Torus models and infrared emission from the dusty veil around AGN

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In collaboration with

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- Wolfgang Duschl & Werner Tscharnuter (Heidelberg)
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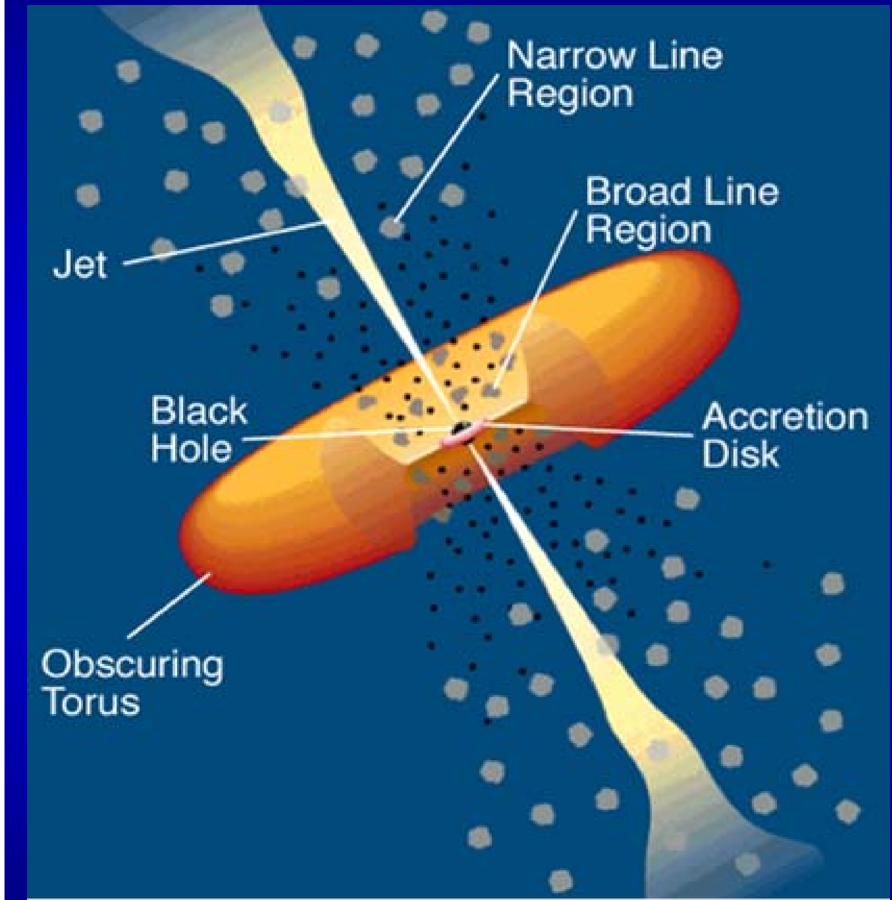
„From the circumnuclear disk in the Galactic Center to thick, obscuring tori of AGNs“
B. Vollmer, T. Beckert, W. J. Duschl 2004, A&A 413, 949

„The dynamical structure of a thick cloudy torus“
T. Beckert, W. J. Duschl (A&A, in press)

Overview

- The CND in the Galactic Center and the Torus in NGC 1068
- Viscosity & Cloud Collisions in a Torus
- Consequences for NIR imaging, IR-spectra, and Unified Schemes

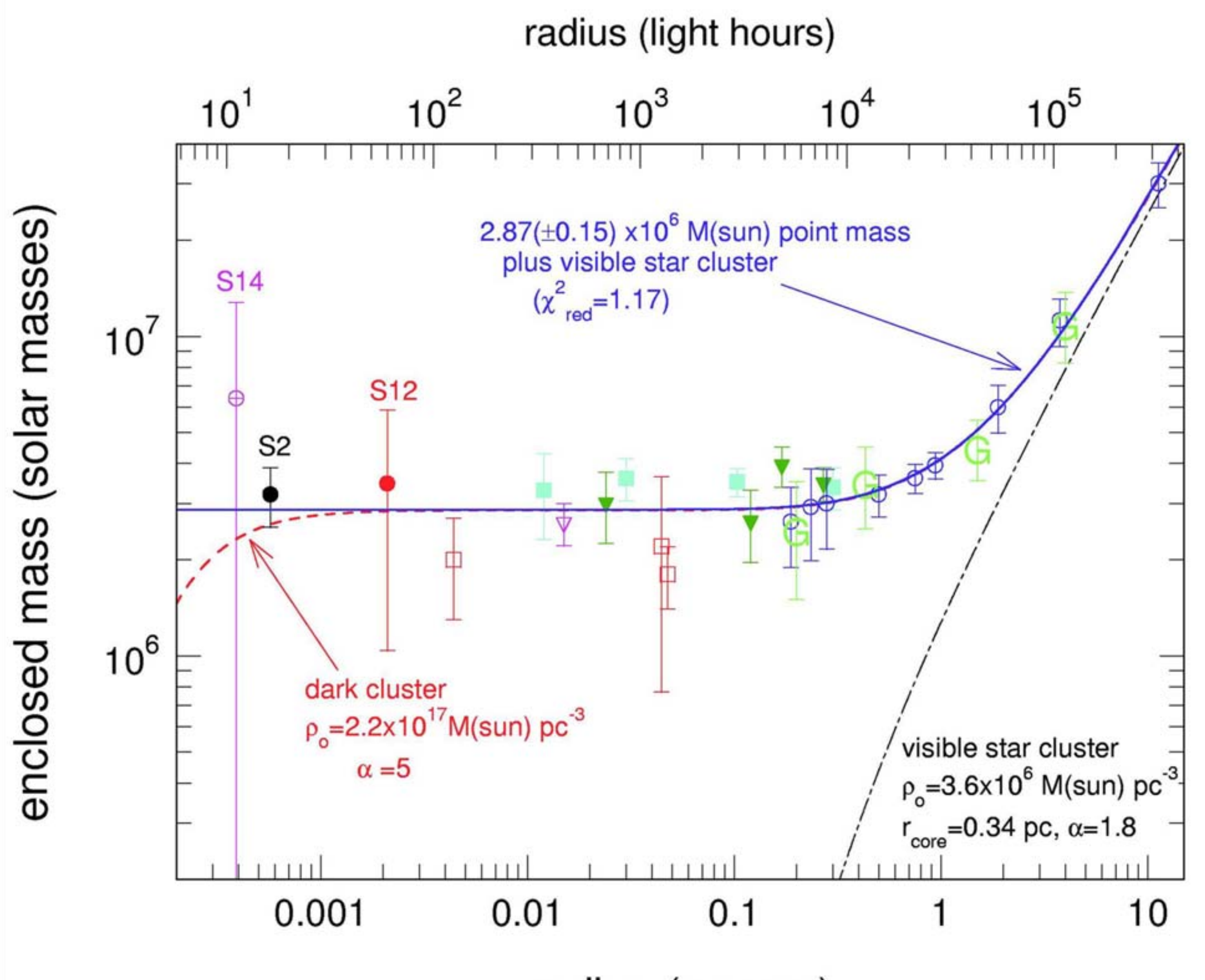
Motivation



- Are the conclusions of Krolik & Begelman (1988) still valid ?
- → How to support and maintain the thickness of the torus ?
- Is the "torus" really a torus ?

