The 10-micron silicate feature in AGN

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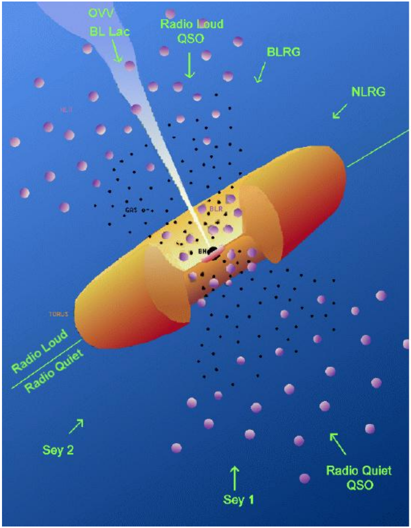
28 June 2011, From Dust to Galaxies, IAP

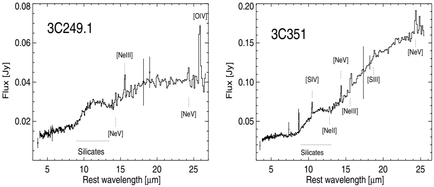
AGN unification



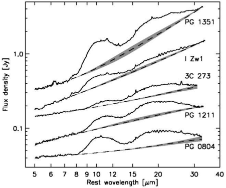
Urry & Padovani 1995

Spitzer solved problems

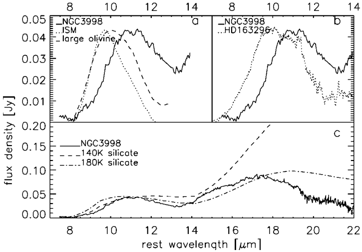
10-micron silicate emission in type 1 sources (long expected)



Siebenmorgen+2005



Hao+2005



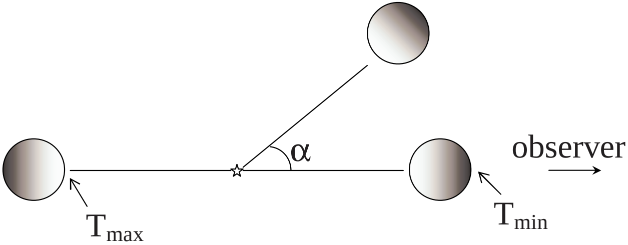
Sturm+2005

Spitzer also brought puzzles

- 10-micron silicate emission in type 2 sources
- Feature shape and peak shifts
- Lack of deep absorption features

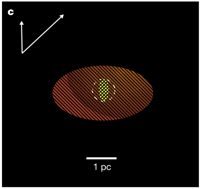
$\Rightarrow$ Address all puzzles with a clumpy dust torus.

Directly illuminated clouds



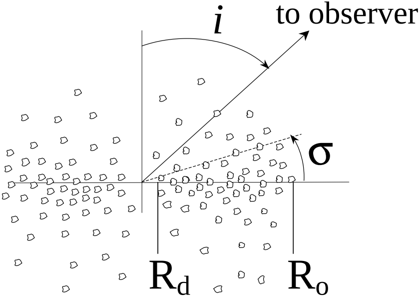
Nenkova+2008b

- Hot bright and cool dark faces
- High and low T at same position and same distance
- We use cold (interstellar) OHM silicates in most cases + graphites from Draine



