Diagnosing Circumstellar Debris Disks

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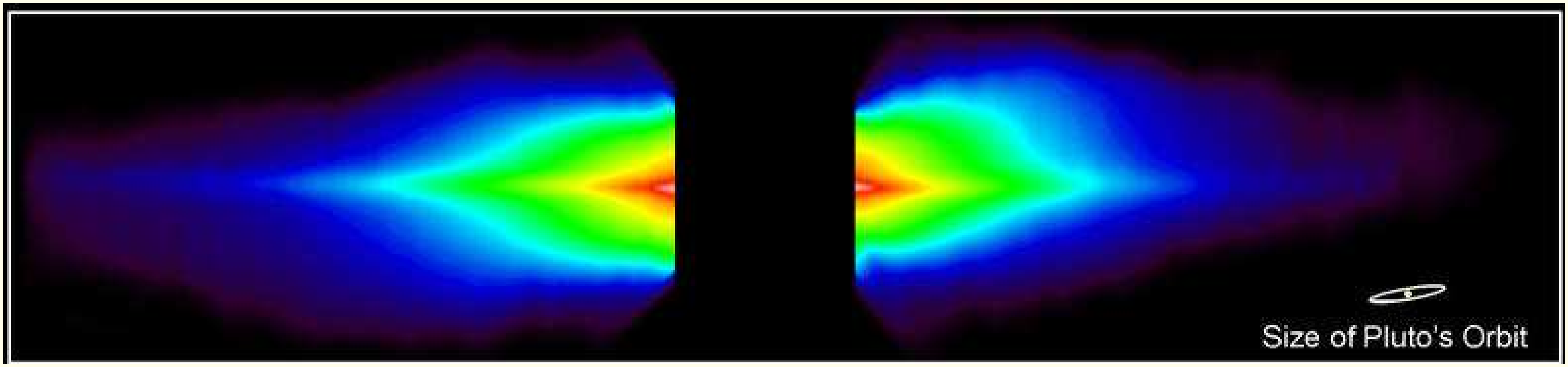
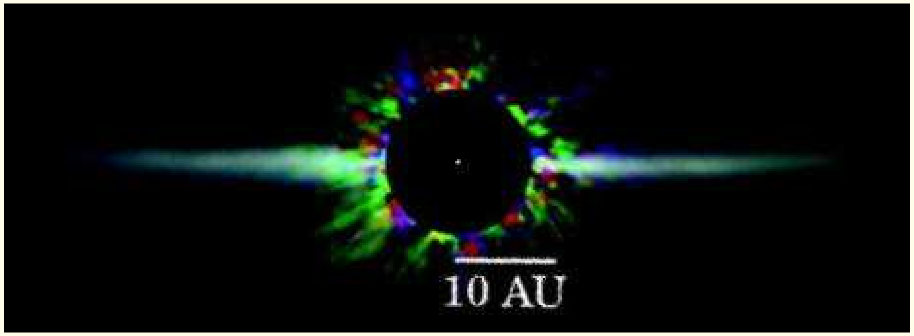


the edge-on debris disk orbiting β Pictoris, from Heap et al (2000)

Dusty circumstellar debris disks:



AU Mic, from Fitzgerald et al 2007

sites of ongoing planet formation?
or planetesimal destruction?

the optimistic view:

- dust lifetimes $\ll$ host star's age
- requires replenishment, presumably by unseen planetesimals
- planetesimals are the seeds of planets

but models of planetesimal collisional/accretional evolution
in outer Solar System show (Stern & Colwell 1997, Kenyon 2002):

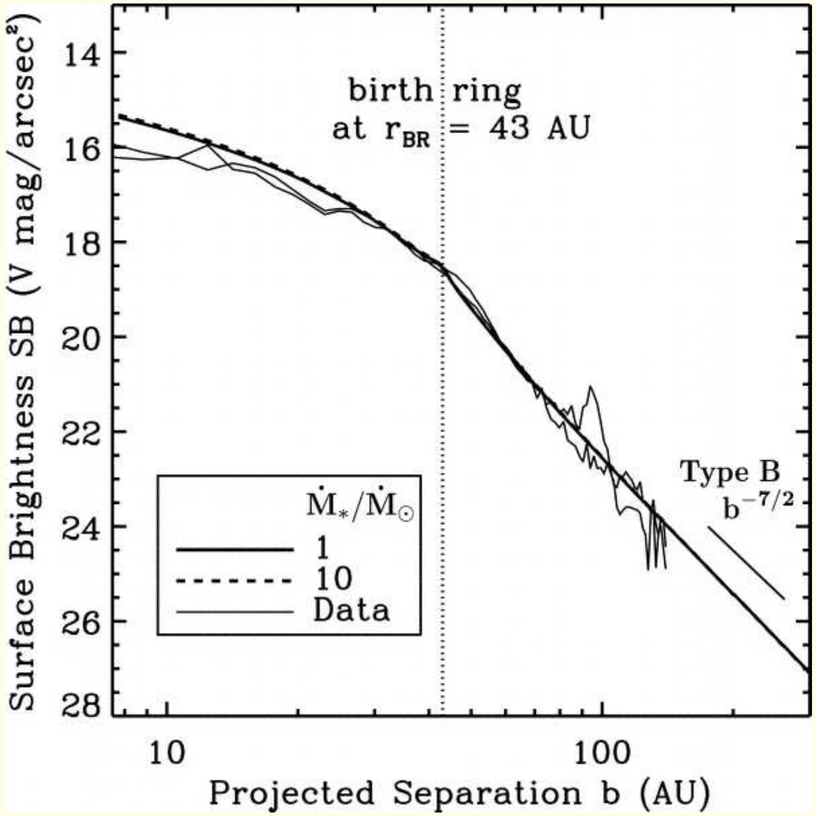
- planet formation in the $r \gtrsim 30$ AU zone is very inefficient, requiring $M_p \sim 30$ $M_\oplus$ just to form a handful of Plutos
- much of the leftover mass then grinds down to dust, blown away by radiation pressure (RP) in $t \sim 500$ Myrs
- characteristic dust mass loss rate is $\dot{M}_d \sim M_p/t \sim 10^{13}$ gm/sec

