What We Know and What We'd Like to Know

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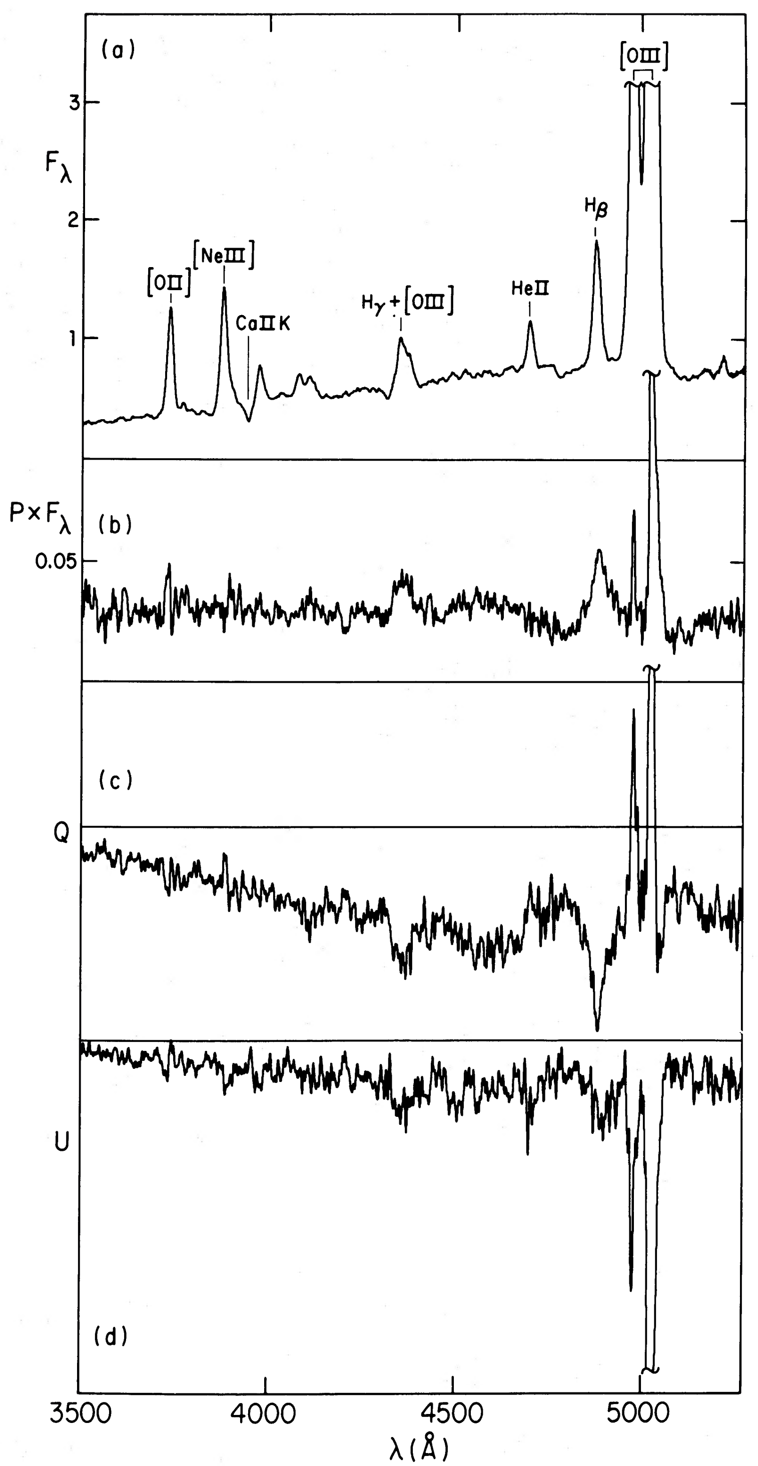
Discovery

Antonucci & Miller (1985) find broad emission lines and a blue continuum in polarized flux from NGC 1068



Immediate inferences:

- Optically thick, dusty obscuration on our line of sight
- Photons can travel through a hole in the center
- In the hole, photons scatter and acquire polarization

Immediate answer to a major question:

- Are type 1 and type 2 AGN intrinsically the same kind of object?

Our Collective Program

- Characterize quantitatively via observations, kinematic models
- Intuit and quantitatively test dynamical models
- Develop the “natural history” of matter in the torus and its hole: what is its origin and what is its fate?

Ordered from most progress to least.

