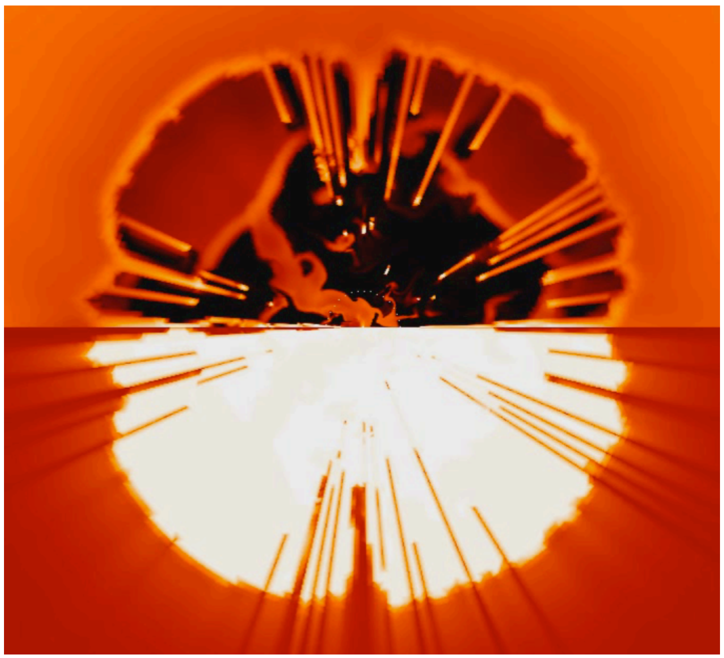
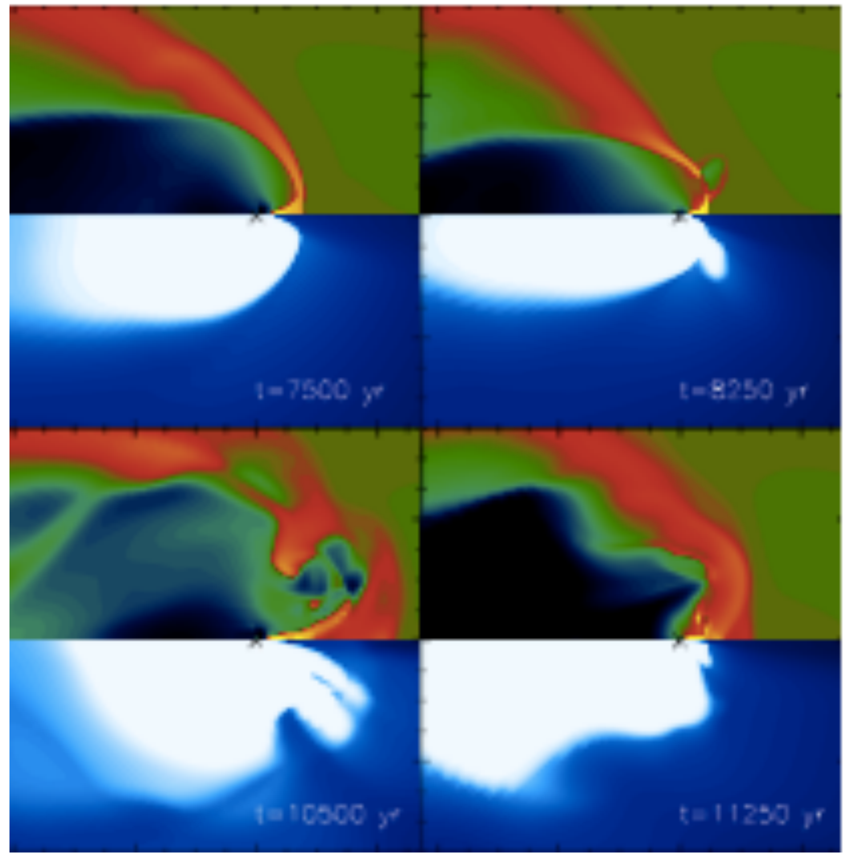
Growth and X-rays from Intermediate mass black holes



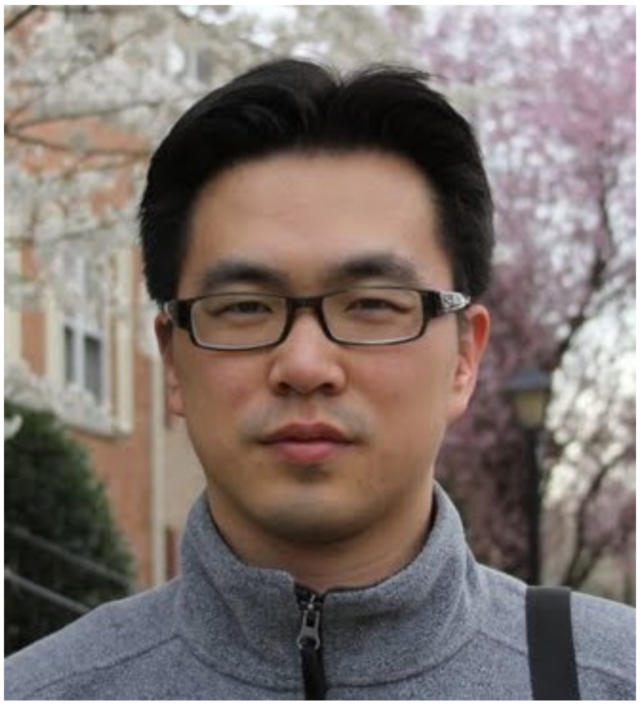


Massimo Ricotti
Institut d'Astrophysique de Paris
and
University of Maryland

Seminar Bologna 2013

Basic question: what is the Bondi accretion rate including the effects of radiation feedback?

Work based on KwangHo Park's PhD Thesis



- PhD 2012 University of Maryland
- Postdoc at Carnegie Mellon (with T. DiMatteo)

- References:

Park & Ricotti 2011, ApJ, 739, 2
Park & Ricotti 2012, ApJ, 747, 9
Park & Ricotti 2013, ApJ, 767, 163

Fueling of BHs

- Complex topic, related to star formation, galaxy formation, galaxy mergers, and feedback effects
- Large body of work in literature on growth of SMBHs at the center of galaxies: complex because of interplay between galaxy and SMBH (e.g., see Luca Ciotti's work, and many others …. di Matteo+, Haiman+, Hernquist+, Ho+, Hopkins+, Johnson+, Milosavljevic+, Nagamine +, Ostriker+, Proga+, Spaans+, Volonteri+, ...etc)

How it all started: Bondi-Hoyle and Eddington Accretion

1) Sphere of influence of the BH's gravity: $\dot{M} = \pi R^2 \rho v$

Obtain the **Bondi radius** setting the escape velocity=sound speed:

$$R = \frac{2GM}{c_s^2}$$

Bondi accretion rate (Bondi 1952):

$$\dot{M} = \frac{4\pi \rho G^2 M^2}{c_s^3}$$

2) Effect of radiation pressure on e$^-$ (Compton scattering)

$$\begin{aligned} L_{\rm bol} = L_{\rm Eddington} &= \frac{4\pi G c m_p}{\sigma_e} M_{\rm BH} \\ &= 1.26 \times 10^{38} {\rm erg\,s^{-1}} \left(\frac{M_{\rm BH}}{M_\odot}\right). \end{aligned} \tag{6}$$

But there is much more:

- Radiation feedback: thermal, rad pressure
  - If ambient gas is neutral: photoionization
- Effect of angular momentum of gas produces a thin disk (alpha-disk)
- Non-trivial boundary conditions and external gravitational potential (stars and dark matter in a galaxy)
- Fueling by stellar winds, mergers, etc.
- Details depend on the halo mass and mass of the BH:
  1. Dwarf and Milky Way size galaxies: gas is mostly neutral
  2. Clusters and massive elliptical galaxies: IC gas is diffuse and collisionally ionized

However, for IMBHs the Bondi radius is small with respect to galactic scales several of these complications are less relevant

Philosophy of our approach

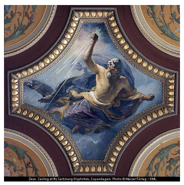
- We take one step back: try to understand the Bondi problem with radiation feedback:

$$L = \eta \, (dM_{rmin}/dt)c^2$$

- 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 perhaps SMBH in large scale cosmological simulations
- Results are qualitatively different with respect to Bondi's equations + surprising rich phenomenology even with very simple IC!
- Simulations focus on IMBHs in first galaxies (high-density), but our analytical scaling relationships apply to wide range of BH masses (with the many caveats mentioned before)

Numerical Simulations

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



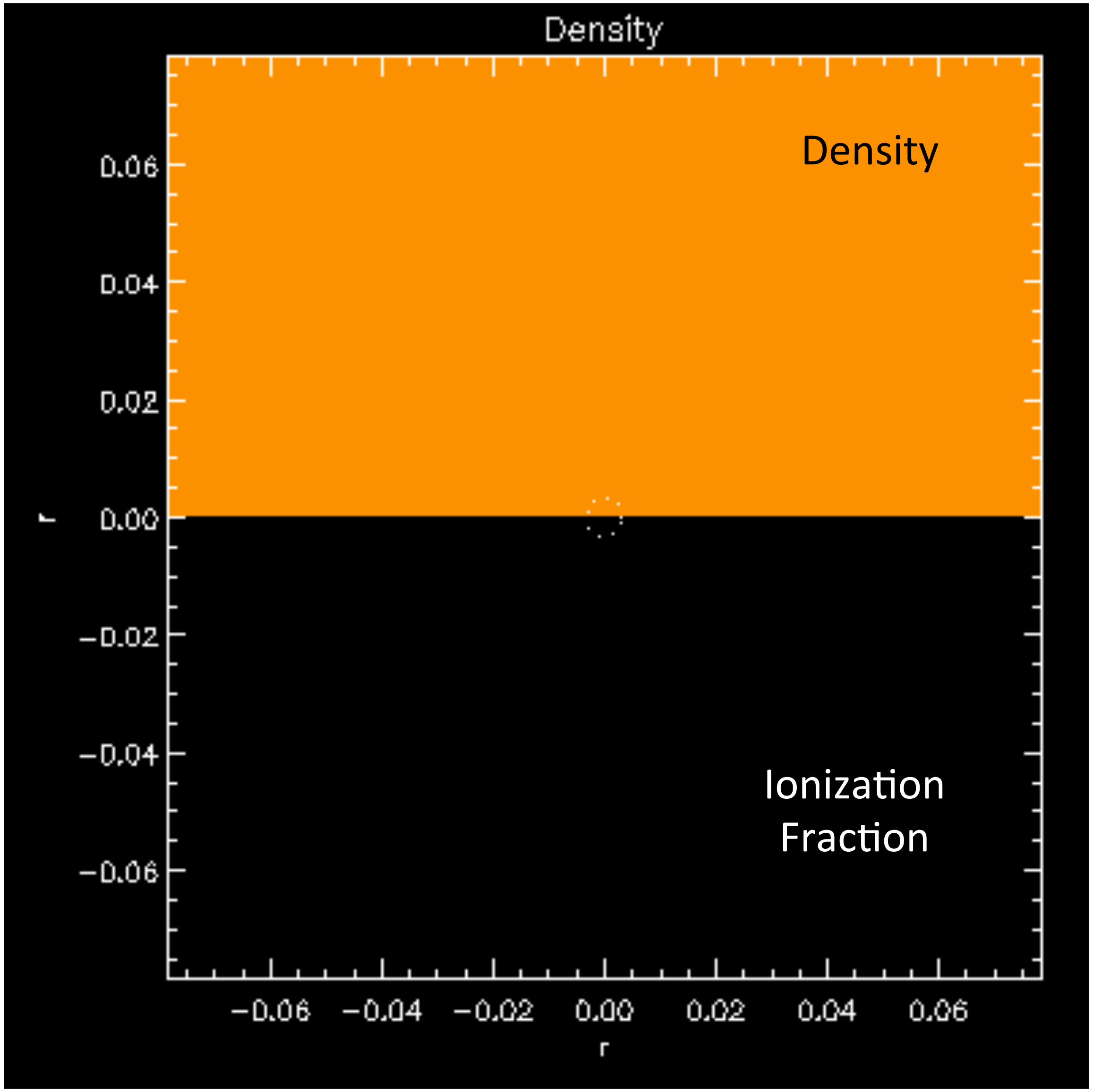
  - 1D and 2D Hydrodynamics + ray-tracing module
  - Photoheating & Photoionization, Radiation pressure, Compton Heating
  - Multi species : HI, HII, HeI, HeII, HeIII, e^-
  - IC: Uniform density and zero angular momentum
  - Log grid in radial direction (resolve from Bondi radius to10^{-3}-10^{-4} Bondi)
- **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

Outline

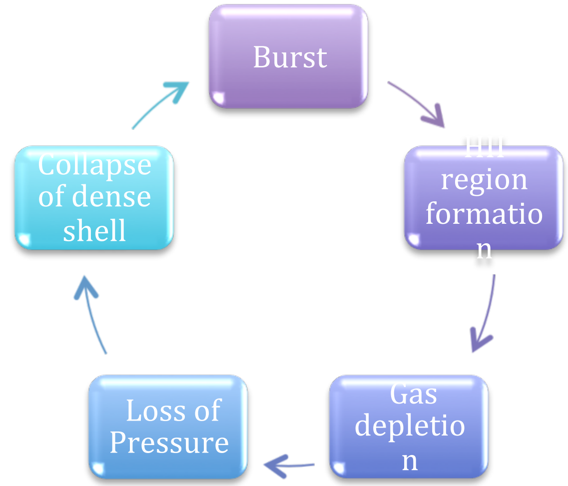
I. **Bondi accretion with RT (stationary IMBHs)**

