Spectral energy distribution calculations for fragmenting protostellar disks

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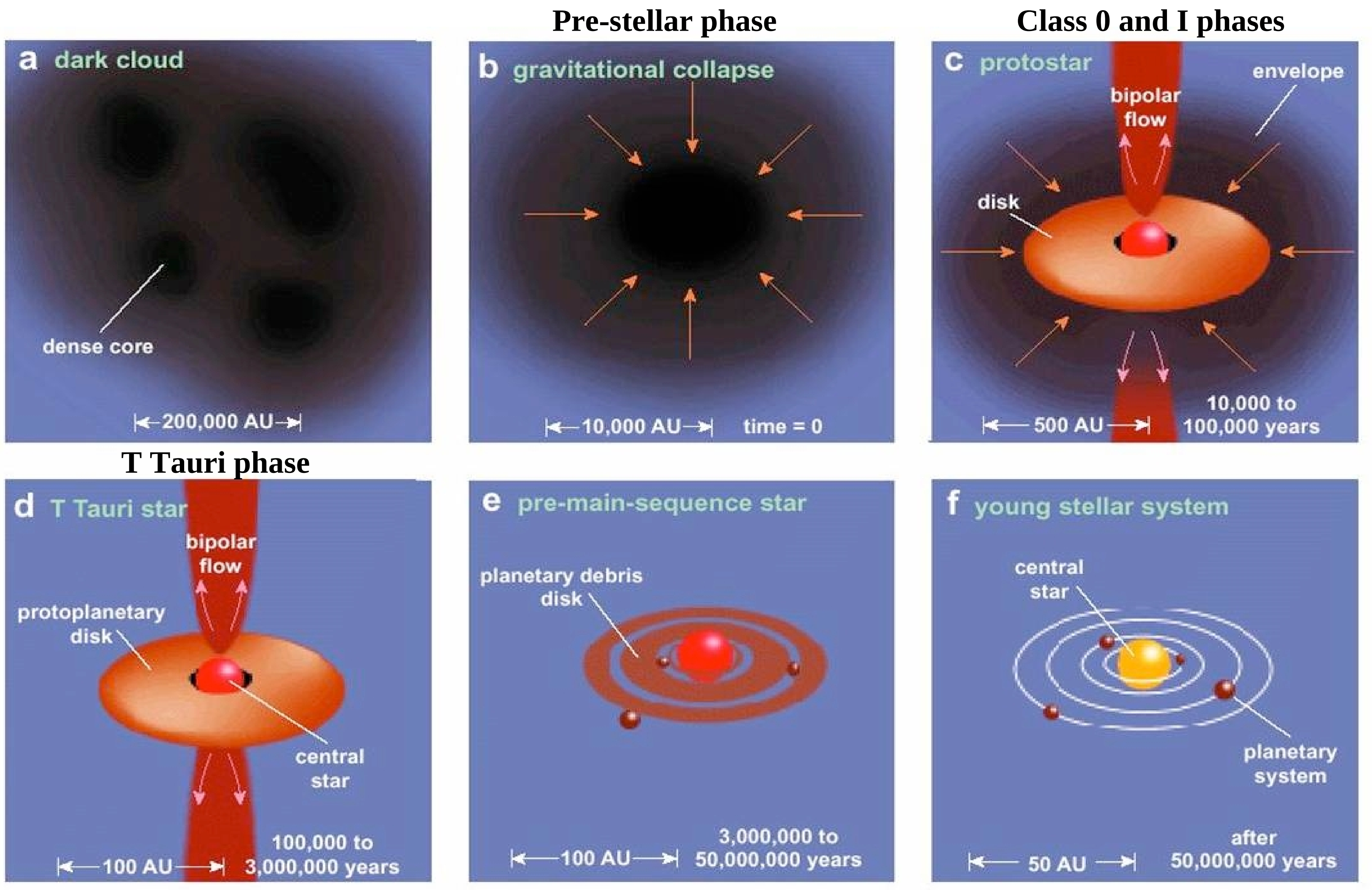
Motivation

