The Obscuring Torus

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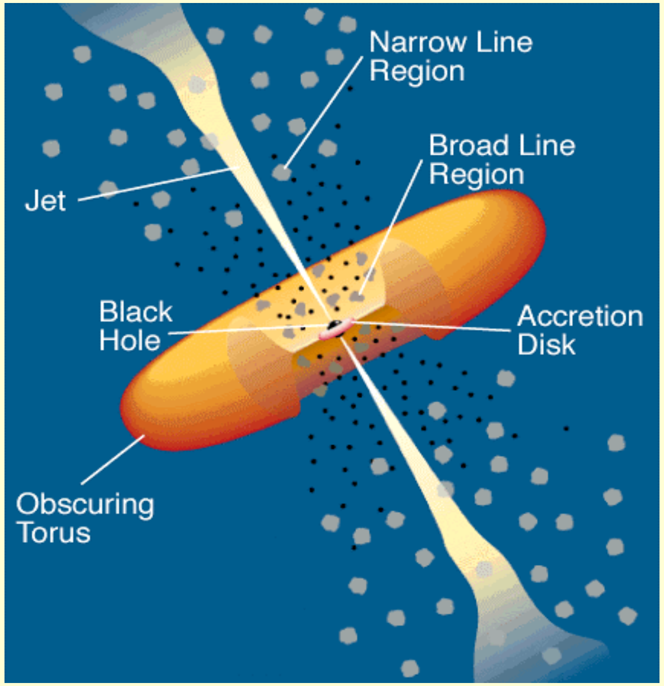
Outline

- Lecture 1: The Torus — observations, general properties
- Lecture 2: Clumping — its handling and implications
- Lecture 3: So what IS the Torus?

Unification Scheme for AGN

$M \sim 10^{6} - 10^{10}\ M_{\odot}$
$R_s \sim 10^{11} - 10^{15}$ cm



Toroidal

Obscuration

Required by

Unification

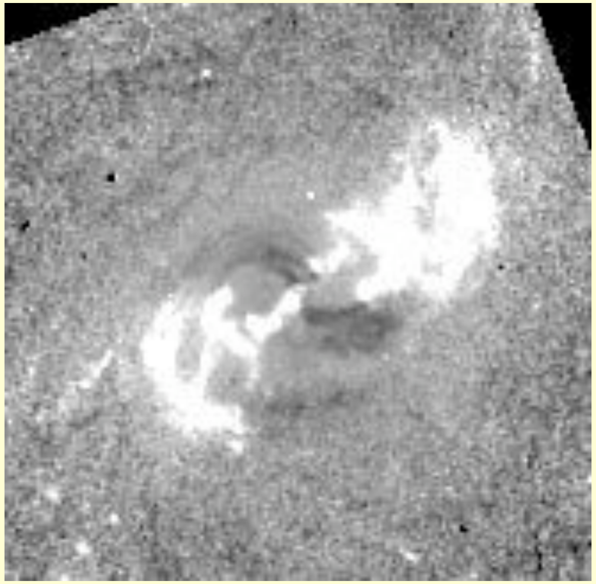
Schemes

Obscuring matter — optically thick dusty clouds

Krolik & Begelman ‘88

Unification – The Essence

- Source appearance controlled by viewing angle
- Clumping could explain the whole effect
- Ionization cones – toroidal obscuration



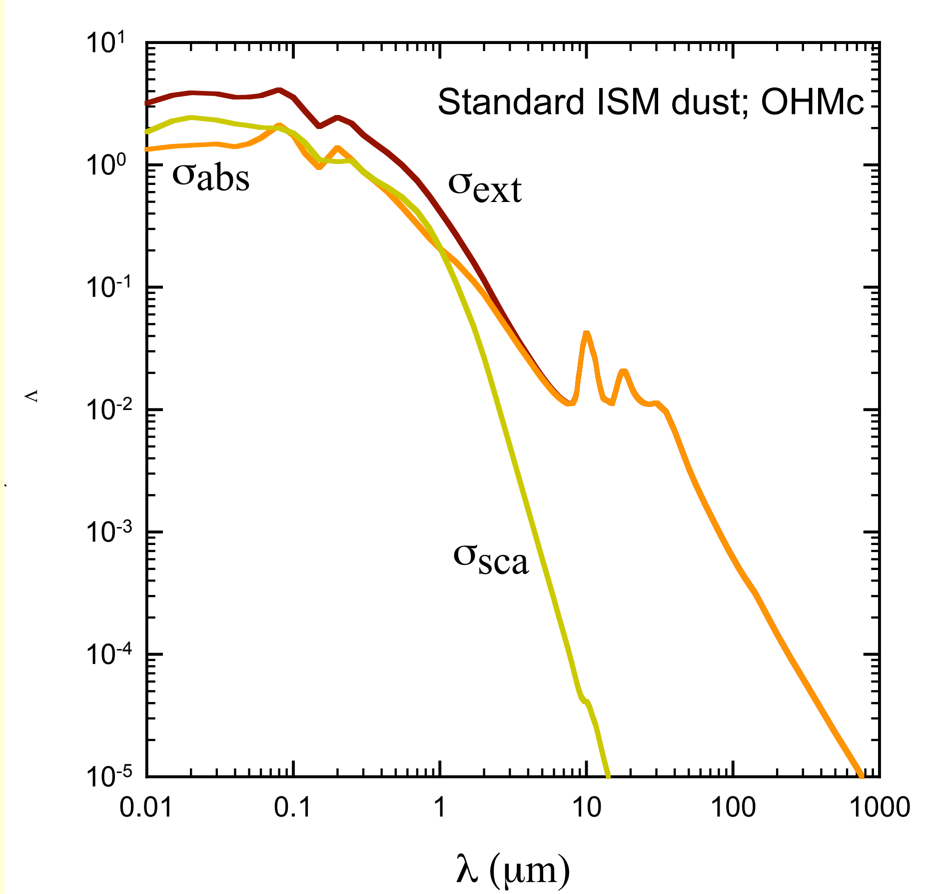
Quillen et al ‘99

Dust — Generalities

- $N_H \approx 2\times10^{21}\,\tau_V\ \mathrm{cm}^{-2}$
- $n_d(a) \propto a^{-3.5}$, $0.005\,\mu\mathrm{m} \le a \le 0.25\,\mu\mathrm{m}$ (MRN)
- Roughly equal mix of silicate and graphite

$\tau_\lambda = \int n_d \sigma_\lambda\, d\ell$

$n_d\sigma_V/n_H \approx 5\times10^{-22}\ \mathrm{cm}^2$



Dust Temperature

Radiative equilibrium:

$$\int \sigma_{a\lambda} B_\lambda(T)\, d\lambda = \int \sigma_{a\lambda} J_\lambda d\lambda \qquad J_\lambda = \int I_\lambda d\Omega / 4\pi$$

