Simulations of Black Hole Fueling and AGN Feedback in Early-Type Galaxies: Toward a deeper physical understanding

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Goals

- Kennicutt's Conference Introduction: Understanding of BH fueling and feedback are in an embryonic state.
- Implement a physically rich AGN feedback model
- Ensure that physically relevant length and timescales are resolved
- How does BH accretion affect energy, mass, and momentum balance of galactic gas?

Related work

- DiMatteo, Springel + Hernquist 2005
- Levine, Gnedin, Hamilton + Kravtsov 2008, 2010
- Alvarez, Wise + Abel 2009
- Johansson, Naab + Burkert 2009
- Debuhr, Quataert, Ma + Hopkins 2010, 2011
- Hopkins + Quateart 2010
- Kim, Wise, Alvarez + Abel 2011

Basic Picture

- Early-Type Galaxy with initial population of stars, no gas
- Gas supplied by evolving stars, cools unstably, falls to center of galaxy
- Simulation domain 2.5 pc to 250 kpc, run for 10 Gyr

Length and Timescales

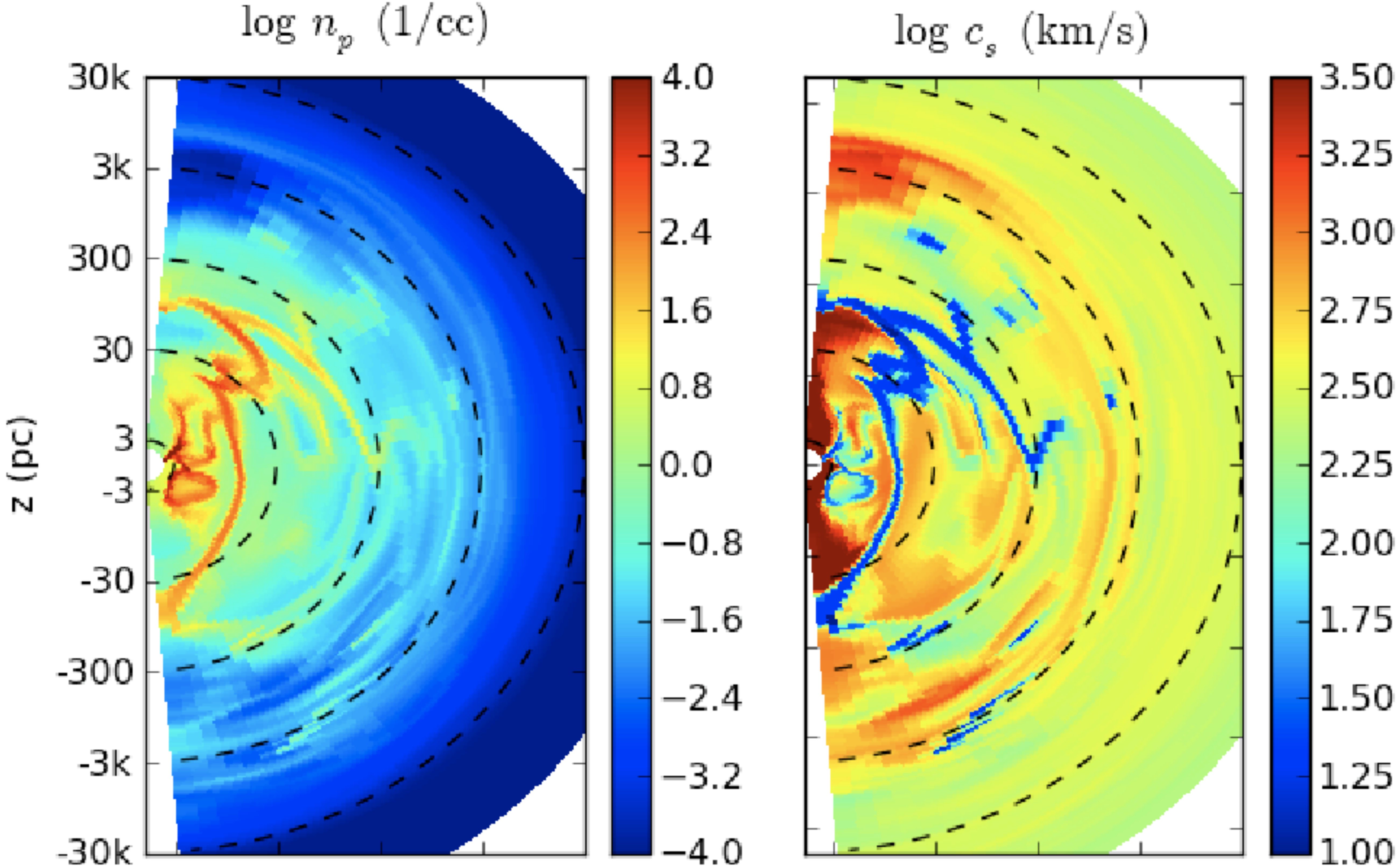
- Bondi radius of HOT gas: ~5 pc
- Sphere of influence of the black hole: ~20 pc
- Accretion disk timescales: ~10^4 yr
- Stellar evolution timescales (source of infalling gas): ~10^9 yr
- Galactic Length Scales: ~kpc
- Smallest cells: 0.2 pc
- Courant time in smallest cells: ~1 yr

