Accretion onto Black Holes from Large Scales Regulated by Radiative Feedback

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How do we estimate accretion rate onto BHs?

- Bondi accretion (1952)
  - Accretion onto point mass
  - Source at rest respect to the gas
  - Steady and Spherically Symmetric Accretion
  - No feedback is considered

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

- Eddington Luminosity
  - Mass-Energy conversion by BHs
  - Maximum luminosity for a given BH mass

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

Eddington-limited Bondi-Hoyle rate

Motivation

- Large body of work in literature on growth of SMBHs at the center of galaxies: complex because of interplay between galaxy and SMBH (eg, Volonteri+,Haiman+, Spaans+, Johnson+,Ciotti+, Ostriker+, Novak+, Proga+, Nagamine+, Di Matteo+, Hernquist+, Hopkins+, etc)
- Bondi-Hoyle problem with radiation feedback:

$$L = \eta(dM/dt)c^2$$

- Simple initial conditions (IC) + parametric study = analytic modeling
- Aim is to have more accurate formulae than the Bondi equations to model accretion onto IMBH and SMBH in large scale cosmological simulations
- Results are qualitatively different than Bondi formulae + surprising rich phenomenology even with very simple IC!
- Simulations focus on first IMBHs, but our analytical scaling relationships apply to wide range of BH masses (with some caveats)

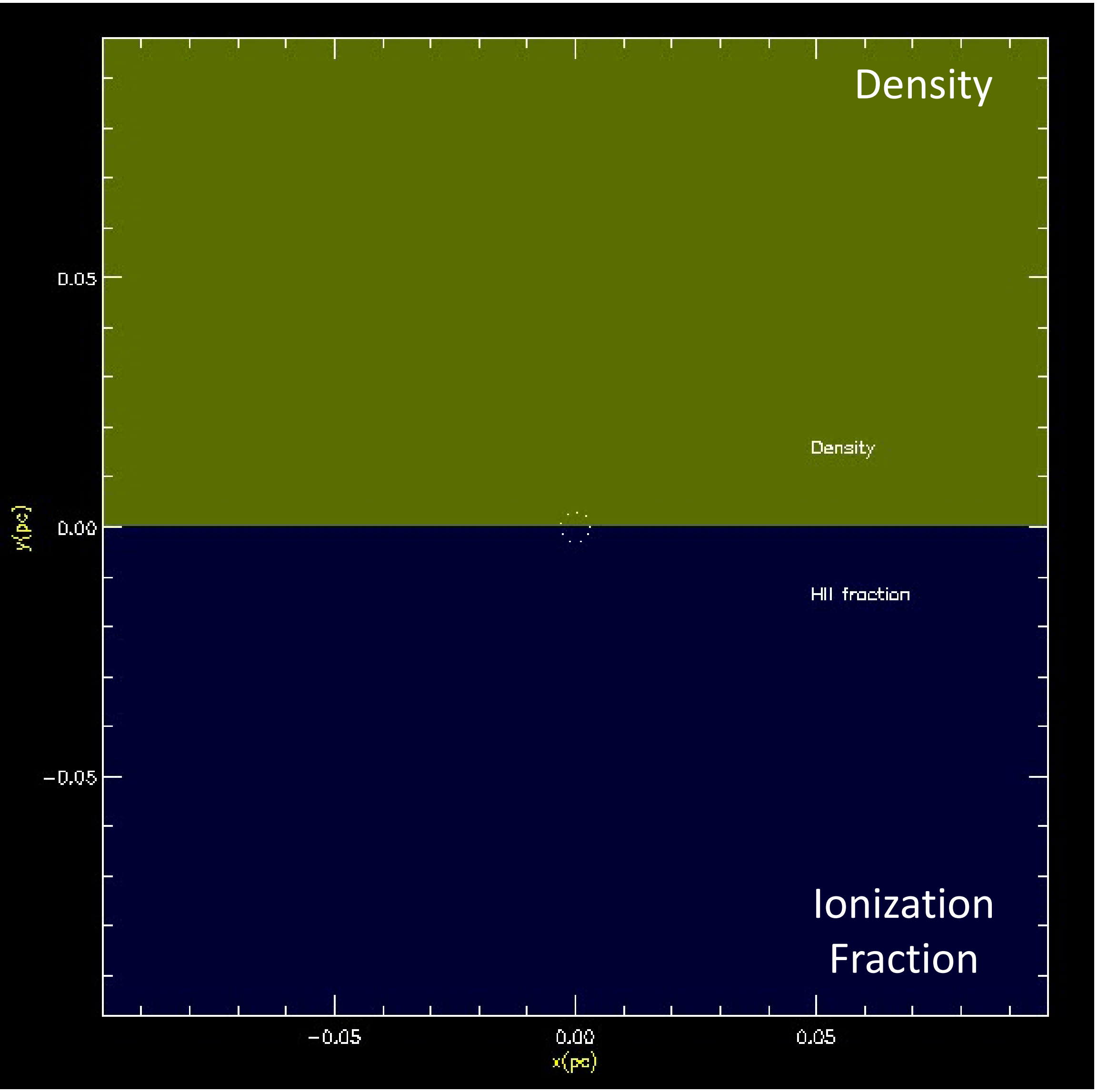
Radiation-Hydrodynamic Simulations

- **ZEUS-MP (Hayes et al. 2006) + Radiative Transfer (Ricotti et al. 2001)**

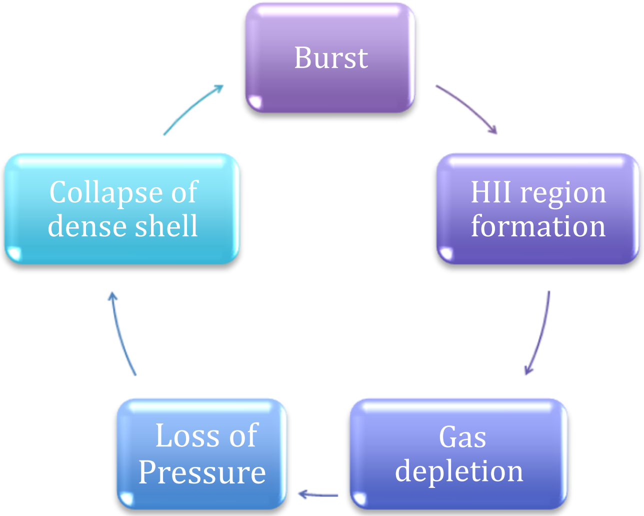
  - Hydrodynamics + 1D ray-tracing module
  - Photoheating & Photoionization, Radiation pressure
  - Multi species : HI, HII, HeI, HeII, HeIII, e^-
  - IC: Uniform density and zero angular momentum
  - Log grid in radial direction (to 10^{-5}-10^{0}pc for 100 M_{sun})

- **Parameters explored for IC:**
  - Mass : 100-10,000 M_{sun}
  - Density : 10^2– 10^7 cm^{-3}
  - Temperature of the gas : 3000-14000 K
  - Radiative efficiency : 0.002-0.1
  - Power law spectra with spectral index : 0.5-2.5

