Dusty windshield

Radiative magnetohydrodynamics simulations of IR and UV radiation pressure on dusty AGN tori

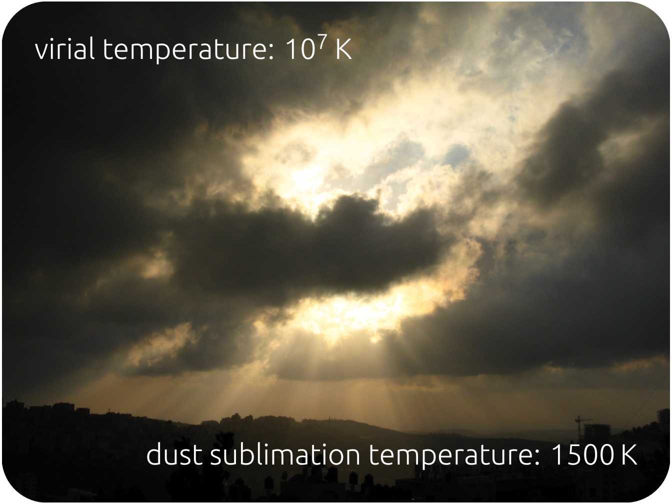
Chi-Ho (Edwin) Chan

with Julian H. Krolik (JHU)

Hebrew University of Jerusalem
& Tel Aviv University

December 13, 2018

Geometrical thickness of the obscuring torus

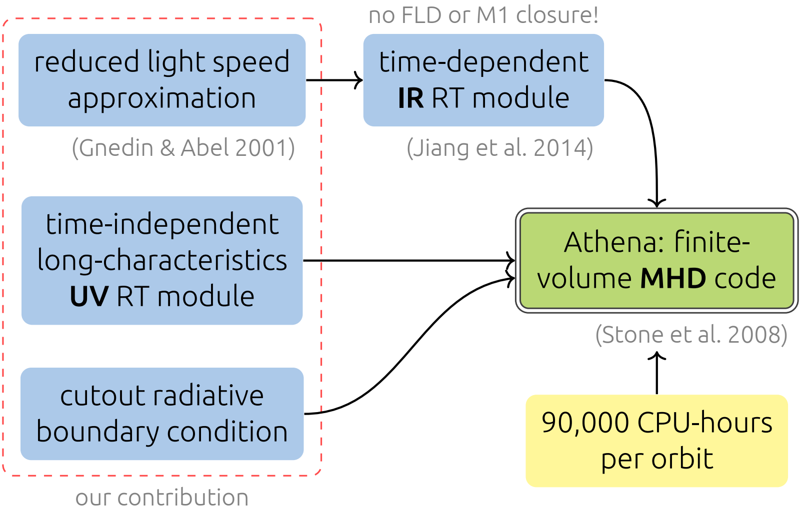


Dynamical models of the obscuring torus

- Warped disk (e.g., Phinney 1989)
  blocks large solid angle only with severe warps and twists
- Clumpiness (Krolik & Begelman 1988)
  needs unusual magnetic field structure to counter inelastic collisions
- Magnetocentrifugal wind (e.g., Königl & Kartje 1994)
  needs large-scale magnetic fields
- Direct magnetic support (Lovelace et al. 1998)
  needs large-scale magnetic fields
- Supernovae (e.g., Wada & Norman 2002)
  needs more energy than observed
- Stellar ejecta (e.g., Schartmann et al. 2009)
  ties torus lifetime to starburst
- **Radiative support** (e.g., Chan & Krolik 2016, 2017)
  has not been fully explored with self-consistent simulations

