Radiation-regulated Accretion onto Intermediate-Mass Black Holes

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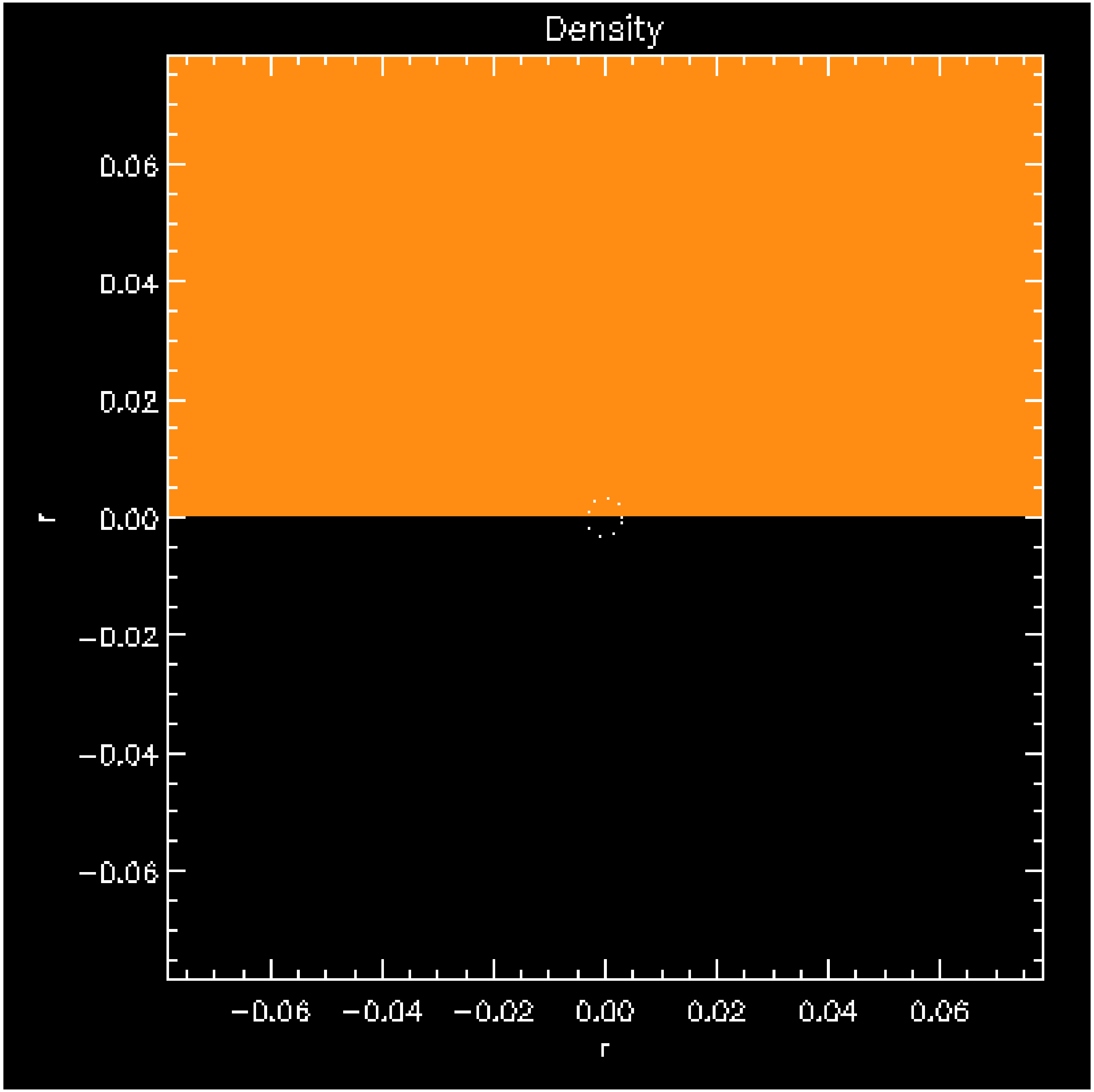
KITP lunch talk

Numerical 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^-
  - Spherical coordinates
  - Uniform density and zero angular momentum
- Parameters explored
  - Mass : 100-800 M_{sun}
  - Density : $10^3 – 10^7$ cm^{-3}
  - Temperature of the gas : 3000-14000 K
  - Radiative efficiency : 0.002-0.1
  - Spectral index : 0.5-2.5

