Planet formation in layered disks

(R. Wünsch, H. Klahr, M. Różyczka, A. Gawryszczak)

1. **Protoplanetary disks**

   (observational evidence, properties, formation)

2. **Planet formation**

   (Core accretion vs. Gravitational instability, dust sedimentation, grain growth, accretion of gas, eventual migration, dust-gas dynamics - drag force)

3. **Layered disk**

   (basic model, physical processes, properties of layered accretion, numerical model)

4. **Ring instability**

   (2D simulations, mechanism, analytical description, effect of irradiation)

5. **Layered disk evolution - minioutbursts**

   (residual viscosity in DZ, rings vs. minioutbursts, analytical description, mechanism of mini-outburst, stationary states)

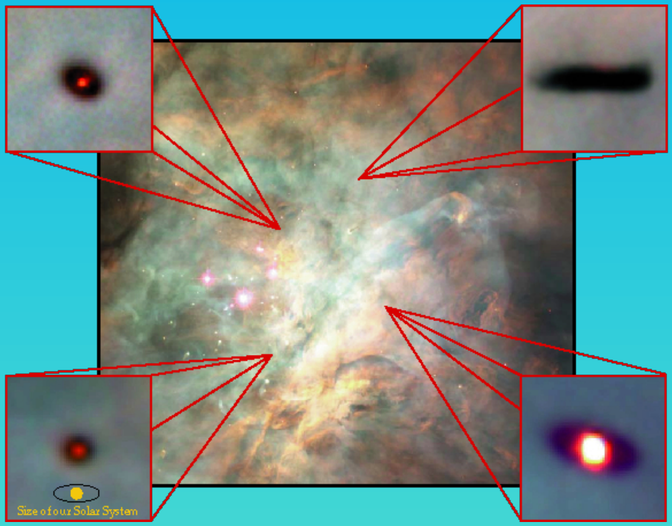
6. **Decay of the ring into vortices**

   (3D simulations of the Rosby wave instability)

Richard Wünsch, Astronomical Institute, CAS, Prague

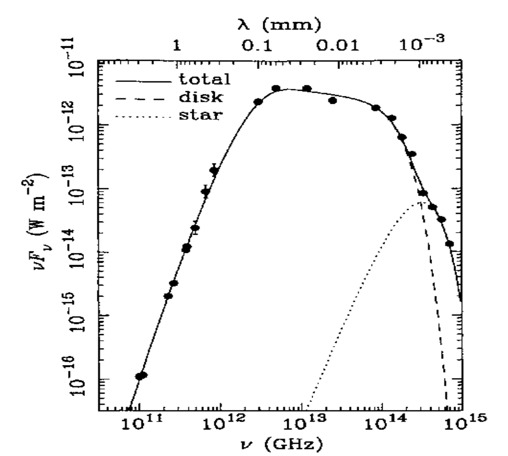
Drawing Credit: David A. Hardy, ROE, ATC, NSF, NASA

Protoplanetary disks: observational evidence



Optical/NIR:

- Asymmetric profiles of forbidden emission lines `(Edwards et al., 1987)`
- Stellar light scattered on dust particles `(Beckwith et al., 1989)`
- Dark silhouettes in Orion nebulae and other HII regions



(a) SED for HL Tau

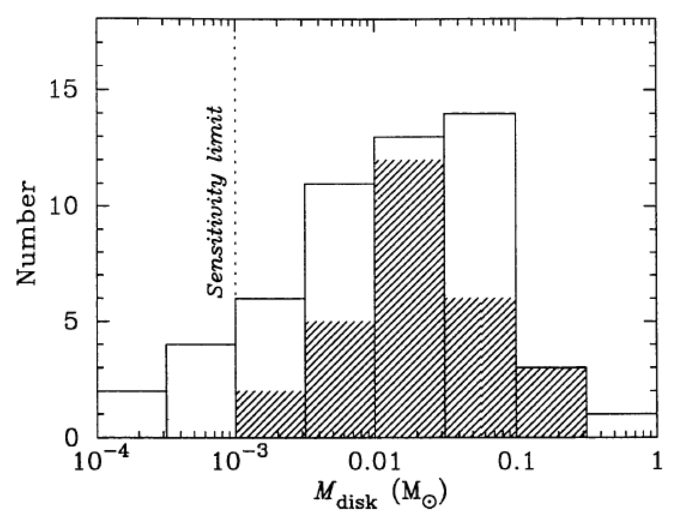
Millimeter/submillimeter, FIR:

- Broadband emission from the dust `(Beckwith et al., 1990)`
- CO rotational transitions suggest Keplerian rotational profile

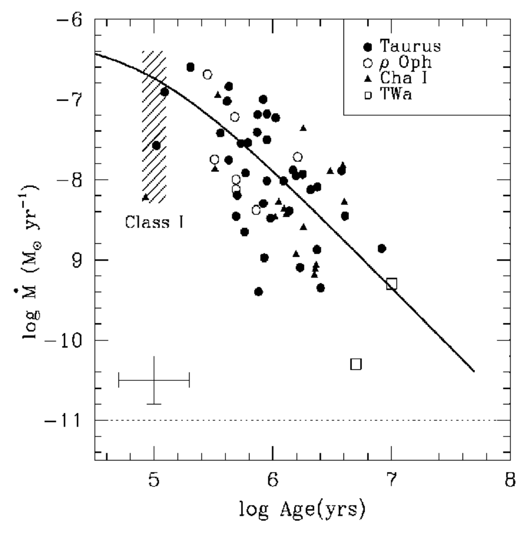
Protoplanetary disks: observed properties

- Frequency: cca 50% of TTS
- Mass: 0.01 - 0.1 M$_{\odot}$ (from optically thin mm emision)
- Size: 100 - 1000 AU
- Lifetime: $\sim 10^{7}$ yr (from ages of TTS)
- Accretion rate: 10^{-9} - 10^{-6} M$_{\odot}$yr^{-1}
  (from optical/UV excess from inner boundary layer)

Chandler (1998)