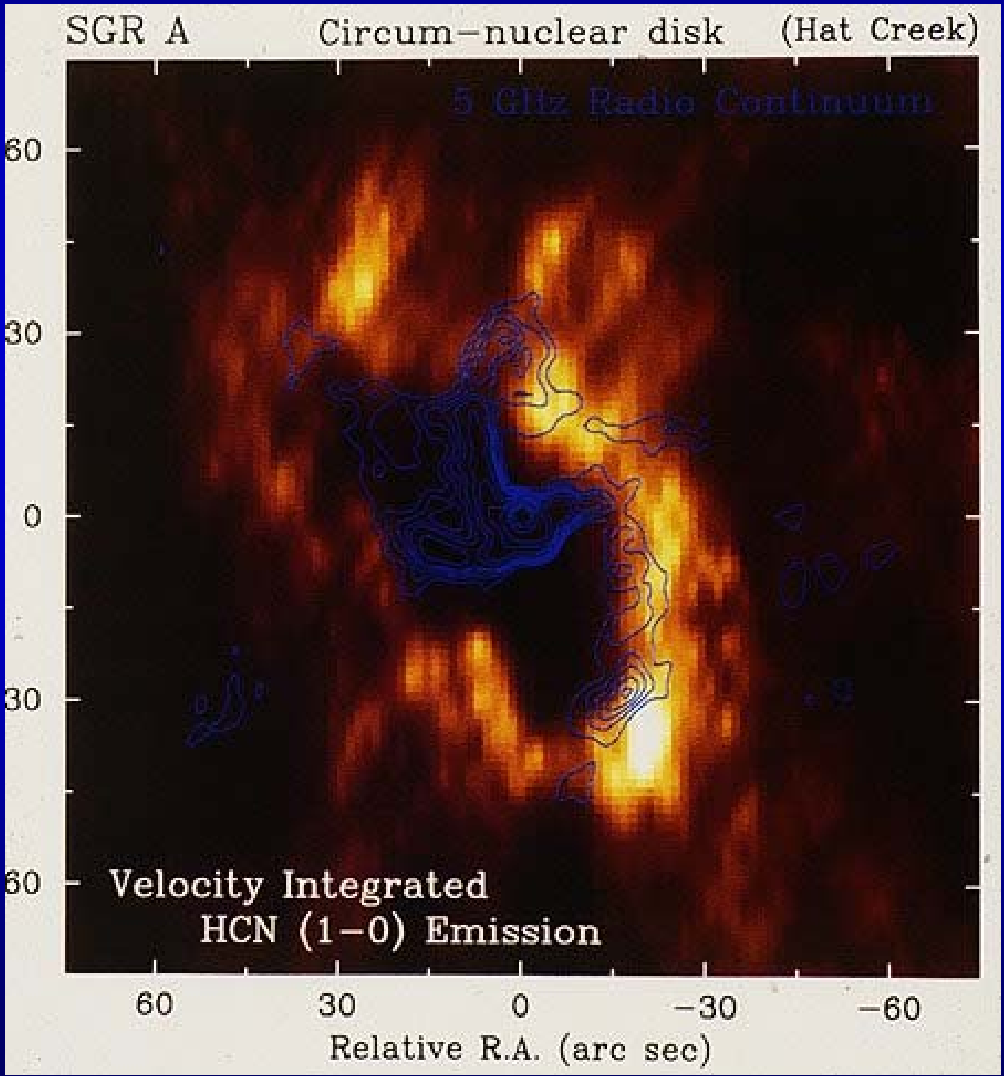
Do we have the correct picture in mind ?

The Mass Distribution (GC)



(Ott et al. 2003)

In our Galactic Centre

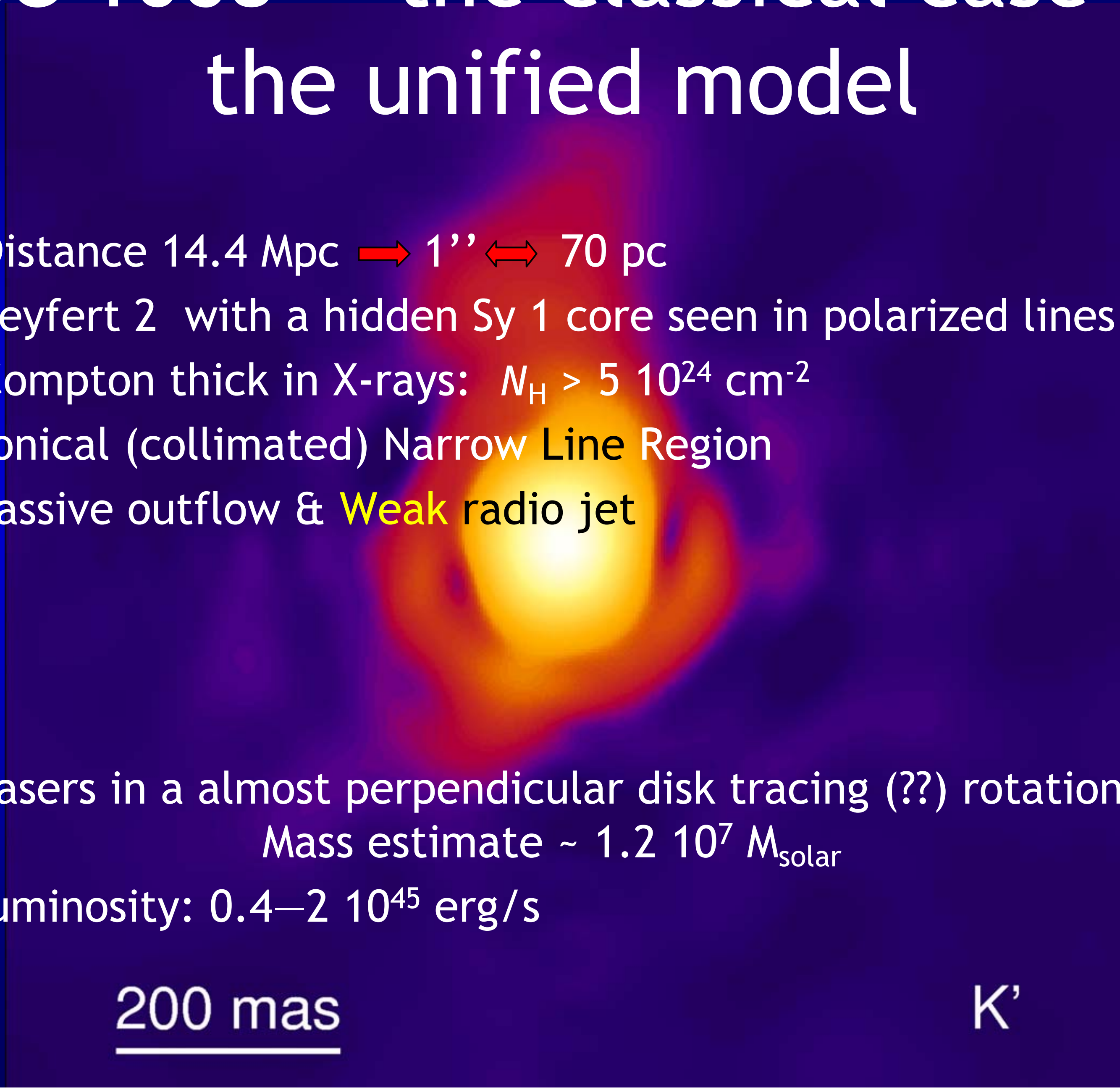


The CND:

