バイナリーブラックホール

探査に向けて

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Hayasaki (PASJ, 2009)

2010/March/3@大阪市大

Outline

1. Introduction
   Hierarchical scenario ⇒ binary BHs

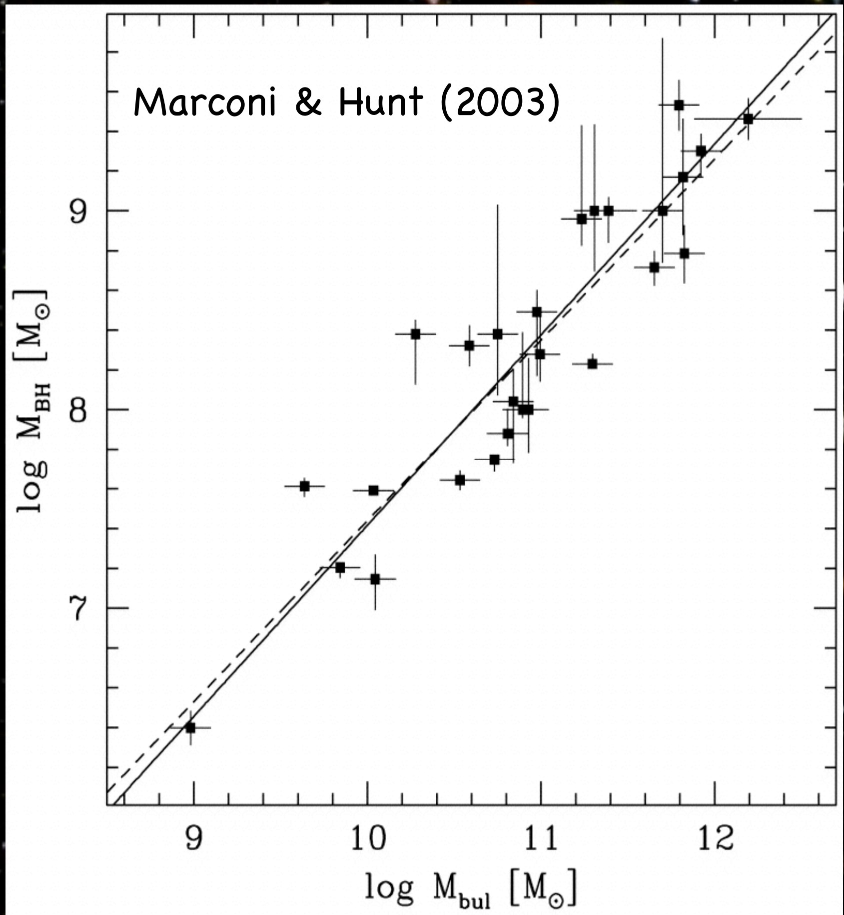
2. Our Approach
   Binary BHs with the triple disk

3. Main messages
   i. Signals from binary BHs
   ii. Evolution of binary BHs
   iii. Mass Function of binary BHs

4. Summary&Discussions

1. Introduction

Co-evolution of Galaxies and BHs



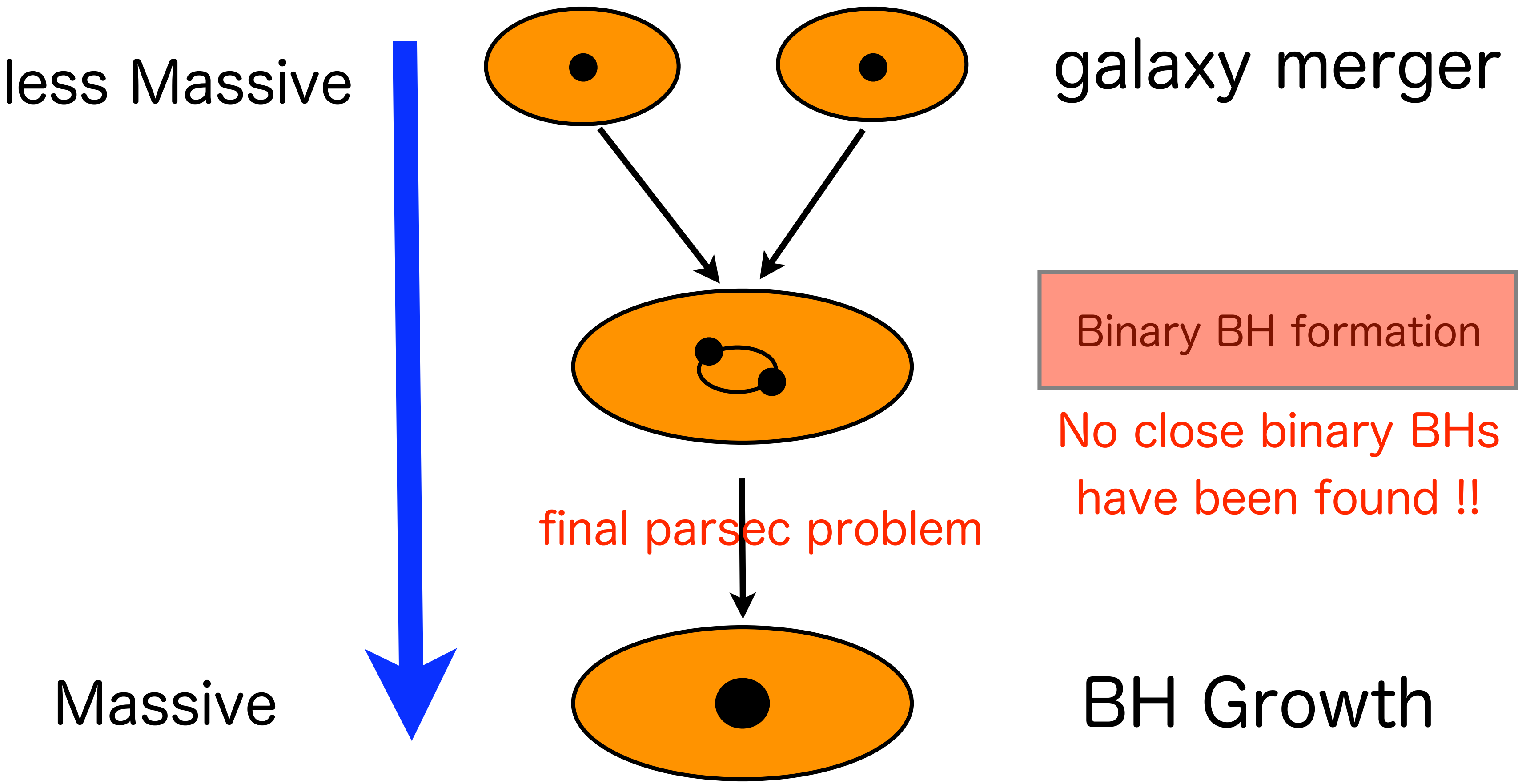
Kormendy & Richstone (1995)
Margorrian et al. (1998)
Ferrraruse & Merritt (2000)
Gebhardt et al.(2000)

$$M_{\rm bh} \approx 0.002 M_{\rm bul}$$

The relation requires BH growth.

"Hubble's Deepest View Ever of the Universe Unveils Earliest Galaxies". NASA. March 9, 2004.
http://hubblesite.org/newscenter/archive/releases/2004/07/. Retrieved December 27, 2008.

Hierarchical Structure Formation



Probing close binary BHs is a key to understand this scenario.

Our Goal

Existence of massive binary BHs

↓

Missing Link of

hierarchical structure formation

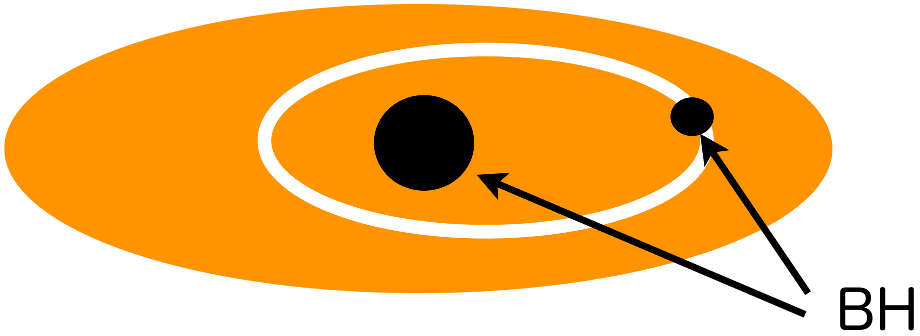
To give a feasible method to detect close binary BHs

2. Our Approach

Type of gaseous disk models

(I) Inspiral system (cf. type II migration) ：

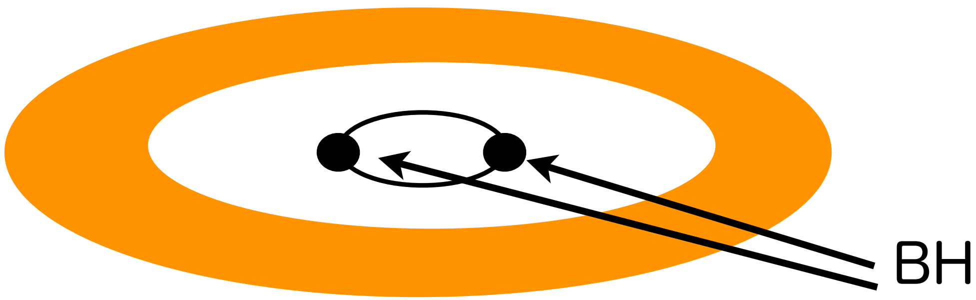
Ivanov et al.(1999); Goldman & Rix (2000); Bogdanovic et al(2008); Corrales et al.(2009)