The need for high resolution

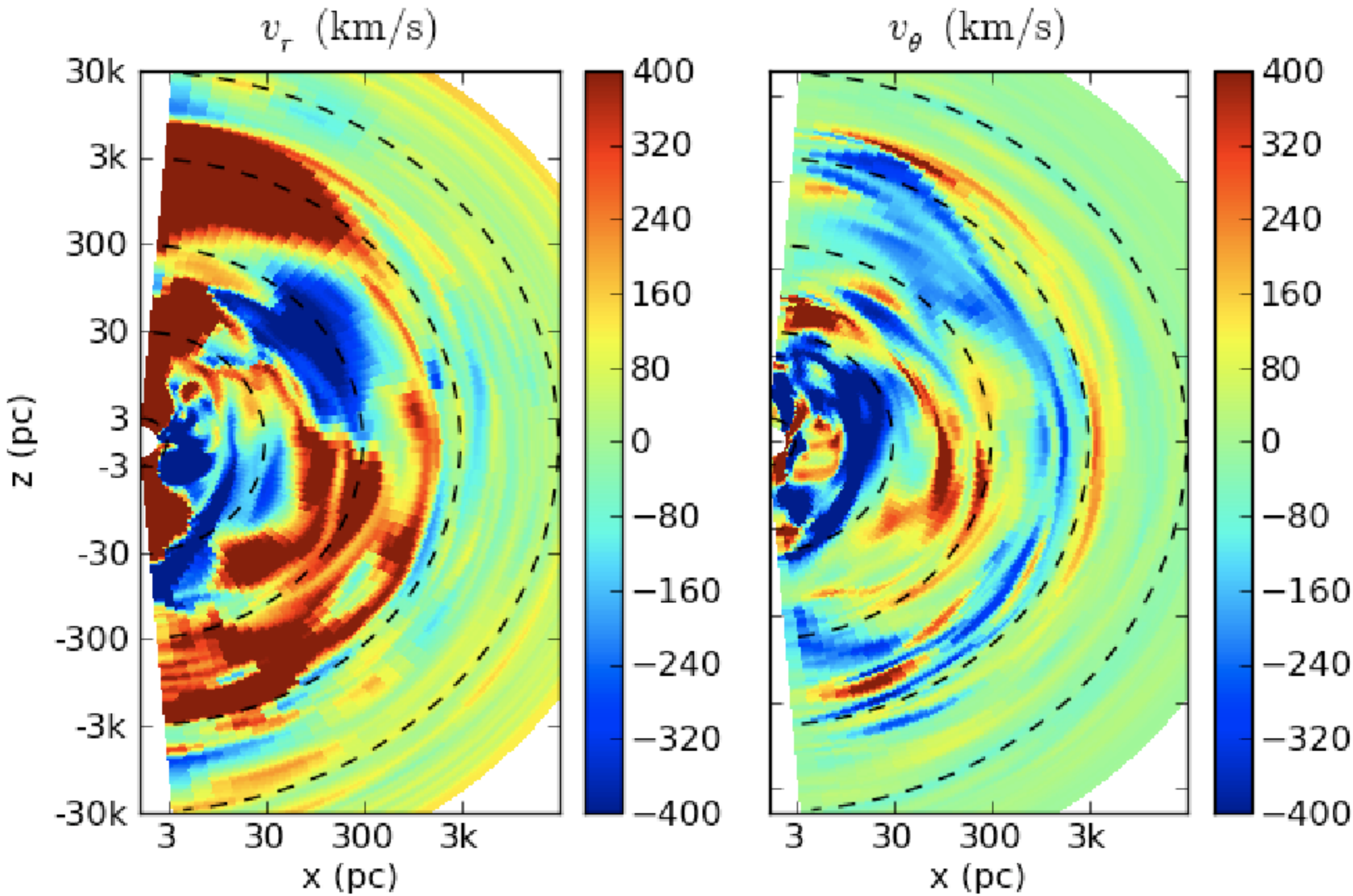
- Bondi Radius depends strongly on sound speed $$R_B = \frac{GM}{c_s^2}$$
- Radiative AGN Heating depends strongly on radius $$H \propto \frac{1}{r^2}$$
- Sufficiently strong heating can cause the Bondi radius to “overtake” the gas
- Gas inside the Bondi radius corresponding to the Compton temperature is energetically required to interact with the BH.
- The simulation should resolve the Bondi radius for gas at the Compton temperature

