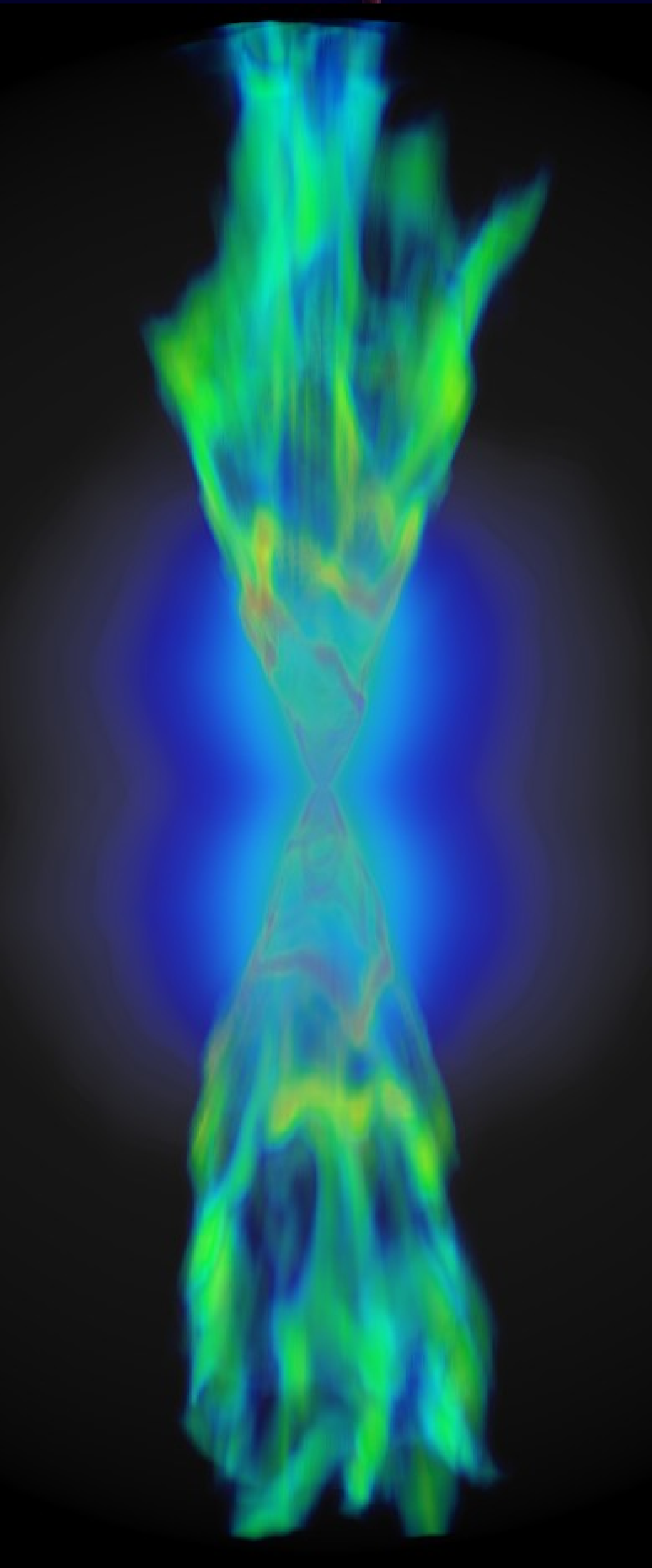
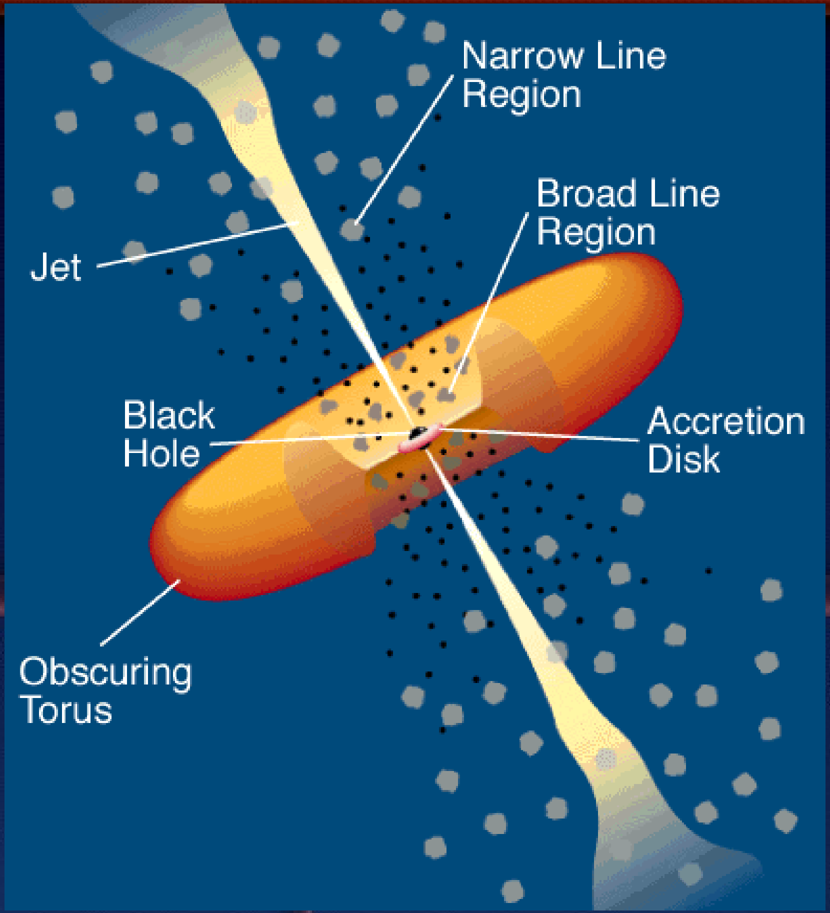


