潮汐破壊事象及びバイナリーブラックホールにおける降着円盤形成

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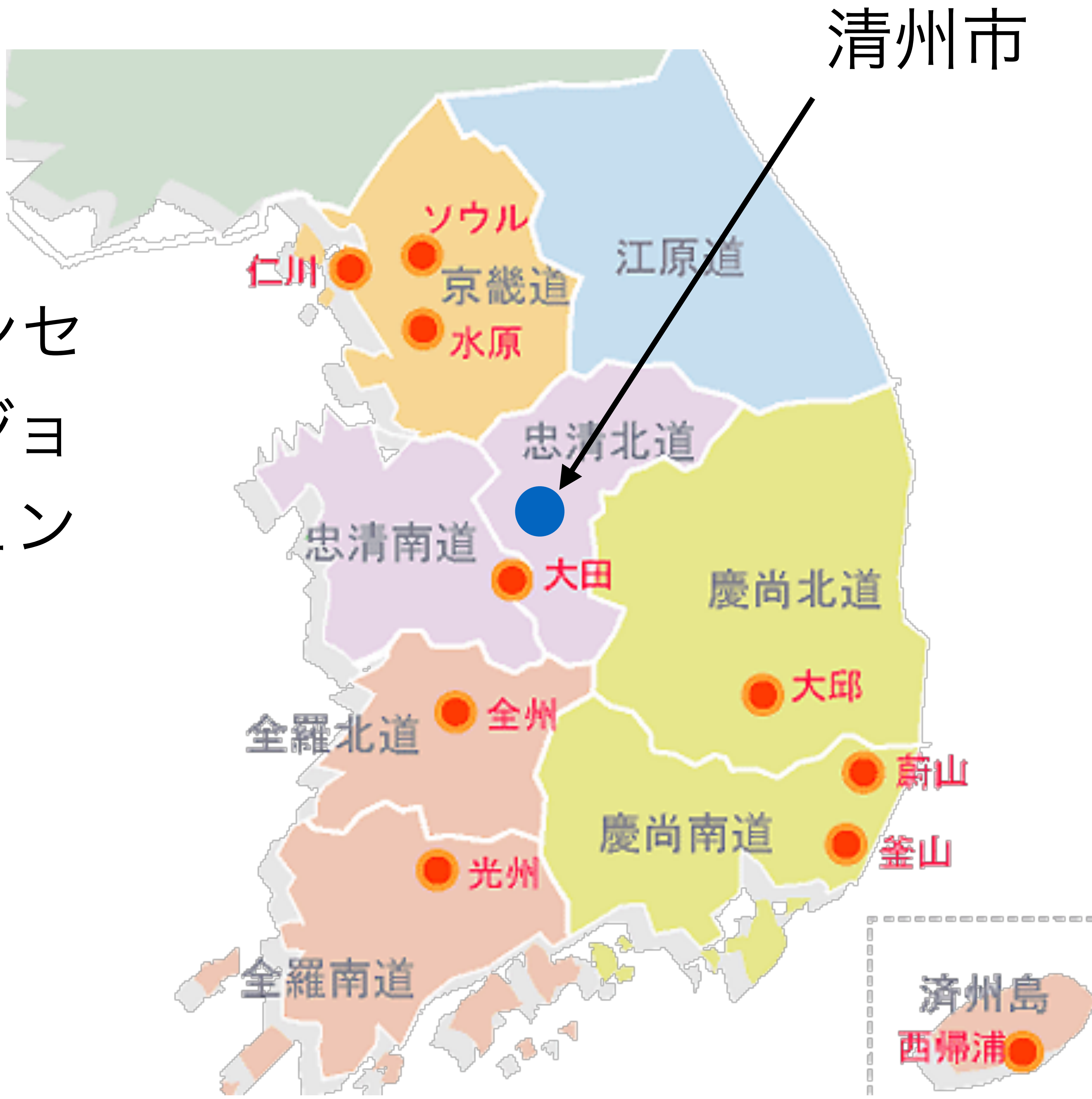
韓国の天文・宇宙物理学研究機関

1. ７大学（ソウル、ヨンセイ、キョンヒー、セジョン、**チュンブク**、チュンナム、ジョンボク）

2. KASI, KIAS, APCTP, and IBS

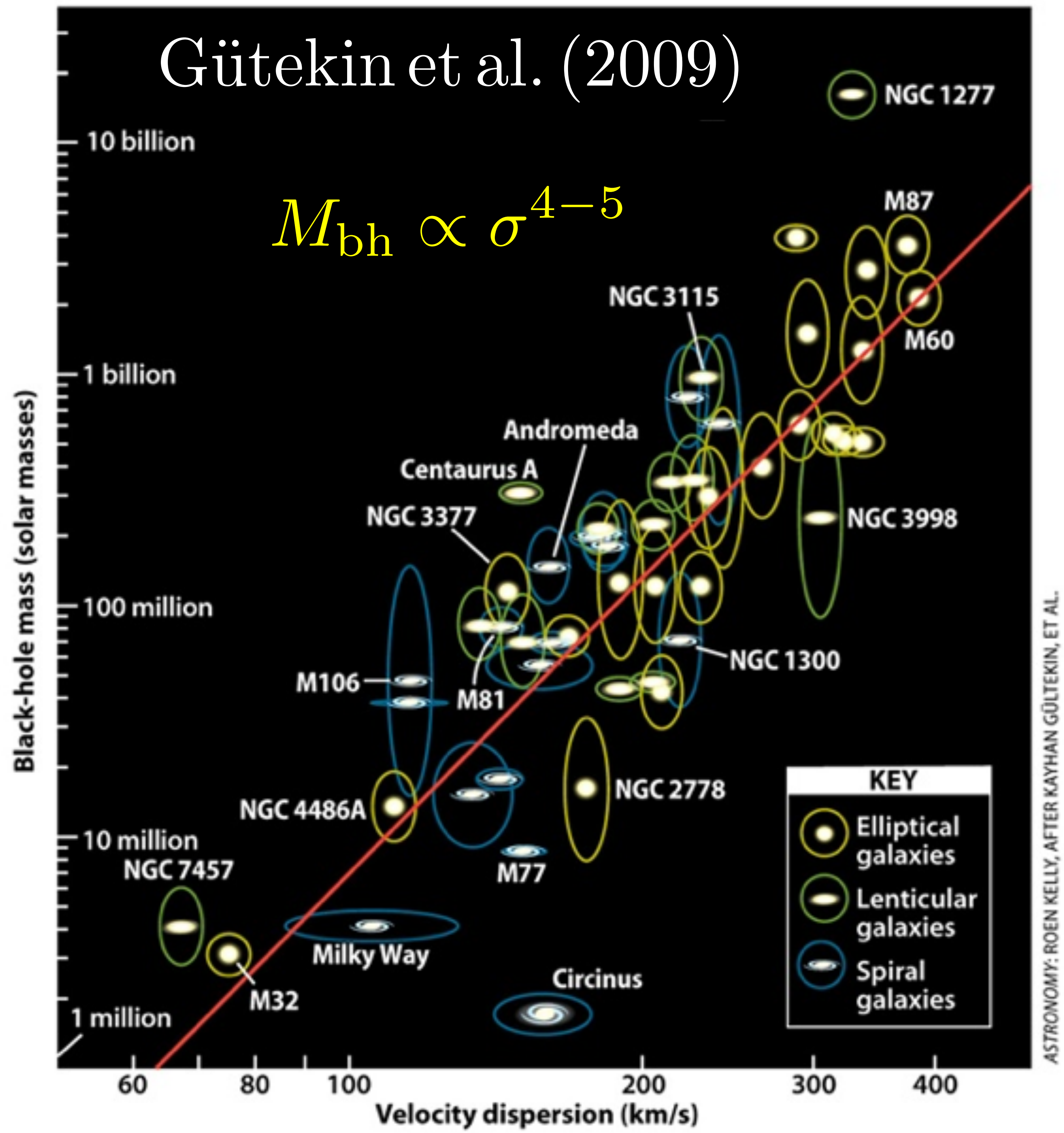


Supermassive black holes

- Supermassive black holes are universal objects located at the center of galactic nuclei

Kormendy & Richstone (1995)

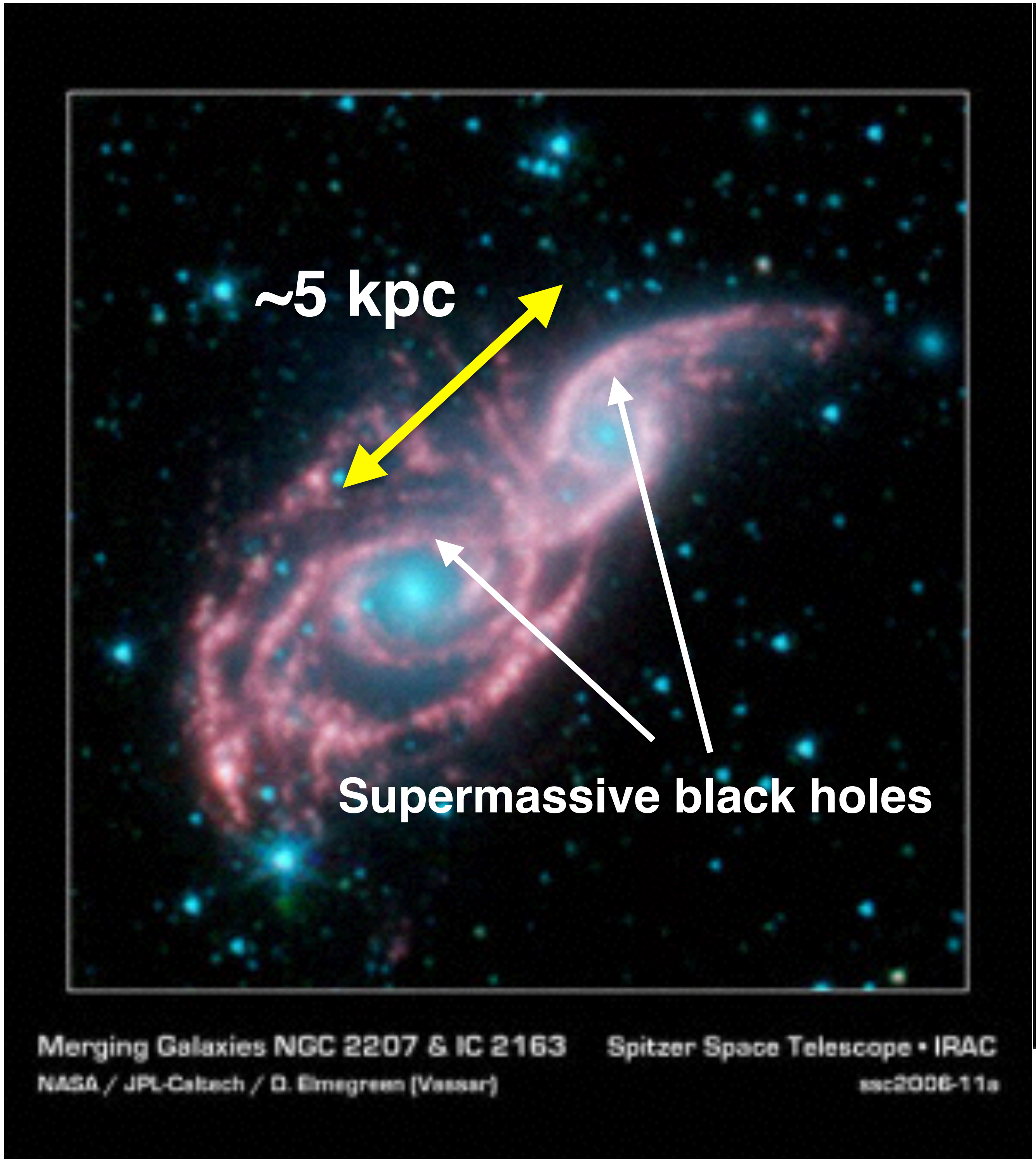
- Black hole mass correlates to the bulge mass (stellar velocity dispersion) or $M_{bh} \sim 0.006 M_{bulge}$ (Maggorian relation) Magorrian et al. (1998)
- There is no correlation in some galaxies.