$B_\lambda(T) = \pi^{-1}\sigma T^4 b_\lambda(T)$:

$$\boxed{\pi^{-1}\sigma T^4 \sigma_{aP}(T) = \int \sigma_{a\lambda} J_\lambda d\lambda}$$

$$J_\lambda = J_{\lambda e} + J_{\lambda diff} \qquad J_{\lambda e} = J_e\, j_\lambda \qquad J_e = L/4\pi r^2 \times (1/4\pi)$$

$$\boxed{\frac{\sigma_{ap}(T)}{\sigma_{ae}} \sigma T^4 = \frac{L}{16\pi r^2}(1+\delta)}$$

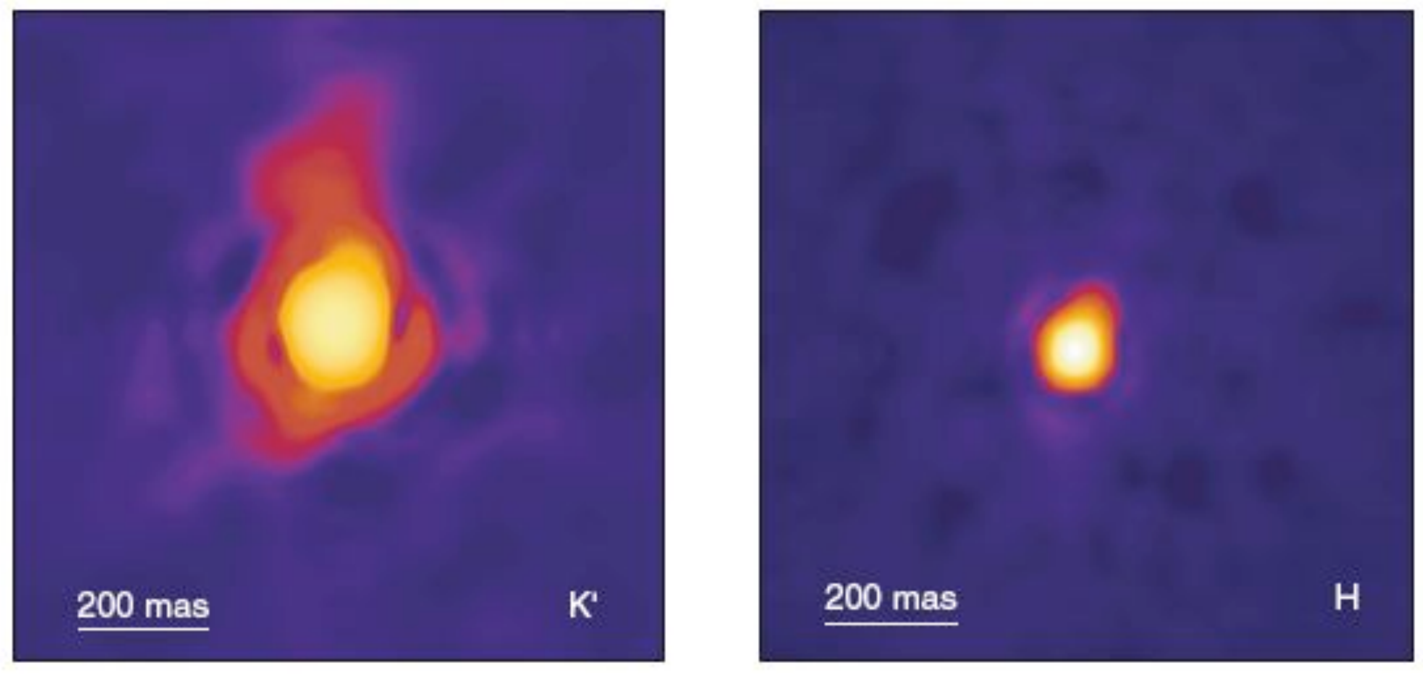
$$\delta = \int \sigma_{a\lambda} J_{\lambda diff} d\lambda / \sigma_{ae} J_e$$

Dust Temperature (2)

$$\frac{\sigma_{ap}(T)}{\sigma_{ae}}\,\sigma T^4 = \frac{L}{16\pi r^2}(1+\delta)$$

- $T \sim r^{-0.4}$ $\lambda \sim 10\mu m\ (300K/T) \sim r^{0.4}$
- With $T_{sub} = 1500$ K, shortest emission at $\lambda \sim 2\mu m$
- Larger grains are cooler
- AGN dust sublimation radius:

$$R_d \approx 0.4\left(\frac{L}{10^{45}\ \mathrm{erg\,s^{-1}}}\right)^{1/2}\left(\frac{1500\,K}{T_{sub}}\right)^{2.6}\mathrm{pc}$$