Our recent radiative magnetohydrodynamics simulations

Simulation code



Simulation parameters

extrapolatable to realistic AGNs

Luminosity

0.1 times Eddington

Central mass

0.8 solar mass

IR opacity

20 times Thomson
if below sublimation

UV opacity

80 times Thomson
if below sublimation

Optical depth

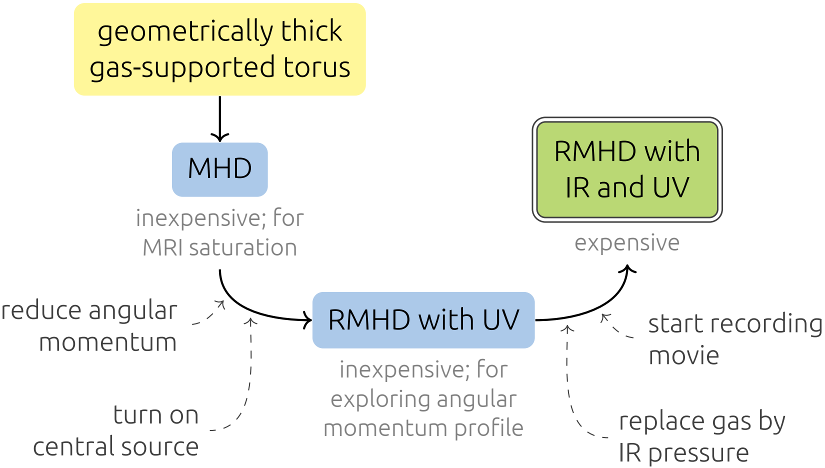
Thomson: 2
infrared: 40

Angular momentum

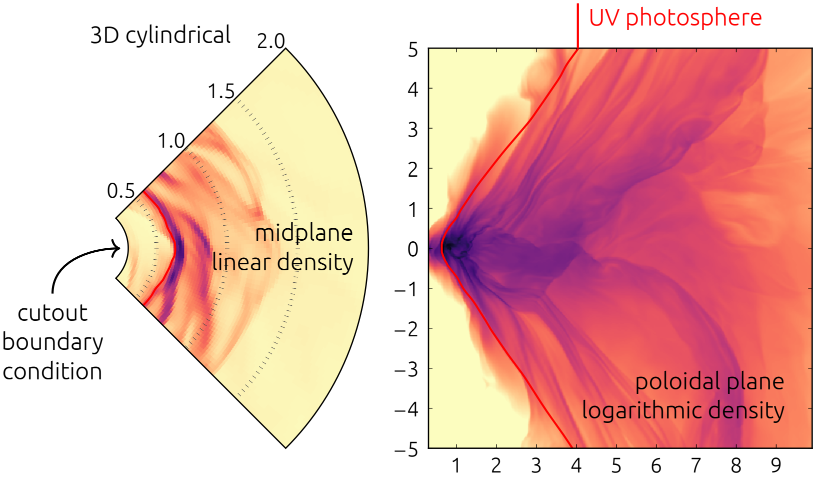
flat radial profile

genuinely arbitrary

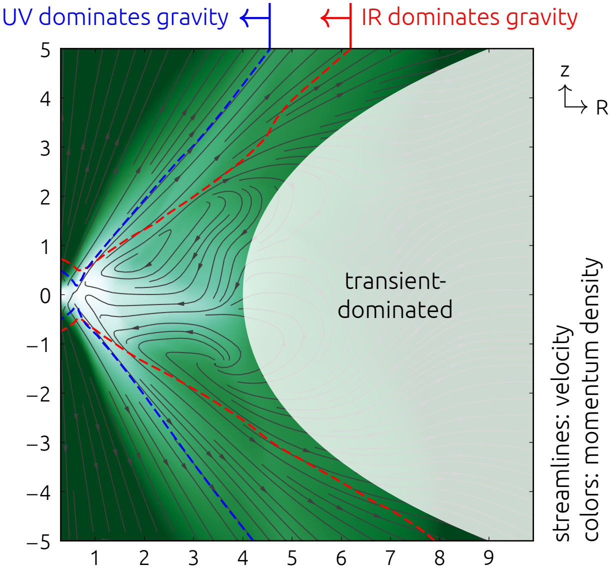
Simulation strategy



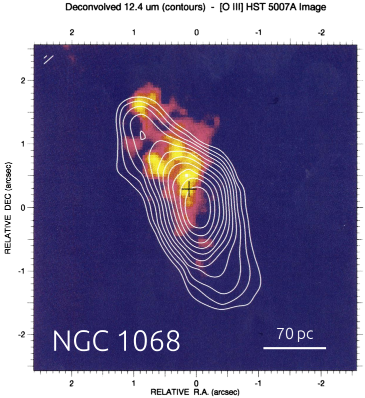
Simulation domain



Radiation-driven inflow–outflow



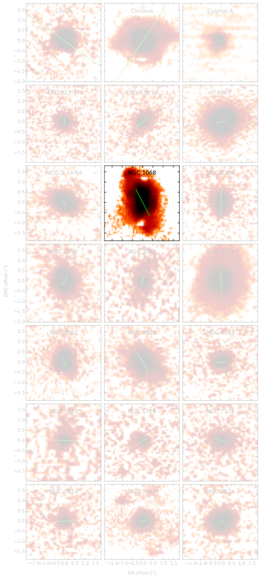
Dust in polar regions of AGNs



(Braatz et al. 1993)

