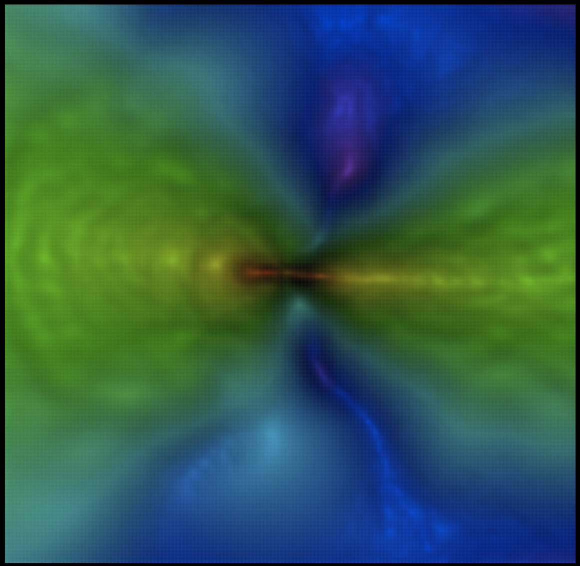
Radiation Pressure on the Dusty Torus

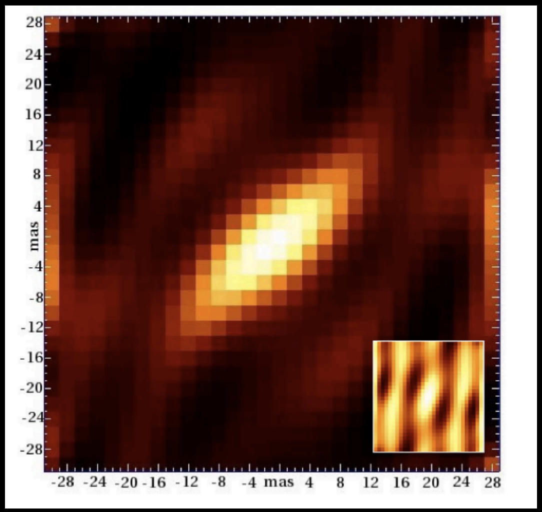


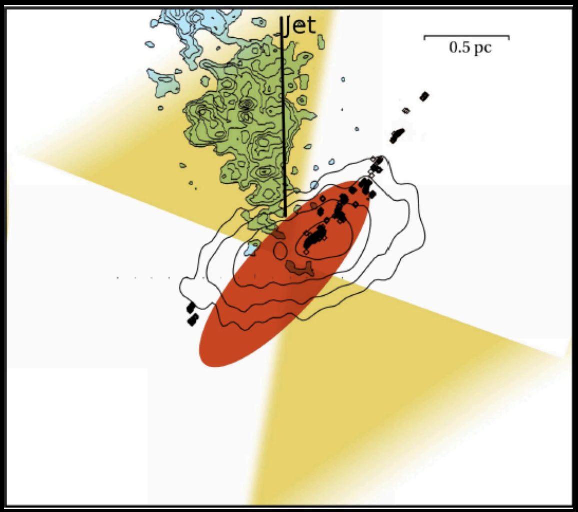
Nathaniel Roth

Daniel Kasen, Phil Hopkins, Eliot Quataert

Evidence for the Torus

- Direct observations: NGC 1068 (Jaffe+ 2004 and follow-ups)





Raban+ 2009

- Unified AGN model; Abundance of Type 2 quasars (e.g. Reyes+ 2008)

Goal – Quantify role of dust radiation pressure in feedback on torus and galaxy

- Torus scale– "dynamic torus" (see also Dorodnitsyn/Bisnovatyi-Kogan/Kallman)
- Galaxy (kpc) scale - move beyond spherically symmetric estimates (Murray+ 2005)

$$F_{\rm rad} = \tau \frac{L}{c} \qquad \tau \approx 10$$

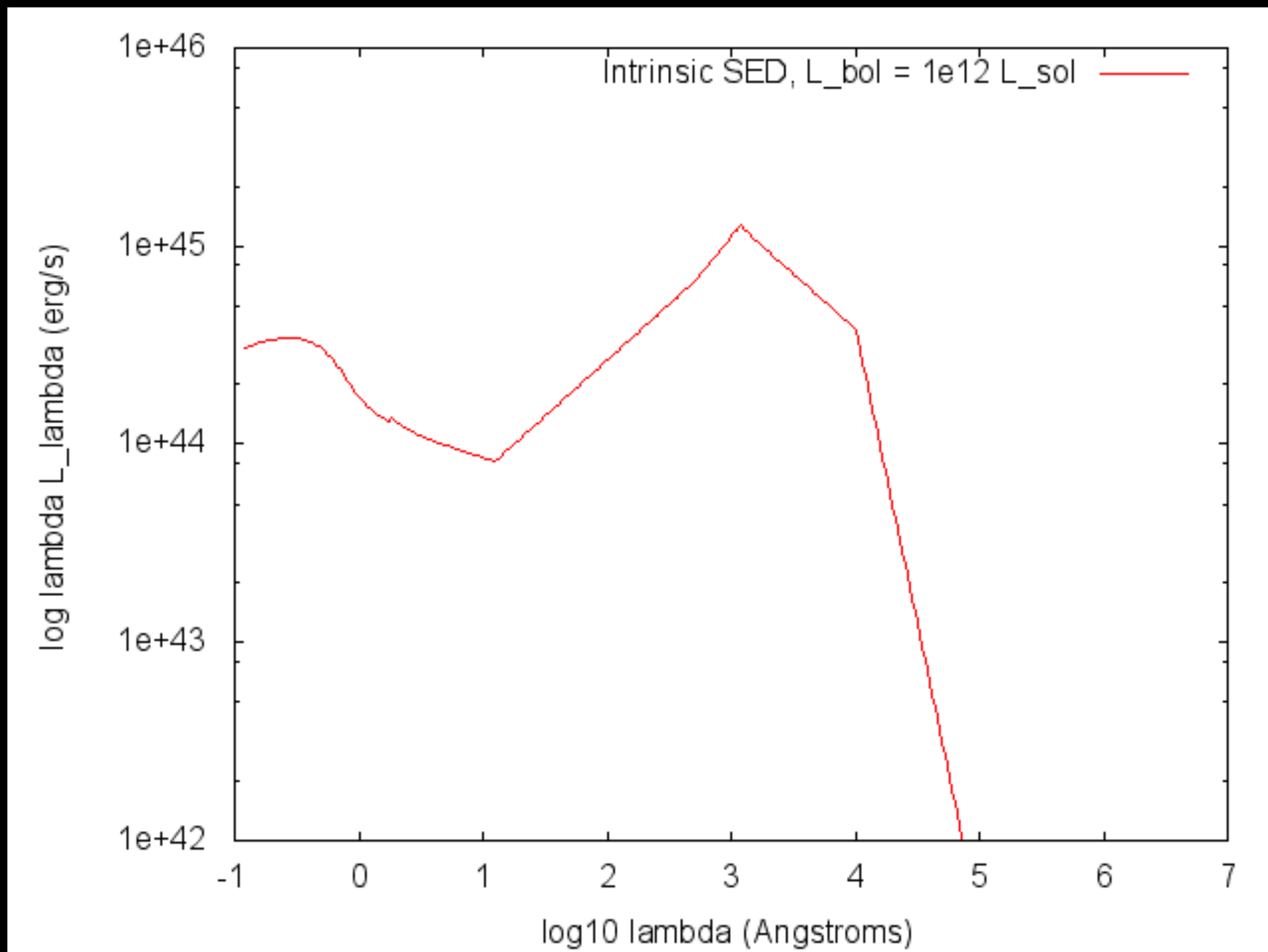
(DeBuhr+ 10)