Periodic Luminosity Bursts



$\eta=0.1$, $M_{bh}= 100\ M_{sun}$, $T_{inf}=10^4$ K, $n_H = 10^5\ cm^{-3}$



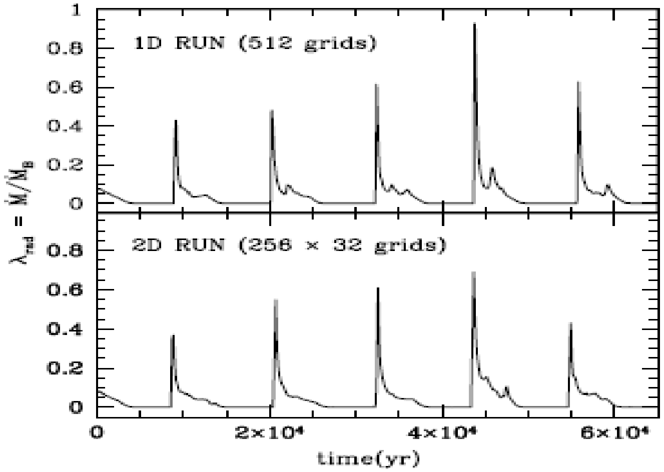
Burst

HII region formation

Gas depletion

Loss of Pressure

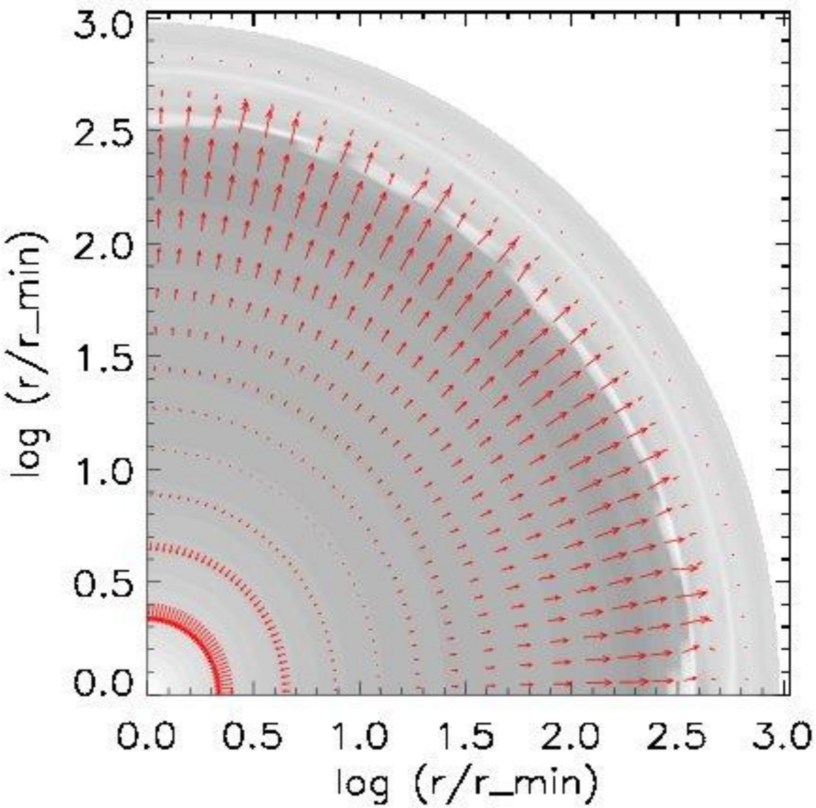
Collapse of dense shell



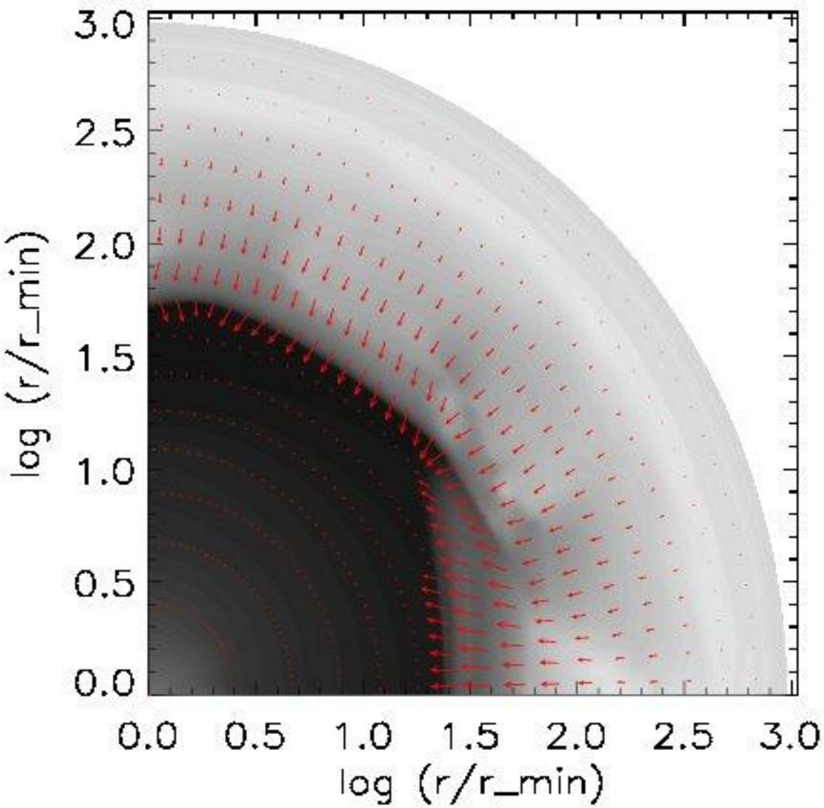
- Milosavljevic, Couch & Bromm 2009
- Park & Ricotti 2011
- Li 2011

Gas depletion & Collapse of I-front

Gas depletion & Dense shell formation

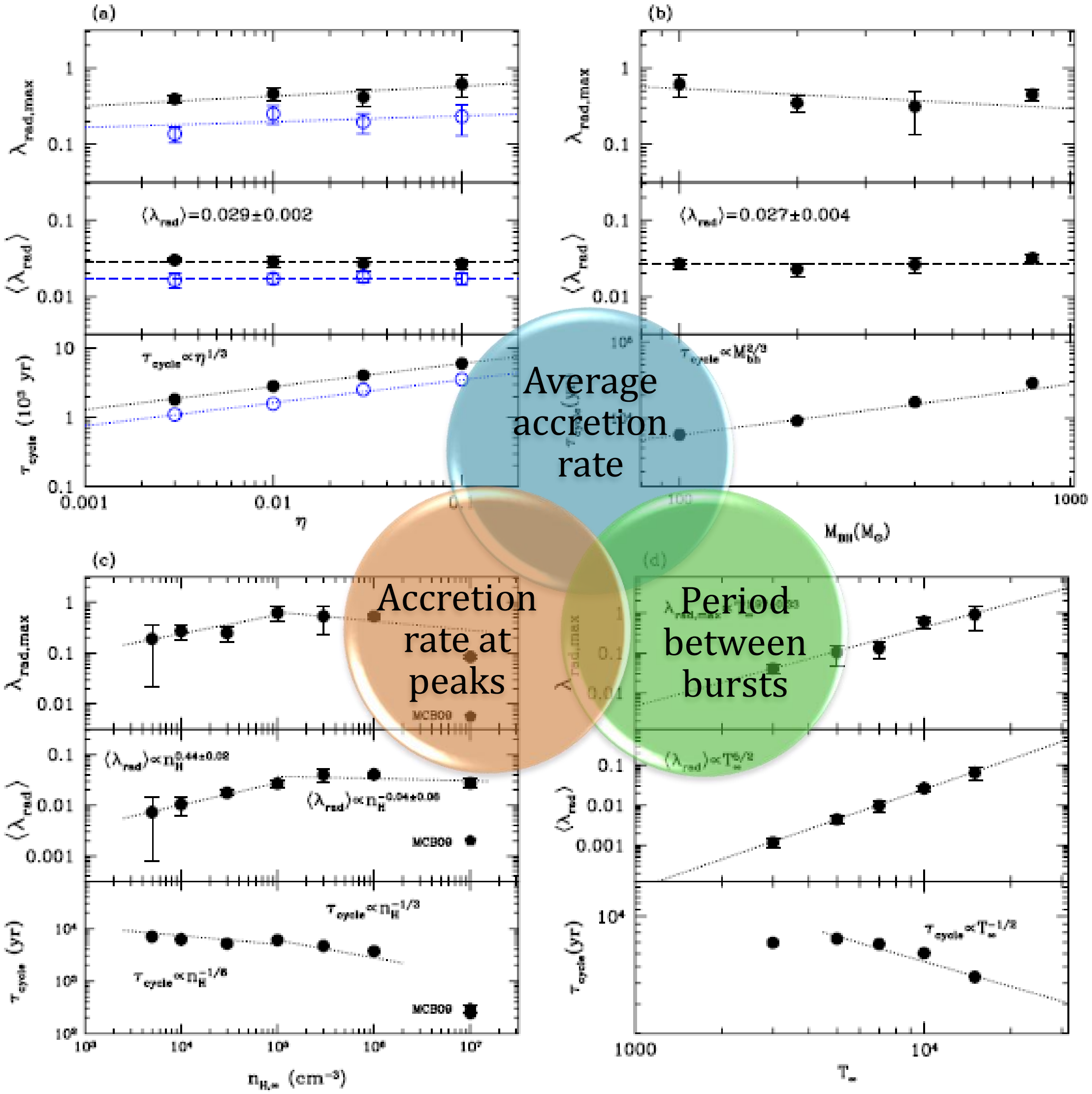


Collapse of dense shell



Park & Ricotti 2011

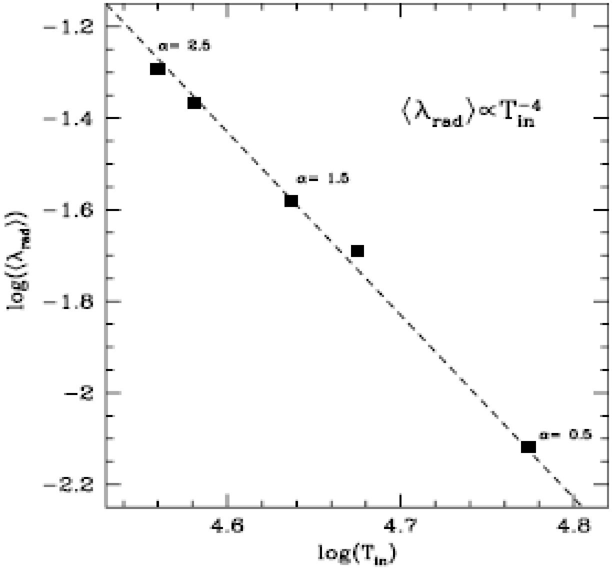
Parameter Space Exploration



Average accretion rate

Accretion rate at peaks

Period between bursts



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 rate proportional to thermal pressure of ambient gas

