Rapid Black Hole Growth under Anisotropic Radiation Feedback

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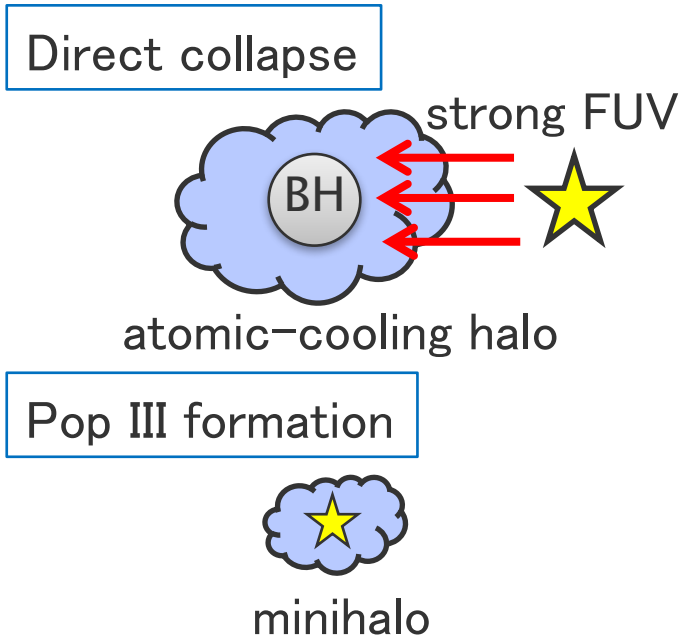
INTRODUCTION

The origin for high-z supermassive BHs

quasar image
(Credit: ESO/M. Kornmesser)

- high-z supermassive BHs (SMBHs)
  - 10^9 M_{sol} BH@z～7（1Gyr after Big Bang） (e.g., Mortlock + 2011)
  - ～100 BHs@z>6 ⇒ n_{BH}～1/cGpc^3
    (e.g., Fan + 2001, Venemans + 2013)

- Formation scenarios
  - Direct collapse BH (M_{seed} ～ 10^5 M_{sol})
    growth time ○ number density △
  - Pop III remnant BH (M_{seed} ～ 10^2 M_{sol})
    growth time △ number density ○



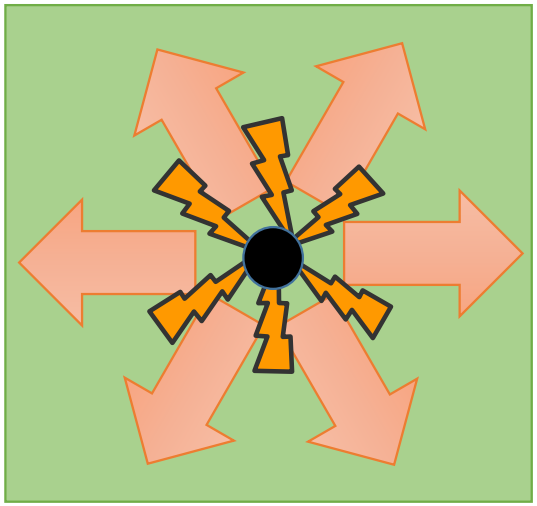
Q: How efficient can BHs grow?

Efficiency for BH accretion

Isotropic BH radiation

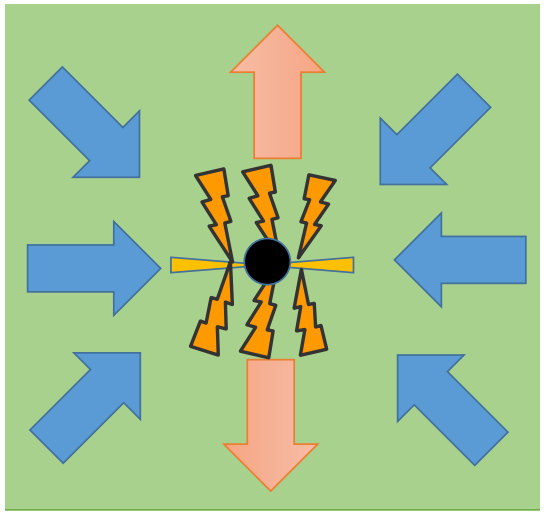
(Park&Ricotti 11, Milosavljevic+ 09)

- Feedback works in all directions
- Suppressed to ～1/100 of the accretion rate w/o feedback（Bondi rate）
- Efficient accretion possible in a very dense medium (Inayoshi+ 16)



Anisotropic BH radiation

- Separation of the regions for feedback and accretion?
- Efficient accretion possible??

