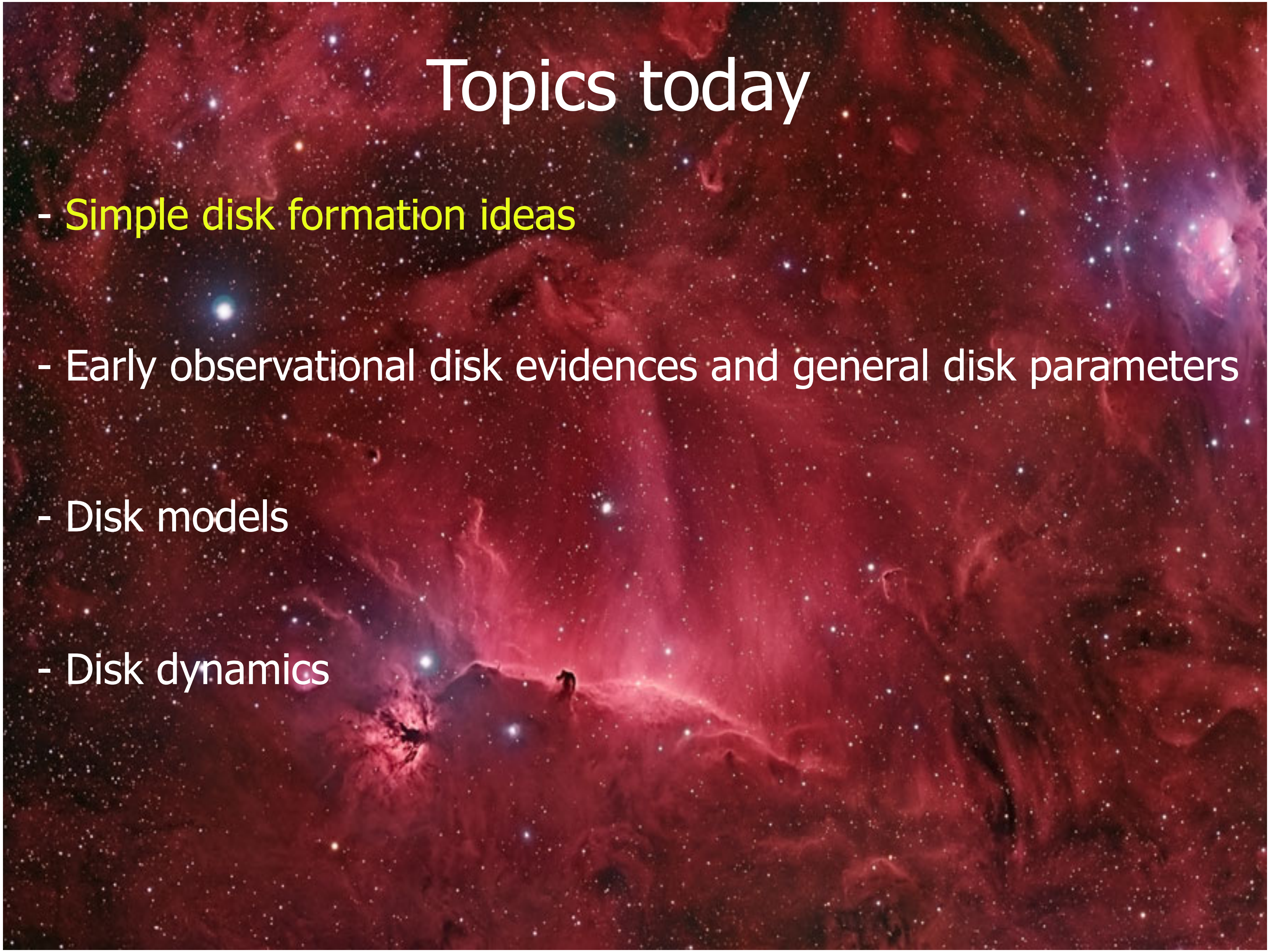
Outflows and Jets: Theory and Observations

Summer term 2011
Henrik Beuther & Christian Fendt

15.04 Today: Introduction & Overview (H.B. & C.F.)
29.04 Definitions, parameters, basic observations (H.B.)
06.05 Basic theoretical concepts & models (C.F.)
13.05 Basic MHD and plasma physics; applications (C.F.)
20.05 Radiation processes (H.B.)
27.05 Observational properties of accretion disks (H.B.)
03.06 Accretion disk theory and jet launching (C.F.)
10.06 Outflow interactions: Entrainment, instabilities, shocks (C.F.)
17.06 Outflow-disk connection, outflow entrainment (H.B.)
24.06 Outflow-ISM interaction, outflow chemistry (H.B.)
01.07 Outflows from massive star-forming regions (H.B.)
08.07 Observations of extragalactic jets (C.F.)
15.07 Theory of relativistic jets (C.F.)

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ss11.html
beuther@mpia.de, fendt@mpia.de



Topics today

- Simple disk formation ideas

- Early observational disk evidences and general disk parameters

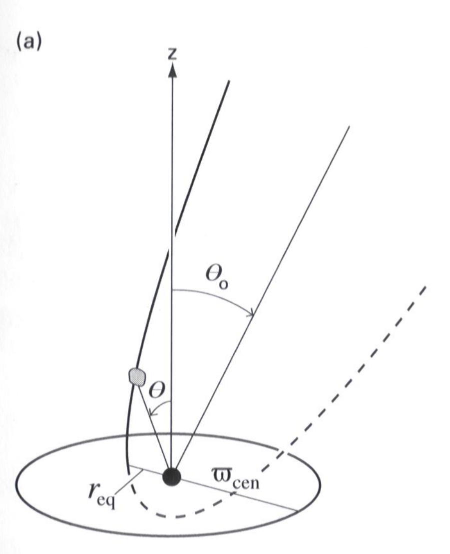
- Disk models

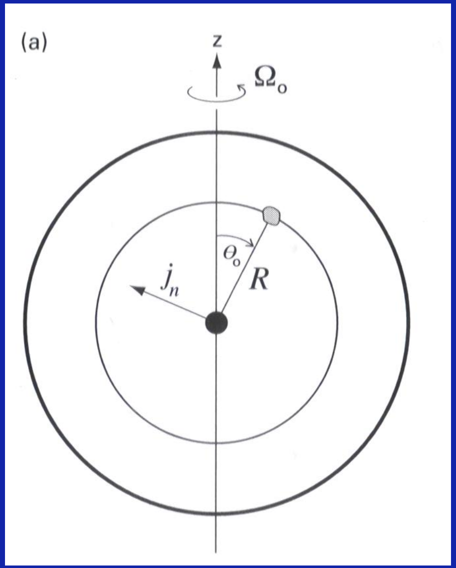
- Disk dynamics

Rotational effects

Matter within central region can conserve angular momentum during collapse.

Since $F_{cen} = mv^2/r = 2Gmm_*/r^2$ (with $E_{kin} = E_{pot}$ → $v^2 = 2Gm_*/r$) grows faster than $F_{grav} = Gm_*m/r^2$ each fluid element veers away from geometrical center.
→ Formation of disk





The larger the initial angular momentum j of a fluid element, the further away from the center it ends up → centrifugal radius ω_{cen}

$$\omega_{cen} \sim a_t \, \Omega_0^2 \, t^3/16 = 0.3\,\mathrm{AU}\,(T/10\mathrm{K})^{1/2}\ (\Omega_0/10^{-14}\mathrm{s}^{-1})^2\ (t/10^5\mathrm{yr})^3$$

ω_{cen} can be identified with disk radius. Increasing with time because in inside-out collapse rarefaction wave moves out → increase of initial j.