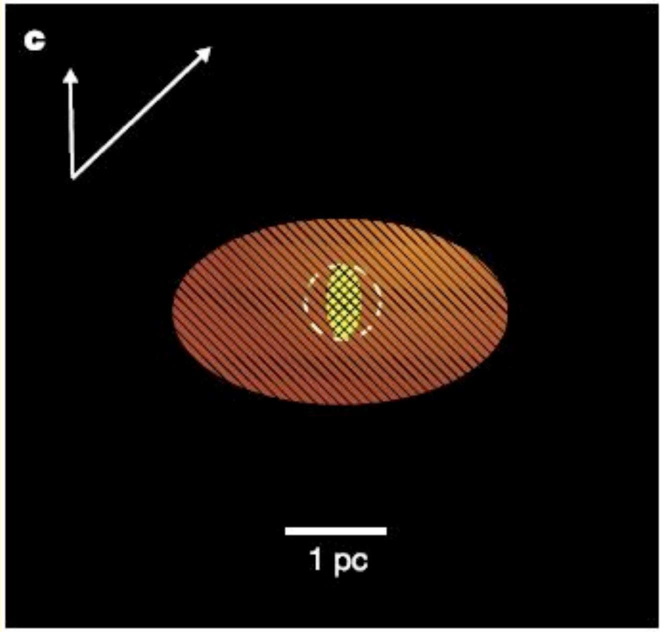
Weigelt+ 04

bispectrum
specle
interferometry

NGC 1068

D = 14.4 Mpc

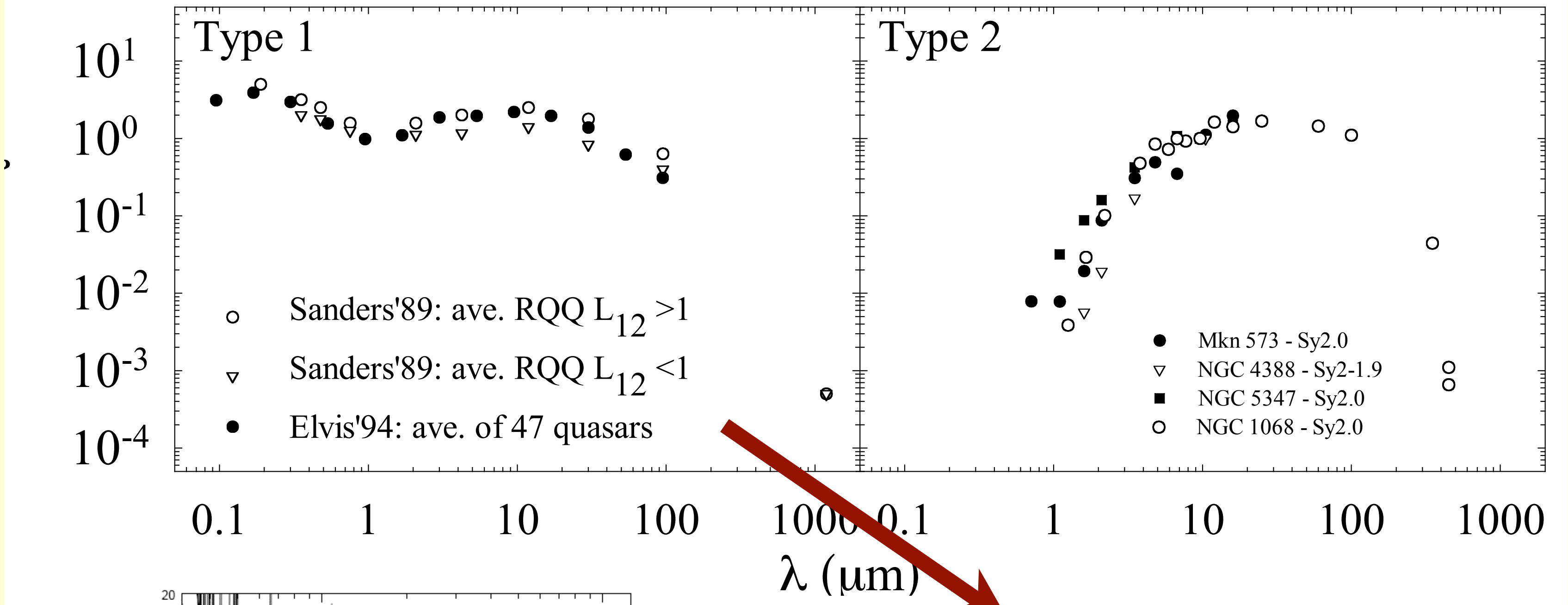
0.1” = 7.2 pc

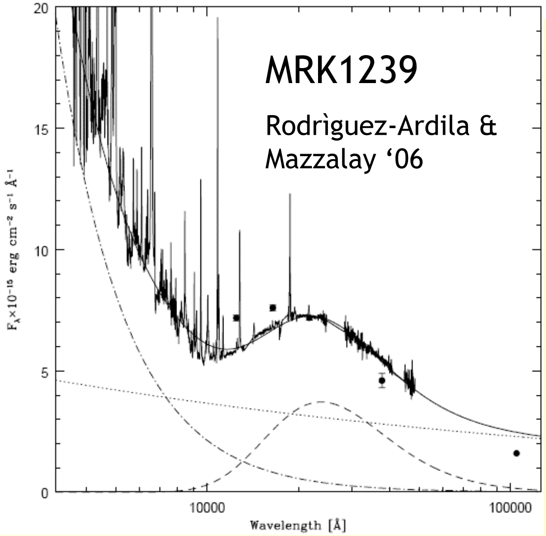


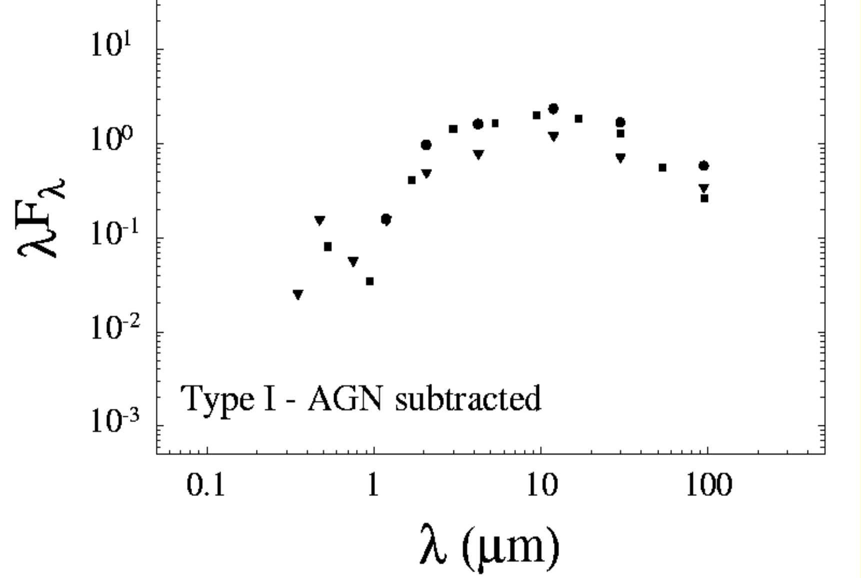
Jaffe+ 04

VLTI 8-13 μm

