Growth of Seed Black Holes in the early Universe

KwangHo Park

Georgia Tech Center for Relativistic Astrophysics
College of Sciences

Massimo Ricotti (UMD), Chris Reynolds (UMD),
Priyamvada Natarajan (Yale),
Tamara Bogdanović (GT), John Wise (GT)

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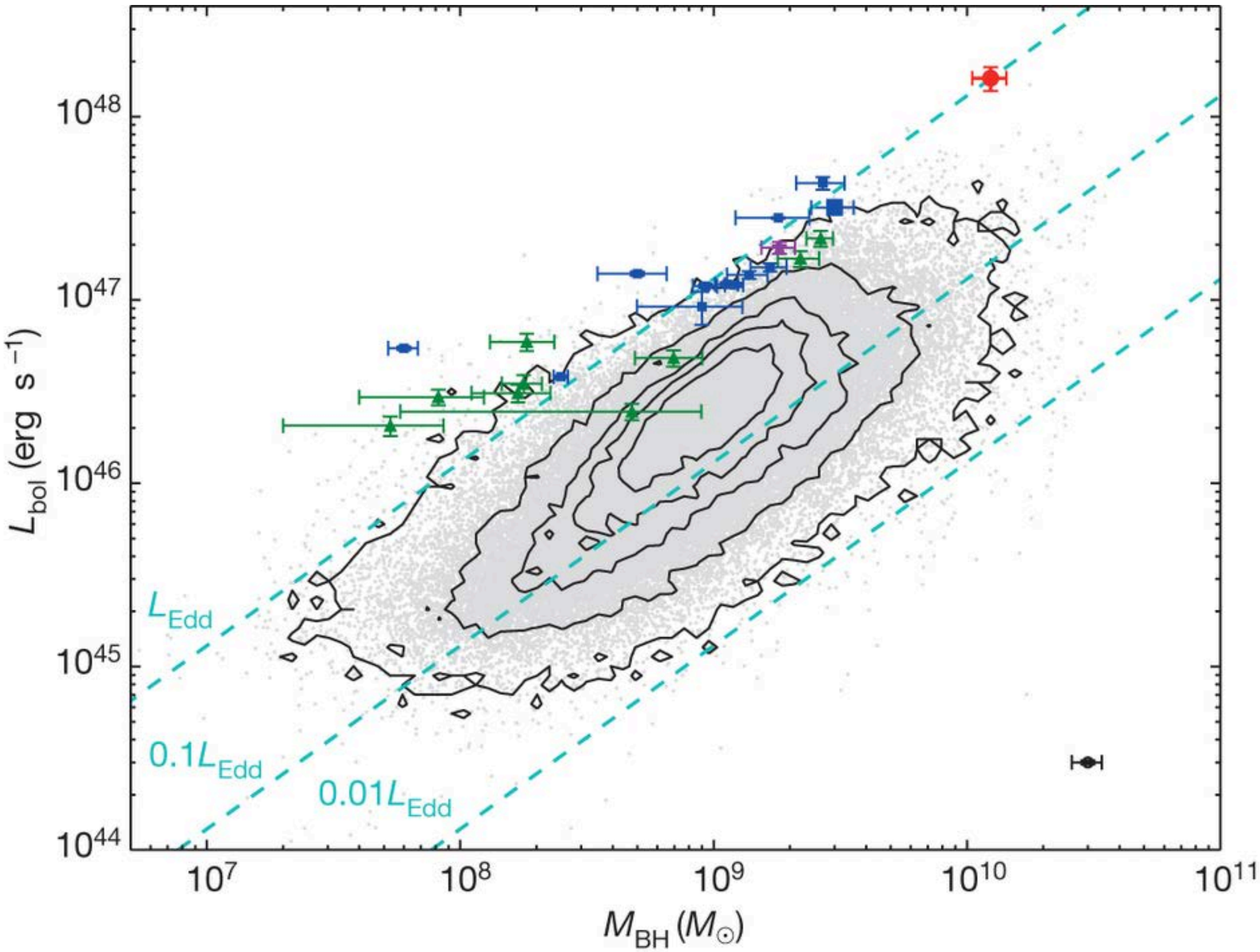
Observation

Quasars at z=6-7
BH mass ~10^8 - 10^9 M_{sun}

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

We have a big problem...



- Quasars – actively accreting BHs
- At z~7 (age ~ 700 Myr), 10^8-10^9 solar mass quasars are observed
- Red symbol : 13 billion solar mass at z=6.3
- Grey contour : low redshift SDSS quasars

Wu et al. (2015)

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 : $\sim 10^5\ M_\odot$

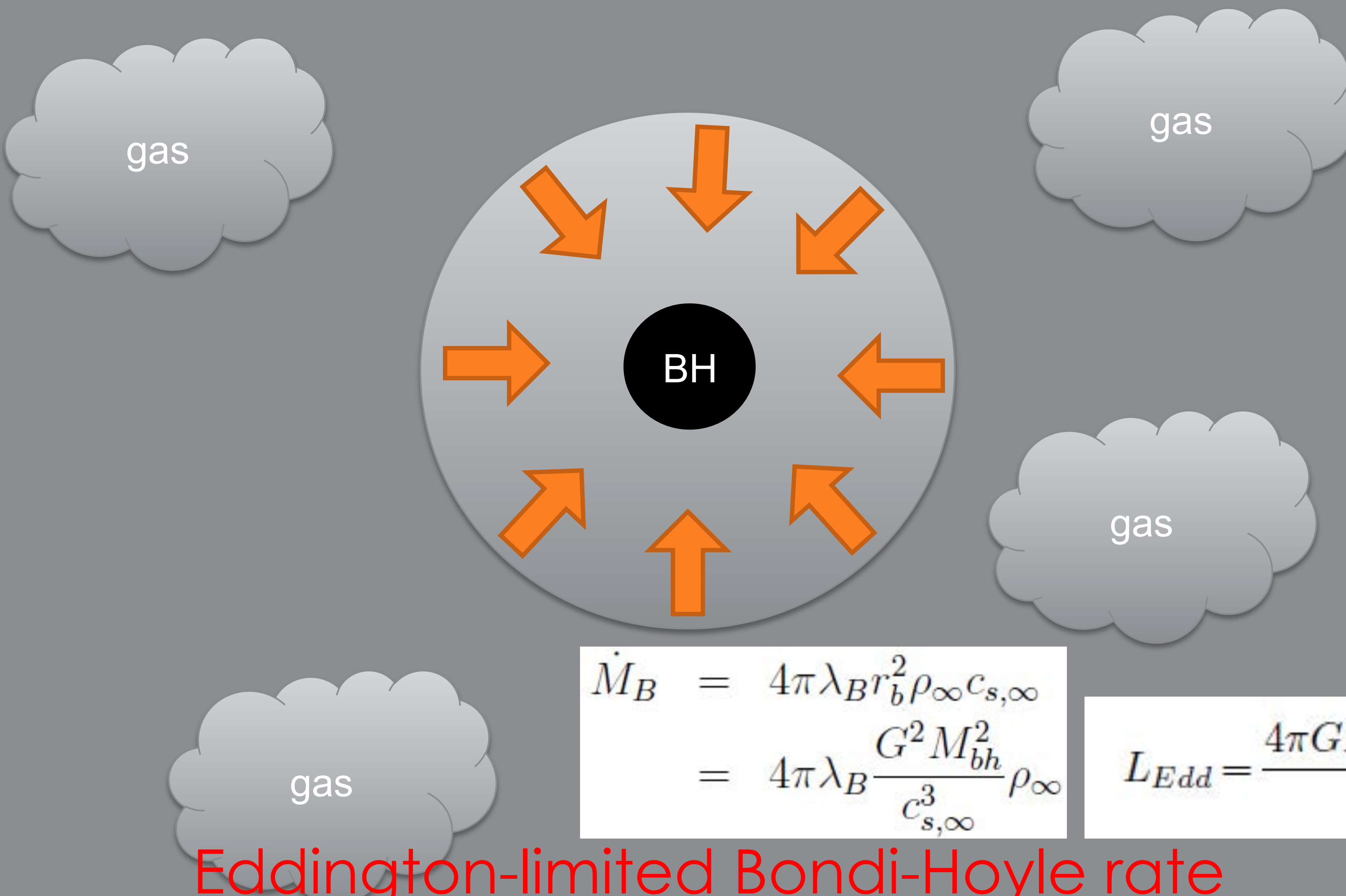
- E.g., Pop III remnants
  - Initial mass should increase by 7 orders of mag
  - Should Accrete at Eddington rate for ~700 Myr

- Estimation of grow rate is important!

Volonteri 12
Natarajan 11

How do we estimate an accretion rate onto a BH?