Topics today

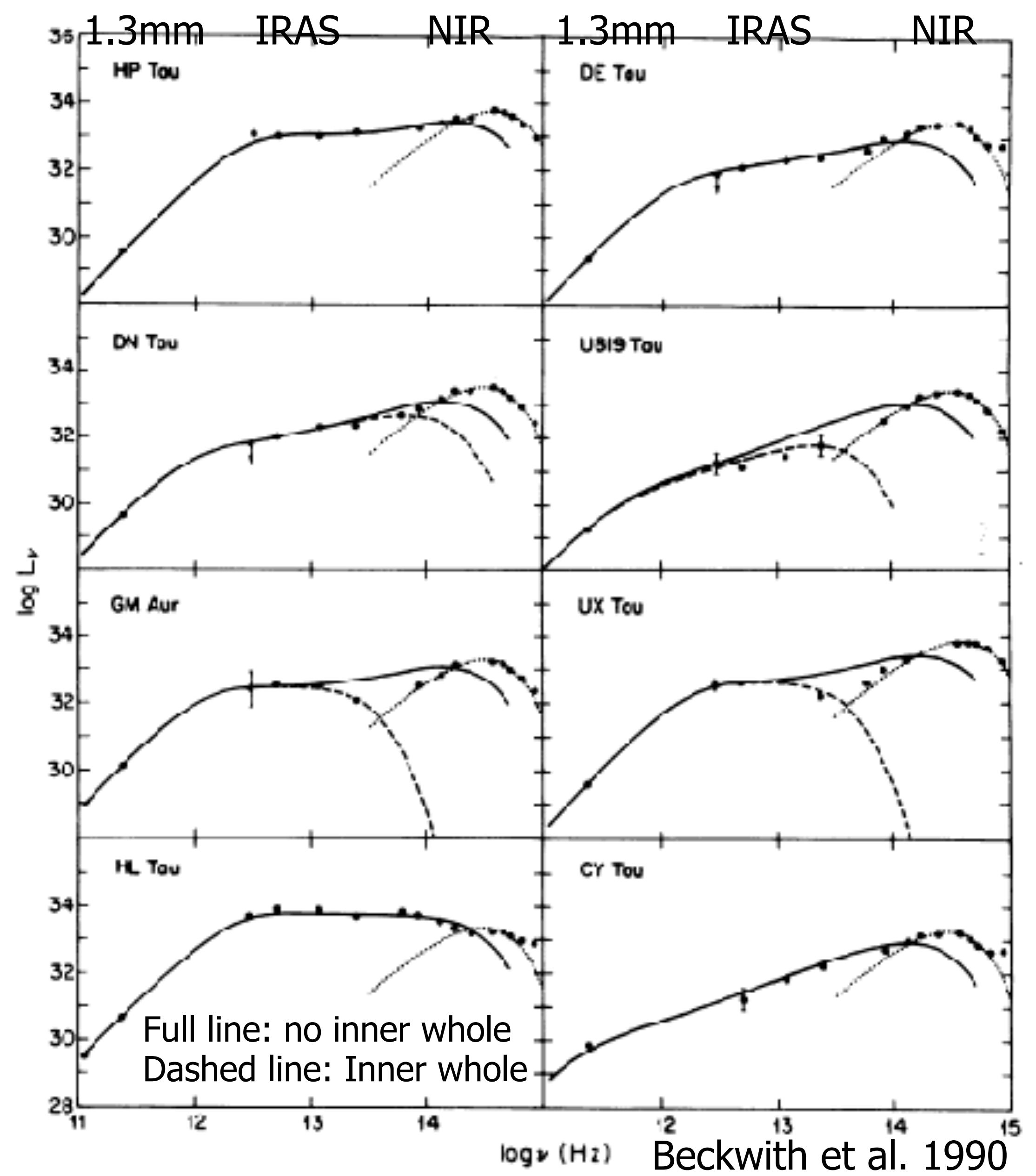
- Simple disk formation ideas

- Early observational disk evidences and general disk parameters

- Disk models

- Disk dynamics

Early disk indications and evidence

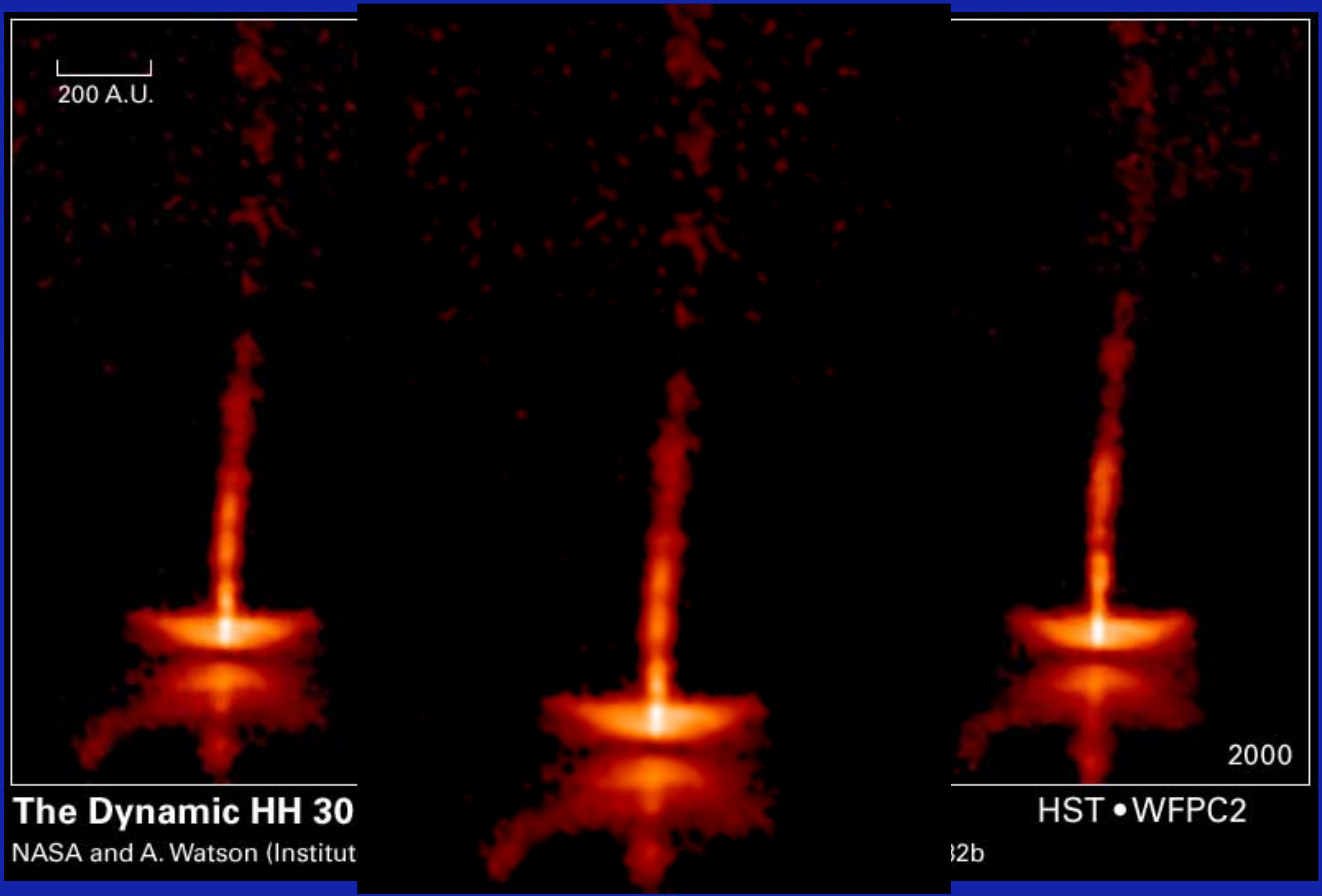


Full line: no inner whole
Dashed line: Inner whole

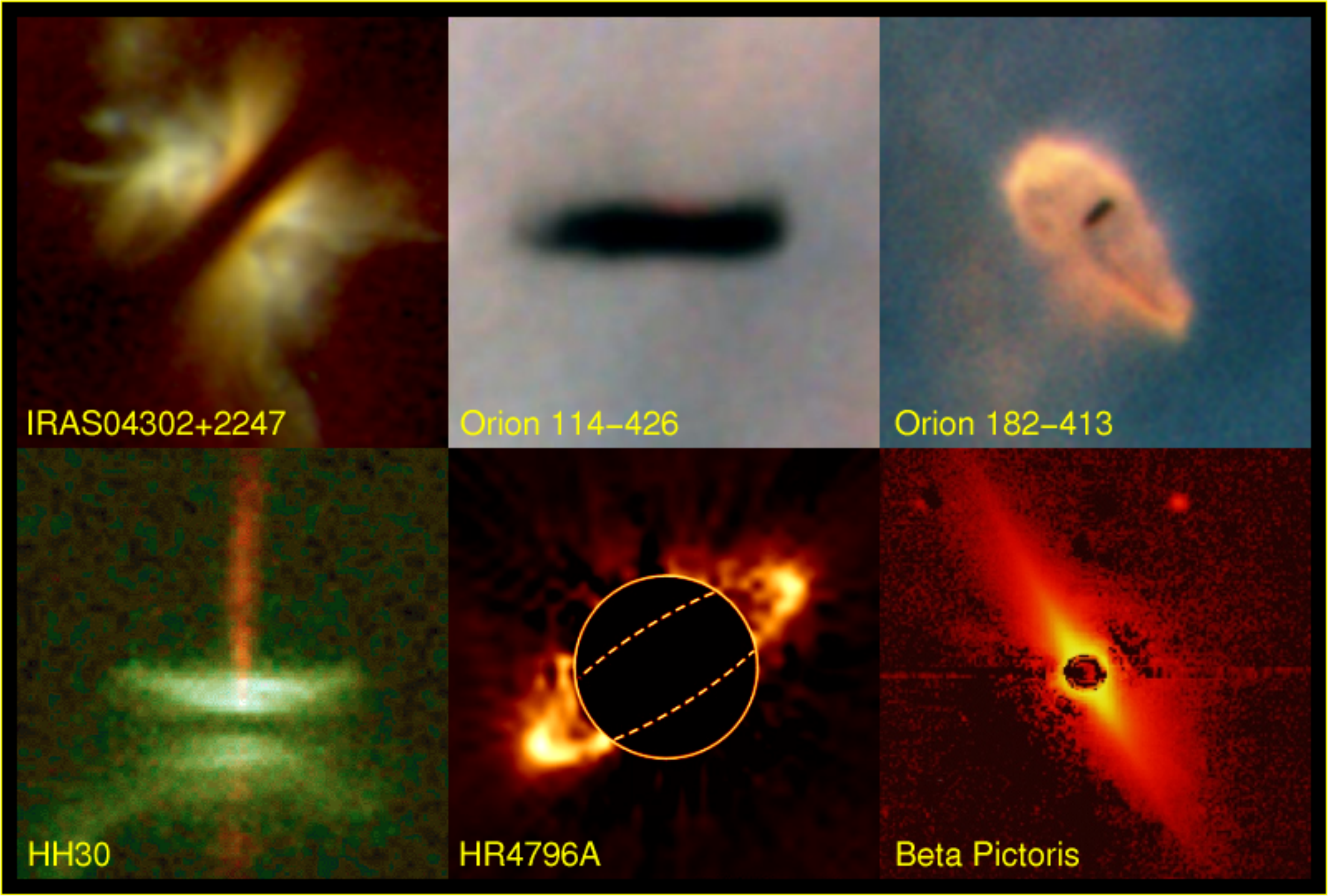
Beckwith et al. 1990

Early single-dish observations toward T-Tauri stars revealed cold dust emission.
In spherical symmetry this would not be possible since the corresponding gas and dust would extinct any emission from the central protostar.
→ Disk symmetry necessary!