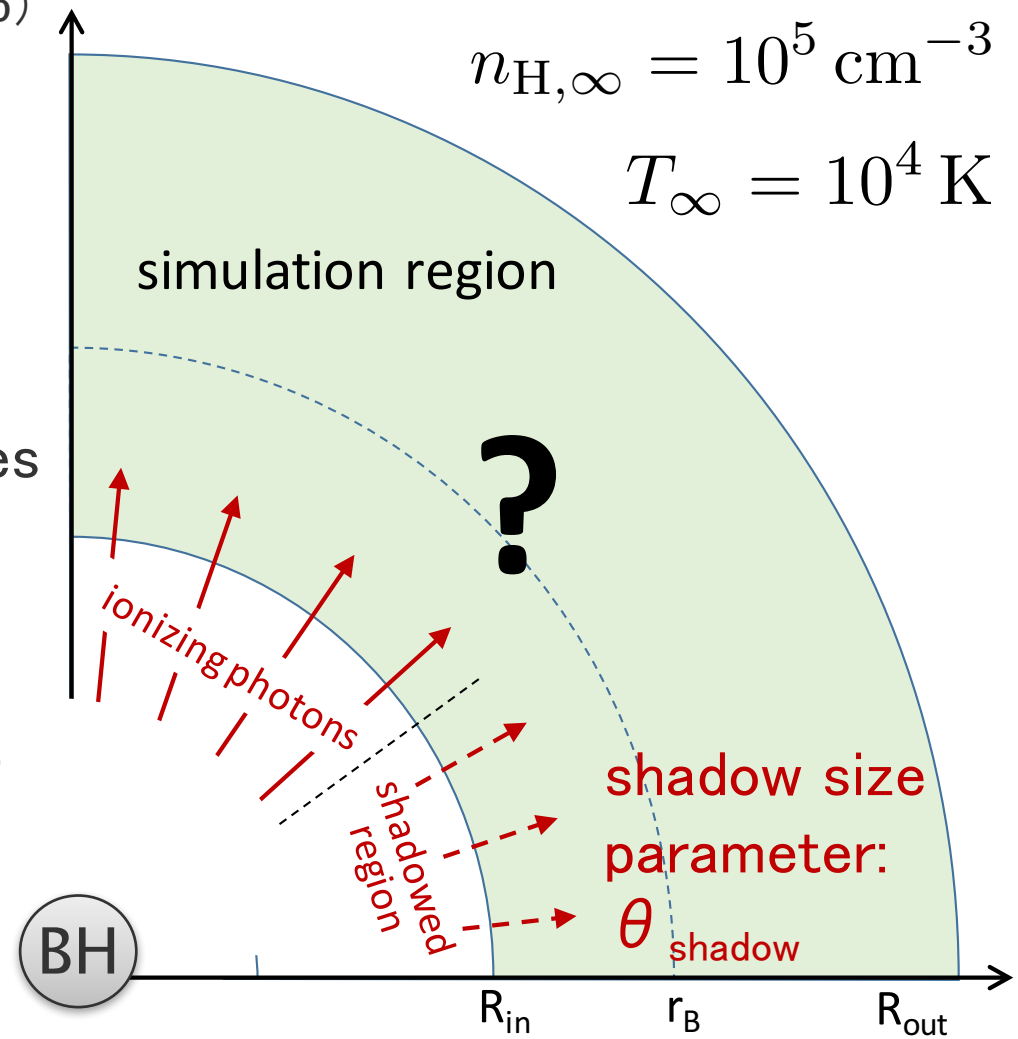


METHOD

Code & Numerical settings

(modified ver. of Hosokawa+ 2015)

- PLUTO3.0
  2D RHD (hllc)
- N_r x N_θ = 512x144
- 1day x 144core/model
- chemical/thermal processes
  H, H+, He, He+, He++, e
- Rad. transfer
  ray tracing in r direction
  multi frequency (128 bins)
- BH gravity
- Subgrid radiation model
  std+slim disks (watarai+ 00)
  direction dependence



$n_{\rm H,\infty} = 10^5\,{\rm cm}^{-3}$

$T_\infty = 10^4\,{\rm K}$

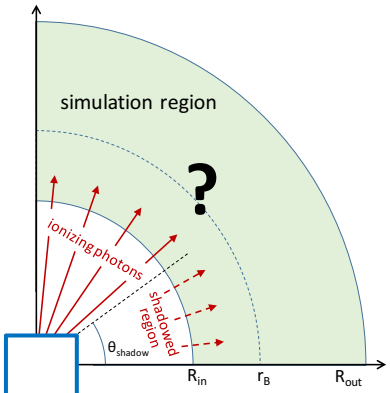
$M_{\rm BH} = 10^3 M_\odot$

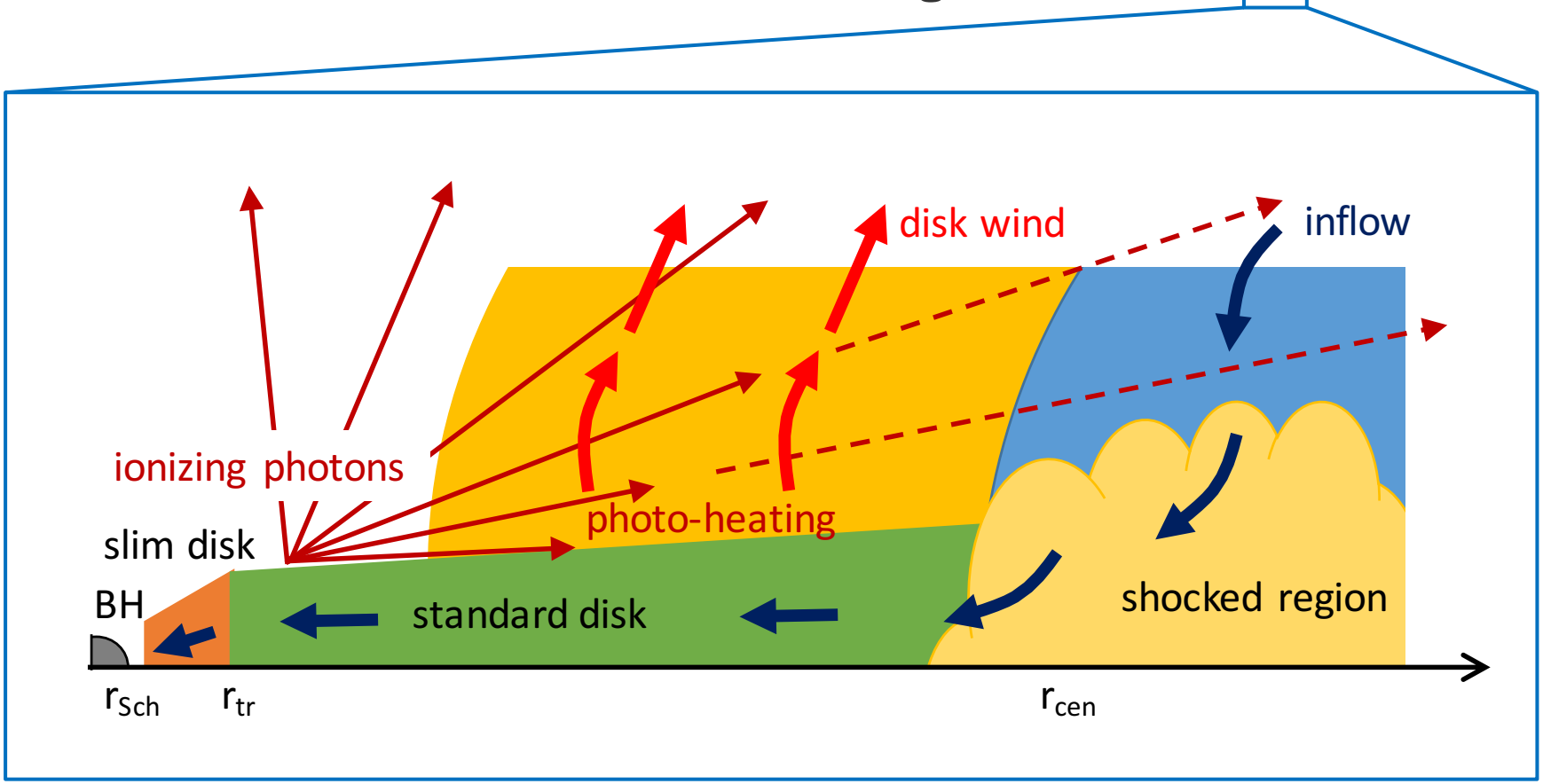
(∼maximum mass for Pop III; Hirano+ 15)