Bondi Accretion (1952)

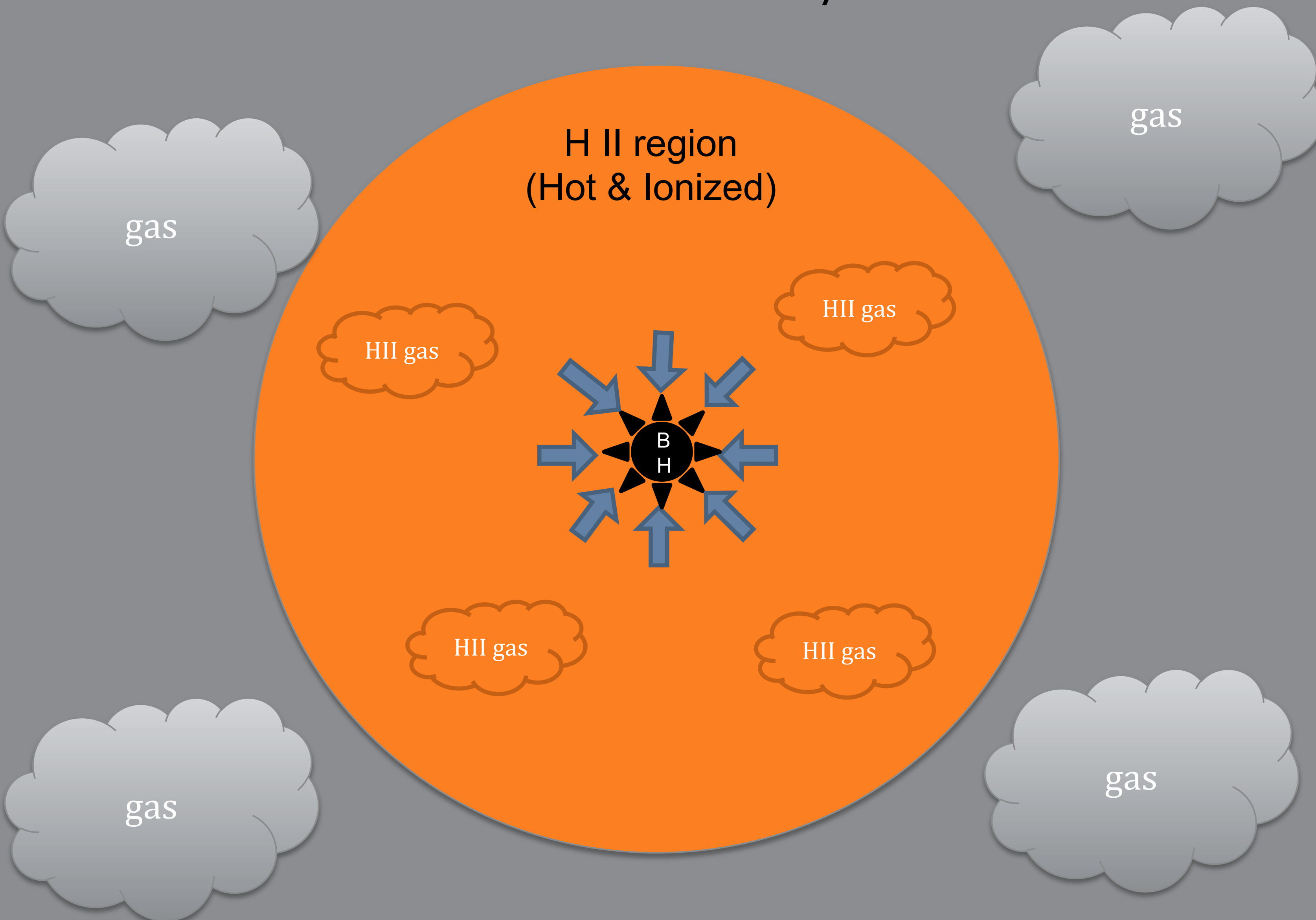


$$\begin{aligned}\dot{M}_B &= 4\pi\lambda_B r_b^2 \rho_\infty c_{s,\infty} \\ &= 4\pi\lambda_B \frac{G^2 M_{bh}^2}{c_{s,\infty}^3}\rho_\infty\end{aligned}$$

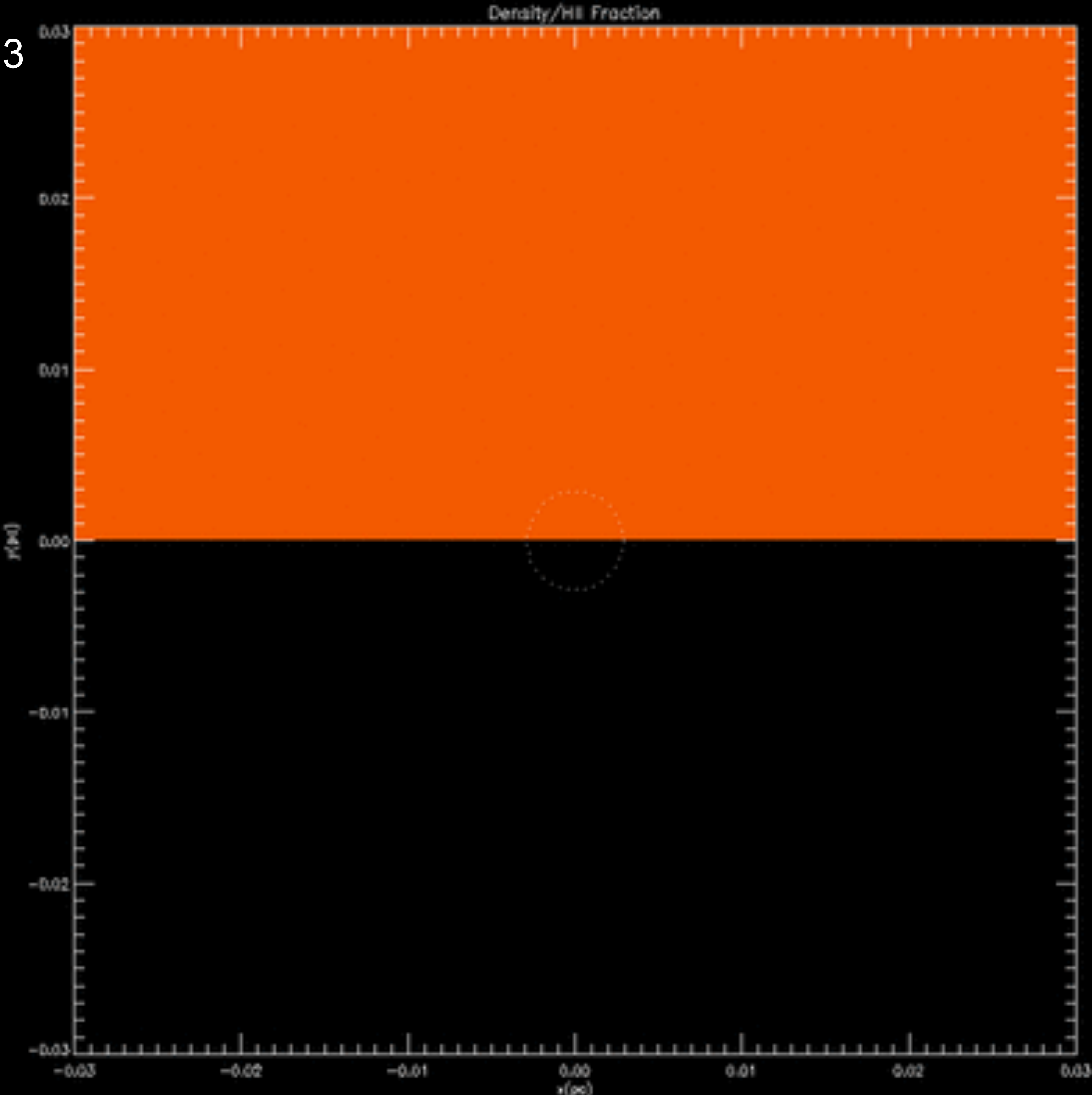
$$L_{Edd} = \frac{4\pi G M_{bh} m_p c}{\sigma_T}$$

Eddington-limited Bondi-Hoyle rate

Radiative Feedback by Black Holes



0.03



y (pc)

