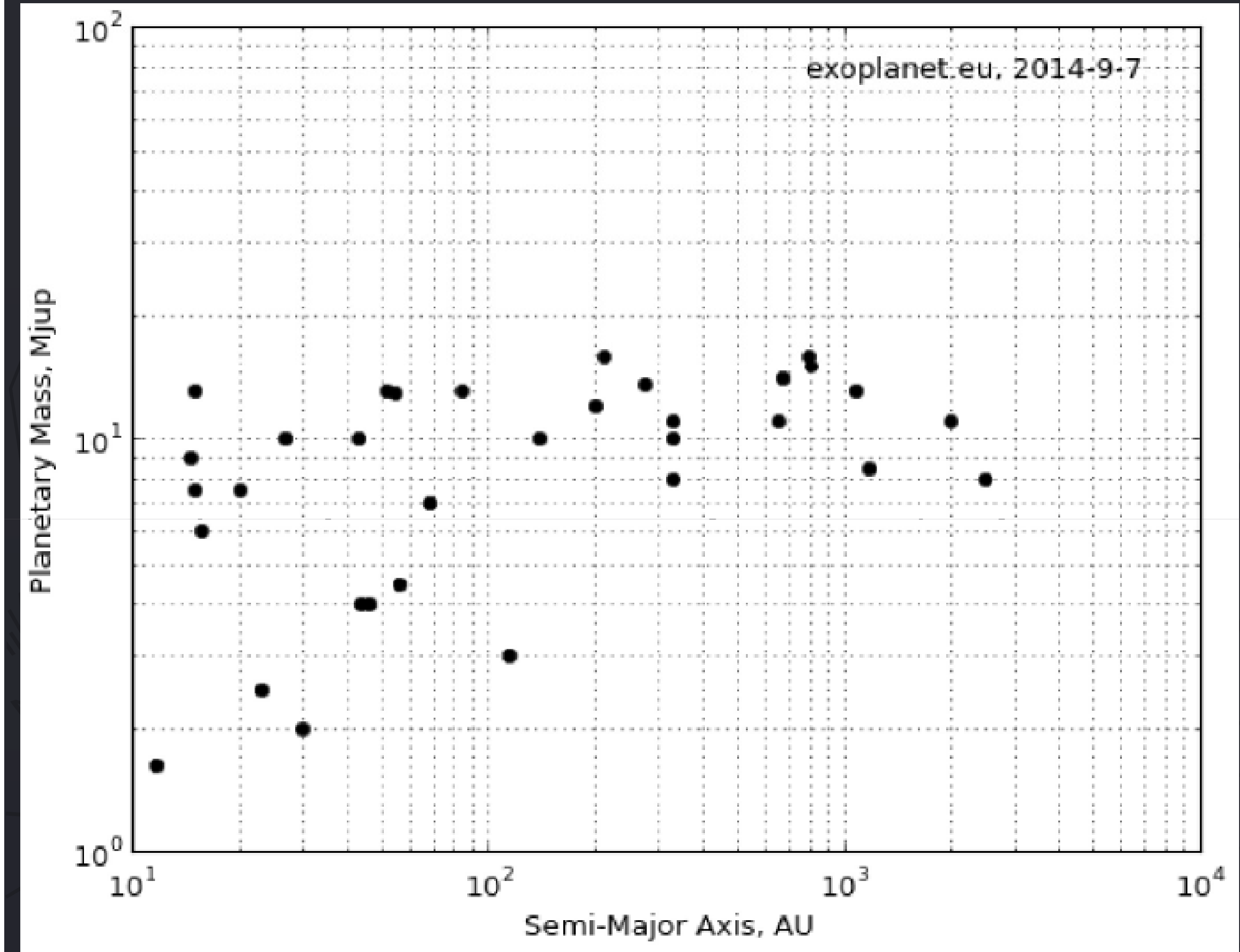
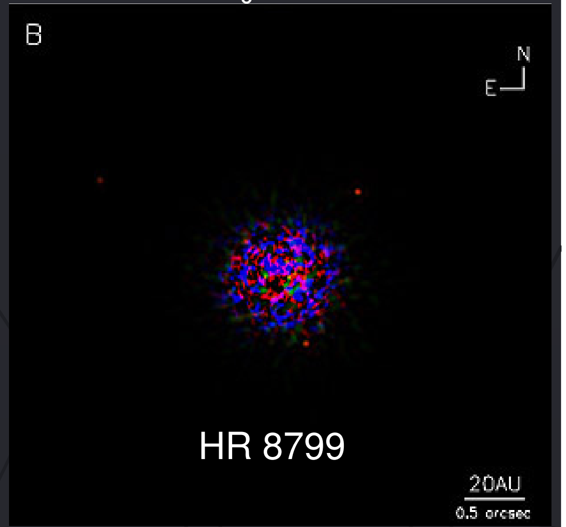
Giant planets on wide orbits (> 10 AU)