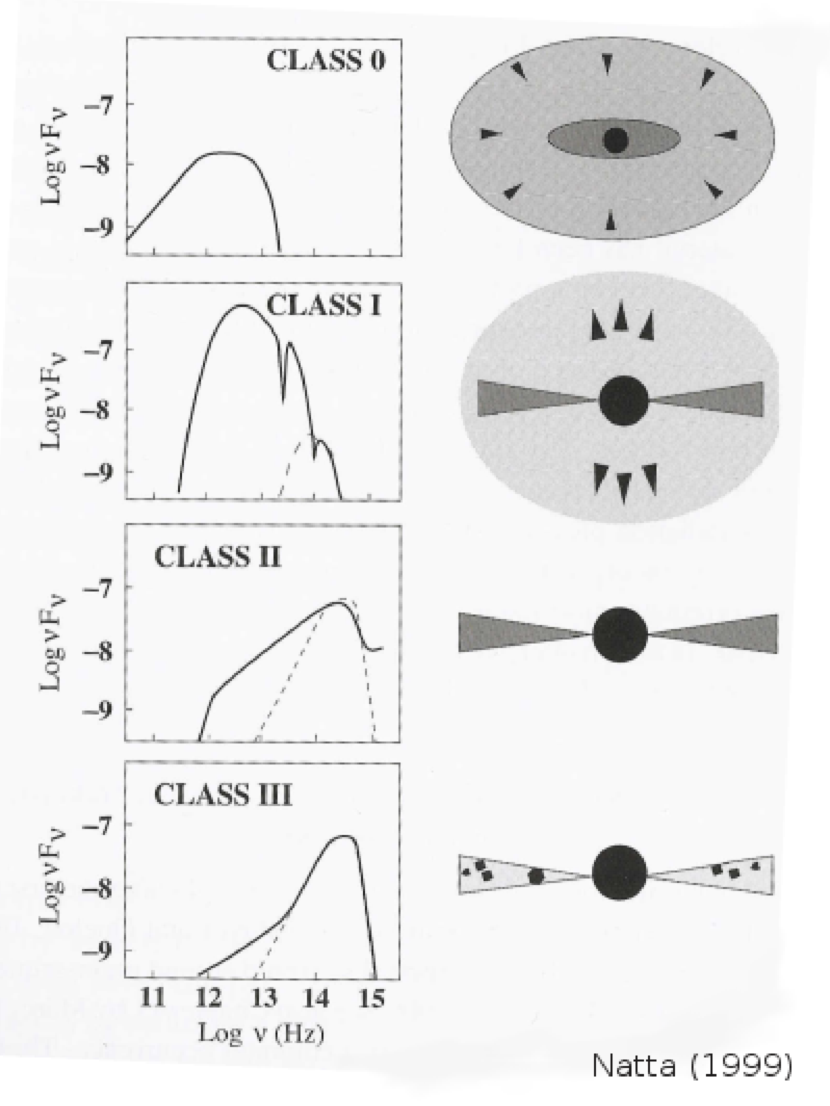


Muzerolle et. al (2000)



Protoplanetary disks: formation and evolution

- Class 0:
  - *protostar and disk formed by a collapse of molecular core (10^4 yr)*
  - *deeply embedded within an infalling envelope of dust and gas (visible in FIR only)*
- Class I ($\sim 10^5$ yr):
  - *star accretes matter through the disk, bipolar outflow*
  - *still embedded → strong absorption features*
- Class II ($\sim 10^7$ yr):
  - *surrounding material largely dissipated, infall of matter terminated*
  - *protostar & optically thick disk*
  - *planets are supposed to form*
- Class III:
  - *gaseous disk almost dispersed (accretion, photo-evaporation)*
  - *debris disk: secondary dusty disk formed by solid body collisions*



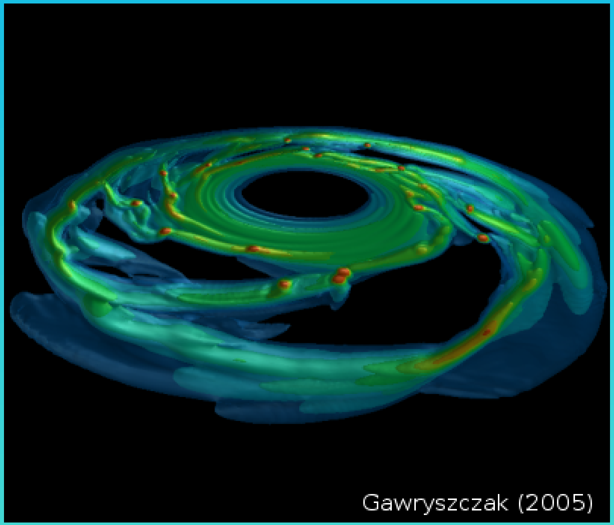
Natta (1999)

Planet formation: GI or CA?

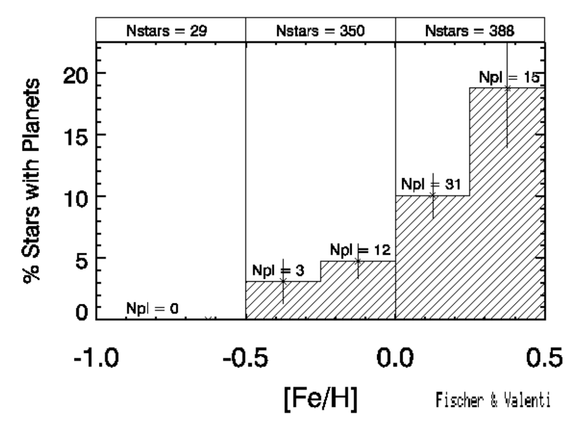
- two competitive hypotheses of giant gas planets formation:

Gravitational instability (Cameron, 1978)

- massive and cold disk, $Q \equiv \frac{c_s \kappa}{\pi G \sigma} < 1.5$
- fast $\sim 10^3$ yr
- ruled out in mid-1980s - models suggested $M_{\rm Jup,core} \sim 15-30$ $\mathrm{M}_\oplus$;
  today: $M_{\rm Jup,core} \sim 6$ $\mathrm{M}_\oplus$



Gawryszczak (2005)



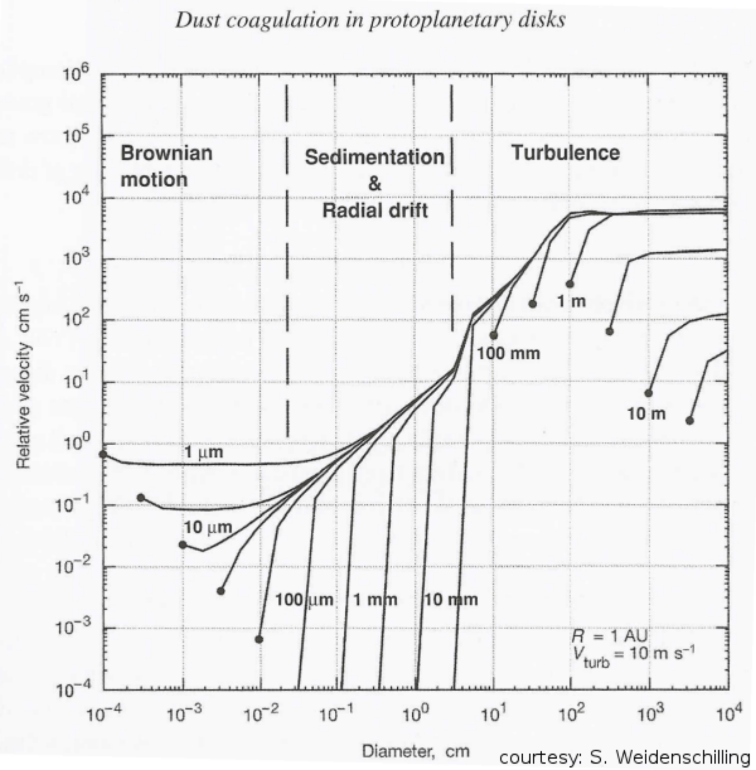
Fischer & Valenti

Core accretion (Safronov, 1969)

