“Dynamical Constraints for Obscuration by Dust in a Torus”

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In collaboration with

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- Gerd Weigelt (Bonn)
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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 accepted)

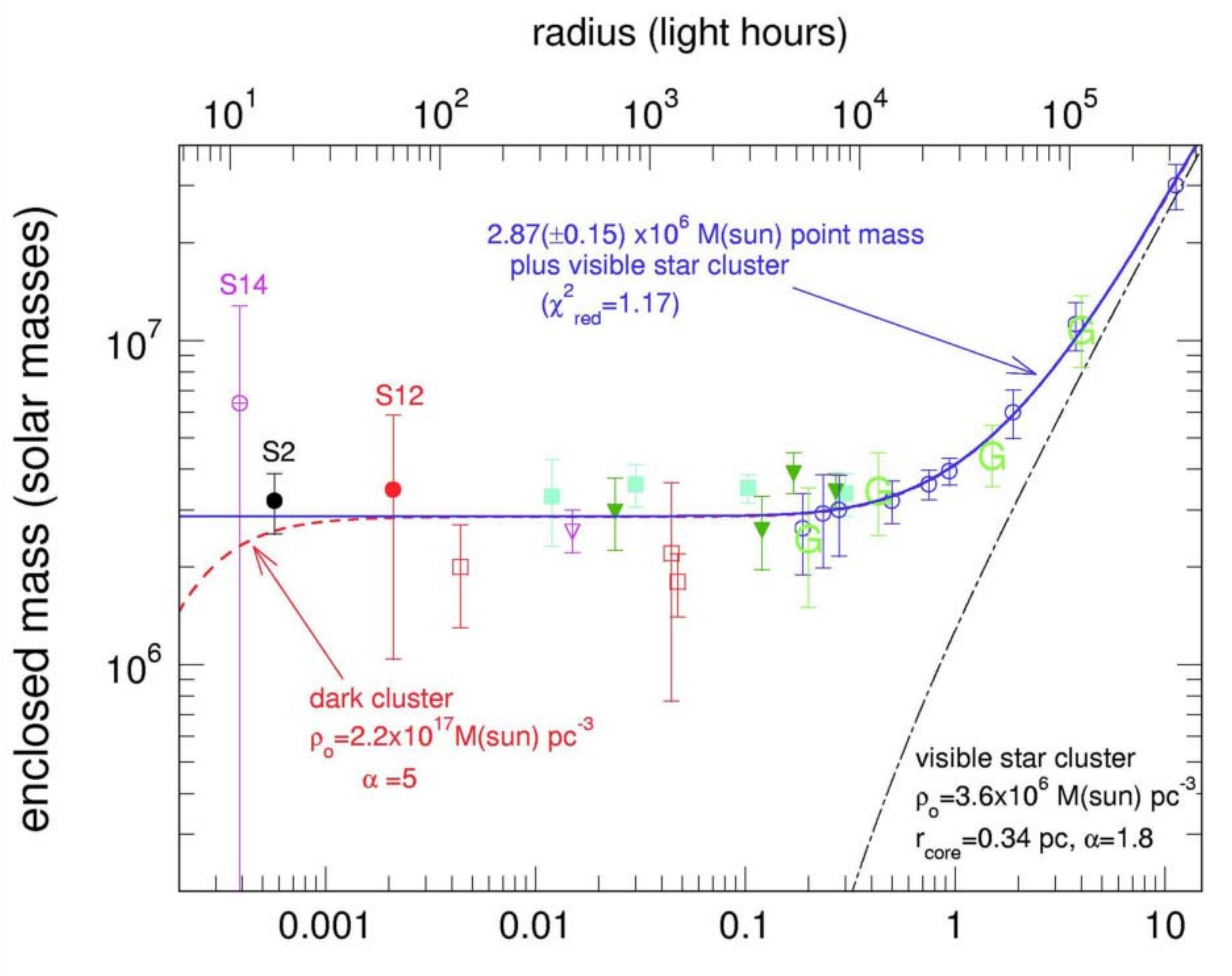
Overview

- NIR-Observations of NGC 1068
- Viscosity & Cloud Collisions in a Torus
- Consequences for NIR imaging and Unified Schemes

Motivation

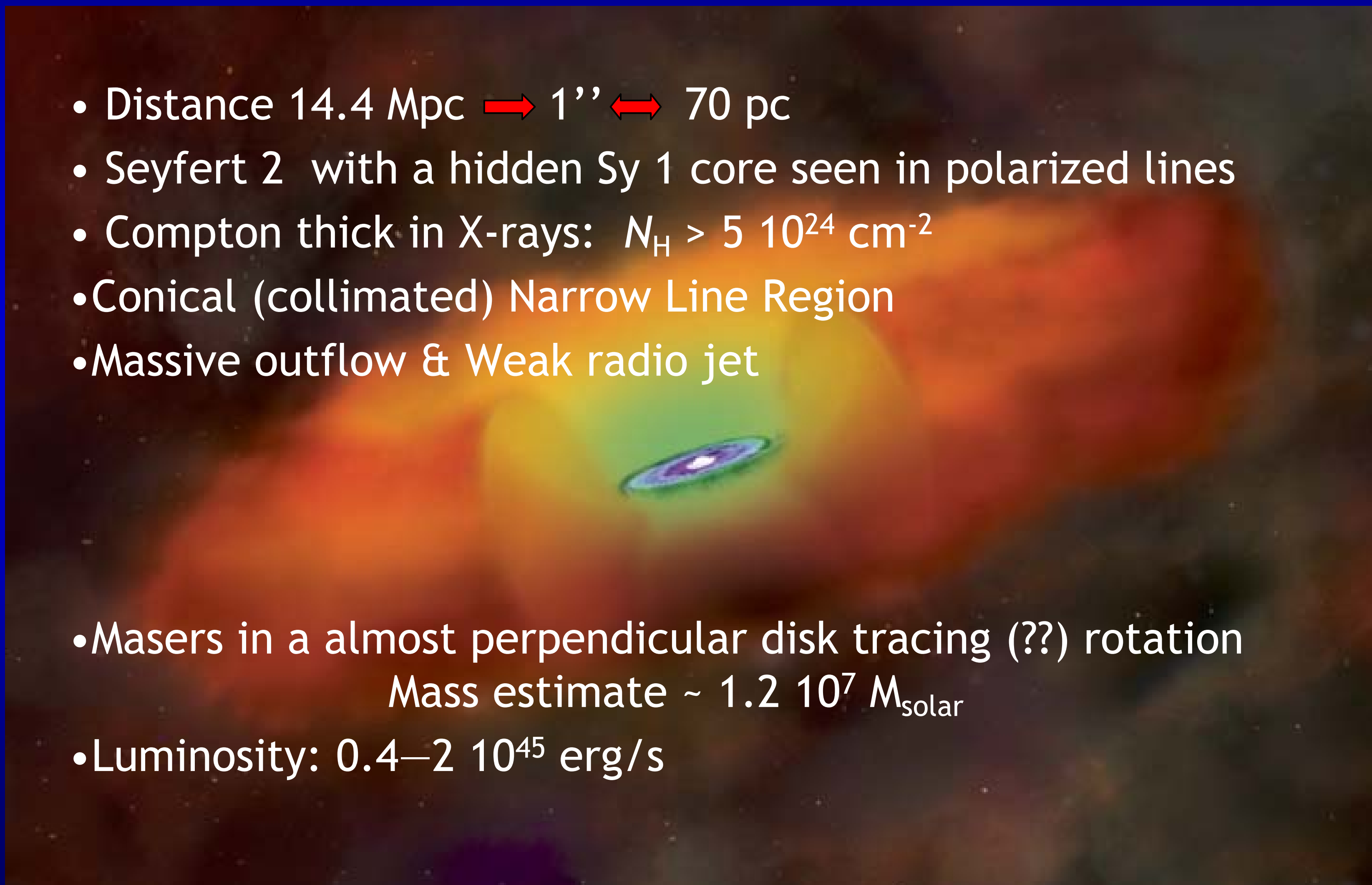
- Unified schemes of AGN assume dusty torus
- What are the requirements to make it work ?
- Are the conclusions of Krolik & Begelman (1988) still valid ?
- → How to support and maintain the thickness of the torus ?

