Possibility of the Detection of Proto-Planets

Toward the observation of proto-planetary disks with growing proto-planets.

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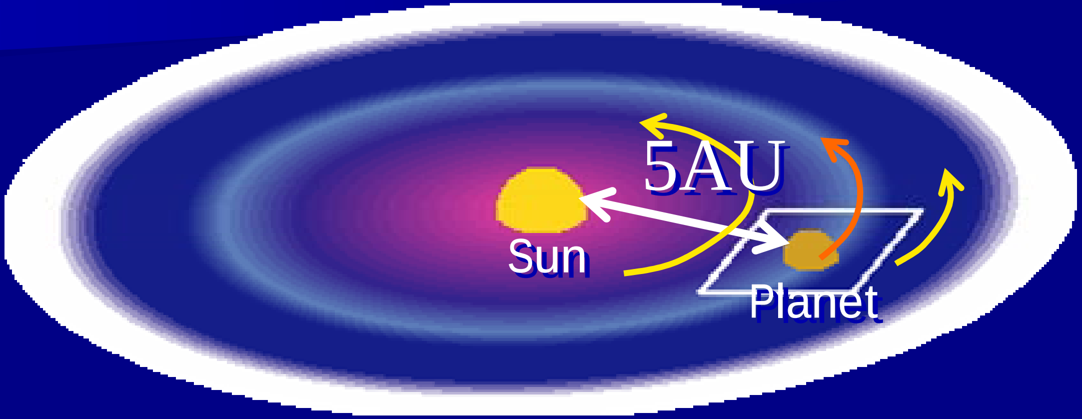
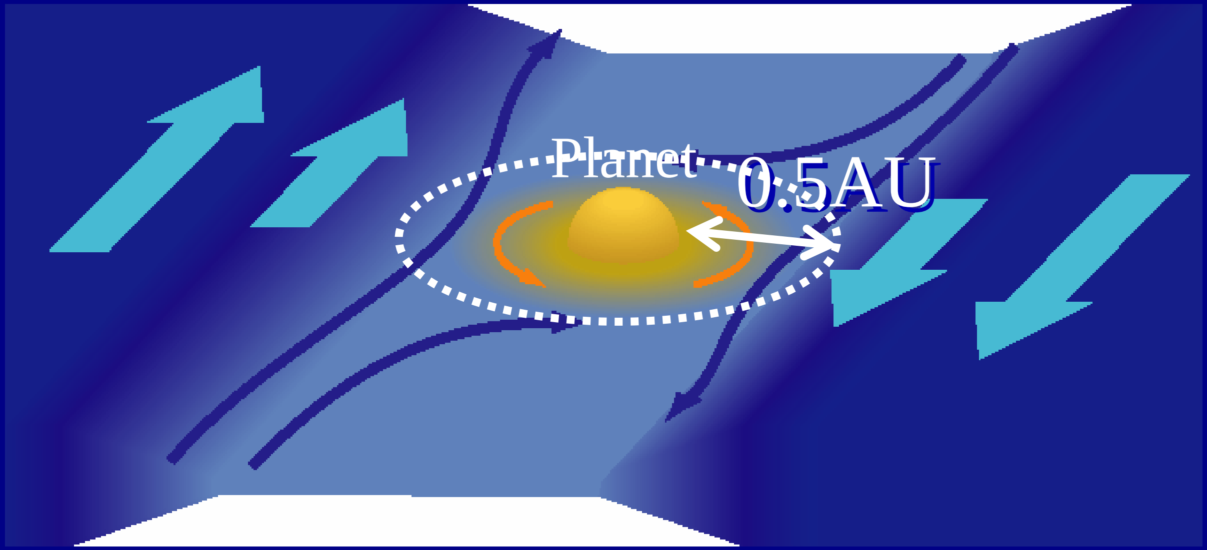
A growing proto-planet in a proto-planetary disk





The planets shine luminously!

- The gas accretion rate onto the proto-planets is high. (The growth timescale ~ $10^{4\text{-}5}$ yr)

  (e.g., Lubow & Seibert 1999, Tanigawa & Watanabe 2002)

  ⇒ The planet should shine very luminously!

  ⇨ We may be able to detect the growing proto-planets.

  ⇒ SED or Spatially resolved image

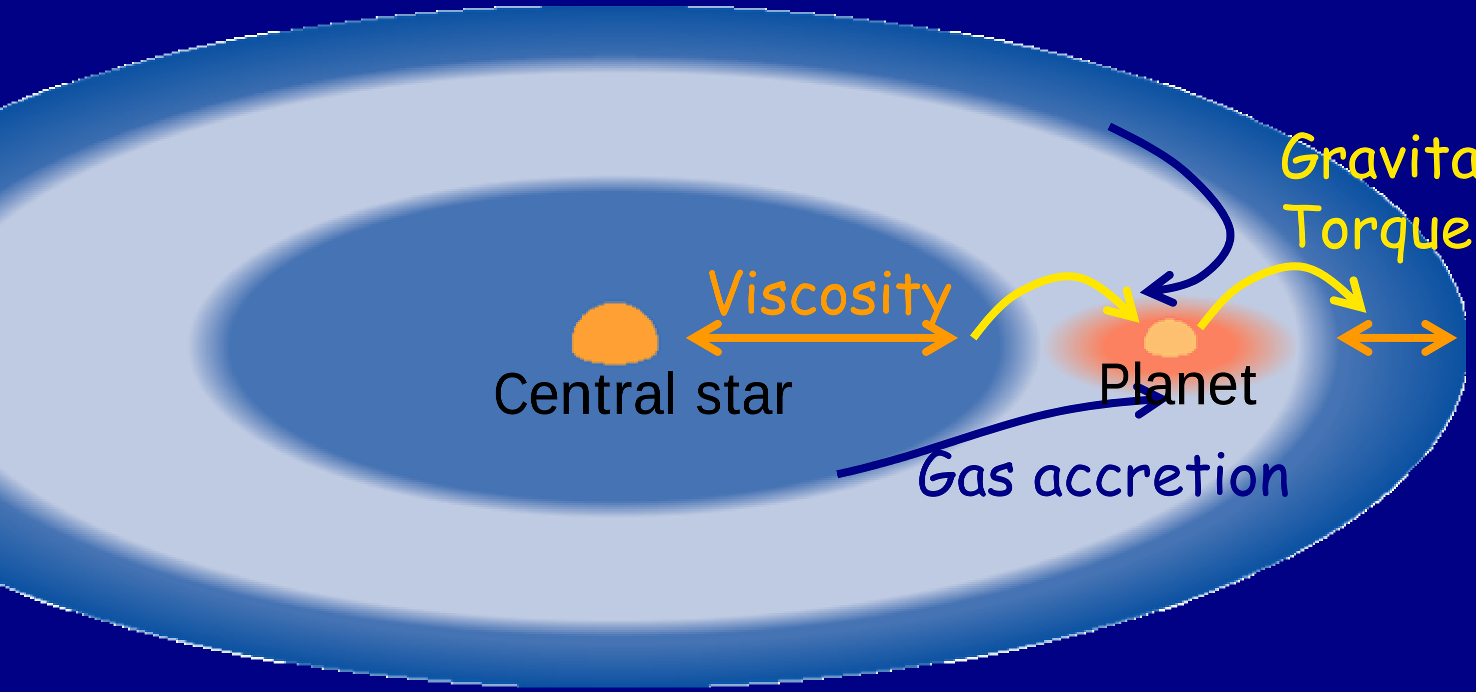
- However, the detection possibility is not studied well.
  - The maximum luminosity, the duration.
  - Dependence of some unknown parameters.
    - Disk mass, viscosity, and planet location.

The purpose of this study

- Investigate the detection possibility of the growing proto-planets in the proto-planetary disks.
  - Numerical simulations of the co-evolution of a proto-planetary disk and an embedded growing planet.
    - The accretion rate onto the proto-planet.
    - The maximum luminosity and the duration.
  - The SED of the proto-planetary disk with the growing planet.
  - The model image of the proto-planetary disk with the growing planet.