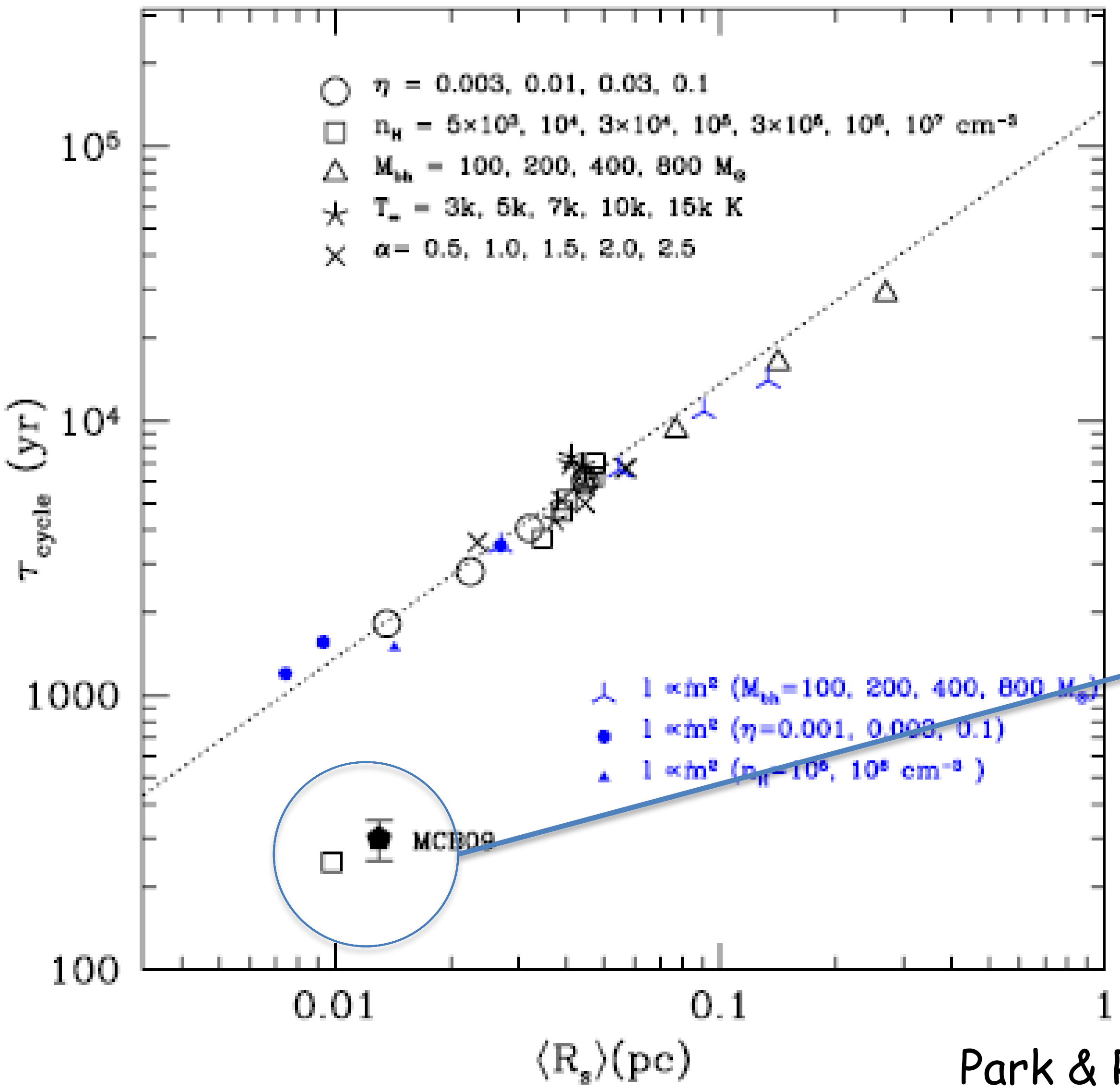
And very sensitive to the temperature inside the HII region

$$\langle \lambda_{\rm rad} \rangle \simeq 1\%\, T_{\infty,4}^{2.5} \left(\frac{T_{\rm in}}{6 \times 10^4\ {\rm K}} \right)^{-4}$$

↓

$$\langle \dot{M} \rangle \approx (4 \times 10^{18}\ {\rm g\ s^{-1}}) M_{\rm bh,2}^2 \left(\frac{n_{\rm H,\infty}}{10^5\ {\rm cm^{-3}}} \right) T_{\infty,4} \left(\frac{\bar{E}}{41\ {\rm eV}} \right)^{-1}$$

Period between bursts and the sound crossing time of HII region



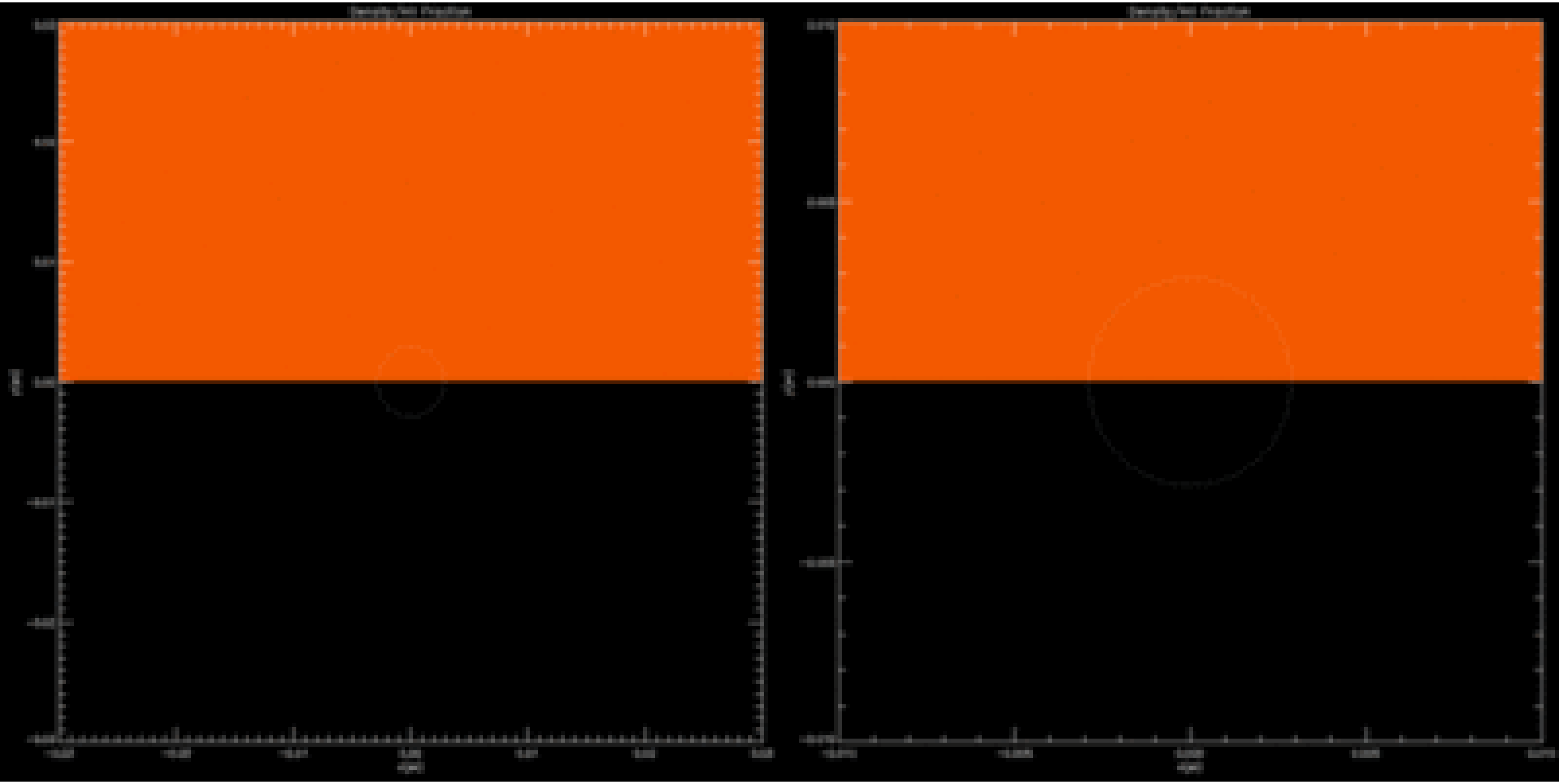
$$\tau_{cycle} \propto \langle R_s \rangle = \left(\frac{3N_{ion}}{4\pi\alpha_{rec}n_H^2} \right)^{\frac{1}{3}}$$

$$\tau_{cycle} \propto \eta^{\frac{1}{3}} M_{bh}^{\frac{2}{3}} \rho_\infty^{-\frac{1}{3}} T_\infty^{-\frac{1}{2}}$$

The model fails for simulationswith highest gas density (10^7 cm^{-3}), but Milosavljevic et al. 2009 had a similar cycle