- Self-consistently determine the value of τ and and its dependence on system parameters, variation with polar angle

Method

- Monte Carlo radiative transfer (Kasen+ 06)
- Wavelength dependent dust opacities and scattering albedos (Draine+ 03)
- Dust reprocesses UV to IR. IR diffuses out
- Dust temperature calculated iteratively assuming LTE
- Compton scattering of x-rays (Klein-Nishina differential cross-section)

Source SED (versus wavelength)



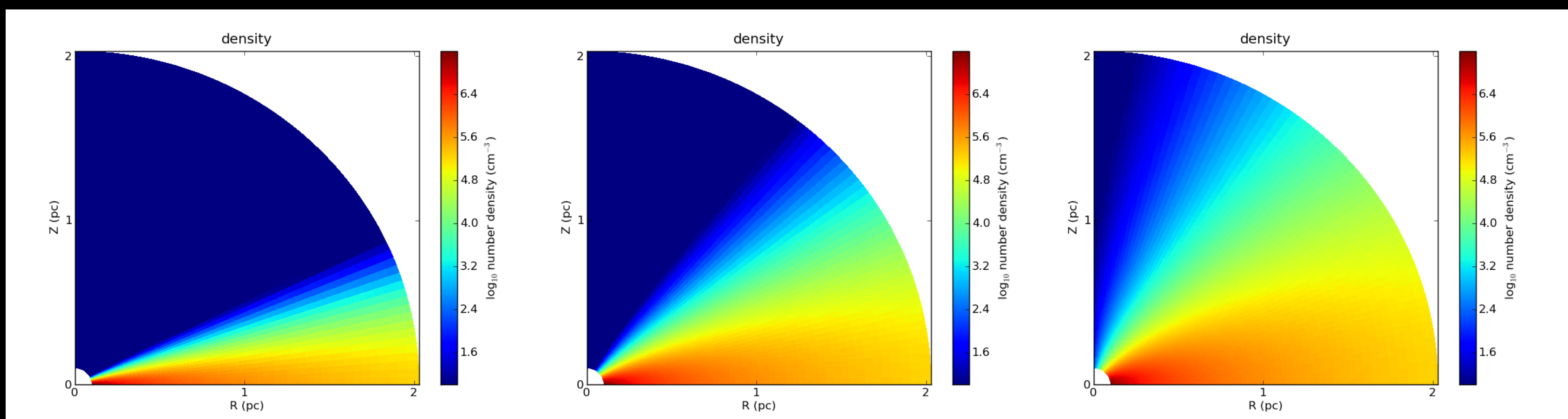
(Marconi+ 04)

Parameterized Torus (Puffy Disk) Models

Not just a donut! See recent work by Dorodnitsyn/Bisnovatyi-Kogan/Kallman, Hopkins/Hayward/Narayan/Hernquist