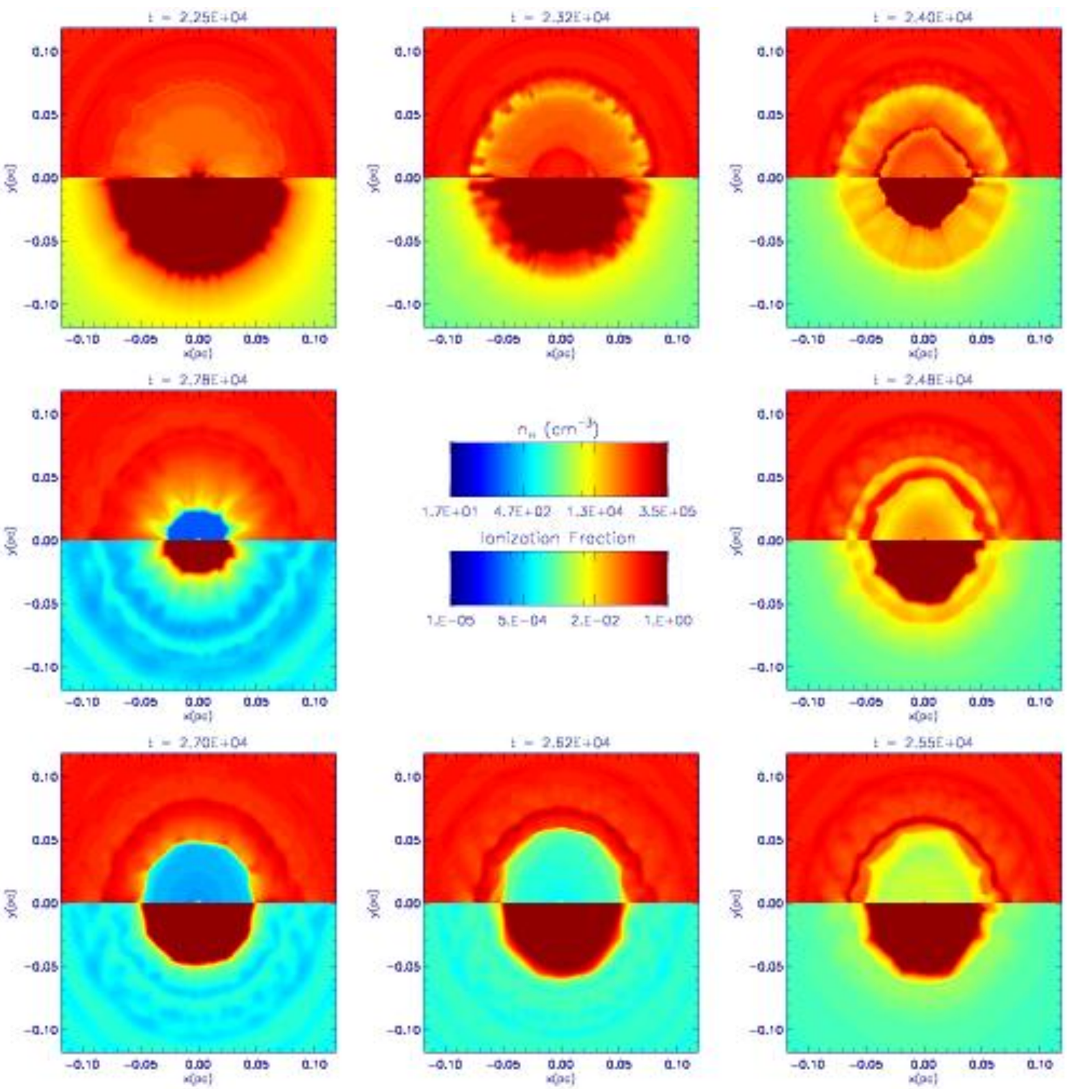


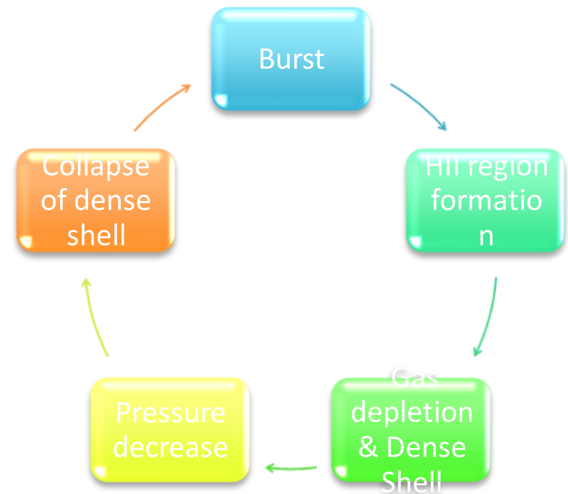
Density

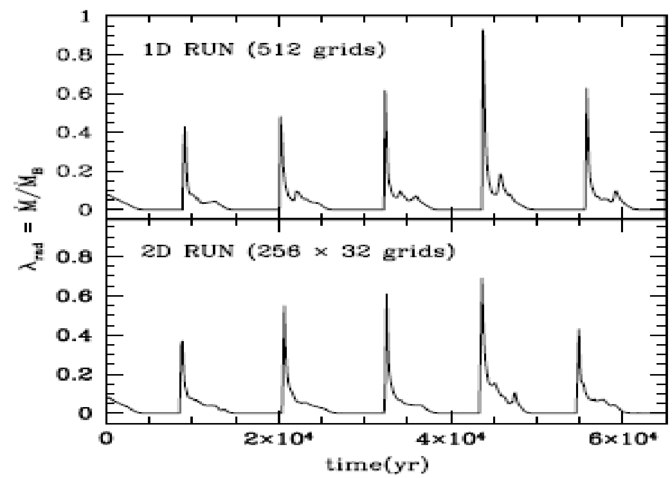
Ionization Fraction

Eta=0.1, Mbh= 100 Msun, Tinf=10^4 K, n = 10^5 cm^3

Quasi-periodic Oscillation



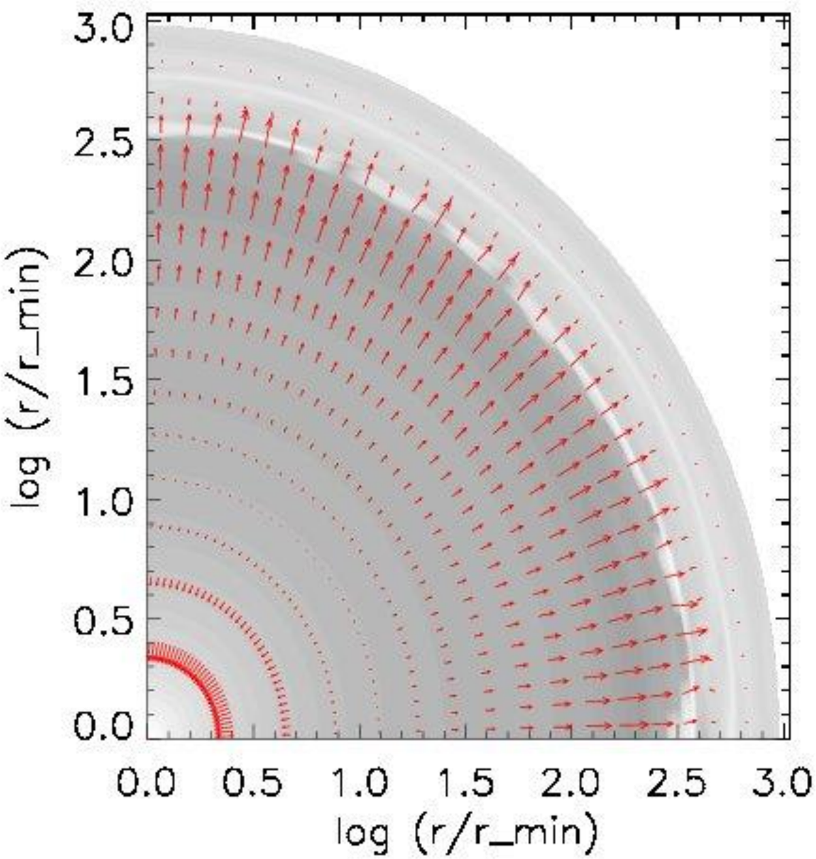




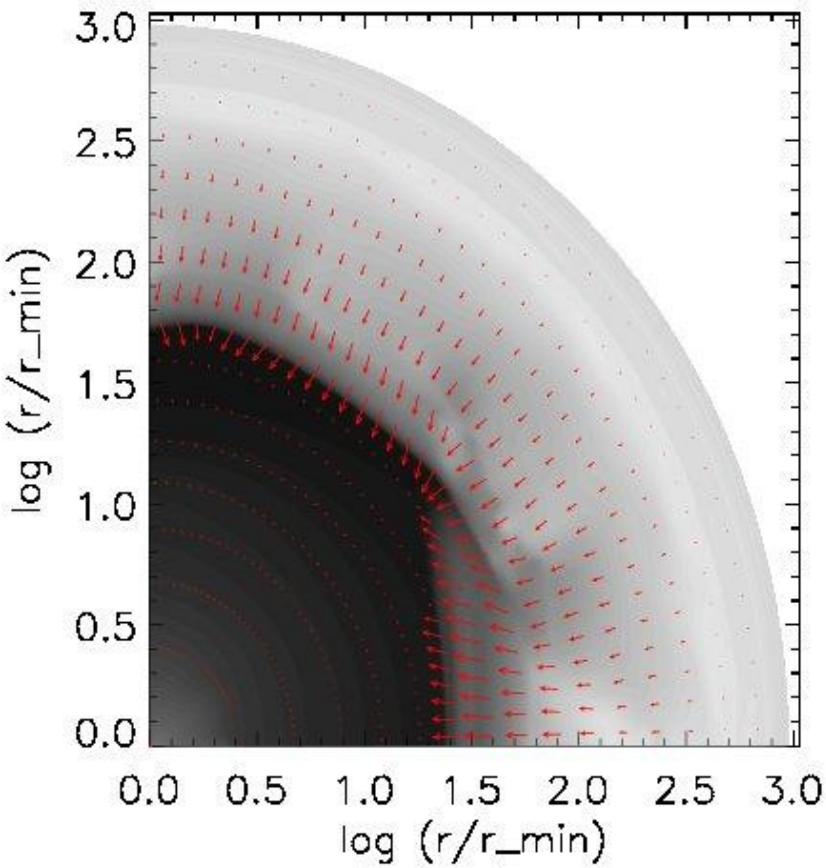
- *Milosavljevic, Couch & Bromm 2009*
- *Park & Ricotti 2011, 2012*
- *Li 2011*