Calculation Model

The co-evolution of a proto-planetary disk and an embedded planet:



This situation is translated into 1-D problem to be simulated.
(1-D: r-direction, averaged in azimuthal direction)

Equations for a 1-D disk and a planet

Mass conservation

Disk $$\frac{\partial}{\partial t}\Sigma + \frac{1}{r}\frac{\partial}{\partial r}(r\Sigma v_r) = -\underline{w(r,t)}$$

Planet $$\frac{dM_{\rm p}}{dt} = \int_{r_{\rm min}}^{r_{\rm max}} 2\pi r\, \underline{w(r,t)}\, dr$$

Gas accretion

$$w(r,t) = \Sigma(r,t)\, S(M_{\rm p}, r)$$

(Tanigawa & Watanabe 2002)

Conservation of angular momentum

Disk $$\frac{\partial}{\partial t}(\Sigma j) + \frac{1}{r}\frac{\partial}{\partial r}(j r \Sigma v_r) = \underset{\text{Viscosity}}{\underline{\frac{1}{r}\frac{\partial}{\partial r}\left(\nu_t \Sigma r^3 \frac{d\Omega}{dr}\right)}} + \Sigma\underline{\dot{h}(r, M_{\rm p})}$$

Planet $$\xcancel{\frac{dJ_{\rm p}}{dt} = \int_{r_{\rm min}}^{r_{\rm max}} 2\pi r \Sigma\, \underline{\dot{h}(r, M_{\rm p})}\, dr}$$

Angular momentum exchange

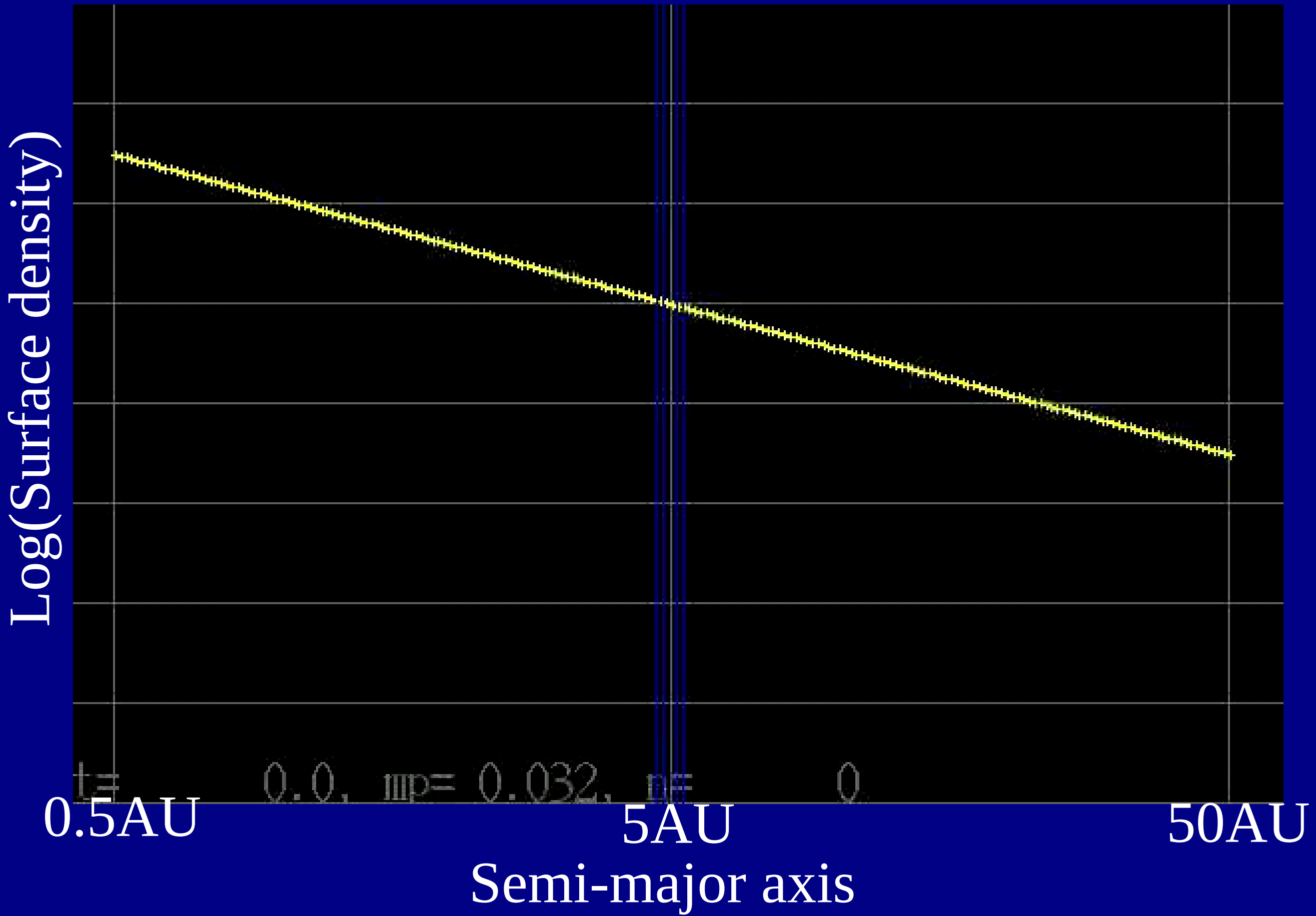
$\nu_t = \alpha c h$ α viscous disk (Shakura and Sunyaev 1973)

$$\dot{h} = \frac{4}{9\pi}\left(\frac{\Delta r}{a}\right)^{-4}\left(\frac{M_{\rm p}}{M_*}\right)^2 r^2 \Omega^2 \frac{\Delta r}{|\Delta r|}$$

Impulse approximation
(Lin and Papaloizou 1979)

Result (the case with typical parameters)

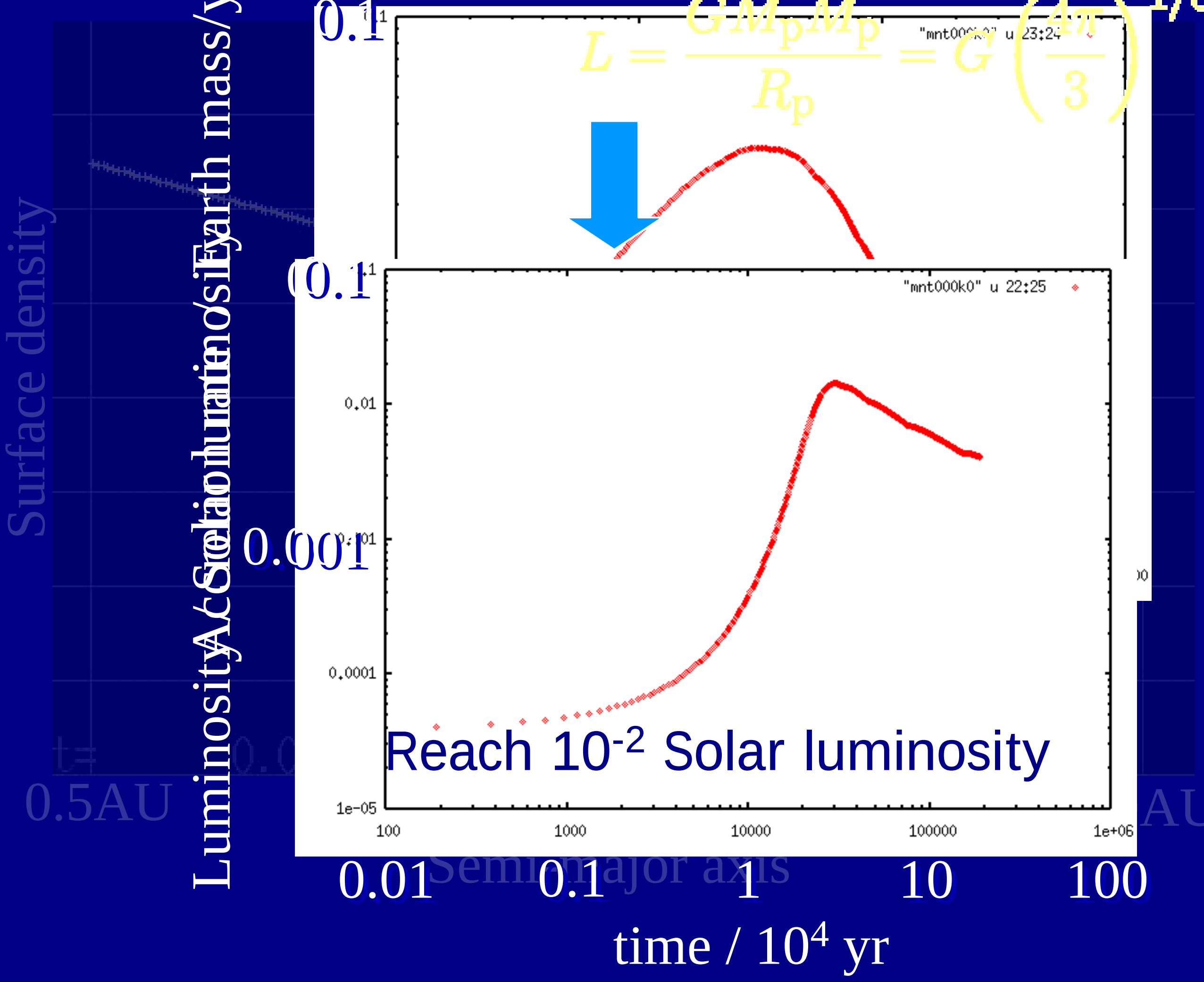
$a=5.2\text{AU}$, $\alpha=0.002$, $\Sigma=\Sigma_H$