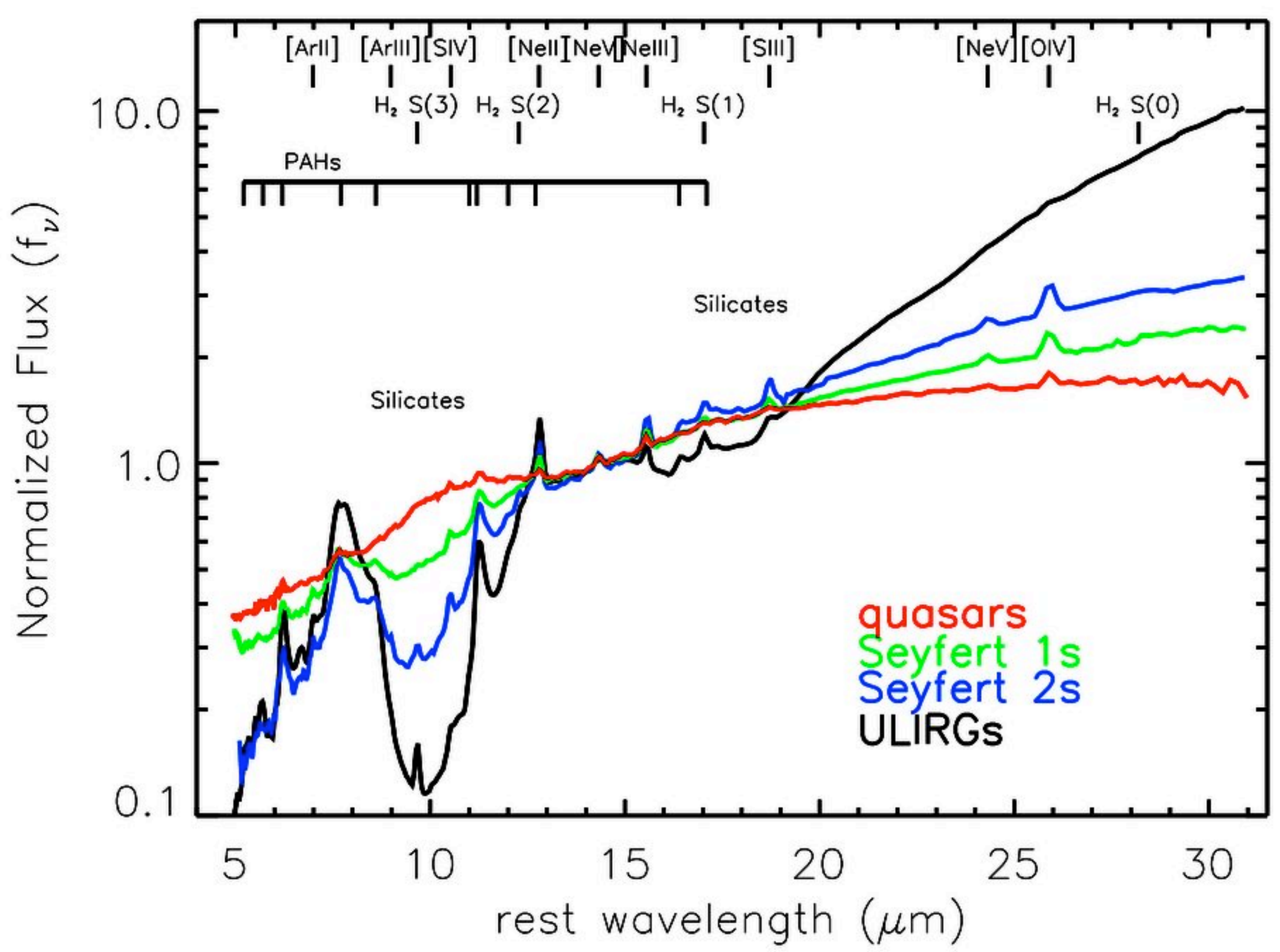
Unification Prediction — SED: 2 = 1 – AGN







Average SED's

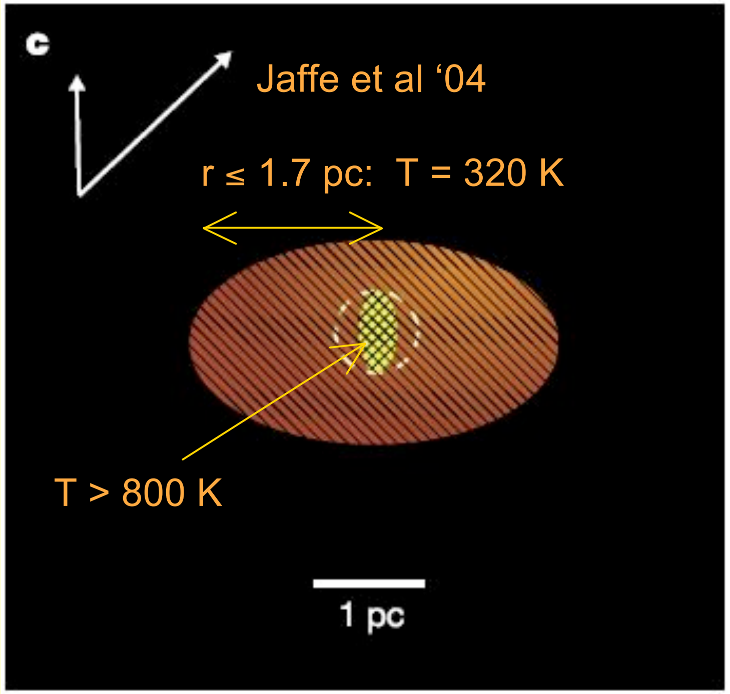


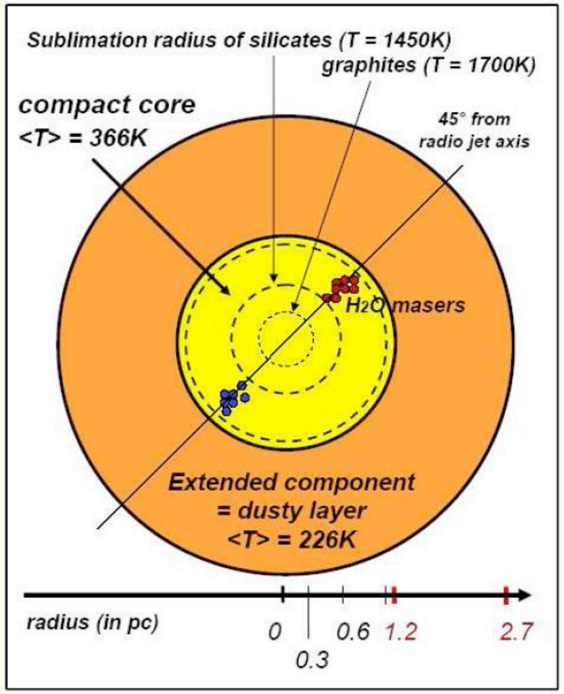
Hao+ '07

(Mixed units! $\nu F_\nu = \lambda F_\lambda$)

IR Puzzle #1

VLTI – NGC1068:





Poncelet et al '06

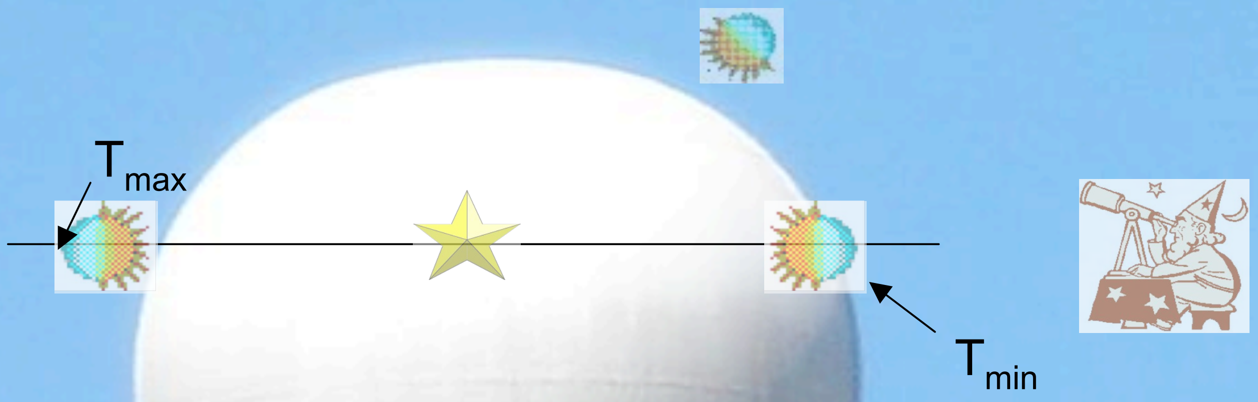
$L_{bol} = 2 \cdot 10^{45}$ erg s^{-1} (Mason et al '06)

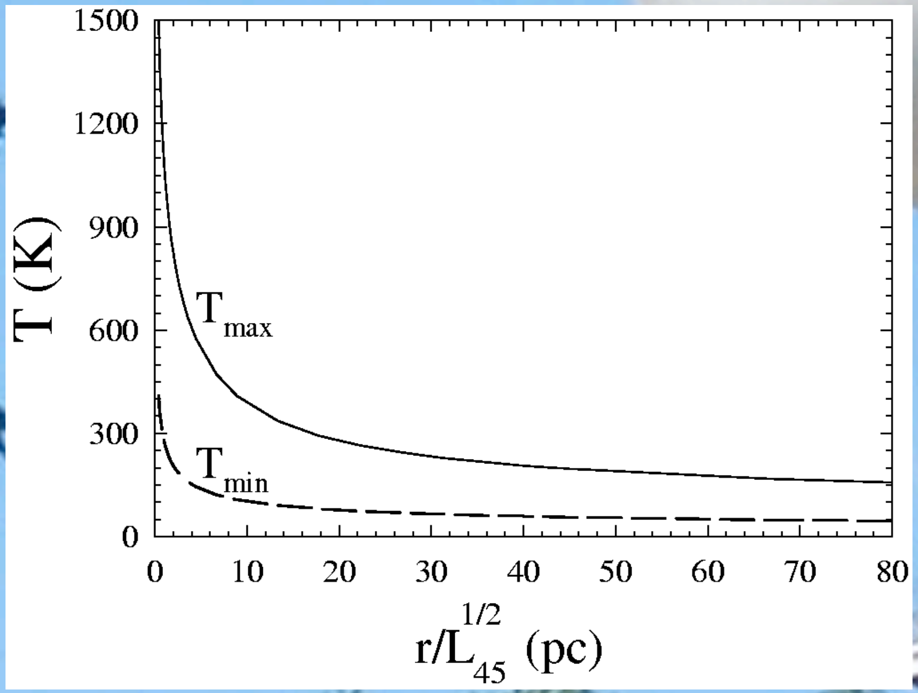
$T(r = 2pc) = 960$ K

$r(T = 320$ K$) = 26$ pc

$r(T = 226$ K$) = 57$ pc

Temperature in a Clumpy Medium





- Smooth density –
  T & R uniquely related
- Clumpy density –
  different T at same R
  different R, same T

Torus Properties – Obscuration

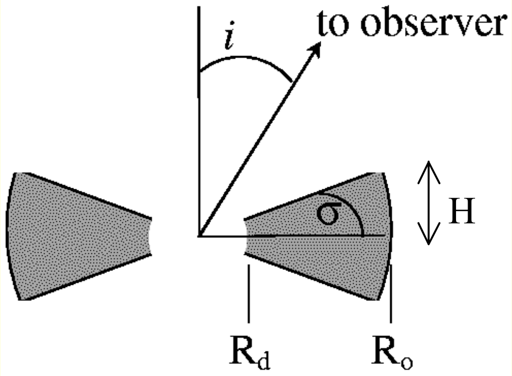
- Equatorial τ_V >~ 30 – 40
- N_H >~ 10^{23} cm^{-2}

Torus Properties — Unification Statistics

f_2 — fraction of obscured sources = $N_2/(N_1 + N_2)$

Seyferts: $f_2 = 70\%$ Schmitt+ ‘01

$f_2 = 50\%$ Hao+ ‘05



$f_2 = \sin\sigma = 0.5 - 0.7$

$\sigma \approx 30^\circ - 45^\circ$

$H/R_o \sim 1$

f_2 decreases with luminosity (Simpson 05, Hao+ 05)
— “receding torus” (Lawrence 91)

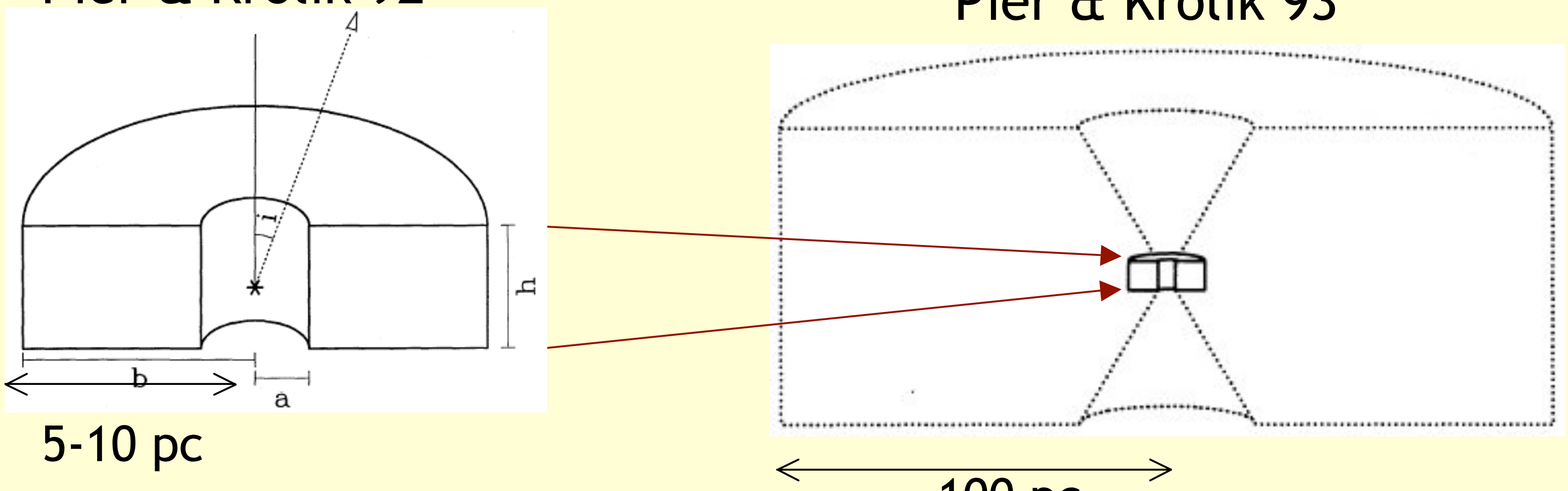
Basic Premise

AGN type determined purely by viewing angle

Torus Properties – Size

- From type 1 vs 2 – H/R ~ 1
- R = ?
- Must rely on IR emission
  - Early estimates R ~ 100’s of pc