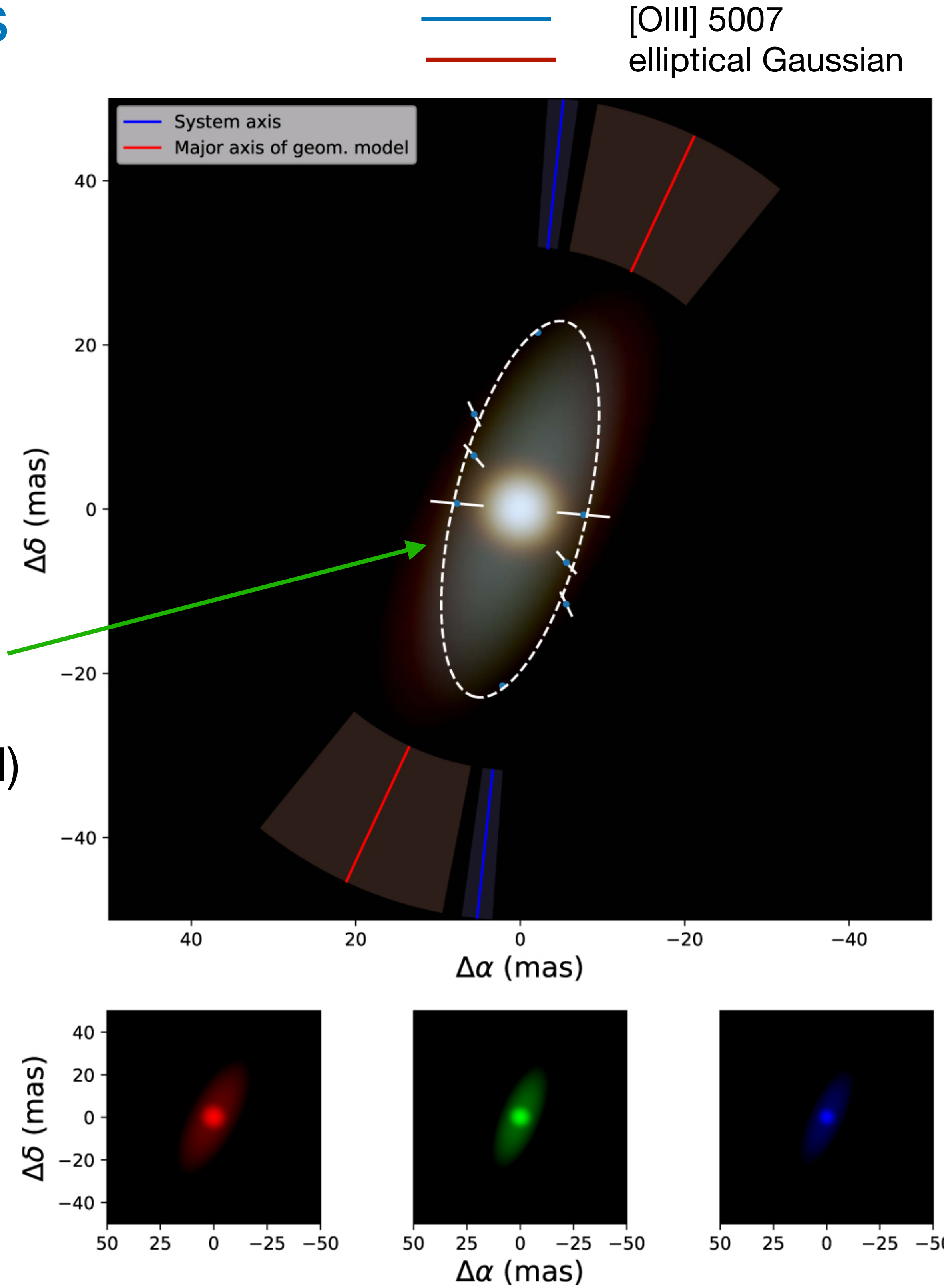
Properties to Describe

- Global lengthscale, geometry
- Density, temperature, chemical/ionization state: mean, radial and vertical profiles, internal structure, range of variation—over time and for different examples
- Velocity (at least line-of-sight)

Tools

IR Interferometry—global lengthscale, geometry

E.g., ESO323-G77



2/3 light radius

10 pc major axis (Gaussian HM)