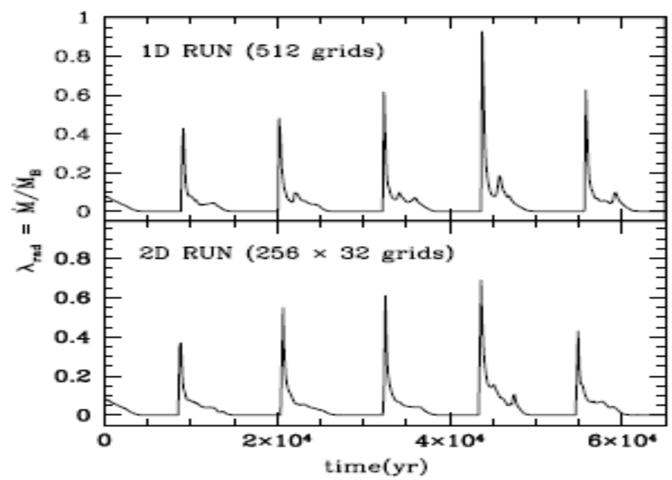
II. Bondi-Lyttleton accretion with RT (moving IMBHs)

Periodic Luminosity Bursts



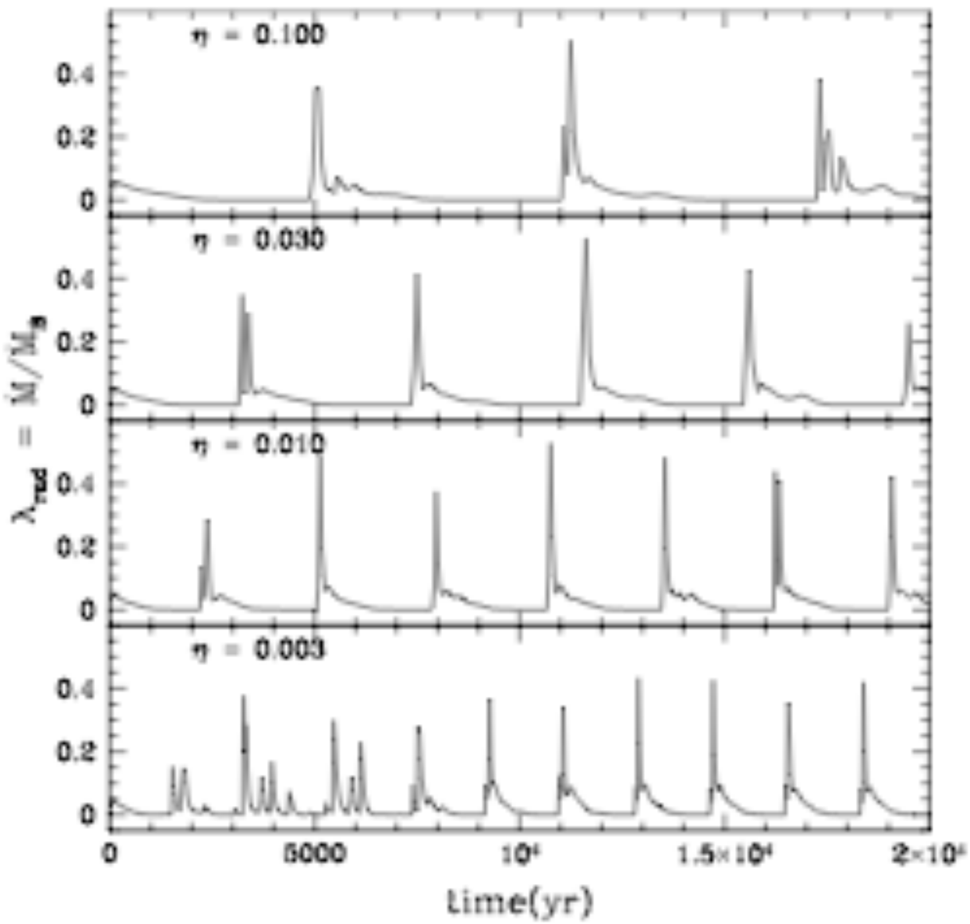
$\eta=0.1$, $M_{bh}= 100\ M_{sun}$, $T_{inf}=10^4$ K, $n = 10^5\ cm^{-3}$





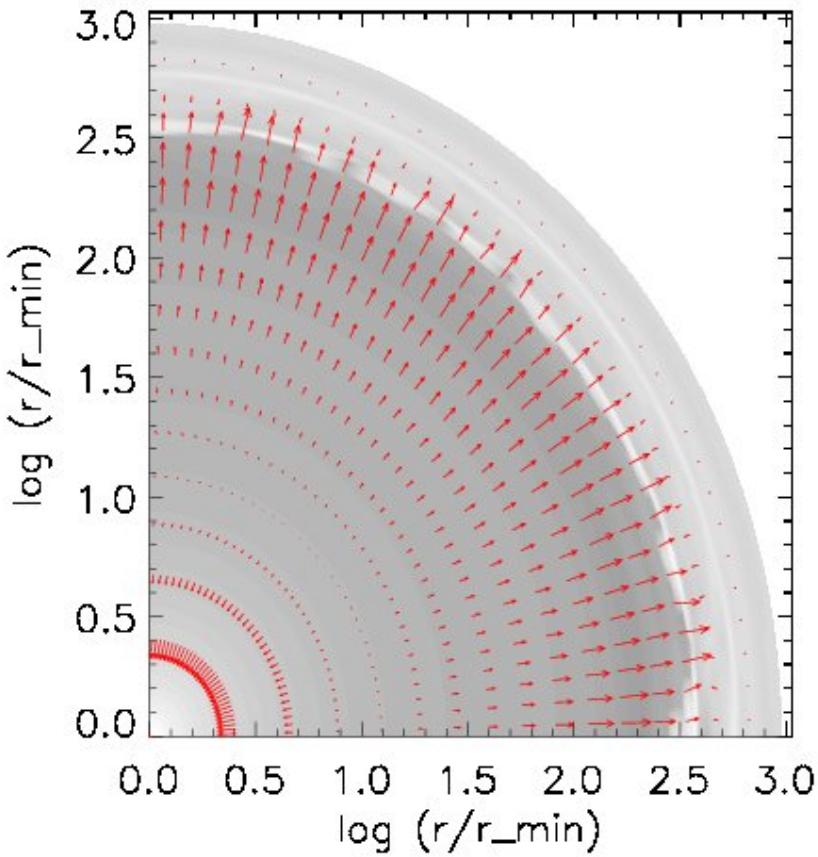
- *Milosavljevic, Couch & Bromm 2009*
- *Park & Ricotti 2011, 2012*
- *Li 2011*

Periodic FREDs

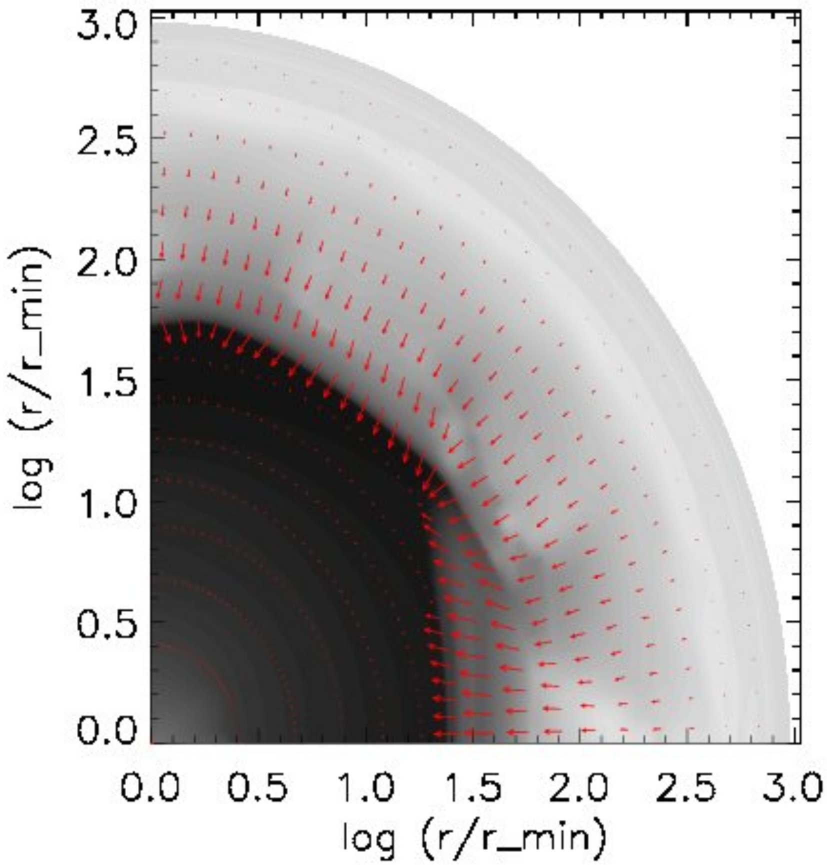


Gas depletion & Collapse of I-front

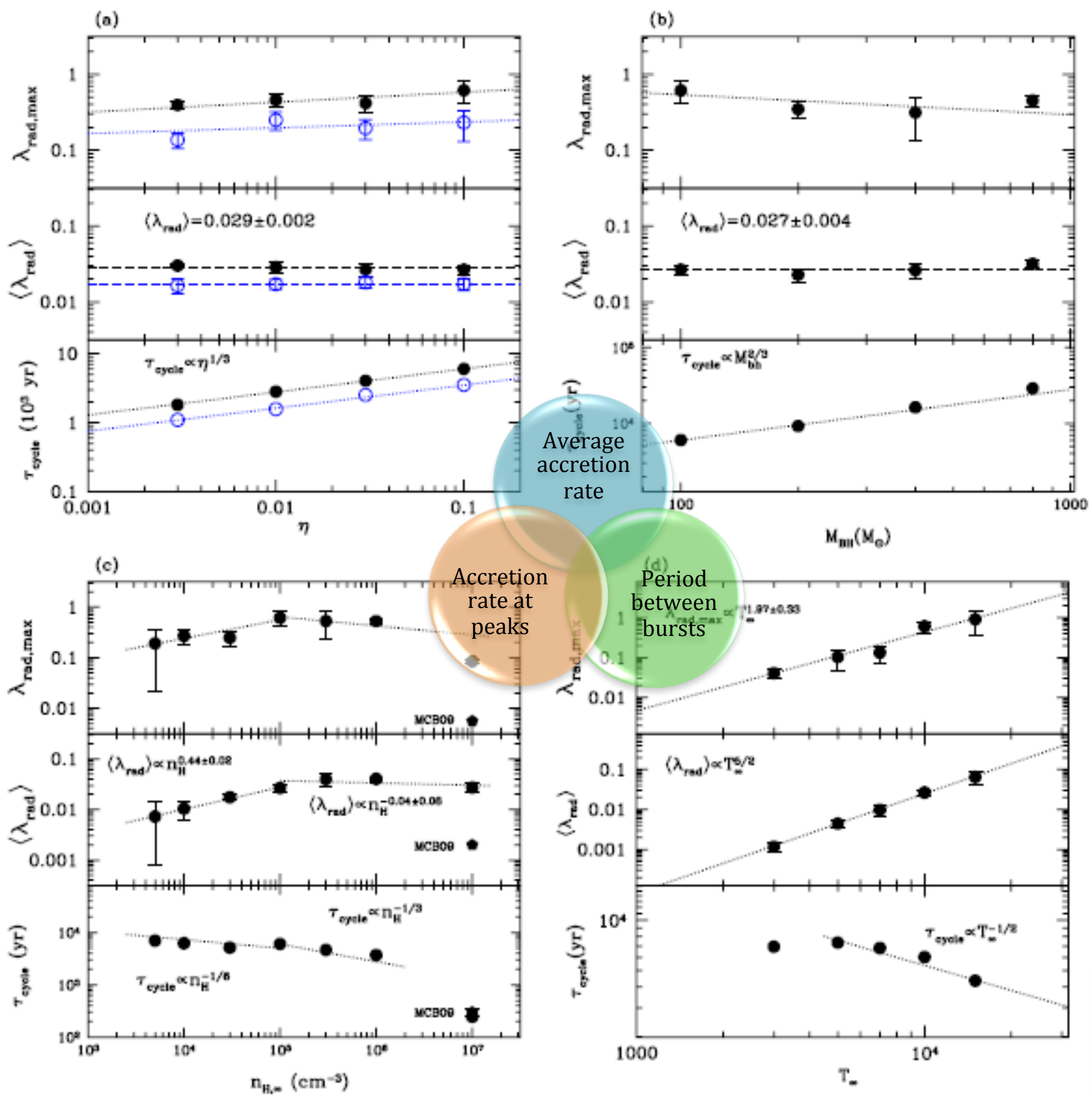
Gas depletion & Dense shell formation

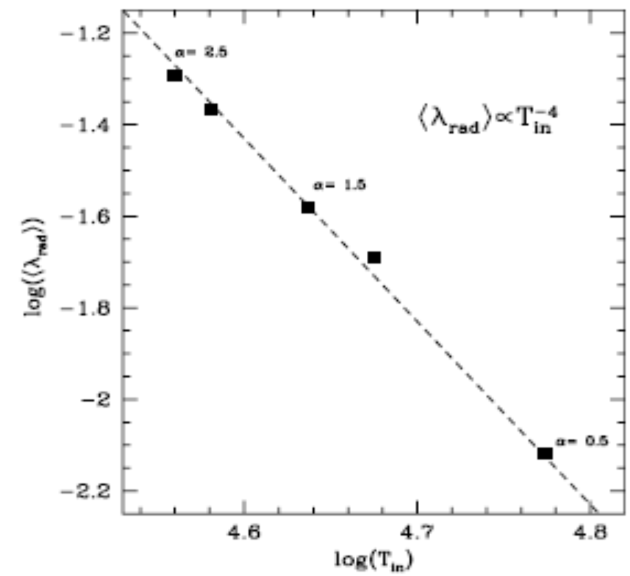


Collapse of dense shell



Parameter Space Exploration





Hydrogen heating/cooling only

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

w/ Helium heating/cooling

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

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

Modeling: Mean Accretion Rate

Simple model explains all sim. results:

1) Bondi formula inside the HII region

$$\langle \dot{M} \rangle = 4\pi \lambda_B r_{\rm acc}^2 \rho_{\rm in} c_{s,\rm in},$$

2) Pressure equilibrium in/out HII region:

$$\rho_{\rm in} \approx \rho_\infty \frac{T_\infty}{T_{\rm in}} = \rho_\infty \left(\frac{c_{s,\infty}}{c_{s,\rm in}} \right)^2 .$$

Accretion rate in units of Bondi rate:

$$\langle \lambda_{\rm rad} \rangle \simeq \lambda_B \frac{r_{\rm acc}^2 \rho_{\rm in} c_{s,\rm in}}{r_{b,\infty}^2 \rho_\infty c_{s,\infty}} \simeq \frac{1}{4}(1.8)^2 \left(\frac{\rho_{\rm in}}{\rho_\infty} \right) \left(\frac{c_{s,\rm in}}{c_{s,\infty}} \right)^{-3}$$

$$\simeq 3\% T_{\infty,4}^{2.5},$$

Accretion rate proportional to thermal pressure of ambient gas

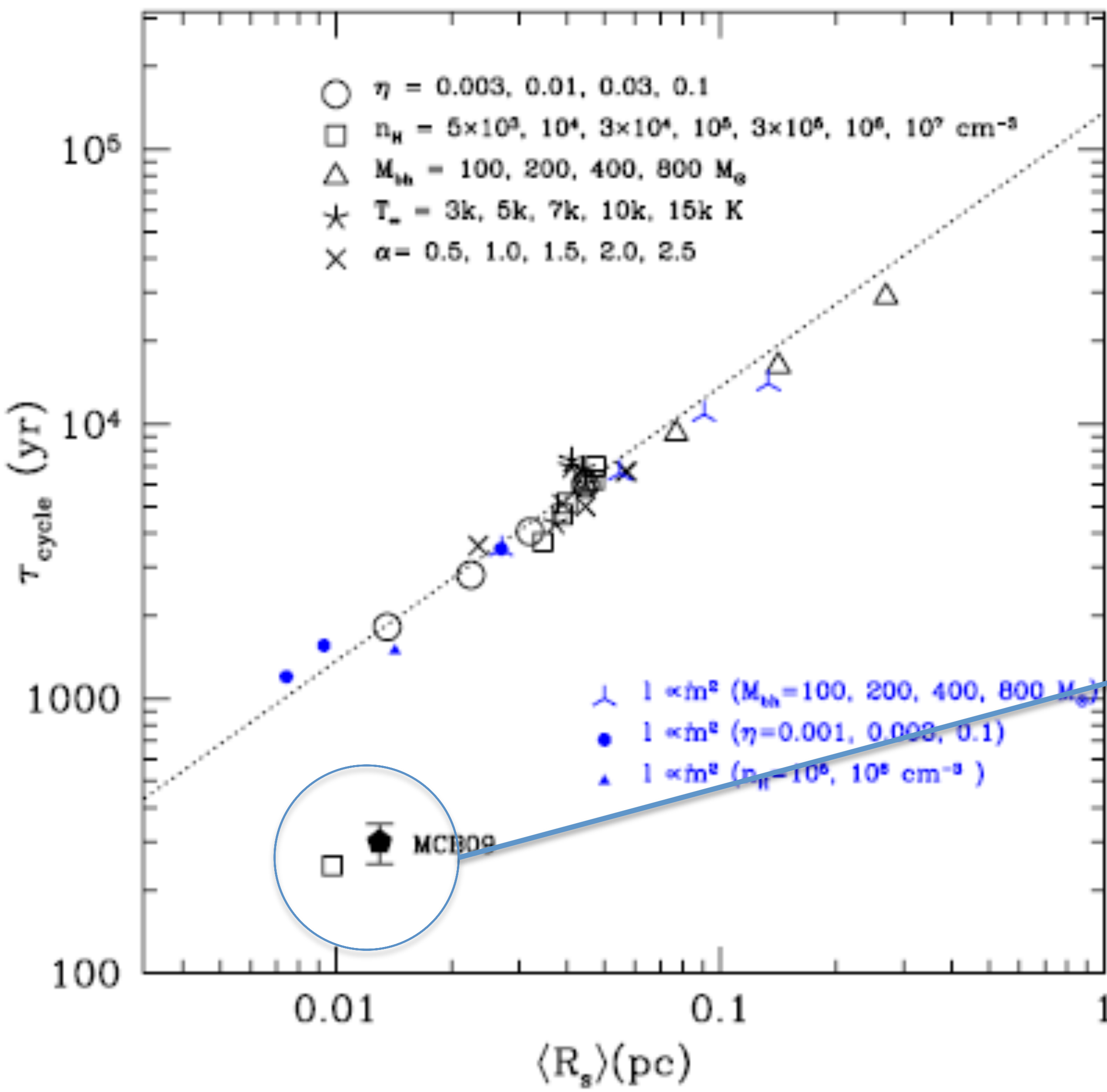
And very sensitive to the temperature inside the HII region

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

$$\Downarrow$$

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

Period between bursts is 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 simulations with highest gas density (10^7 cm^{-3})