Origin of the 100’s pc Torus – Modeling IR emission



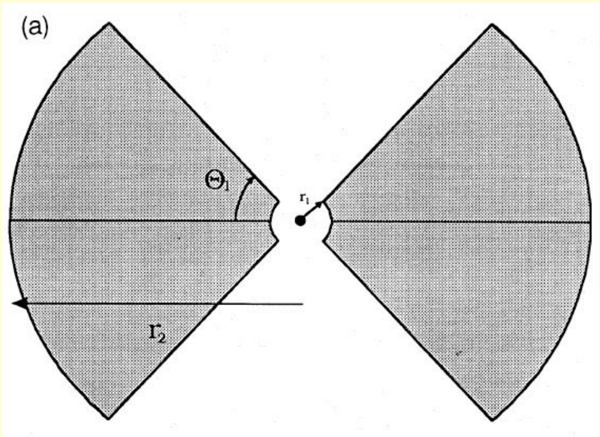
Pier & Krolik 92

5-10 pc

Pier & Krolik 93

~100 pc

- Dearth of IR emission in smooth-density models T ↔ r
  - Granato et al ’94, ‘97:
    - Uniform density
    - R_{out} ~ 100 – 300 pc



Torus Size — Observations

- NGC1068: 2μm imaging – R ~ 1 pc (Weigelt+ 04)
  8—13μm VLTI – R ~ 2 pc (Jaffe+ 04)

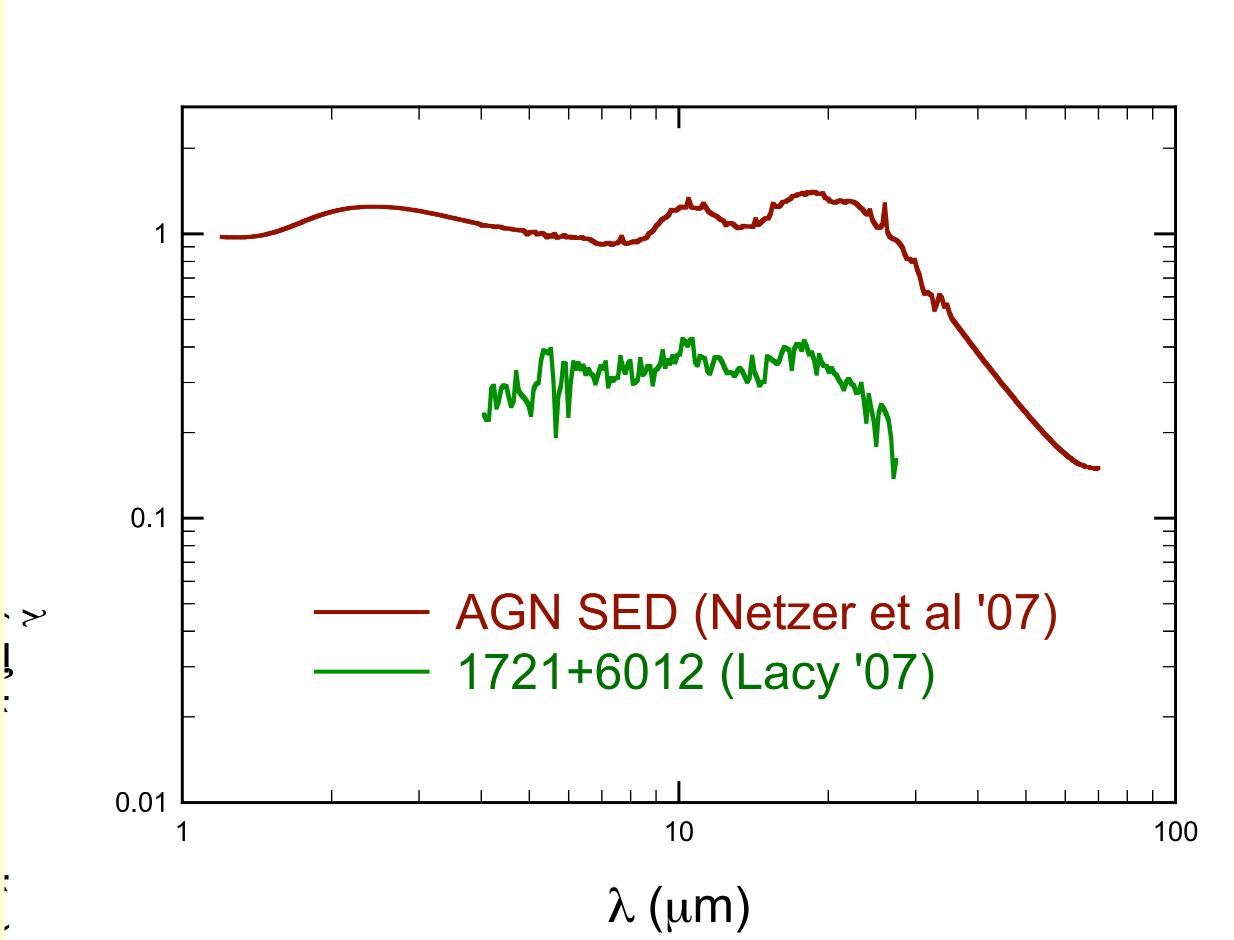
- Cen A: 8—13μm VLTI – R ~ 0.3 pc (Meisenheimer+ 07)

- Circinus: 2μm – R ~ 1pc (Prieto+ 04)
  8 & 18μm – R < 2 pc (Packham+ 05)

- NGC1097 & NGC5506: 2μm – R < 5 pc (Prieto+ 04)

All observations are consistent with R_{out}/R_d no larger than ~20–30, and perhaps even only ~5–10

