The Obscuring Torus (2)

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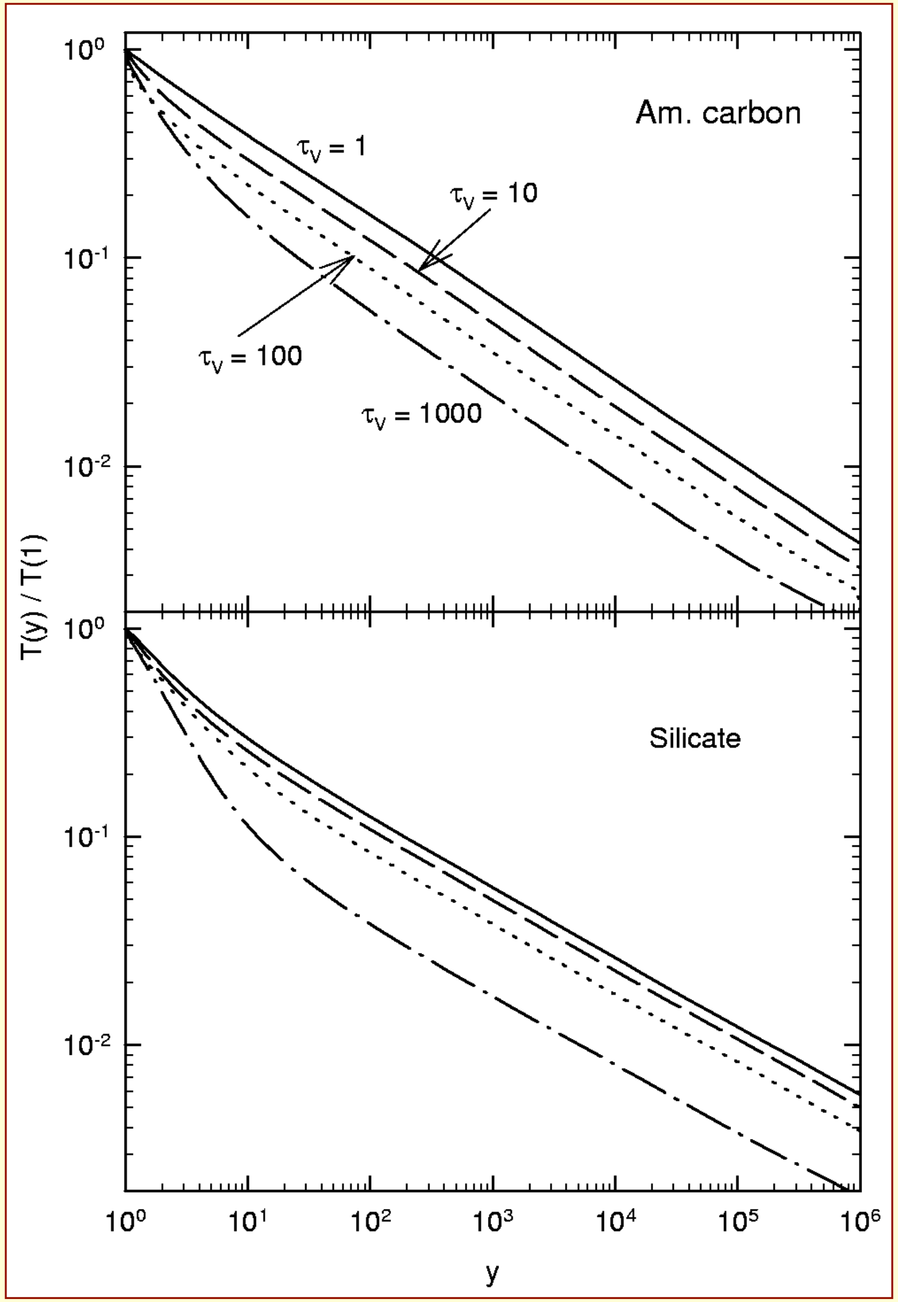
Dust Temperature Profile

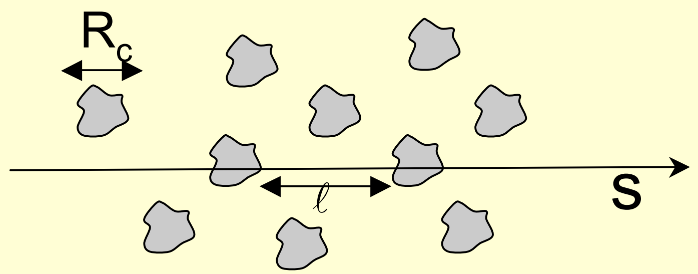


Ivezic & Elitzur 97

Clumpy Media Modeling

- Nenkova, Ivezic & Elitzur 2002, ApJL 570, L9
- Elitzur, Nenkova & Ivezic 2003, astro-ph/0309040
- Elitzur 2006, astro-ph/0612458

Clumpy Medium



n_c (pc^{-3})

filling factor: $\phi = n_c V_c << 1$

$\phi = n_c A_c R_c = R_c/\ell << 1$

$n_c, R_c \Rightarrow \phi, N = n_c A_c = 1/\ell$ (pc^{-1})

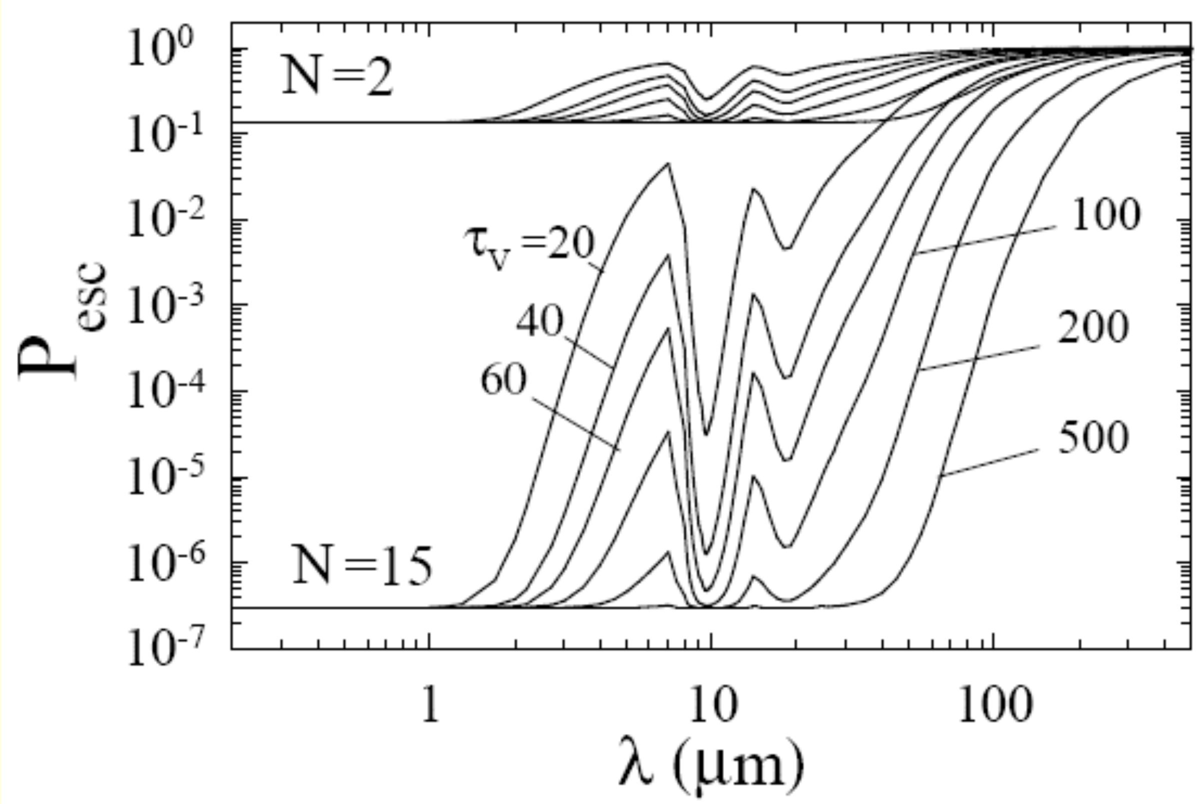
segment ds: $d\mathcal{N}(s) = N(s)ds$ emission: $S_{c\lambda} d\mathcal{N}(s)$

☜ Natta & Panagia 84: $P_{esc} = e^{-t}$; $t = \mathcal{N}(s)(1 - e^{-\tau})$

☜

$$I_{C\lambda} = \int e^{-t} S_{c\lambda} N(s) ds$$

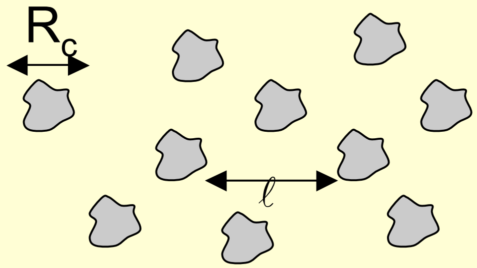
☞



N =2
N =15
τ_V =20
40
60
100
200
500
P_{esc}
λ (μm)

☞

Example: N_{tot} cubic clouds of size R_c in a cubic volume of size L:



n_c (pc^{-3})

$$n_c = N_{tot}/L^3$$

$$\phi = n_c R_c^3 = N_{tot}(R_c/L)^3$$

$$N = n_c R_c^2 = \frac{N_{tot}}{L}\left(\frac{R_c}{L}\right)^2$$

$$\mathcal{N} = NL = N_{tot}\left(\frac{R_c}{L}\right)^2$$

$$N_{tot} = \mathcal{N}^3/\phi^2$$

Monte Carlo Results

$\tau_{av} = \mathcal{N}(1 - e^{-\tau})$?

