Vertical Oscillation of Protoplanetary Disk (PP disk): 1D multi color Radiation Hydrodynammical Simulations

Hot upper atmospheres and cold main disk oscillate in the opposite directions.

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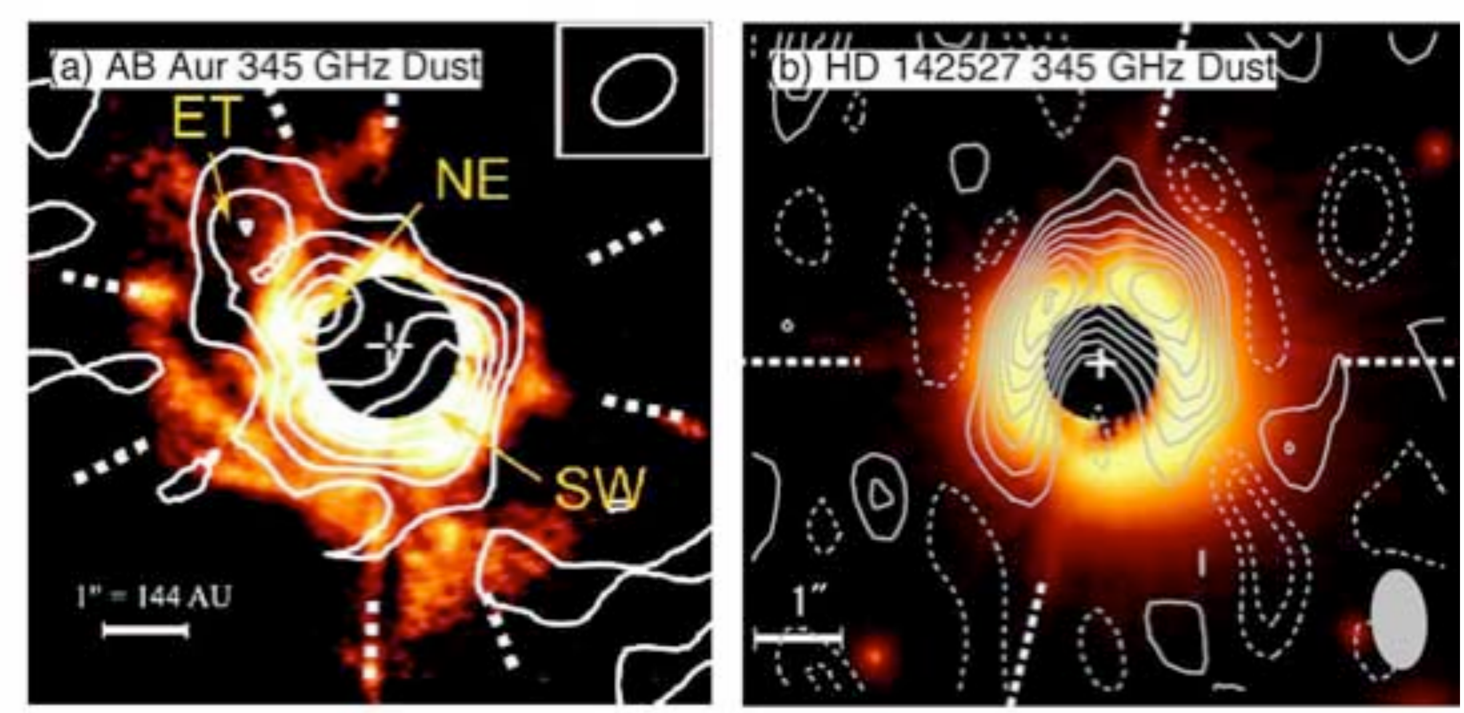
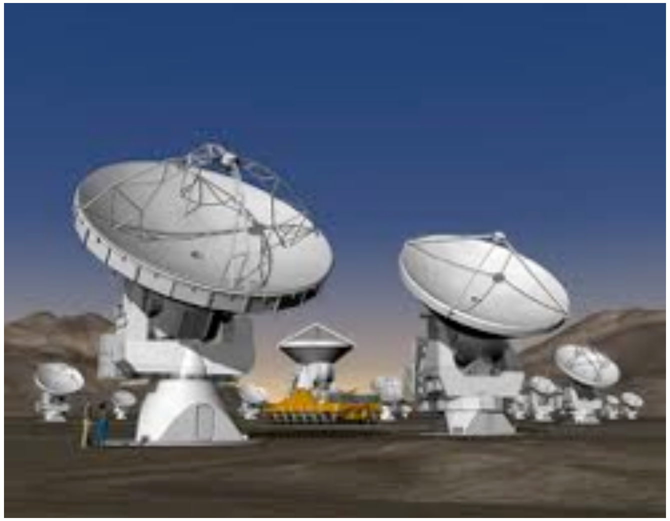
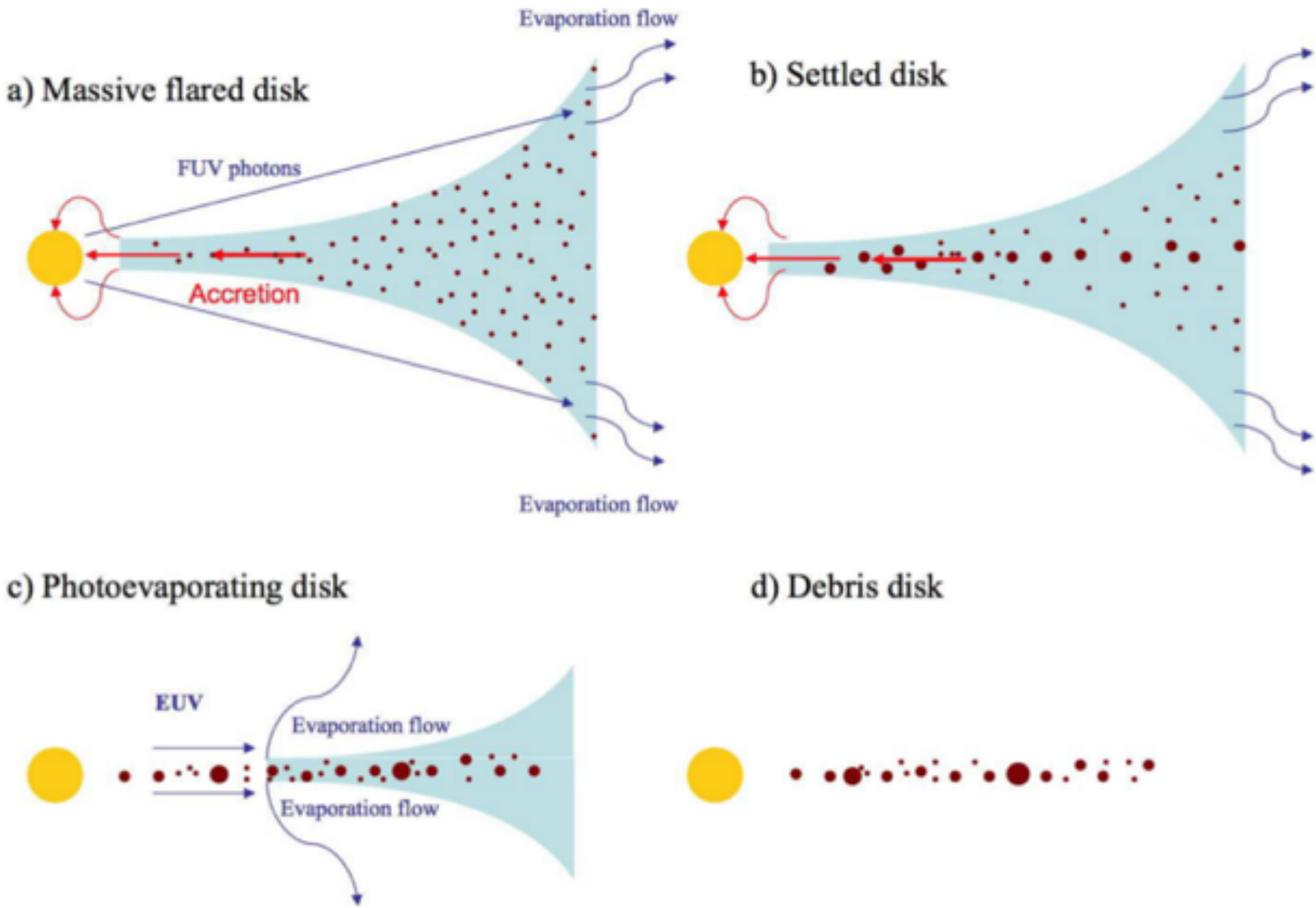
PP disk@ 1.6μm(H)+345 GHz



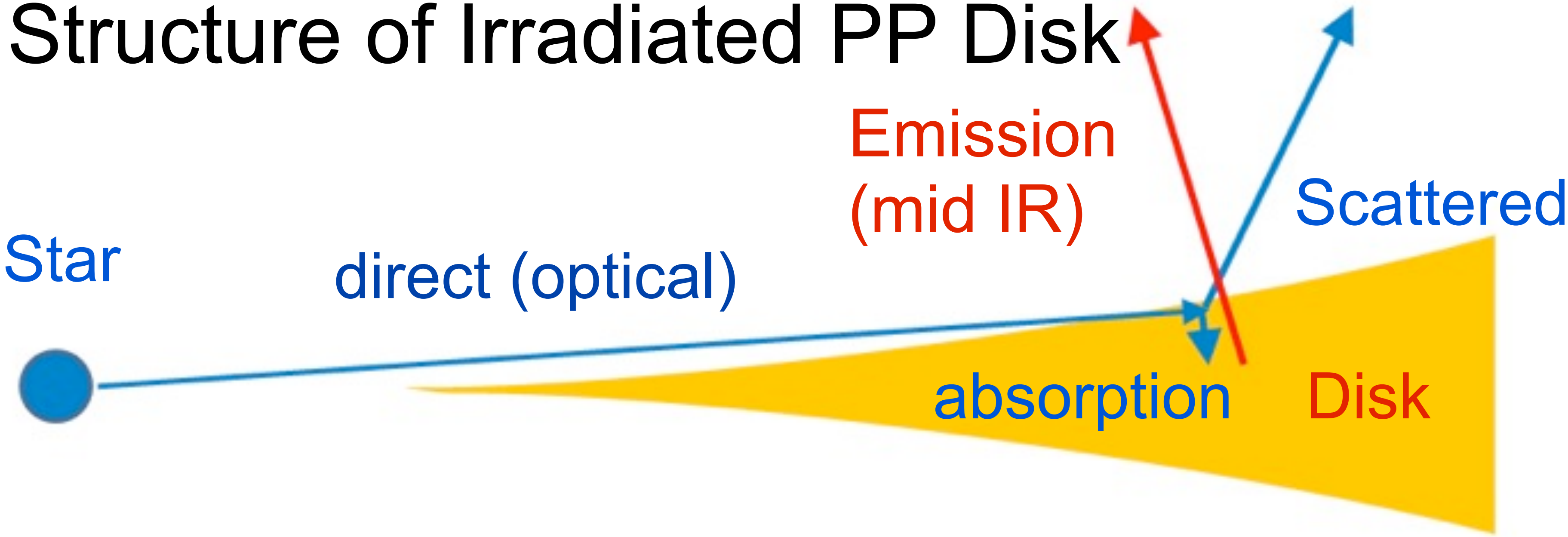
Lin+06 & Ohashi+07 taken with SMA overlaid on Fukagawa+02 (Subaru)
Much better images will be taken with ALMA