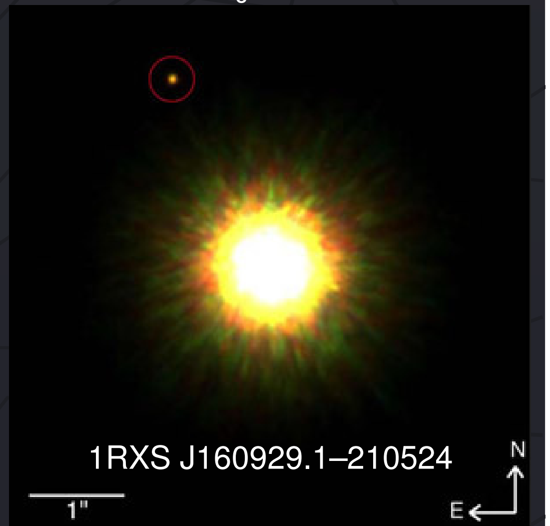


33 planets in total

M ~ 5-7 M_J; R ~ 30-70 AU



M ~ 8 M_J; R ~330 AU

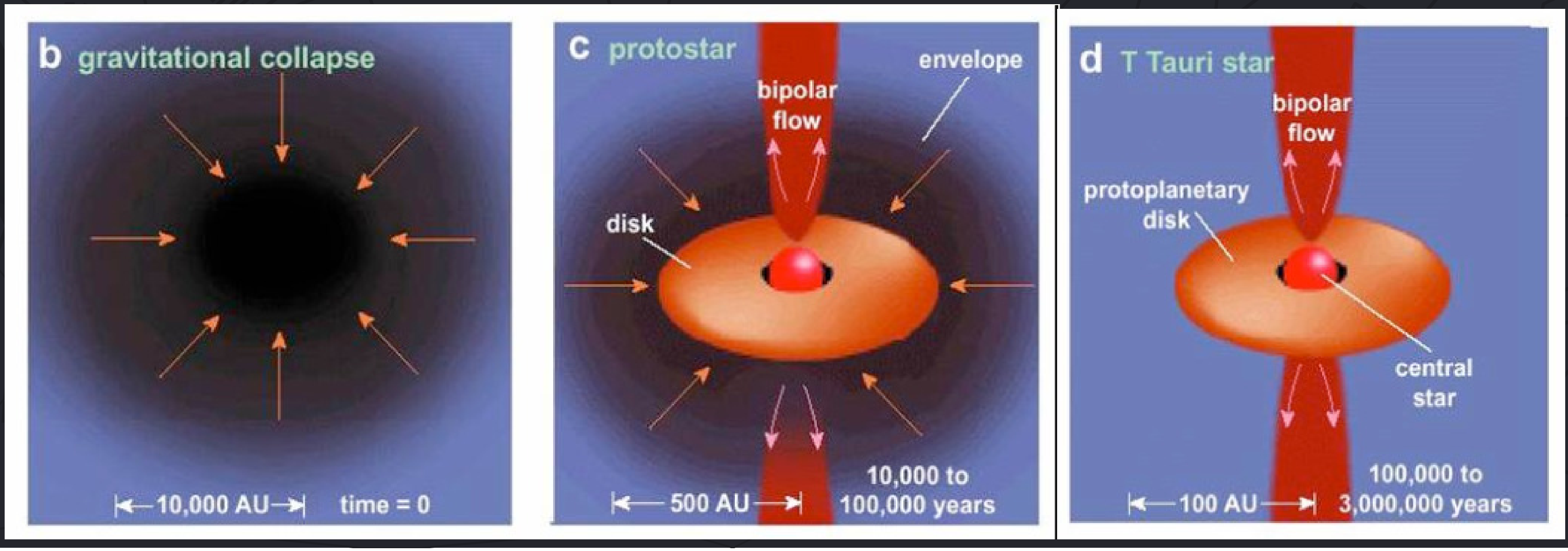


Isolated disk models may be misleading when studying disk fragmentation

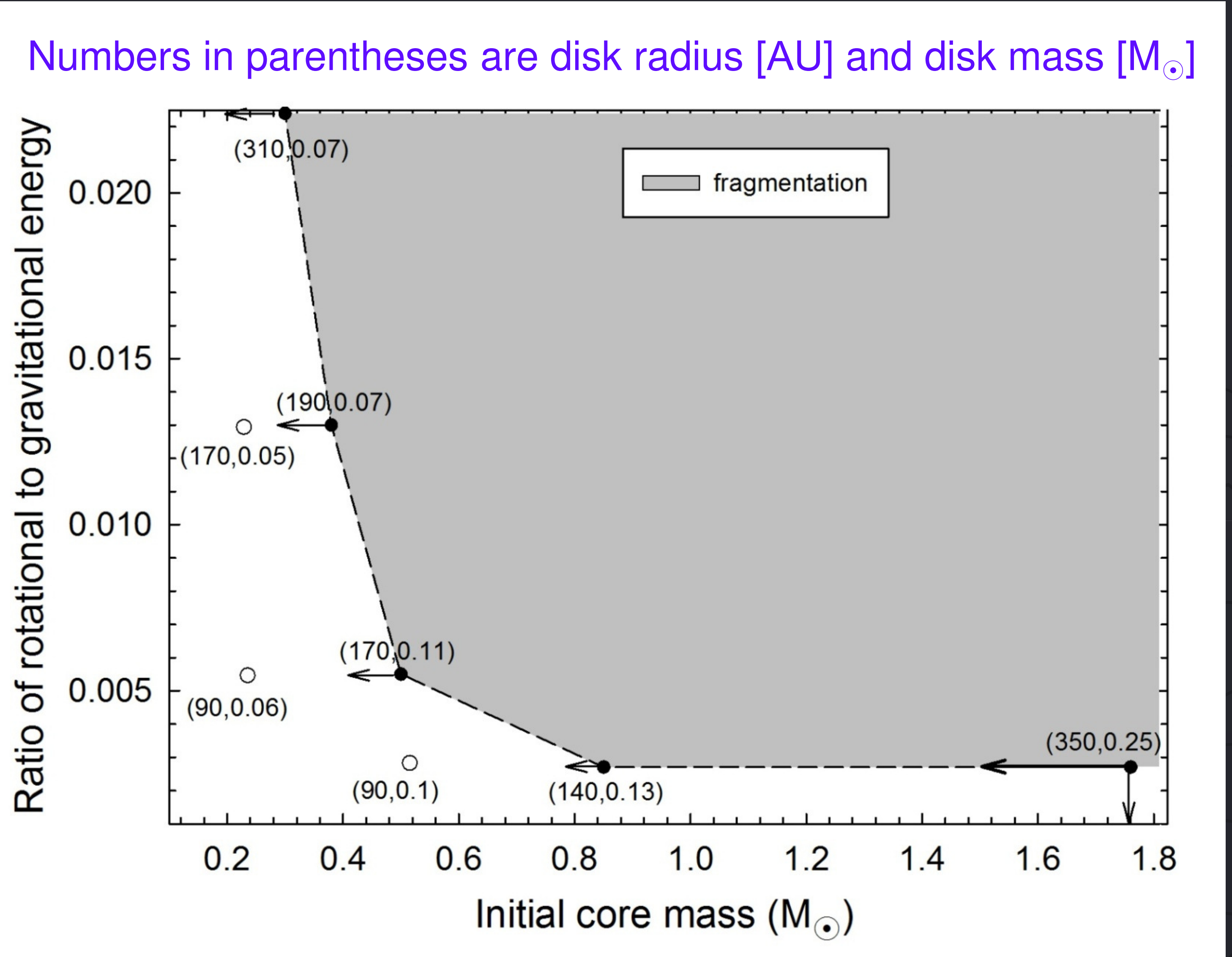
1. Not known if the chosen disk/star configuration is realizable in nature
2. No information on the likelihood or efficiency of disk fragmentation.
3. No information on disk fragmentation in the embedded phase, when the disk supposed to be most massive.