Physically Rich Feedback Model

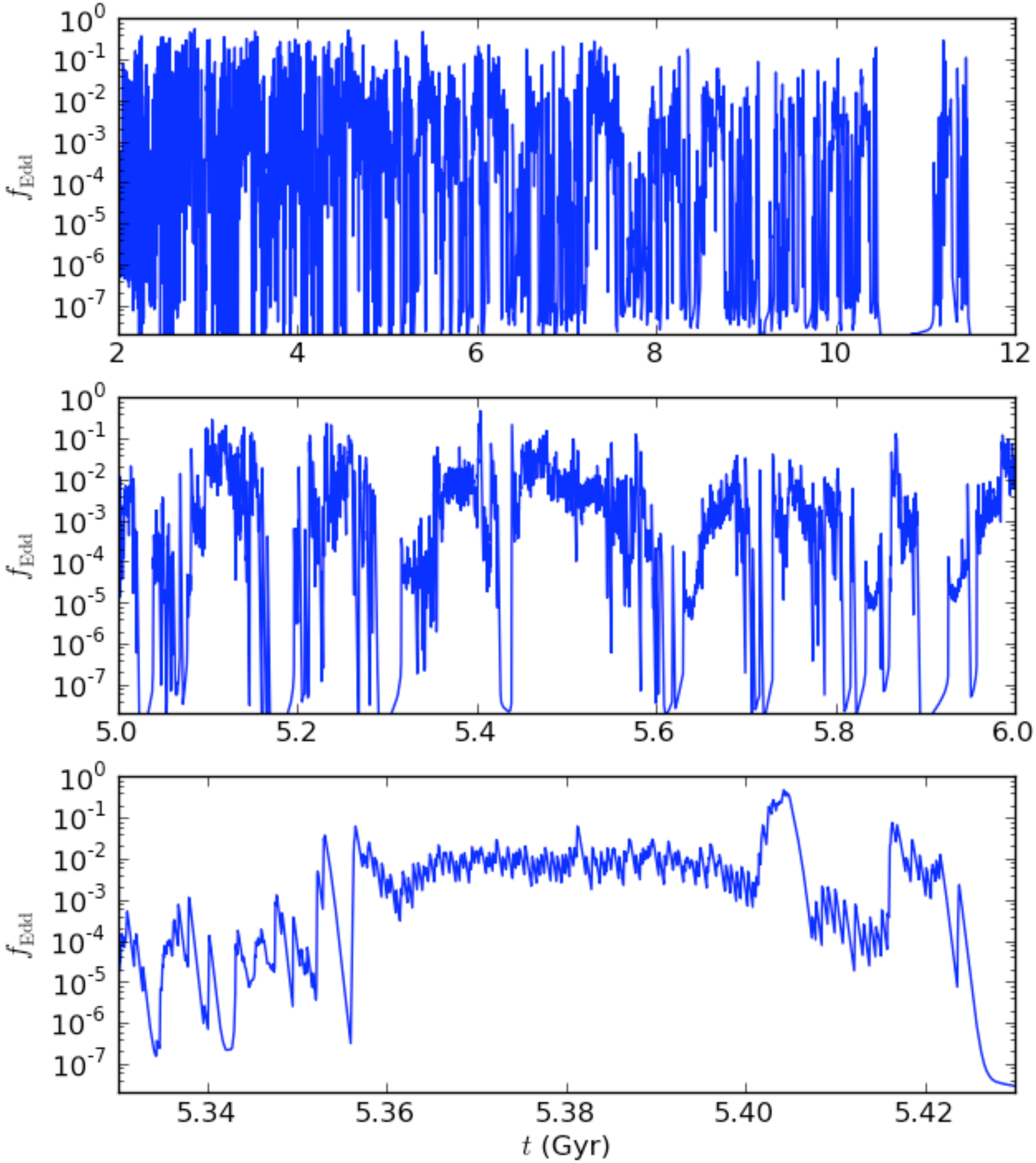
- Radiative and Mechanical Feedback via Energy and Momentum
- Mechanical Feedback via 10,000 km/s Wind driven off of (sub-resolution) Accretion Disk
- Radiative Transfer of AGN and Stellar Photons due to Dust Opacity
- Dust Destruction via Sputtering, Creation via Stellar Winds, Molecular Clouds
- Compton Scattering/Heating, Photoionization Heating/Opacity, Atomic Cooling, Bremstr.
- Star Formation, Supernovae