Gas depletion & Collapse of I-front

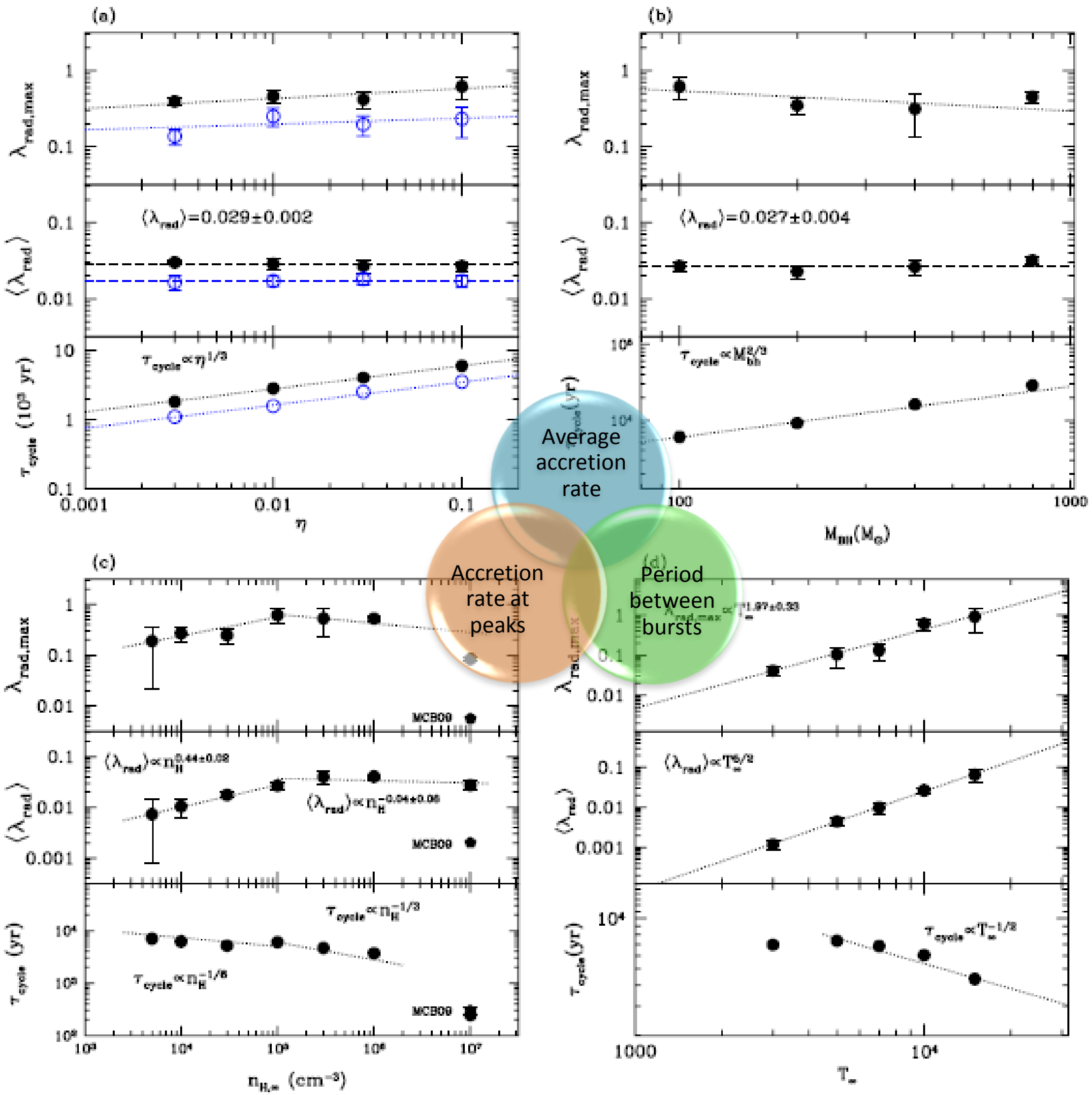
Gas depletion & Dense shell formation

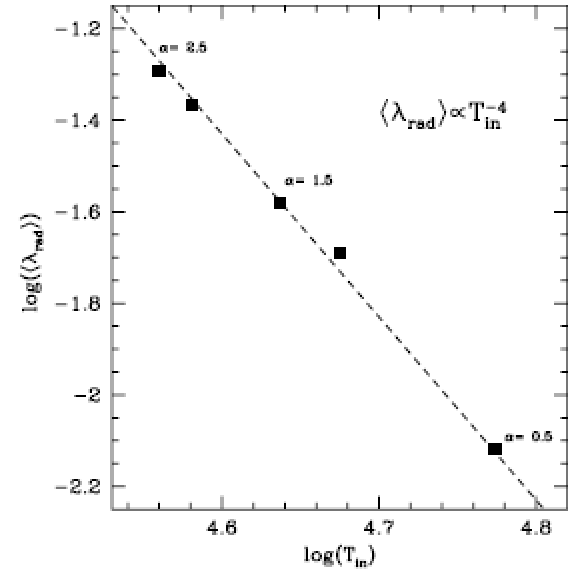


Collapse of dense shell



Parameter Space Exploration





Hydrogen heating/cooling only

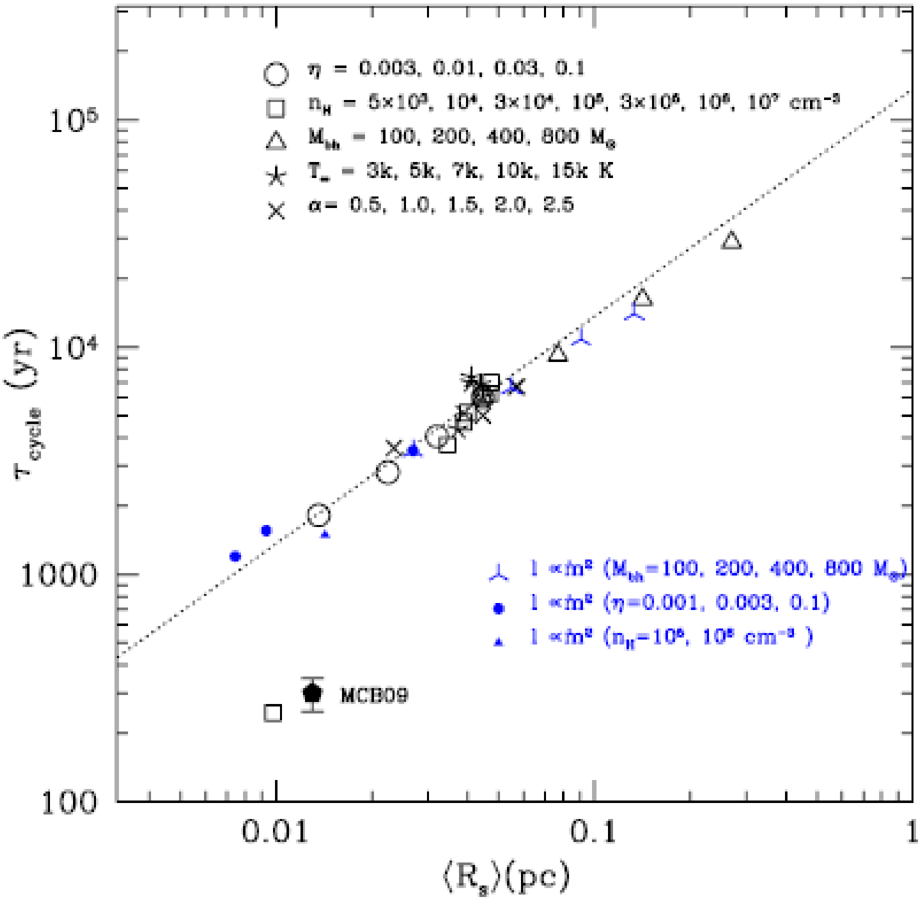
$$\langle \lambda_{\rm rad} \rangle \simeq 3\%\, T_{\infty,4}^{2.5} \left(\frac{T_{\rm in}}{4 \times 10^4\ {\rm K}} \right)^{-4}$$