Global models that self-consistently follow Cloud → Disk transition

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



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

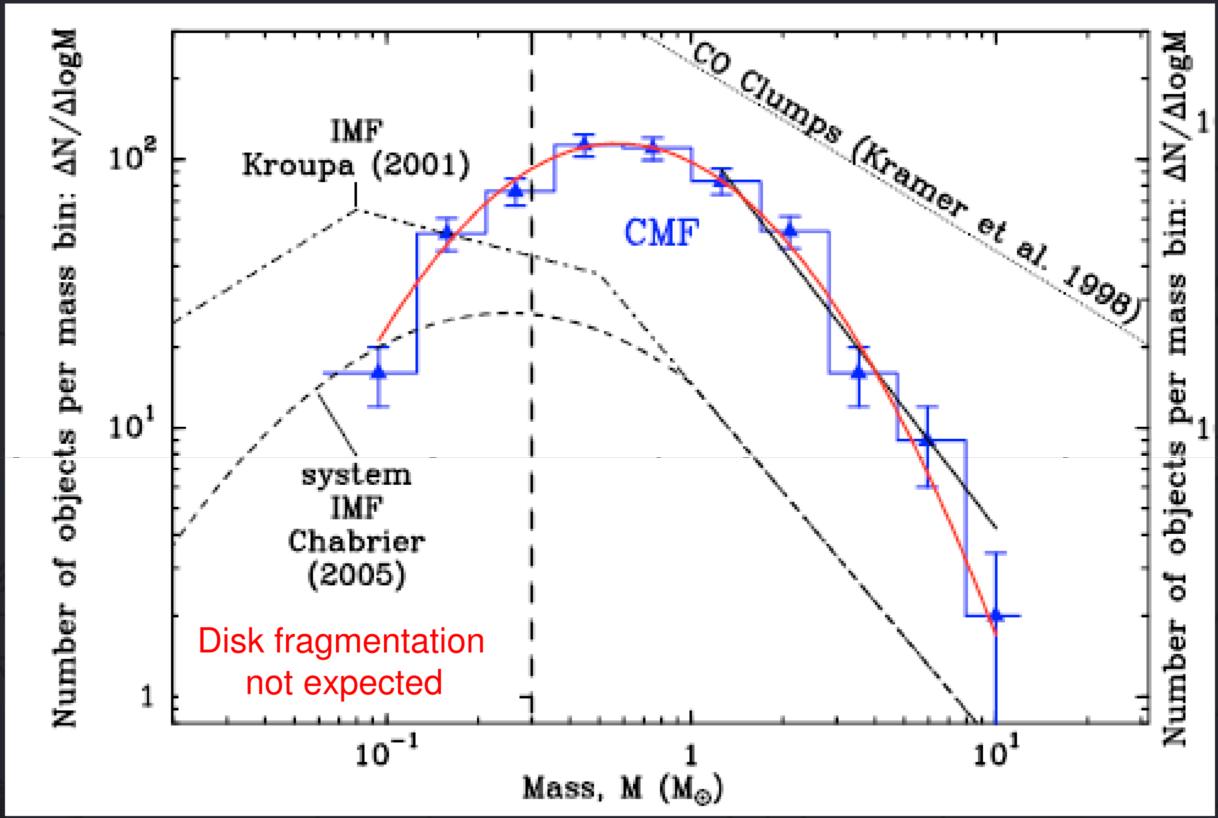


Disk fragmentation was not detected for cores with mass < 0.3 $M_\odot$ and beta < 0.3%

Based on numerical hydrodynamics simulations of Vorobyov (2012, A&A, 552, 129)

Initial parameters of pre-stellar cores such as mass and angular momentum determine the likelihood of disk fragmentation.

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



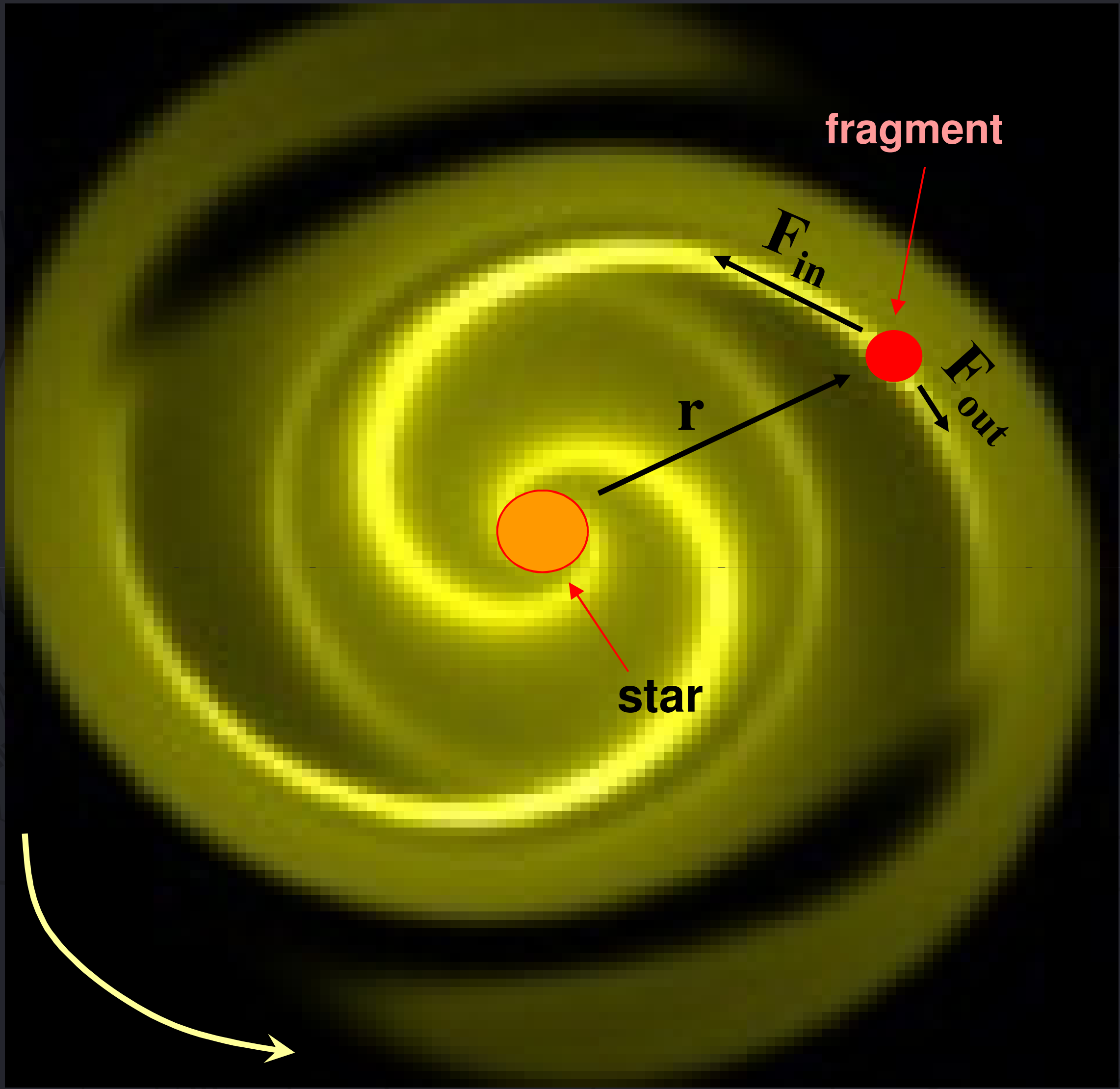
The beta parameter of pre-stellar cores varies from 0.01% to 7%
(Caselli et al. 2002)