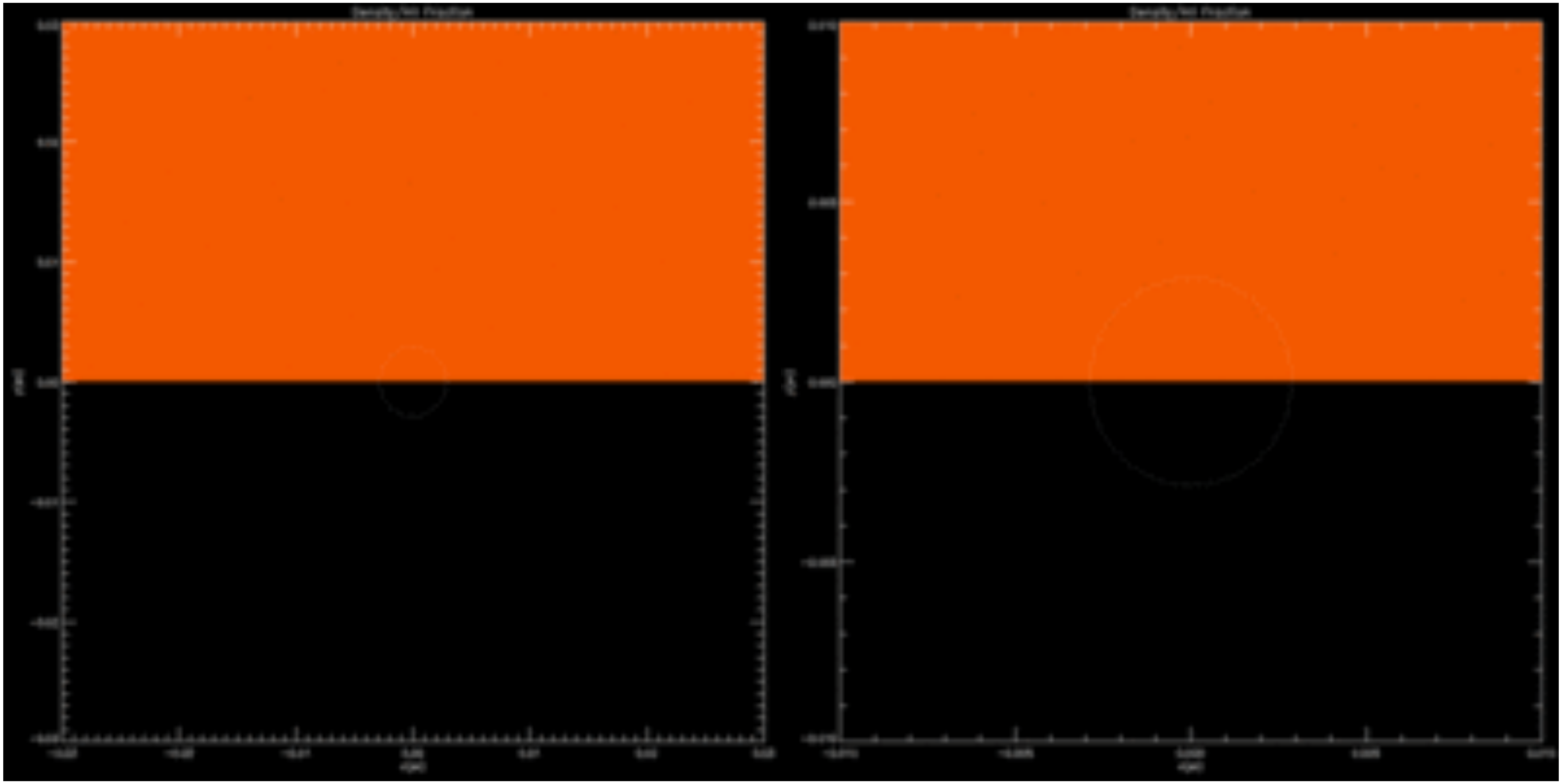
Two Distinct Modes of Oscillations

Mode-I

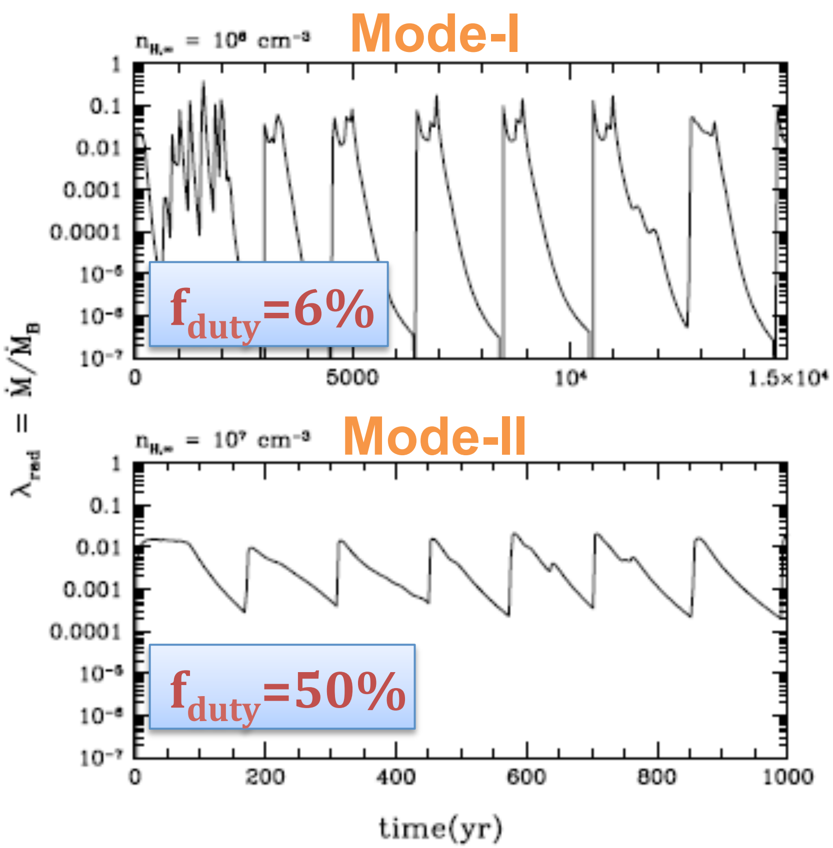
$n = 10^6\ cm^{-3}$

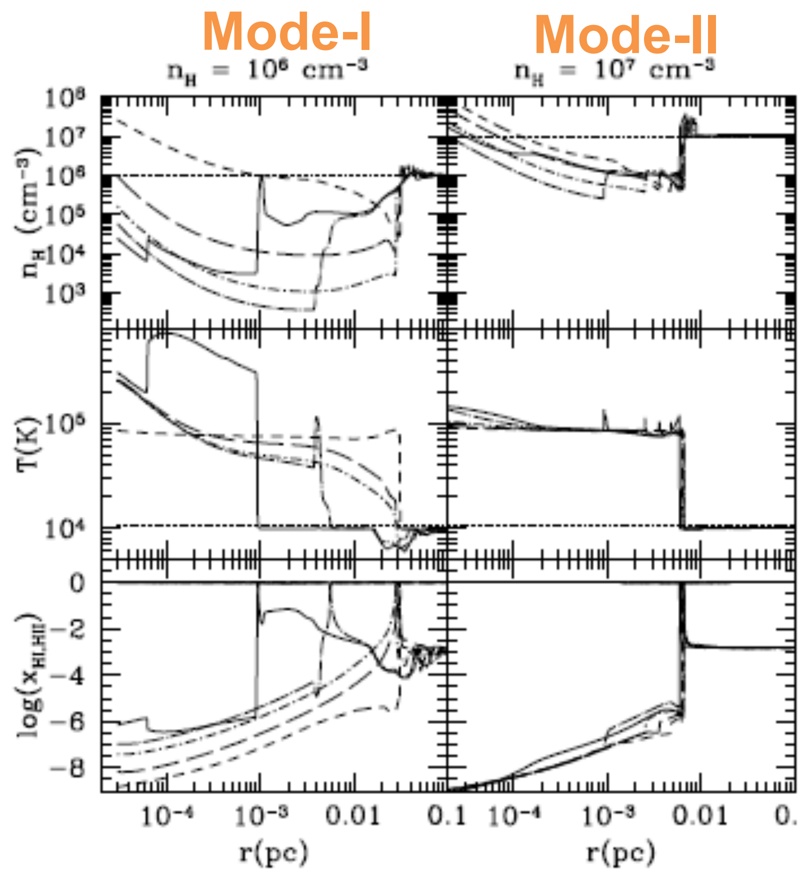
Mode-II

$n = 10^7\ cm^{-3}$



Two Distinct Modes of Oscillations





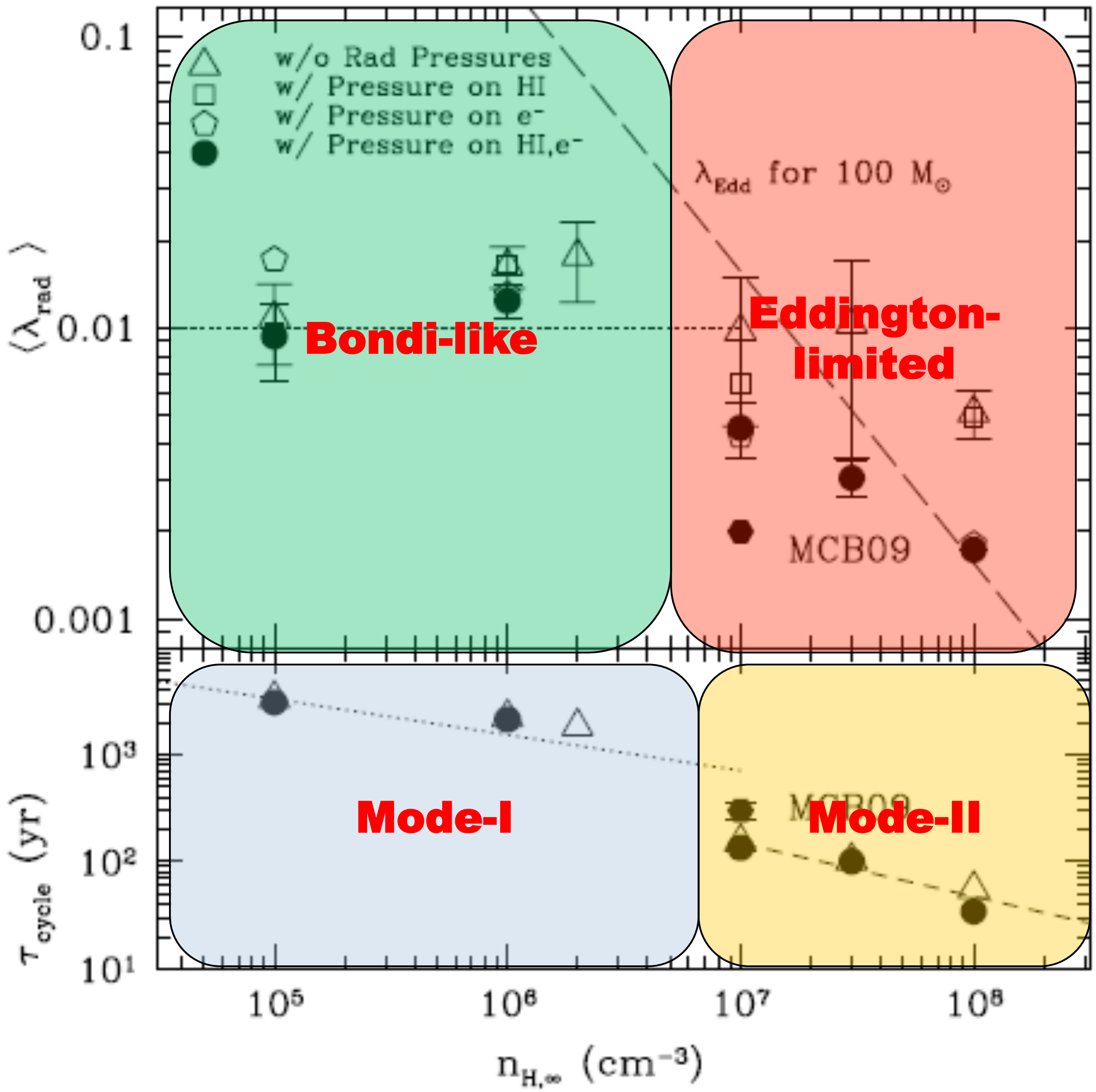
$$\tau_{on} \equiv \frac{\langle \lambda_{rad} \rangle}{\lambda_{rad,max}} \tau_{cycle},$$

f_{duty} increases in mode-II oscillations.

Makes Eddington-limited accretion efficient

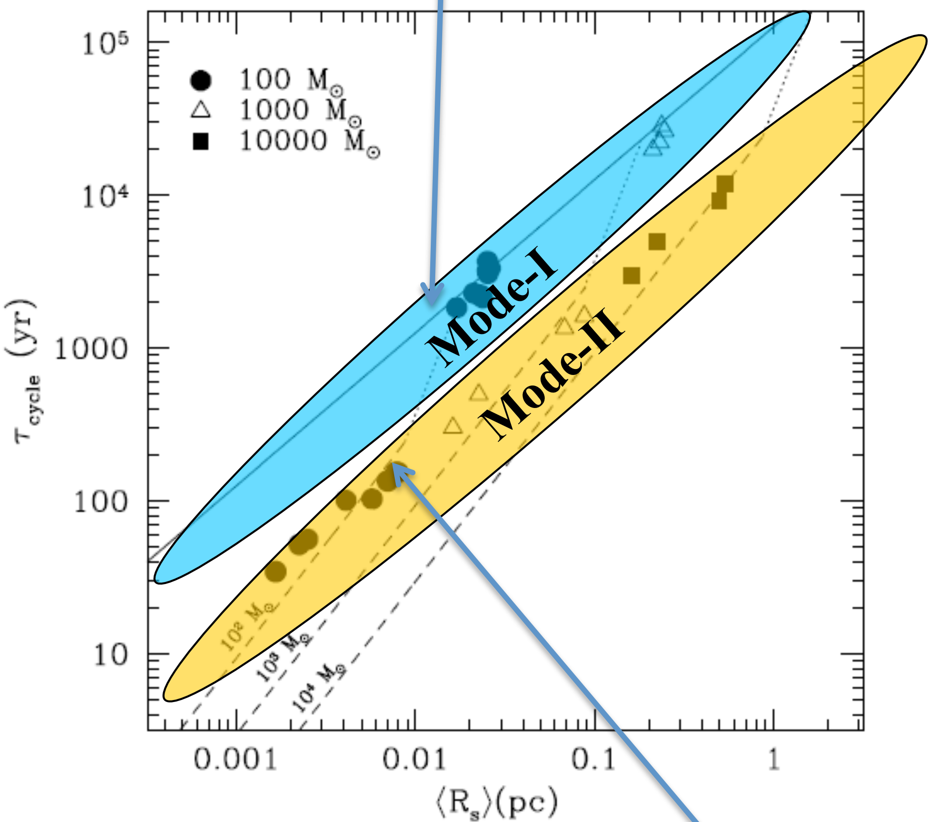
$$f_{duty} \equiv \frac{\tau_{on}}{\tau_{cycle}} = \frac{\langle \lambda_{rad} \rangle}{\lambda_{rad,max}}$$

Transition to Eddington-limited Regime



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

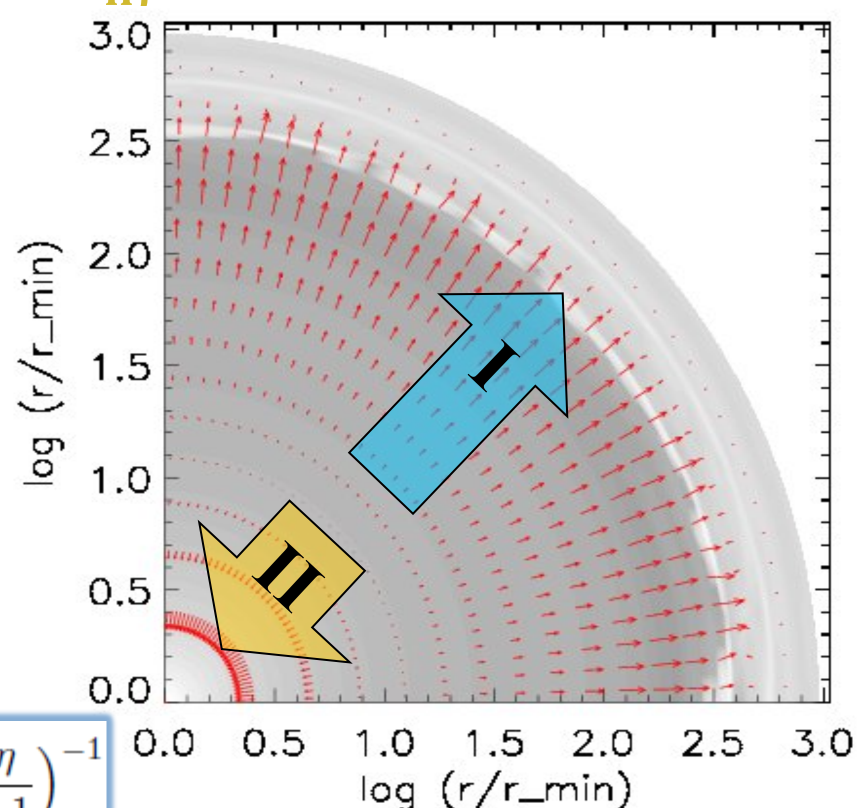
$$n^{\rm cr}_{\rm H,\infty} \sim (5\times10^6\ {\rm cm^{-3}}) M_{\rm bh,2}^{-1} T_{\rm in,*}^{7/4} \left(\frac{\bar{E}}{41\ {\rm eV}}\right)^{-1}$$



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

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)



Summary Part-I

1. Very inefficient accretion: ~1% of Bondi rate (because accretion rate determined by gas temperature and density inside the HII region).
2. Accretion rate proportional to thermal pressure

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

3. Two distinct accretion modes:
   I. Mode-I f_{duty}=6% (I-front collapse)
   II. Mode-II f_{duty}~ 50% (thus, mean accretion rate can approach Eddington limit)

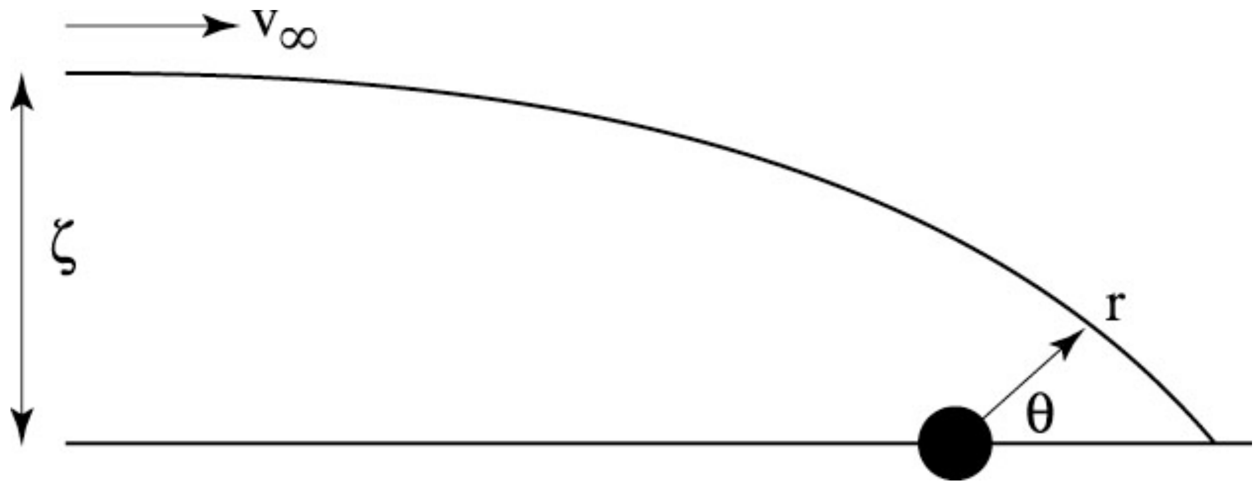
$$\tau_{\mathrm{cycle}} = \begin{cases} \tau_{\mathrm{cycle}}^{\mathrm{I}} \approx (0.1\ \mathrm{Myr})\ M_{\mathrm{bh},2}^{2/3} \eta_{-1}^{1/3} (\frac{n_{\mathrm{H},\infty}}{1\ \mathrm{cm}^{-3}})^{-1/3} (\frac{\bar{E}}{41\ \mathrm{eV}})^{-3/4} \\ \tau_{\mathrm{cycle}}^{\mathrm{II}} \approx (1\ \mathrm{Gyr})\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