w/ Helium heating/cooling

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

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

Period between bursts vs. Size of Strömgren Sphere



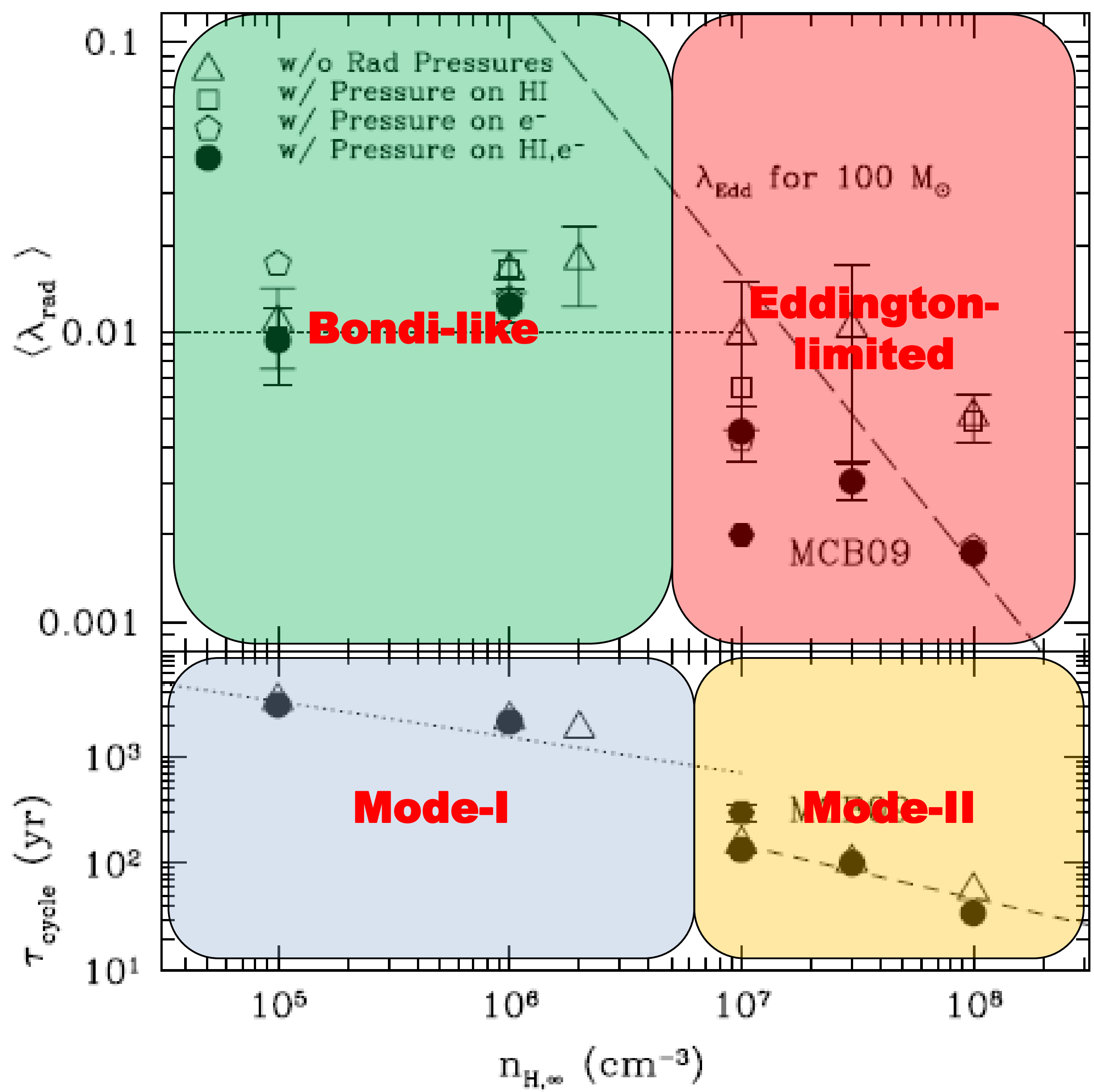
$$\tau_{cycle} \propto \langle R_s \rangle = \left(\frac{3N_{ion}}{4\pi\alpha_{rec} n_H^2} \right)^{\frac{1}{3}}$$

$$= \left(\frac{3}{4\pi\alpha_{rec} n_H^2} \right)^{\frac{1}{3}} \left(\eta \lambda_{rad} \pi \frac{G^2 M_{bh}^2}{c_{s,\infty}^3} \rho_\infty c^2 \right)^{\frac{1}{3}}$$