11.8—12.2 μ   10.2—10.6 μ   8.6—9 μ

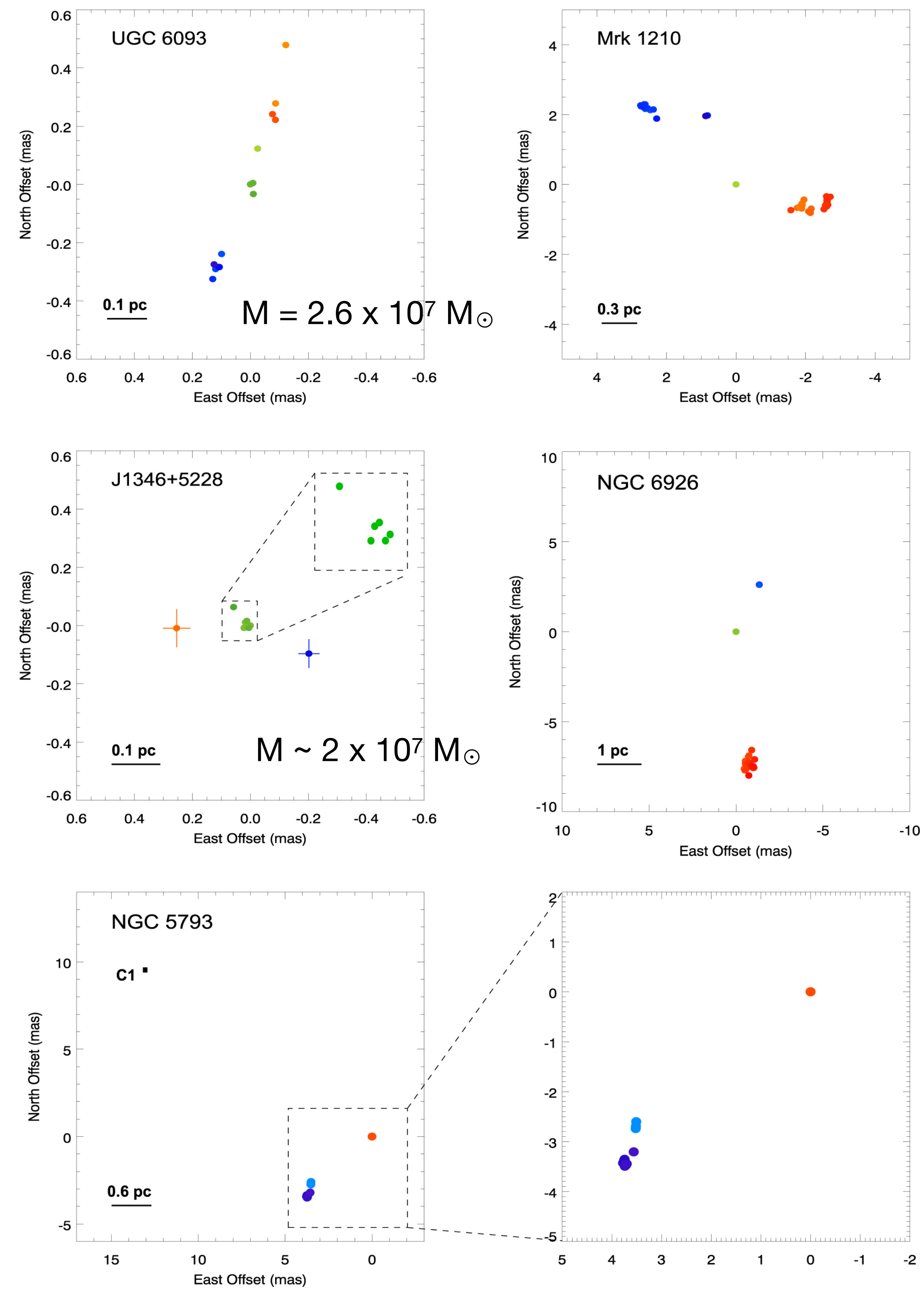
Leftley et al. 2018

Limited u-v coverage —> parameterized image models

Tools

H_2O masers—line-of-sight velocity profile, central mass

- v_{rot} ~ 100—300 km/s
- sometimes, but not always, straight + Keplerian —> mass;
- strong amplification on our l-o-s depends on details of excitation, velocity shear



Zhao et al. 2018 (MCP)

Tools

ALMA—-line-of-sight velocity, velocity dispersion, density, temperature, molecular state

E.g., NGC 1377

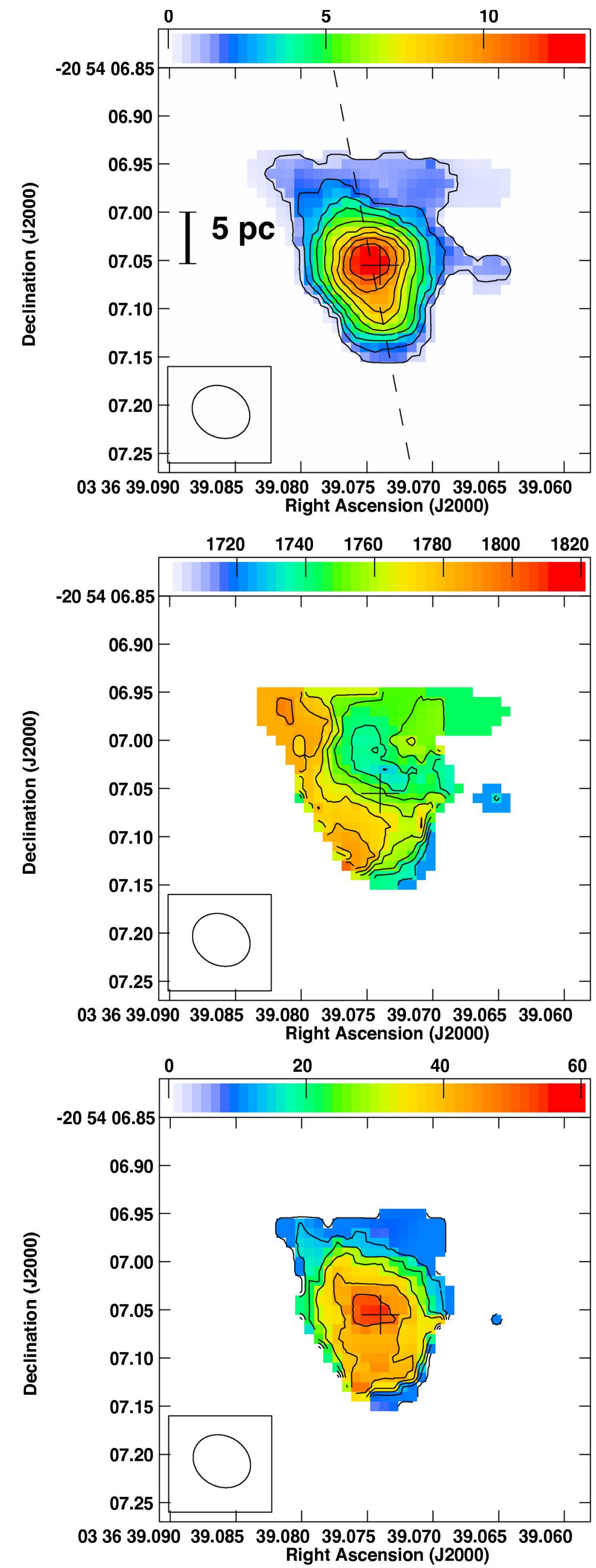
CO J=6—>5 because lower J lines are optically thick, temperature high enough to populate J=6 (and above).

