Growth of most massive black holes in the early universe

KwangHo Park

Georgia Tech Center for Relativistic Astrophysics
College of Sciences

Tamara Bogdanović (GT), John Wise (GT)
Massimo Ricotti (UMD), Chris Reynolds (U of Cambridge)
Tiziana Di Matteo (CMU), Priyamvada Natarajan (Yale)

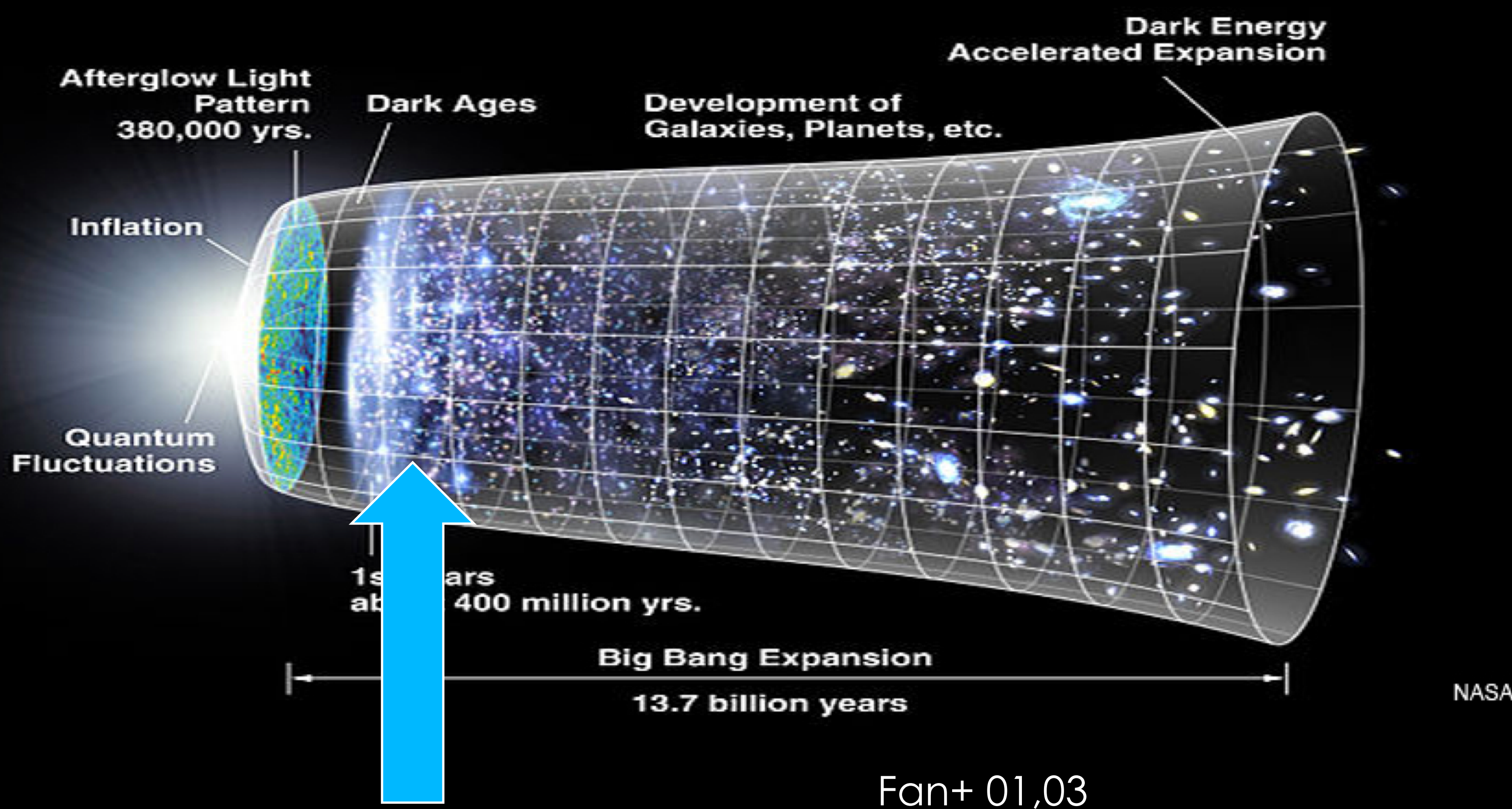
KIAS

November 7, 2018

Outline

- Radiation-regulated accretion
  - Billon solar mass black holes at z~6-7?
  - Radiation-driven **turbulent** accretion (Park, Wise, & Bogdanović, 2017)
- Hyper-accretion
  - Breaking spherical symmetry (Park+ in prep)
- Bulge-driven fueling (Park+ 2016)
  - A possibility for hyper-accretion

Motivation: Quasars in the early universe



Quasars (actively accreting BHs) are observed at z~6-7!

Fan+ 01,03
Willot+ 03,10
Mortlock +11
Wu+ 15

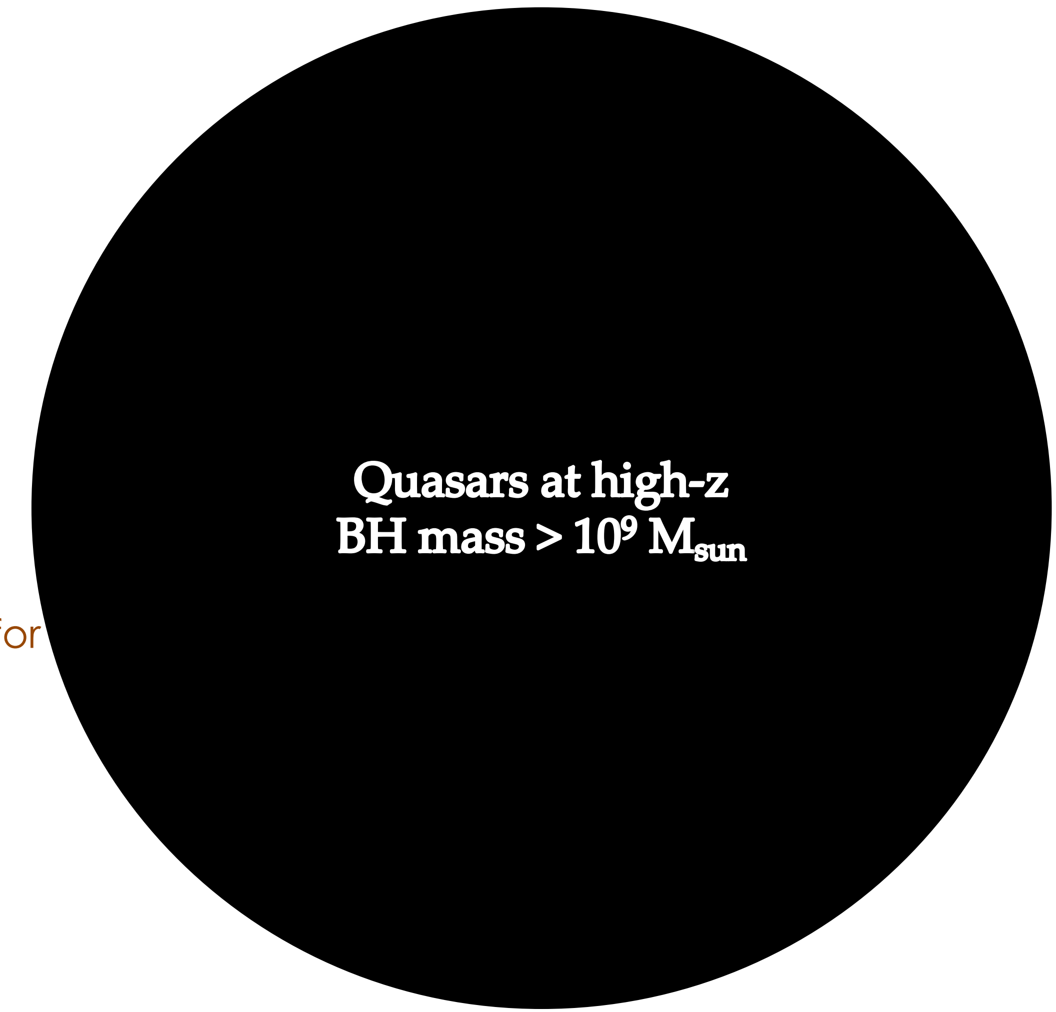
Initial Mass of Seed Black Holes

- Seed BH Formation Scenarios (IMBH)
  - Pop III remnants : $\sim 10^2 M_\odot$
  - Stellar collapses : $\sim 10^4 M_\odot$
  - Direct collapse : $\sim 10^5 M_\odot$

- E.g., Pop III remnants
  - Initial mass should increase by 7 orders of mag
  - Should Accrete at Eddington rate for ~700 Myr

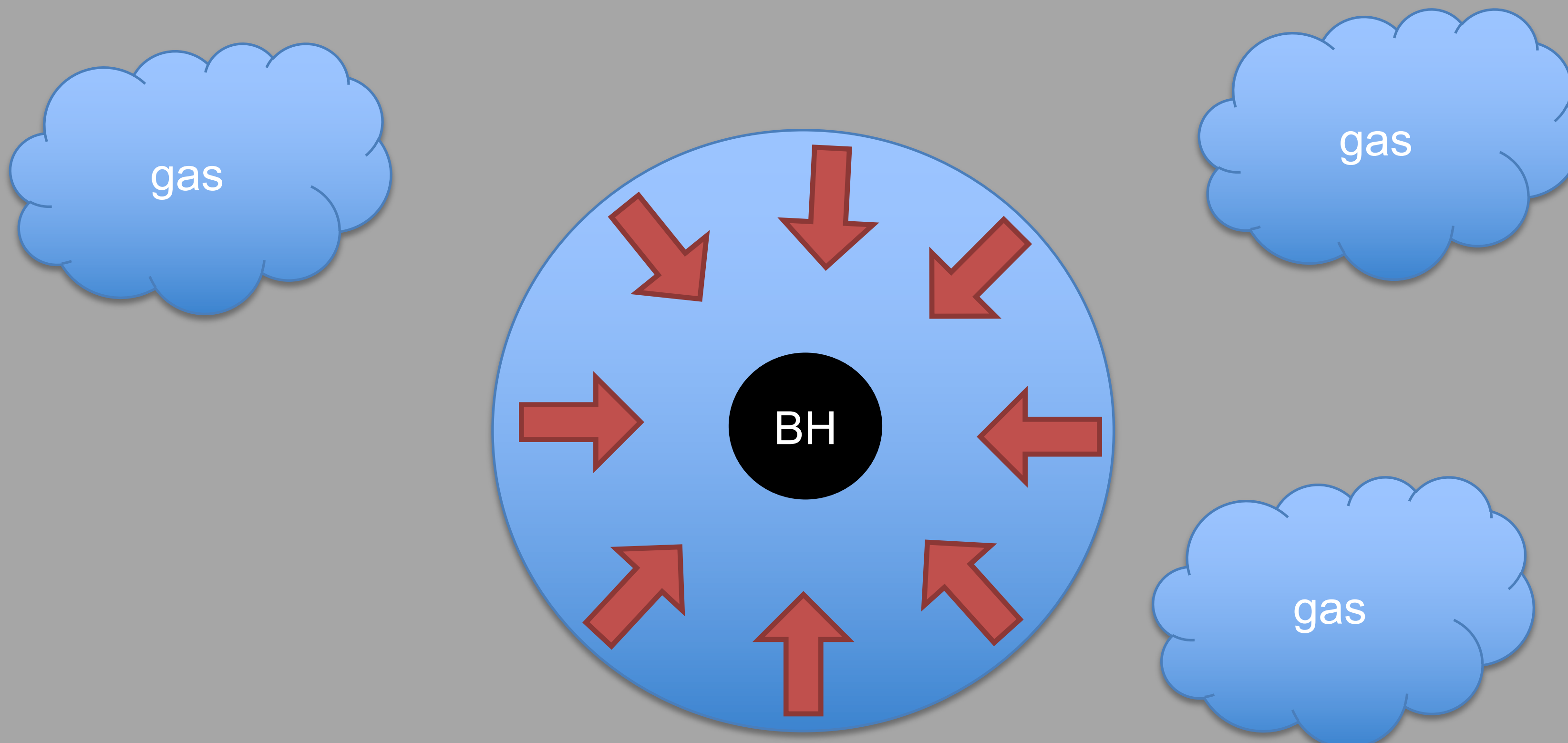
- Estimation of grow rate is important!