Large-Scale Radiation-Driven Outflows in Active Galactic Nuclei

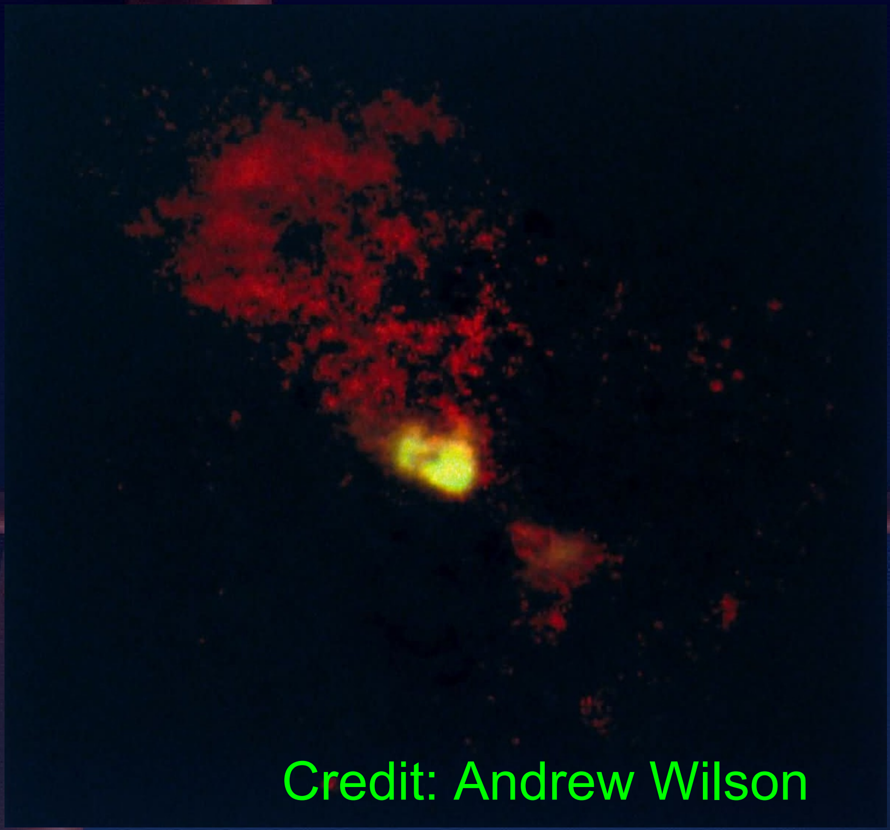
Ryuichi Kurosawa (Cornell)

Collaborator: Daniel Proga (UNLV)

Narrow Line Region (NLR)

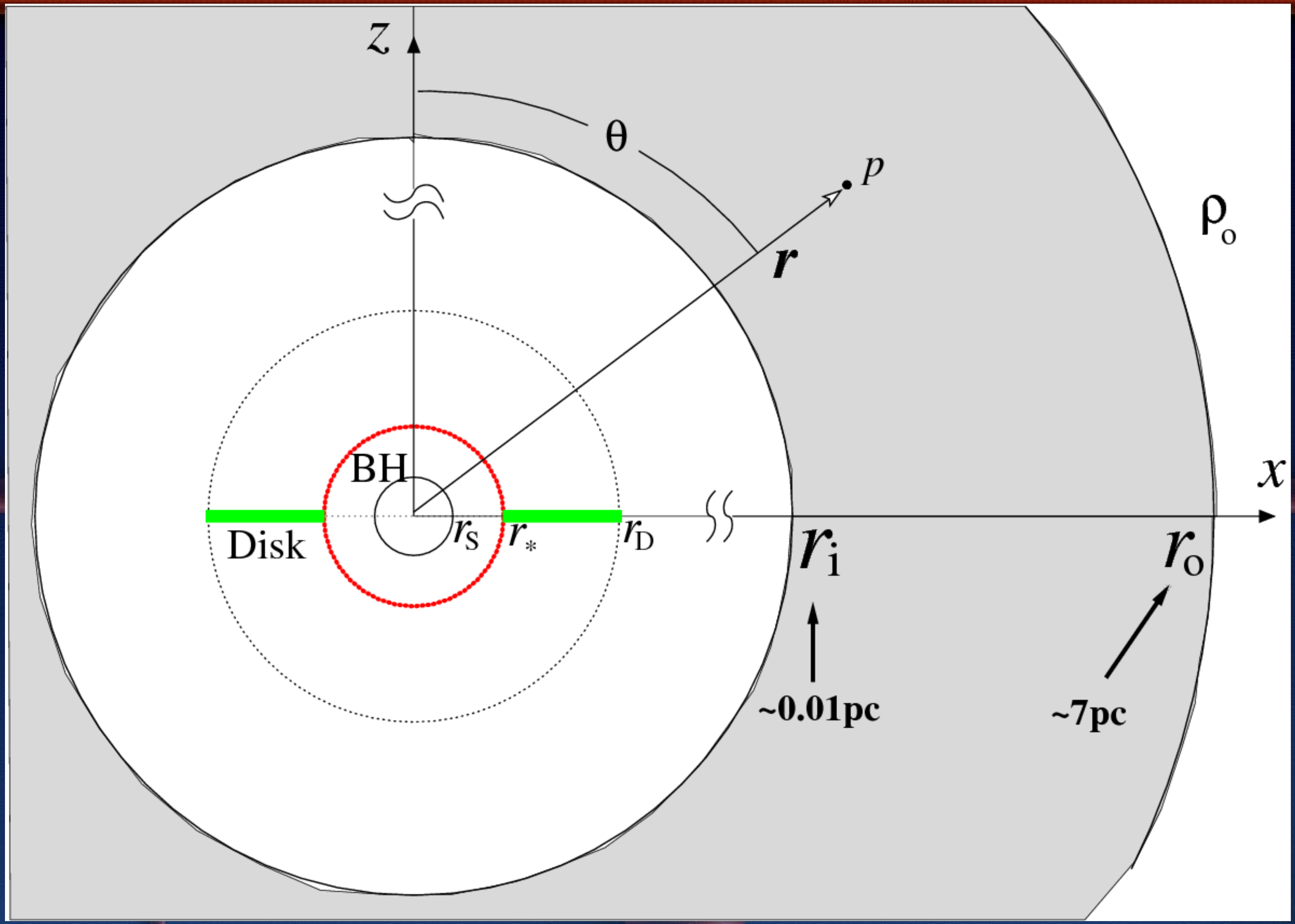


Bi-conical flow in NGC5728, Seyfert 2 (HST)



- Narrow line emitting clouds located at large distances (1--100 pc)
- Lower density, lower velocity compared to Broad Line Region (BLR)
- Clouds in bi-cone outflow are illuminated and photoionized by strong radiation source at center.
- Kinematics and ionization state give a hint for what is powering the wind!