Dispersion ~ 60 km/s at ~ 1pc

total intensity

l-o-s velocity

velocity dispersion



Aalto et al. 2017

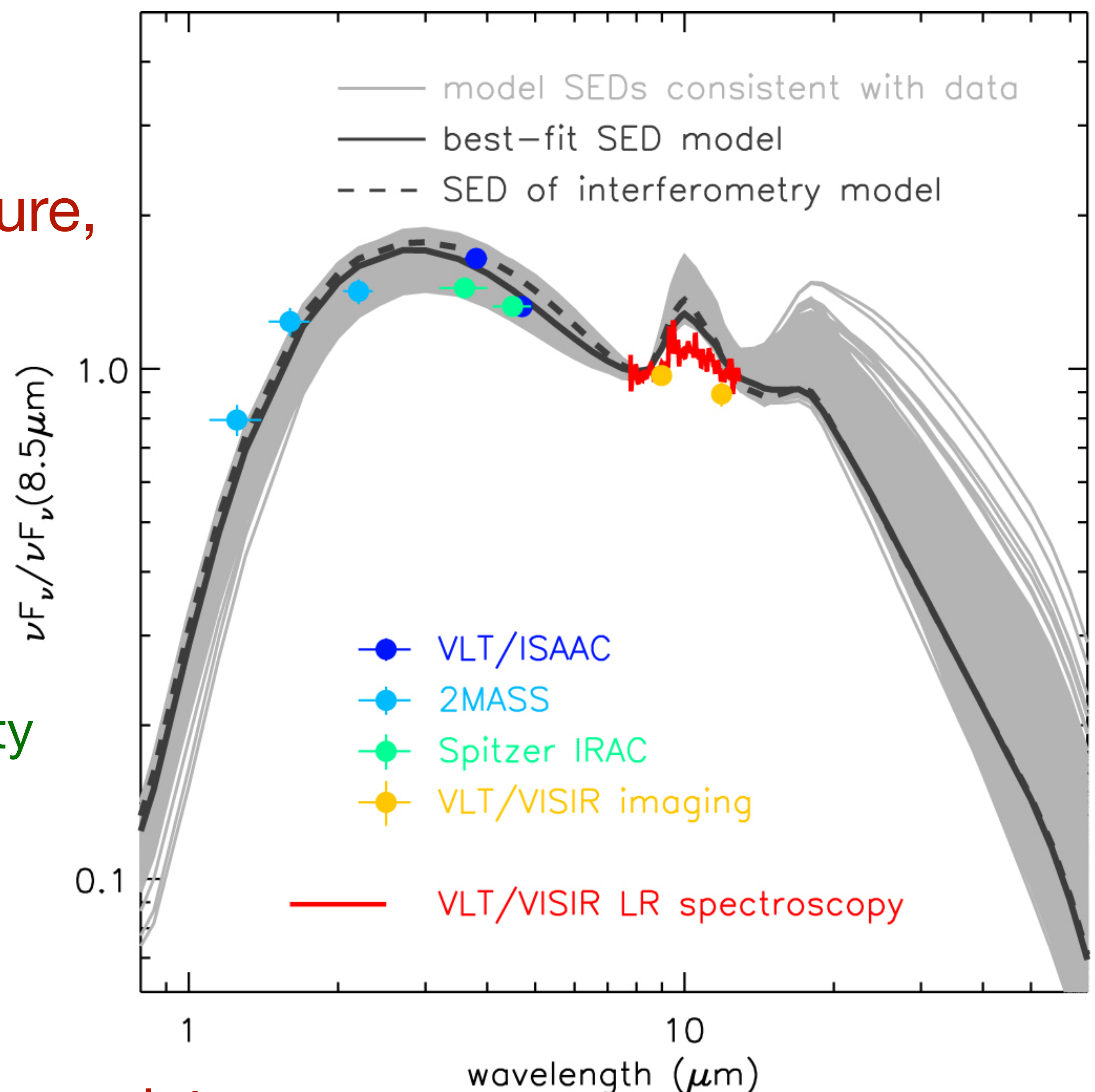
Tools

IR spectra—temperature, optical depth, dust composition

Directly demonstrates dust temperature, obscuration area and solid angle

Optical depth obscures interior, must integrate over surface; requires radiation transfer + geometric model for interpretation