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

(2) Circumbinary disk system

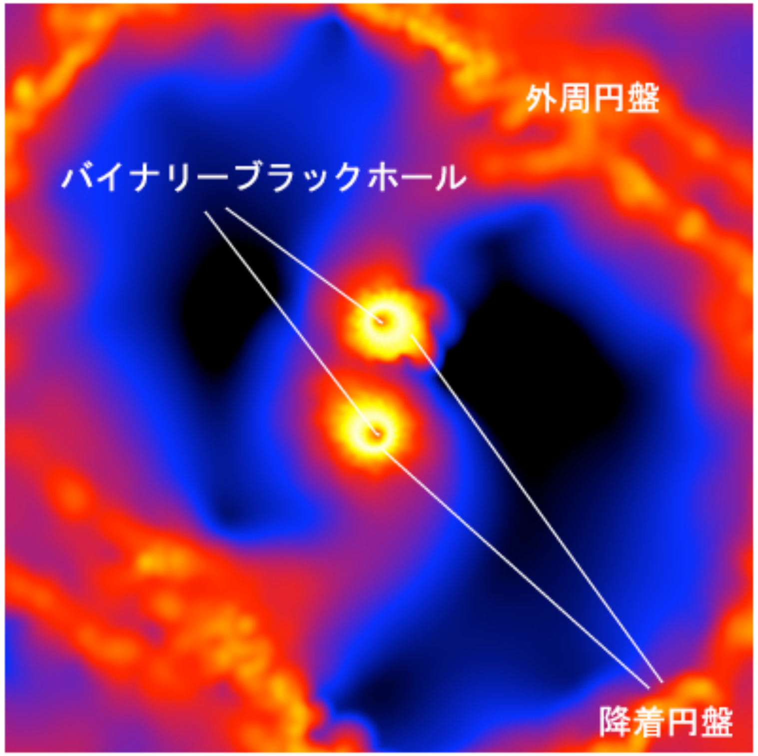
Armitage&Natarayan (2005); Milosvejeric Merritt (2008); KH & Okazaki (2009); Cuadra et al.(2009)



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

Proposed Model

Triple disk model



← sub-pc scale →

KH, Mineshige & Sudou. (2007);
KH, Mineshige & Ho (2008);
KH & Mineshige (2008); KH (2009);
KH, Ueda, Isobe(arXiv:1001.3612);

Disadvantage

How does the mass is suppled to the circumbinary disk ?

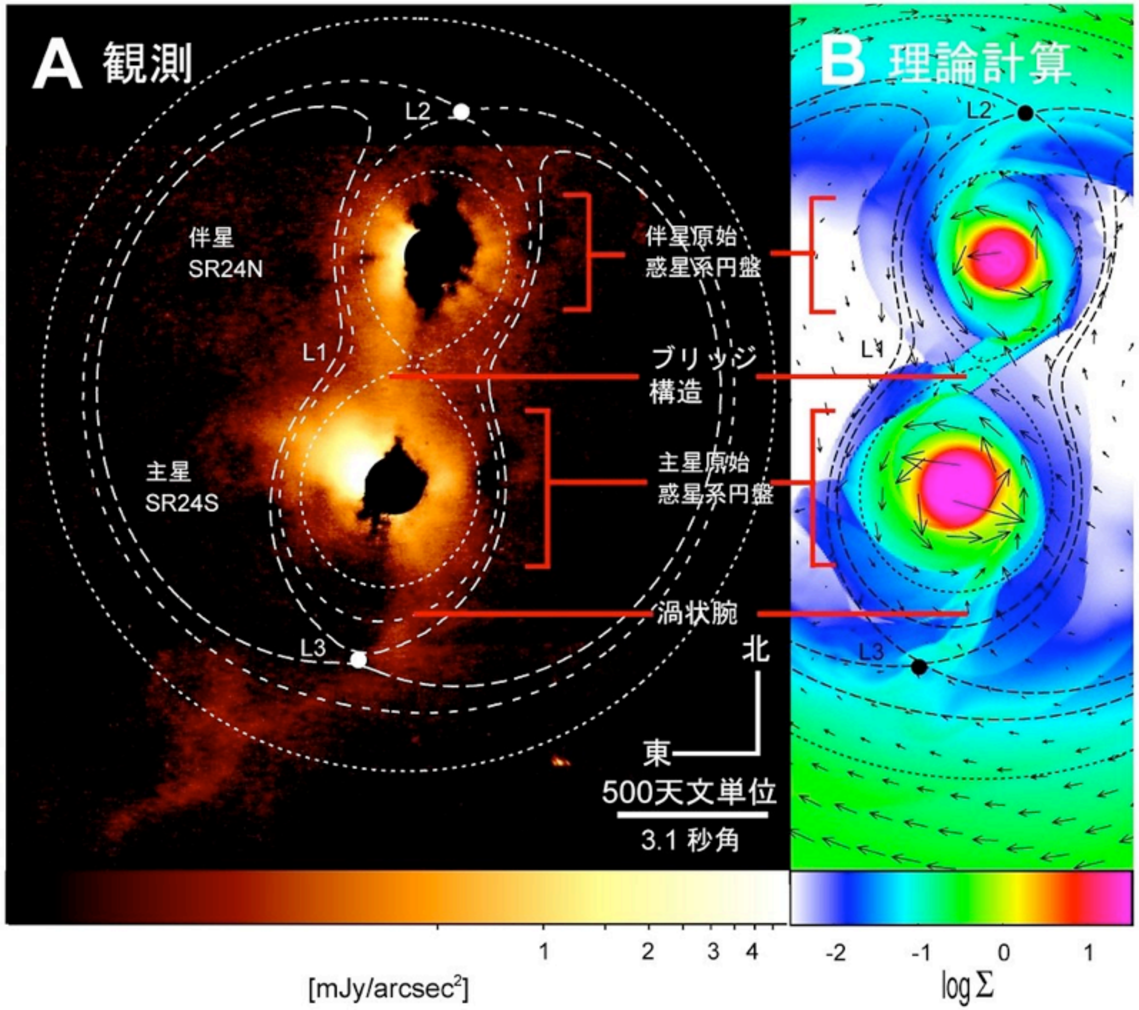
Advantage

Accretion disks are expected to show X-ray light variations

Triple disk model makes it possible to study how binary BHs look like.

原始連星系円盤

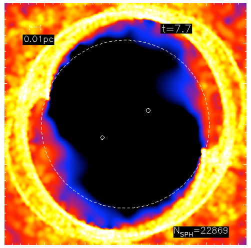
Mayama et al. (2009)

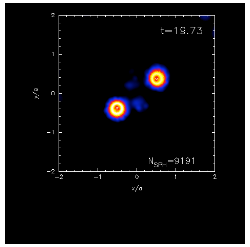


Method

1. 3D Smoothed Particle Hydrodynamics(SPH) (Bate et al. 1995; KH & Okazaki 2004, 2005,2006)

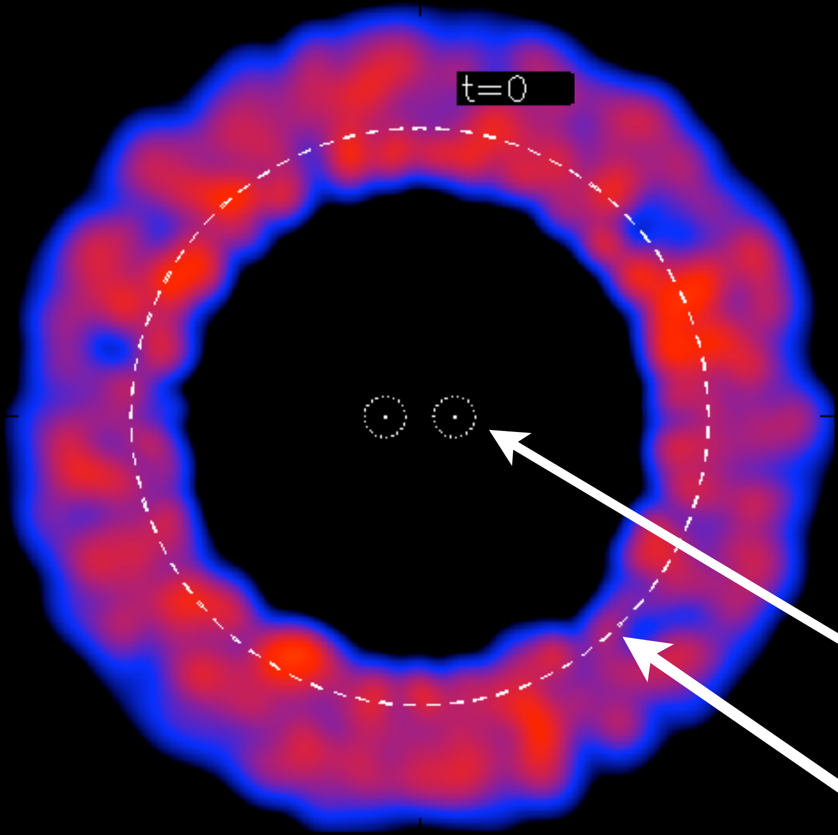
2. Simulations are divided into two stages.
   First stage: Circumbinary disk simulation
   Second stage: Accretion disk simulation





3. The Shakura-Sunyaev viscosity parameter is adopted ($\alpha_{\rm SS} = 0.1$).

Initial Settings for circumbinary disk simulation



- SPH particles are distributed outside of the 1:3 OLR radius, where the angular frequency of gas particles is 1/3 of angular frequency of the binary.

- Isothermal equation of state

Effective Roche radius of each black hole.

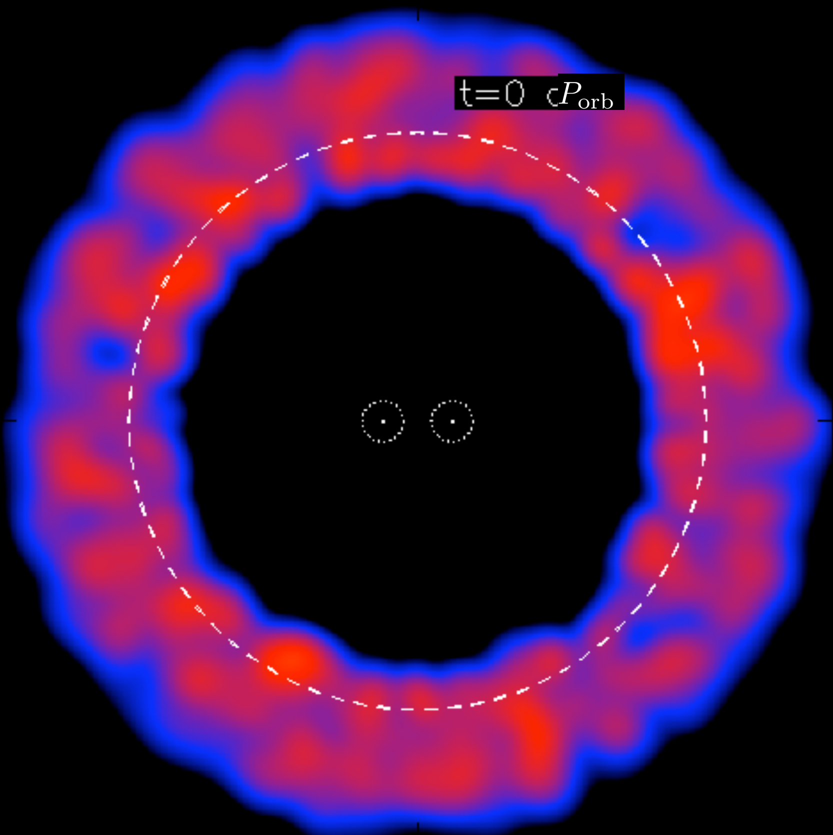
1:3 Outer Lindblad resonance radius (Artymobicz & Lubow 1994)

