A Road to Supermassive Black Hole Merger

KH (2009)

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Outline

1. Introduction

   Hierarchical scenario ⇒ binary BHs ⇒ BH merger:

   Final parsec problem

2. Our Approach to the problem

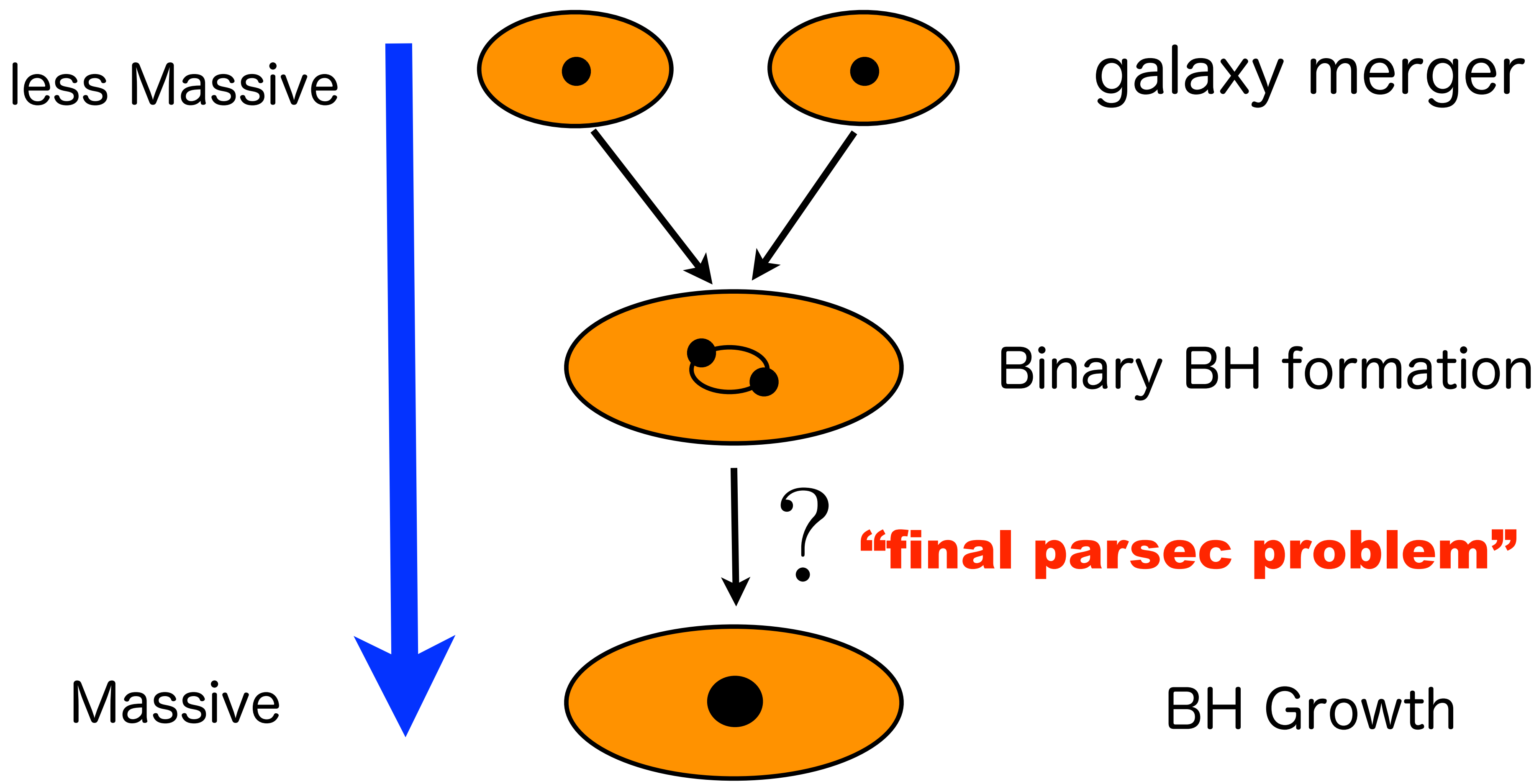
   Binary BH with triple disk ⇒ BH merger

3. Observational implications
   i. The number of binary BHs in nearby AGNs
   ii. Signals from binary BHs

4. Summary & Discussion

INTRODUCTION

Hierarchical Structure Formation Scenario



Solving final parsec problem is a key to understanding this scenario.