Bondi radius $(\sim 10^9 r_{\rm Sch})$

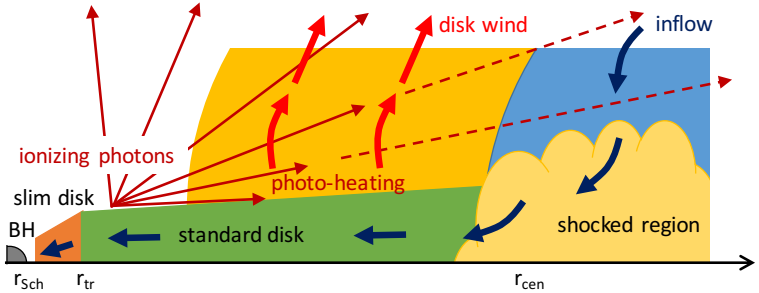
Subgrid radiation model I: Expected inner structure

- Ionizing photons emitted from hot inner region
- absorbed/scattered in the outer region





Subgrid radiation model II: Anisotropy



- Flux@inner boundary

$$f = \frac{L}{4\pi R_{\rm in}^2}\mathcal{F}(\theta)$$

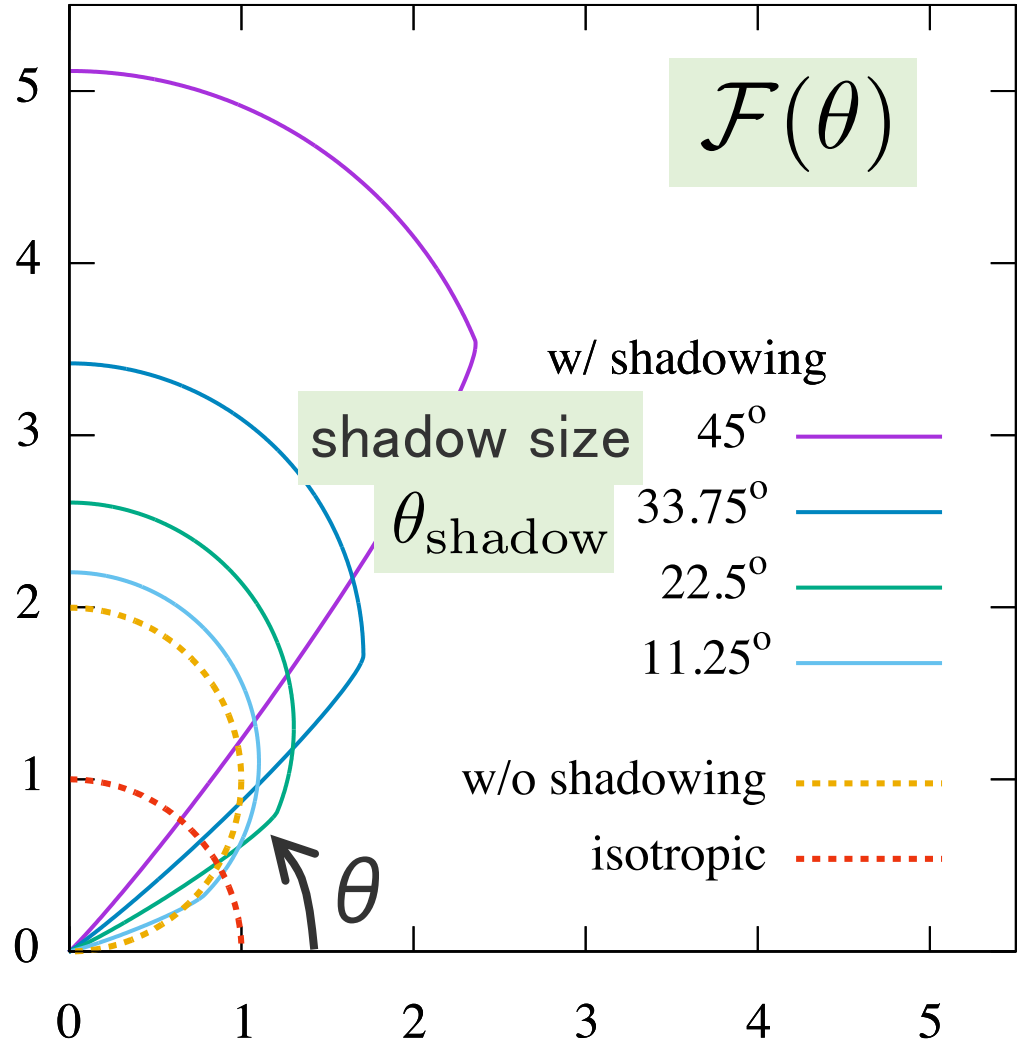
- Anisotropy
  = (disk) x (shadow)