Result (the case with typical parameters)

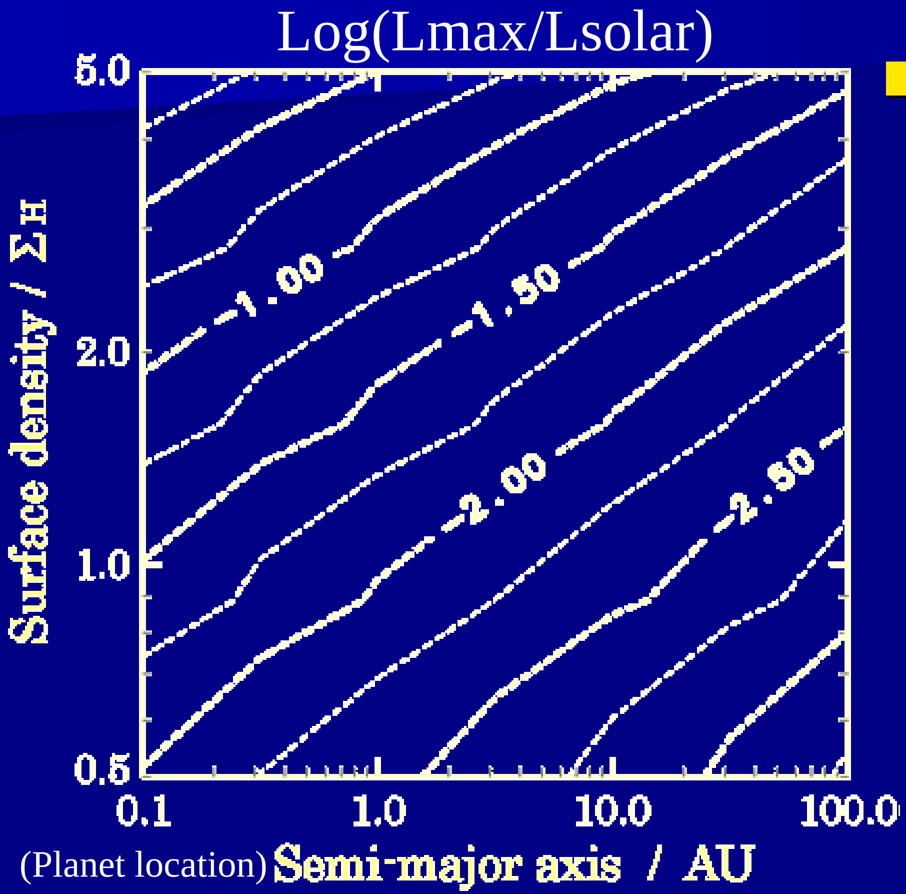
Gas accretion energy

$$L = \frac{G M_\mathrm{p} \dot{M}_\mathrm{p}}{R_\mathrm{p}} = G\left(\frac{4\pi}{3}\right)^{1/3} \rho_\mathrm{p}^{1/3} M_\mathrm{p}^{2/3} \dot{M}_\mathrm{p}$$



Reach 10^{-2} Solar luminosity

Result（parameter search）



- Dependence of
  - Planet location: Weak
    - When the planet is far from the central star,
      - The maximum mass is large.
      - The accretion rate is small.
  - Surface density : Strong
    - When the surface density is high,
      - The maximum mass is large.
      - The accretion rate is large.

Fitting by
Power function:

$$L_{\rm max} \sim 6\times10^{-3} L_\odot \left(\frac{a}{5{\rm AU}}\right)^{-0.4}\left(\frac{\Sigma_0}{\Sigma^{\rm H}}\right)^{2.0}\left(\frac{\alpha}{0.001}\right)^{1.0}$$

$$\dot{M}_{\rm max} \sim 1.5\times10^{-2} M_\oplus \left(\frac{a}{5{\rm AU}}\right)^{-0.8}\left(\frac{\Sigma_0}{\Sigma^{\rm H}}\right)^{1.6}\left(\frac{\alpha}{0.001}\right)^{0.7}{\rm yr}^{-1}$$

Calculation of the SED

- The sum of following four components:
  - Central star : Sun (black body radiation for 5780K)
  - Proto-planetary disk : Passive disk

$$\sigma T^4 = \frac{L_*}{8\pi r^2}\left[\frac{4}{3\pi}\left(\frac{R_*}{r}\right) + f\frac{h_a}{r}\left(\frac{d\ln h_a}{d\ln r} - 1\right)\right]$$

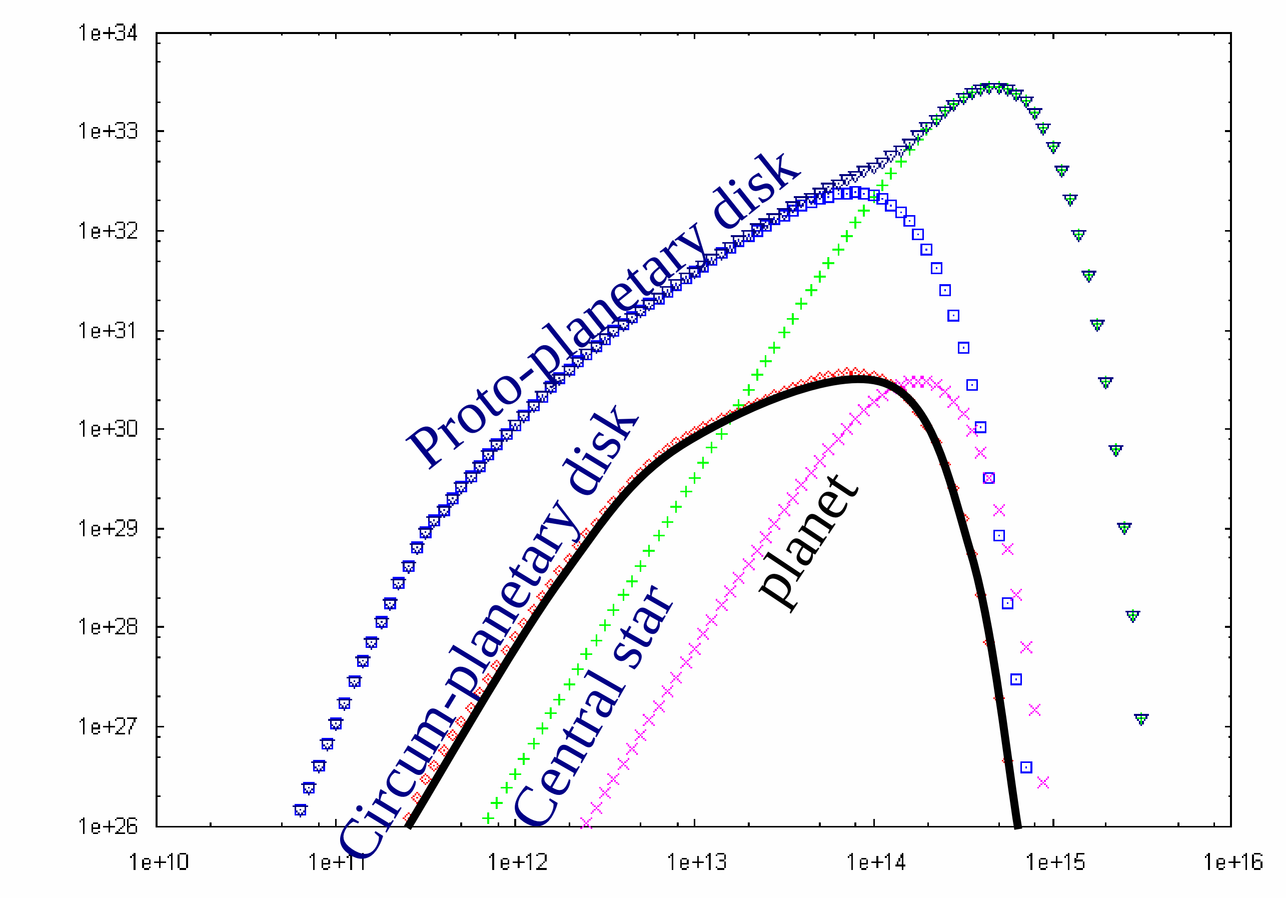
(f: dust sedimentation factor)