Possible SED Indication

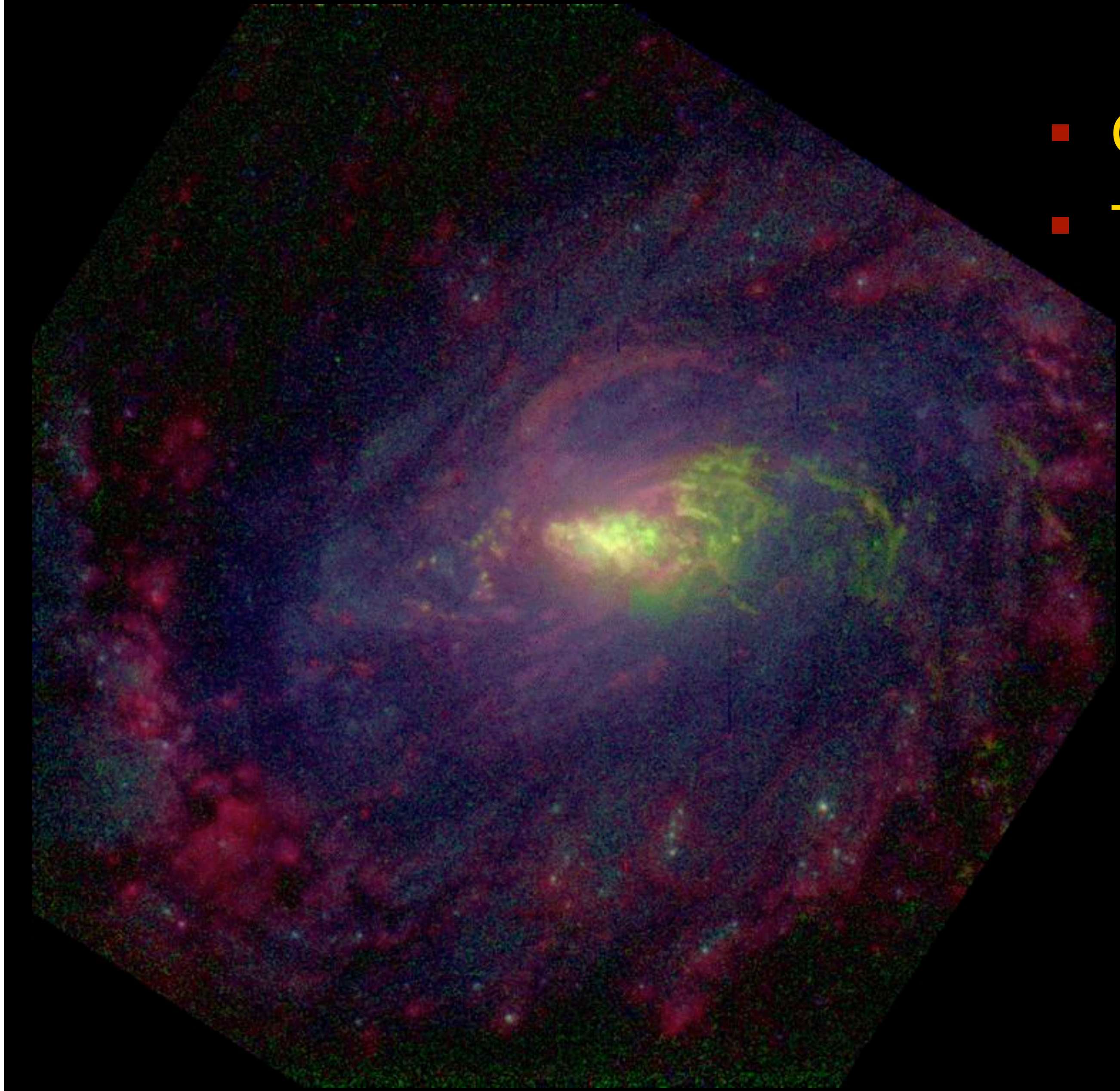


Fall-off at λ > 20 μm — no dust cooler than ~200 K?

Torus orientation & the host galaxy

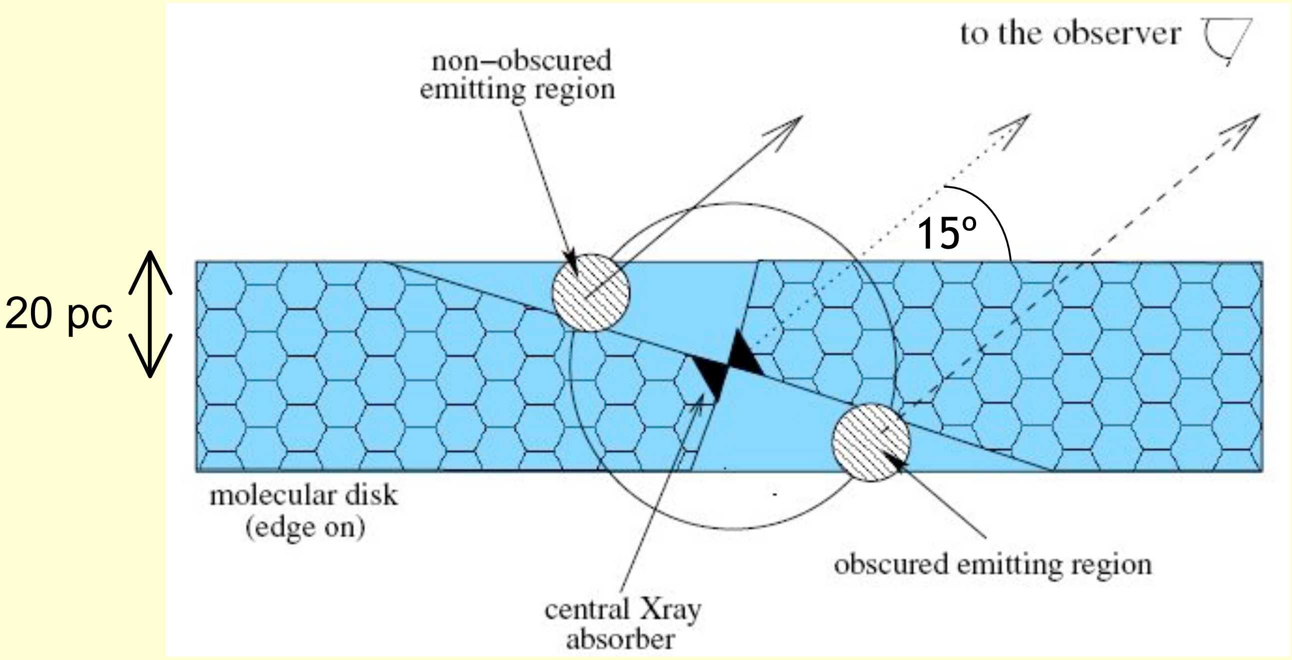
- AGN axis (jet) randomly oriented with respect to
  - galactic disk in Syefert galaxies (Kinney et al 00)
  - nuclear dust disk in radio galaxies (Scmitt et al 02)