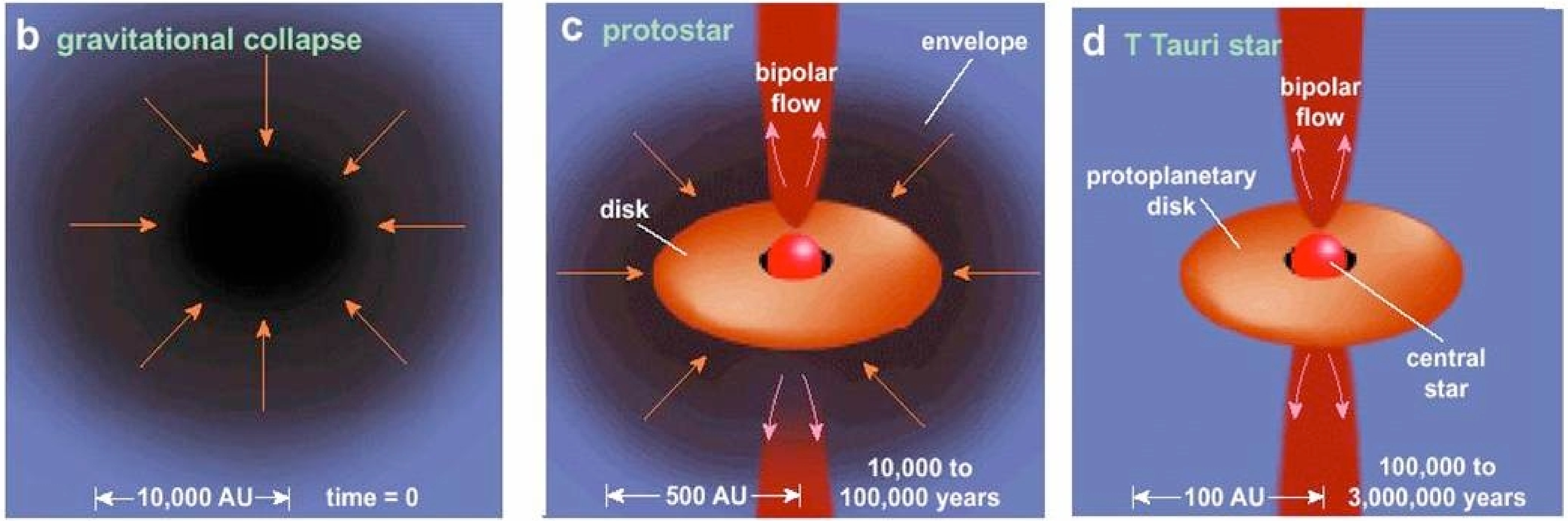
Main stages of protostellar disk evolution



Motivation

Global models that self-consistently follow Cloud => Disk transition

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



Disk formation and evolution, and planet formation, are integral parts of the star formation process

§ 1+1D models (Hueso & Guillot 2005; Visser et al. 2009; Rice at al. 2010),

§ 2D models (Yorke & Bodenheimer 1999; Boss & Hartmann 2001; Vorobyov & Basu 2006, 2010, Zhu et al. 2009),

§ 3D models (Krumholz et al. 2007; Kratter et al. 2010; Machida et al. 2009, 2010).

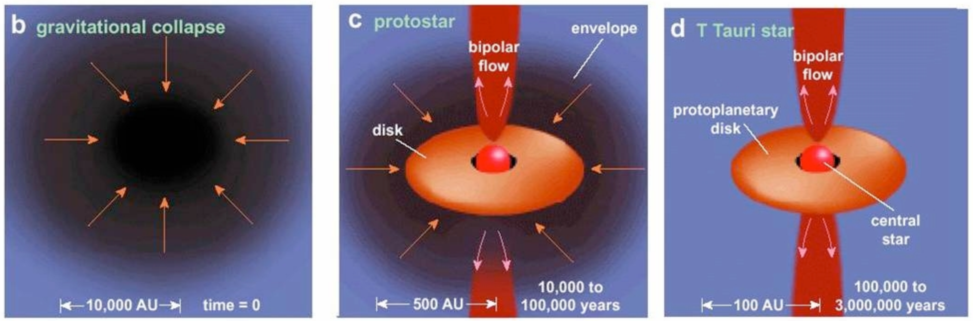
Motivation

Numerical scheme of Vorobyov & Basu model

Accretion rates onto the star

Hydro code → **Stellar evolution code**

Photospheric & accretion luminosities



- Collapse of pre-stellar cloud,
- Formation of the central star (approximated by a point object inside a central sink cell),
- Disk formation and long-term evolution (up to 1 Myr),
- Finite-difference Eulerian code on polar coordinates,
- Third-order accurate advection (PPA),
- Log-spaced grid in radial direction (Vorobyov & Basu 2006, 2010).

- Stellar mass, radius, temperature, etc.,
- Stellar chemical abundances,

Baraffe et al. 1998, 2002, 2003;
Chabrier et al. 2000;
Chabrier & Baraffe 2000.

The aim: To perform a comprehensive study of spectral energy distribution (SEDs) shape of fragmenting protostellar disks and to find observational signatures that can unambiguously point to the presence of massive fragments in protostellar disks, which can be precursors of giant planets and brown dwarfs.