  - Planet : Gas accretion energy
    - The kinetic energy at the planet surface is assumed to be converted to thermal energy.
  - Circum-planetary disk : Active disk (steady accretion)

$$\sigma T^4 = \frac{L_p}{8\pi r^2}\left[\frac{4}{3\pi}\left(\frac{R_p}{r}\right) + f\frac{h_a}{r}\left(\frac{d\ln h_a}{d\ln r} - 1\right)\right] + \frac{G M_p \dot{M}_p}{8\pi r^3}$$

    - The disk size is assumed to be the Hill radius.
- Dust size is assumed to be single size (0.1mm)

SED



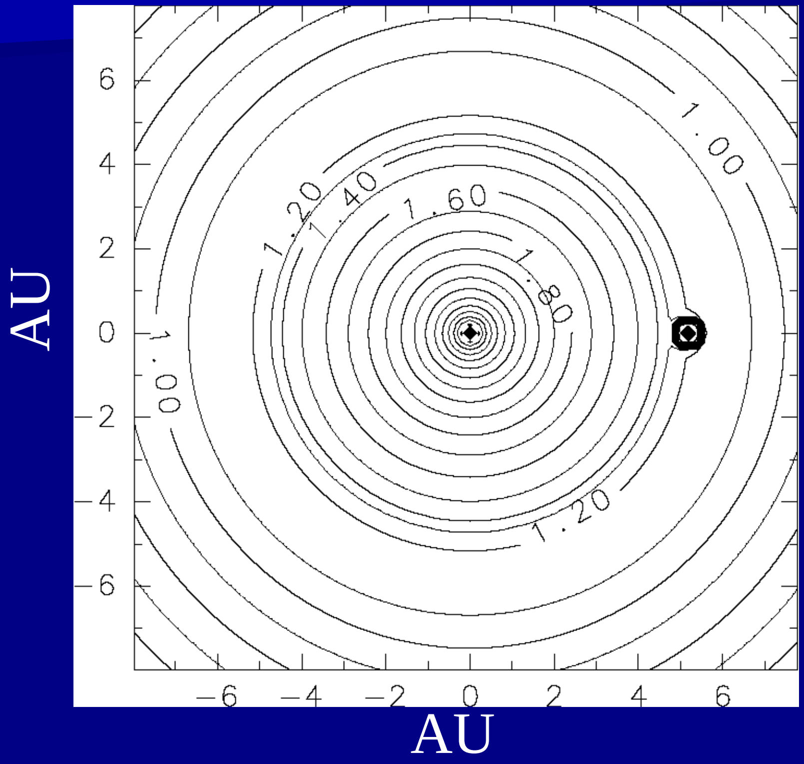
Luminosity * Frequency

10^10 10^12 10^14 10^16

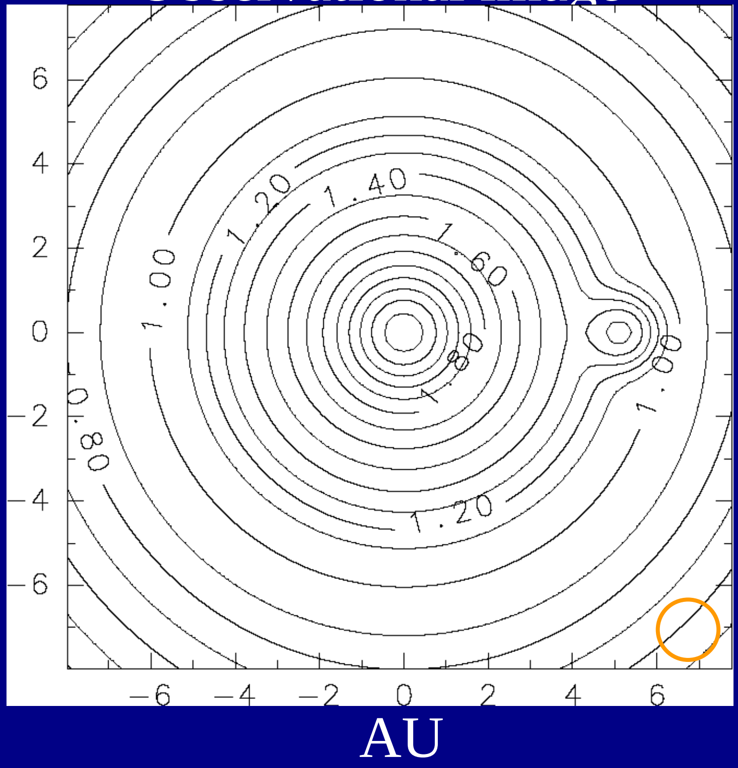
Frequency (Hz)

