Evolution of viscous protoplanetary disk with convective regions

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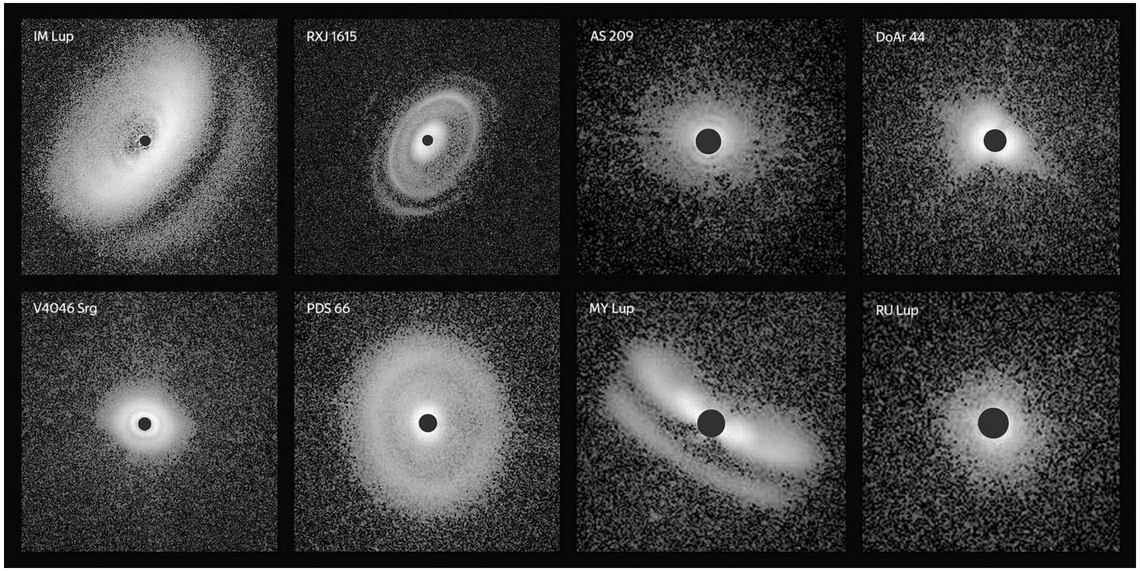
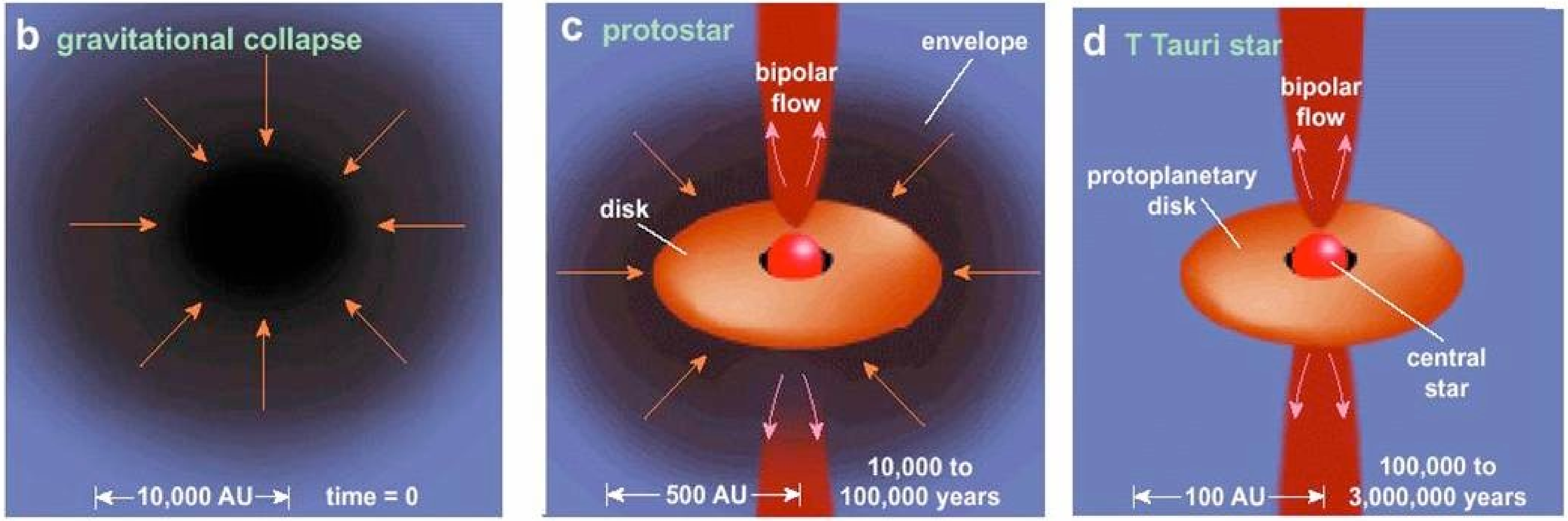


St. Petersburg, 2019

General overview of star formation and yearly evolution of protoplanetary disk

Prestellar phase | Protostellar phase | T Tauri phase

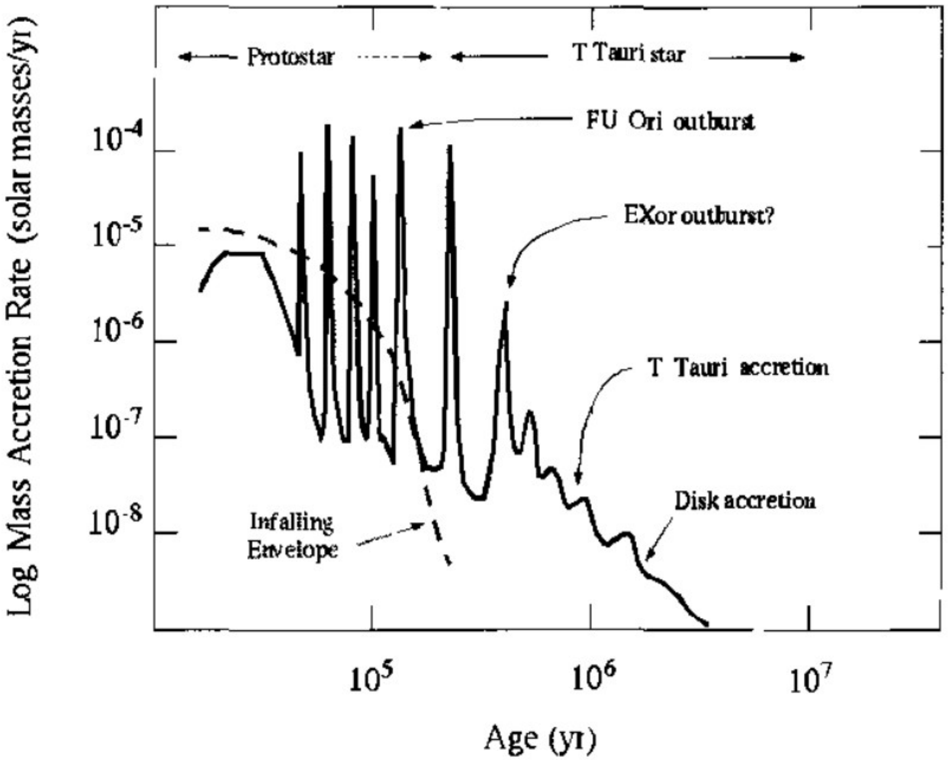


The mechanisms of mass and angular momentum transfer in accretion disks are still under debate

There are indications that disk accretion in protostellar and T Tauri phases is non-monotonic / episodic.