Outline

I. Bondi accretion with RT (stationary BHs)

II. Bondi-Lyttleton accretion with RT (moving IMBHs)

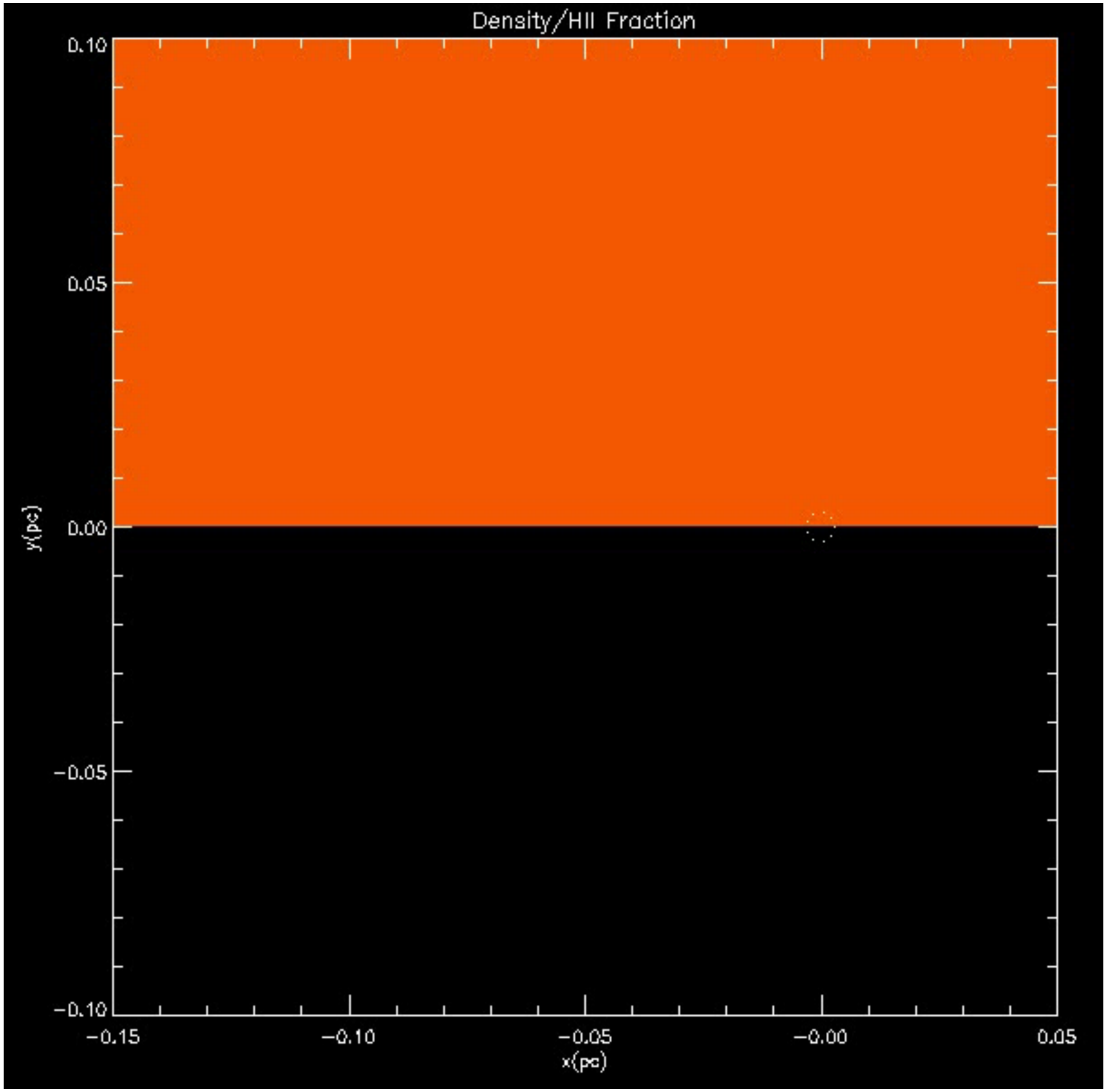
Bondi-Hoyle-Lyttleton Accretion



$$\dot{M}_{\rm HL} = \pi\zeta_{\rm HL}^2 v_\infty \rho_\infty = \frac{4\pi G^2 M^2 \rho_\infty}{v_\infty^3}$$

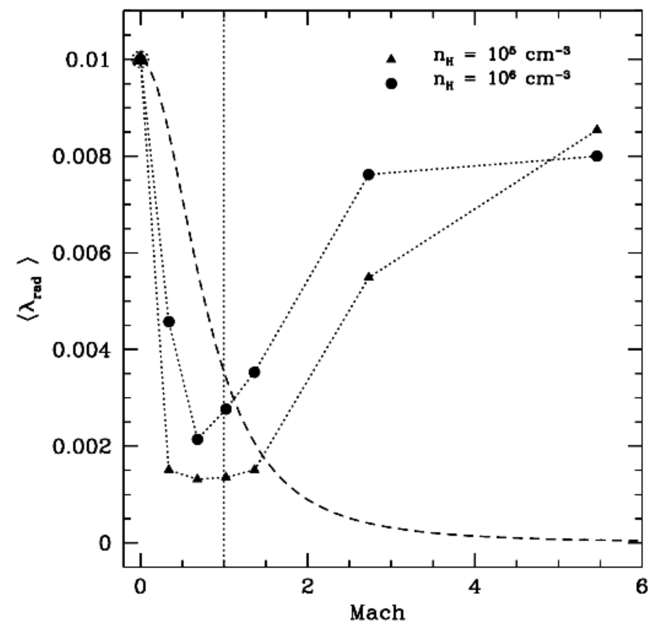
$$\dot{M}_{\rm BH} = \frac{4\pi G^2 M^2 \rho_\infty}{(c_\infty^2 + v_\infty^2)^{3/2}}$$

Moving IMBH + Radiative Feedback
(Park & Ricotti, 2013)

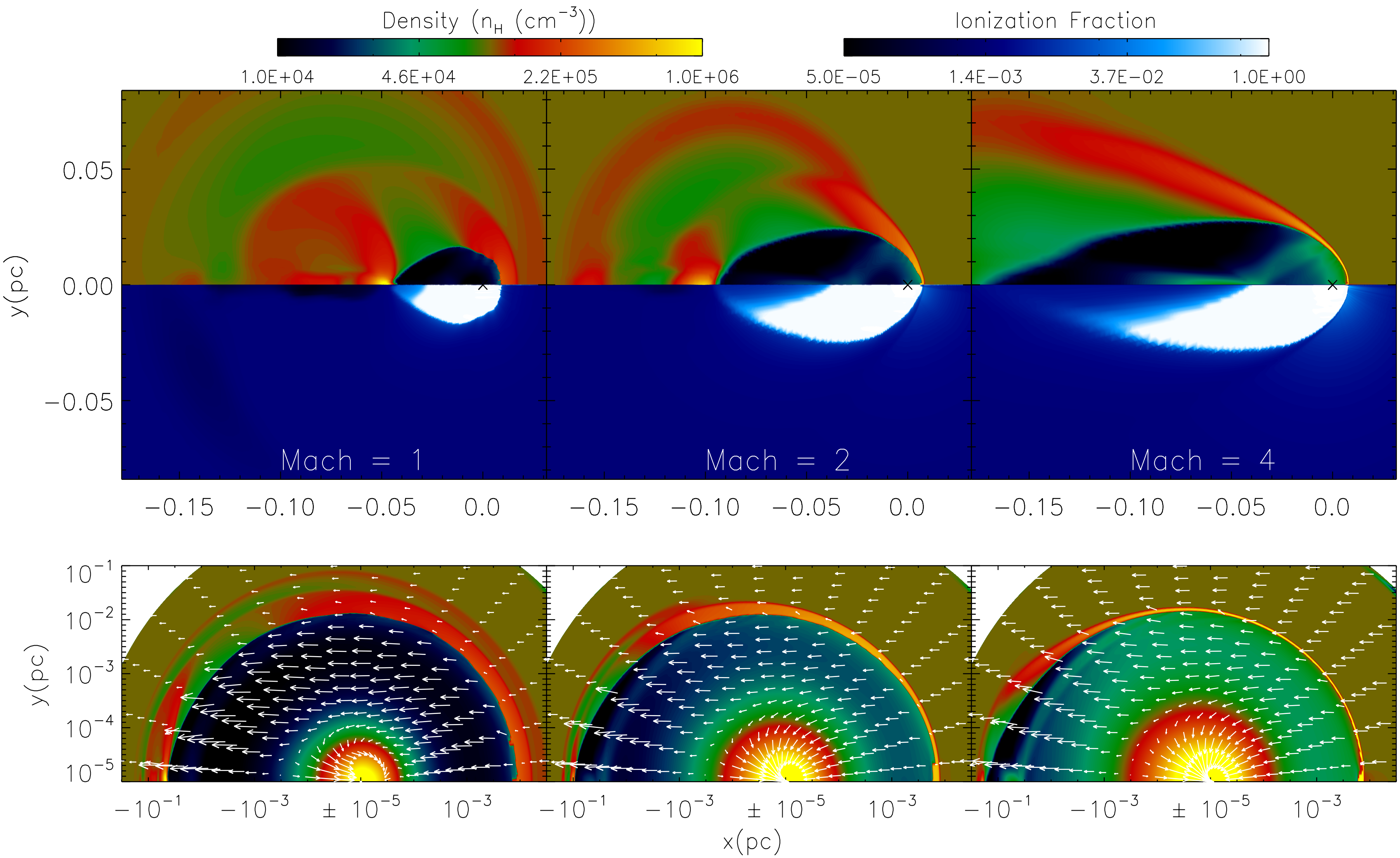


- Bondi-Hoyle-Lyttleton accretion rate

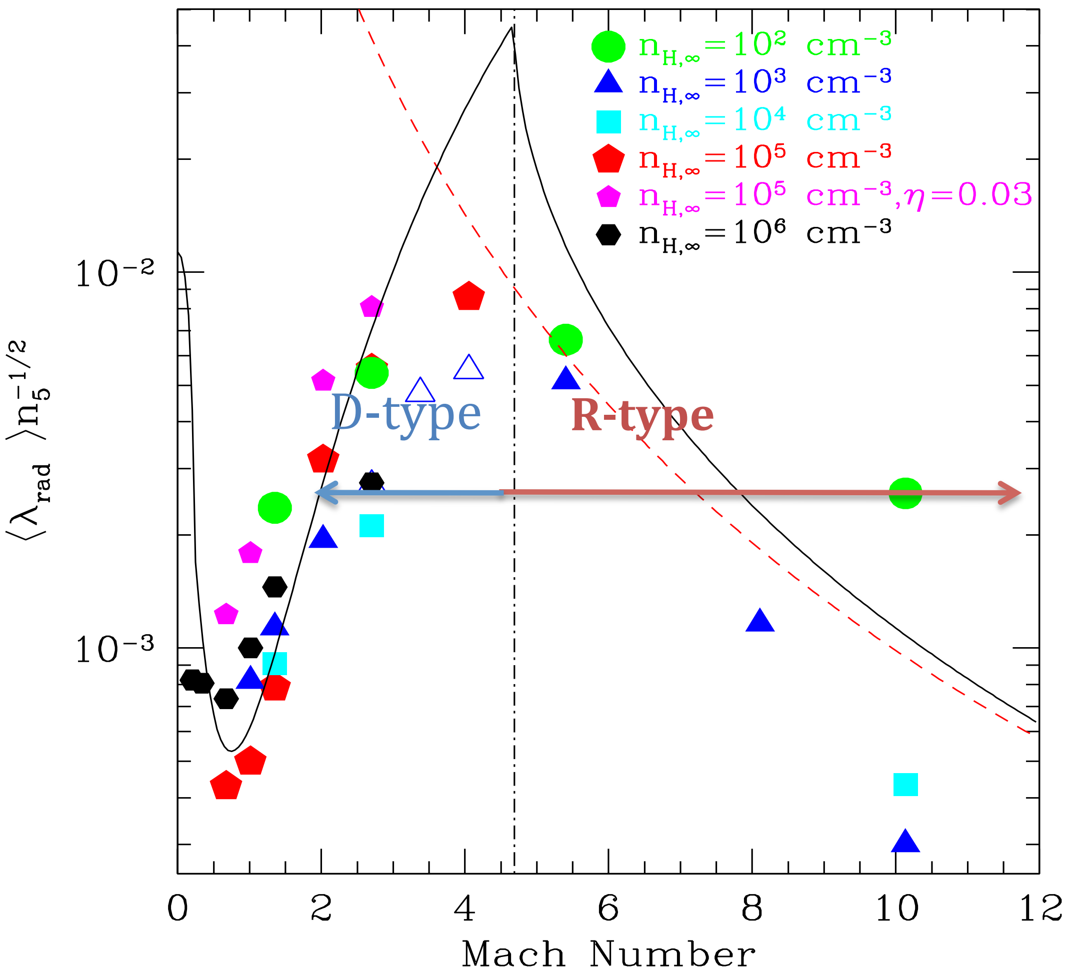
$$\dot{M} = \frac{4\pi G^2 M^2 \rho_\infty}{(c_\infty^2 + v_\infty^2)^{3/2}}$$



D-type ionization front + bow shock



Accretion Rate



Modeling based on Simulations:

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

Modeling: Accretion Rate

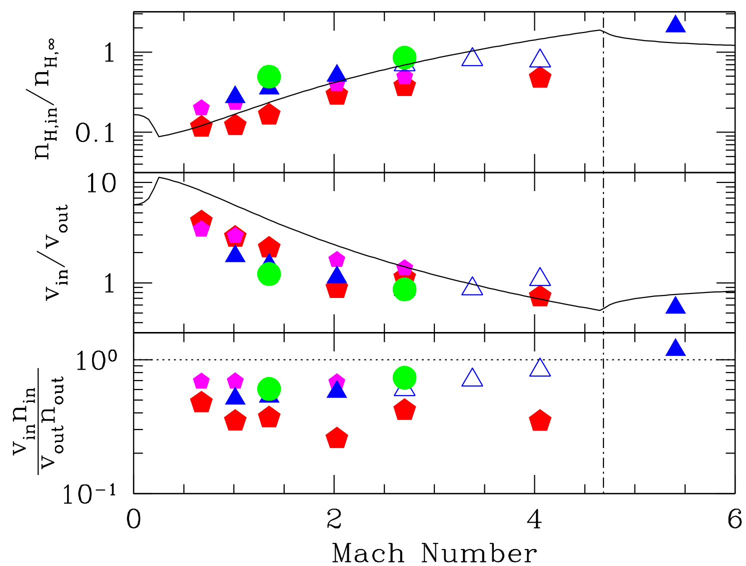
- Transition from D-type to R-type I front:

$$v_R \sim 2c_{s,in}$$

- D-type front: isothermal shock stops the gas flow and transforms the problem into Bondi problem downstream of the front.