Our Goal

Close binary BHs

↓

Missing Link

of hierarchical structure formation scenario

To explain how binary BHs merge

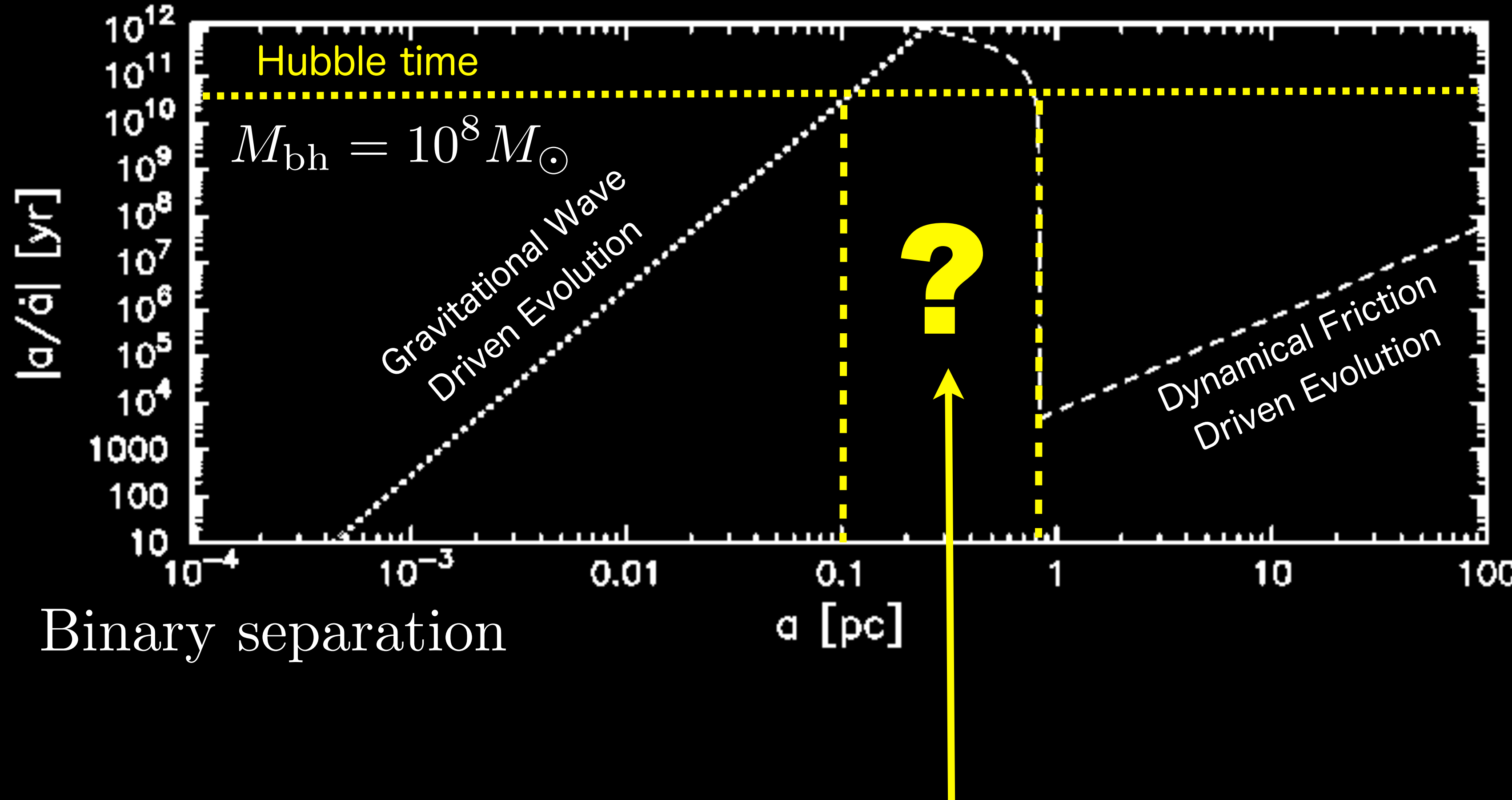
2. Our Approach

A Solution for Final Parsec Problem

Evolution of Binary BHs

Binary BHs mainly evolve via three stage processes.

Begelman et al. (1980)

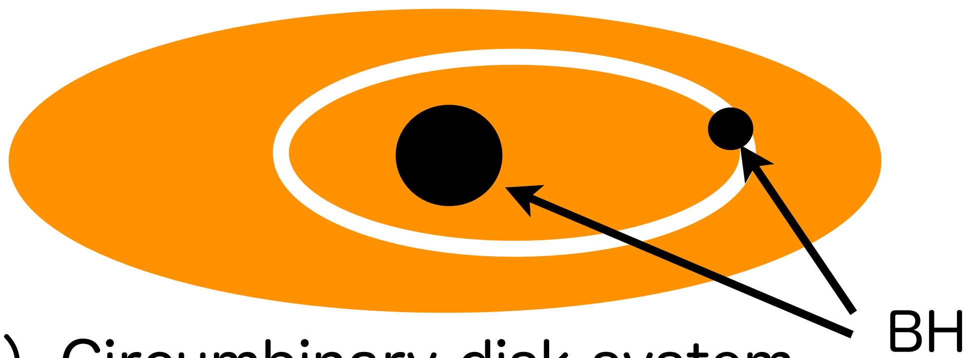


a : Binary separation

Final Parsec Problem

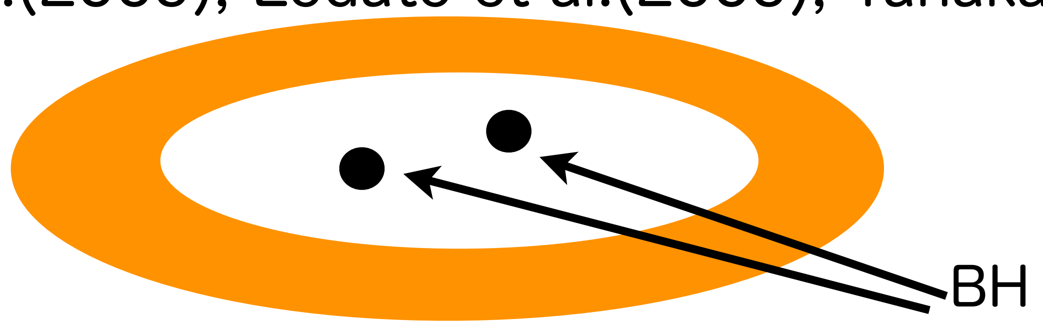
Type of gaseous disk models

(I) Inspiraling system (cf. type II migration for a planetary disk) : Ivanov et al.(1999); Goldman & Rix (2000); Bogdanovic et al(2008); Haiman, Kocsis, & Menou(2009)



$$M_{\rm pri} >> M_{\rm sec}$$

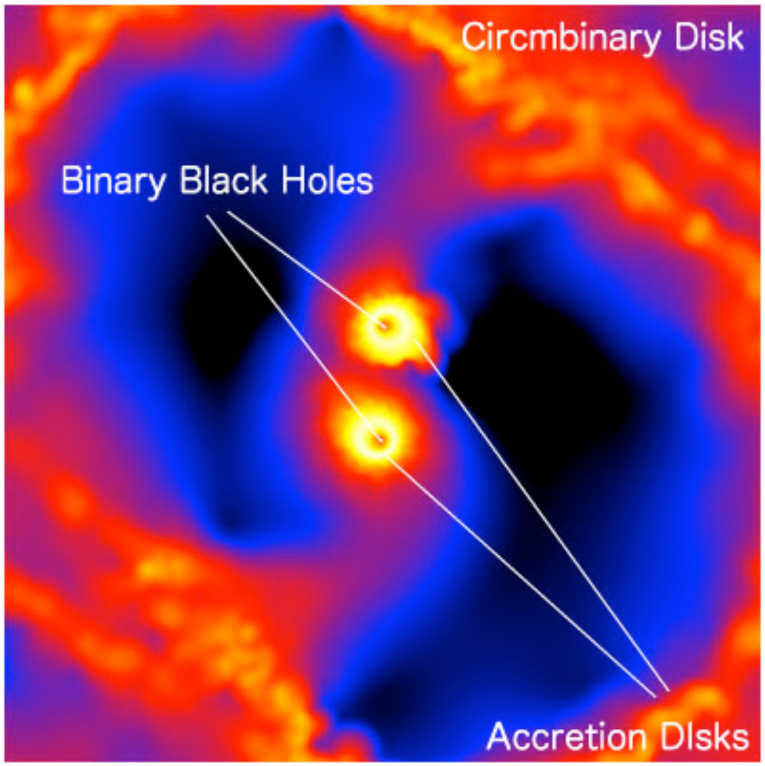
(2) Circumbinary disk system
Armitage&Natarayan (2002,2005); Milosavljevic & Phinny (2005); MacFadyen & Milosavljevic(2008);KH&Okazaki(2009); Cuadra et al.(2009); Lodato et al.(2009); Tanaka & Menou(2010)



$$M_{\rm pri} \sim M_{\rm sec}$$

Proposed Model

Triple disk model



← $\lesssim$ pc scale →

KH, Mineshige & Sudou. (2007);
KH, Mineshige & Ho (2008);KH (2009);
KH, Ueda, & Isobe(2010);

Advantage of this model

1.CB disk absorbs angular momentum of binary BHs and is also reservoir of accreting material.