Williams & Cieza '11

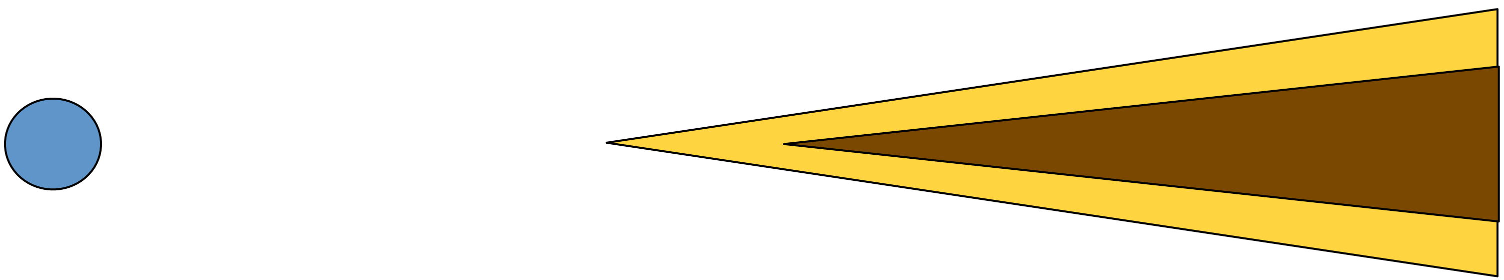
Structure of Irradiated PP Disk



Two Layer Model

Chiang & Goldreich '97

Hot Surface Layer + Cool Main Disk



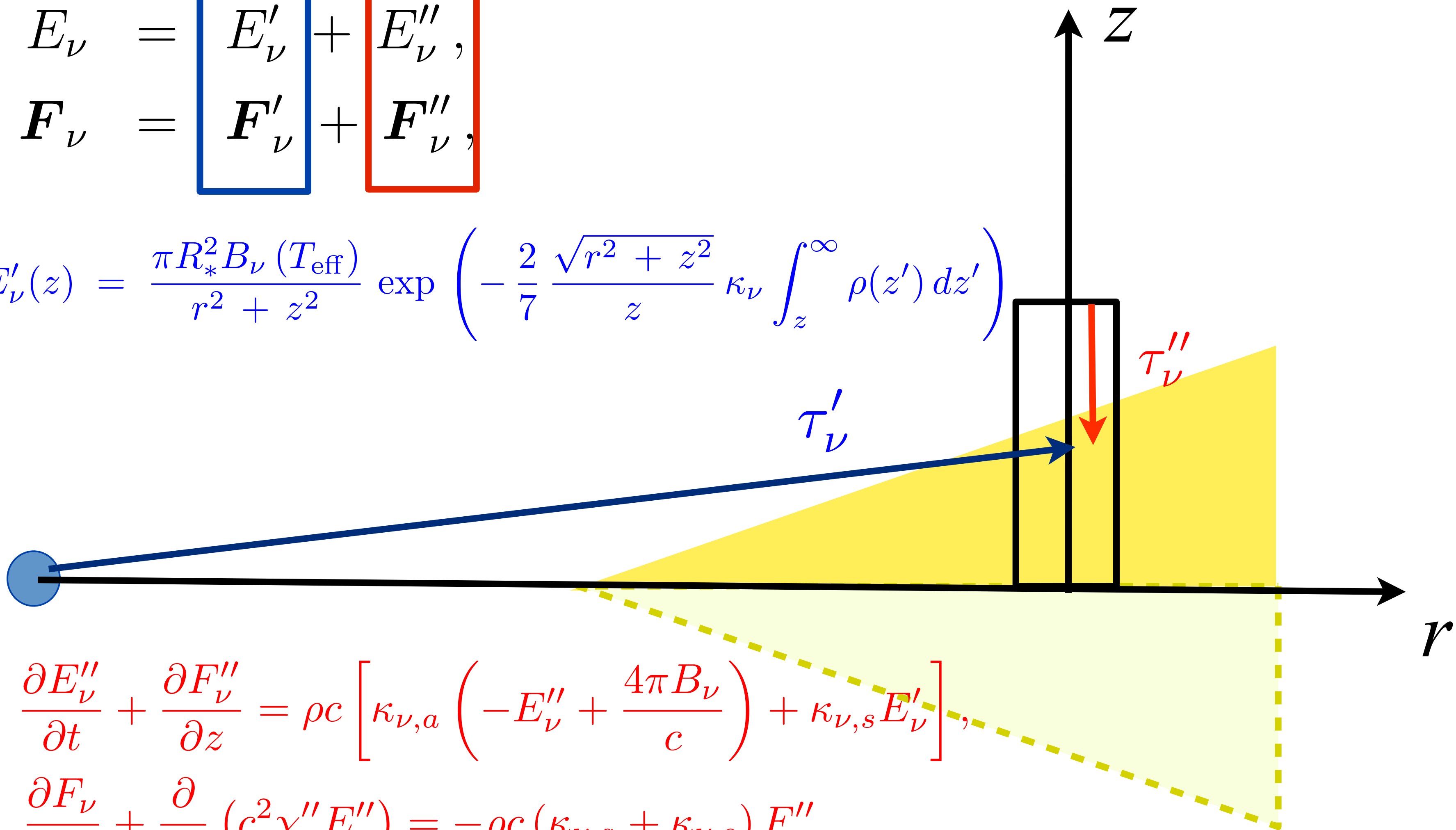
$$T_{\mathrm{s}} >> T_{\mathrm{d}}$$

1D Grazing Recipe

stellar — scattered+emission

$$E_\nu = E'_\nu + E''_\nu,$$
$$\boldsymbol{F}_\nu = \boldsymbol{F}'_\nu + \boldsymbol{F}''_\nu,$$

$$E'_\nu(z) = \frac{\pi R_*^2 B_\nu(T_{\rm eff})}{r^2 + z^2} \exp\left(-\frac{2}{7}\frac{\sqrt{r^2+z^2}}{z}\kappa_\nu \int_z^\infty \rho(z')\,dz'\right)$$



$$\frac{\partial E''_\nu}{\partial t} + \frac{\partial F''_\nu}{\partial z} = \rho c\left[\kappa_{\nu,a}\left(-E''_\nu + \frac{4\pi B_\nu}{c}\right) + \kappa_{\nu,s}E'_\nu\right],$$
$$\frac{\partial F_\nu}{\partial t} + \frac{\partial}{\partial z}\left(c^2\chi''_\nu E''_\nu\right) = -\rho c\left(\kappa_{\nu,a} + \kappa_{\nu,s}\right)F''_\nu,$$

M1 model Eq.

Radiation Hydrodynamics

assumption : $T_{\rm gas} = T_{\rm dust}$

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}\left(\rho v_z\right) = 0\,,$$

$$\frac{\partial v_z}{\partial t} + v_z \frac{\partial v_z}{\partial t} + \frac{1}{\rho}\frac{P}{\partial z} + \frac{GMz}{\left(r^2 + z^2\right)^{3/2}} = 0\,,$$

$$T\frac{ds}{dt} = \int_0^\infty \kappa_{\nu,a}\left[cE_\nu - 4\pi B_\nu(T)\right] d\nu\,.$$

$$\alpha \frac{\partial E''_\nu}{\partial t} + \frac{\partial F''_\nu}{\partial z} = \rho c \left[\kappa_{\nu,a}\left(-E''_\nu + \frac{4\pi B_\nu}{c}\right) + \kappa_{\nu,s}E'_\nu\right],$$

$$\alpha \frac{\partial F_\nu}{\partial t} + \frac{\partial}{\partial z}\left(c^2\chi''_\nu E''_\nu\right) = -\rho c\left(\kappa_{\nu,a} + \kappa_{\nu,s}\right)F''_\nu,$$

speed reduction : $\alpha = 10^{-4} \rightarrow c = 30\ \mathrm{km\ s^{-1}}$

We solve the above partial differential equations **explicitly**.

Our finite difference scheme is designed so that all the physical variables approach to the equilibrium ones in the limit of $\Delta t = \infty$.