Do disk observations support this finding...

that planet-formation is lossy and inefficient at $r \gtrsim 30$ AU?

To address this,

- develop a model of a debris disk
- fit to observations
- hopefully say something about the disk's prospects for planet formation



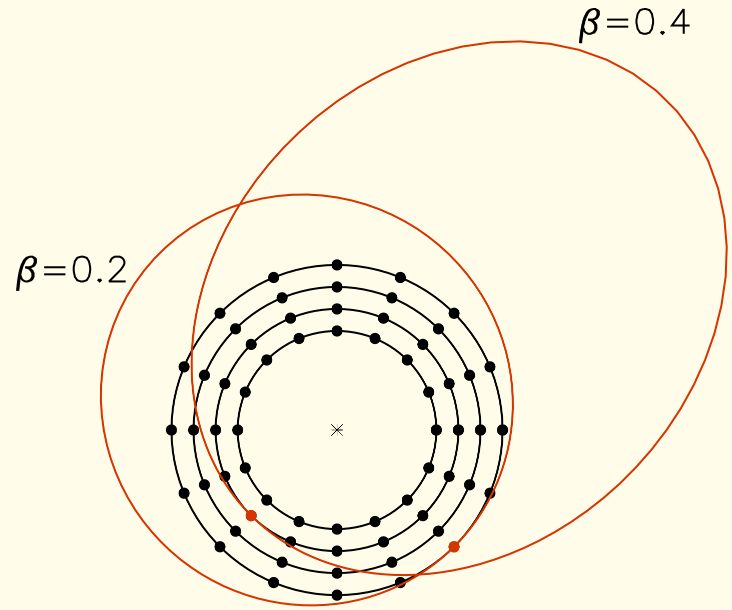
AU Mic surface brightness
from Strubbe & Chiang (2006)

The relevant physics is described in Strubbe & Chiang (2006),

- unseen planetesimals collide & generate dust
- RP lofts smaller grains into wide orbits, $r \sim 100$'s of AU
- collisions among dust shatter grains until $R < R_{\text{blowout}}$

The model:

- quantize the problem, so $\int \rightarrow \sum$
- $\mathbf{1 \leq N_r \leq 5}$ circular planetesimal rings that produce dust at $\mathbf{N_\ell = 100}$ longitudes
- dust have $\mathbf{N_R = 200}$ dust size-bins
- dust production rate is power-law in size, $\boldsymbol{d\dot{N}(R) \propto R^{-q}}$



Dust grains have size parameter $\boldsymbol{\beta = \frac{RP}{G}} \sim 0.6/R_{\mu\text{m}}$ (if star is solar),

and dust orbit elements are simple functions of β (S&C2006):

$$\boldsymbol{a(\beta) = \frac{1-\beta}{1-2\beta} r_p} \quad \text{and} \quad \boldsymbol{e(\beta) = \frac{\beta}{1-\beta}}$$

so bound dust have $\boldsymbol{\beta < \frac{1}{2}}$ and radii $\boldsymbol{R > R_{\text{blowout}}}$