Spatially resolved image

Model image

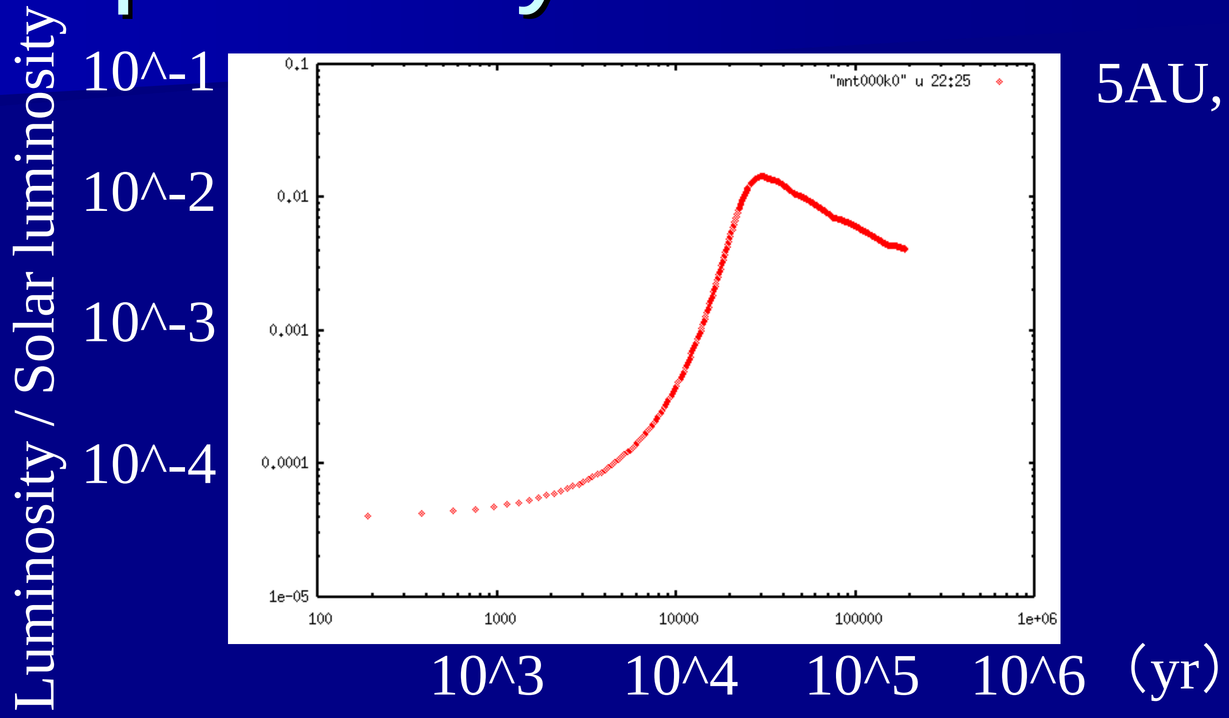


Observational image



(@Taurus(140pc), 850GHz, 0.01”)

Duration of the shining and possibility of the detection



5AU, α =0.002

$$\frac{\text{The duration of shining luminously } 10\text{^}5 \text{ yr}}{\text{The lifetime of proto-planetary disks } 10\text{^}7 \text{ yr}} \sim 1\%?$$

How to narrow down the target objects will be important.

Summary

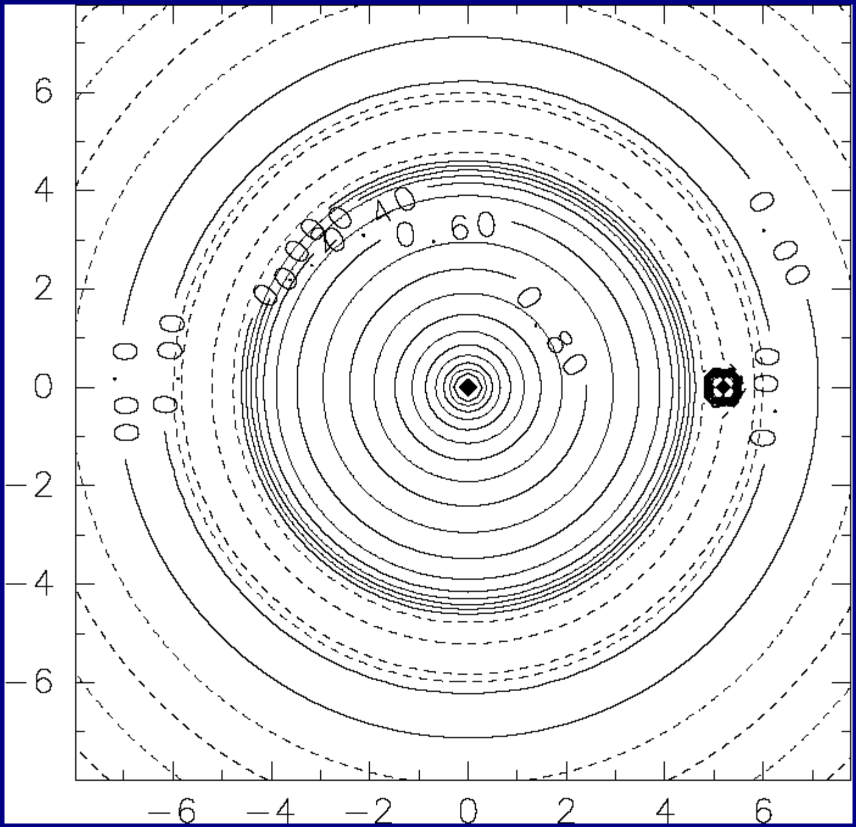
- The co-evolution of a 1-D viscous disk and the embedded planet was simulated.
  - Maximum luminosity reaches 10^{-2} Solar luminosity.
- SED of the proto-planetary disk with a growing proto-planet was calculated.
  - The planet and the circum-planetary disk are hard to be seen in SED.
- If we can resolved spatially (~1AU), we can detect that.
  - We can observe the time variation of the image.
  - The possibility ~1%. How to narrow down the candidate will be important.

Dust and the Opacity

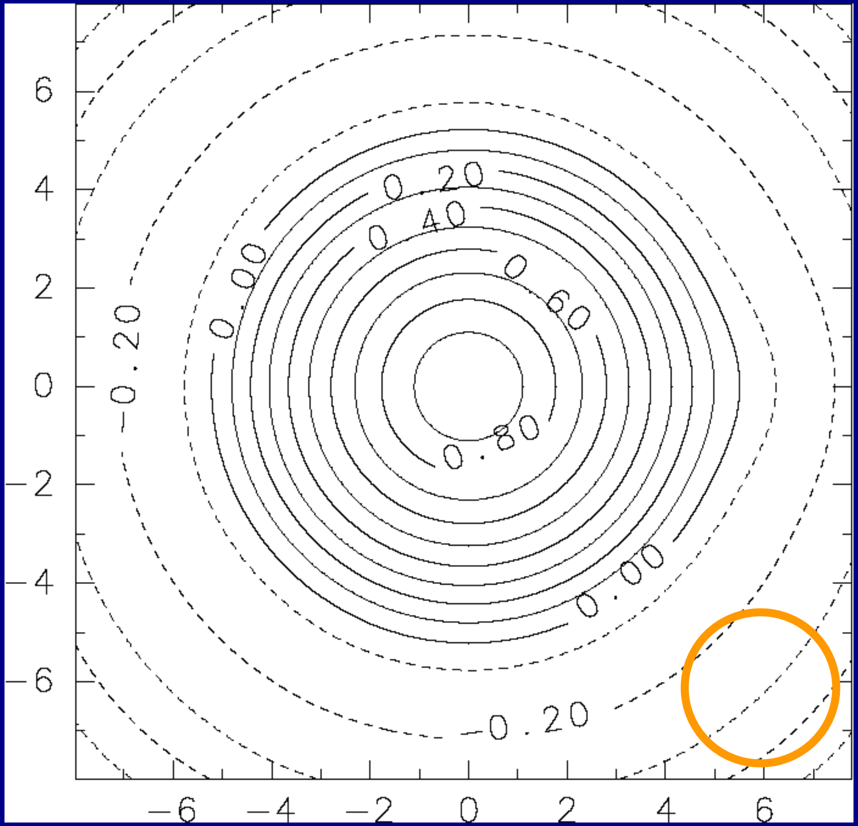
- Dust size is assumed to be single size for simplicity.
- Dust opacity
  - $\kappa = a\,(\nu_p / 10^{13}\mathrm{Hz})^2$
    - If $\nu > \nu_*$, $\nu_p = \nu_*$
    - Otherwise, $\nu_p = \nu$
    - Where $\nu_* = 10^{13}\mathrm{Hz}\,(r / 30\mu\mathrm{m})^{-1}$
    - $T<170$: $a=400$, $170<T<1600$: $a=300$