$$\mathcal{F}(\theta) = f_{\rm disk}(\theta)\, f_{\rm shadow}(\theta)$$

  - Rad. from a thin-disk

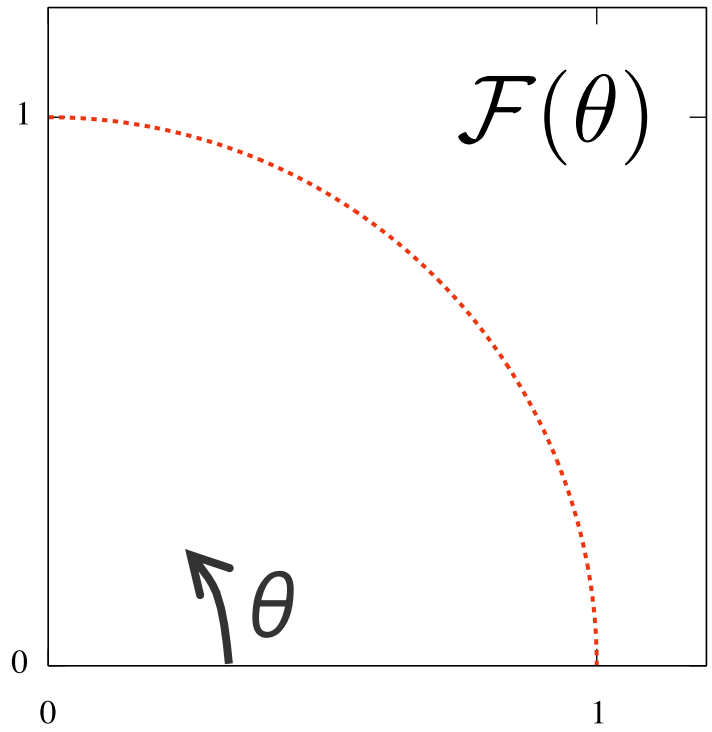
$$f_{\rm disk}(\theta) = \sin\theta$$

  - Shadowing effect
    $f_{\rm shadow}(\theta)$ (right panel)



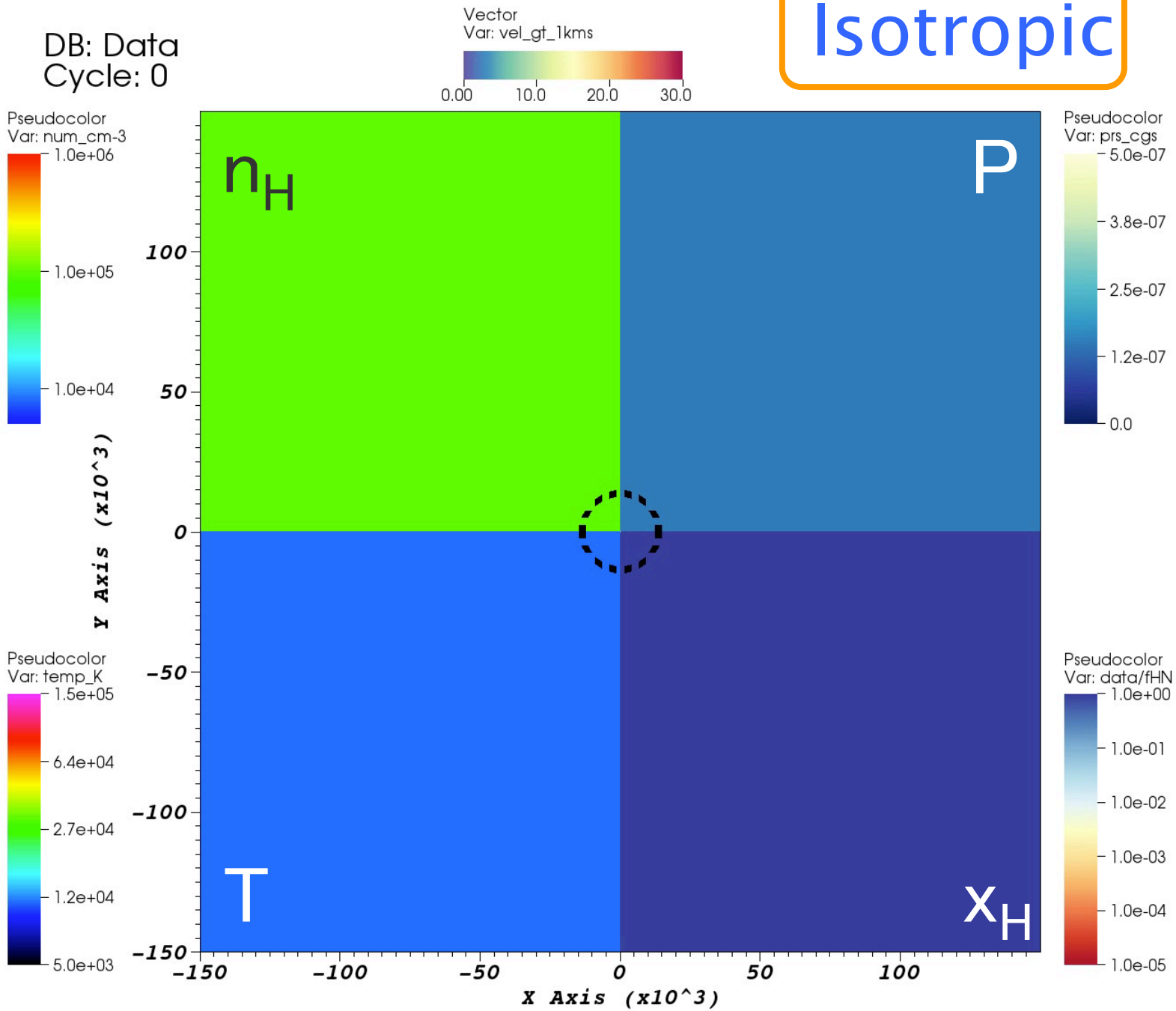
(normalized to reproduce L by angular integration)