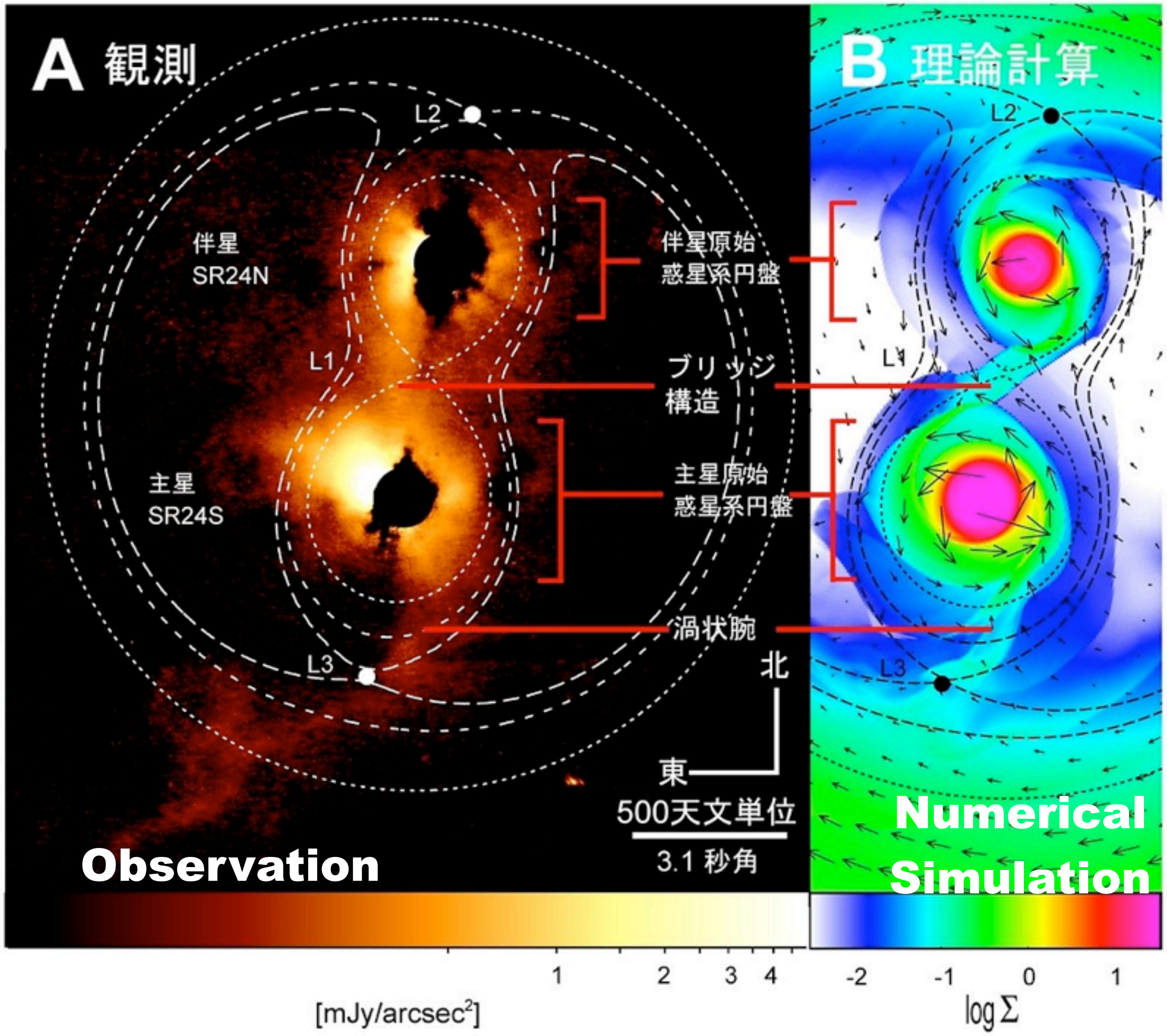
2.X-ray/UV variations from accretion disks provide observational signatures of binary BHs

Triple disk model makes it possible to study how binary BHs evolve and what they look like.

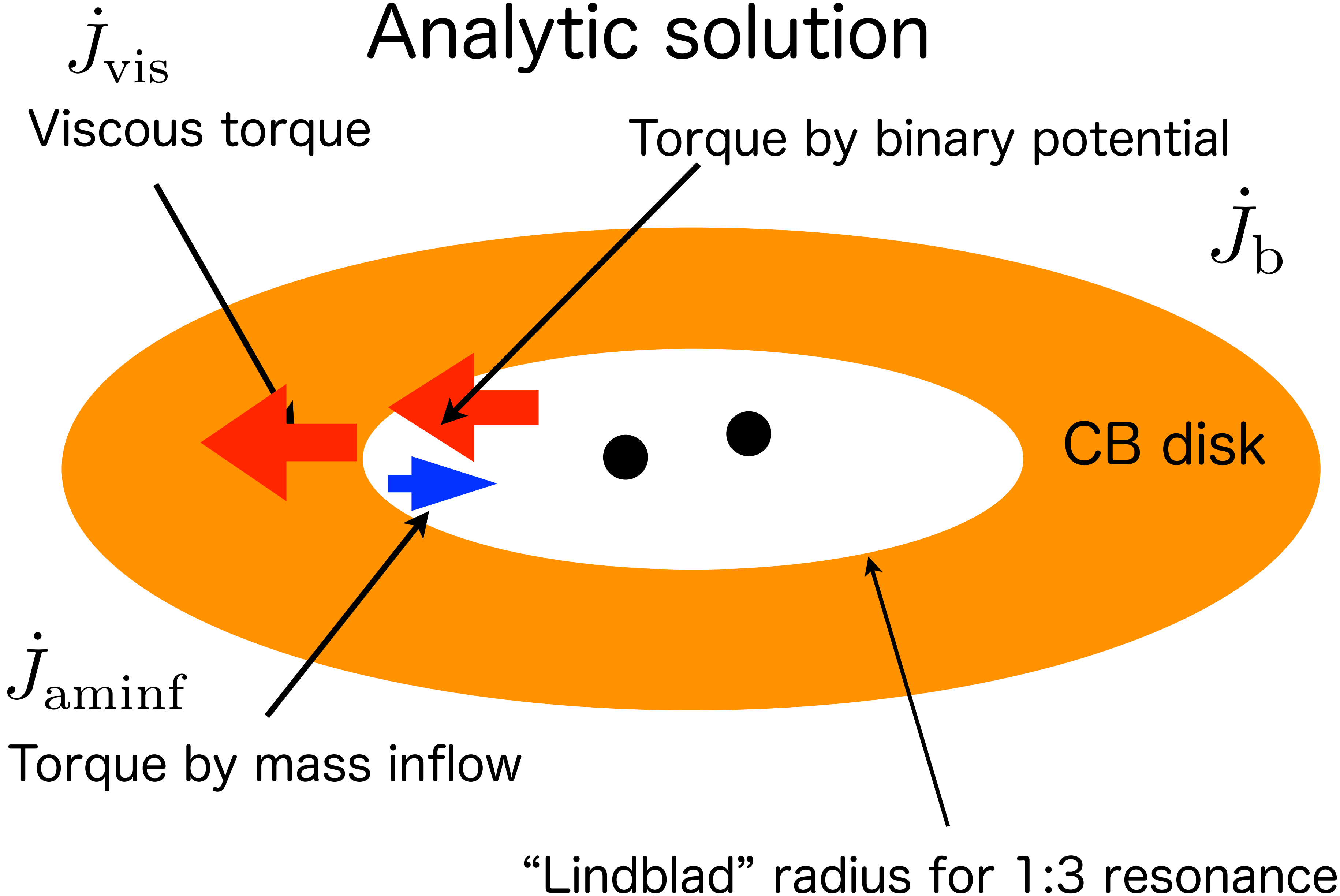
Young Star-binary System

Mayama et al. science, (2010)

Direct imaging of two planetary disks by the infrared interferometer



Angular Momentum Balance: Analytic solution



Basic Equations

KH (2009), KH,Ueda & Isobe (2010)