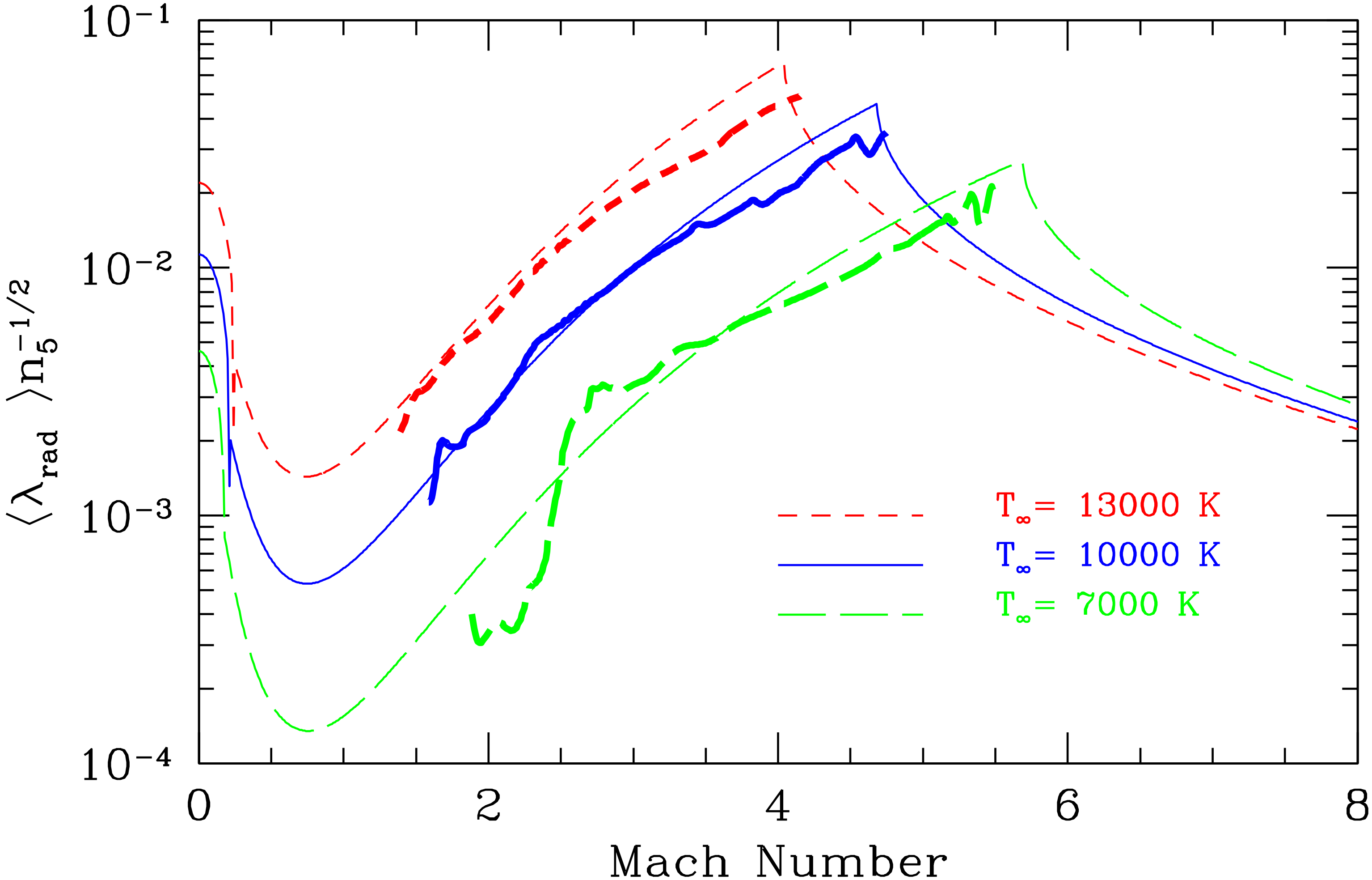
$$\langle \lambda_{\rm rad} \rangle \equiv \frac{\dot{M}}{\dot{M}_B} = \frac{\rho_{\rm in}}{\rho_\infty}\left(\frac{c_{s,\infty}}{c_{s,\rm in}}\right)^3 \frac{1}{(1+\mathcal{M}_{\rm in}^2)^{3/2}}$$

$$= \frac{\Delta_\rho}{\Delta_T^{3/2}} \frac{1}{(1+\mathcal{M}_{\rm in}^2)^{3/2}}.$$

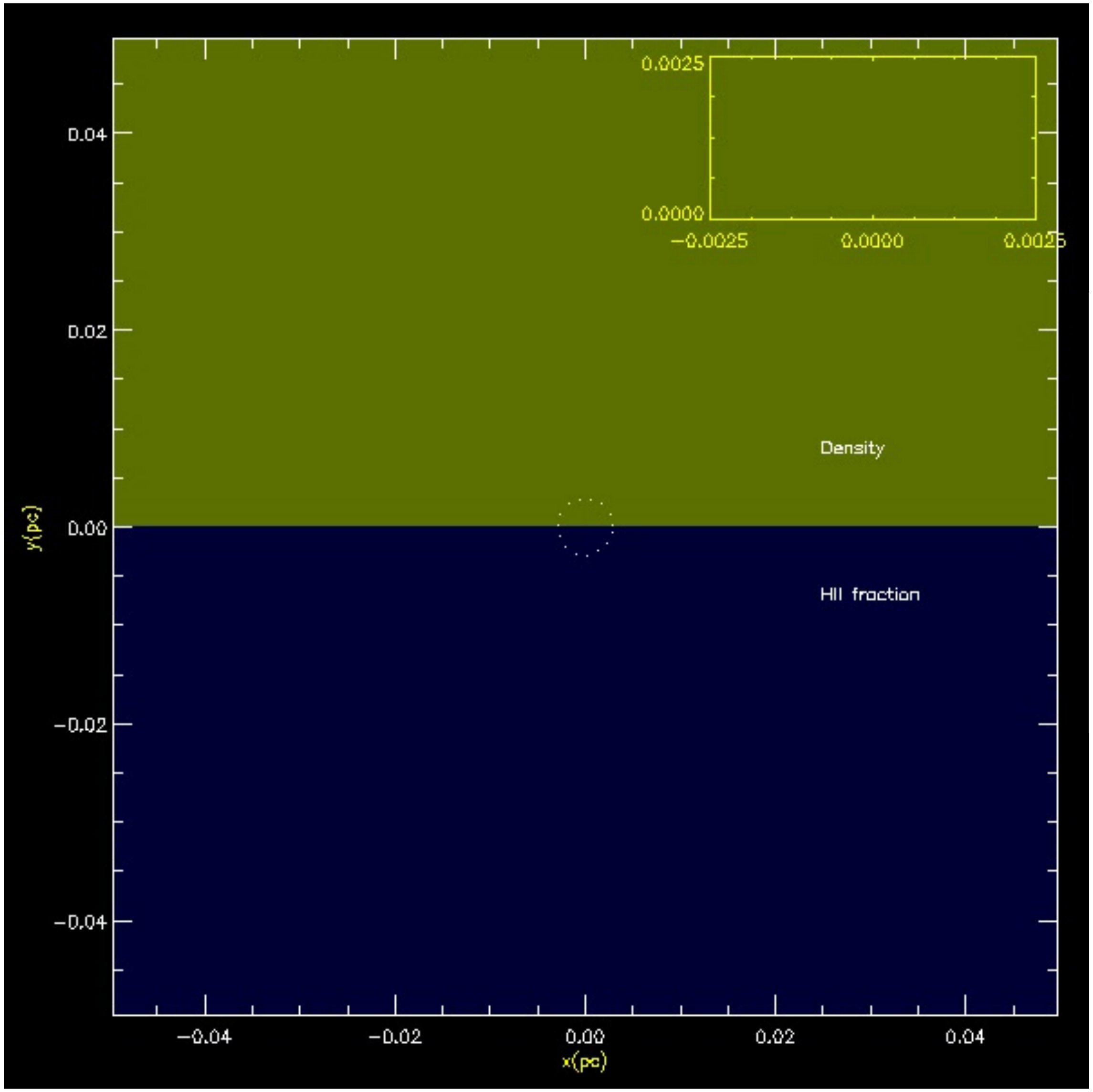


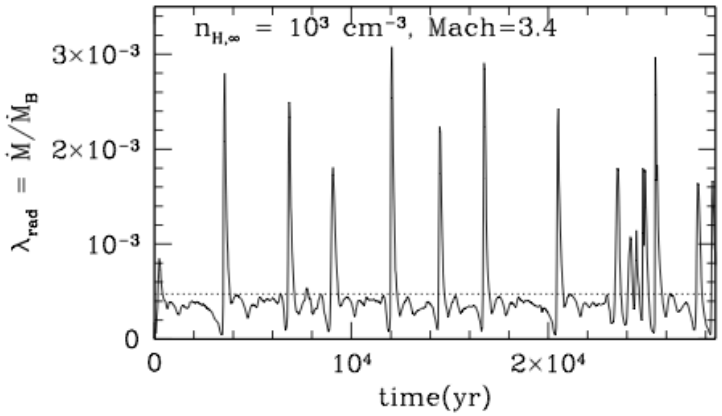
Where $\Delta_\rho \approx (v/v_R)^2$ and $\Delta_{T=}$const. are the density and temperature inside the HII region in units of the values outside.

BH in Wind-tunnel Experiment

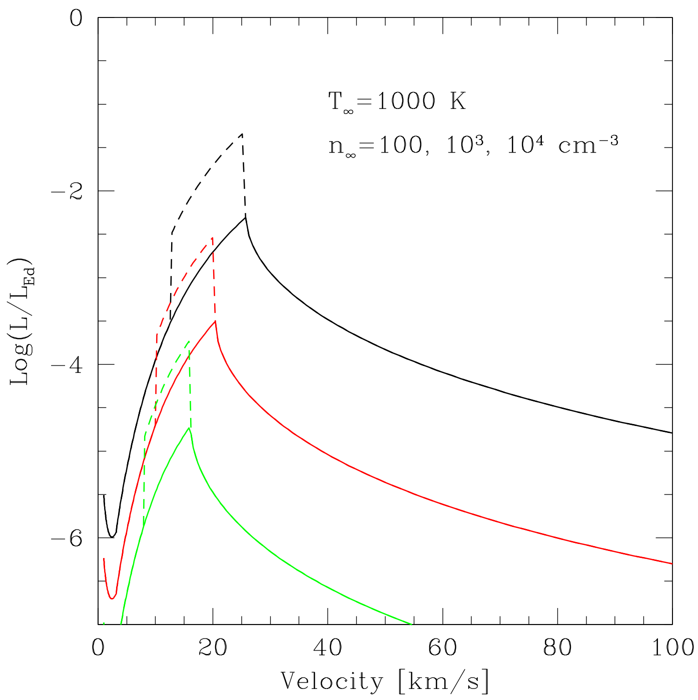


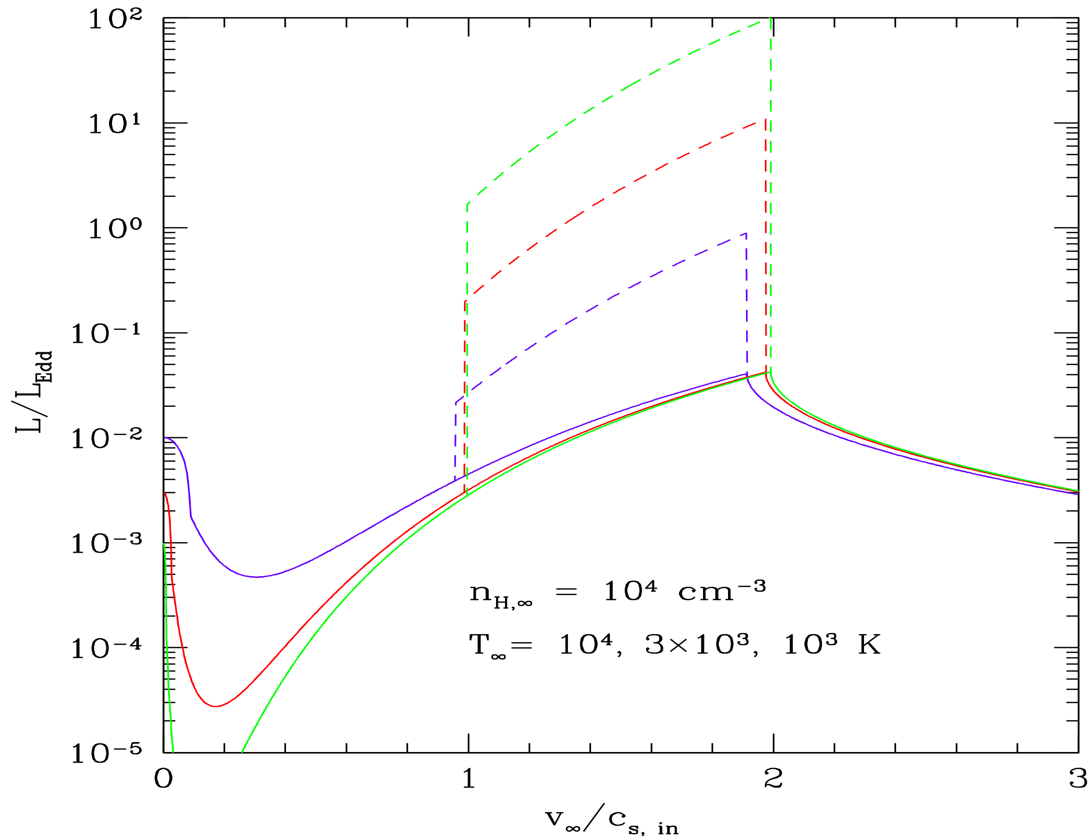
Shell instability and periodic oscillations





IMBH grow fastest if moving at 20 km/s





A Few Applications of these Results

Early Universe:

- IMBH from PopIII remnants: many moving IMBHs? Growth rate faster and total X-ray output larger than miniquasars at high-z!
- X-ray heating and pre-ionization
- X-ray/FIR background fluctuations (see Nico's work: Cappelluti et al 2012)

ULXs in local galaxies:

- IMBHs moving through a dense cloud? Can be visible due to periodic luminosity bursts.