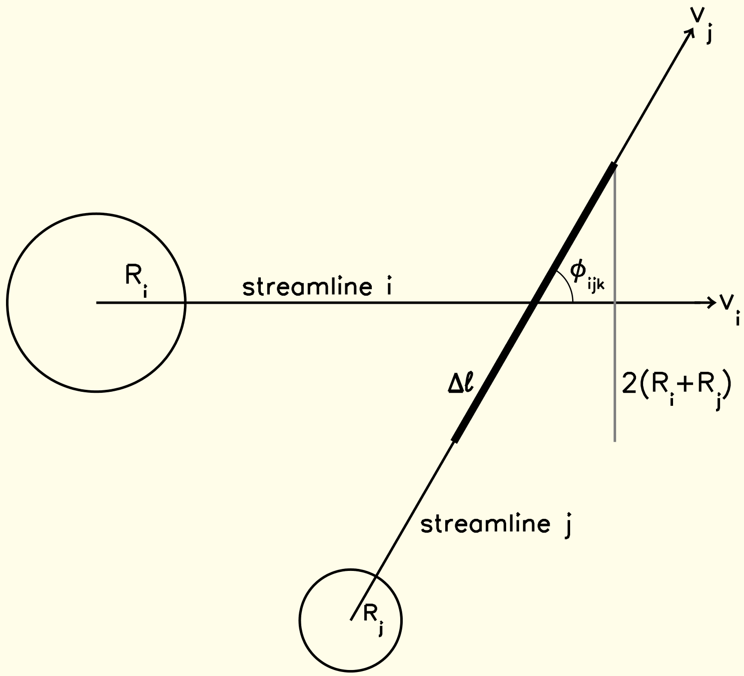
where $\boldsymbol{R_{\text{blowout}} \sim 1\ \mu}$m (when solar)

Dust abundance obeys rate equation:

$N_i(t) =$ no. of grains of radius R_i in orbit $a_i, e_i, \tilde{\omega}_i$

$$\frac{dN_i}{dt} = P_i - \sum_j \alpha_{ij} N_i N_j$$

$=$ production - destruction



which is solved numerically for $N_i(t)$

$\alpha_{ij} =$ probability per time for a grain in orbit i to collide with grain in orbit j
$\quad = $ function$(a_i, a_j, e_i, e_j, \tilde{\omega}_i, \tilde{\omega}_j, R_i, R_j)$

Impact must also be fast enough for grain j to shatter grain i:

$$|\mathbf{v}_j - \mathbf{v}_i|^2 \gtrsim Q^\star \left(\frac{R_i}{R_j}\right)^3$$

where $Q^\star$ is dust strength

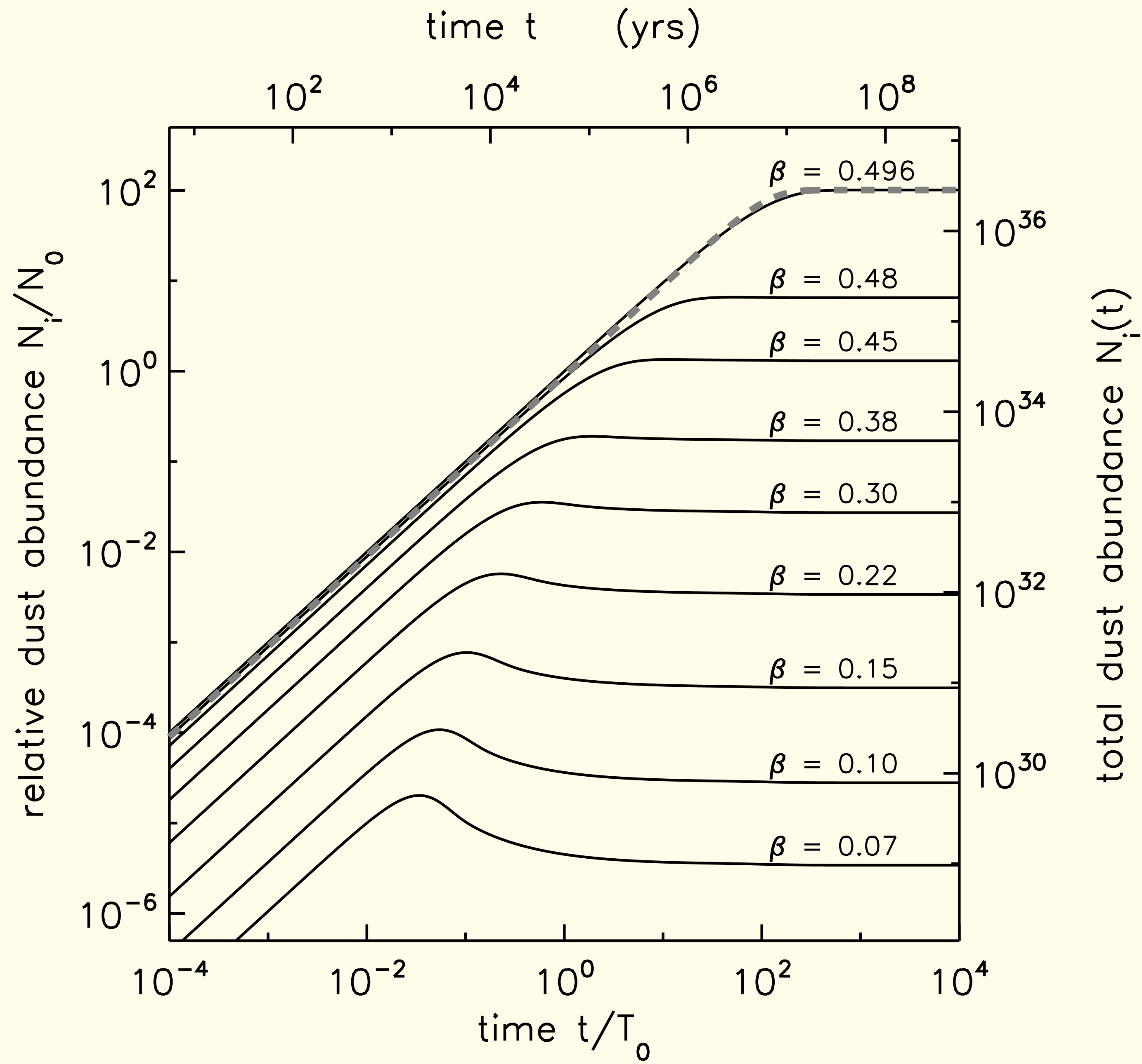
Example:

