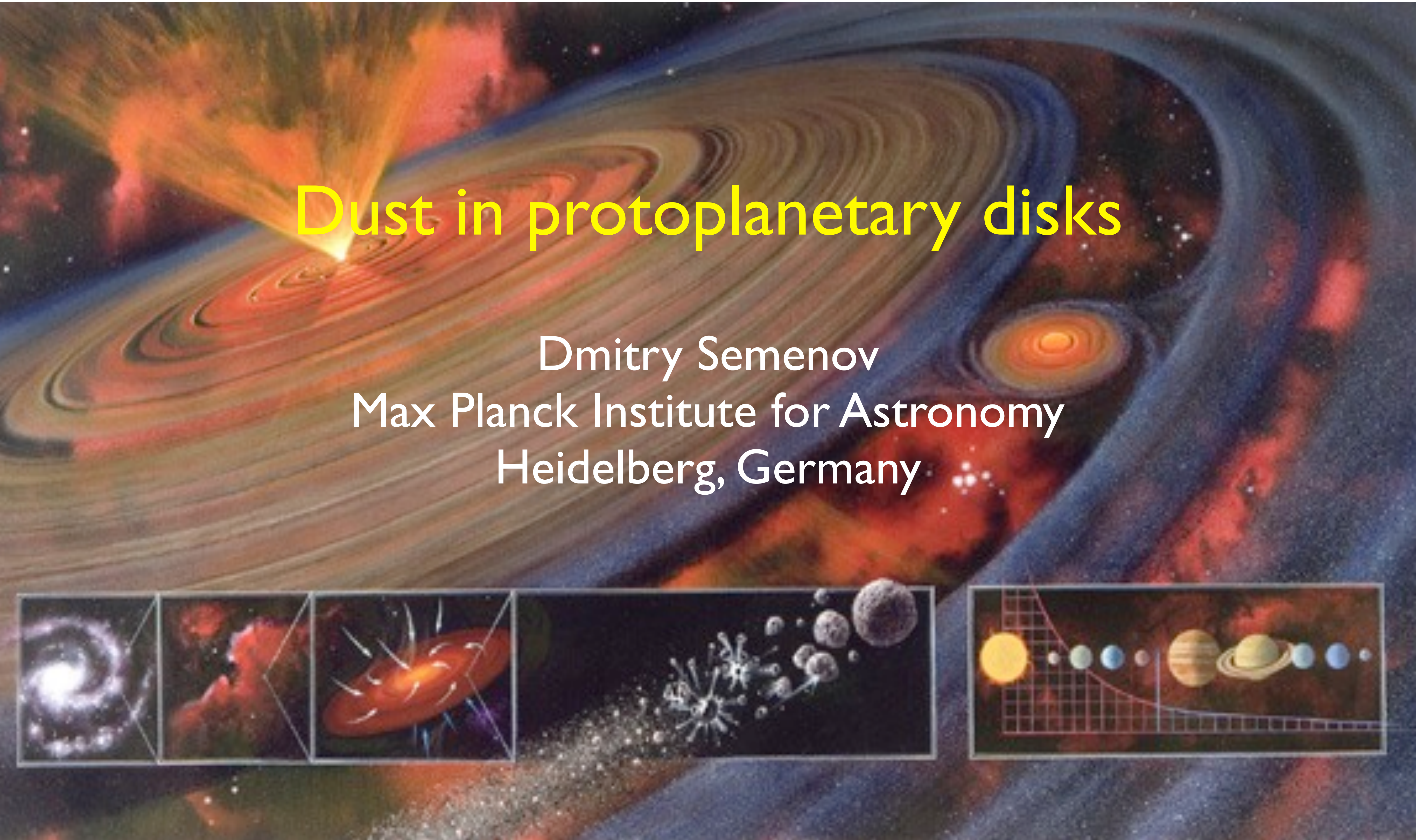
Dust in protoplanetary disks

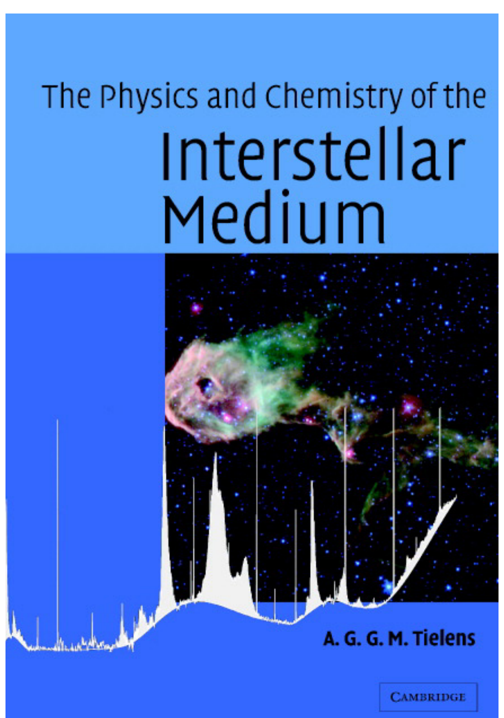
Dmitry Semenov
Max Planck Institute for Astronomy
Heidelberg, Germany

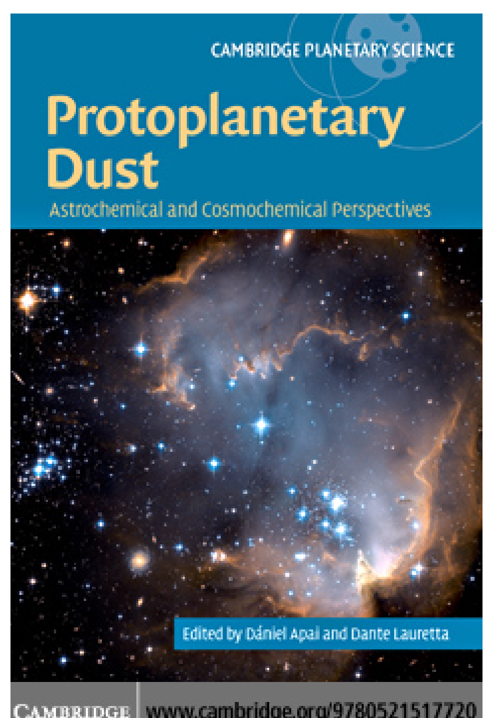


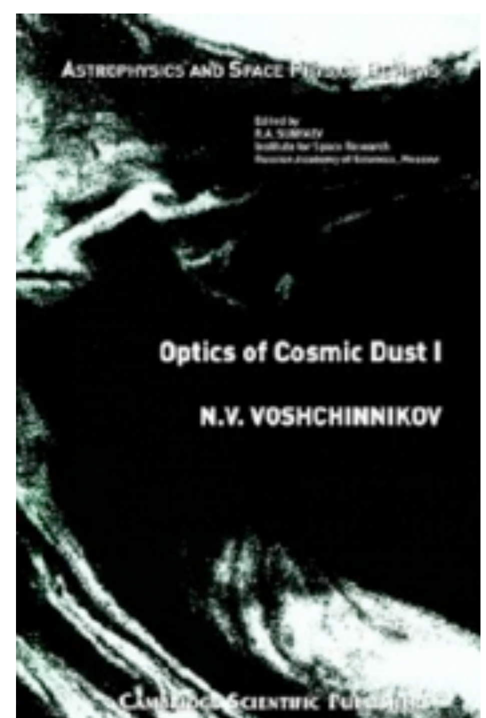
http://www.alma.inaf.it/attachments/article/118/Lecture12-Semenov.pdf

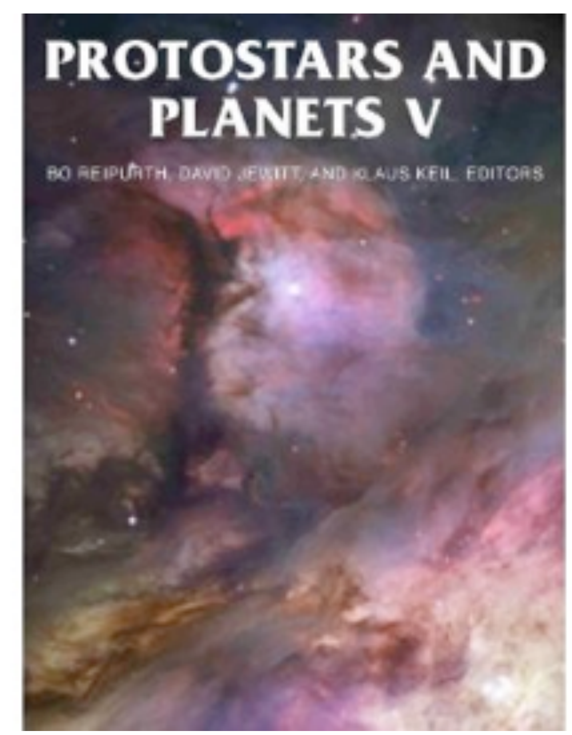
Suggested literature

- A. G.G.M. Tielens, "The Physics and Chemistry of the ISM" (2007), CUP
- B. Draine, "Astrophysics of Dust n Cold Clouds" (2003), astro-ph/0304488
- "Protoplanetary Dust" (2010), eds. D. Apai & D. Lauretta, CUP
- "Protostars & Planets V" (2005), Part VI, eds. B. Reipurt et al., Univ. Arizona P.
- N.V. Voshchinnikov, "Optics of Cosmic Dust I/II" (>2004), CUP



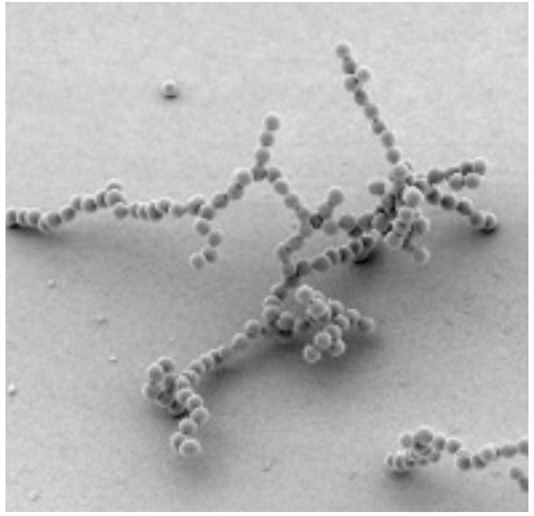


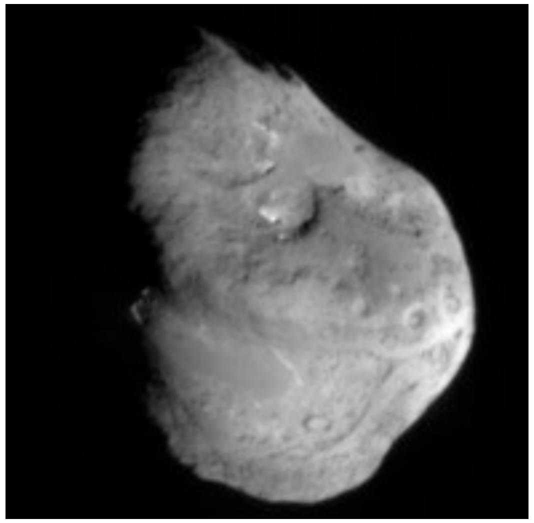


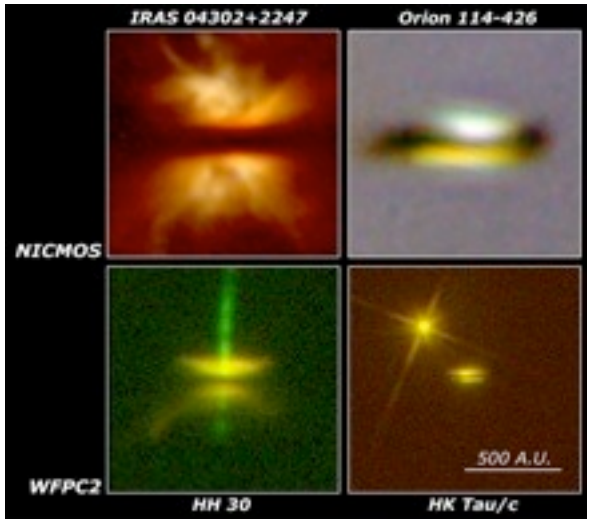


Outline

- The role of dust
- Light interaction with grains
- Structure & evolution of protoplanetary disks (PPDs)
- Evolution of dust in PPDs
- Observations of dust in PPDs
- ALMA observations

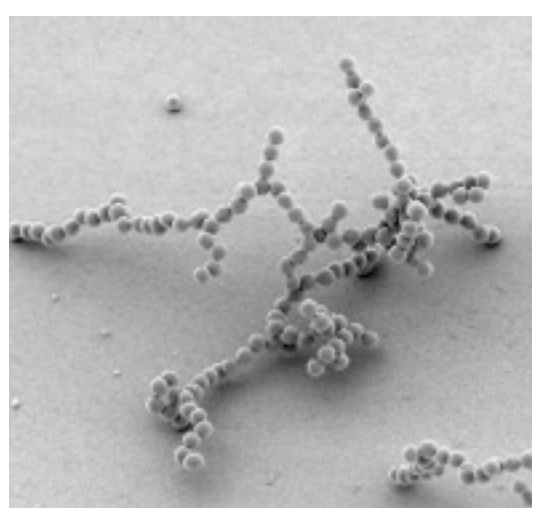


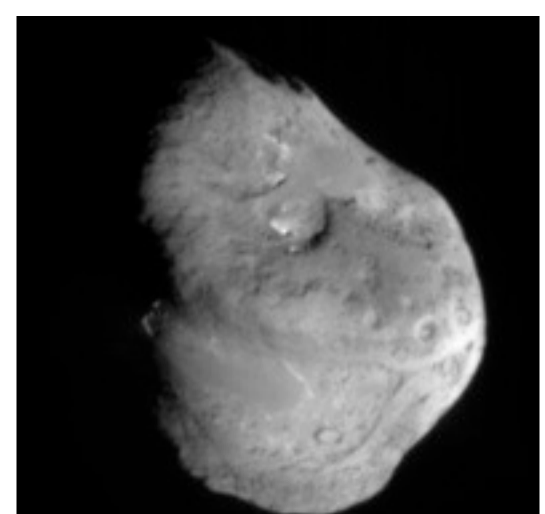


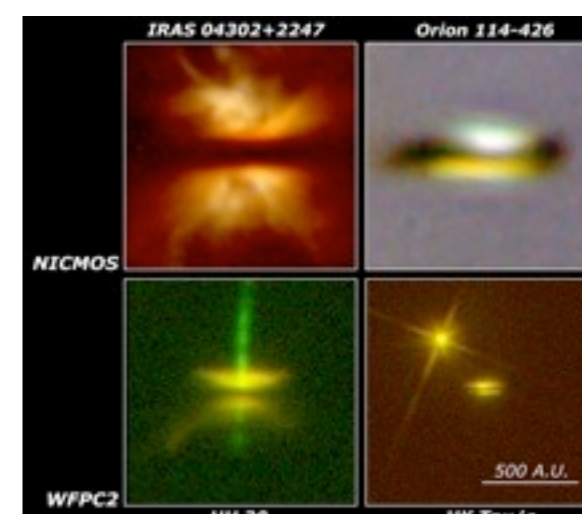


The role of dust in star-formation

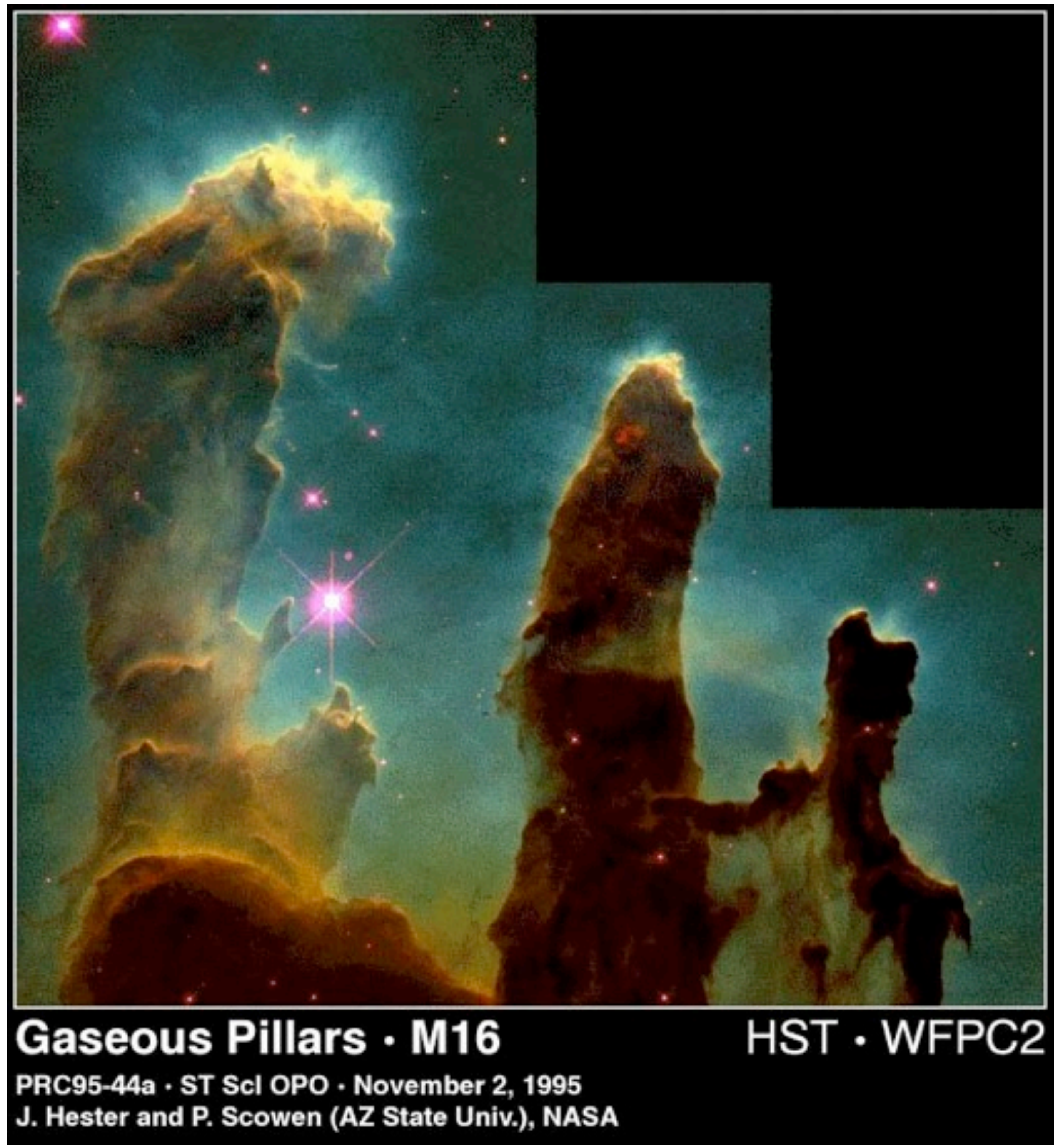
- Dust: ~25Å–1cm
- Widespread, 1% by mass (ISM)
- Opaqueness of matter
- Heating & cooling
- Sink of heavy elements (>Na)
- Provides surface for catalytic reactions & adsorption







I. Light interaction with grains



Basics definitions

- Extinction = absorption + scattering: $Q_{\rm ext} = Q_{\rm abs} + Q_{\rm sca}$
- Cross-section for grain of radius "a": $C_{\rm ext} = \pi a^2 Q_{\rm ext}$
- Size parameter for a wavelength "λ": $x = \dfrac{2\pi a}{\lambda}$
- Complex refractive index: $m = n - ik$
- Single-scattering albedo: $\omega = 1 - Q_{\rm sca}/Q_{\rm ext}$
- Phase function: p(θ)
- Polarization: full Stokes vector (I,Q, U,V)
- Different theories for various combinations of x and m
- Measured refractive indices are needed

Distinct regimes of light scattering

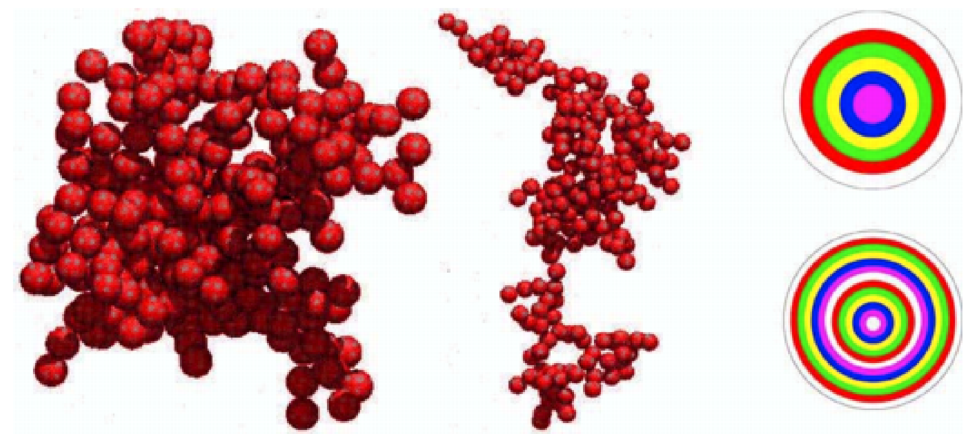
- Small dielectric grains (Rayleigh limit): $x \to 0, |mx| \to 0$

$$Q_{\rm abs} \propto a, Q_{\rm sca} \propto a^4, p(\theta) = 3/4(1+\cos^2\theta)$$