Upwind Reconstruction of the Radiation Field

$$I^*_{j+1/2}(\boldsymbol{n}) = \begin{cases} I_j(\boldsymbol{n}) & (\mu > 0) \\ I_{j+1}(\boldsymbol{n}) & (\mu < 0) \end{cases}$$

$I_{j+1}(\boldsymbol{n})$ ← → $I_j(\boldsymbol{n})$

$$\begin{pmatrix} E_j \\ \boldsymbol{F}_j \end{pmatrix} = \begin{pmatrix} E_j \\ \boldsymbol{f}_j E_j \end{pmatrix} \qquad \begin{pmatrix} E_{j+1} \\ \boldsymbol{F}_{j+1} \end{pmatrix} = \begin{pmatrix} E_{j+1} \\ \boldsymbol{f}_{j+1} E_{j+1} \end{pmatrix}$$

$$\begin{pmatrix} \boldsymbol{F}^*_{j+1/2} = \boldsymbol{F}^{(+)}_j + \boldsymbol{F}^{(-)}_{j+1} \\ \mathrm{P}^*_{j+1/2} = \mathrm{P}^{(+)}_j + \mathrm{P}^{(-)}_{j+1} \end{pmatrix}$$

$$\begin{pmatrix} \boldsymbol{F}^*_{j+1/2} \\ \mathrm{P}^*_{j+1/2} \end{pmatrix}$$

$$I_\nu(\boldsymbol{n}) = \frac{3E_\nu}{8\pi}\frac{(1-\beta^2)^3}{3+\beta^2}(1-\boldsymbol{\beta}\cdot\boldsymbol{n})^{-4}$$

$$\beta = \frac{3f}{2+\sqrt{4-3f^2}}, \qquad \boldsymbol{\beta} = \beta\frac{\boldsymbol{F}}{|\boldsymbol{F}|}$$

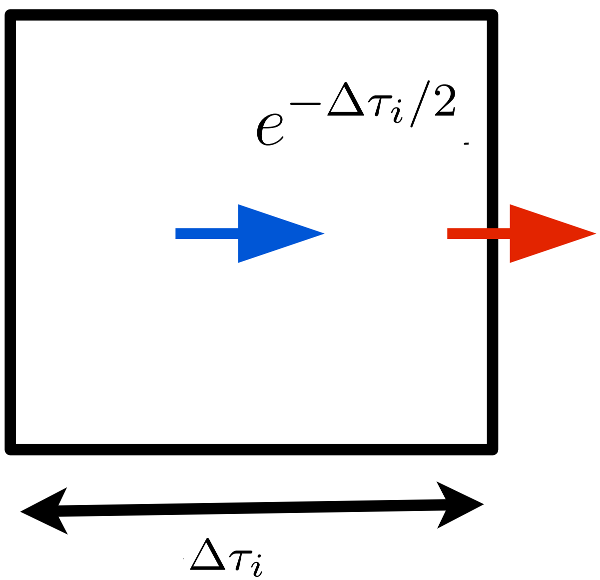
Kinetic Reconstruction

Kanno, Harada, & Hanawa 2013, PASJ in press

Absorption & Emission within Cell

$$F'^{(+)}_{\nu,x,i+1/2,j,k} = e^{-\Delta\tau_i/2} F^{(+)}_{\nu,x,i+1/2,j,k} + \left(1 - e^{-\Delta\tau_i/2}\right) \frac{S_\nu}{4}$$

Flux at boundary absorption Flux at center Emission



$\Delta\tau_i$: optical depth

approaching to diffusion limit when $\Delta\tau_i$ is large

MUSCL for 2nd order in space

$$P'^{(+)}_{\nu,x,i+1/2,j,k} = e^{-\Delta\tau_i/2} P^{(+)}_{\nu,x,i+1/2,j,k} + \left(1 - e^{-\Delta\tau_i/2}\right) \frac{S_\nu}{6}$$

41 colors

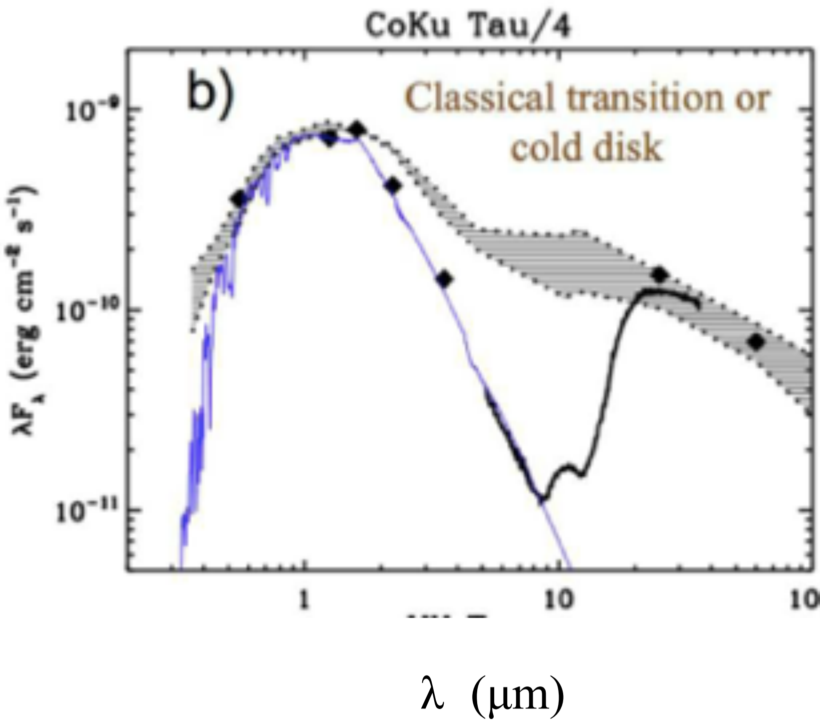
$$0.1\ \mu\mathrm{m} \leq \lambda \leq 1\ \mathrm{mm}$$

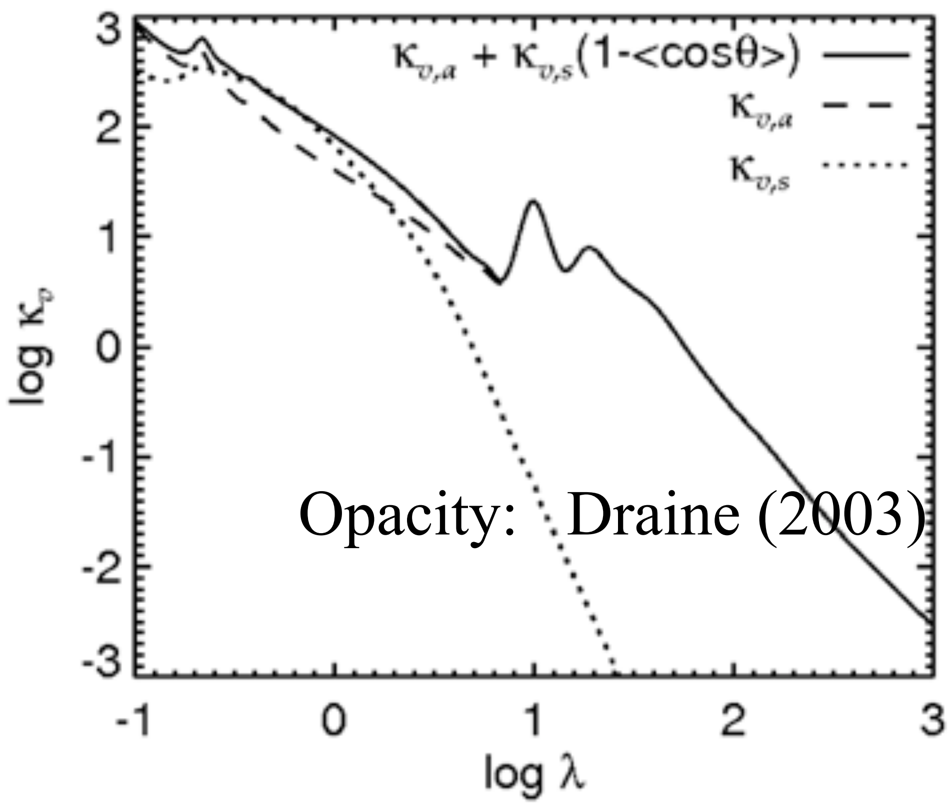
$$\Delta \log \lambda = \Delta \log \nu = 0.1$$