- collisional accumulation of dust
  $\rightarrow$ solid core ~ 10 $\mathrm{M}_\oplus$
- disk gas accretion, ev. migration
- $P(\text{planet})$ depends on Z
- $t_{\rm pl.form.}$ comparable to disk life-time

Dust coagulation

- $0.1\mu m$ grains → 100 km bodies (12 orders of magnitude in size)
  - *complex dust-gas interaction (critical param. $v_{\mathrm{rel}}, \rho_{\mathrm{dust}}$)*
  - **collision:** *sticking, bouncing, restructuring, erosion, destruction*
  - *Brownian motion, turbulence, sedimentation into dust layer, drag force (radial drift, trapping), gravitational instability of dust layers, . . .*



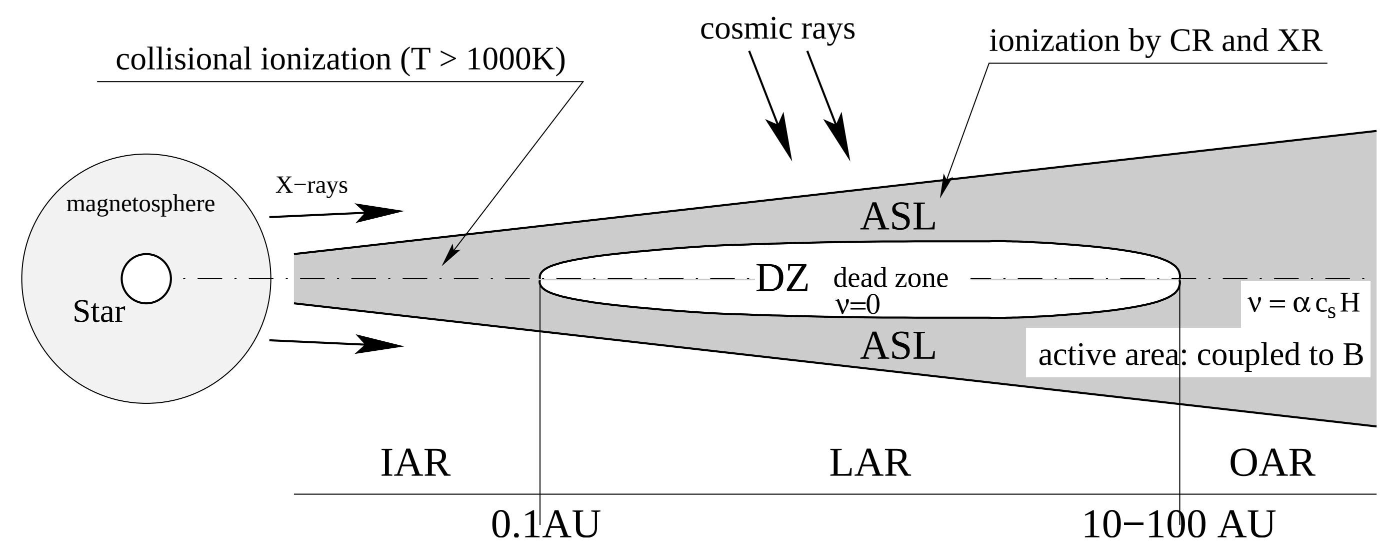
courtesy: S. Weidenschilling

Drag force

$$\left.\begin{array}{l}\dfrac{D\mathbf{v}_{\mathrm{gas}}}{Dt} = -\nabla P + \rho\nabla\Phi \\ \dfrac{D\mathbf{v}_{\mathrm{dust}}}{Dt} = \rho\nabla\Phi\end{array}\right\} \frac{D(\mathbf{v}_{\mathrm{dust}} - \mathbf{v}_{\mathrm{gas}})}{Dt} = \nabla P$$

Dust tends to climb up the pressure gradient!
→ radial drift, trapping in rings, spirals, vortices

Layered-disk: basic idea (Gammie, 1996)



- angular momentum transfer - MRI (Balbus & Hawley, 1991)
- parts of the disk are not ionized enough to be well coupled to the magnetic field
- inner active region (IAR) - collisional ionization
- layered accretion region (LAR) - surface active layers (ASL) ionized by cosmic rays shield the dead zone (DZ) near the mid-plane
- outer active region (OAR) - low surface density, CR are able to ionize whole disk

Layered-disk: physical processes

- MRI occurs for: $Re_M \equiv \frac{V_A H}{\eta} > 1 - 10^2$ `(Fromang et al., 2002)`
- Alfven velocity related to α-viscosity: $V_A = \alpha^{1/2} c_s$
- resistivity η related to the ionization degree $x = n_e/n_H$:

$$\eta = 6.5 \times 10^3 x^{-1} \mathrm{cm}^2 \mathrm{s}^{-1}$$

- using $H = c_s/\Omega$, magnetic Reynolds number is:

$$Re_M = 7.4 \times 10^{13} x \alpha^{1/2} \left(\frac{R}{AU}\right)^{3/2} \left(\frac{T}{500K}\right) \left(\frac{M}{M_\odot}\right)^{-1/2}$$

- collisional ionization: $x = x(\rho, T)$ `(Umebayashi, 1983)`

$$x \sim \log(\rho), \qquad x(T) = \begin{cases} 10^{-16} & \text{for} \quad T \leq 800\ K \\ 10^{-13} & \text{for} \quad T \sim 900\ K \\ 10^{-11} & \text{for} \quad T \geq 1000\ K \end{cases}$$

- CR ionization: stopping depth $\Sigma_0 \sim 100\ \mathrm{g/cm}^2$

`(Umebayashi & Nakano, 1981)`

$$x = \left(\frac{\zeta}{\beta n_H}\right)^{1/2} = 1.6 \times 10^{-12} \left(\frac{T}{500\mathrm{K}}\right)^{1/4} \left(\frac{\zeta}{10^{-17}\mathrm{s}^{-1}}\right)^{1/2} \left(\frac{n_H}{10^{13}\mathrm{cm}^{-3}}\right)^{-1/2}$$