Model Configuration



- Radiation source 1. X-ray emitting spherical corona region (RED)
- Radiation source 2: UV emitting flat accretion disk (GREEN)
  - has ~ |cosϴ| dependency (geometrical foreshortening)

Model: Equations

$$\frac{D\rho}{Dt} + \rho \boldsymbol{\nabla} \cdot \boldsymbol{v} = 0, \quad (1)$$

$$\rho \frac{D\boldsymbol{v}}{Dt} = -\boldsymbol{\nabla} P + \rho \boldsymbol{g} + \rho \boldsymbol{g}_{\mathrm{rad}}, \quad (2)$$

$$\rho \frac{D}{Dt}\left(\frac{e}{\rho}\right) = -P \boldsymbol{\nabla} \cdot \boldsymbol{v} + \rho \mathcal{C}, \quad (3)$$

where ρ, e, P and $\boldsymbol{v}$ are the mass density, energy density, pressure, and the velocity of gas respectively. Also, $\boldsymbol{g}$ is the gravitational force per unit mass. The Lagrangian/co-moving derivative is defined as $D/Dt \equiv \partial/\partial t + \boldsymbol{v} \cdot \boldsymbol{\nabla}$.

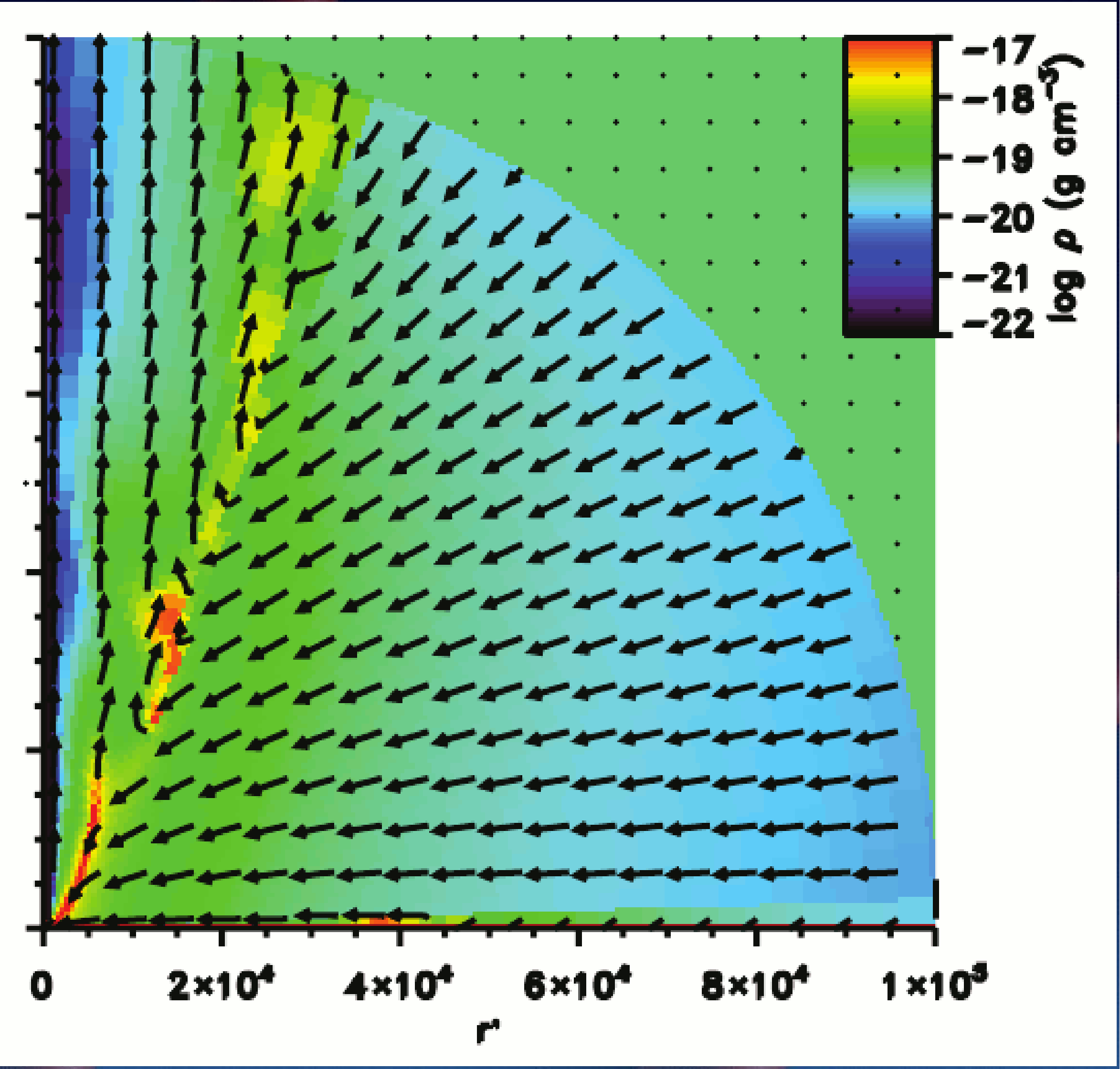
- Added radiation force (g_{rad}) and radiative cooling ($\mathcal{C}$) terms.
- Use ZEUS-MP (Eulerian hydro code) for numerical simulations (e.g. Hayes et al. 2006).