E.g., torus with power-law probability density for dust clouds with Gaussian vertical distribution plus cone with power-law probability density of clouds within some opening angle (Hoenig & Kishimoto 2017)



Leftley et al. 2018

ESO 323-G77

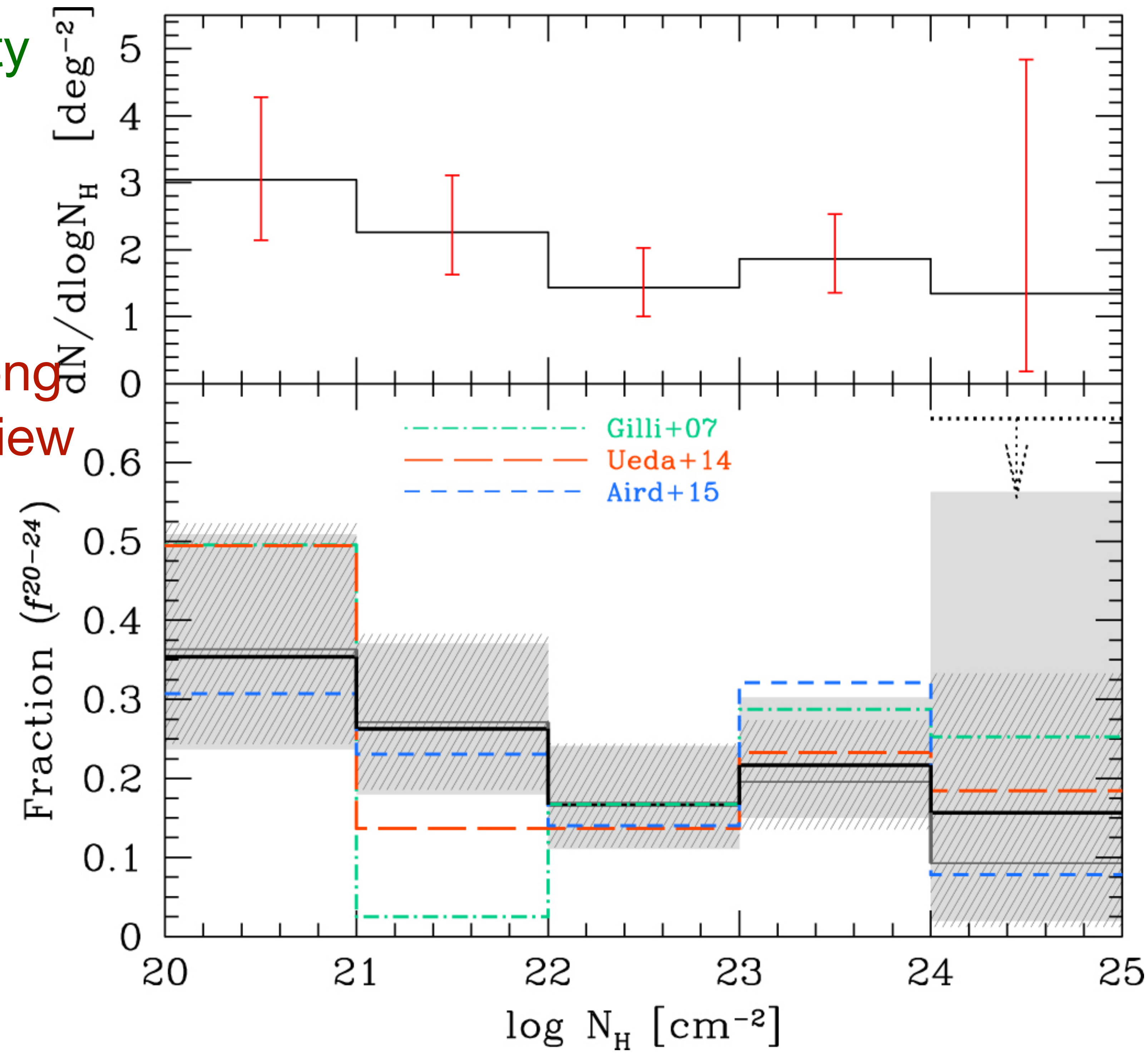
Parameterized models can only show consistency; what is the physical basis of clumping?