- Huge grains (geometric optics): $x \to \infty, 2x|m-1| \to \infty$

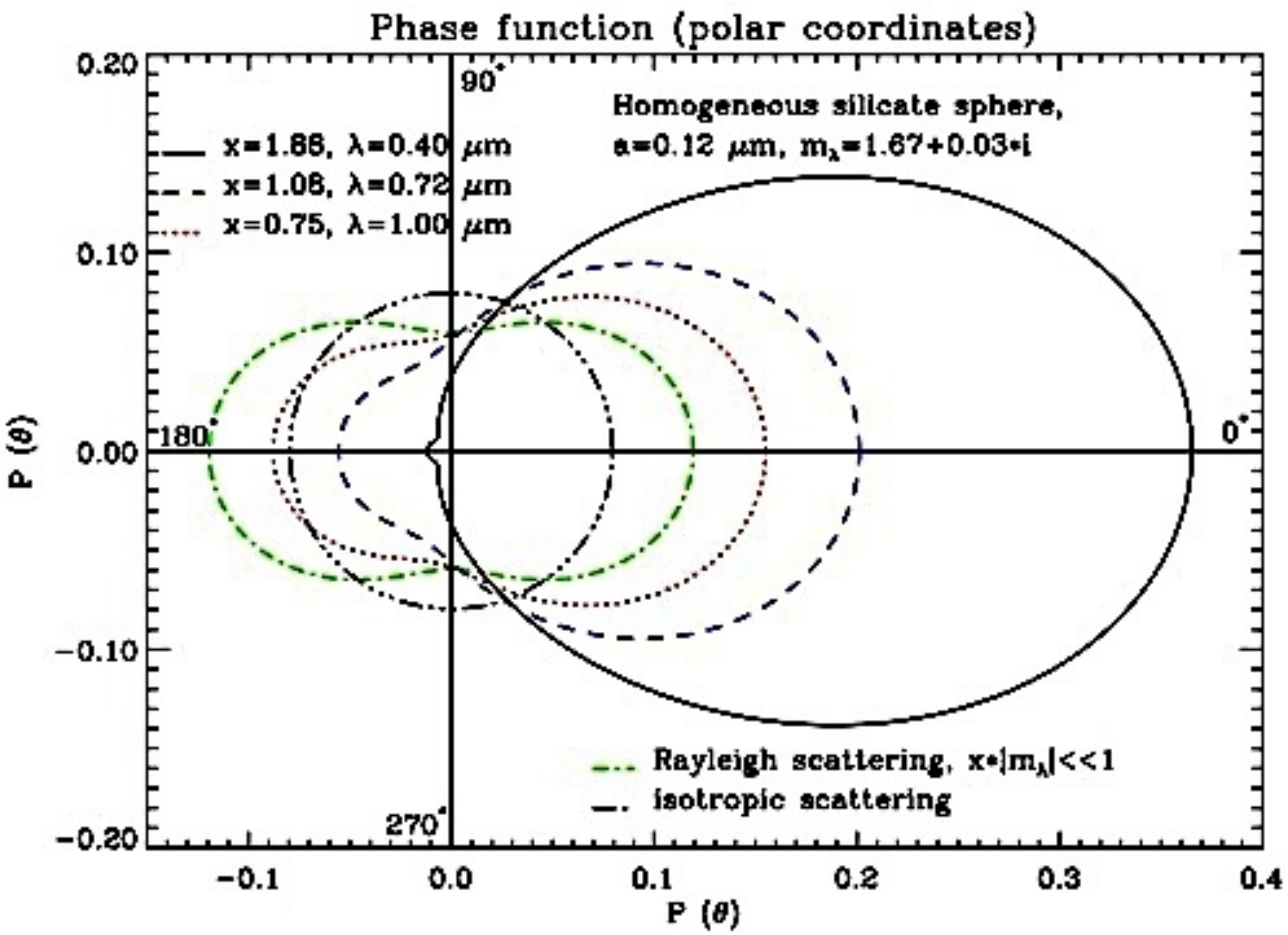
$$Q_{\rm ext} = 2,$$
$$4kx \gg 1 : Q_{\rm abs} = 2,$$
$$4kx \ll 1 : Q_{\rm abs} \sim a$$

forward scattering

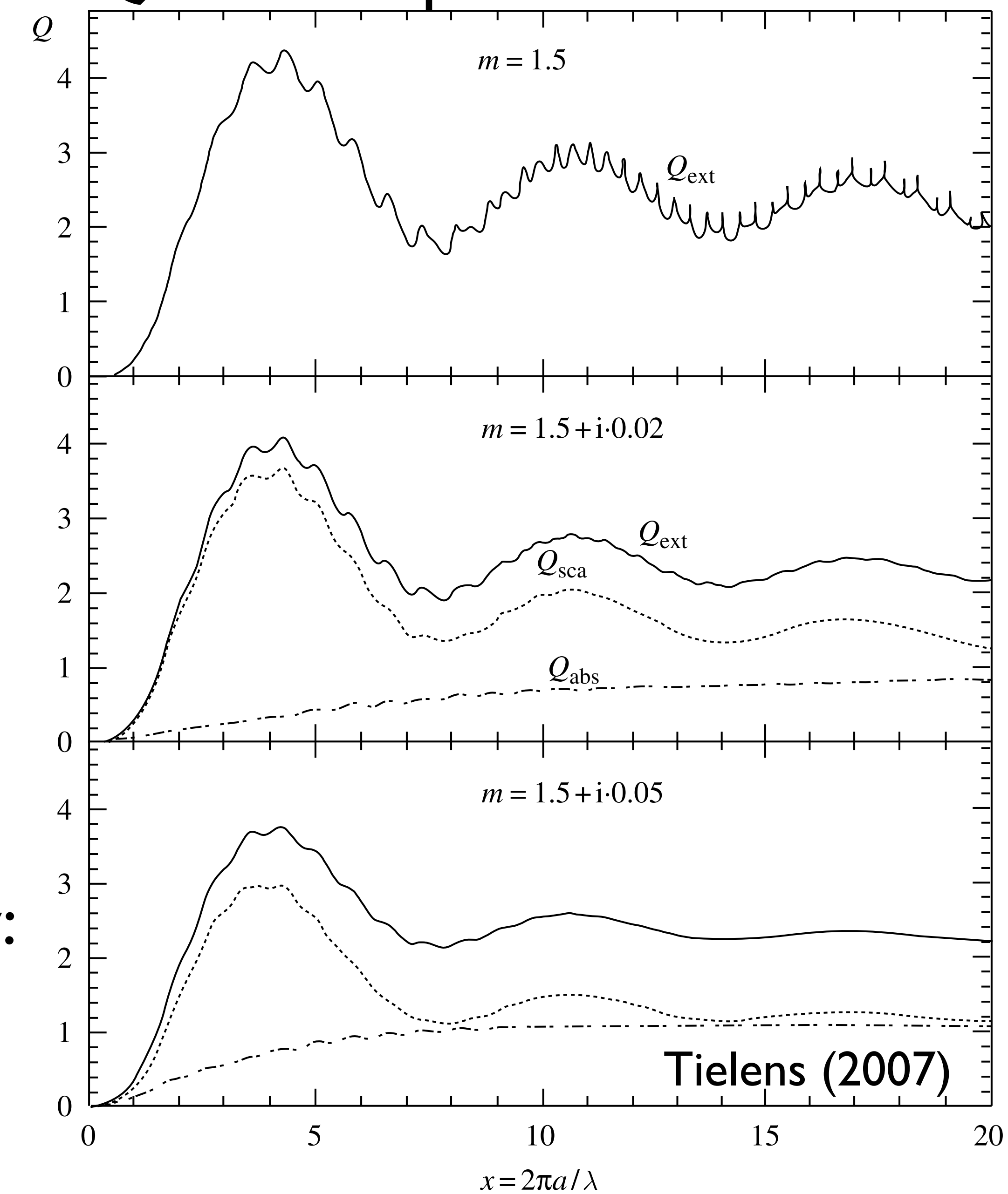


- Intermediate case: need exact theory
  - Mie theory for homogeneous spheres (Mie 1908)
  - Multilayered spheres (Voshchinnikov et al. 2004)
  - Infinite/finite cylinders (Bohren & Huffman 1983)
  - Spheroidal particles (Asano 1979)
  - Discrete Dipole Approximation for arbitrary 3D particles (Purcell & Pennypacker 1973)

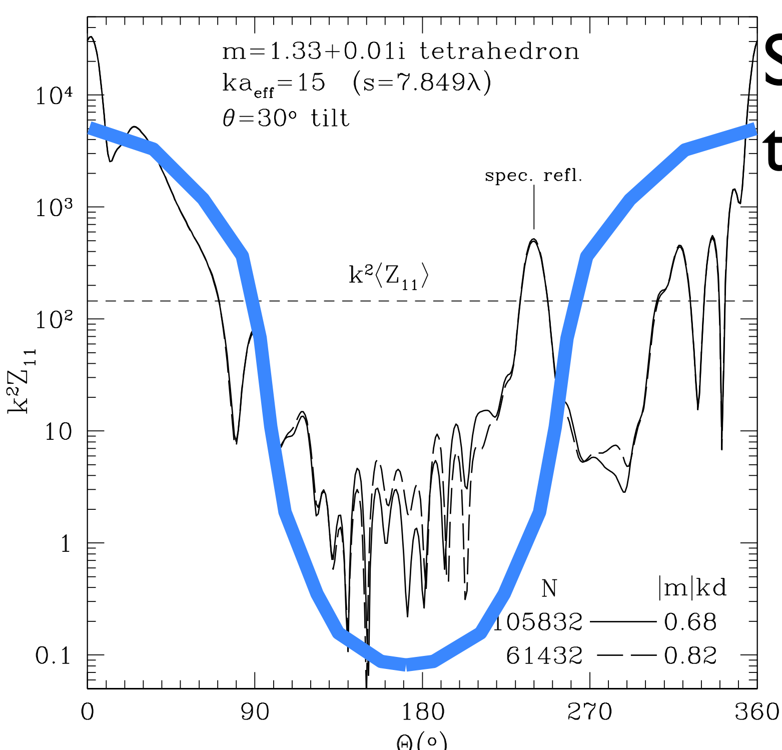
Light interaction with grains: examples



Q-factors: sphere



Scattering efficiency: tetrahedron

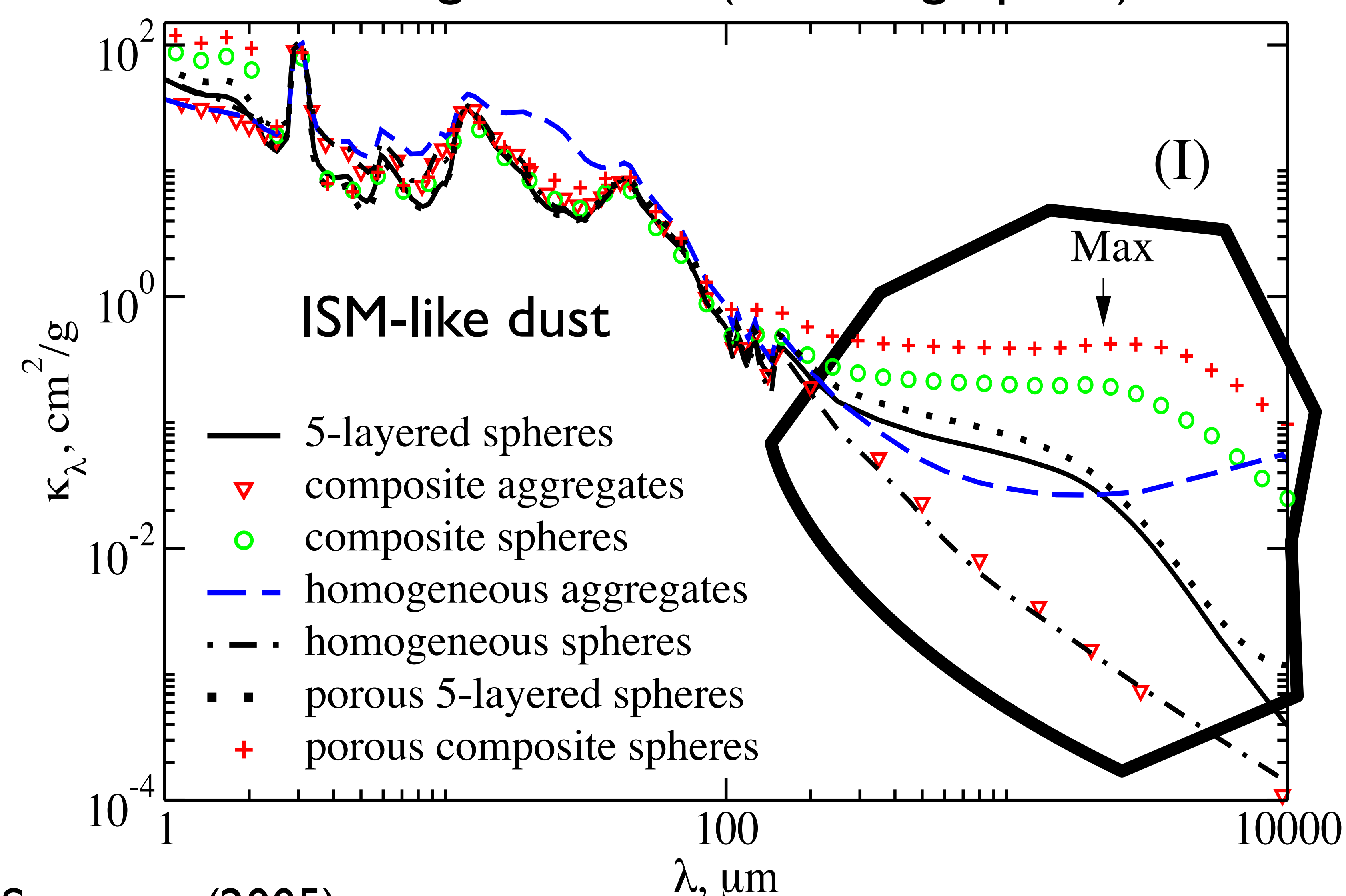


Draine (2000)

- Database of optical constants & properties:
  http://www.mpia-hd.mpg.de/HJPDOC/index.php

Light interaction with grains: opacities

- Extinction per unit mass of gas (cm²/g): $\kappa(\nu) \propto \pi a^2 Q_{\rm ext}(\nu, a) N_{\rm gr}(a) \dfrac{m_{\rm d}}{m_{\rm g}}$
- Disks are optically thick: λ ≲ 100 μm
- Dust mass in PPDs at distance *D* with flux S_ν: $M_{\rm dust} = \dfrac{S_\nu D^2}{k_\nu B_\nu(T_{\rm dust})}$
- Grain sizes, topology, porosities
- Conducting materials (Fe, FeS, graphite)



Semenov (2005)

$\kappa(\nu) = \kappa_{230}(\nu/230\mathrm{GHz})^{\beta_1}$

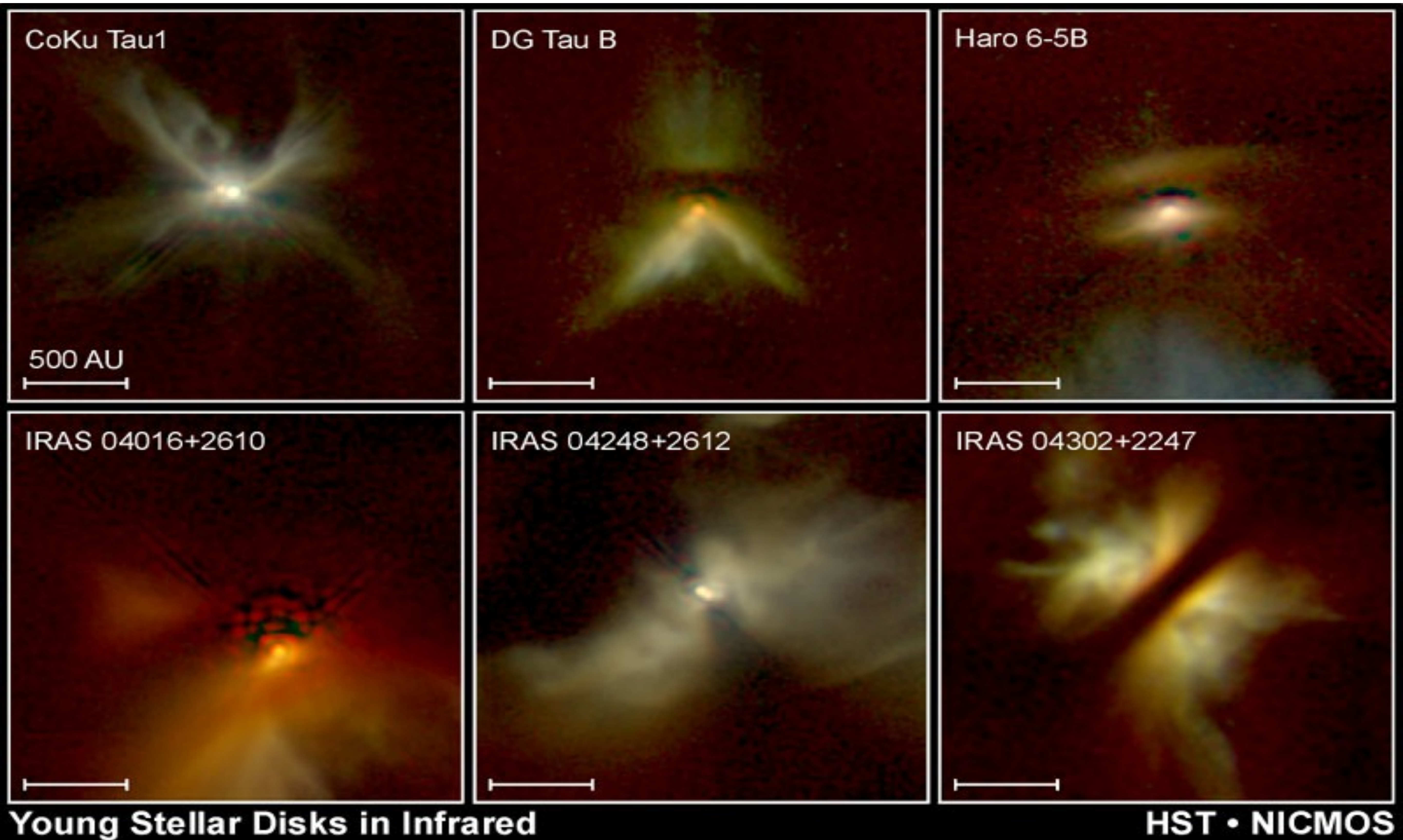
Dust emissivity slope β:

- ~2 for small ISM dust
- >0.5 for large grains

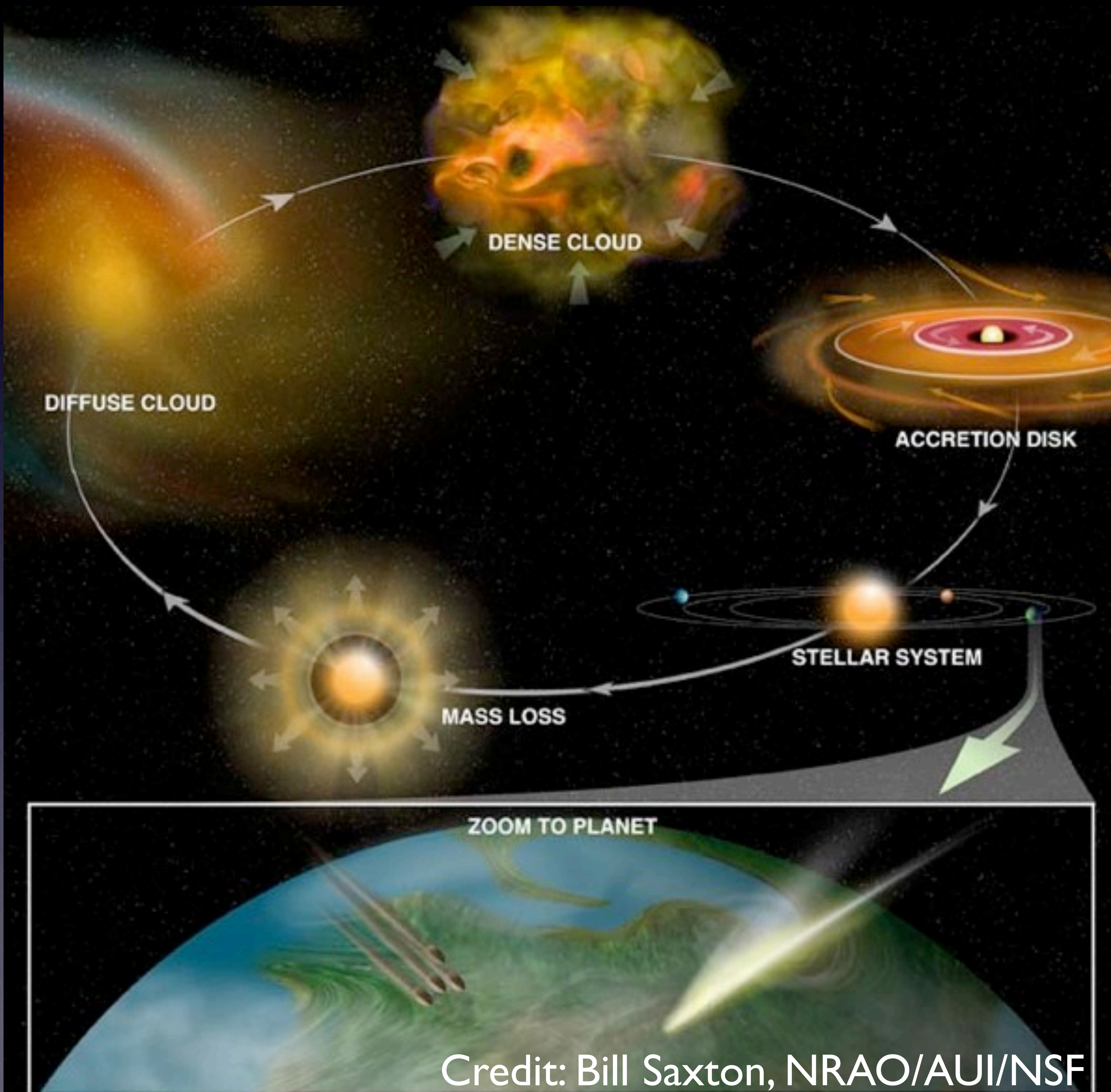
I. Light interaction with grains: Summary

- Opacities
- Thermal balance
- Dust emissivity slope varies at >100µm
- Sizes, topology, porosity, conducting materials
- Tools & databases of optical constants & properties

II. Structure and evolution of protoplanetary disks



Life cycle of dust in Galaxy



- Nucleation and initial growth in AGB shells
- Mixing & growth in the ISM
- Collapse of a dense cloud
- Rotating accretion disk
- Gas and dust "dispersal"
- Formation of planetary system
- A new AGB star at the end

Disk structure & evolution

- Conservation & redistribution of angular momentum
- Gas viscosity
- Gravity
- Equation of state
- Initial mass
- Initial angular speed of a cloud

- Characteristics: R_{disk}, M_{disk}, T_{dust}, T_{gas}, surface density, accretion rate, ...