Models Setup

- Mass: $M_{BH}=10^8 M_{sun}$
- Luminosity: $L=2x10^{12}\ L_{sun}$
  - Eddington Ratio: $\Gamma = L/L_{Edd} = 0.6$
- SED: 95% UV (disk) and 5% X-ray (corona)
- Slowly rotating gas enters from outer boundary

Axi-Symmetric Model with Rotation by Proga et al. (2008)

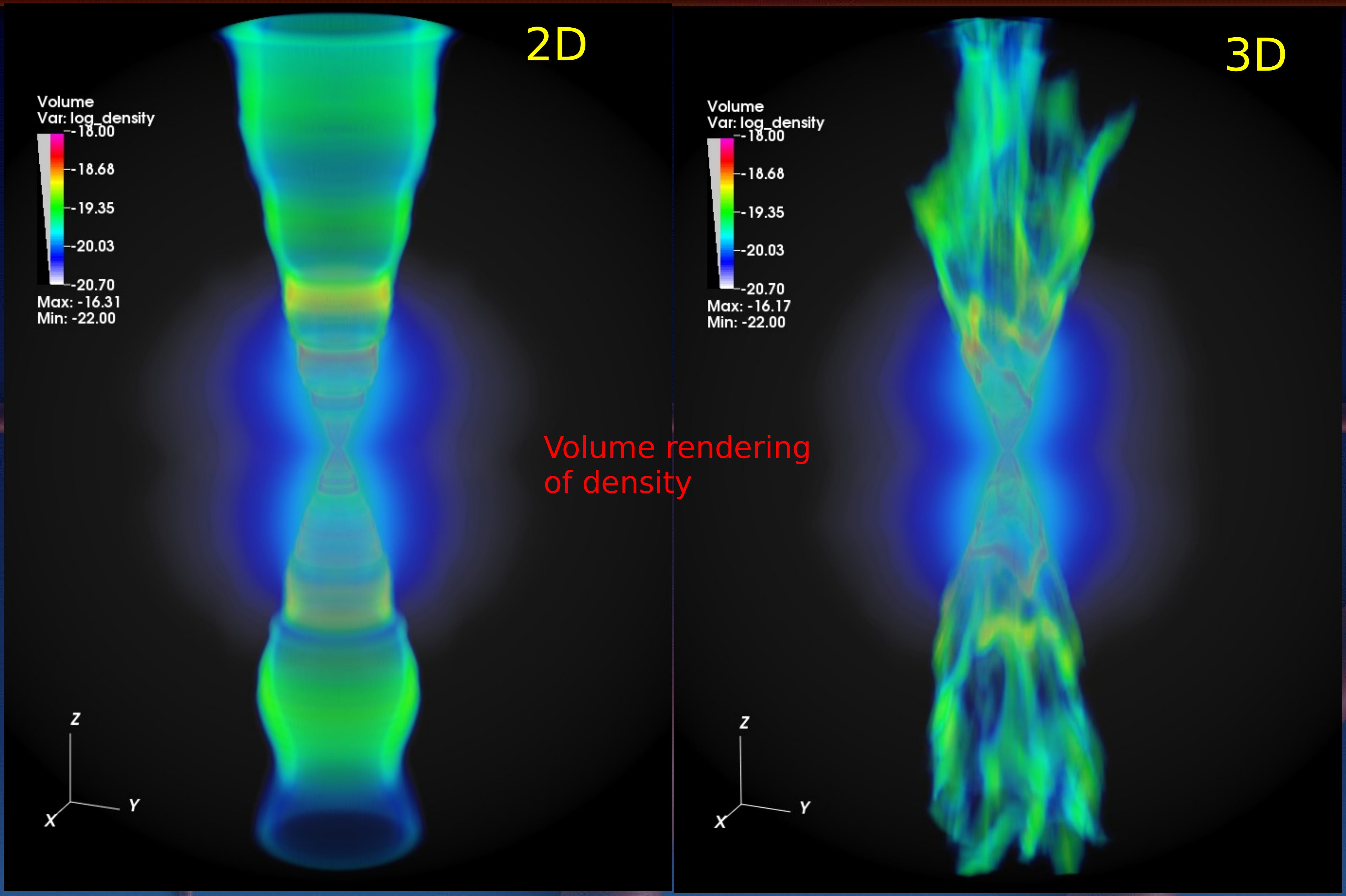
- Found that high density clumpy structures which resembles clouds formed
- The structures moves outward
- This should look like rings (axi-symmetric model)
- The rings stable?
- Clouds in NLR?
- What would happen in 3D simulations?