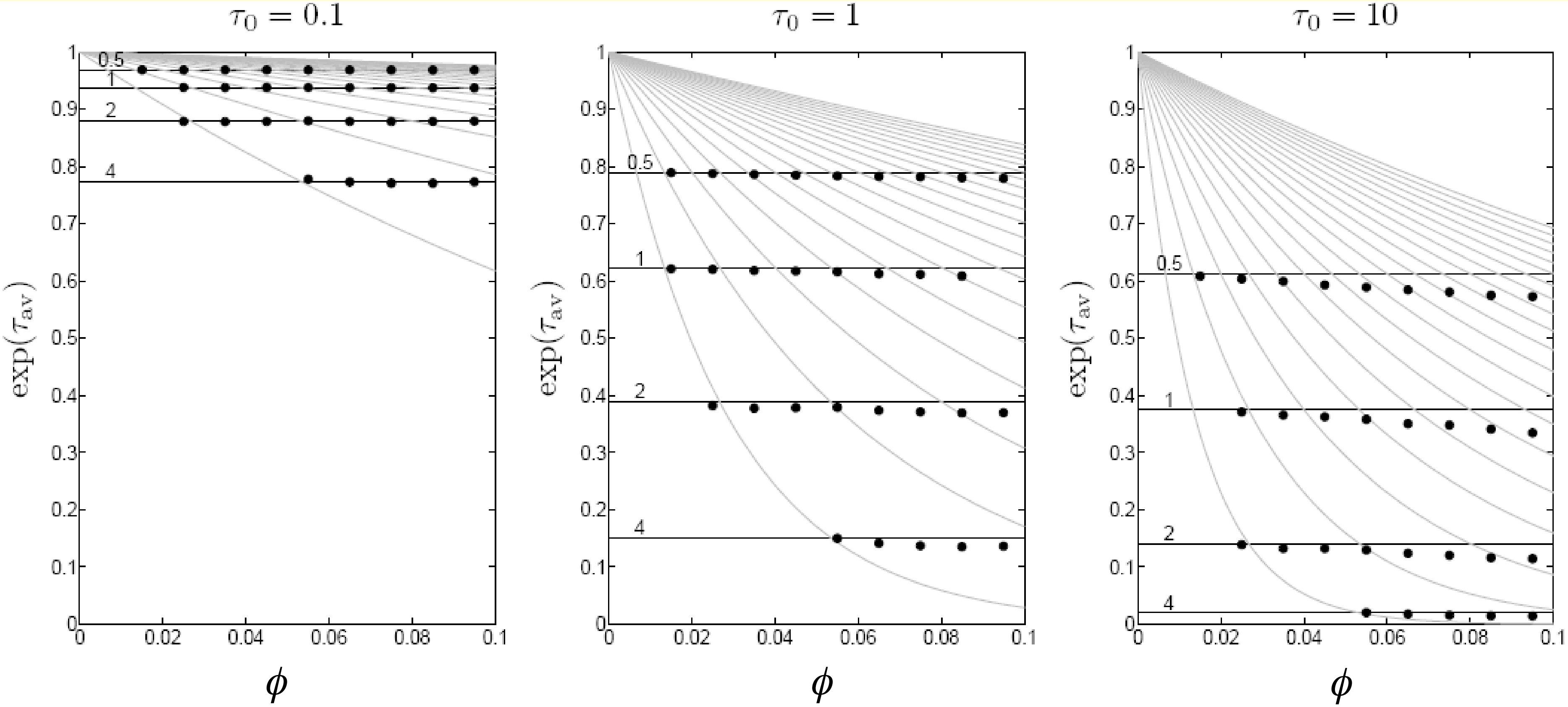
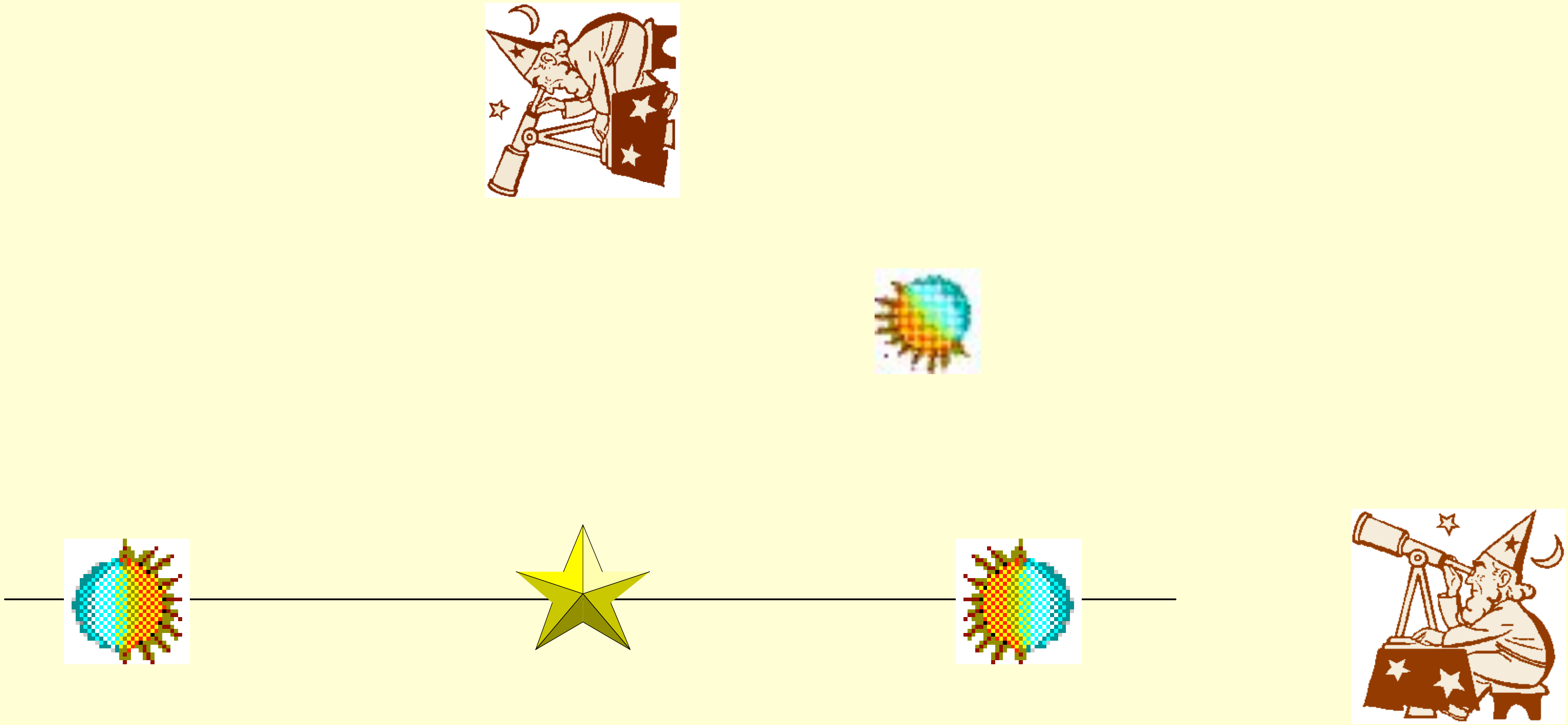


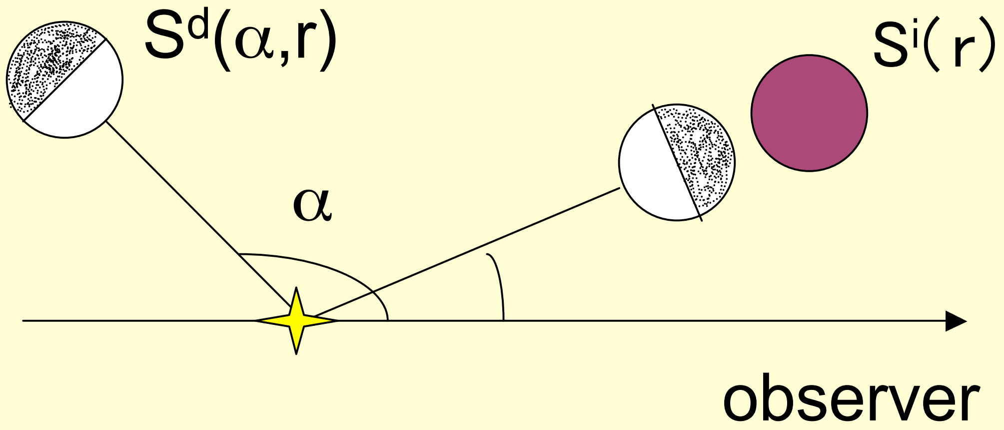
Fig. 1.— Averaged response function $\exp(\tau_{av})$ versus filling factor ϕ for τ_0=0.1, 1 and 10. Filled circles and horizontal black lines indicate the results from numerical simulations and theoretical predictions respectively, using $\mathcal{N}$=0.5, 1, 2 and 4. The errorbars are comparable to the size of the circles. Gray curved lines trace the loci defined by $R/L = 0.01, 0.02 \ldots, 0.2$ increasing from the left.

Conway, Elitzur & Parra 07

Cloud Emission - Anisotropy



Direct & Indirect Heating

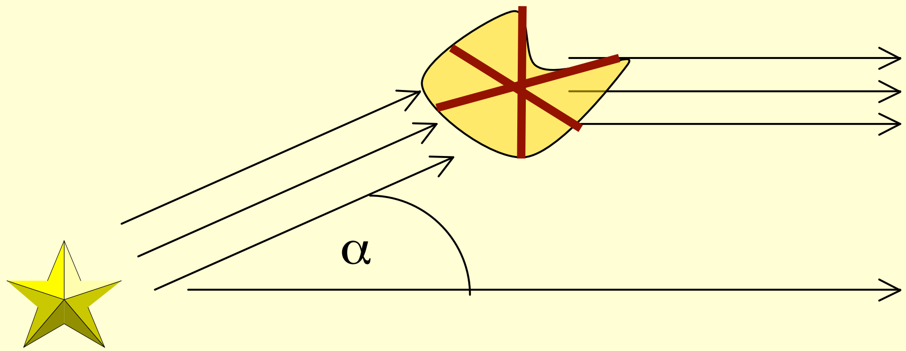


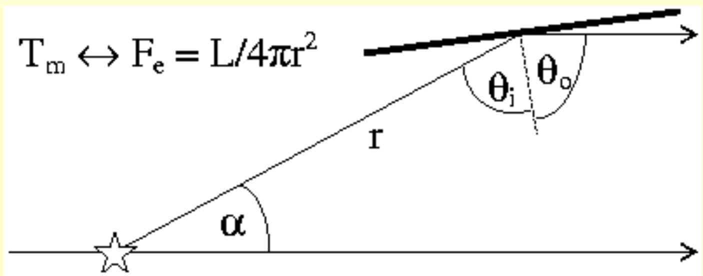
Composite source function:

$$S_c(\alpha,r) = p\,S^d(\alpha,r) + (1 - p)\,S^i(r)$$

$$p(r) = e^{-\mathcal{N}(r)}$$

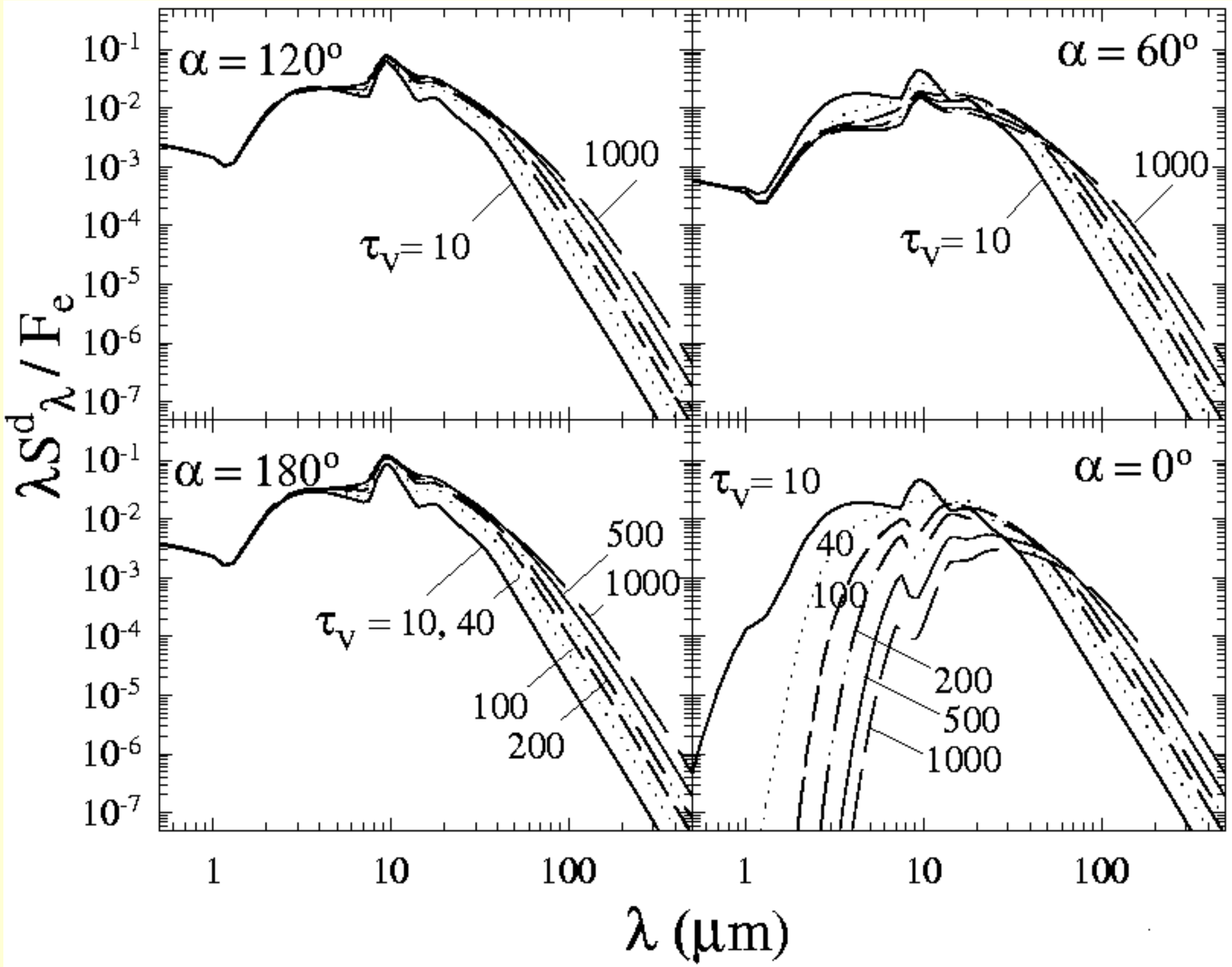
Directly-heated Cloud Modeling





Solutions by DUSTY http://www.pa.uky.edu/~moshe/dusty/

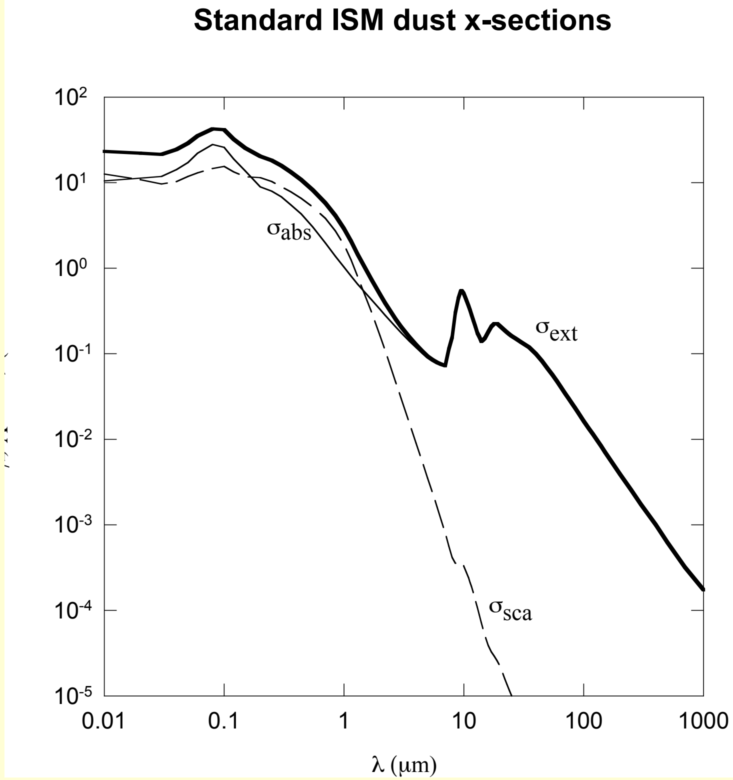
Directly Illuminated Clouds



Nenkova+ 07

Silicate Features — Basics

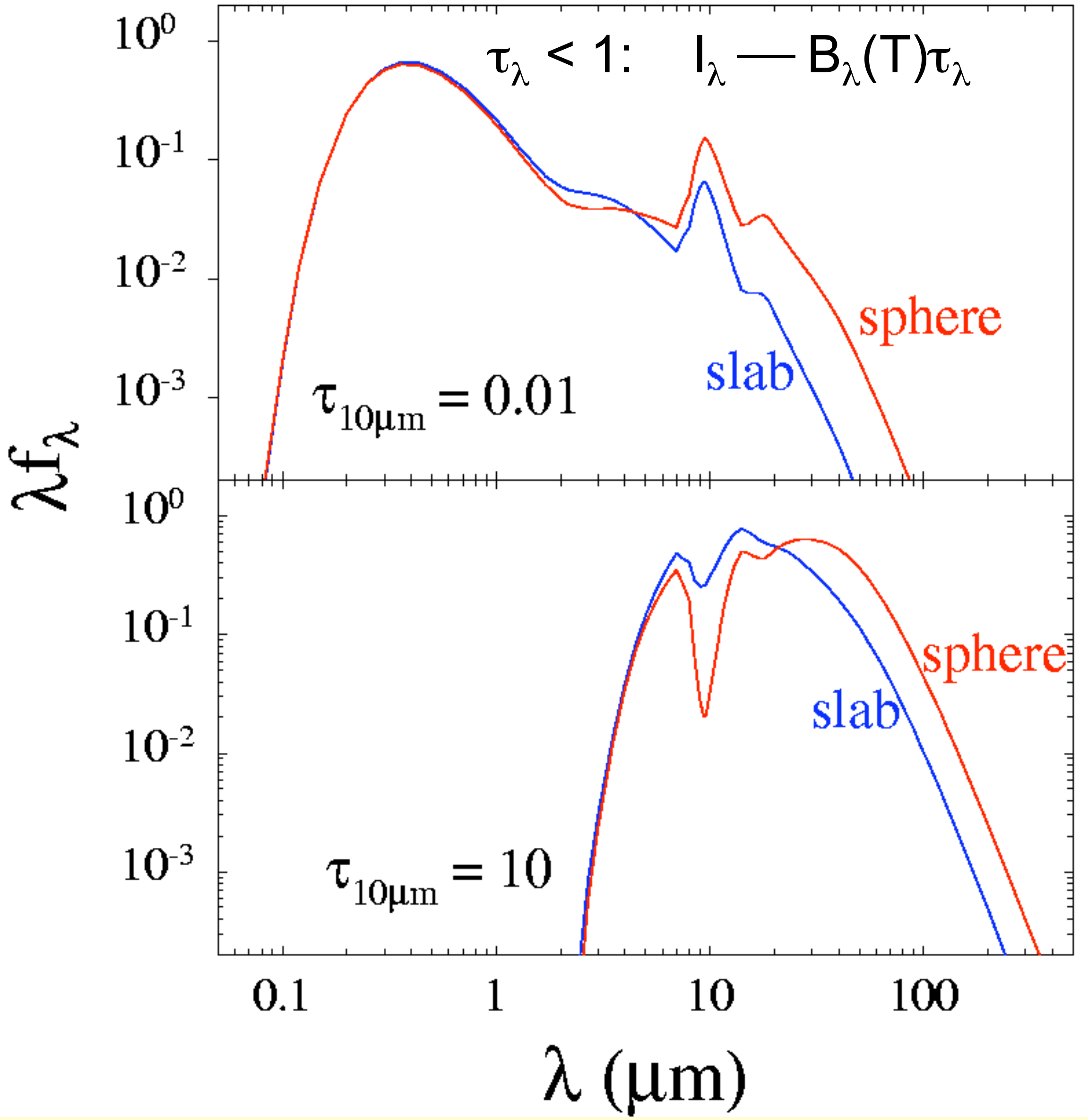
$I_\lambda = B_\lambda(T)[1 - \exp(-\tau_\lambda)] \quad \{+ I_{in}\exp(-\tau_\lambda)\}$