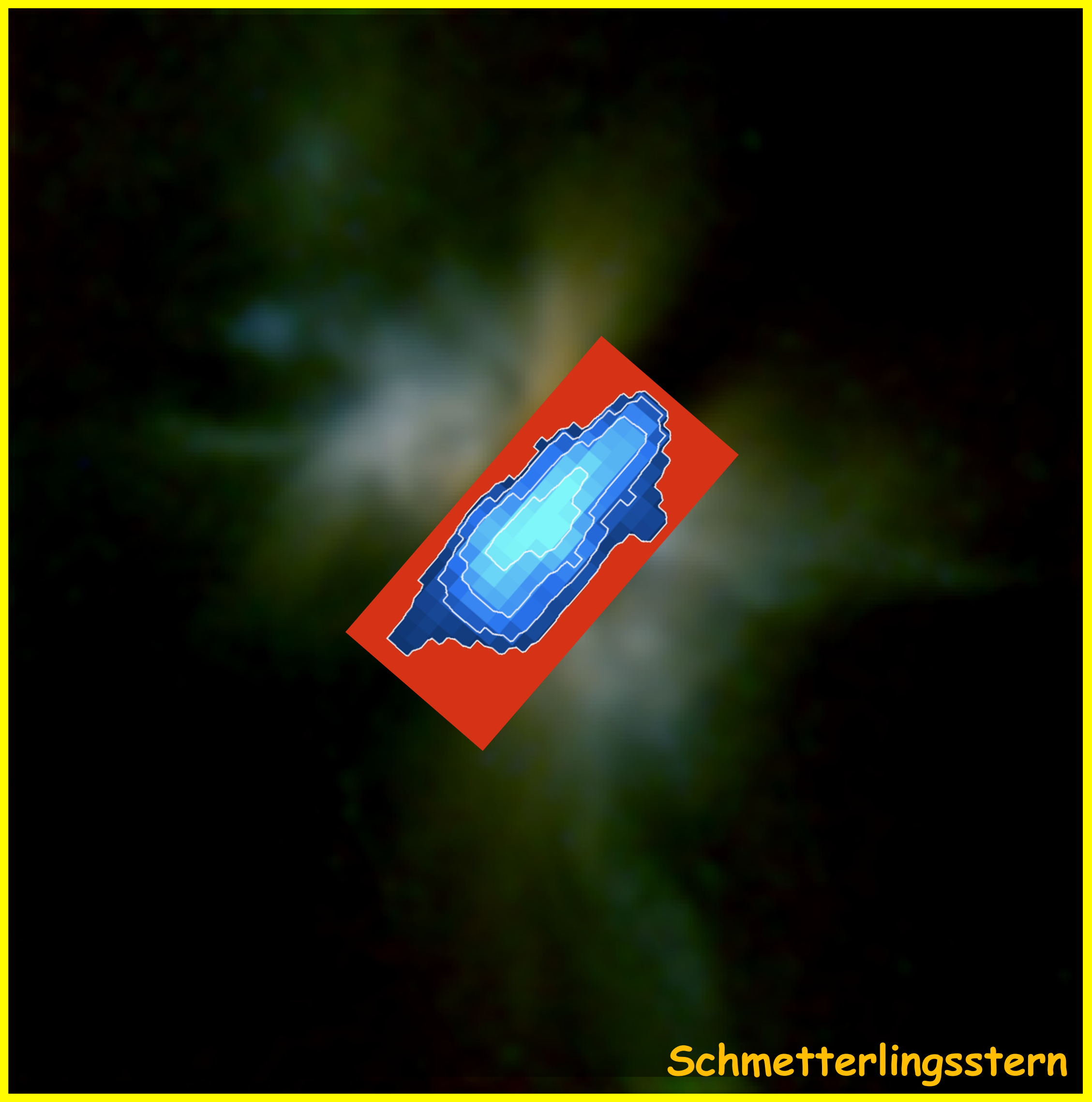
HH30, one of the first imaged disks



Optical disk examples

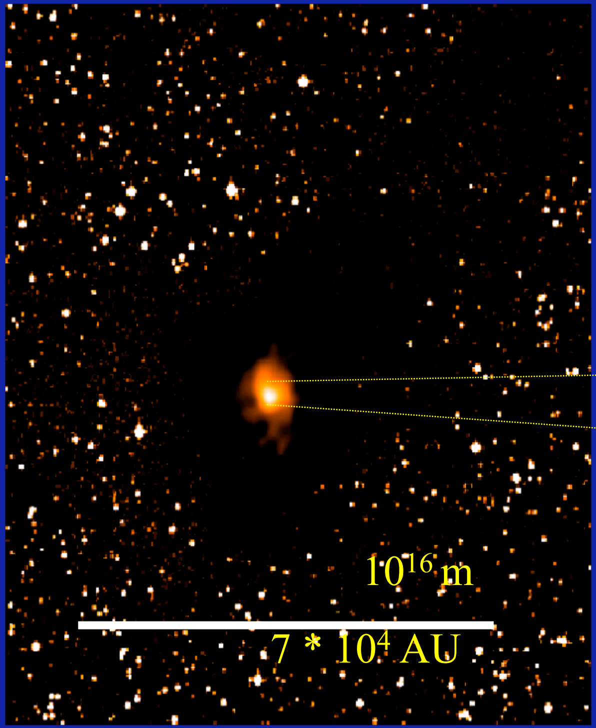


The Butterfly star

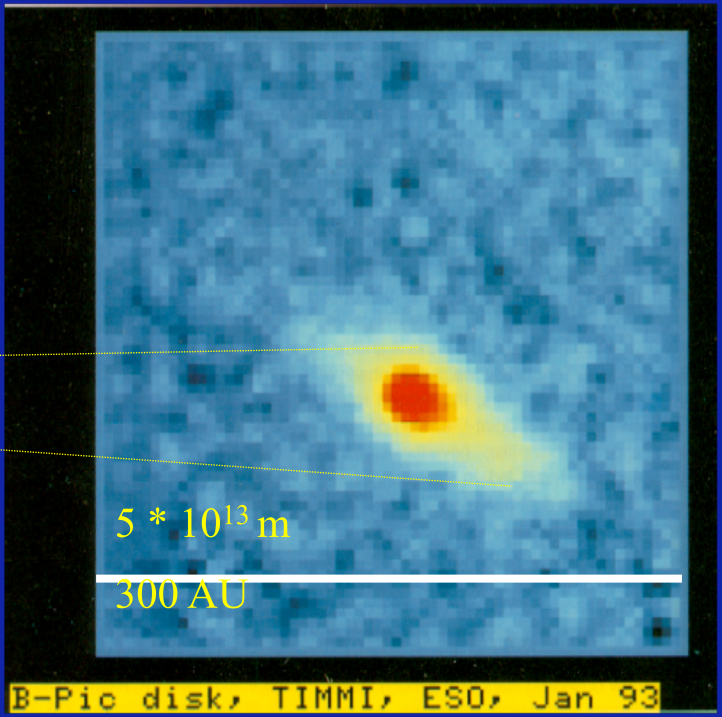


Wolf et al. 2003

Approximate disk size-scales

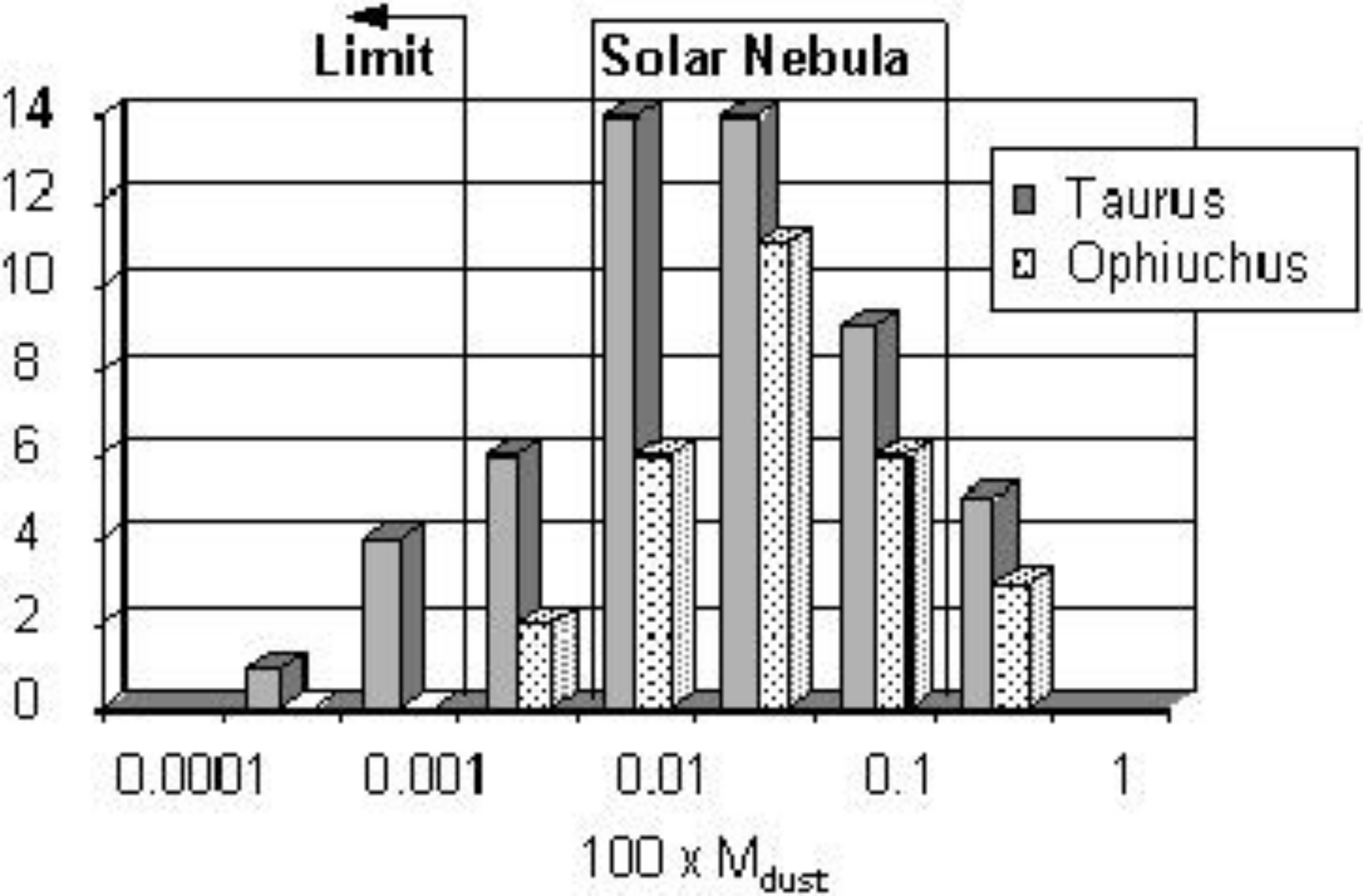


Molecular cloud core



Circumstellar dust disk

Disk masses

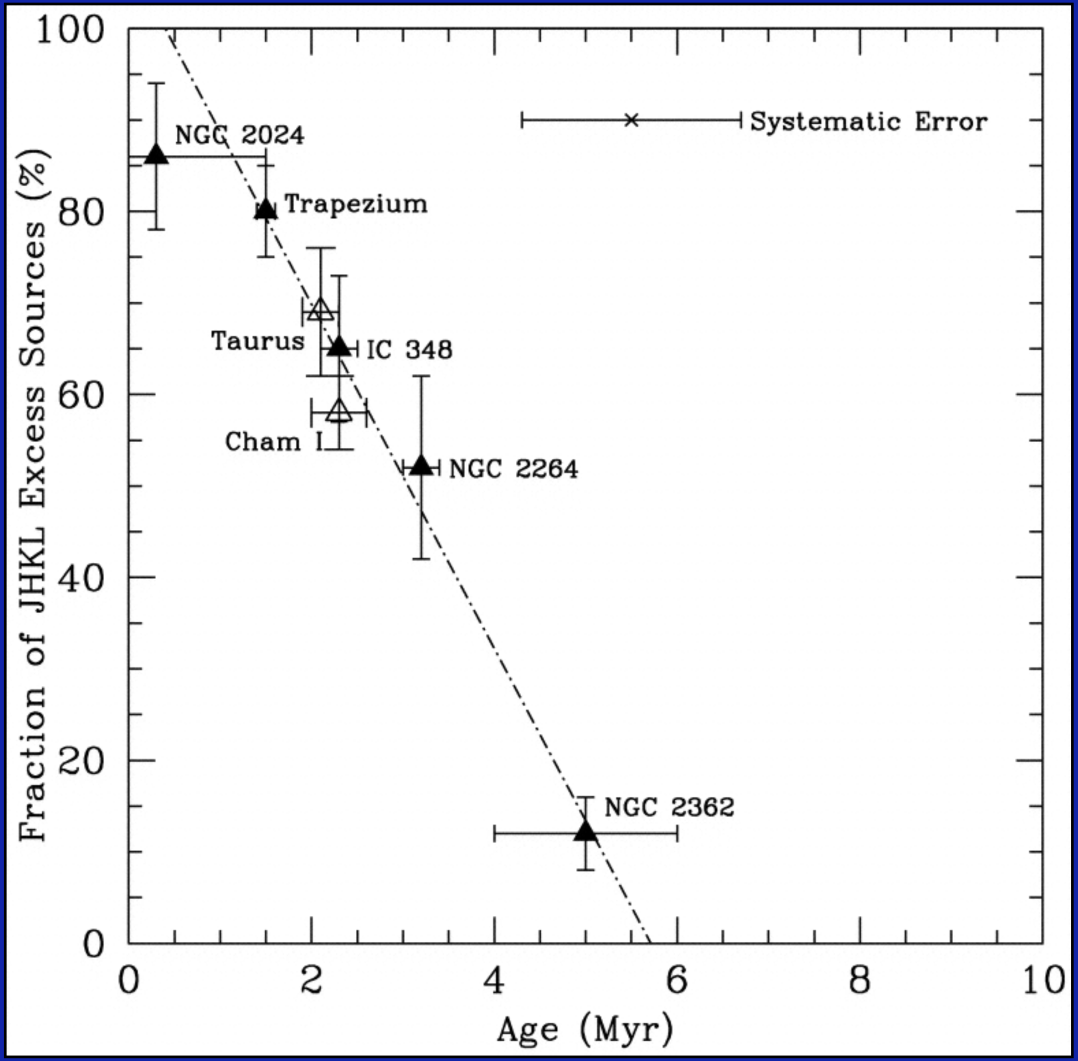


- Theories of early solar system require disk masses between 0.01 and 0.1M_{sun}.