Tools

X-ray spectra—column density on individual lines of sight

Broad range suggests either diverse torus densities or strong dependence on direction of view

Principal difficulty is sample selection; X-ray energies observed strongly correlated with N_H



Zappacosta et al. 2018

Dynamics

- Fundamental problem—

N(1)/N(2) —> H/R ~ 1, but in hydrostatic equilibrium, c_s/v_{orb} = H/R ~ 1; c_s/v_{orb} ~ 1 implies temperatures much too high for dust to survive

- Possible alternatives—

  > clumped gas, supersonic random motions

  > torus is dynamic, not static—but how, exactly?

  > support from magnetic fields?

  > support from radiation force?

  thermal IR dust opacity ~ 20—30 x Thomson

  —> L/L_E >~ 0.1 —> dynamically significant F_{rad}

  > H/R ~ 1 applies in places, but not everywhere

  > instead of H/R ~ 1, the disk is warped

Simulations: The Contemporary Gateway to Dynamics

Much physics necessary for a complete description:

MHD (magnetic pressure support, angular momentum transport, outflows)

Radiation transport and forces (gas equation of state, vertical support, outflows)

Photoionization; dust sublimation, spallation (defining the inner edge and dynamics within the hole)

Implementing any one of these, much less all of them self-consistently, is impossible with analytic methods.

Some Conceptual Results from Simulations

- Fat orbiting structures in dynamical equilibrium must have sub-Keplerian angular momentum

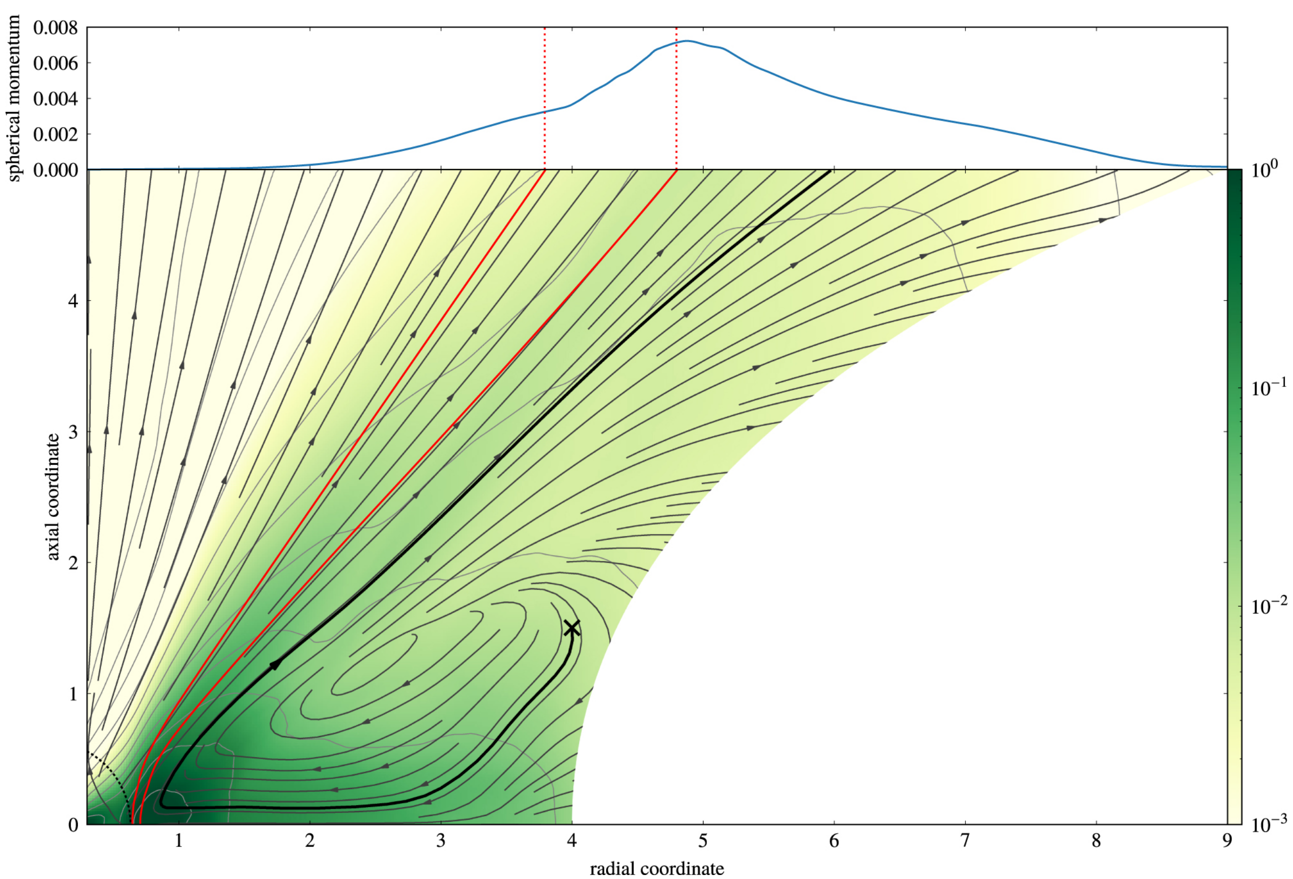
  Pressure great enough for $H/R \sim 1$ implies energy density $\sim \rho\, v_{orb}^2$;