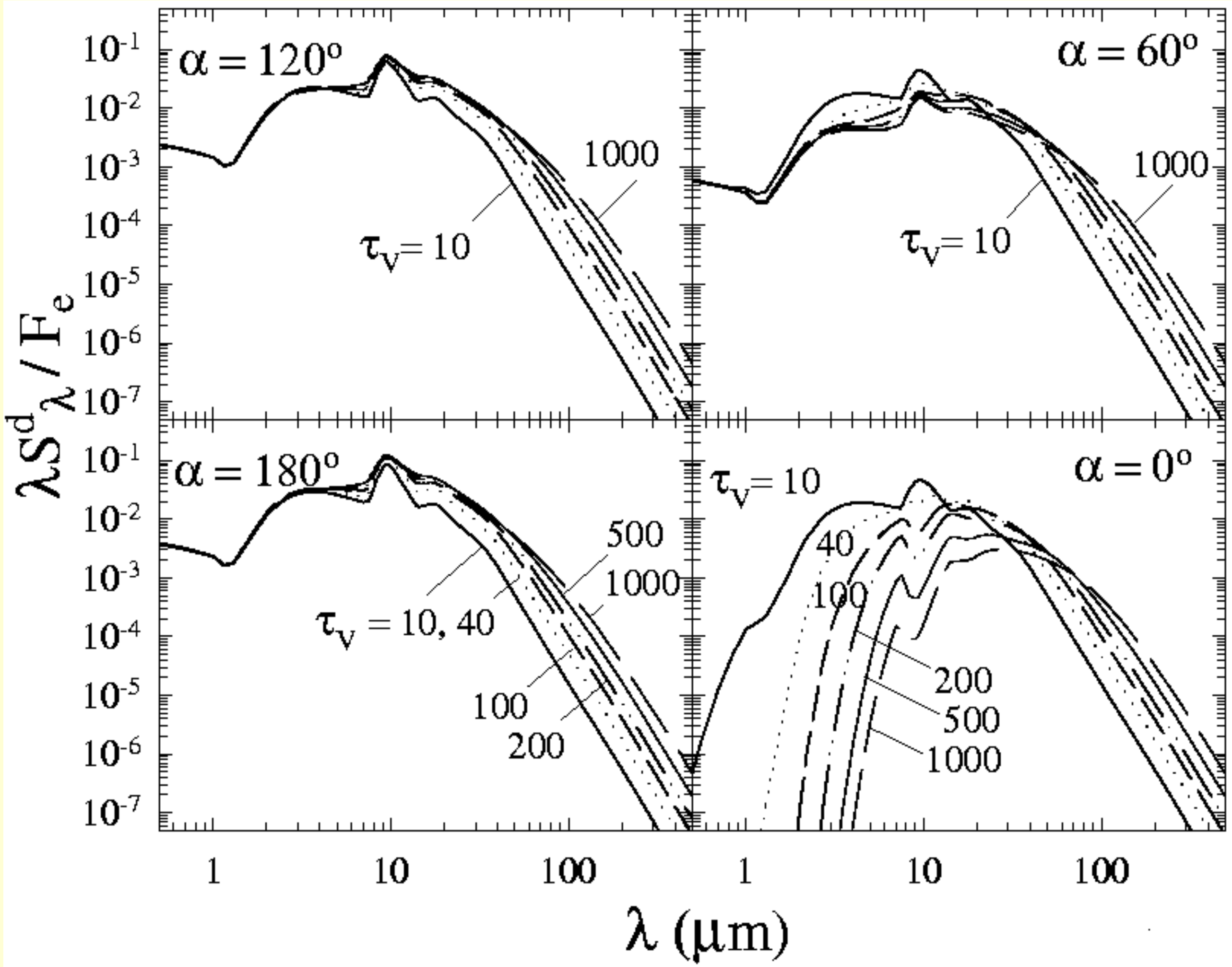
$\tau_\lambda > 1$: I_λ — $B_\lambda(T)$

T gradient ⇒

absorption feature:

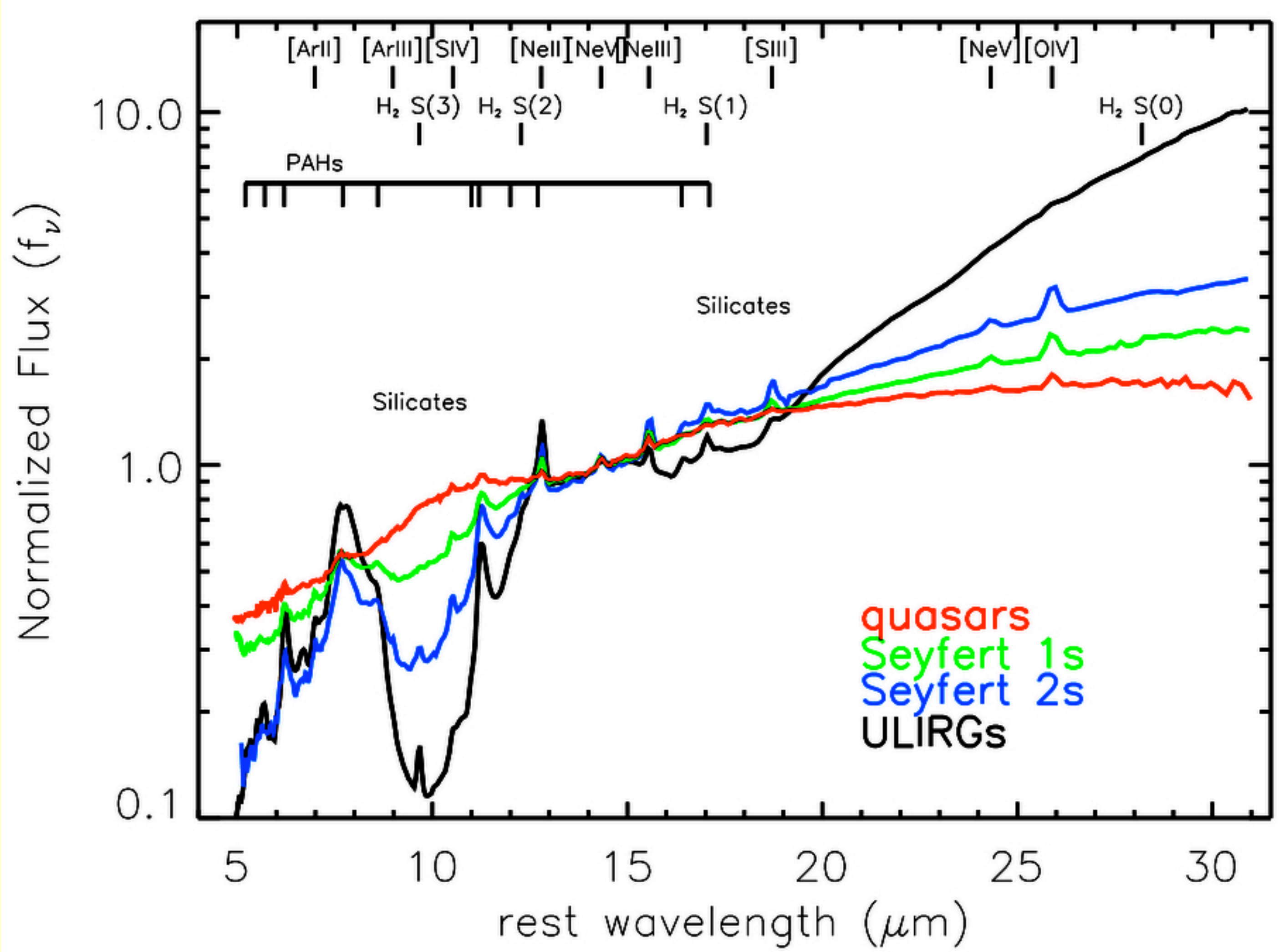


Directly Illuminated Clouds



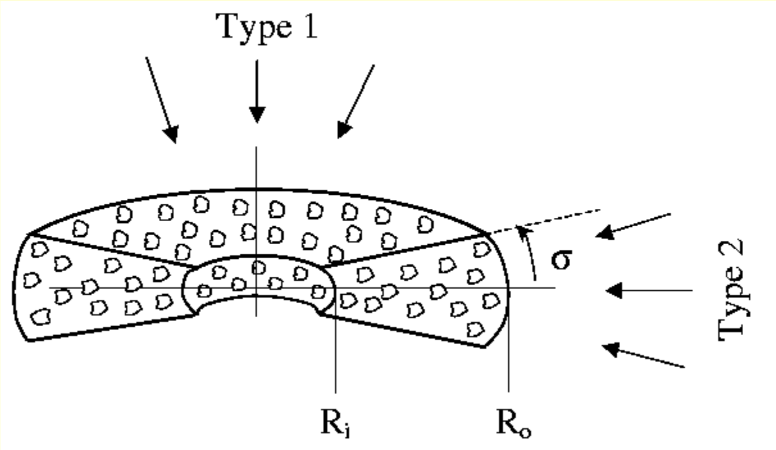
Nenkova+ 07

Average SED's



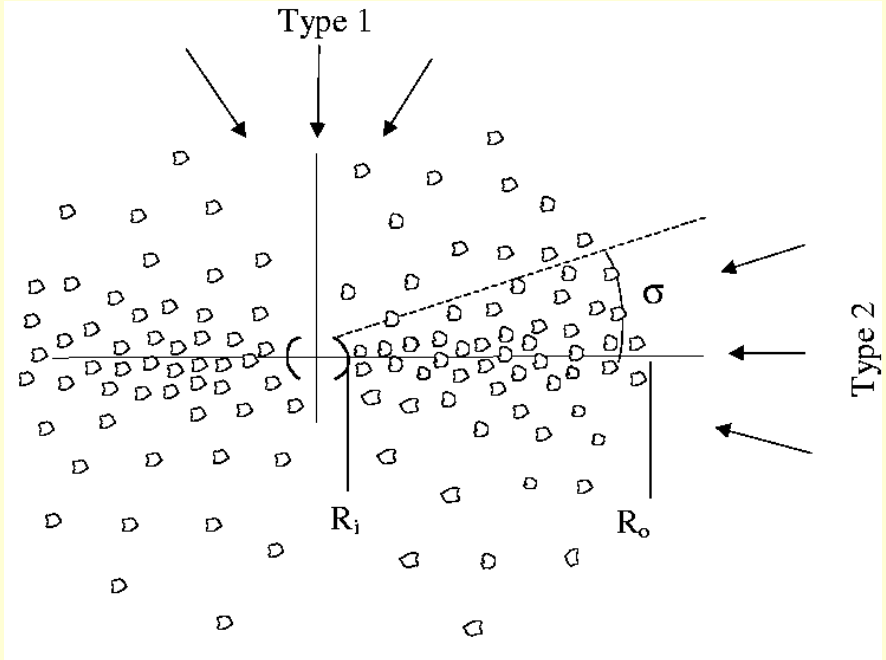
Hao+ '07

AGN Modeling:



sharp edge

Gaussian edge



$$\mathcal{N}_T(\beta) = \begin{cases} \mathcal{N}_T(0) & \beta < \sigma \\ 0 & \beta > \sigma \end{cases}$$

$$\mathcal{N}_T(\beta) = \mathcal{N}_T(0)\,\exp(-\beta^2/\sigma^2)$$

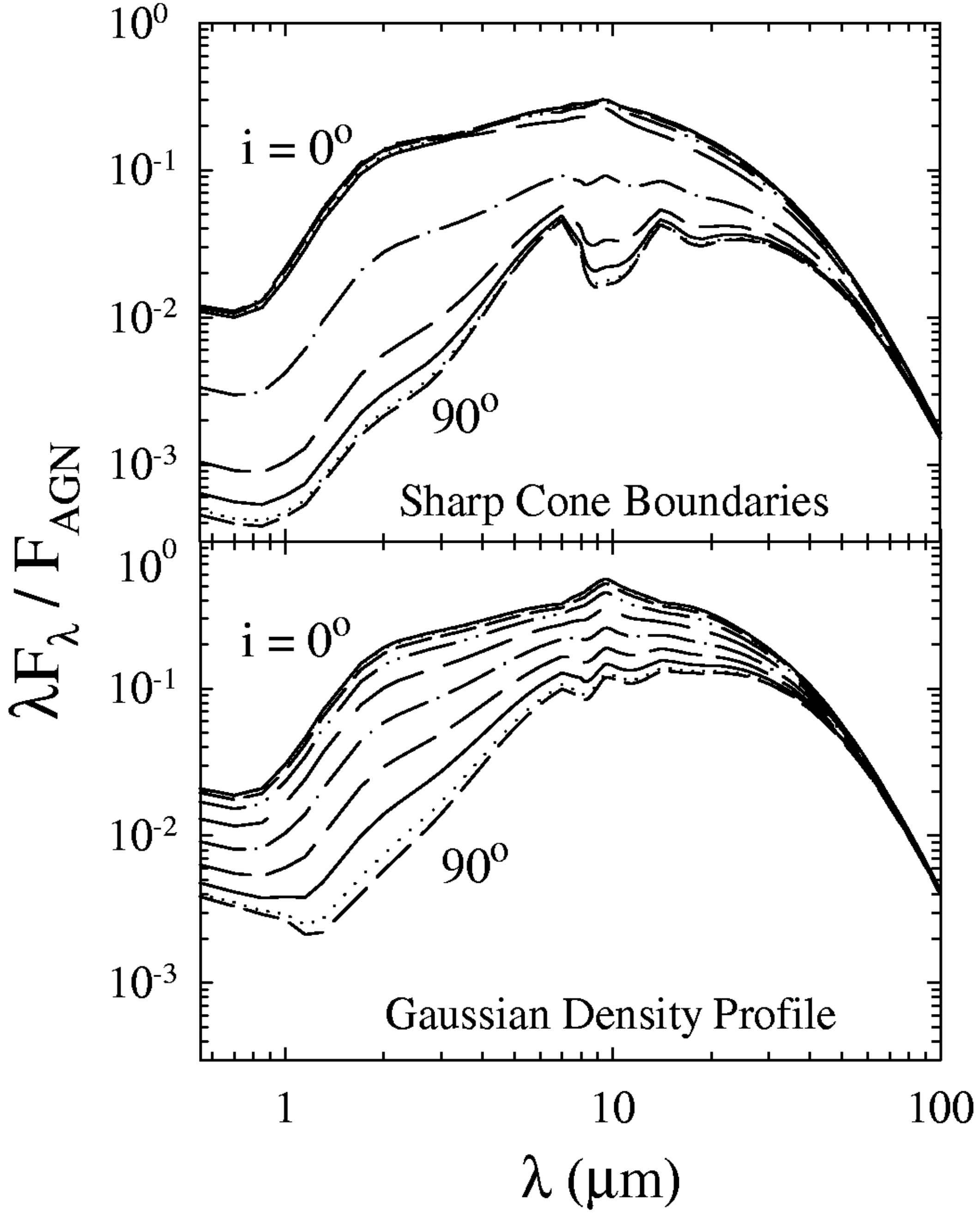
$Y = R_o/R_d$: $T_d = 1500$ K   ($R_d = 0.4\text{pc}\ L^{1/2}{}_{45}$)

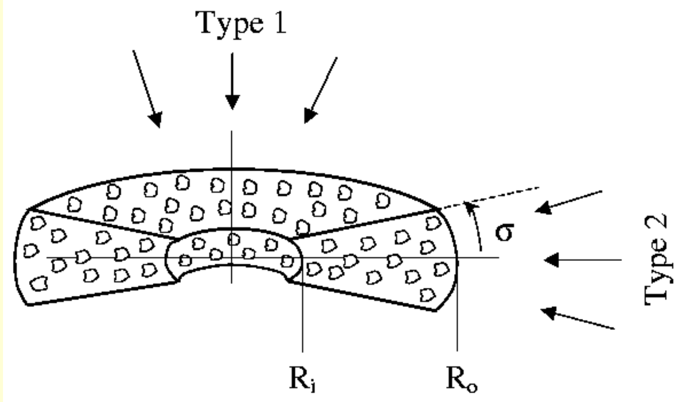
$\mathcal{N}_0 = \mathcal{N}_T(0)$, σ, q: $N(r,\beta) \propto \mathcal{N}_T(\beta)/r^q$

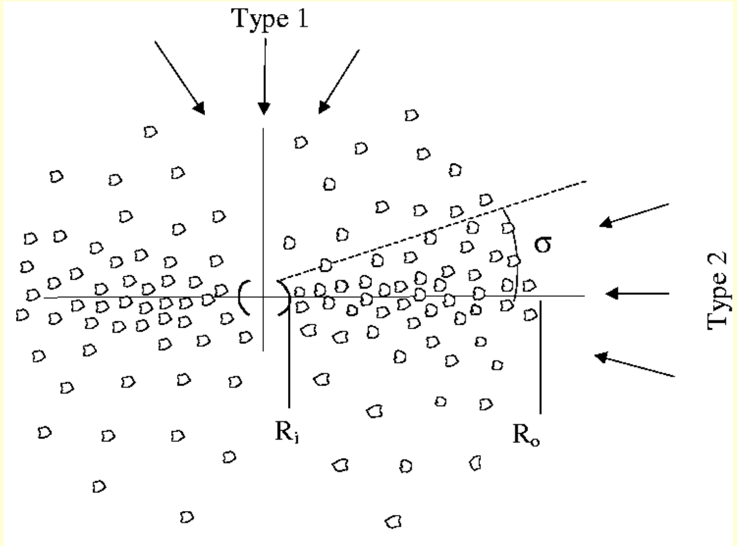
τ_V

$\mathcal{N}_0 = 5$, $\tau_V = 60$, $q = 1$, $Y = 30$, $\sigma = 45^o$

Geometry Effects

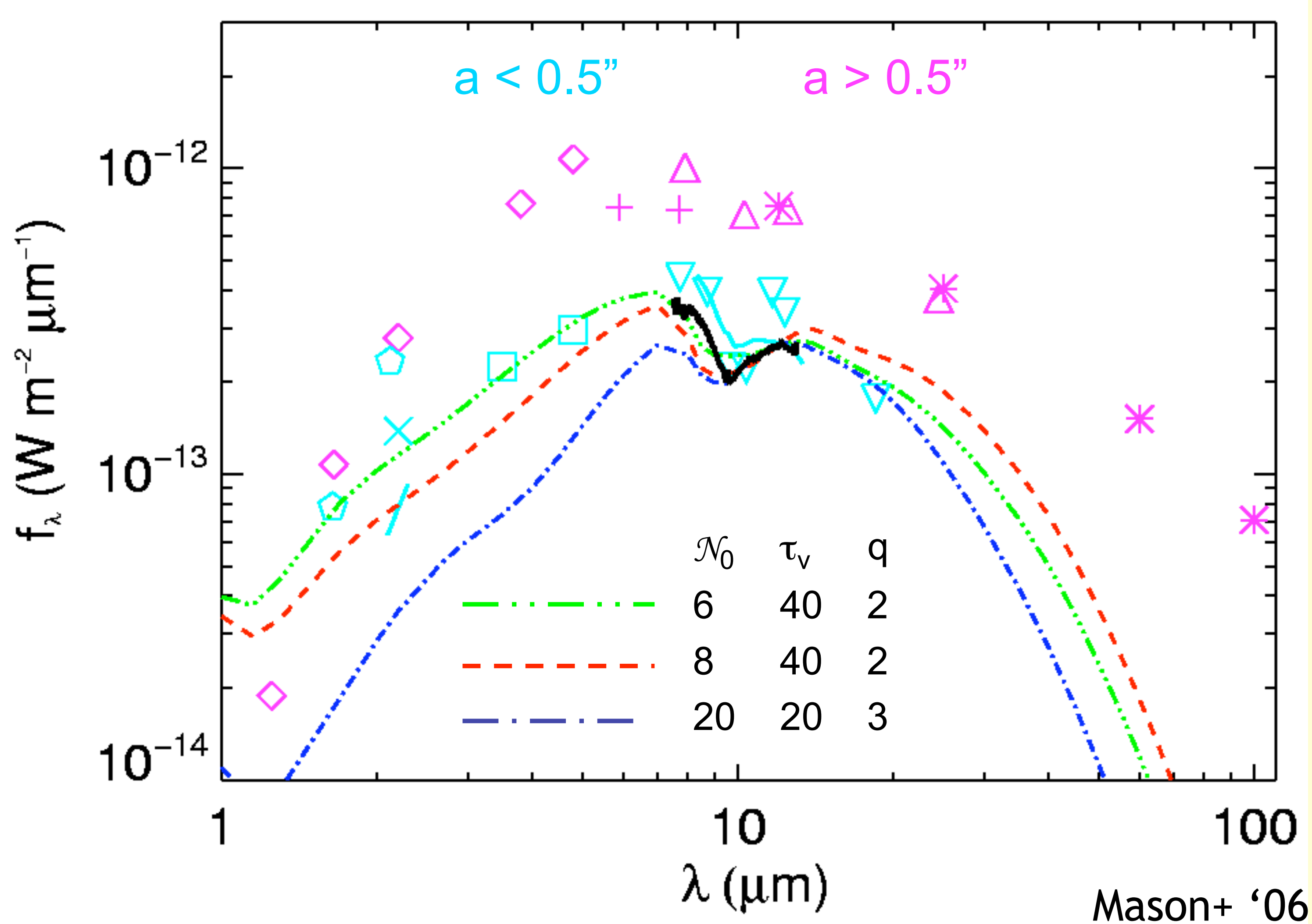






$N \propto \mathcal{N}_0 \exp(-\beta^2/\sigma^2)/r^q$

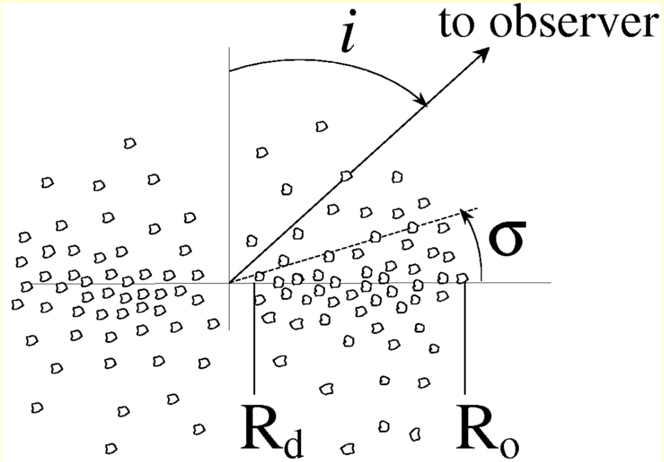
Modeling NGC1068 — Equatorial Viewing!