Main conclusion: a sizeable fraction of cores are unlikely to produce fragmenting disks!

Survival of fragments. Runaway inward migration.

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

Survival of fragments



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

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

$$\frac{d\mathbf{L}_{fr}}{dt} = \Gamma_{in} + \Gamma_{out}$$

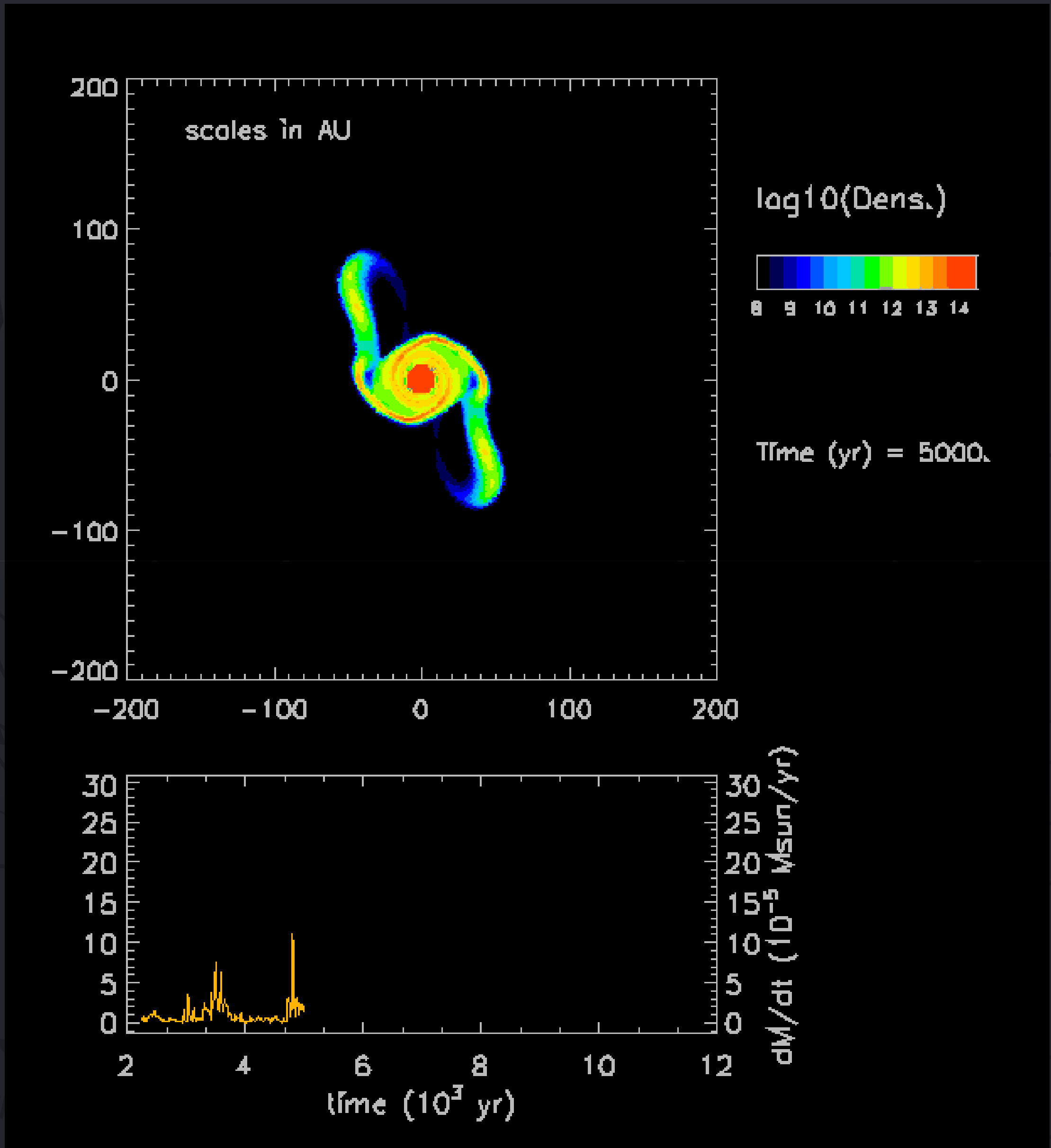
Fragments may stay at quasi-stable orbits for as long as $\Gamma_{in} > \mathrm{abs}(\Gamma_{out})$