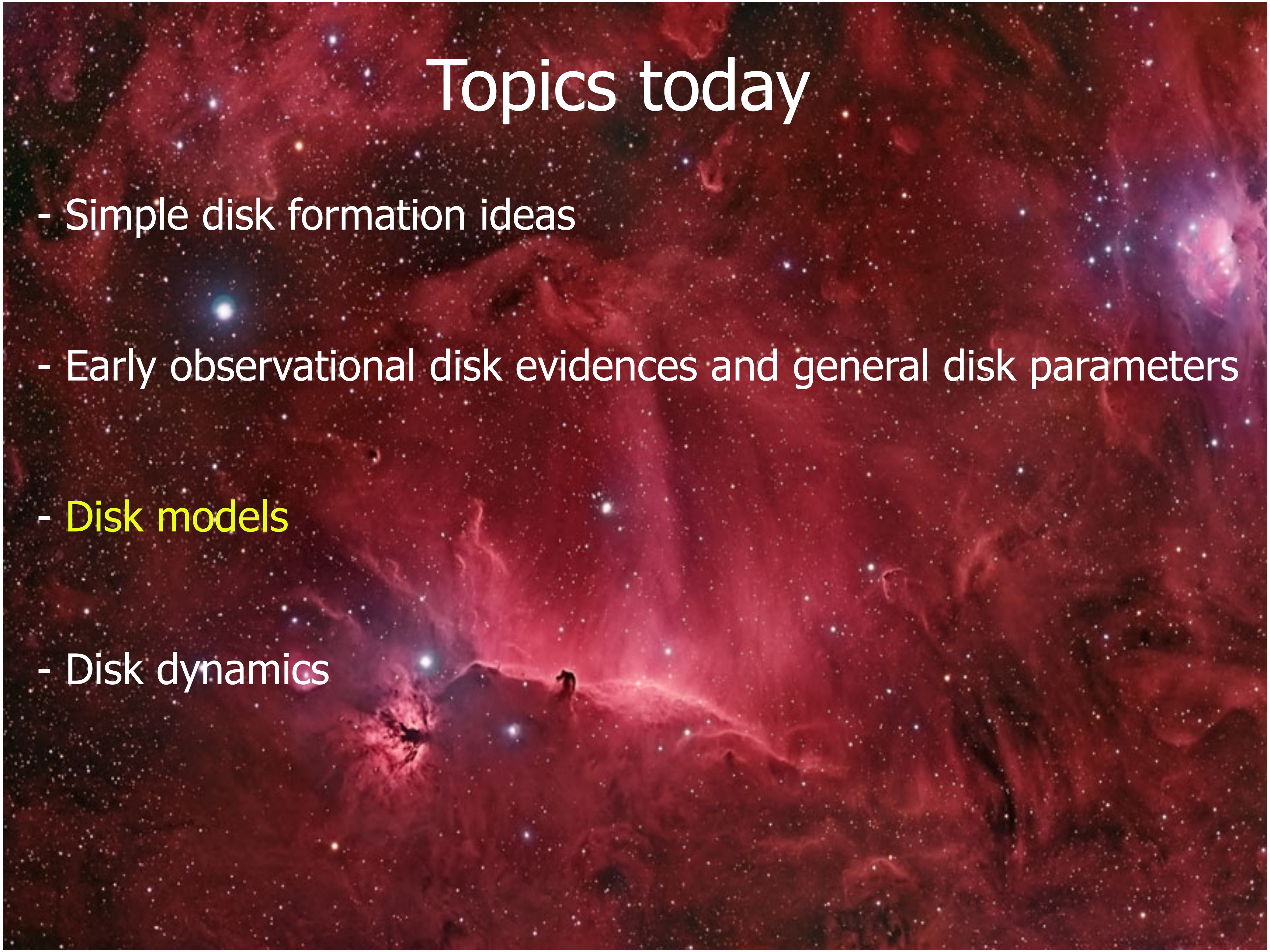
→ Typical disk systems apparently have enough disk mass to produce planetary systems.

Beckwith et al. 1990, Andre et al. 1994

Disk ages



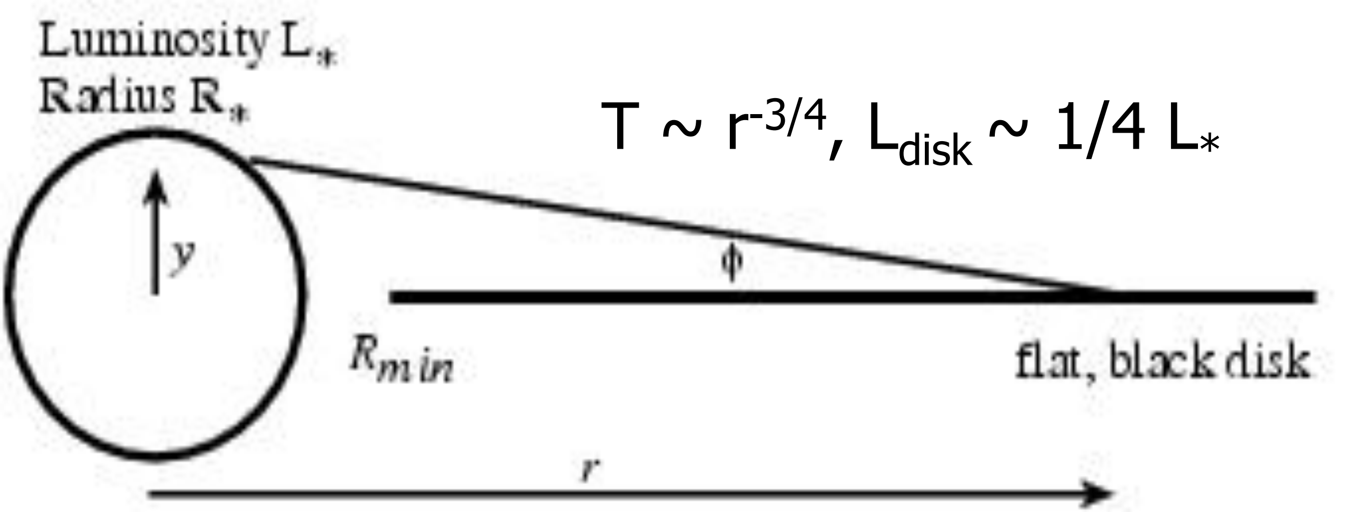
Haisch et al. 2001



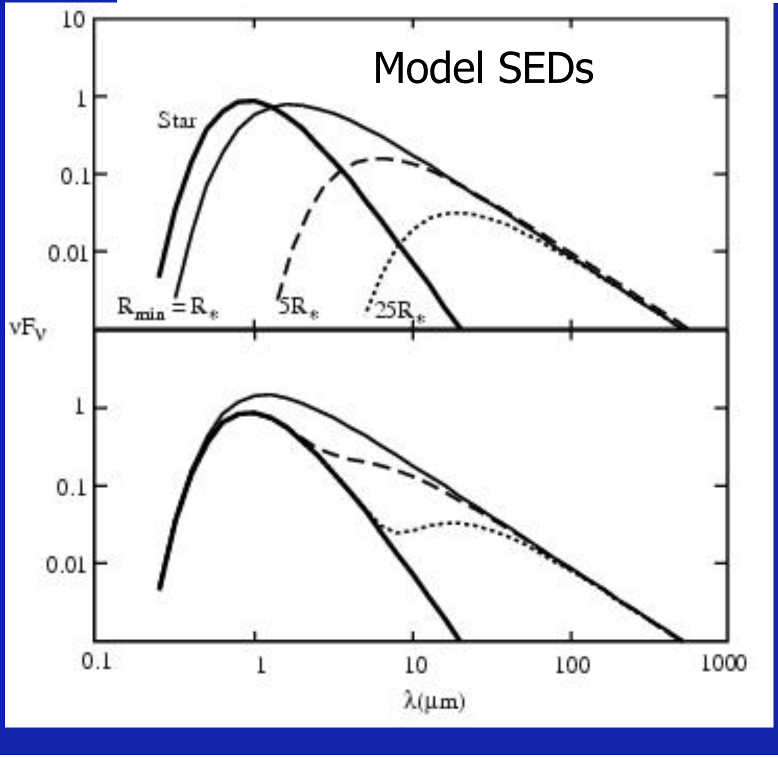
Topics today

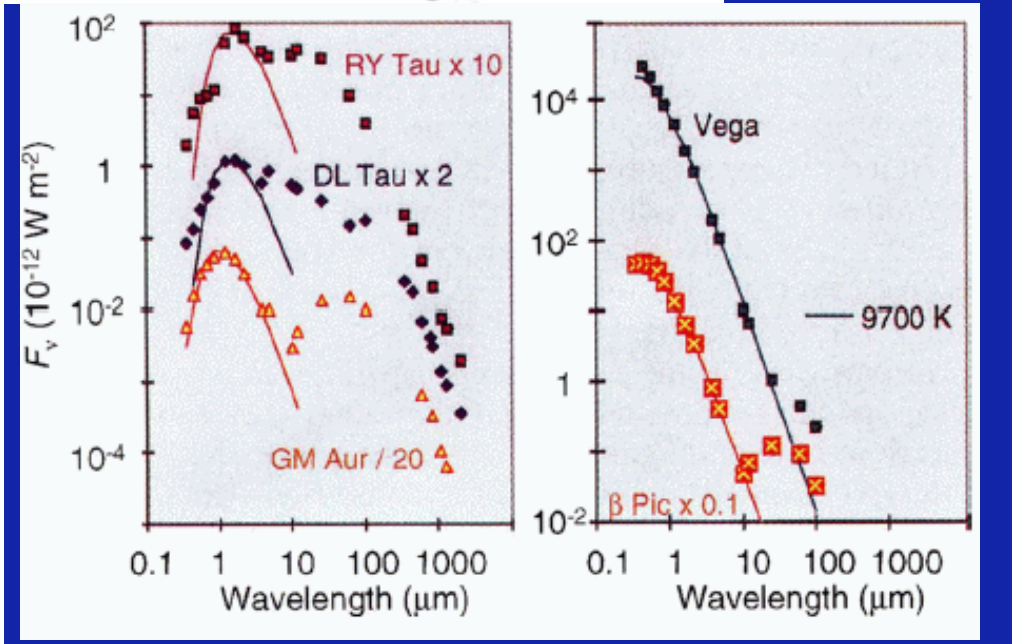
- Simple disk formation ideas
- Early observational disk evidences and general disk parameters
- Disk models
- Disk dynamics

Simple case: flat, black disk



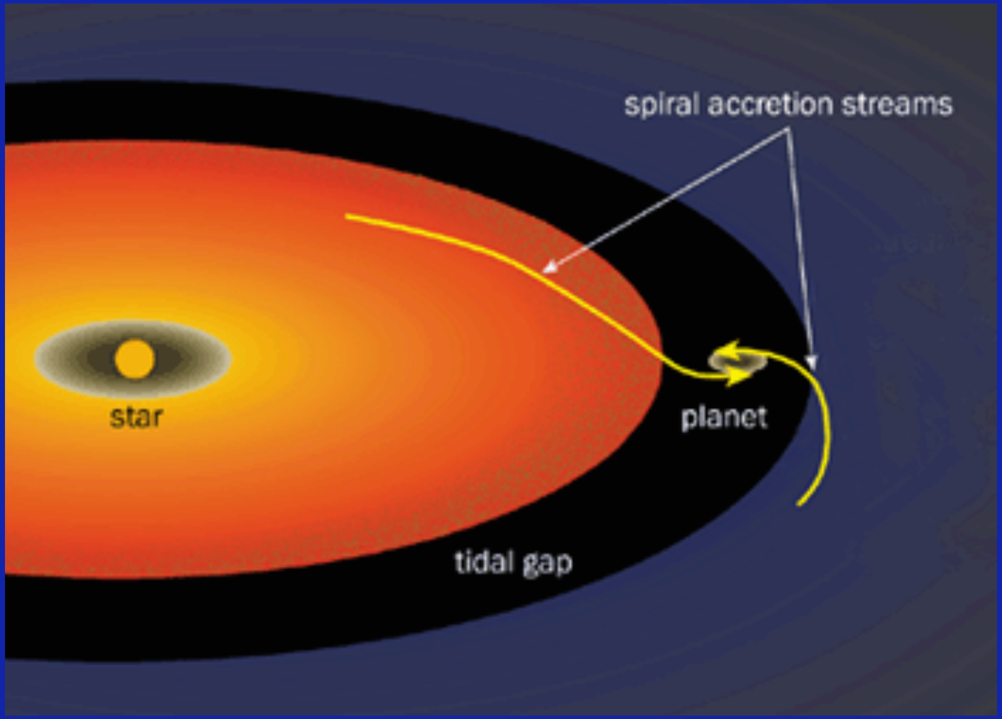
$T \sim r^{-3/4}$, $L_{disk} \sim 1/4\ L_*$