Density

Ionization Fraction

-0.03

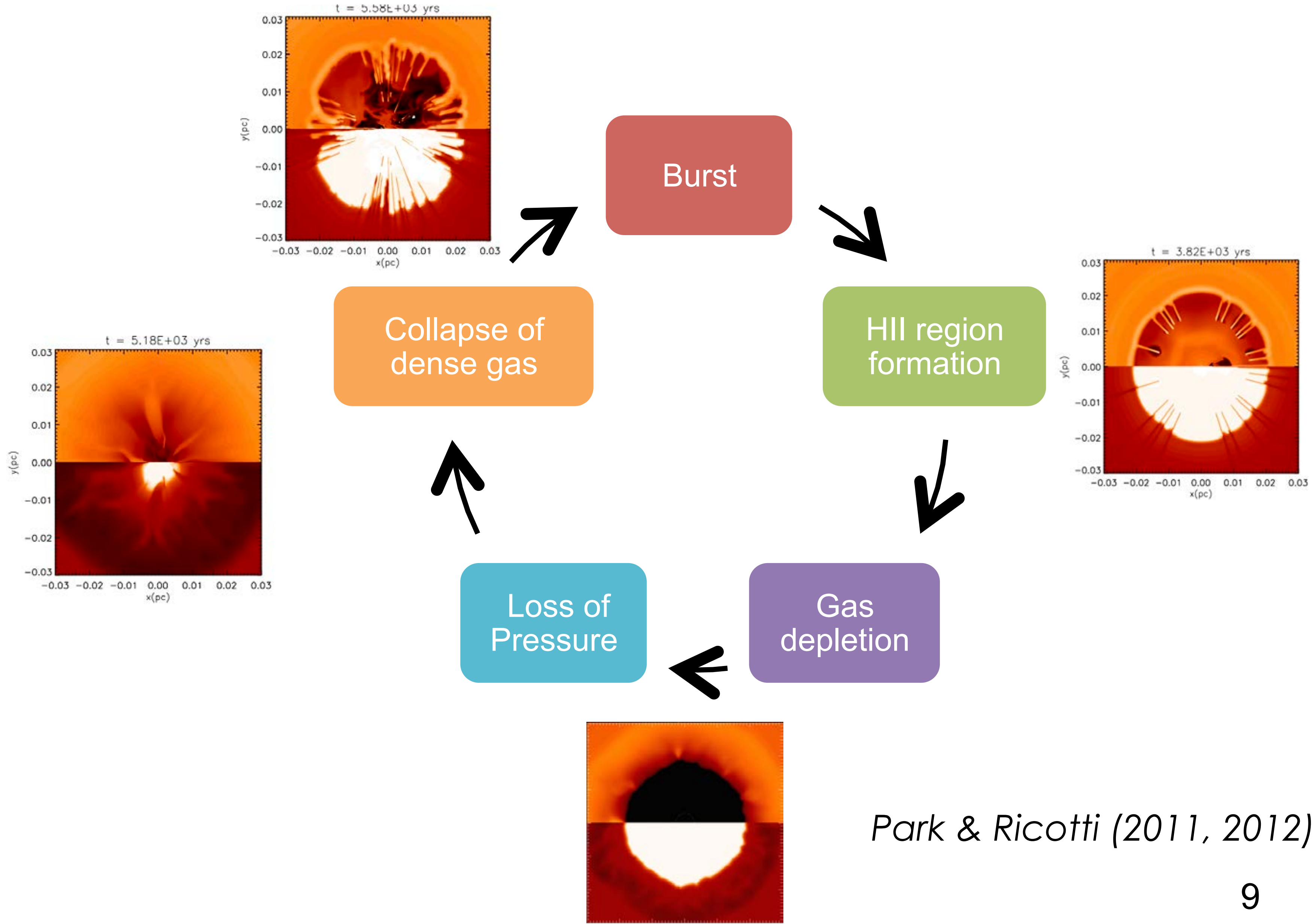
x (pc)

0.03

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

Radiation-regulated accretion

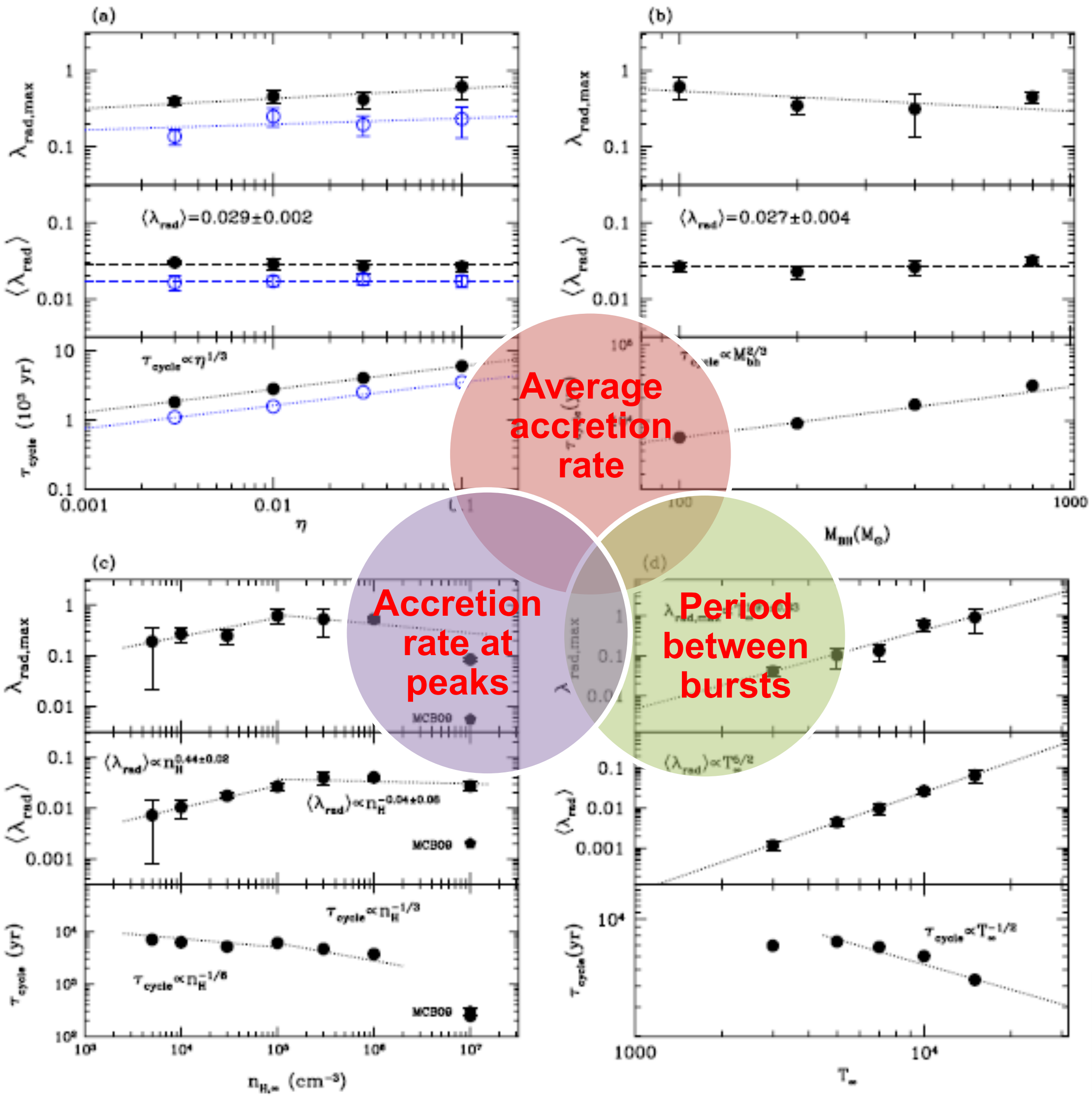
Periodic oscillation of accretion rate due to accretion/feedback loop

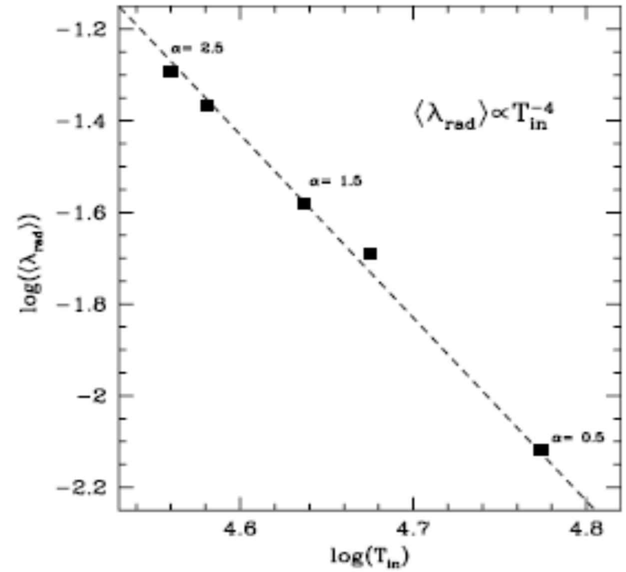


Park & Ricotti (2011, 2012)