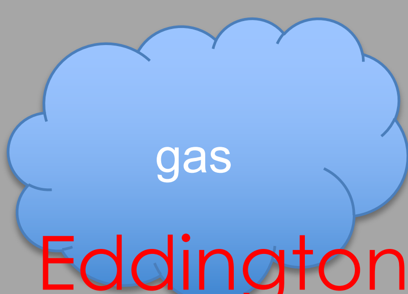
Volonteri 12
Natarajan 11



How do we estimate an accretion rate onto a BH?

Bondi Accretion (1952)



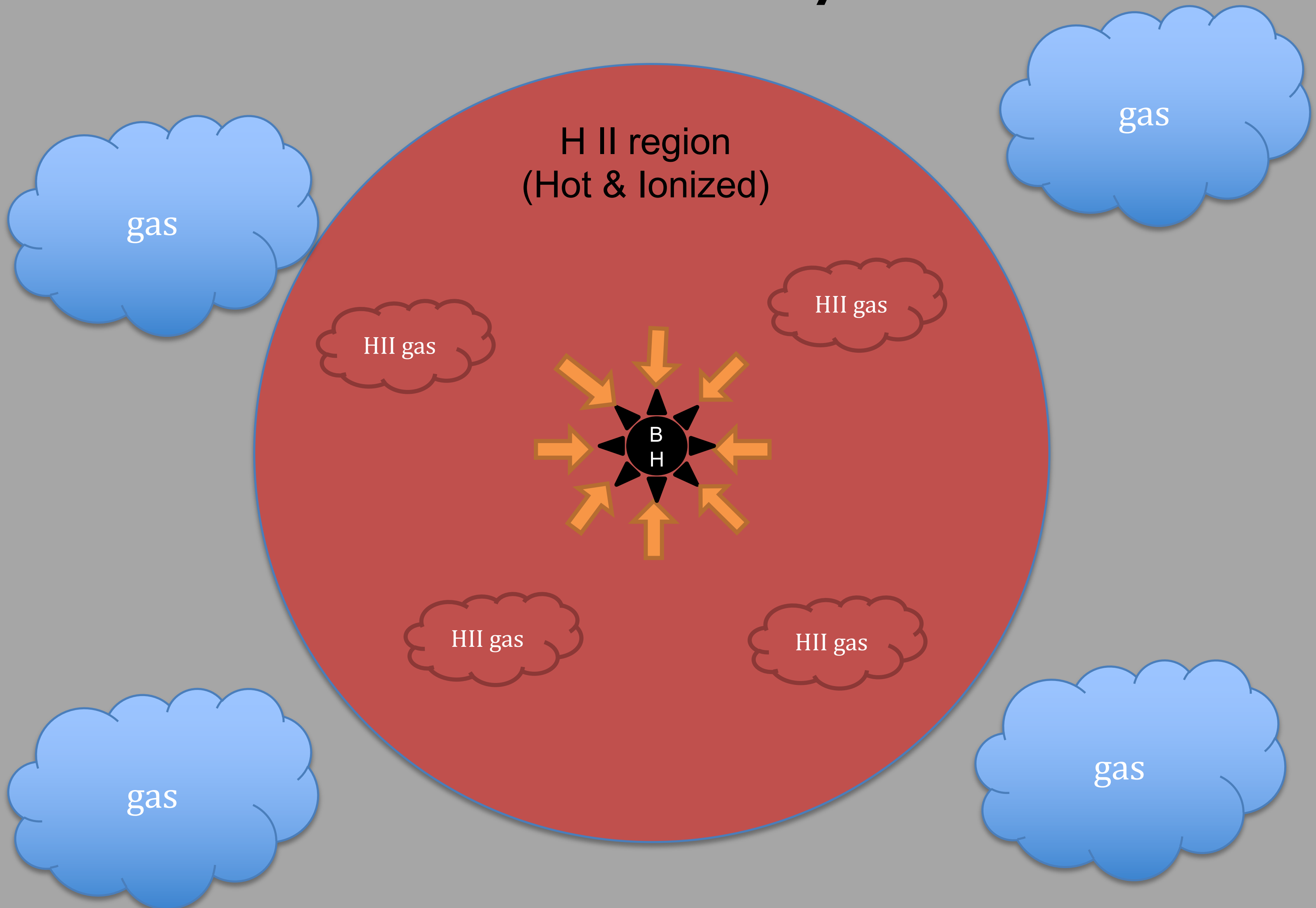


$$\dot{M}_B = 4\pi\lambda_B r_b^2 \rho_\infty c_{s,\infty}$$
$$= 4\pi\lambda_B \frac{G^2 M_{bh}^2}{c_{s,\infty}^3} \rho_\infty$$

$$L_{Edd} = \frac{4\pi G M_{bh} m_p c}{\sigma_T}$$

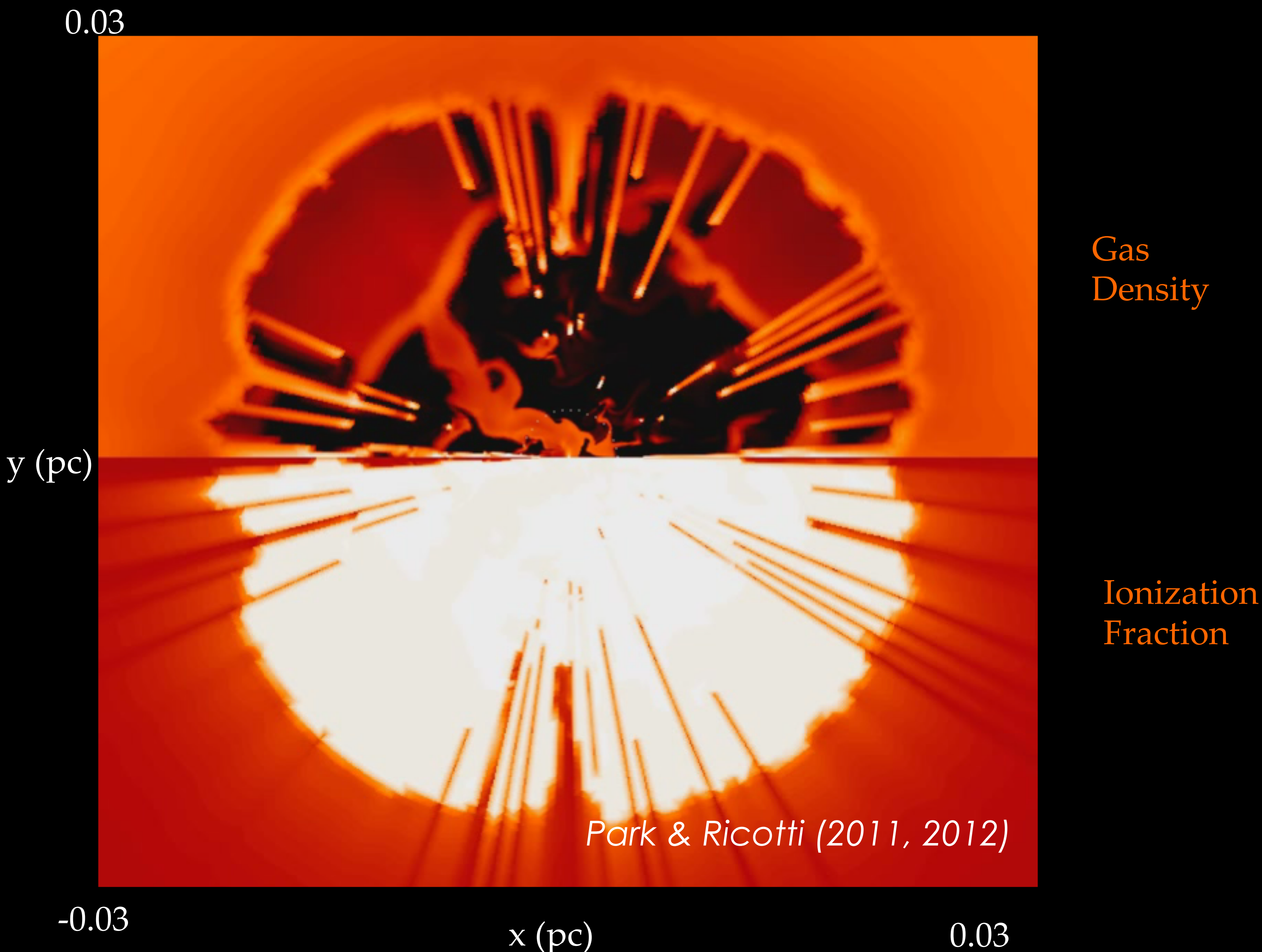
Eddington-limited Bondi-Hoyle rate

Radiative Feedback by Black Hole



Radiation-regulated Accretion

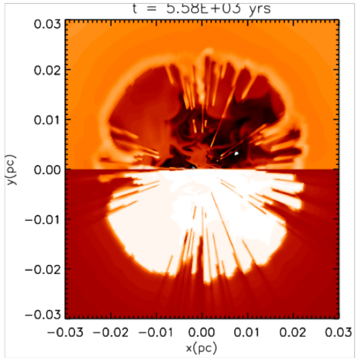
Classical Bondi problem
+ Radiative Feedback

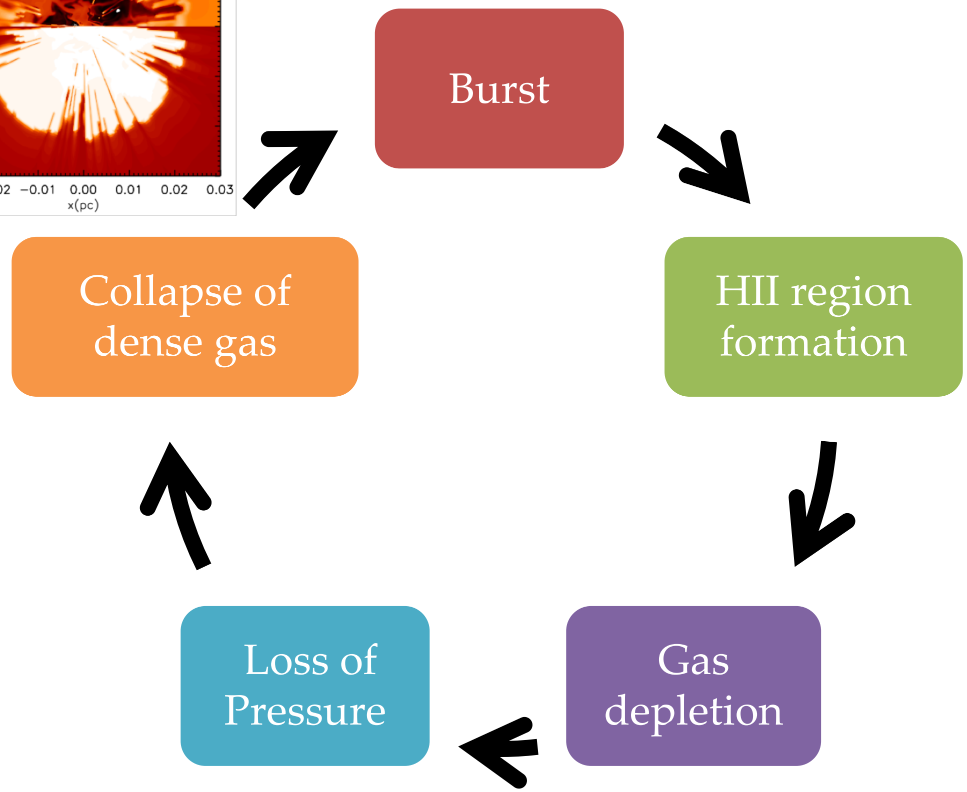


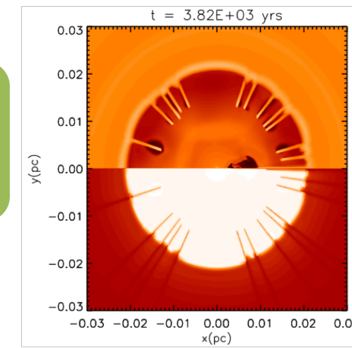
η=0.1, M_{bh}= 100 M_{sun}, T_{inf}=10^4 K, n_H = 10^6 cm^{-3}