In the embedded 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)

Migration of fragments onto the protostar and the mass accretion bursts



Initial core mass = 1.0 Msun

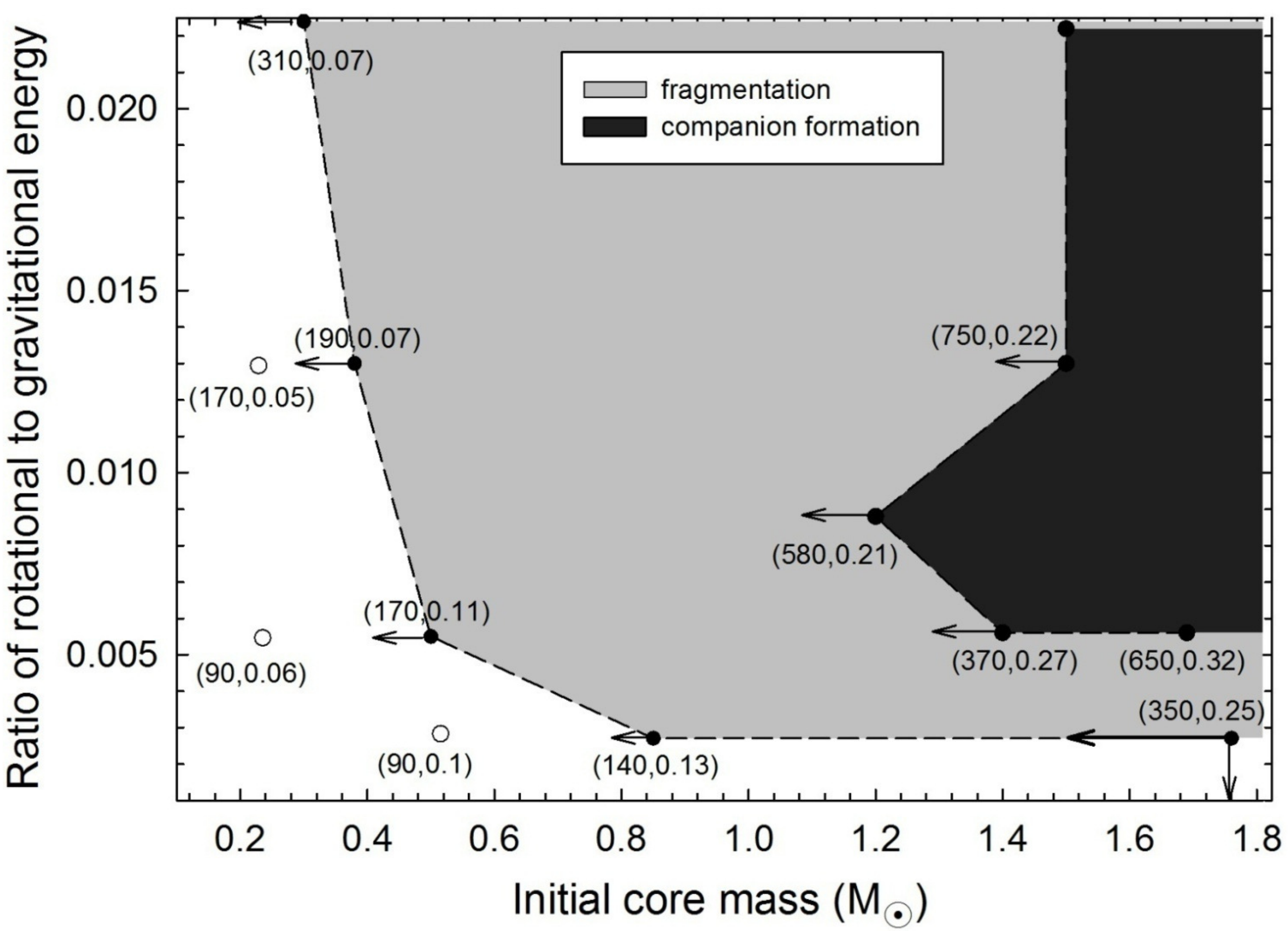
Face-on view of the disk
Black regions – infalling envelope
(off scale)