Radiation-regulated accretion

accretion rate is suppressed by ~2 orders of mag





Hydrogen heating/cooling only

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

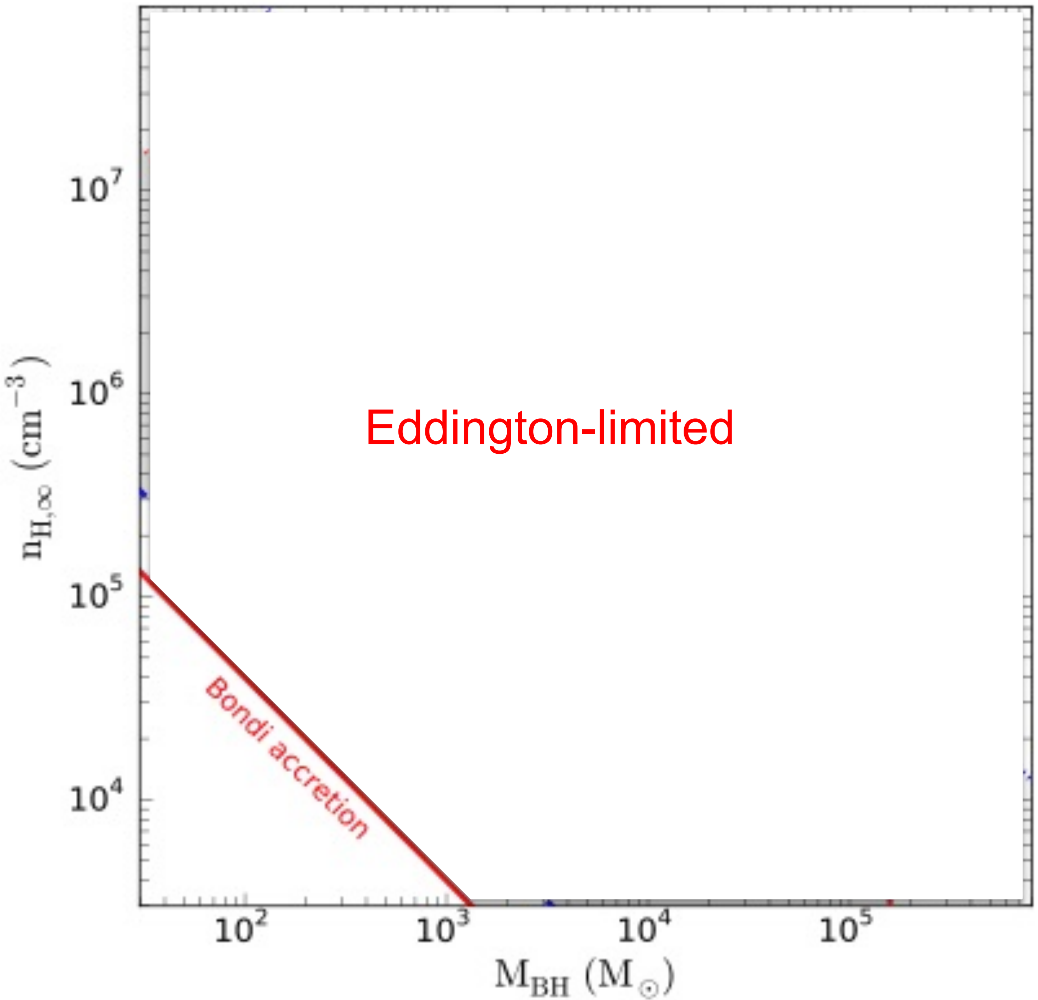
w/ Helium heating/cooling

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

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

Accretion regimes

Mode I, Mode II, super-Eddington

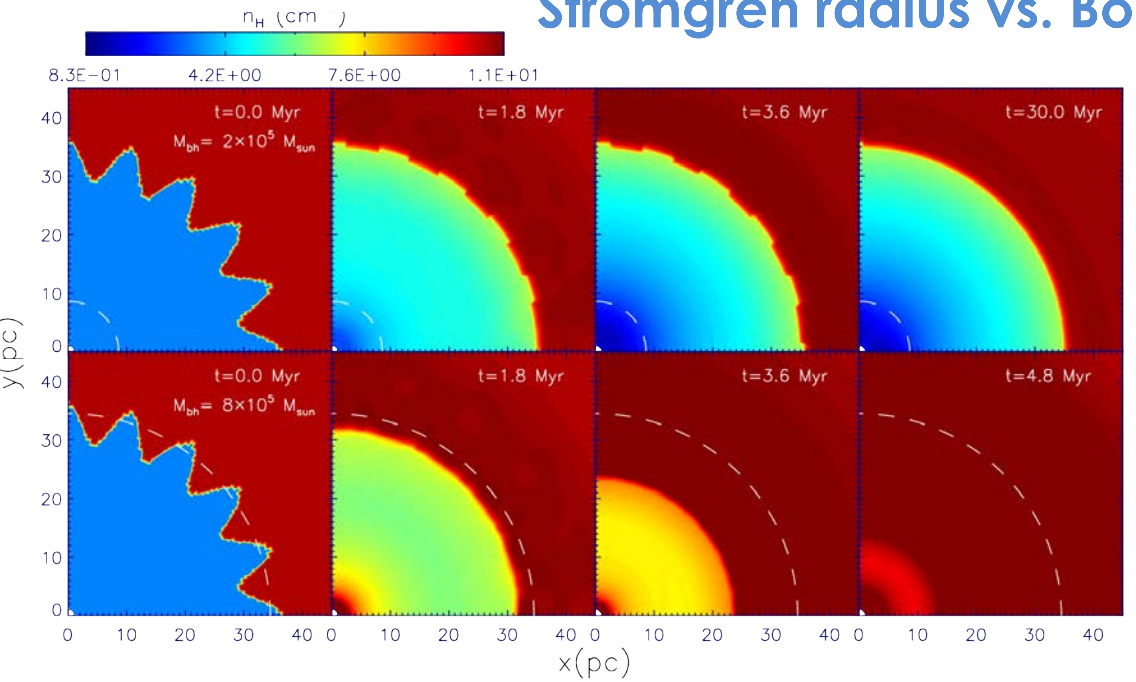


Park & Ricotti (2012)

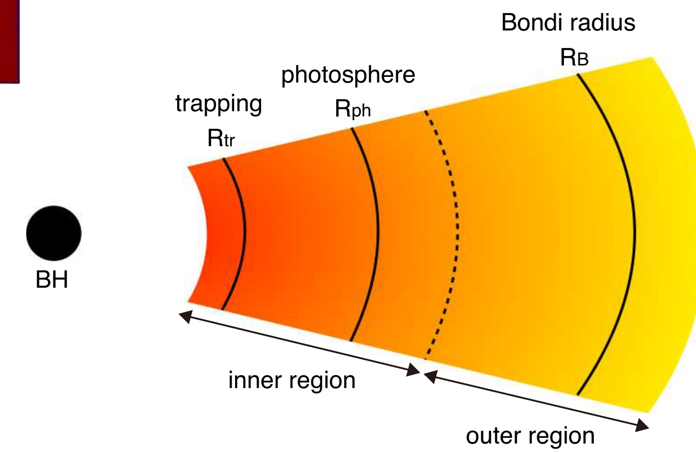
- Different accretion regimes as a function of BH mass & Gas density
  - **Mode I** : ~ 1 percent of Bondi rate, 5-6 orders of difference between max/min accretion rates
  - **Mode II** : Eddington-limited, 1-2 orders of mag difference between max/min accretion rates.
  - **super-Eddington** : at high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

Hyper-accretion ?