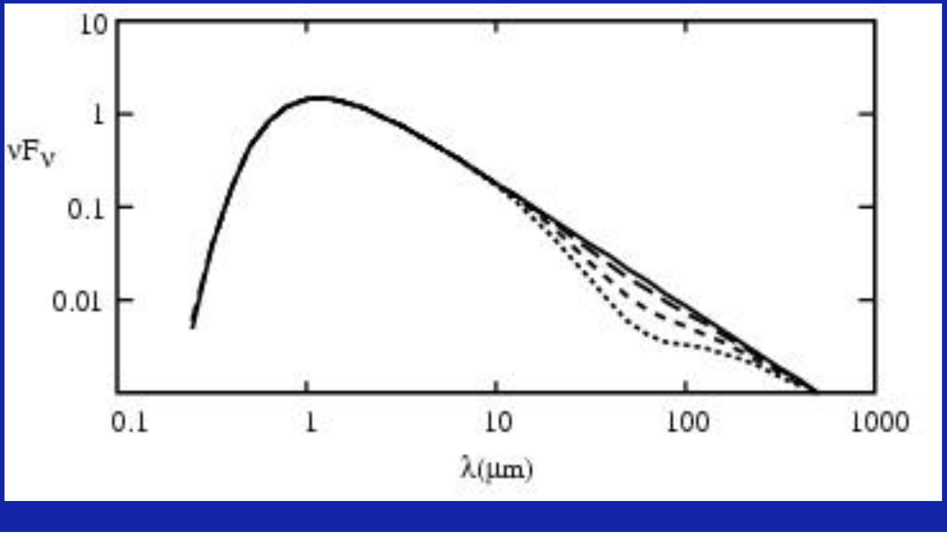




Beckwith et al. 1996, 1999

Effects of gaps on disk SED

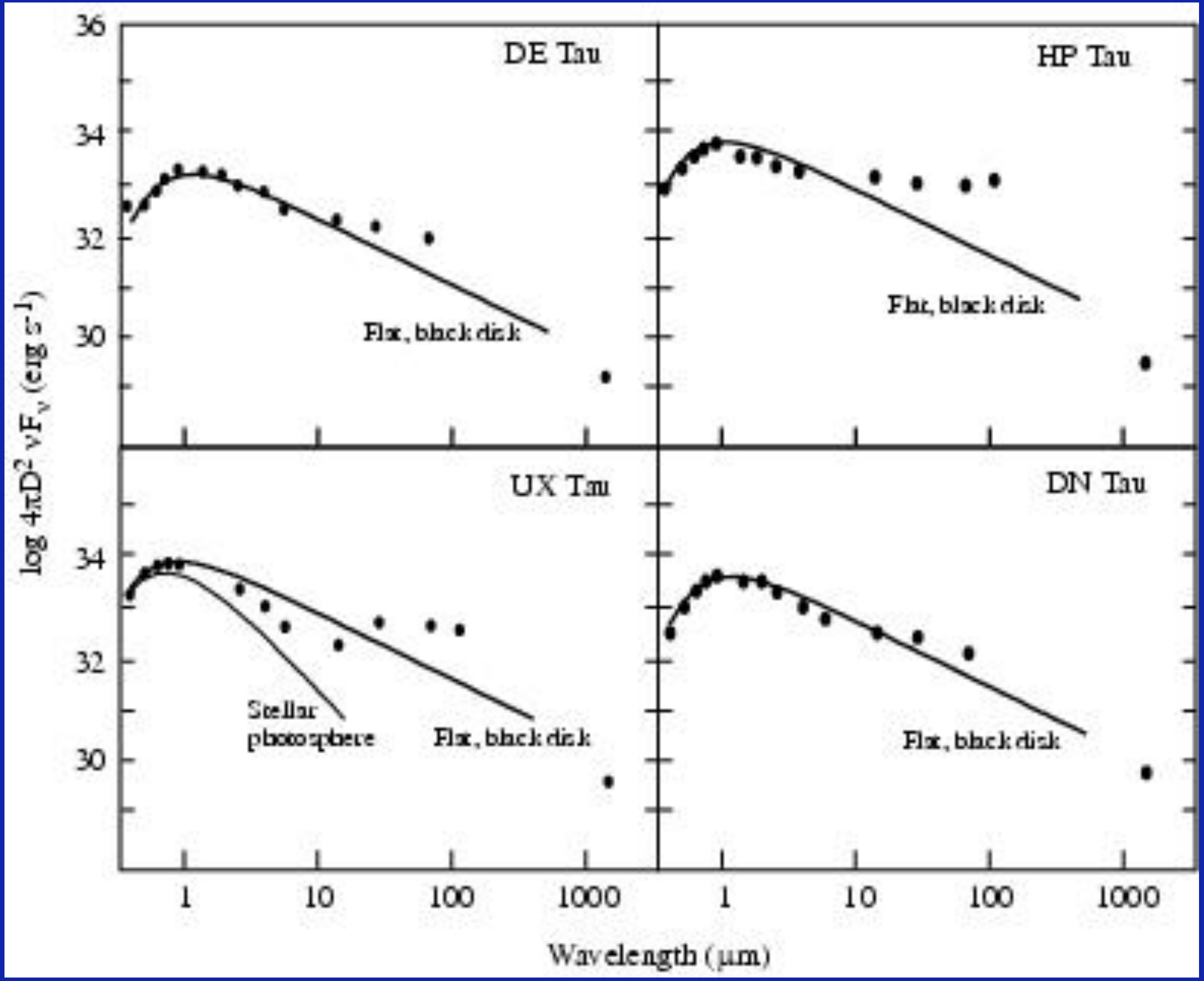




Full line: no gap
Long-dashed: gap 0.75 to 1.25 AU
Short-dashed: gap 0.5 to 2.5 AU
Dotted: gap 0.3 to 3 AU

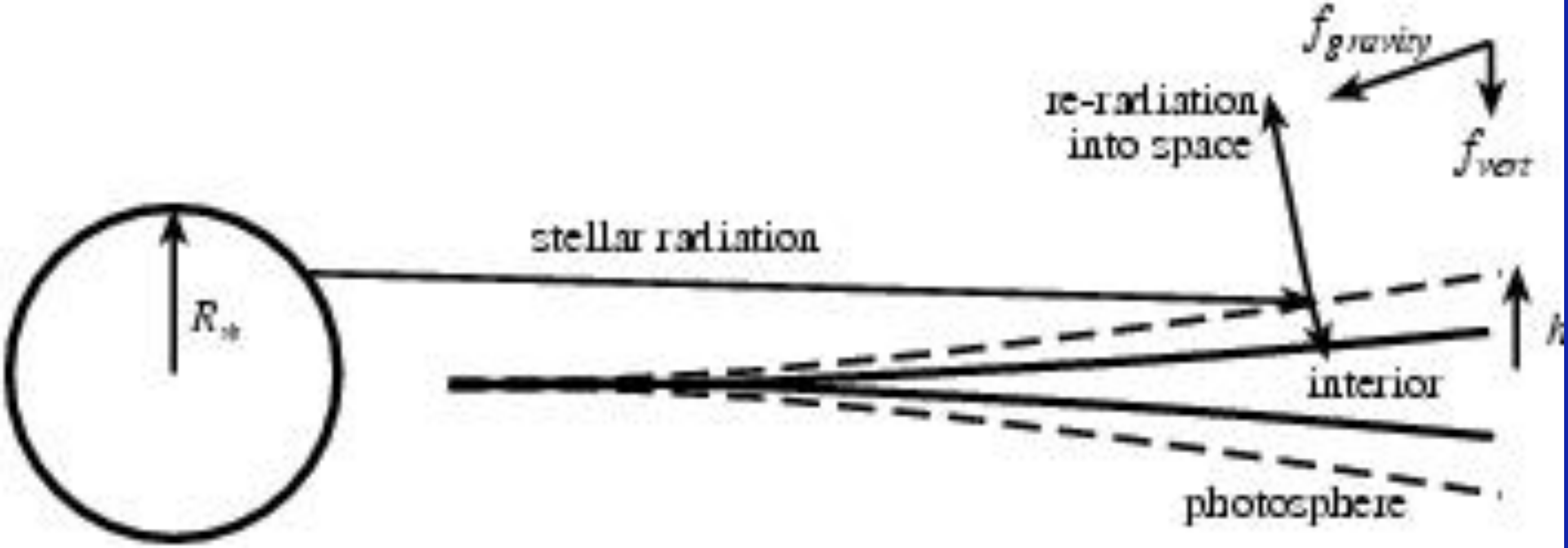
To become detectable gap has to cut out at least a decade of disk size.

Additional FIR excess



- Data indicate that outer disk region is hotter than expected from flat, black disk model → Disk flaring

Disk flaring

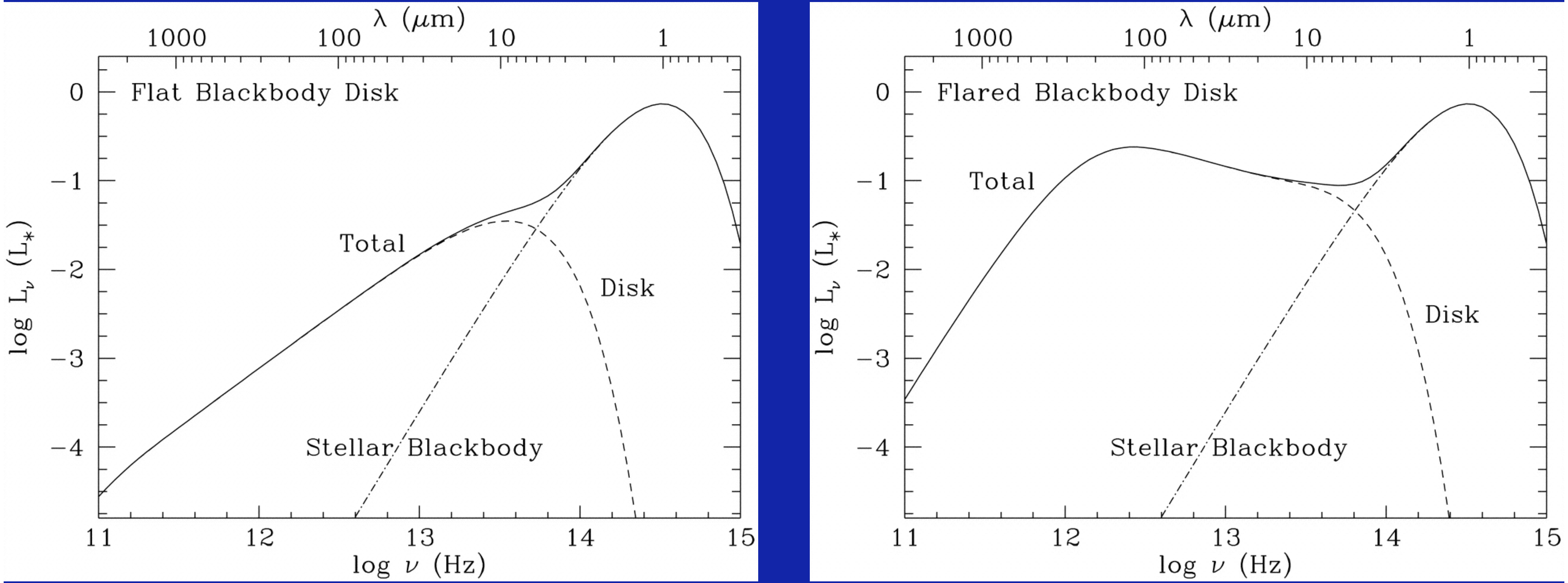


The scale height h of a disk increases with radius r because the thermal energy decreases more slowly with increasing radius r than the vertical component of the gravitational energy:

$$E_{vert,\,grav} \sim h/r * GM_*/r \sim E_{therm} \sim kT(r) \qquad \text{with } T(r) \sim r^{-3/4}$$