$r_p = 50$ AU p'mal ring
$\dot{M}_d = 10^{13}$ gm/sec
$Q^\star = 10^6$ ergs/gm (weak)
$I = 0.1$ rad $= 6^\circ$

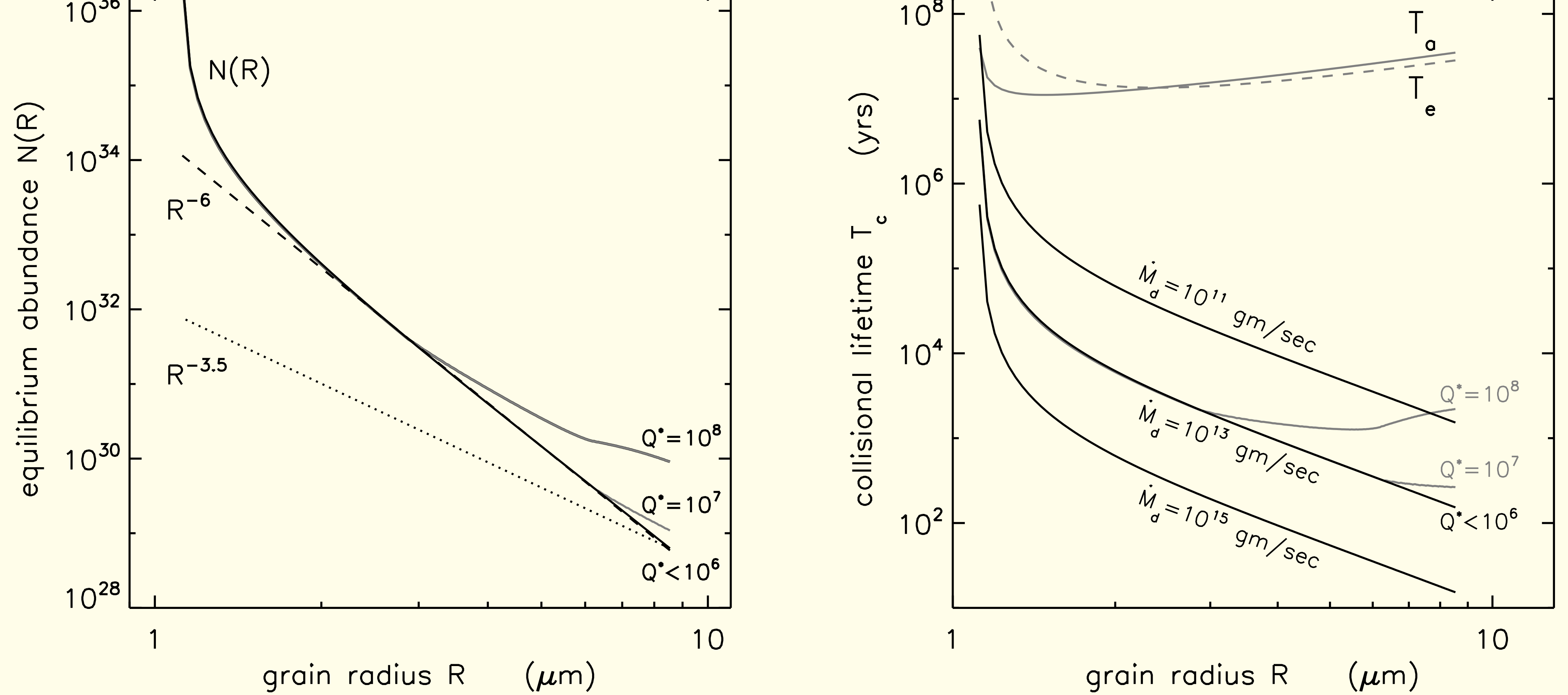
rate equation
provides scale-factors:

abundance
$N_0 \propto r_p^{7/4}\sqrt{I\dot{M}_d}$

timescale
$T_0 \propto r_p^{7/4}\sqrt{I/\dot{M}_d}$



$\Rightarrow$ heavier dust production results in a more massive debris disk
that settles faster into collisional equilibrium