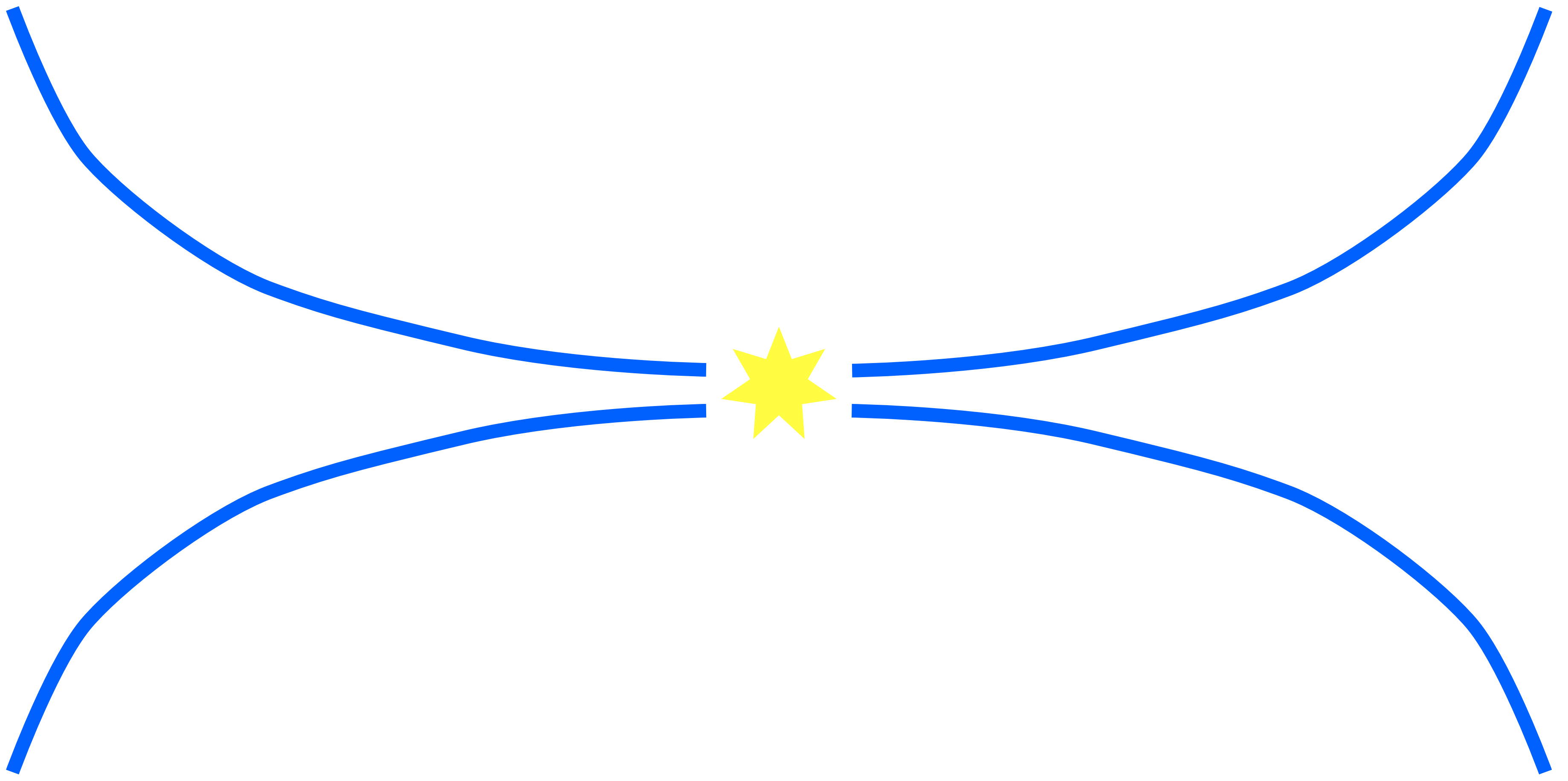
Disk vertical structure

- Equation of state: $P = c_{\rm s}^2 \rho$
- Hydrostatic equilibrium: $\frac{dP}{dz} = \rho \Omega_{\rm K}^2 z$
- Assuming isothermal structure in z-direction:
  - Density profile: $\rho = \rho_0 \exp(-\frac{z^2}{H^2})$
  - Disk pressure scale height: $H = \sqrt{2} c_{\rm s} \Omega_{\rm K}^{-1}$
  - *H* ~0–5

Disk shape

- Assume power-law model for temperature: $T \propto r^{-q}, c_\mathrm{s} \propto r^{-q/2}$
- Keplerian rotation: $\Omega_\mathrm{K} = \sqrt{GM_*/r^3} \propto r^{-3/2}$
- Aspect ratio: $H/r = \sqrt{2}c_\mathrm{s}/r\Omega_K \propto r^{(1-q)/2}$

- Flaring disks when *(1-q)/2>0, q<1*
- A typical disk with *q=1/2*: $H/r \propto r^{1/4}$



Disk radial structure

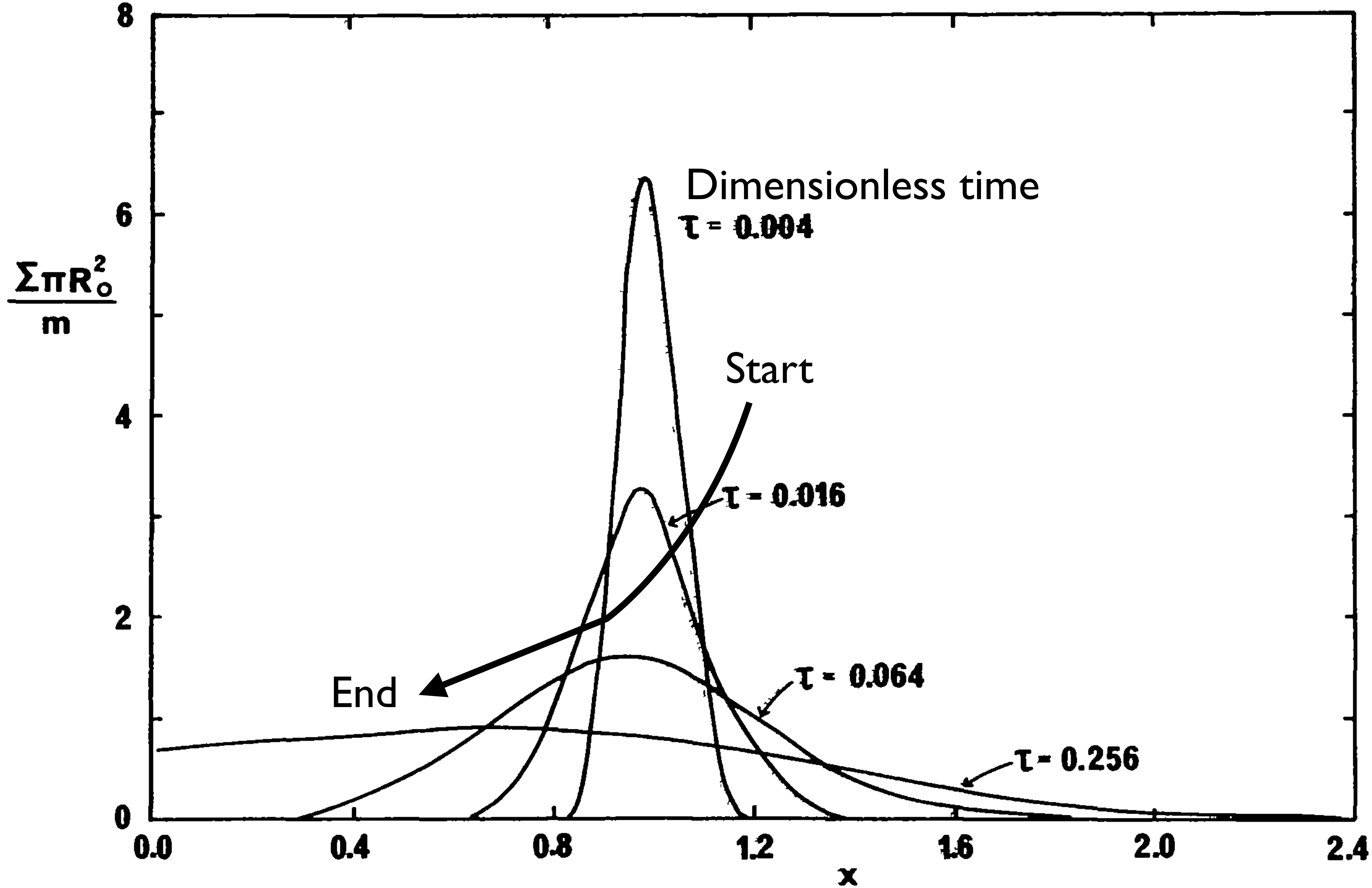
- Anomalous viscosity (Shakura & Sunyaev 1973): $\nu = \alpha c_\mathrm{s} H$
- α ~0.01 (MHD turbulence), ~1 (gravitational instability)
- Conservation & redistribution of angular momentum

- Vertically-integrated quantities
- Classical model of 1D viscous evolution (Pringle 1981, Linden-Bell & Pringle 1974, Shakura-Sunyaev 1973):

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{R}\frac{\partial}{\partial R}\left[R^{1/2}\frac{\partial}{\partial R}\left(\nu \Sigma R^{1/2}\right)\right]$$

- "Early" disk: $\Sigma(r) \propto r^{-1}$
- "Late" disk: $\Sigma(r) \propto r^{-3/2}$

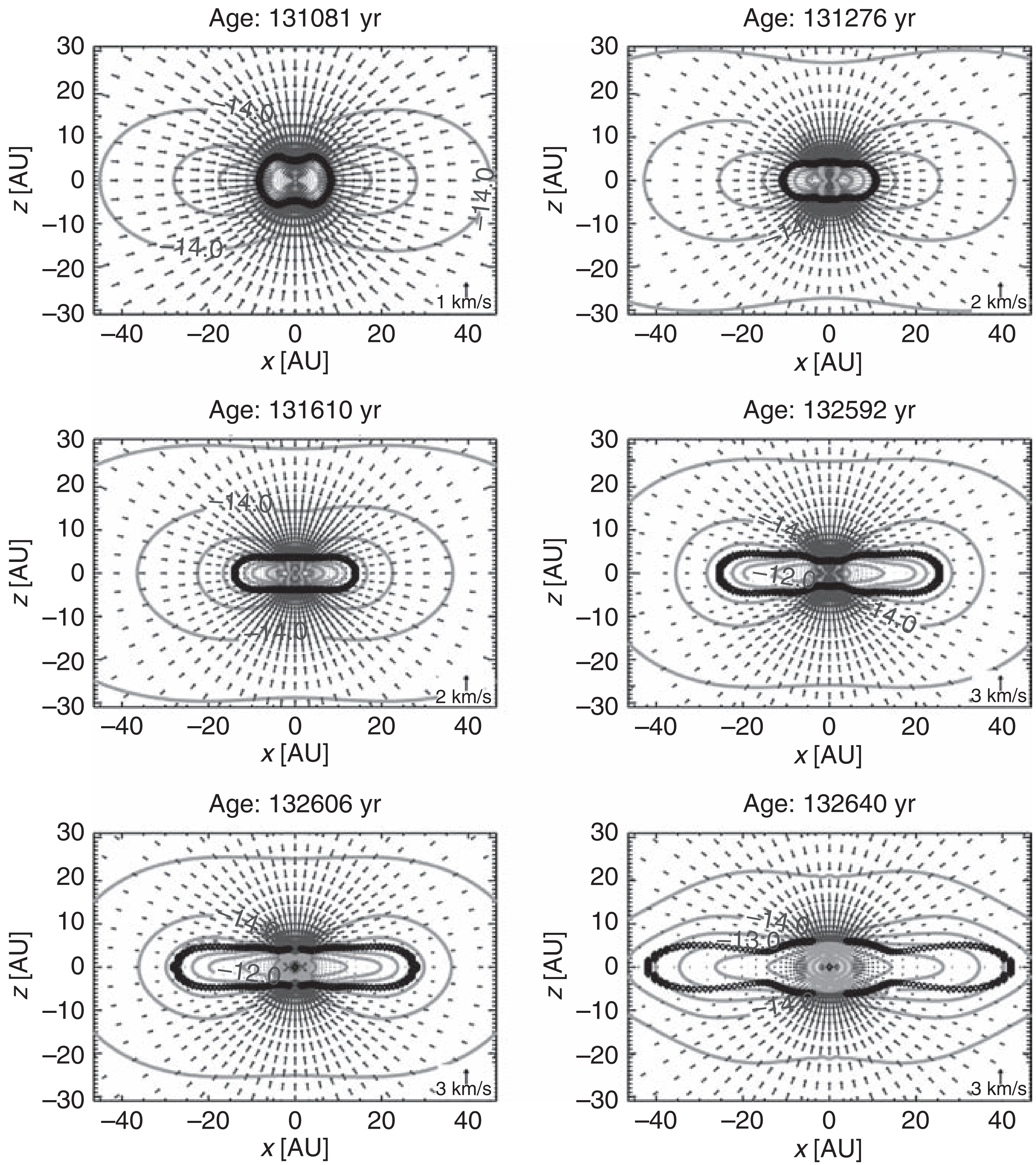
Evolution of disk: 1D

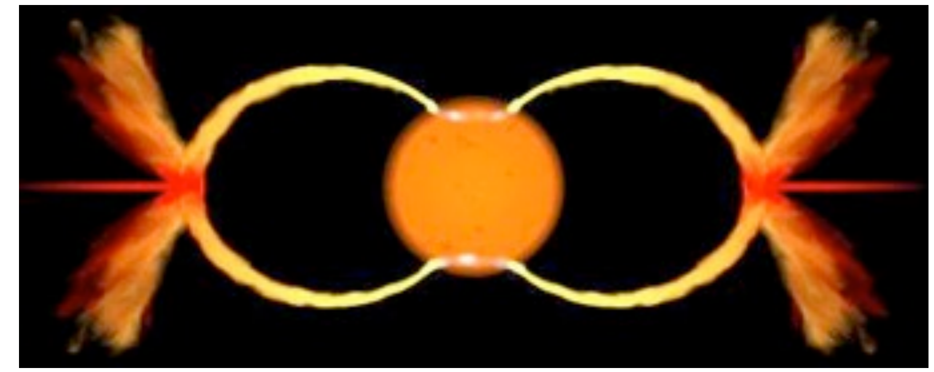


Surface density: Power-law with tapered edge

Pringle (1981)

Evolution of disk: 2D



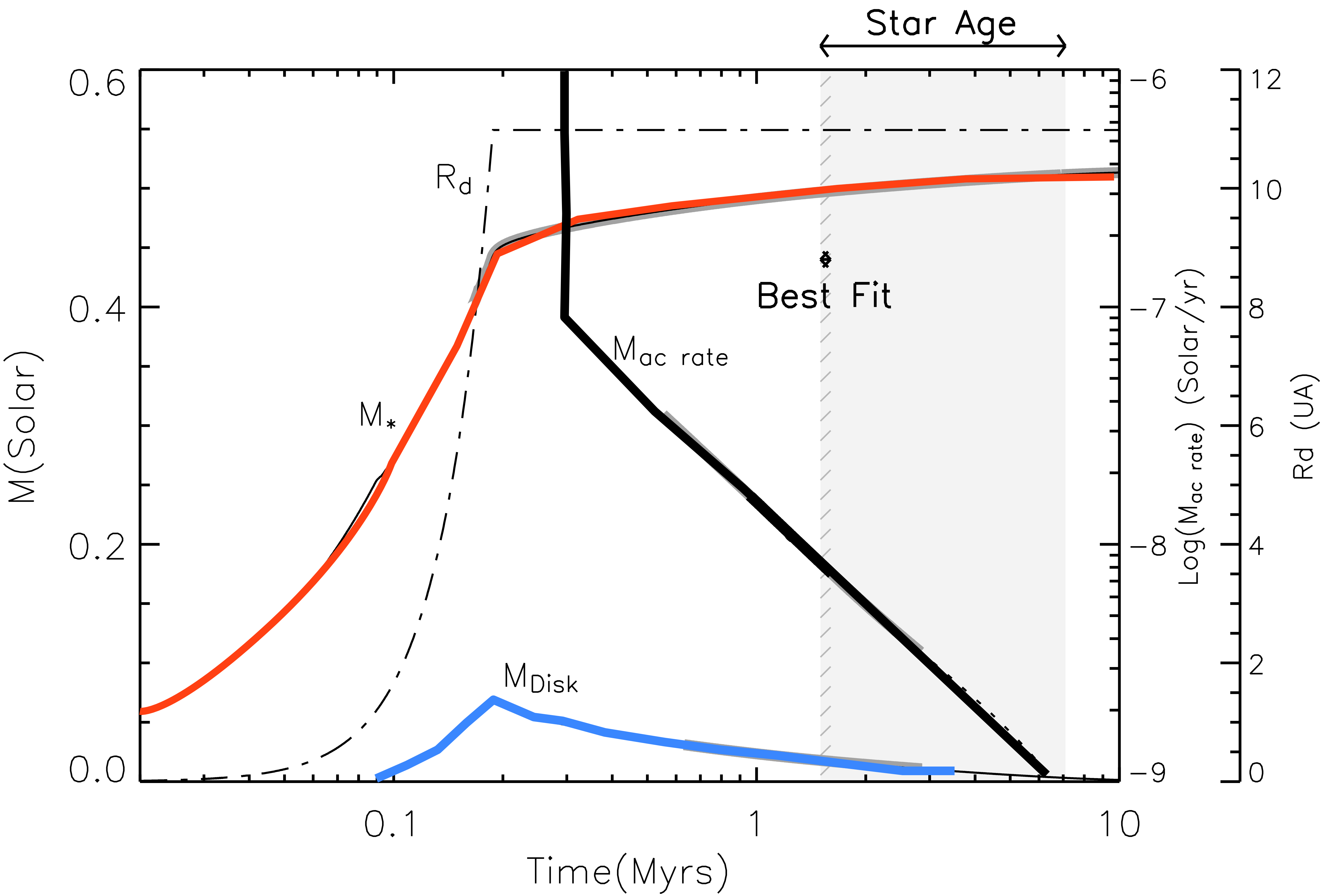


- Supersonic to subsonic transition (black line)
- Accretion flow (arrows)

- Shock passage: destruction of molecules and grains
- Accretion heating
- Initial disk is decreting disk
- Rapid phase: ~0.1–0.5 Myr

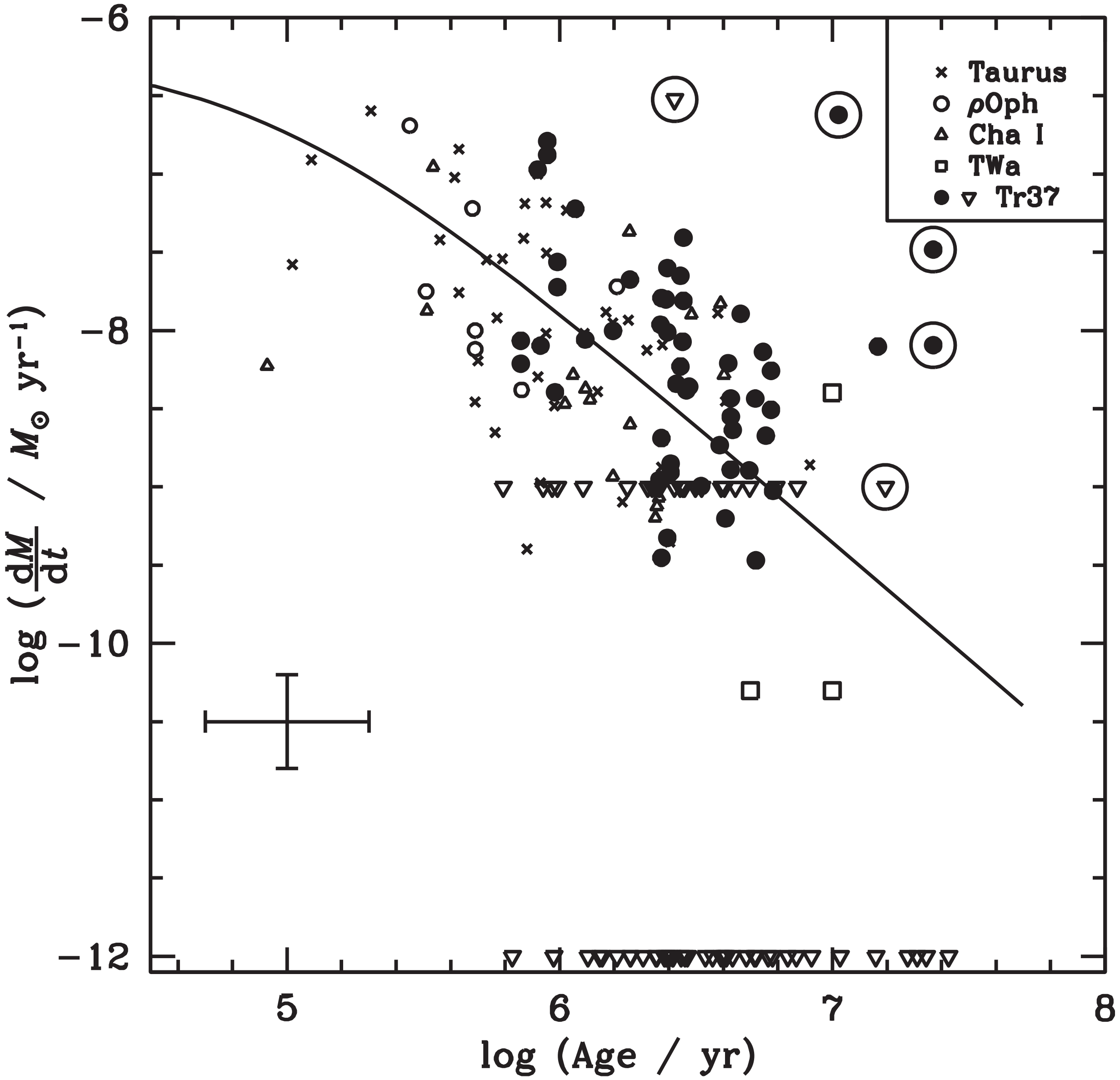
Gail & Hoppe (2010)