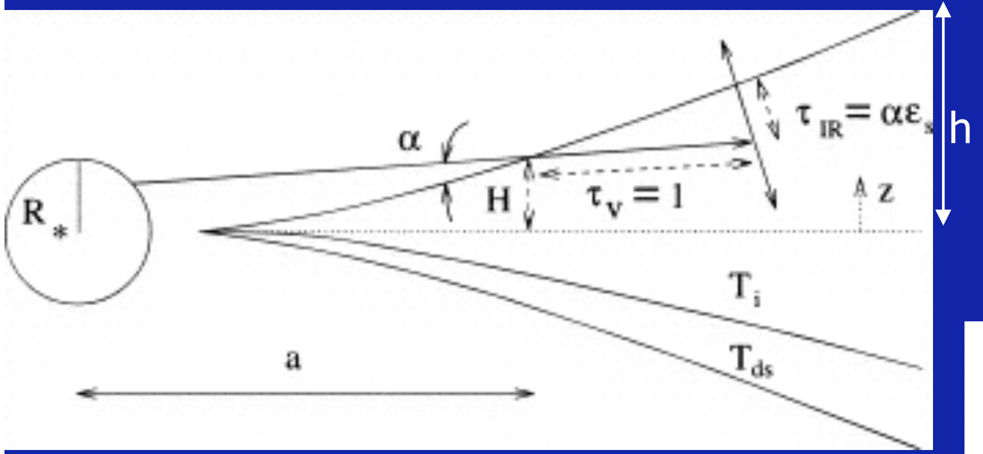
$$\rightarrow h \sim k/GM_*\, r^{5/4}$$

Hydrostatic equilibrium, radiative transfer models for flared disks I

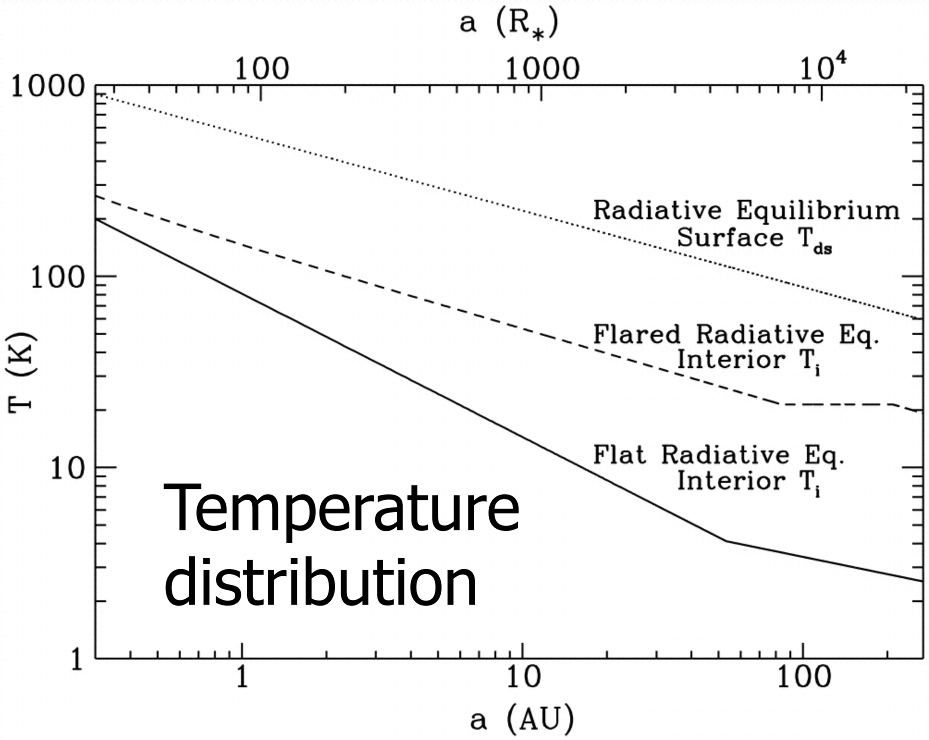


Chiang & Goldreich 1997

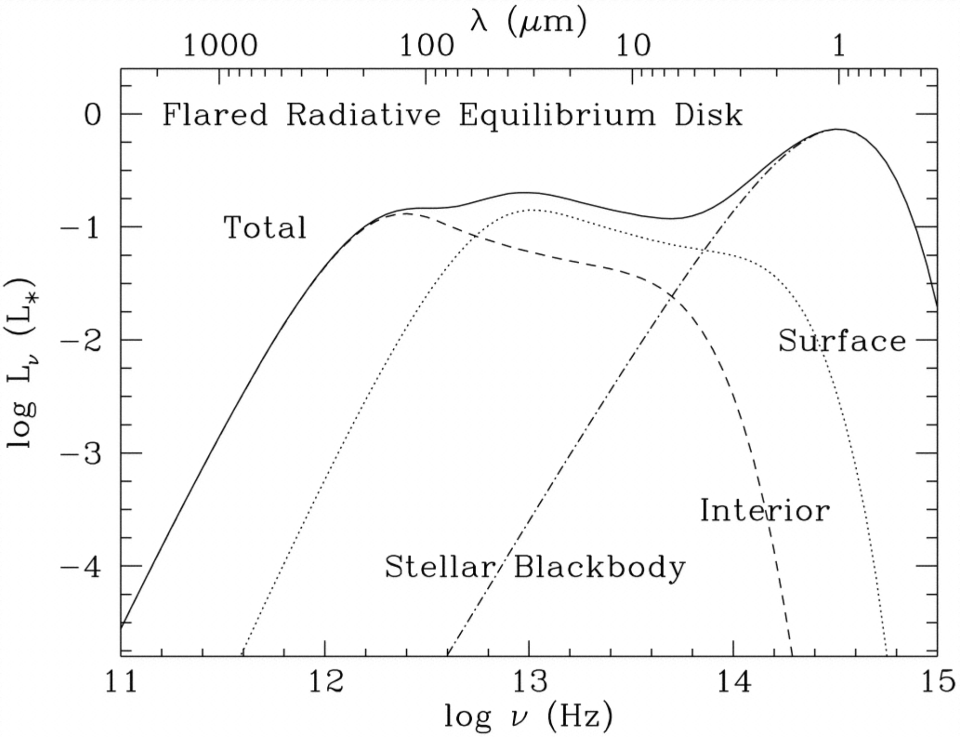
Hydrostatic equilibrium, radiative transfer models for flared disks II