log n_p (1/cc)
log c_s (km/s)
z (pc)
30k
3k
300
30
3
-3
-30
-300
-3k
-30k
4.0
3.2
2.4
1.6
0.8
0.0
−0.8
−1.6
−2.4
−3.2
−4.0
3.50
3.25
3.00
2.75
2.50
2.25
2.00
1.75
1.50
1.25
1.00

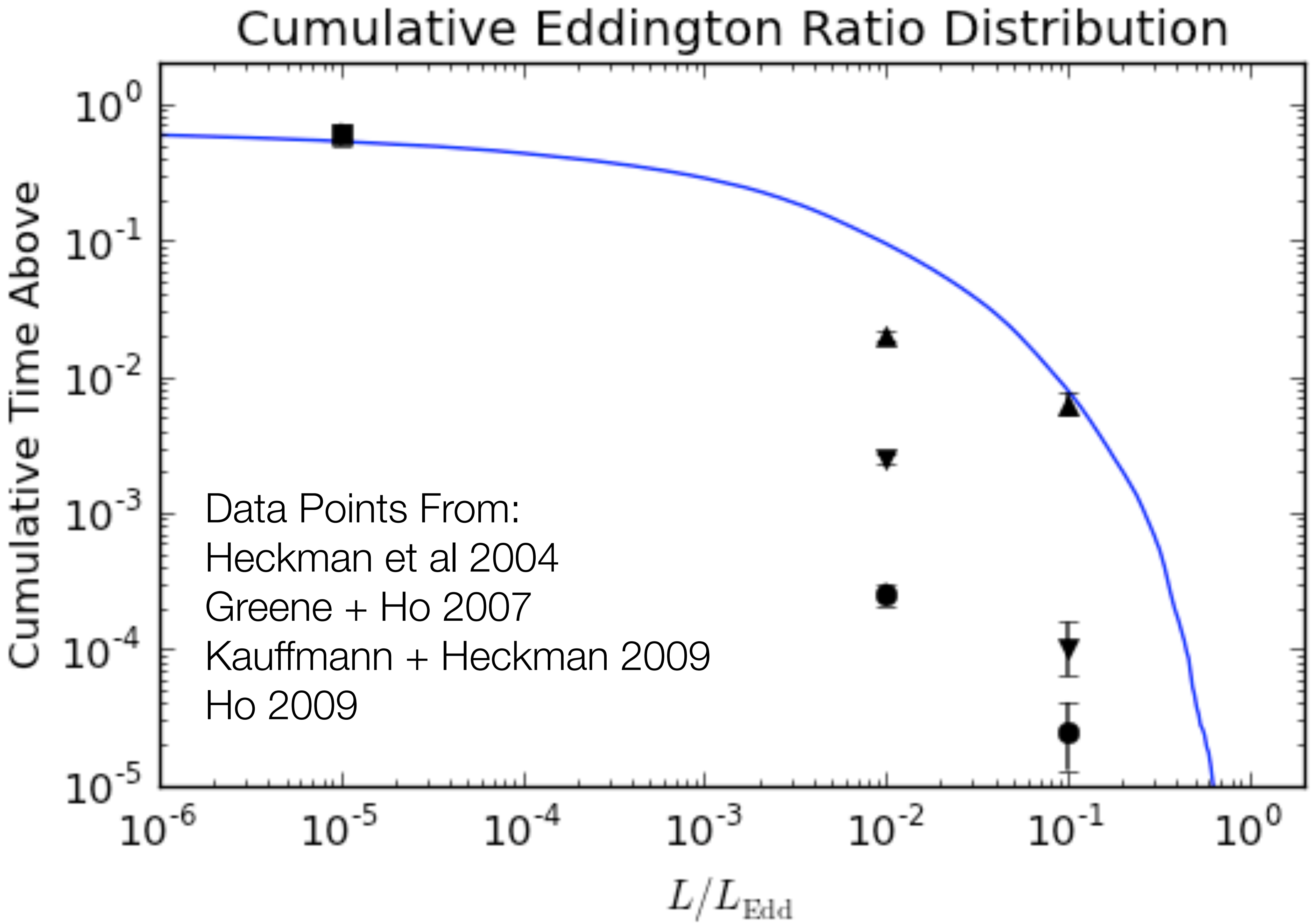


v_r (km/s)
v_θ (km/s)
30k
3k
300
30
3
-3
-30
-300
-3k
-30k
z (pc)
3
30
300
3k
x (pc)
400
320
240
160
80
0
−80
−160
−240
−320
−400