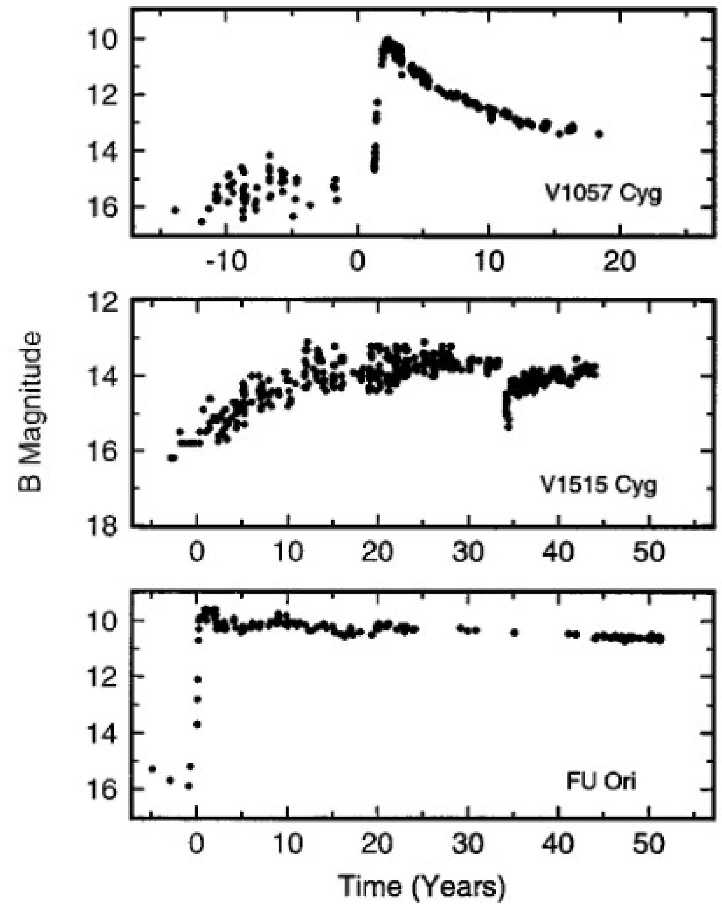
Episodic accretion scenario for yearly evolution of protoplanetary disks

Proposed accretion rate history for a typical young star (Hartmann 1998)



- Resolves the inconsistency between low accretion rates and short lifetimes of ptotoplanetary disks
- Explains the origin of FU Ori and EX Lupi type objects

Luminosity evolution of FU Ori type objects

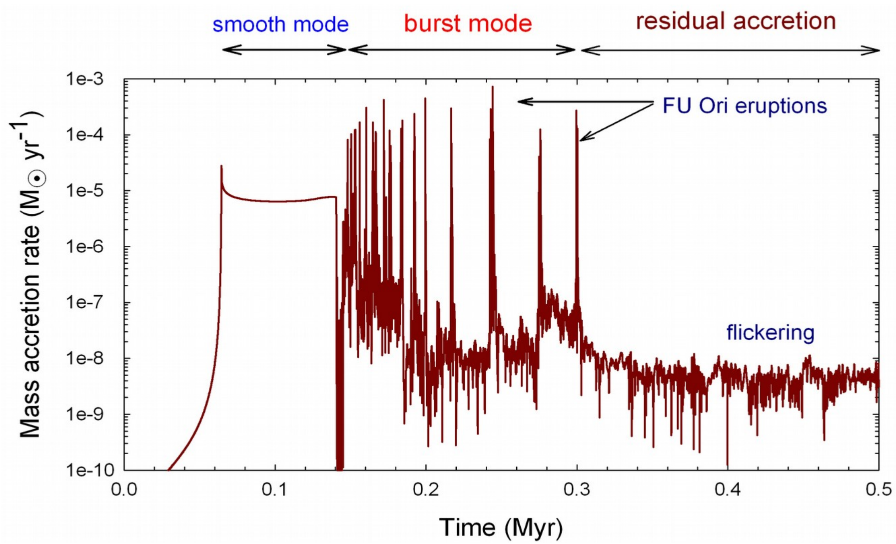


Hartmann & Kenyon, ARAA (1996)

Example: model of gravitationally unstable disk

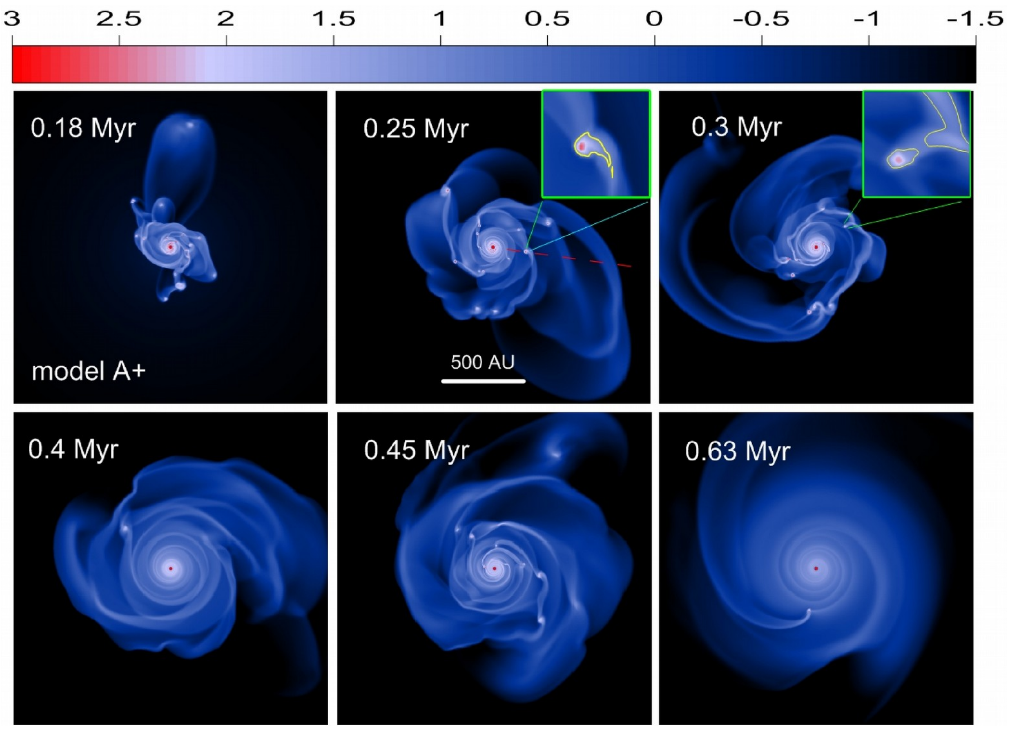
The luminosity outbursts are associated with fragments falling onto the star which are formed and migrating in gravitationally unstable disk

The calculated accretion rate



Vorobyov & Basu, ApJ (2006)

The evolution of surface density distribution in 2+1D model of protostellar disk



Vorobyov & Pavlyuchenkov, A&A (2017)

Is the convection an important process in protostellar disks?

On the structure and evolution of the primordial solar nebula

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Summary. A self-consistent accretion disc model is proposed for the primordial solar nebula. In this model convective motion not only transports energy in the *z*-direction but also provides a mechanism for viscous coupling in the disc so that energy stored in shear motion can be dissipated. We find that a steady state accretion disc model can be constructed. Conditions for the primordial solar nebula to contain the present planetary mass are obtained.

Is the convection an important process in protostellar disks?