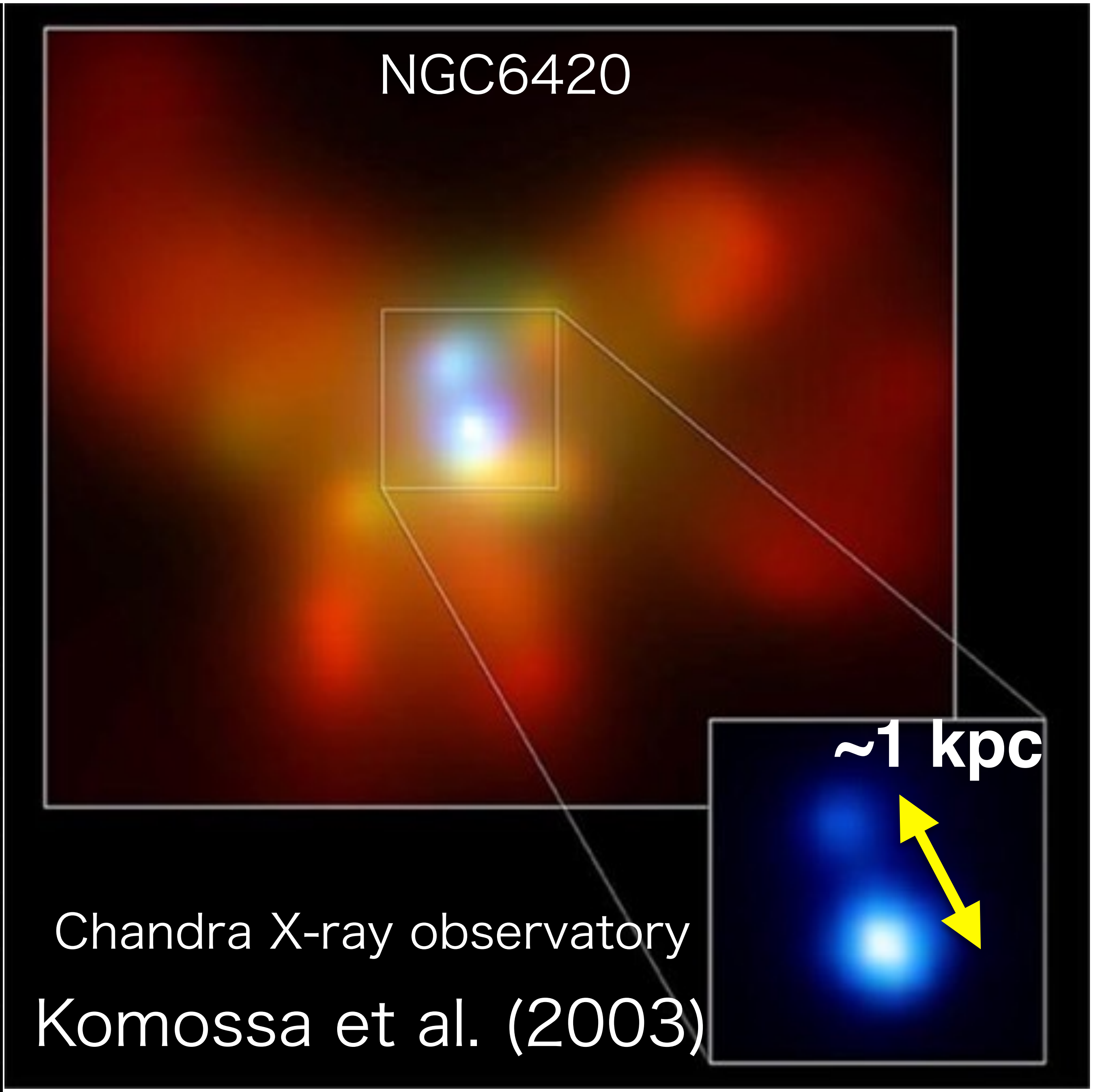
http://www.astronomy.com/News-Observing/Ask%20Astro/2013/07/Supermassive%20black%20holes.aspx