$M_* = 2.2\ \mathrm{M_o}$

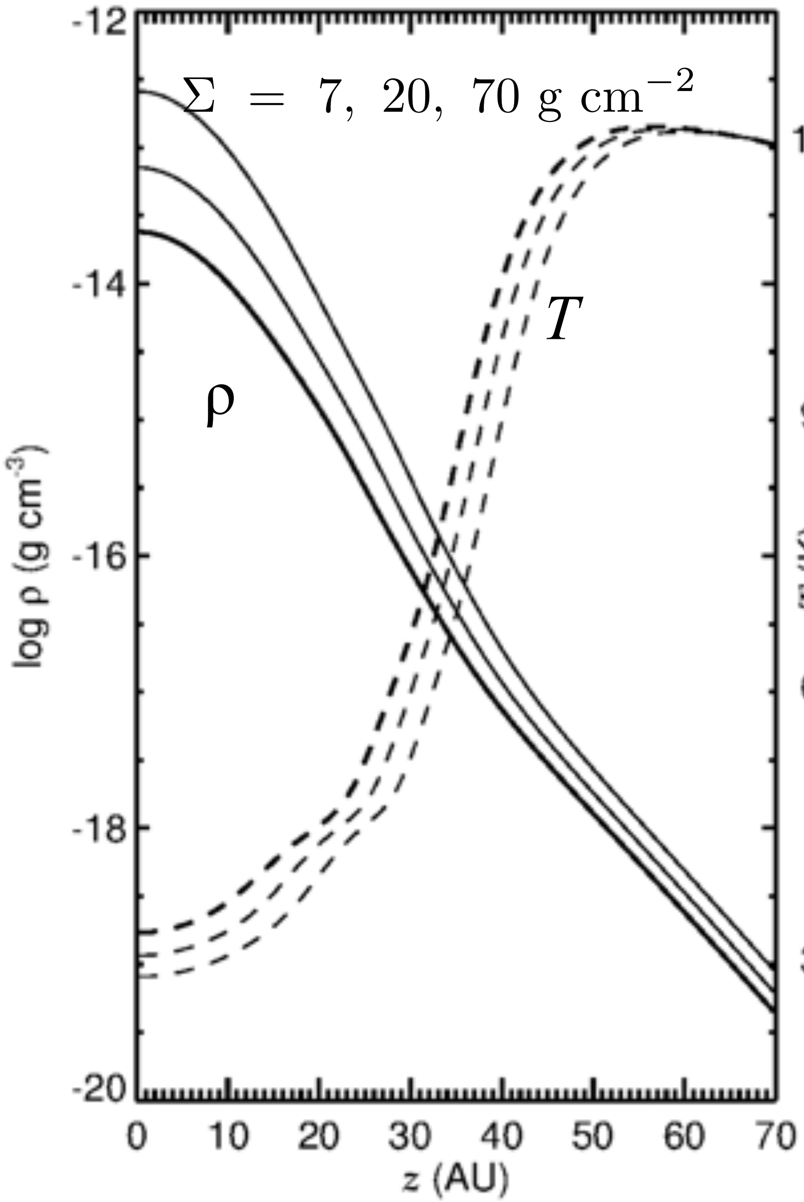
$T_{\mathrm{eff}} = 6250\ \mathrm{K}$

$R_* = 3.8\ \mathrm{R_o}$





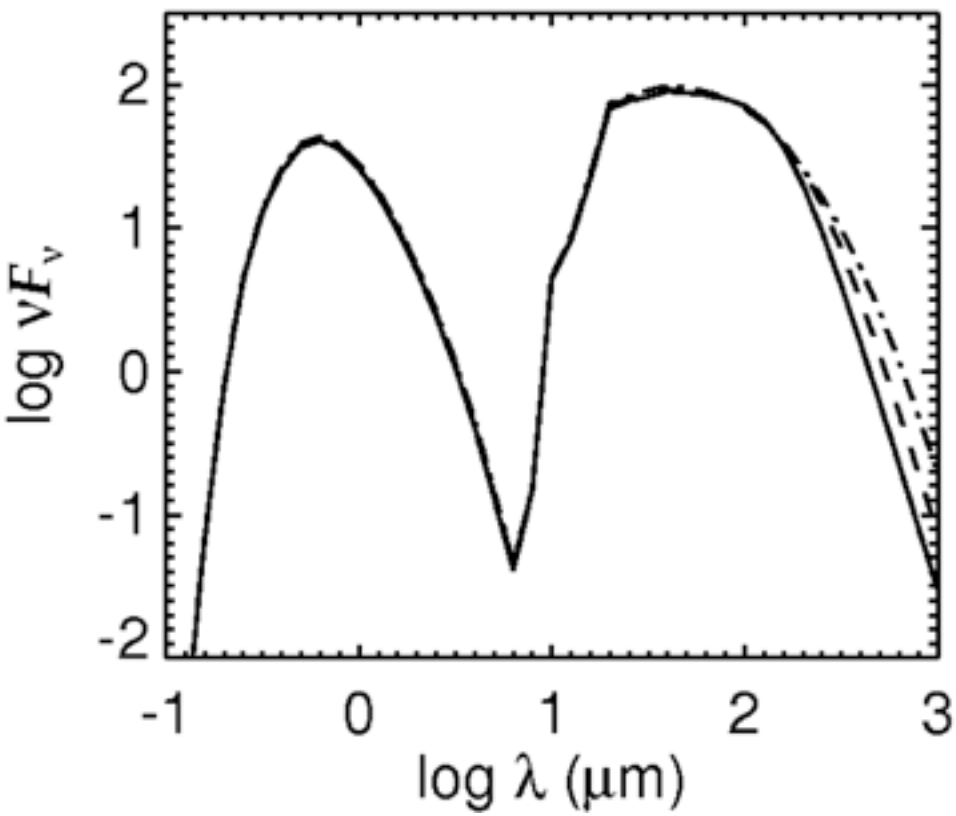
Initial model (Equilibrium)