Summary Part-II

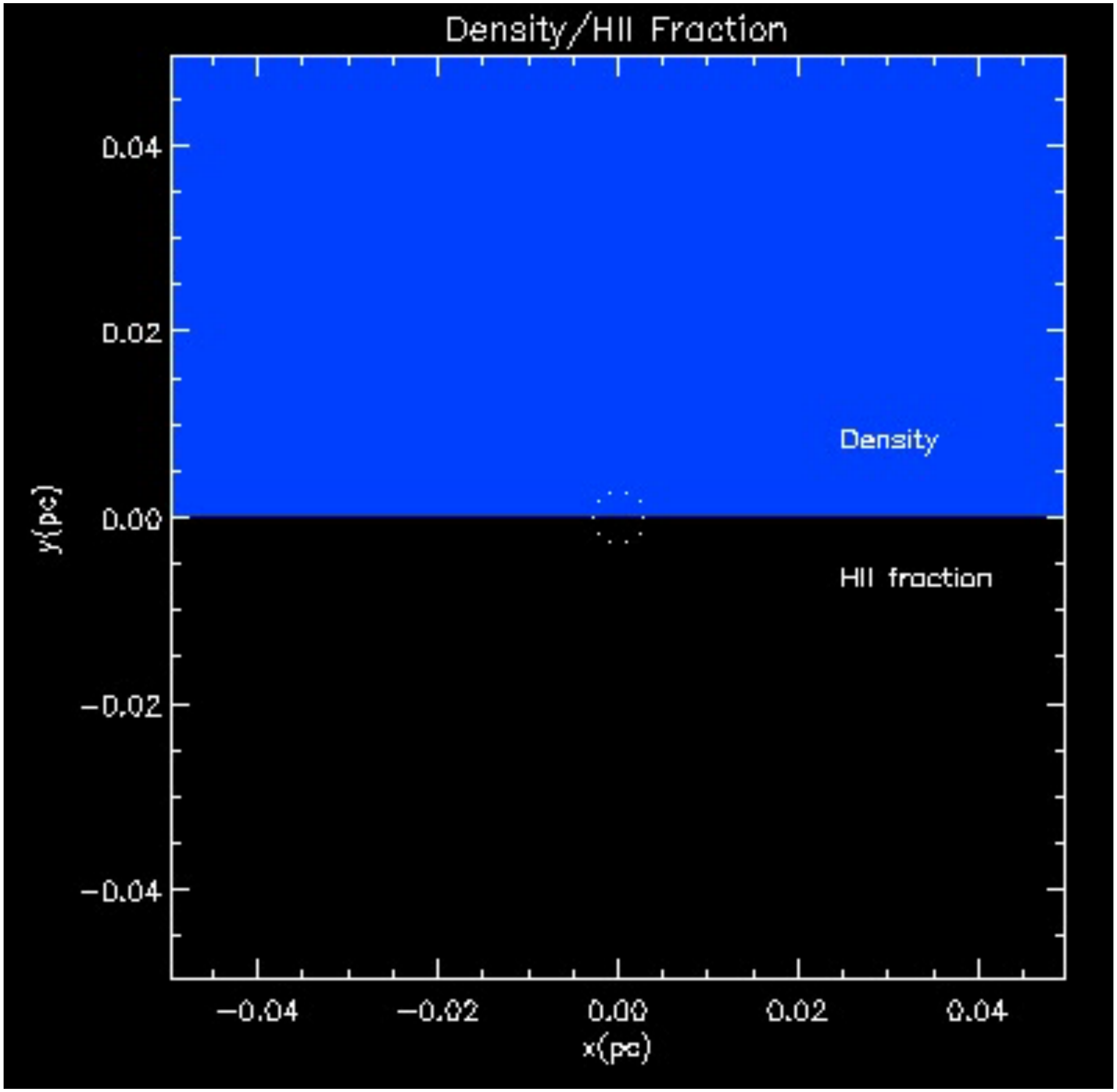
1. D-type I-front and bow-shock modify the accretion flow onto the BH
2. Accretion rate increases with increasing BH velocity: peaks at $v=2c_{s,in}\sim 20\text{-}30$ km/s
3. Growth rate can be faster than for non-moving BH because is independent of temperature of the medium!
4. Thin shell instability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

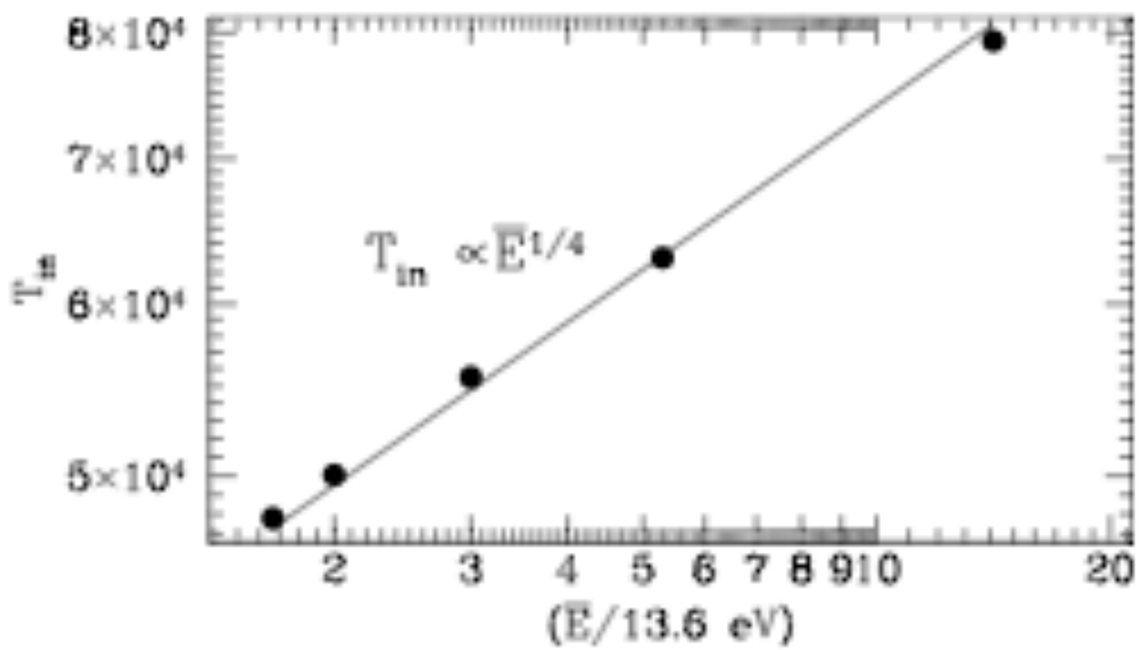
Backup slides

$$\Delta_{\rho} \equiv \frac{\rho_{\rm in}}{\rho_{\infty}} = \frac{\rho_{\rm in}}{\rho_{\rm sh}} \frac{\rho_{\rm sh}}{\rho_{\infty}}$$

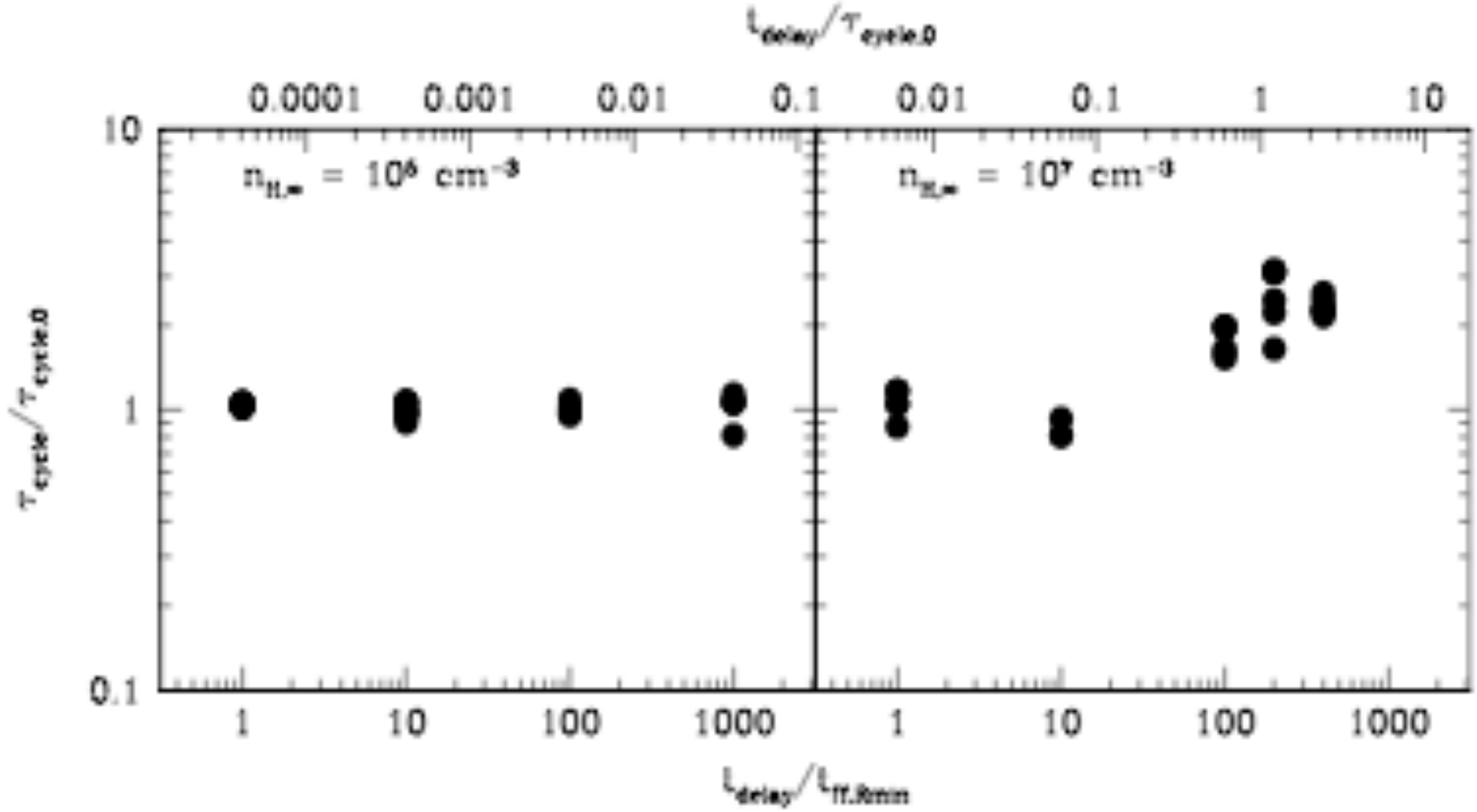
$$\approx \frac{\mathcal{M}^2}{2\Delta_T} \approx 2\left(\frac{\mathcal{M}}{\mathcal{M}_R}\right)^2 \quad \text{for } \mathcal{A} \sim 1,$$

Moving black holes + Radiative Feedback
(Park & Ricotti, 2013)