- Ring of clouds seen in molecular emission with central cavity
- Not a thick torus H/R < 0.1
- Derived accretion rate: 10^{-3} M_{solar}/yr
- Cloud Mass 20 M_{solar}
- Volume filling factor: 4 10^{-3}
- 'Optical depth': $\tau = 1/15$

NGC 1068 — the classical case for the unified model

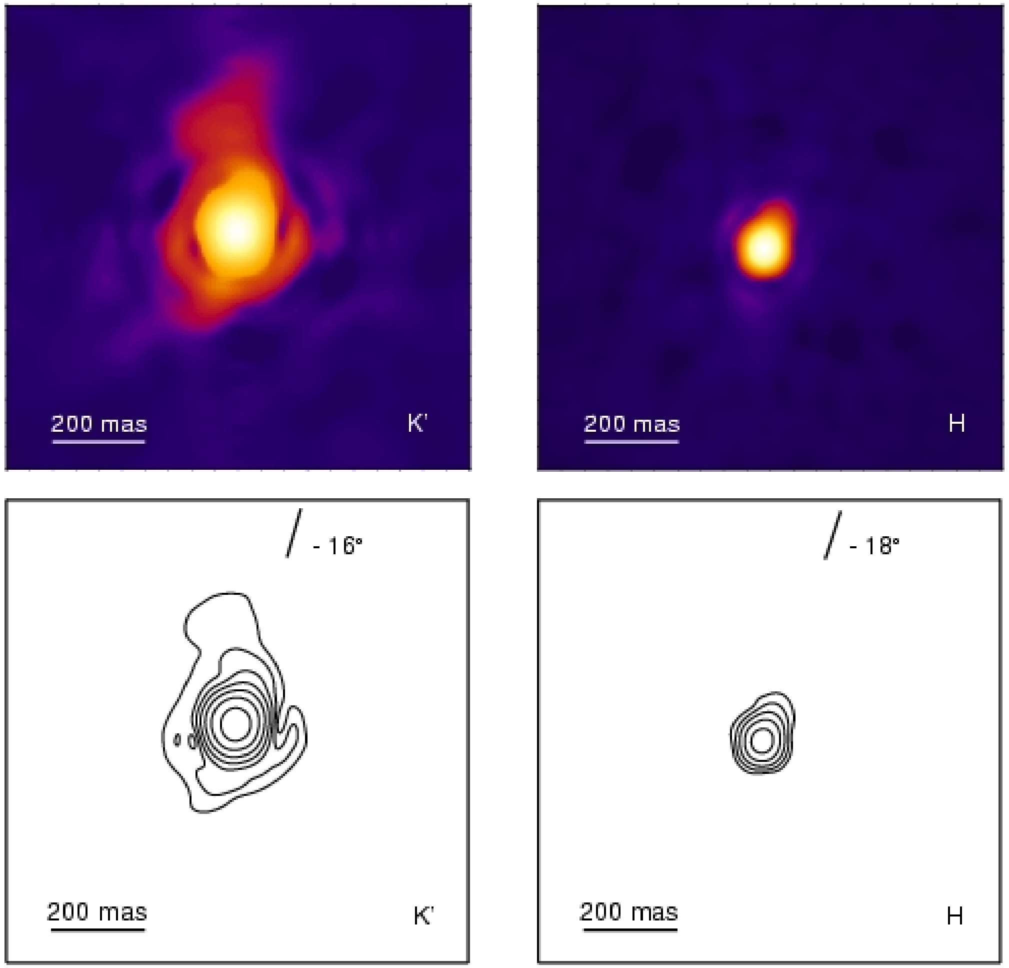
- Distance 14.4 Mpc ⇒ 1'' ⇔ 70 pc
- Seyfert 2 with a hidden Sy 1 core seen in polarized lines
- Compton thick in X-rays: $N_H > 5\ 10^{24}\ cm^{-2}$
- Conical (collimated) Narrow Line Region
- Massive outflow & Weak radio jet