The Mass Distribution (GC)



(Ott et al. 2003)

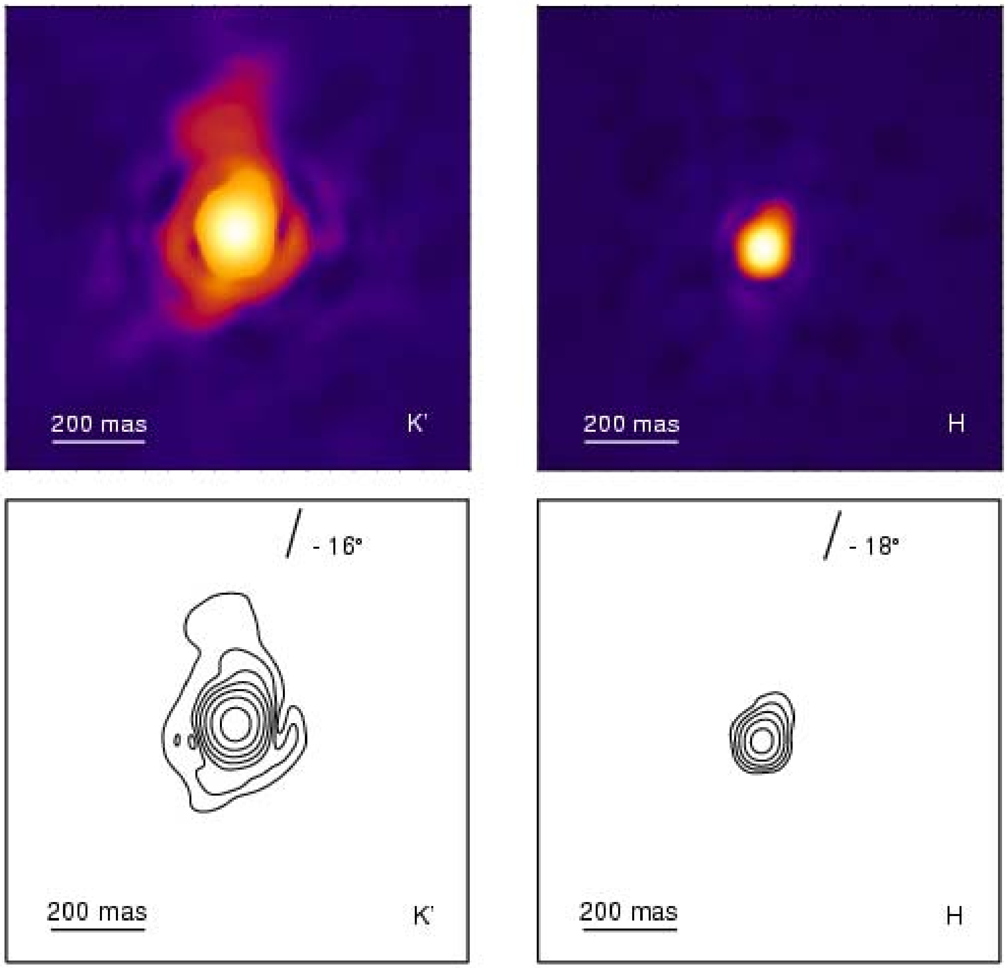
NGC 1068 — the classical case for the unified model