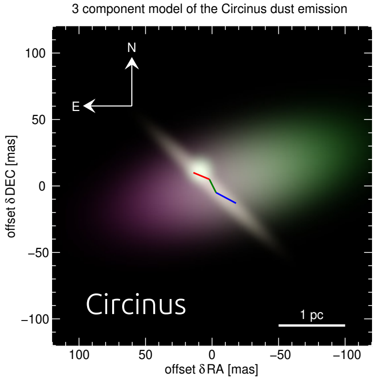
colors: [O III] λ 5007
contours: 12.4 μm

(Asmus et al. 2016)



orange: 12 μm
green: system axis (100 pc)

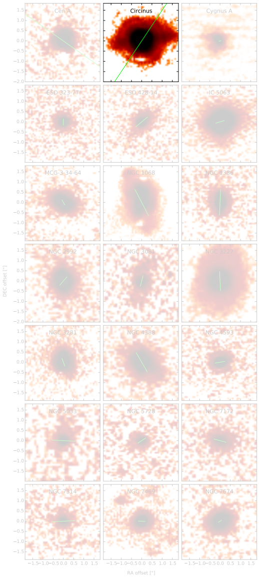
Dust in polar regions of AGNs



(Tristram et al. 2014)

colors: dust model from VLTI
line: maser disk

(Asmus et al. 2016)



orange: 12 μm
green: system axis (100 pc)

Radiation-driven outflow

- **Kinematics** fits expectations

$$\dot{M}_{\rm wind} \sim \frac{L_{\rm UV}}{c v_\infty} \qquad \frac{L_{\rm kin}}{L_{\rm UV}} \sim \frac{v_\infty}{c} \qquad v_\infty^2 \equiv \frac{GM}{R_{\rm in}} \frac{L_{\rm UV}}{L_{\rm E}} \frac{\kappa_{\rm UV}}{\kappa_{\rm T}}$$

- **Mass loss rate** and **speed** match observed

$$\dot{M}_{\rm wind} \sim 0.9\,\mathrm{M_\odot\,yr^{-1}} \times \left(\frac{M}{10^7\,\mathrm{M_\odot}}\right)^{3/4} \left(\frac{L_{\rm UV}/L_{\rm E}}{0.1}\right)^{3/4}$$

$$v_\infty \sim 800\,\mathrm{km\,s^{-1}} \times \left(\frac{M}{10^7\,\mathrm{M_\odot}}\right)^{1/4} \left(\frac{L_{\rm UV}/L_{\rm E}}{0.1}\right)^{1/4}$$

temporal variation: 10%

Radiation-driven outflow explains AGN **outflows**

Radiation-driven outflow

- **Covering fractions** are close to observed type-2 fraction

$$0.71 \lesssim C_{\mathrm{IR}} \lesssim 0.73$$
$$0.77 \lesssim C_{\mathrm{UV}} \lesssim 0.82$$
$$0.78 \lesssim C_{\mathrm{soft}} \lesssim 0.83$$

due to inflow and outflow; same for any central mass

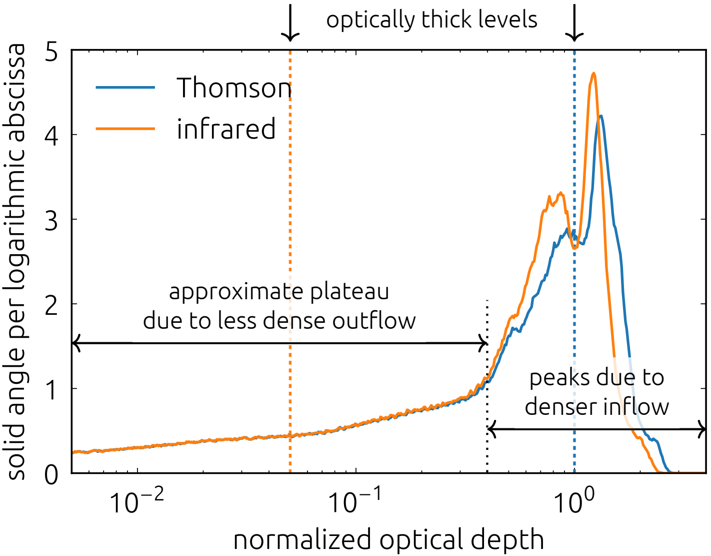
$$0.15 \lesssim C_{\mathrm{hard}} \lesssim 0.28$$