  if isotropic, this pressure substitutes for rotational support

Some Conceptual Results from Simulations

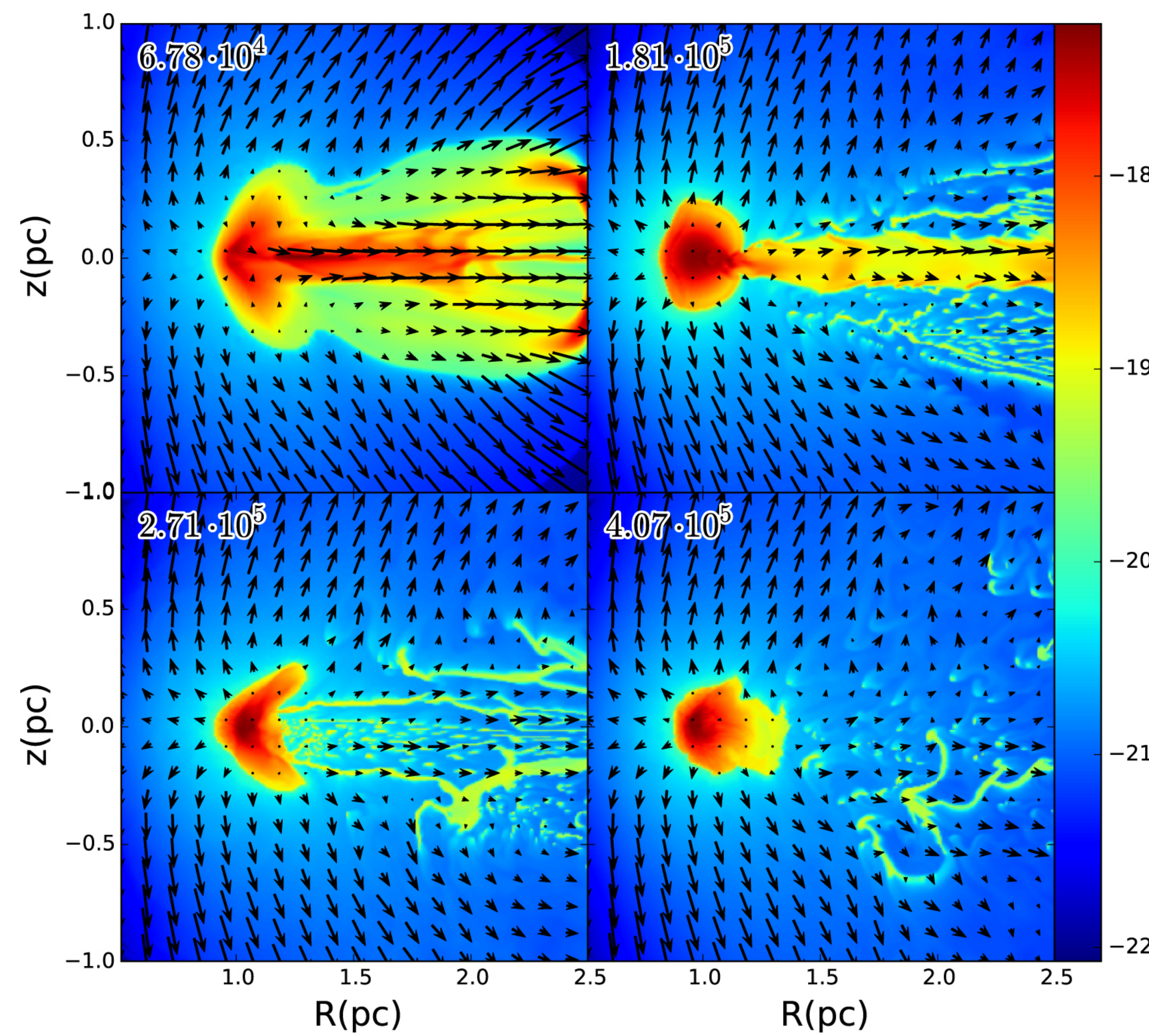
- Radiation-driven wind along the torus inner edge almost inescapable; neutral column density ~1 IR optical depth