Stromgren radius vs. Bondi radius



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



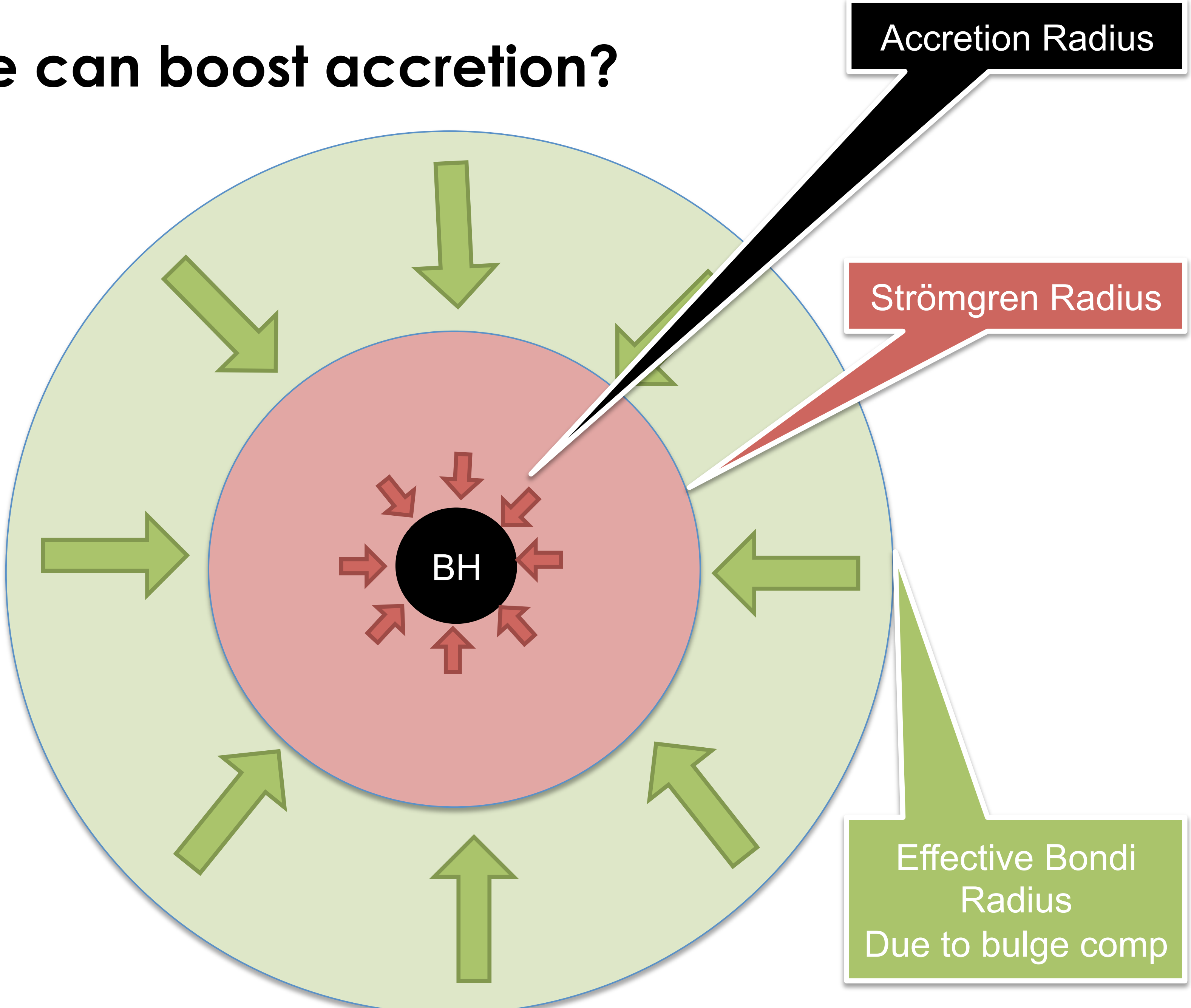
Inayoshi, Haiman & Ostriker (2016)
Sakurai et al. (2016)

Sugimura et al. (2016) : Anisotropic radiation
Park et al. in prep

Bulge-driven Growth of Seed Black Holes

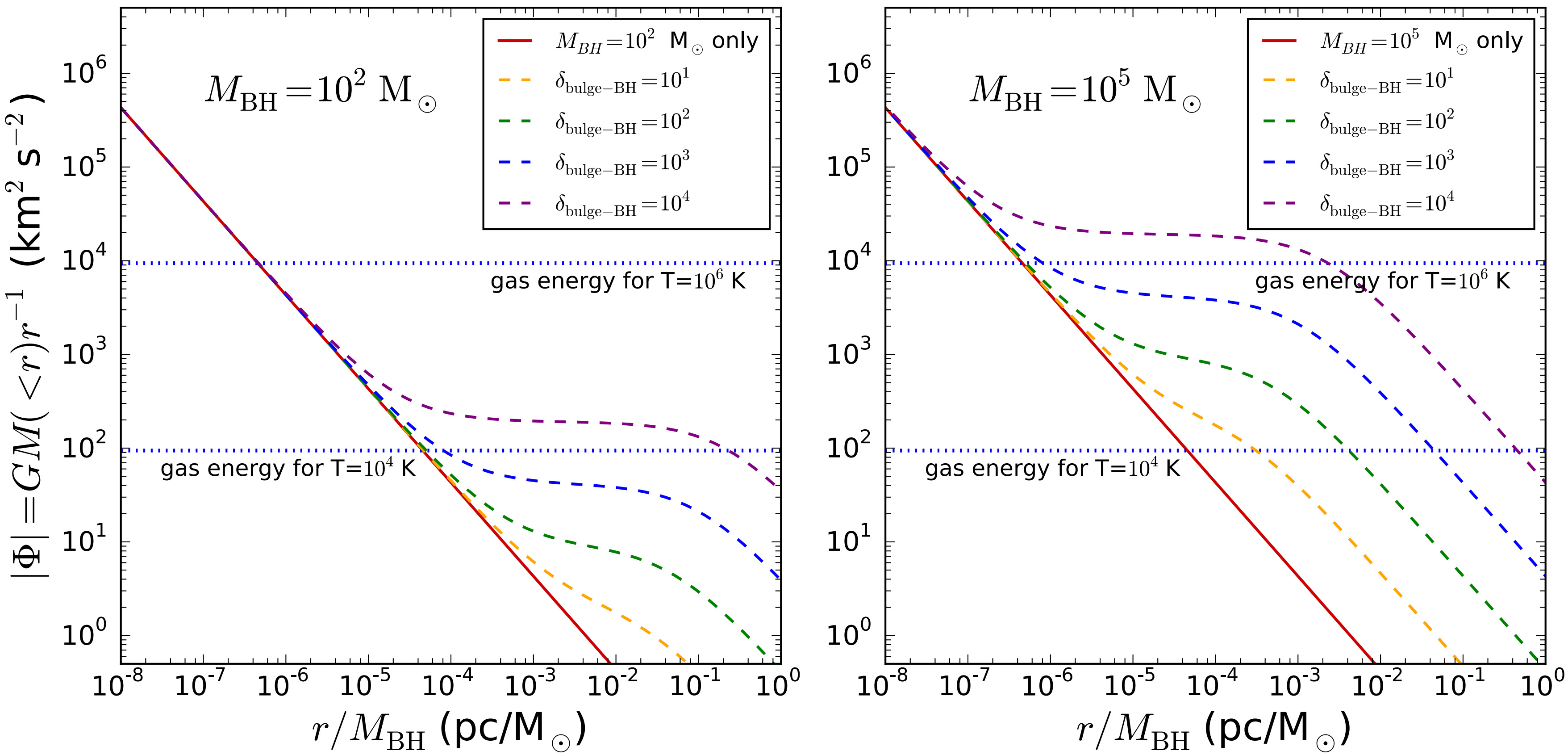
Only the gravitational potential of a BH has been considered so far....

Bulge can boost accretion?