due to inflow; dependent on central mass

- Flat **column density distribution** agrees with X-ray studies

Radiation-driven outflow explains AGN **obscuration**

Radiation-driven outflow



Radiation-driven outflow

- **Covering fractions** are close to observed type-2 fraction

$$0.71 \lesssim C_{\mathrm{IR}} \lesssim 0.73$$
$$0.77 \lesssim C_{\mathrm{UV}} \lesssim 0.82$$
$$0.78 \lesssim C_{\mathrm{soft}} \lesssim 0.83$$

due to inflow and outflow; same for any central mass

$$0.15 \lesssim C_{\mathrm{hard}} \lesssim 0.28$$

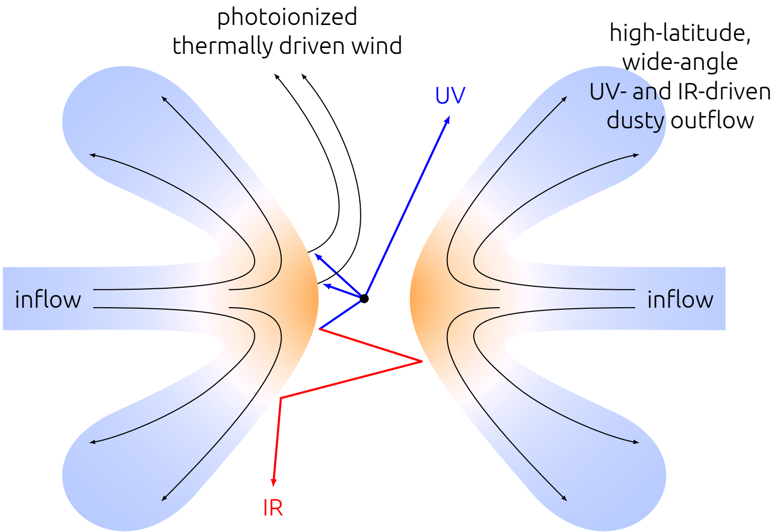
due to inflow; dependent on central mass

- Flat **column density distribution** agrees with X-ray studies

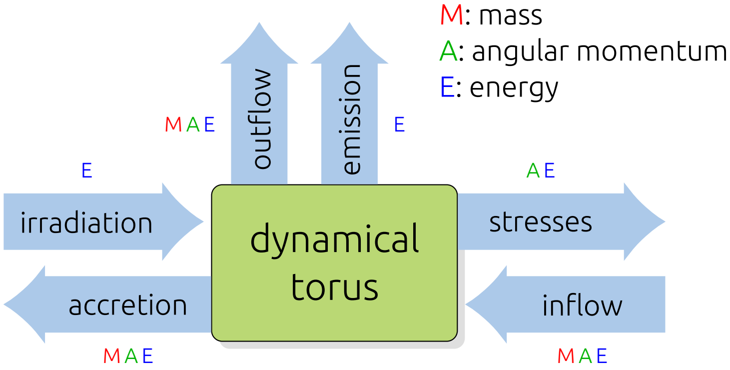
Radiation-driven outflow explains AGN **obscuration**

Lessons about torus-scale inflow and outflow

Cartoon of inflow–outflow torus model

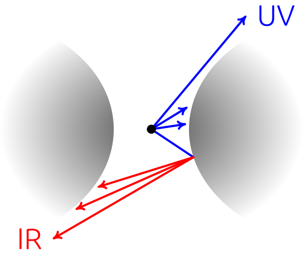


Torus as a flow-through system



Constraint from mass

- UV and IR shave off high-latitude dusty gas
- Mass loss rate is 1 $M_\odot\ \mathrm{yr}^{-1}$
- But assuming $M = 10^7\ M_\odot$, $L_{\rm UV}/L_{\rm E} = 0.1$, $\tau_{\rm T} = 1$:

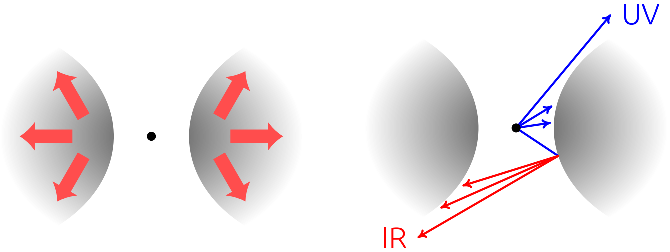


Mass	$\sim 2\pi r_{\rm ds}^2 \tau_{\rm T}/\kappa_{\rm T}$	$\approx 7 \times 10^3\ M_\odot$
Orbital period	$2\pi (GM/r_{\rm ds}^3)^{-1/2}$	$\approx 5 \times 10^3$ yr

Mass must be **resupplied** from galactic scales

Constraint from angular momentum

1. Isotropic pressure delivering vertical support also provides radial support
2. Direct UV and reprocessed IR provide additional outward radial momentum



Angular momentum must be **sub-Keplerian**

Constraint from angular momentum

Observational evidence

- NGC 4258

  Eddington ratio: 0.0002 to 0.02
  dynamics: Keplerian rotation

- Circinus

  Eddington ratio: 0.18
  dynamics: Keplerian rotation with outflow

- NGC 1068

  Eddington ratio: 0.33 to 1.06
  dynamics: rotation falls off more slowly than Keplerian

- MCP megamasers resembling Keplerian disks

  Eddington ratio: 2×10^{-3}
  dynamics: Keplerian at large radii, sub-Keplerian at small radii

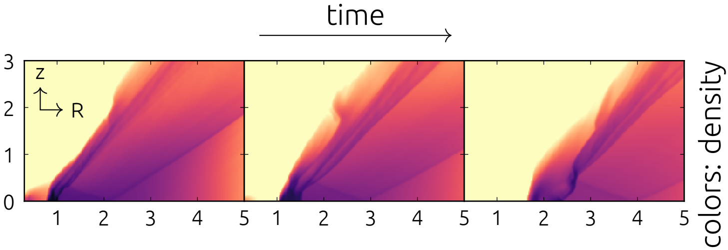
Constraint from angular momentum

3. Accretion toward inner edge requires low angular momentum
   - Inflow timescale due to stresses is $\sim [\alpha (H/R)^2 \Omega]^{-1}$
   - Mass influx at all radii, as determined by inflow timescale, must be comparable to mass outflux

Angular momentum must be **low** or rapidly removed

Constraint from energy

- Radiation does positive work on outflows
- Binding energy of torus decreases
- Torus eventually becomes unbound



Energy must be kept **low**

Constraints on inflow of steady-state torus

1. Mass must be resupplied from galactic scales
2. Angular momentum must be sub-Keplerian
3. Energy must be kept low

How can mass resupply satisfy constraints 2 and 3?

- Stresses in inflow rapidly remove angular momentum and energy
- Mass resupply has inherently low angular momentum and energy