1. Energy eq. $\dot{E}_{\rm b}/E_{\rm b} \approx -\dot{a}/a$ a: semi-major axis
2. Angular momentum eq. $\dot{J}_{\rm b}/J_{\rm b} \approx \dot{a}/2a$
3. Torque balance eq. $\dot{J}_{\rm b} = -\dot{J}_{\rm vis} + \dot{J}_{\rm aminf}$
4. Adiabatic Invariant $\dot{E}_{\rm b} = \Omega \dot{J}_{\rm b}$

Solution

Orbital decay rate:

$$\frac{\dot{a}}{a} \approx -\frac{1}{t_c}$$

Orbital decay timescale:

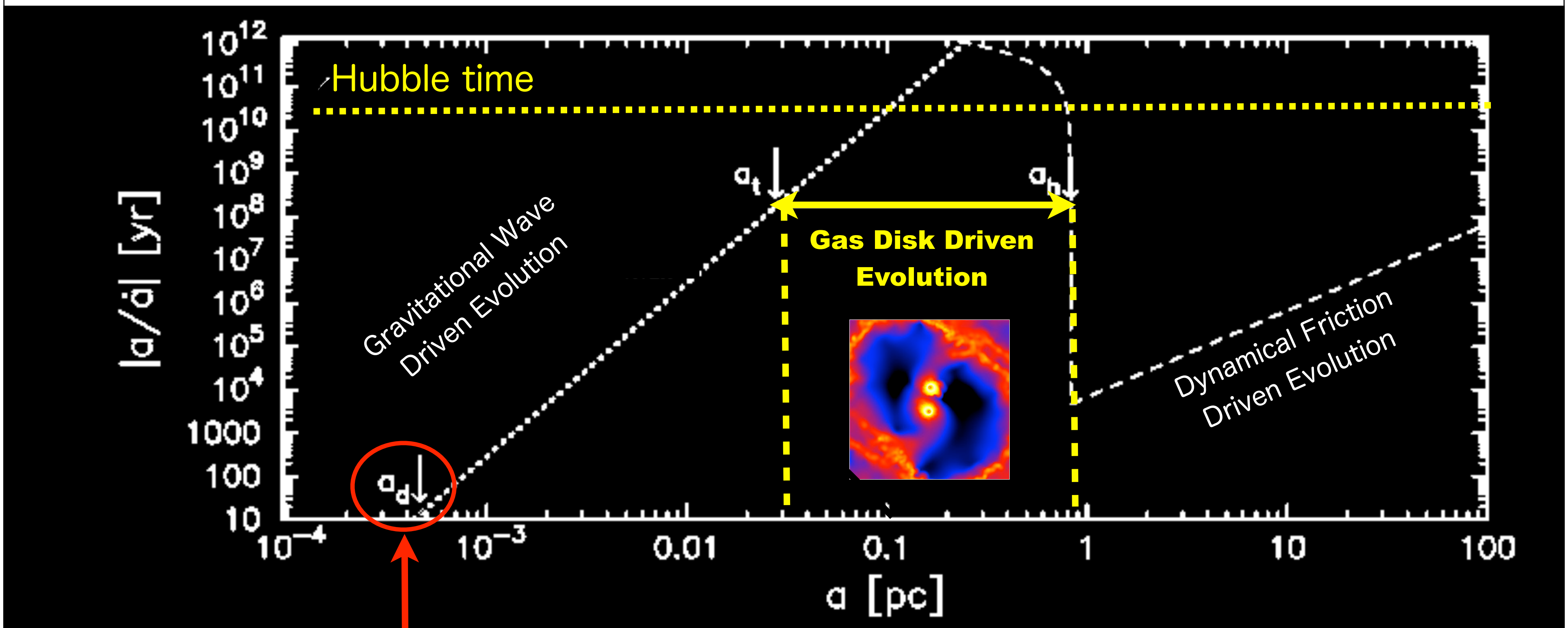
$$t_c \sim 3\times 10^8 [\mathrm{yr}] \frac{\mathrm{q}}{(1+\mathrm{q})^2}\left(\frac{0.1}{\eta}\right)\left(\frac{\epsilon}{0.1}\right)$$

ϵ : mass-to-energy conversion efficiency

η: Eddington Ratio

A Solution for Final Parsec Problem

KH (2009), KH,Ueda & Isobe (2010)

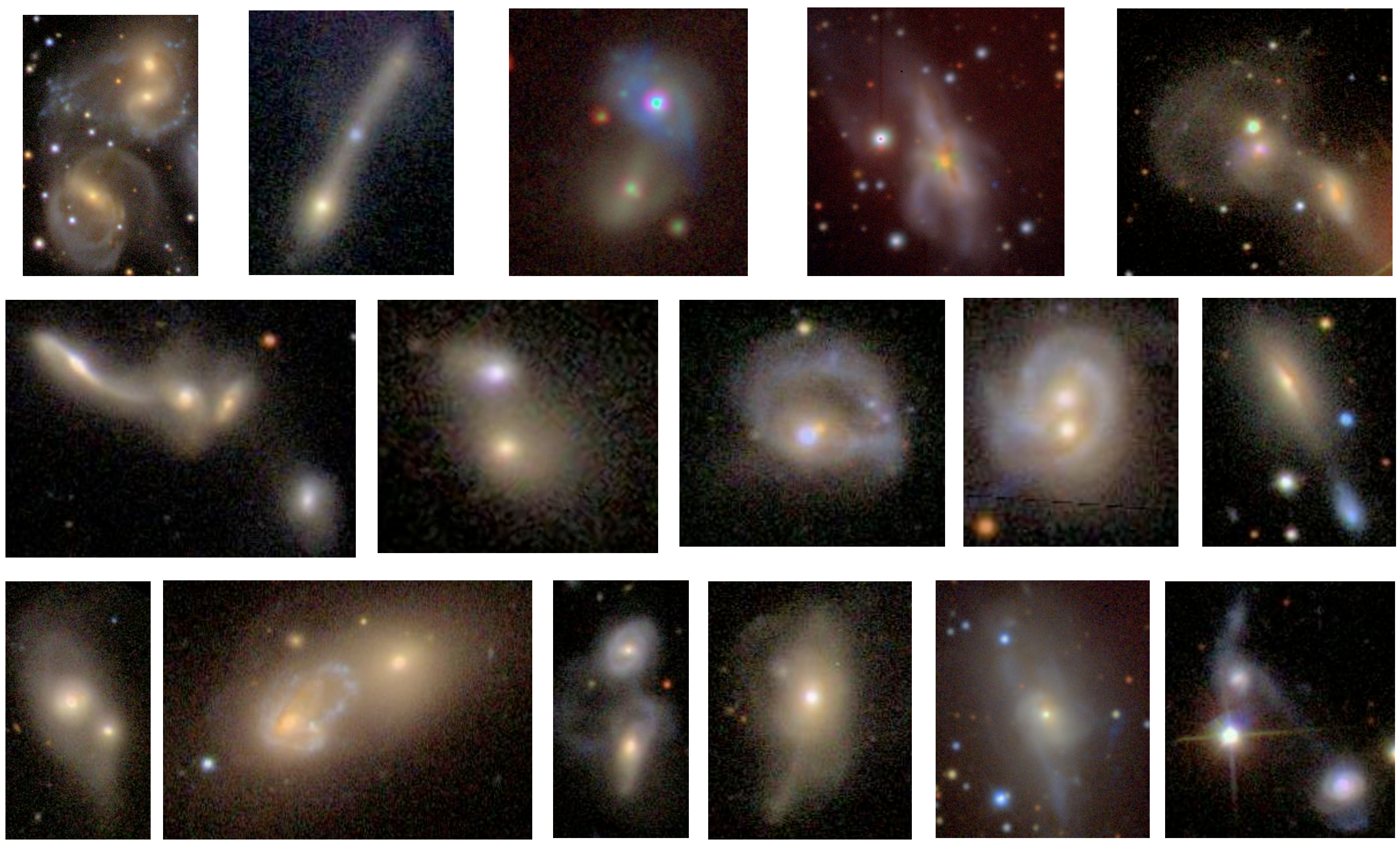


Decoupling radius (Taka Tanaka's talk)