Effective Bondi radius

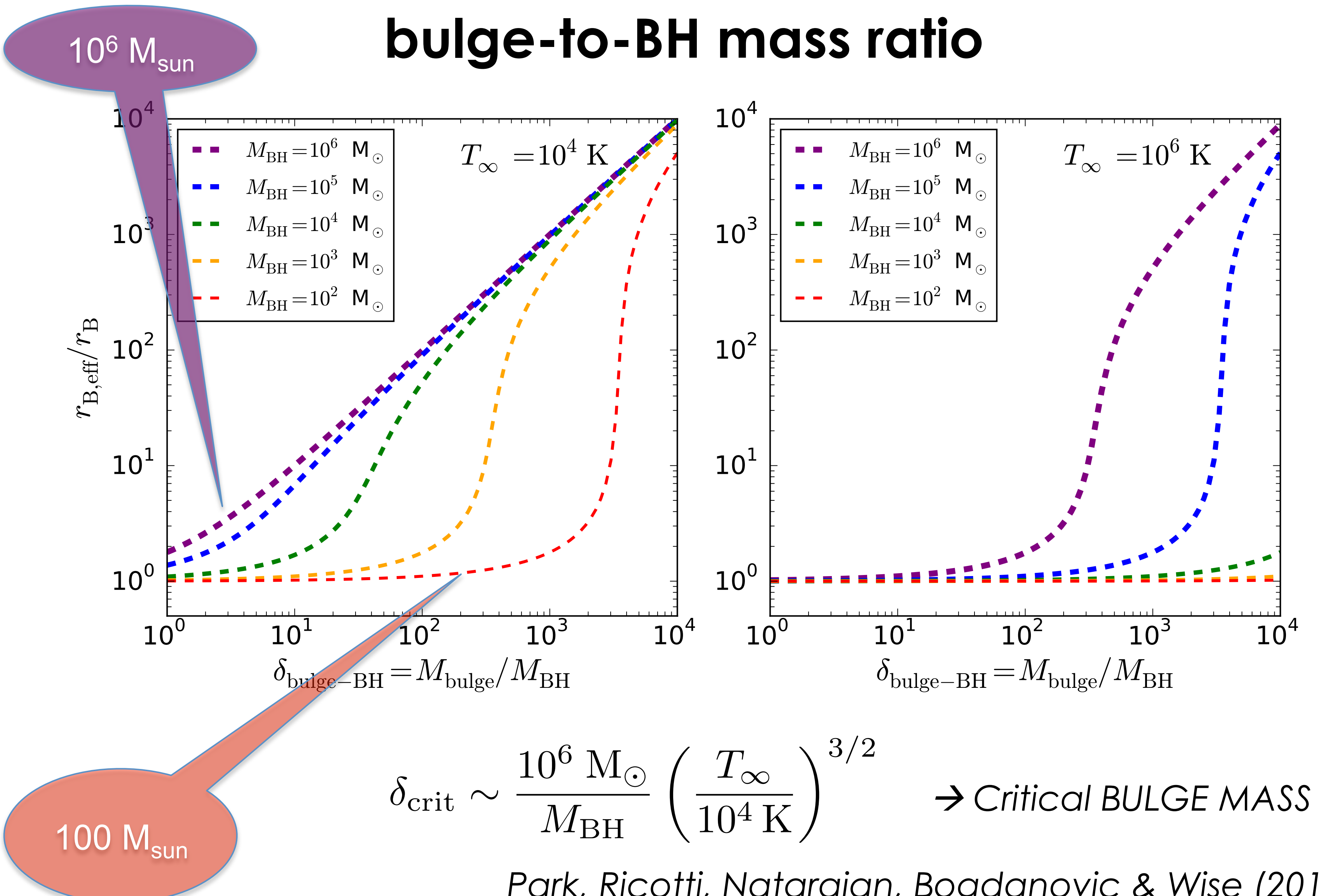
increased Bondi radius due to bulge



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

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

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

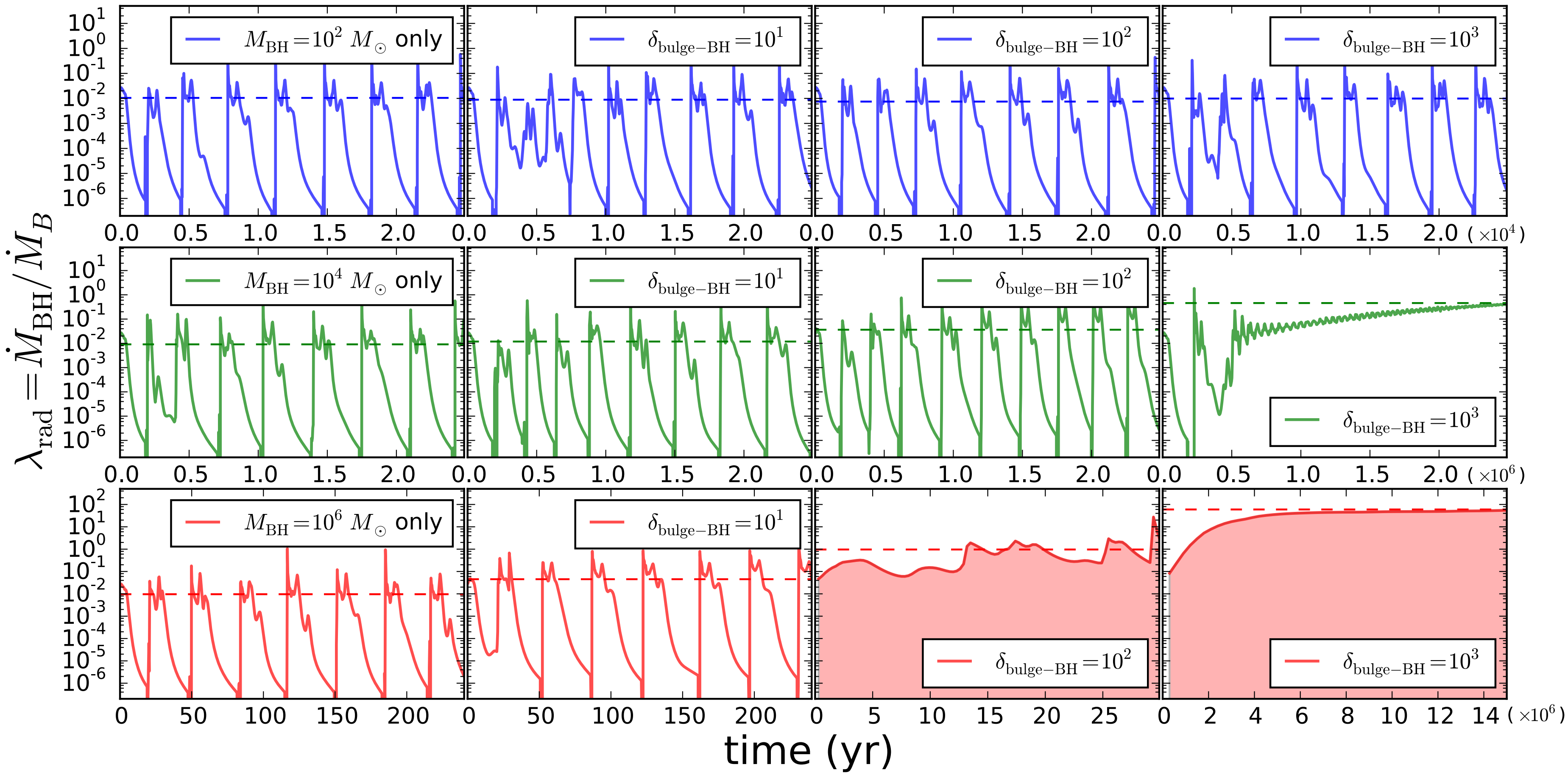


$$\delta_{crit} \sim \frac{10^6\ M_\odot}{M_{BH}} \left(\frac{T_\infty}{10^4\ K}\right)^{3/2}$$

→ *Critical BULGE MASS*

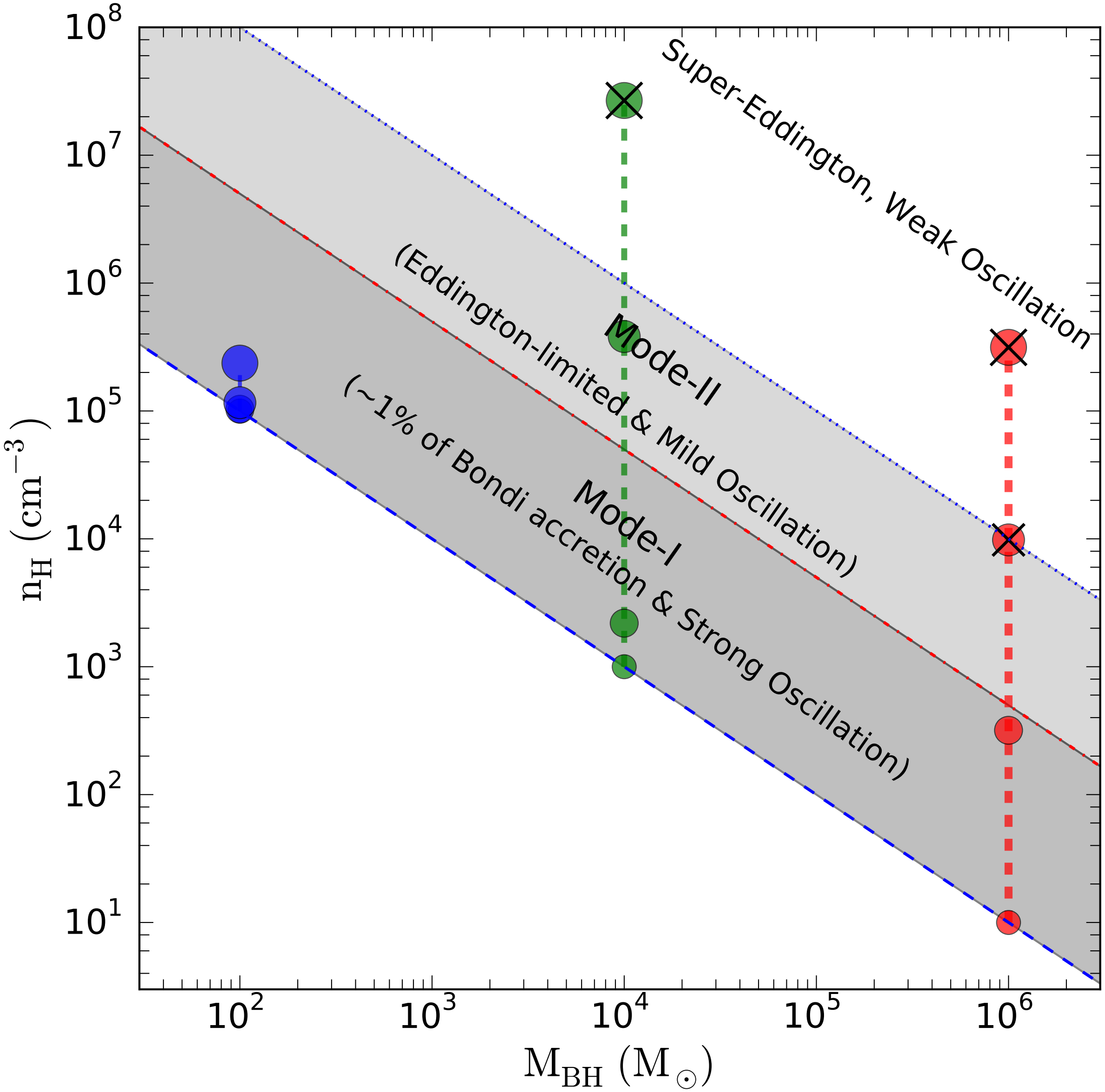
Park, Ricotti, Natarajan, Bogdanovic & Wise (2016)