Research tasks:

- To construct the method of SEDs calculations for the young stellar objects (YSOs) using the physical parameters of YSOs from numerical hydrodynamics models (Vorobyov & Basu 2006, 2010);
- To perform the numerical simulations for a number of protostellar disk realizations, paying specific attention to systems that show disk fragmentation;
- To determine if massive fragments can leave unambiguous signatures in the SEDs and if these signatures can be seen at different viewing angles;
- To establish the possibility to detect massive fragments in protoplanetary disks with biggest modern telescopes.

Calculation algorithm

Integral SED from systems

$$F = F_{disk} + F_*$$

Disk

$$F_{disk} = F_d + F_{sc}$$

F_d – flux from disk,

F_{sc} – flux from sink cell.

Protostar

$$F_n^* = \frac{\pi R_*^{\,2}}{d^2} B_\nu(T_{eff}^*),$$

R_* – protostellar radius,

T_{eff} – effective temperature of the protostar:

$$T_{eff}^* = \sqrt[4]{\frac{L_{acr} + L_{ph}}{4p\, R_*^2\, s}},$$

L_{acr} – accretion luminosity,

L_{ph} – photospheric luminosity.

Calculation algorithm

Flux from every specific grid cell of the disk

$$F_d = \frac{S \cos\omega}{d^2} B_\nu(T_{eff})(1 - e^{-\Sigma \kappa_\nu \sec\gamma}),$$

S – physical area of a grid cell (i,j),

ω – normal angle between a grid cell (i,j) of the disk surface and the line of sight,

γ – inclination angle of the disk with respect to the observer,

d – distance to YSO, set to 100 pc,

Σ – surface density of each grid cell (i,j).

Opacity

$$\kappa_\nu = \kappa_0 \left(\frac{\nu}{\nu_0} \right)^\beta ,$$

$\beta = 1$,

$\kappa_0 = 0.1 \mathrm{cm}^2 \mathrm{g}^{-1}$,   Beckwith et al. 1990.

$\nu_0 = 1000$ GHz,

Effective temperature

$$T_{eff} = \max\{T_{irr}, T_{surf}\},$$

T_{irr} – stellar/background irradiation of the disk surface,

T_{surf} – temperature of active viscous/shock heating of the disk interiors.

Calculation algorithm

Flux from the sink cell

$$F_{sc} = \frac{4p \cdot \cos g \cdot hn^{3}}{d^{2}c^{2}} \int_{R_{in}}^{R_{out}} \frac{1 - e^{-\Sigma(r)k_{n}\sec g}}{e^{\frac{hn}{kT(r)}} - 1} r\,dr,$$

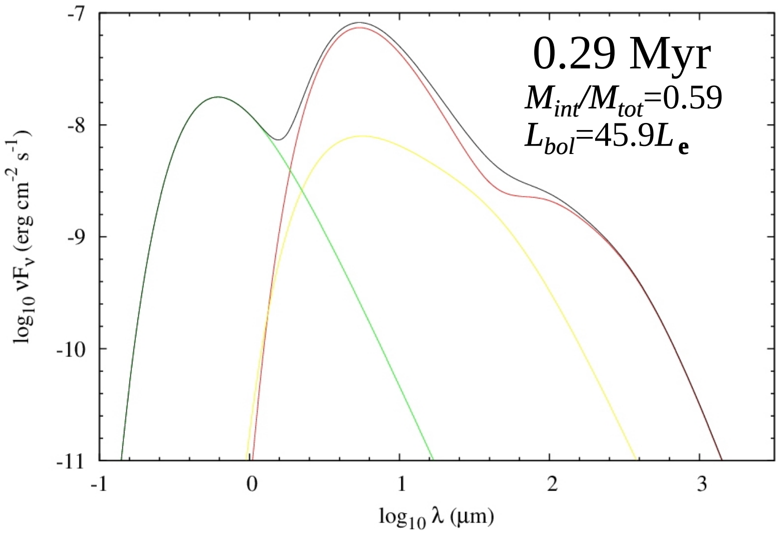
R_{in} – inner edge of the disk,
R_{out} – the boundary between disk and sink cell,
$T(r)$ – effective temperature distribution,
$\Sigma(r)$ – surface density distribution:

