Gravitational waves from the Papaloizou-Pringle instability in black hole-torus systems

Kenta Kiuchi (YITP)

with Masaru Shibata (YITP), Pedro J. Montero (MPA), José A. Font (Valencia Univ.)

Ref.) PRL 106 251102 (2011)

YUKAWA INSTITUTE FOR THEORETICAL PHYSICS

K computer

Outline

1. Introduction and formation of black hole-torus systems
2. Instabilities in black hole-torus systems
   2.1 Runaway instability (Axisymmetric mode)
   2.2 Papaloizou-Pringle instability (Non-Axisymmetric mode)
3. Gravitational waves associated with the instabilities
4. Summary

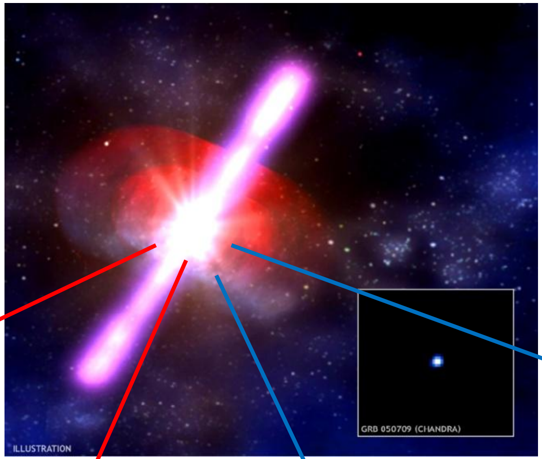
0. Introduction

Numerical Relativity = Solving Einstein eqs. + (magneto) hydrodynamics (+ radiation field) to explore extreme physics

- Experiments of high energy phenomena on computers
- Theoretical prediction of gravitational waves (LCGT(KAGRA) project)

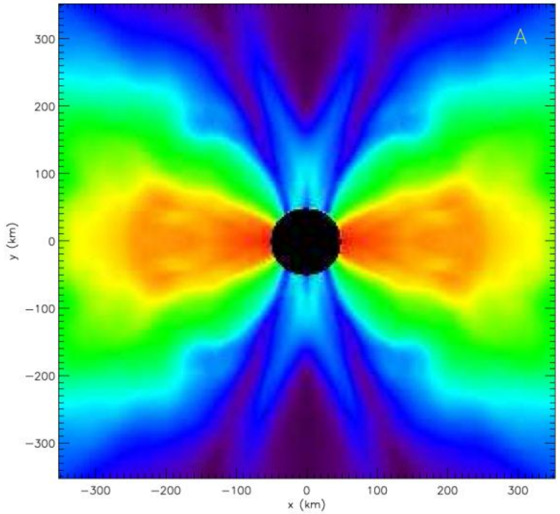
1. Formation of black hole-torus systems

Gamma Ray Burst

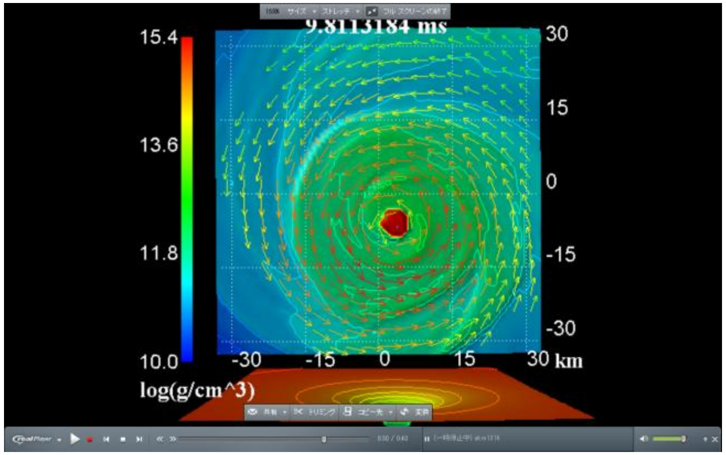


Collapsar scenario for LGRB (Woosley 93)

Merger hypothesis for SGRB (Narayan+ 92)



Collapse of massive star (MacFadyne & Woosley 99)