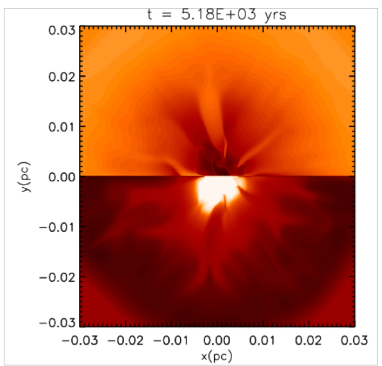
Radiation-regulated accretion

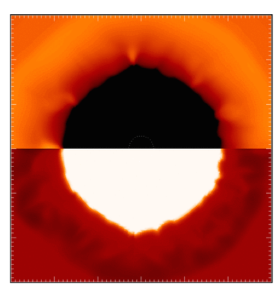
Periodic oscillation of accretion rate due to accretion/feedback loop





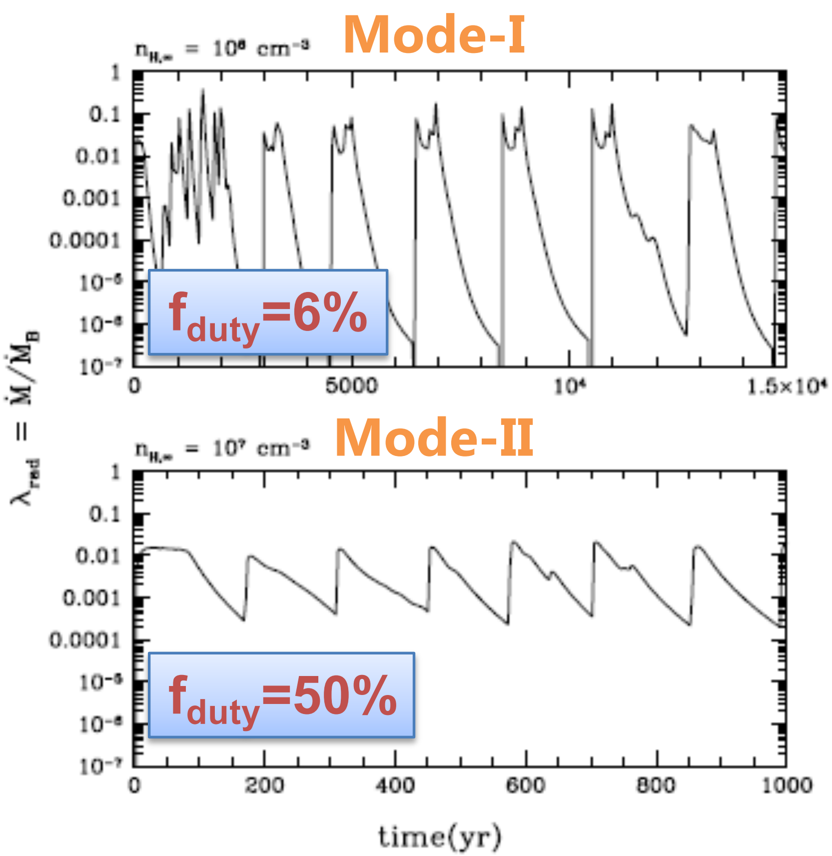


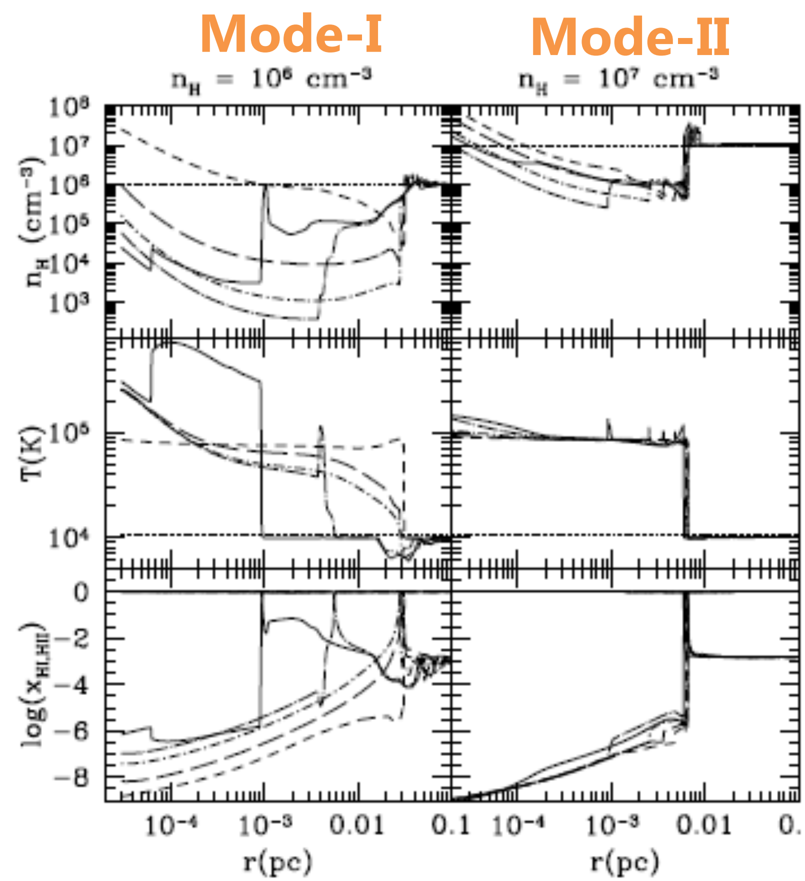




Park & Ricotti (2011, 2012)

Mode-I vs Mode-II Oscillations





f_{duty} increases in mode-II oscillations. Makes Eddington-limited accretion efficient

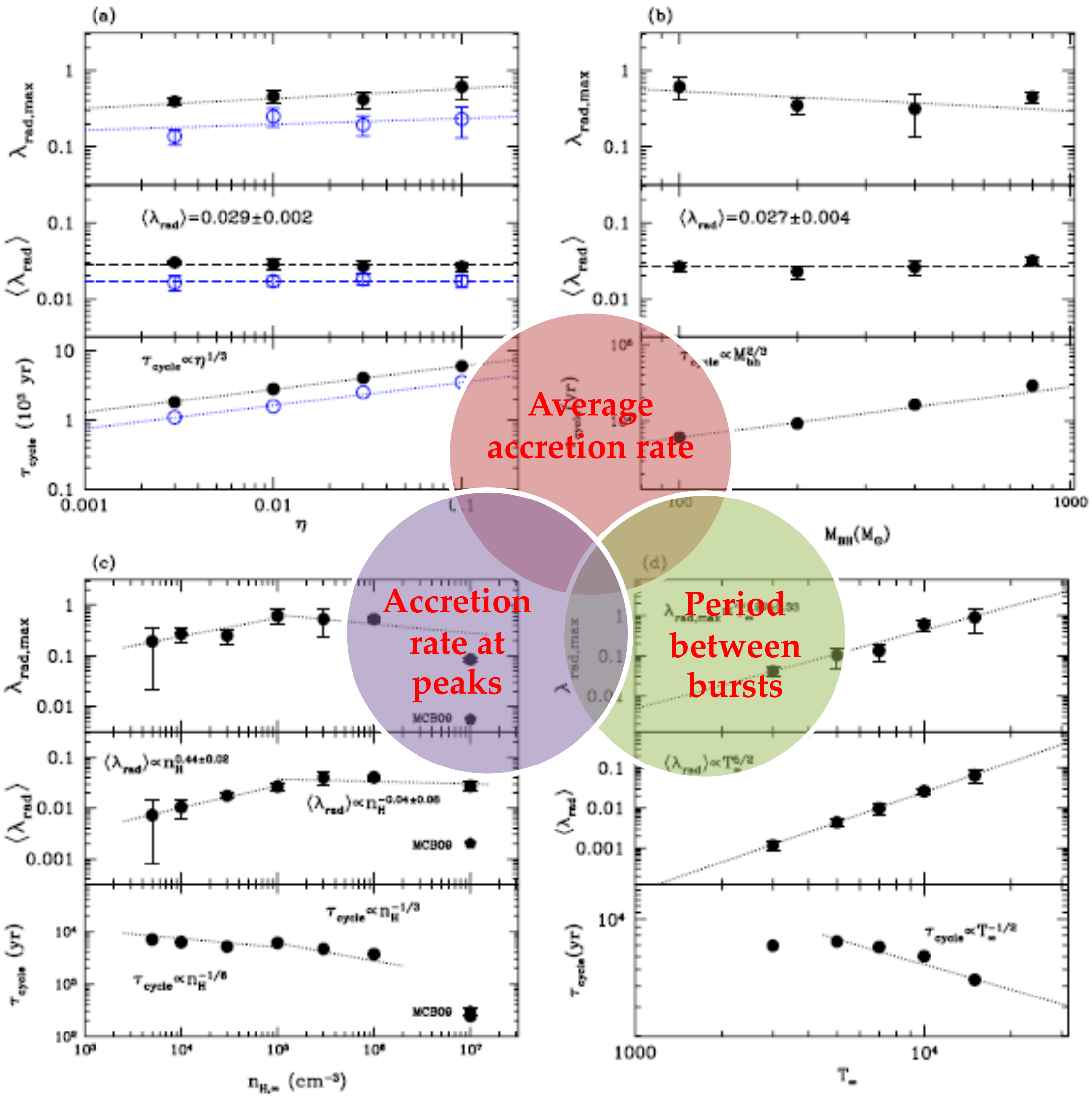
$$\tau_{on} \equiv \frac{\langle \lambda_{rad} \rangle}{\lambda_{rad,max}} \tau_{cycle},$$

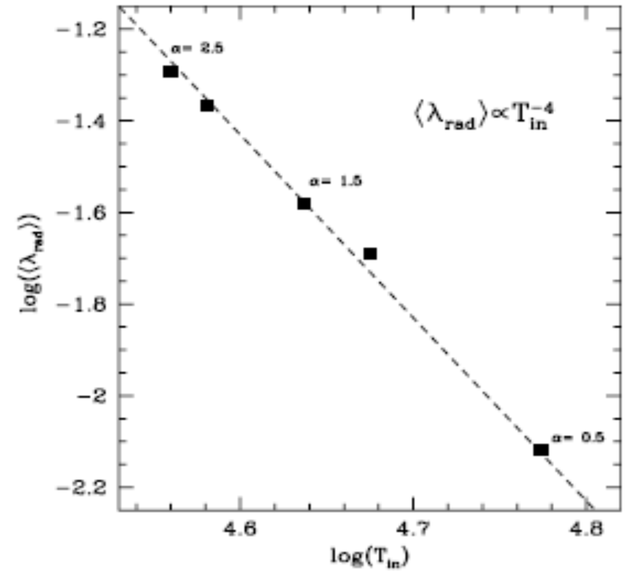
$$f_{duty} \equiv \frac{\tau_{on}}{\tau_{cycle}} = \frac{\langle \lambda_{rad} \rangle}{\lambda_{rad,max}}$$