350 GHz image

Model image



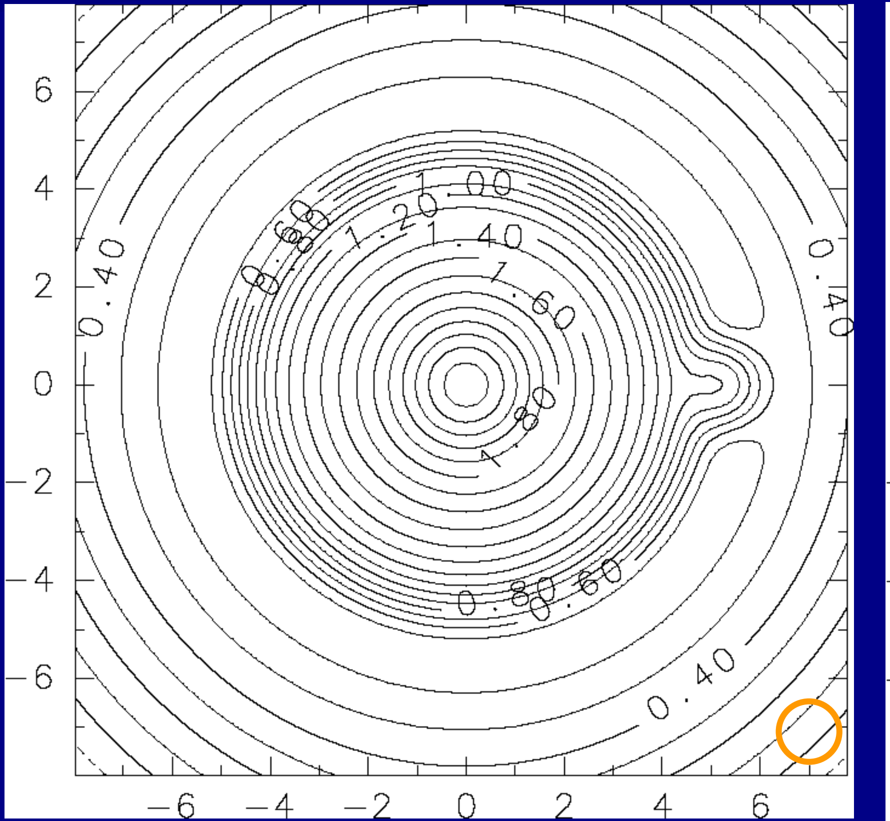
Observational image



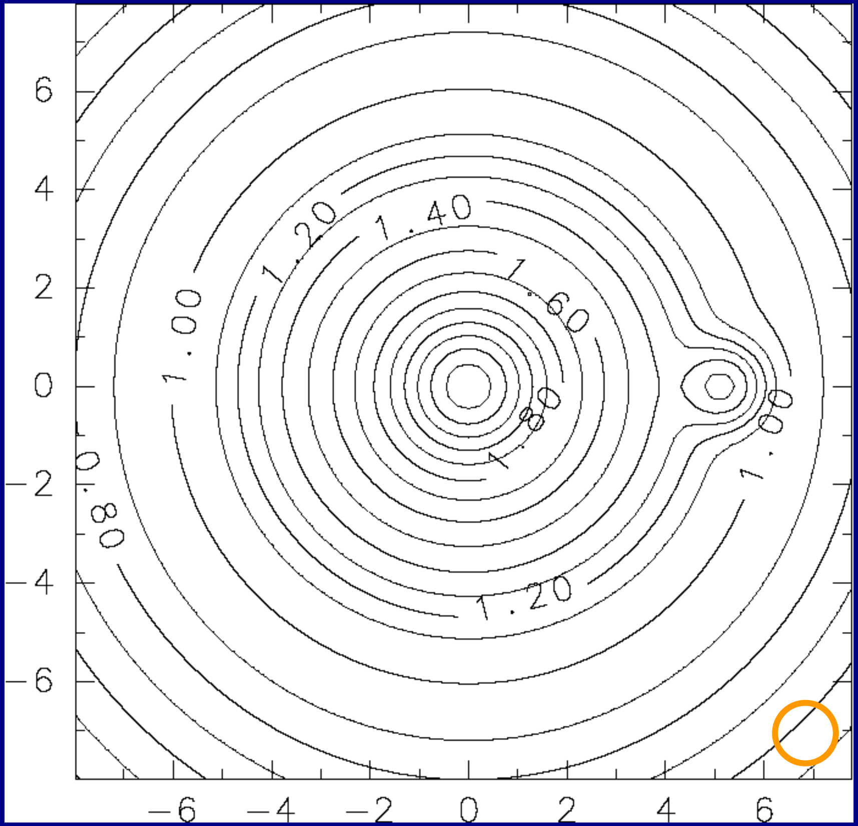
(@Taurus(140pc), 350GHz, 0.024”)

Dust size dependence

r_{dust} = 1mm



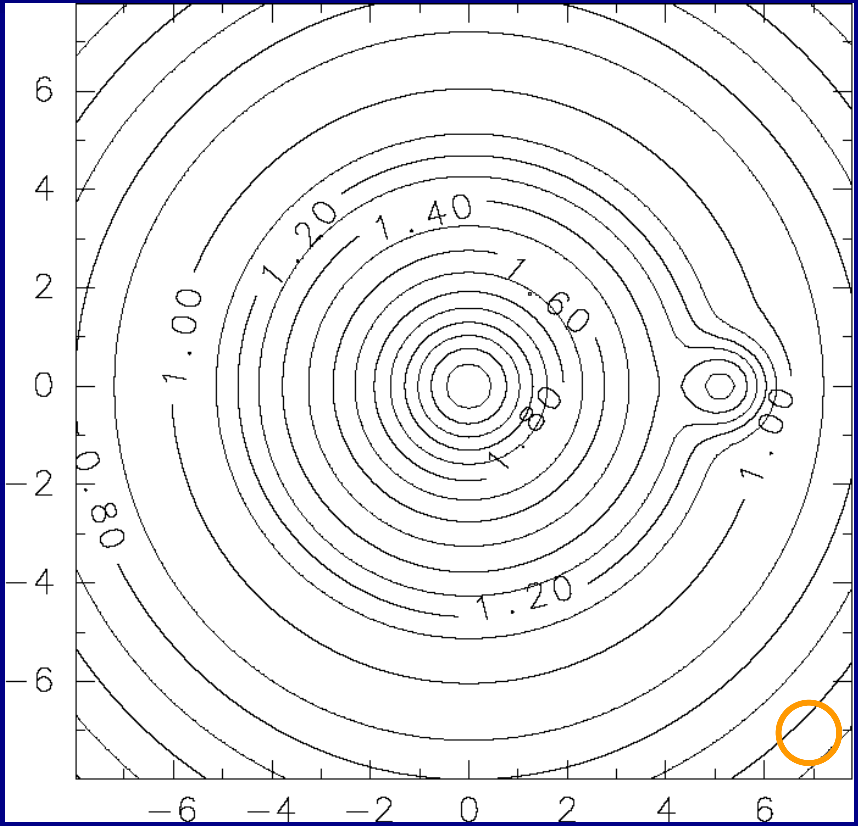
r_{dust} = 0.1mm



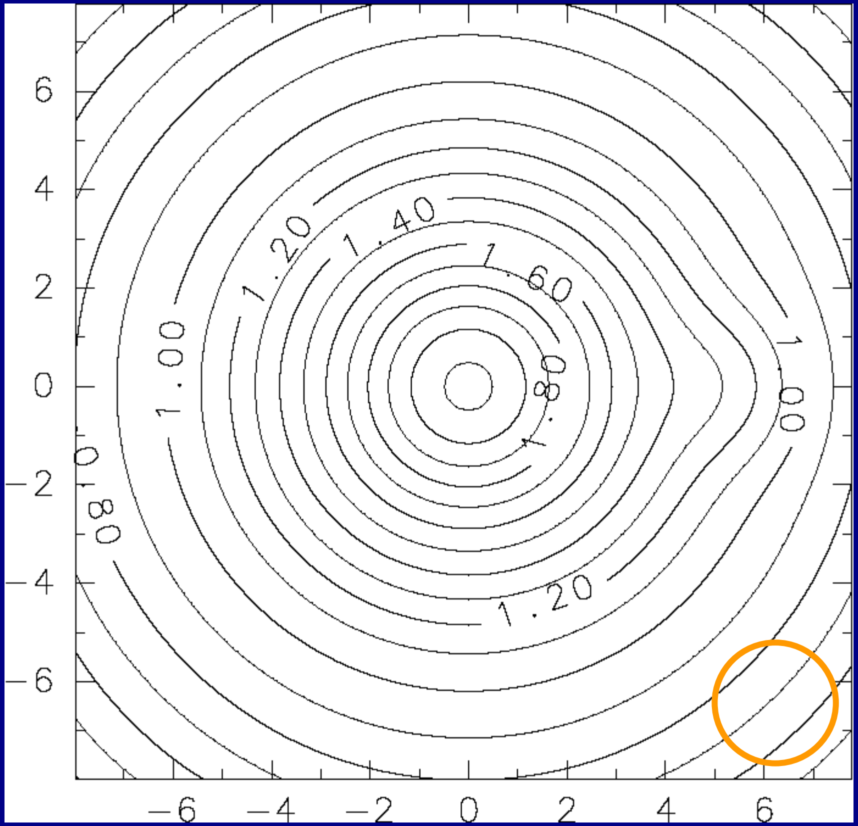
(@Taurus(140pc), 850GHz, 0.01”)