Jaffe+2004

CLUMPY torus model



Nenkova+2008b

radial cloud distribution
r^{-q}

clouds/ray in equatorial plane
N_0

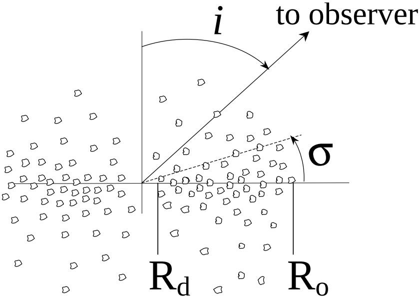
angular torus width
σ

torus thickness
$Y = R_o/R_d$

single cloud optical depth
τ_v

observer viewing angle
i

CLUMPY torus model



Nenkova+2008b

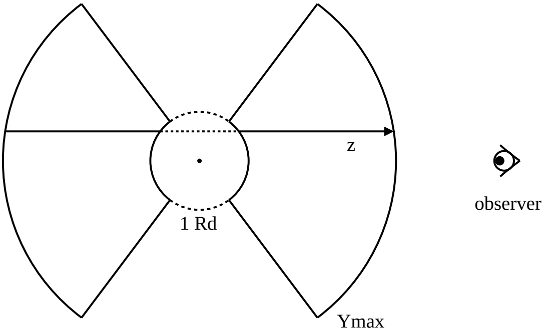
Cloud number per radial ray

$$N(i) = N_0 \, e^{-(\frac{90-i}{\sigma})^2}$$

Escape probability

$$P_{esc} = e^{-N(i)}$$

Torus emission

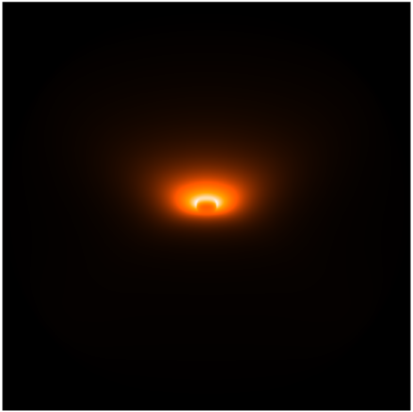


For each (x,y) in sky plane, integrate along path z

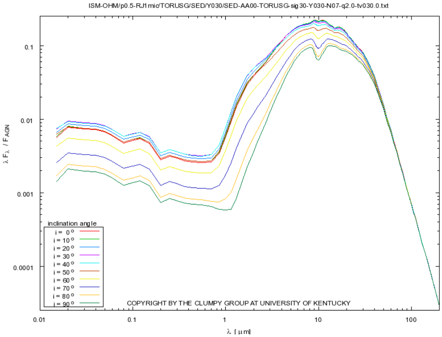
$$I_{\lambda}^{C}(z) = \int^{z} P_{esc}(z', z)\, S_{C,\lambda}(z')\, N_{C}(z')\, dz'$$

▸ torus emission (additional)

Brightness Maps and Spectral Energy Distributions



$Y = 20$, $\sigma = 25^o$, $i = 60^o$, $\lambda = 10\ \mu$m



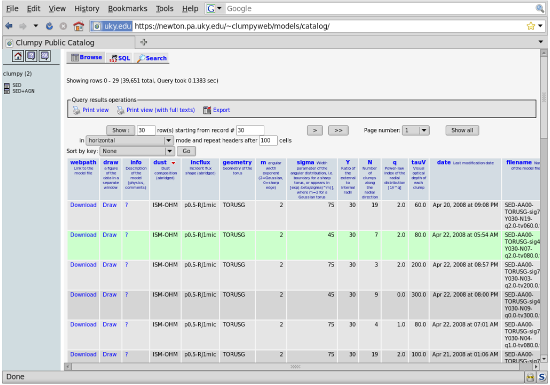
CLUMPY fluxes

$$f = \frac{\lambda F_\lambda}{F_{AGN}}$$

Model database

Database of model SEDs

http://www.pa.uky.edu/clumpy/



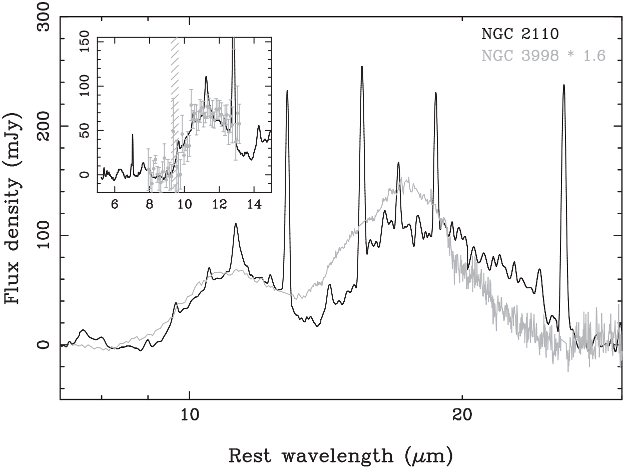
- Large parameter space covered
- $\sim$ 1.3 million models
- freely accessible
- can run own models

Puzzle 1: 10-micron emission in type 2 sources

(Direct evidence for clumpiness)