Binary BHs Can Merge Within The Hubble Time By Interactions With Triple Disk

3. Mass Distribution of Binary Massive BHs in Nearby AGNs

KH, Ueda & Isobe (2010)



Koss et al. (2010)

Assumptions

1. Galaxy mergers form binary BHs & trigger AGN activity.
2. Merged galaxies remain AGN for one billion years.

Mass distribution of binary BHs

=

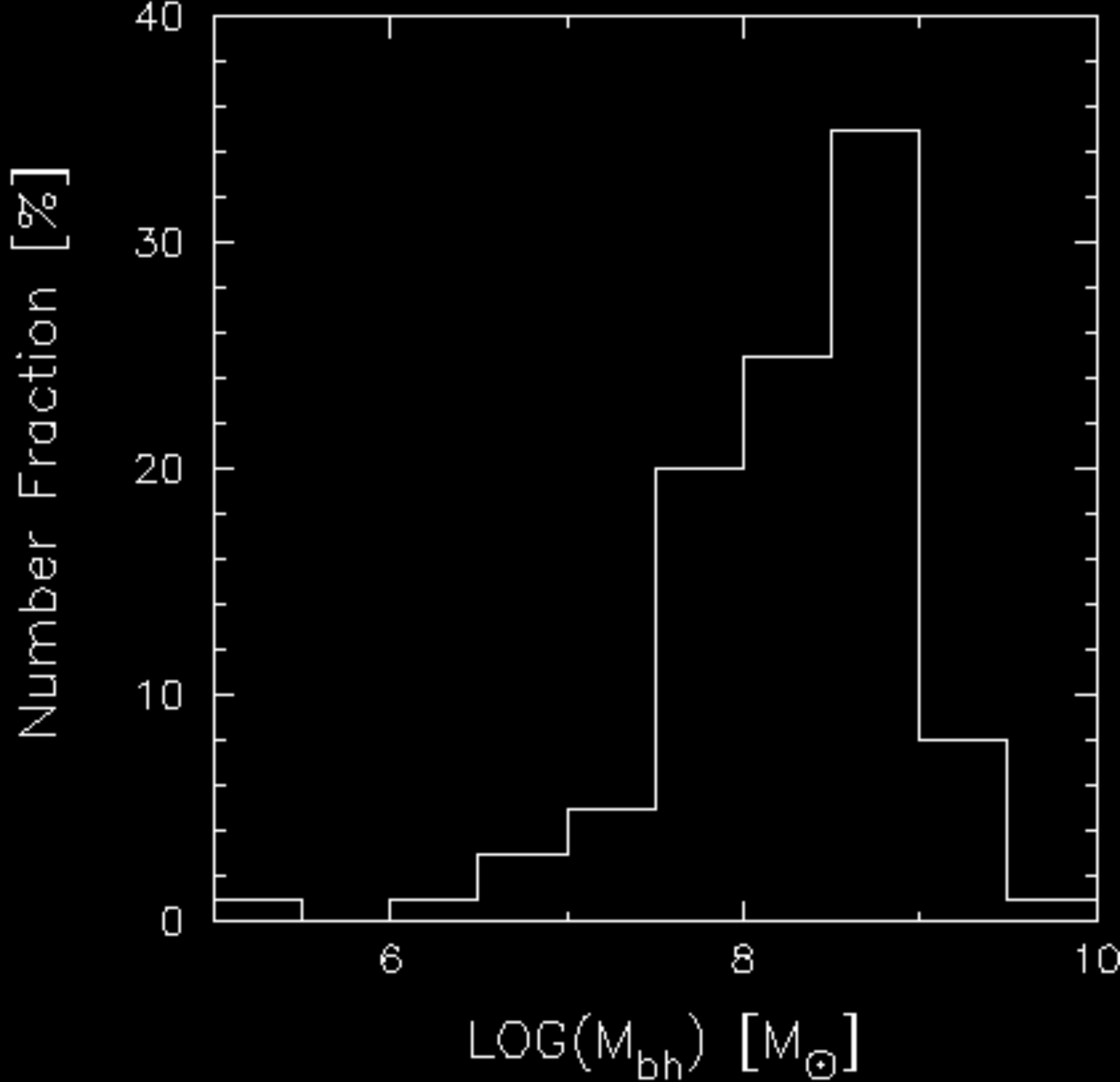
Observed BH mass distribution in AGNs

×

Probability for finding binary BHs

BH Number Fraction of Nearby AGNs

Swift/BAT (15-200keV) (Winter et al.2009)



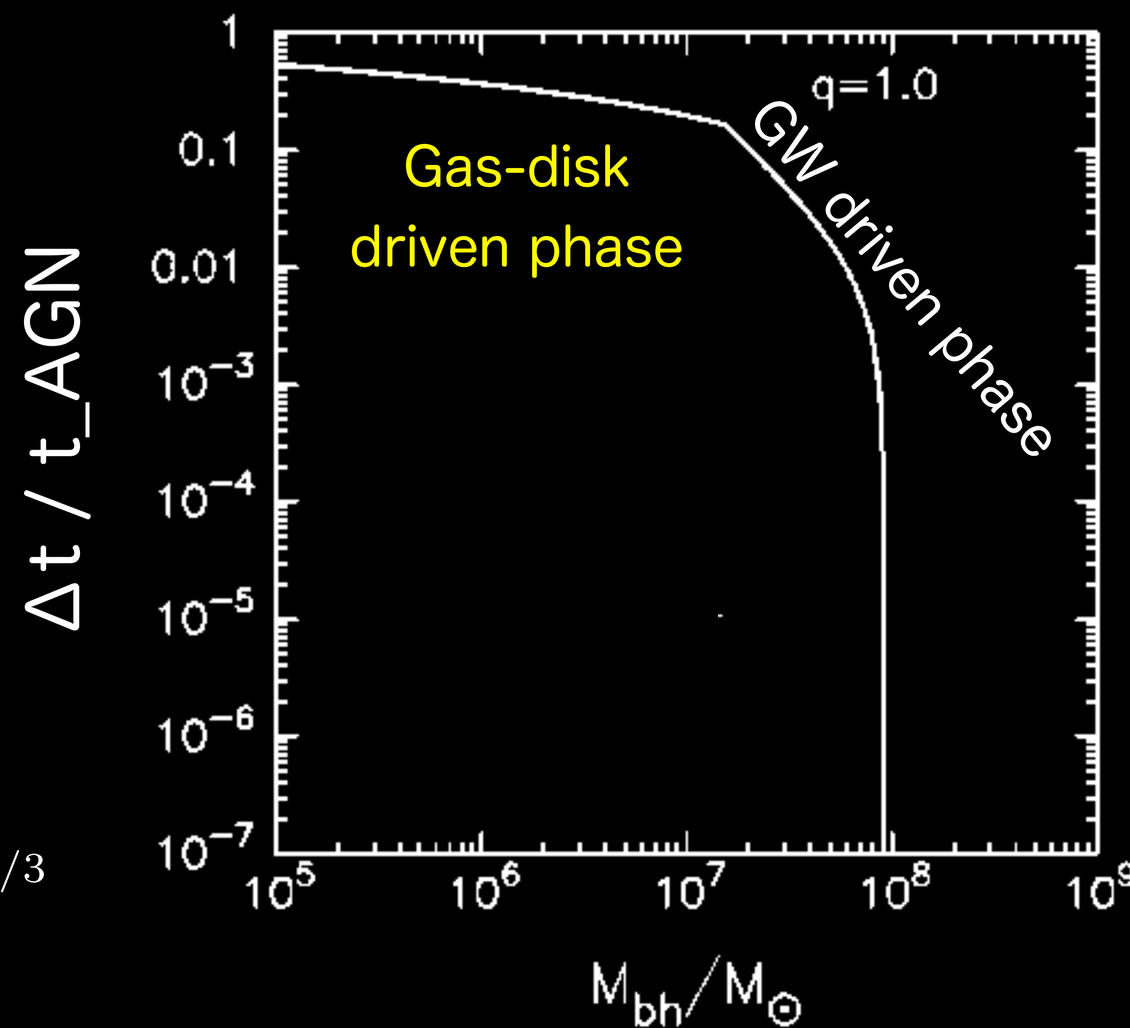
Mass-dependence of probability for finding binary BHs with an orbital period less than 10 years