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

- **Average size of HII region determines period between bursts**

Transition to Eddington-limited Regime



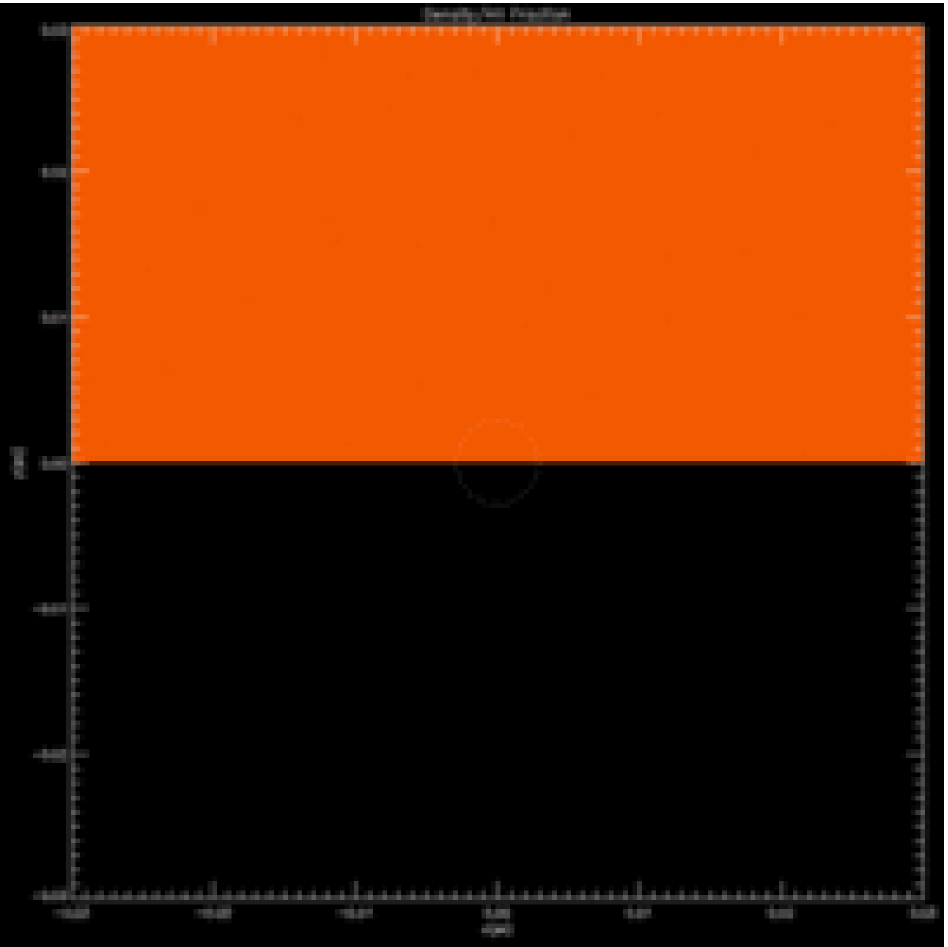
Two Distinct Modes of Oscillations

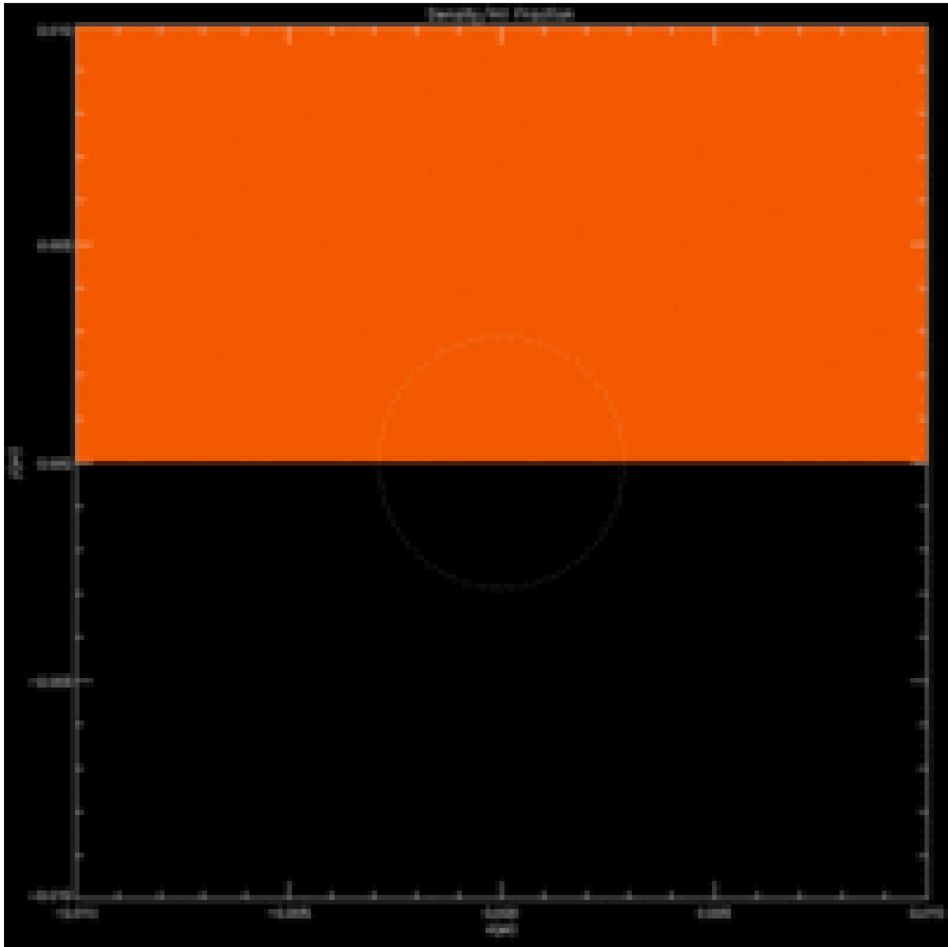
Mode-I

n = 10^6 cm^3

Mode-II

n = 10^7 cm^3





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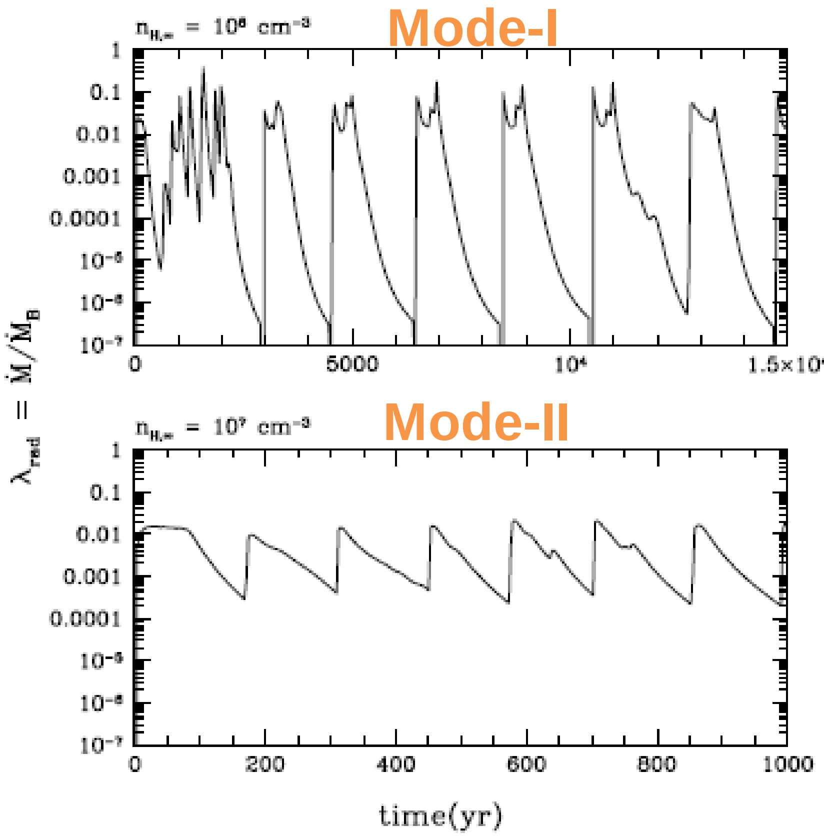
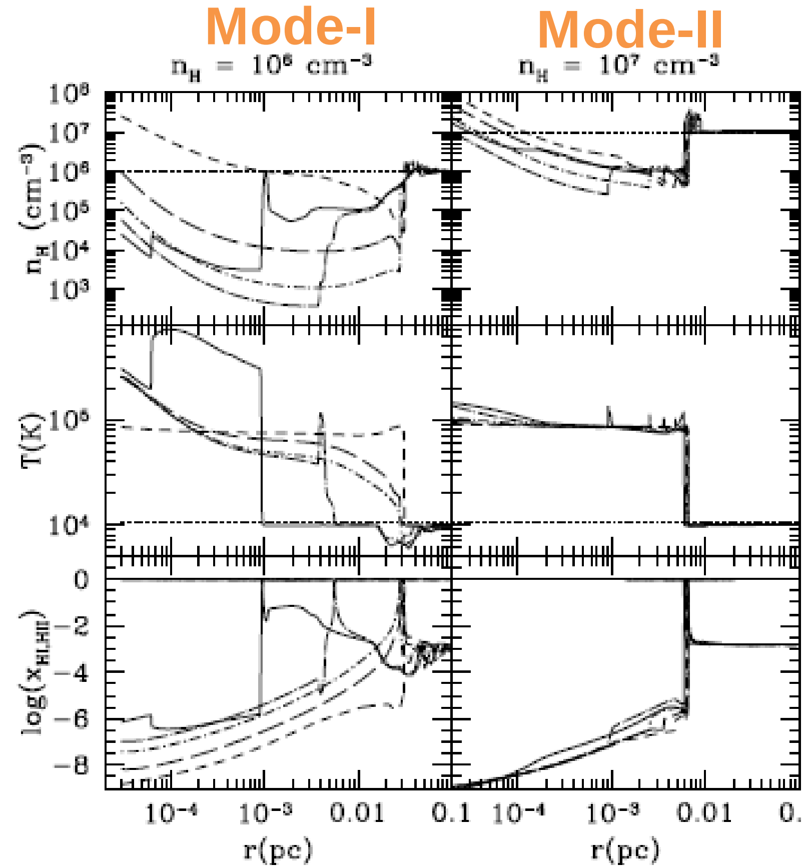