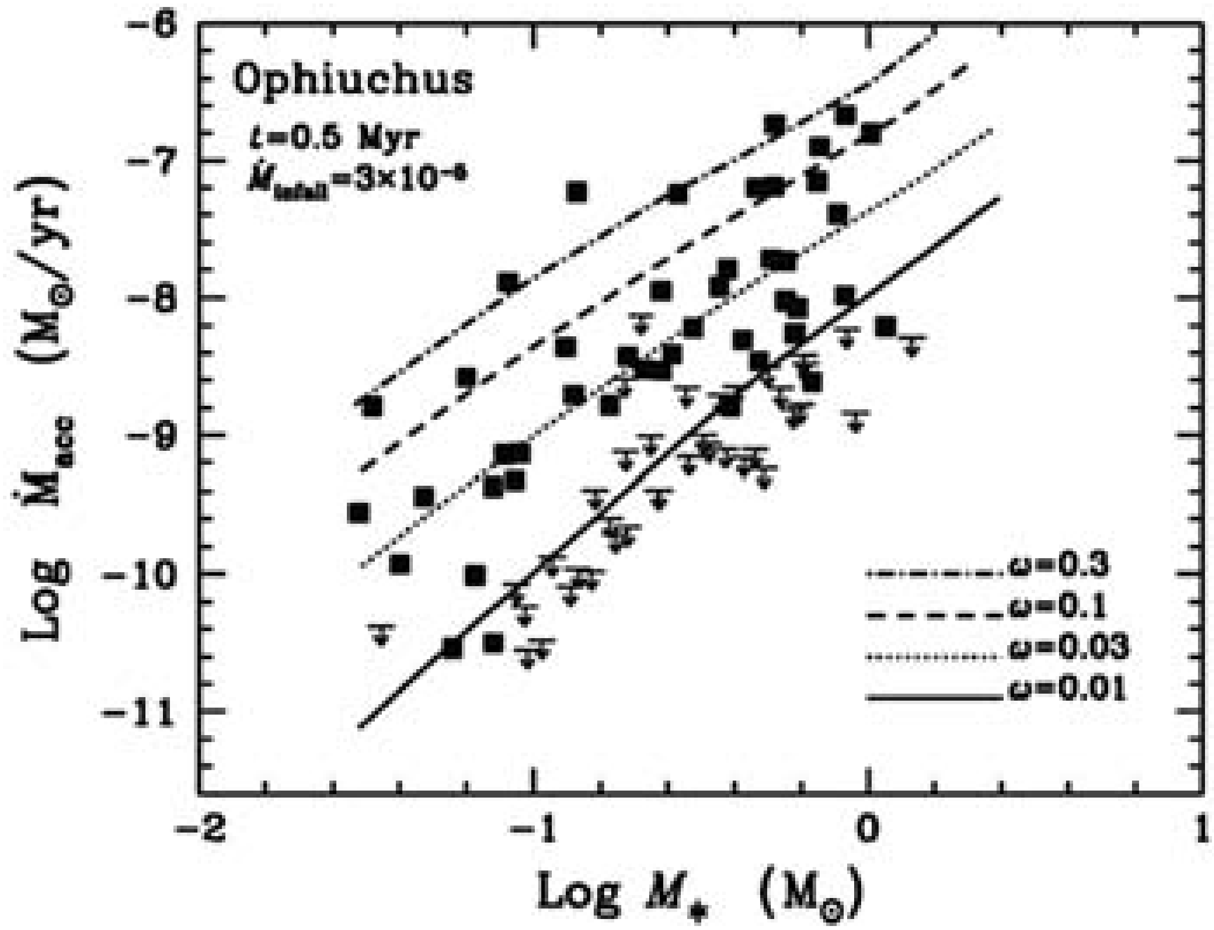
Evolution of a star and a disk



Hueso & Guillot (2005)

Mass accretion rate vs Age





- Mass accretion ceases with time: t_{end} ~10–30 Myr
- Mass accretion rate at given age depends on initial angular momentum

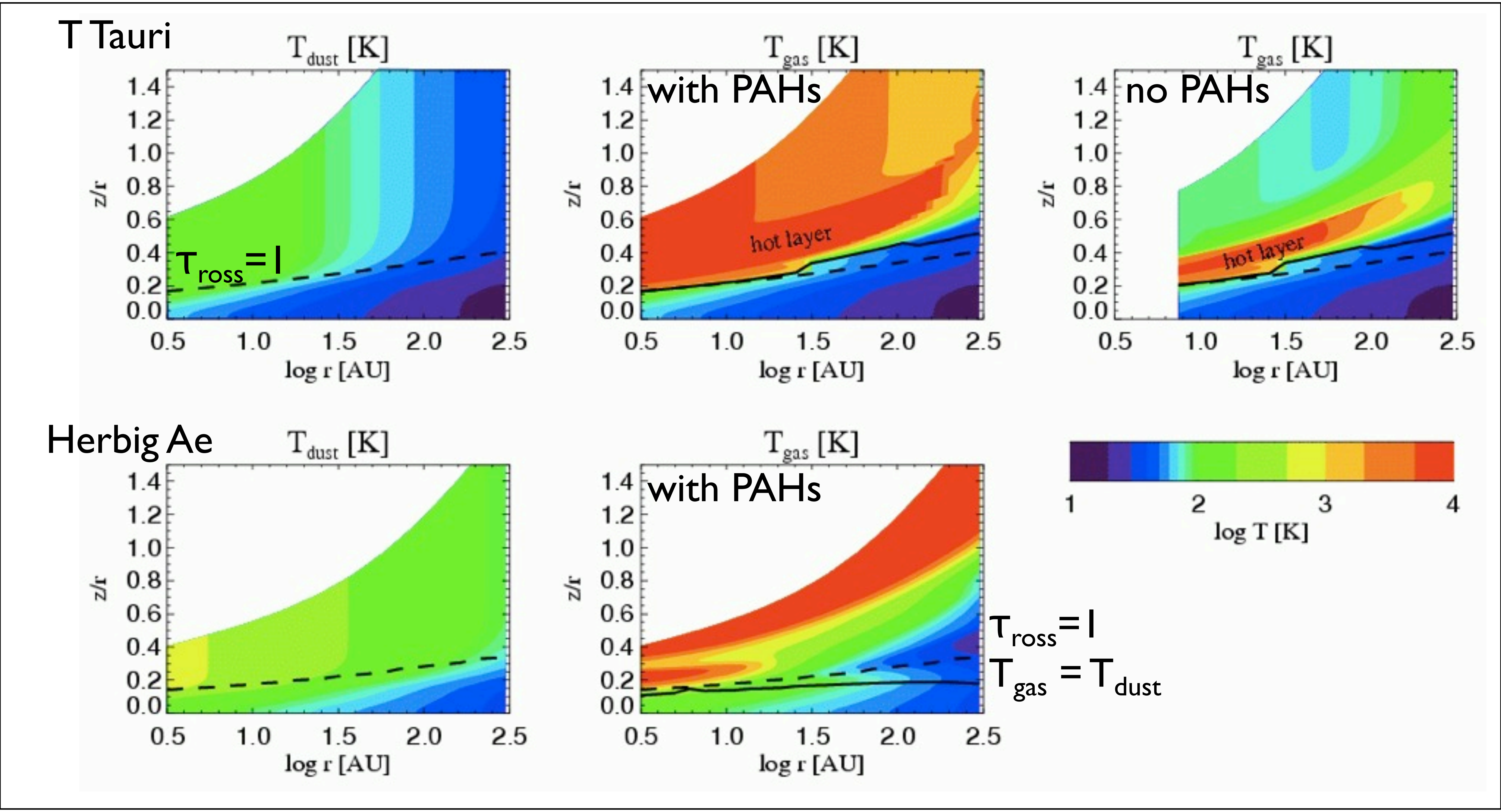
Ciesla & Dullemond (2010)

Detailed disk models

- 1+1/2D passive models (D'Alessio et al. 1998, Dullemond & Dominik 2004):
- Radiation of a central star
- Radiative transfer:
  - plane-parallel/2D,
  - frequency-averaged (grey),
  - frequency-dependent
- Heating & cooling of gas
- Hydrostatic equilibrium

- 3D MHD models (e.g., Flock et al. 2011):
- ~10–100 orbital periods
- Isothermal or simple power-law for T
- Local disk patches
- Realistic turbulence

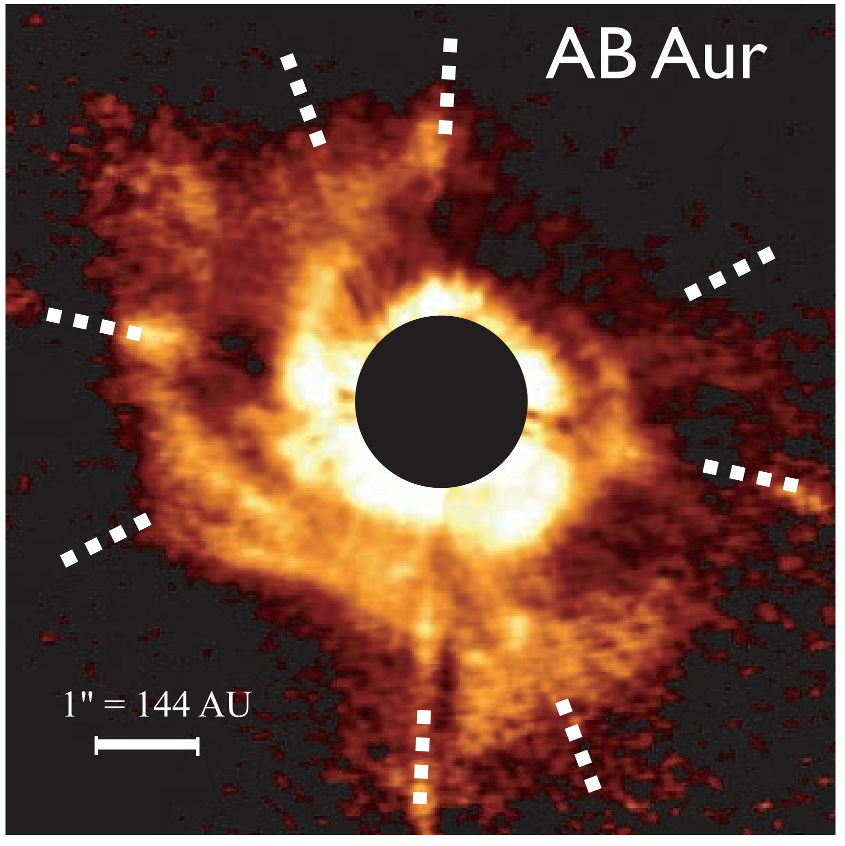
Passive steady-state disk: 2D

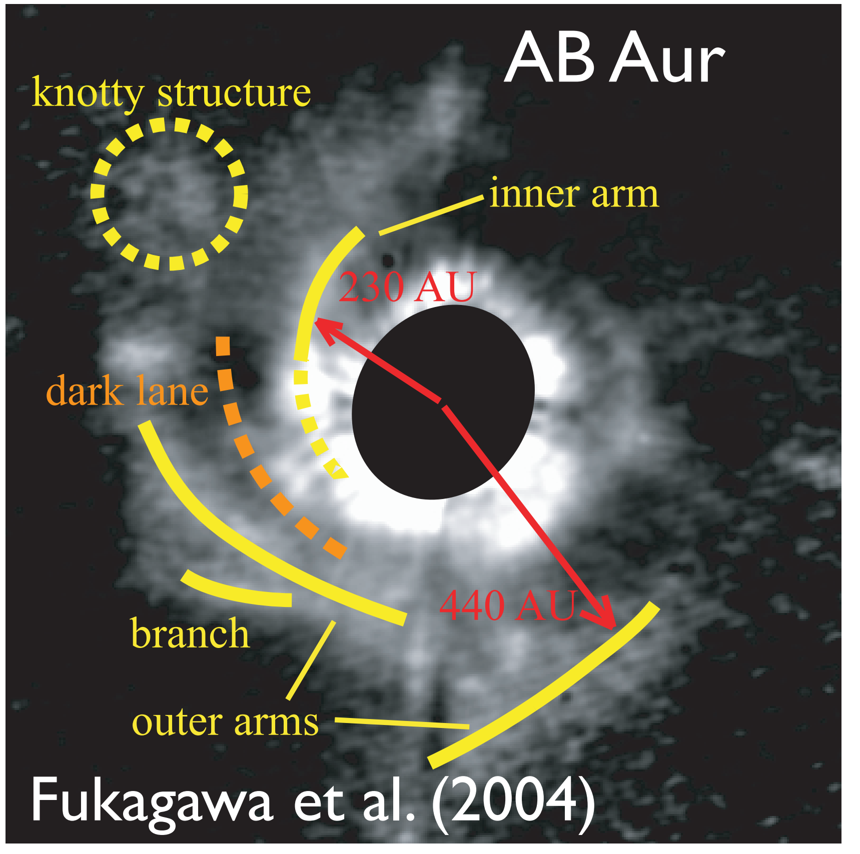


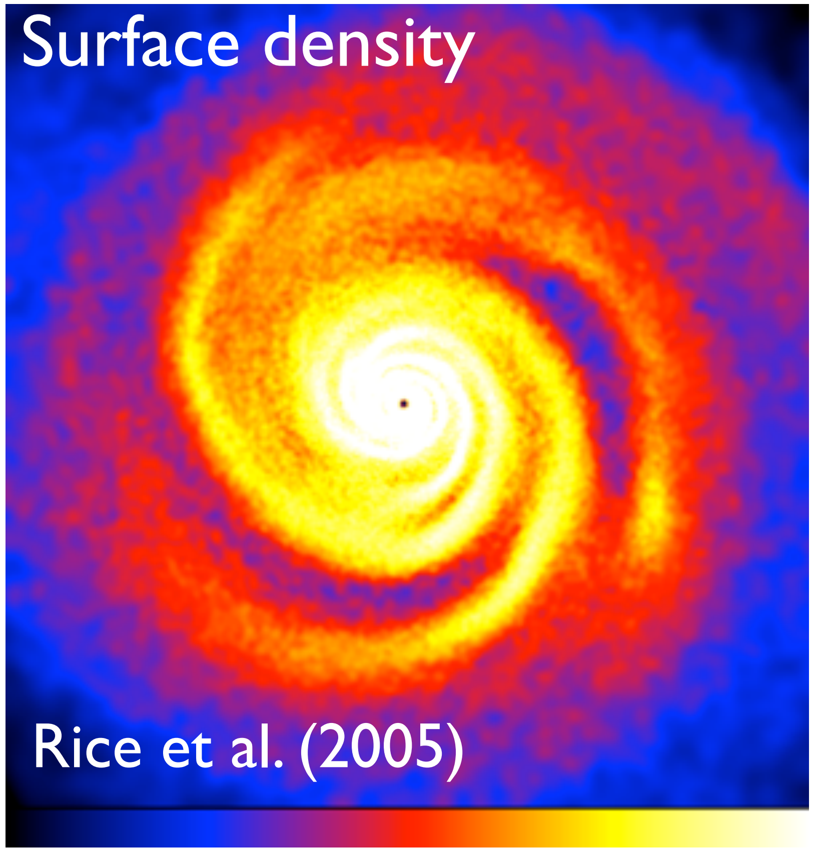
Flaring disks, $T_{gas}>T_{dust}$ in atmosphere

Kamp et al. 2005; Jonkheid et al. 2004; Nomura & Millar 2005; Woitke et al. 2009

Real disks: 3D!

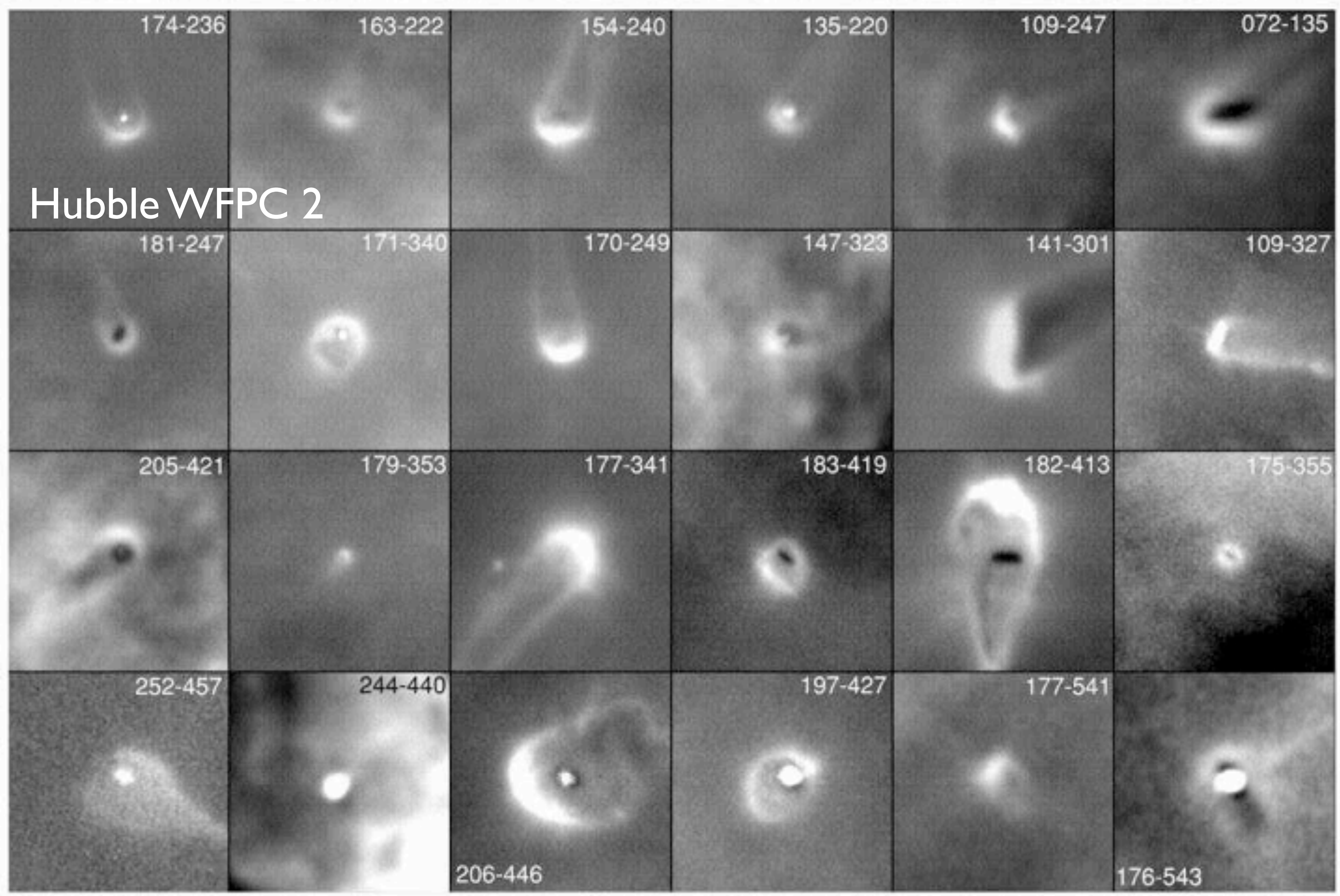






- Gravitational instabilities
- Interaction with a nearby star
- Planet-disk interactions
- Large-scale turbulent waves

Photoevaporation of disks



- UV/X-ray radiation from the star: 1–10 AU
- Superheated atmosphere gas flows away
- T Tauri star: $M_{evap} \sim 10^{-9}$–10^{-8} M_{Sun}/year
- Clearing of inner regions

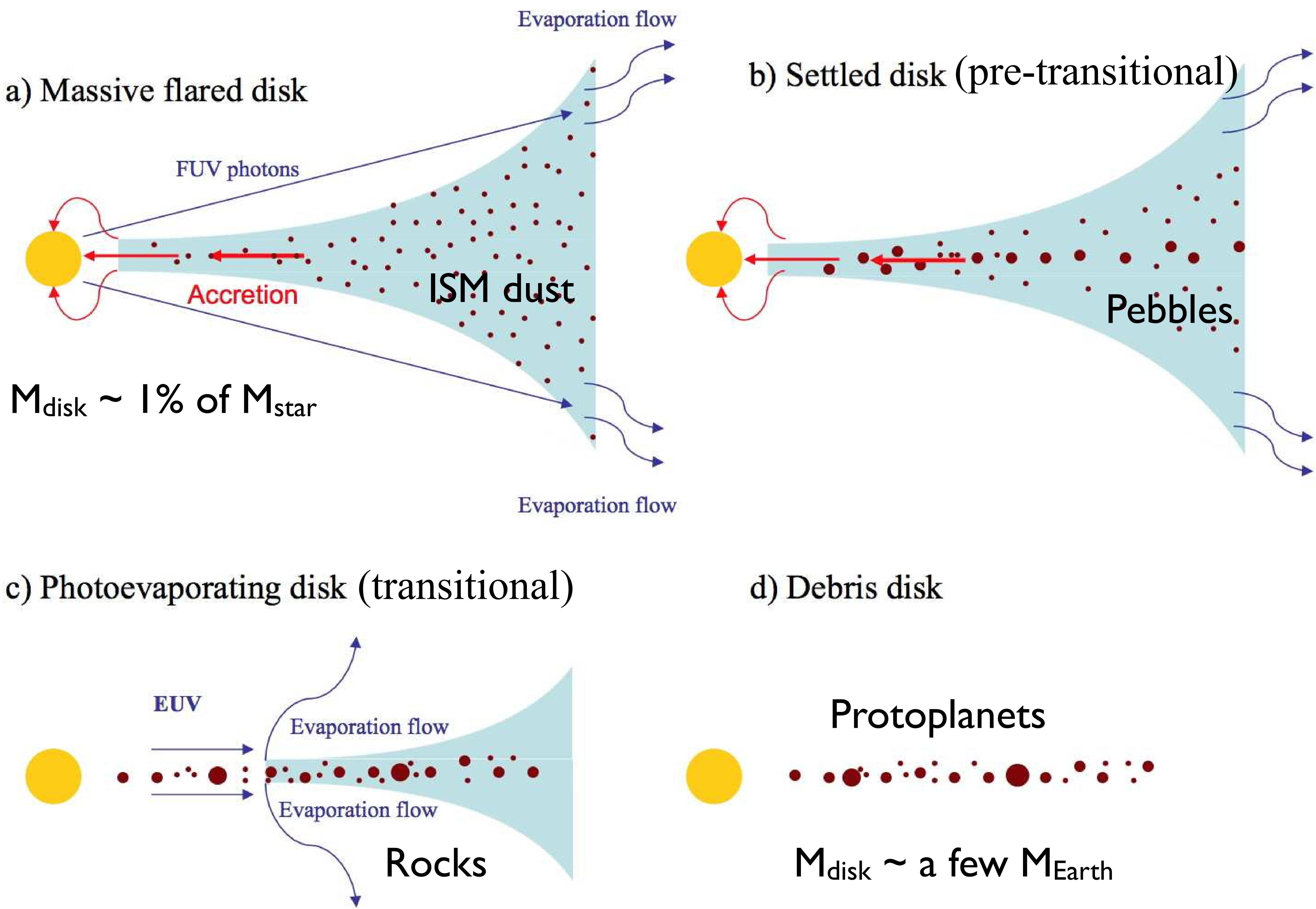
Gorti et al. (2009)

II. Structure and evolution of PPDs: Summary

- Outcome of cloud collapse: ~ 0.1–0.5 Myr
- Anomalous viscosity (turbulence)
- M_{acc} ceases with time
- M_{acc} depends on initial angular momentum
- "Early" disks: accretion heating
- "Late" disks: passively reprocess L_*
- 3D structure
- $\Sigma(r, t)$ can depart from a power law
- Photoevaporation