Observational evidence for merging galaxies and binary AGNs

Merging galaxies

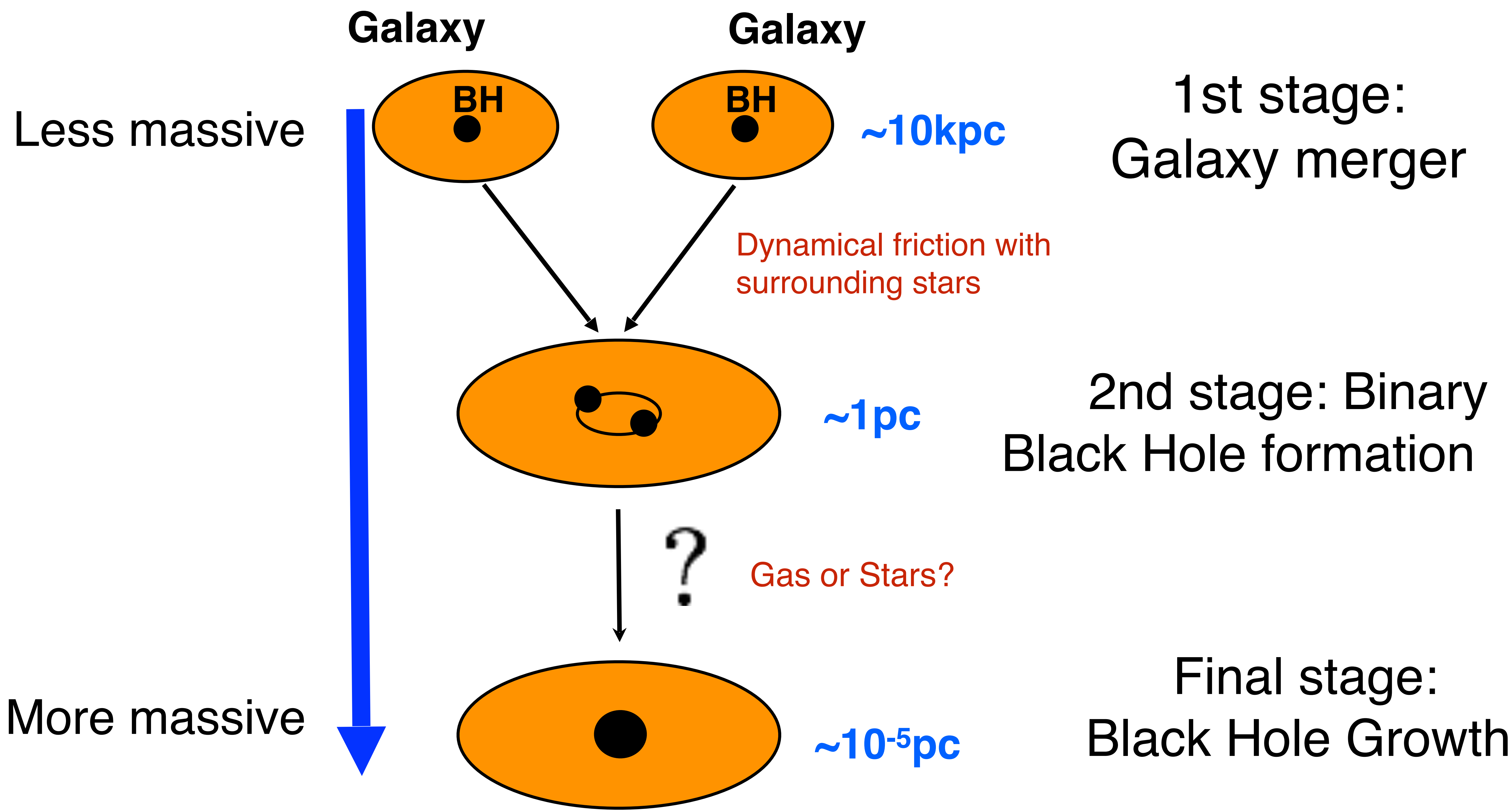


Binary AGNs



http://www2011.mpe.mpg.de

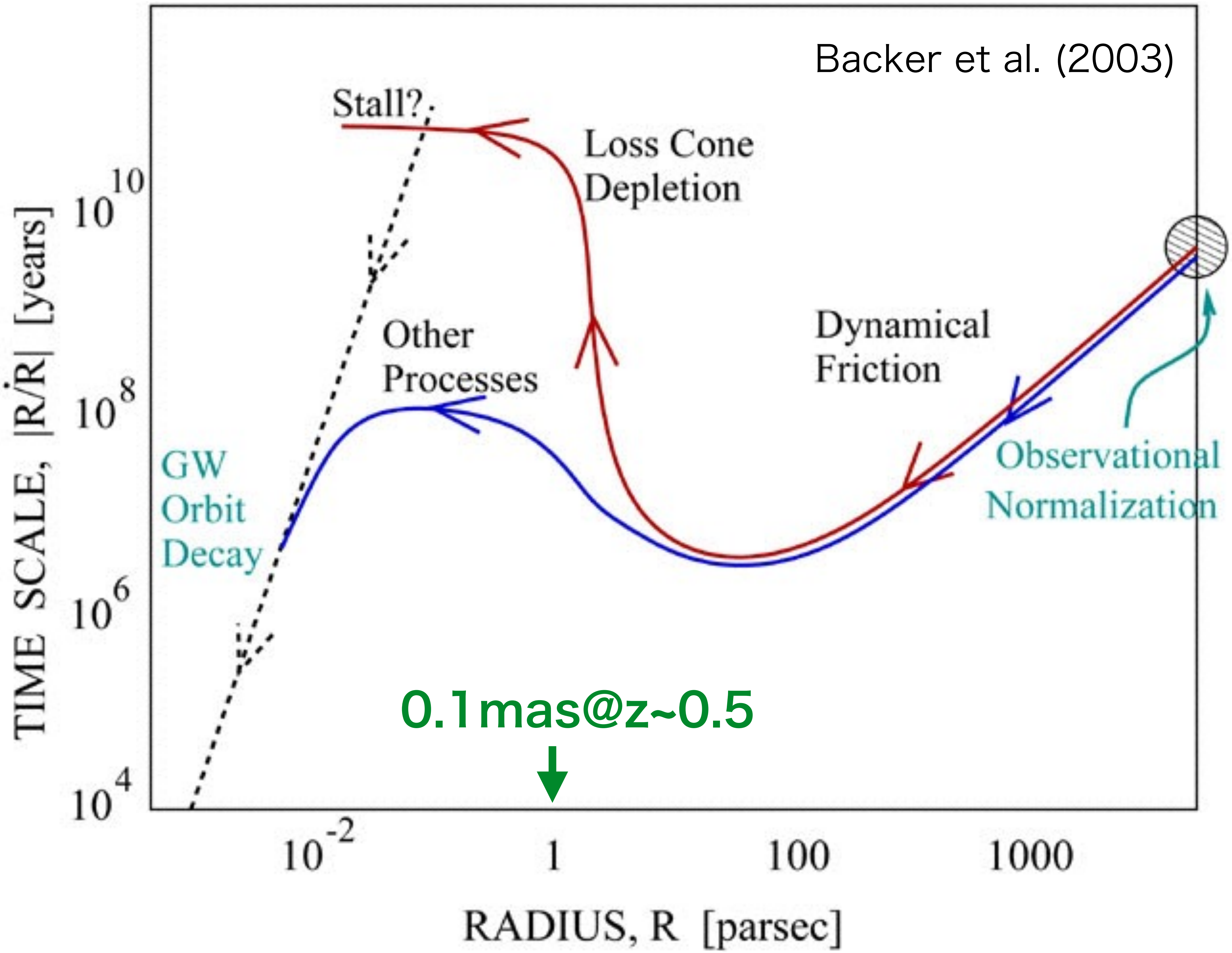
Galaxy to Black Hole Merger

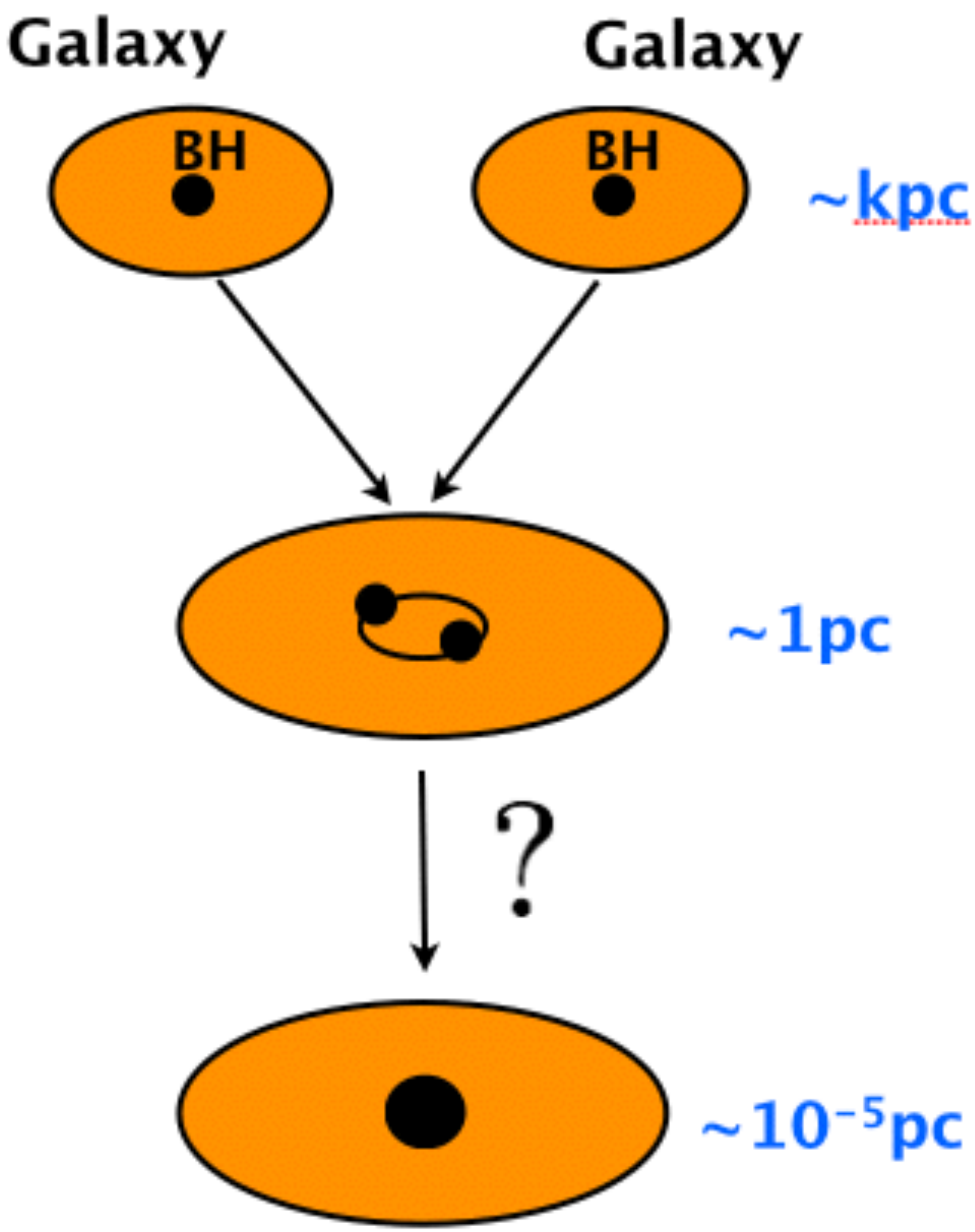


1. **Currently, difficult to observe ~1pc binary black holes**
2. **No simple mechanism for ~1pc binary black holes to merge**

Current picture of binary SMBH evolution

Begelman, Blandford & Rees (1980)