The probability
=
Δt / t_AGN

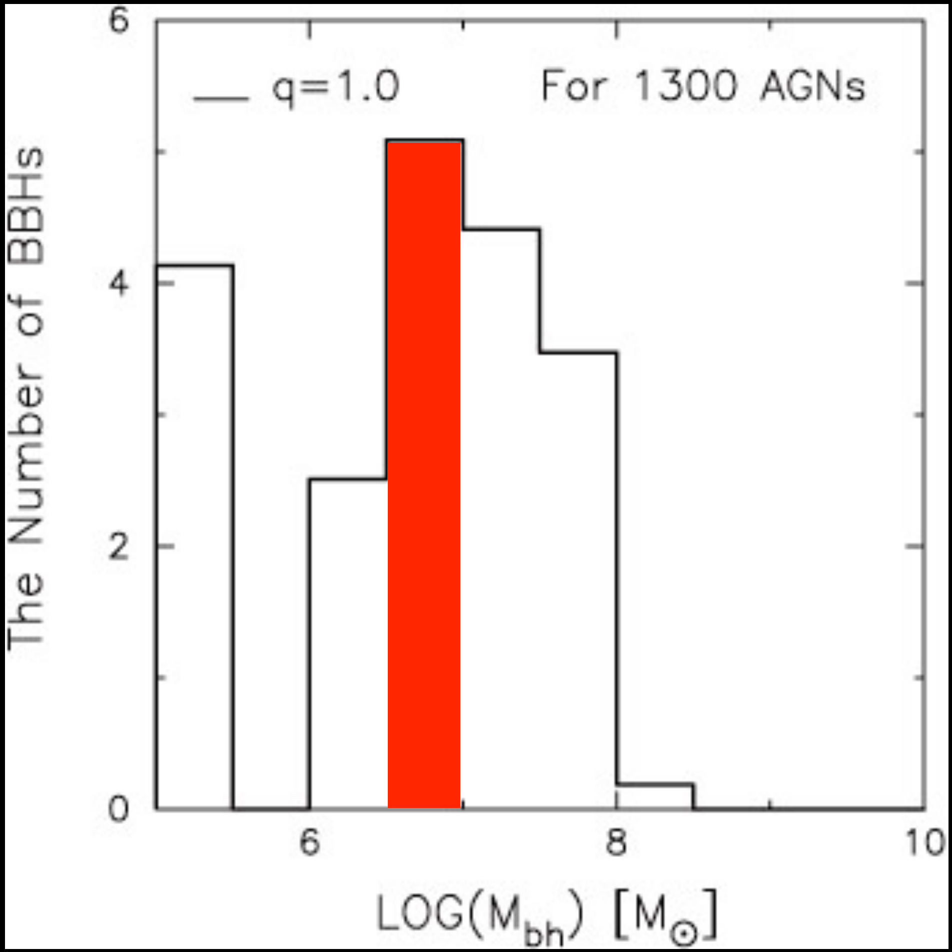
$$\Delta t \approx \int_{a_{10}}^{0} \frac{1}{\dot{a}} da$$

$$t_{\rm AGN} = 10^9 {\rm yr}$$

$$a_{10} \sim 2 \times 10^{-5} [{\rm pc}] \left(\frac{\rm M_{bh}}{\rm M_\odot} \right)^{1/3}$$



Predicted mass distribution of detectable binary BHs in nearby AGNs



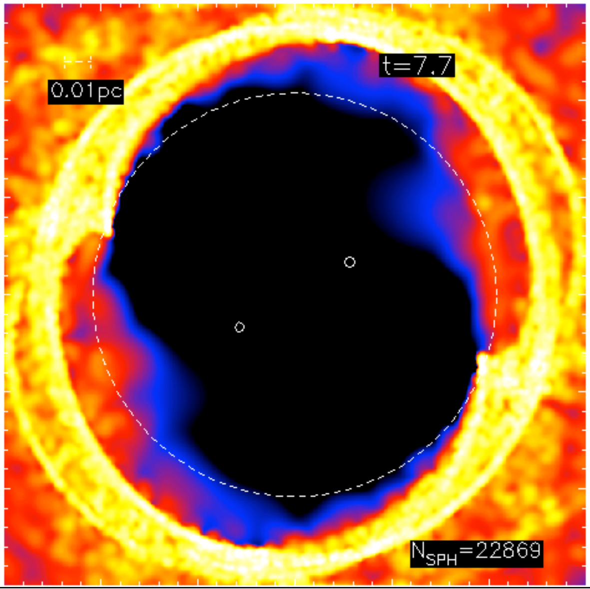
Prediction: 1~2% of nearby AGNs are close binaries.
Focus on AGNs of M_{bh}~$10^7 M_{sun}$!! (13% binary BHs)