Mason+ '06

L_{Bol} — $2 \cdot 10^{45}$ erg s^{-1}

Clumpy Torus Modeling



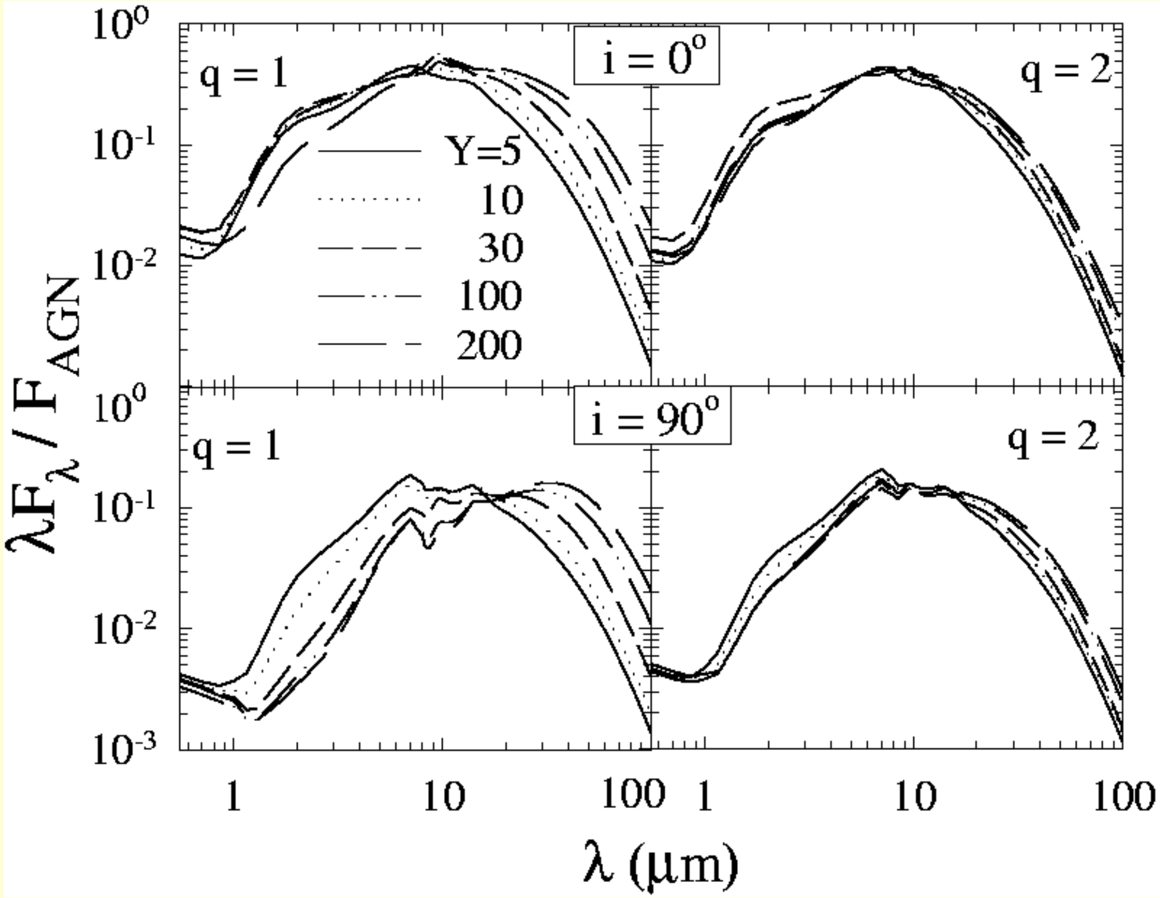
- $\mathcal{N}_0$ = 5 – 10 clouds
- σ = 30° - 60°
- τ_V = 40 – 120
- q = 1 – 2
- $R_d = 0.4 L^{1/2}_{45}$ pc; $R_o \geq 5\, R_d$

$N \propto \mathcal{N}_0 \exp(-\beta^2/\sigma^2)/r^q$

Standard ISM dust works fine

Nenkova et al '02; '07

Large q — SED Independent of R_{out}

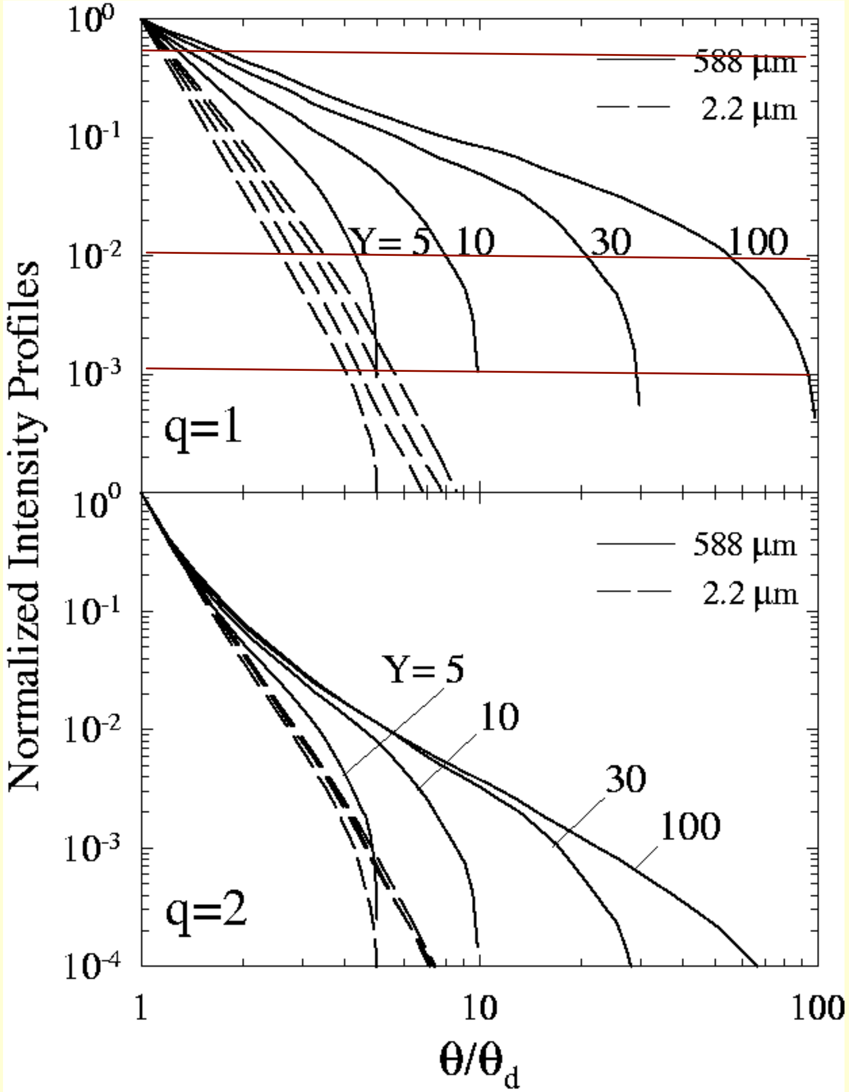


$R_d = 0.4\,\mathrm{pc}\ L^{1/2}_{45}$

$Y = R_o/R_d$

$N \propto r^{-q} \exp(-\beta^2/\sigma^2)$

So how big really is the torus?



½ max

1% max

0.1% max

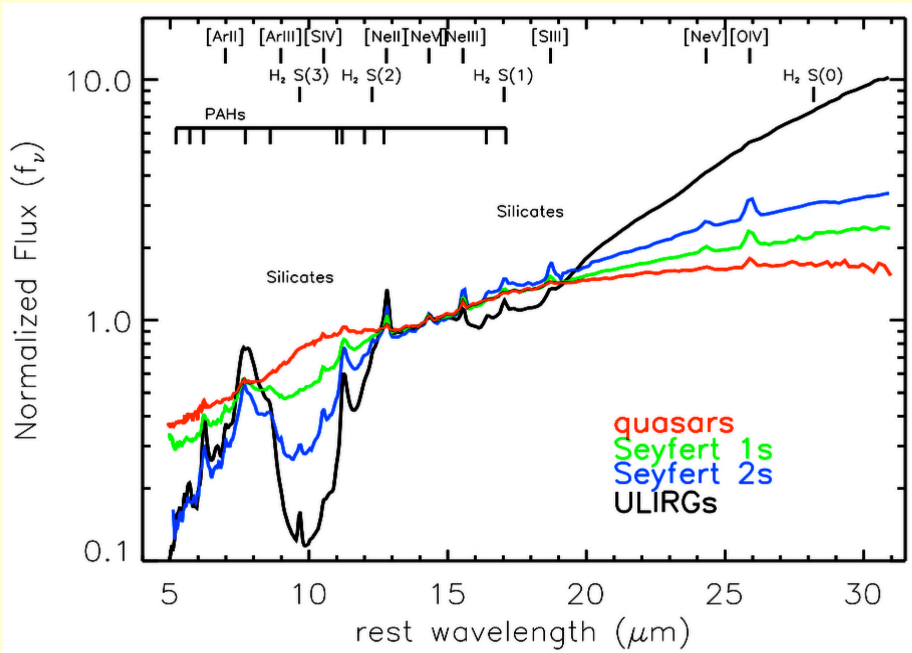
NGC 1068: $\theta_d \approx 0.02''$

ALMA?