UV and IR radiation force on dust



Chan & K. 2017

photoionization heating



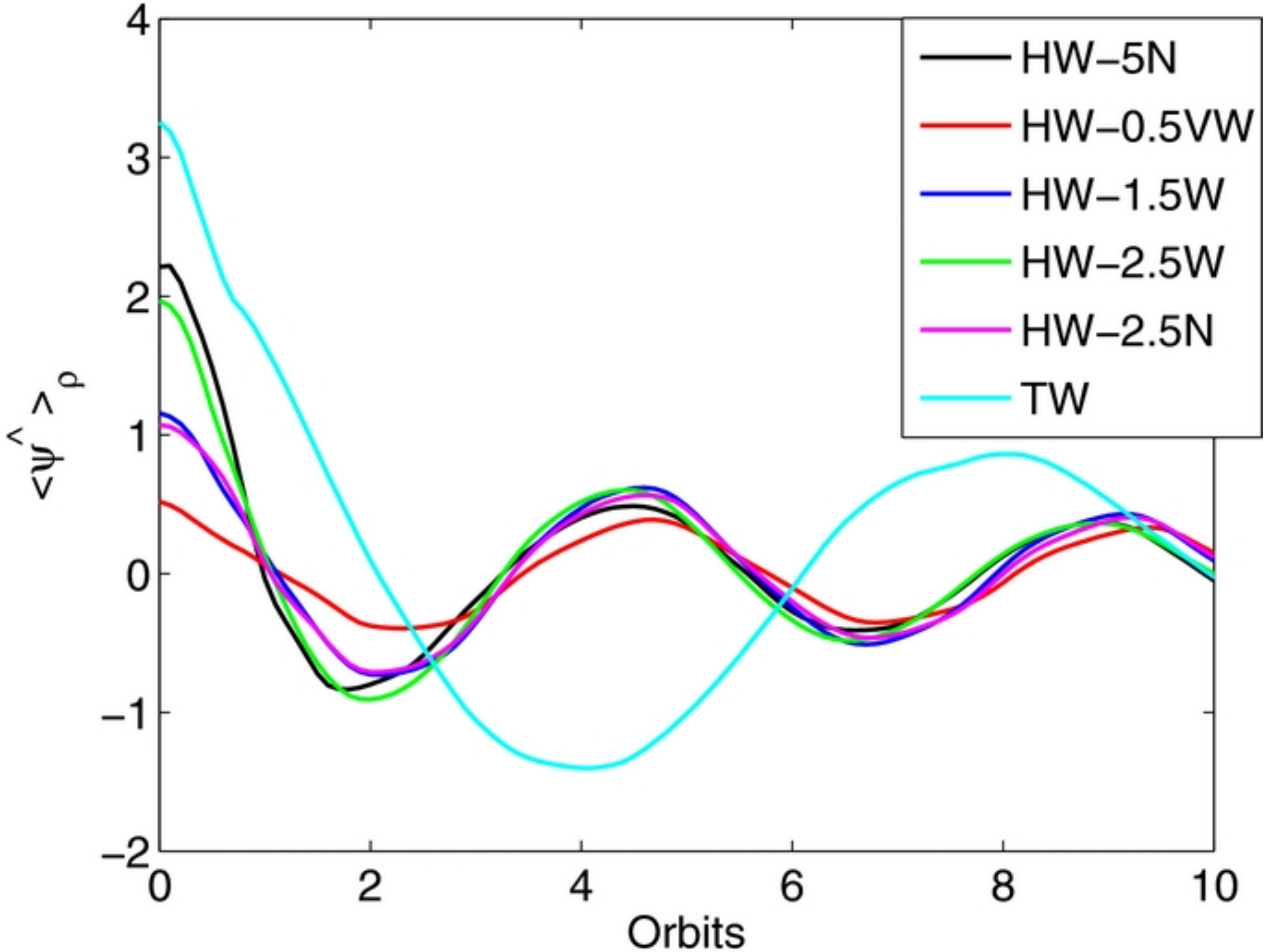
Dorodnitsyn & Kallman 2016

Some Conceptual Results from Simulations

- Warps must be maintained

Warps in disks —> radial pressure gradients —> transonic radial flows —> angular momentum mixing —> flattening on an orbital timescale

$$\hat{\psi} \equiv |\partial \hat{\ell} / \partial \ln r| / (h/r)$$



Sorathia et al. 2013

Origin and Fate of Torus Material

- What is the source?

  interstellar clouds from surrounding ISM on elliptical orbits?

  smooth(er) flow made from merged stellar winds?

  Cf. Bondi accretion rate ~ 80 n_4 Δv_{40}^{-3} M_7 $M_\odot$/yr

- What holds back (or retards) the inflow to build up the observed large column densities?

  Is it angular momentum-limited?

- Where does the matter go after passing through the torus inner edge?

What fraction exits in a wind, and is it fully unbound? Is it the X-ray warm-absorber?

Where does the captured fraction go, and in what state?

Is there a feedback loop (with an inflow-timescale delay) between captured torus matter and "evaporation" from the torus inner edge?

Conclusions

For the participants of this meeting to determine!