- Masers in a almost perpendicular disk tracing (??) rotation

  Mass estimate ~ $1.2\ 10^{7}\ M_{solar}$
- Luminosity: 0.4—$2\ 10^{45}$ erg/s

NGC 1068 – NIR speckle images

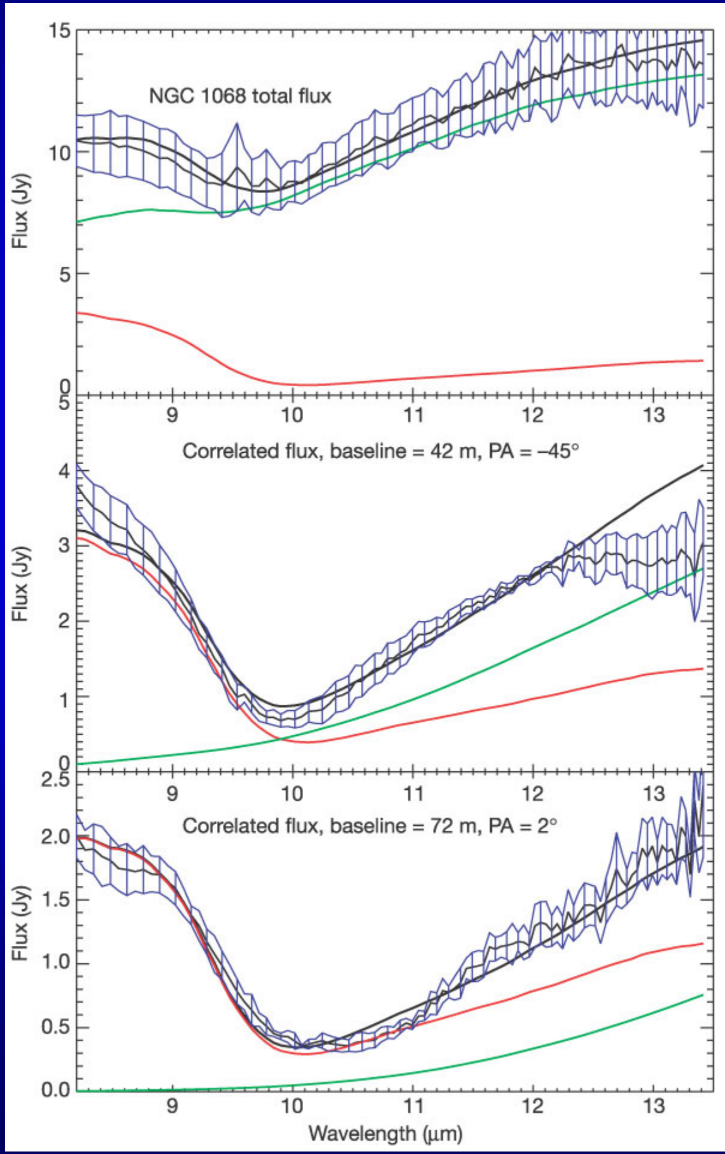


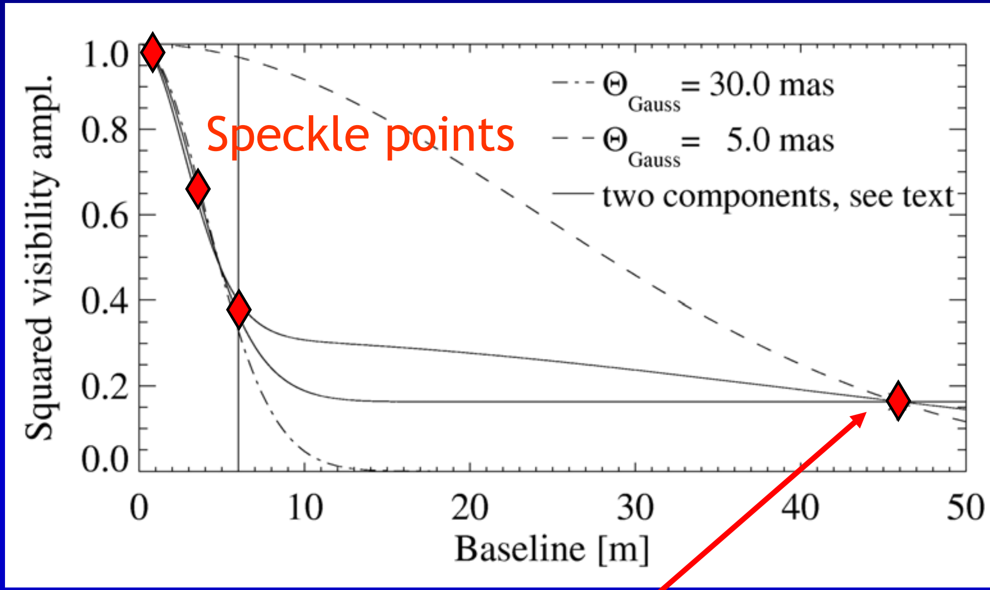
Weigelt et al. 2004, and his talk here

Core:
18 x 40 mas
= 1.3 x 2.8 pc
Flux: 350 mJy

& extended emission

Infrared Interferometry (VLTI)





VINCI (2.2 µm) T = Tsub (< 3 mas)

→ < 0.2 pc → Substructure

(Wittkowski et al. 2004)

MIDI: Two-Comp.: T=320 K (30 x 50 mas)

& T > 800 K (≤ 10 mas)

(Jaffe et al. 2004)

The Model: Conditions - Assumptions

- Dust can only survive in cold clouds !!!
  $\sigma \sim 50$ km/s ⟶ $T \sim 10^5$ K
- Equilibrium structure in the combined potential of Black Hole & quasi-isothermal star cluster
- Radial accretion flow due to cloud-cloud collisions
- Mass is supplied at an outer radius (ISM, starburst ring, bar driven accretion)

The Accretion Scenario

- Cloud-Cloud Interactions:

  effective viscosity
  (Goldreich & Tremaine 1978)

  $$\nu_{\mathrm{eff}} = \frac{\tau}{1+\tau^2}\frac{\sigma^2}{\Omega}$$

  dimensionless collision frequency $\tau = \omega_{\mathrm{coll}}/\Omega$

- Mass accretion from differential rotation & angular momentum redistribution

- Vertical scale height $H = \sigma/\Omega = l_{\mathrm{coll}}\tau$

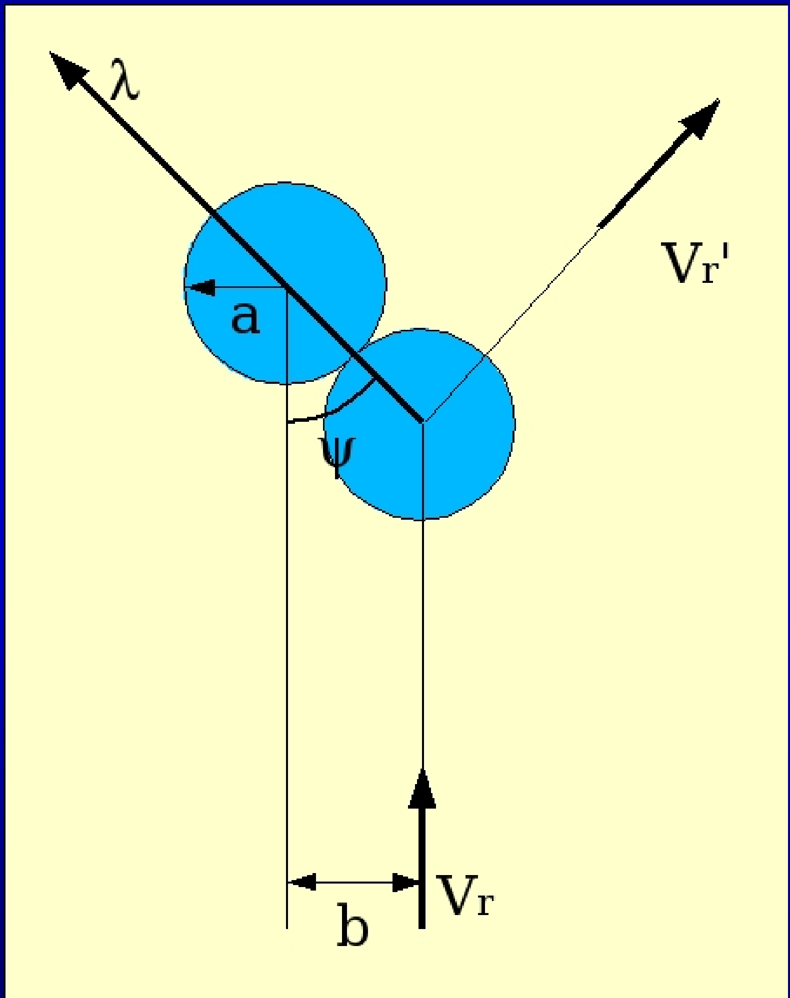
The collisional particle disk:

- Symmetries of a thin accretion disk
- Keplerian rotation & vertical hydrostatic equilibrium
- Triaxial Gaussian velocity distribution
- Viscosity follows

$$\nu = \sin(2\delta)\,\frac{\sigma_2^2 - \sigma_1^2}{2R(-\Omega')}$$

$$N = \tfrac{1}{2}\sin(2\delta)\,\Sigma\,R^2(\sigma_2^2 - \sigma_1^2)$$

Cloud Collisions



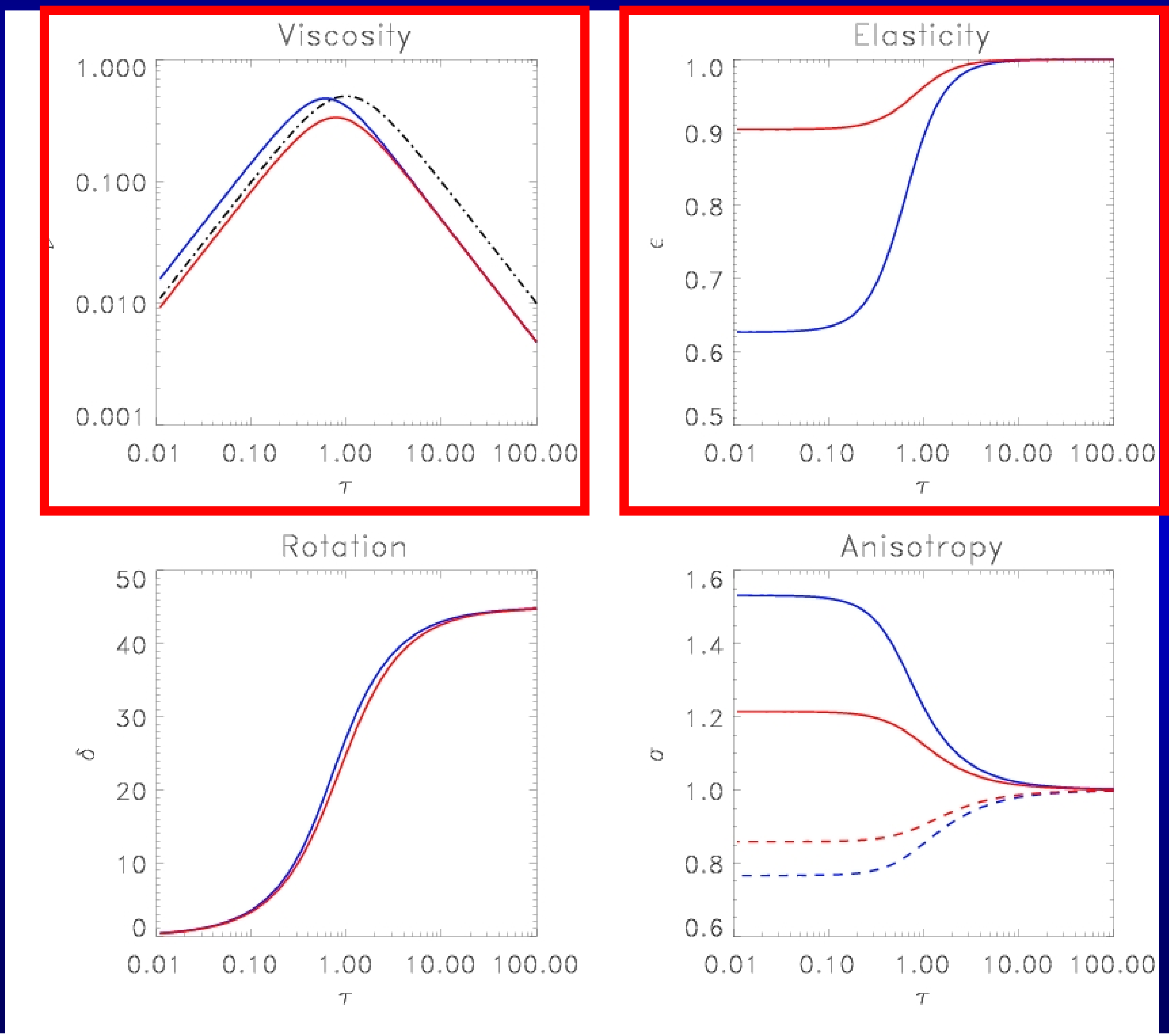
Goldreich & Tremaine (1978): Only momentum along λ is lost in inelastic collisions (assumption)

→ Elasticity ε

Coefficient of restitution

Only ½ (1- ε^2) of the kinetic energy is dissipated.