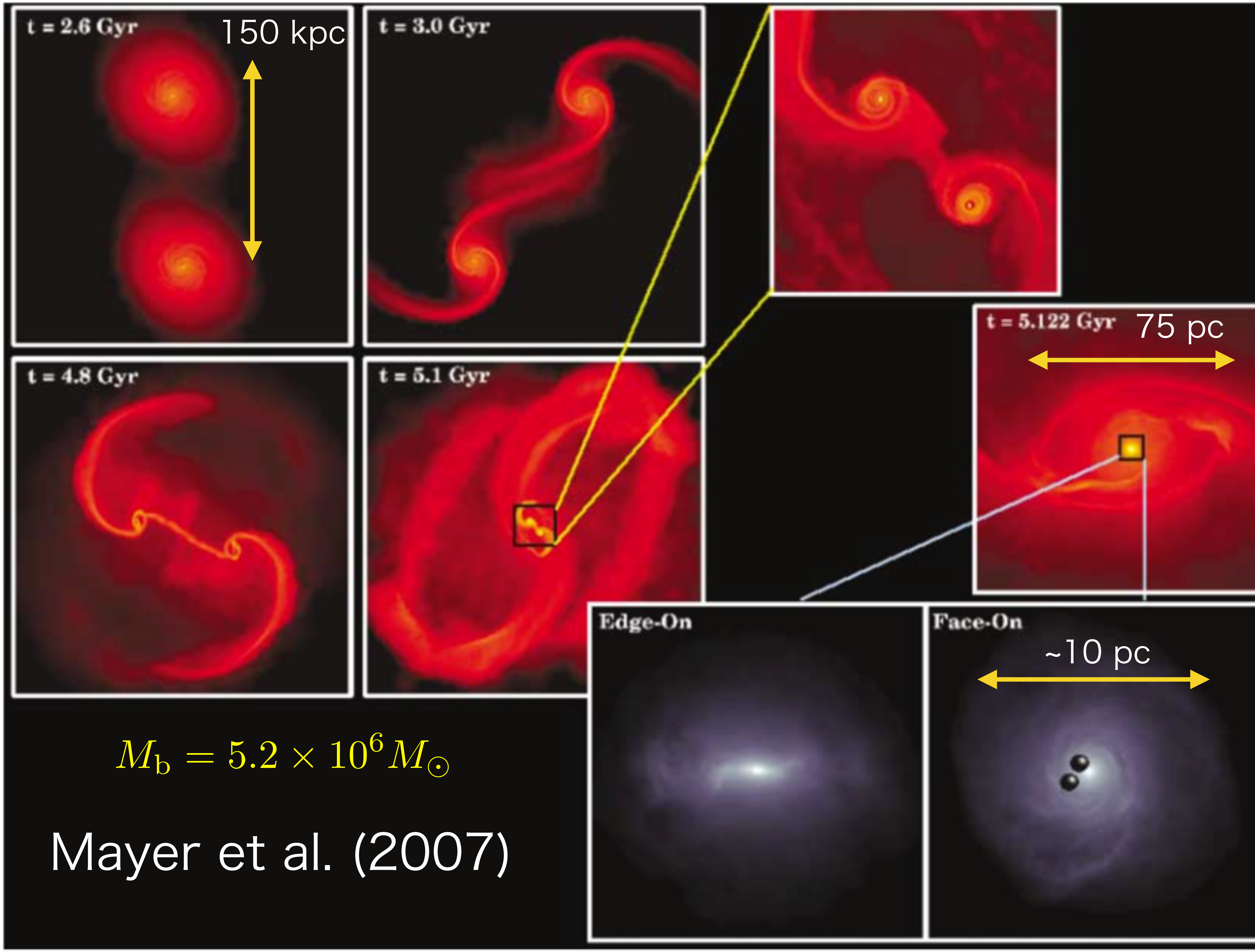




Formation of binary and surrounding nuclear gas disk

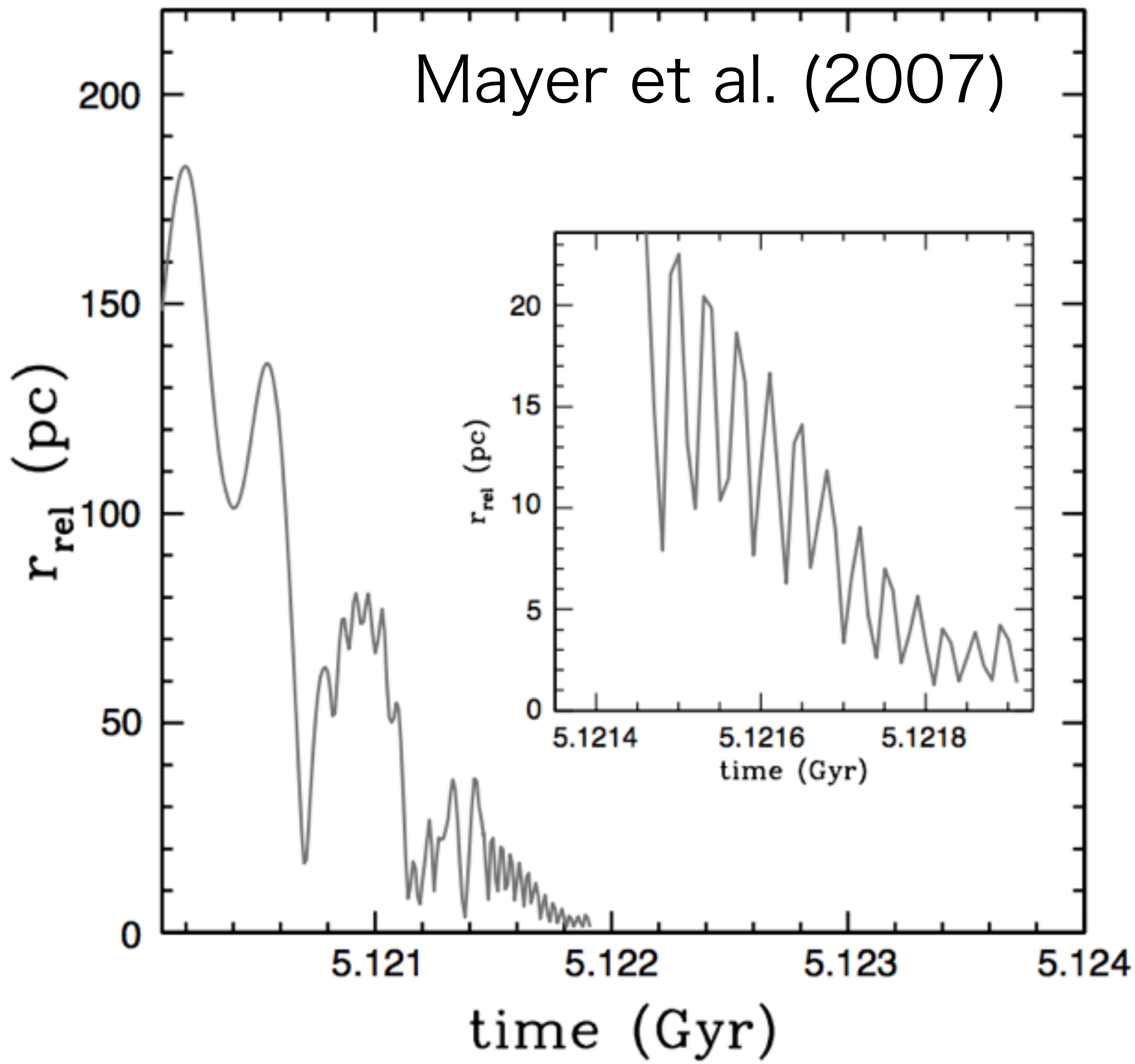
Escala et al. 2005 ;
Mayer et al. (2007);
Dotti et al.(2007);
Chapon et al.(2013)
and more.

Formation of circum-nuclear disk around binary SMBHs

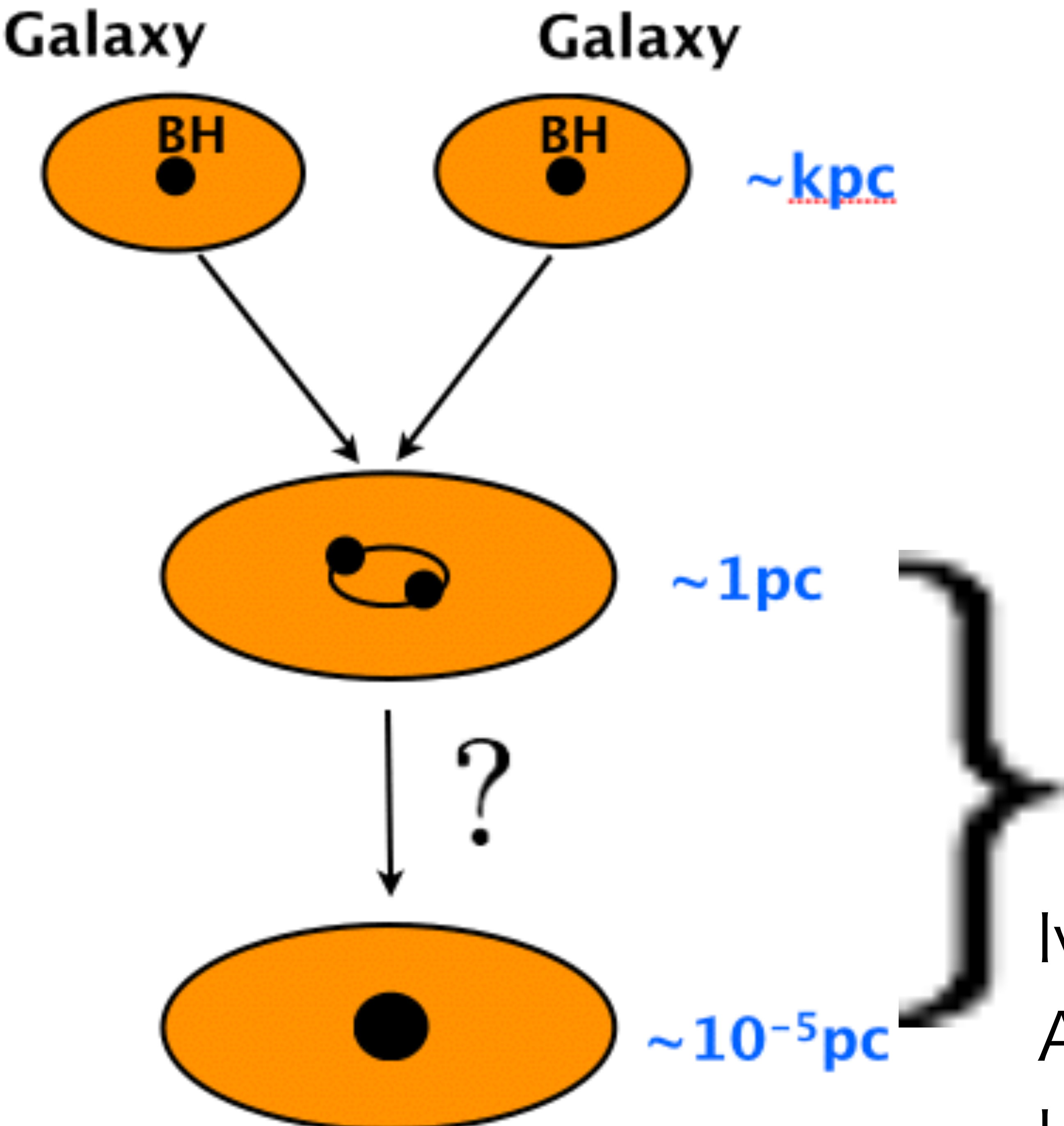


~10 pc scale disk forms around the binary SMBHs

Formation of binary SMBHs inside gas disk



Formation of binary SMBHs on ~1pc scale



Co-evolution of binary and gas disks

Ivanov et al. (1999);
Armitage & Natarayan (02,05);
Hayasaki et al.(07,08); Hayasaki(09);
Cuadra et al.(2009);
Nixon et al. (2013) and more.

Main issues

1. How disks evolve and affect the orbital evolution

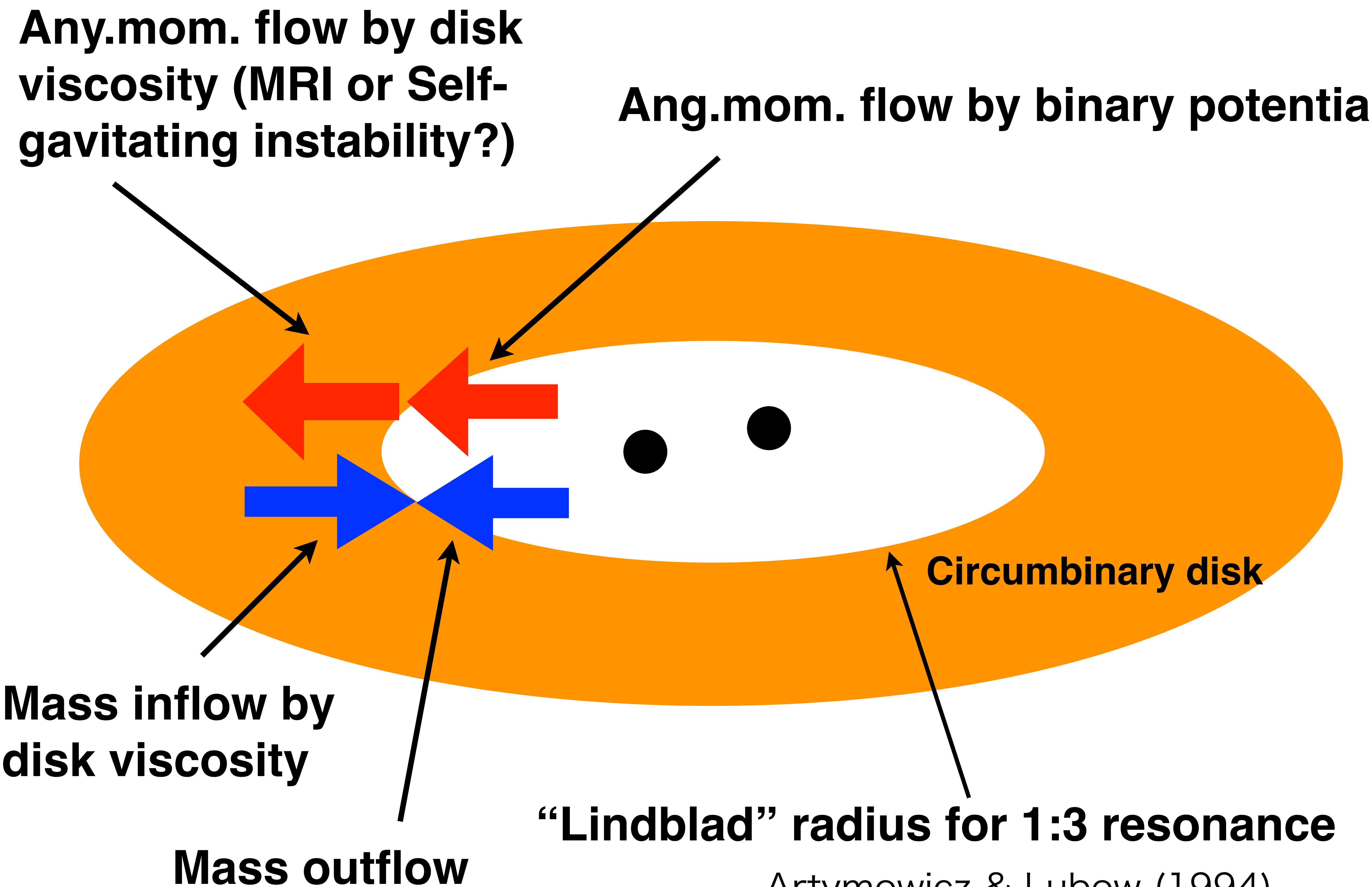
~~2. How disks produce emitted spectrums and light~~

curves

Artymowicz & Lubow (1996); Hayasaki et al.(07,08); Bogdanovi´c et al. 2008; MacFadyen & Milosavljevi´c 2008 ; Farris et al. (2011,2012); Hayasaki et al. (2013), and more.