Log density slices, upper hemisphere, azimuthal symmetry

h/R = 0.1 h/R = 0.2 h/R = 0.3



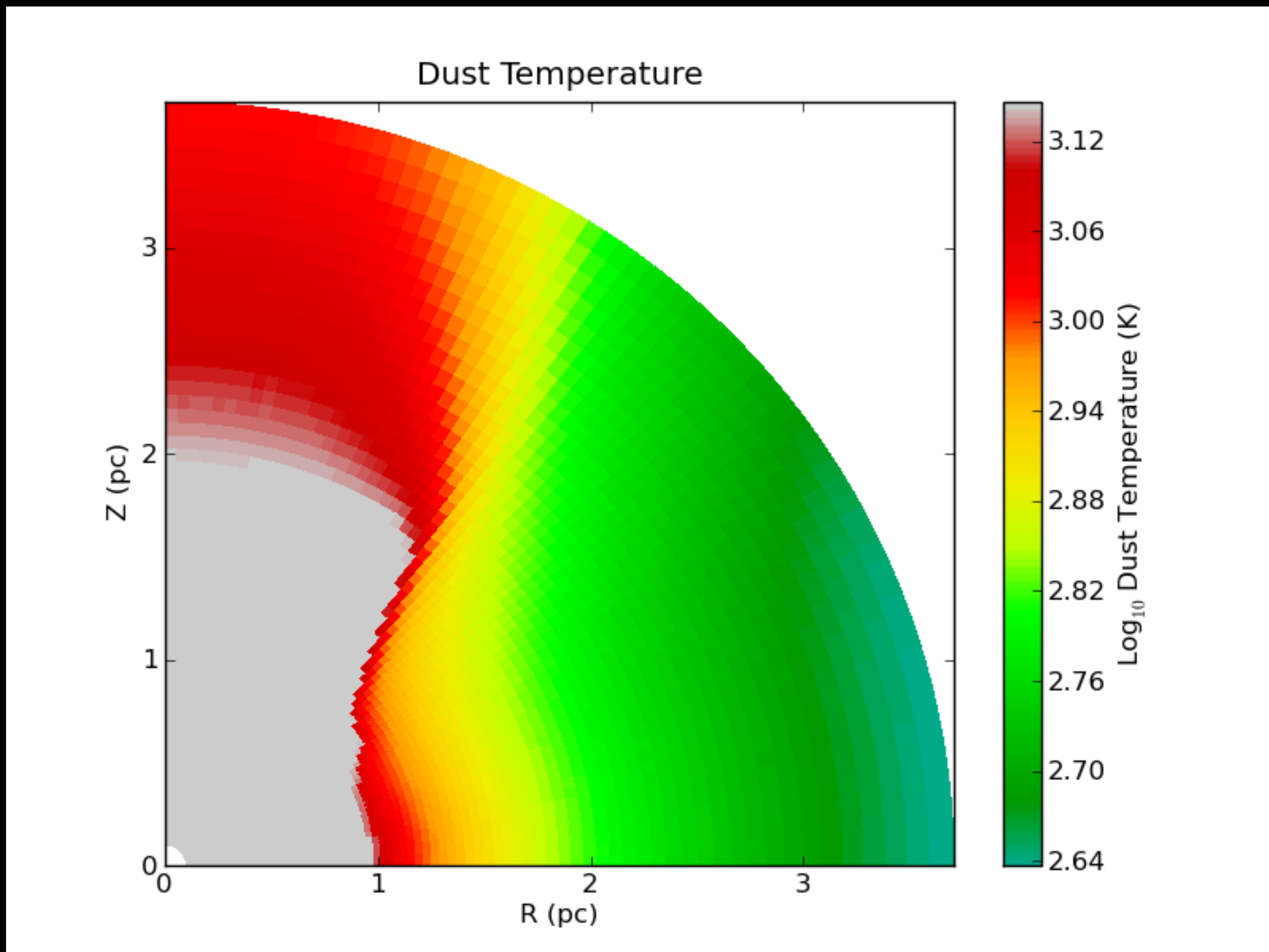
3 pc

$N_H = 10^{25}$ cm^{-2} for all three slices above

Number densities range from ~10^7 to 10 cm^{-3}

Dust Temperature and Sublimation

L/L_{Edd} = 1.0 h/R = 0.3 $M_{BH} = 10^8\ M_{sol}$ $N_H = 10^{25}\ cm^{-2}$



3 pc

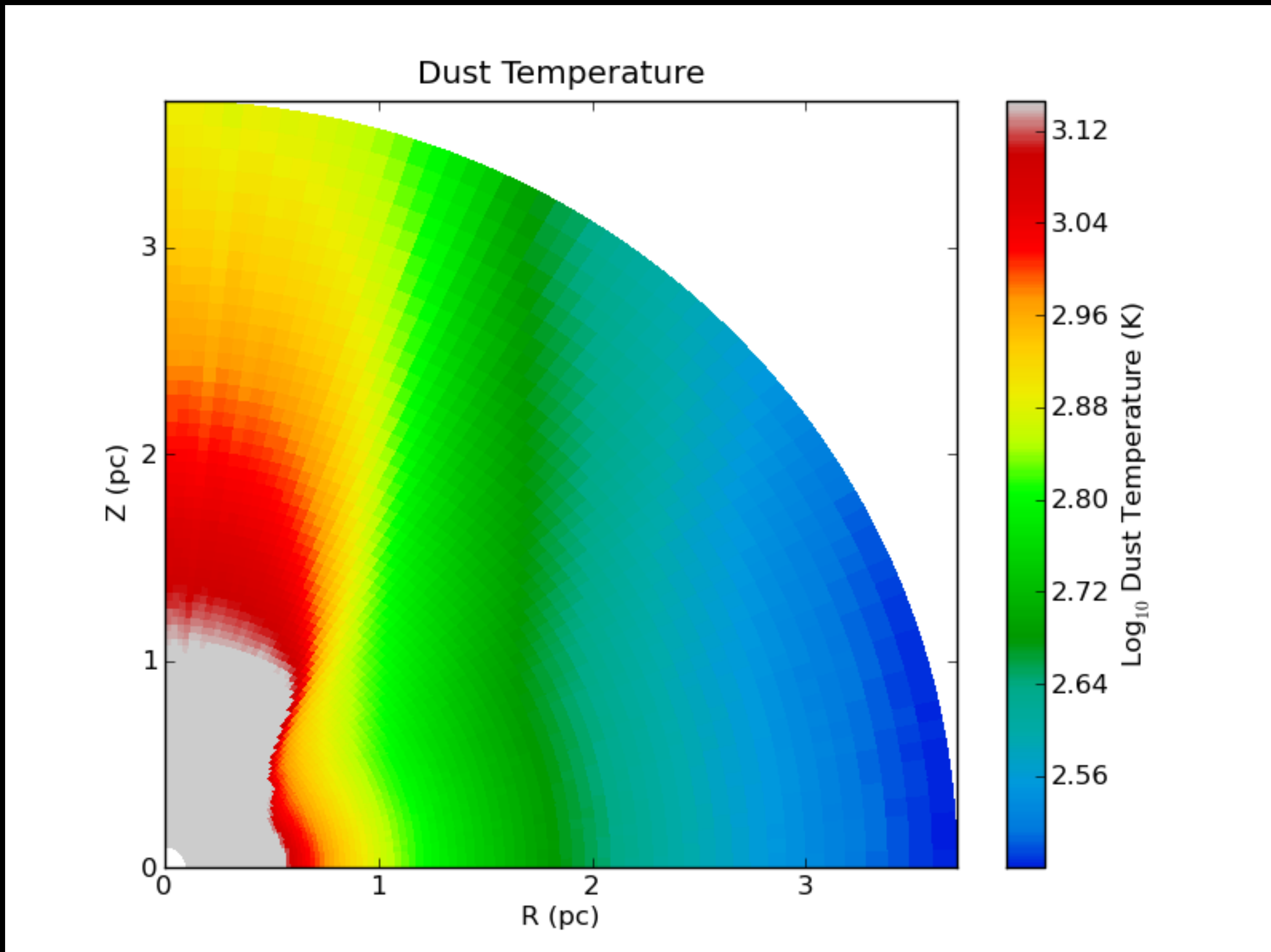
White: > 1400 K

Blue-Green: 430 K

Dust Temperature and Sublimation