4. Feasible Method to Detect Binary BHs

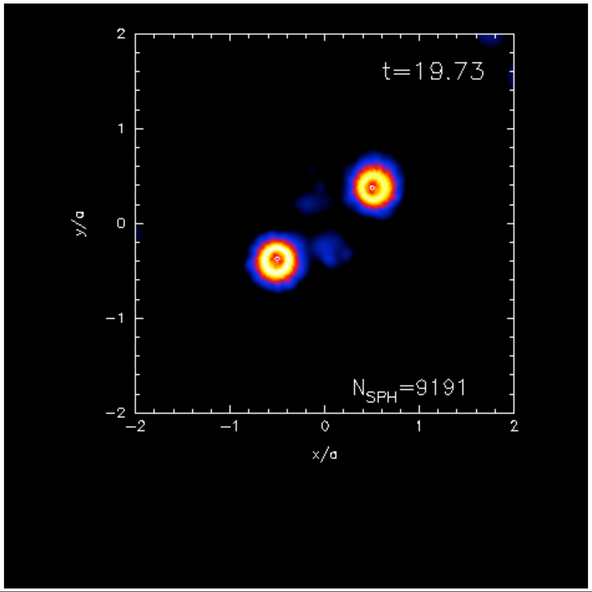
Method

1. 3D Smoothed Particle Hydrodynamics(SPH)
   (Bate et al. 1995; KH & Okazaki 2004, 2005,2006)
2. Simulations are divided into two stages.
   First stage: CB disk simulation
   Second stage: Accretion disk simulation
3. We obtain X-ray light curves from the accretion disk simulation