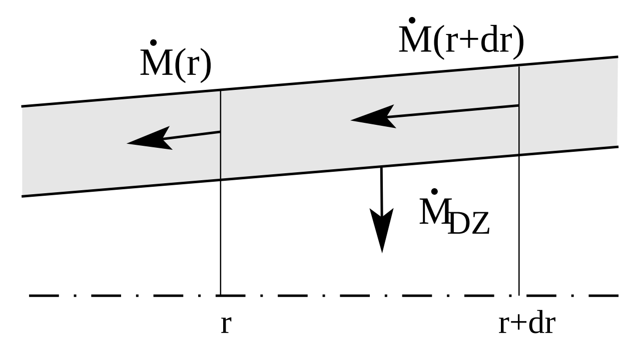
Properties of the layered accretion

- description of the layered accretion region:

$$\dot{M} = 6\pi r^{1/2}\frac{\partial}{\partial r}(2\Sigma_a \nu r^{1/2}), \quad \nu = \alpha c_{s,i} H_a, \quad \frac{9}{4}\Sigma_a \nu \Omega^2 = \sigma T_e^4$$

$$T_i^4 = \frac{3}{8}\Sigma_a \kappa(\rho_i, T_i) T_e^4, \quad c_{s,i}^2 = H_\mathrm{a}(H_\mathrm{a} + H_\mathrm{DZ})\Omega^2$$

- solution: $\dot{M}(r),\ T_e(r),\ T_i(r),\ \ldots \rightarrow$ power-laws, exponents dependent on the opacity $\kappa = \kappa(\rho_i, T_i)$
- $\Sigma_a = \mathrm{const} \ \Rightarrow\ \dot{M} = \dot{M}(r)$ increasing with r
- accumulation of mass in DZ: $\dot{\Sigma}_\mathrm{DZ} = \frac{1}{2\pi r}\frac{\partial \dot{M}}{\partial r}$
- accretion cannot be steady - when Σ_DZ is high enough, DZ mass is accreted in an outburst like event
  $\Rightarrow$ suggested as mechanism for FU Orionis outbursts `(Gammie, 1996)`



Numerical model

- based on RHD code TRAMP: `(Klahr et al., 1999)`
- radiation transfer: flux limited diffusion approximation
- 2D axially symmetric in spherical (r, θ) coords.
- viscosity:

  $\alpha_a = 10^{-2}$

  (surface layers:

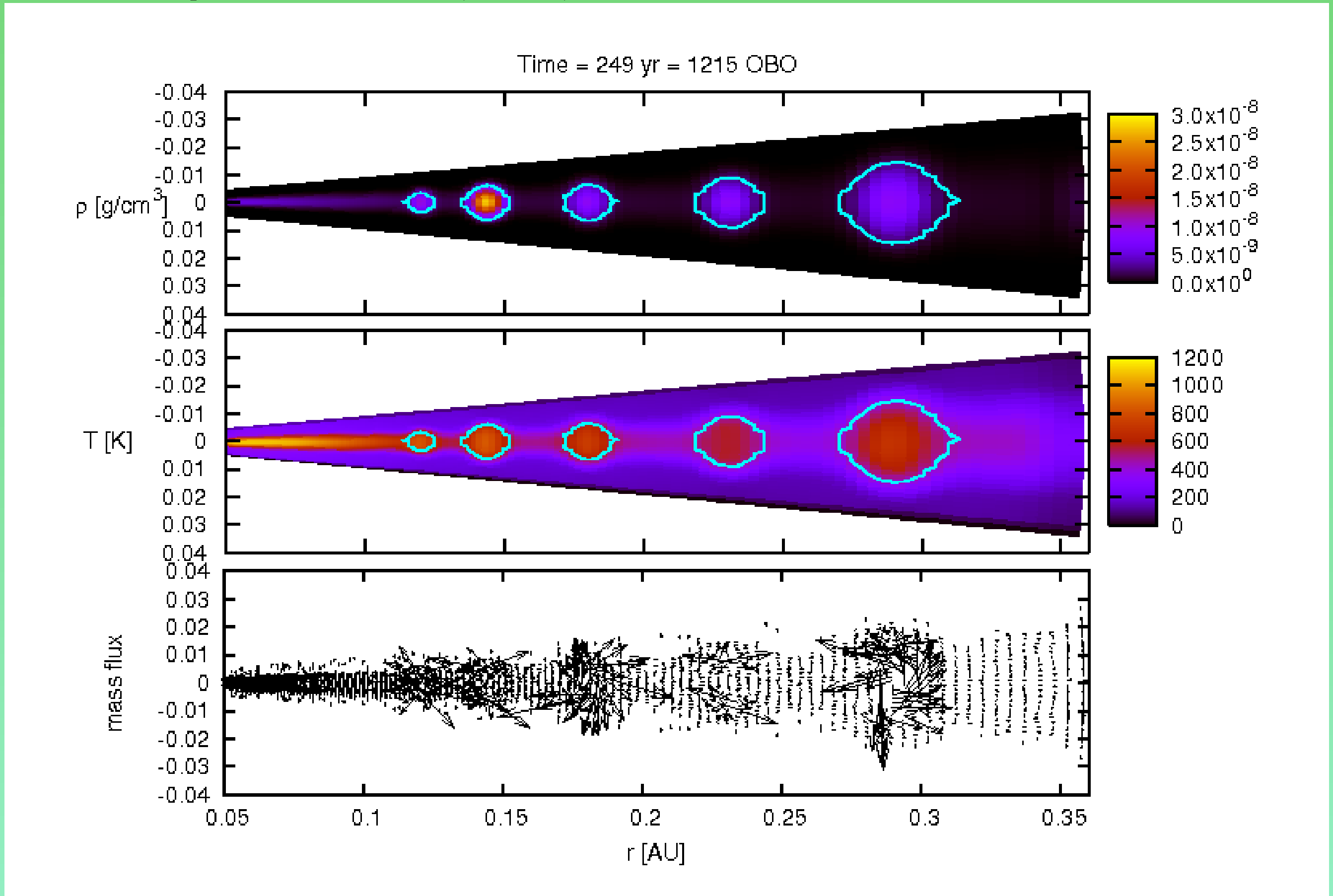
  $\Sigma_a = 100 \mathrm{g\,cm}^{-2}$

  and inner region:

  $T > 1000\mathrm{K}$)