Dust collisional lifetimes: $T_c(R) = \frac{N(R)}{P(R)}$

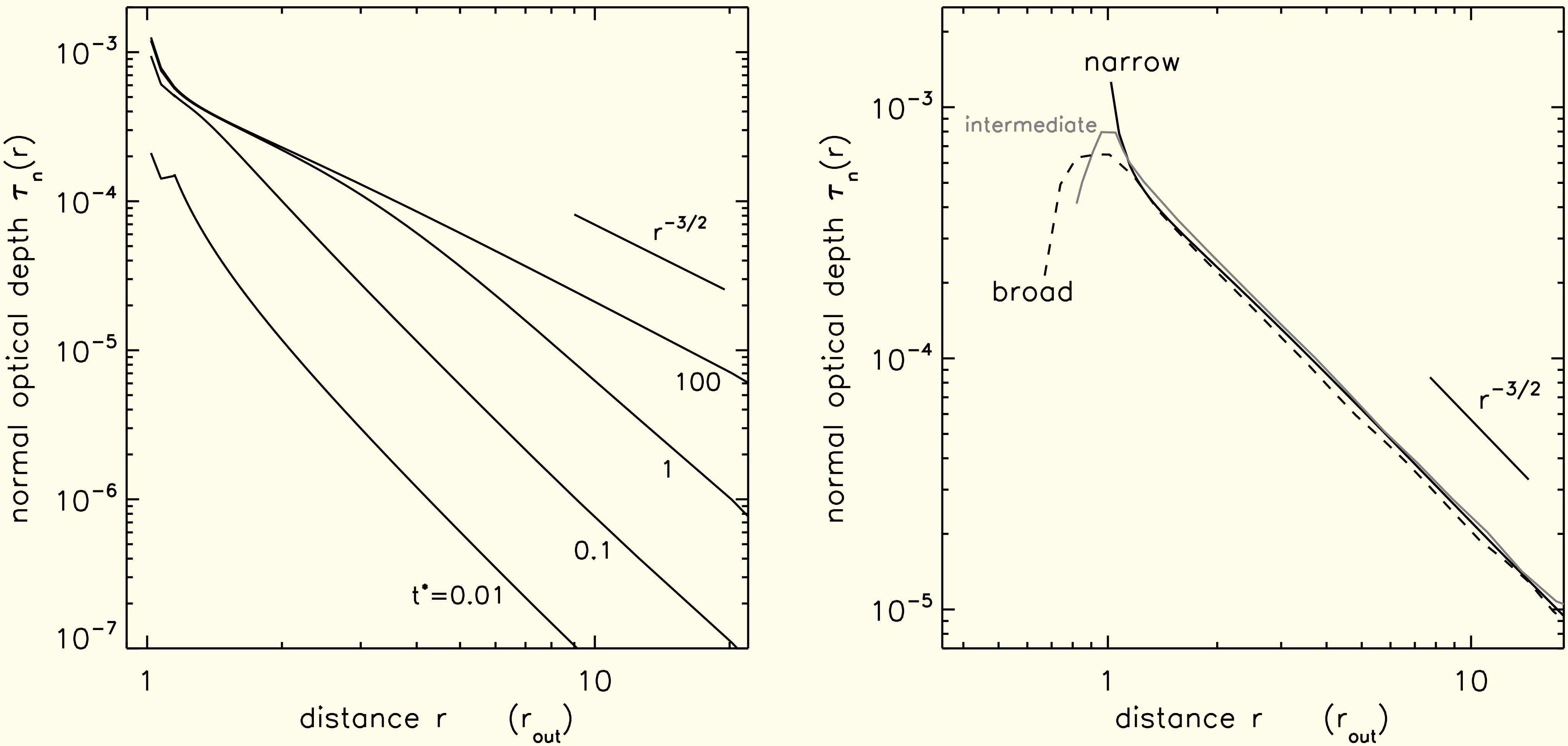
when dust grains are weak, $Q^\star < 10^6$ ergs/gm, all collisions are destructive,

$T_c \propto \dot{M}_d^{-1/2}$ and $T_c \propto R^{-2}$ for $R \gtrsim 2R_{\text{blowout}}$

$\Rightarrow$ large grains have **short** lifetimes due to bombardment by abundant small grains

increasing $Q^\star$ increases lifetime of large dust that are confined to planetesimal disk