10-micron silicate emission in type 2 sources

Seyfert 2 galaxy NGC2110



Mason et al. 2009

Fitting the SED of SST1721+6012

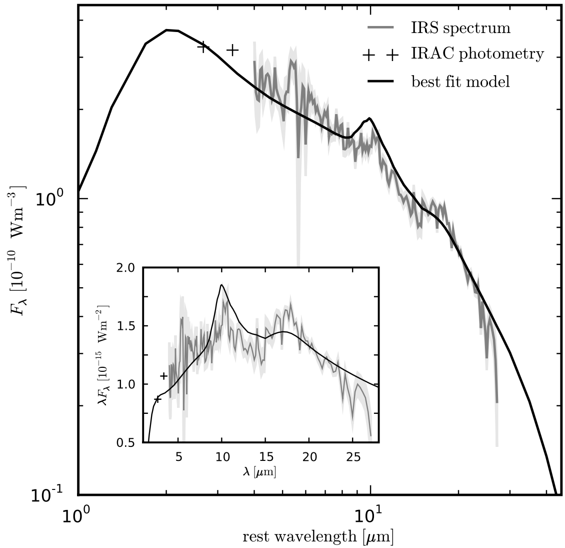
- fit Spitzer SED of a type 2 QSO with CLUMPY model SEDs ▸ more
- find best-fit model among all
- derive model parameters (statistics, Bayesian analysis)

CLUMPY model fluxes:

$$f = \frac{\lambda F_\lambda}{F_{AGN}} \rightarrow F_{AGN} \text{ sets scale}$$

Best fit model

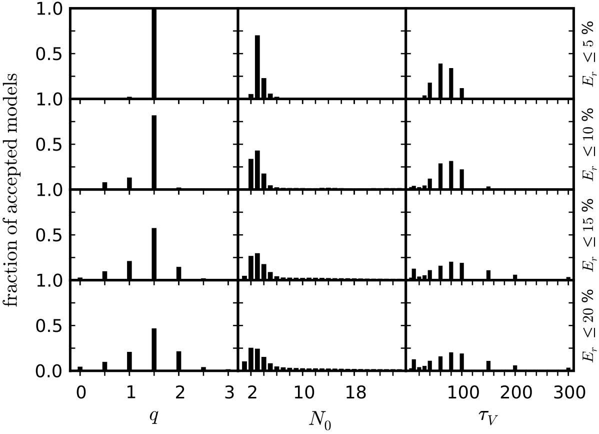
Type-2 quasar SST1721+6012, $z = 0.325$



Best-fit model for SST1721+6012

$$\begin{aligned} q &= 1.5 \\ N_0 &= 3 \\ \tau_v &= 80 \\ Y &= 30 \\ \sigma &= 20 \\ i &= 60 \end{aligned}$$

Well-constrained CLUMPY parameters



$E_r \leq 5\%$
199 models

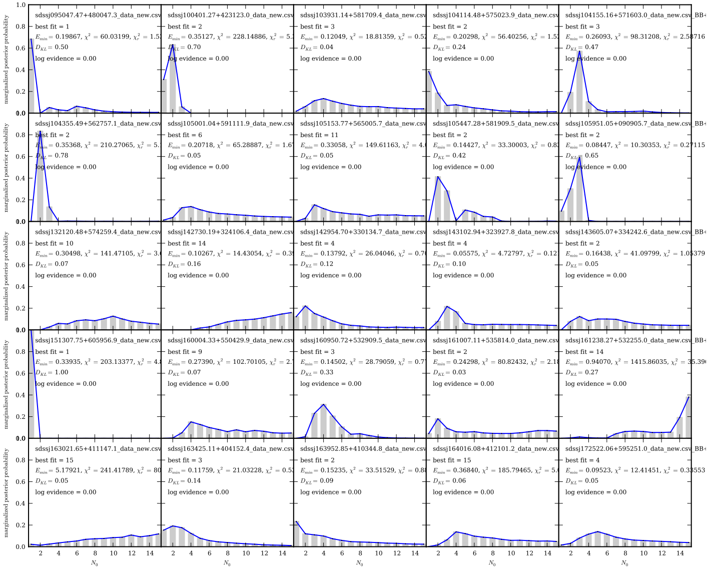
$E_r \leq 10\%$
1691 models

$E_r \leq 15\%$
5210 models

$E_r \leq 20\%$
12854 models

Bayesian analysis - marginalized posteriors

likelihood $\propto e^{-\chi^2/2}$



Puzzle 2: Feature shape and peak shifts

(Dust composition or radiative transfer effect?)