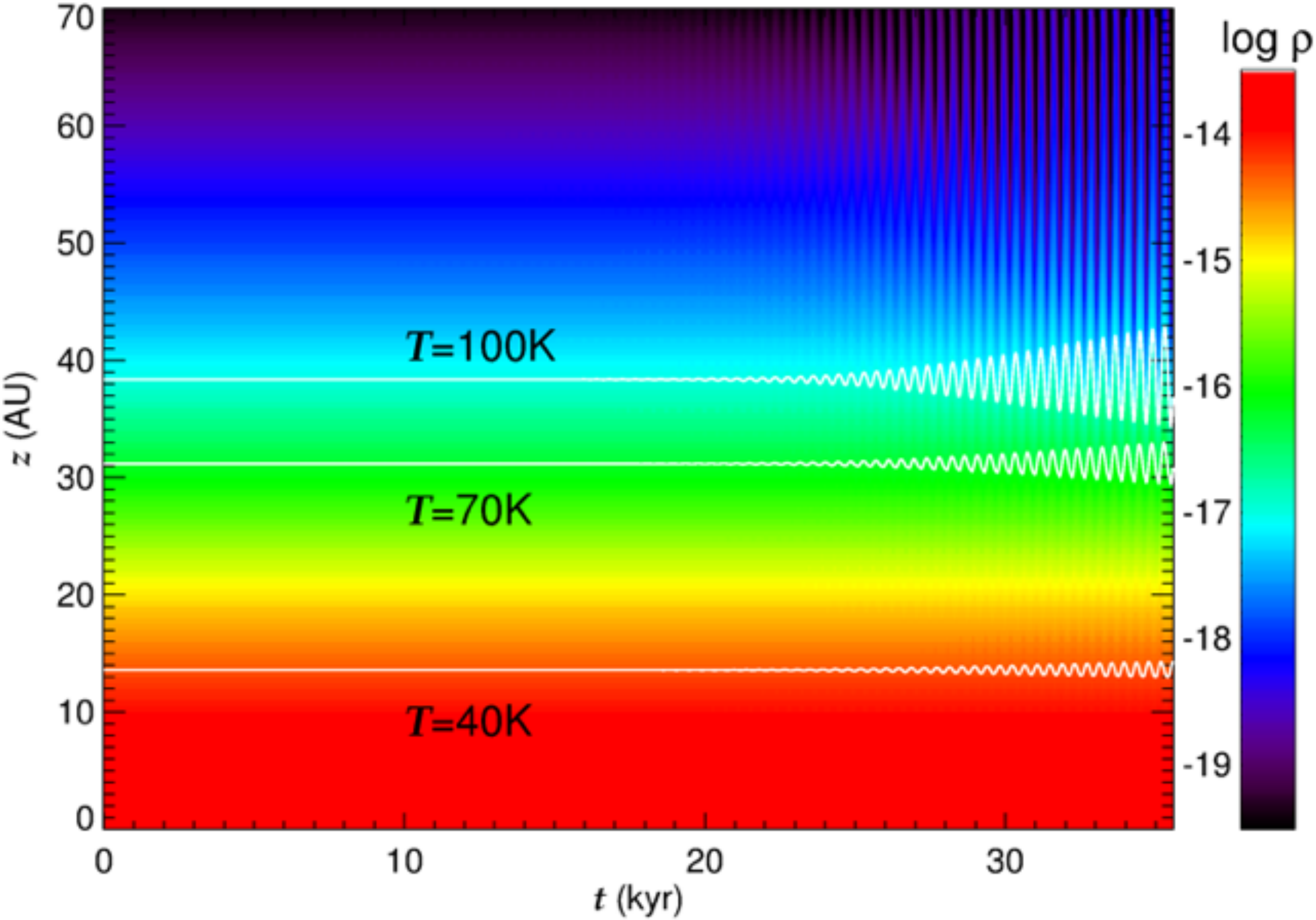
Model 1: $\Sigma = 7$ g cm^{-2}

$r = 100$ AU

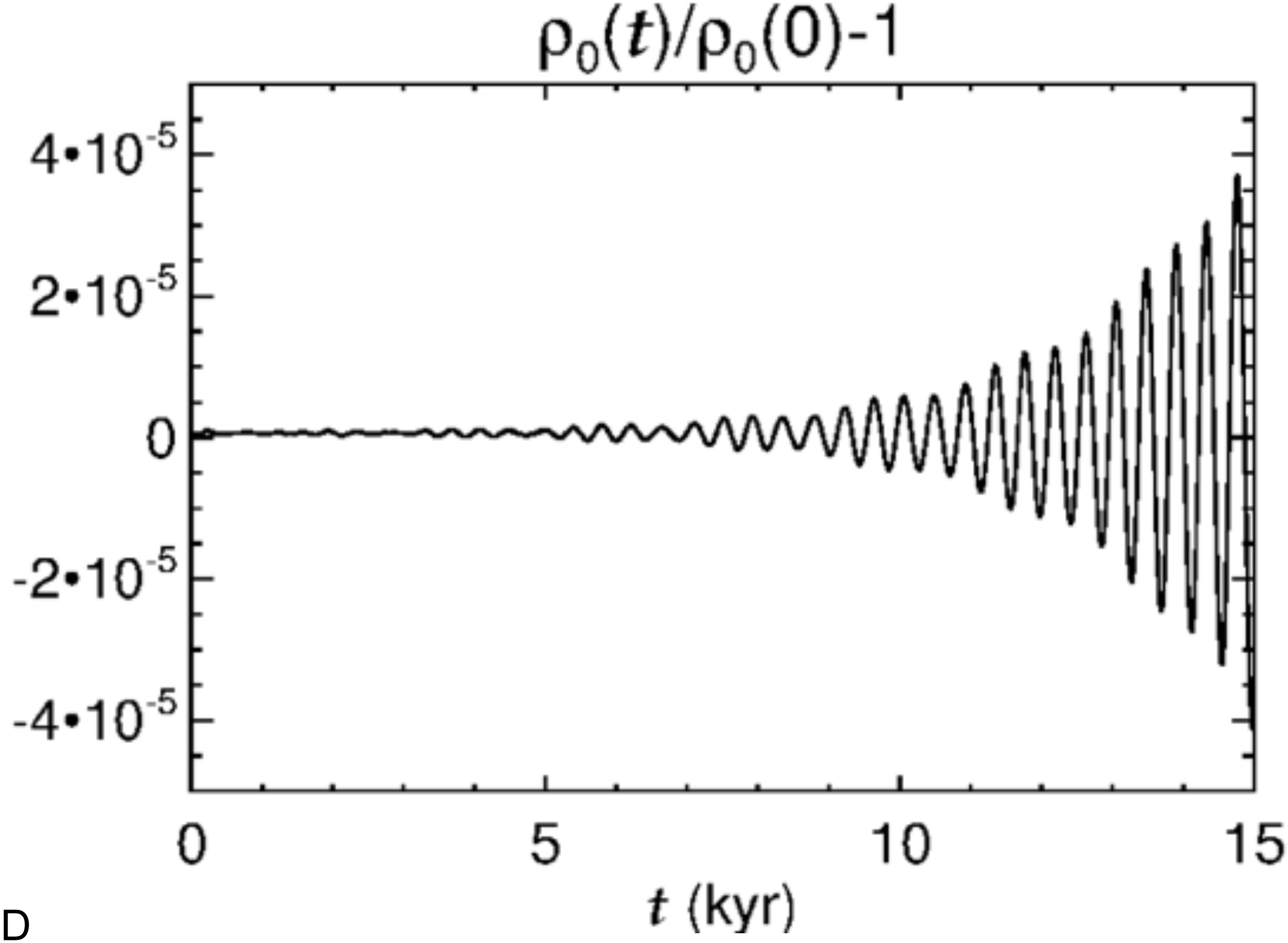
$z_{\max} = 70$AU, $\Delta z = 0.5$ AU



Model 1: overview

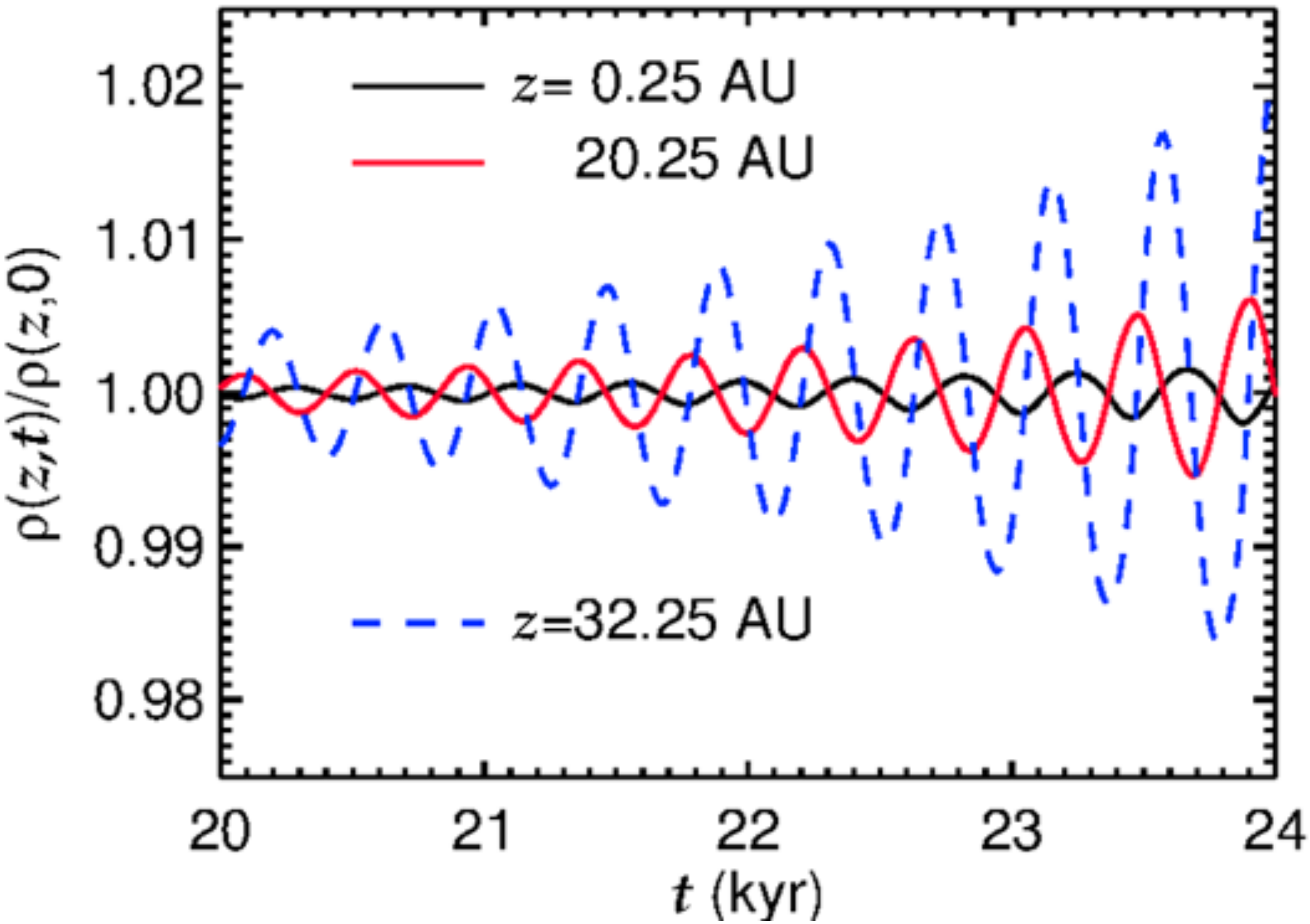


Early density oscillation at z = 0.25 AU



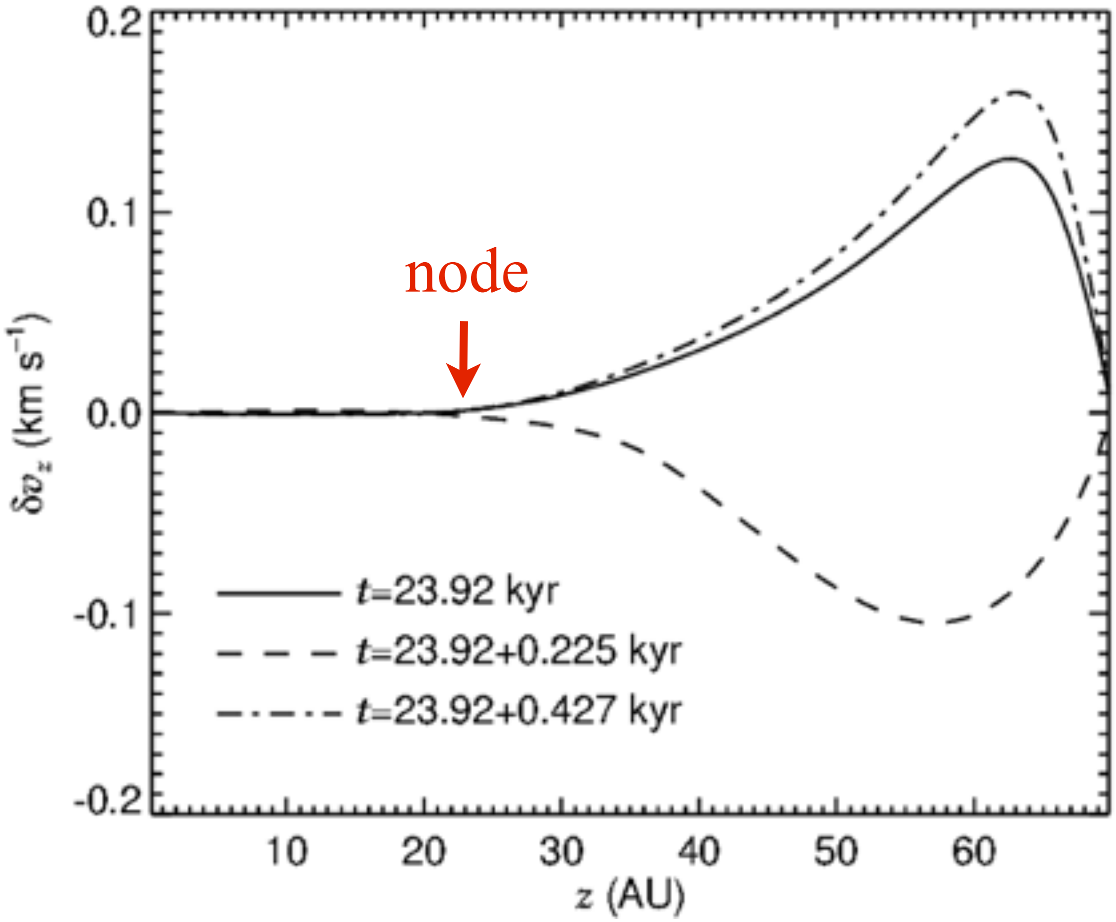
D

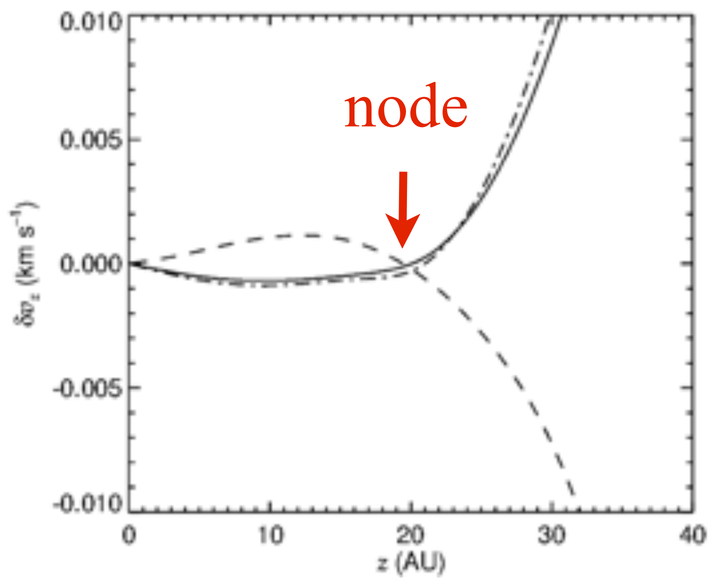
density fluctuation at various heights



Period = 420 yr, *e*-folding growth timescale = 2,000 yr.