Movie: 3D Model

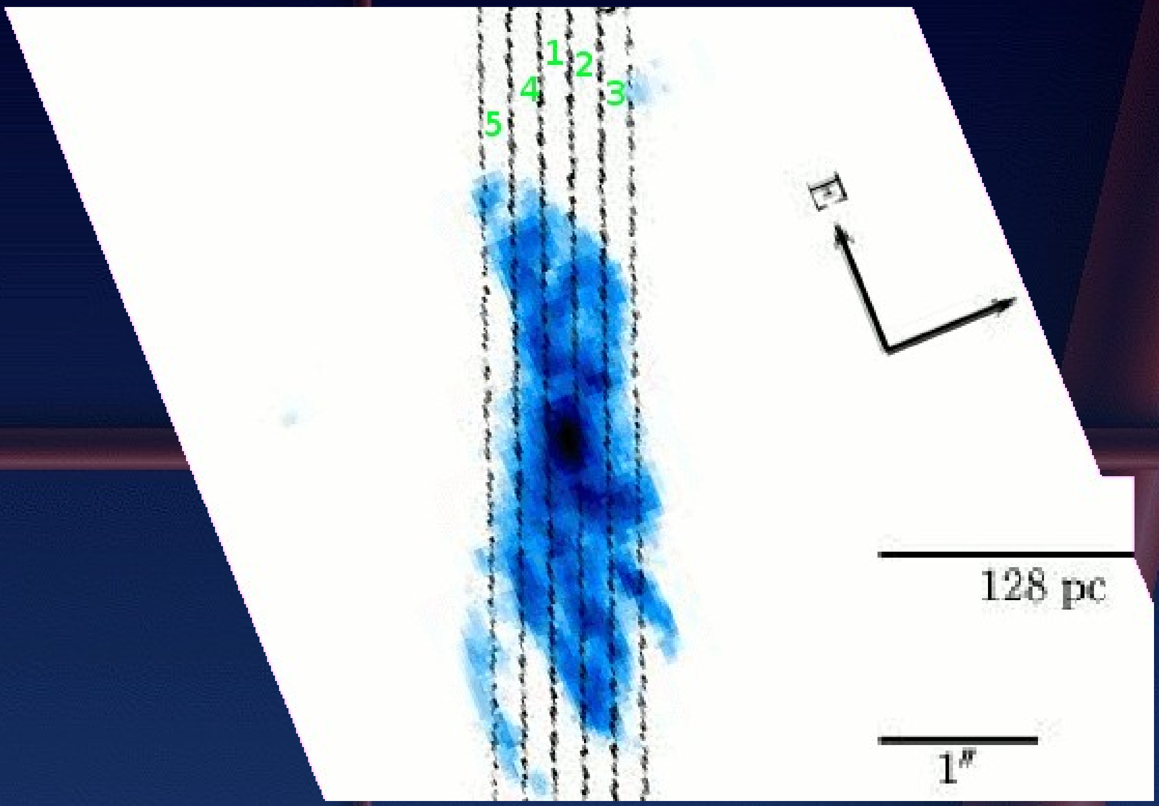
See Kurosawa & Proga (2009, ApJ, 693, 1929) for details.

Bi-Conic Outflows in 2D and 3D Models



- Ring structures seen in 2D break up into pieces in 3D (shear and thermal instabilities) ==> Possible way to form clouds in NRL?

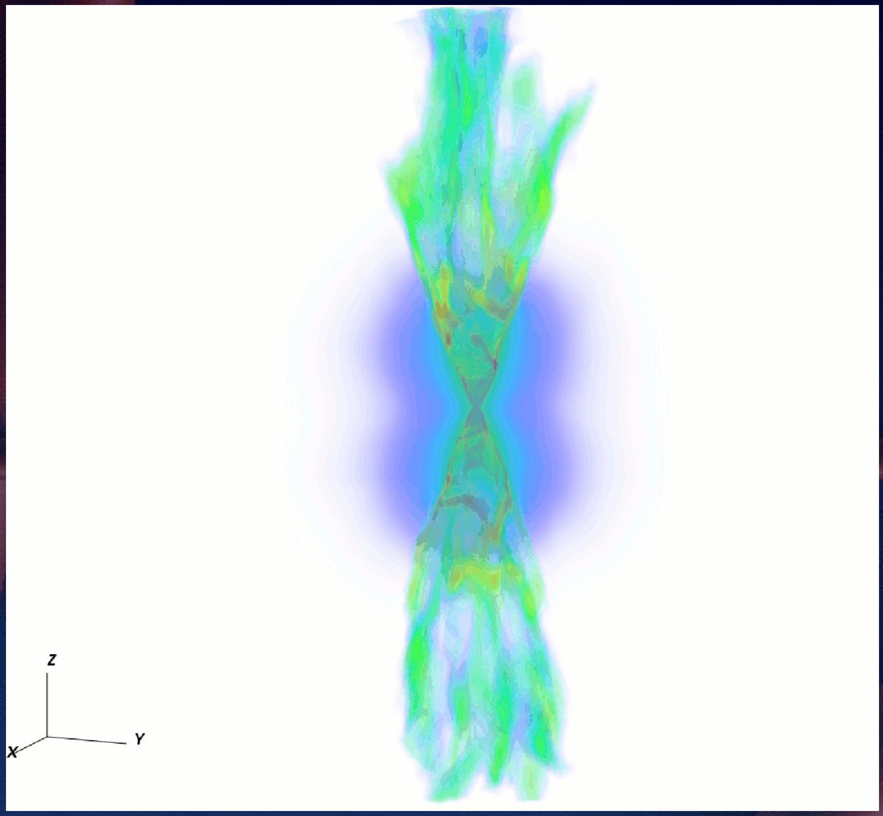
Just for Fun..



Seyfert 2 NGC 4151 in [O III] 5007
HST STIS Observation by Das et al. (2005)