Convection in Astrophysics
Proceedings IAU Symposium No. 239, 2006
F. Kupka, I. W. Roxburgh & K. L. Chan, eds

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Thermal convection in accretion disks

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Abstract. For a long time it was believed that thermal convection could serve as the driving mechanism for turbulence and angular momentum transport in accretion disks. Even it is meanwhile accepted that convection had to leave that role to the magneto rotational instability, it is still an important effect arising in a realistic treatment of accretion disks, i.e. with proper thermodynamics and radiation transport. We review the history of thermal convection in astrophysical disks and show the relevant analytic and numerical work, including energy transport by convection and the effect of "negative" Reynolds stresses. We will also place the convective instability into the context of the magnetorotational instability and planet–disk interaction.

Our model

The evolution of axially-symmetrical, geometrically thin, Keplerian disk without radial pressure gradients is prescribed by the Pringle equation (Pringle ARAA (1981)):

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[\sqrt{R}\frac{\partial}{\partial R}\left(\nu\sqrt{R}\Sigma\right)\right] + W$$

where W is the infall rate of gas from envelope. The evolution of such disk is controlled by the radial profile of viscosity coefficient. In our model, it is given by:

$$\nu = \nu_{\rm bg} + \tilde{\nu}_{\rm c}.$$

$\nu_{\rm bg}$ – background viscosity which provides continuous gas accretion

$\tilde{\nu}_{\rm c}$ – convective viscosity which depends on the convection parameters at given radius

Background viscosity is provided by some undefined mechanism (such as magneto-rotational or gravitational instability)

We describe the background viscosity phenomenologically with the power law:

$$\nu_{\rm bg} = \nu_0 \left(\frac{R}{R_{\rm AU}}\right)^{\beta},$$

where parameters $\nu_0 = 10^{15}{\rm cm}^2{\rm s}^{-1}$ and $\beta = 1$ are selected to reproduce surface density profiles and accretion rates towards observed protoplanetary disks:

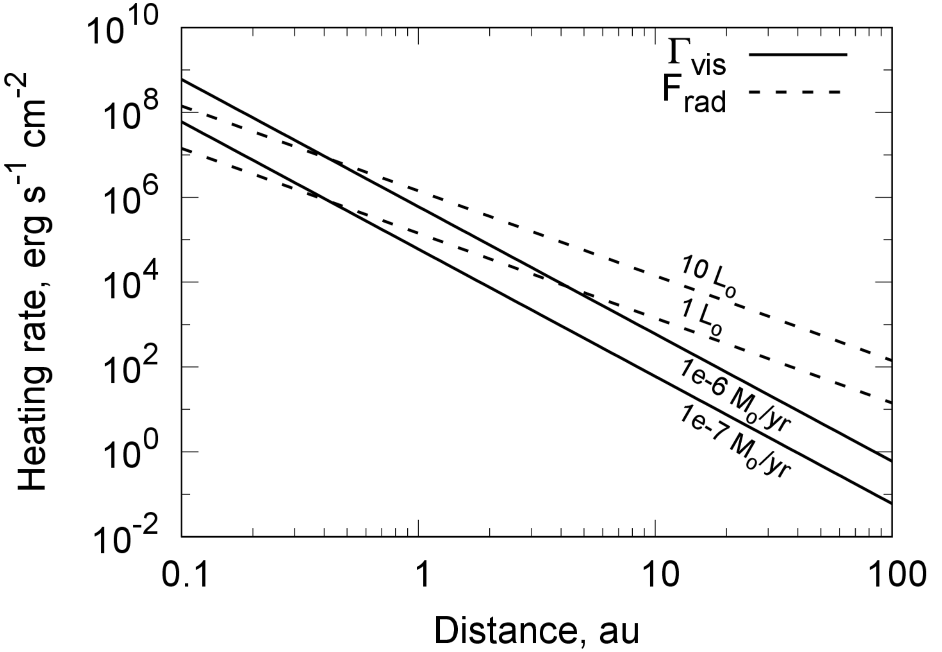
$$\Sigma \propto R^{-1}$$
$$\dot{M} \sim 10^{-7} M_{\odot}/{\rm yr}$$

Williams et al. A&A (2011)
Hartmann et al. ApJ (1998)

The viscosity dissipation rate (per unit surface):

$$\Gamma_{\rm vis} = \frac{9}{4}\frac{GM_\odot}{R^3}\nu\Sigma.$$

The viscous heating in optically thick media can induce convective instability.



Viscous and radiative heating for stationary accretion disk

Convective viscosity is non-zero in convectively unstable regions, it is introduced as:

$$\nu_{\mathrm{c}} = \gamma \, H V_{\mathrm{c}},$$

γ – the fraction of mass in convectively unstable region

H – disk height

V_{c} – velocity of convective elements (eddies)

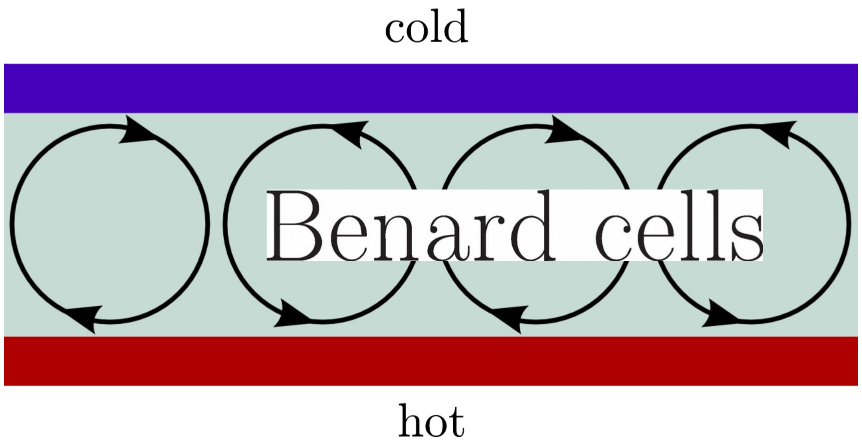
Velocity of convective eddies is found assuming that the whole viscous heating is transferred into kinetic energy of the gas:

$$\Gamma_{\mathrm{vis}} = \frac{\rho_0 V_{\mathrm{c}}^2}{2} V_{\mathrm{c}},$$

The resulting distribution of convective viscosity is additionally smoothed over the radius using the Gaussian function of width *H*:

$$\tilde{\nu}_{\mathrm{c}}(R) = \frac{\int\limits_{R_{\mathrm{in}}}^{R_{\mathrm{out}}} \nu_{\mathrm{c}}(r) \mathrm{e}^{-\frac{(R-r)^2}{2H^2}} dr}{\int\limits_{R_{\mathrm{in}}}^{R_{\mathrm{out}}} \mathrm{e}^{-\frac{(R-r)^2}{2H^2}} dr}$$

The radial extent of convective region should not be smaller than the disk height!