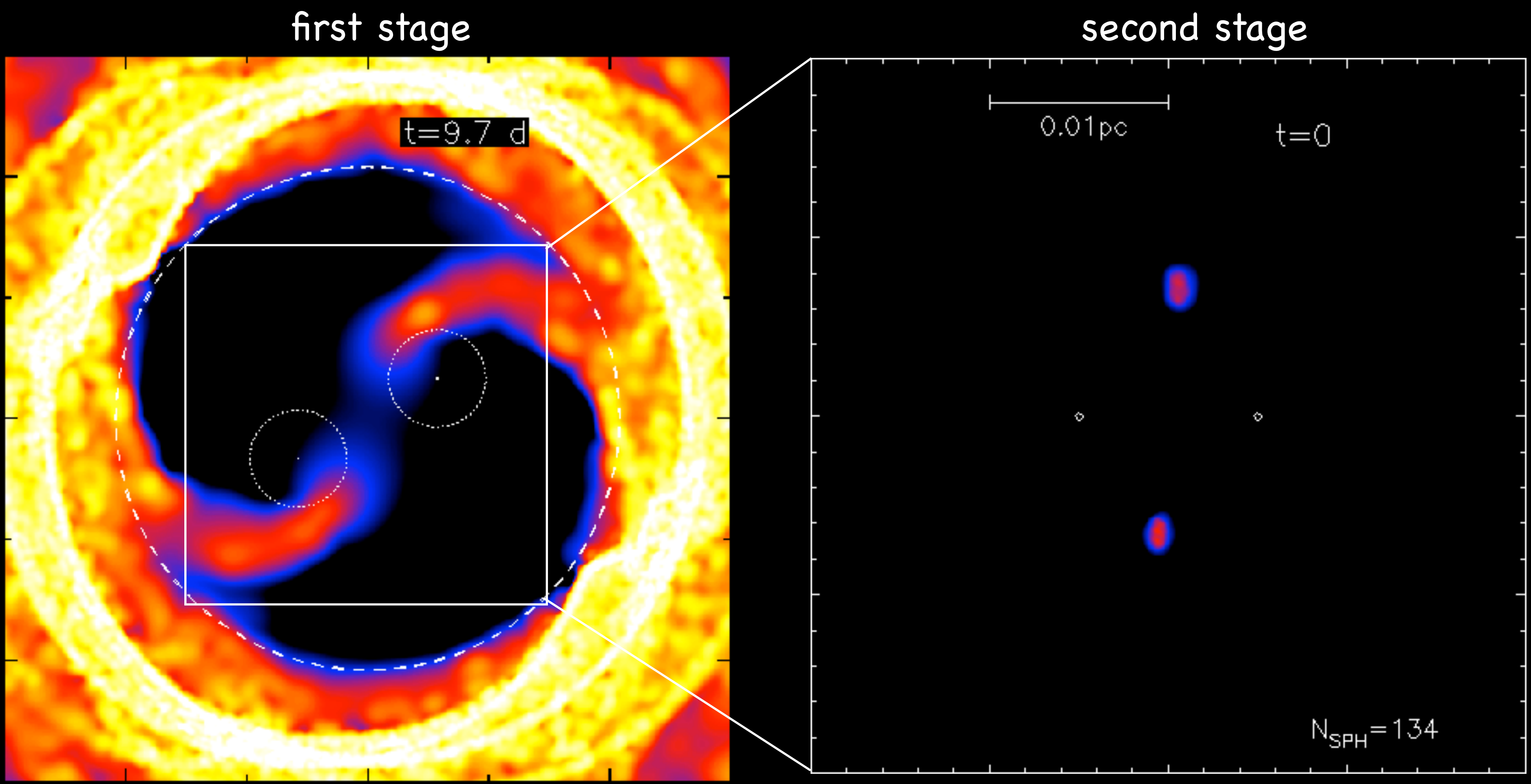
CB disk simulation



Accretion disk simulation



Two-stage simulation

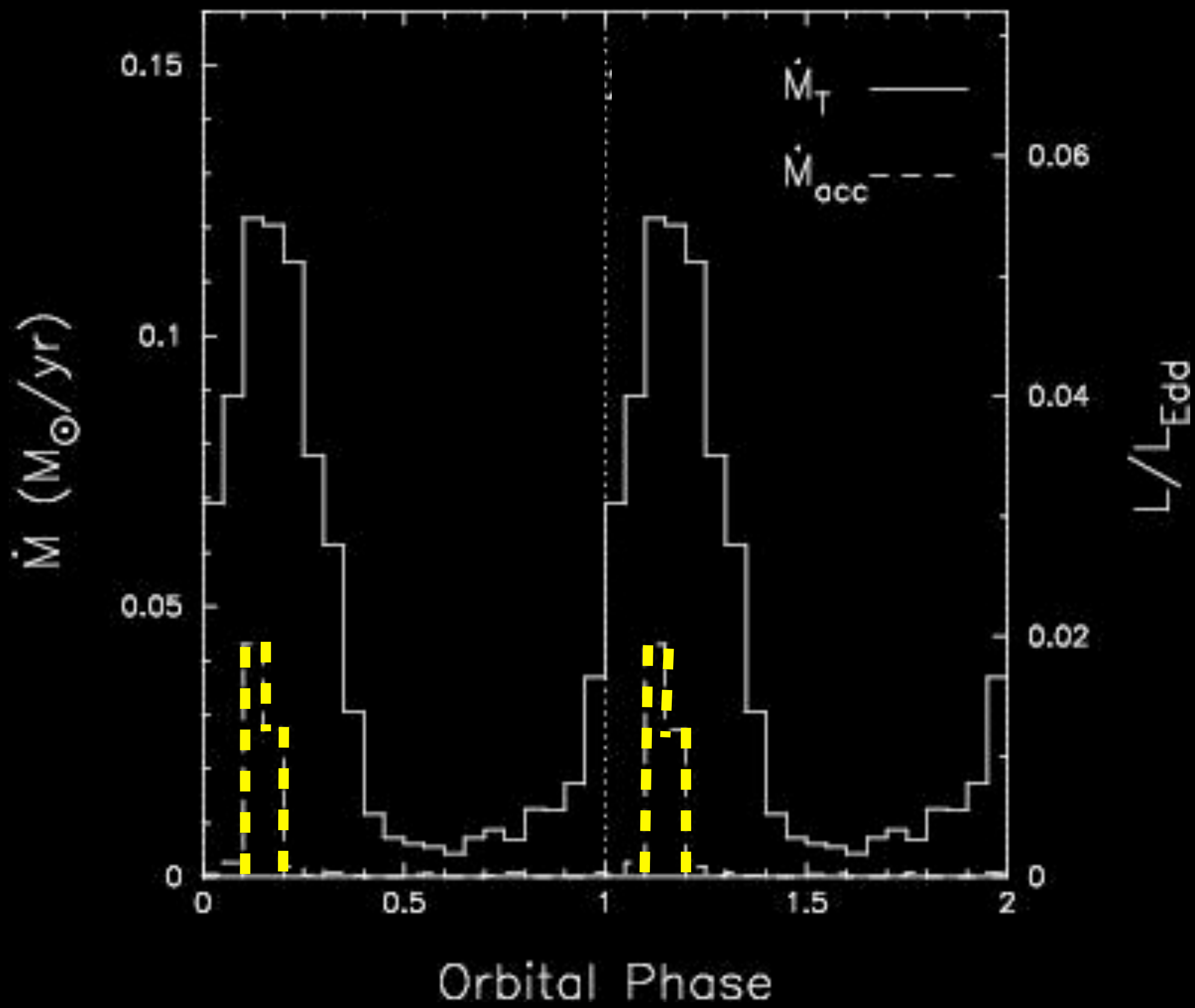


KH, Mineshige & Ho (ApJL, 2008)

$$a = 0.01\,\mathrm{pc}, \mathrm{e} = 0.5,$$
$$M_{\mathrm{tot}} = 10^8 M_\odot, P_{\mathrm{orb}} \simeq 9.4\,\mathrm{yr},$$
$$r_{\mathrm{in}} = 5.0 \times 10^{-3} a \sim 10 r_{\mathrm{bh}}$$

X-ray Light Curve

$$L_x = \epsilon_x \dot{M}_{\rm acc} c^2$$



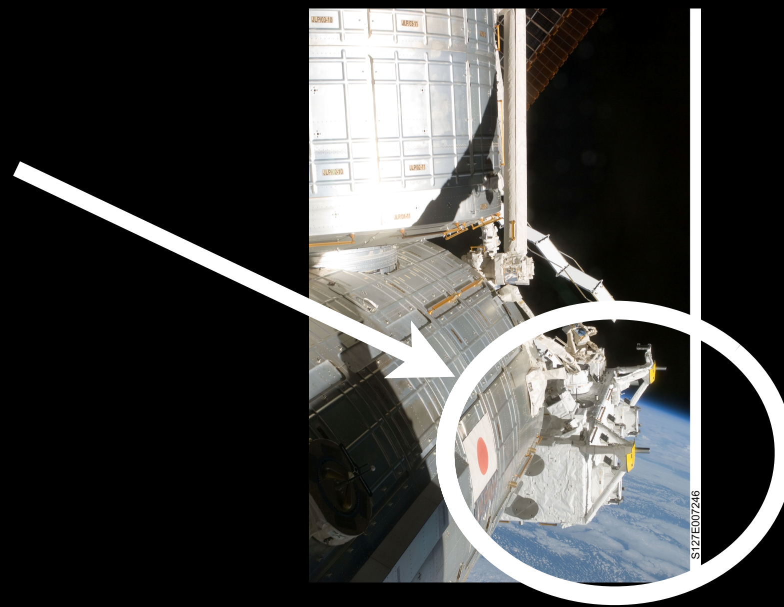
$$e = 0.5$$

MAXI

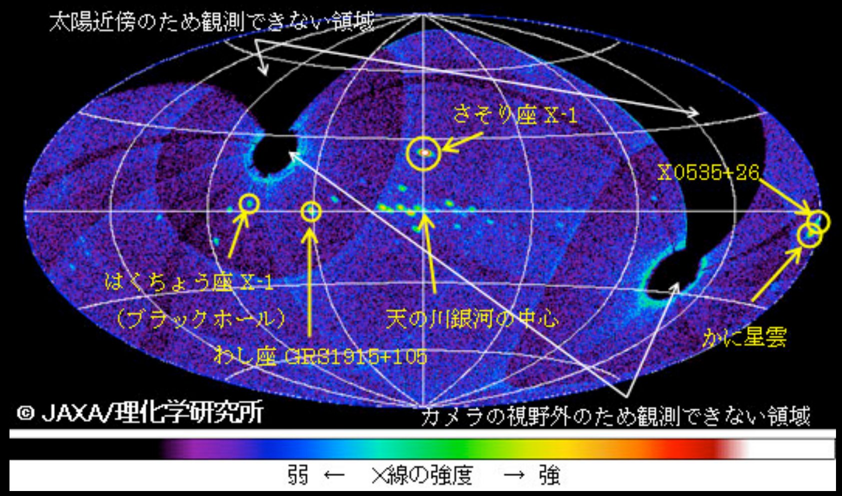
- Monitor of All-Sky X-ray Image (MAXI) :16/July/2009(Launch)
- To create X-ray color Movies
- Flux limit: 0.2mCrab
- Energy band: 0.5 - 30keV

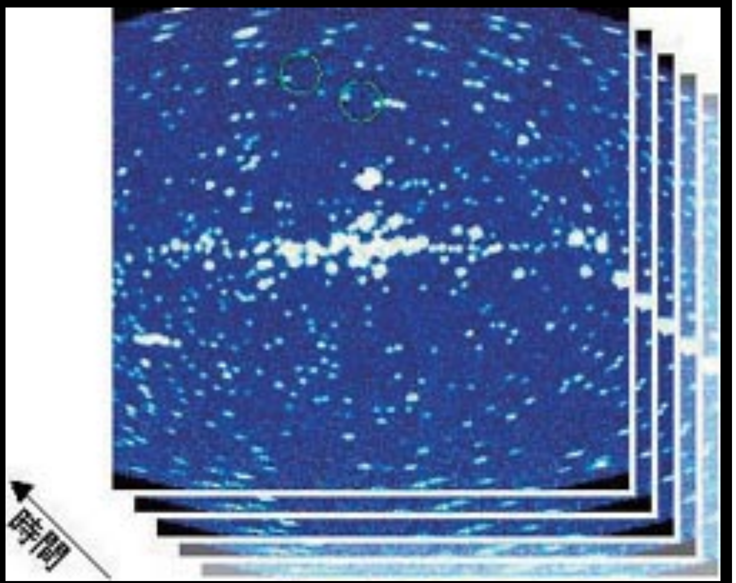
$$L_{\rm limit} \approx 3.7 \times 10^9 \left(\frac{r}{\rm Gpc}\right)^2 \left(\frac{M_{\rm bh}}{M_\odot}\right)^{-1} L_{\rm edd}$$

(credit: JAXA)



Matsuoka et al.(2009)





Summary

1. Accretion disks are formed around binary massive BHs by mass transfer from CB disk, forming a triple disk (two accretion disks and CB disk around them).
2. Binary massive black holes can merge within the Hubble time by interaction with the triple disk. [It gives one of solutions for Final Parsec Problem]
3. Evolution of a binary with the triple disk predicts 1~2% of nearby AGNs have close binaries in their centers; 13% for Mbh ~10^7Msun
4. X-ray/UV light curve is predicted to show significant periodic variation.
5. We can verify our scenario by X-ray instruments such as MAXI and/or Swift/BAT.

Thank you for your attention