Disk optical depth τ



Surface brightness (SB) of edge-on disk

β Pic, AU Mic are seen edged-on

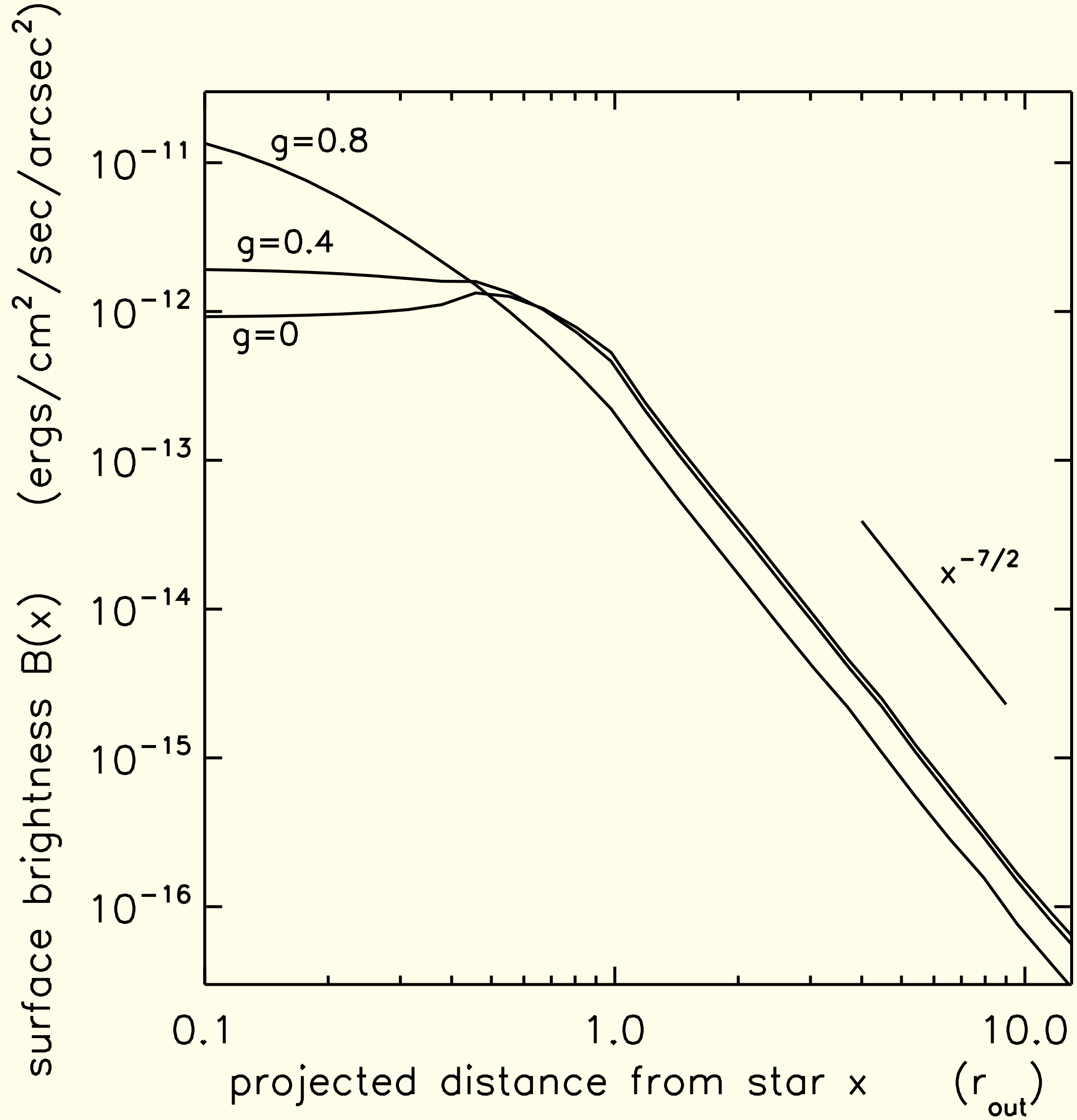
their SB is sensitive to asymmetry in light scattering

$$g = \int \Phi(\phi) \cos\phi d\Omega$$

when $g = 0$ (isotropic scattering) inner SB($x < r_{in}$) is flat if pl'tesimal disk has donut-hole

if $|g| \gtrsim 0.7$ (forward scattering), then SB has a knee-bend where LOS passes thru planetesimal disk