Park & Ricotti 2011

Two Distinct Modes of Oscillations



Mode-I

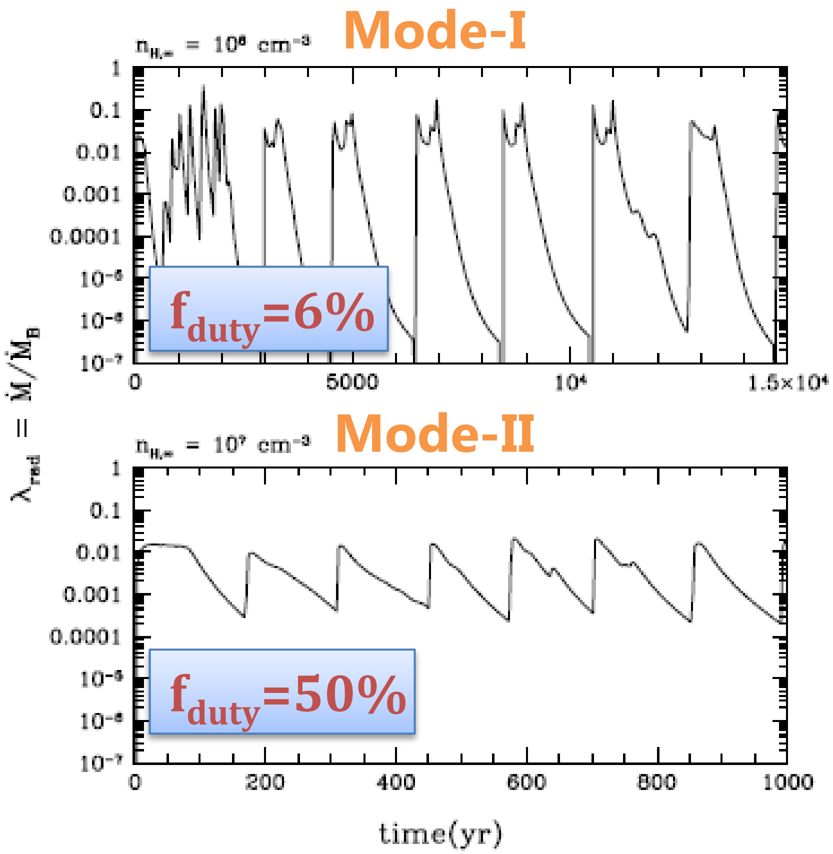
$n_H = 10^6\,cm^{-3}$

Mode-II

$n_H = 10^7\,cm^{-3}$

Park & Ricotti 2012

Two Distinct Modes of Oscillations

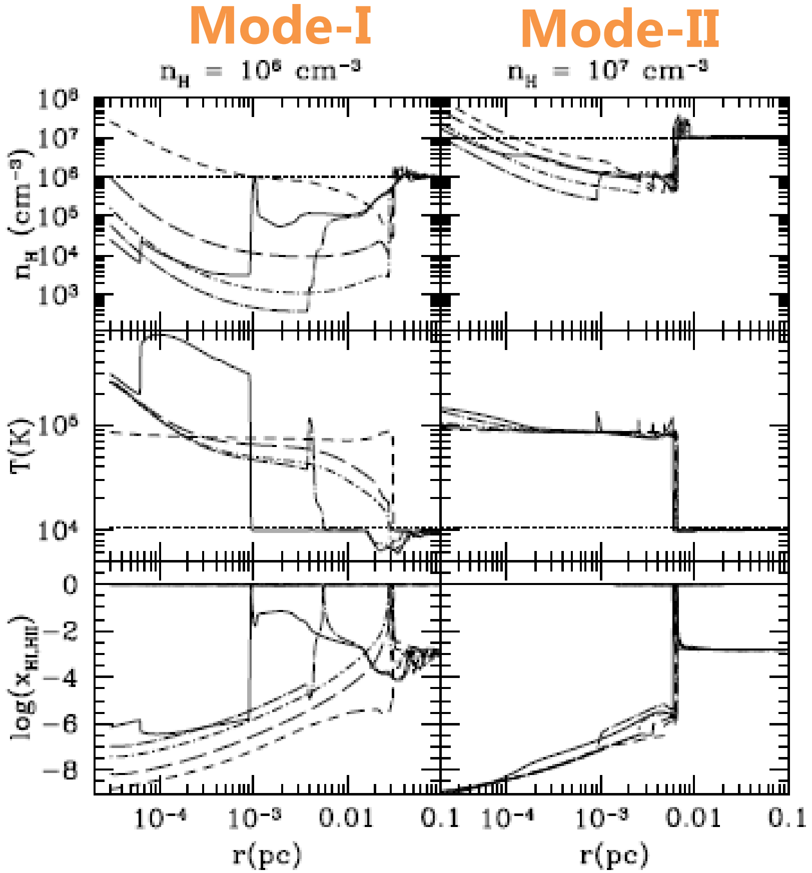


Mode-I

f_{duty}=6%

Mode-II

f_{duty}=50%



Mode-I

Mode-II

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

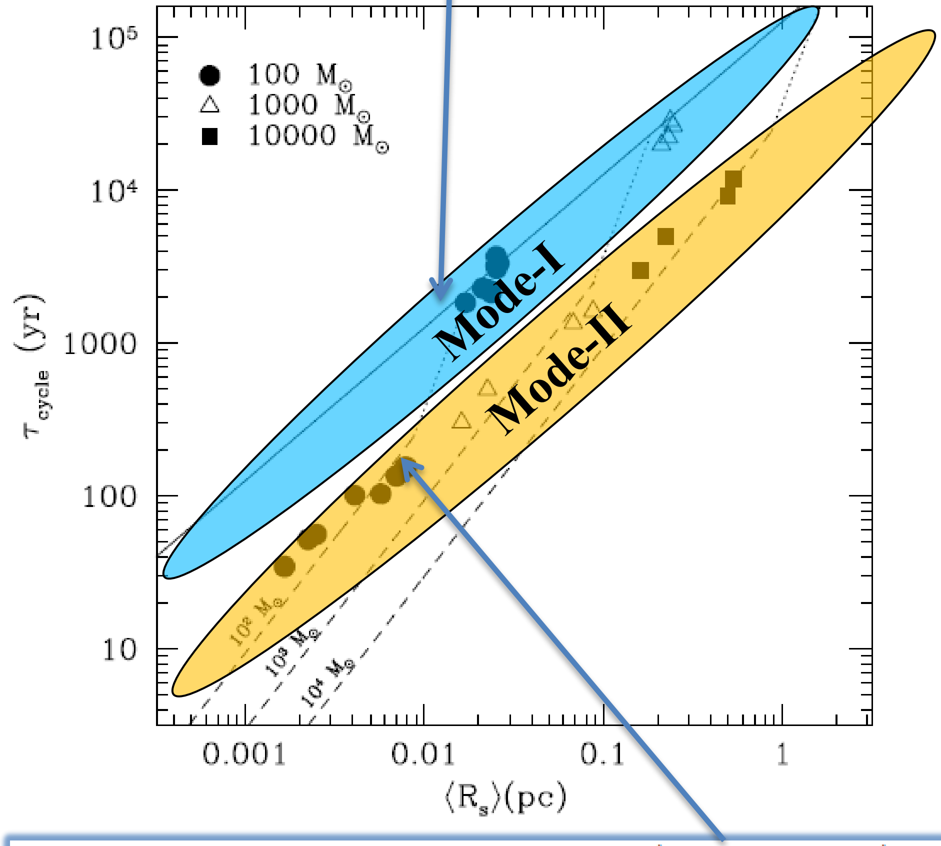
f_{duty}increases in mode-II oscillations.
Makes Eddington-limited accretion efficient

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

Park & Ricotti 2012

What determines T_{cycle} in mode-I and mode-II?

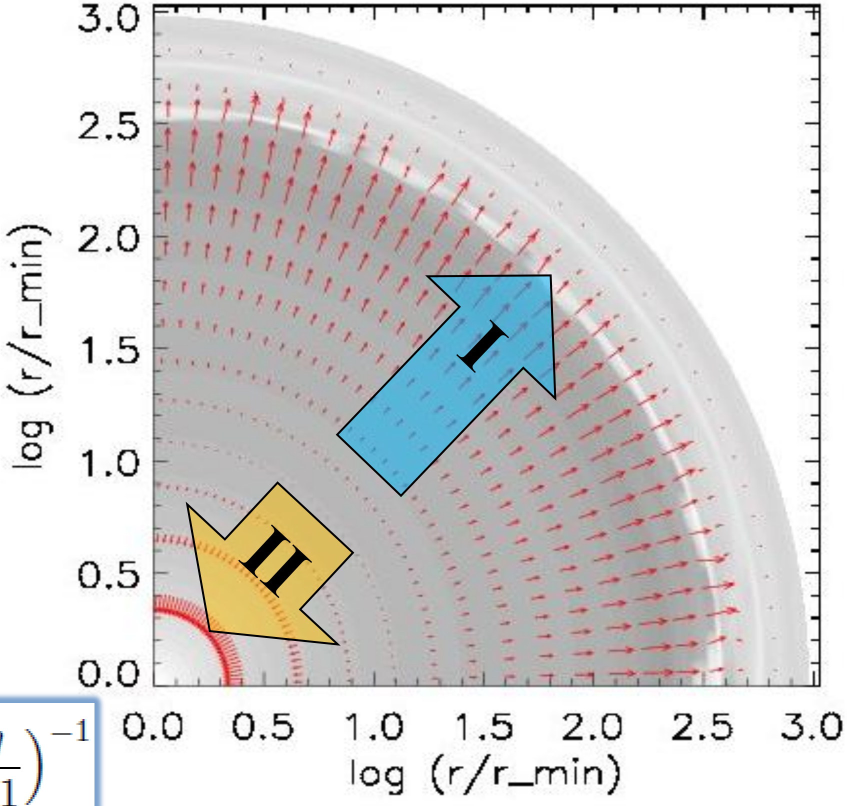
$$n^{\rm cr}_{\rm H,\infty} \sim (5\times10^6\ {\rm cm^{-3}})\, M_{\rm bh,2}^{-1}\, T_{\rm in,*}^{7/4} \left(\frac{\bar{E}}{41\ {\rm eV}}\right)^{-1}$$



$$n^{\rm Edd}_{\rm H,\infty} \sim 4\times10^6\ {\rm cm^{-3}} \left(\frac{M_{\rm bh}}{10^2\ M_\odot}\right)^{-1} \left(\frac{T_\infty}{10^4\ {\rm K}}\right)^{-1} \left(\frac{\eta}{0.1}\right)^{-1}$$