How different they are from single black hole cases

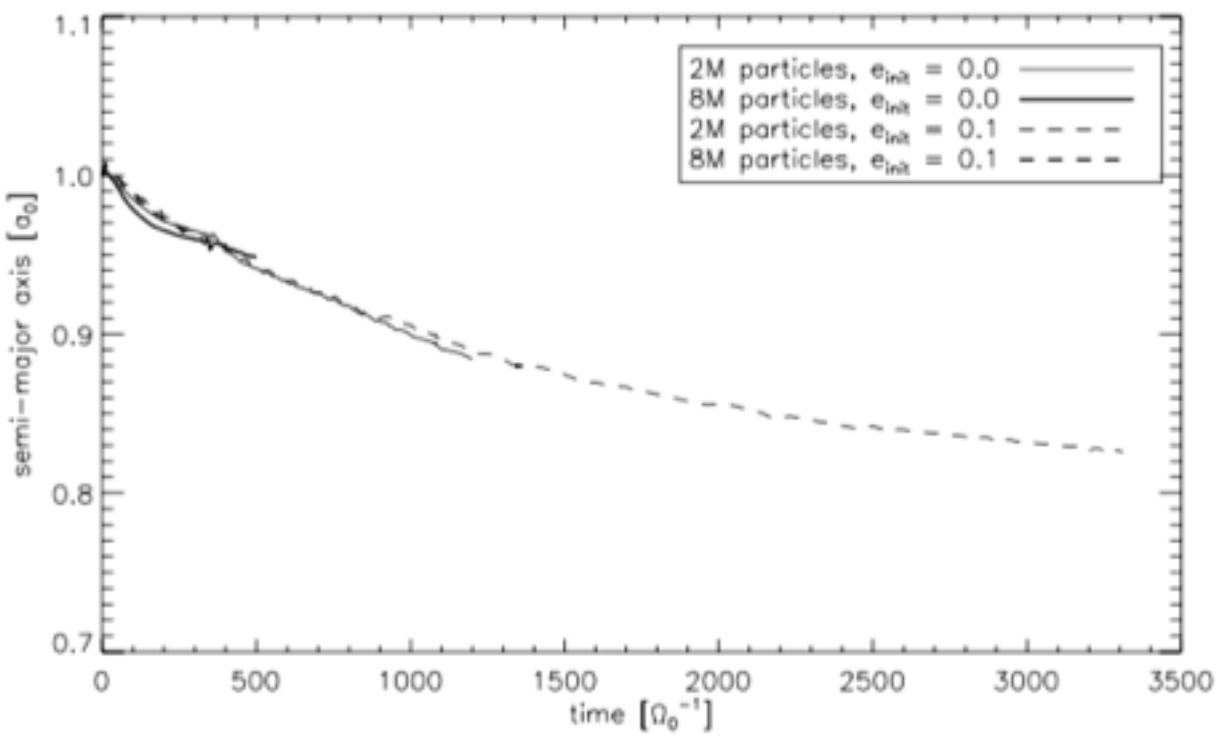
Angular momentum redistribution



Artymowicz & Lubow (1994)

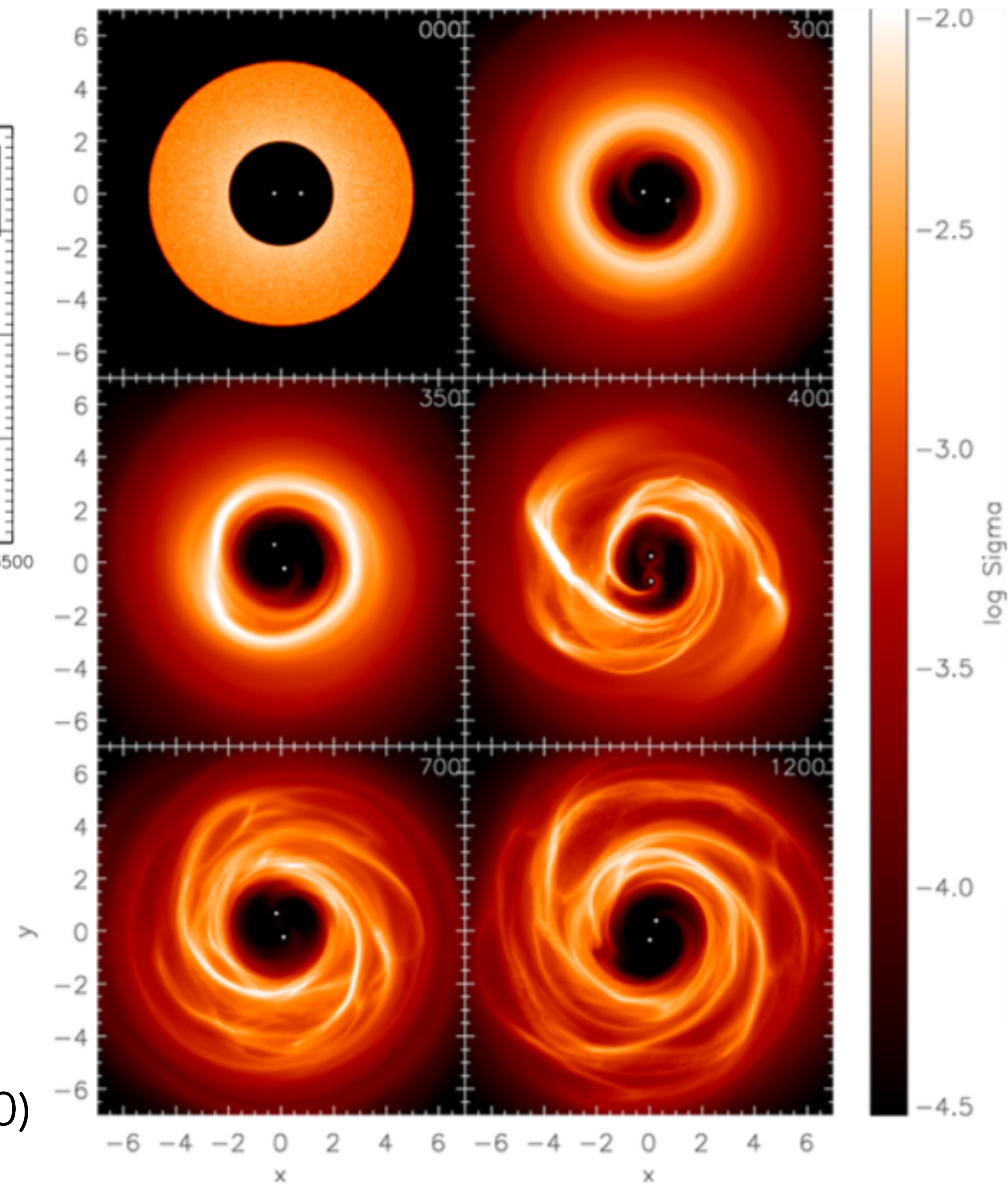
Co-evolution of circumbinary disk and binary

Cuadra et al.(2009)



$$\Omega_0^{-1} = \sqrt{a_0^3/GM}$$

$$t_{\rm disk} \sim 3 \times 10^4\, \Omega_0^{-1}$$



cf. Ivanov et al.(1999);
Hayasaki (09); Hayasaki et al. (2010)

Circumbinary disks:others

1. Circumbinary disk warping and tearing

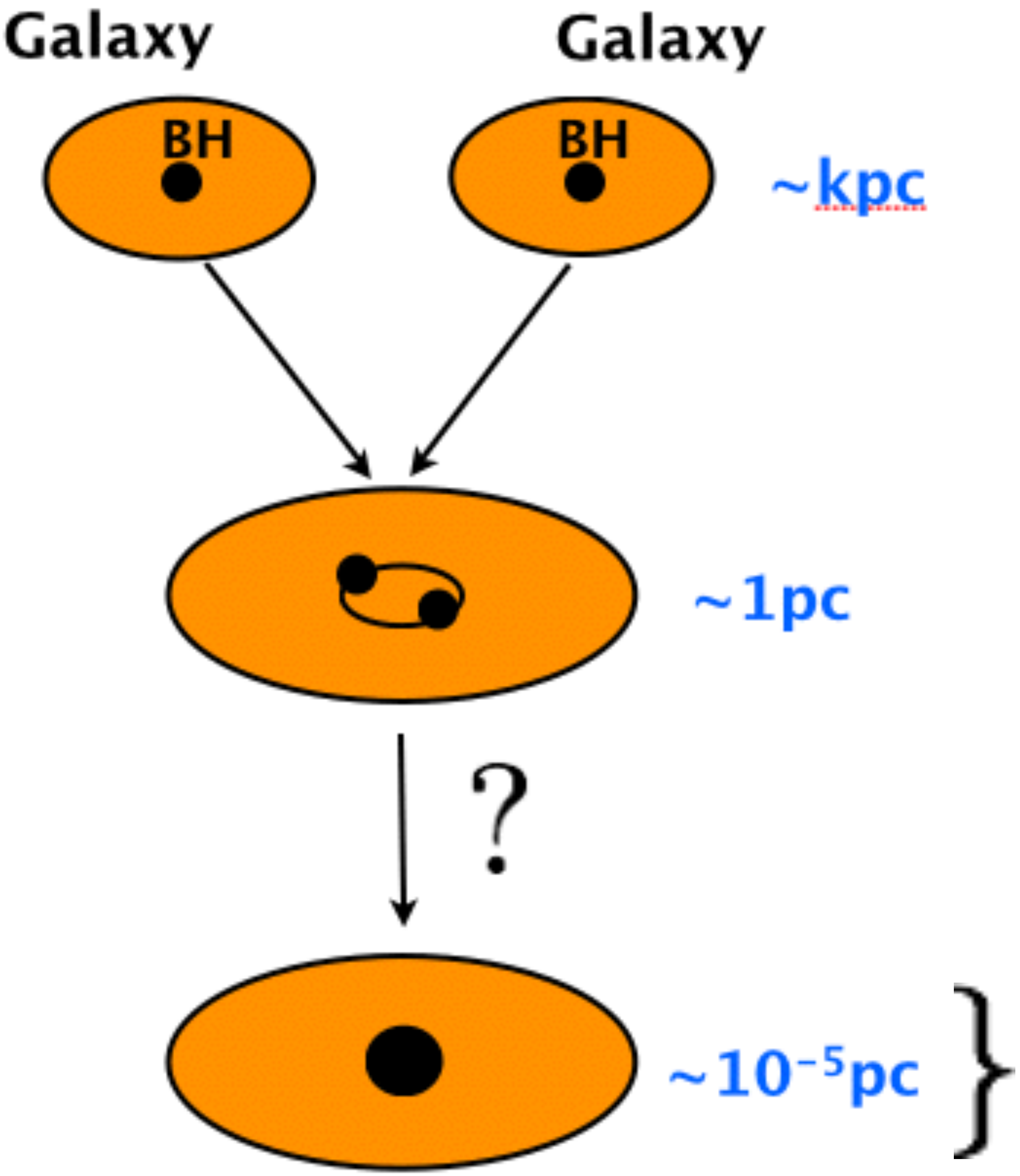
Nixson et al. 2013; Hayasaki et al.(2014a,b); Hayasaki et al.(2015)