Park & Ricotti 2012

Accretion is suppressed

Parameter Space Exploration





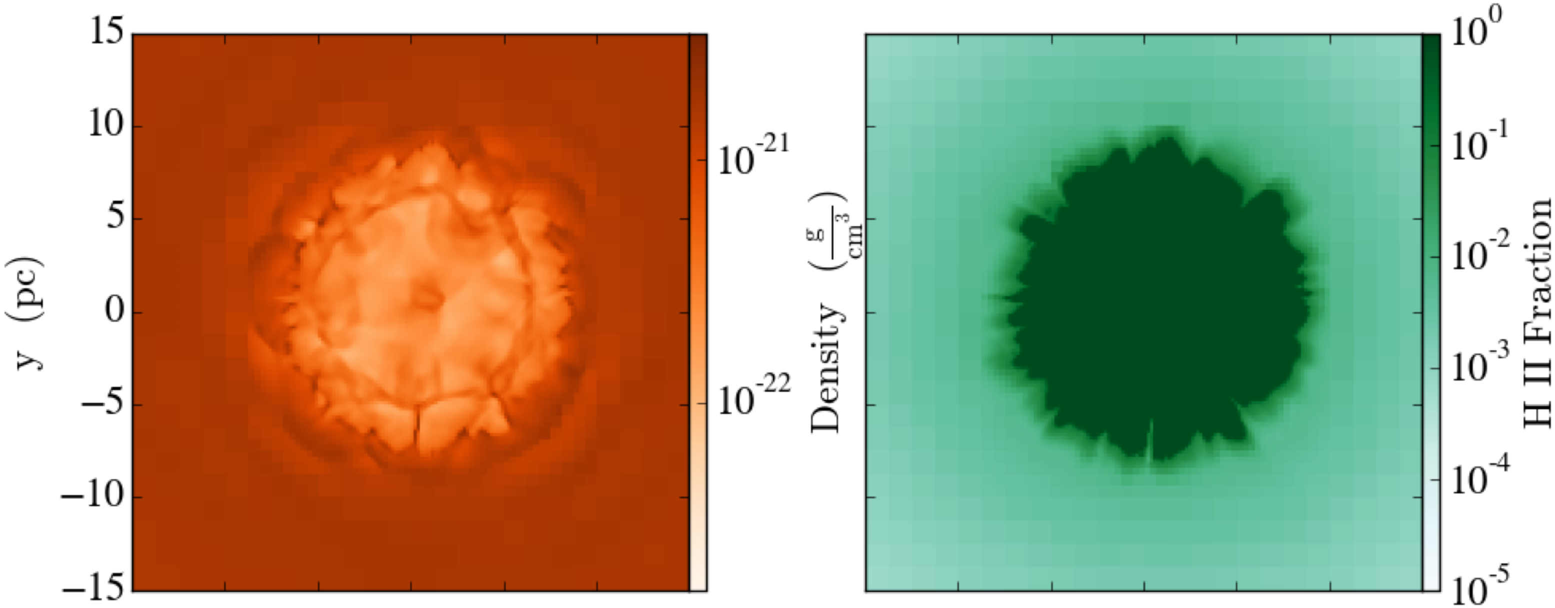
Hydrogen heating/cooling only

$$\langle\lambda_{\rm rad}\rangle \simeq 3\%\, T_{\infty,4}^{2.5}\left(\frac{T_{\rm in}}{4\times10^4\,{\rm K}}\right)^{-4}$$

w/ Helium heating/cooling

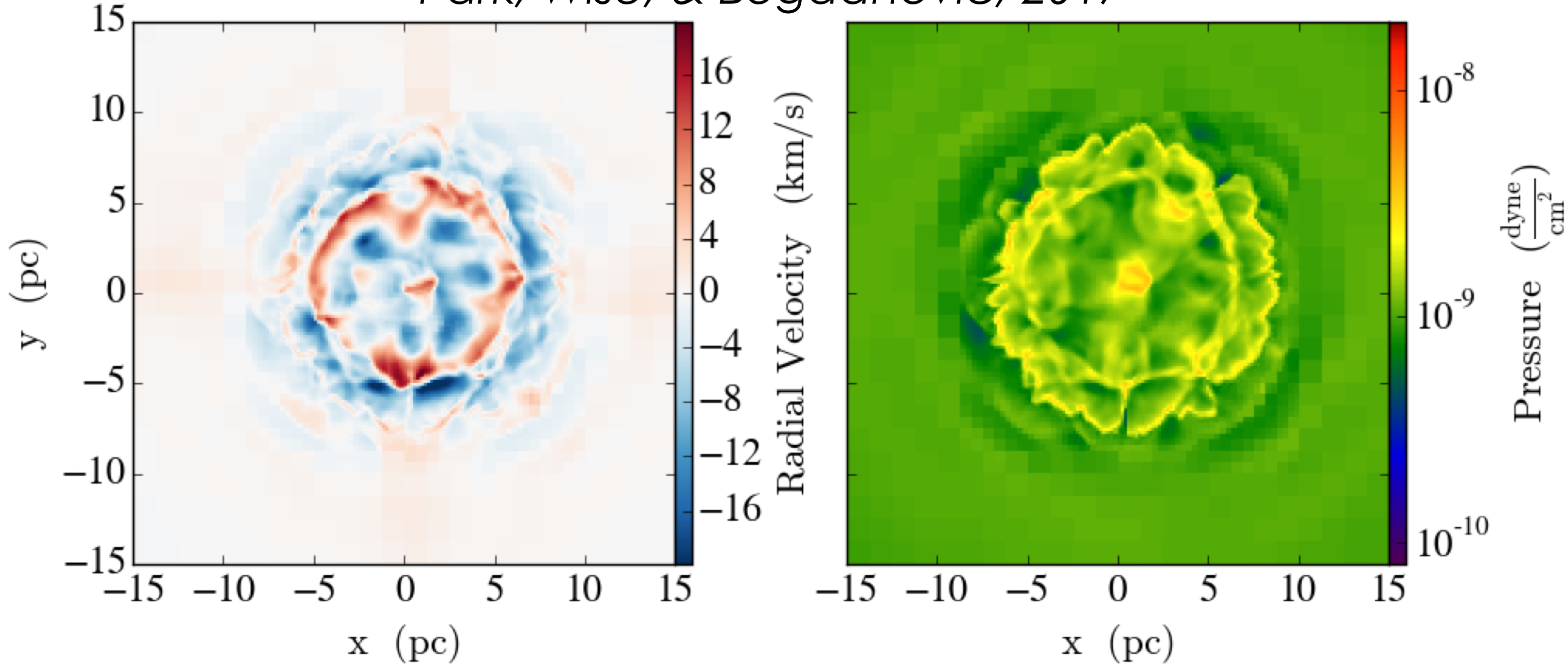
$$\langle\lambda_{\rm rad}\rangle \simeq 1\%\, T_{\infty,4}^{2.5}\left(\frac{T_{\rm in}}{6\times10^4\,{\rm K}}\right)^{-4}$$

$$f_{\rm duty} \sim 6\%\, \eta_{-1}^{-0.13}\, n_{\rm H,5}^{0.14}\, T_{\infty,4}^{0.5}$$



Radiation-driven turbulent accretion (3D simulations)

Park, Wise, & Bogdanovic, 2017

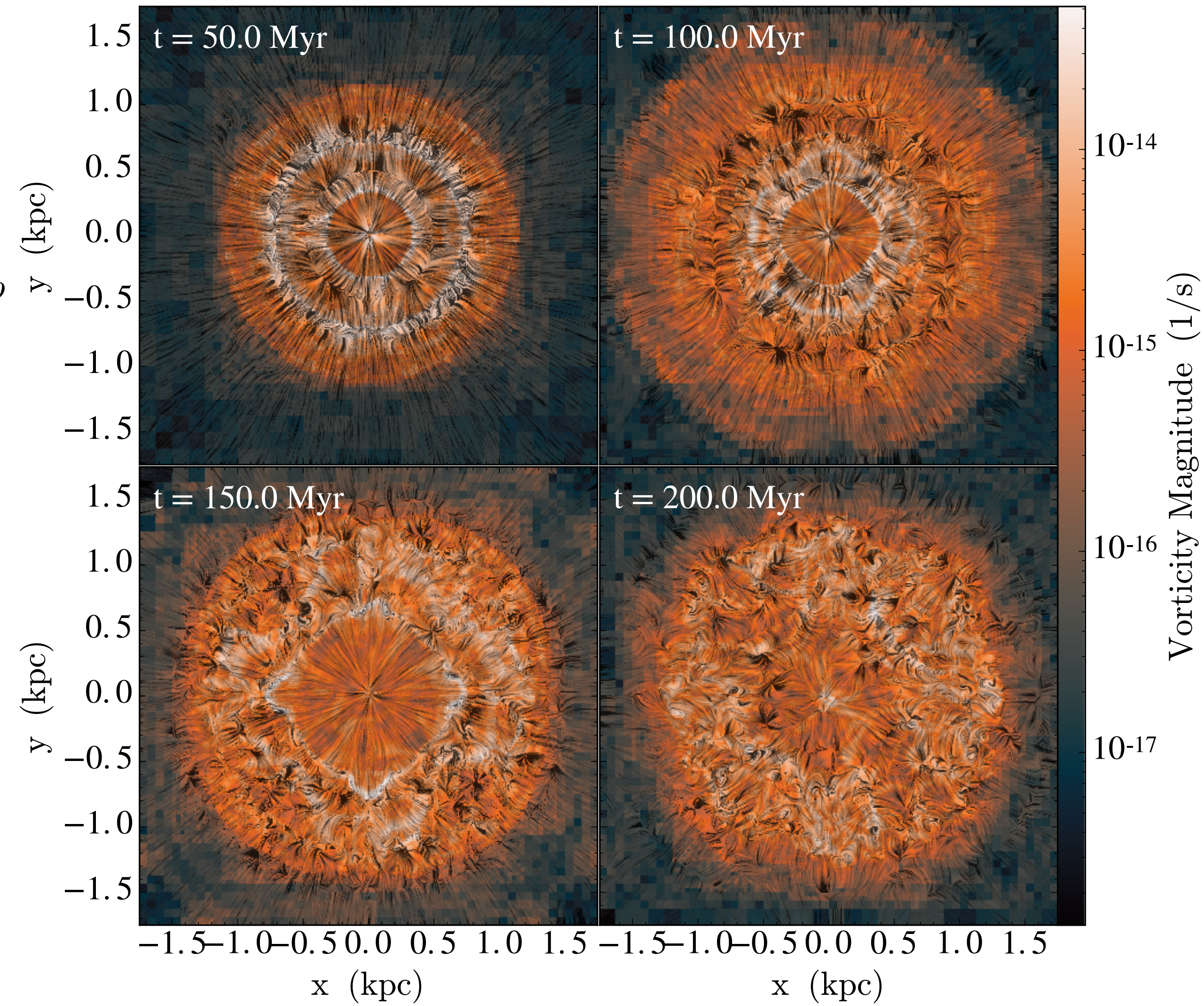


Vorticity and turbulence

$$\vec{\omega} = \vec{\nabla} \times \vec{v}$$

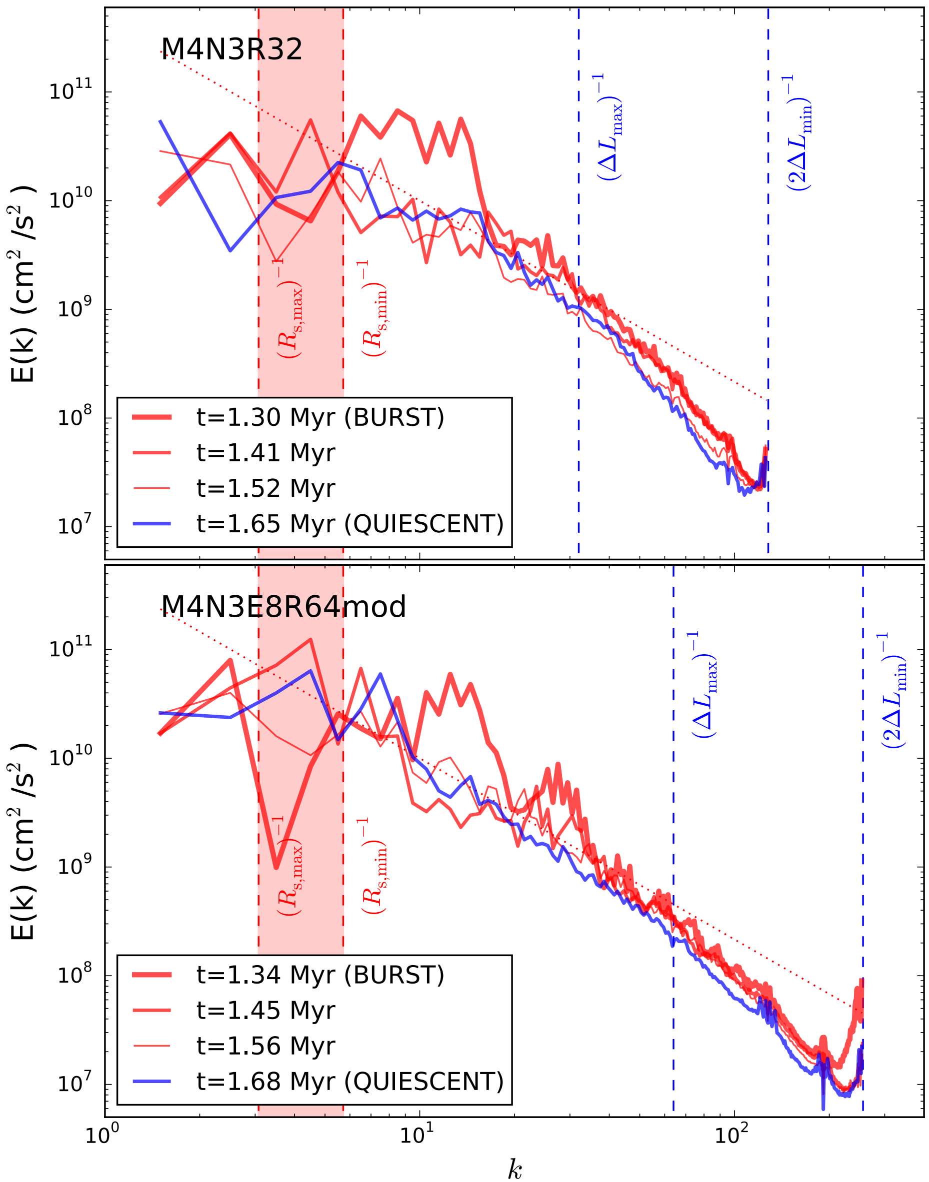
$$\frac{D\vec{\omega}}{Dt} = \frac{\partial \vec{\omega}}{\partial t} + (\vec{v} \cdot \nabla)\vec{\omega} = \frac{1}{\rho^2} \nabla \rho \times \nabla p$$

$$|\vec{\omega}|^2 \sim \frac{GM_{\rm BH}}{\langle R_s \rangle^3} \propto \frac{n_\infty}{M_{\rm BH}}$$