velocity perturbation





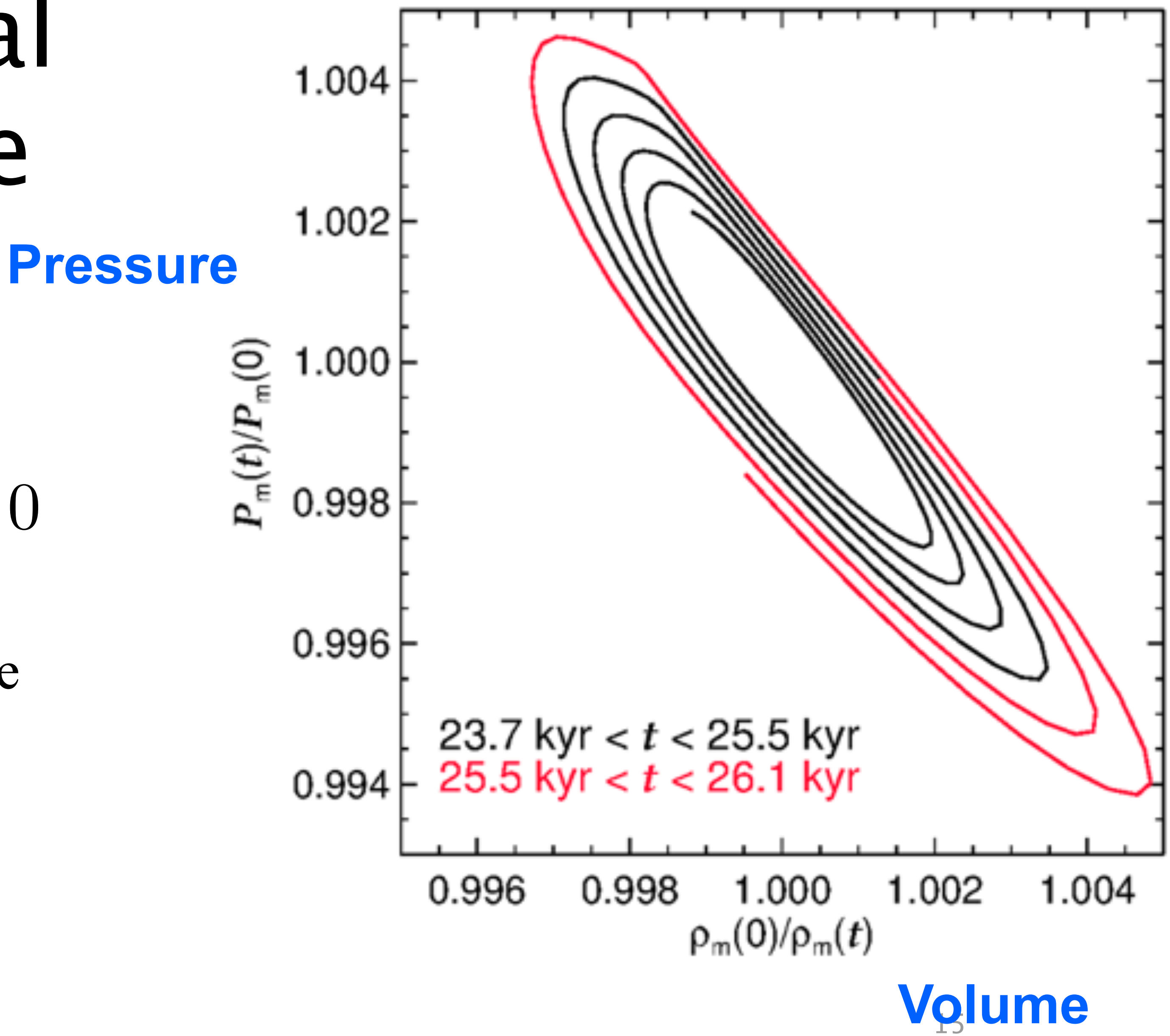
Upper layers expands to receive more stellar light, when the disk main body is compressed.