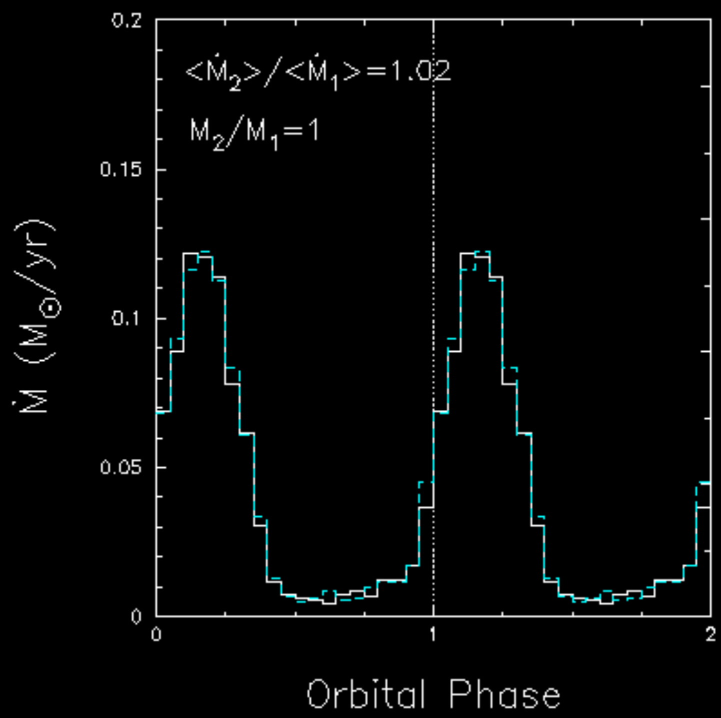
$$a = 0.01\mathrm{pc}, \mathrm{e} = 0.5, \mathrm{r_{out}} = 2.8\mathrm{a},$$
$$q = 0.1, M_{\mathrm{bh}} = 10^8 M_{\odot}, P_{\mathrm{orb}} \simeq 9.4\mathrm{yr},$$
$$\dot{M}_{\mathrm{input}} = 1 M_{\odot}/\mathrm{yr}$$

3. Model Predictions

(i)Signals from the binay BH system

Mass-transfer rate from the CBD to each BH



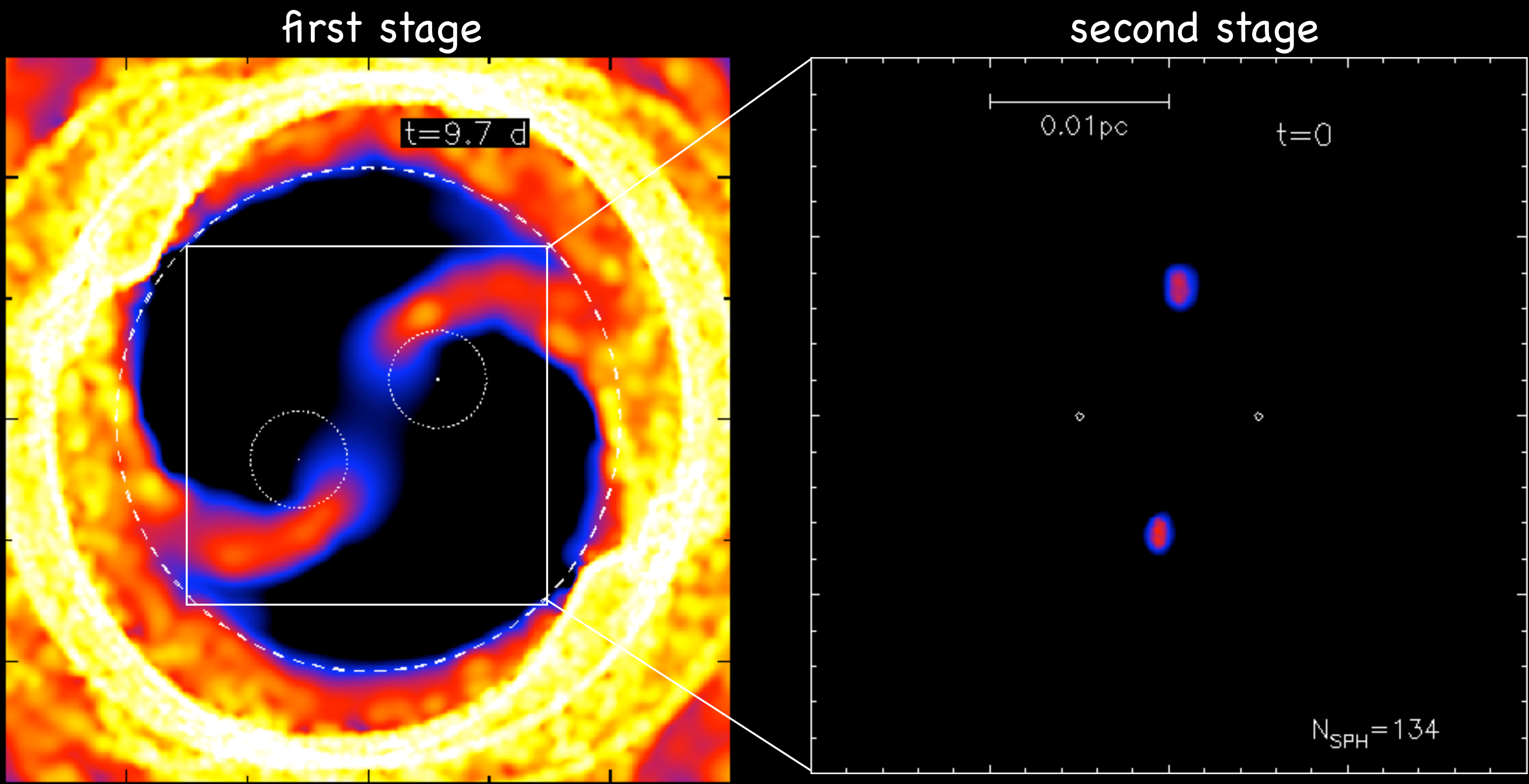


Second stage simulation

1. Setting the mass-transfer rate
   as a new boundary condition

2. Adoption of an energy equation
   (Viscous heating＝radiative cooling)

Two stage simulation



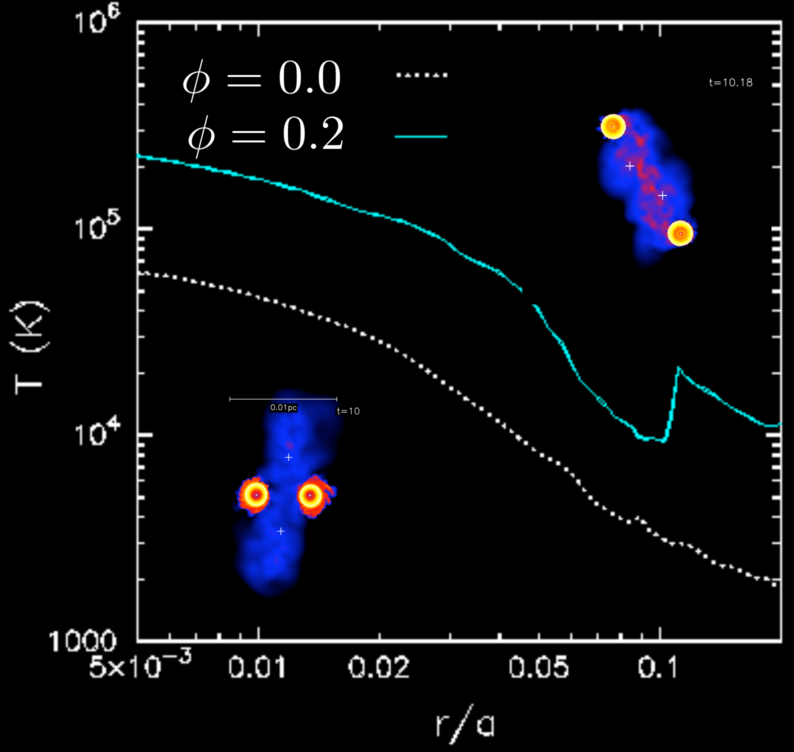
KH, Mineshige & Ho (ApJL, 2008)

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

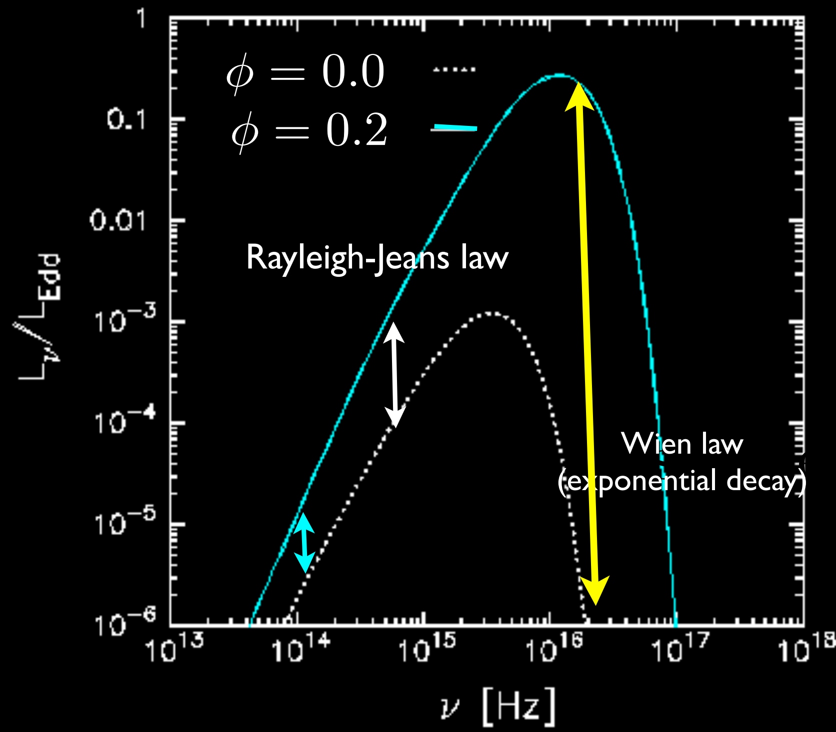
Radial profile of temperatures and Spectral Energy Distributions (SEDs)