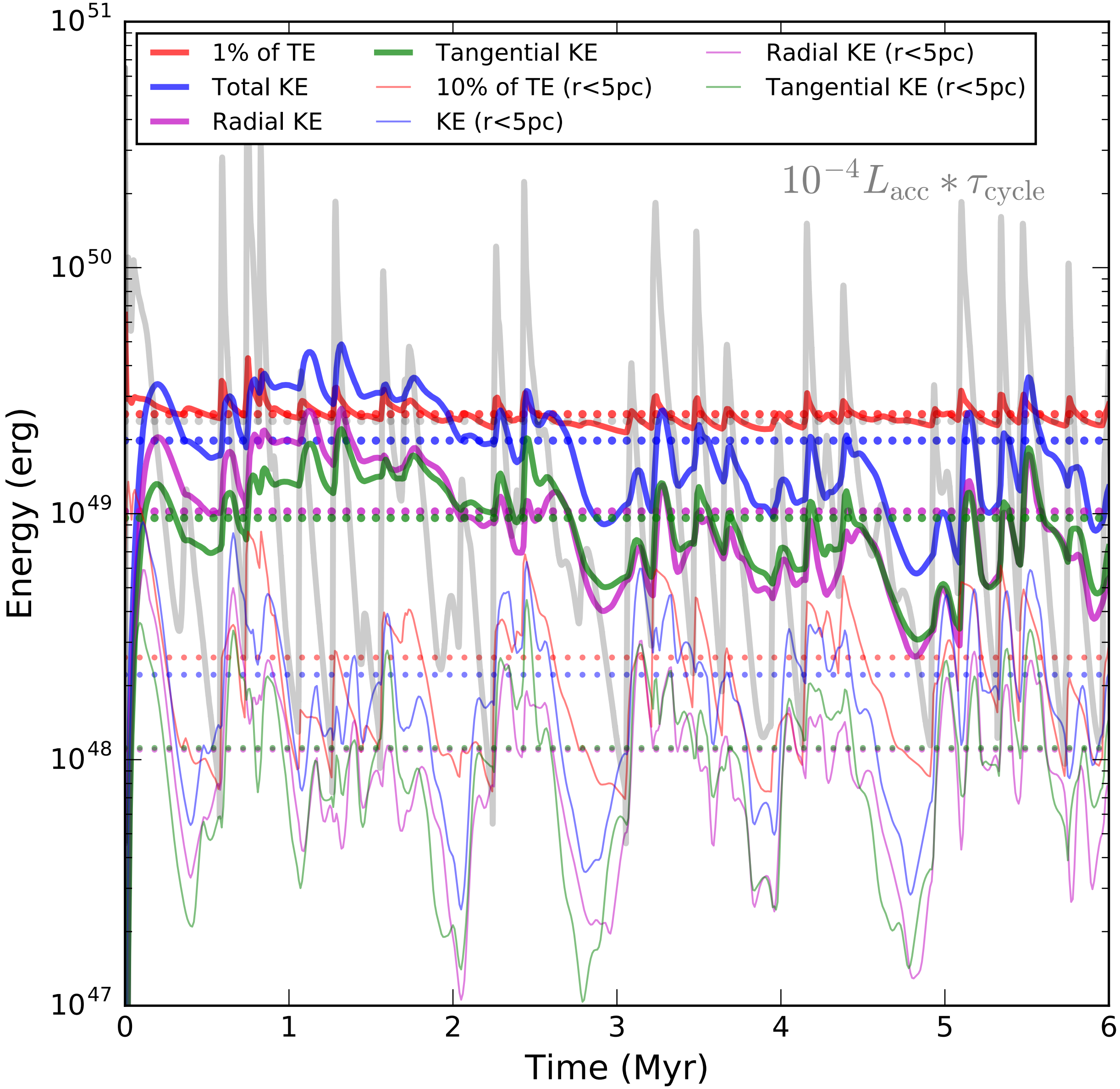


Line integral convolution of velocity field
Park, Wise, & Bogdanovic 2017

E(k): Turbulent Kinetic Energy: Typical Kolmogorov
Park, Wise, & Bogdanovic 2017



Turbulence is important?

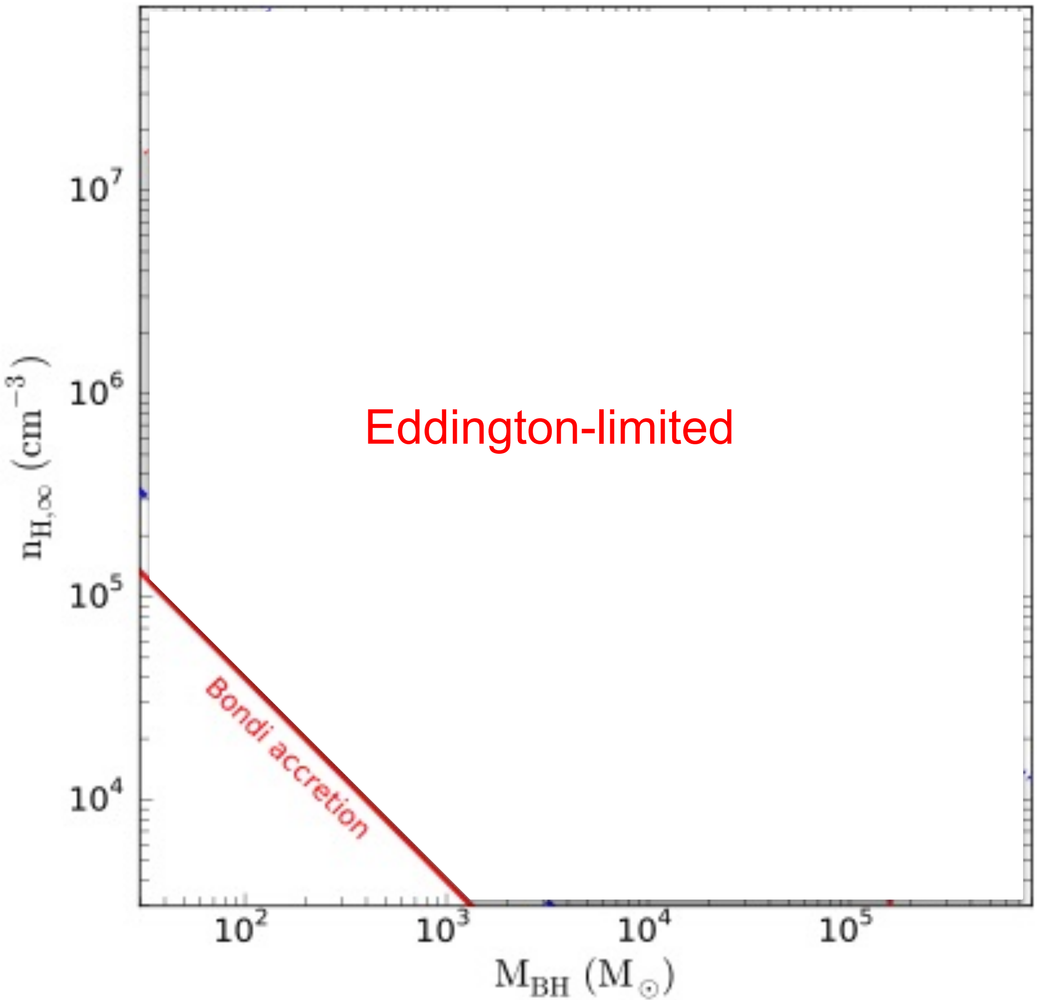


1D/2D vs. 3D simulations

	1D/2D (Park+11,12)	3D (Park+ 17)
Code	ZEUS-MP	ENZO + Moray
# of energy bins	40-100	4-8
Coordinate system	Spherical (r, theta)	Cartesian (x,y,z) with Adaptive Mesh Refinement
Resolution	Highest at r_{min}	Near the BH & around I-Front
Gas motion	Laminar	Laminar + Turbulent
Method for accretion rate	Mass flux at r_{min}	Bondi rate inside HII region
Amplitude of Mdot	~5-6 orders of mag	~2-3 orders of mag
mean accretion rate & period	consistent	consistent
Extensibility	Single BH, spherically symmetric or axisymmetric accretion	Non-spherically symmetric accretion, multiple BHs, Cosmological set-up

Accretion regimes

Mode I, Mode II, super-Eddington



- Different accretion regimes as a function of BH mass & Gas density
  - **Mode I** : ~ 1 percent of Bondi rate, 5-6 orders of difference between max/min accretion rates
  - **Mode II** : Eddington-limited, 1-2 orders of mag difference between max/min accretion rates.
  - **super-Eddington** : at high M_{BH} and n_H

- Low accretion rate : only ~1 percent of Bondi rate

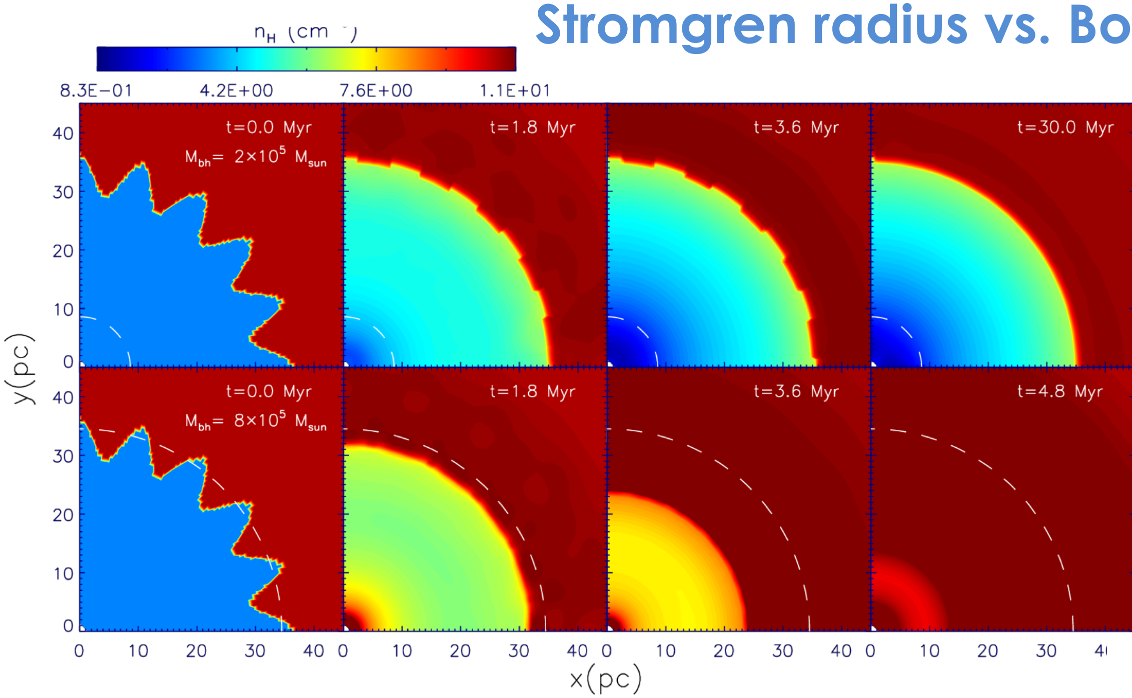
Park, Ricotti, Natarajan, Wise, Bogdanovic (2016)

Hyper-accretion regime

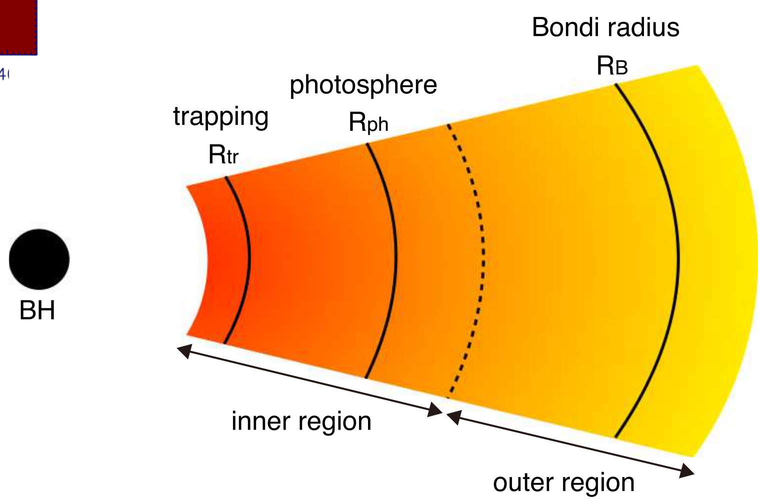
Radiative Feedback is not important any more?
Back to Bondi accretion?