Calculation of vertical disk structure

UV heating and viscous heating

$$S = S_{\rm star} + S_{\rm bg} + \frac{\Gamma_{\rm vis}}{\Sigma}$$

$$S_{\rm star} = \frac{L_*}{4\pi r^2}\,\kappa_{\rm uv}\,\exp\left(-\tau_{\rm star}/\mu\right)$$

$$S_{\rm bg} = D\,\sigma T_{\rm bg}^4\,\kappa_{\rm uv}\,\exp\left(-2\tau_{\rm bg}\right)$$

Diffusion of IR radiation

$$c_{\rm V}\frac{\partial T}{\partial t} = \kappa_{\rm P} c(E - aT^4) + S$$

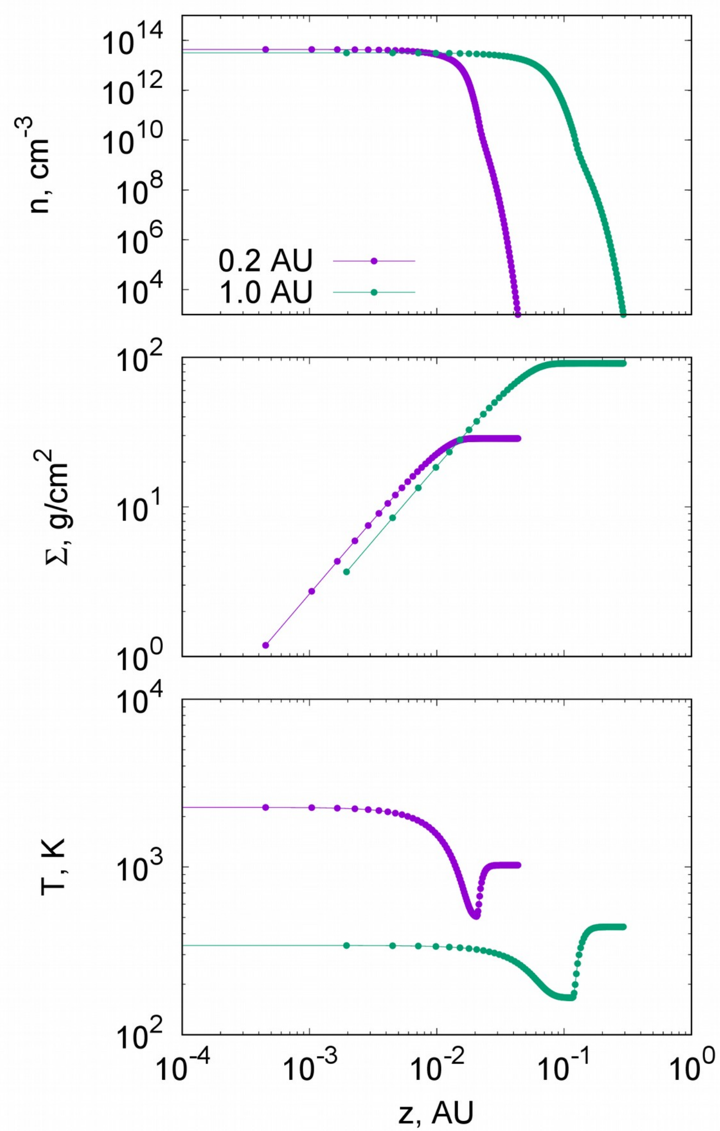
$$\frac{\partial E}{\partial t} - \frac{\partial}{\partial z}\left(\frac{c}{3\rho\kappa_{\rm R}}\frac{\partial E}{\partial z}\right) = -\rho\kappa_{\rm P} c(E - aT^4)$$

Hydrostatic equilibrium

$$\frac{1}{\rho}\frac{dP}{dz} = -\frac{GM_*}{r^3}z - 2\pi G\Sigma$$

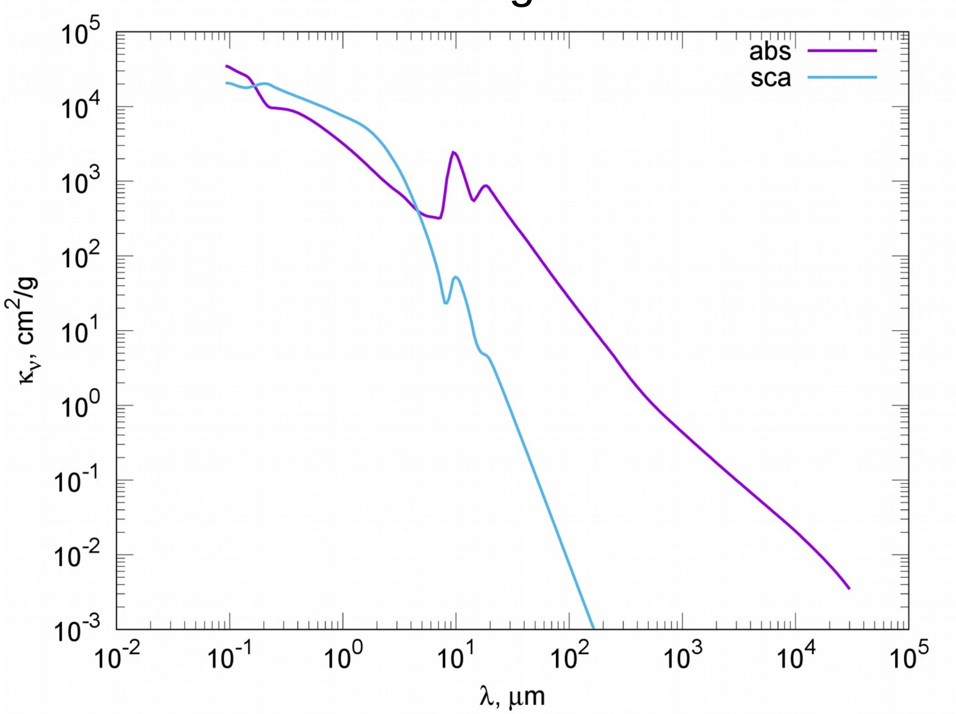
Vorobyov & Pavlyuchenkov, A&A(2017)

Distributions of density and temperature in z-direction

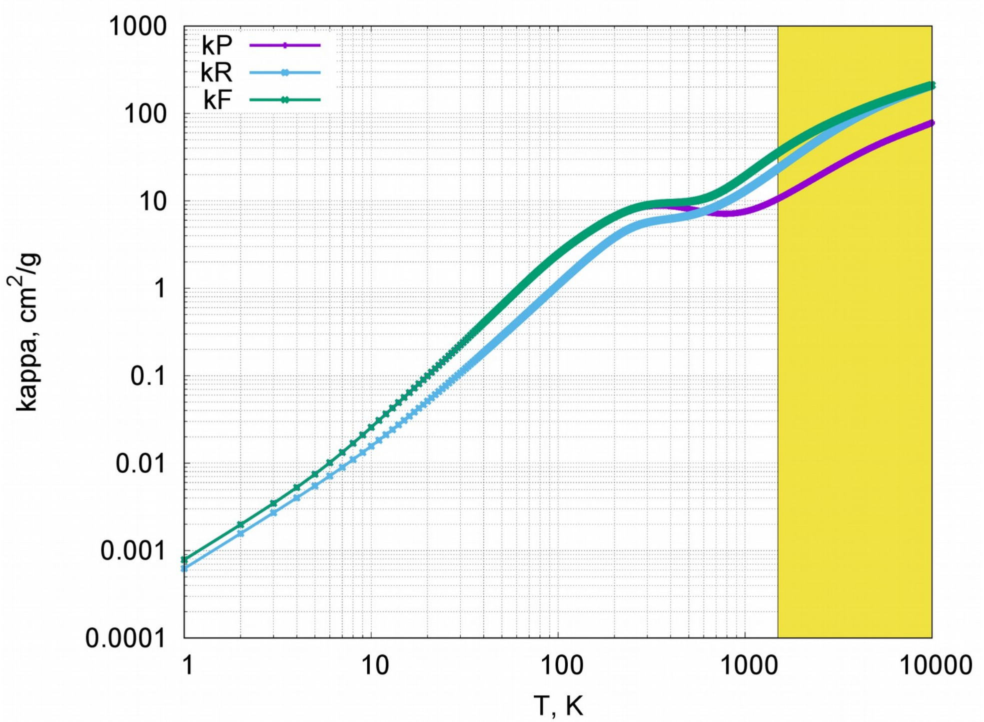


Important element of the radiative transfer model is use of realistic dust opacities