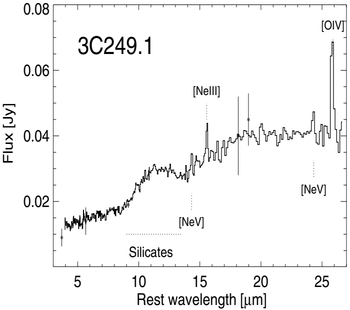
Feature shape and peak shifts

Astronomical silicate dust peaks around $\sim 9.8\ \mu$m

Modeled silicate dusts peak at

Draine et al. 2000	$\sim$9.48 μm
Ossenkopf, Henning, & Mathis 1992	$\sim$10.0 μm

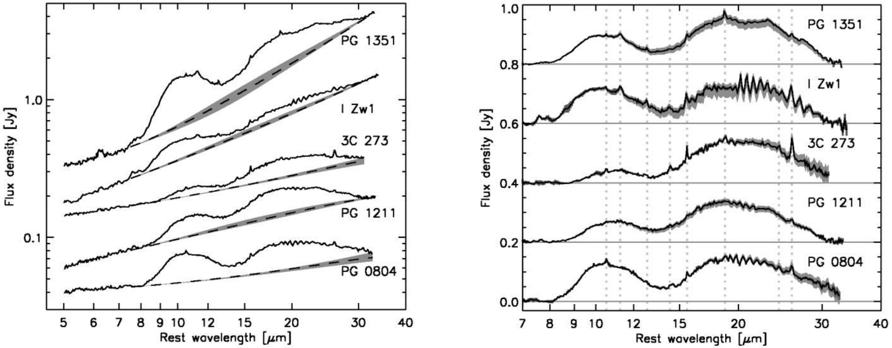
Yet...



Siebenmorgen et al. 2005

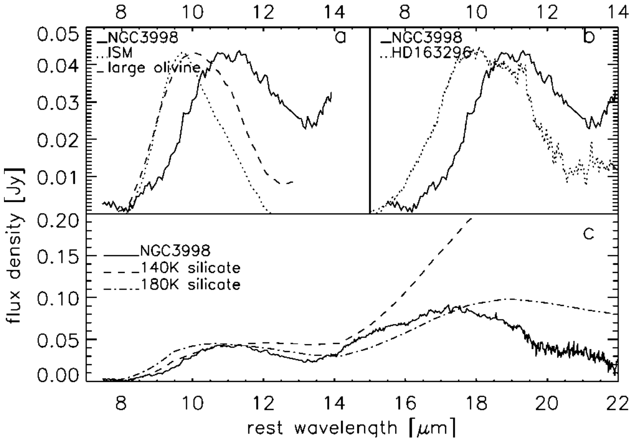
Subtraction of continuum

More examples...



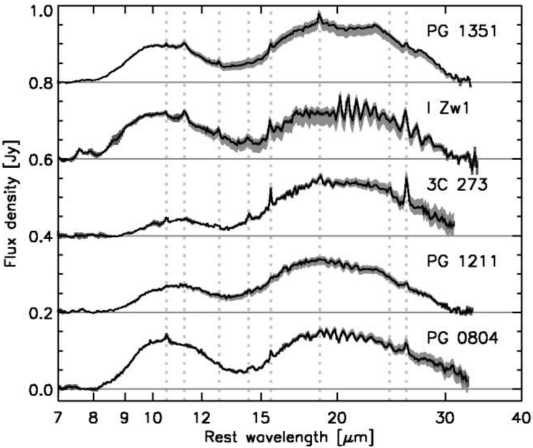
Hao et al. 2005

Fitting with more exotic dusts



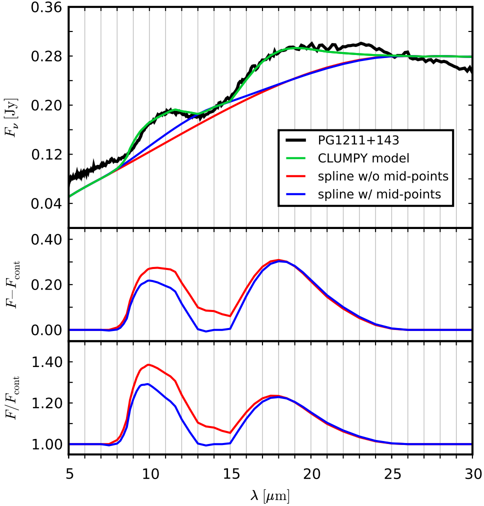
Sturm et al. 2005

Fitting with CLUMPY and **standard** dust



Hao et al. 2005

Defining a continuum



Best-fit model for PG1211+143

$$
\begin{aligned}
q &= 0 \\
N_0 &= 5 \\
\tau_V &= 20 \\
Y &= 20 \\
\sigma &= 25 \\
i &= 60
\end{aligned}
$$