Opening angle ~33°

~14 pc

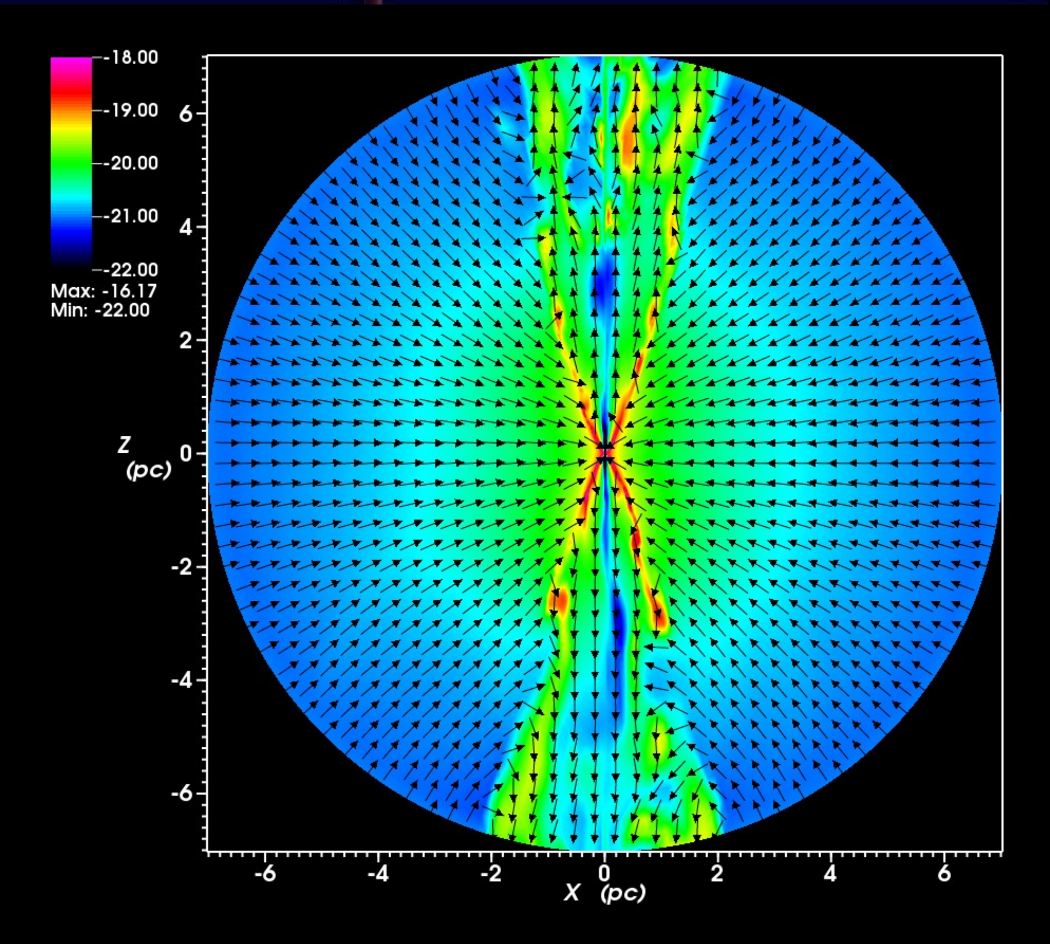


Our model

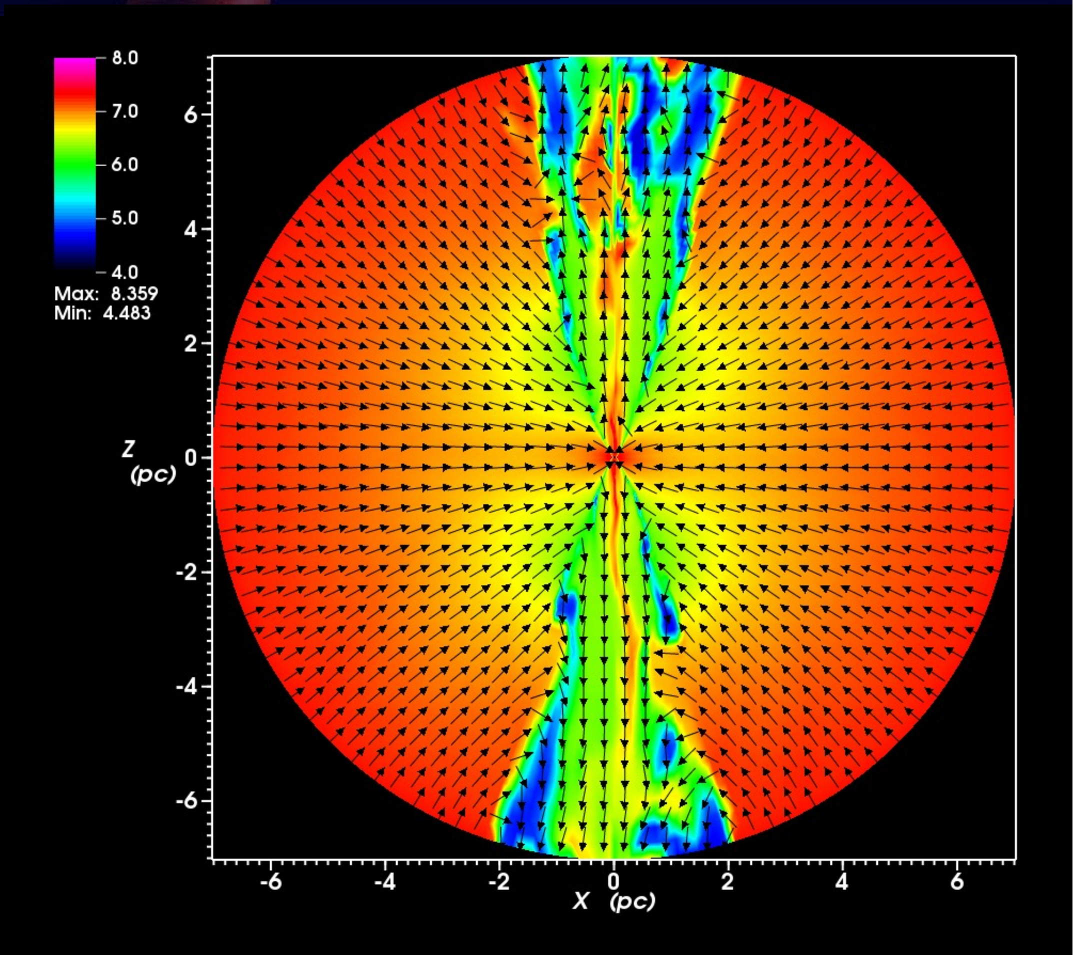
Opening angle ~30°

Density and Temperature Maps

Density

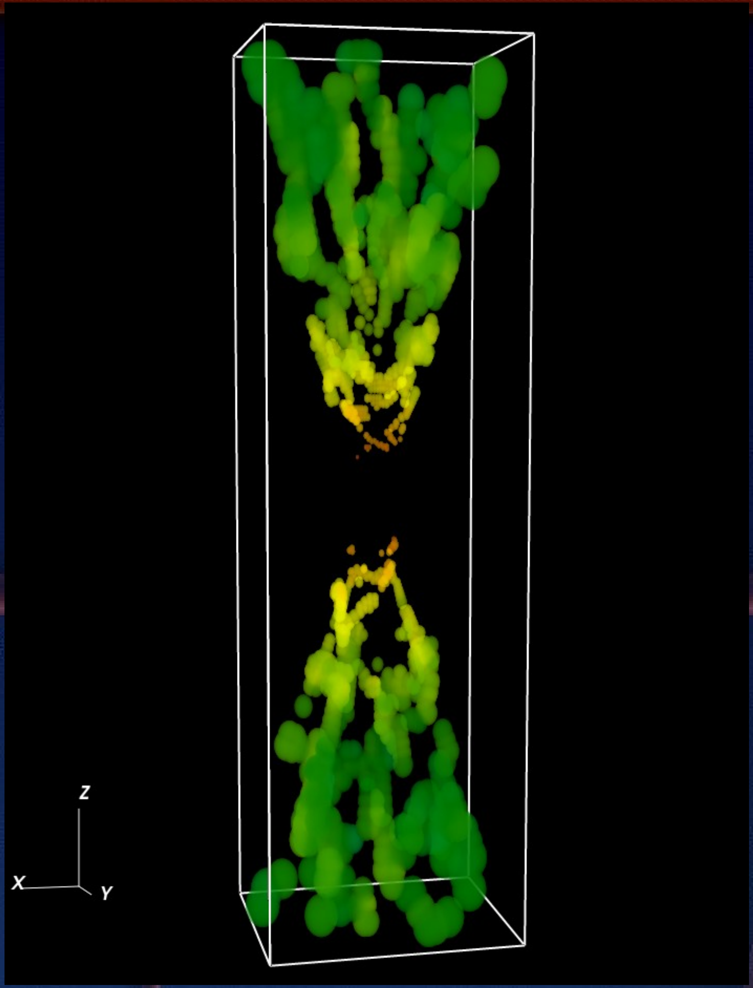


Temperature



- Non-axisymmetry develops.
- High density and low temperature regions => Resembles “cold clouds” in NRL!

Cold Clouds and Virial Mass



- Define "cold clouds": gas with $\rho > 1.6\times10^{-20}$ g cm^{-3} and $T < 1.6\times10^{5}$ K (Similar to observed values of NLR)
- Compare mass estimated from virial theorem with the mass actually used
- $M_{vir} = V^2R/G$