RESULTS



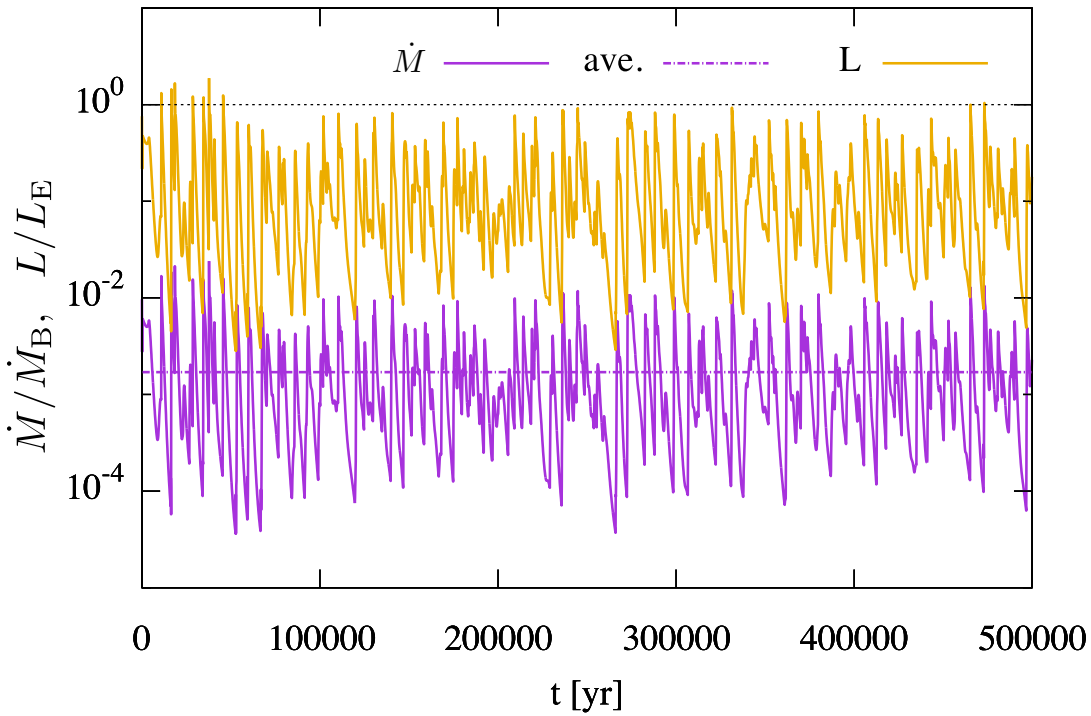
ISOTROPIC RADIATION

Isotropic


DB: Data
Cycle: 0
Vector
Var: vel_gt_1kms
0.00
10.0
20.0
30.0
Pseudocolor
Var: num_cm-3
1.0e+06
1.0e+05
1.0e+04
n_H
Pseudocolor
Var: prs_cgs
5.0e-07
3.8e-07
2.5e-07
1.2e-07
0.0
P
Pseudocolor
Var: temp_K
1.5e+05
6.4e+04
2.7e+04
1.2e+04
5.0e+03
T
Pseudocolor
Var: data/fHN
1.0e+00
1.0e-01
1.0e-02
1.0e-03
1.0e-04
1.0e-05
x_H
Y Axis (x10^3)
X Axis (x10^3)
100
50
0
-50
-100
-150
-150
-100
-50
0
50
100

Acc. rate（isotropic）

Bondi rate： $\dot{M}_{\rm B}$
（No feedback）

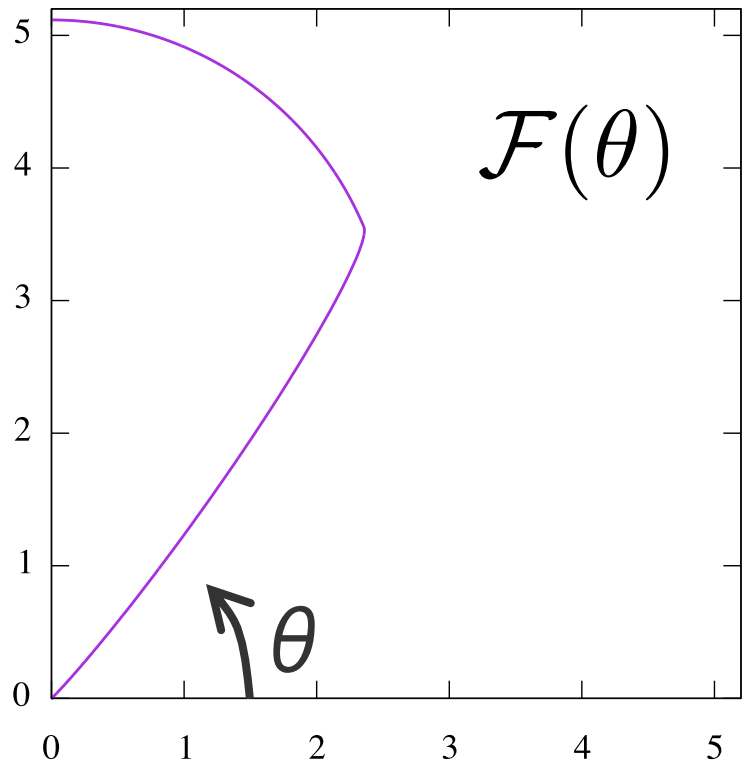


- Reproduce the former work
（Park&Ricotti 11, Milosavljevic+ 09）
- Oscillation of acc. rate
- Very low ave. acc. rate