2. Another way to form circumbinary disks [Direct disruption of molecular cloud by binary SMBHs]

Dunhill et al. (2014)

3. Afterglow and precursor of black hole merger

(Milosavljevi´c & Phinney 2005; Tanaka & Menou 2010



Tidal Disruption Events

Scientific motivations for TDEs

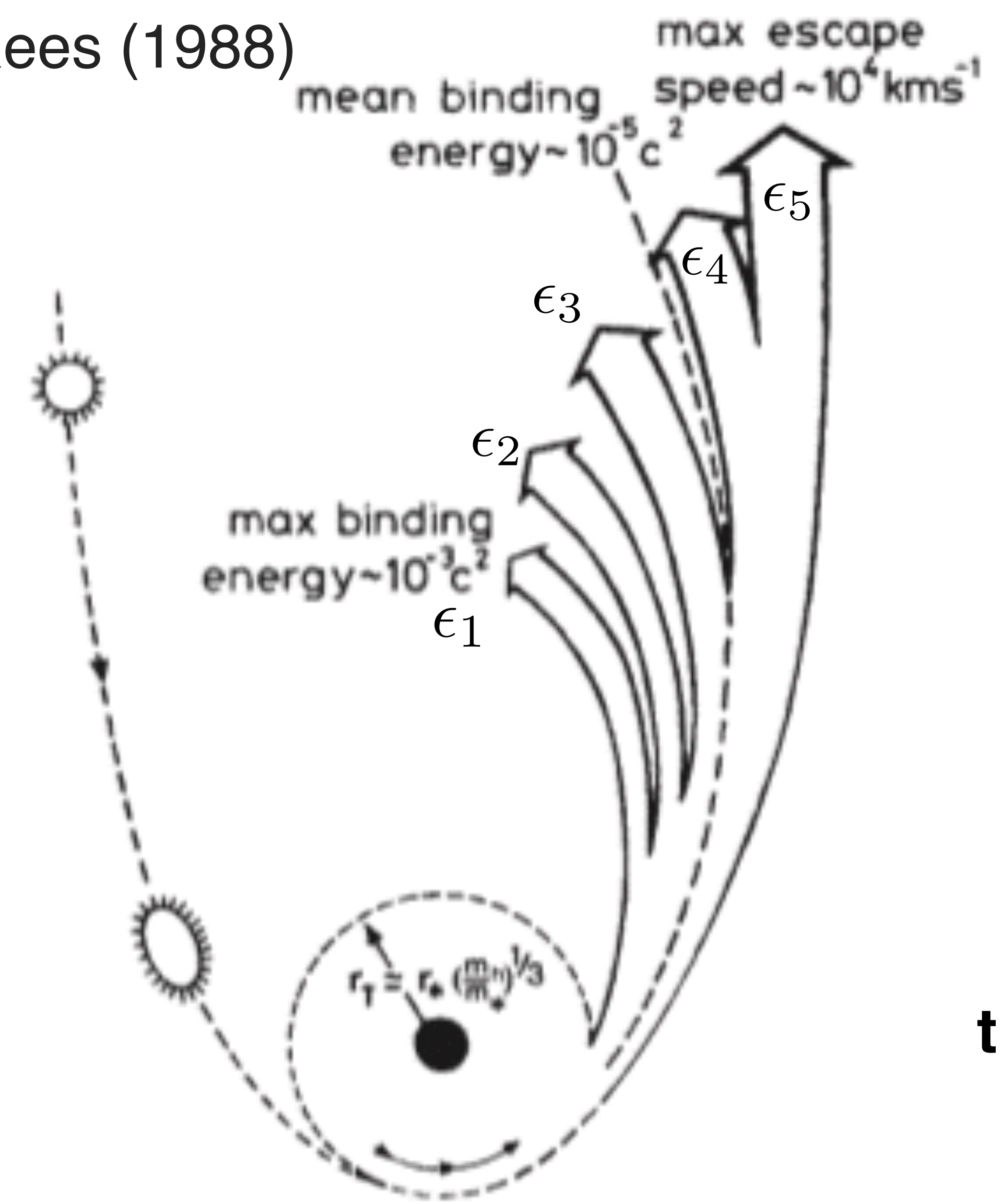
1. Probe of quiescent supermassive black holes
2. Contribution to black hole growth (tidal disruption rate)
3. Laboratory for super-Eddington accretion/Jet physics
4. Candidates for gravitational wave sources

Good phenomena for multi-messenger astronomy

Tidal Disruption of star by SMBH

TDE Standard Picture

Rees (1988)



Tidal disruption radius (Tidal force=self-gravity force):

$$r_{\rm t} = \left(\frac{M_{\rm BH}}{m_*}\right)^{1/3} r_*$$

Δε: Spread in debris energy by tidal force

$$\Delta\epsilon = \frac{GM_{\rm BH}}{r_{\rm t}} \frac{r_*}{r_{\rm t}}$$

ε: Debris specific energy

if ε>=0	Stellar debris flies away from the black hole
if ε< 0	Stellar debris is bounded by the black hole's gravity and falls back to black hole

t: Fallback time for most tightly bound debris

$$t_{\rm fall} \sim 0.1\,{\rm yr} \left(\frac{r_*}{R_\odot}\right)^{3/2} \left(\frac{m_*}{M_\odot}\right)^{-1} \left(\frac{M_{\rm BH}}{10^6 M_\odot}\right)^{1/2}$$

Current major problem is how accretion disk is formed

Accretion Disk Formation

There are arguments whether/how an accretion disk is formed around the black hole after stellar debris falls back (Rees 1988, Cannizzo 1990, Kochenck 1994, and more): What causes strong shock to thermalize debris orbital energy, leading to debris circularization?

1. Tidal compression at the periastron (Carter & Luminet 1982; Ramirez-Ruiz & Rosswog 2009; Guillochon et al. 2013, and more)

2. **Debris crossings due to relativistic perihelion shift (Rees 1988; Hayasaki et al.2013; Hayasaki et at. 2015, Bonnerot et al. 2015)**

GR Effects (Schwarzschild space-time)

Hayasaki et al.(2013)

- **Why do we consider GR effects?**

Apsidal GR precession is strong for small periastron distances.

We expect that it can cause the orbital crossing of the stellar debris.

- **How do we model GR effects?**

For simple GR treatment, pseudo Newtonian potentials are incorporated into the SPH code.

Wegg (2012):

$$U(r) = c_1 \frac{GM_{\rm BH}}{r} - \frac{(1-c_1)GM_{\rm BH}}{r - c_2 r_{\rm g}} - \frac{c_3 GM_{\rm BH}}{r}\frac{r_{\rm g}}{r}$$

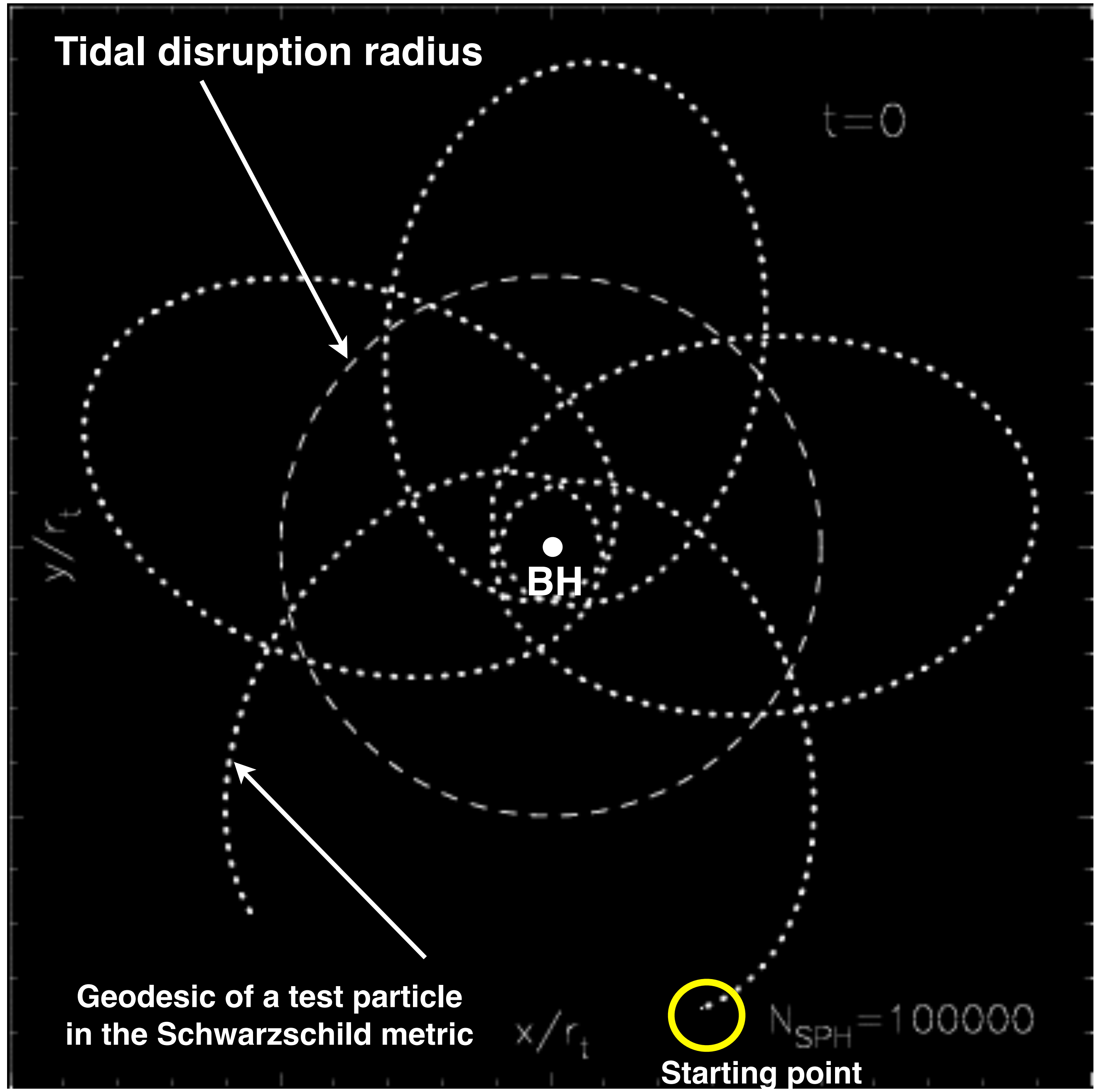
where $c1=-(4/3)(2+6^{1/2})$, $c2=4*6^{1/2}-9$, $c3=-(4/3)(2*6^{1/2}-3)$

Newtonian if c1=1, c2=c3=0 : Paczynski-Wiita PN if c1=c3=0, c2=1

We modeled only GR precession effect by incorporating pseudo-Newtonian potential (Wegg 2012) into SPH.