$n_{vert} \sim \exp(z^2/2h^2)$

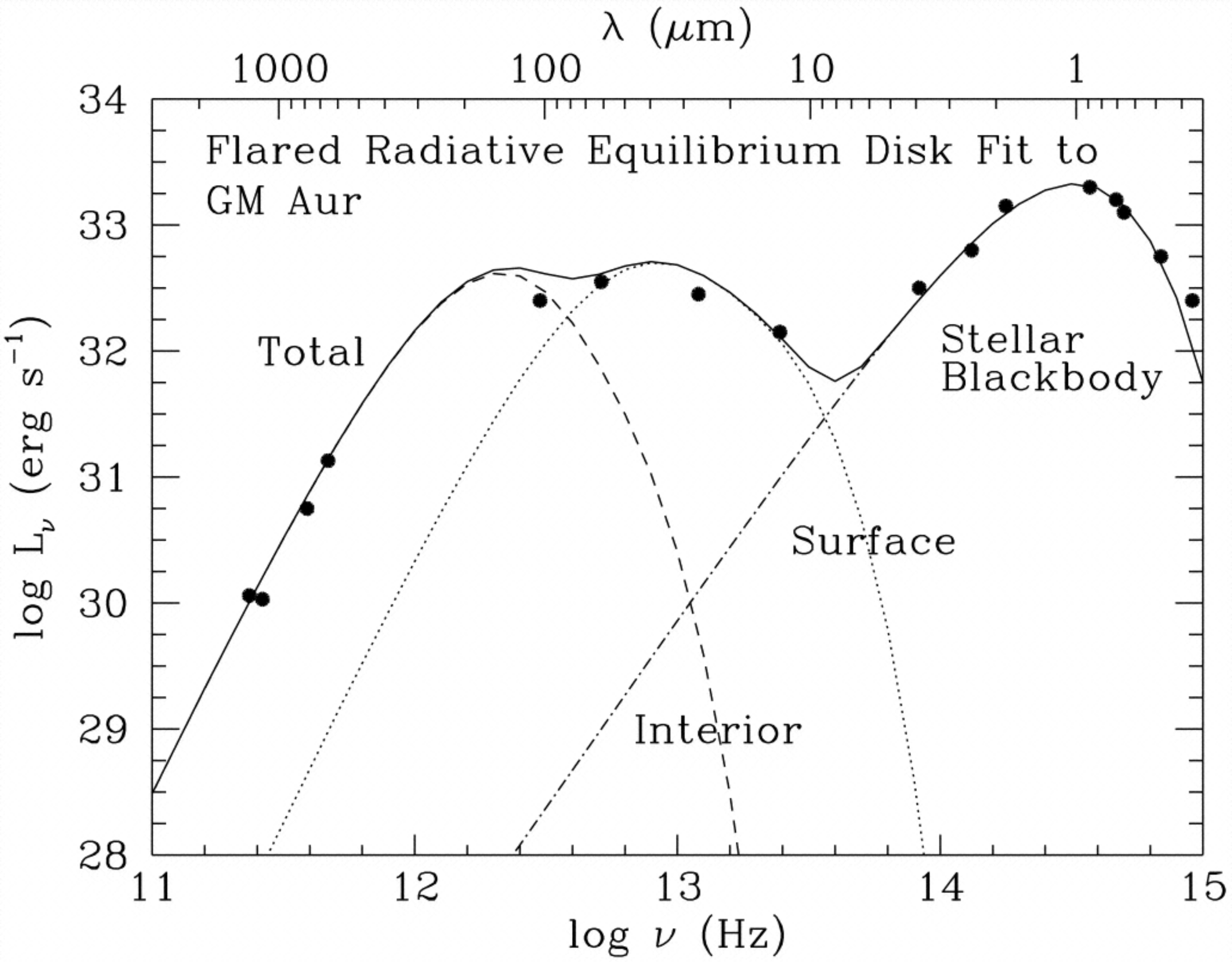


Temperature distribution



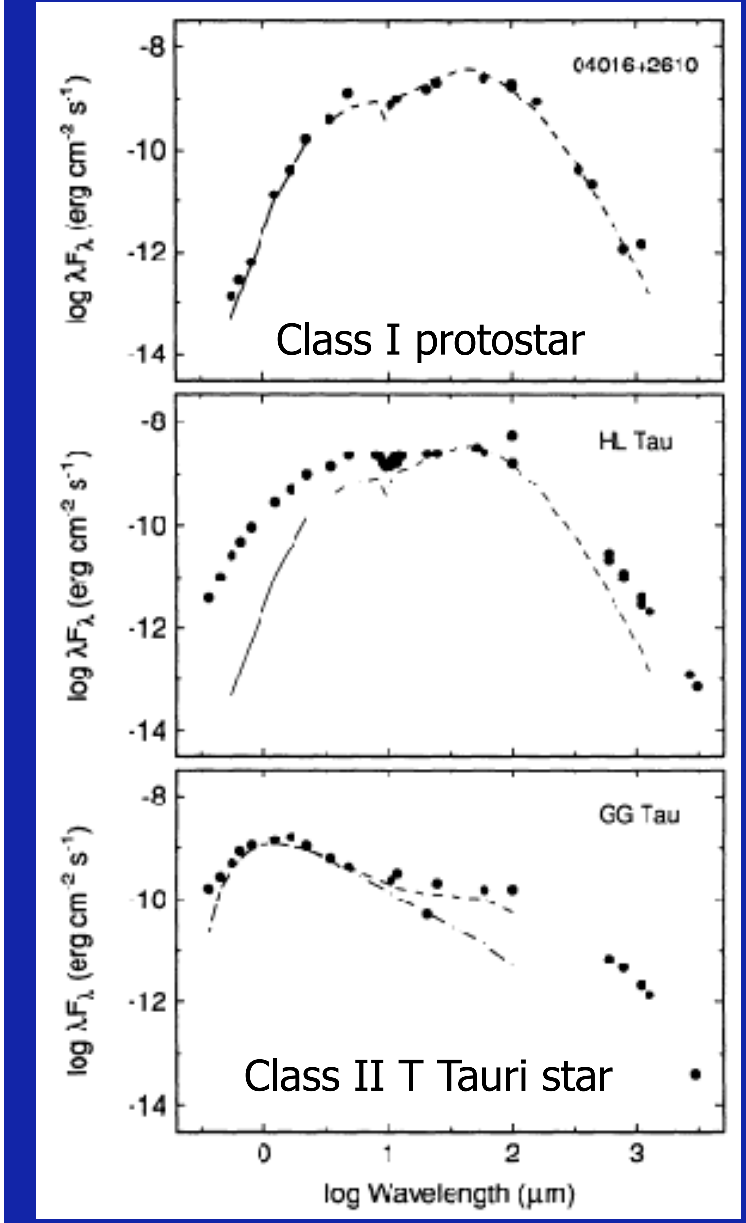
Chiang & Goldreich 1997

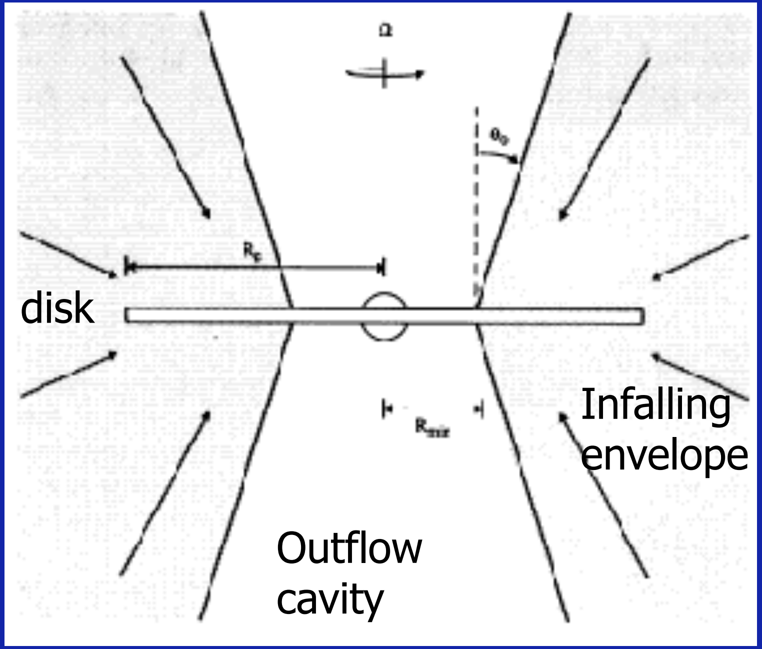
Hydrostatic equlibrium, radiative transfer models for flared disks III



Chiang & Goldreich 1997

Flat spectrum disks

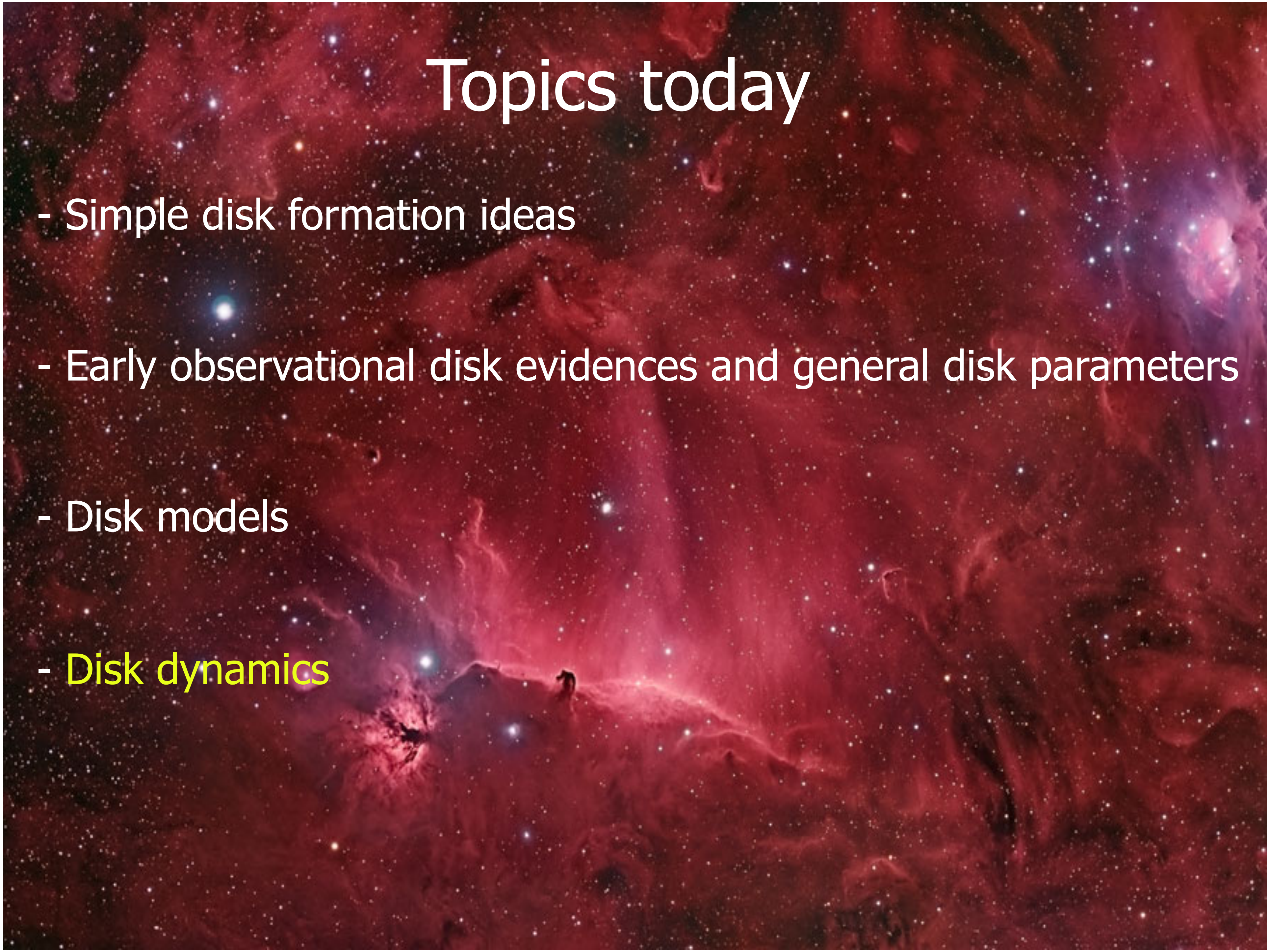




- Flat-spectrum sources have too much flux to be explained by heating of protostar only.
- In very young sources, they are still embedded in infalling envelope → this can scatter light and cause additional heating of outer disk.

→ Flat spectrum sources younger than typical class II T Tauri stars.

Calvet et al. 1994, Natta et al. 1993



Topics today

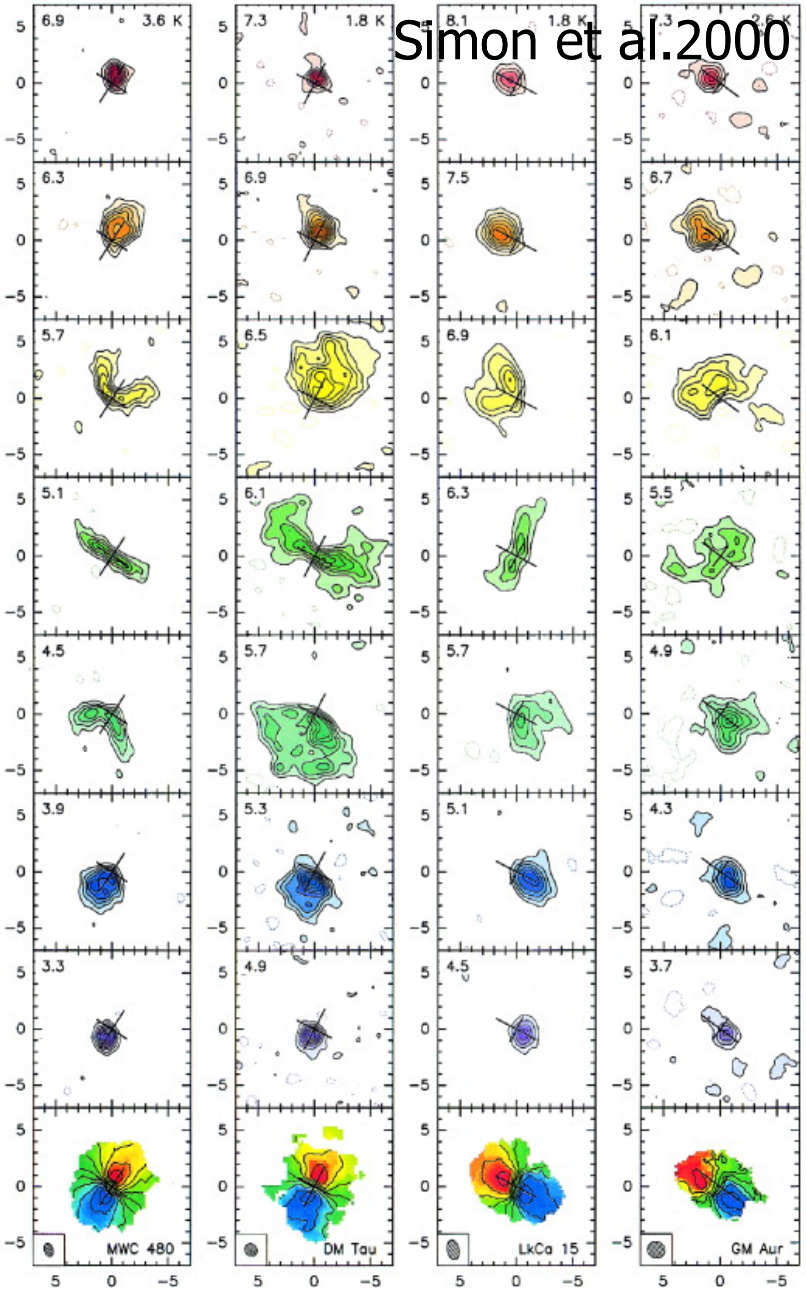
- Simple disk formation ideas

- Early observational disk evidences and general disk parameters

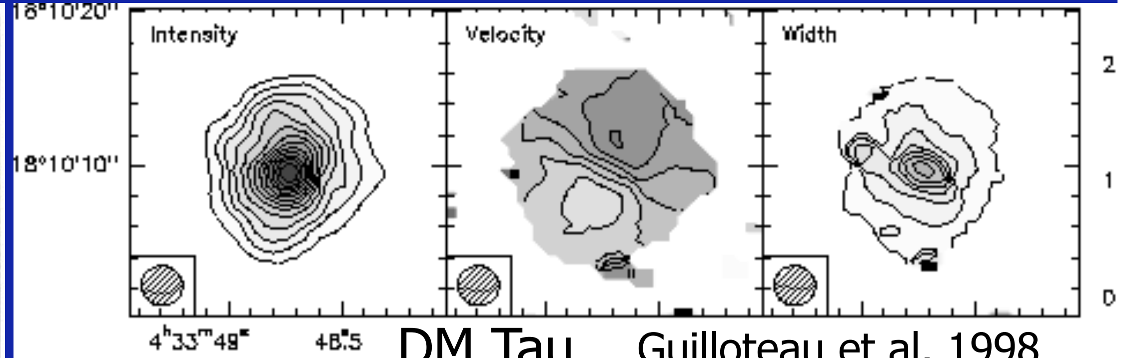
- Disk models

- Disk dynamics

Disk dynamics: Keplerian motion



Simon et al.2000

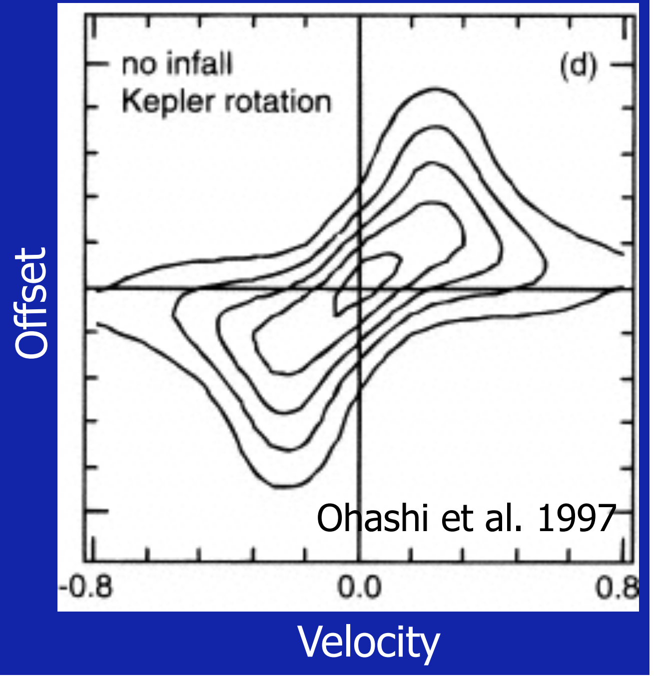


DM Tau Guilloteau et al. 1998

For a Keplerian supported disk, centrifugal force should equal grav. force.