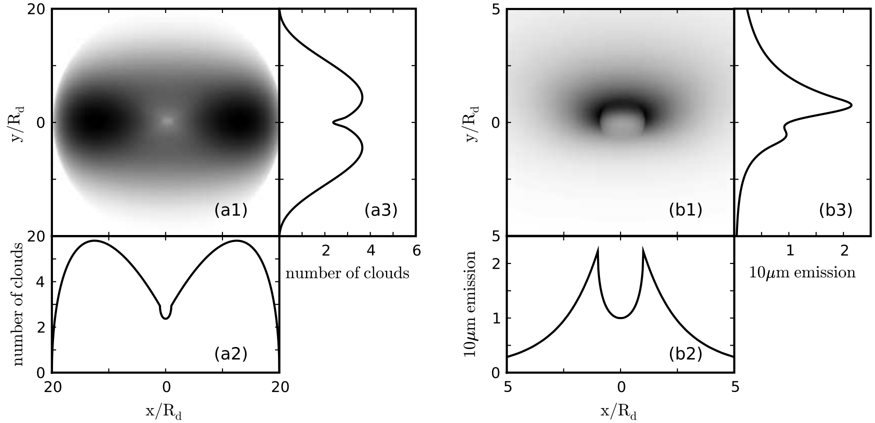
Flat, shifted peaks with...

- standard dust
- clumpy rad. transfer

defining a continuum: see Sirocky+2008

Origin of 10μm emission

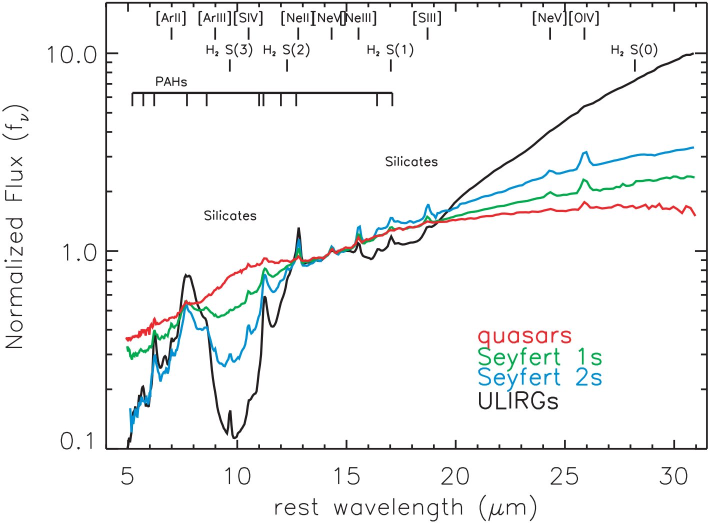
$$q = 0,\ N_0 = 5,\ \tau_v = 20,\ Y = 20,\ \sigma = 25,\ i = 60,$$
$$P_{esc} \approx 31\%$$



Puzzle 3: Distribution of feature strengths

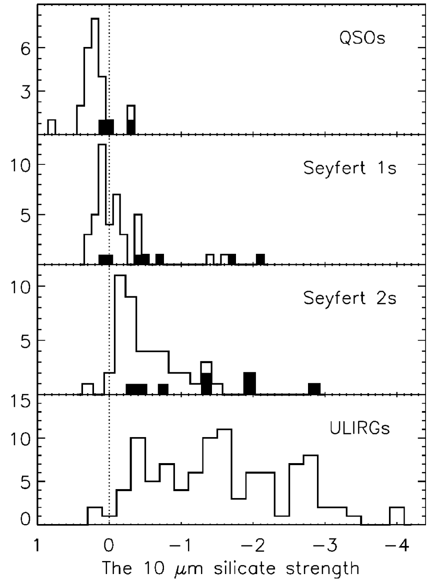
(Lack of deep absorption features)

Lack of deep absorption features



Hao et al. 2007

Observed distributions of S_{10}



Feature strength

$$S_{10} = \ln \frac{F(\lambda)}{F_{cont}(\lambda)}$$

From Hao et al. 2007 sample...