Resolution dependence

0.01”



0.02”

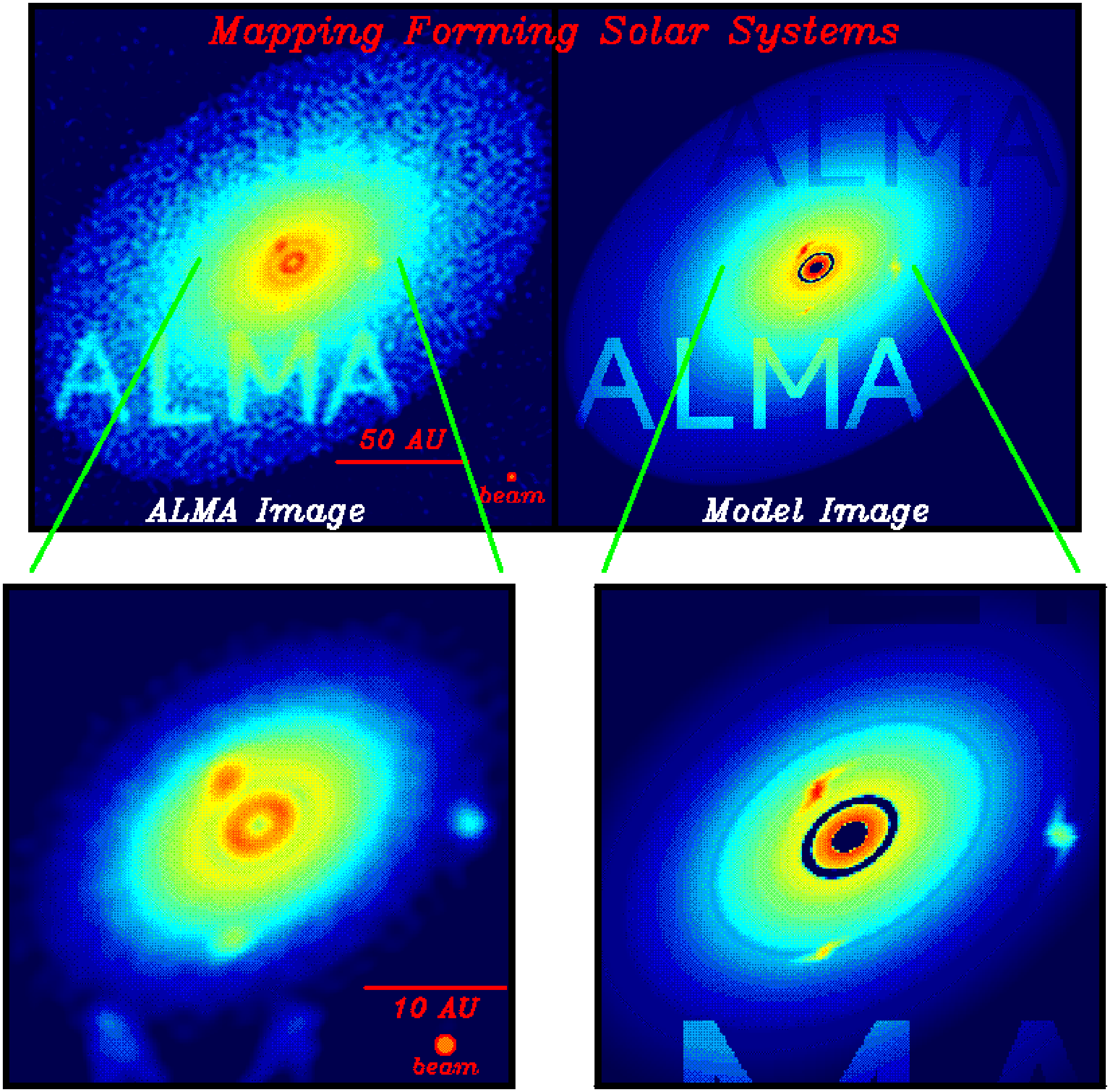


850GHz

Table 1: ALMA (1 Sigma) Point Source Sensitivity for 64 x 12m Antennas in 60s

Frequency (GHz)	**Continuum (mJy)**	**(1 km s^{-1}); mJy**	**(25 km s^{-1}); mJy**
35	.015	3.9	0.77
90	.031	5.1	1.0
140	.035	4.5	0.90
230	.060	6.1	1.2
345	.14	11.	2.2
409	.25	19.	3.8
650	1.9	120.	23.
850	3.5	183.	37.

(ALMA web site http://www.alma.nrao.edu/)



(ALMA web site http://www.alma.nrao.edu/)