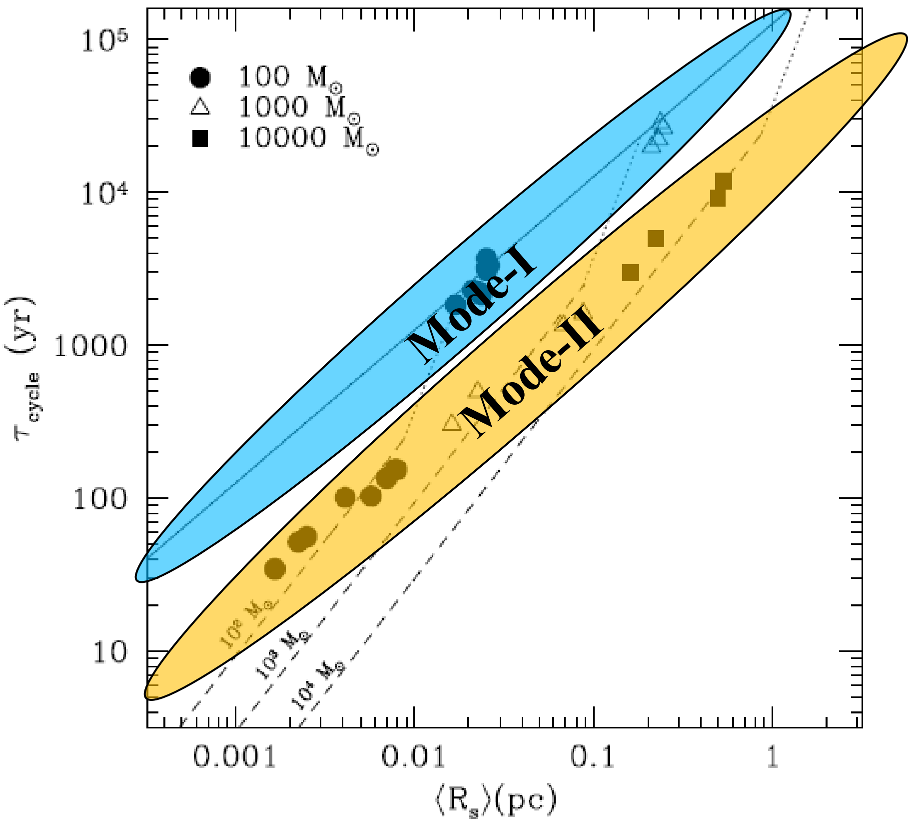


$$\tau_{on} \equiv \frac{\langle \lambda_{rad} \rangle}{\lambda_{rad,max}} \tau_{cycle},$$

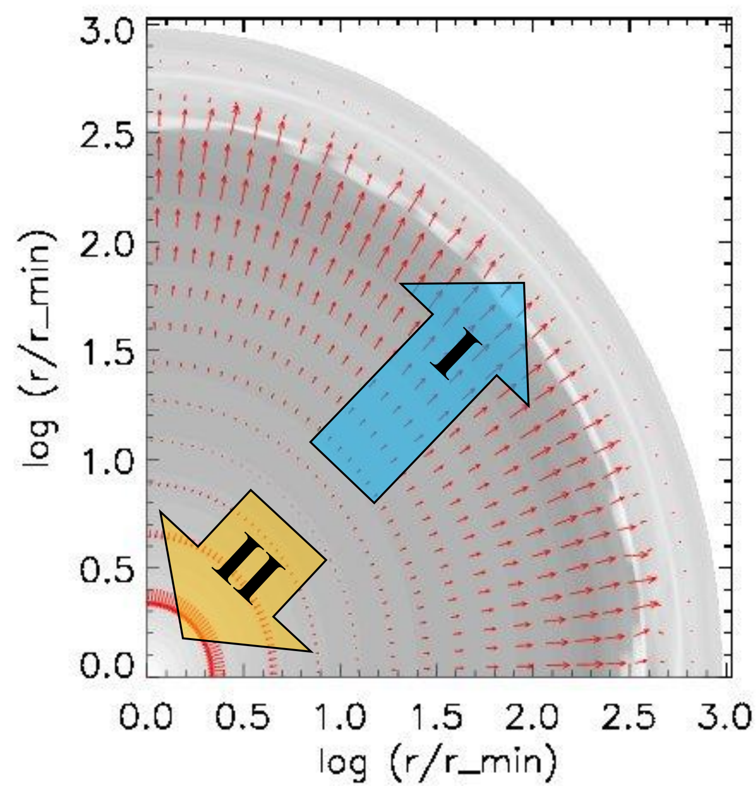
- f_{duty} increases in Mode-II oscillation driven by density wave. -> Make Eddington-limited accretion efficient

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

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



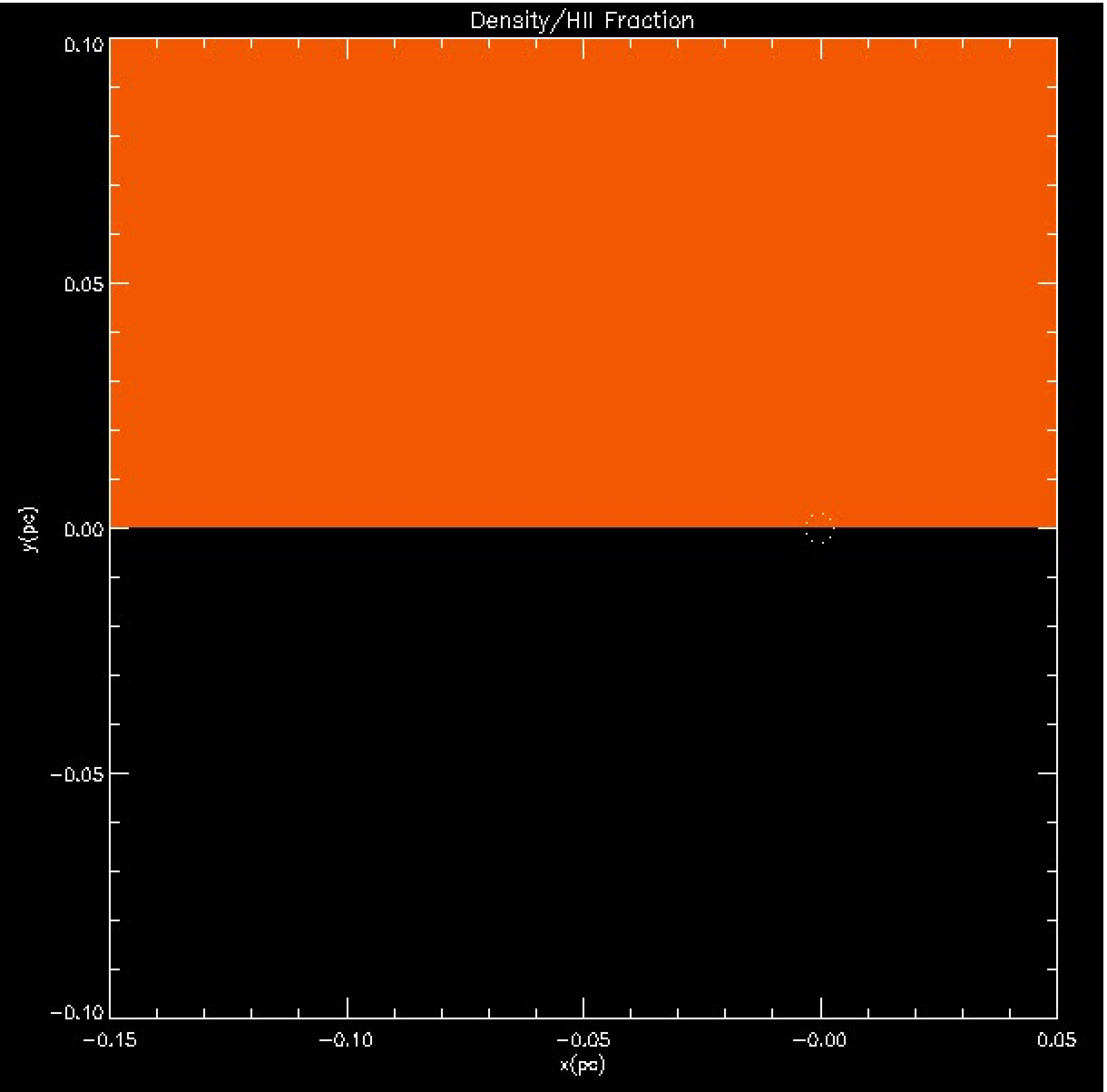
- Gas depletion time scale
  - T_{cycle} ~ <Rs> : outflow (Mode -I)
  - T_{cycle} ~ $<Rs>^3$: accretion by BH (Mode -II)
  - T_{cycle} ~ $<Rs>^{3/2}$: Eddington-limited