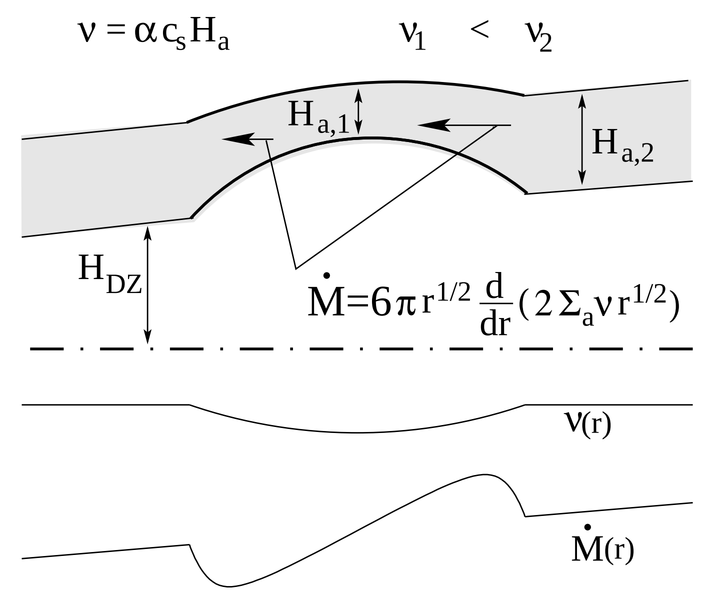
  $\alpha_{DZ} = 0$

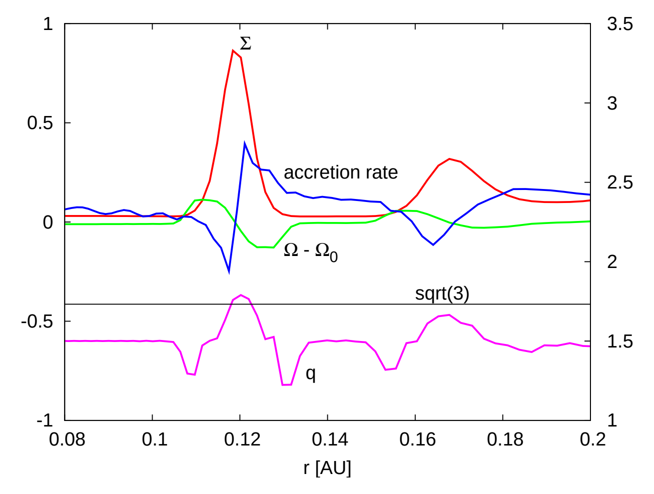
  (elsewhere - dead zone)
- rings formed!



Ring instability - mechanism

- dead zone decomposes into rings
- ring instability mechanism:
  - *thickness of surface layer* H_a *depends on the dead zone thickness* H_DZ *(due to different vertical gravity)*
  - H_a *is smaller in the ring-like perturbation* $\Rightarrow \nu$ *is smaller there, too*
  - $\dot{M}$ *depends on derivative of* $\nu \Rightarrow$ *it is smaller in inner edge and higher in outer edge of the ring*
  - *enhanced mass accumulation in the ring* $\Rightarrow$ *positive feedback*



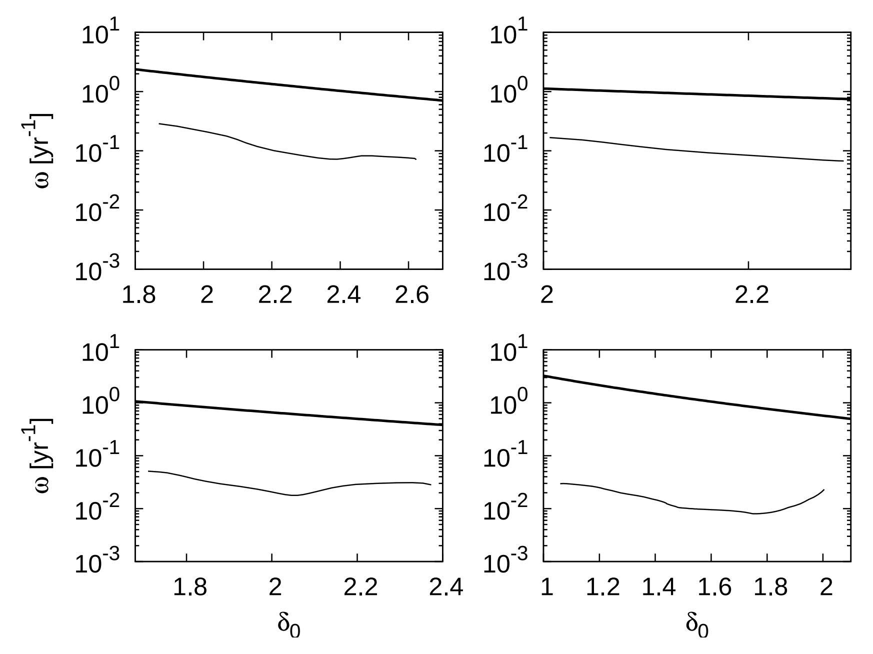


- rings may trap the dust → higher ρ_dust supports dust coagulation
- rings may decay due to the hydrodynamic instability, if $q > \sqrt{3}$ $(\Omega \sim r^{-q})$

`(Papaloizou & Pringle, 1985)`

Ring instability - anl. description, irradiation

- analytical dispersion relation based on linearized equations was found
- qualitative agreement, numerical ring growth rate is 1-2 orders of magnitude smaller (radiation transport, convective flows make viscosity profiles shallower)