- Found R~3.3 pc, $V \sim 1.4\times10^{4}$ km/s
- $M_{actual} = 1.989\times10^{41}$ g, $M_{vir} = 1.22\times10^{41}$ g → (40% less!)
- Consistent with previous studies: M_{vir} estimated for high Γ (0.6 used here) system underestimates the actual mass! (c.f. Krolik 2001, Marconi et al. 2008)

New Models (back to 2-D)

- Relaxed the assumption of constant accretion luminosity (L_a)
  - ➔ L_a now coupled with mass-inflow rate (at the inner boundary)!
- Study the dependency of the flow on the density at the outer boundary (ρ_o)

Flow Geometry Depends on Γ

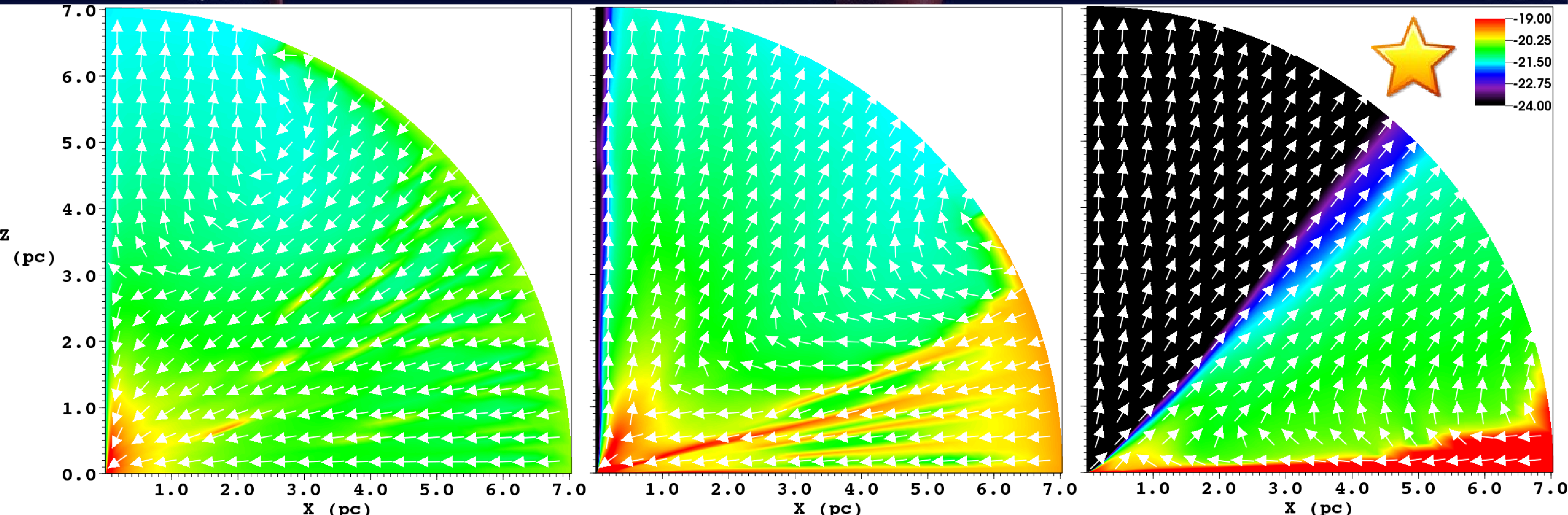
Kurosawa et al. (2009)