Hyper-accretion

Stromgren radius vs. Bondi radius

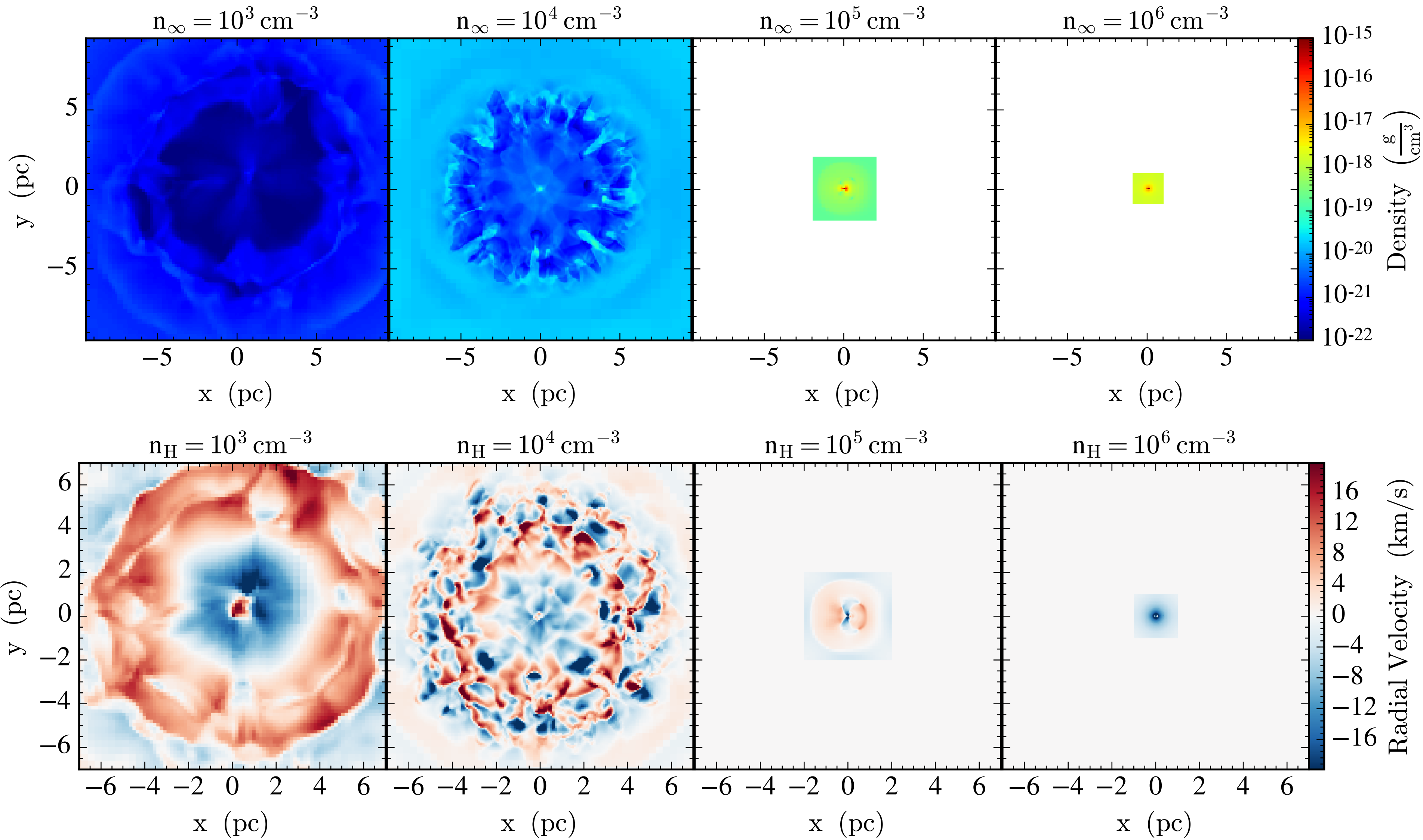


Park, Ricotti, Di Matteo, & Reynolds (2014a)

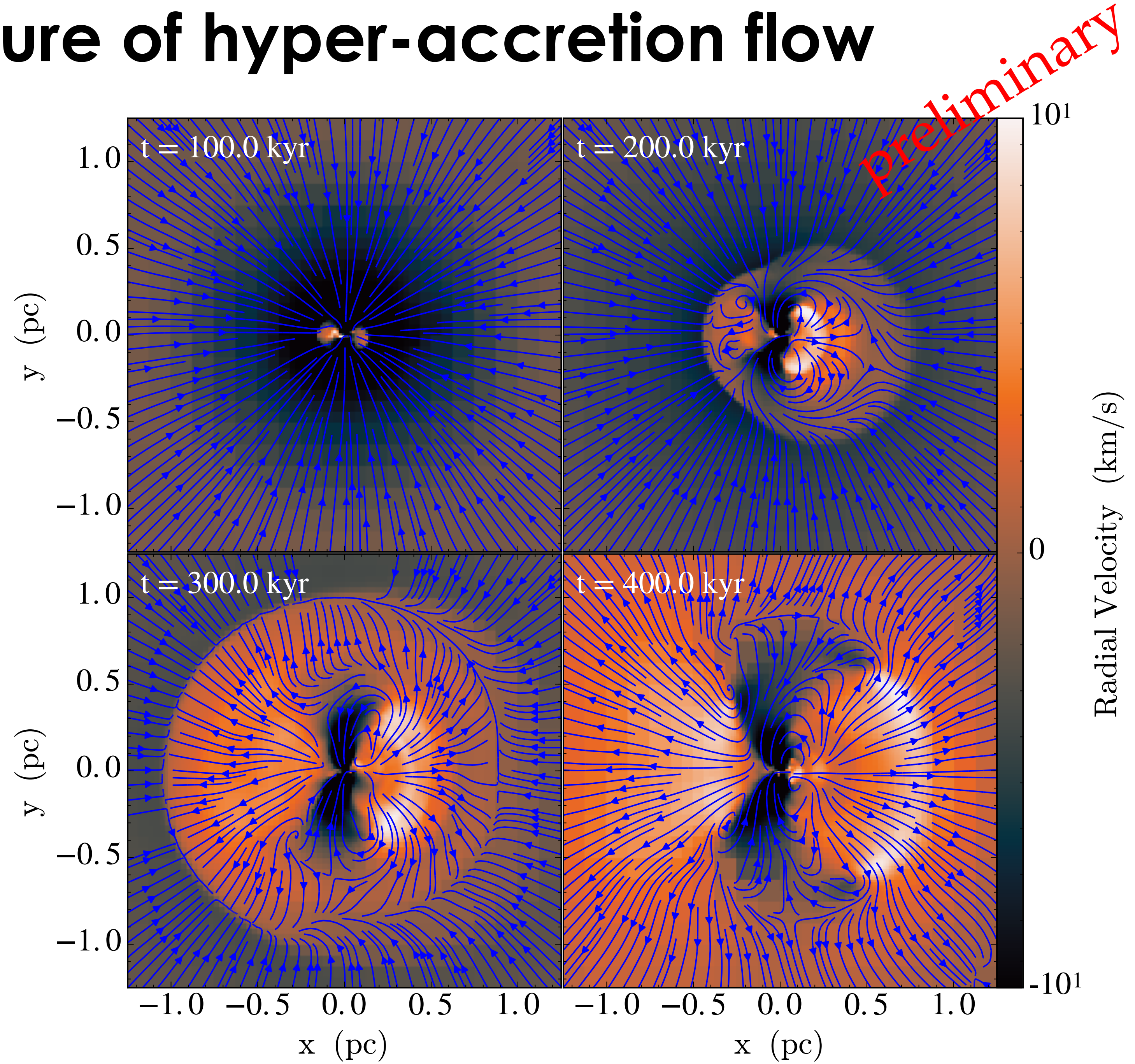


Inayoshi, Haiman & Ostriker (2016)
Sakurai et al. (2016)