Frequency-dependent absorption and scattering coefficients



Temperature-dependent Planck and Rosseland opacities

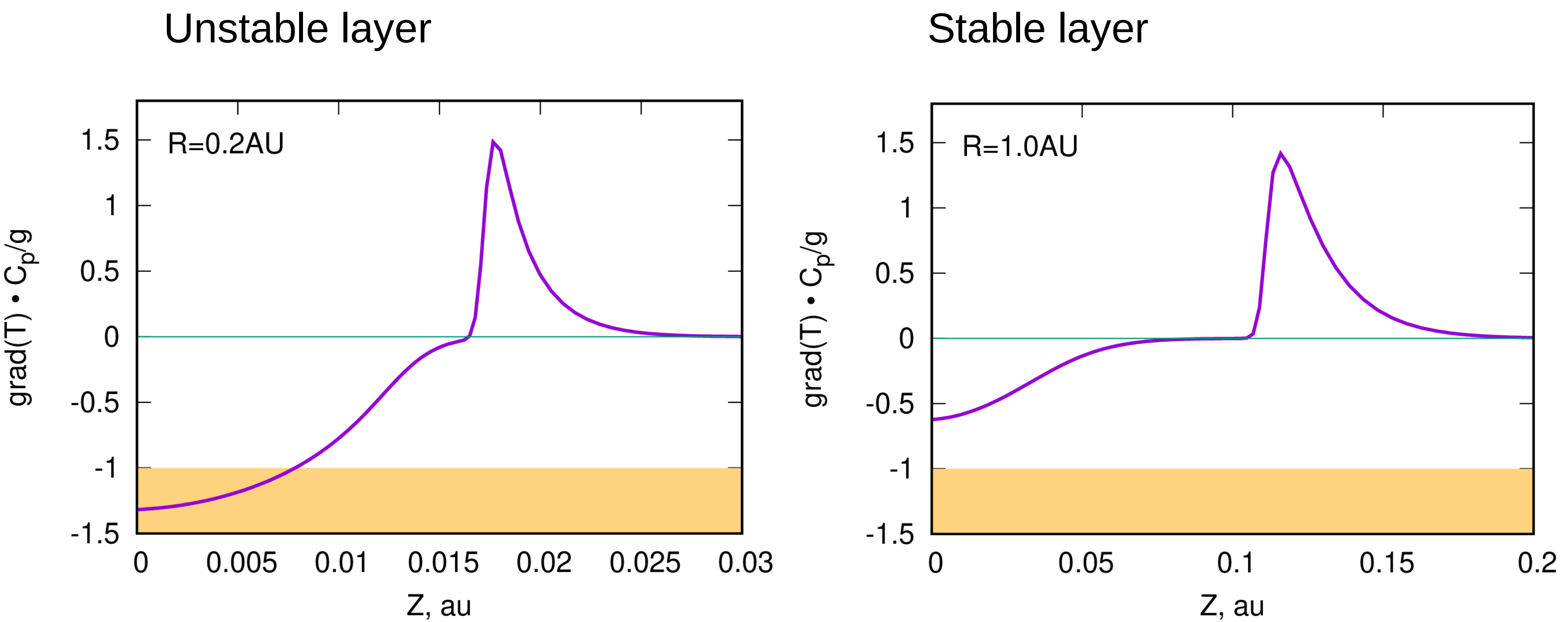


Yellow bar is the temperature range where opacities are not appropriate due to the dust evaporation

Identification of convectively unstable regions

$$\frac{dT}{dz} < -\frac{g(z)}{c_P}$$

Ratio of temperature gradient to adiabatic gradient as a function of z-coordinate for the flash phase



Convectively unstable region is shown with beige color

Infall rate from envelope onto disk (setup of W):

$\dot{M} = 10^{-7} M_{\odot}/\mathrm{yr}$ in a ring 10 – 20 AU

Estimation of the centrifugal radius for prestellar core L1544

Density profile:

$$n = \frac{n_0}{1 + \left(\frac{R}{R_{\mathrm{core}}}\right)^2}$$

$$R_{\mathrm{core}} = 3 \times 10^3 \mathrm{AU}$$
$$M_{\mathrm{core}} = 1.2 M_{\odot}$$
$$\Omega = 8 \times 10^{14} \mathrm{s}^{-1}$$

Centrifugal radius:

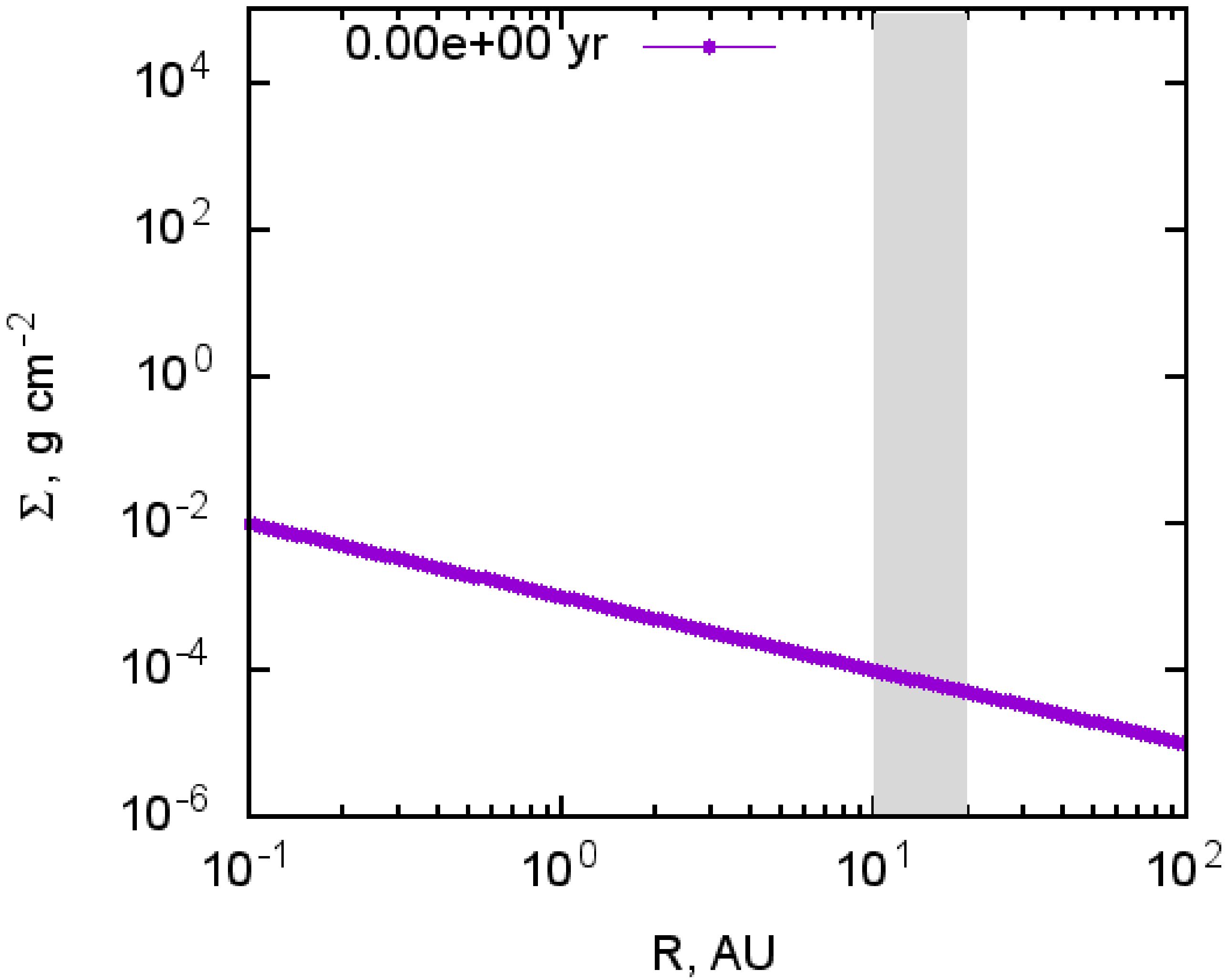
$$R_{\mathrm{acc}} = \frac{\Omega^2 R_{\mathrm{core}}^4}{G M_{\mathrm{core}}}$$

$$R_{\mathrm{acc}} = 11 \mathrm{AU}$$

Chacón-Tanarro et al. A&A(2019)
Klapp et al. ApJ(2014)