where SB(x) $\propto x^{-7/2}$ indicates planetesimal r_{out}



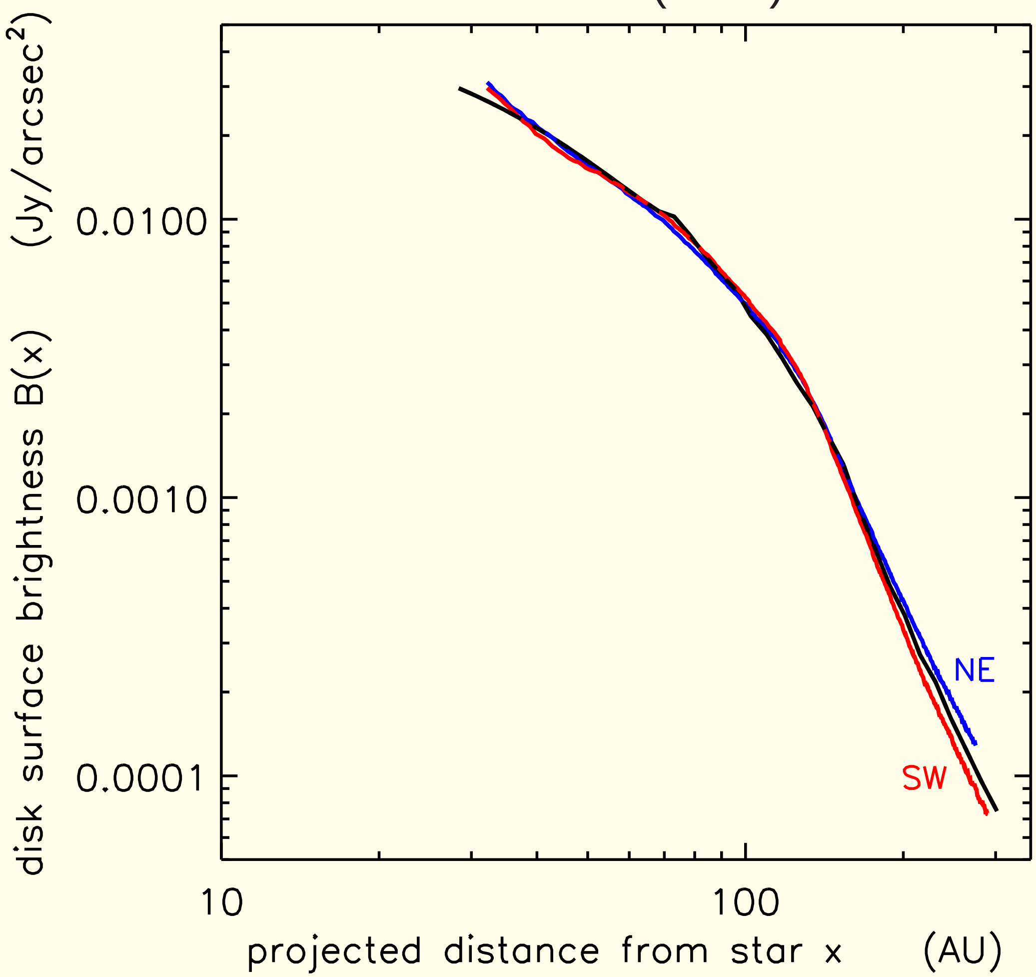
planetesimals reside at $r_{in} < r < r_{out}$ where $r_{in} = 0.5 r_{out}$

Diagnosing β Pictoris

fit requires:

- broad planetesimal disk,
  $75 \lesssim r_p \lesssim 150$ AU
- heavy dust production
  $\dot{M}_d \sim 3 \times 10^{15}$ gm/sec
  ($300\times$ higher than S&C model)
- grains are probably reflective.
  I assumed $Q_s = 0.7$,
  similar to Saturn's icy rings
  - note $SB \propto Q_s\sqrt{\dot{M}_d}$,
    if $Q_s = 0.1$ (dark dust)
    then $\dot{M}_d \uparrow \times 100$
- dust size dist' has $q = 2.5$,
  shallower than Dohnanyi $q = 3.5$
- dust grains are strong,
  $Q^\star \sim 10^8$ ergs/gm,
  to preserve large grains at $x \sim 100$ AU

optical HST observations by
Golimowski et al (2006)