- 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

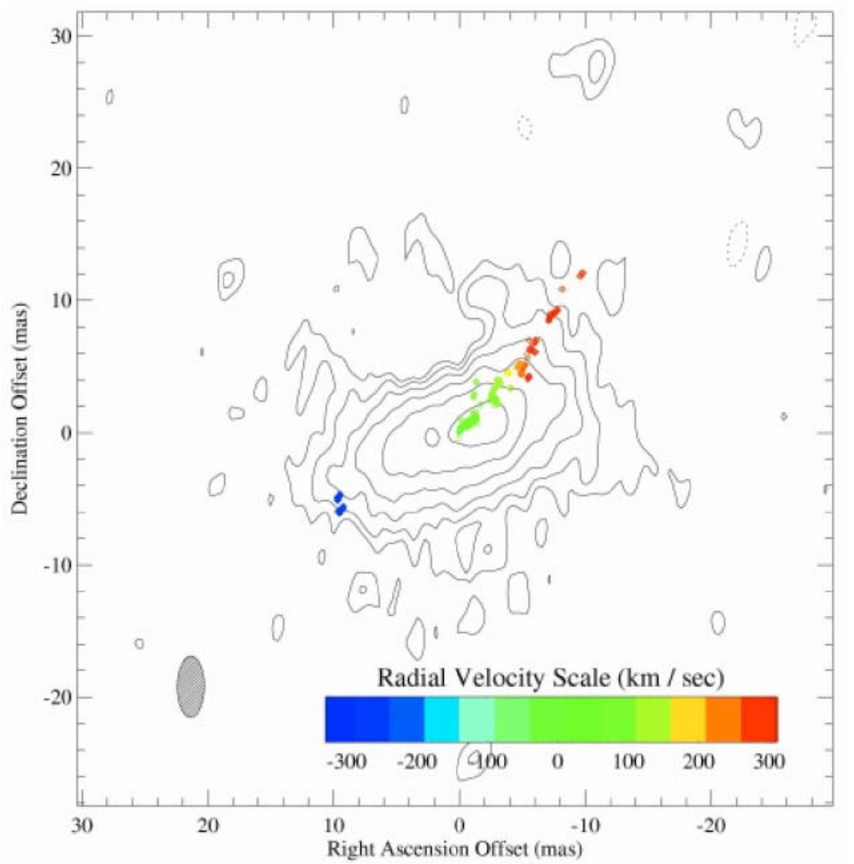


(Weigelt et al. 2004, A&A accepted)

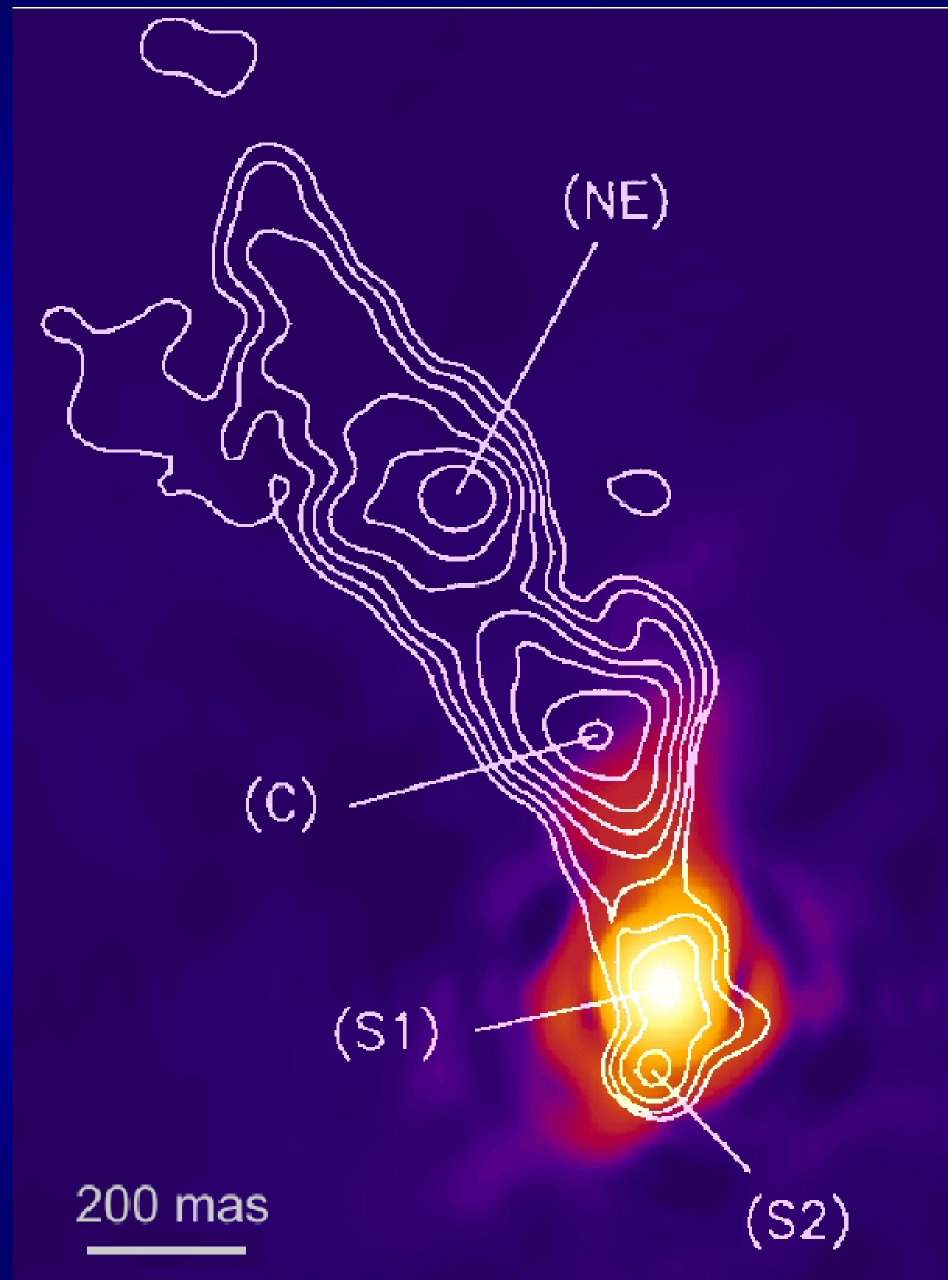
Core:
18 x 40 mas
= 1.3 x 2.8 pc
Flux: 350 mJy