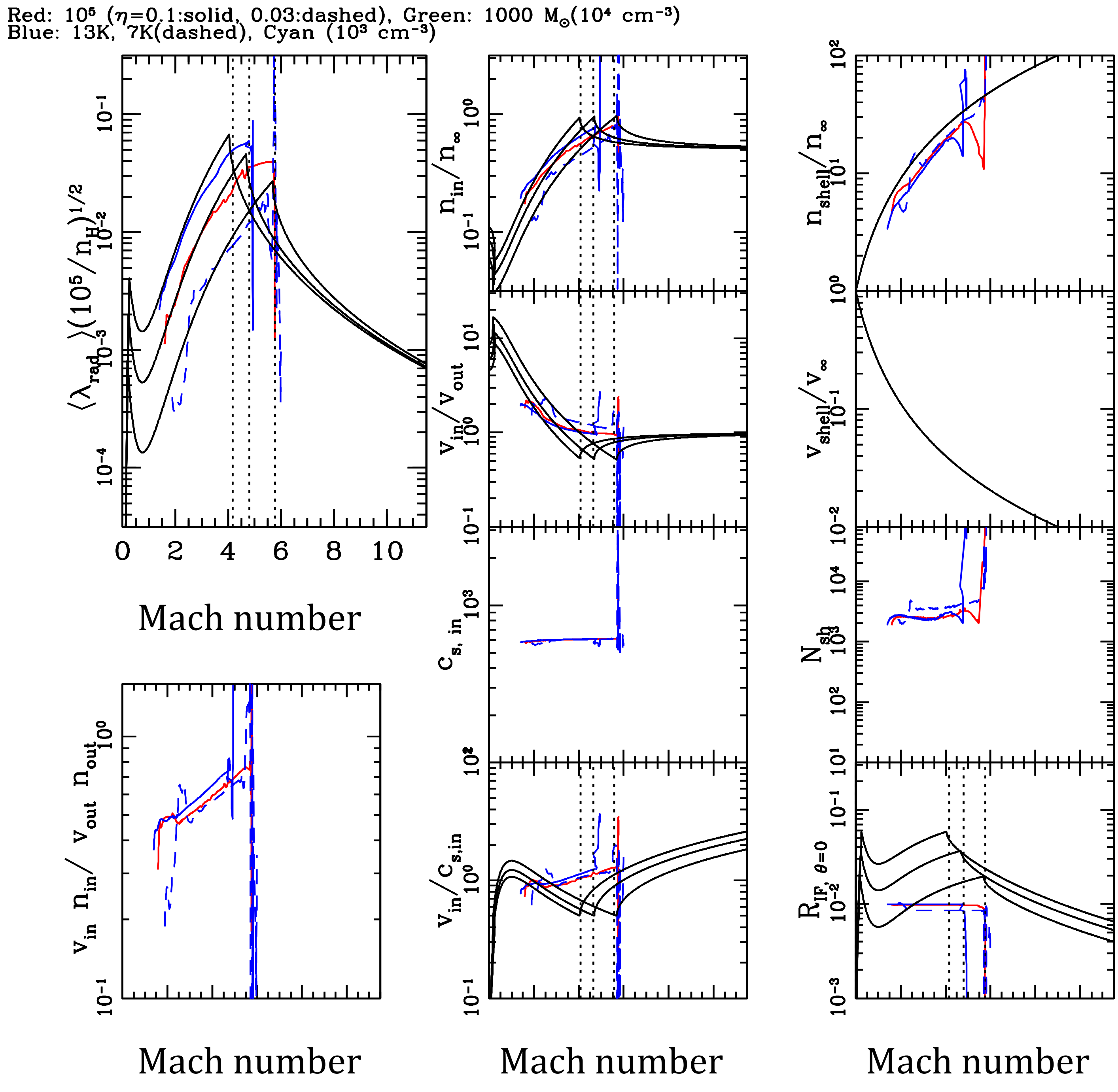




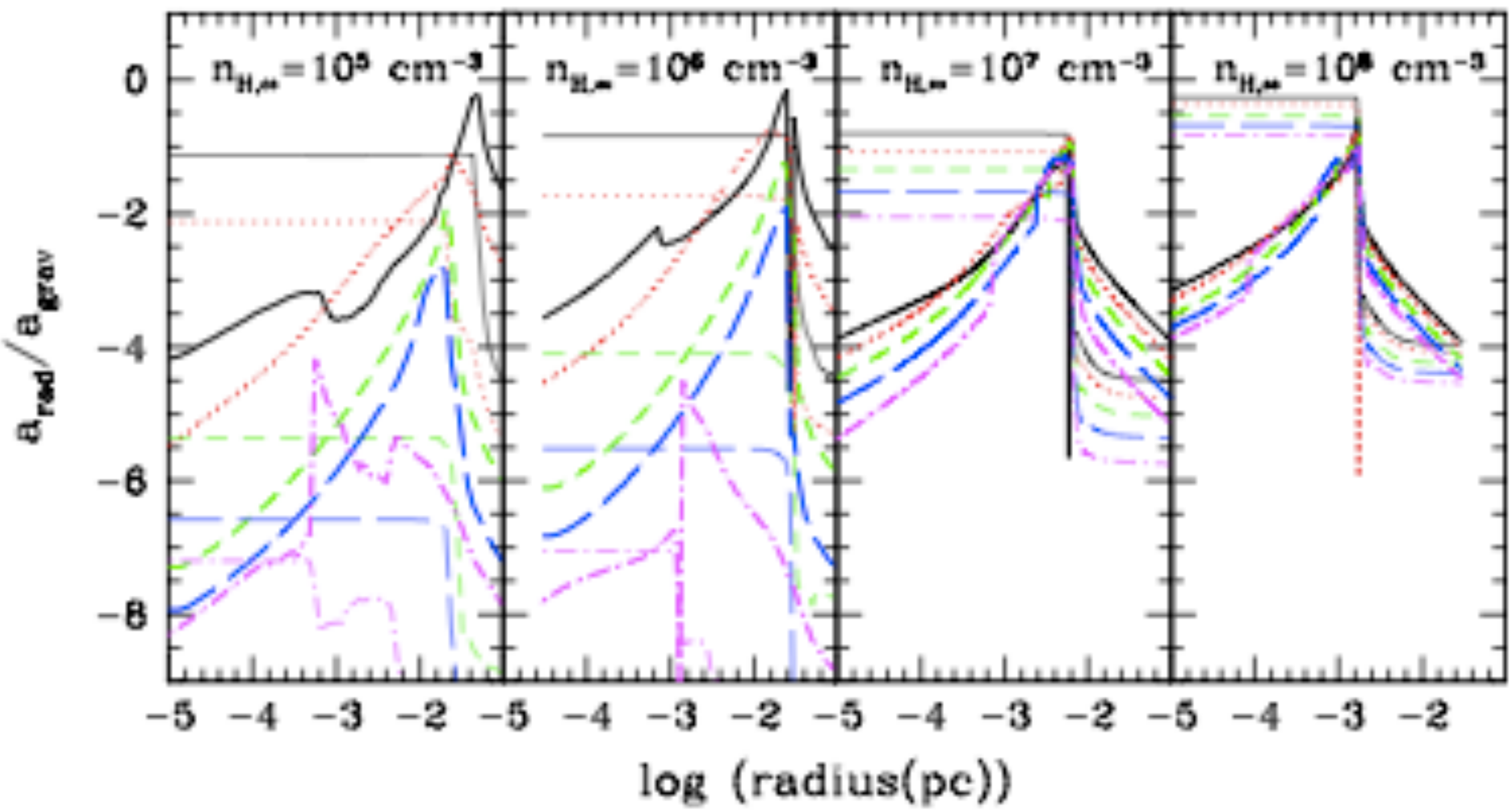
8×10^4
7×10^4
6×10^4
5×10^4
T_{in}
$T_{in} \propto \bar{E}^{1/4}$
2
3
4
5
6
7
8
9
10
20
$(\bar{E}/13.6\ eV)$



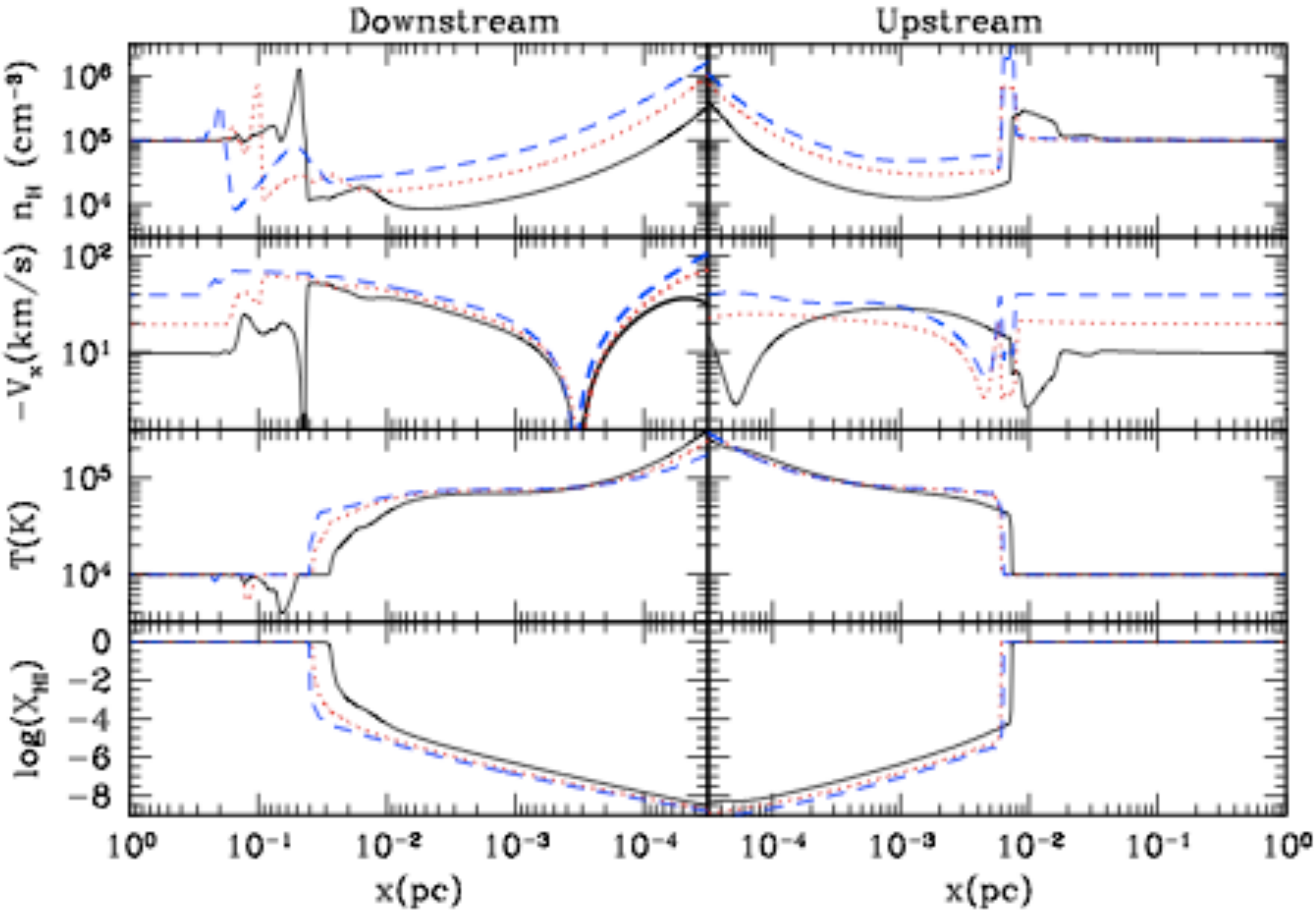
$t_{delay}/\tau_{cycle,0}$
0.0001
0.001
0.01
0.1
0.01
0.1
1
10
$n_{H,\infty} = 10^6\ cm^{-3}$
$n_{H,\infty} = 10^7\ cm^{-3}$
$\tau_{cycle}/\tau_{cycle,0}$
10
1
0.1
1
10
100
1000
1
10
100
1000
$t_{delay}/t_{ff,Rmin}$



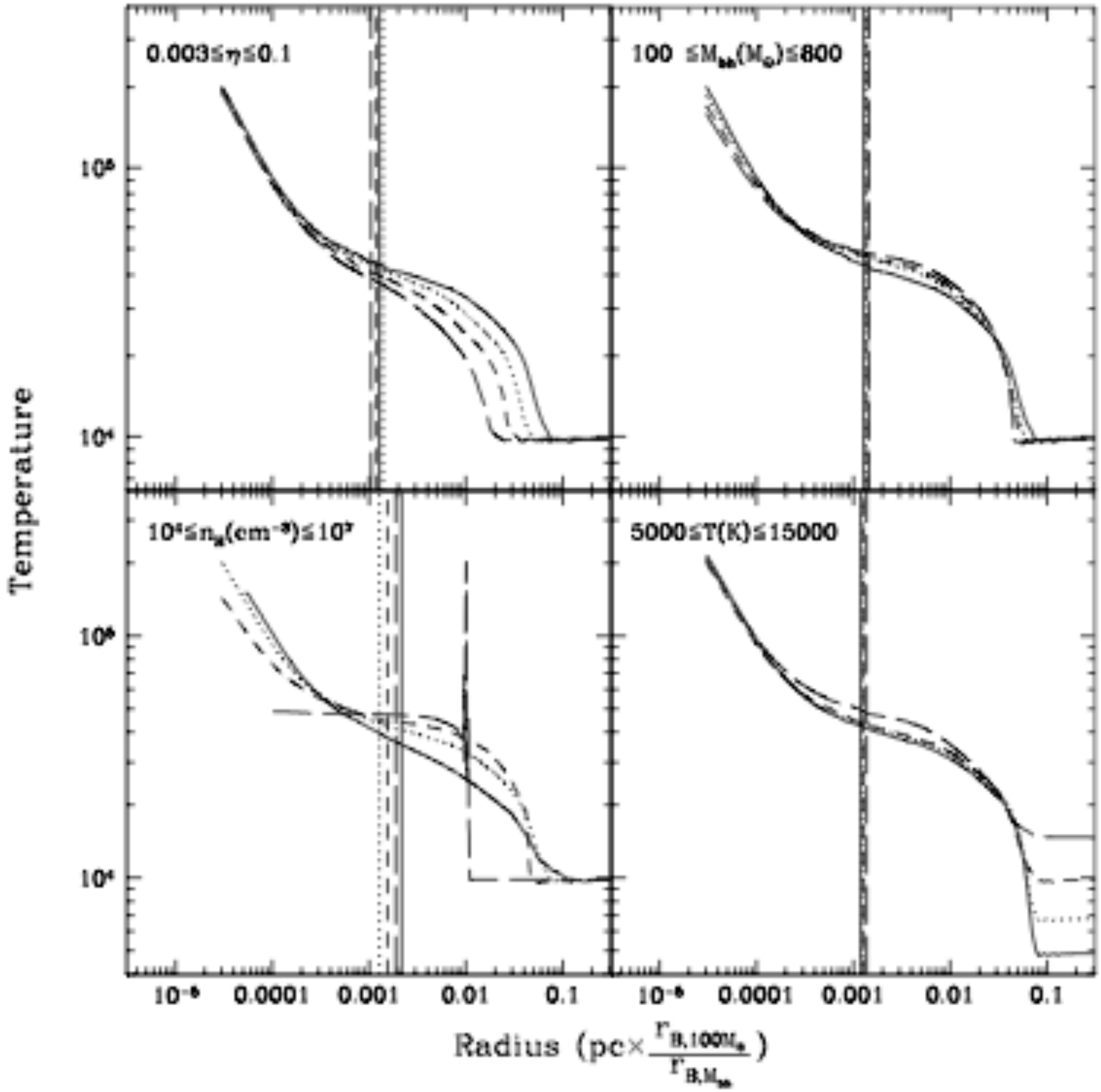
Red: 10⁵ (η=0.1:solid, 0.03:dashed), Green: 1000 M⊙(10⁴ cm⁻³)
Blue: 13K, 7K(dashed), Cyan (10³ cm⁻³)
⟨λrad⟩(10⁵/nH)^1/2
nin/n∞
nshell/n∞
vin/vout
vshell/v∞
cs, in
Nsh
vin/cs,in
RIF, θ=0
vin nin/ vout nout
Mach number
Mach number
Mach number
Mach number



$n_{H,\infty}=10^5$ cm^{-3}
$n_{H,\infty}=10^6$ cm^{-3}
$n_{H,\infty}=10^7$ cm^{-3}
$n_{H,\infty}=10^8$ cm^{-3}
a_{rad}/a_{grav}
log (radius(pc))



Downstream
Upstream
n_H (cm^{-3})
10^6
10^5
10^4
$-V_x$(km/s)
10^2
10^1
T(K)
10^5
10^4
log(X_{HI})
0
−2
−4
−6
−8
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0
x(pc)
x(pc)


0.003≤η≤0.1
100 ≤M_bh(M_☉)≤800
5000≤T(K)≤15000
Temperature
0.0001
0.001
0.01
0.1
Radius