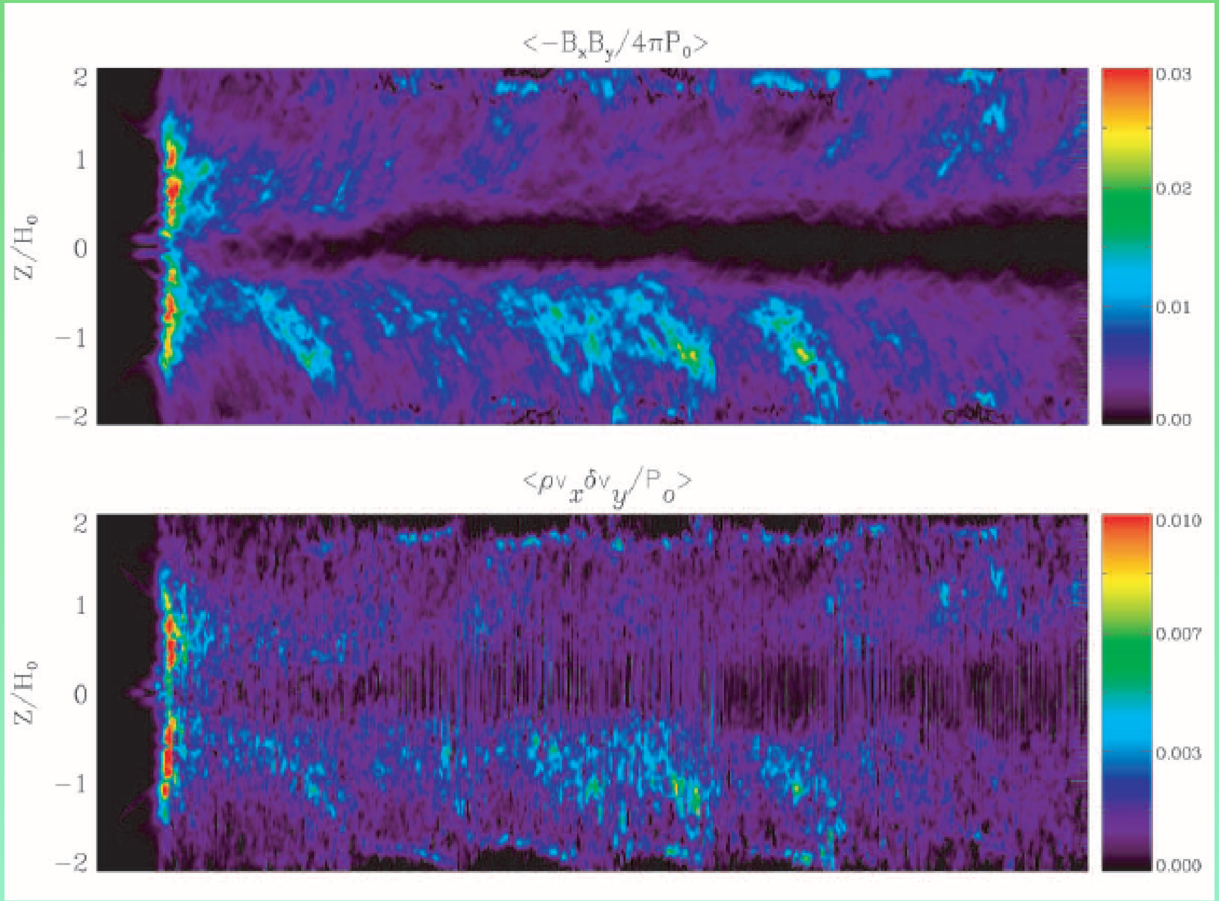


Irradiation

- analytical approximative approach: $T_i^4 = \frac{3}{8}\tau T_e^4 + W T_\star^4$
- vertical structure of the unperturbed disc changes substantially at higher radii ($r > 10$ AU) and for the flaring disk only
- ring inst. can be slowed down, but not suppressed completely

Viscosity in the dead zone - motivation

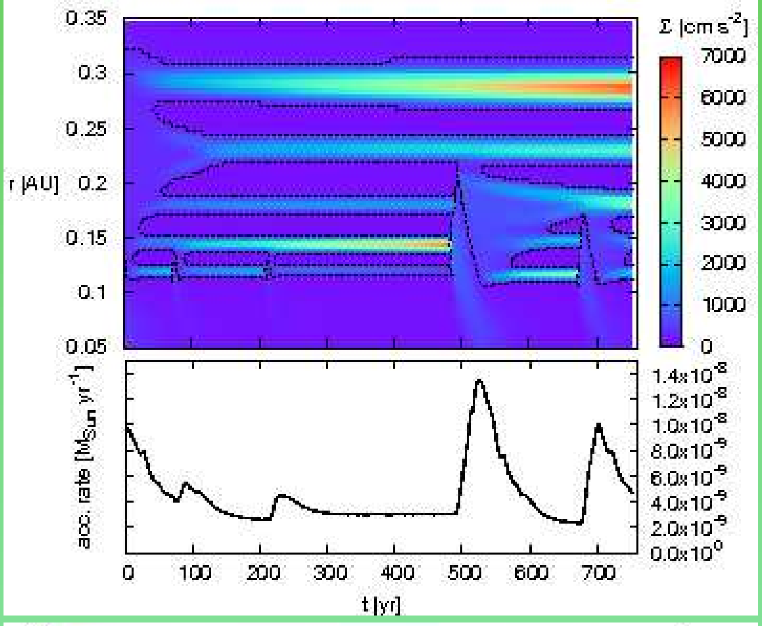
- indications for a small viscosity in the dead zone
- purely hydrodynamic turbulence excited by waves propagating from MRI-active surface layers `(Fleming & Stone, 2003)`
- viscosity in DZ $\sim 10\%$ viscosity in active parts

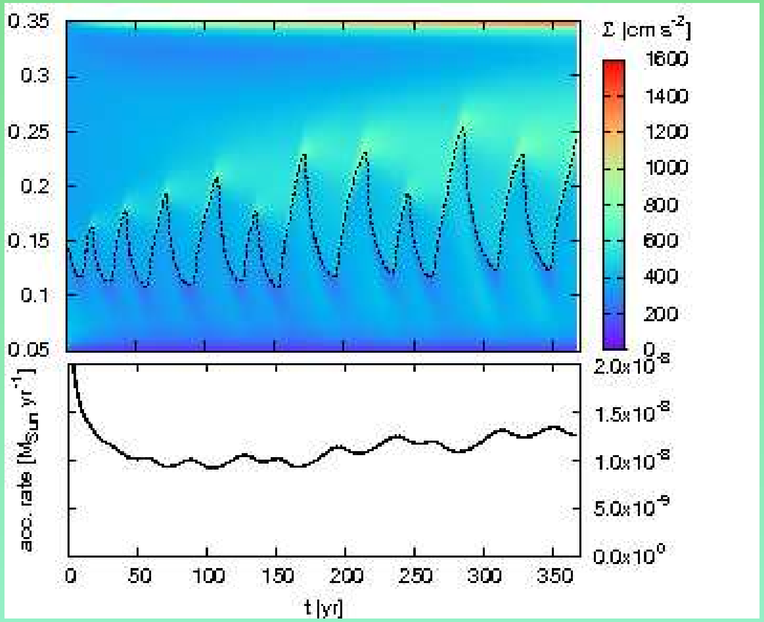


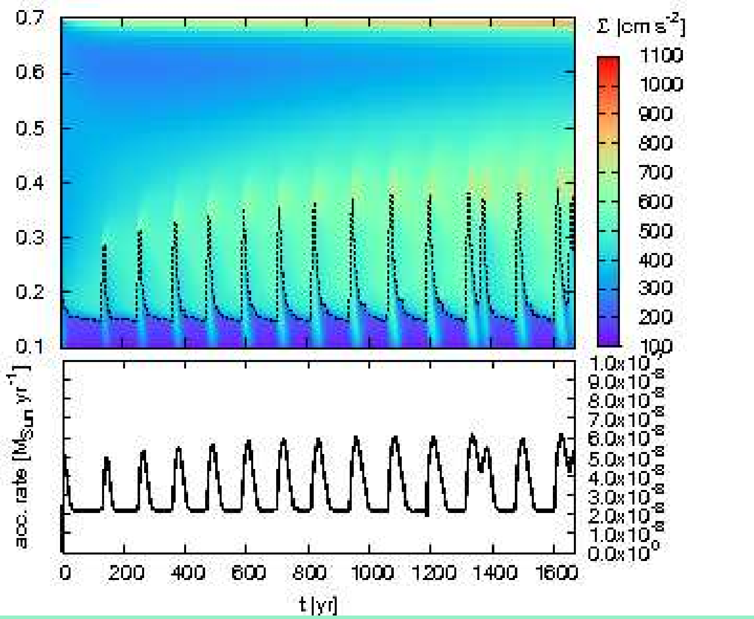
- ▷ *3D shearing-box non-ideal MHD simulation*
- ▷ *time evolution of Maxwell and Reynolds stress tensors along a vertical ray (with a given r and ϕ)*
- ▷ *Top: Maxwell stress tensor traces MHD turbulence*
- ▷ *Bottom: Reynolds stress tensor traces pure hydrodynamic turbulence*

Results - minioutbursts

- **Right:** $\alpha_a = 0.01$, $\alpha_{\rm DZ} = 0 \Rightarrow$ rings
- **Bottom left:** $\alpha_a = 10^{-2}$, $\alpha_{\rm DZ} = 10^{-3}$ $\Rightarrow$ mini-outbursts, smooth $\dot{M}_{\rm IB}$
- **Bottom right:** $\alpha_a = 0.02$, $\alpha_{\rm DZ} = 2 \cdot 10^{-3} \Rightarrow$ very short mini-outbursts, $\dot{M}_{\rm IB}$ varies 1 order of mag.