Mass accretion rate at 5 AU
$10^{-5}\ M_{\odot}$ / year

Vorobyov & Basu (2006, 2010)

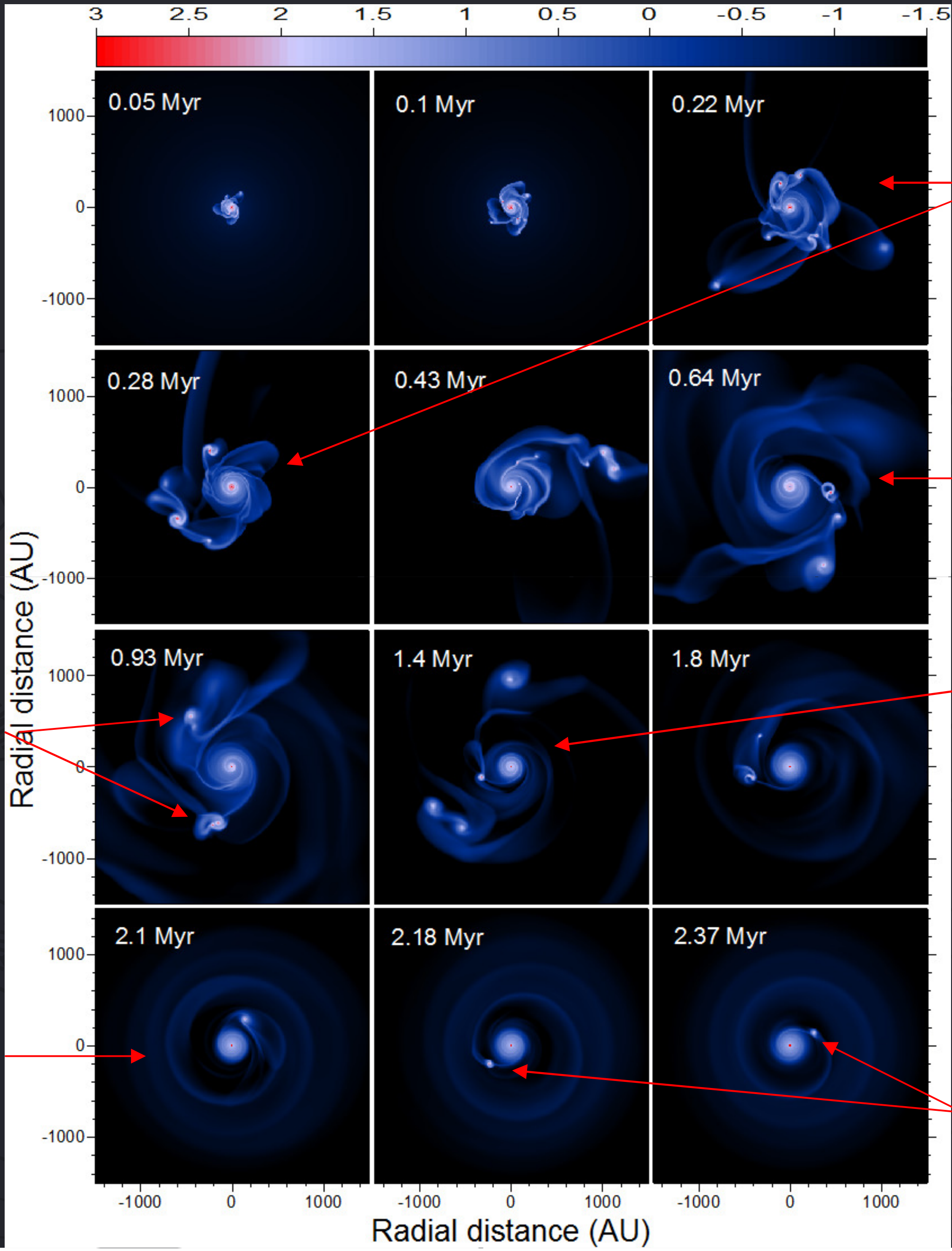
Planet formation domain in the beta – M_{core} phase space

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



The planet formation domain is much smaller than the fragmentation domain because only most massive and extended disks can sustain fragmentation not only in the embedded phase (when fragmentation is favoured by mass loading from the envelope, but fragments are unlikely to survive) but also in the T Tauri stage (when fragmentation is rare but fragments are likely to survive).