III. Dust evolution in PPDs

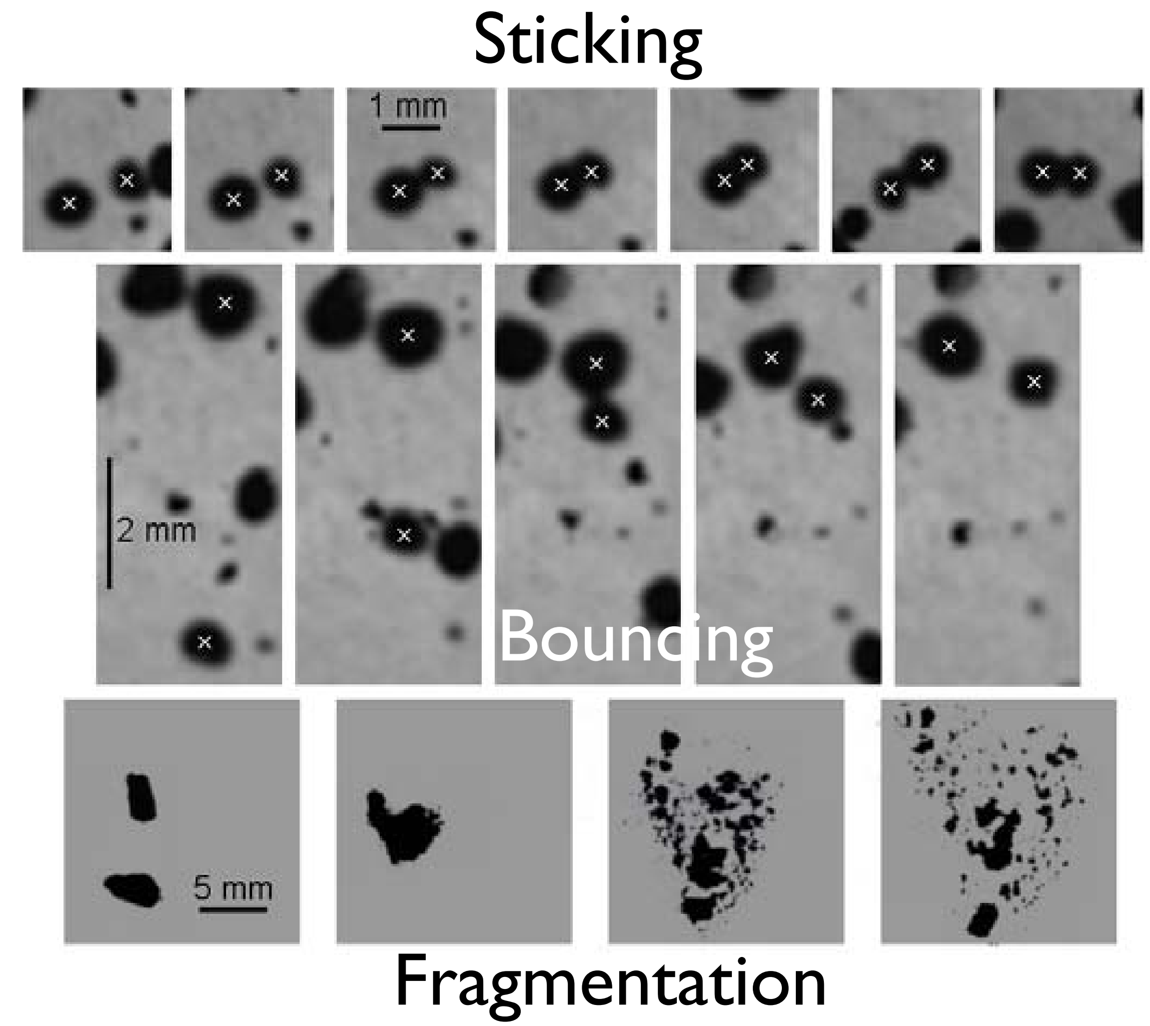
Dust evolution in disks: ~1–10 Myr



Williams & Cieza (2011)

Dust evolution in a nutshell

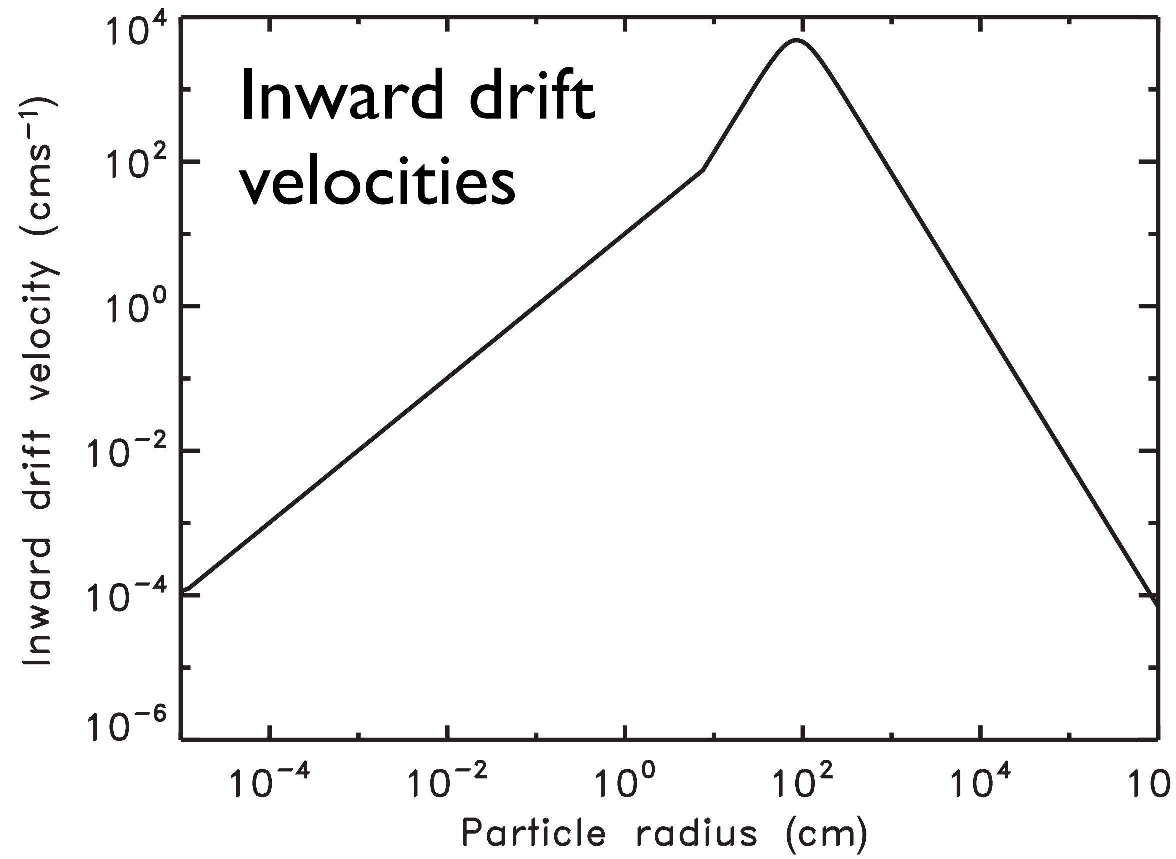
- <10 cm/s collisions due to Brownian motion
- Sticking
- >1μm–1cm grains sediment
- Rain drops-like growth regime
- Fragmentation (*V*>10–100m/s)
- Erosion
- Turbulence returns small grains upward
- Inward drift
- Mostly proved by experiments



Weidenschilling et al. (1993), Blum (2010)

How to pass a 1m-barrier?

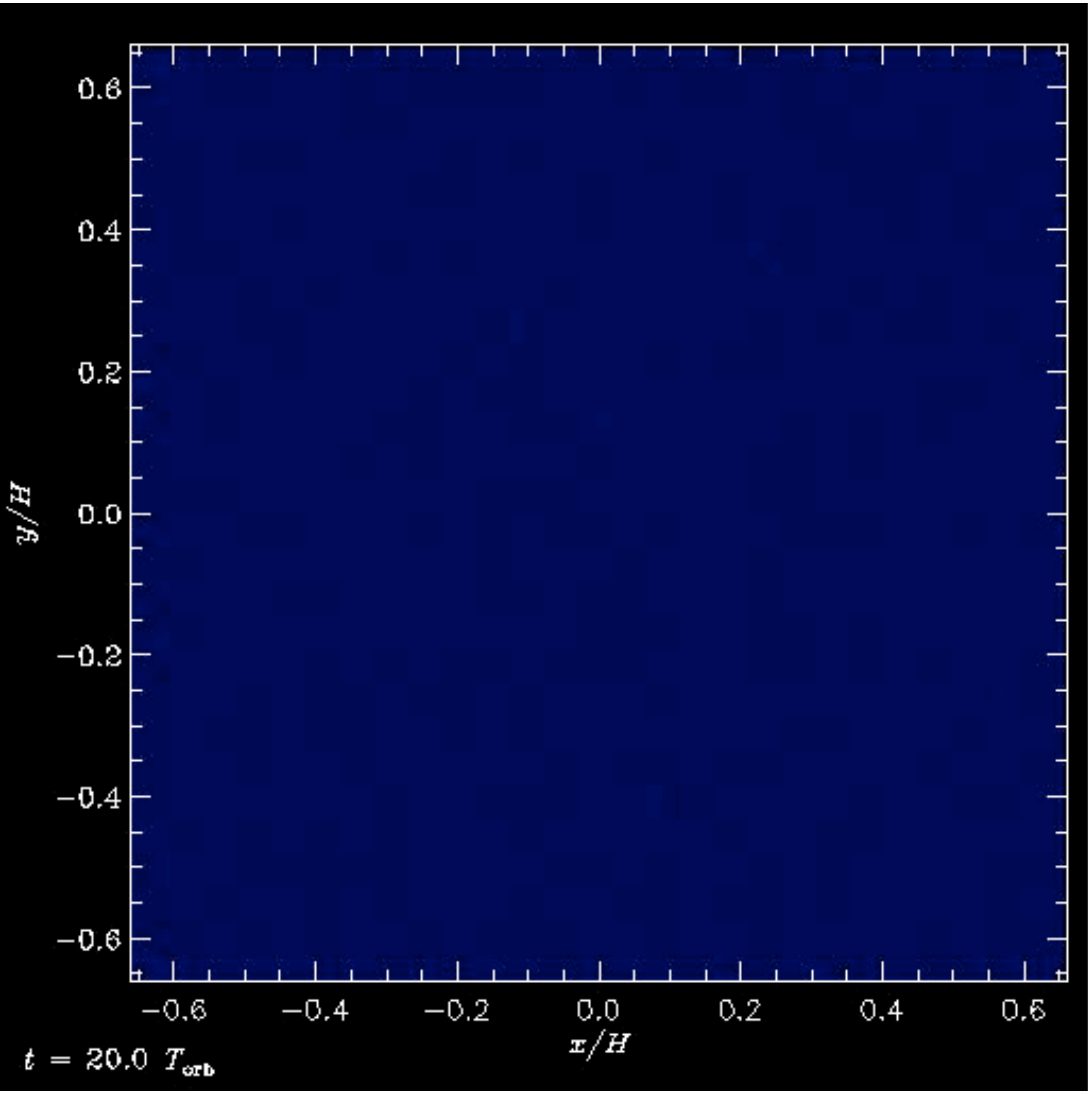
- Big grains ⇒ 100% Keplerian rotation
- Radial pressure gradient ⇒ gas orbits at 99% Keplerian velocity
- Head wind: inward drift
- 1m particle: ~10^4 years from 100 AU
- Vertical settling: ~1 Myr @ 1 AU for 1μm
- Vertical stirring: ~10^4 years @ 100 AU
- Coagulation: ~0.1–2 Myr



Possible mechanisms:
- Gravitational instabilities
- Aerodynamic collection of eroded debris
- Restructuring of fluffy aggregates
- Rapid grain growth in pressure bumps

Ciesla & Dullemond (2010)

A plausible growth mechanism >1m



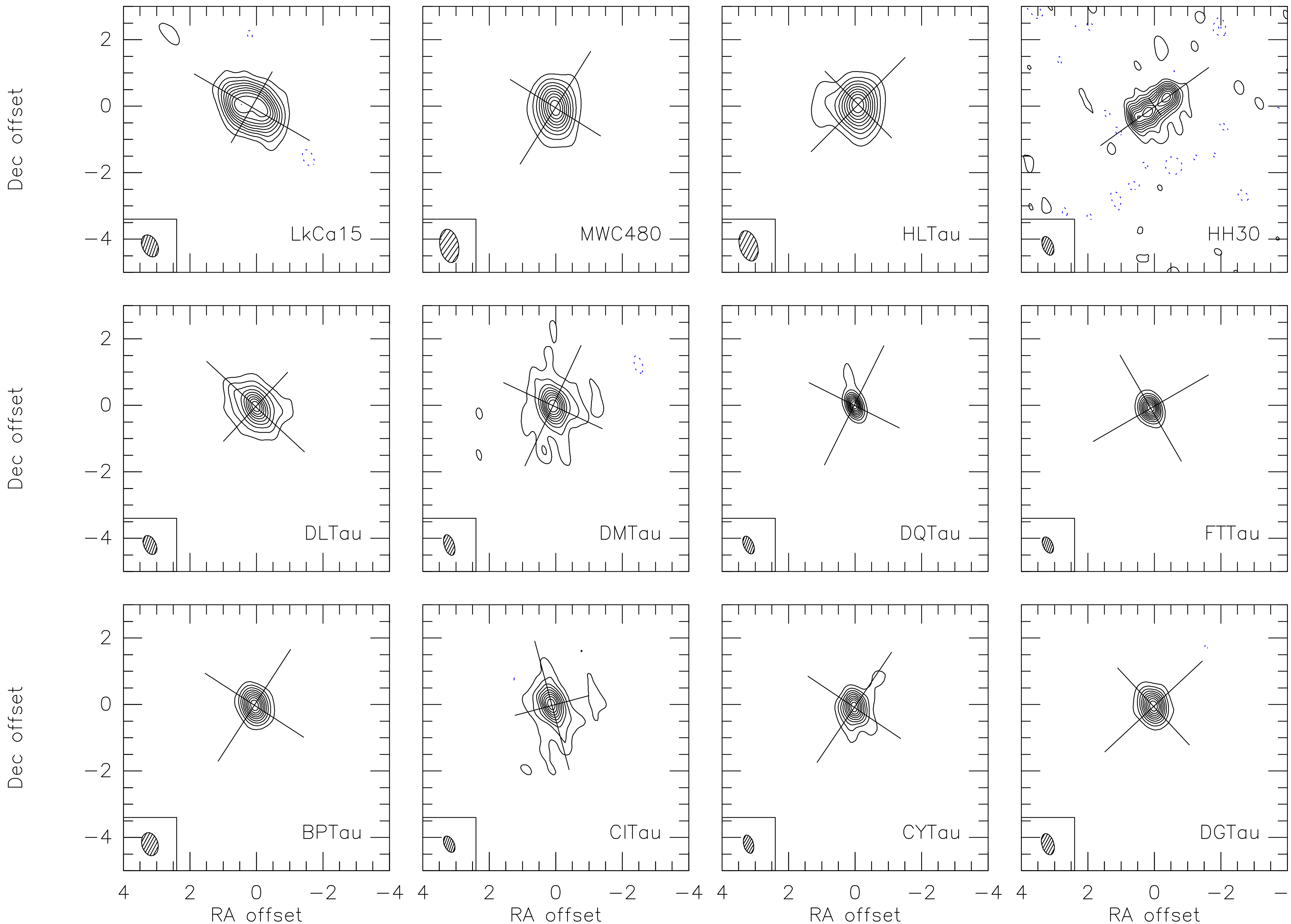
- Corotating patch in midplane
- Weak MHD turbulence
- Density fluctuations
- ~1m-sized "bricks" concentrate in pressure bumps
- Self-gravitation bounds clumps >10 orbital periods
- Local gravitational instabilities
- Mass concentrations ~10^{-4} M_{Earth}

Brauer et al. (2008), Johansen et al. (2011)

III. Dust evolution in PPDs: Summary

- Dust growth ~0.1–2 Myr
- Coagulation, sedimentation, fragmentation, stirring, inward drift
- Inward drift: ~10^3–10^4 years for 1m-particles @ 100 AU
- 1m-barrier for growth
- Self-gravitation & growth in pressure maxima

IV. Dust in protoplanetary disks and the early Solar nebula

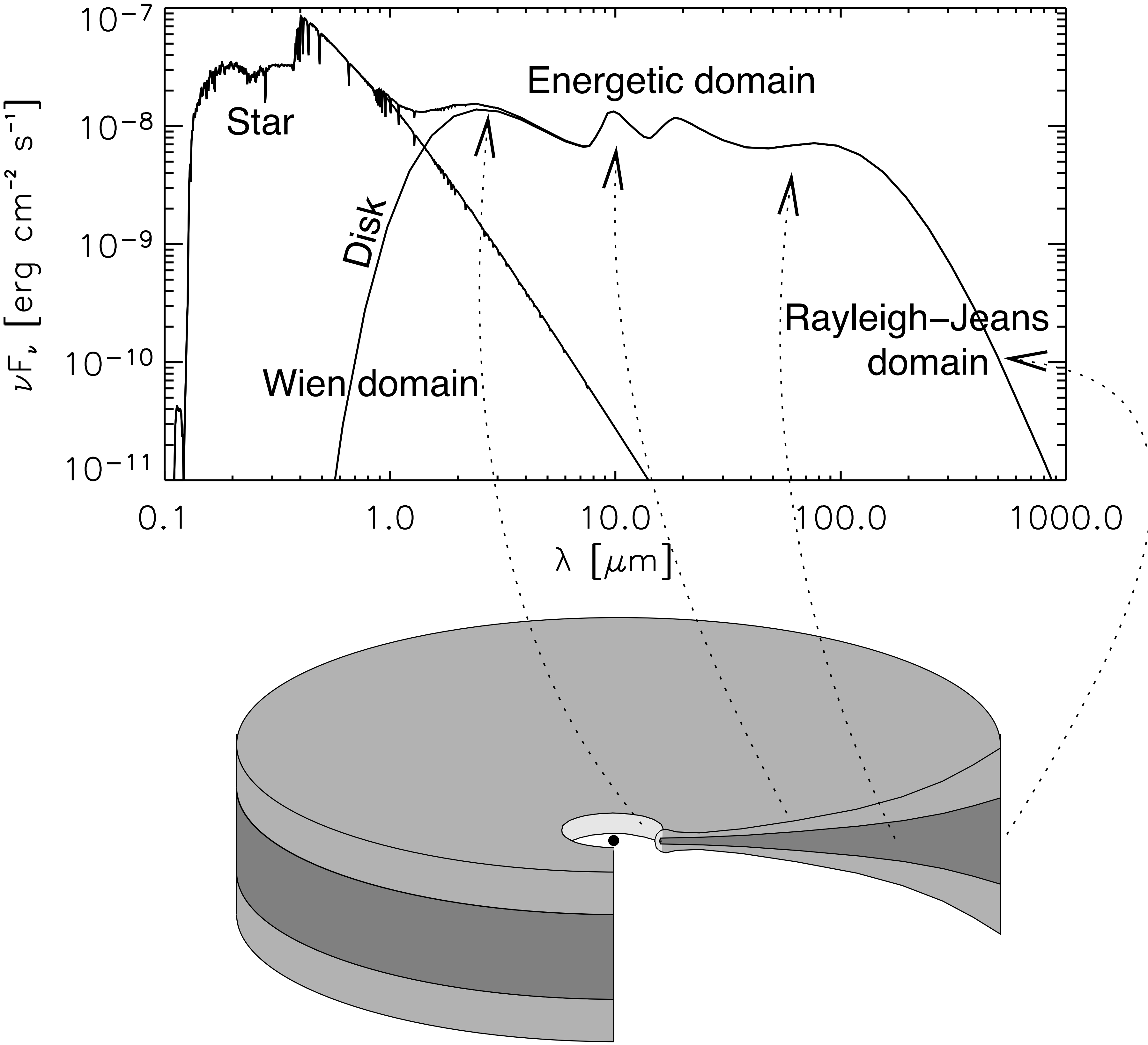


Observational techniques

- IR features
- Spectral Energy Distribution (SED)
- Emission at mm–cm wavelengths
- Resolved IR-mm images
- Surveys of PPDs of various ages

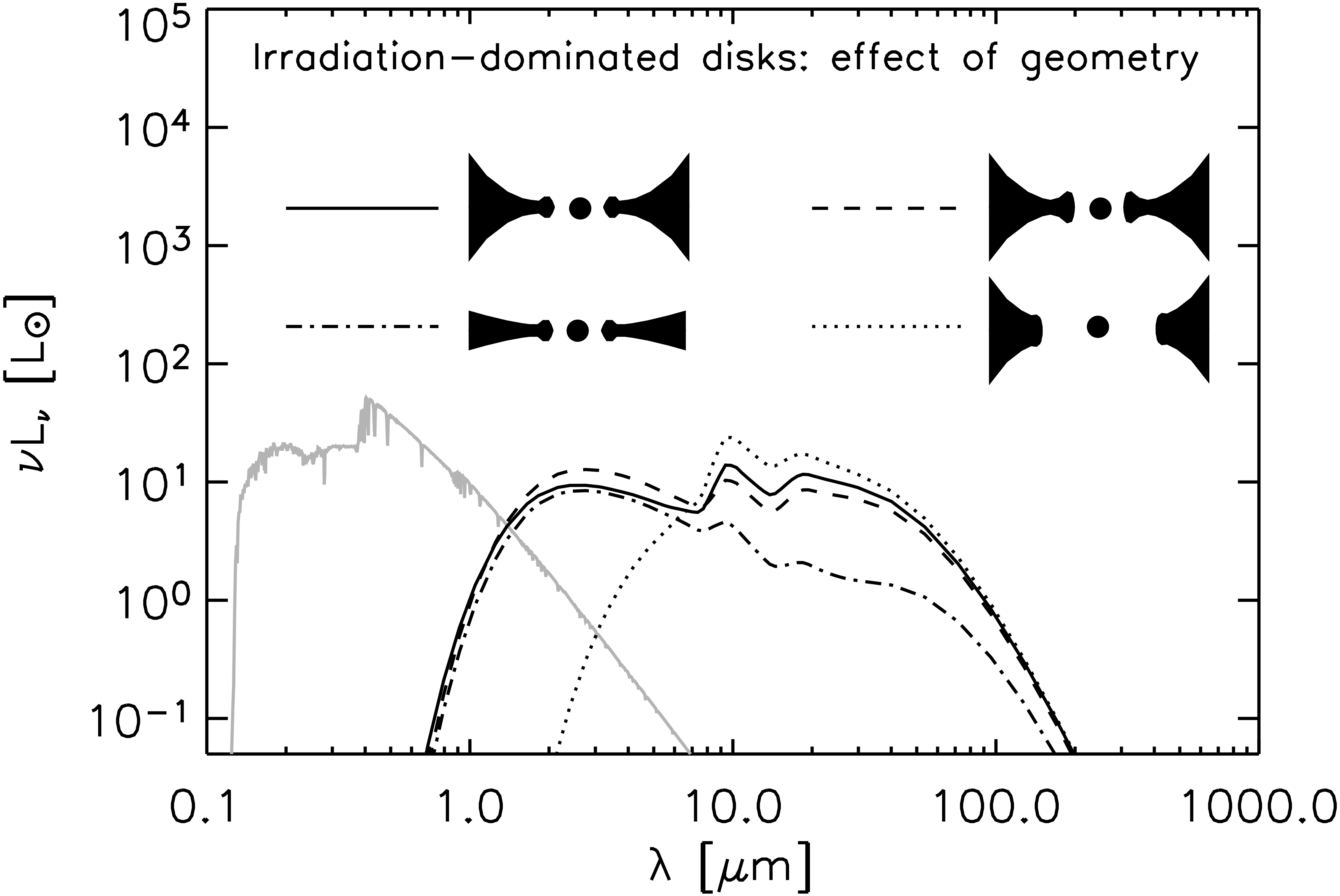
- Composition of meteorites
- Composition of cometary/IDP grains
- Isotopic dating
- Condensation sequence