Results for a thin disk



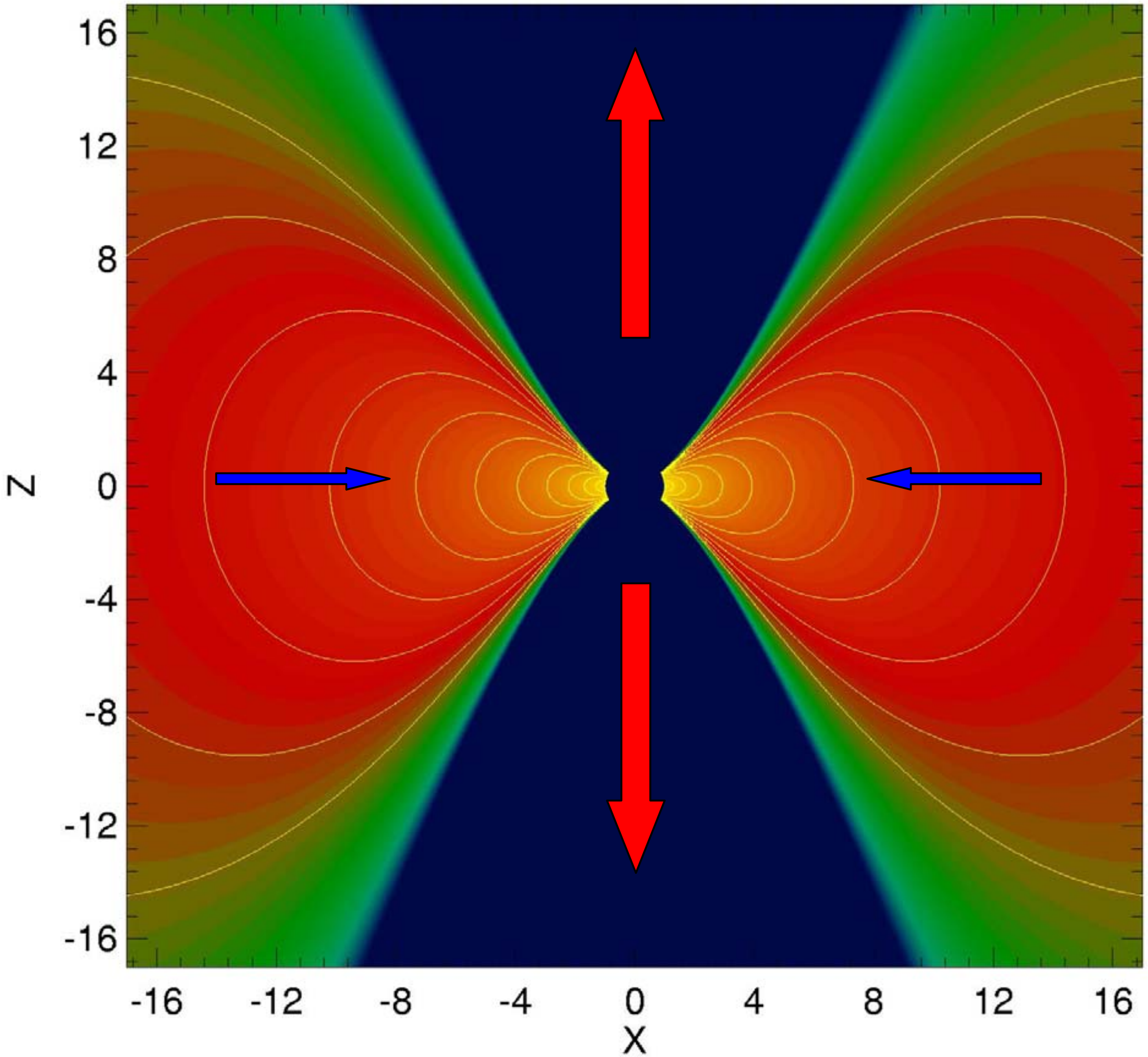
Modifications for a thick torus

1. Advective terms
   (change of σ^2 and compression)
2. No collective effects (enhanced viscosity via non-local interactions; Wisdom & Tremaine 1988)

$$\sigma >> R_{\mathrm{Cloud}} \left| \frac{\partial \Omega}{\partial \log R} \right| \quad \Rightarrow \quad \Phi_{\mathrm{V}} << 0.35\tau$$

3. **ε ⟶ τ (ε & τ ⟶ Mdot)**
4. Elasticities ε as low as 0.3 are possible
   (45 % of kinetic energy can be dissipated
   in collisions)

The vertical structure



Exact solution
for the density

in an arbitrary
external potential

with a vertical
cut-off height

Example for NGC 1068

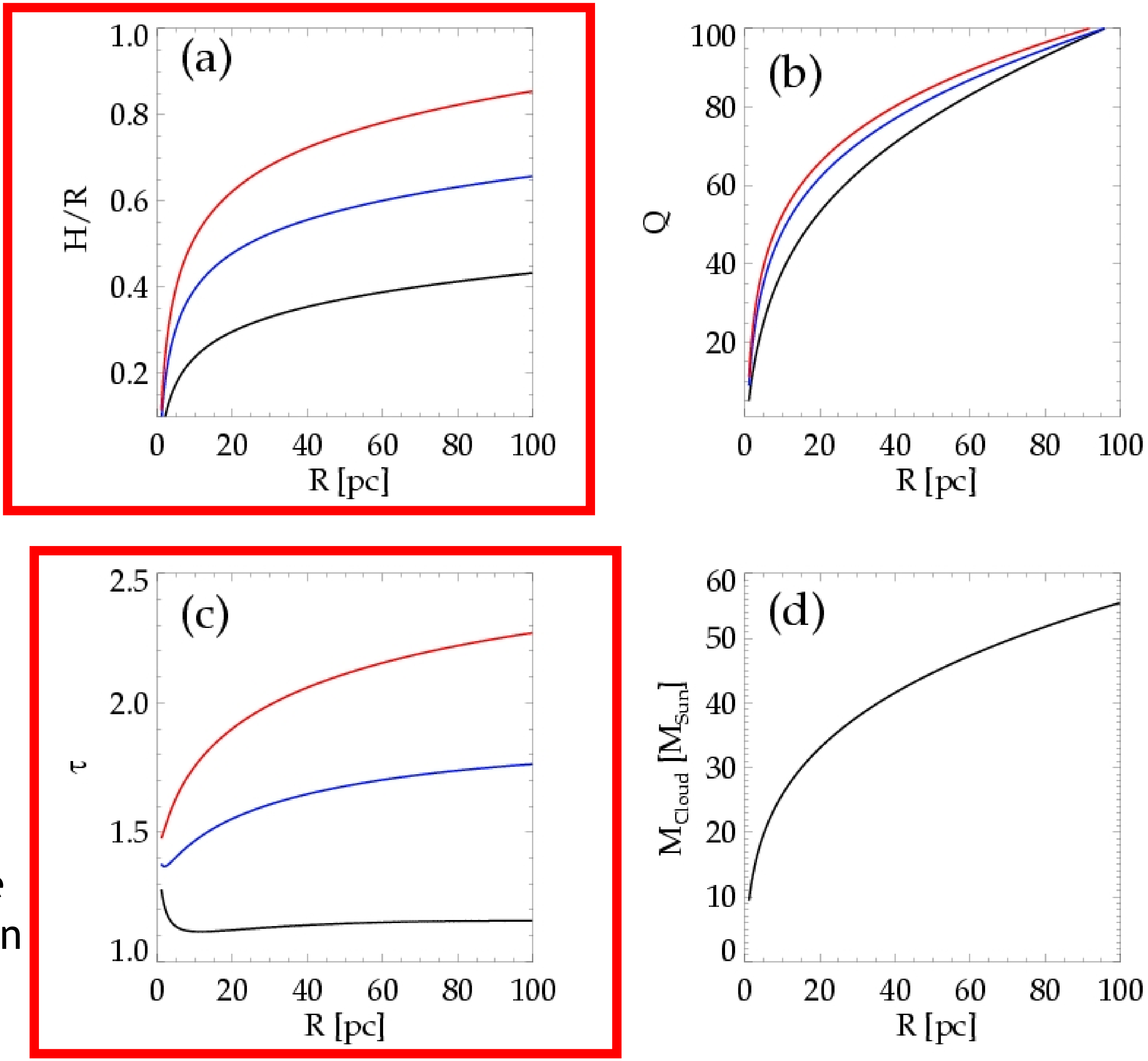
Cloud Properties

- Tidal forces limit size of the largest clouds (→ shear-limit)
- Largest Clouds dominate appearance
- Quasi-stable clouds hold together by self-gravity

$$R_{\text{Cloud}}(c_S, M_{\text{Cloud}}) \rightarrow l_{\text{Coll}} = \frac{1}{n\pi R_{\text{Cloud}}^2}$$

- Typical cloud mass $M \approx 30 M_{\text{solar}}$
- Obscuration implies $\tau \approx 1 \ldots 2.5$