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



Park et al. (2016)

Transition of Accretion Regimes

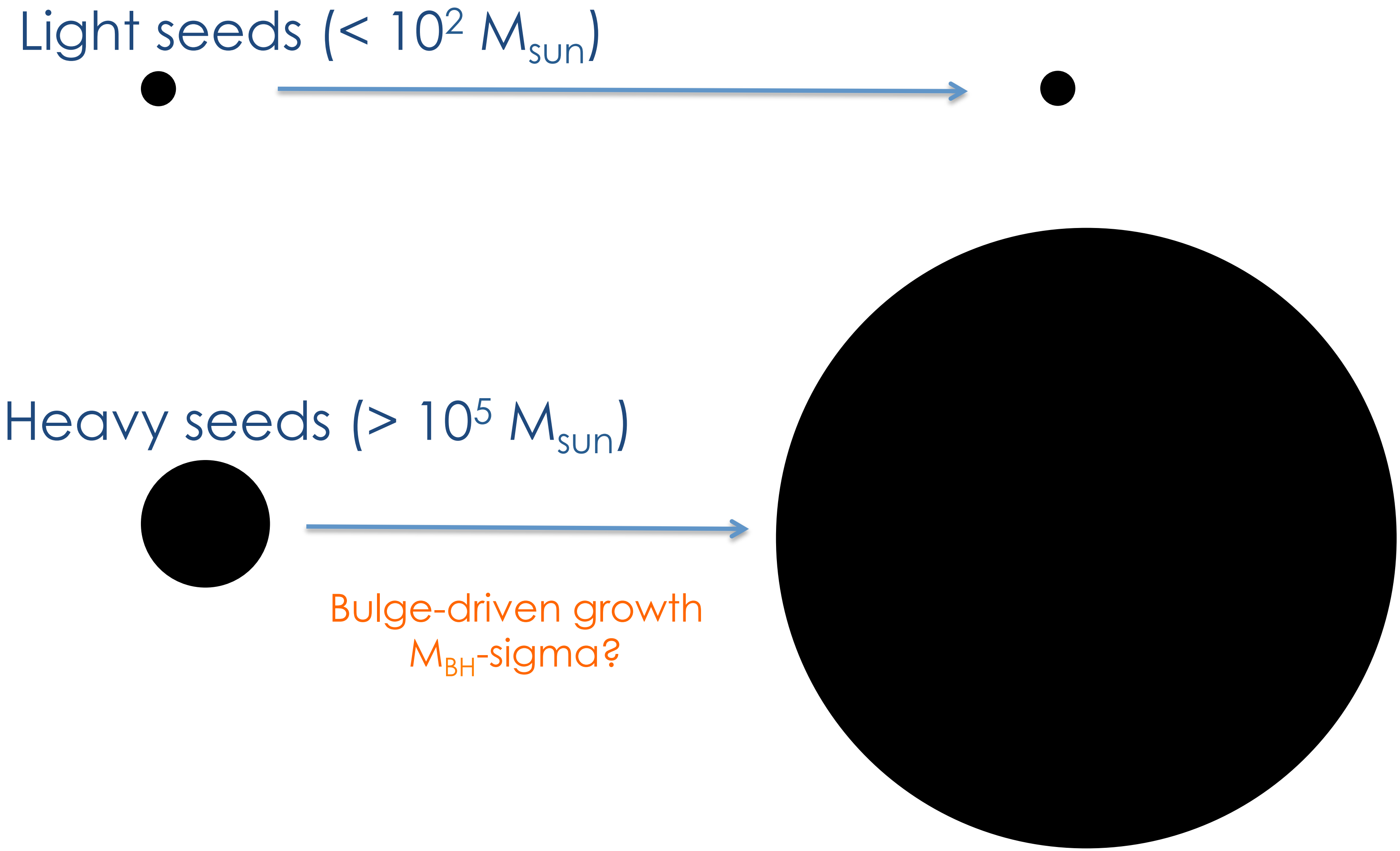


$$\dot{M}_{\rm BH} = \dot{M}_{\rm B} \left(\frac{r_{\rm B,eff}}{r_{\rm B}} \right)^{\beta}$$

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

Park et al. (2016)

Growth of light vs. heavy seed black holes



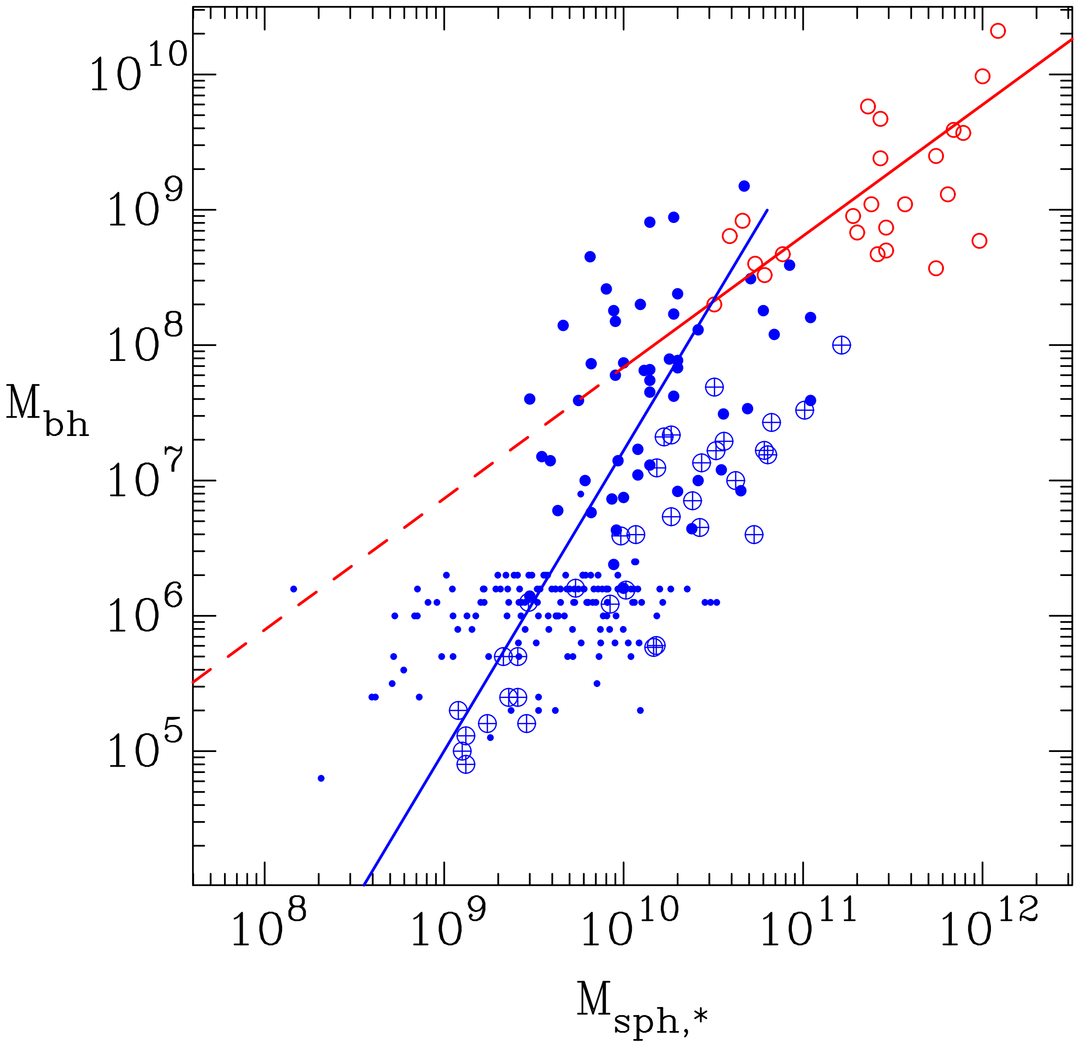
Work in progress :