Transition to hyper-accretion regime



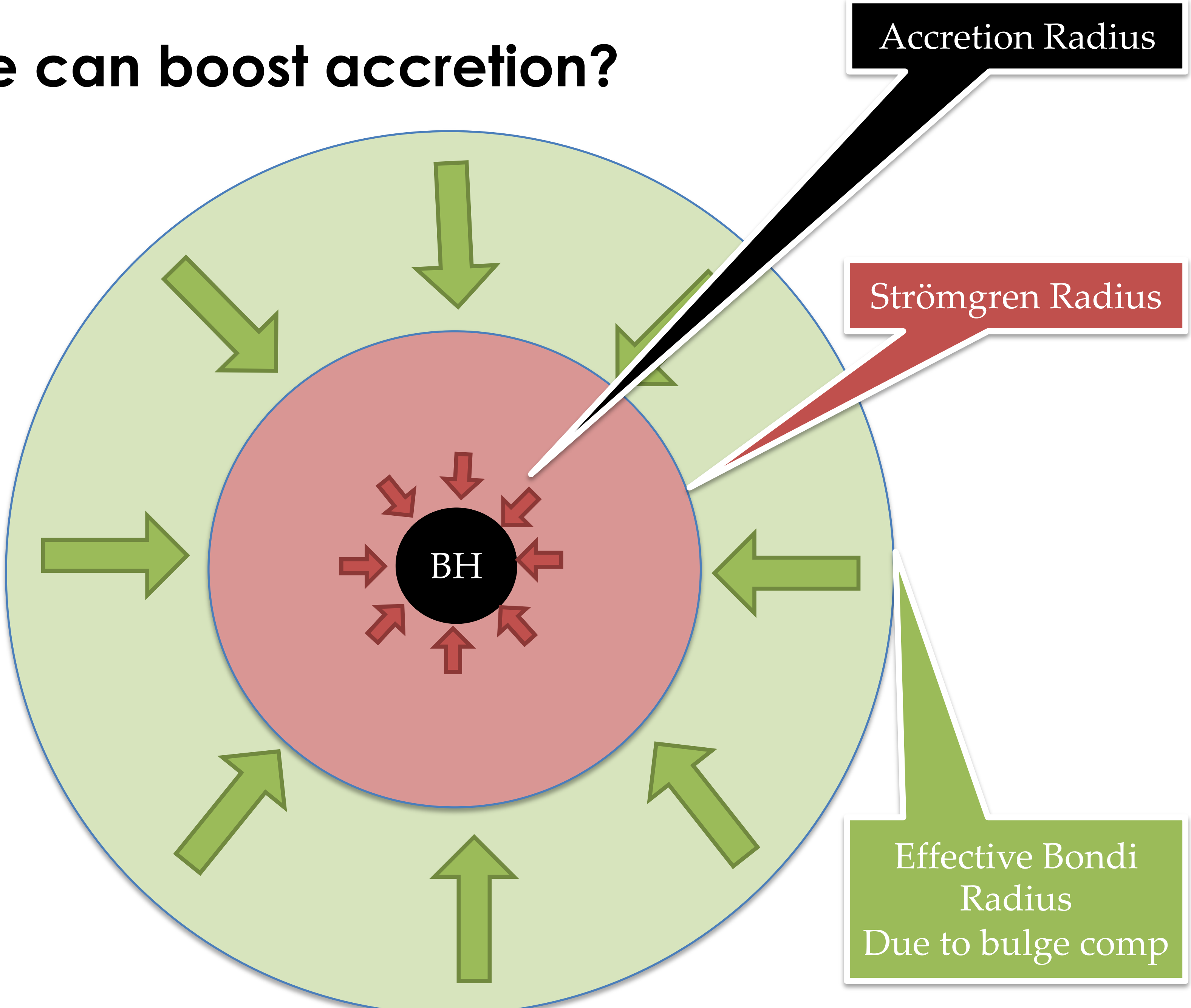
3D structure of hyper-accretion flow



Bulge-driven growth of seed BHs

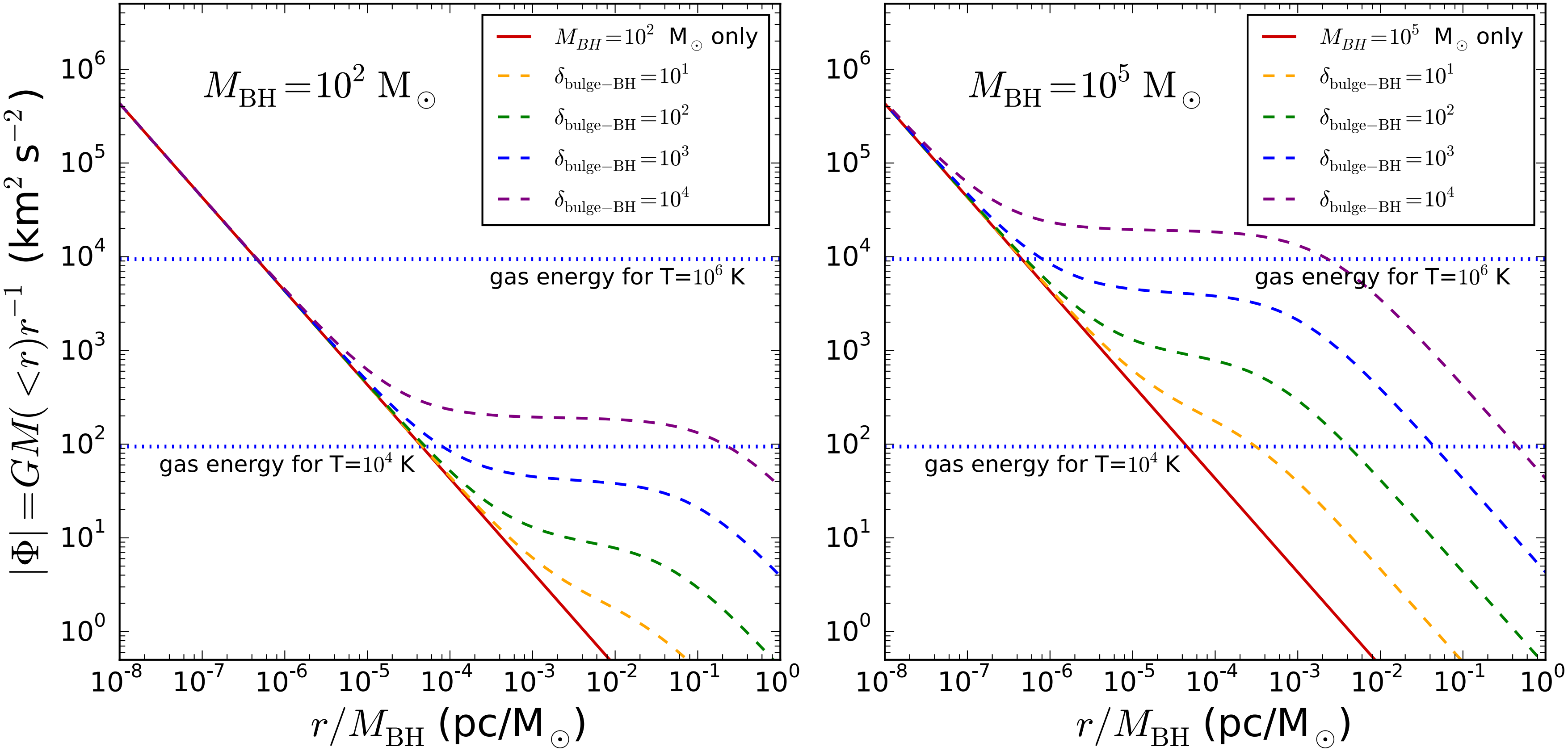
a possibility for hyper-accretion regime

Bulge can boost accretion?



Effective Bondi radius

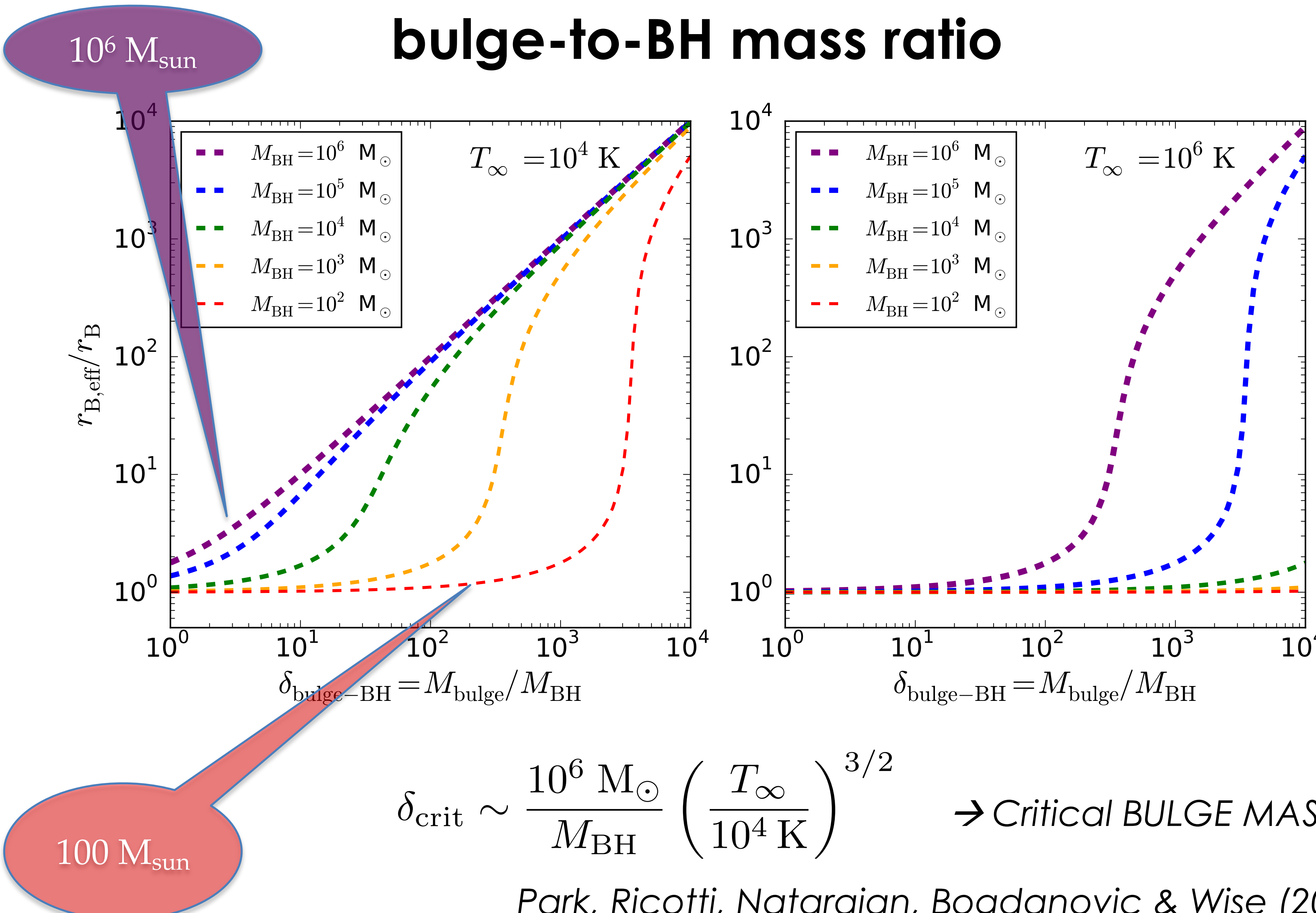
increased Bondi radius due to bulge



$$\frac{GM_{\rm BH}}{r_{\rm B,eff}} \equiv c_\infty^2$$

- Bulge : Hernquist (1990) profile
- Gas temperature
- BH Mass

Effective Bondi Radius as a function of bulge-to-BH mass ratio

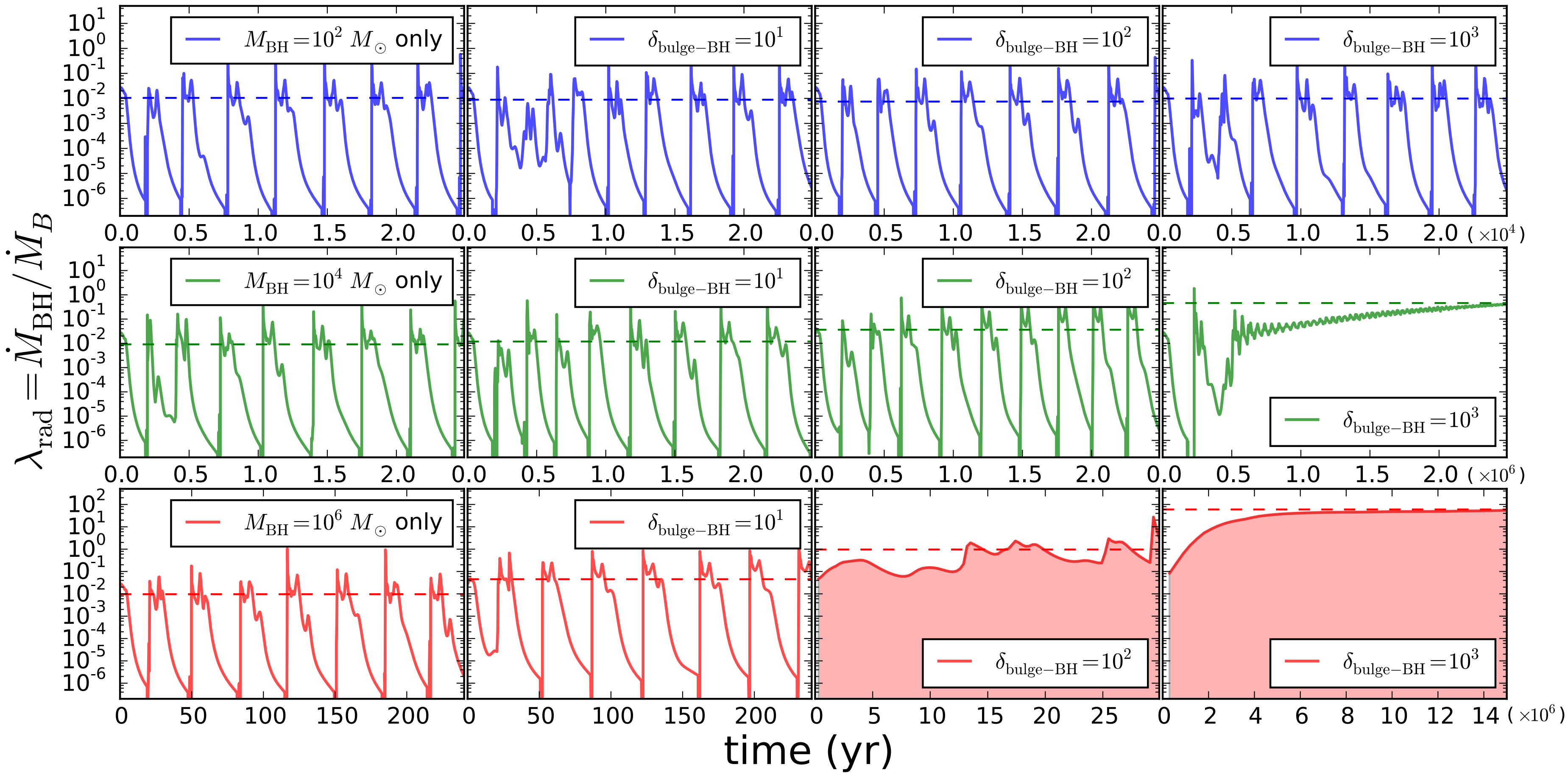


$$\delta_{crit} \sim \frac{10^6\ M_\odot}{M_{BH}} \left(\frac{T_\infty}{10^4\ K} \right)^{3/2}$$