$L/L_{Edd} = 0.3$ $h/R = 0.3$ $M_{BH} = 10^8\ M_{sol}$ $N_H = 10^{25}\ cm^{-2}$

3 pc



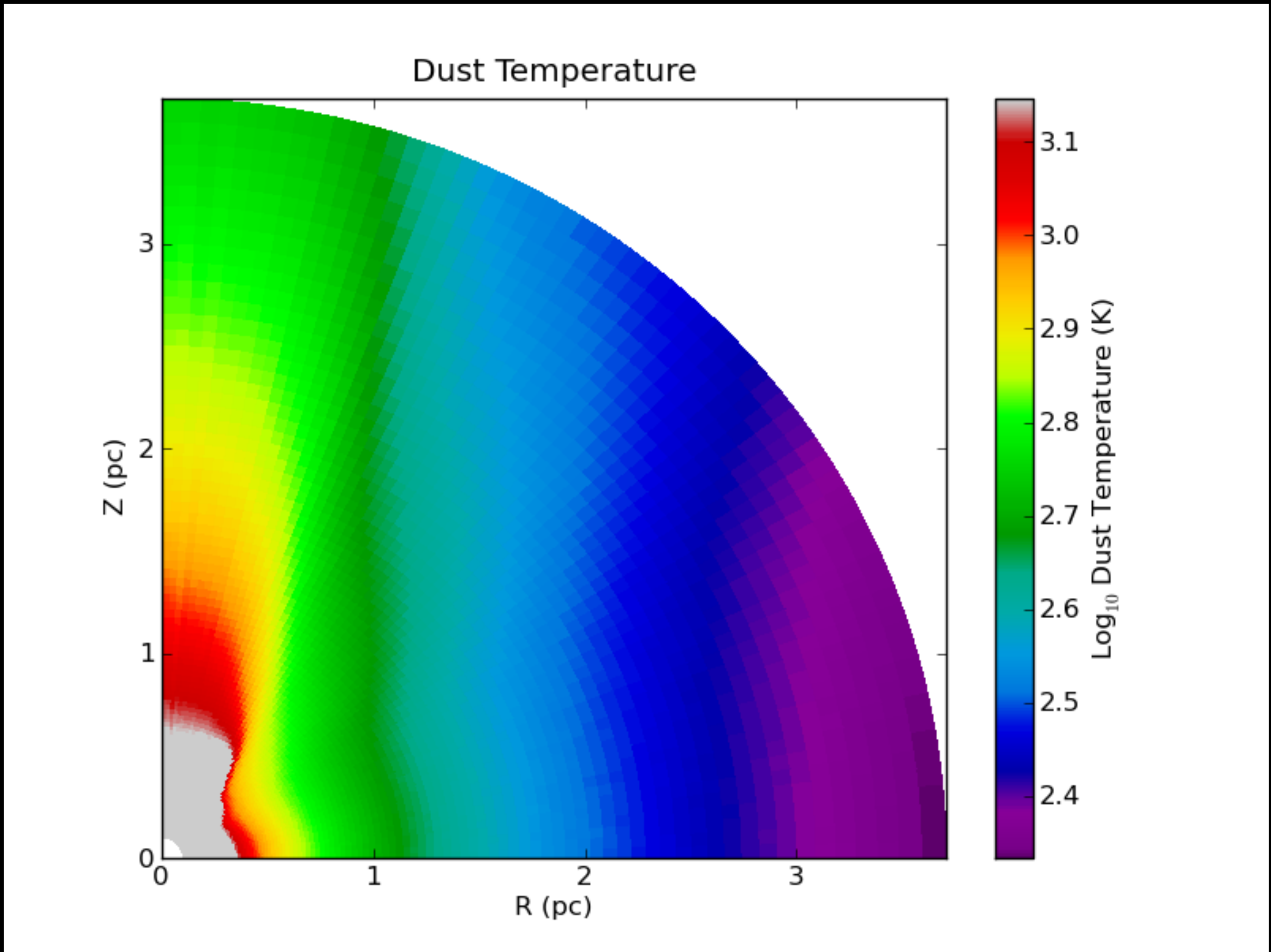
White: > 1400 K

Blue: 300 K

Dust Temperature and Sublimation

$L/L_{Edd} = 0.1$ $h/R = 0.3$ $M_{BH} = 10^8\ M_{sol}$ $N_H = 10^{25}\ cm^{-2}$

3 pc

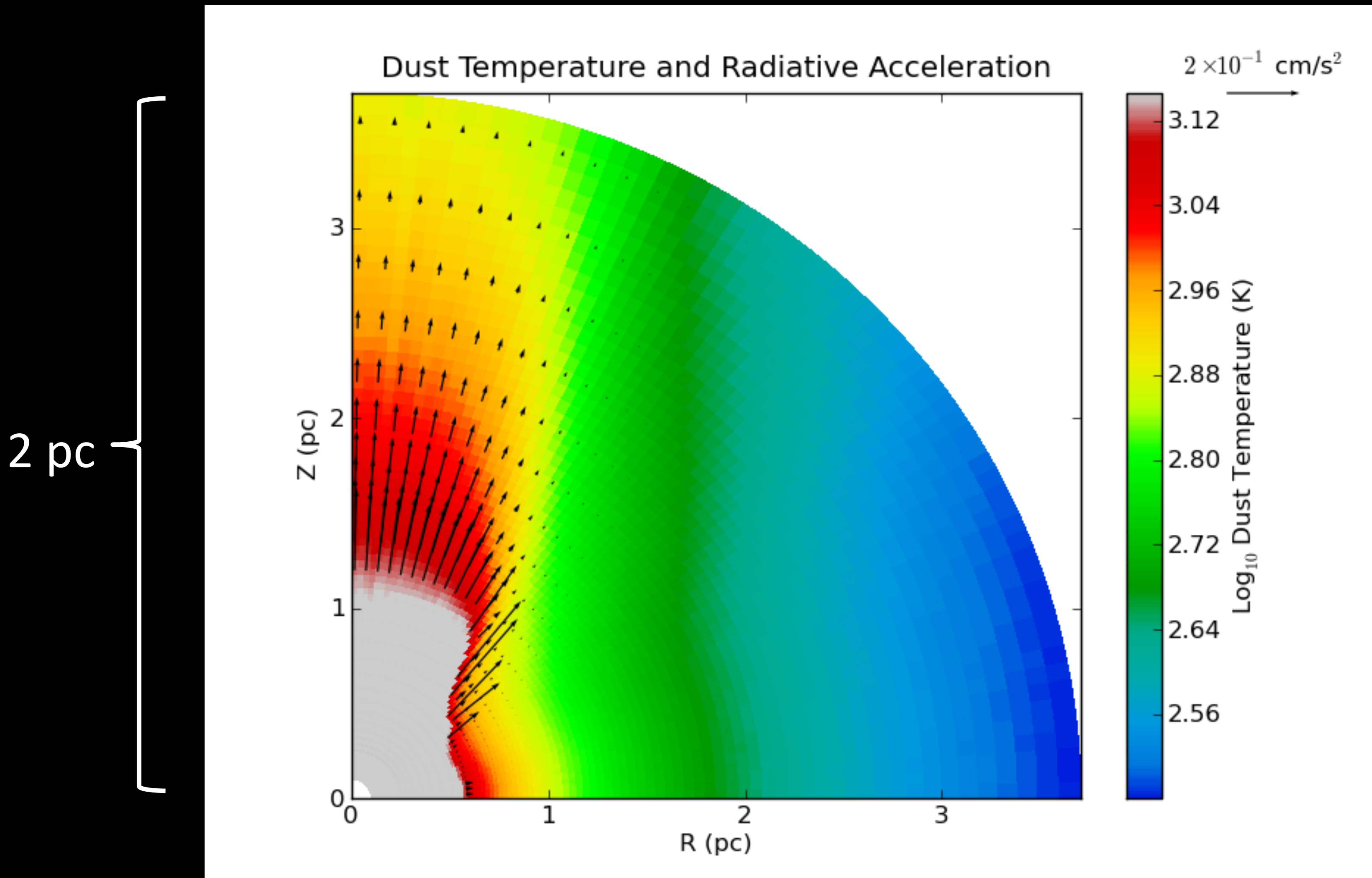


White:
> 1400 K

Violet:
220 K

Acceleration from radiation alone

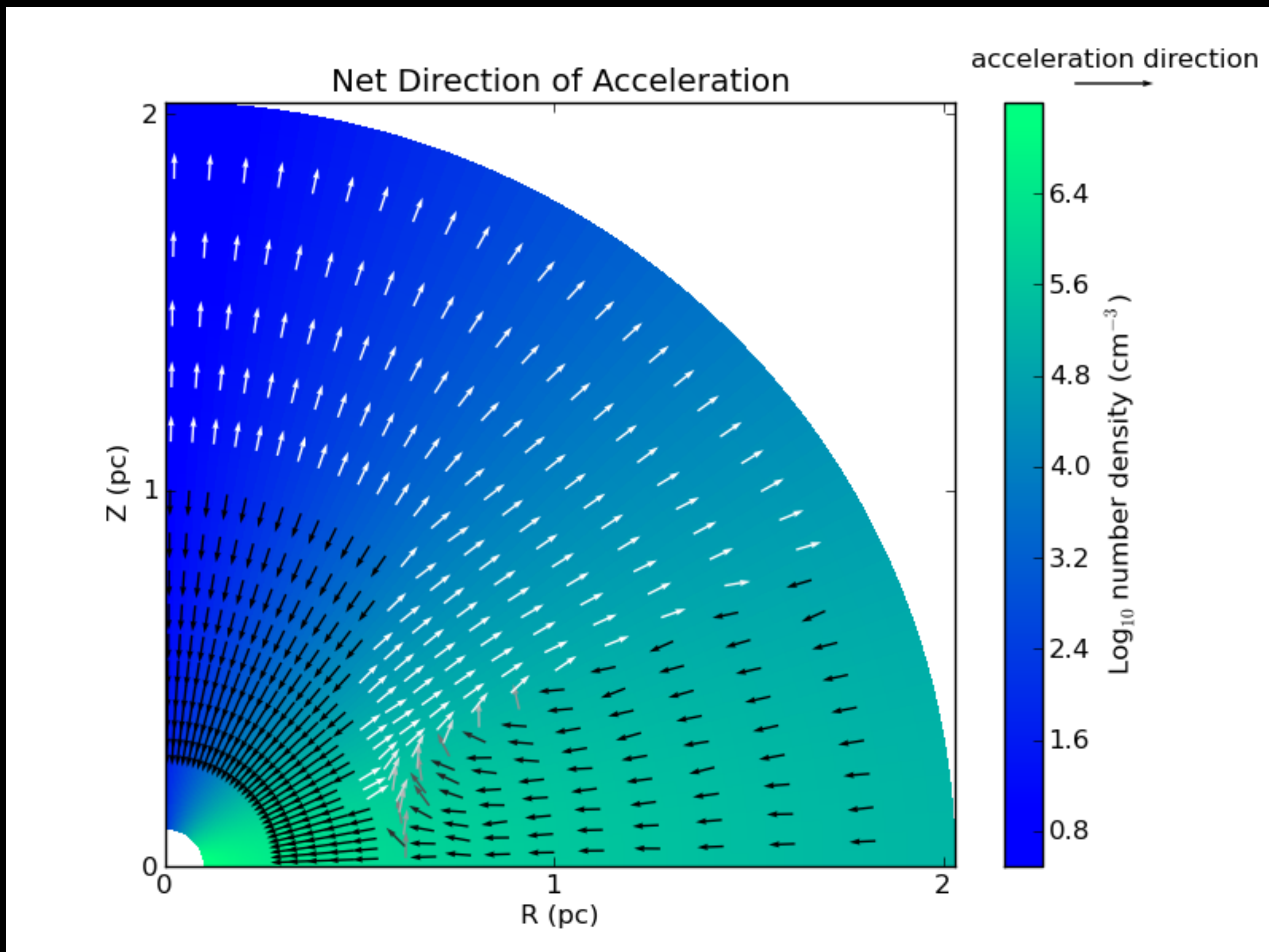
$L/L_{Edd} = 0.3$ $h/R = 0.3$ $M_{BH} = 10^8\ M_{sol}$ $N_H = 10^{25}\ cm^{-2}$