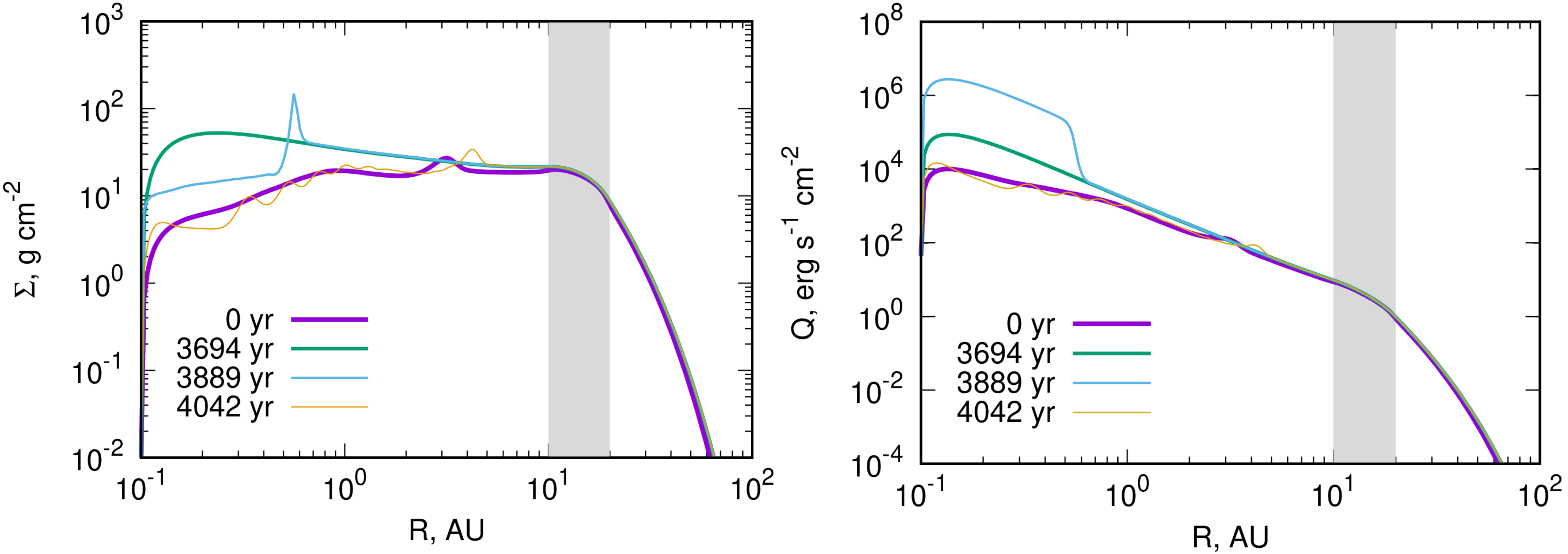
Model results

Evolution of surface density distribution



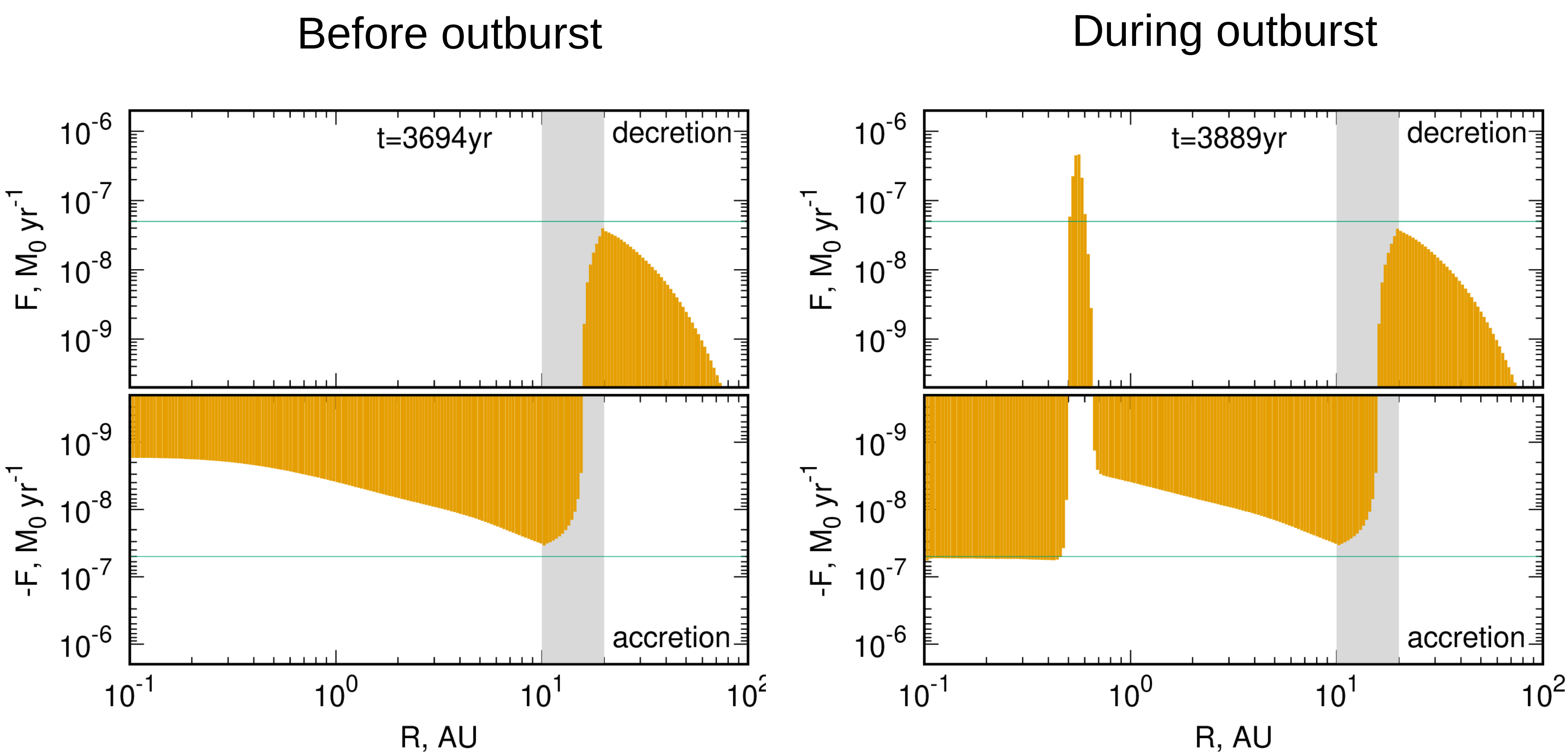
The region of infall from envelope is shown with gray bar

The evolution of surface density and viscous heating rate distributions for several moments illustrating the development of the accretion outbreak



Zero time corresponds to the end of the previous accretion outburst.
Vertical bar shows the area of gas accretion from the envelope.