& extended emission

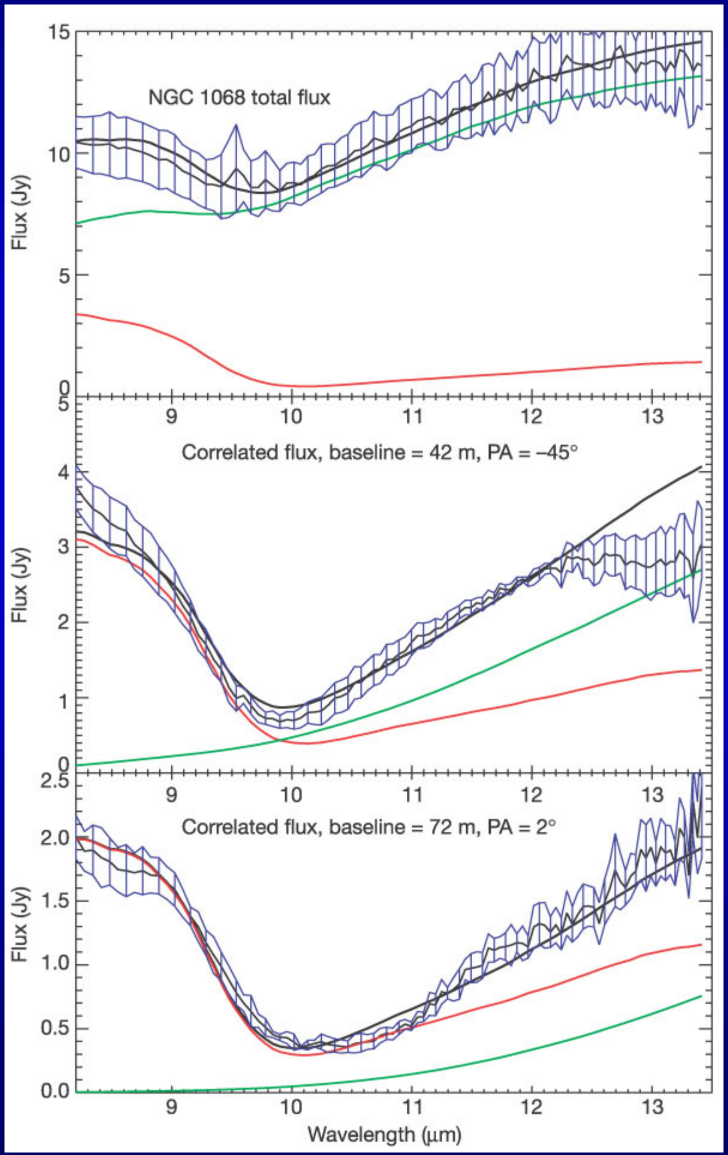
NGC 1068
The radio-NIR view

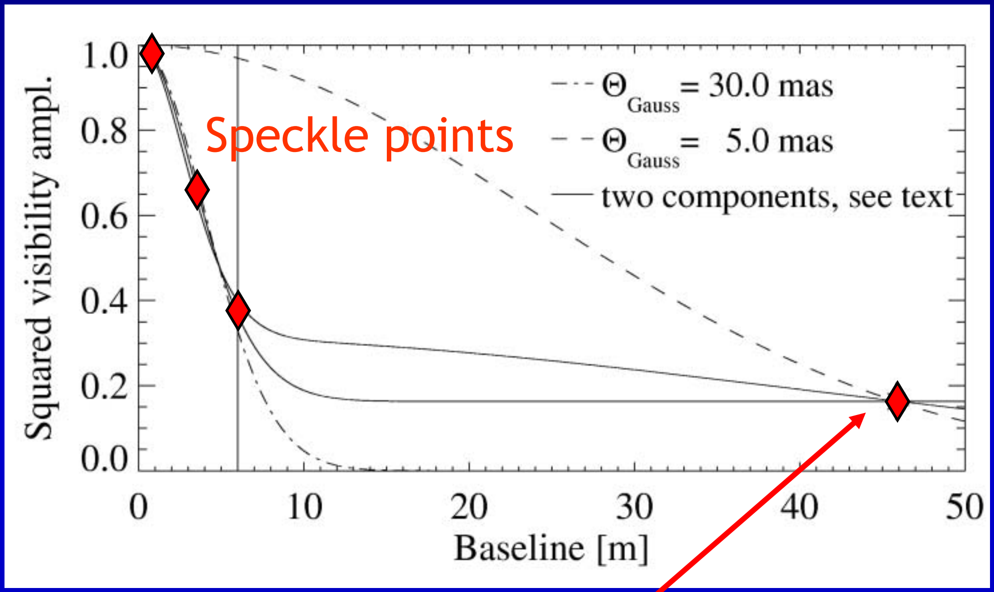


(Gallimore et al. 2004, preprint)



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
- Equilibrium structure in the combined potential of Black Hole & quasi-isothermal star cluster

$$\dot{M} = \text{const.}$$

- 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)

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

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

- Mass accretion from differential rotation & angular momentum redistribution

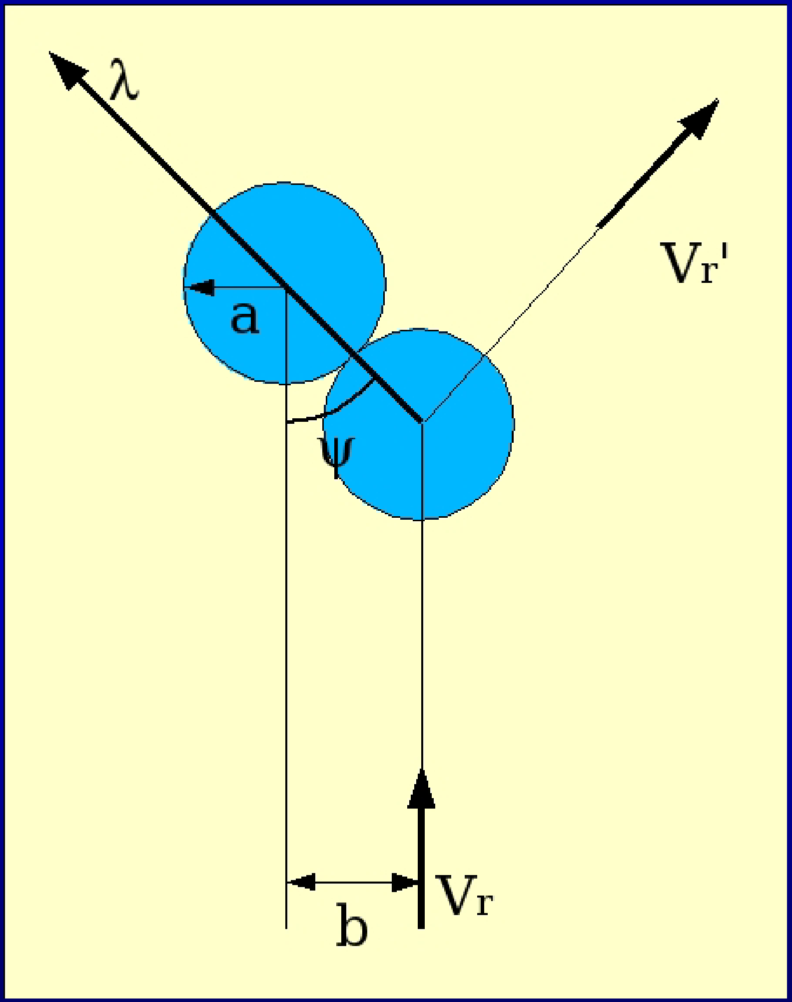
- Vertical scale height $H = \sigma/\Omega = l_{\text{coll}}\tau$