Newtonian potential simulation (e=0.8, β=5)

- Dotted line shows the geodesic of a test particle
- Dashed circle shows the tidal disruption radius
- Central point represents the black hole



$$\beta = \frac{r_{\rm t}}{r_{\rm p}}$$

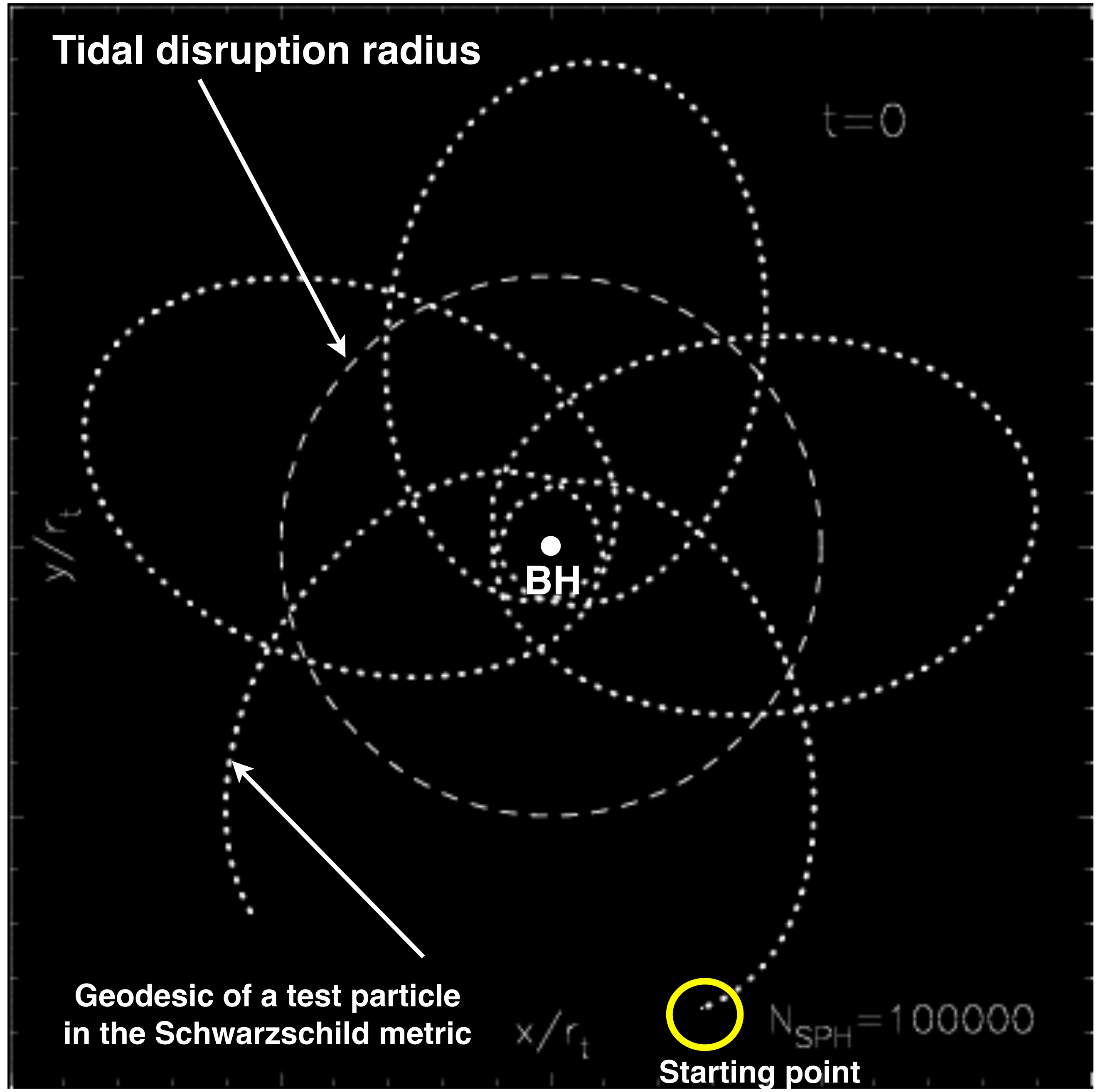
Stellar debris orbits around the black hole, following the Keplerian third law

Pseudo-newtonian potential simulation (e=0.8,β=5)

•Dotted line shows the geodesic of a test particle

•Dashed circle shows the tidal disruption radius

•Central point represents the black hole

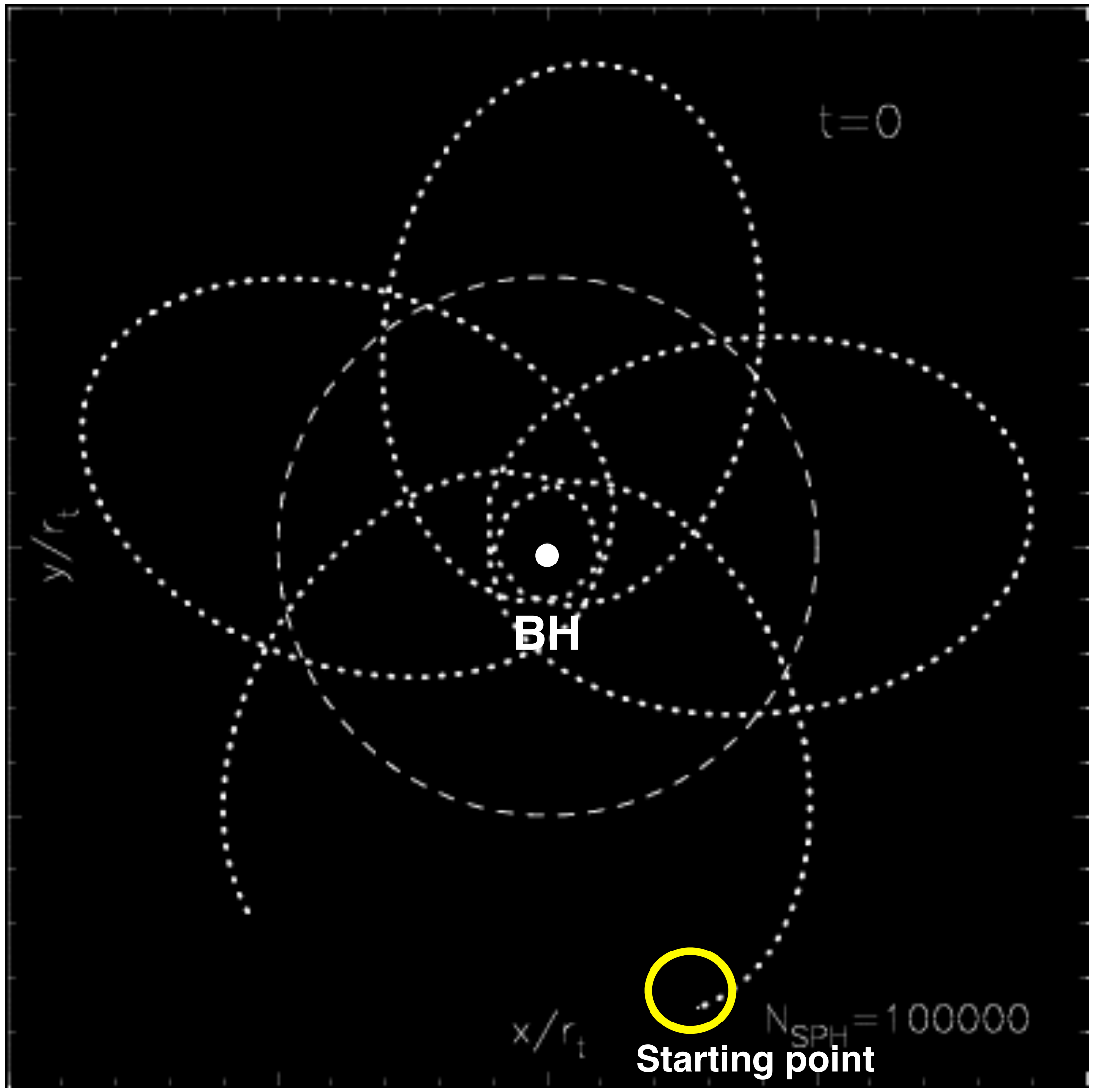


$$\beta = \frac{r_\mathrm{t}}{r_\mathrm{p}}$$

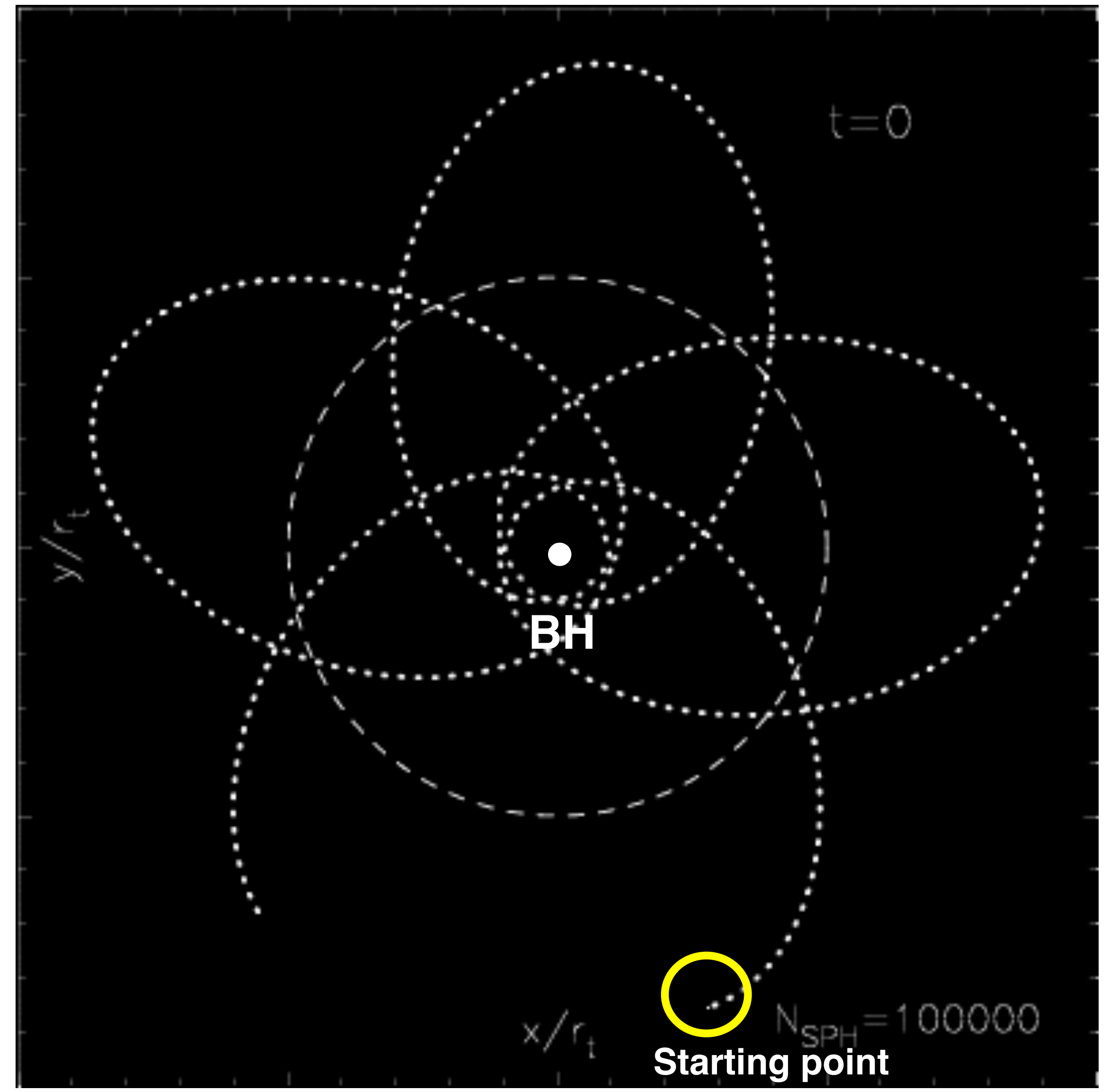
Accretion disk is formed around the black hole due to shock energy dissipation of orbital crossings induced by perihelion shift