KH, Mineshige & Ho (2008)

Temperature



SEDs



ϕ : Orbital phase

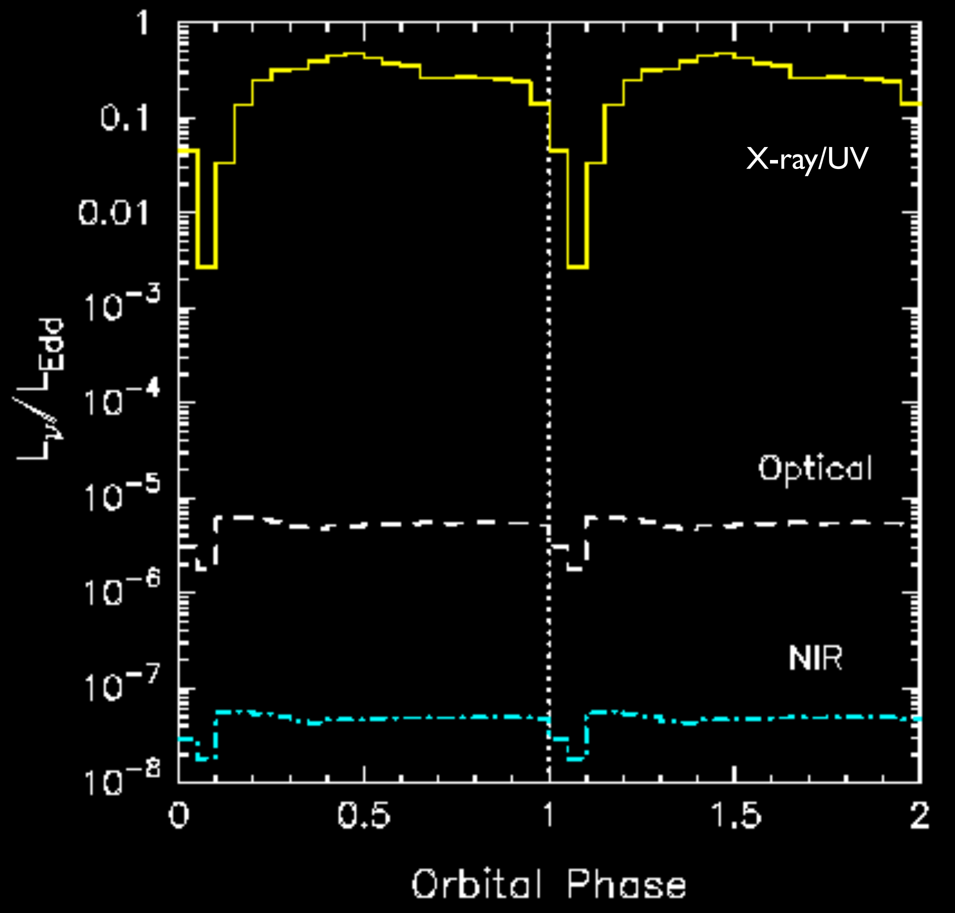
$$L_\nu = d^2 \nu F_\nu$$

d : Distance from the earth

ν : Frequency F_ν : Flux

Light Curve (UV, Opt, IR)

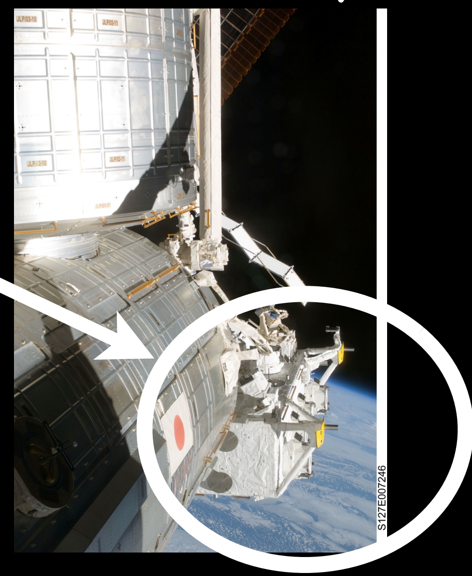
KH, Mineshige & Ho (2008)



Prediction 1: Significant light variation of X-ray

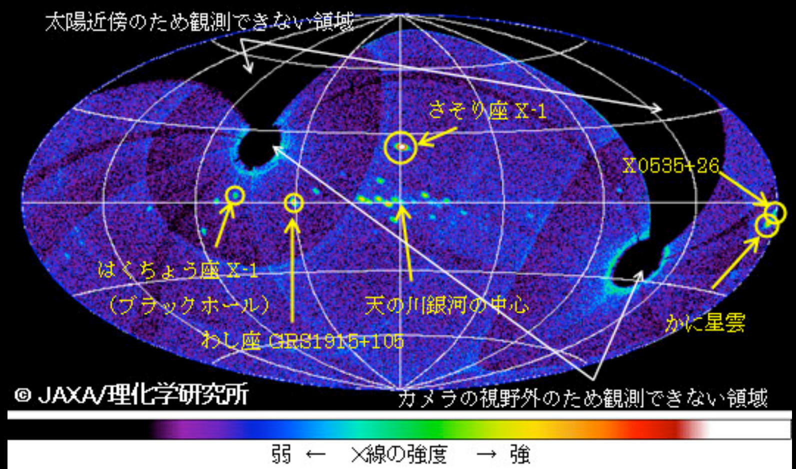
What is MAXI?

(credit: JAXA)

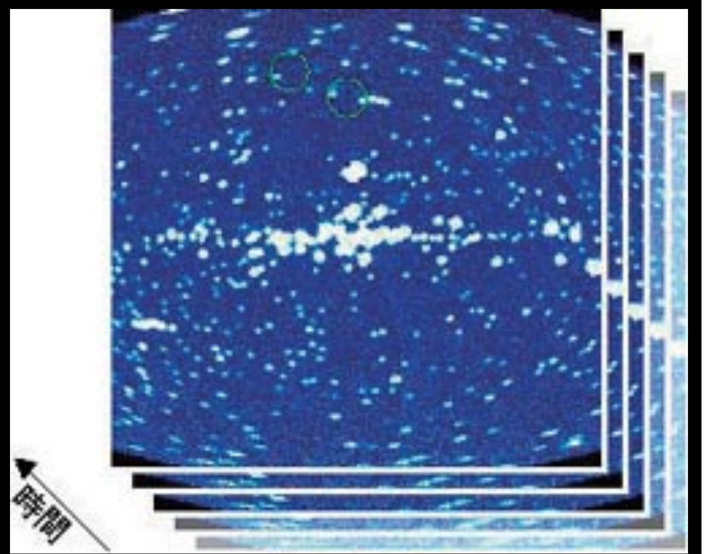


- Monitor of All-Sky X-ray Image (MAXI) :16/July/2009(Launch)
- To create X-ray color Movies
- Flux limit: 0.2mCrab
- Energy band: 0.5 - 30keV

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



Matsuoka et al.(2009)

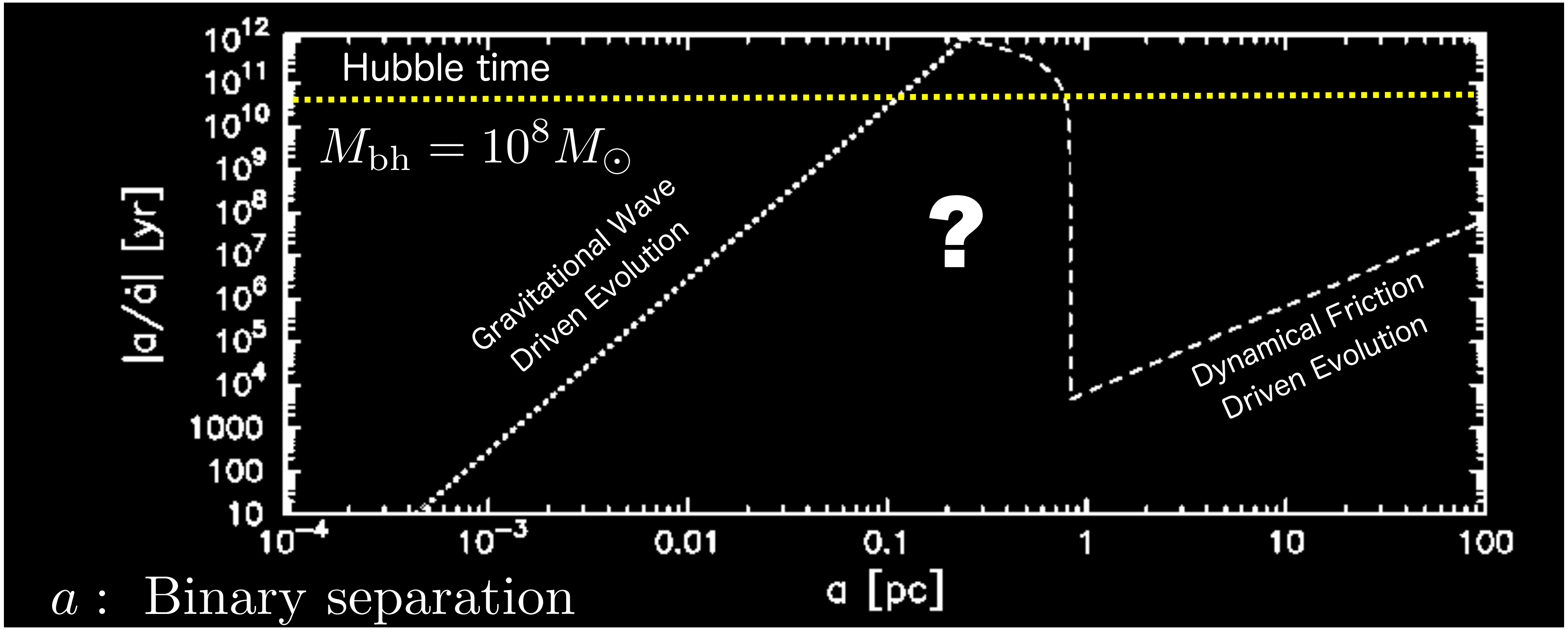


(ii) Evolution of binary massive black holes

A solution for final parsec problem

I. Evolution of Binary BHs1

Begelman et al. (1980)



Binary BHs mainly evolve via three stage processes.