The collisional particle disk:

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

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

Cloud Collisions



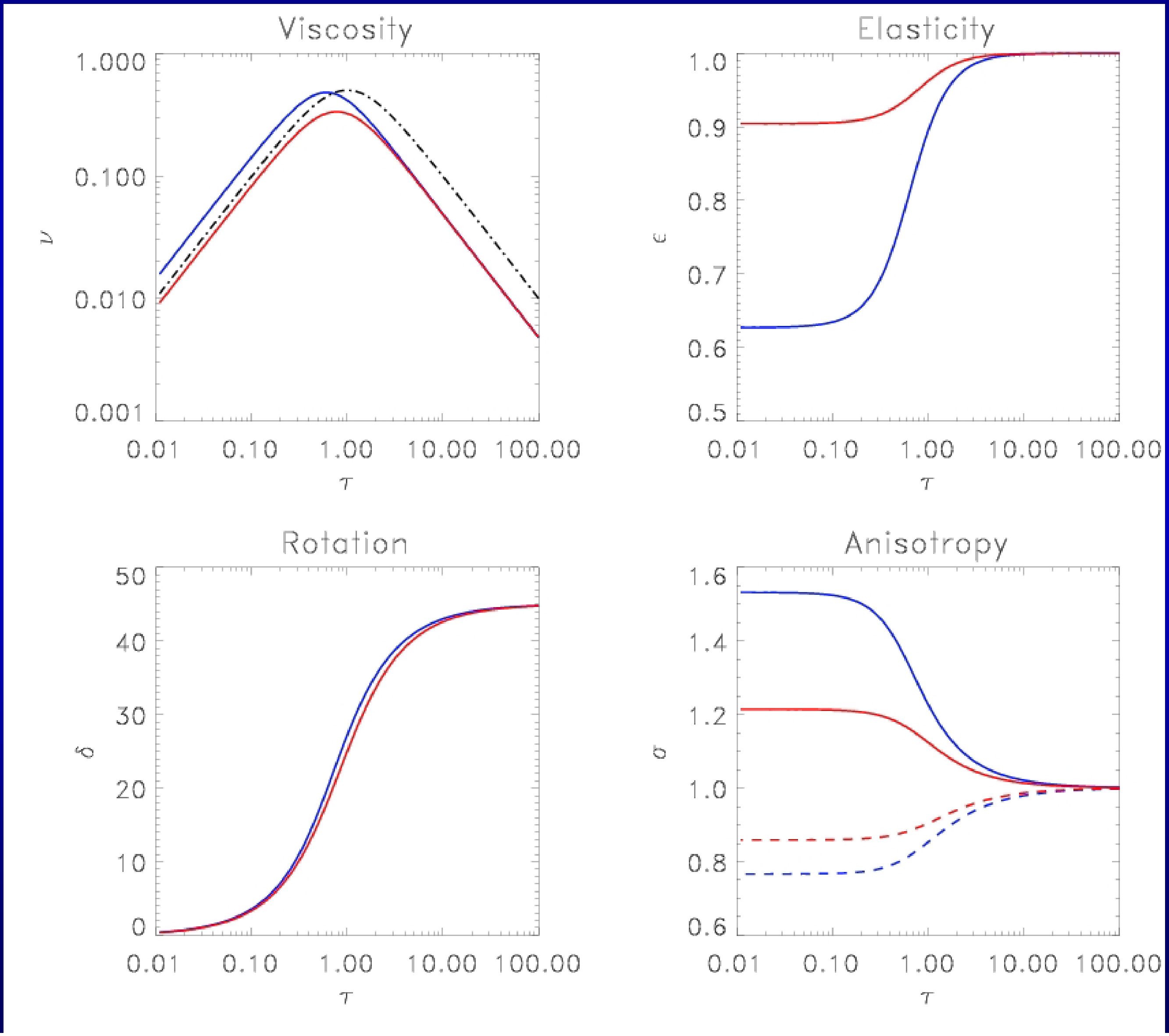
Goldreich & Tremaine (1978): Only momentum along λ is lost in inelastic collisions (assumption)

→ 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

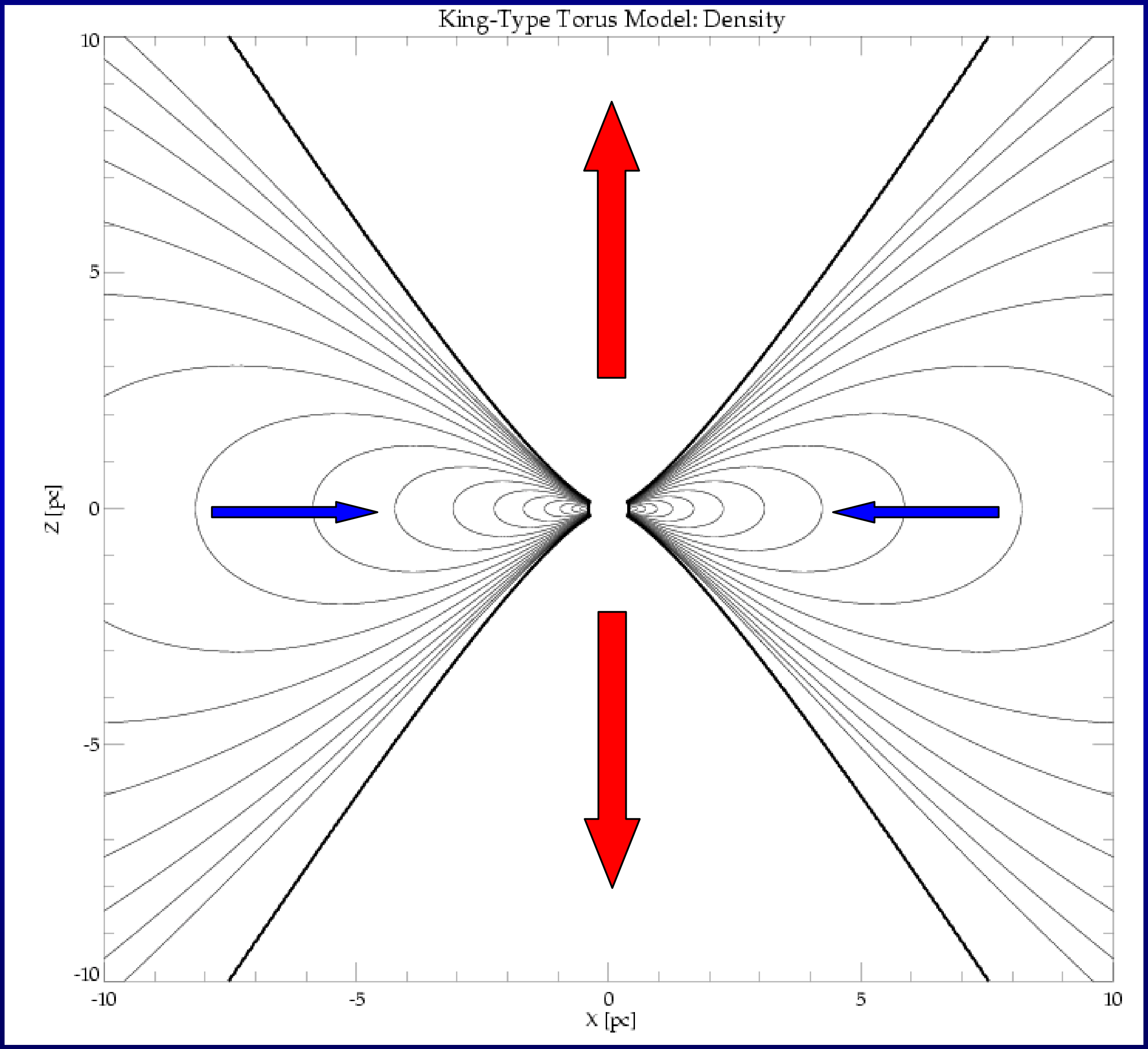
1. Advective terms (change of σ^2 and compression)
2. No collective effects (enhanced viscosity via non-local interactions; Wisdom & Tremaine 1988)