IR Puzzle #2

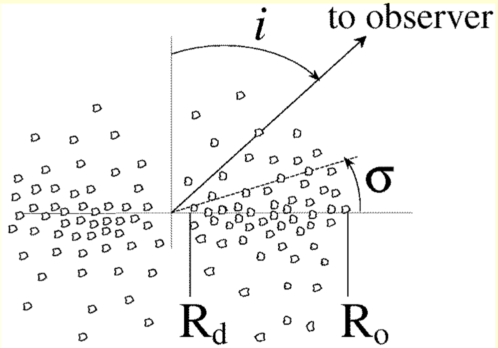
While its obscuration is highly anisotropic, the torus emission is nearly isotropic:

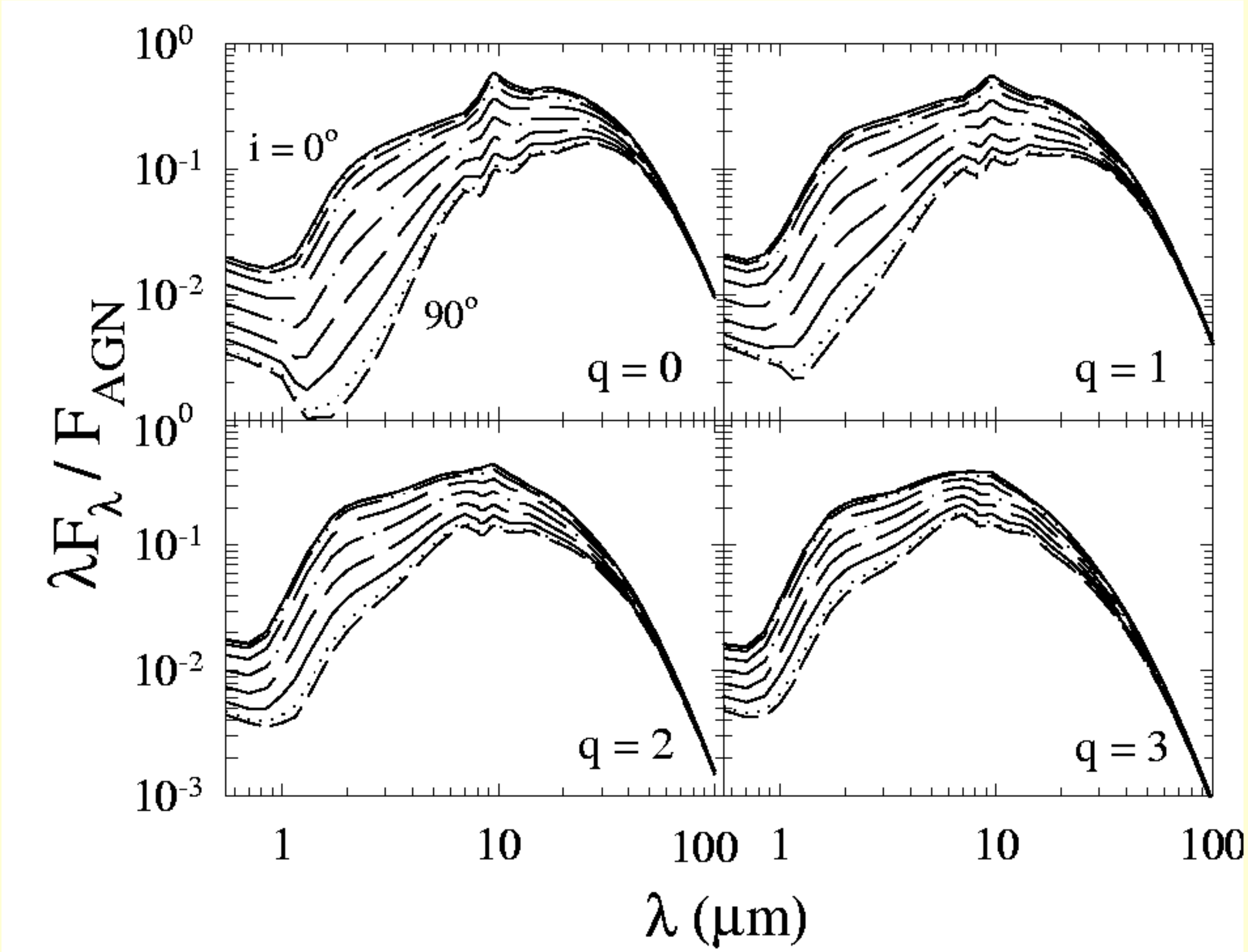
Lutz et al ’04 — 6μm vs 2-10 keV x-rays
Horst et al ’06 — 12μm vs 2-10 keV x-rays
Buchanan et al ’06 — 5-35μm vs radio



Hao+ 07

Clumpy Torus – Radial Density Variation





$N \propto \mathcal{N}_0 \exp(-\beta^2/\sigma^2)/r^q$

$\mathcal{N}_0 = 5$

$\sigma = 45°$

$Y = 30$ τ

$_V = 60$

Large q (steep radial decline) –

Anisotropic obscuration with nearly isotropic emission!

Silicate Features — Clumpy Torus Models

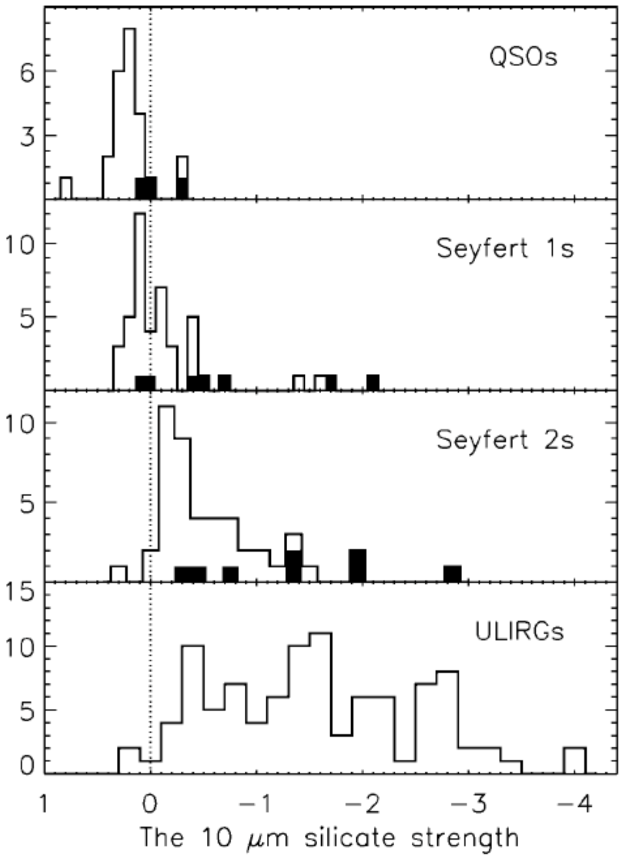
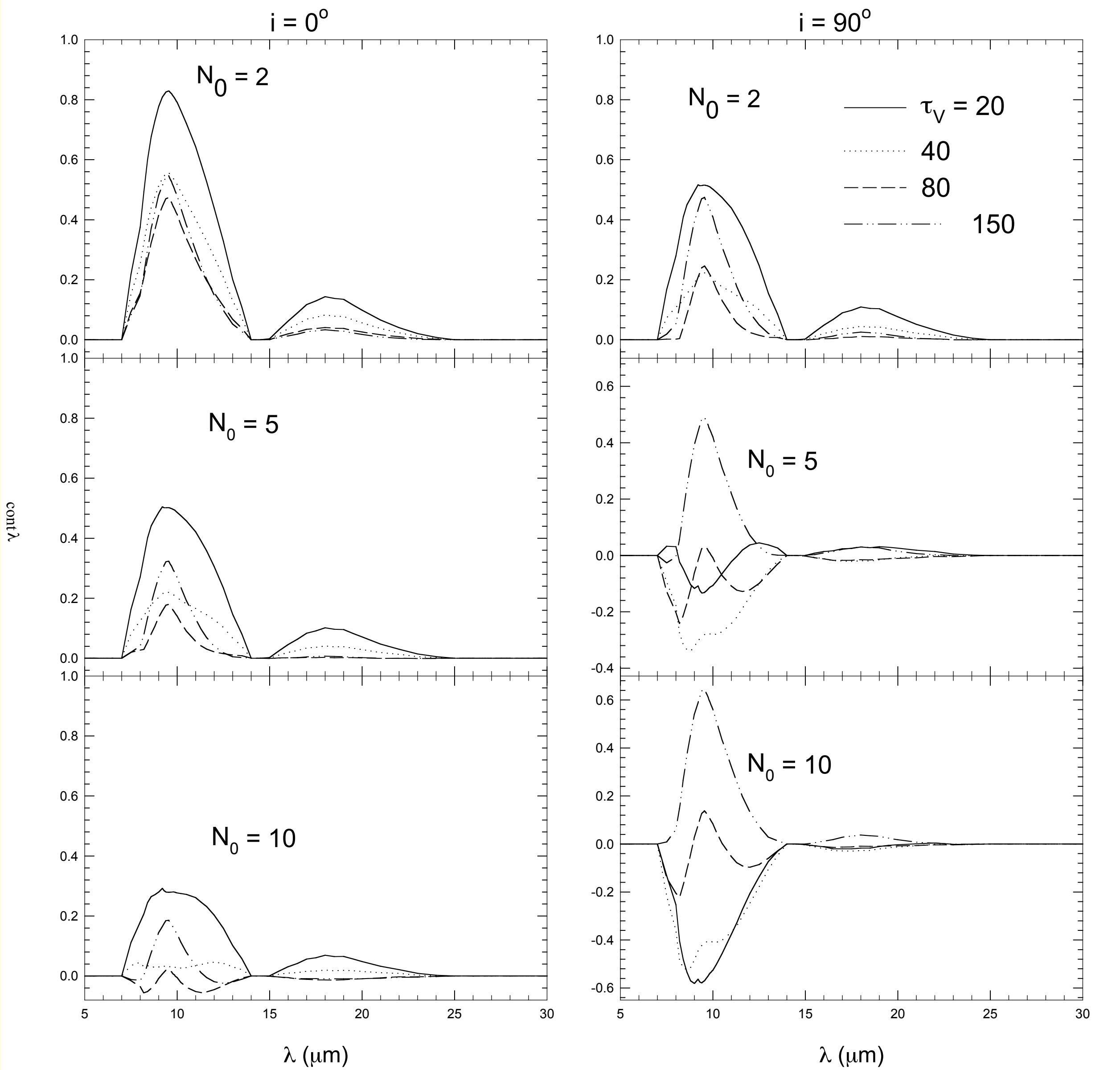


FIG. 2.—Distribution of the 10 μm silicate strength, S_{10}, for QSOs, Seyfert 1s, Seyfert 2s, and ULIRGs. Silicate absorption increases to the right. In QSOs, Seyfert 1s, and Seyfert 2s, the distributions of sources that are also in the ULIRG sample are shaded. The averages of the 10 μm silicate strengths are 0.20 for quasars, −0.18 for Seyfert 1s, −0.61 for Seyfert 2s, and −1.56 for ULIRGs. The range of the silicate strengths are $0 \le S_{10} \le 0.4$, $-0.7 \le S_{10} \le 0.3$, $-1.6 \le S_{10} \le 0$, $-4 \le S_{10} \le 0.2$ for most quasars, Seyfert 1s, Seyfert 2s, and ULIRGs.