Net direction of acceleration (w/ gravity)

$L/L_{Edd} = 0.3$ $h/R = 0.3$ $M_{BH} = 10^8\ M_{sol}$ $N_H = 10^{25}\ cm^{-2}$

2 pc



Estimating mass ejection rate

- For steady state wind: $$F_{\rm rad} = \dot{M} v_\infty$$

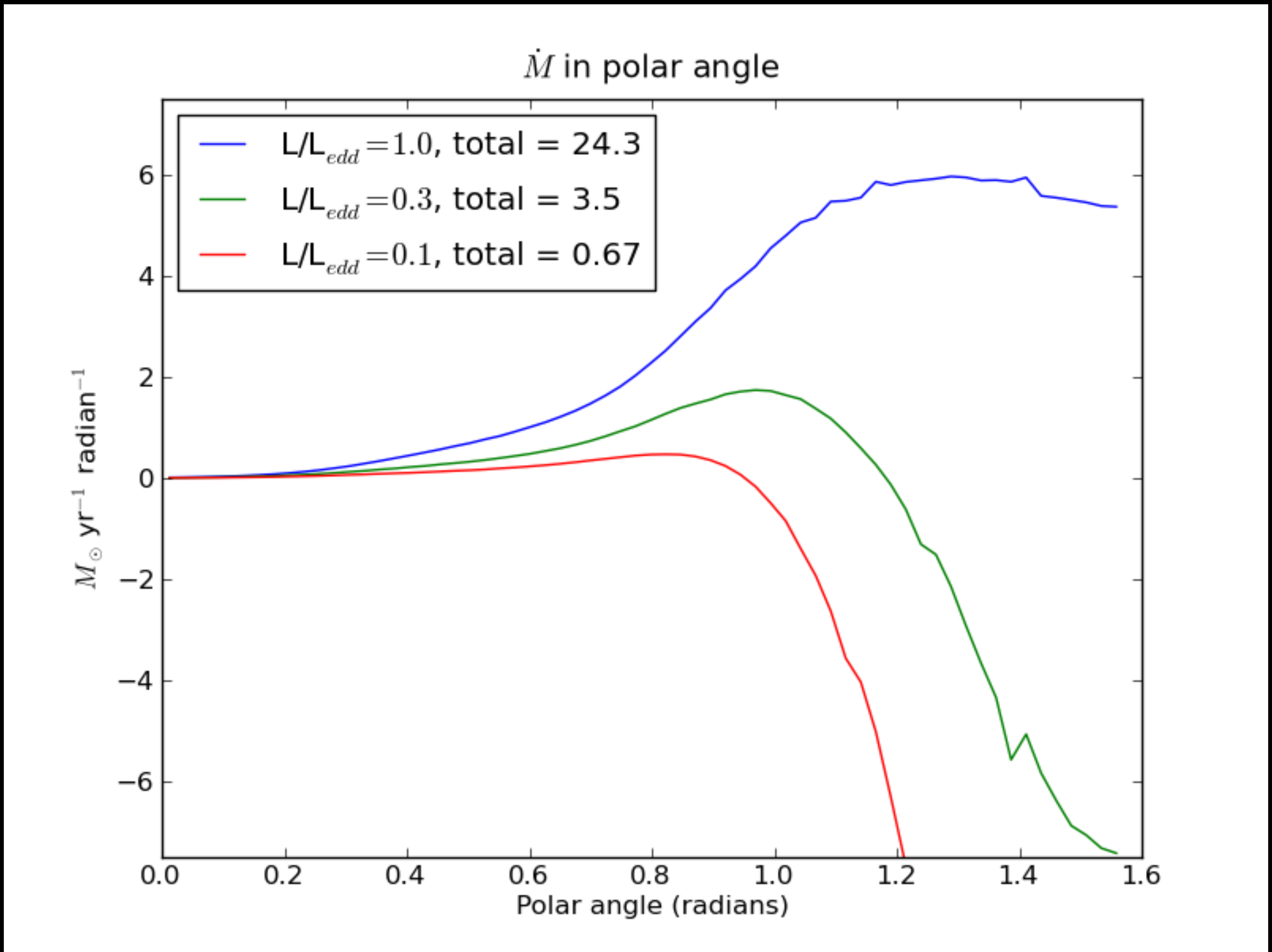
- Terminal velocity, to order of magnitude, set by acceleration at edge of sublimation region
- Acceleration time: $$t_0 = \sqrt{\frac{2r_0}{a_0}}$$

- Terminal velocity estimate:

$$v_\infty \approx a_0 t_0 = \sqrt{2 a_0 r_0}$$

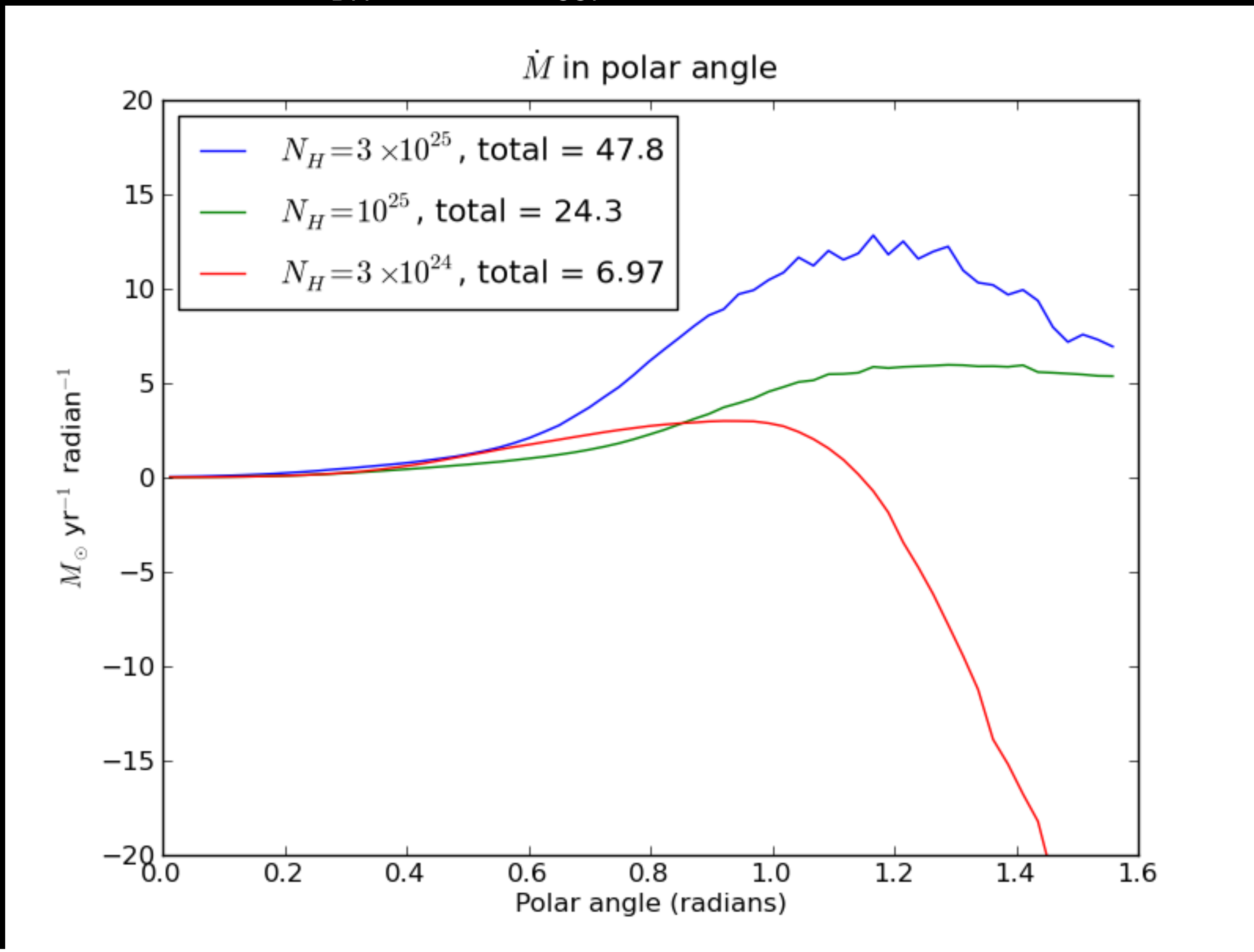
Mass ejection rate in polar angle

$M_{BH} = 10^8 M_{sol}$ $N_H = 10^{25}$ cm^{-2}



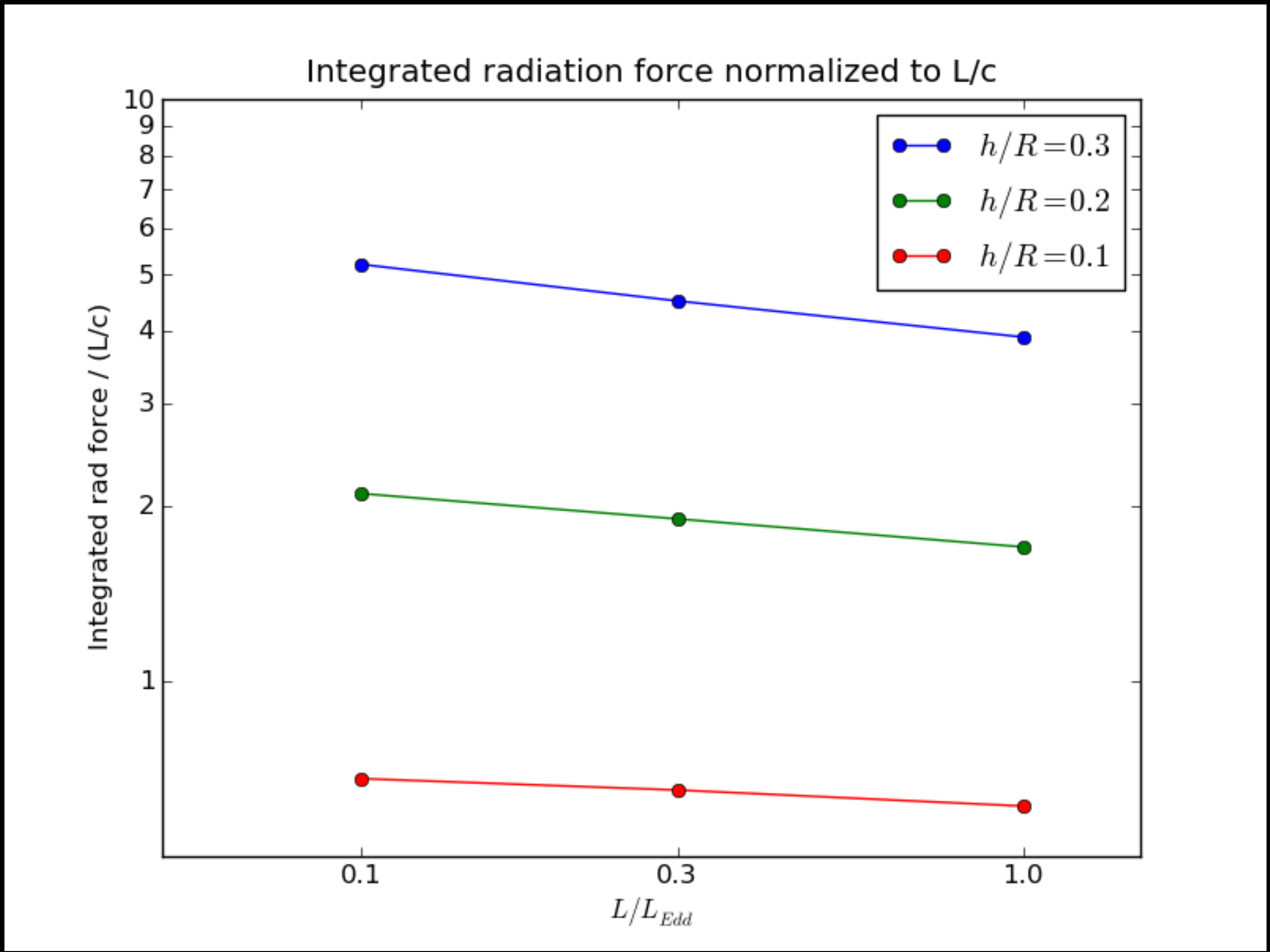
Mass ejection rate in polar angle

$M_{BH} = 10^8\ M_{sol}$ $L/Ledd = 1$

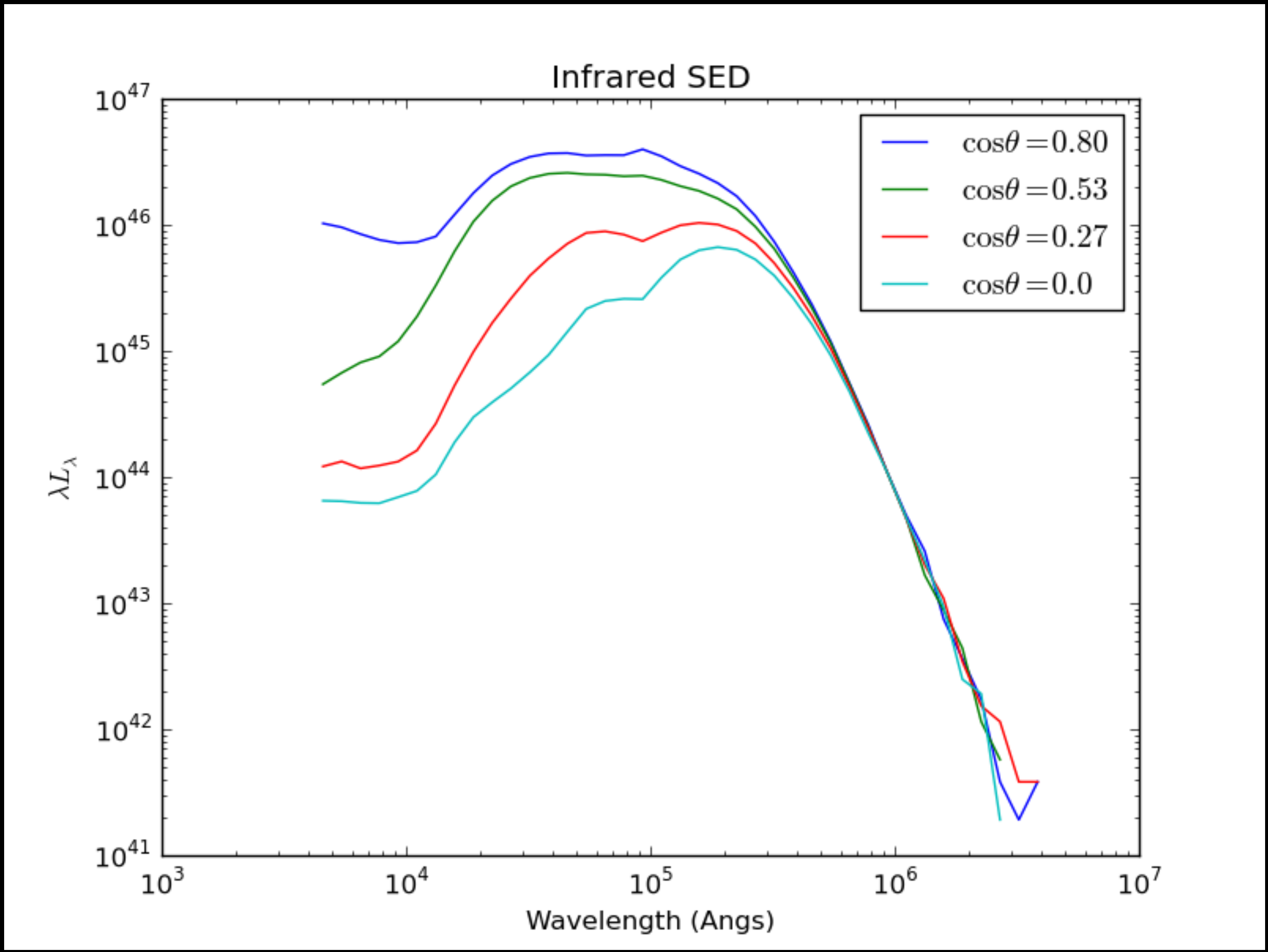


Integrated radiation force
Dependence on opening angle and luminosity

$M_{BH} = 10^8\ M_{sol}$ $N_H = 10^{25}\ cm^{-2}$



Outgoing IR SEDs



Conclusions

- Radiation pressure on dust can provide large force (up to 7 times L/c for parameters chosen)
- Monte Carlo radiative transfer self-consistently tracks dust sublimation and radiative acceleration