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

3. Elasticities ε as low as 0.3 are possible (45 % of kinetic energy can be dissipated in collisions)

ε determines τ

The vertical structure



Exact solution for the density

in an arbitrary external potential

with a vertical cut-off height

Example for NGC 1068

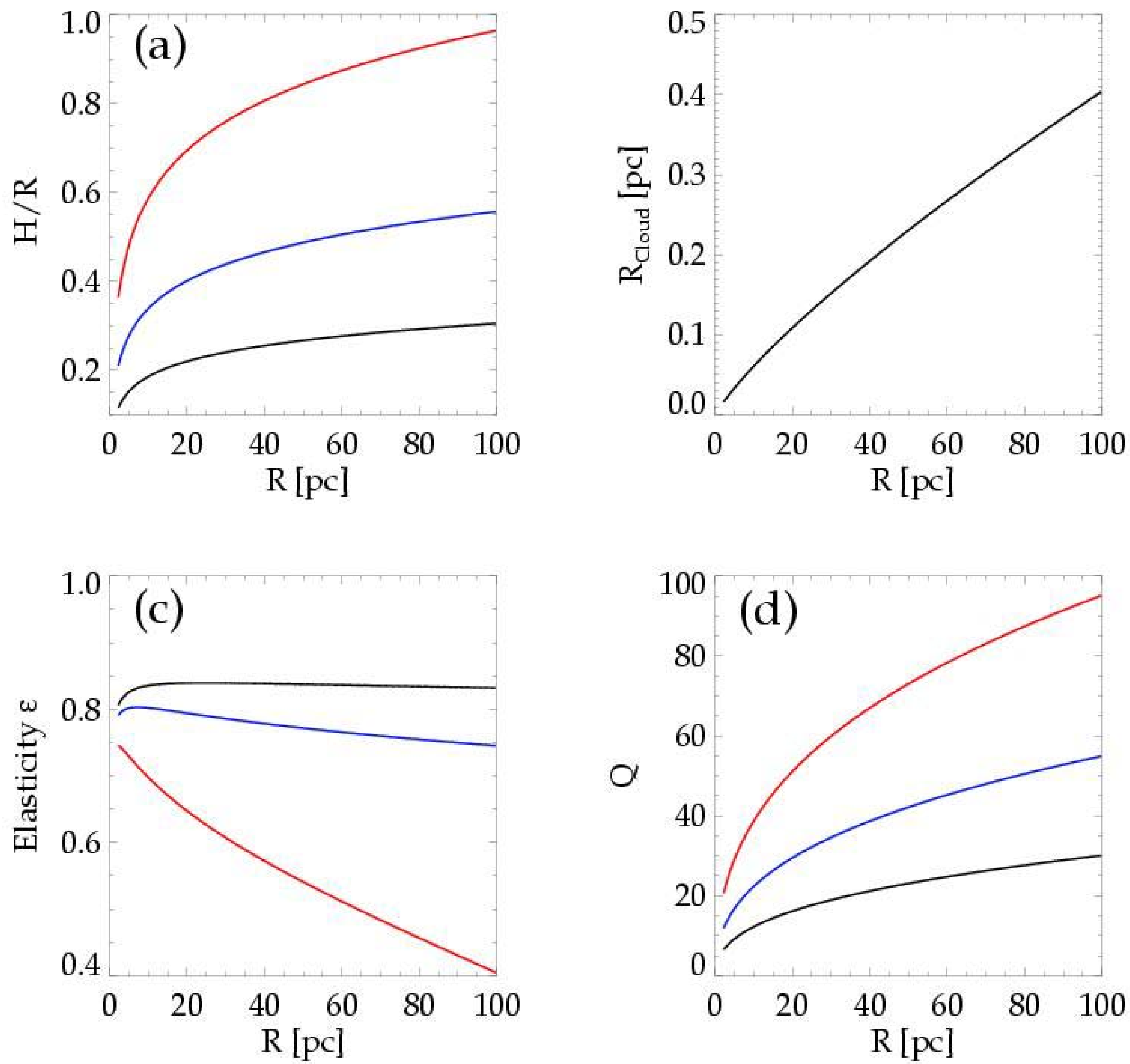
Cloud Properties

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

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

- Typical cloud mass $M \approx 50 M_{\mathrm{solar}}$
- Obscuration implies $\tau \approx 1$