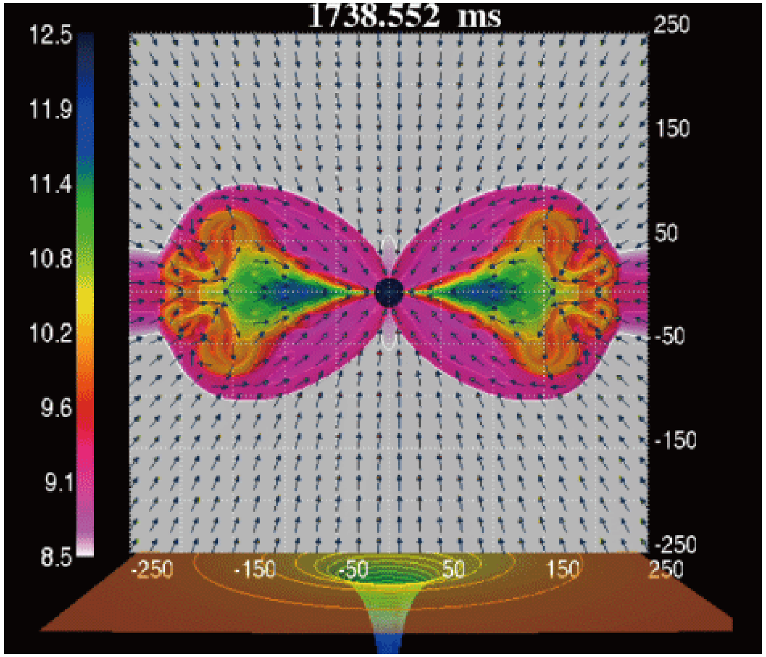


Binary neutron star merger (Kiuchi+ 09)

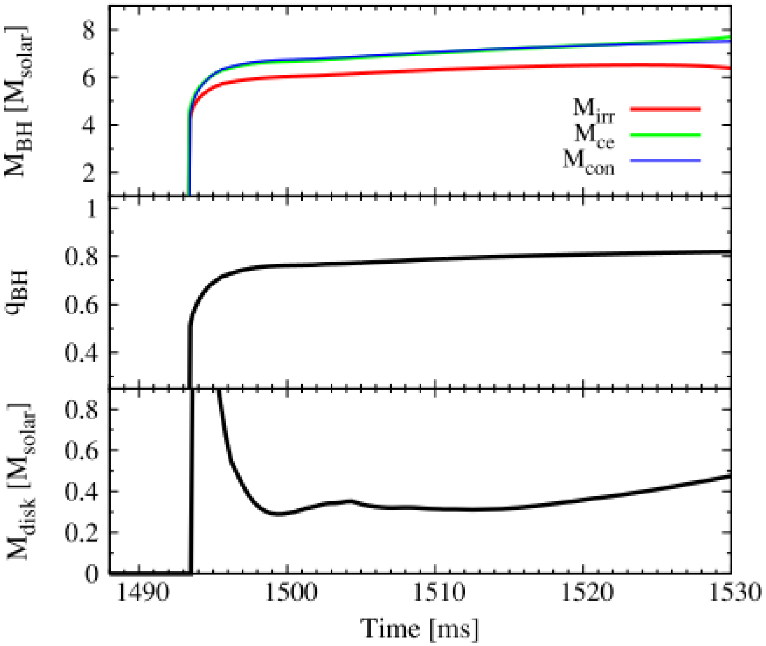
1. Formation of black hole-torus systems

Death of massive stars (Sekiguchi san's talk)

Density on meridional plane



M_{BH} / M_{torus} evolution (Sekiguchi & Shibata11)