- Can parameterize the acceleration based on BH luminosity and gas geometry
- To do: Consider effects of rotation, shock heating, clumpy medium. Incorporate into hydro simulations based on global properties of the density structure

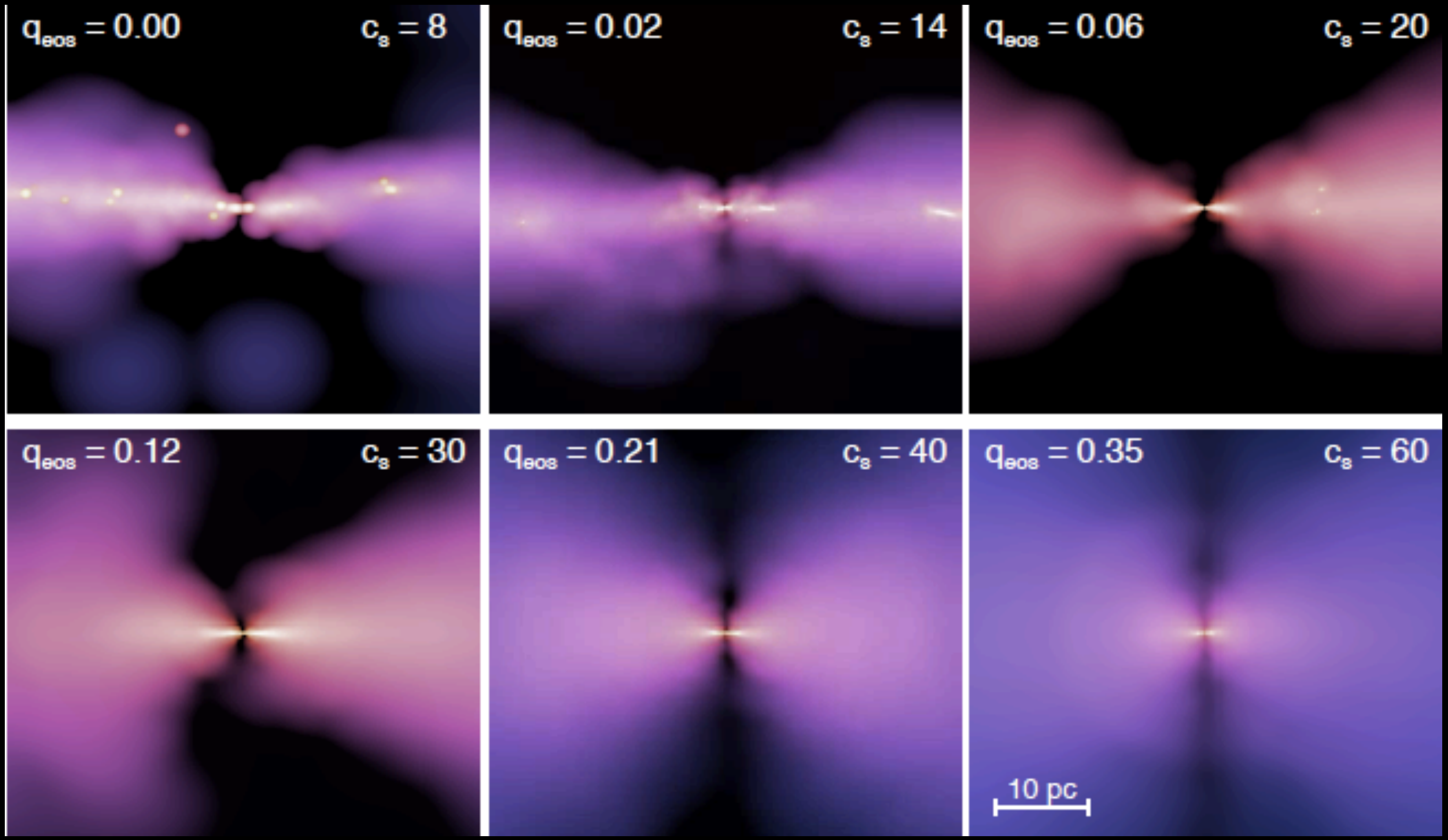
Acknowledgments

- Thanks to Jason Dexter for helpful conversations
- This research is supported in part by the Department of Energy Office of Science Graduate Fellowship Program (DOE SCGF), made possible in part by the American Recovery and Reinvestment Act of 2009, administered by ORISE-ORAU under contract no. DE-AC05-06OR23100.

Extras

The Dynamic Dusty Torus

Edge-on view. Brightness indicates column density.
Each panel is a simulation with different stellar feedback