$z = 0.25$ AU

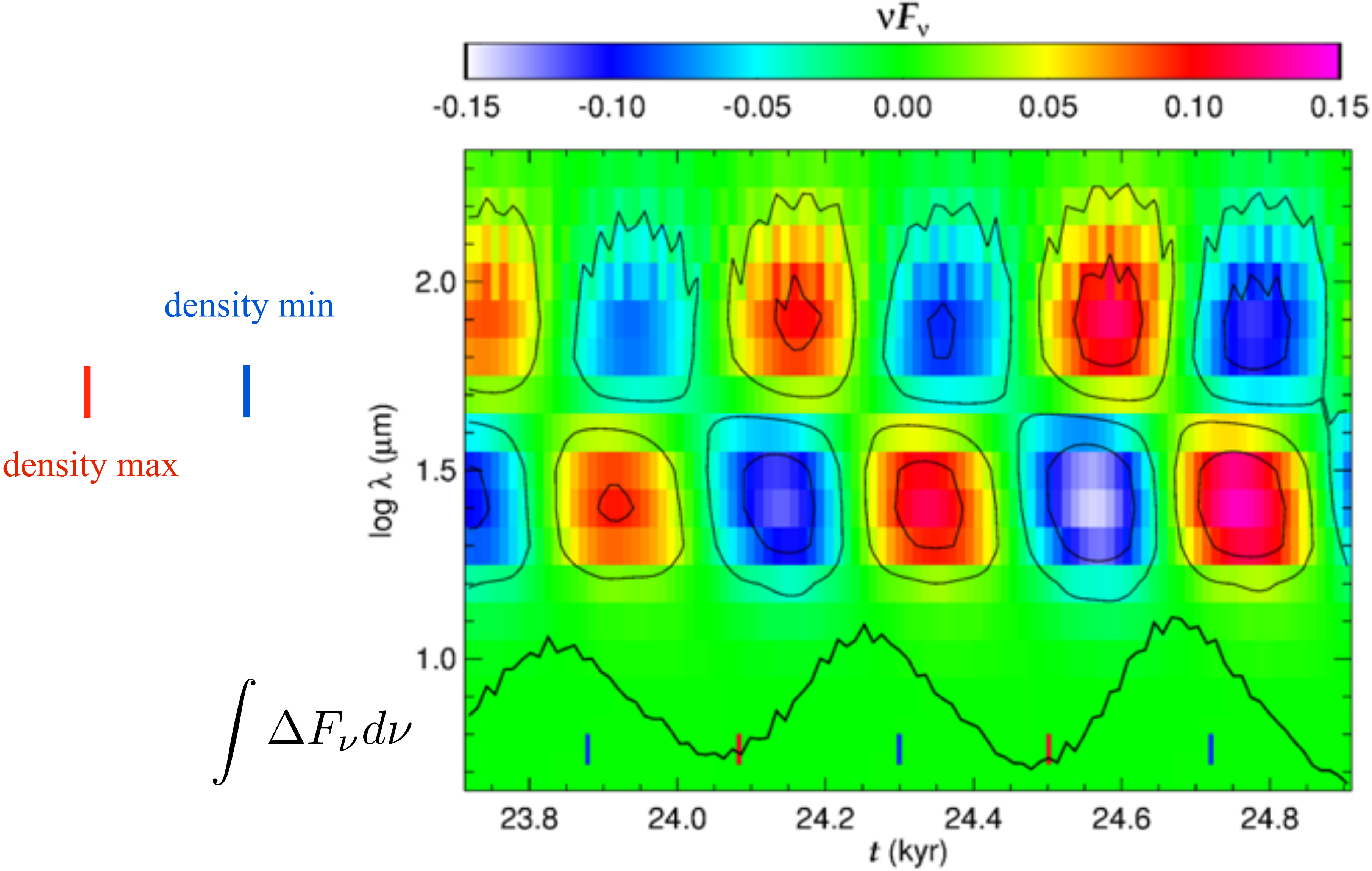
thermal engine

$$\oint P dV > 0$$

rotates clockwise

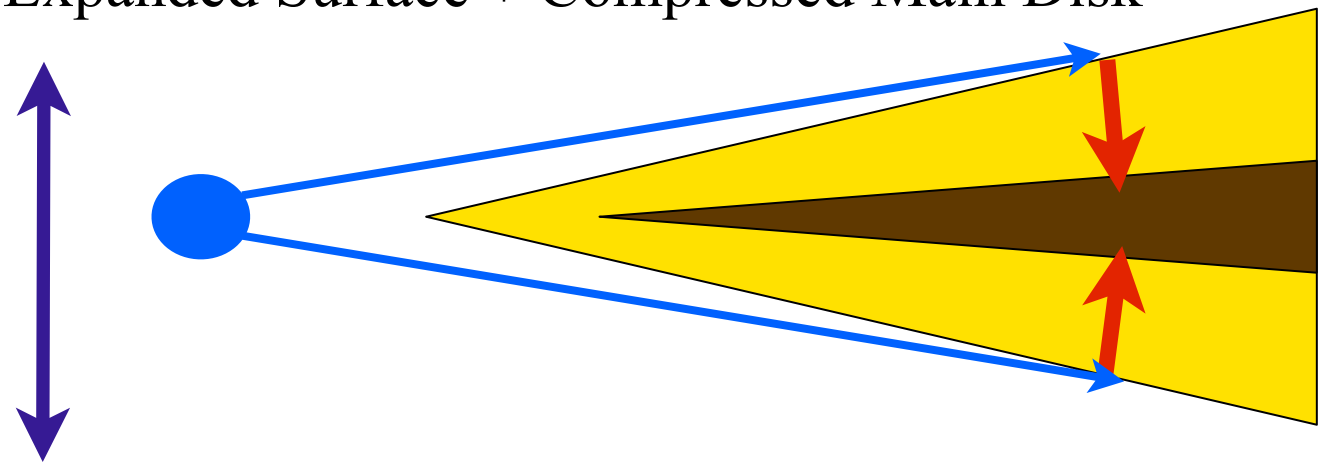


Variation in Radiative Flux @ z = 19.75 AU



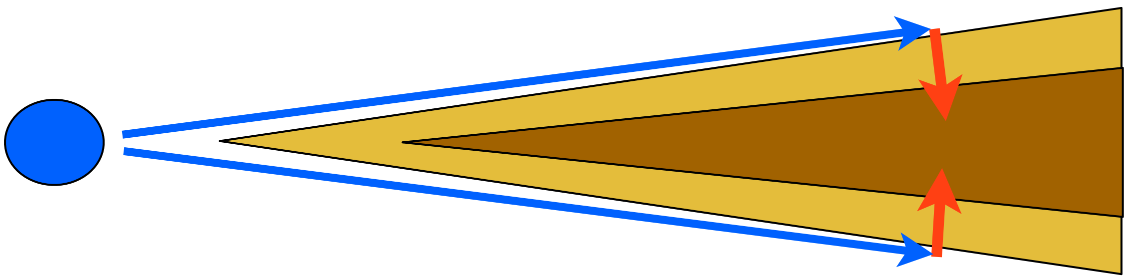
Excitation Mechanism

Expanded Surface + Compressed Main Disk



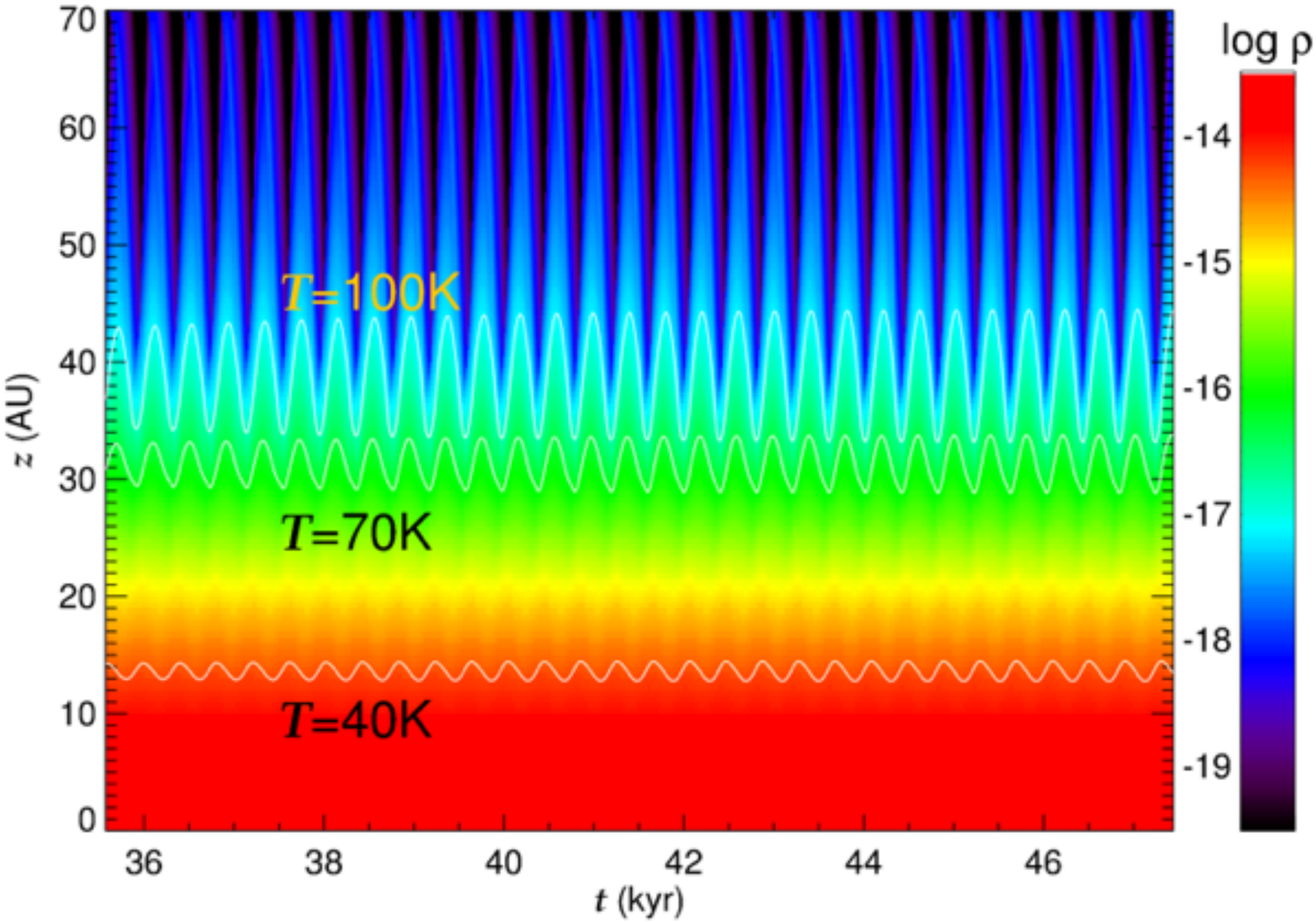
Excess Heating

Compressed Surface + Compressed Main Disk

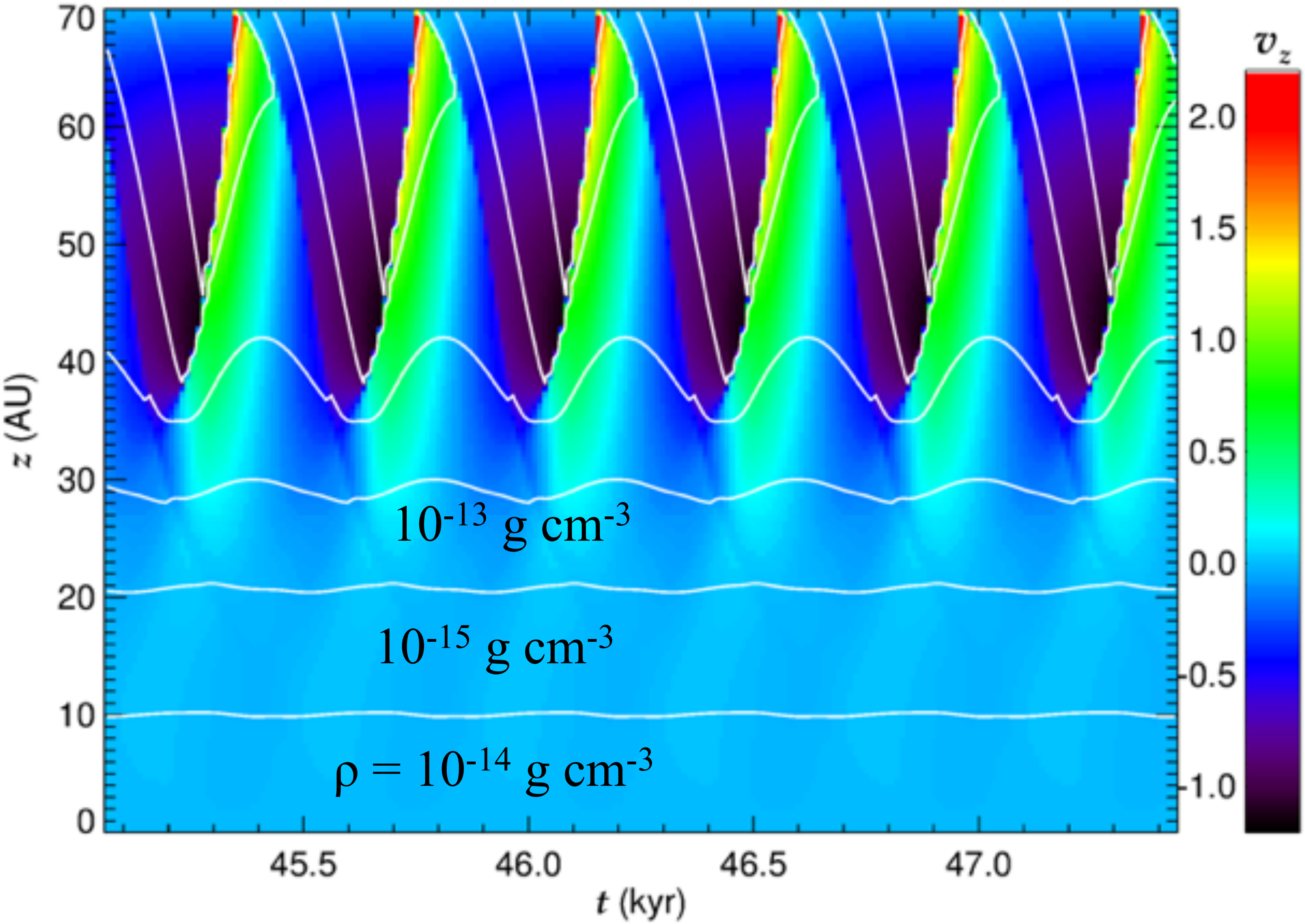


Heating Deficiency

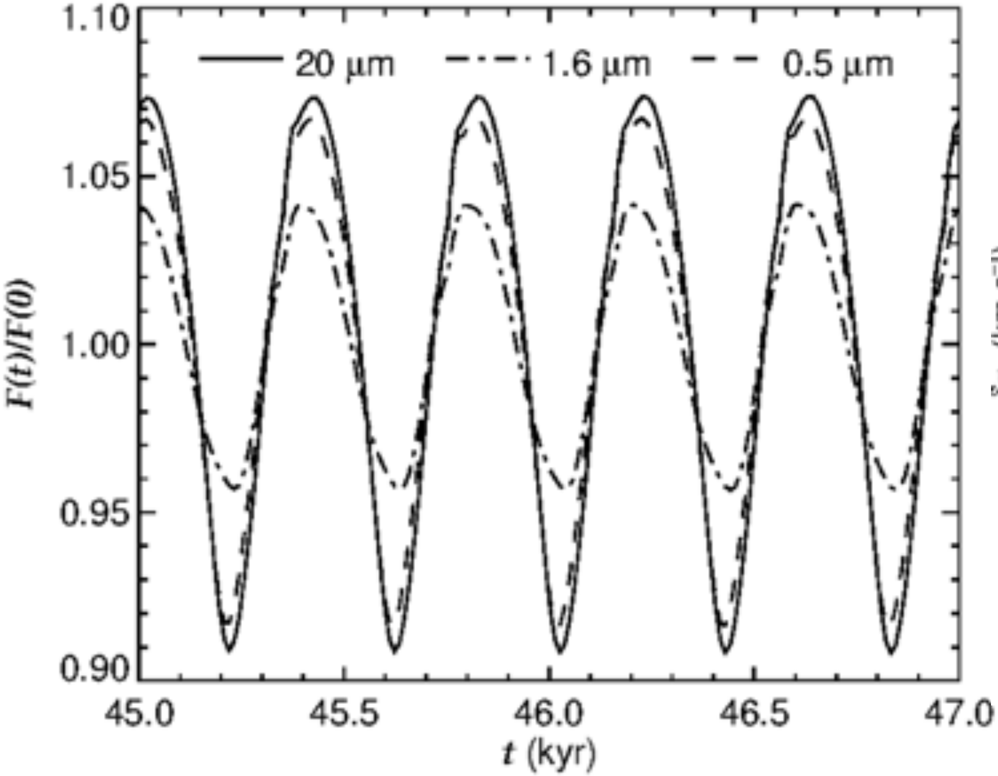
Limit Cycle Oscillation

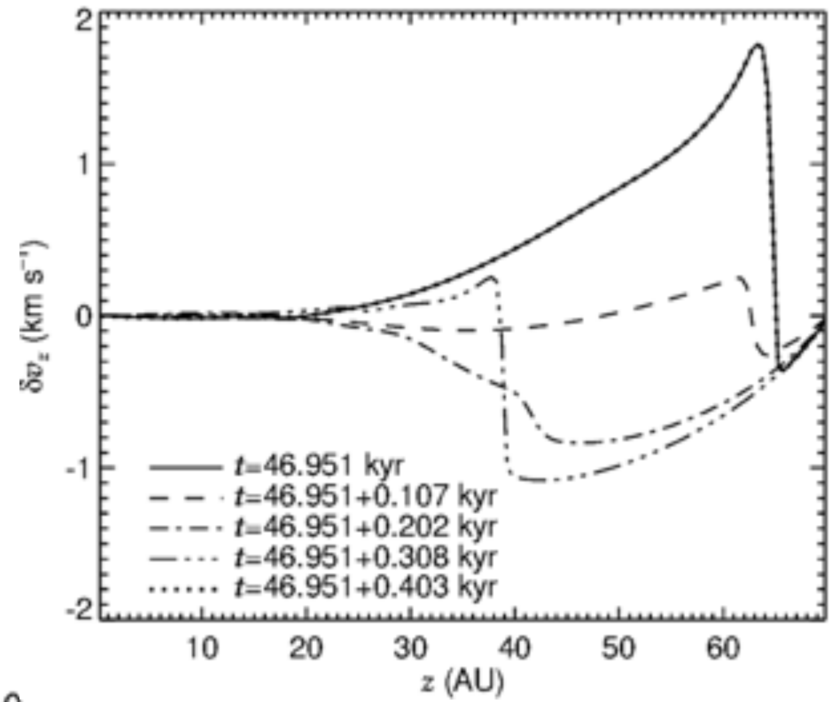


Mass Ejection



Light variation and mass ejection