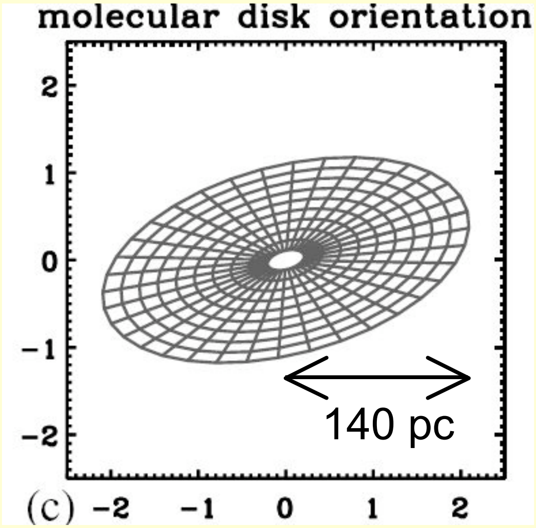
NGC 1068



- Galaxy ~ face on
- Torus ~ edge on (≤5°):
  - H_2O masers
    Gallimore+ 01
  - NLR kinematics
    Crenshaw+ 00

NGC 1068, CO & H_2 observations





Galliano et al ’03: H/R ~ 0.15

Schinerer+ 00: at R ~ 70 pc, H ~ 9 – 10 pc ⇒ H/R ~ 0.15

Not “the torus”!

X-ray Absorption

- Generally, X-ray continuum absorbing column:
  - type 1: $N_H < 10^{21}$ cm^{-2} (+ line WA; George+ 98)
  - type 2: $N_H \sim 10^{22} - 10^{25}$ cm^{-2}, mean = $3 \cdot 10^{23}$ cm^{-2}; 30 – 50% Compton thick ($N_H > 10^{24}$ cm^{-2}; Bassani+ 99)
  - Absorption-corrected type 2 spectra & luminosities are similar to type 1 (Smith & Done 96; Turner+ 97)

Orientation-dependent Absorption

X-ray emission

- Kα iron line equivalent width:
  - type 1 – typically ~ 150 eV (Nandra & Pounds 94)
  - type 2 – wide distribution ~ 100 – 1000 eV (Turner+ 97);
    a few 1 – 5 keV (Levenson+ 02)

Torus Reprocessing

But… X-ray & UV/optical Torus not the same!

- ~10—30% of type 2 AGN are not obscured in X-ray
  - Galaxy emission “hides” broad lines? (Severgnini+ 03, Silverman+ 05)
- ~5—15% of type 1 are X-ray obscured, including Compton thick (Perola+ 04, Eckart+ 06, Gallagher+ 06)

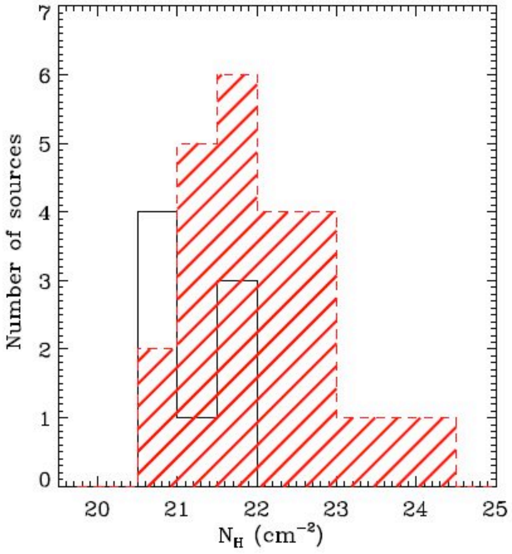


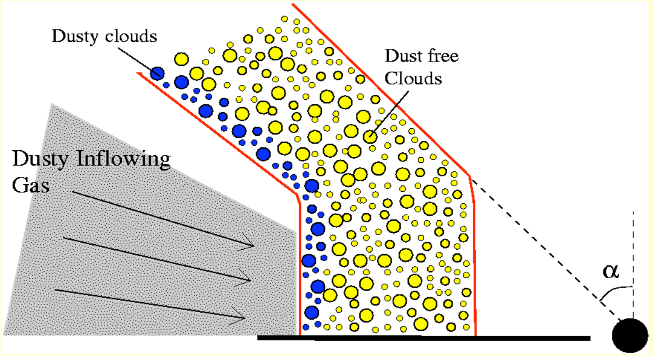
FIG. 9.— Intrinsic column density (N_H) distribution for BL AGN (empty histogram) and NOT BL AGN (hatched histogram) with intrinsic absorption in excess of the Galactic column density.

Mainieri+ 07

Dusty vs X-ray Torus

- X-ray time variations – absorbing clouds across l.o.s.

Risality+ 02

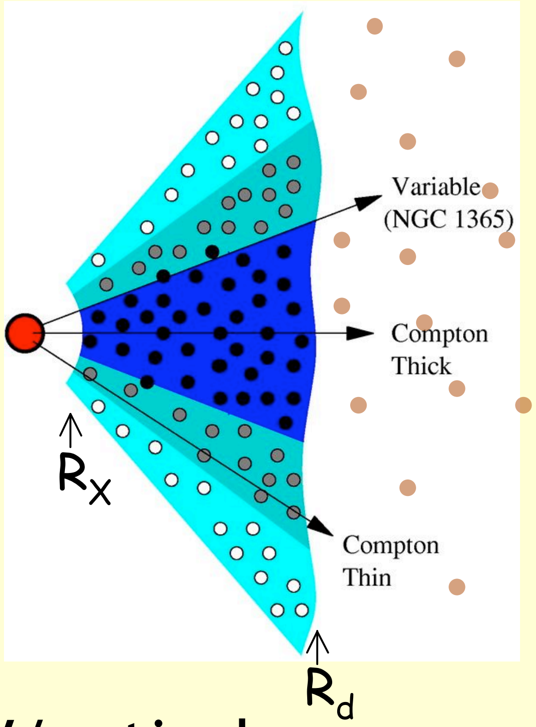


- 2-day flips, Compton thin ↔ thick in NGC1365

Risaliti+ 07

- X-ray absorption by dust-free clouds, which may even be the majority

Dusty vs X-ray Torus (2)



- Dust-free clouds absorb *only* X-rays
- Dusty clouds absorb *both* X-rays *and* UV/optical
- N_H(X-rays) > N_H(UV/optical), as observed (Maiolino+ 01)
- X-ray obscured type 1 are expected

Clumpy Emission vs Obscuration

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