Layered disc with $\alpha_{\mathrm{DZ}} \neq 0$

- analytical description of layered disc with $\alpha_{\mathrm{DZ}} \neq 0$:

$$\dot{M} = 12\pi r^{1/2} \frac{\partial r}{\partial} (\nu_a \Sigma_a + \nu_{\mathrm{DZ}} \Sigma_{\mathrm{DZ}}), \qquad T_m^4 = \frac{3}{8} \kappa T_e^4 \frac{\alpha_a \Sigma_a^2 + \alpha_{\mathrm{DZ}} \Sigma_{\mathrm{DZ}} (\Sigma_{\mathrm{DZ}} + 2\Sigma_a)}{\alpha_a \Sigma_a + \alpha_{\mathrm{DZ}} \Sigma_{\mathrm{DZ}}}$$

$$T_e^4 = \frac{9}{4\sigma} \Omega^2 (\nu_a \Sigma_a + \nu_{\mathrm{DZ}} \Sigma_{\mathrm{DZ}})$$

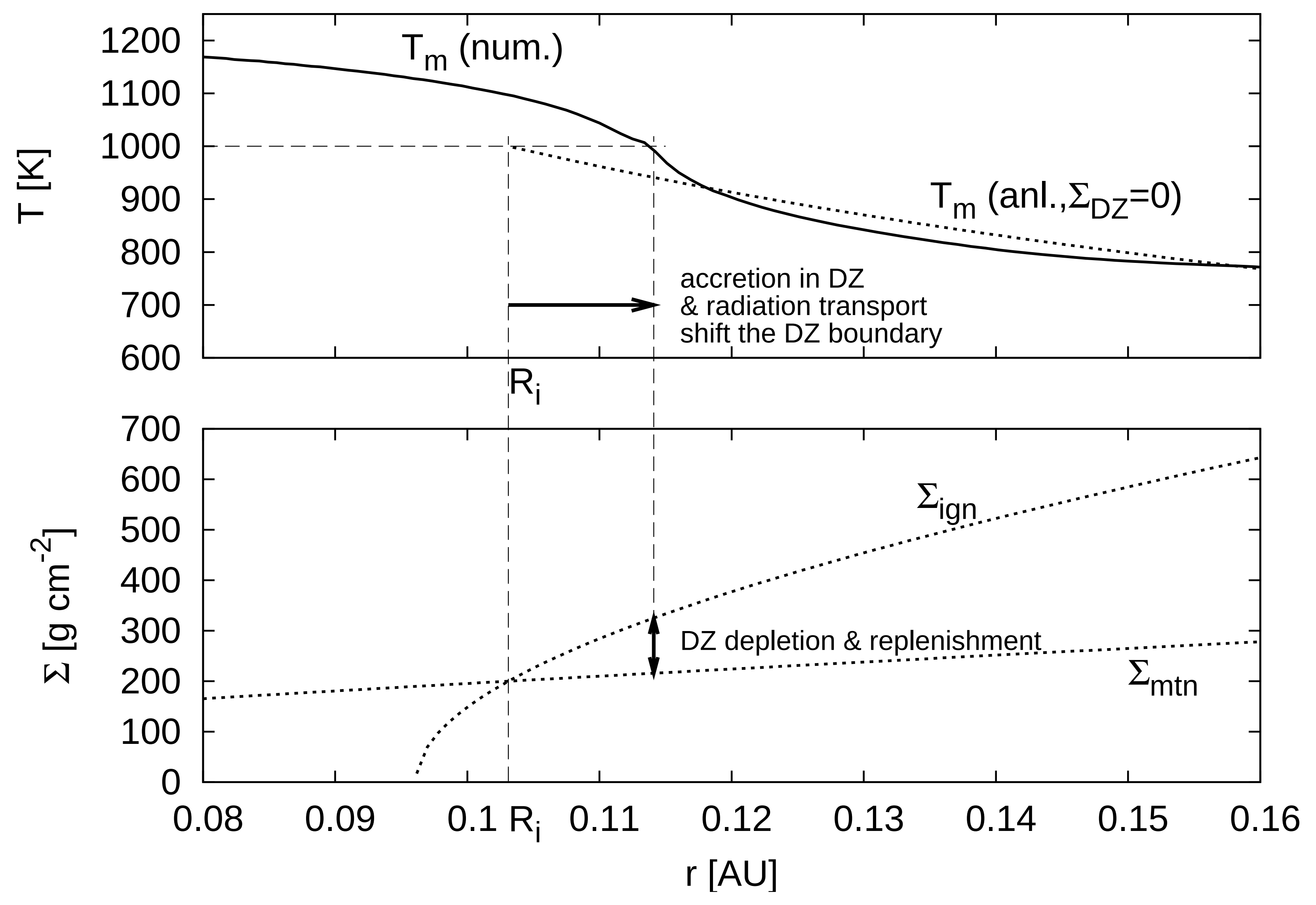
- mid-plane temperature T_m depends on the surface density $\Sigma = 2(\Sigma_a + \Sigma_{\mathrm{DZ}})$ (contrary to LD with $\alpha_{\mathrm{DZ}} = 0$)
- ignition surface density

$$\Sigma_{\mathrm{ign}} = 2 \left(\frac{320\sigma}{27} \frac{\mu m_{\mathrm{H}}}{k_{\mathrm{B}} \Omega \alpha_{\mathrm{DZ}}} T_{\mathrm{lim}}^{5/2} - \frac{\alpha_a - \alpha_{\mathrm{DZ}}}{\alpha_{\mathrm{DZ}}} \Sigma_a^2 \right)^{1/2}$$

- surface density necessary to maintain the disc active

$$\Sigma_{\mathrm{mtn}} = \left(\frac{1280 \sigma \mu m_{\mathrm{H}}}{27 k_{\mathrm{B}} \alpha_a \Omega} \right)^{1/2} T_{\mathrm{lim}}^{5/4}$$