- Remove ULIRGs
- Measure S_{10}
- Remove outliers

Yields 59 type 1 and 39 type 2 sources

Synthetic distributions of S_{10}

- **Type is just a probability**
  Assign... Type 1 when $P_{esc} > 1/2$
  Type 2 when $P_{esc} < 1/2$

- **Real parameter sampling is unknown**
  Chose physically reasonable parameters (Nenkova+2008a,b):

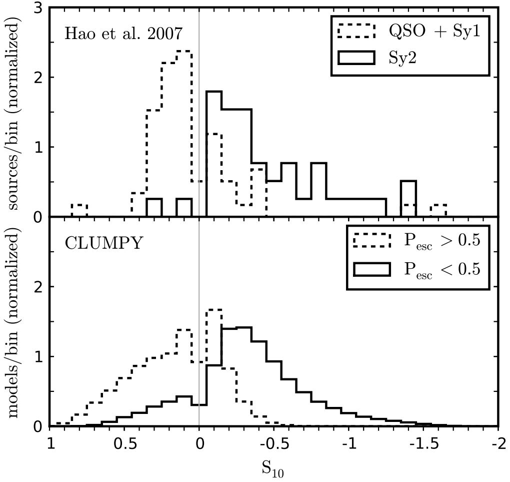
$$q = 0 - 3 \qquad N_0 = 1 - 15 \qquad \tau_v = 30 - 100$$

$$\sigma = 15 - 50 \qquad Y = 10 - 100 \qquad i = 0 - 90$$

Uniform sampling

Yields 340k type 1 and 500k type 2 models

Compare observed and synthetic distributions of S_{10}



Both distributions have...

- very similar ranges
- very similar medians

Synthetic distribution...

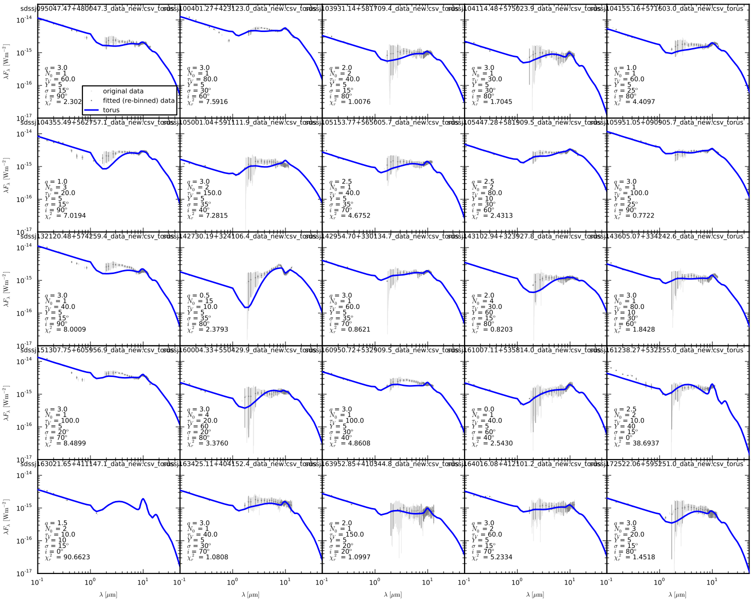
- partitions clearly into both types
- not very sensitive to exact selection criteria

Summary

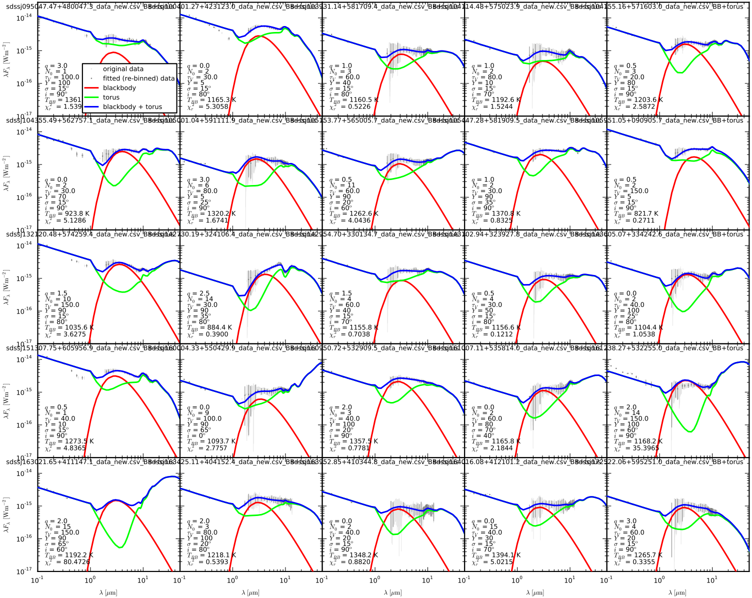
A clumpy dust torus explains all of these:

- Silicate features in **emission** from type 2 sources
- Broad emission features with shifted peaks and **standard** dust
- **No** deep absorption features and observed distribution of S_{10}

Problem: hot BB



Problem: hot BB



Thank you for your attention!

robert@pa.uky.edu

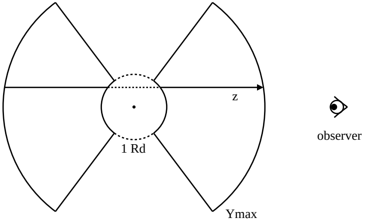
http://www.pa.uky.edu/clumpy/

Additional slides

Torus emission

For each (x,y) in sky plane, integrate along path z

$$I_\lambda^C(z) = \int^z P_{esc}(z', z)\, S_{C,\lambda}(z')\, N_C(z')\, dz'$$

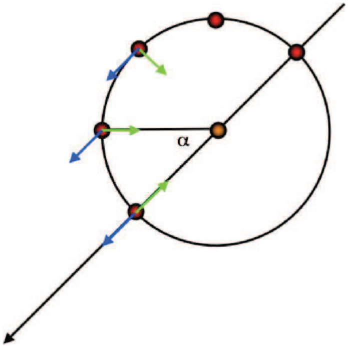


$S_{C,\lambda}(z')$	cloud source function at z' ▸ more
N_C	local cloud number per unit length
$P_{esc}(z', z)$	probability for photons generated at z' to escape through rest of path z

▸ back

Indirectly illuminated clouds

- Heated by isotropic radiation bath
- Thermalized (one temperature)
- Diffuse SFN depends on distance only



back

Local cloud source function

Direct cloud source function

$$S_{C,\lambda}^{dir}(r,\alpha)$$

Diffuse cloud source function

$$S_{C,\lambda}^{diff}(r)$$

Local cloud source function

$$S_{C,\lambda}(z') = p(r,\beta)\, \underbrace{S_{C,\lambda}^{dir}(r,\alpha)}_{\text{direct SFN}} + [1 - p(r,\beta)]\, \underbrace{S_{C,\lambda}^{diff}(r)}_{\text{diffuse SFN}}$$

back

Fitting

Goal: minimize fitting error

$$\chi^2 = \sum_{j=1}^{N} \left(\frac{F_{AGN} \cdot f_j^m - \lambda_j F_j^o}{\sigma_j} \right)^2$$

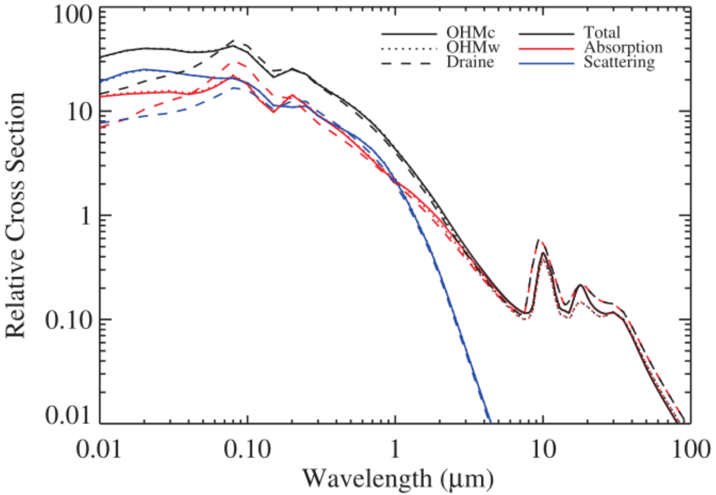
$$\chi_r^2 = \chi^2 / N_{\mathrm{dof}}$$