“Final Parsec Problem”

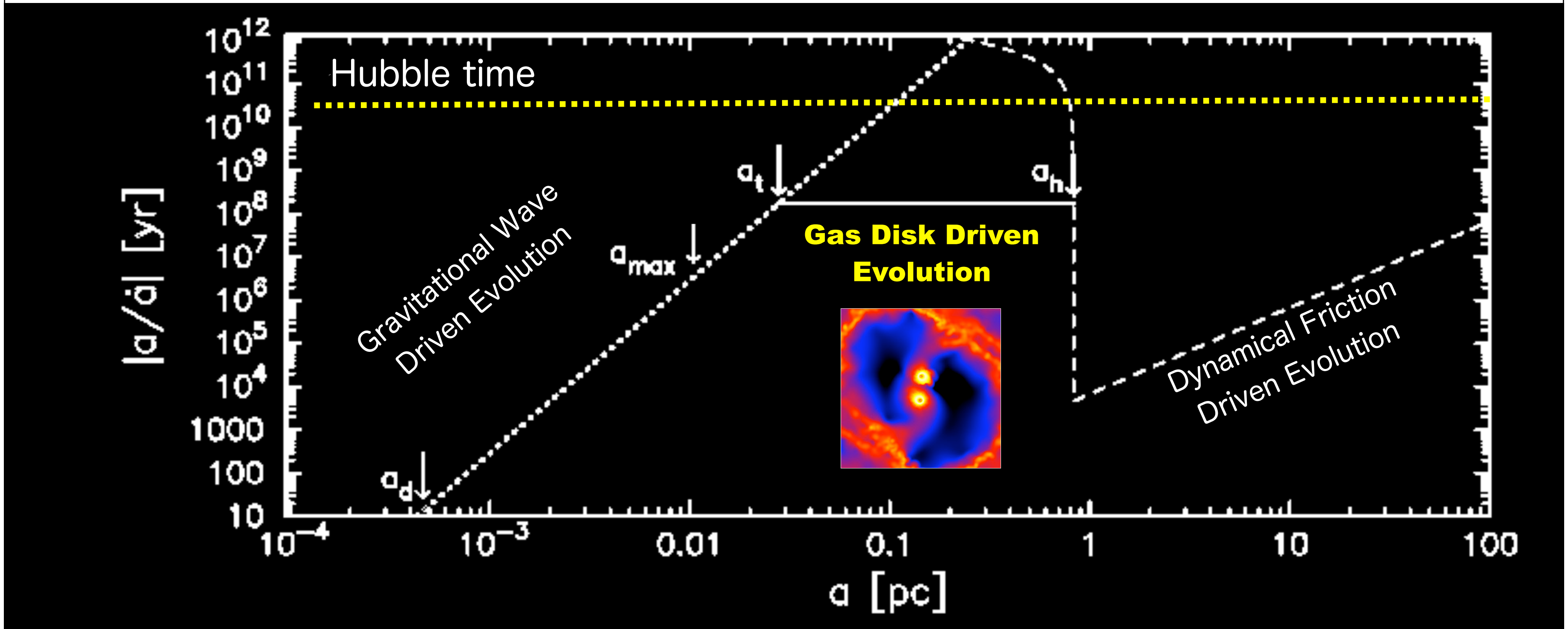
Key idea to solve the final parsec problem

- Interaction with Stars (Star cluster, dwarf galaxy)
  Roos(1981), Ebisuzaki et al.(1991), Quilan(1996), Quinlan&Harquist(1997), Makino(1997), Matsubayashi et al.(2007), Matsui & Habe(2009), Iwasawa & Makino (in prep)

- Interaction with gas
  Ivanov & Paparoizou(1999), Goldman & Rix (2000), Armitage&Natarayan(2002,2005), Hayasaki et al.(2007,2008), Dotti et al.(2007), Hayasaki(2009),Cuadra et al.(2009), Lodato et al. (2009),Hayasaki & Tanaka (in prep)

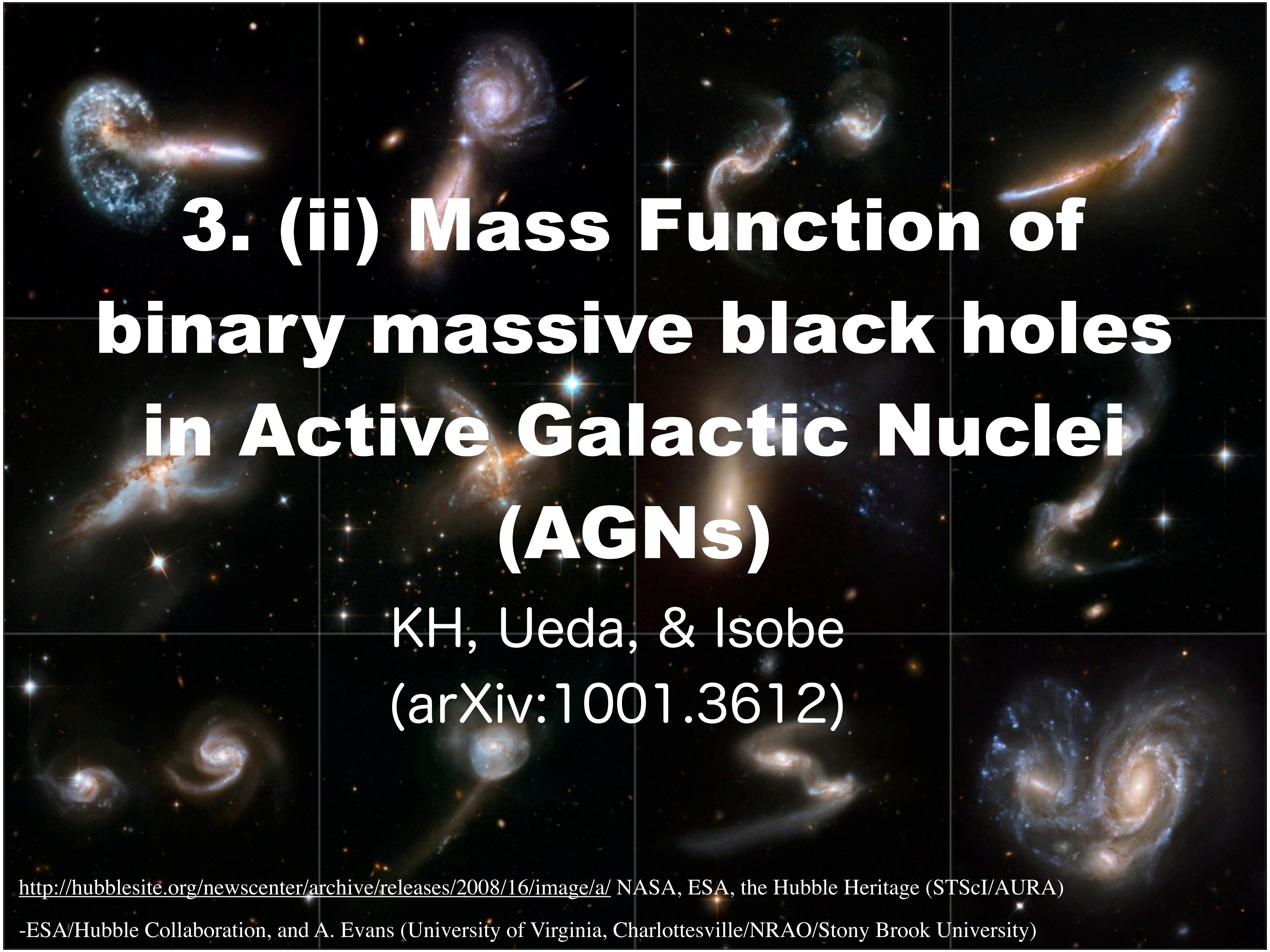
II. Evolution of Binary BHs

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



Interaction with circumbinary disk makes the binary decayed.

Interaction with the circumbinary disk allows binary BHs to merge within a Hubble time



3. (ii) Mass Function of binary massive black holes in Active Galactic Nuclei (AGNs)

KH, Ueda, & Isobe

(arXiv:1001.3612)

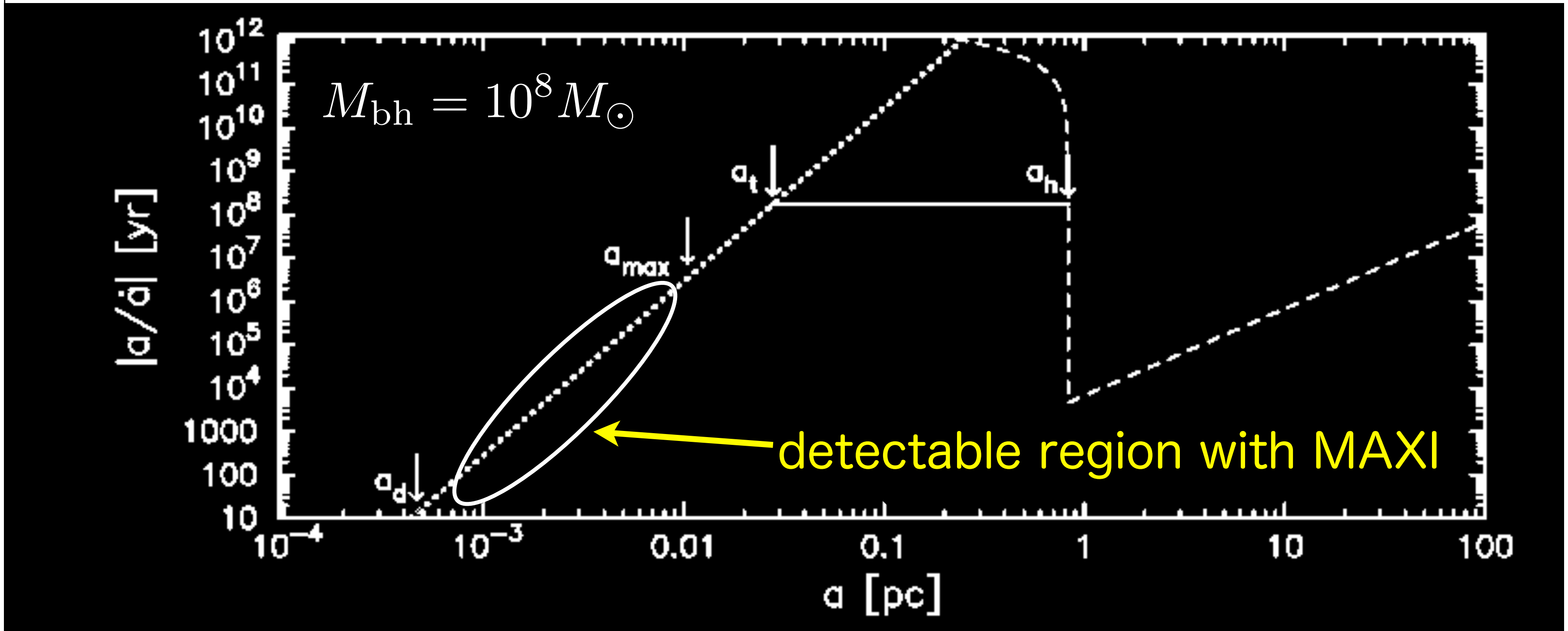
http://hubblesite.org/newscenter/archive/releases/2008/16/image/a/ NASA, ESA, the Hubble Heritage (STScI/AURA)