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

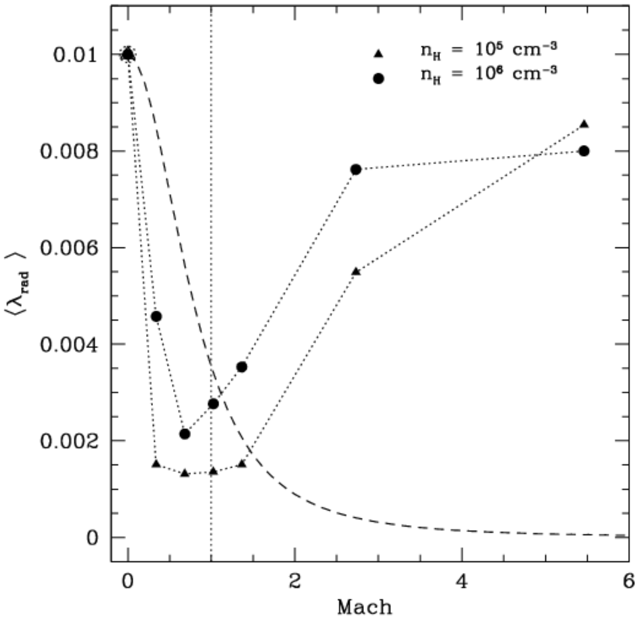
$$n_{\mathrm{H},\infty}^{\mathrm{Edd}} \sim 4\times10^{6}\ \mathrm{cm}^{-3} \left(\frac{M_{\mathrm{bh}}}{10^2\ M_\odot}\right)^{-1} \left(\frac{T_\infty}{10^4\ \mathrm{K}}\right)^{-1} \left(\frac{\eta}{0.1}\right)$$

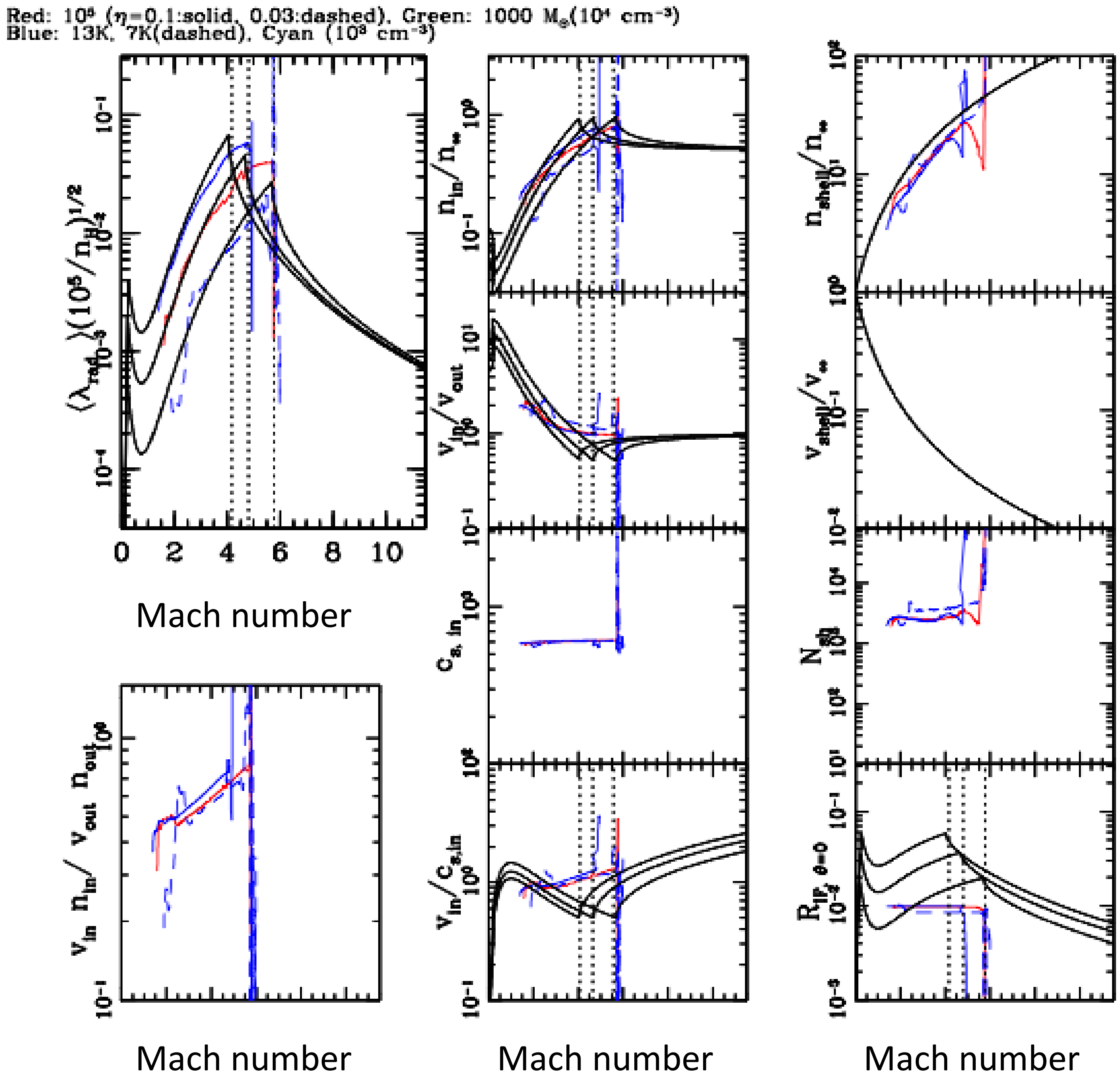
Moving black holes + Radiative Feedback
(Park & Ricotti, 2012b, in preparation)