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



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

The embedded phase ends at 0.65 Myr

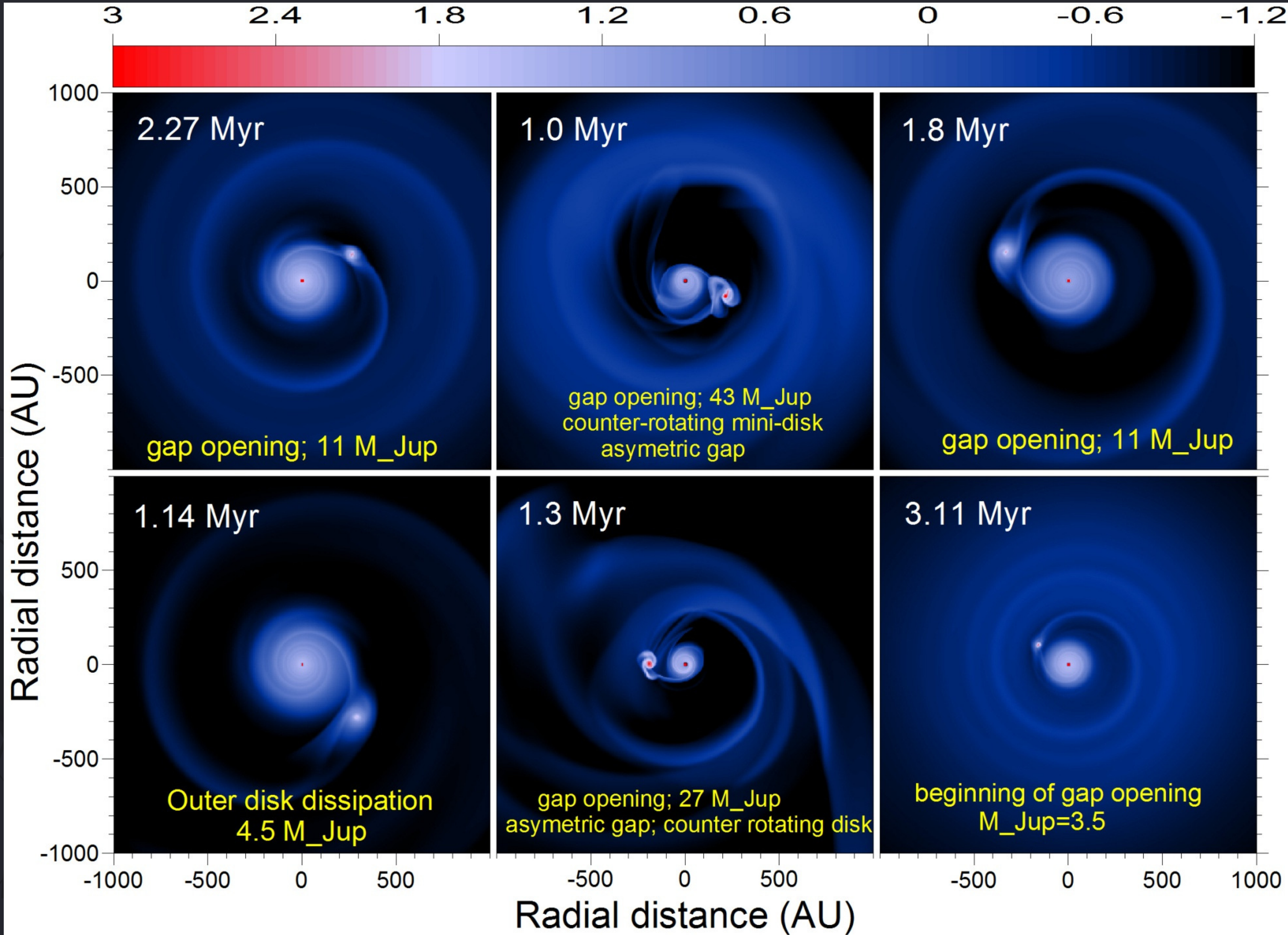
Two fragments survived through the embedded phase

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 and observations

	modeling	observations	Conclusions and reasons for mismatch
Object mass	3.5 – 43 M_{Jup}	1.7 – 40 M_{Jup}	Disks do not grow massive enough to form upper mass BDs and VLM stars?
Orbital distance	178 – 415 AU	10 – 2300 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)

Concluding remarks on the formation of wide-orbit planets