Spectral Energy Distribution



Dullemond et al. (2007)

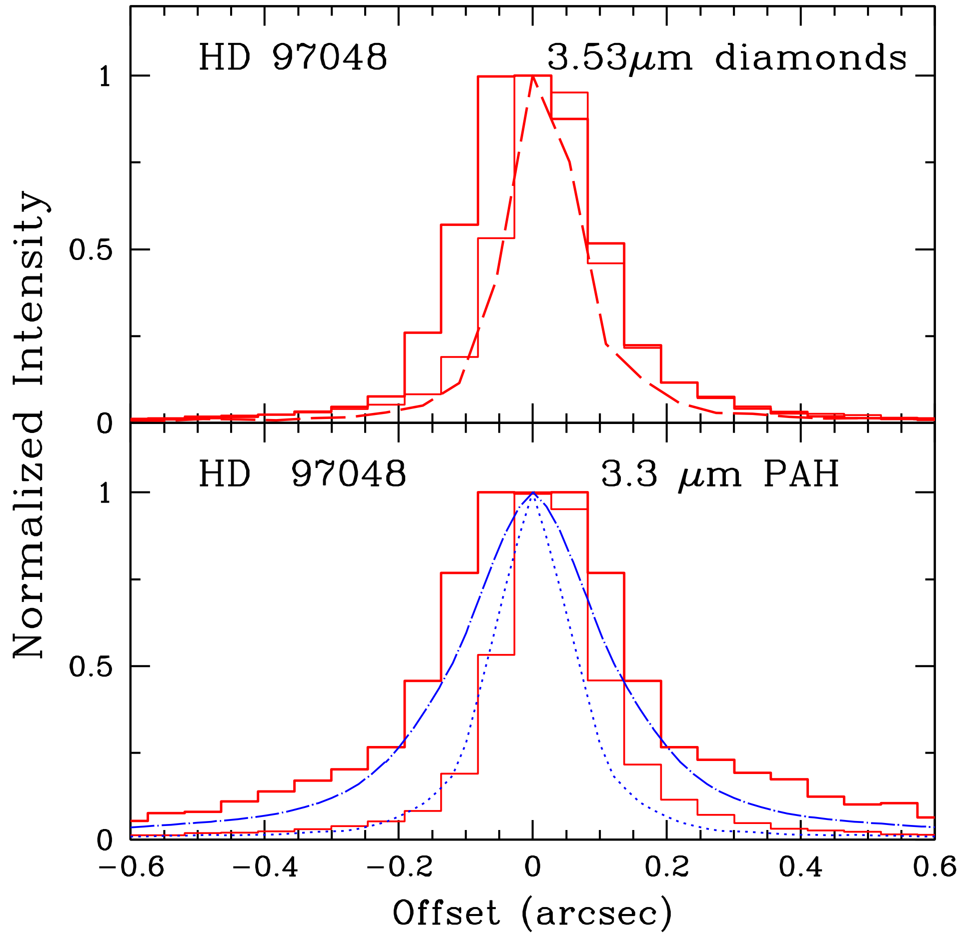
SEDs: Signatures of dust evolution

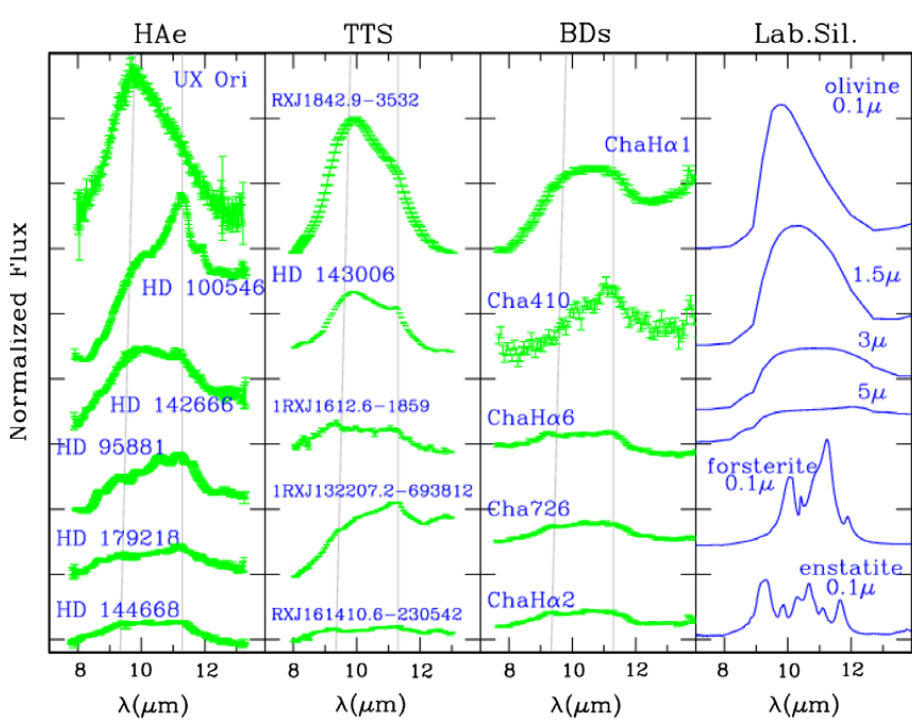


Dullemond et al. (2007)

Face-on PPDs: "warm" dust in emission

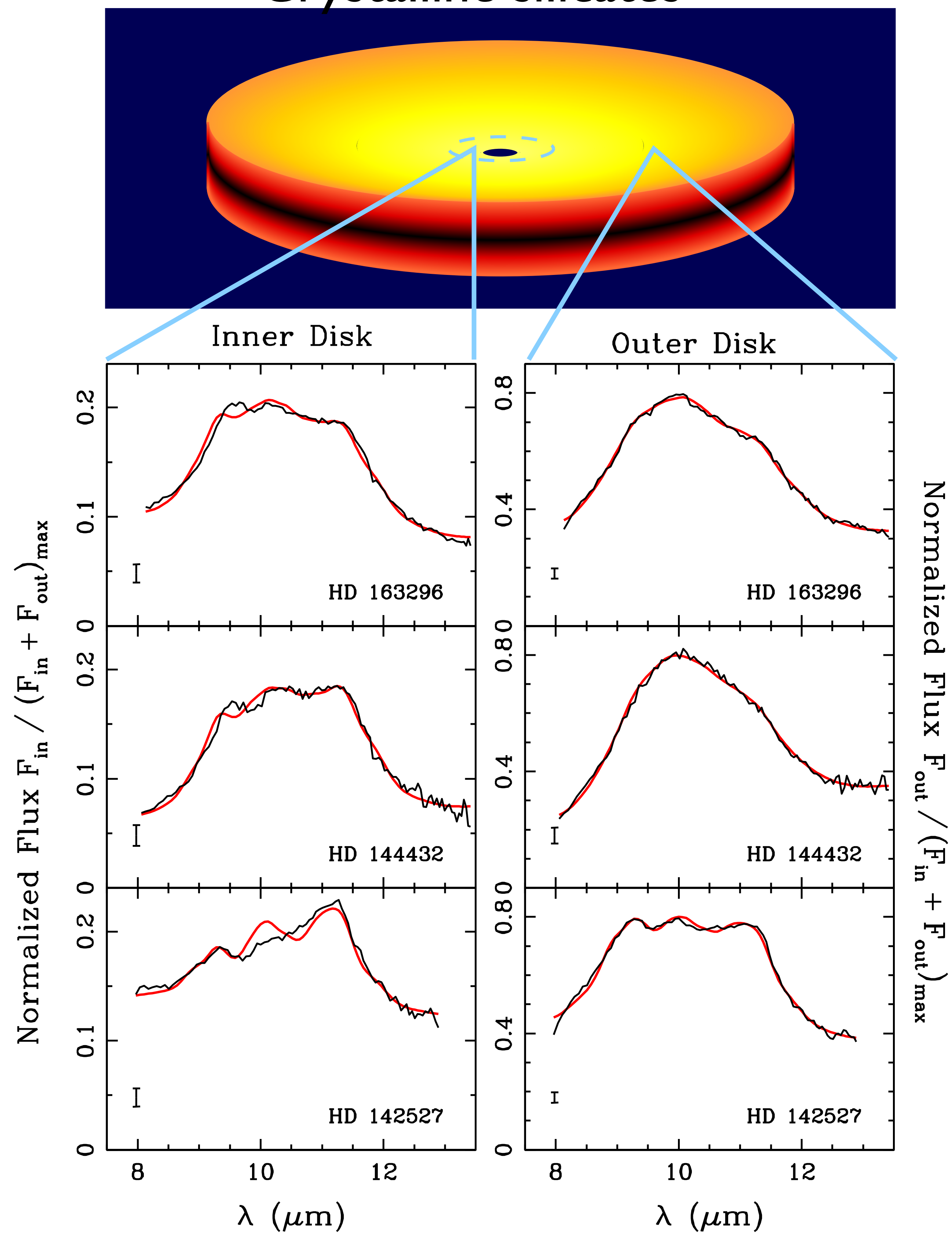
PAHs & diamonds





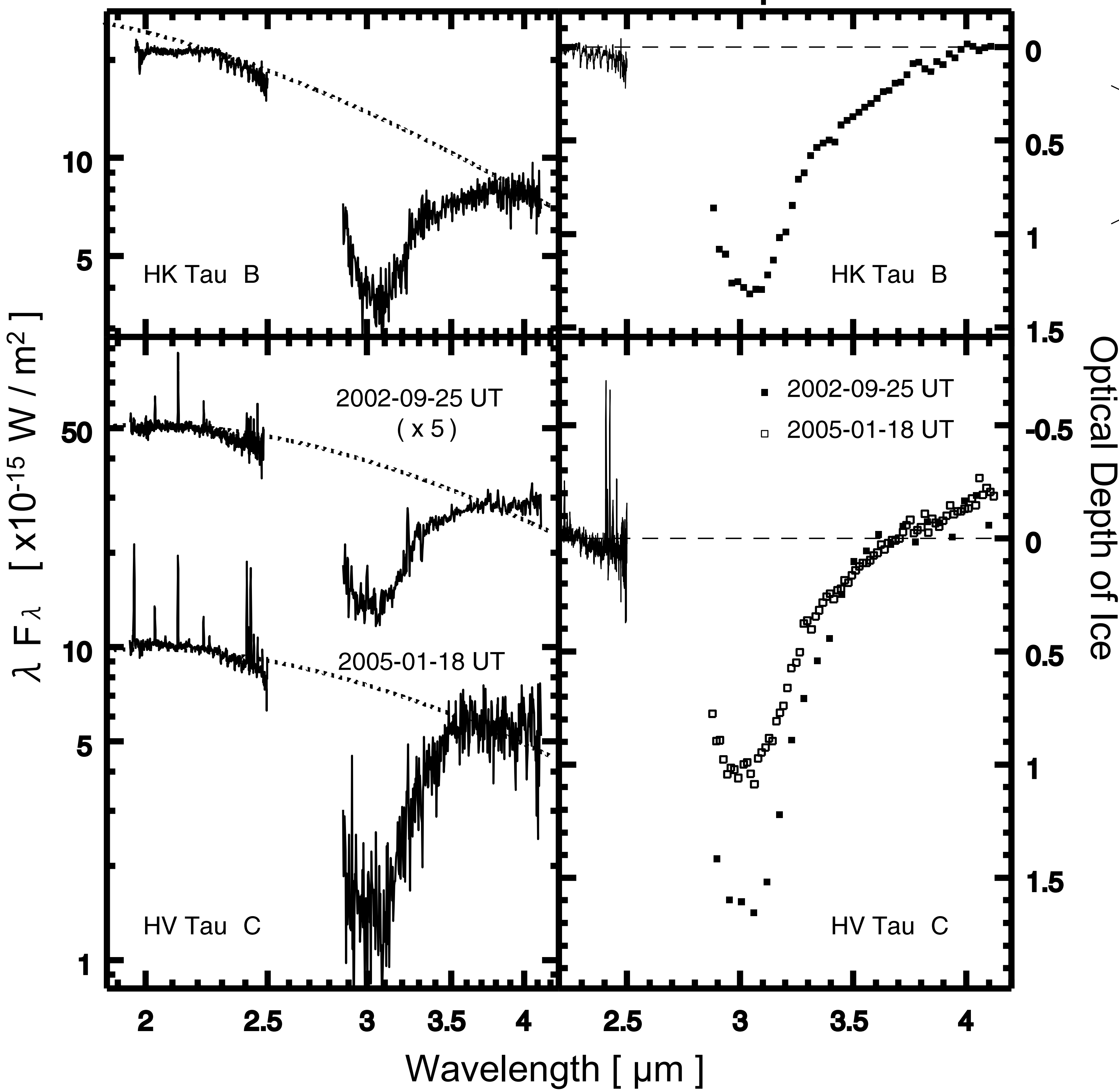
Testi & Leurini (2008)

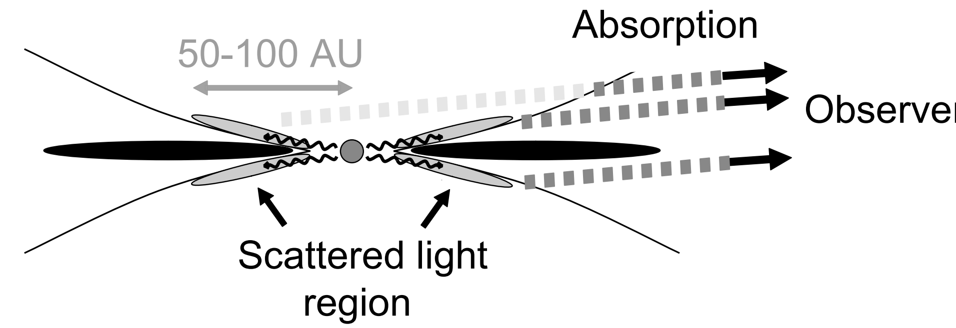
Crystalline silicates



Edge-on PPDs: "cold" dust in absorption

Water ice bands at 3μm





Terada et al. (2007)

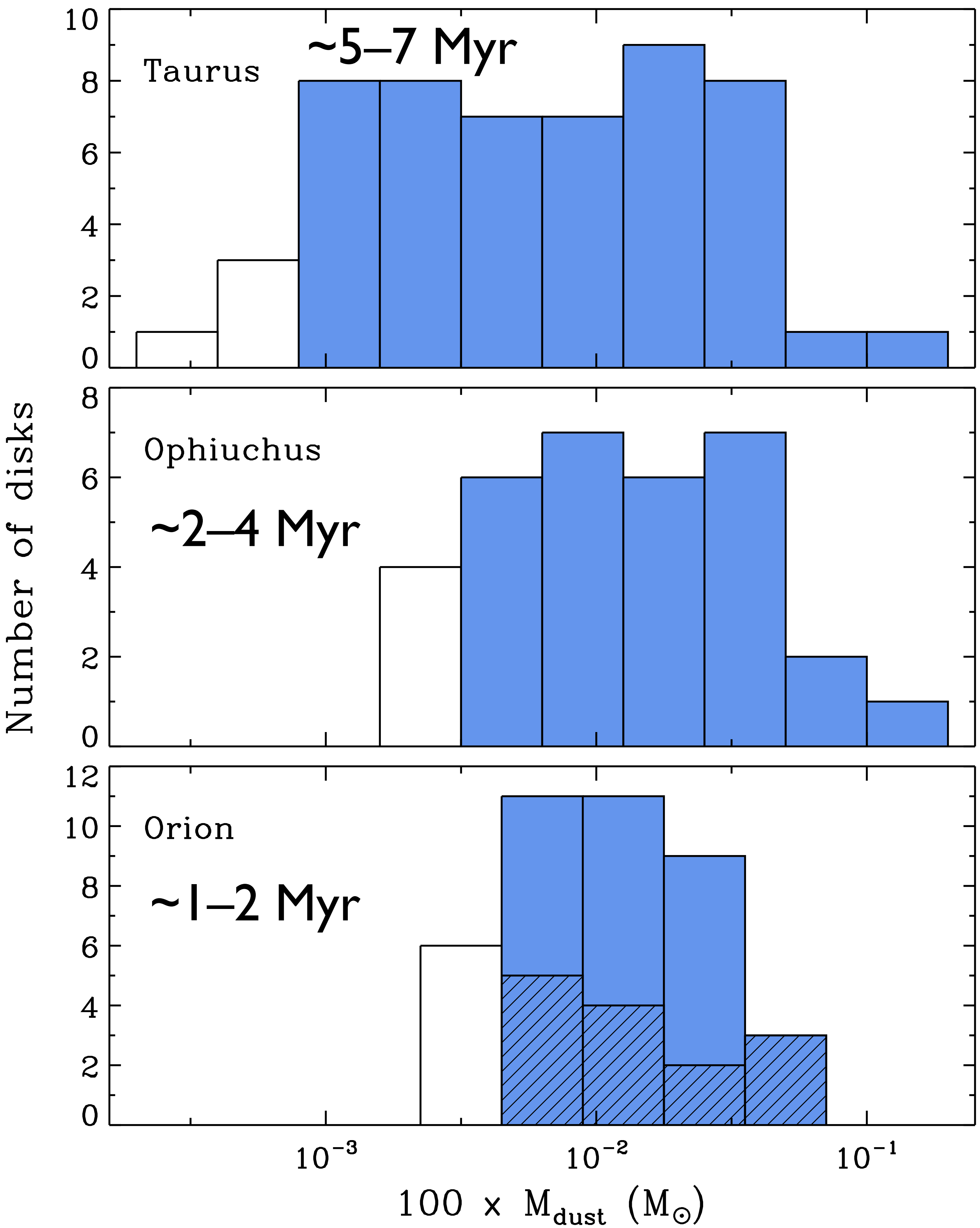
IR dust features:

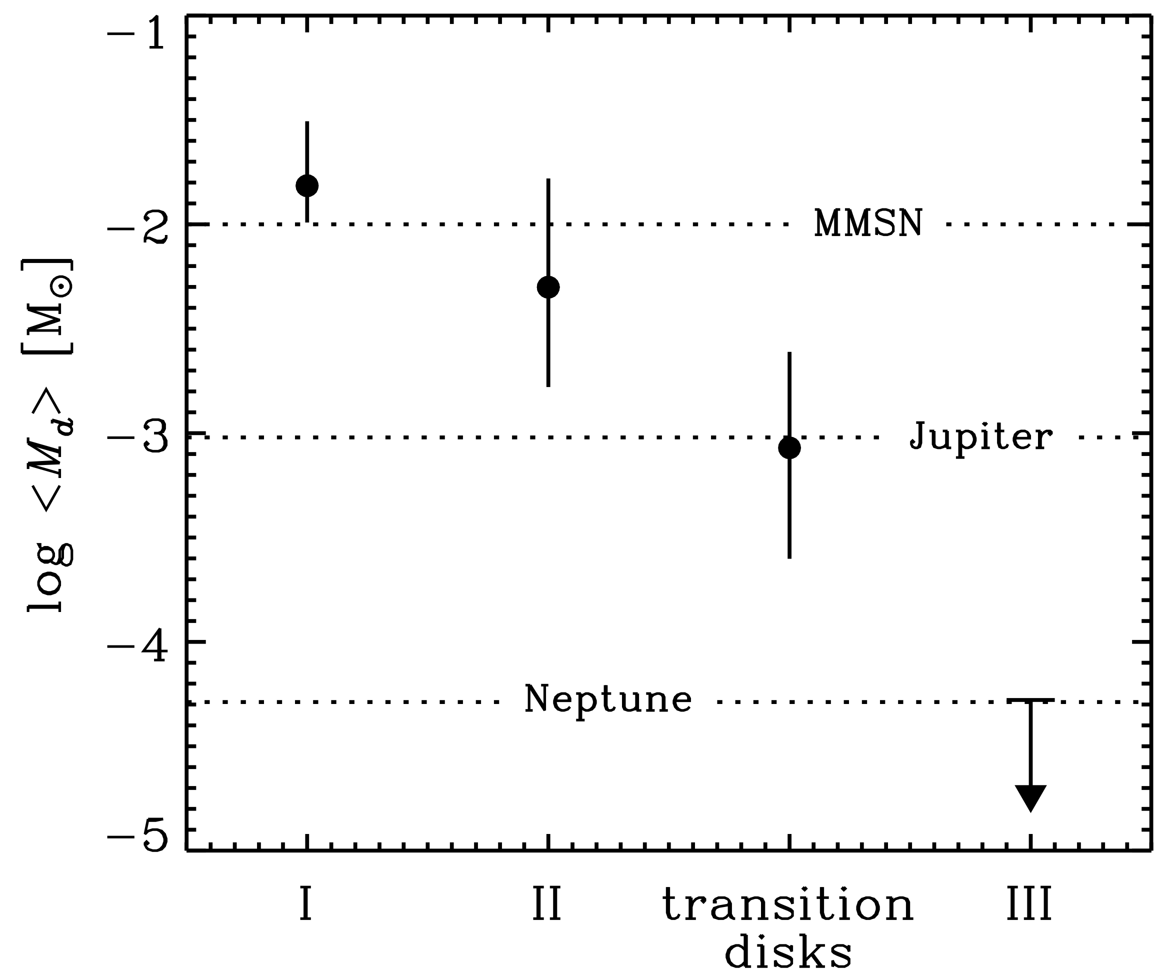
- Vibrational bands (stretching, bending): 3–100μm
- Water ice: 3μm
- PAHs: 3.3, 6.2, 7.7-7.9, 8.6, 11.3 and 12.7μm, etc.
- (Nano)diamonds: 3.43, 3.53μm
- (ISM) Hydrogenated amorphous carbon: 3.4, 6.8, 7.2μm
- Amorphous silicates: 9.8, 18μm
- Crystalline silicates: 10.2, 11.4, 16.5, 19.8, 23.8, 27.9, 33.7, 69μm
- Iron sulfides: ~23μm
- Featureless: Fe, FeO, organics, ...