Radial Structure



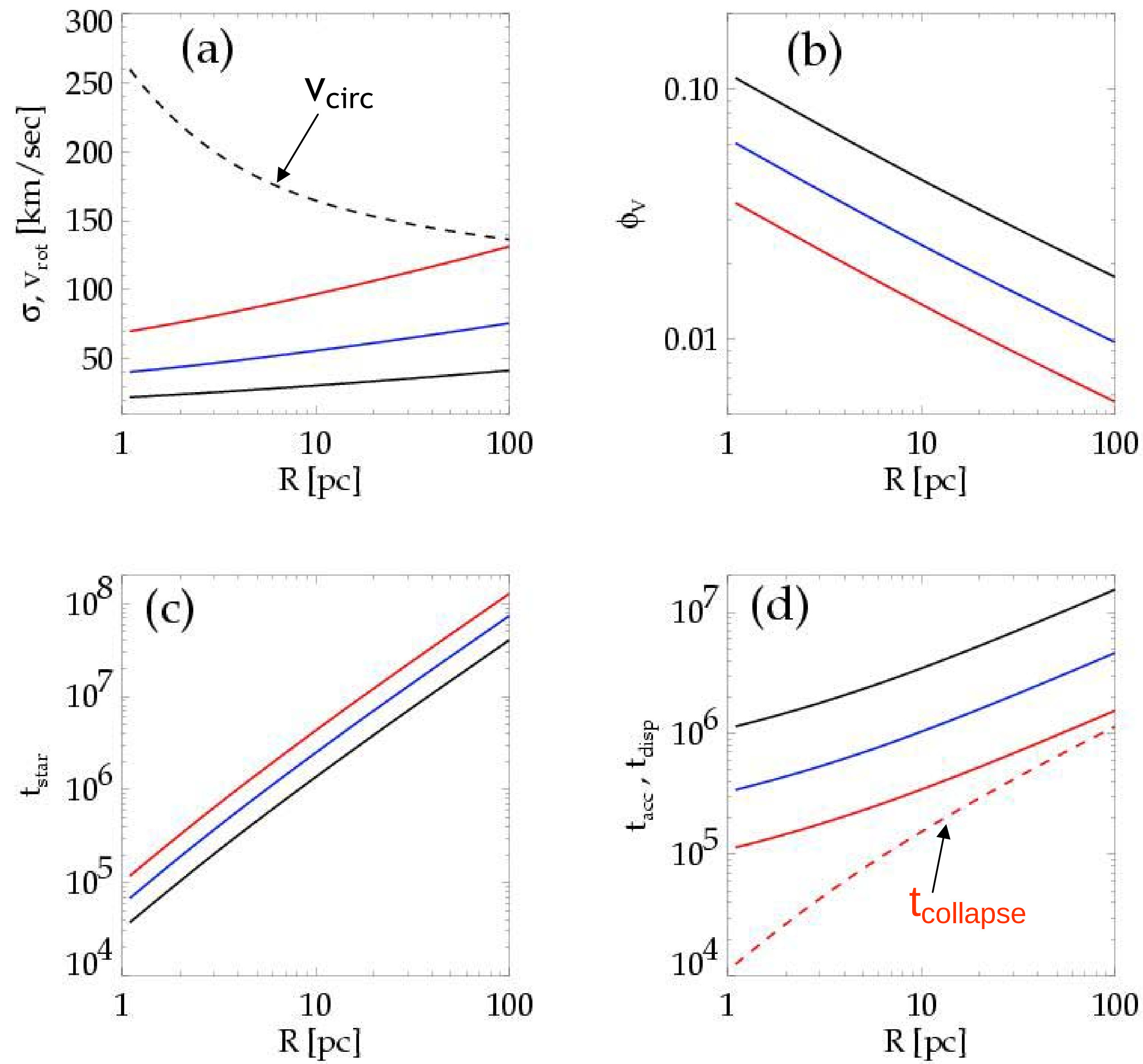
Red: m = 30

Blue: m = 10

Black: m = 3

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

Radial Structure



Red: m = 30

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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 ($4 \cdot 10^5$ 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 or