Radial Structure



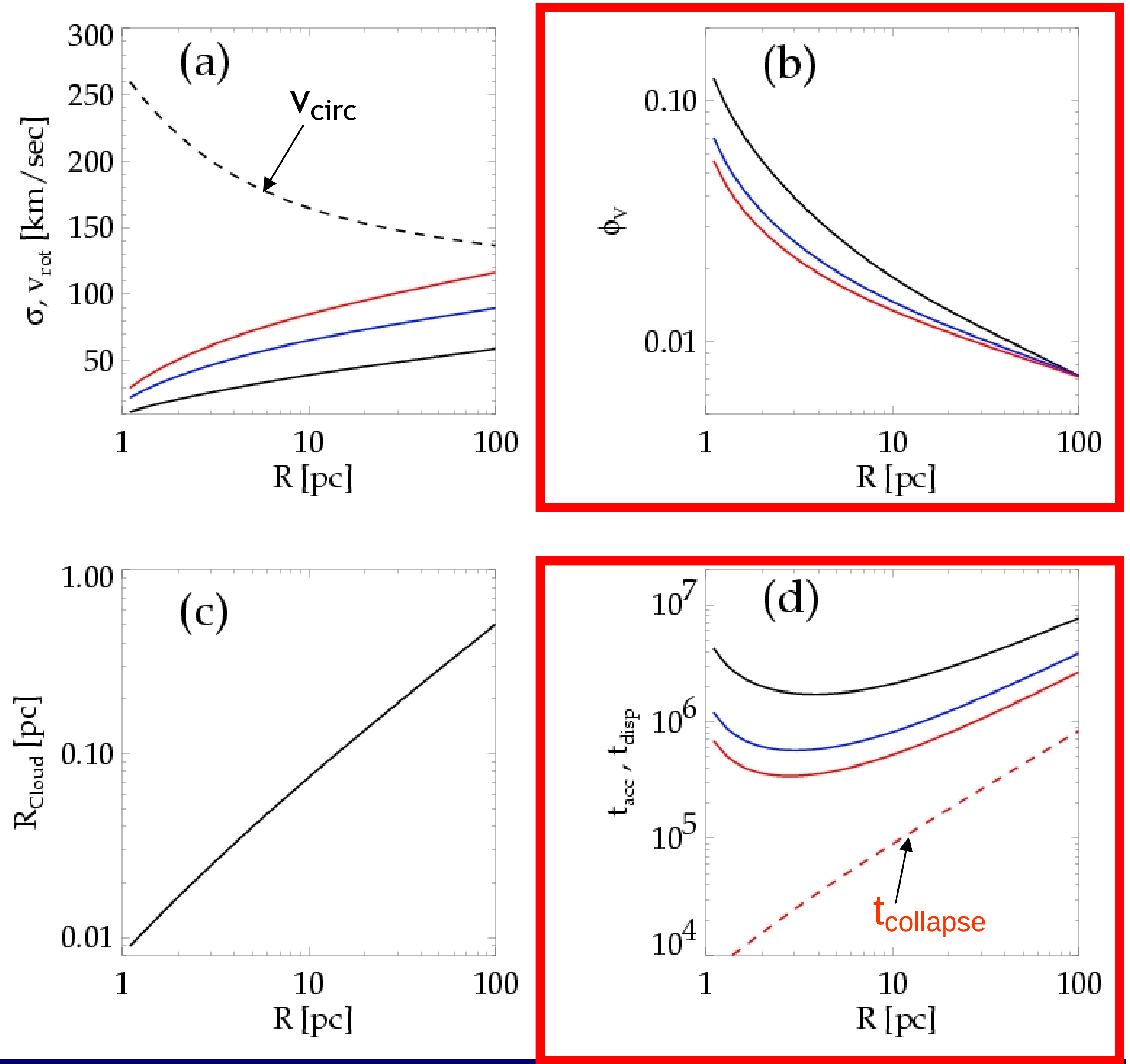
Red: m = 15

Blue: m = 8

Black: m = 2

m : mass accretion rate in units of the Eddington rate of the black hole

Radial Structure



Red: m = 15

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m : mass accretion rate in units of the Eddington rate of the black hole

Timescales

1. Geometrically thick accretion flows (tori) rotate slightly sub-Keplerian (4 ·10^5 yr at 10 pc)
   Vertical hydrostatic equilibrium can be achieved on an orbital timescale

2. The accretion timescale (viscous timescale) < 10^6 yr at 10 pc

$$t_{\mathrm{acc}} \propto \tau^{-1} \dot{M}^{-1} R$$

3. Collapse time is the shortest timescale involved

$$t_{\mathrm{Collapse}} = \frac{0.2}{\tau(1-\varepsilon)} t_{\mathrm{Orbit}}$$

Without energy gains from accretion or other processes a $\tau \sim 1$ torus would collapse to a thin disk within an orbital timescale