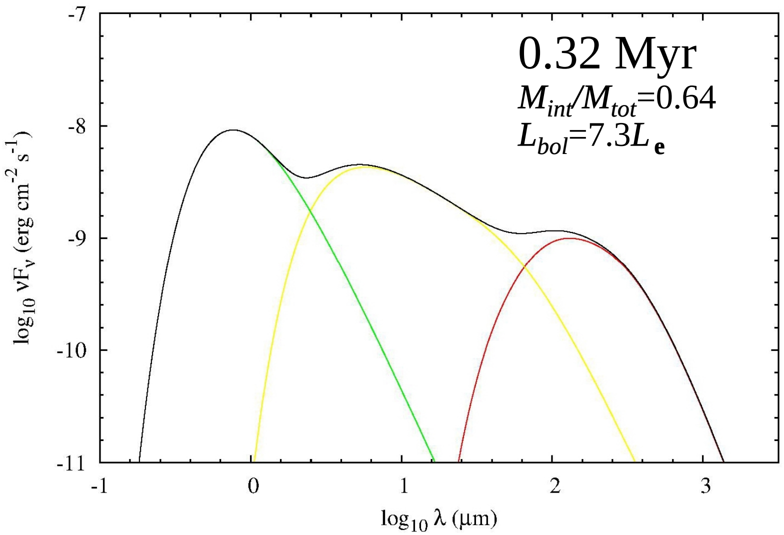
$$\Sigma(r) = \Sigma_{0}\left(\frac{r}{r_{0}}\right)^{-p},$$

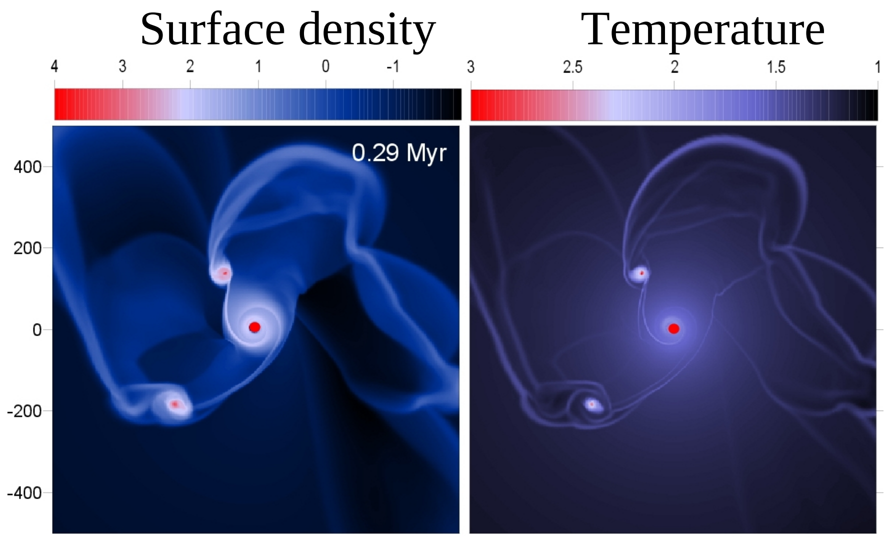
p = 1.0–1.5, as typical value for irradiated and viscous disks (Beckwith et al. 1990).

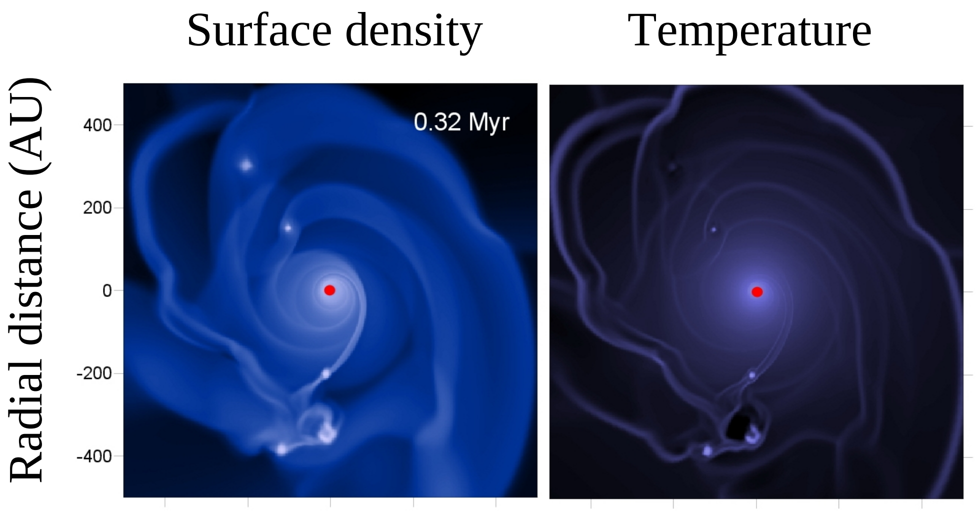
Spectral energy distribution

For systems with initial core mass $1.23M_e$, located face on (0.29 Myr and 0.32 Myr)