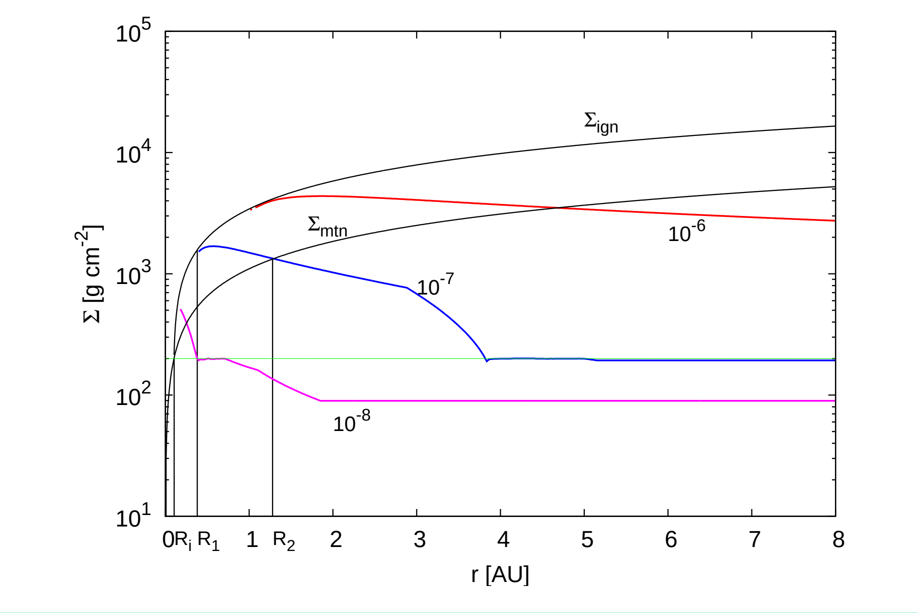
Mini-outbursts - mechanism



Stationary states

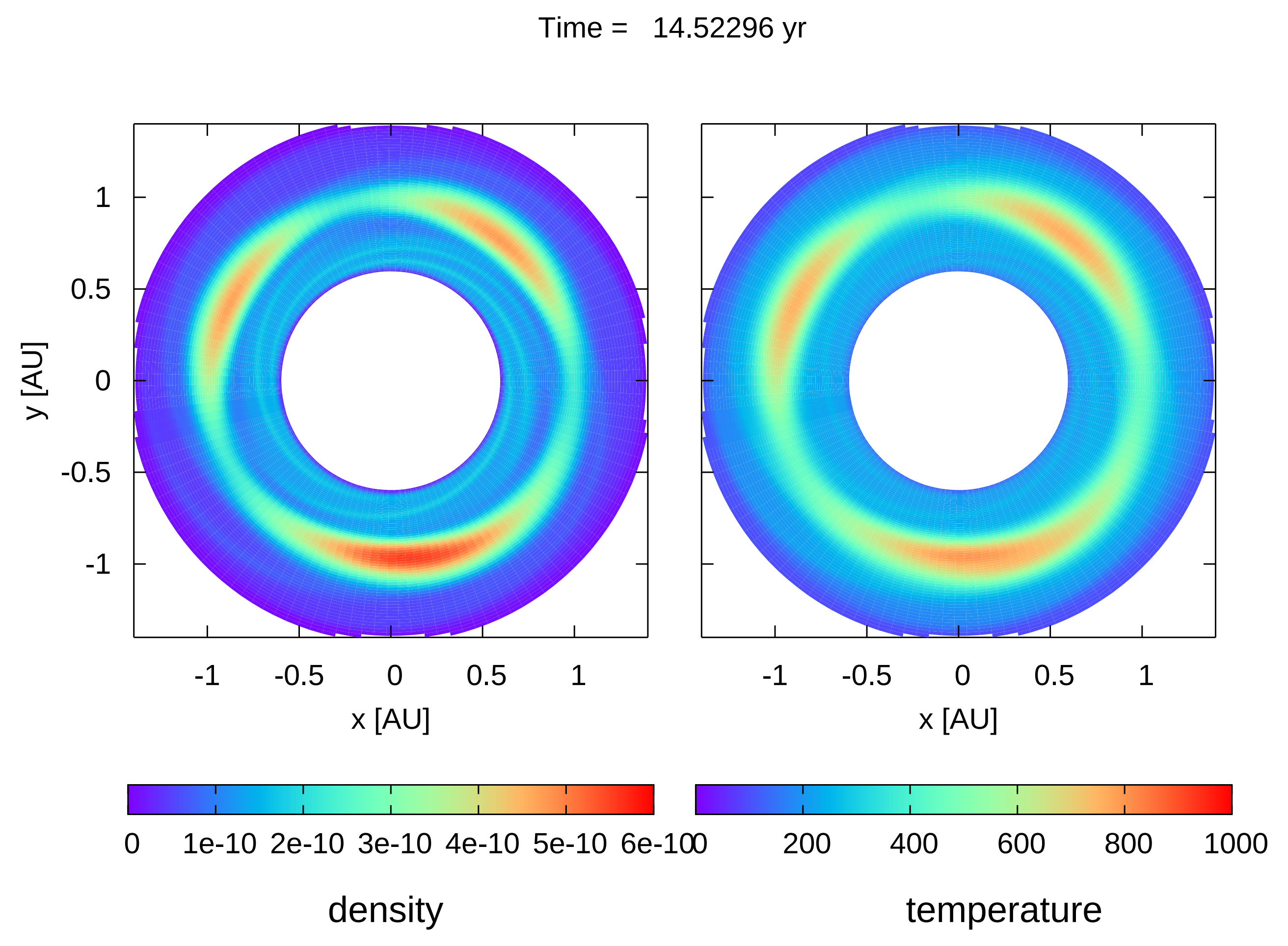
- we search for stationary surface density profiles using 1D code similar to `Stepinski (1999) or Armitage et al. (2001)`
- numerically solve equation $\dot{\Sigma} = \frac{1}{2\pi r}\frac{\partial \dot{M}}{\partial r}$
- determines T_m from Σ, decides if LD or αD, computes $\dot{M}$, advects mass between cells
  - ▷ *stationary solution exist above* R_1
  - ▷ *part of DZ between* R_1 *and* R_2 *can be ignited externally*
  - ▷ *it contains mass*

$2.0 \times 10^{-7}\mathrm{M}_\odot$ *for* $\dot{M} = 10^{-8}\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$
$2.7 \times 10^{-4}\mathrm{M}_\odot$ *for* $\dot{M} = 10^{-7}\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$
$0.01\mathrm{M}_\odot$ *for* $\dot{M} = 10^{-6}\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}$



Decay of the ring into vortices

- 3D simulation of the ring (64x51x128)
- Rossby wave instabity (shear, similar to Helmholtz-Kelvin)
  - ▷ *analytical description* (Papaloizou & Pringle, 1985; Lovelace et al., 1999), *2D simulations* (Hawley, 1987; Finn et al., 2000)
  - ▷ *does it work in 3D?*
  - ▷ *for which parameters? (viscosity, opacity law, resolution)*
  - ▷ *combined HD - N-body simulations suggest dust particle concentration* (Johansen, et al., 2007)



Planet formation in vortices - a new idea?

Descartes (1644): Concerning the creation of all of the Planets:

". . . the extremely large space which now contains the vortex of the first heaven was formerly divided into fourteen or more vortices. . . So that since those three vortices which had at their centers those bodies that we now call the Sun, Jupiter, and Saturn were larger than the others; the stars in the centers of the four smaller vortices surrounding Jupiter descended toward Jupiter. . .

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