Hao+ 07

Torus Mass

$M = \int m_H n_H dV = m_H \int n_H \, r^2 dr \, d\Omega$ $\qquad N_H = \int n_H d\ell$

- $\phi = 1$: $\quad M_{tot} = m_H \; N_H \; \Omega \; \langle r^2 \rangle_{gas}$
- $\phi < 1$: $\quad M_{tot} = m_H \; N_{H,tot} \; \Omega \; \langle r^2 \rangle_{clouds}$

$$M_{Torus} \propto N_H R_d^2 \approx 10^3 \sin\sigma \, N_{H,23} \, L_{45} Y \, I_q(Y) \;\; M_\odot$$

The Eddington Luminosity

$$F_{grav} = \frac{GMm_p}{r^2} \qquad F_{rad} = \sigma_T \frac{L/c}{4\pi r^2}$$

$$\Gamma = \frac{F_{rad}}{F_{grav}} = \frac{\sigma_T L}{4\pi G c m_p M} = \frac{L}{L_{Edd}}$$

$$L_{Edd} = \frac{4\pi G c m_p}{\sigma_T} M$$

$$L_{Edd} = 1.3\times10^{38}\ \mathrm{erg\ s^{-1}}\ M/M_\odot = 1.3\times10^{45}\ \mathrm{erg\ s^{-1}}\ M_7$$

Torus Mass (2)

$$M_{Torus} = 1.6\times10^{3} \sin\sigma \, N_{H,23} \, L_{45} Y \, I_q(Y) \;\; M_\odot$$

$$\frac{M_{Torus}}{M_{BH}} = 2\times10^{-4} \frac{L}{L_{Edd}} \sin\sigma \, N_{H,23} Y \, I_q(Y)$$

$$I = \begin{cases} Y/3 & q = 0 \\ Y/2\ln Y & q = 1 \\ 1 & q = 2 \end{cases}$$

Total number of Torus Clouds

$$n_{tot} = \int n_c dV$$

$$N_c = n_c A_c = n_c R_c^2 \qquad\qquad \phi = n_c V_c = n_c R_c^3$$

$$n_{tot} = \int N_c^3/\phi^2 \, dV$$

$$n_{tot} \approx \mathcal{N}_0^3/\phi^2$$

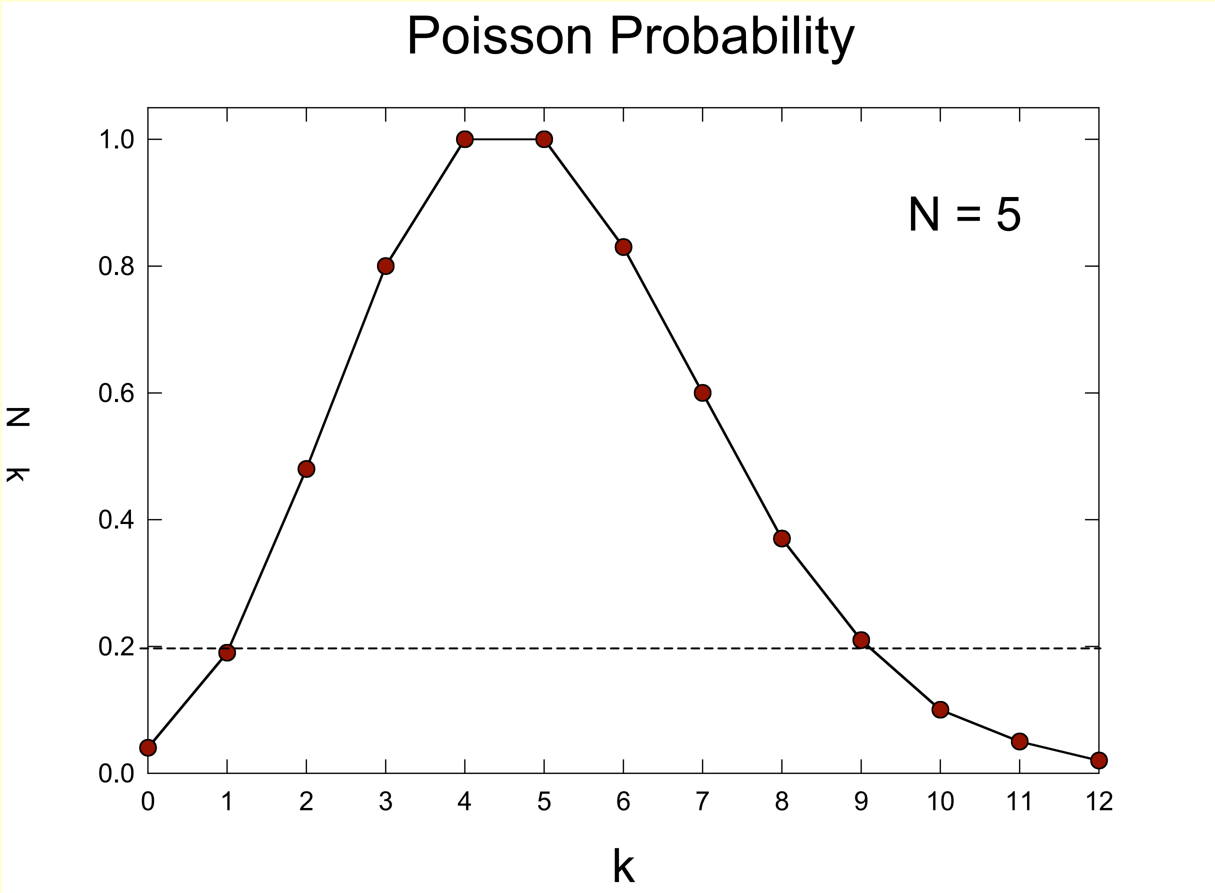
Example: $\phi = 10\% \quad \Rightarrow \quad n_{tot} = 100\mathcal{N}_0^3 \approx 10^4 — 10^5$

Clumpy Emission vs Obscuration

- IR emission – average over many los
- x-ray absorption – single los

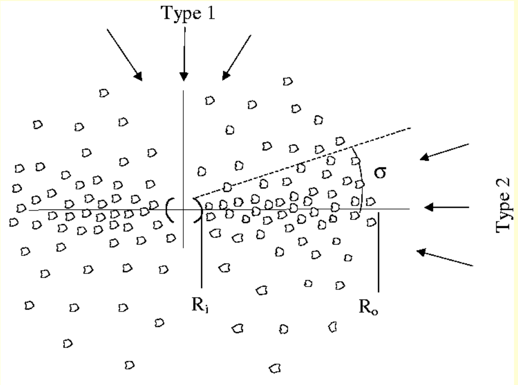
$P_k \propto N^k/k!$

$P_5 = 18\%$

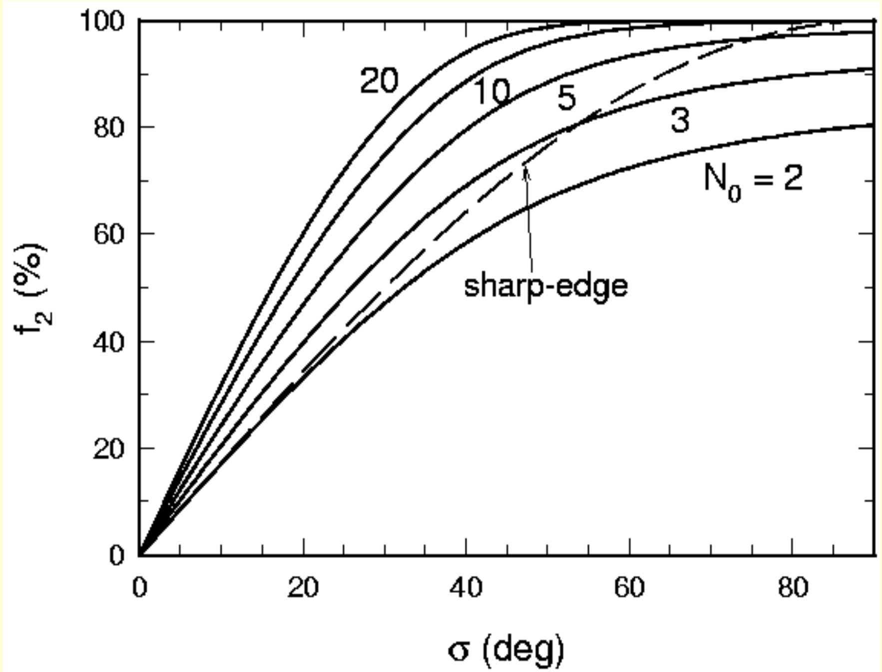


Clumpy Unification

$N_c(\beta) = \mathcal{N}_0 \exp(-\beta^2/\sigma^2)$



AGN type is a viewing-dependent probability!



- Type 1 sources from "type 2 viewing", and vice versa
- Flips between type 1 & 2 (Aretxaga et al 99)
- L variations of f_2 may arise from either σ or N_0 or both

f_2 depends on both σ and $\mathcal{N}_0$!