N	number of fitted wavelengths
f_j^m	model flux at wavelength j
$\lambda_j F_j^o$	observed flux at j
σ_j	observations errors at j

CLUMPY model fluxes: $f^m = \frac{\lambda F_\lambda}{F_{AGN}} \rightarrow$ find F_{AGN} (the scaling)

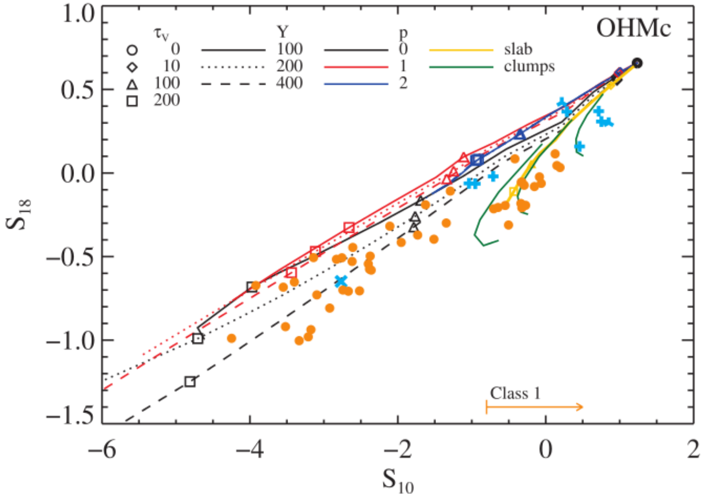
back

Dust absorption coefficients



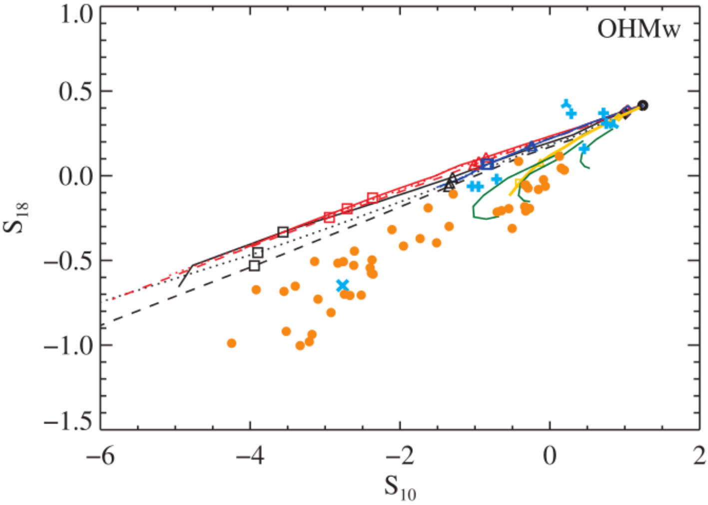
Sirocky+2008

Feature-feature diagram: OHMc silicates



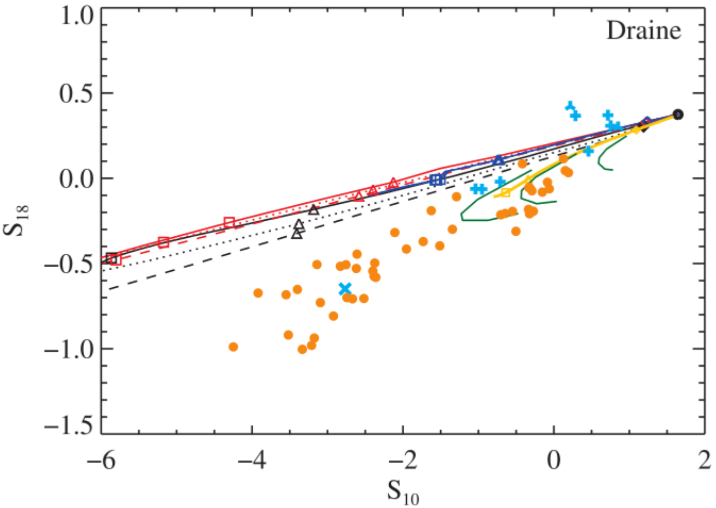
Sirocky+2008

Feature-feature diagram: OHMw silicates



Sirocky+2008

Feature-feature diagram: Draine silicates



Sirocky+2008