Radial distributions of accretion-decretion flux



The positive value of the flux (the upper part of each distribution) corresponds to the flow from the star, the negative value (the lower part of the distribution) corresponds to flow towards the star. The vertical bar shows the area of gas accretion from the envelope.

Development of convection in a disk is the process with positive feedback

Increase of accretion flow

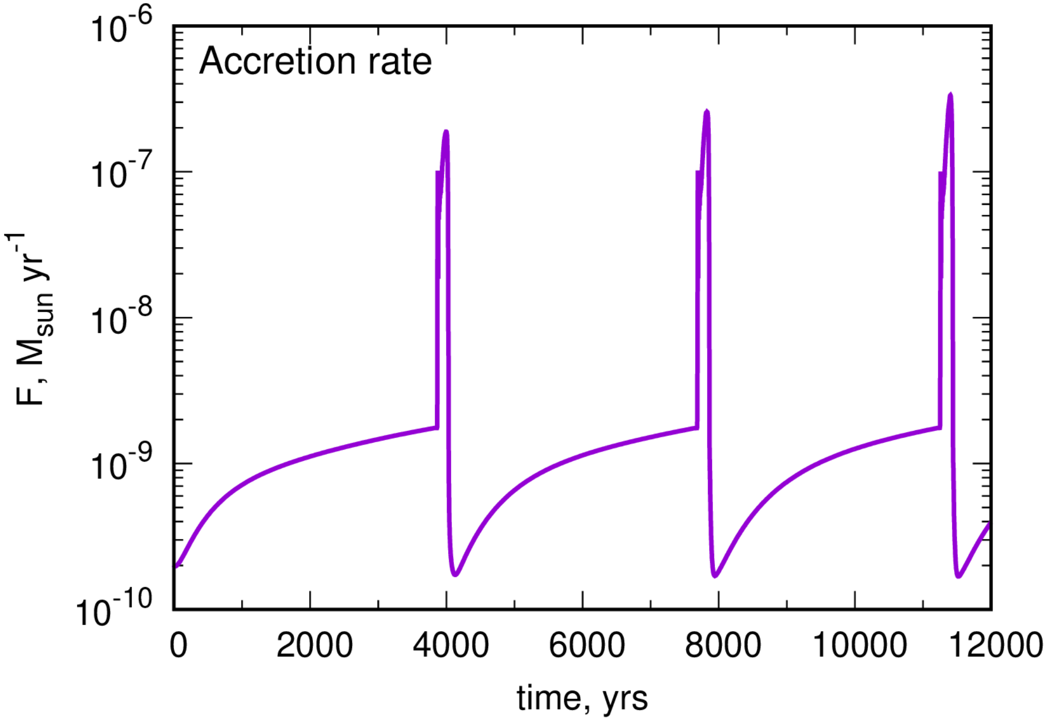
Increase of viscous heating and temperature

Gain of convective instability

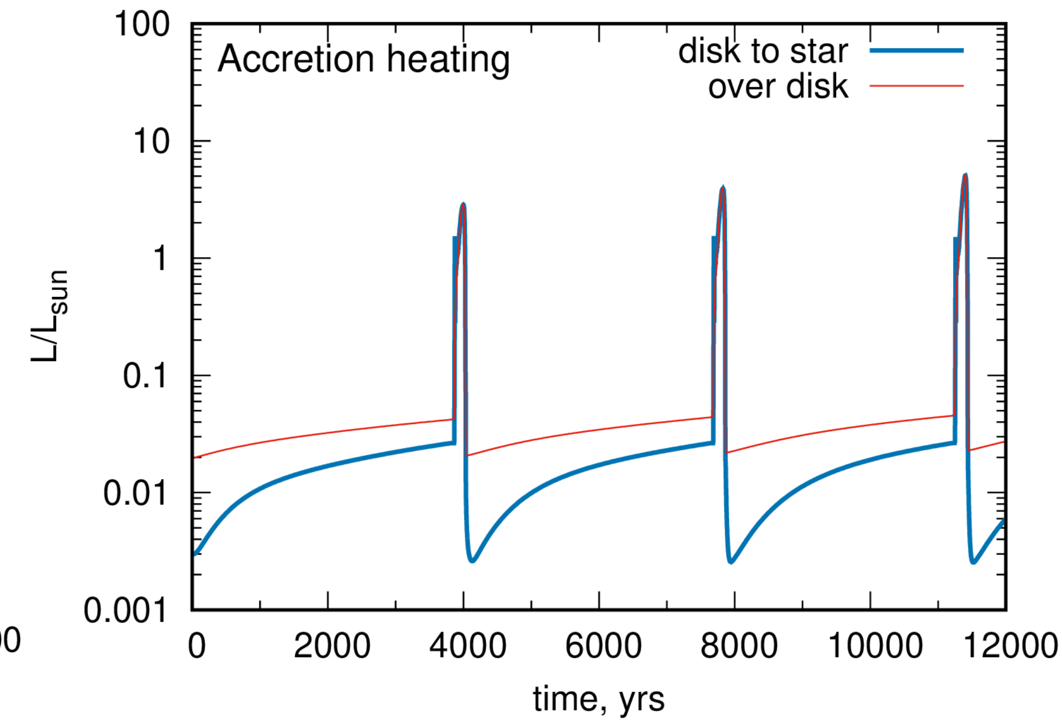
In our model, convection is self-sustaining only for short periods in the inner regions of the disk, while the role of background viscosity is important for ensuring its launch

The evolution of accretion rate and luminosity after establishment of a episodic accretion mode