$$\dot{M} \sim 0.17\%\ \dot{M}_{\rm B}$$

（1/500 time lower than No FB case）

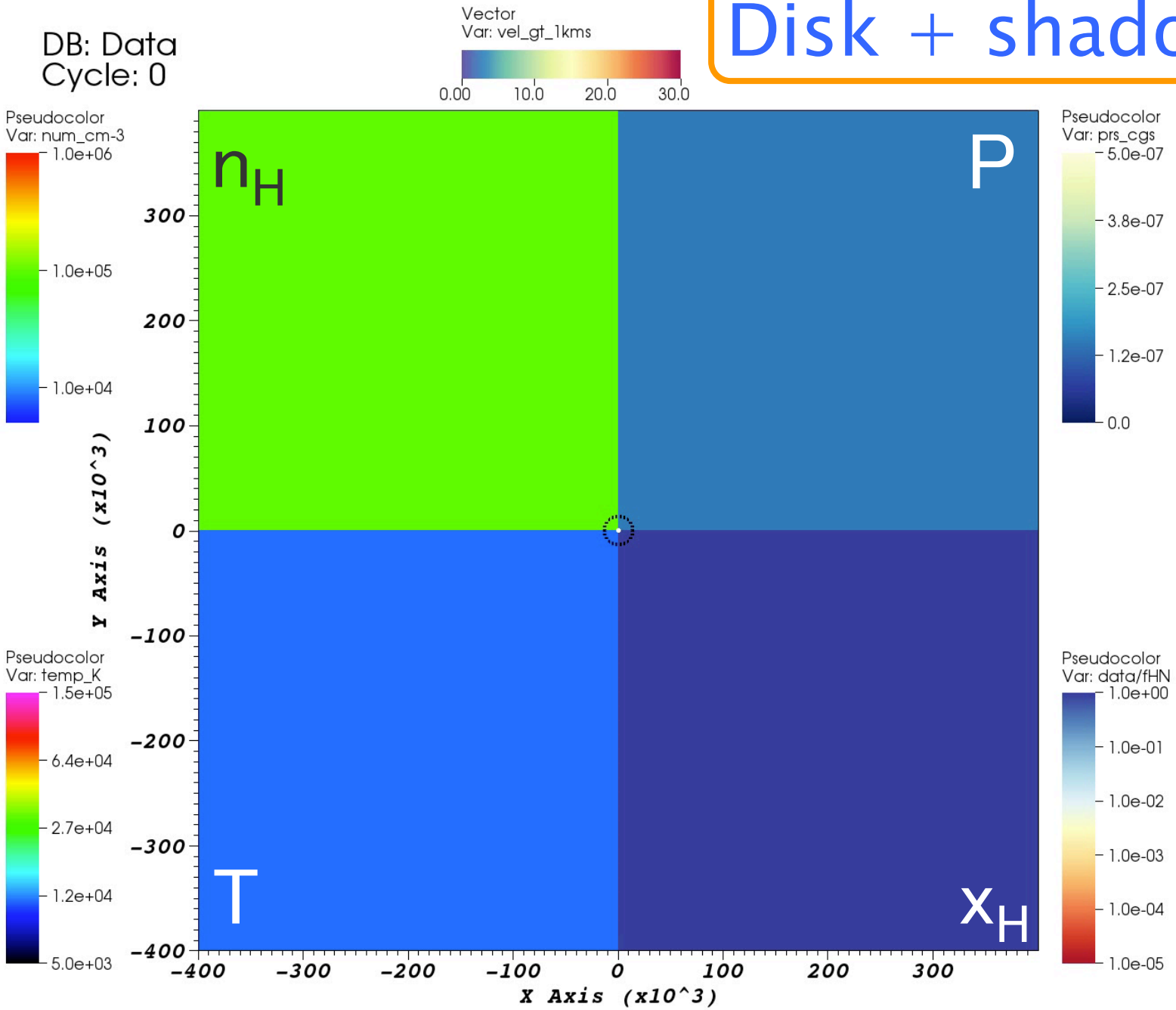
Growth of BHs needs too long time.



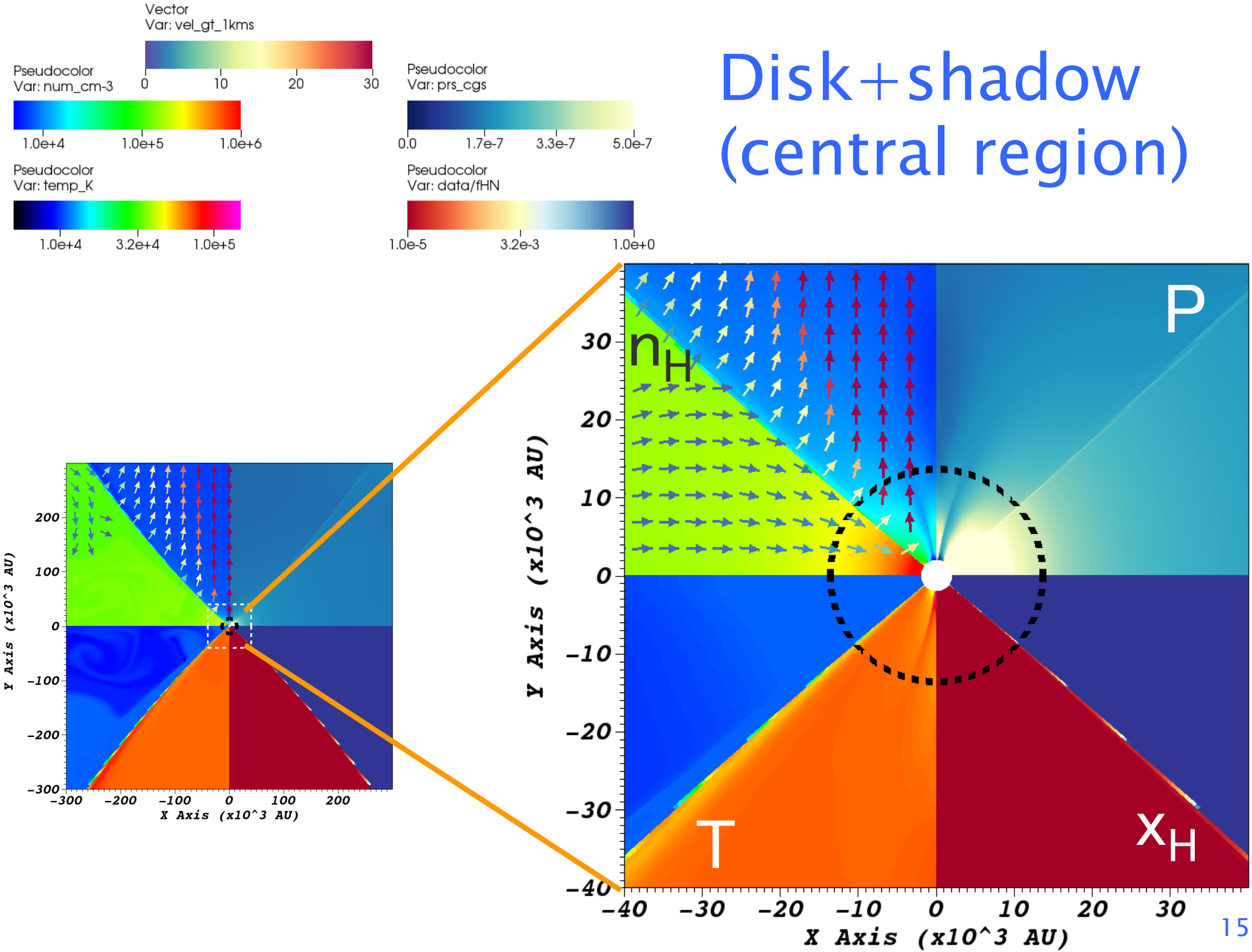
DISK RADIATION W/ SHADOWING EFFECT

(CASE FOR $\Theta_{SHADOW} = 45^{O}$)