→ *Critical BULGE MASS*

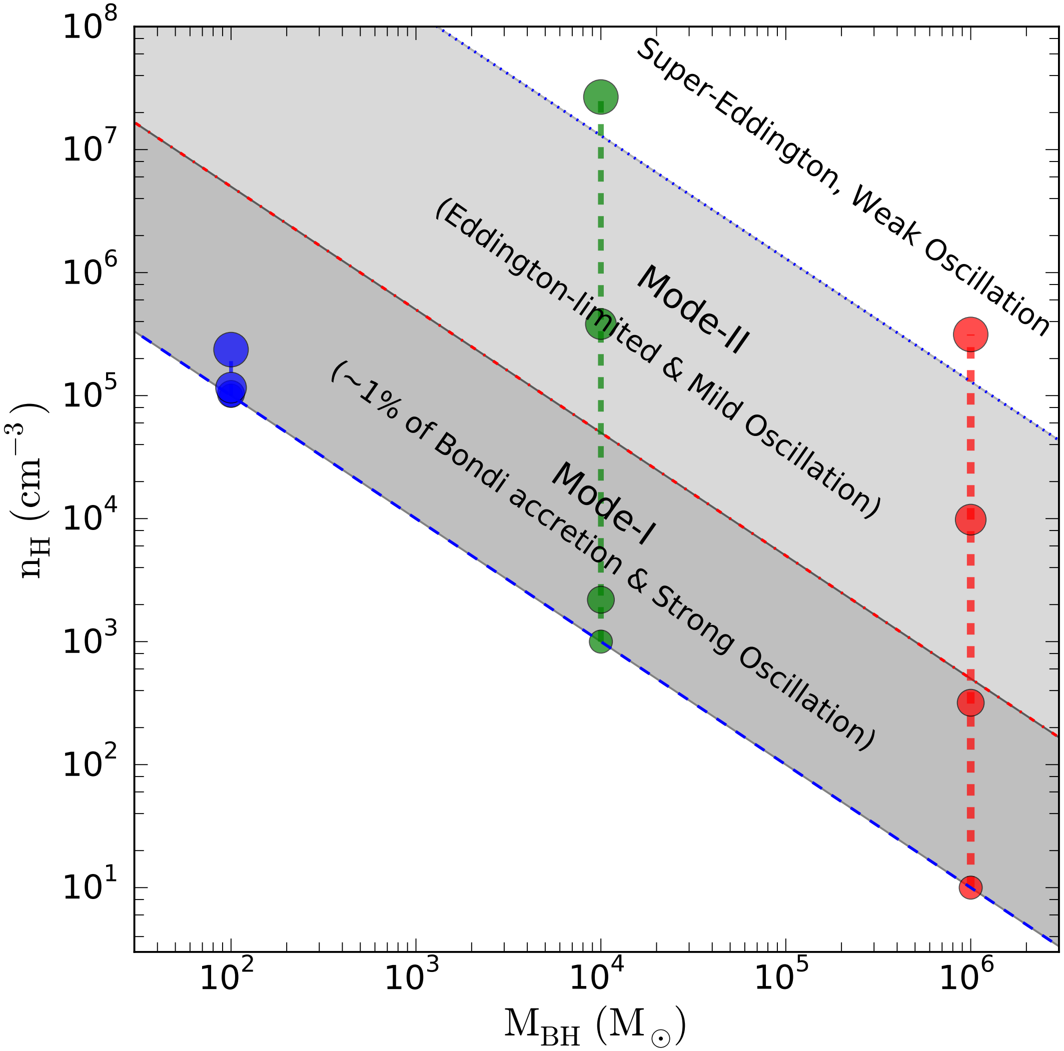
Park, Ricotti, Natarajan, Bogdanovic & Wise (2016)

Accretion rate as a function of bulge-to-BH ratio
with radiative feedback



Park, Ricotti, Natarajan, Bogdanovic & Wise (2016)

Transition of Accretion Regime due to bulge component

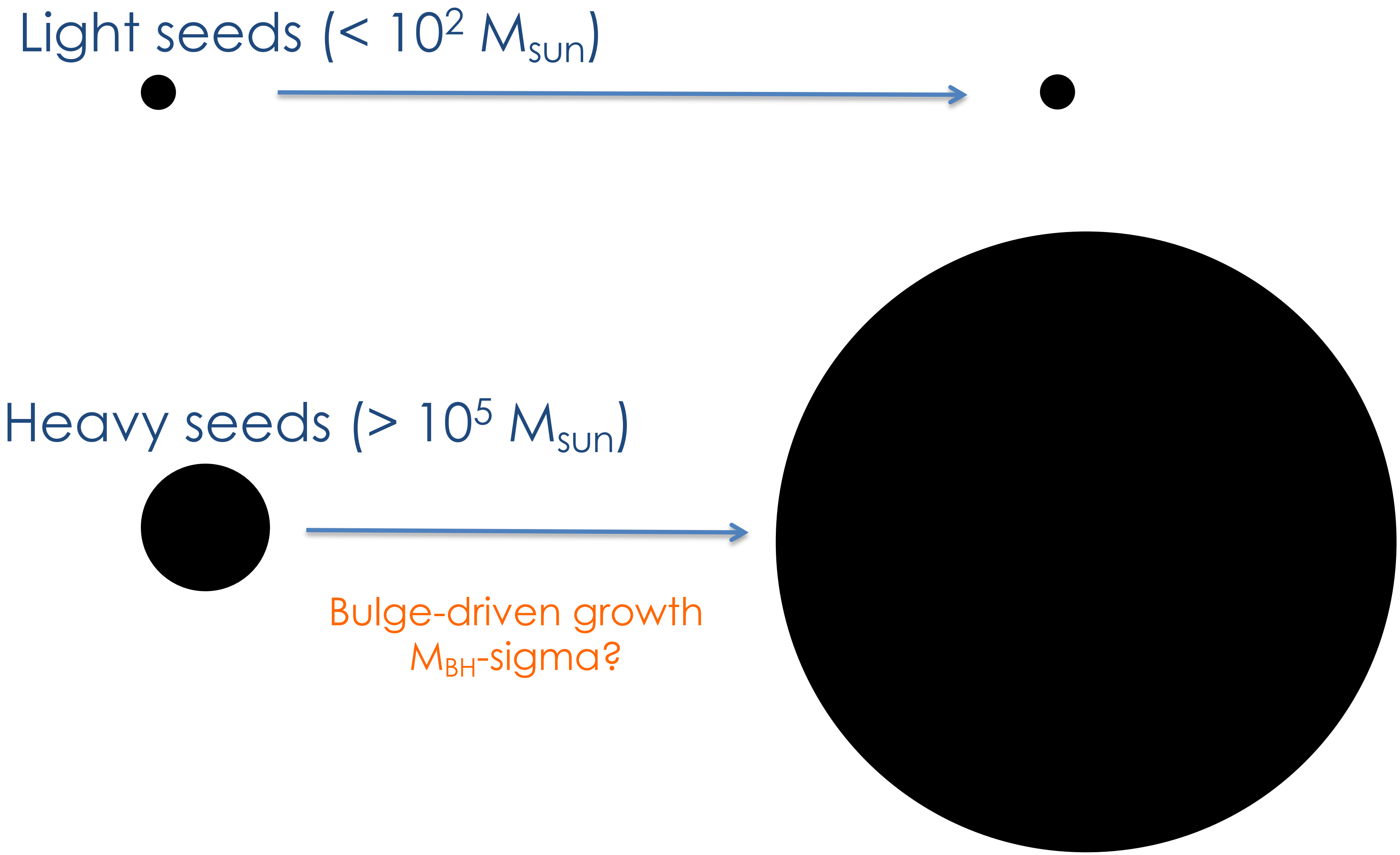


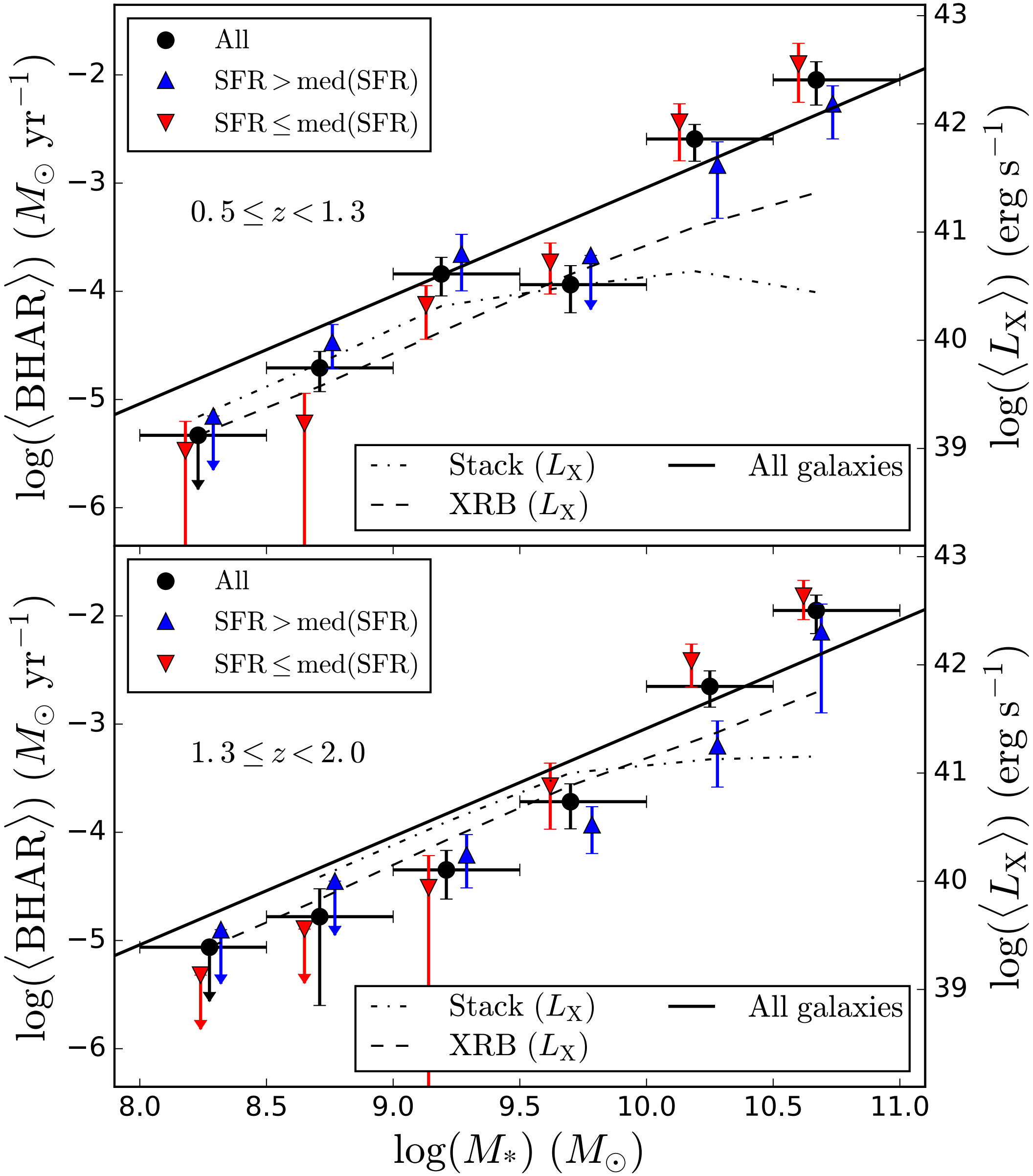
$$\dot{M}_{\rm BH} = \dot{M}_{\rm B} \left(\frac{r_{\rm B,eff}}{r_{\rm B}} \right)^{\beta}$$

$$\dot{M}_{\rm BH} \sim \dot{M}_{\rm B} \frac{M_{\rm bulge}}{M_{\rm bulge,crit}}$$

Park, Ricotti, Natarajan, Bogdanovic & Wise (2016)

Growth of light vs. heavy seed black holes





BH GROWTH IS MAINLY LINKED TO HOST-GALAXY **STELLAR MASS** RATHER THAN **STAR FORMATION RATE** !!

Yang et al. (2017)

Summary

- **Radiative feedback** from BHs efficiently **suppresses** accretion rate onto BHs (~1% of Bondi rate) and accretion rate shows highly **oscillatory** behavior.

- **Hyper-accretion** is a mechanism that can explain the rapid growth of seed BHs in the early universe. Build-up of stellar **bulge** component may enhance accretion rates onto **heavy seeds**.