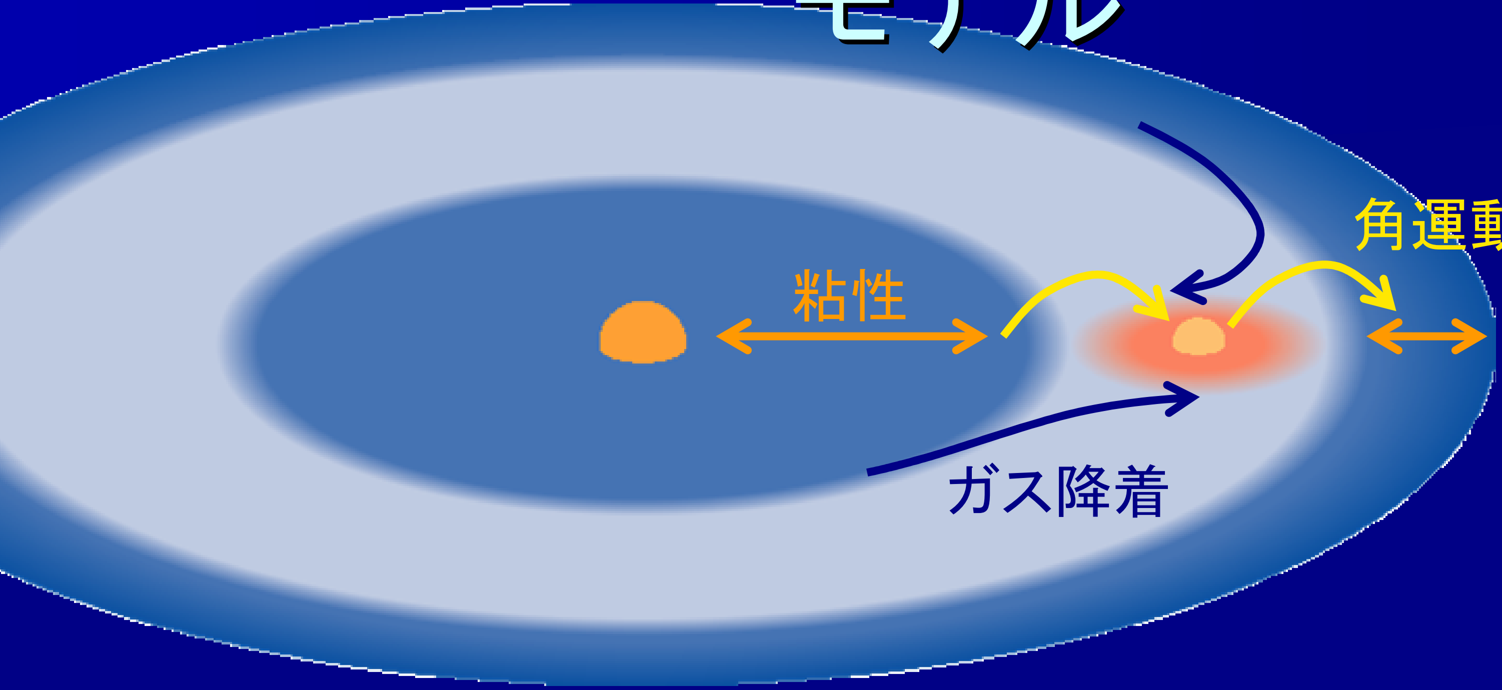
Eddington limit

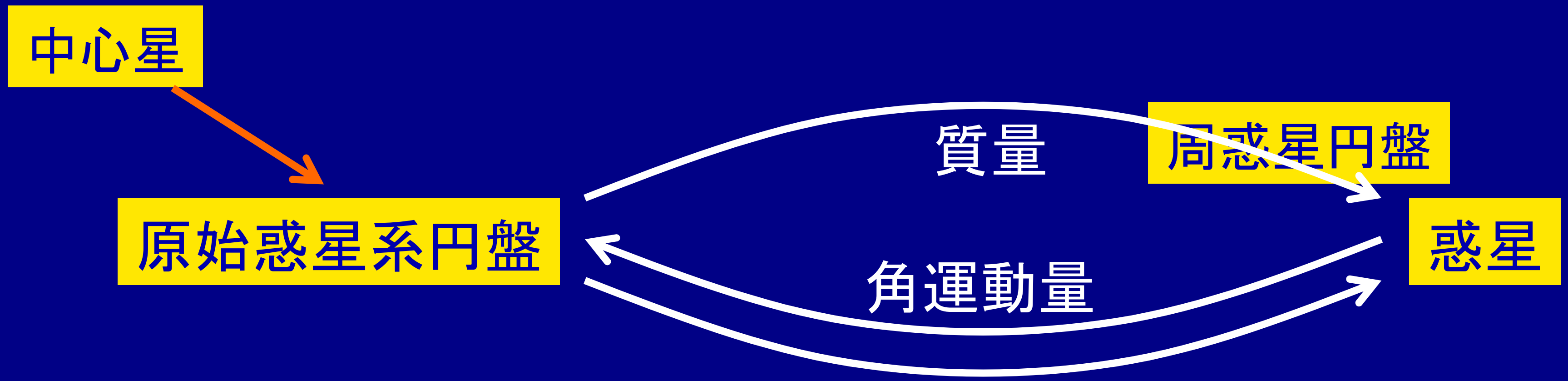
- Gives the maximum luminosity for the spherical symmetric gas accretion.
  - This maximum luminosity is realized under the balance of the force on the accreting gas between the gravitational force of the central object and the radiation pressure from the accretion energy.

惑星配置の謎

- 発見された系外の巨大ガス惑星の軌道分布は多様
  - その原因は不明
  - 形成段階を直接観測できれば大きな手がかりに
- ALMAなどの高空間分解能観測により、近い将来数AUを分解可能
  - 惑星形成が起こるスケール(~1AU) を分解可能
  - 事前に観測可能性について議論する必要あり

モデル




中心星

質量

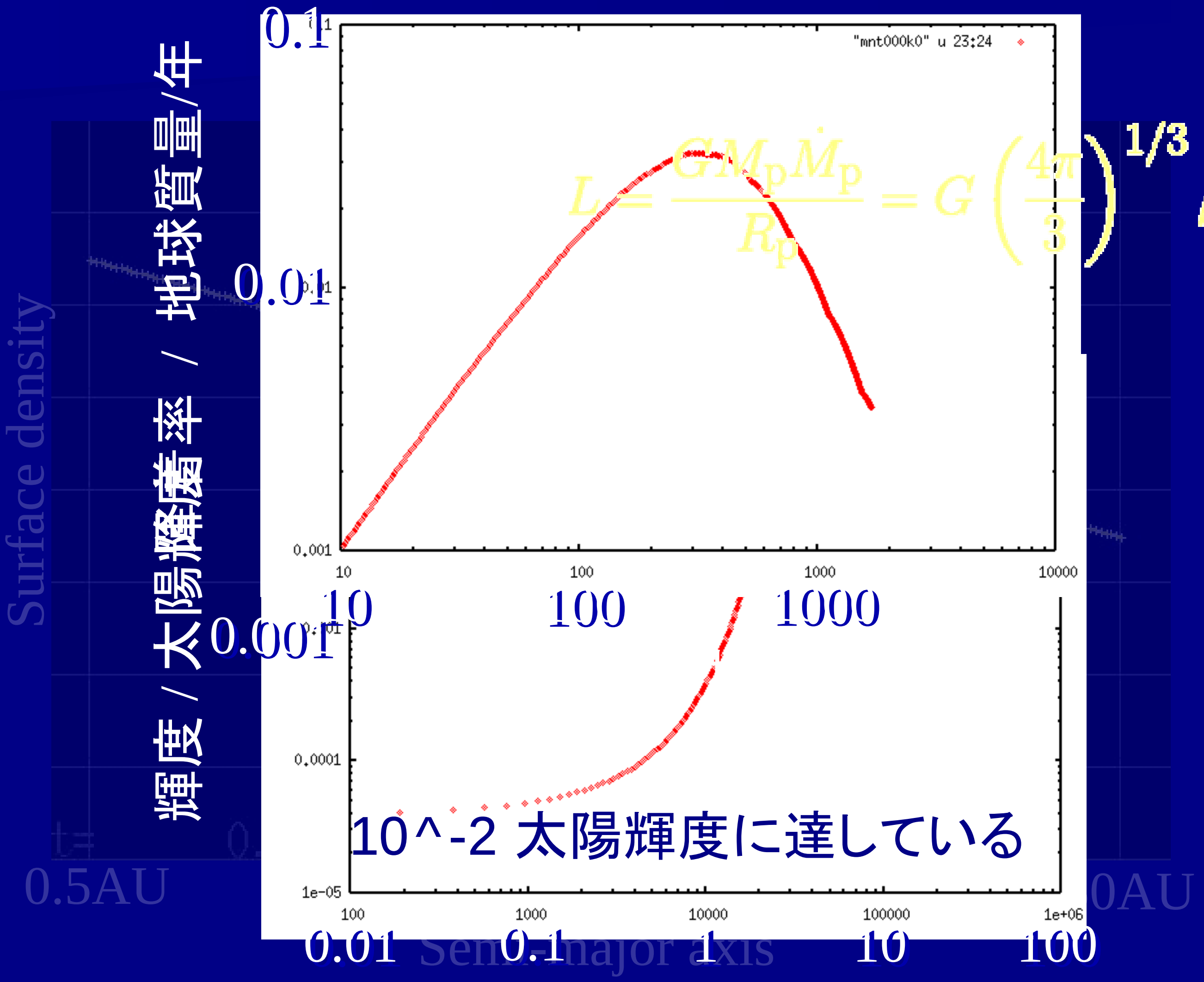
周惑星円盤

原始惑星系円盤

惑星

角運動量

結果(典型例)



$$L = \frac{G M_{\rm p} \dot{M}_{\rm p}}{R_{\rm p}} = G\left(\frac{4\pi}{3}\right)^{1/3} \rho_{\rm p}^{1/3} M_{\rm p}^{2/3} \dot{M}_{\rm p}$$

10^-2 太陽輝度に達している

Can we detect Planets?

- The gas accretion rate onto a proto-planet is high. (The growth timescale ~ 10^5 yr)

  (e.g., Lubow & Seibert 1999, Tanigawa & Watanabe 2002)

  ⇒ The planet should shine very luminously!

  We may be able to detect the growing proto-planets.

  ⇒ SED or Spatially resolved image

  - Growing phase of the gaseous planet is important for the final configuration of the planets in the system

- Many high-resolution observation will up and run in the near future.
  - The scale where the planet formation is occurred (~1AU) can be resolved.
  - The possibility of the detection should be discussed in advance.