Gas depletion time scale

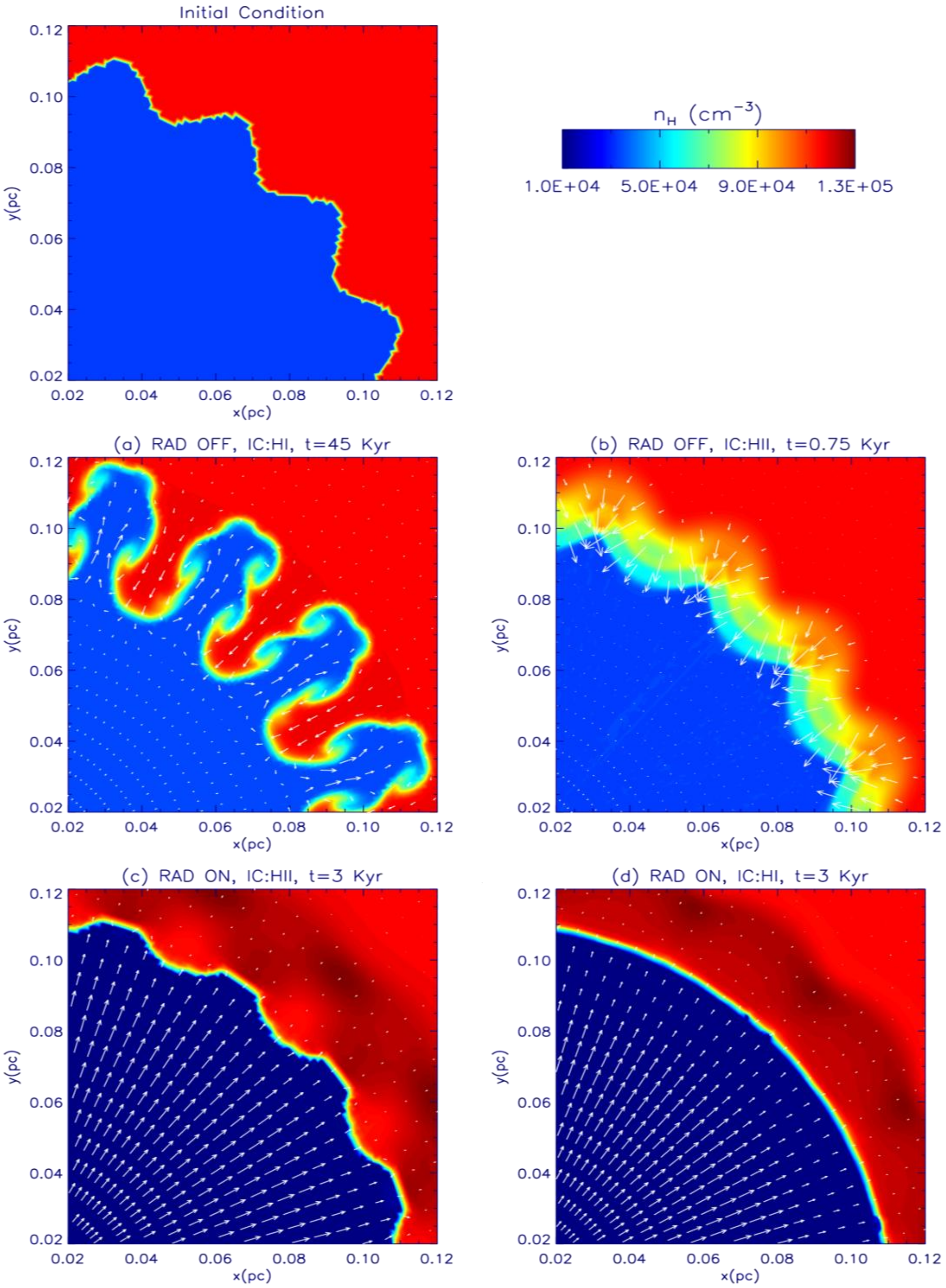
- T_{cycle} ~ <Rs> : outflow (Mode -I)
- T_{cycle} ~ <Rs>^{3} : accretion by BH (Mode -II)
- T_{cycle} ~ <Rs>$^{3/2}$: Eddington-limited (Mode-II)