-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

Method

1. To obtain the timescale of orbital decay from ～kpc to ～submili-pc.
2. To obtain the probability for finding close binary BHs detectable with MAXI.
3. To obtain the mass function of binary BHs using that of nearby observed AGNs.

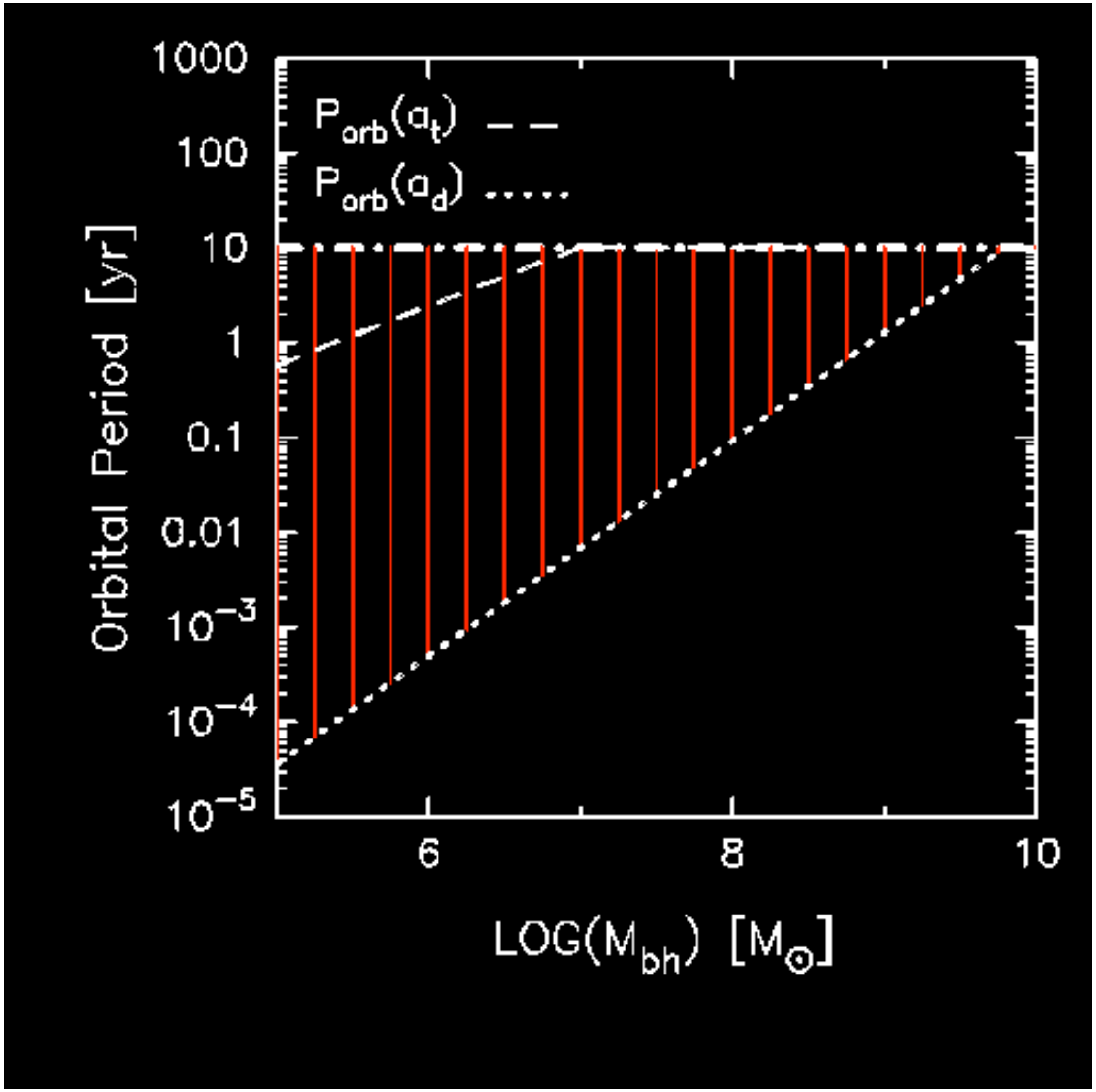
Timescale of the orbital decay



$a_{\rm max}$: Semi-major axis corresponding to the orbital period of 10 yr

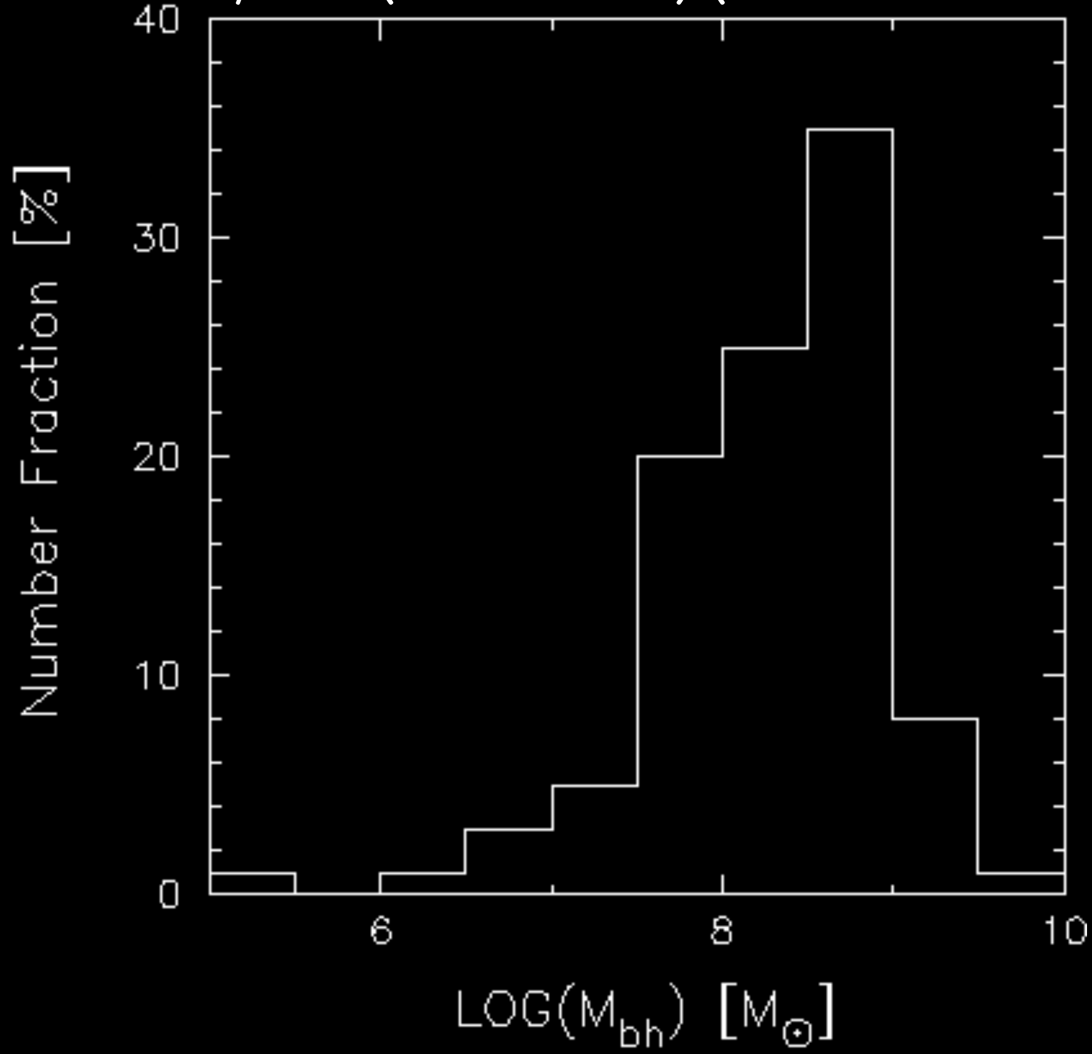
$a_{\rm d}$: the radius where the binary decouple with