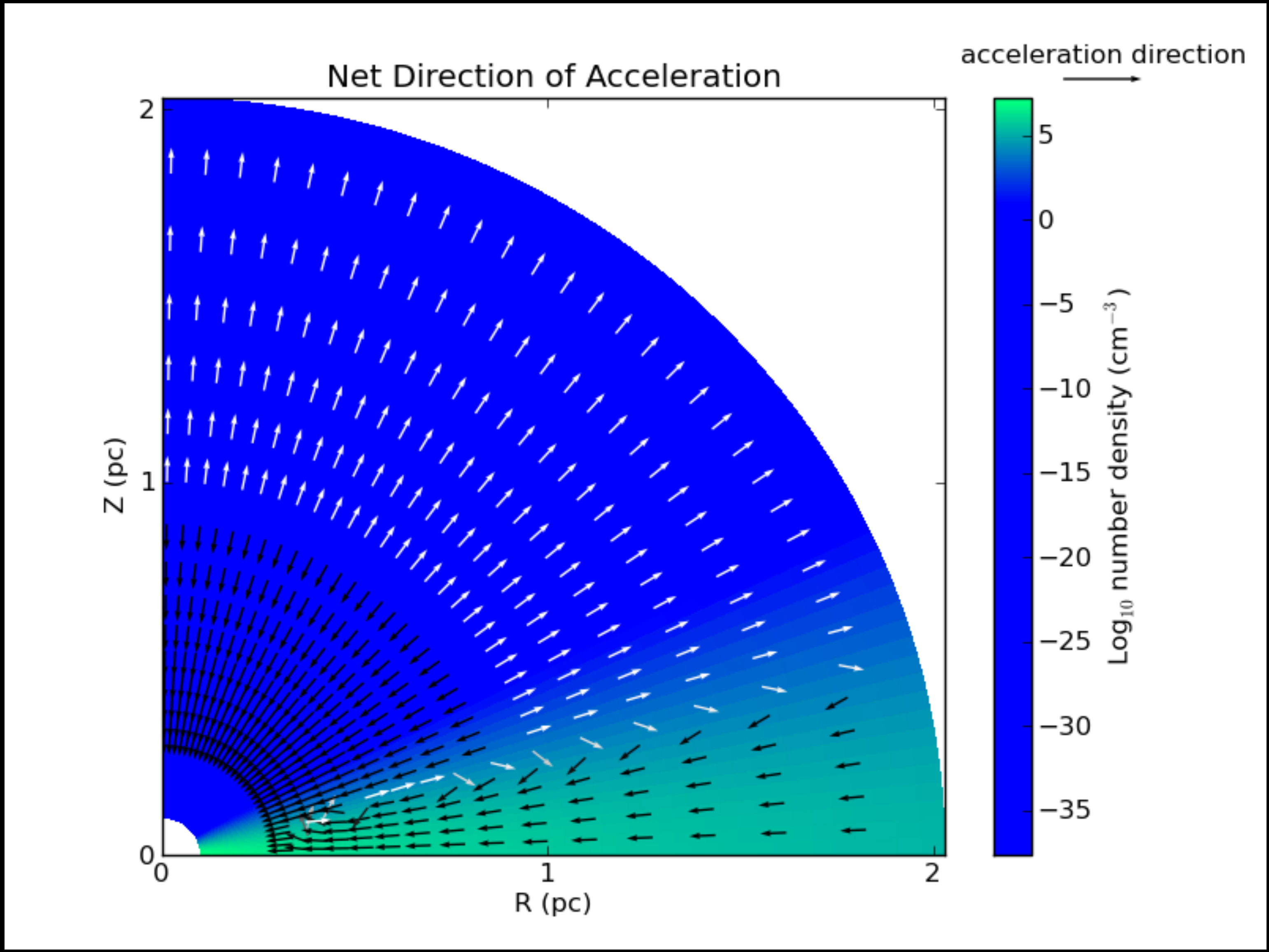


Hopkins+ 11

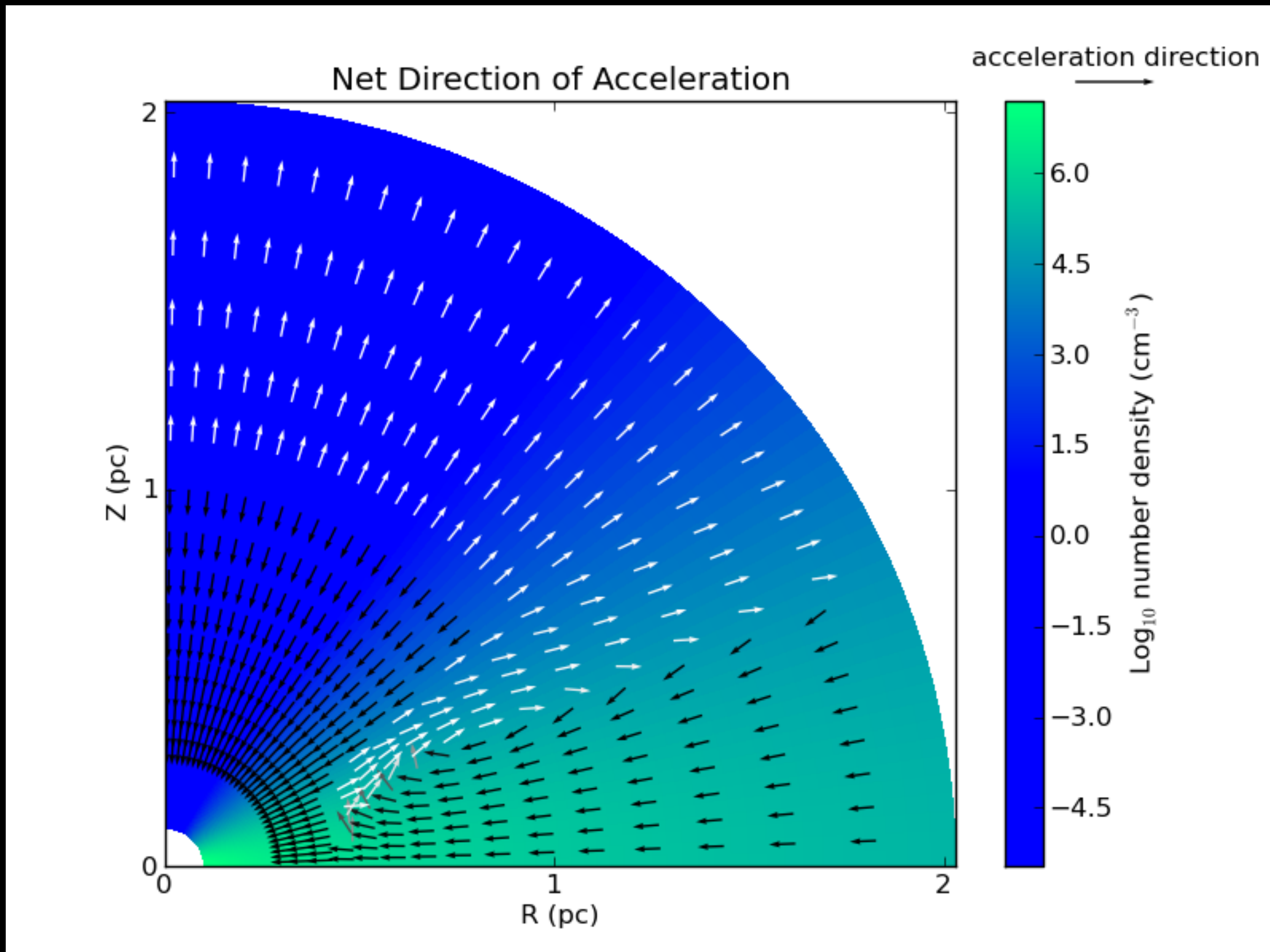
$$\rho(r,\theta) = \rho_0 \left(\frac{r}{r_0}\right)^{-3/2} \exp\left[(h_s/R)^{-2}(\sin\theta - 1)\right]$$

$$v\frac{dv}{dr} = a_0\left(\frac{r}{r_0}\right)^{-2}$$

$$\frac{1}{2}(v_\infty)^2 = 2a_0r_0$$



Net Direction of Acceleration
acceleration direction
Z (pc)
R (pc)
0
1
2
0
1
2
5
0
−5
−10
−15
−20
−25
−30
−35
$\mathrm{Log_{10}}$ number density ($\mathrm{cm^{-3}}$)


Net Direction of Acceleration
acceleration direction
Z (pc)
R (pc)
0
1
2
0
1
2
6.0
4.5
3.0
1.5
0.0
−1.5
−3.0
−4.5
Log_{10} number density (cm^{-3})