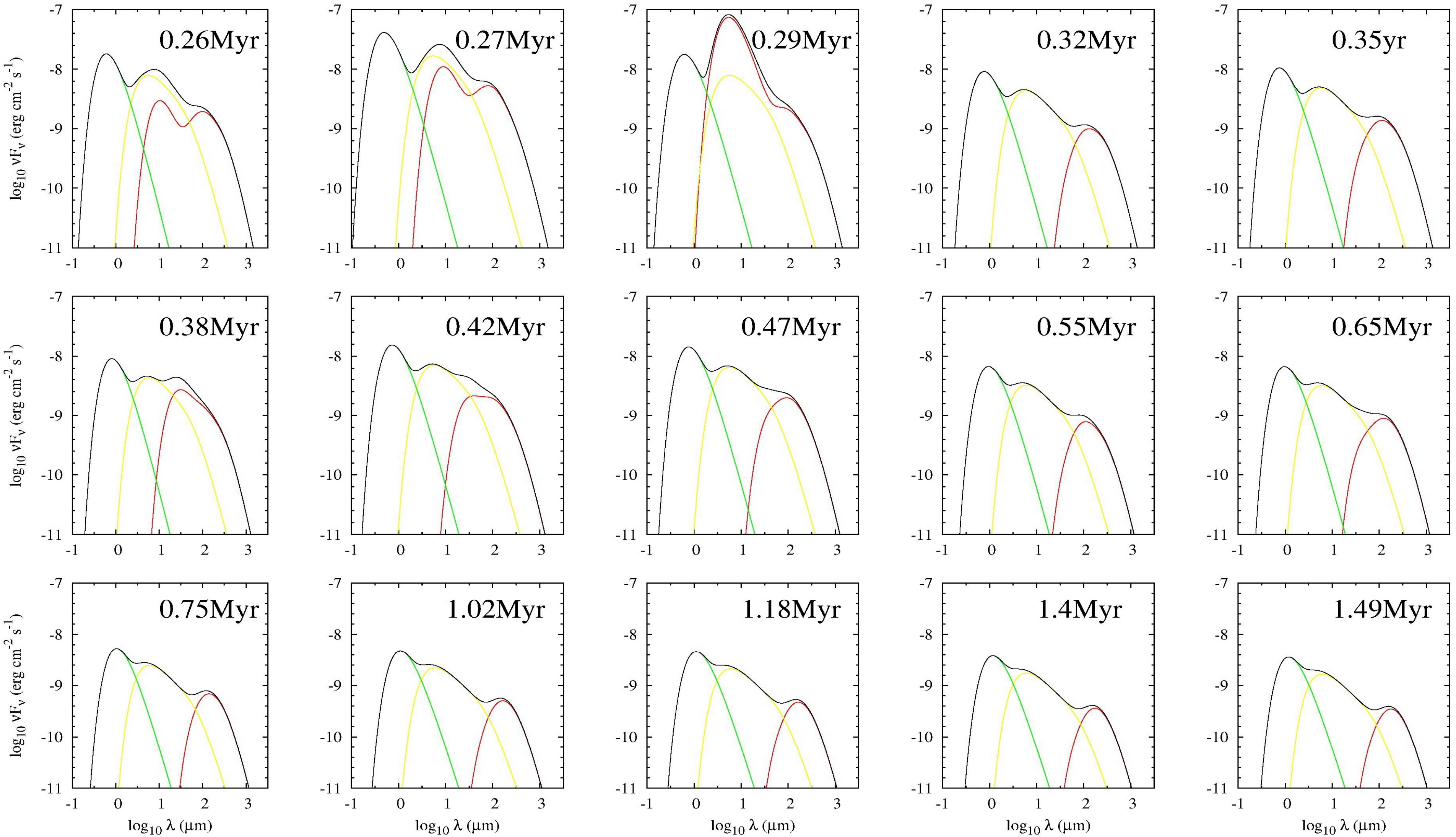






Spectral energy distribution

For systems with initial core mass $1.23M_{e}$, located face on (0.26-1.49 Myr)



Summary

- a method for SEDs construction for fragmenting protostellar disks is developed;
- calculations for systems located face on have been performed;
- preliminary results are showing that by studying the SEDs shape it is possible to establish presence of hot clamps in a protoplanetary disk.

Future work

- Improvement of existing algorithm for SEDs simulations by taking into account non-zero inclination angles of systems;
- constructing of ALMA synthetic images for prototype models that would show unambiguous signatures of disk fragmentation in the SEDs.