Mass dependence of the orbital period



Mass Function of AGNs

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



Probability for finding binary BHs

$N_{\rm b}$: The number of binary BHs

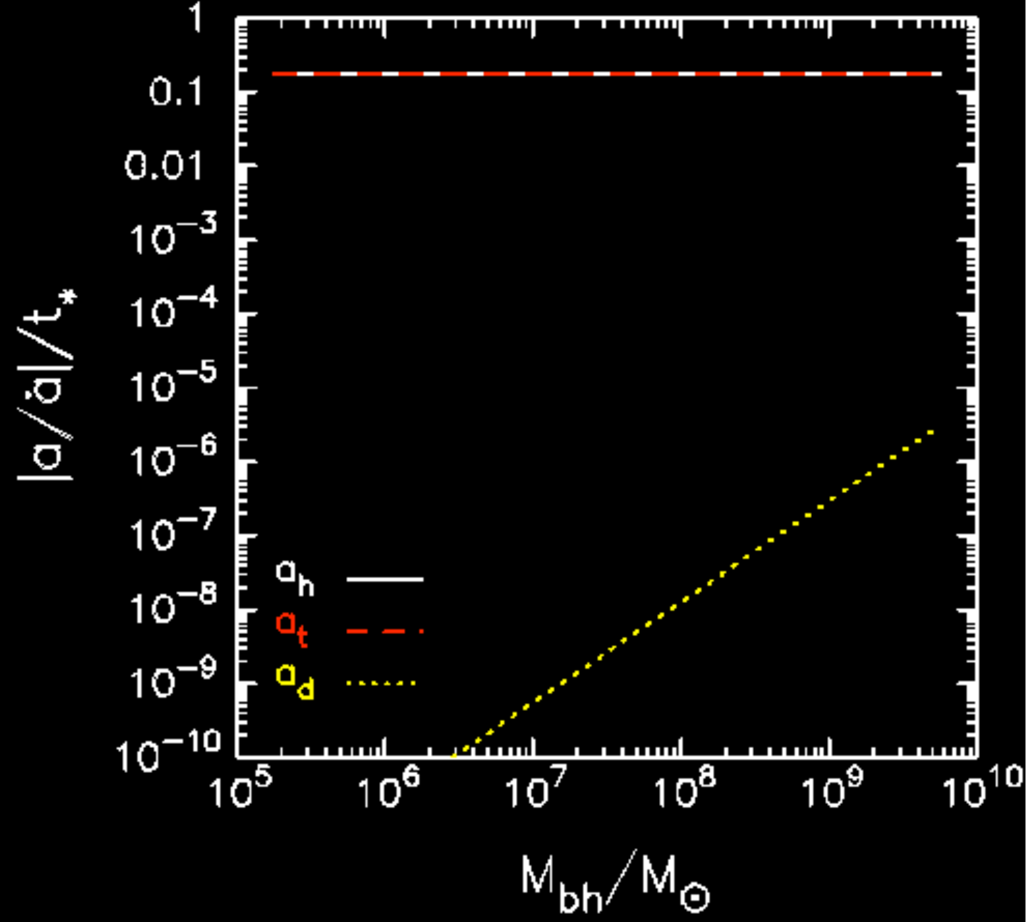
$N_{\rm AGN}$: The number of AGNs

$f_{\rm b}$: Probability for finding binary BHs

$$f_{\rm b} = |a/\dot{a}|/t_*$$

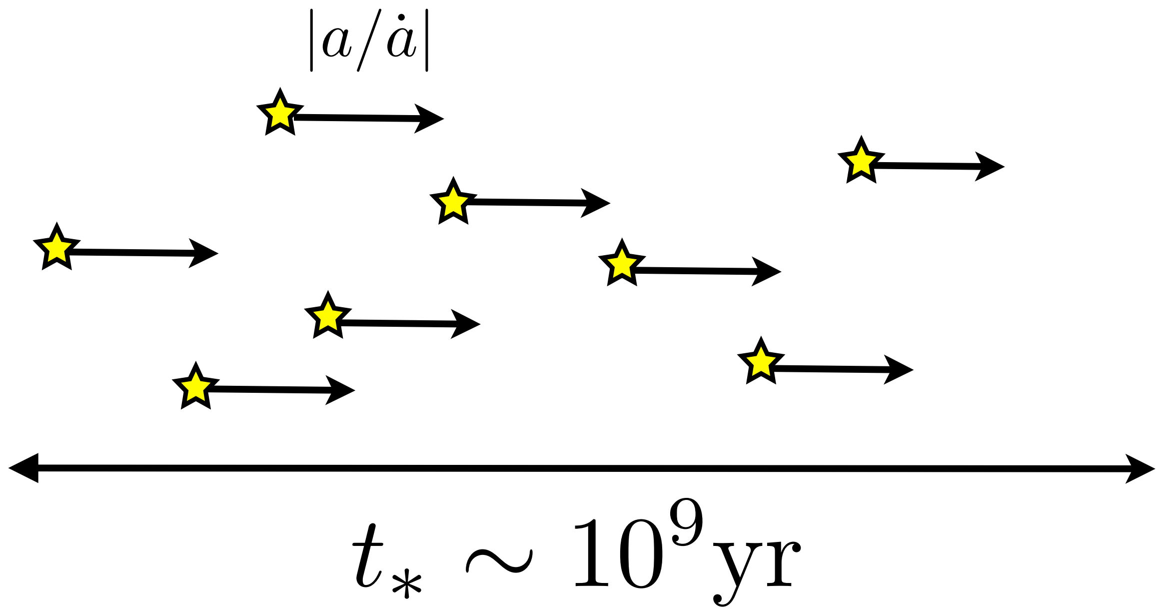
$$N_{\rm b} = f_{\rm b} N_{\rm AGN}$$

$f_{\rm b} =$



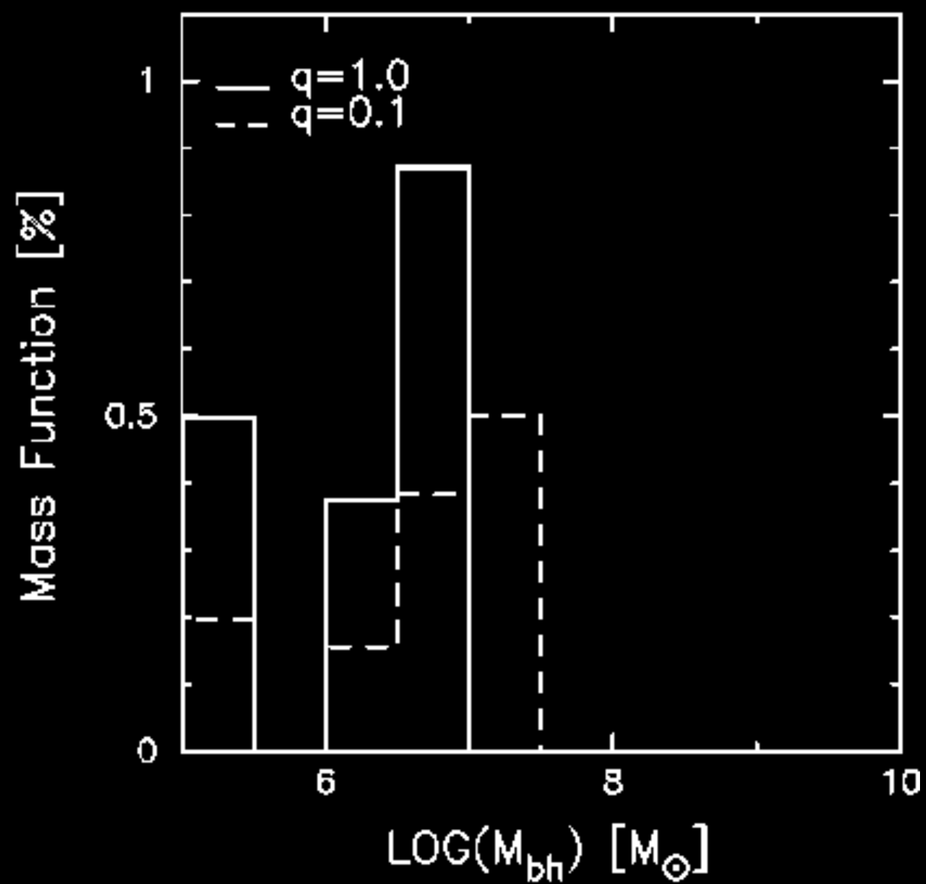
Probability for finding binary BHs II

★ : Starting point of major galaxy merger



$$f_{\mathrm{b}} = |a/\dot{a}|/t_* \qquad t_* > |a/\dot{a}|$$

Mass function of binary BHs



Prediction 2: 1.3%-1.7% of nearby AGNs are close binaries with orbital period less than 10 years.

Summary.

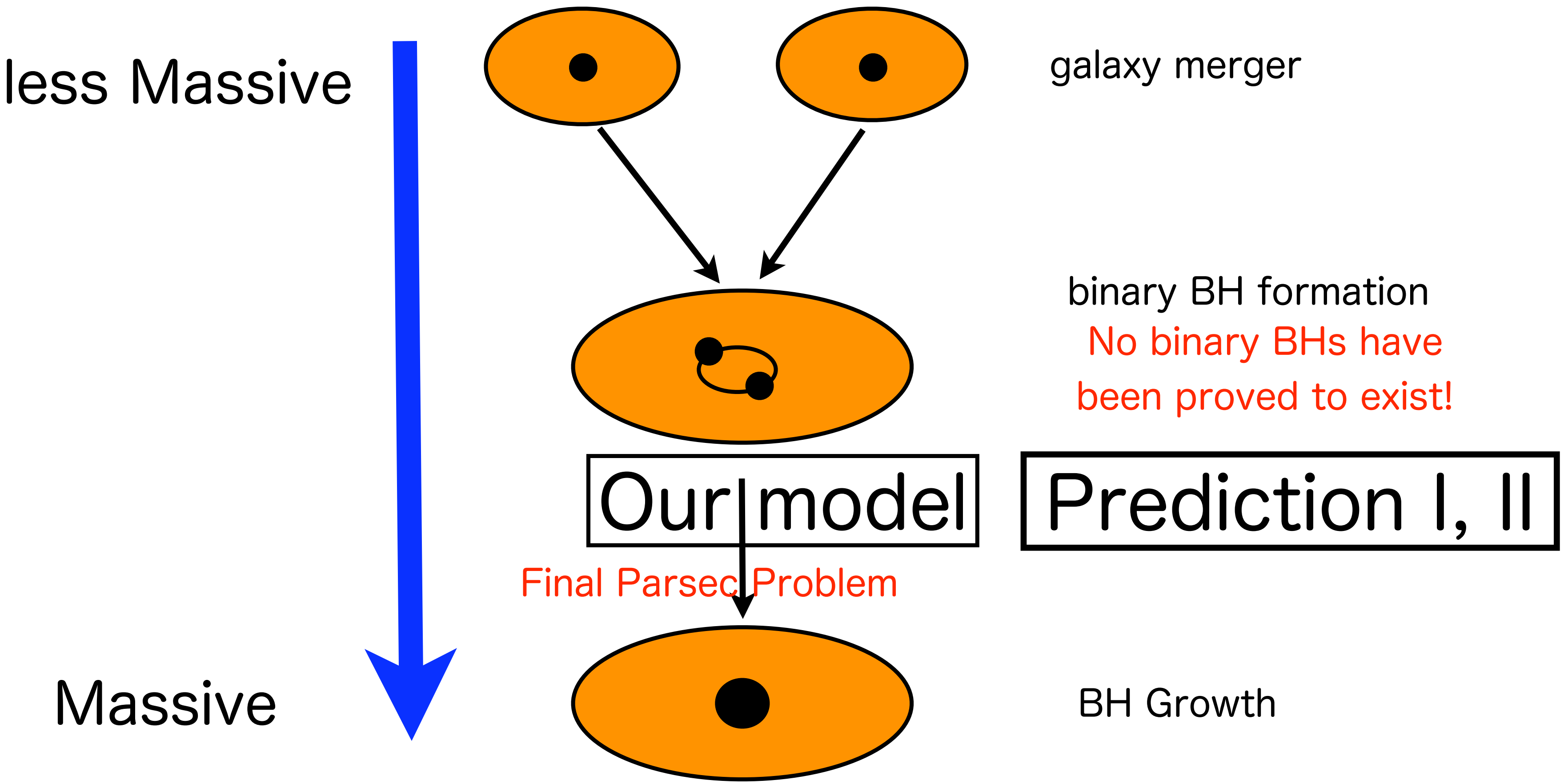
1. The accretion disks are formed around the binary massive BHs by the mass transfer from the circumbinary disk. Then, a binary BH system has a triple disk (two accretion disks and circumbinary disk around them).