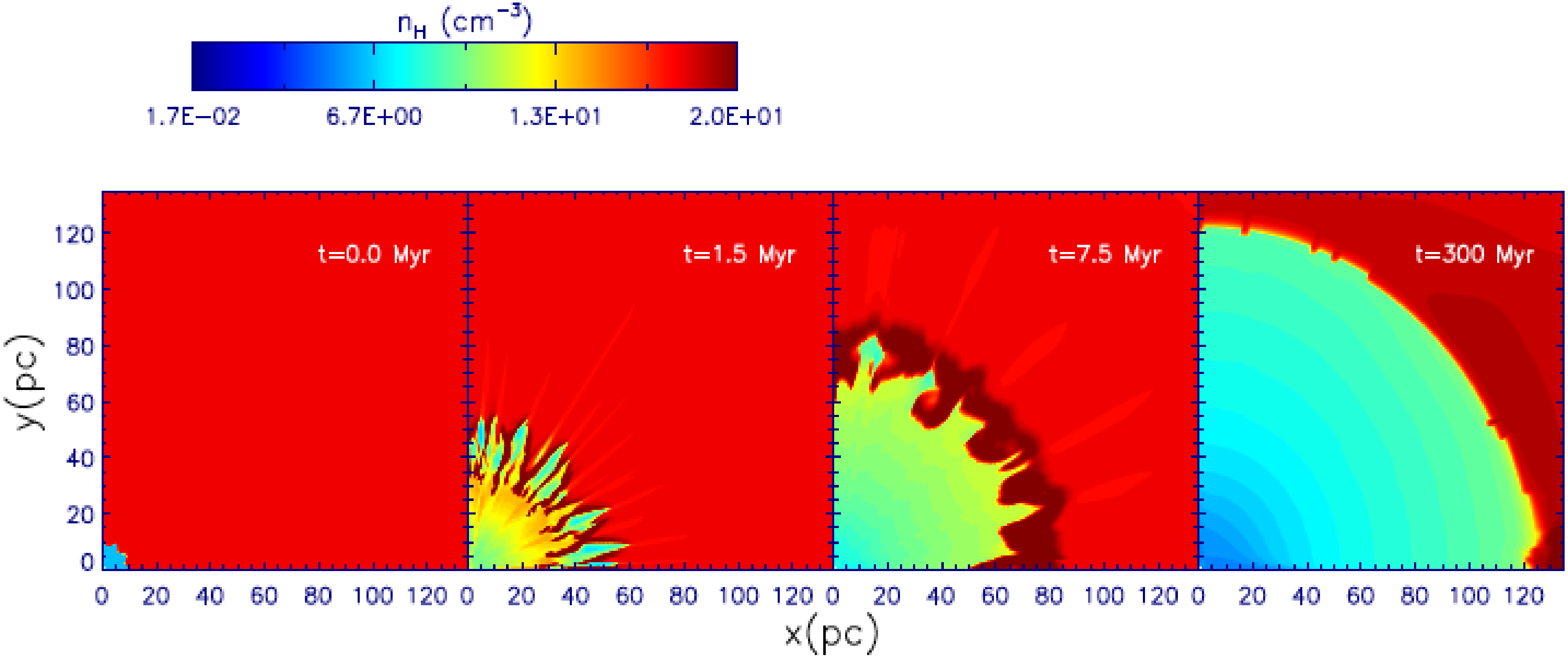
Park & Ricotti 2012

Rayleigh-Taylor Instability at Ionization Front

Park, Ricotti, Di Matteo, & Reynolds 2013
to be submitted



Instabilities when I-front expands

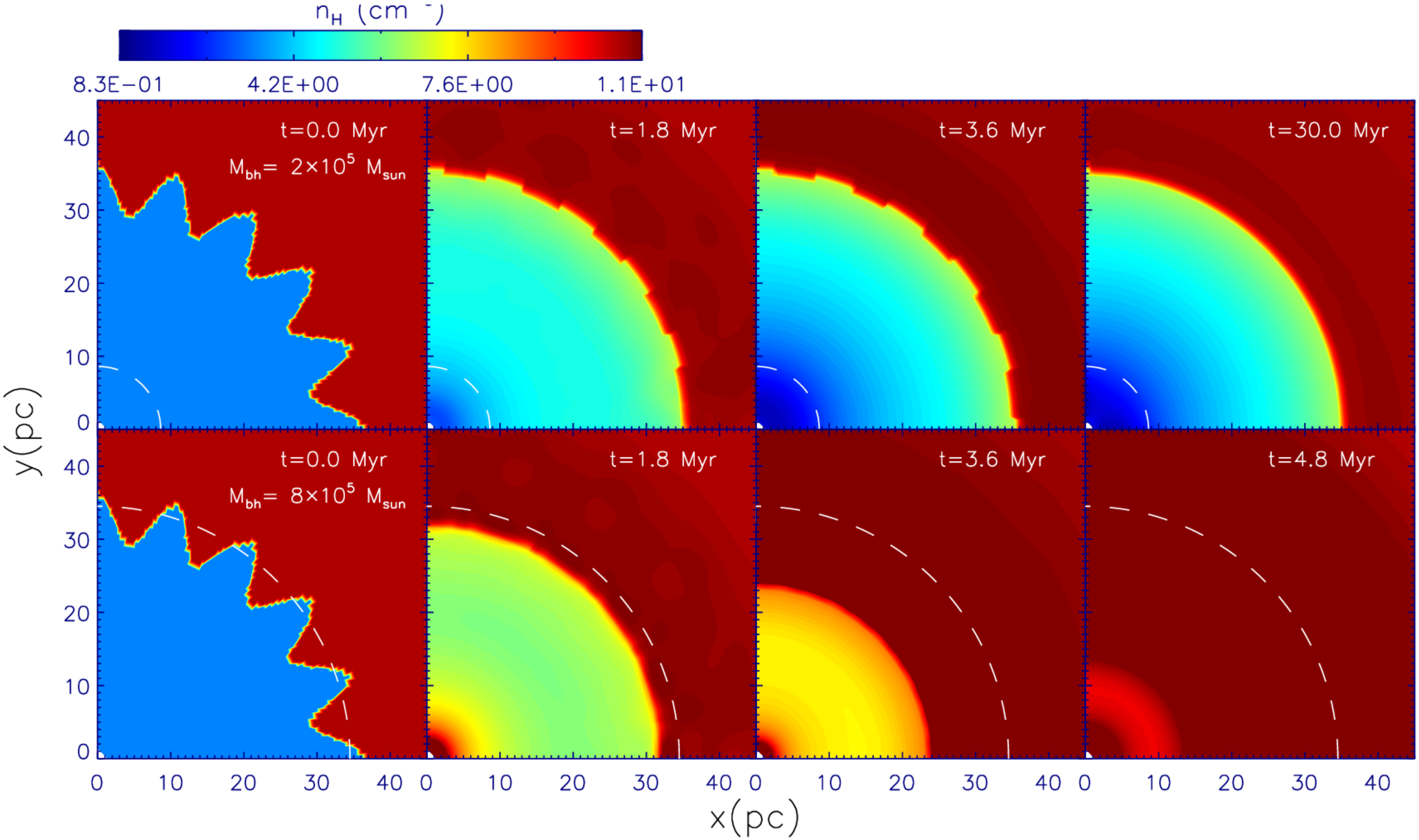


Park, Ricotti, Di Matteo, & Reynolds 2013
to be submitted

See Whalen et al. 2008 for instabilities
of propagating I-Front

Stability of I-Front

Stromgren radius vs. Bondi radius



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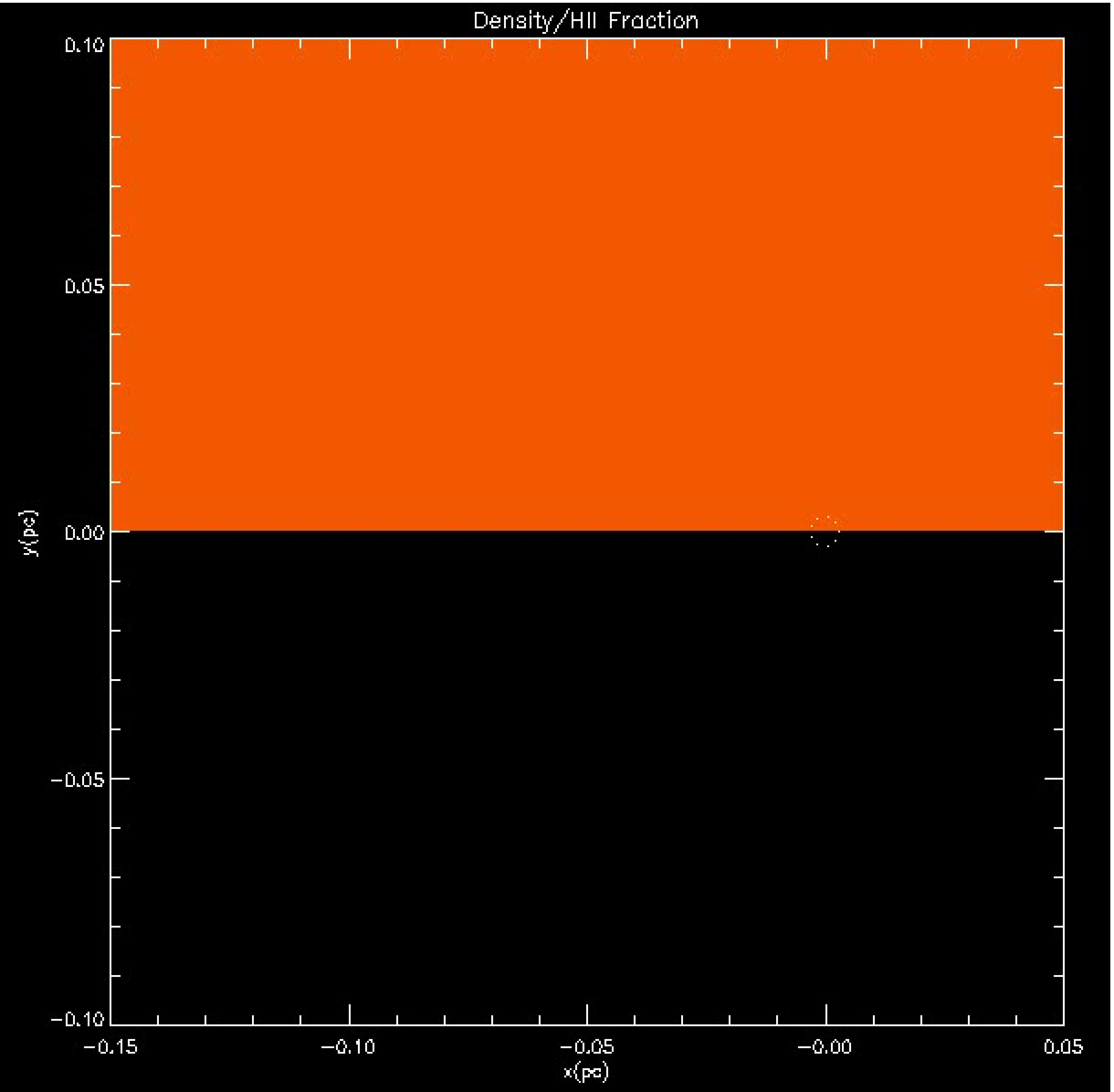
Moving IMBH + Radiative Feedback