- Crystalline silicates requires radial transport

Natta et al. (2006), van den Acker et al. (2004)

Disk masses vs Age

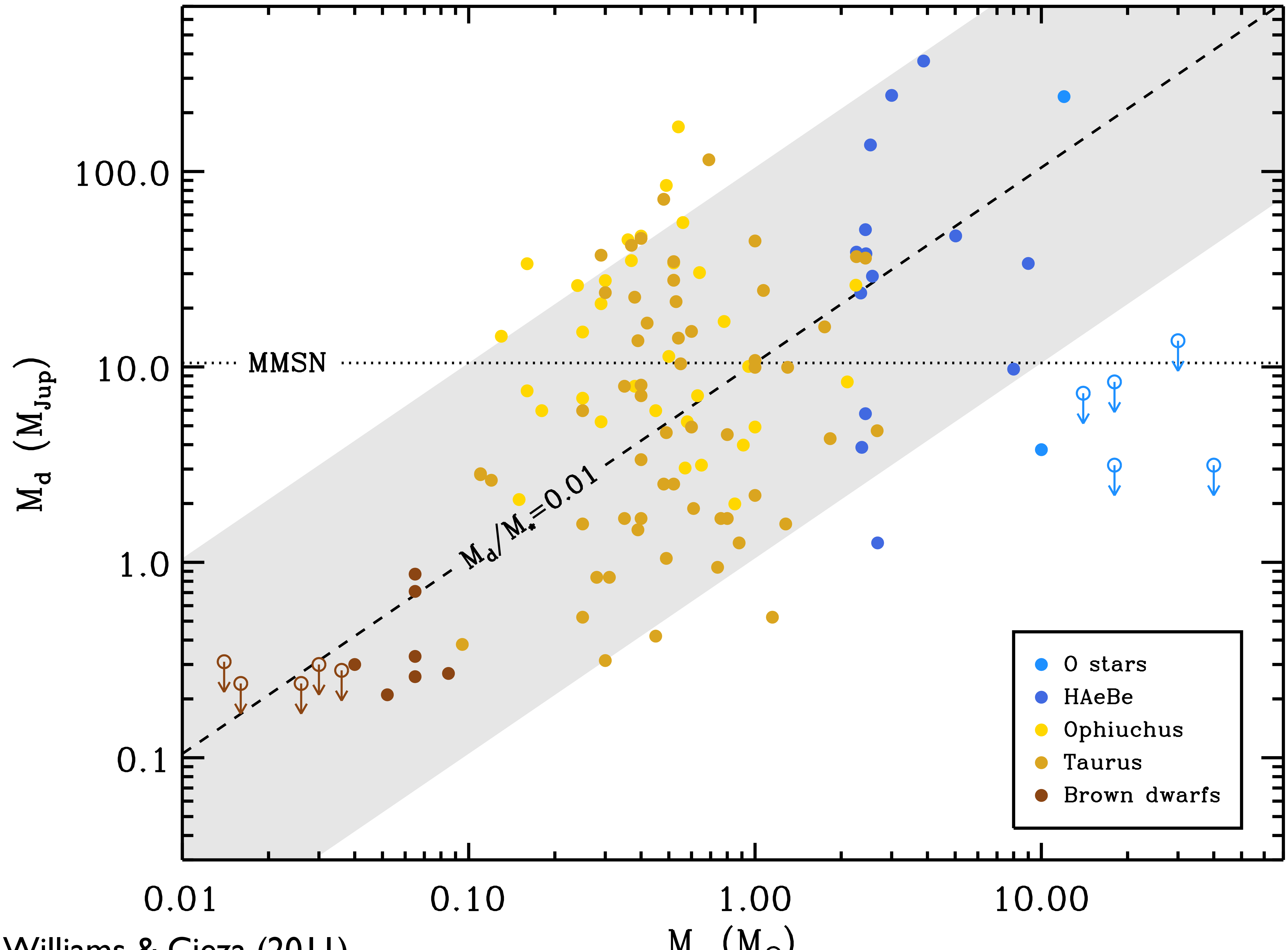




- M_{disk} decreases with age
- $\langle M_{disk} \rangle$ ~1% of M_{Sun}
- Dust opacities at mm are poorly constrained!

Williams & Cieza (2011)

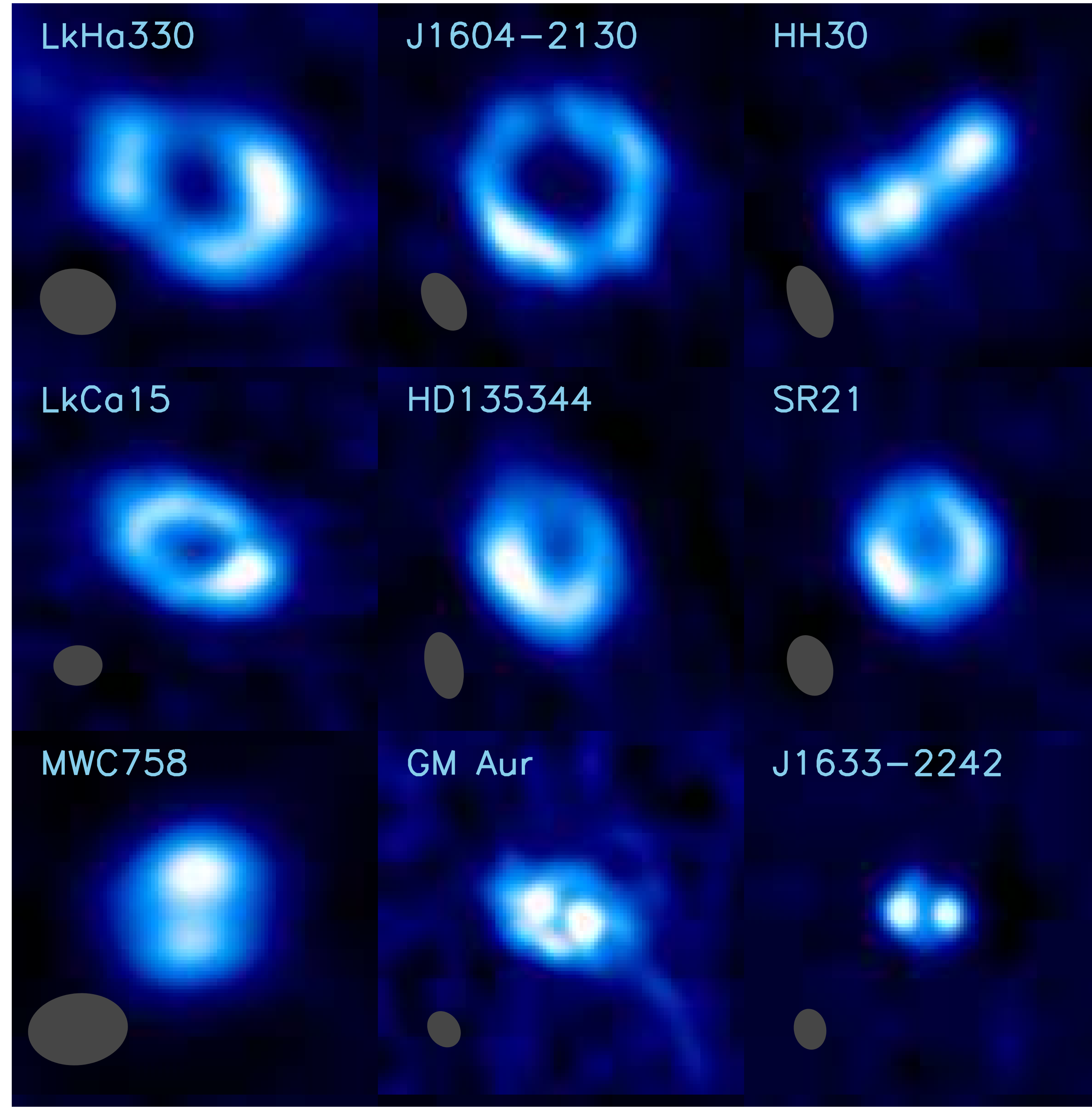
M_{disk} vs M_{star}: no correlation



Williams & Cieza (2011)

Large grains in inner PPDs

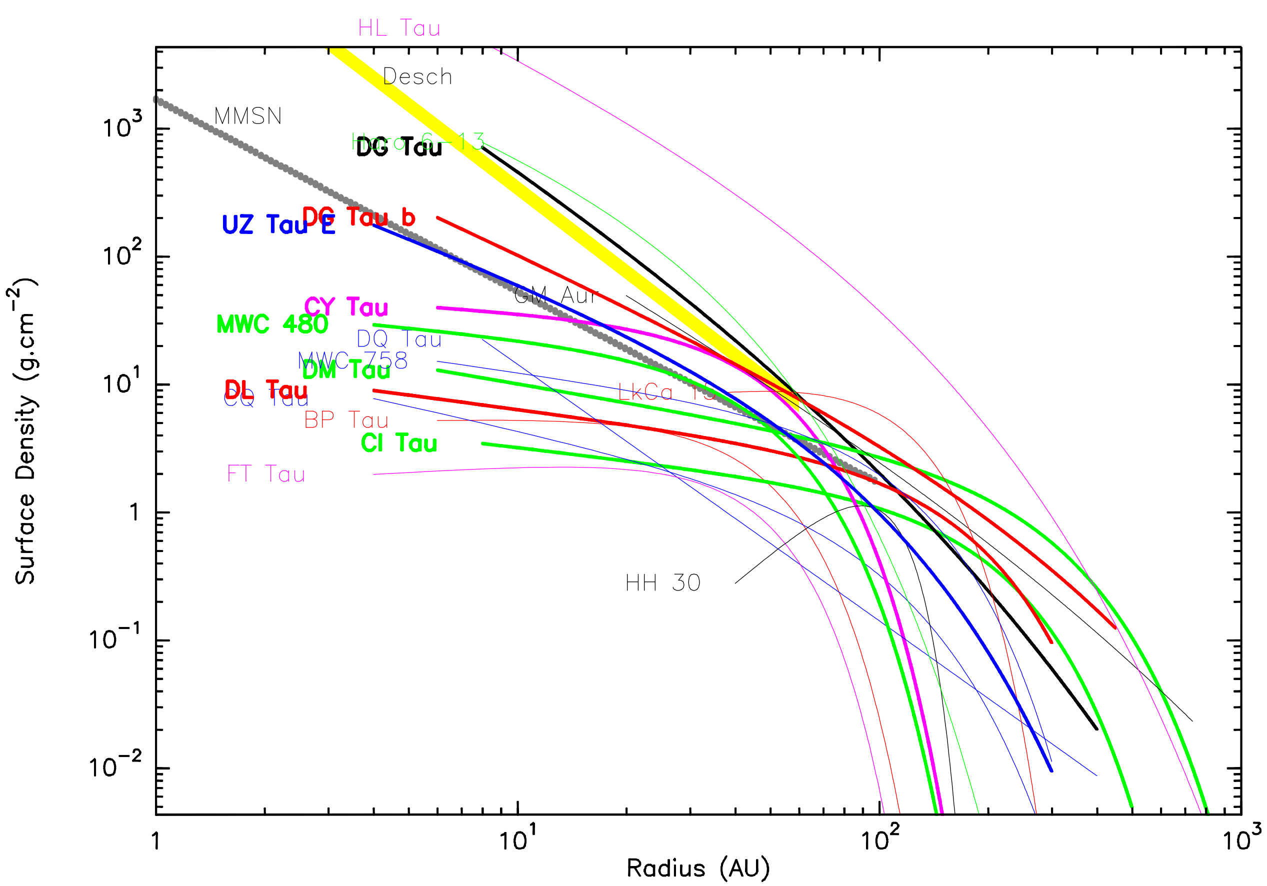
- Silicate band' profiles: up to ~3µm grains
- IR SEDs: small dust gaps
- ~10% of 1–3 Myr disks
- Increase with age
- Resolved inner dust holes
- Gas is still around, accretion still goes on

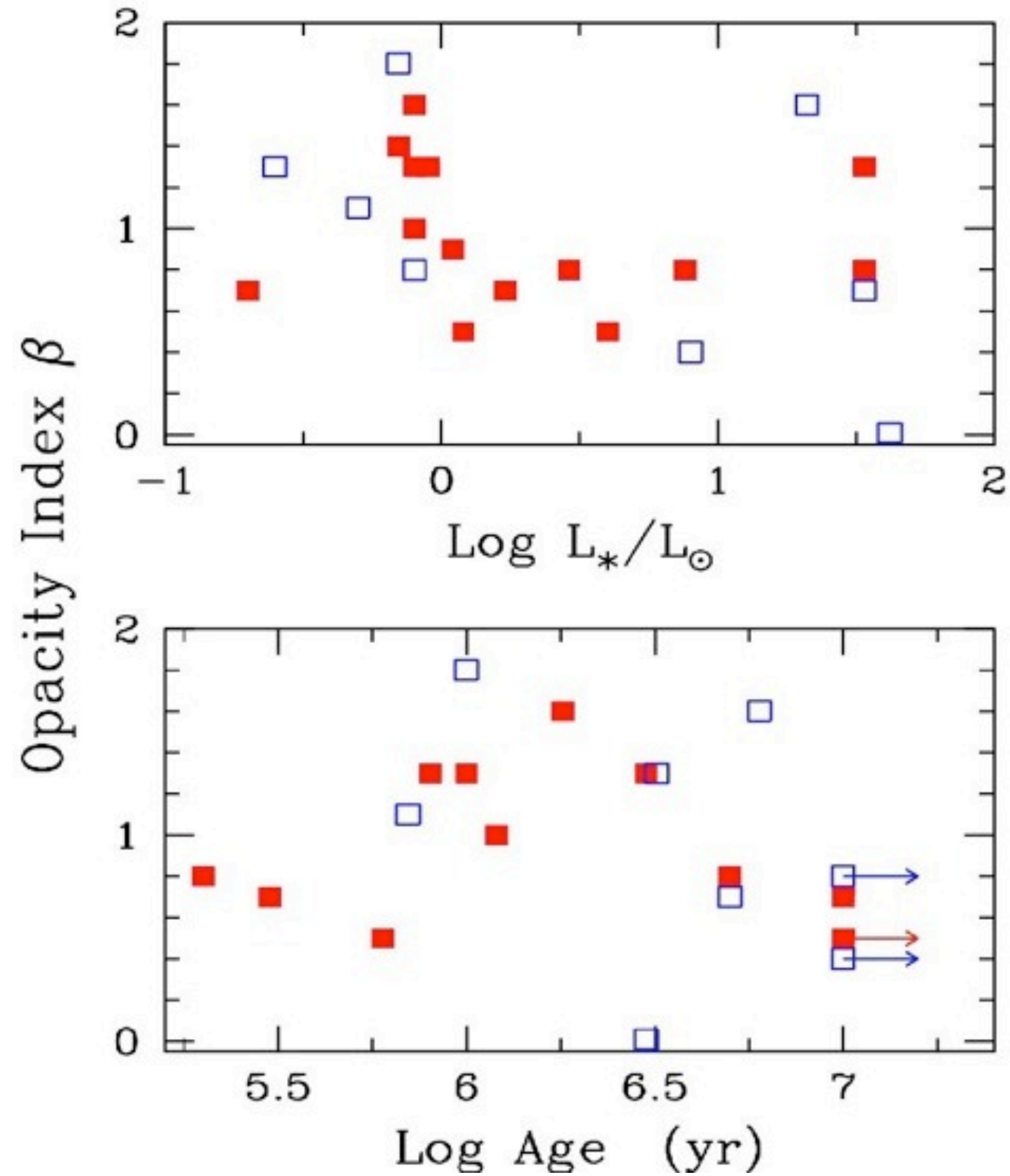


Williams & Cieza (2011)

Large grains in outer PPDs

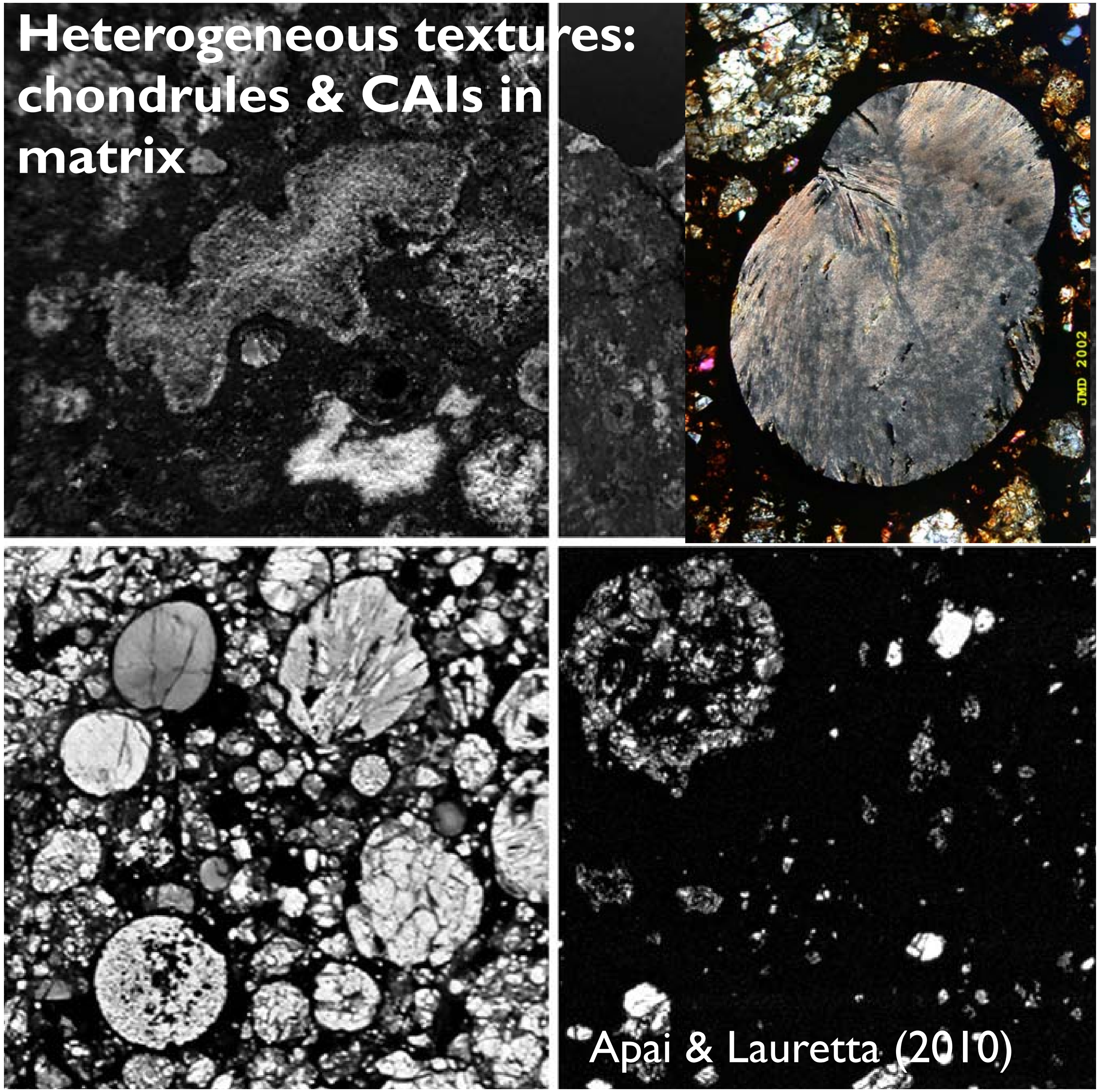
- Dust emissivity β: 0–2
- No correlation with stellar properties
- No correlation with age
- No correlation with dust in inner disk
- Optically thick emission?
- Free-free emission

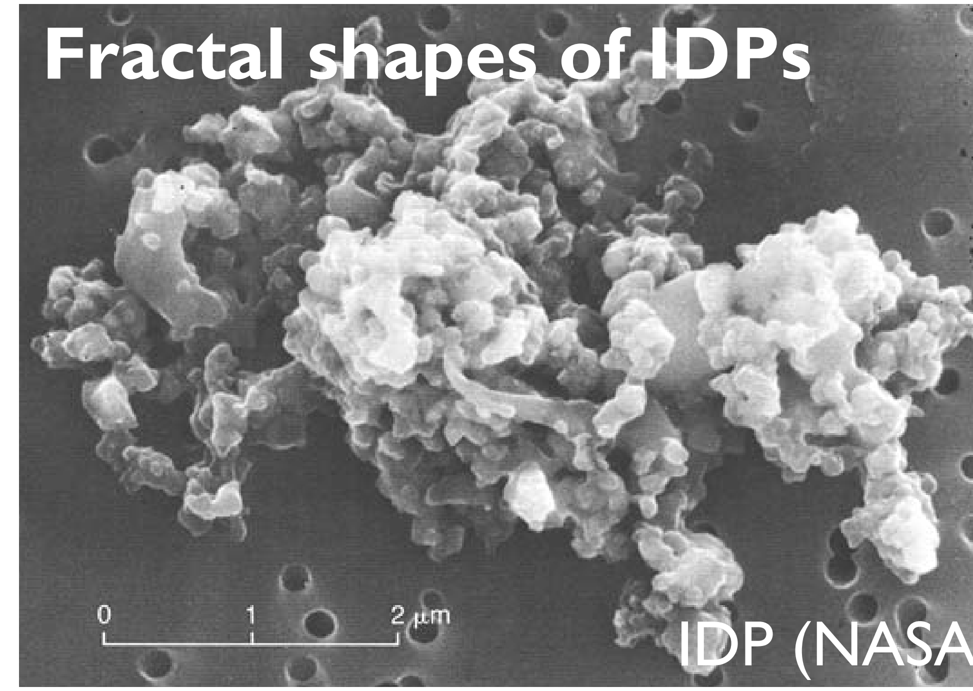


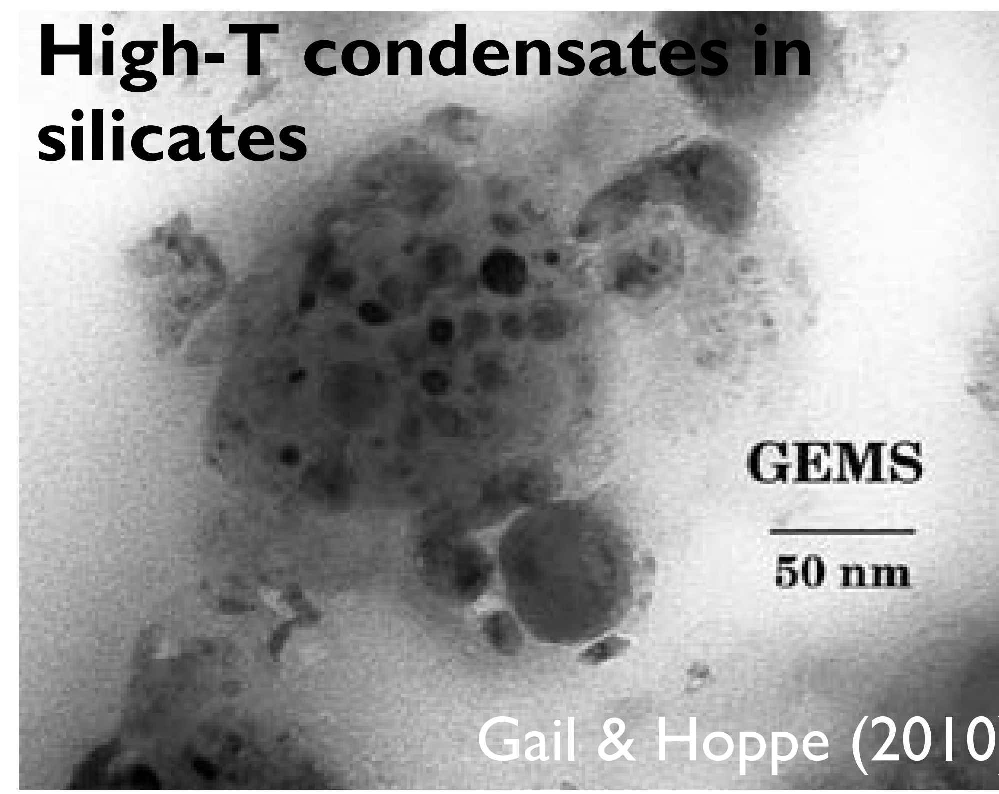


Testi et al. (2003), Natta et al. (2004), Rodmann et al. (2005), Guilloteau et al. (2011)