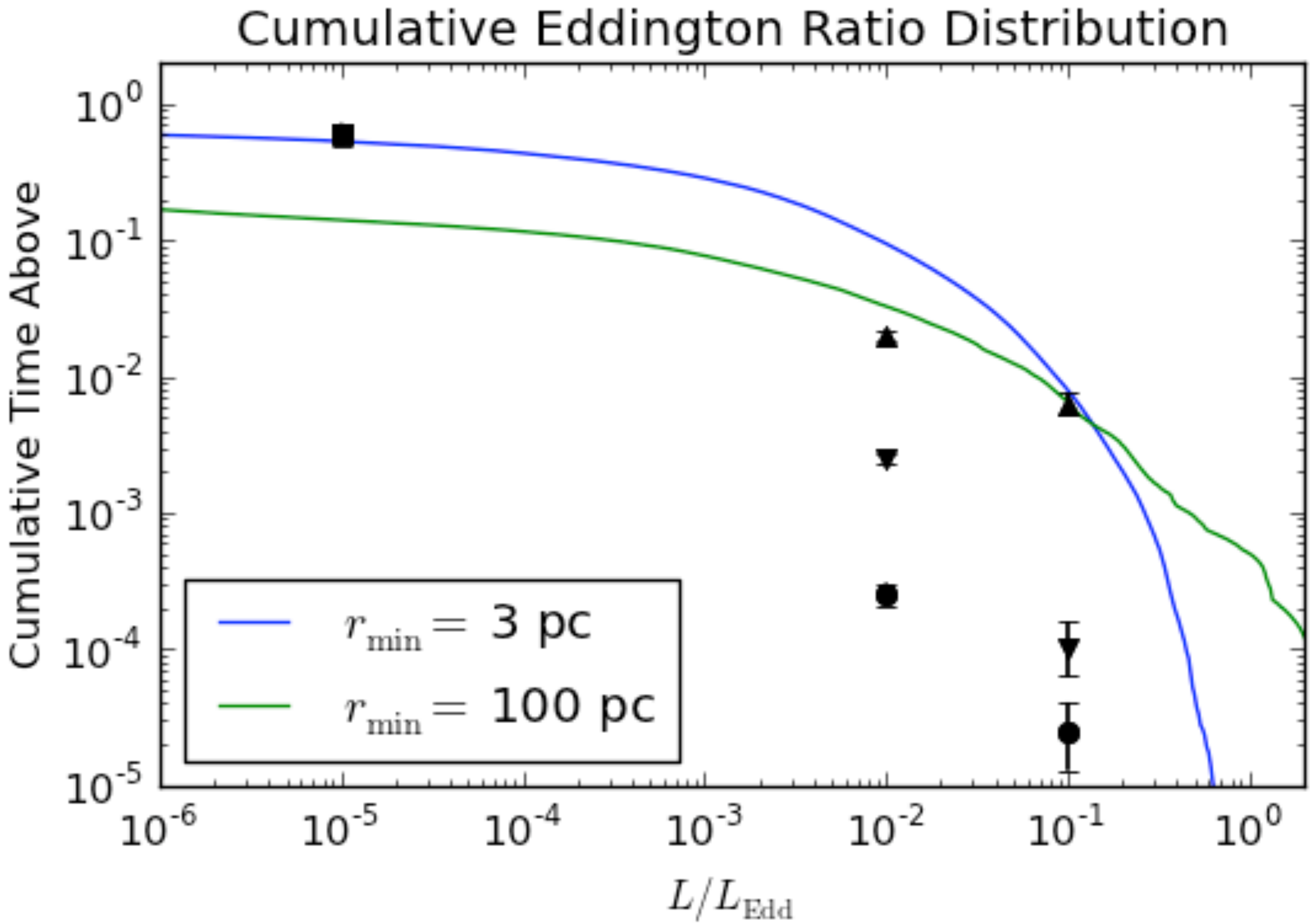


$f_{\rm Edd}$
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
2
4
6
8
10
12
5.0
5.2
5.4
5.6
5.8
6.0
5.34
5.36
5.38
5.40
5.42
t (Gyr)

Effect of Changing Inner Radius



Effect of Changing Inner Radius



Eddington Rate in Point Mass + SIS potential

$$\frac{L\kappa}{4\pi r^2 c} = \frac{GM_{BH}}{r^2} + \frac{2\sigma^2}{r}$$

$$L'_E = L_E \left(1 + \frac{2r\sigma^2}{GM_{BH}}\right)$$

$$L'_E = L_E \left(1 + \frac{2r}{r_{BH}}\right)$$

Effect of Changing Inner Radius

- If BH sphere of influence is unresolved, Eddington ratio will be too high
- Large Eddington Ratio bursts are very effective at heating essentially all of the gas in the galaxy and driving outflows
- Easy to understand: Requiring that

$$\dot{E}_{\rm Mech,BH}\,\tau_{\rm dyn,gal} = E_{\rm thermal,gas}$$

- gives:

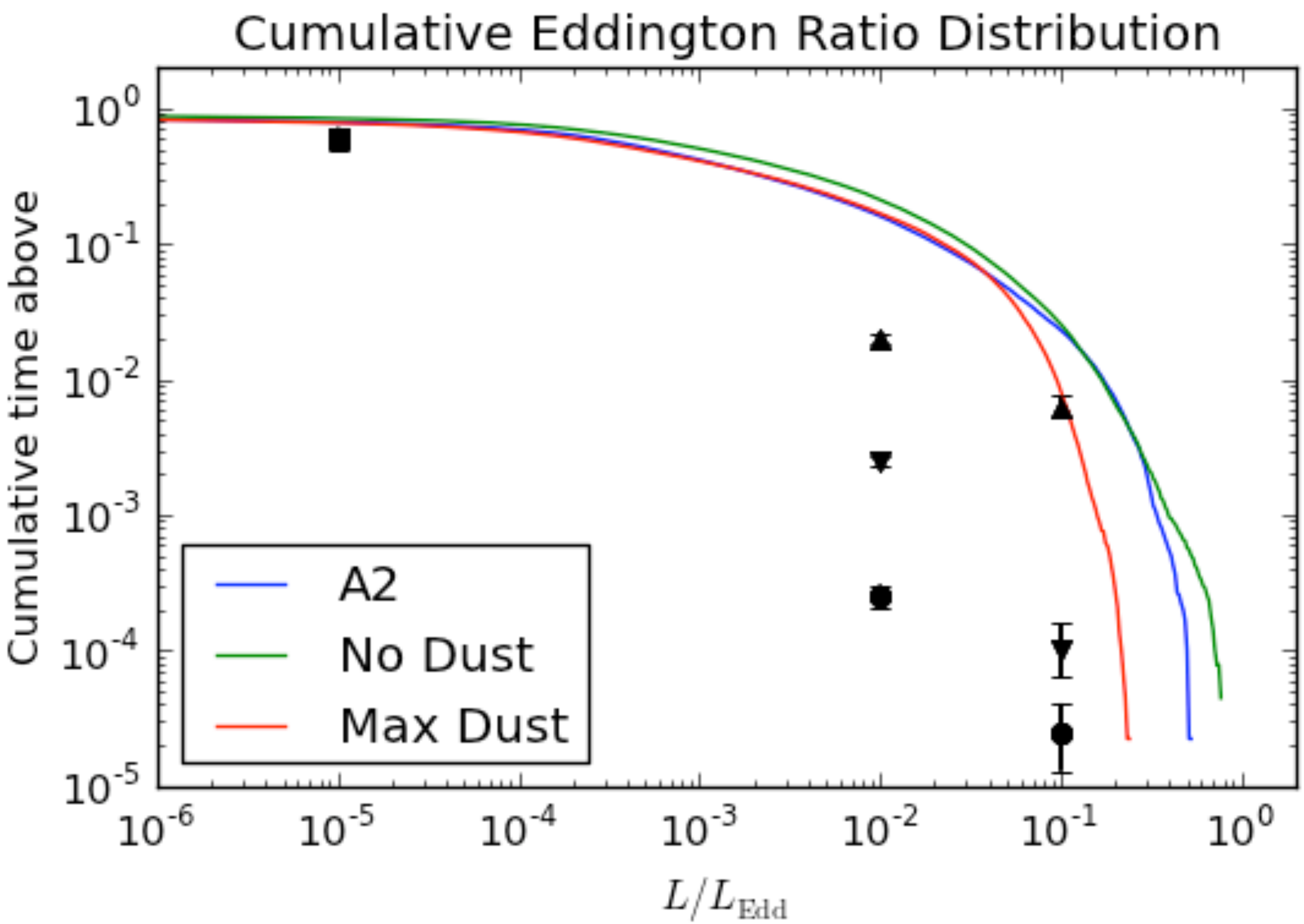
$$f_{\rm Edd} = 1\% \left(\frac{f_{\rm gas}}{1\%}\right)\left(\frac{\epsilon_{\rm rad}}{0.1}\right)\left(\frac{\epsilon_{\rm mech}}{10^{-3}}\right)^{-1}\left(\frac{\sigma}{200\,{\rm km\,s^{-1}}}\right)^{5}\left(\frac{M_{\rm BH}}{10^{8}\,M_{\odot}}\right)^{-1}$$

(e.g. Silk + Rees 98)

Effect of Dust

- BH, Stars emit UV, Optical, IR photons
- As you absorb UV/Optical photons, that energy is added as IR photons
- We solve the radiative transfer equation with scattering, absorption, an arbitrary source of isotropic photons (stars) and a central point source (BH) in the radial direction by taking moments of the equation.