Semi-analytic extension

BH-to-bulge mass ratio evolution

BH-to-Bulge mass ratio in low mass system

Sérsic galaxies shows steeper relations between BH-bulge mass ratio

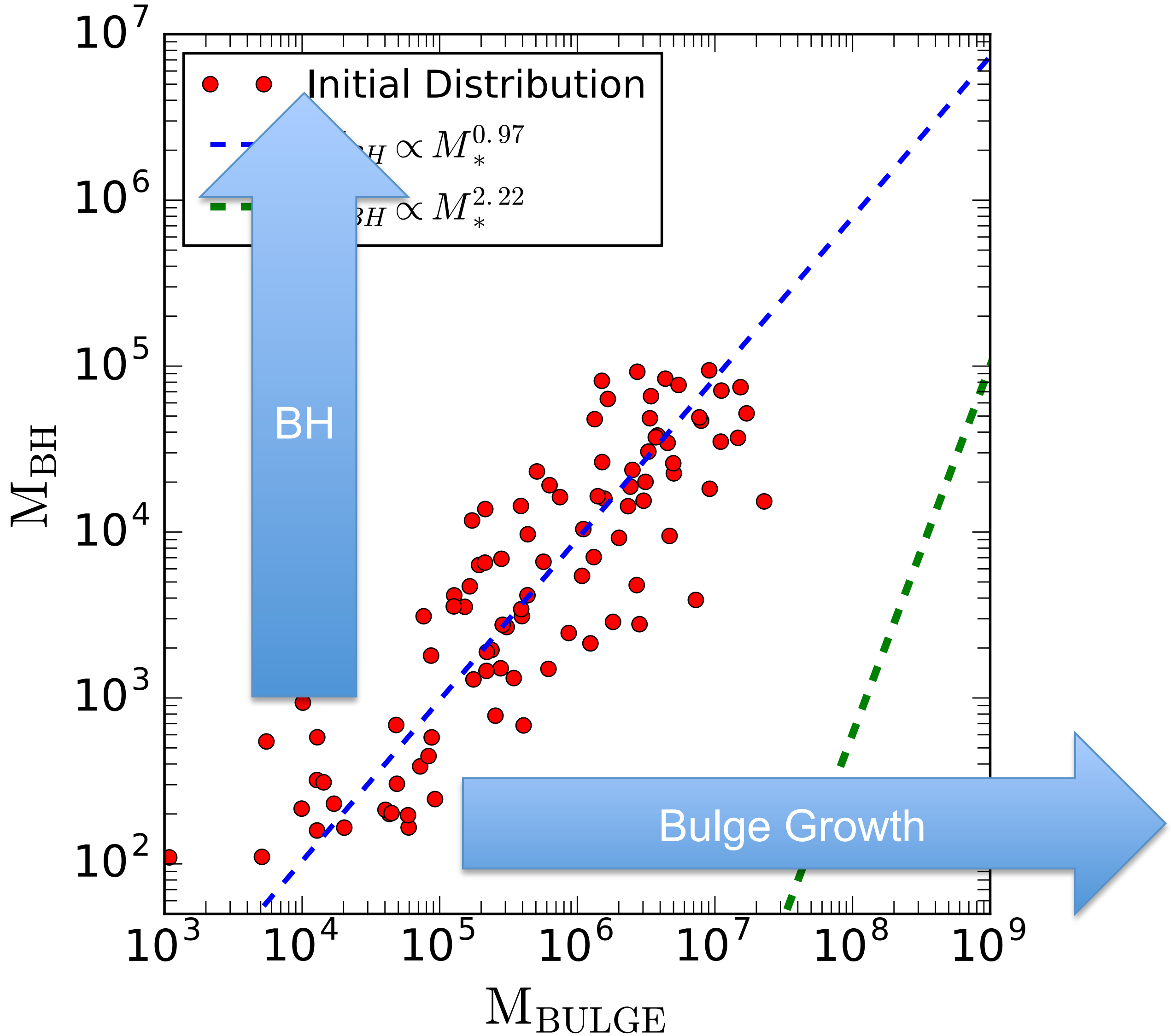


$$\log \frac{M_{\rm BH}}{M_\odot} = (0.97 \pm 0.14) \log \left(\frac{M_{\rm sph,*}}{3.0 \times 10^{11}\, M_\odot} \right) + (9.27 \pm 0.09),$$

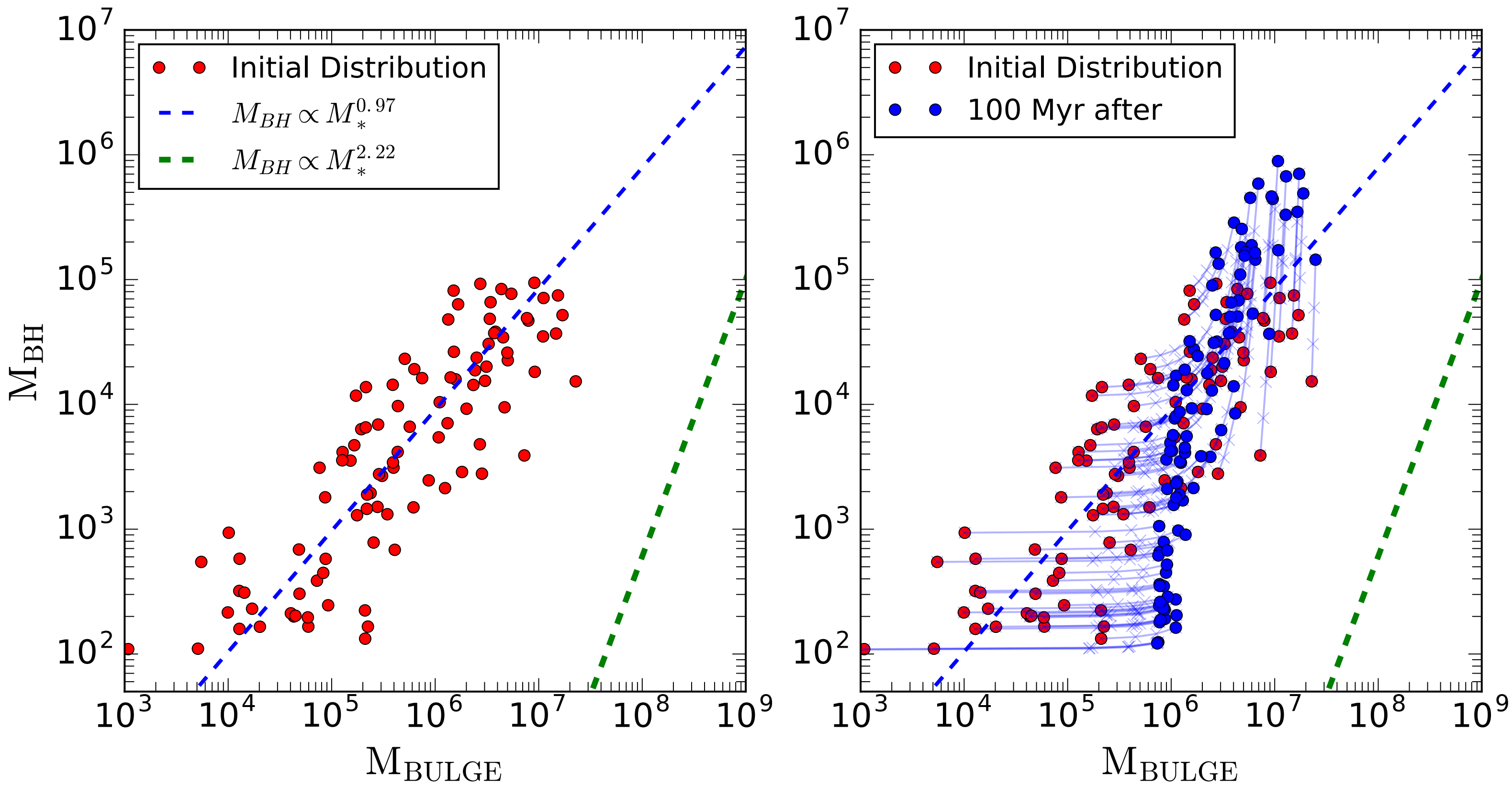
$$\log \frac{M_{\rm BH}}{M_\odot} = (2.22 \pm 0.58) \log \left(\frac{M_{\rm sph,*}}{3.0 \times 10^{10}\, M_\odot} \right) + (7.89 \pm 0.18),$$

Scott et al. (2013)
Graham et al. (2015)
Reines & Volonteri (2015)

Semi-analytic modeling of BH-to-Bulge mass ratio



Semi-analytic modeling of Bulge-to-BH ratio



Park et al. in prep

Growth rate of M_{BULGE} from Chen, Wise + (2014)

Summary

- Bulge-driven accretion
  - the massive bulge increase $r_{B,eff}$, but only when $\delta_{bulge\text{-}BH} > \delta_{crit}$.
  - A minimum bulge mass ~10^6 M_{sun}

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

- Radiation-regulated accretion
  - Light seed (~100 Msun) : δ_{crit} ~ 10^4
    - hard to grow
  - Heavy seeds (> 10^5 Msun) : δ_{crit} ~ 1
    - likely to grow coevally with bulge
- Work in progress :
  - semi-analytic extension