Disk + shadow


DB: Data
Cycle: 0
Vector
Var: vel_gt_1kms
0.00
10.0
20.0
30.0
Pseudocolor
Var: num_cm-3
1.0e+06
1.0e+05
1.0e+04
n_H
P
Pseudocolor
Var: prs_cgs
5.0e-07
3.8e-07
2.5e-07
1.2e-07
0.0
Pseudocolor
Var: temp_K
1.5e+05
6.4e+04
2.7e+04
1.2e+04
5.0e+03
T
x_H
Pseudocolor
Var: data/fHN
1.0e+00
1.0e-01
1.0e-02
1.0e-03
1.0e-04
1.0e-05
Y Axis (x10^3)
X Axis (x10^3)
300
200
100
0
-100
-200
-300
-400

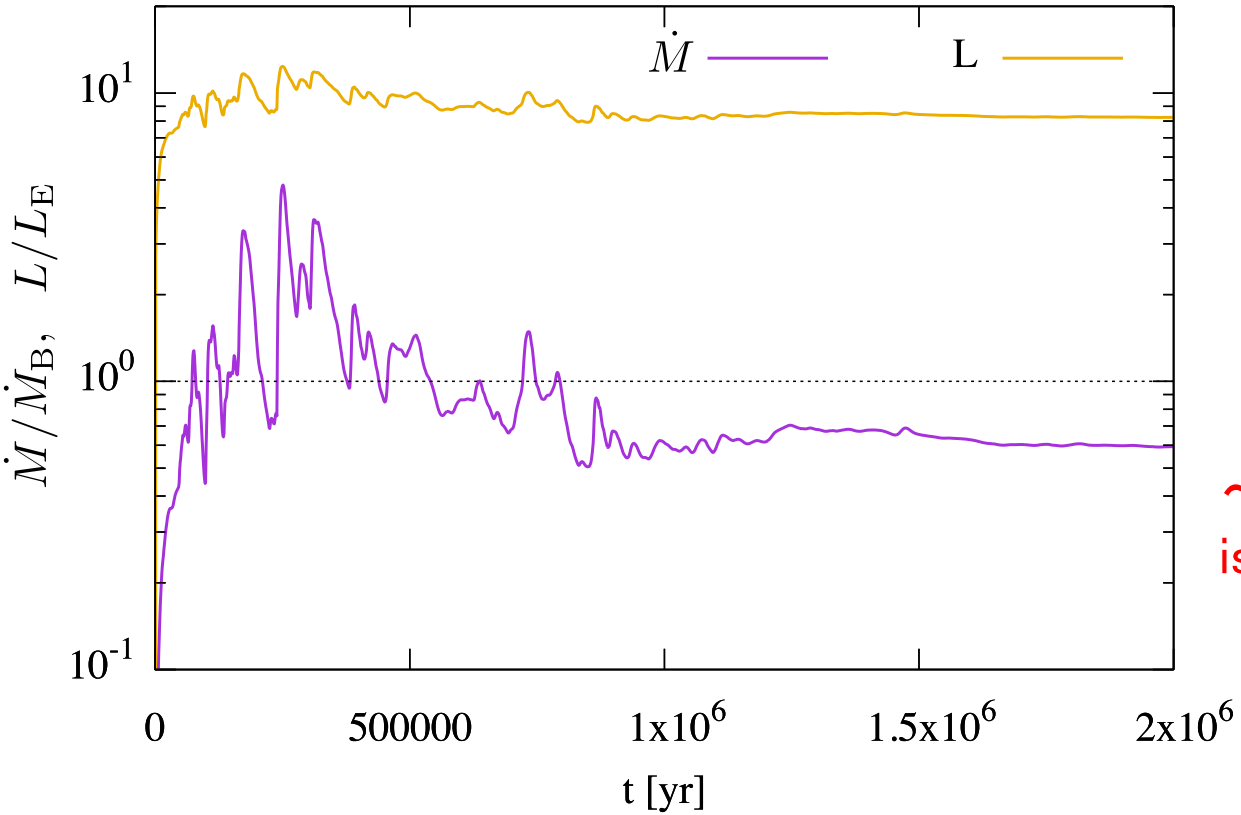
Disk+shadow (central region)



Acc. rate (disk+shadow)

Bondi rate: $\dot{M}_{\rm B}$

(No feedback)

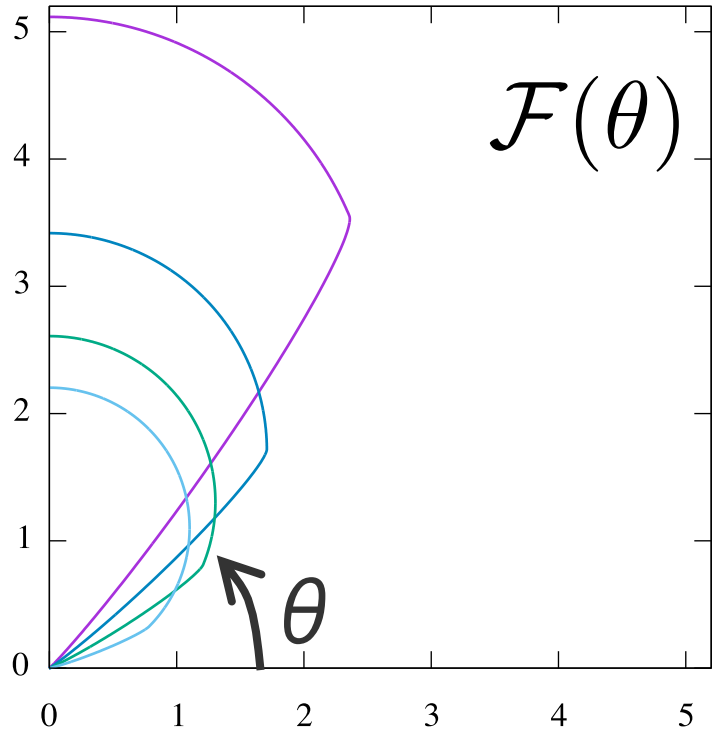


- Stationary accretion
- High accretion rate

$$\dot{M} \sim 60\%\, \dot{M}_{\rm B}$$

～300 times larger than the isotropic case !