Energy gains from accretion is required

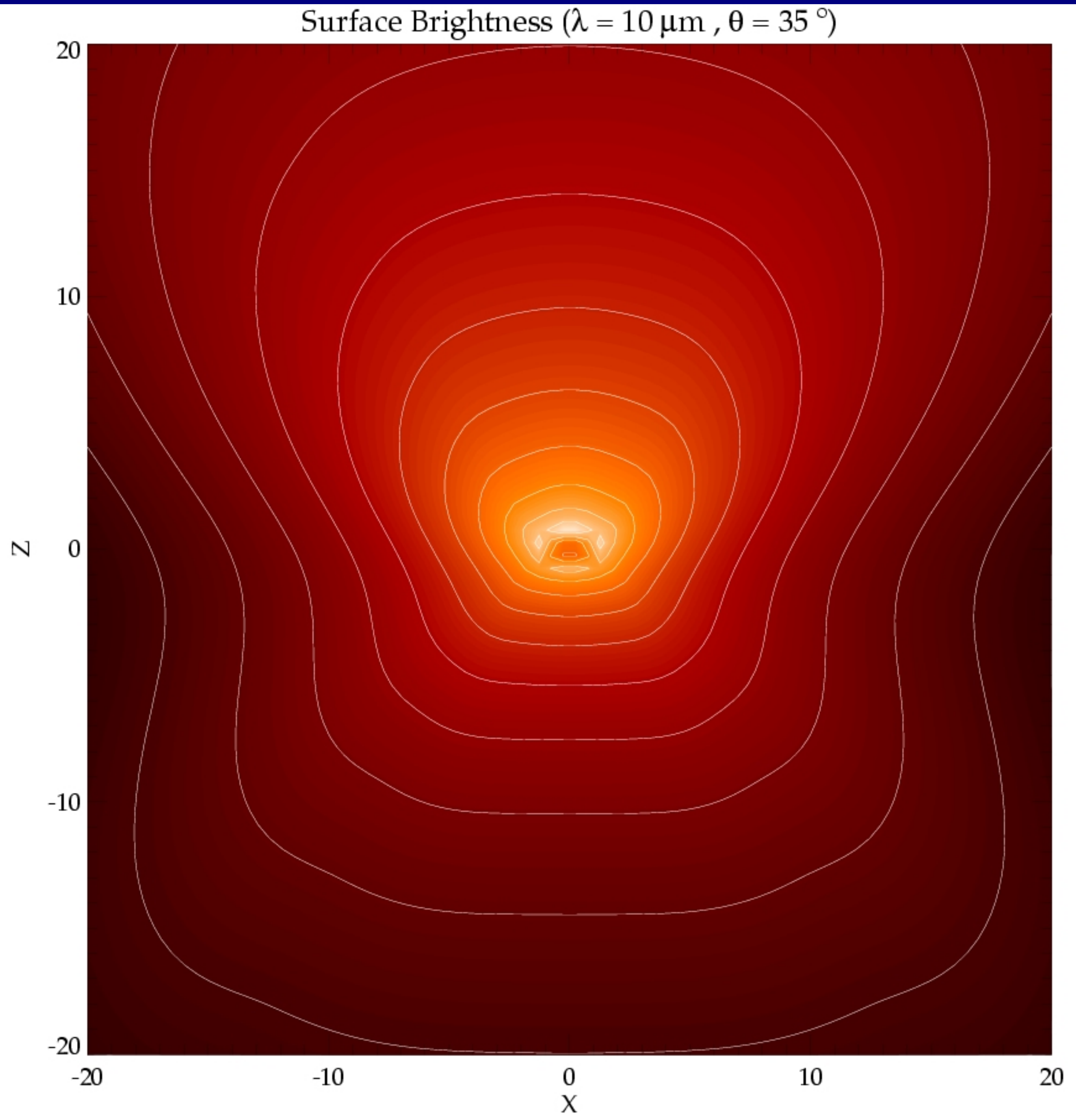
Results

- Required accretion rate: ~ 10 M_{solar}/yr
- Gas Mass 4 Mio. M_{solar} (within 80 pc) ➡ 10^4 Clouds
- Cloud masses: 10 – 60 M_{solar}

  ➡ Clouds are optically thick individually
- Accretion lifetime ~ 1 Mio. years (50 pc)
- Mean free path for Rad. Transfer

$$l_{\mathrm{coll}} \propto R^q; \quad 0.5 \leq q \leq 1.5$$

Appearance in Mid-IR



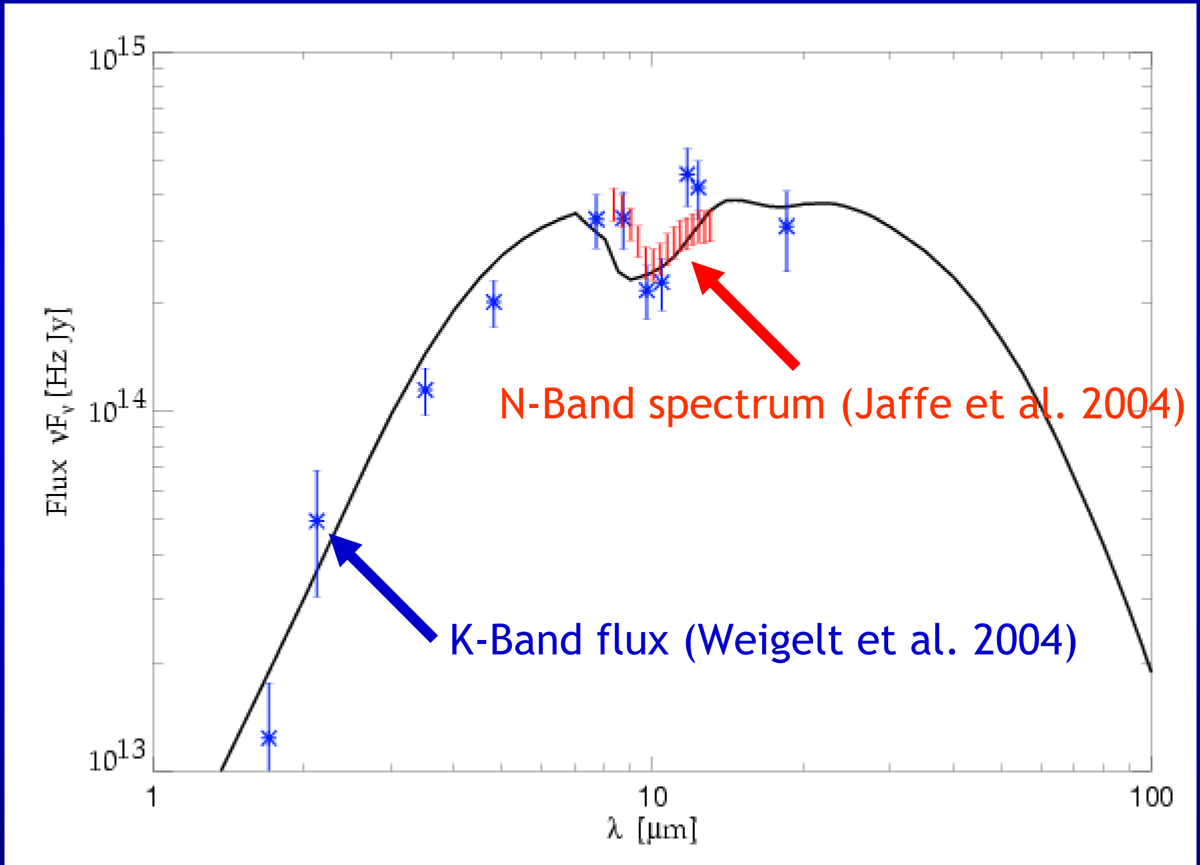
Based on the formalism of Nenkova, Ivezić & Elitzur (2002)

Dynamic range: 4000;

spatial scale in units of the sublimation radius

The IR-Spectrum

Based on the formalism of Nenkova, Ivezić & Elitzur (2002)



Sublimation radius 0.9 pc ; L_{bol} = 2.8 10^{45} erg/s

Degeneracy Mdot - Inclination

Predictions for Evolution

- Surface density

$$\Sigma \sim \tau \frac{M(R)}{2R^2} \frac{c_S}{v_{\rm circ}}$$

- Thickness of Torus

$$H/R \sim \left(\frac{1+\tau^2}{\tau^2} \frac{R\dot{M}}{M(R)\, c_S} \right)^{1/2} \sim \dot{m}^{1/2}$$

- Mean free path

$$\frac{l_{\rm coll}}{R} = \frac{H}{\tau R}$$

- Mean number of clouds (midplane)

$$N \propto \tau \, \dot{M}^{-1/2}$$

Summary

- Geometrically thick tori need huge mass accretion rates
- Anisotropic absorption and almost isotropic emission → spectral fitting ?
- Next question:
- How do cloud collisions really look like ?
- How does circumnuclear starformation feed the torus?
- Dust chemistry ?