Grain evolution in the Solar Nebula







Grain evolution in the Solar Nebula

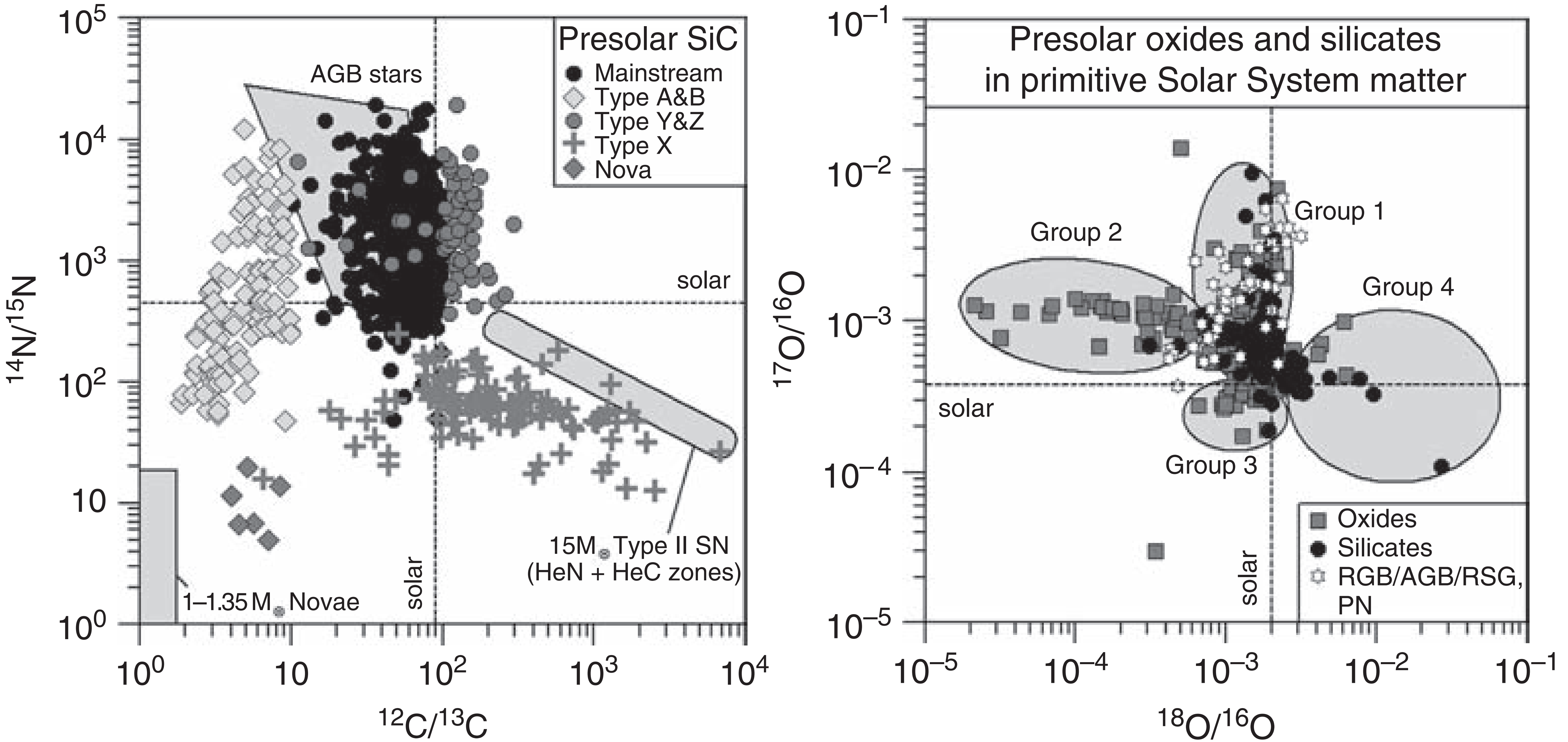
- Most primitive are chondritic meteorites: matrix + chondrules + CAIs
- No signs of alteration & metamorphism (T<50 K)

- Calcium-Aluminum-rich Inclusions (CAIs), 4.571 Gyr:
  - 0.1mm–1cm: mixture of highest-T condensates
  - Multiple high-T events

- Chondrules (molten droplets): ~0–2 Myr after CAIs
  - Single melting-condensation event
  - Peak temperatures: >1800K
  - Initial cooling: ~hours (till ~1000K)
  - Chondrule densities: $>10^{-5}$ cm^{-3}
  - Formation in "clumps": >1000 km

Courtesy of S. Desch

Presolar grains in meteorites



- Survived shock passage & heating in the early Solar Nebula
- What happened to ices & gas?

Gail & Hoppe (2010)

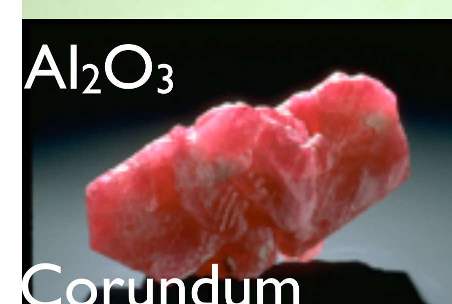
Dust composition

- Water & CO_2 ices (40%)
- Volatile & refractory organics (30%): "CHON"
- Iron-poor amorphous & crystalline silicates (27%)
- Troilite FeS (~2%)
- High-T condensates: Fe, SiC, TiO, Al_2O_3 (<1%)

Component	Elements	Condensation temperature*
Refractory	Al-, Ca-, Ti-oxides, trace (Zr, V, Wo, etc.)	1850–1400 K
Main	Mg-rich silicates, metallic Fe, Ni, Co, Li, Cr	1350–1250 K
Volatile	Sulfides, silicates, metals (Mn, P, Na, Rb, K, F, Zn, Au, Cu, Ag, etc.)	1250–640 K
Highly volatile	C, H, O, N, Cl, Ne, Ar, Xe, Kr, etc.	< 640 K

* Condensation temperatures are given for the pressure of 10^{-4} bar.

Pollack et al. (1994), Semenov et al. (2010)

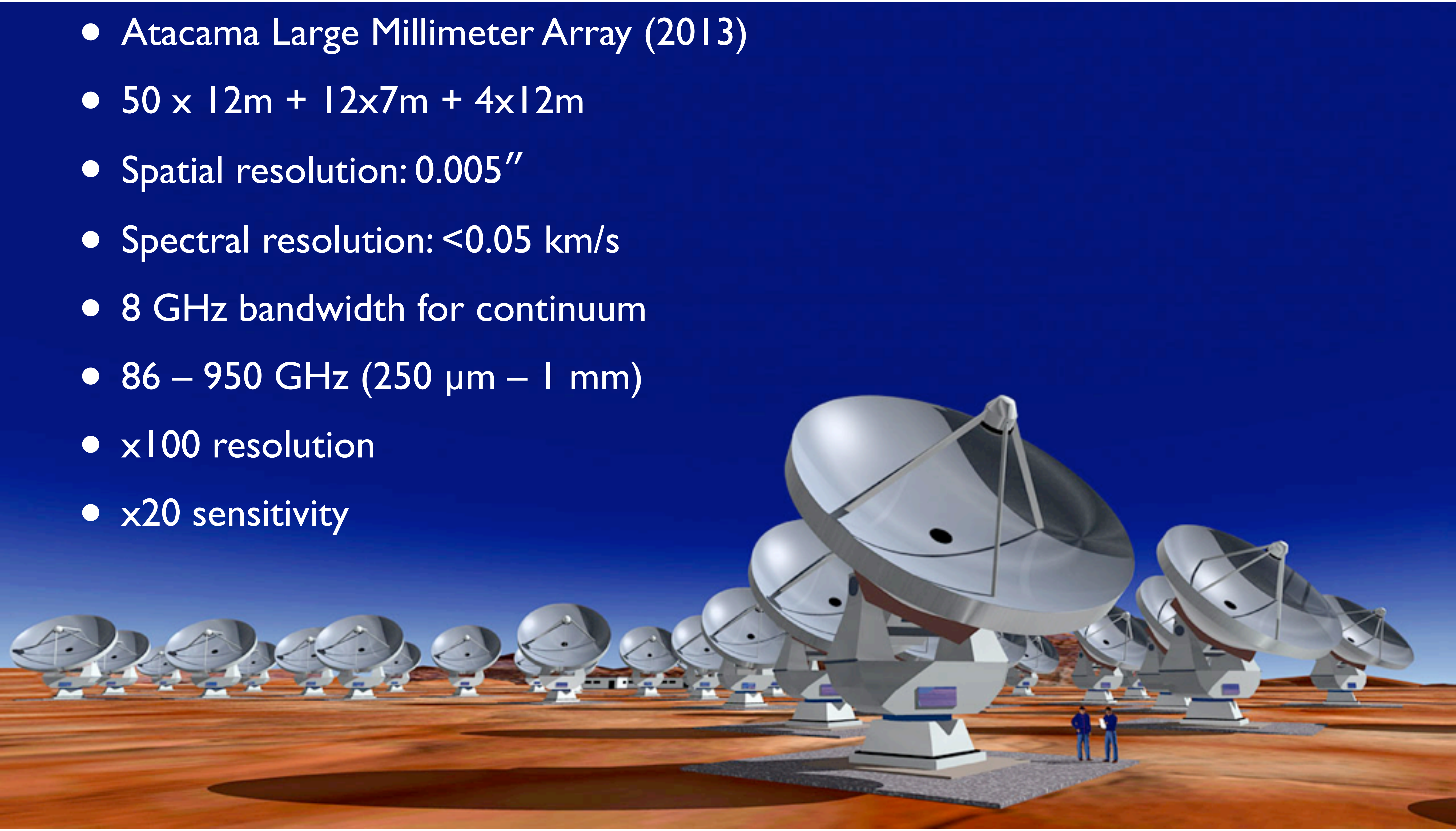


IV. Dust in PPDs & Solar Nebula: Summary

- Disk masses evolve
- M_{disk}: no correlation with M_*, L_*
- Grain sizes evolve
- Gaps & inner holes
- Crystalline silicates in outer disks: transport or shocks?
- Mineralogical composition of meteorites
- ~2 Myr formation of solids in the early Solar System
- Presolar materials in meteorites

VI. The Brave New World: ALMA

- Atacama Large Millimeter Array (2013)
- 50 x 12m + 12x7m + 4x12m
- Spatial resolution: 0.005″
- Spectral resolution: <0.05 km/s
- 8 GHz bandwidth for continuum
- 86 – 950 GHz (250 µm – 1 mm)
- x100 resolution
- x20 sensitivity

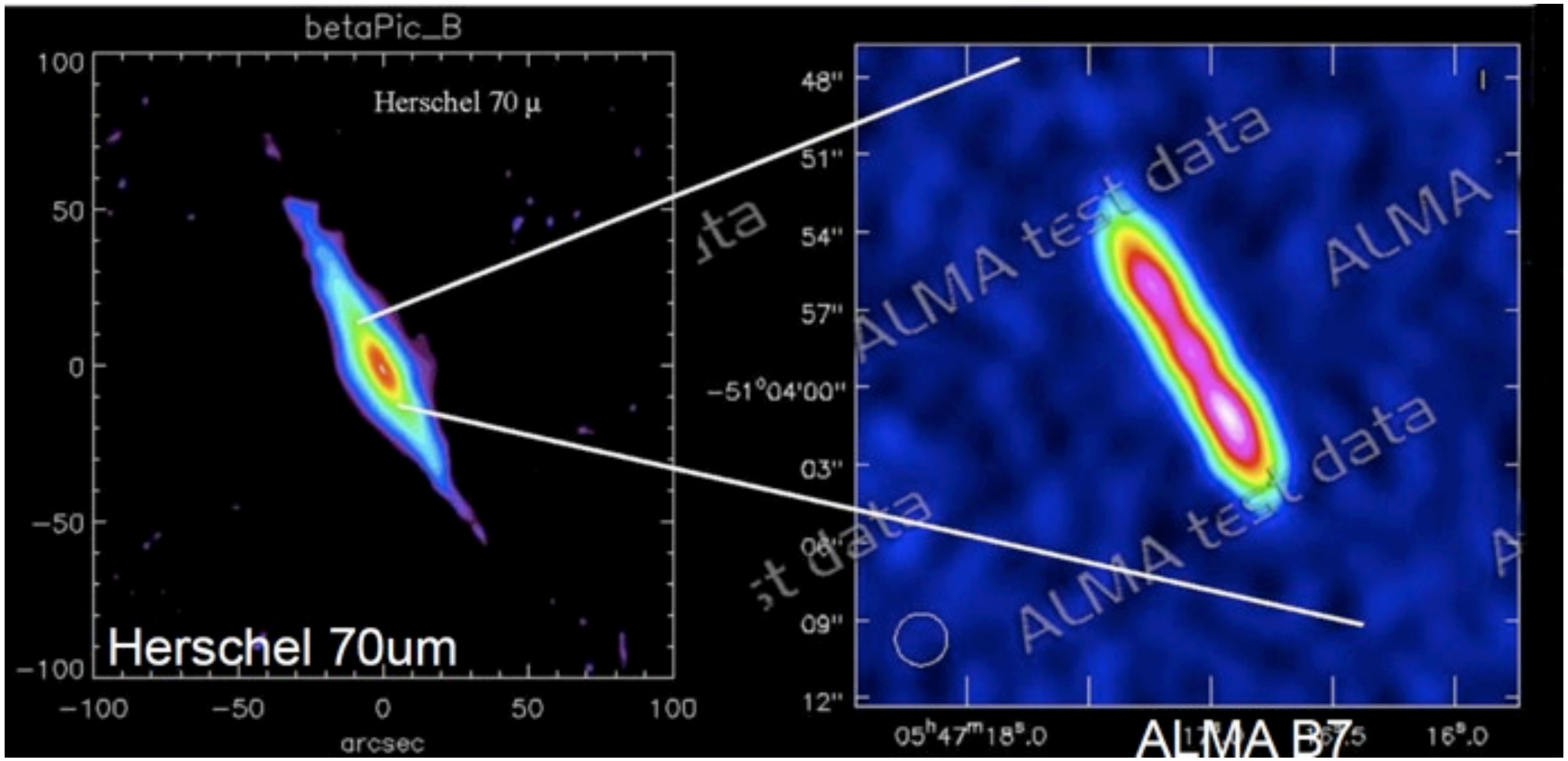


Credit: ALMA (ESO)

ALMA imaging of dust in PPDs:

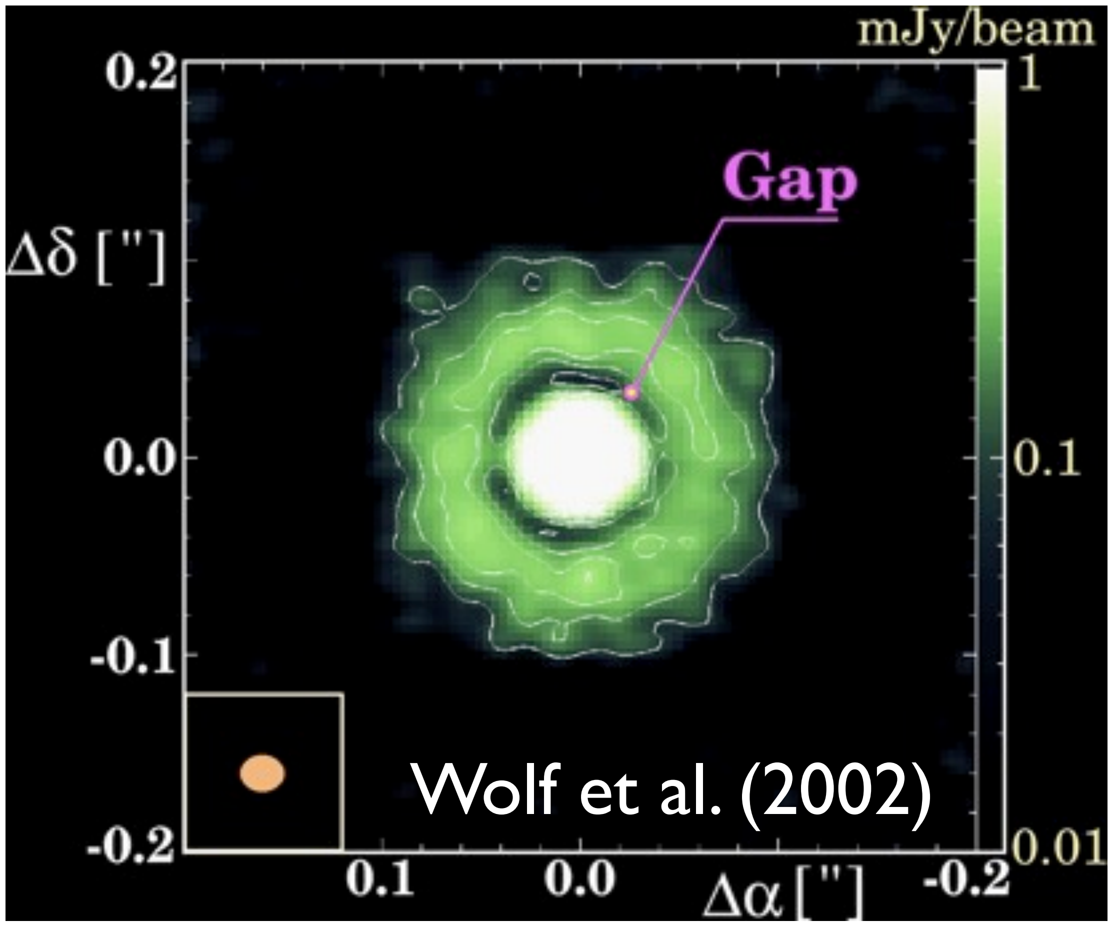
- Dust emissivities: 90GHz–1THz
- Observed fluxes at 1.3mm: 30–1000mJy => 1h to get 0.03mJy @ 0.05"
- Large sample of PPDs: >100
- "Debris" disks
- Spatially resolved images: >0.01"@1THz (~1 AU @ 100 pc)
- Radial gradients of grain sizes
- Total M_{disk}
- Transient, small-scale features
- Gaps & inner holes
- Polarization

ALMA imaging of dust in "debris" disks:

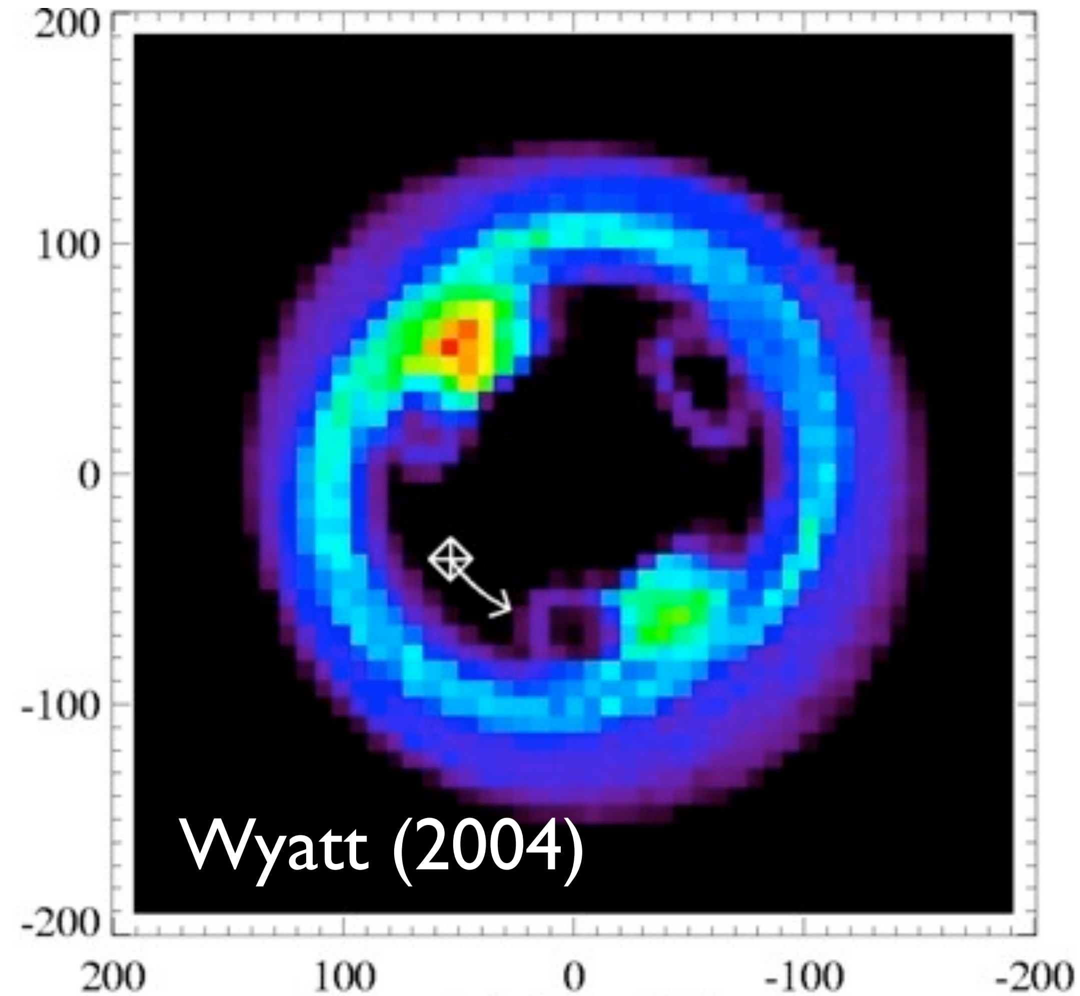


Science Verification observations of β Pictoris at 345 GHz

ALMA imaging of dust in PPDs:



Disk gap at 5 AU opened by 5 M_{Jy} planet



Dust resonances in a "debris" disk