- knee indicates that dust are asymmetric light scatters, $g \simeq 0.7$

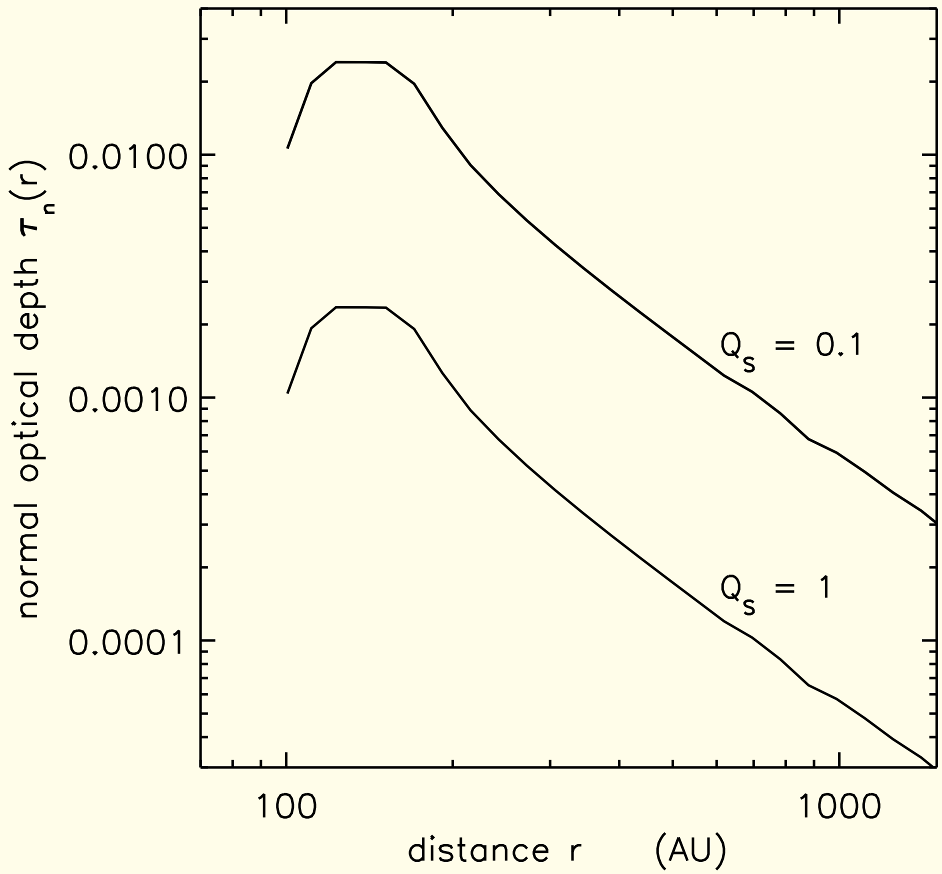
Mass of β Pic Disk

Assuming Bond albedo $Q_s = 0.7$:

- $M_{dust} \simeq 11$ lunar masses
  - comparable to estimate from sub-mm observations by Holland et al (1998)

- dust cross section is $A_{dust} \simeq 2 \times 10^{20}$ km^2

- note star's age $t_\star \simeq 12$ Myrs, so implied mass-loss is $\dot{M}_d t_\star \sim 160$ M$_\oplus$!
  - β Pic's planetesimal disk is (or was) very massive!



inferred optical depth $\tau(r)$ assuming dark $Q_s = 0.1$ and bright $Q_s = 1$ grains

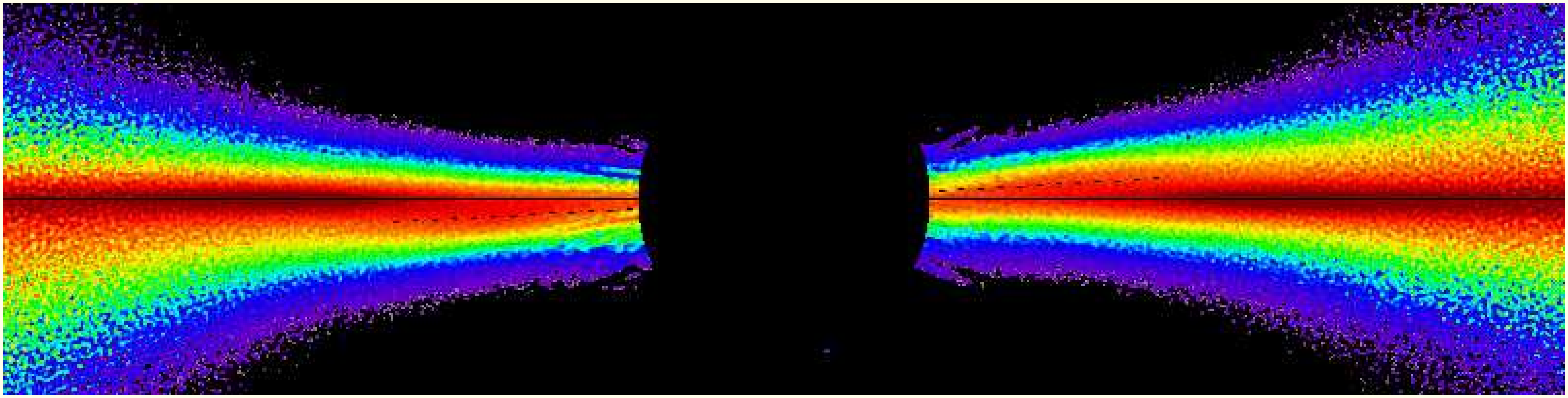
The prospects for planet formation at β Pic are...

...unclear? grim?

- the planetesimal disk is suffering heavy mass loss due to collisional grinding + blowout by RP, $\dot{M}_p \sim 13$ $M_\oplus$/Myr.

- β Pic's planetesimal disk is or was very massive, $M_p \gtrsim 160$ $M_\oplus$ in $75 \lesssim r \lesssim 150$ AU zone

- I suspect that the $r \gtrsim 75$ AU zone at β Pic may be a region of planetesimal destruction, rather than a site of future planet formation



β Pic with radial variations factored out

Next steps

- I also need to model the disk's thermal emission
  - fits to optical + sub-mm observations will allow me to pin down $\dot{M}_d$ and Q_s with greater certainty
- will couple this debris-disk model to Stu W's planetesimal model
  - his code can track the growth and erosion of planetesimals
  - this will produce a more realistic treatment of the disk's dust production rate $\dot{M}_d(t)$ over time
  - will also allow us to infer or else constrain the unseen planetesimal disk mass with greater realism
- preprint will be available
- supported by Hubble Theory/Archive research program