Simulation parameters

Luminosity: 0.1 times Eddington

IR opacity: 20 times Thomson if below sublimation

Optical depth:
- Thomson: 2
- infrared: 40

extrapolatable to realistic AGNs

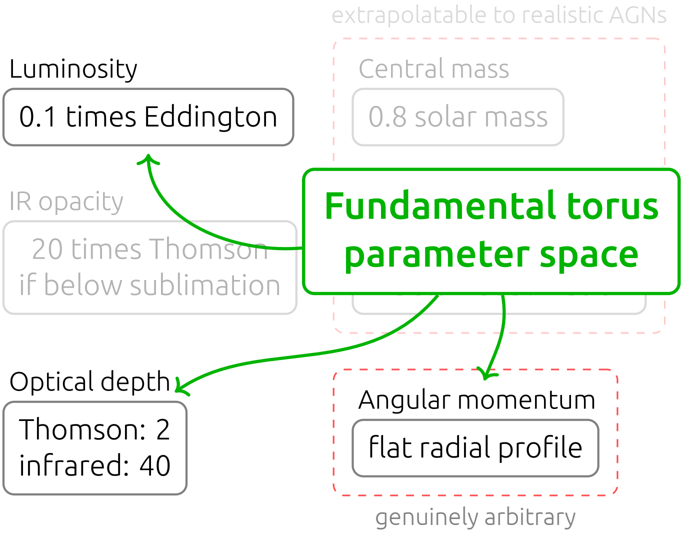
Central mass: 0.8 solar mass

UV opacity: 80 times Thomson if below sublimation

Angular momentum: flat radial profile

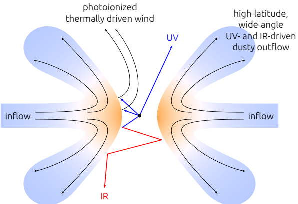
genuinely arbitrary

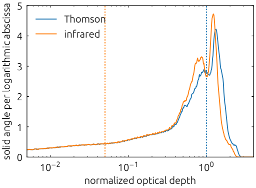
Simulation parameters

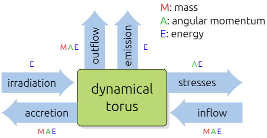


Summary

- Torus in RMHD simulations settles into steady inflow–outflow
- IR in central hole drives high-latitude, wide-angle outflow with expected:
  - kinematics
  - obscuration properties
- Steady-state irradiated tori must:
  - be resupplied with mass
  - have sub-Keplerian rotation







References I

Asmus, D., Hönig, S. F., & Gandhi, P. 2016, ApJ, 822, 109

Braatz, J. A., Wilson, A. S., Gezari, D. Y., Varosi, F., & Beichman, C. A. 1993, ApJL, 409, L5

Chan, C.-H. & Krolik, J. H. 2016, ApJ, 825, 67

Chan, C.-H. & Krolik, J. H. 2017, ApJ, 843, 58

Elvis, M., Wilkes, B. J., McDowell, J. C., et al. 1994, ApJS, 95, 1

Gnedin, N. Y. & Abel, T. 2001, NewA, 6, 437

Hönig, S. F., Kishimoto, M., Antonucci, R., et al. 2012, ApJ, 755, 149

Jiang, Y.-F., Stone, J. M., & Davis, S. W. 2014, ApJS, 213, 7

Königl, A. & Kartje, J. F. 1994, ApJ, 434, 446

Krolik, J. H. 2007, ApJ, 661, 52

Krolik, J. H. & Begelman, M. C. 1988, ApJ, 329, 702

Lovelace, R. V. E., Romanova, M. M., & Biermann, P. L. 1998, A&A, 338, 856

Nenkova, M., Ivezić, Ž., & Elitzur, M. 2002, ApJL, 570, L9

References II

Phinney, E. S. 1989, in NATO Advanced Science Institutes Series C: Mathematical and Physical Science, 290, Theory of Accretion Disks, ed. F. Meyer, W. J. Duschl, J. Frank, & E. Meyer-Hofmeister (Dordrecht: Kluwer), 457

Pier, E. A. & Krolik, J. H. 1992, ApJ, 401, 99

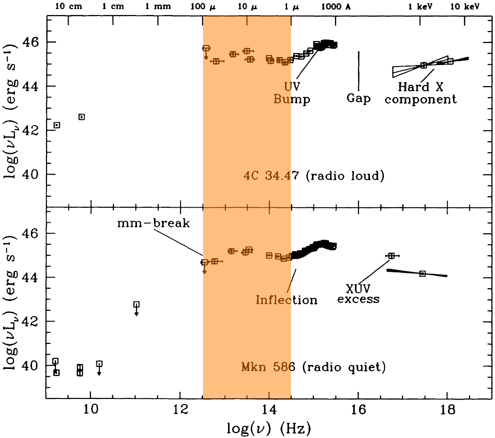
Schartmann, M., Meisenheimer, K., Klahr, H., et al. 2009, MNRAS, 393, 759

Stone, J. M., Gardiner, T. A., Teuben, P., Hawley, J. F., & Simon, J. B. 2008, ApJS, 178, 137

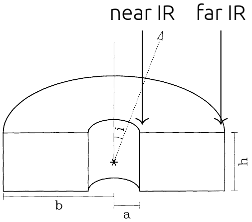
Tristram, K. R. W., Burtscher, L., Jaffe, W., et al. 2014, A&A, 563, A82

Wada, K. & Norman, C. A. 2002, ApJL, 566, L21

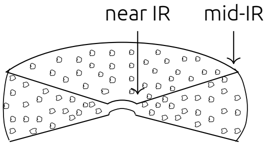
Modeling AGN spectral energy distributions