Accretion rate

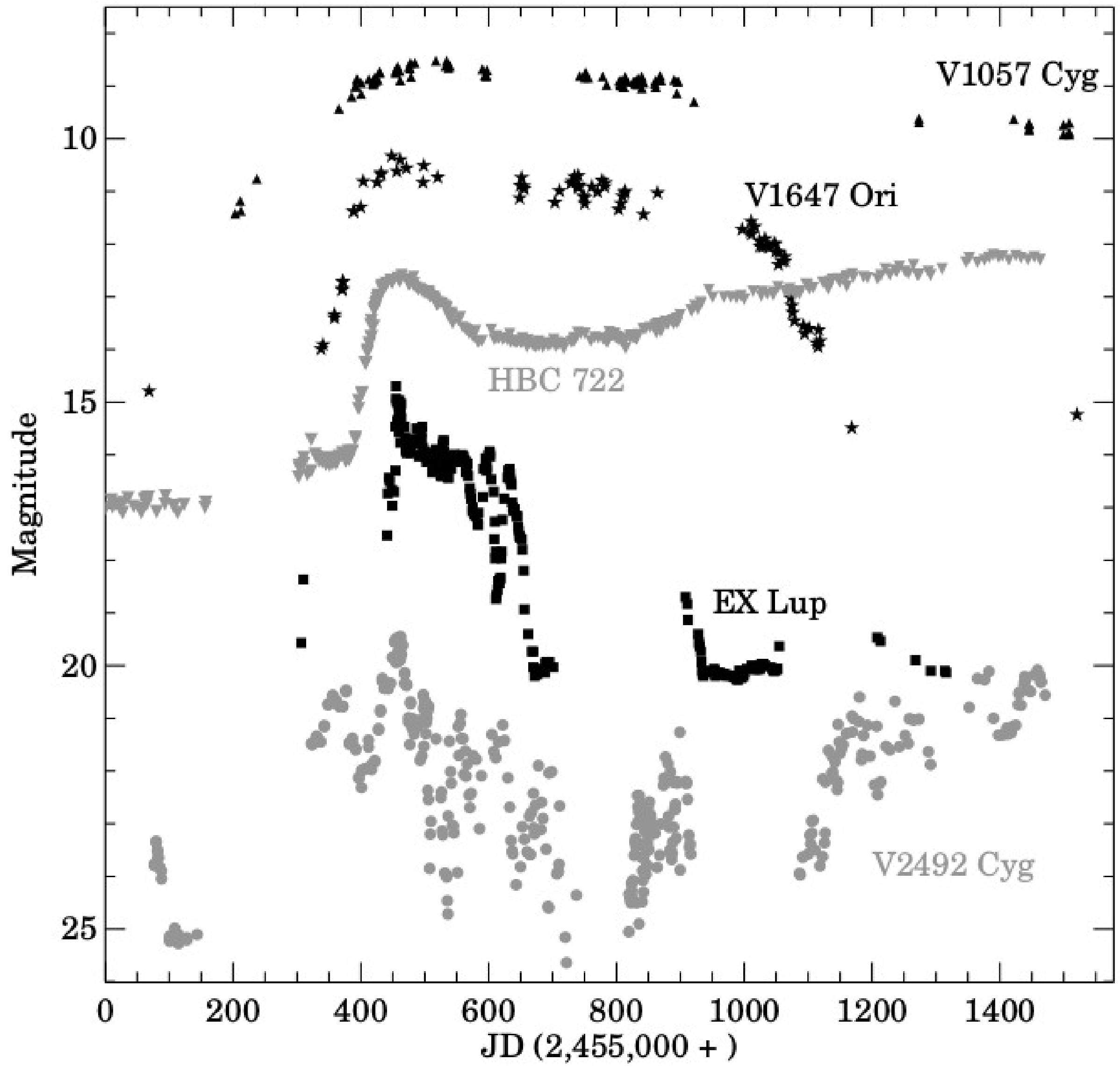


Accretion luminosity



Thin red line corresponds to accretion luminosity of the entire disk.
Thick blue line shows the luminosity which is associated with accretion of gas onto the star from the inner disk edge.

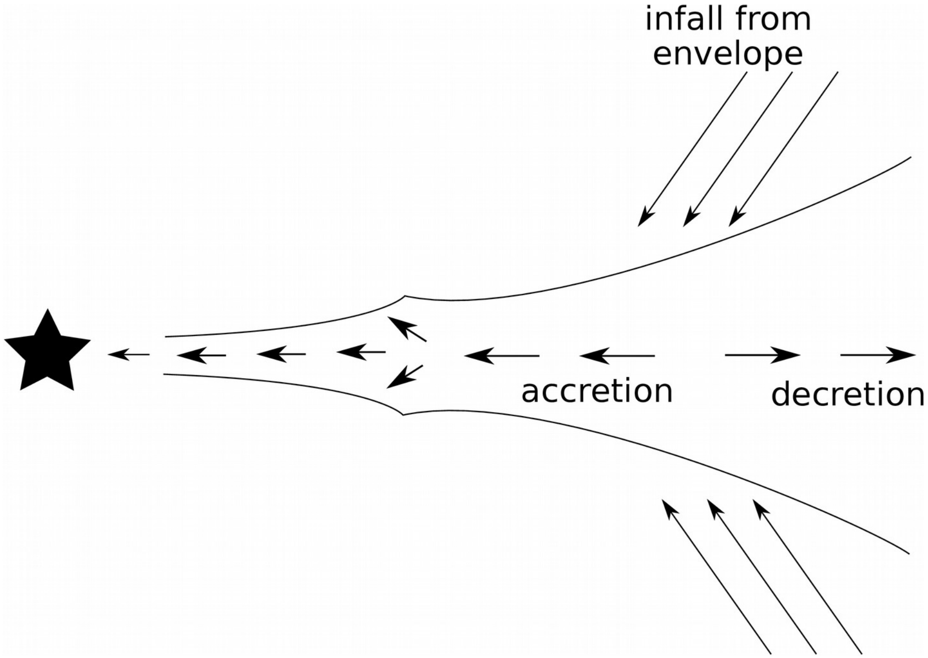
Variety of flaring young stellar objects



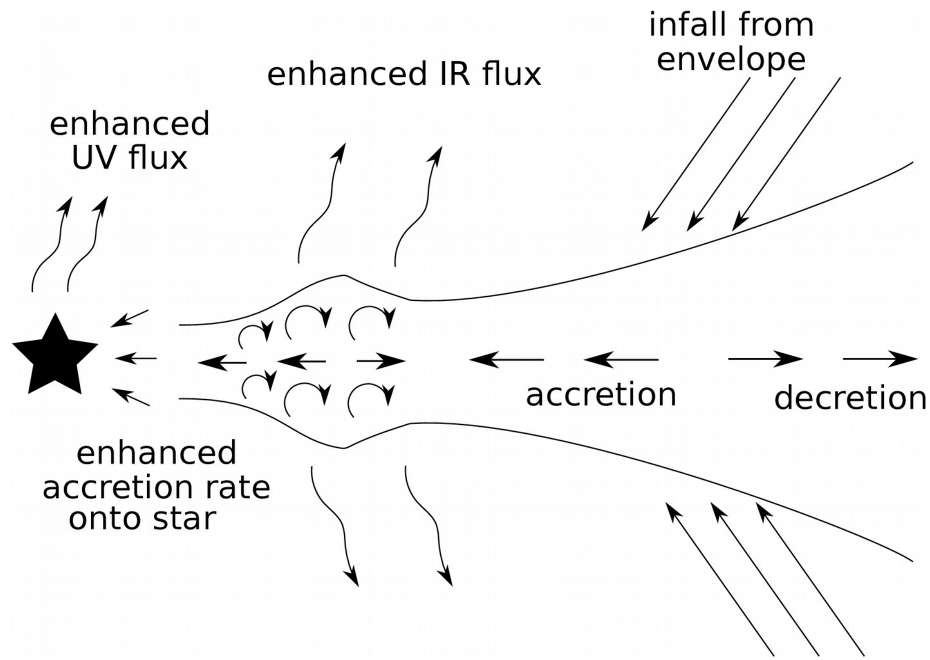
Audard et al., PPVI (2014)

Scheme of the episodic accretion mode in a protoplanetary disk

Accumulation phase



Outburst phase



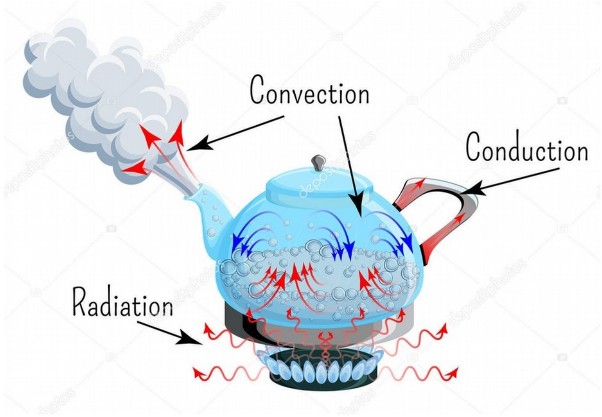
Conclusions

1. The presented model is rather illustrative because of the many underlying physical assumptions. Its main purpose is to demonstrate the possible role of convection as a driver of episodic accretion in protostellar disks.

2. There are a number of points which should be checked to verify the presented picture, such as:

   a) treatment of convective viscosity
   b) evaporation of dust above 1500 K
   c) dissociation and ionization of gas above 2000 K
   d) joint convective and radiative transfer

3. The presented picture need to be supported by more detailed hydrodynamic simulations.




Thank you
for your attention