Effect of Dust



Dust does not seem to make a large difference

Effect of Dust

- For ABSORPTION: photons get used up

$$\frac{dp}{dt} = \frac{L\min(\tau, 1)}{c}$$

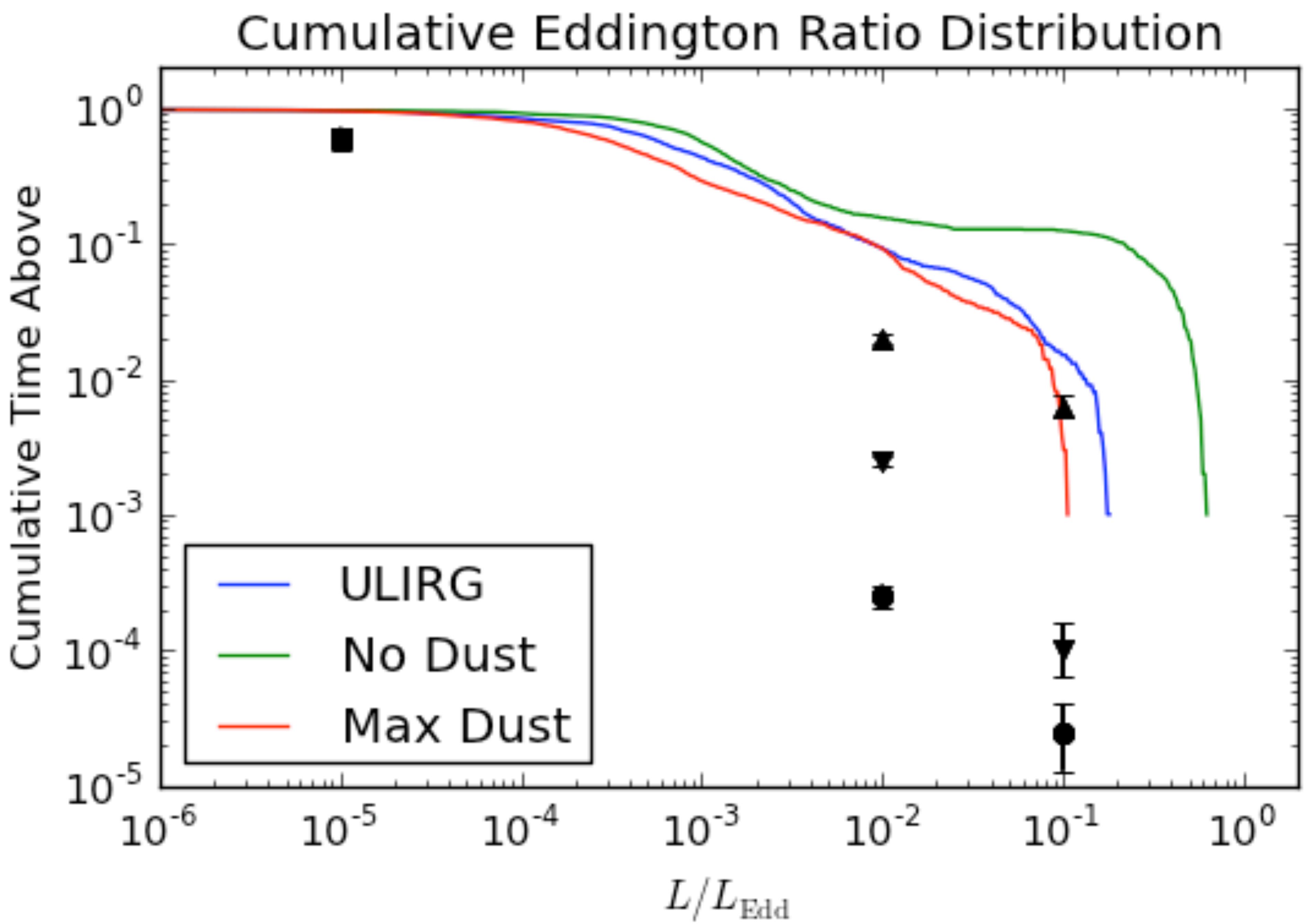
- For SCATTERING: photons build up and diffuse out

$$\frac{dp}{dt} = \frac{L\tau}{c}$$

- Dust opacity in IR only a few times electron scattering opacity in Milky Way, so need ~Compton thick surface densities for scattering of IR photons by dust to make a big difference.

(see Thompson, Quataert + Murray 05
Murray, Quataert + Thompson 05
Debuhr et al 10, 11)

Effect of Dust



Given enough gas, dust can make a large difference

Conclusions

- Momentum injected by broad-line wind is the dominant factor in determining black hole growth
- Physics operating between 3 pc and 100 pc makes a difference!
- Dust does not seem to make a big difference...
- Unless there’s enough gas to be optically thick in the IR (nearly Compton-thick), then it does make a difference