- Bondi-Hoyle accretion rate

$$\dot{M} = \frac{4\pi G^2 M^2 \rho_\infty}{(c_\infty^2 + v_\infty^2)^{3/2}}$$





Red: 10⁵ (η=0.1:solid, 0.03:dashed), Green: 1000 M☉(10⁴ cm⁻³)
Blue: 13K, 7K(dashed), Cyan (10³ cm⁻³)
Mach number
Mach number
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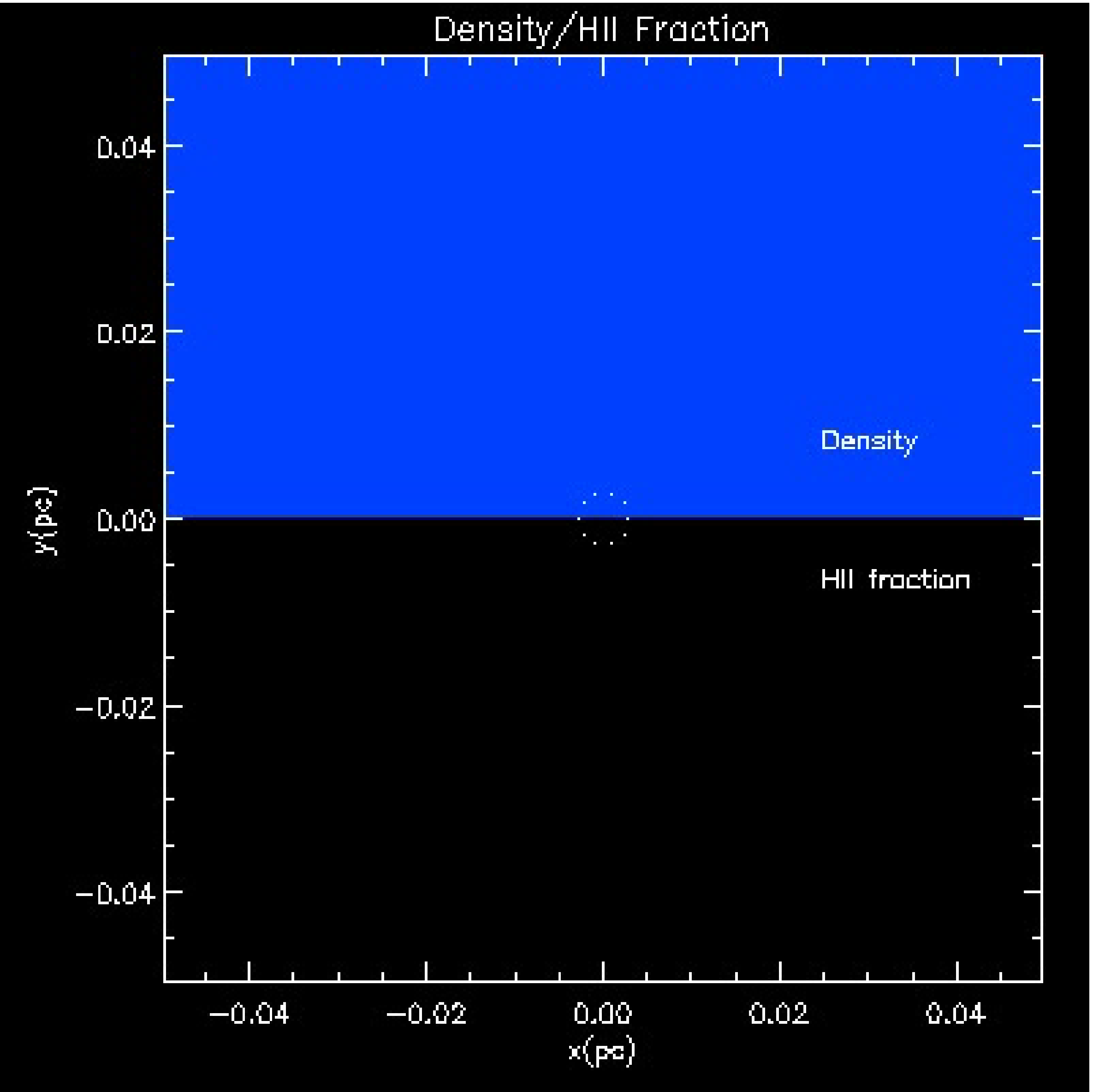

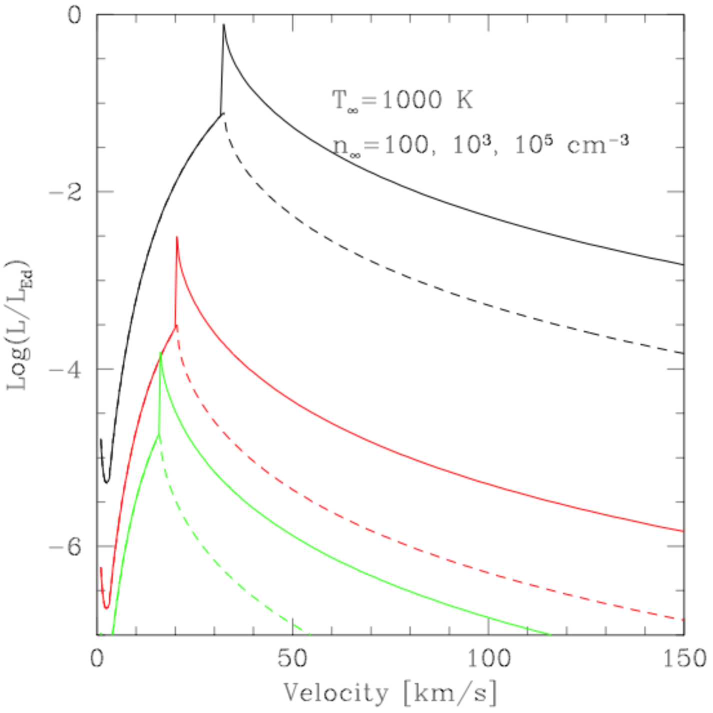

Summary

- In sub-Eddington regime : ~1% of Bondi accretion rate.
- With increasing density and BH mass the accretion becomes Eddington limited.
- Two distinct modes of oscillations :
  - Mode-I (bursts driven by I-front collapse) vs. Mode-II (density wave)
  - f_duty~ 50% at Mode-II
- Eddington limited regime + Mode-II oscillation decrease accretion rate more effectively
- Moderate amount of time delay does not destroy oscillations

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

$$\tau_{\mathrm{cycle}} = \begin{cases} \tau_{\mathrm{cycle}}^{\mathrm{I}} \approx (0.1\ \mathrm{Myr})\ M_{\mathrm{bh},2}^{2/3} \eta_{-1}^{1/3} \left(\frac{n_{\mathrm{H},\infty}}{1\ \mathrm{cm}^{-3}} \right)^{-1/3} \left(\frac{\bar{E}}{41\ \mathrm{eV}} \right)^{-3/4} \\ \tau_{\mathrm{cycle}}^{\mathrm{II}} \approx (1\ \mathrm{Gyr})\ \eta_{-1} \left(\frac{n_{\mathrm{H},\infty}}{1\ \mathrm{cm}^{-3}} \right)^{-1} \left(\frac{\bar{E}}{41\ \mathrm{eV}} \right)^{-7/8}, \end{cases}$$