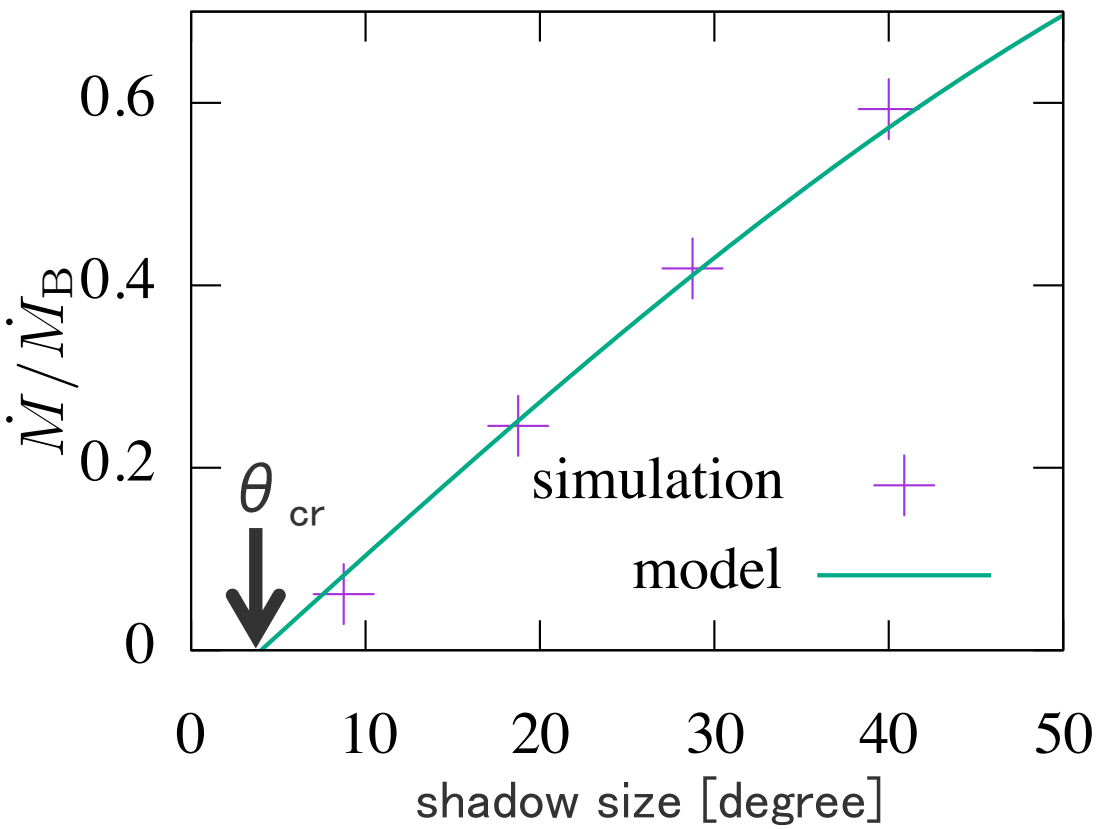
Even Pop III remnant BHs can evolves to SMBHs!



DISK RADIATION W/ SHADOWING EFFECT

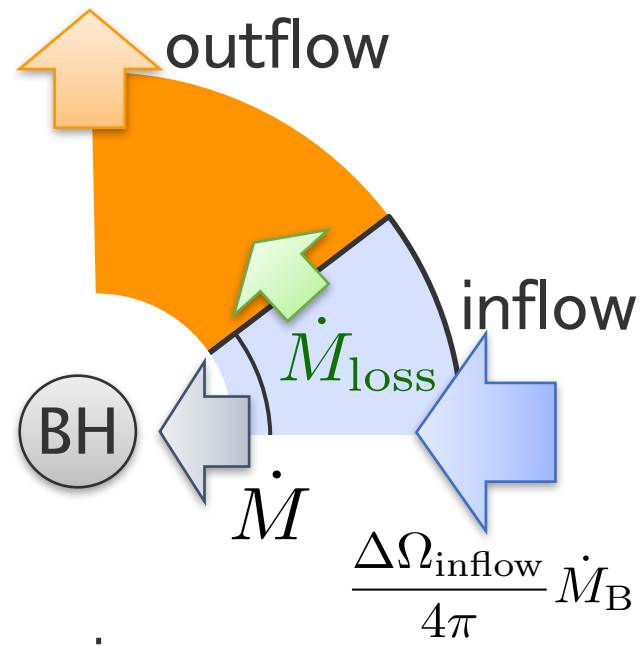
(Θ_{SHADOW} DEPENDENCE)

Shadow size & acc. rate



- Analytical model

$$\dot{M} = \frac{\Delta\Omega_{\rm inflow}}{4\pi}\dot{M}_{\rm B} - \dot{M}_{\rm loss}$$



- Acc. rate is determined by Bondi-like acc. in shadowed solid angle w/ photo-evaporation mass loss
- Critical shadow size ($\theta_{\rm cr}$ ~5°) for acc. in shadowed region

CONCLUSION

Conclusion and discussion

- We have studied BH accretion under anisotropic feedback by performing 2D RHD simulations.

- Very efficient (super-critical) BH accretion occurs if shadowed region around the equatorial plane is assumed.

- In this case, accretion rate is determined by competition between Bondi-like accretion in the shadowed region and photoevaporation mass loss from its surfaces.

- (Although it depends on the density of surrounding medium) Pop III remnant BHs can evolves to SMBHs by z～6 if the Bondi-like accretion in the shadowed region occurs in the Universe.