2. The UV/X-ray light curve from the disks shows the significant variation with the binary orbit, whereas the optical and inferred one exhibit little variation

3. Binary massive black holes can merge within a Hubble time by the interaction with the triple disk.

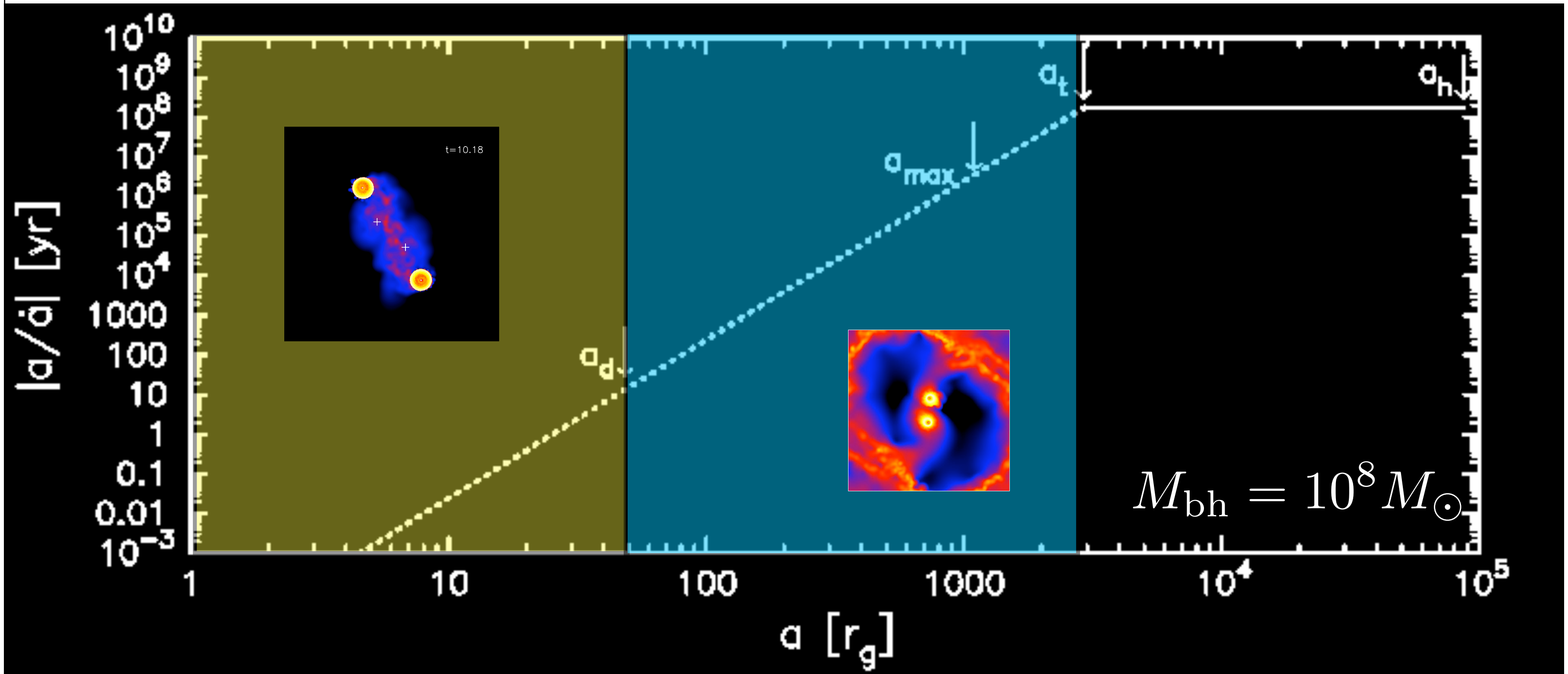
4. 1.3%-1.7% of nearby AGNs have close binaries in their centers.

Hierarchical Structure Formation



Probing close binary BHs is the key to understand this scenario.

議論 1



相対論的取り扱いが必要な領域

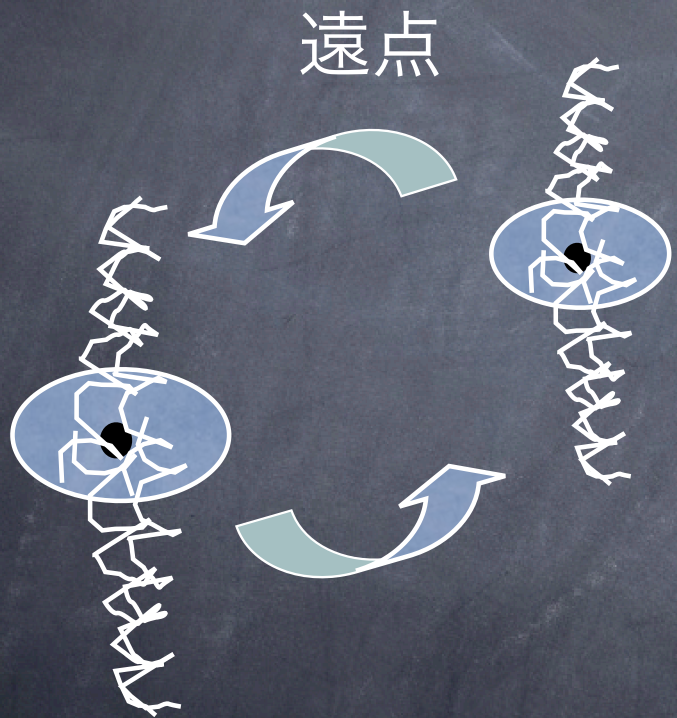
議論２

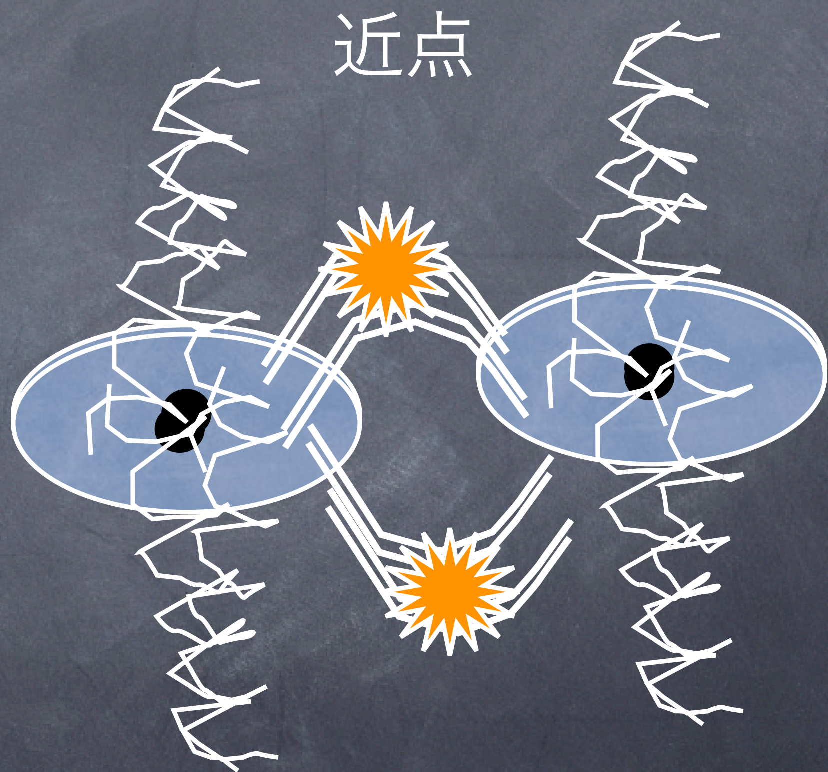
- 三重円盤モデルでどれだけのスピンが得られるか。
- ブラックホール合体時の反跳
- BZプロセス

バイナリーBHスピン進化

議論3

1.disk-disk reconnection





バイナリーBH磁気圏?!というか磁場

将来の課題

ガスとの相互作用で進化するバイナリーBHの文脈で。

- バイナリーBH探査（X/UV線、電波、光・赤外、γ線も？）
- 磁場との相互作用（BZプロセス、磁気流体）。
- 相対論的取り扱い（円盤モデル）。

Future works

- To find close binary black-hole candidates in collaboration with MAXI and identify them as sources of gravitational wave. [theoretical support for the observation].
- Resolution of close binary BHs with submm-VLBI and VSOP2. [theoretical support for the observation]
- Origin of massive black holes (Growth rate, Spin evolution, etc...)[theory]

Acknowledgment

- Supervisors/Ex-supervisors and Advisers

  Atsuo T. Okazaki, Katsuhiko Inagaki, Koukichi Konno, Masayuki Y. Fujimoto, Noboru Kaneko, Satoshi Tanda, Shin Mineshige,Yasuhiro Asano

- Collaborators

  Akiko Kawachi, Atsuo T. Okazaki, Hiroshi Sudou, Luis C. Ho, Keitaro Takahashi, Naoki Isobe, Shigehiro Nagataki, Shin Mineshige, Takahiro Tanaka, Tsuguya Naito, Yoshihiro Ueda, Yuuiti Sendouda

Thank you for your attention.