(Elvis et al. 1994)

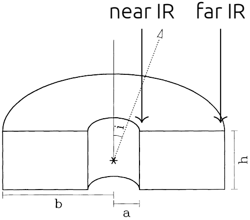


(Pier & Krolik 1992)

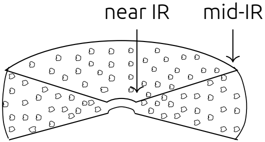


(Nenkova et al. 2002)

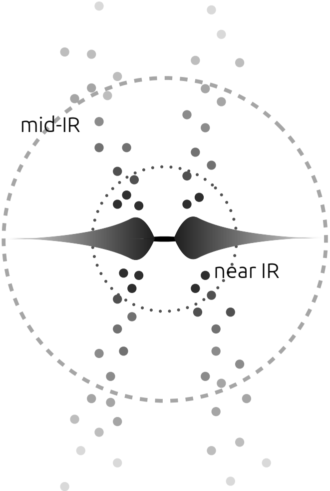
Phenomenological models of the obscuring torus



(Pier & Krolik 1992)



(Nenkova et al. 2002)



(Hönig et al. 2012)

Challenges of simulating irradiated tori

Mass loss and resupply

Angular momentum profile

Radiation anisotropy

Nonlinearity

Binding energy

physical

computational

Accurate radiative transfer

Large number of variables

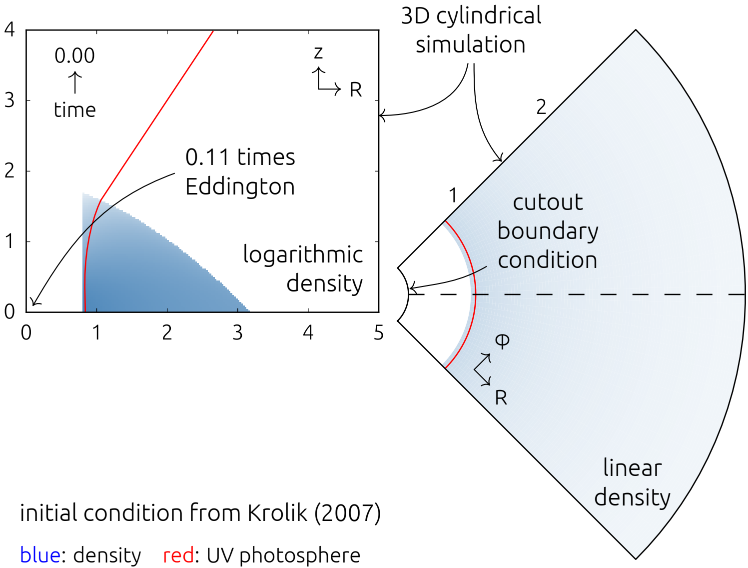
High spatial resolution

Large spatial extent

High temporal resolution

Long simulation duration

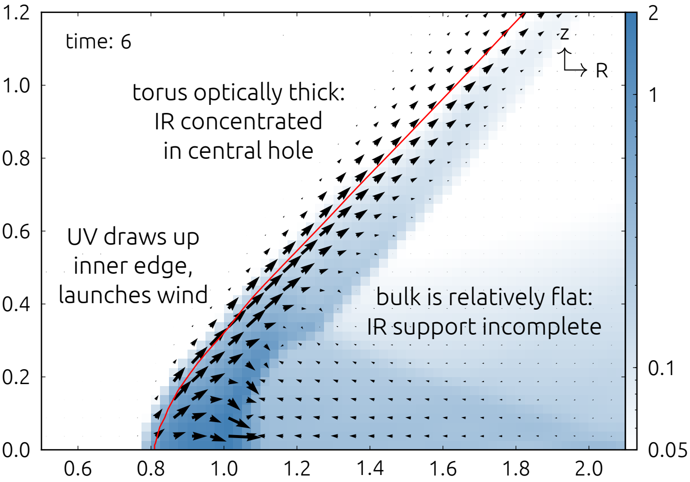
Poloidal and midplane slices of simulation



initial condition from Krolik (2007)

blue: density red: UV photosphere

Radiation-driven outflow



blue: density   red: UV photosphere   arrows: gas momentum