Comparison of two animations

Newtonian potential simulation (e=0.8,β=5)



Pseudo-Newtonian potential simulation (e=0.8,β=5)

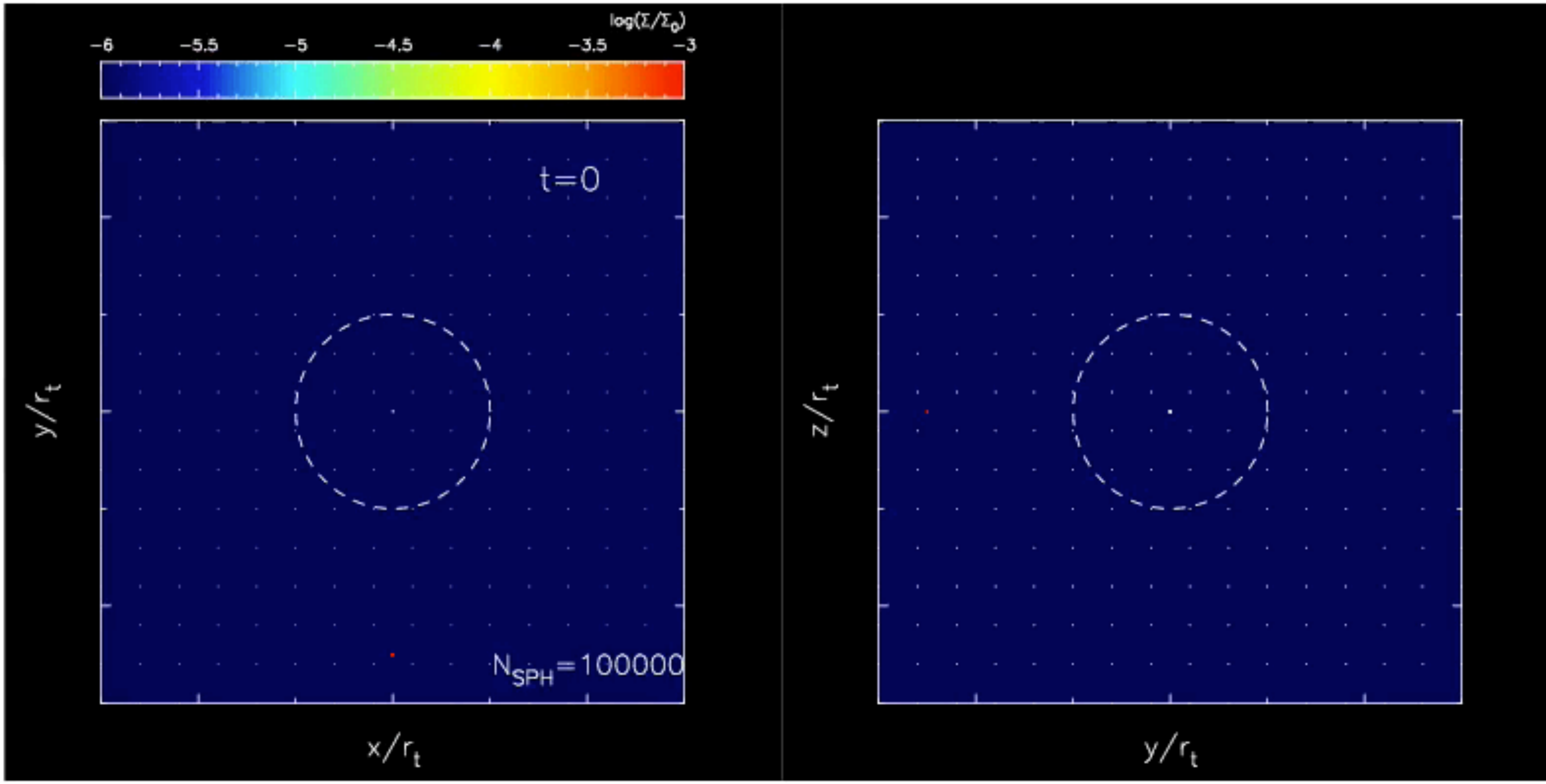


General relativistic precession plays a crucial role in the accretion disk formation around supermassive black hole

Effect of Black Hole Spin on Disk Formation

Hayasaki, Stone, & Loeb (2015, arXiv:1501.05207)

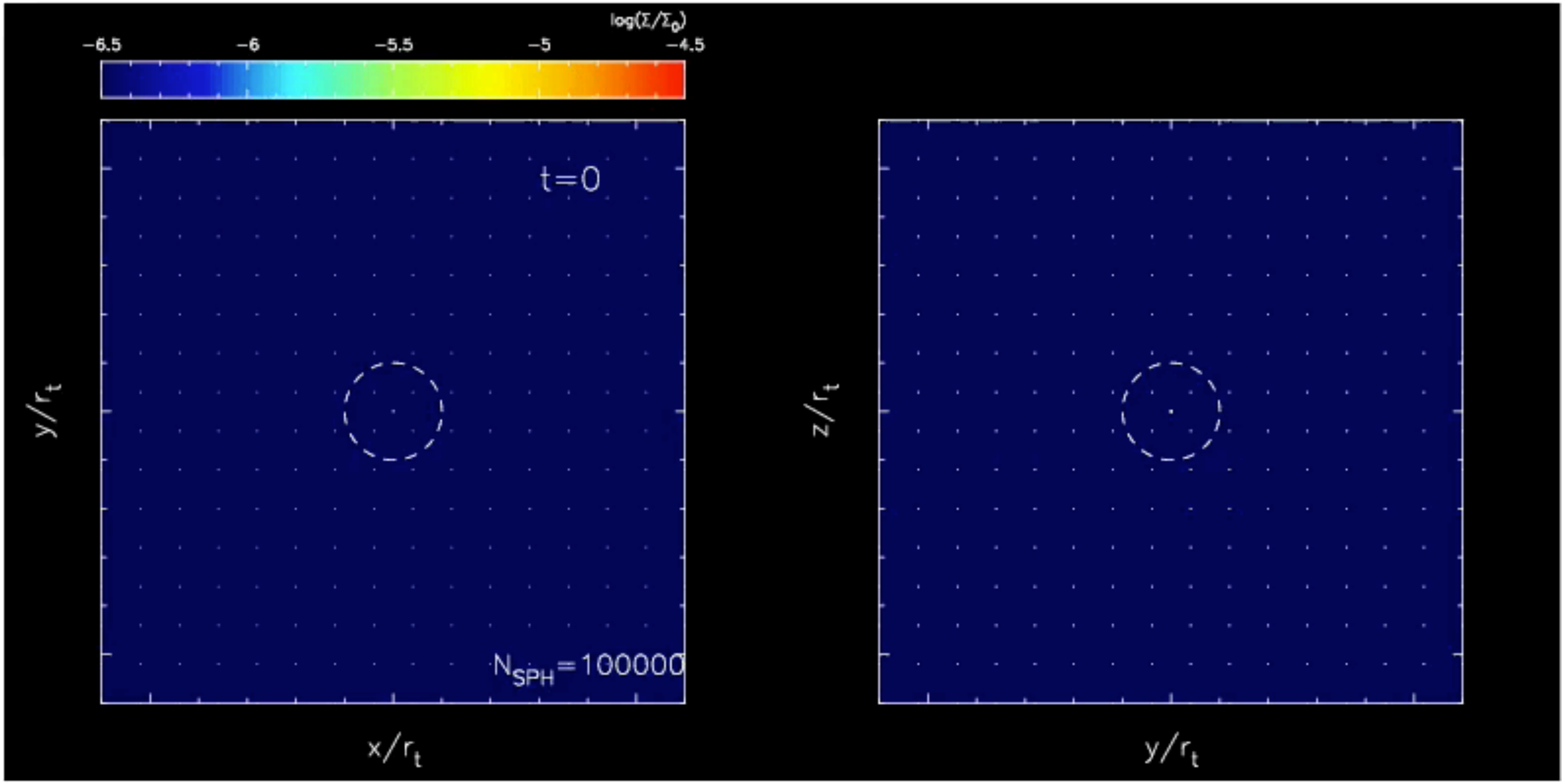
SPH Simulations with Post-Newtonian corrections (BH spin parameter=0.9)



$$a_* = 5/3,\ e_* = 0.7,\ \beta = 2,\ \chi = -0.9,\ i = 90^\circ$$

Disk precesses around BH spin axis (Lense-Thirring Effect)

Radiatively inefficient cooling case



Lense-Thirring precession timescale is remarkably long

Summary

Binary SMBHs

1. Galaxy merger simulations have shown that the circumbinary disk can be naturally formed around the binary.
2. Slef-gravitating circumbinary disk is a promising efficient mechanism to lead to binary orbital decay.
3. A variety of dynamical interaction between disk and binary (Disk warping and tearing)
4. Emitted spectrum and light curves from triple disk

TDEs

1. GR (perihelion shift) plays an important role in accretion disk formation via debris circularization from stars on moderately eccentric orbits.
2. Radiative cooling efficiency affects on structure and evolution of debris circularization. For radiatively efficient cooling case, geometrically thin ring-like structure is formed, whereas geometrically thick disk is formed for radiatively inefficient cooling case.
3. Lense-Thirring effect is observable for radiatively efficient cooling case.
4. Treatment of super-Eddington accretion flows