4. The Circularization radius (angular momentum barrier) must lie within the inner boundary (sublimation radius)

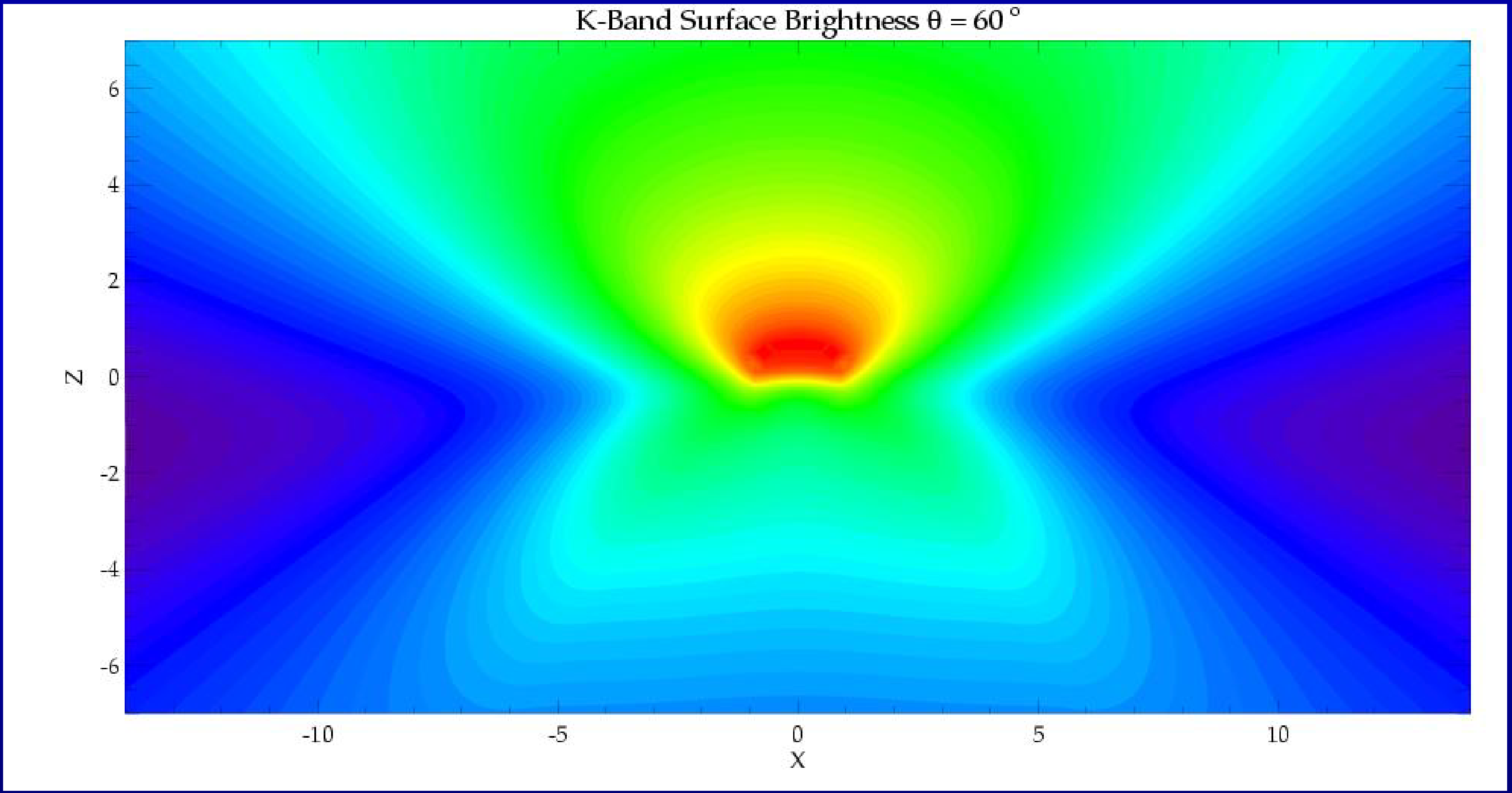
Results

- Required accretion rate: ~ 10 M_{solar}/yr
- Gas Mass 4 Mio. M_{solar} (within 80 pc) → 10^4 Clouds
- Cloud masses: 25 – 100 M_{solar}
  → Clouds are optically thick individually
- Accretion lifetime ~ 1 Mio. years (50 pc)
- Mean free path for Rad. Transfer

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

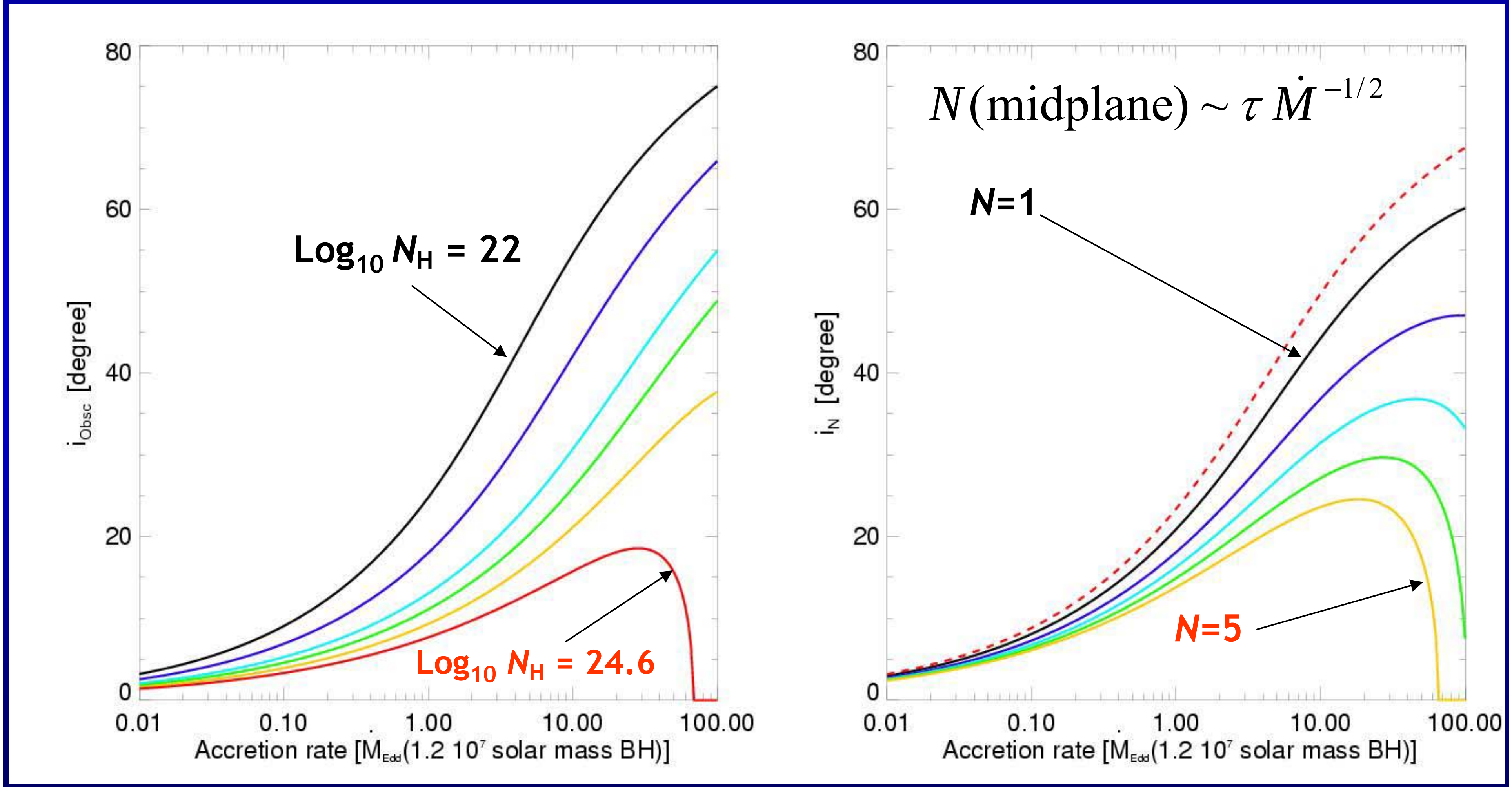
Appearance in NIR

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



Dynamic range: 10^5 ;   spatial scale in units of the sublimation radius

Torus & Unified Scheme



Predictions for Evolution

- Surface density

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

- Thickness of Torus

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

- Mean free path

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

- Mean number of clouds (midplane)

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

Summary

- Dusty tori can be modelled as thick, clumpy accretion flows
- Geometrically thick tori need huge mass accretion rates

$$\dot{M}_{\mathrm{Torus}} > \dot{M}_{\mathrm{Edd,BH}}$$

- Provides a basis for radiative transfer models
  Anisotropic absorption and
  almost isotropic emission → spectral fitting
- Next question:
  How do cloud collisions really look like ?
  How does circumnuclear starformation feed the torus ?