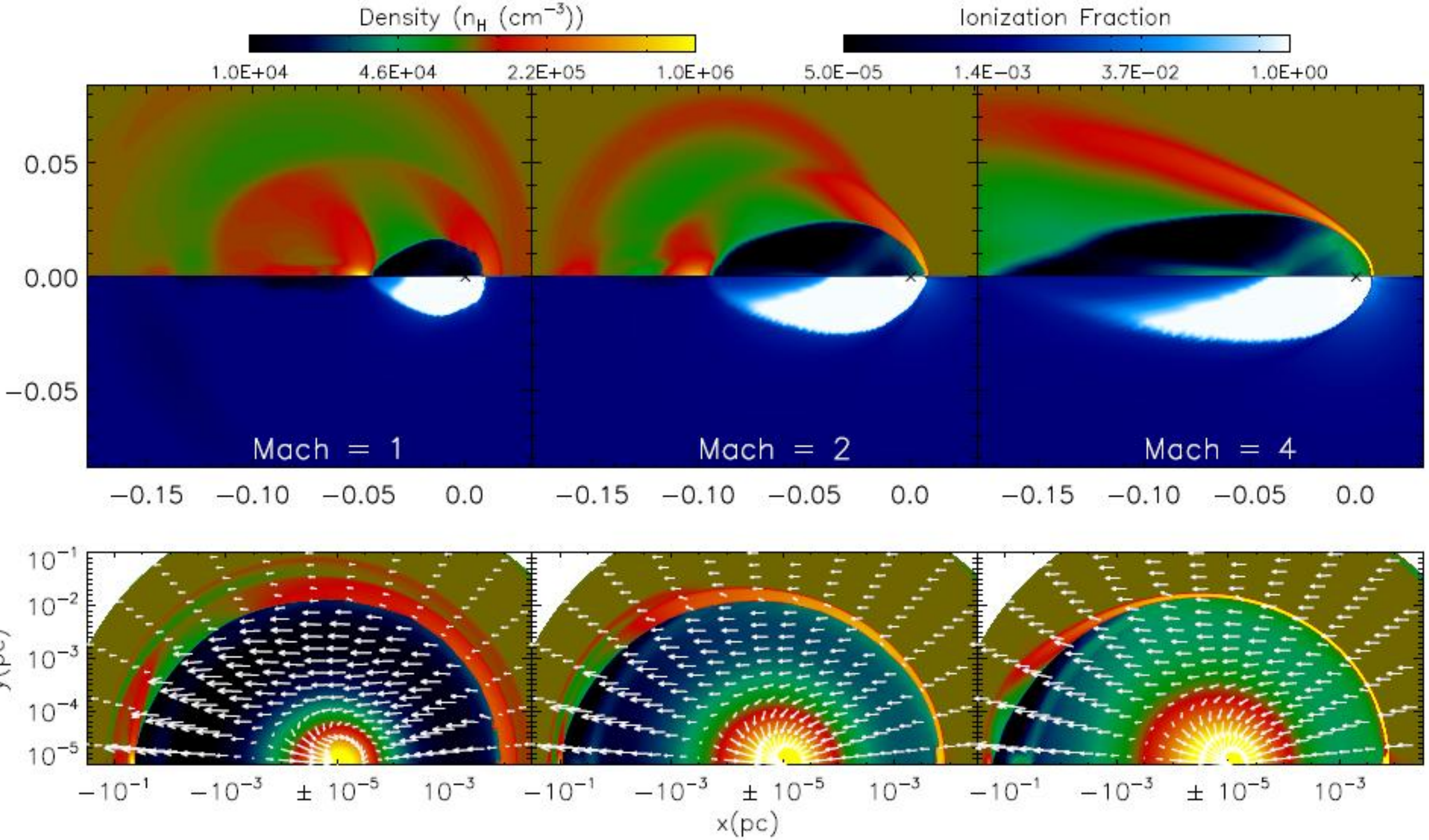


- Bondi-Hoyle-Lyttleton accretion rate

$$\dot{M}_{\rm BHL} = \frac{\dot{M}_{\rm B}}{(1 + v_\infty^2 / c_{s,\infty}^2)^{3/2}}$$

Park & Ricotti 2013

D-type ionization front + bow shock



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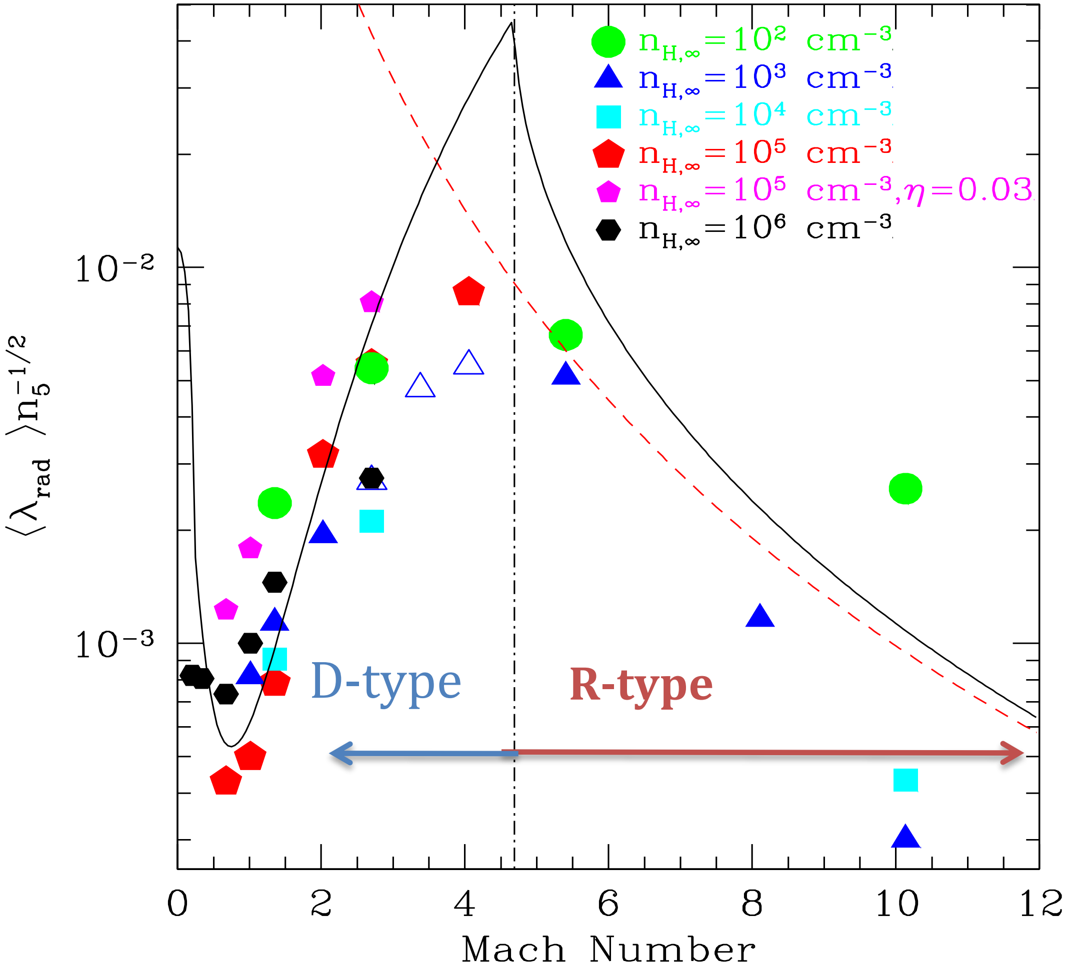

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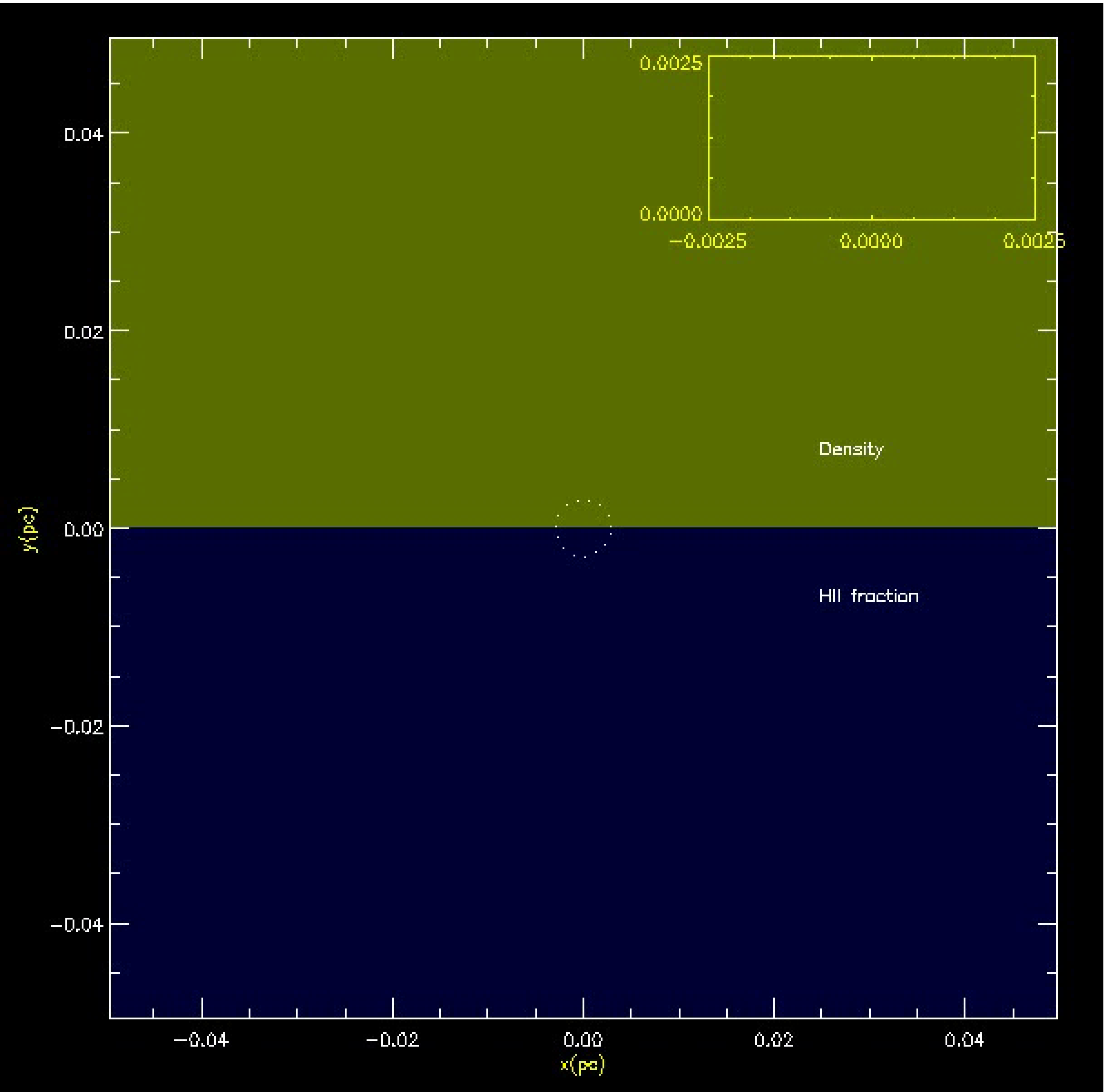
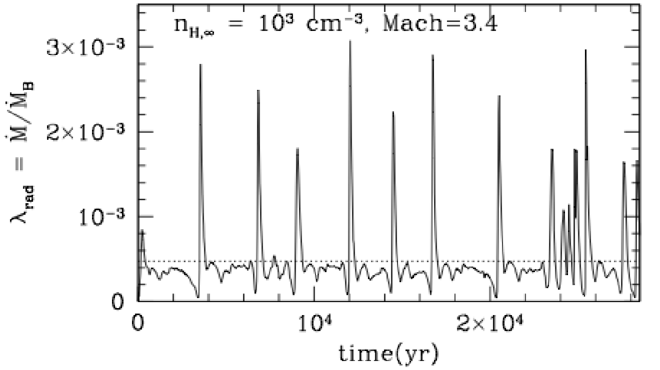
Modeling based on Simulations:

1. Transition from D-type to R-type ionization front
2. Isothermal bow-shock
3. Thin shell instability produce periodic accretion rate

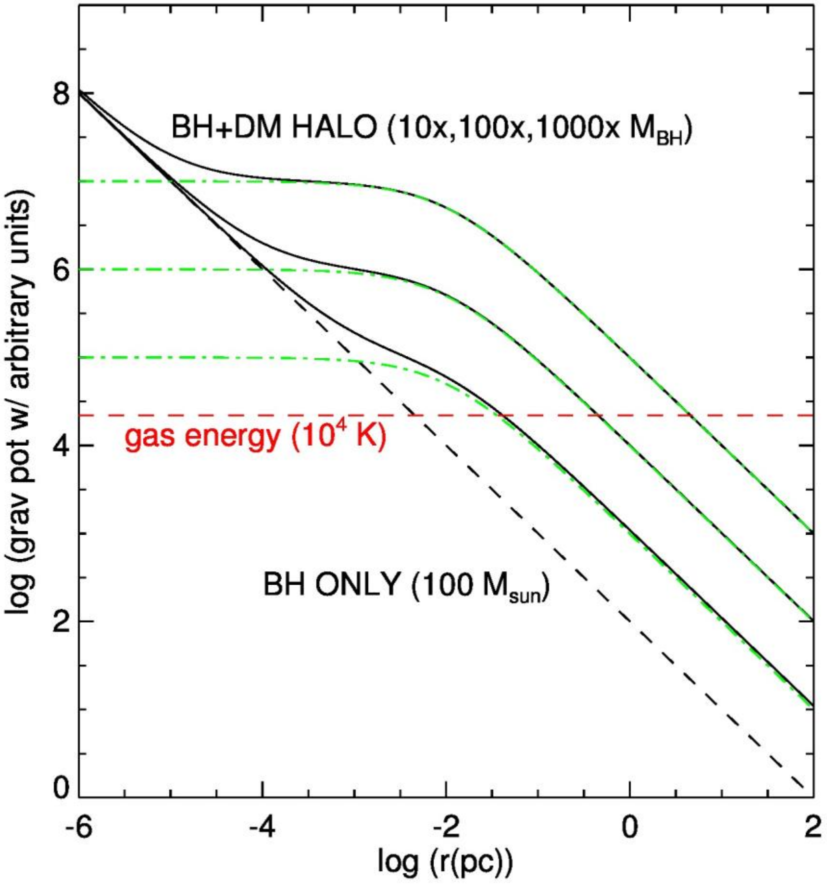
Shell instability and periodic oscillations





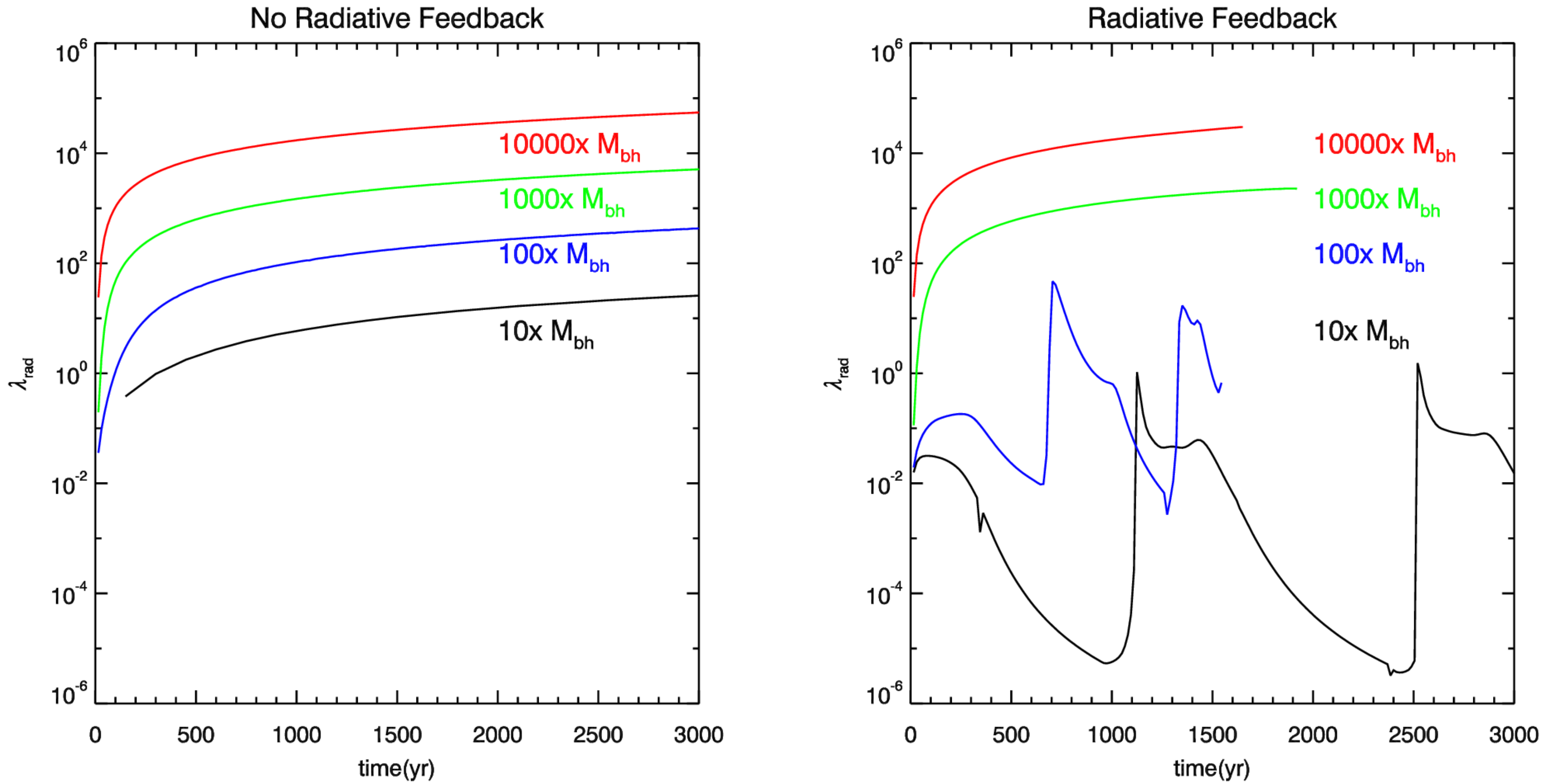
Park & Ricotti 2013

BH accretion in Dark Matter Halo (preliminary)



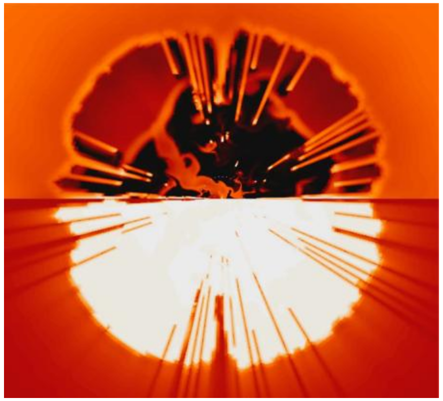
Accretion of BHs in DM halo (preliminary)

No radiation pressure



Park, Di Matteo, & Ricotti 2013
in preparation

Summary



1. Very inefficient accretion: ~1% of Bondi rate.
2. Accretion rate proportional to thermal pressure
3. Two distinct accretion modes
4. RT instability at I-front is suppressed.

1. D-type I-front and bow-shock modify the accretion flow onto the BH
2. Accretion rate increases with increasing BH velocity: peaks at $v=2c_{s,in}\sim$20-30 km/s
3. Growth rate can be faster than for non-moving BH because is independent of temperature of the medium!
4. Thin shell instability produce periodic collapse of the front and periodic pulsation of luminosity. Can be important for ULX modeling.