Density Maps

Γ=0.3
ρ_o=4x10^{-21} g cm^{-3}

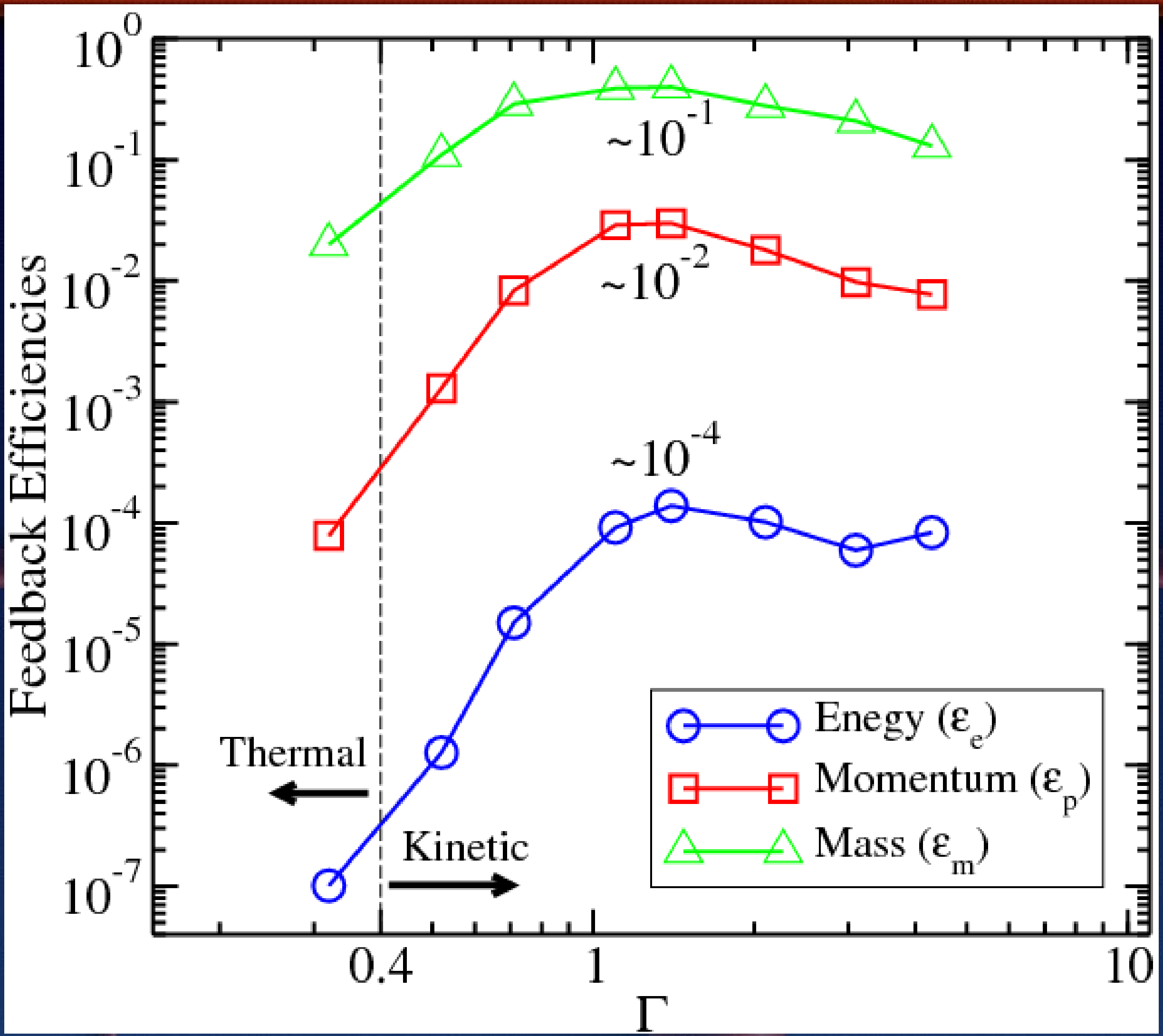
Γ=0.7
ρ_o=2x10^{-20} g cm^{-3}

Γ=4
ρ_o=6.4x10^{-19} g cm^{-3}



- Flow is non-spherical: Inflows near equator and outflow near poles
- As $\Gamma \uparrow$, inflow is squeezed toward equator and outflow widens
- In extreme case (right panel), inflow only occurs near the equator and flow geometry resembles “disk wind”.

Feedback Efficiency (mass, momentum, energy)



- Feedback efficiencies depend on *Γ*

Kurosawa et al. (2009)

- At peak, ~40% of matter will be expelled
- At peak, ~0.1% of accretion luminosity is transfer to the out-flowing gas (too low?)

Feedback Efficiency: Comparisons

Energy

- Others: 5% --- BH Merger Models (e.g. Robertson et al 2006, Sijacki et al. 2007, Di Matteo et al. 2008)
- Ours: $\sim 10^{-5}$ – ~0.1% (depends on Γ)
  - ➔ Due to lack of dust in simulation?
  - ➔ Other feedback machanism is more important? (MHD jet, star formation, supernovae?)

Mass

- Others:
  - 2 – 5% --- X-ray warm absorber (Krongold et al. 2007: NGC 4051 [Seyfert 1])
  - > 8% or >40% – X-ray warm absorber (Krongold et al. 2010: NGC 5548 [Seyfert 1])
- Ours: ~1% – ~40% (depends on Γ)

Conclusion

1. The rings structures found in the axisymmetic model in Proga et al (2008) is not stable in 3-D likely due to shear and thermal instabilities.

2. The broken pieces of the rings resembles the outflowing cold clouds in the NLR of Seyfert galaxies.

3. Energy feedback efficiency of radiation-driven wind is ~100 smaller than the ones found in the BH mass evolution models.

4. Mass feedback efficiency (~10%) found here is consistent with the observations (warm absorber studies).