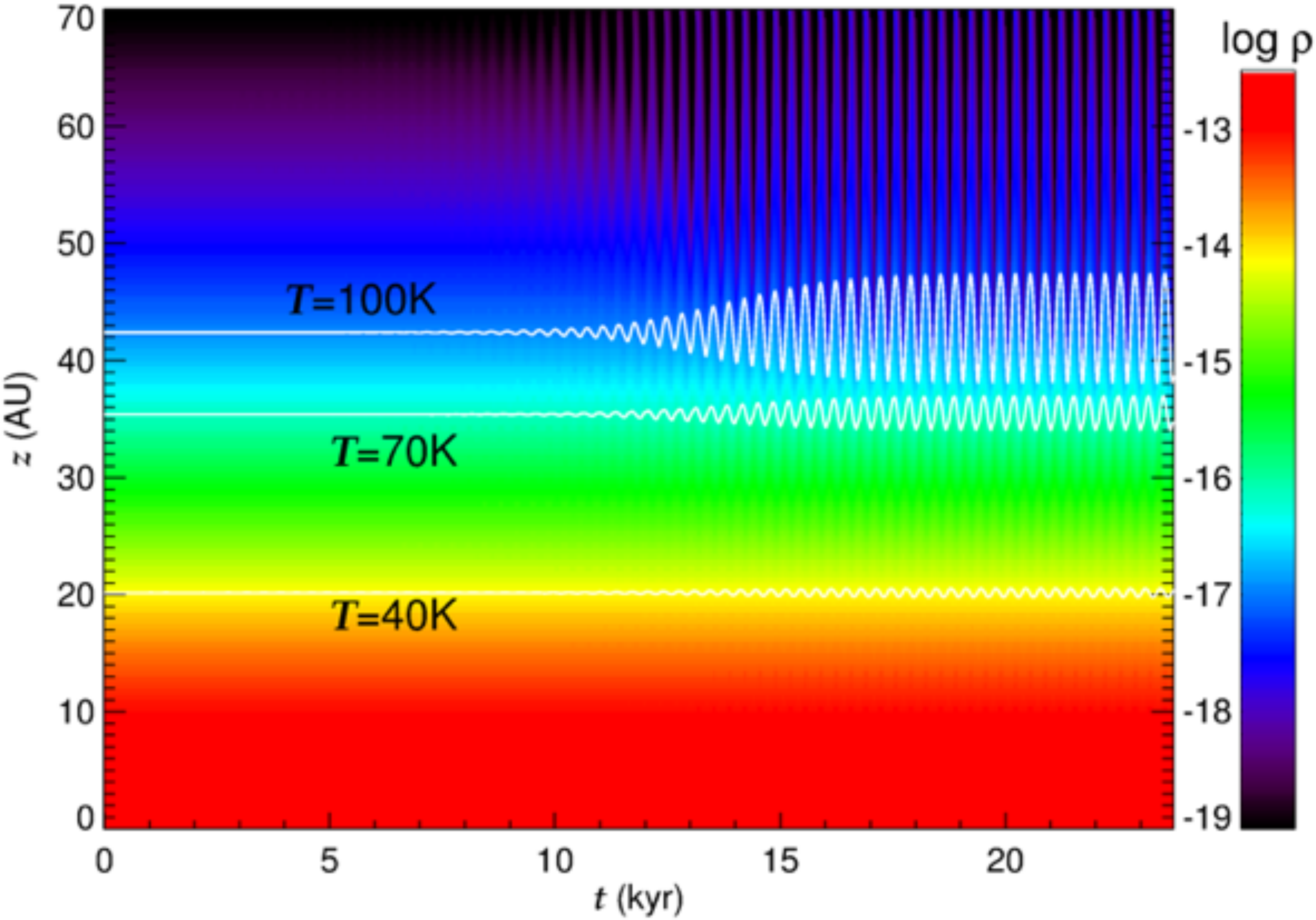




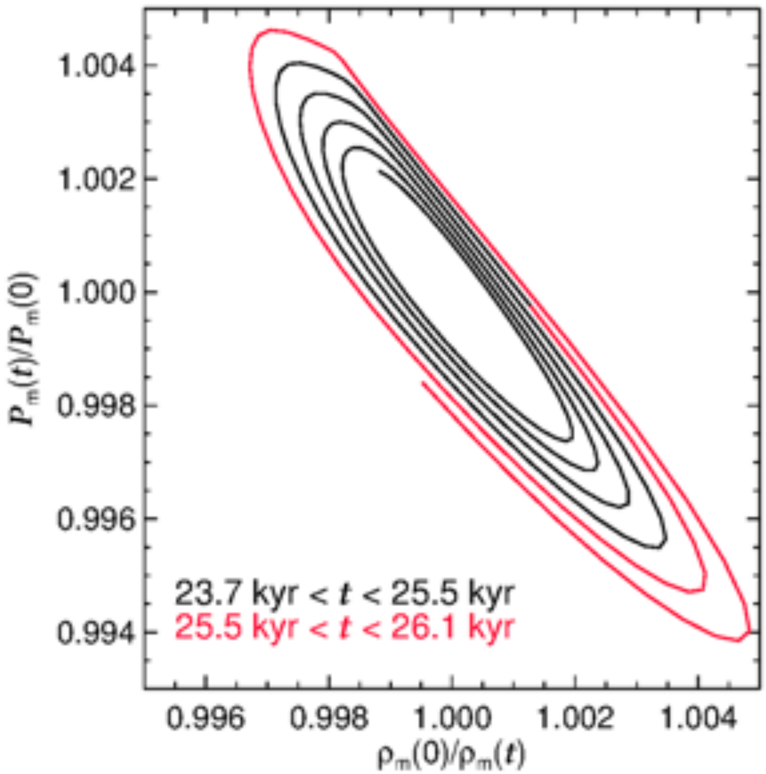
Doppler shift in CO lines

The period is 2/3 of the Keplerian.

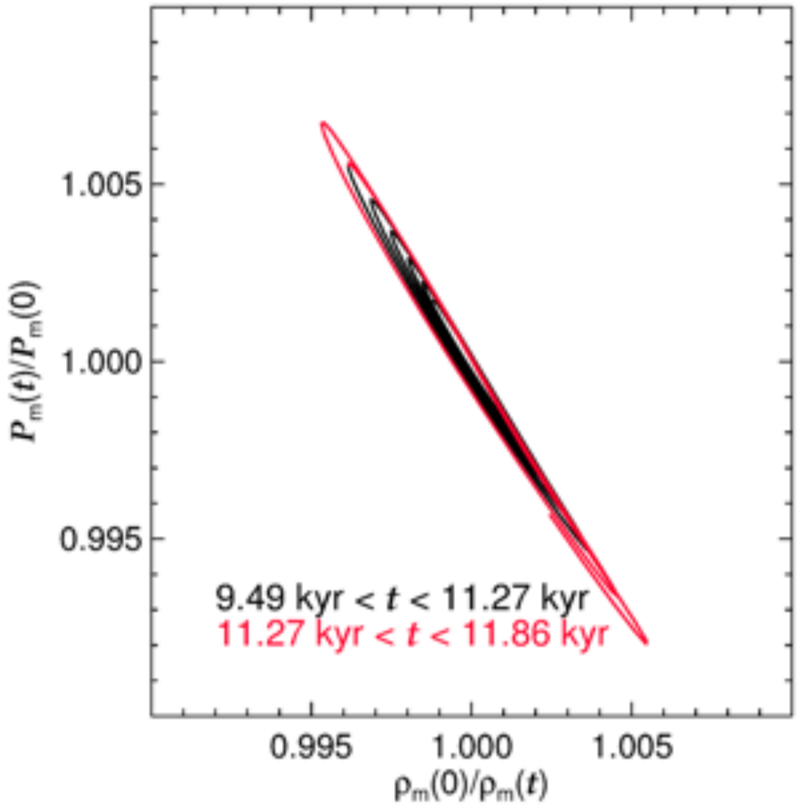
High Surface Density (Σ = 70 g cm^{-2})



PV diagram



Σ =7 g cm^{-2}



Σ =70 g cm^{-2}
almost adiabatic

$$\tau_{\rm th} \gg \tau_{\rm dyn}$$

Summary and Implications

- PP disks are overstable against vertical oscillation with a node, since they have hot cold inner disk and hot surface layers.
- The vertical oscillation affects appearance and evolution of PP disks.
- 2D RHD simulations are desired. Flaring of an annulus may result in a