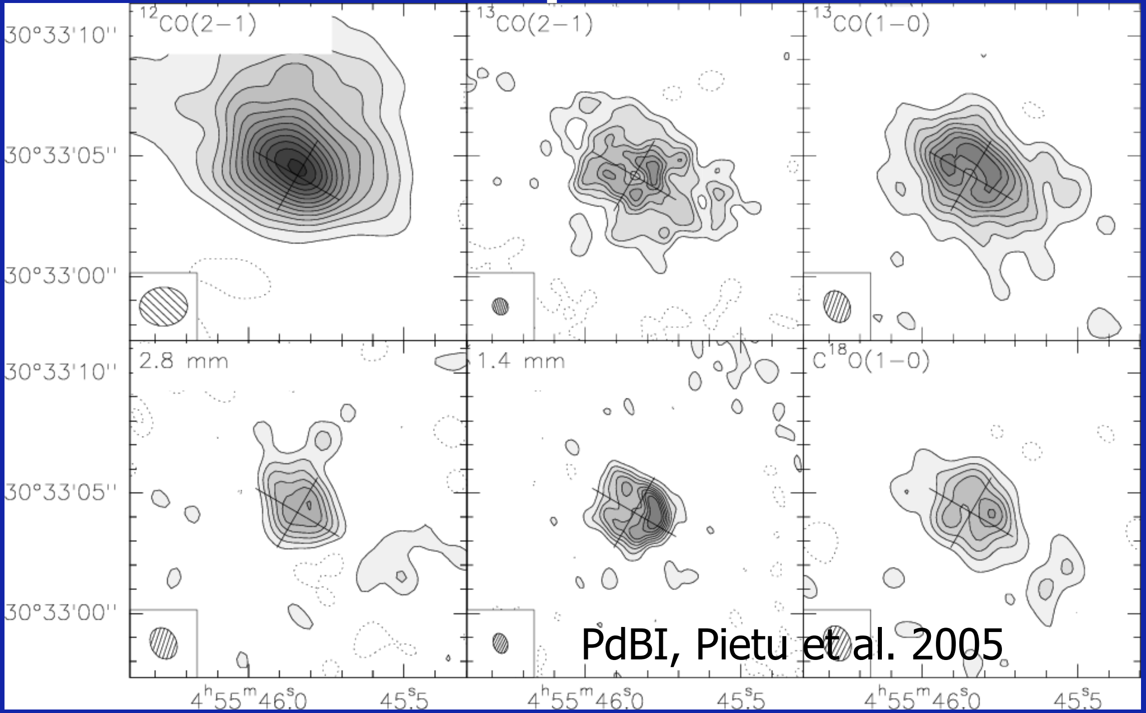
$$F_{cen} = mv^2/r = F_{grav} = Gm_*m/r^2$$

→ $v = (Gm_*/r)^{1/2}$

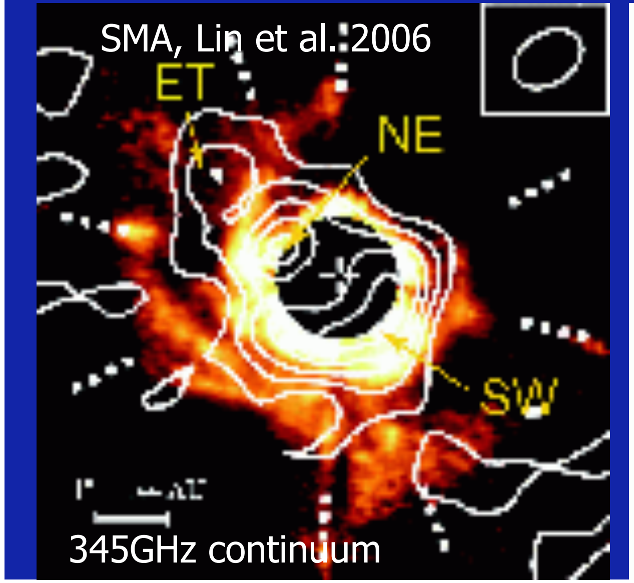


Ohashi et al. 1997

Non-Keplerian motion: AB Aur

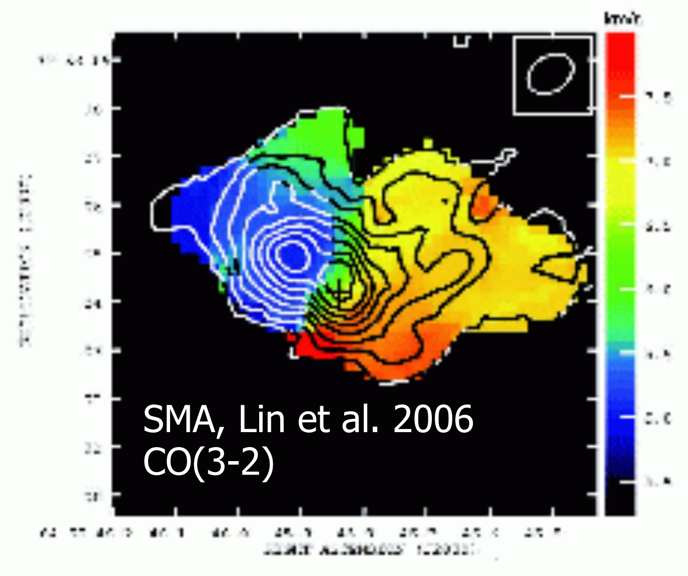


PdBI, Pietu et al. 2005



SMA, Lin et al. 2006

345GHz continuum

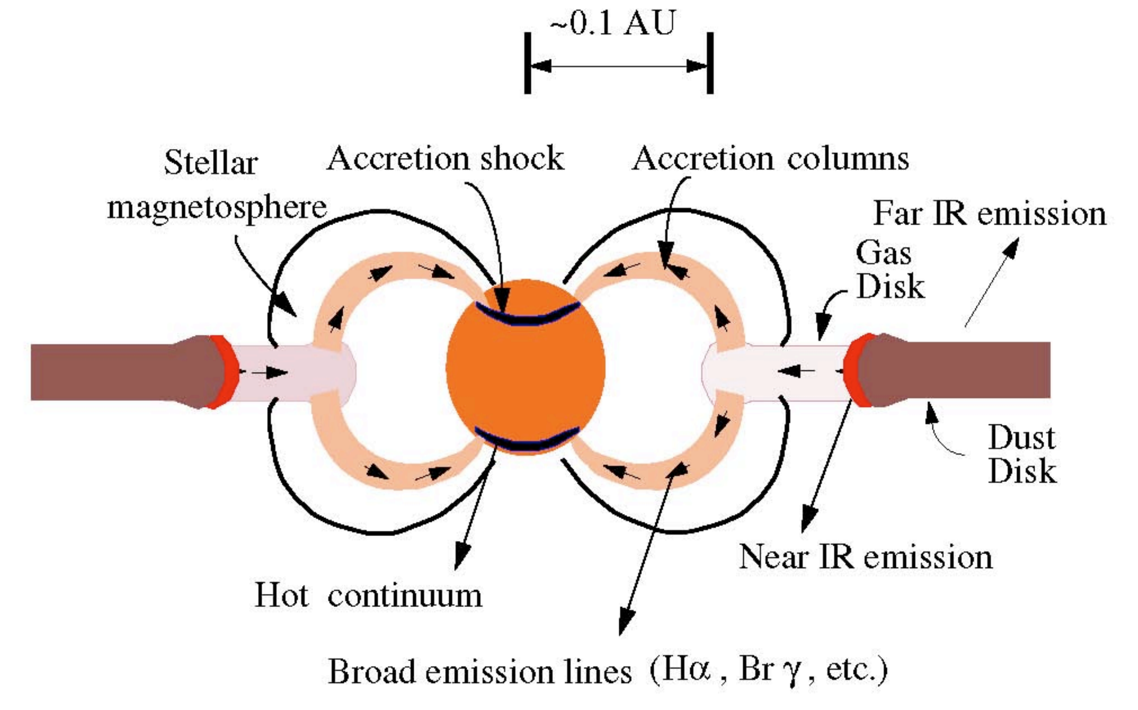


SMA, Lin et al. 2006
CO(3-2)

- Central depression in cold dust and gas emission.
- Non-Keplerian velocity profile $v \propto r^{-0.4+-0.01}$

- Possible explanations
  - Formation of low-mass companion or planet in inner disk.
  - Early evolutionary phase where Keplerian motion is not established yet (large envelope).

Accretion and mass transport



Equilibrium between F_{cen} and F_{grav}: $m r \omega^2 = G m m_*/r^2 \Rightarrow \omega = (G m_*/r^3)^{1/2}$

→ no solid body rotation but a sheared flow → viscous forces
→ mass transport inward, angular momentum transport outward, heating

The inner disk is warm enough for large ionization: matter and magnetic field are coupled well → accretion columns transport gas from disk to protostar

Summary

- Disks are expected from angular momentum considerations.

- The SEDs of disk sources show strong FIR excess. SEDs allow to analyze various disk aspects:
    - Radial and vertical disk morphology, flaring of disks
    - Evolutionary stages
    - Inner holes
    - Gaps maybe due to planets

- Observable in NIR in absorption and in (sub)mm line/continuum emission.

- Disk lifetimes a few million years.

- T Tauri disks usually in Keplerian motion, younger disks may deviate.

Zodiacal light

Etienne Leopold Trouvelot (1827-1895)

Bob Shobbrook, Siding spring, 2 hours after sunset.

Zodiacal light is caused by reflection of dust in the ecliptic plane. The dust is re-processed dust (not from the original formation) from comets and astroids.

Outflows and Jets: Theory and Observations

Summer term 2011
Henrik Beuther & Christian Fendt

15.04 Today: Introduction & Overview (H.B. & C.F.)
29.04 Definitions, parameters, basic observations (H.B.)
06.05 Basic theoretical concepts & models (C.F.)
13.05 Basic MHD and plasma physics; applications (C.F.)
20.05 Radiation processes (H.B.)
27.05 Observational properties of accretion disks (H.B.)
03.06 Accretion disk theory and jet launching (C.F.)
10.06 Outflow interactions: Entrainment, instabilities, shocks (C.F.)
17.06 Outflow-disk connection, outflow entrainment (H.B.)
24.06 Outflow-ISM interaction, outflow chemistry (H.B.)
01.07 Outflows from massive star-forming regions (H.B.)
08.07 Observations of extragalactic jets (C.F.)
15.07 Theory of relativistic jets (C.F.)

More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ss11.html
beuther@mpia.de, fendt@mpia.de