Courtesy to Y. Sekiguchi

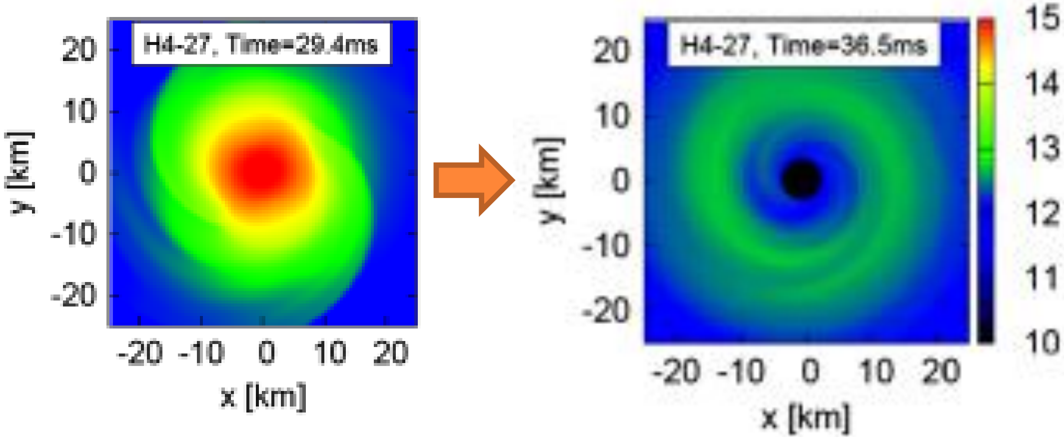
Torus mass / Black hole mass ~ O(0.01)

but, strongly depend on the rotation

1. Formation of black hole-torus systems

Merger of compact binary

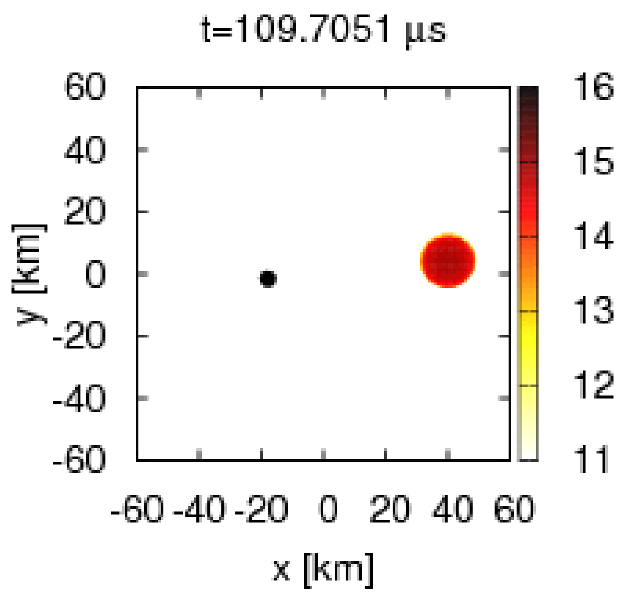
NS-NS merger (Kiuchi+10, Hotokezaka+11)



$0 \lesssim M_{torus} / M_{BH} \lesssim 0.07$

‣ $M_{torus} / M_{BH} \nearrow$ for the long-lived hyper massive neutron stars

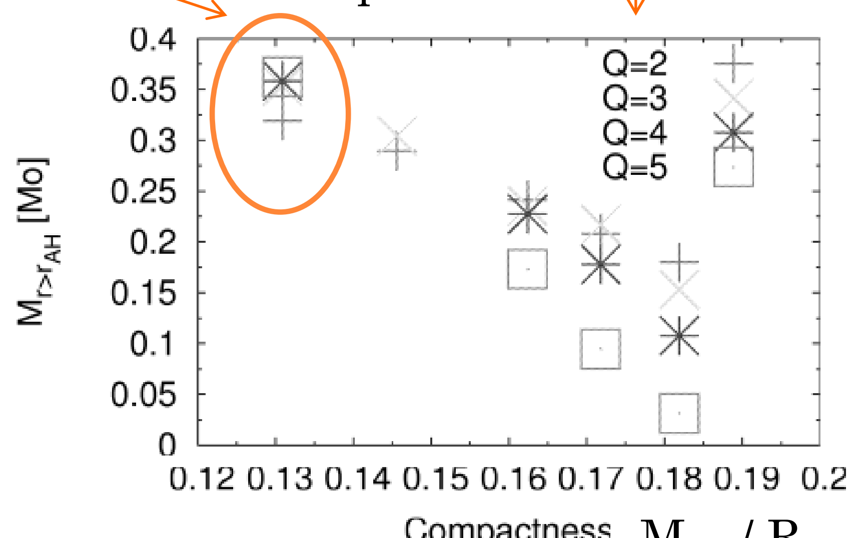
BH-NS merger (Kyutoku+11) $M_{torus} / M_{BH} \sim O(0.1)$



BH spin a=0.75

M_{BH}/M_{NS}

Torus mass / Msolar



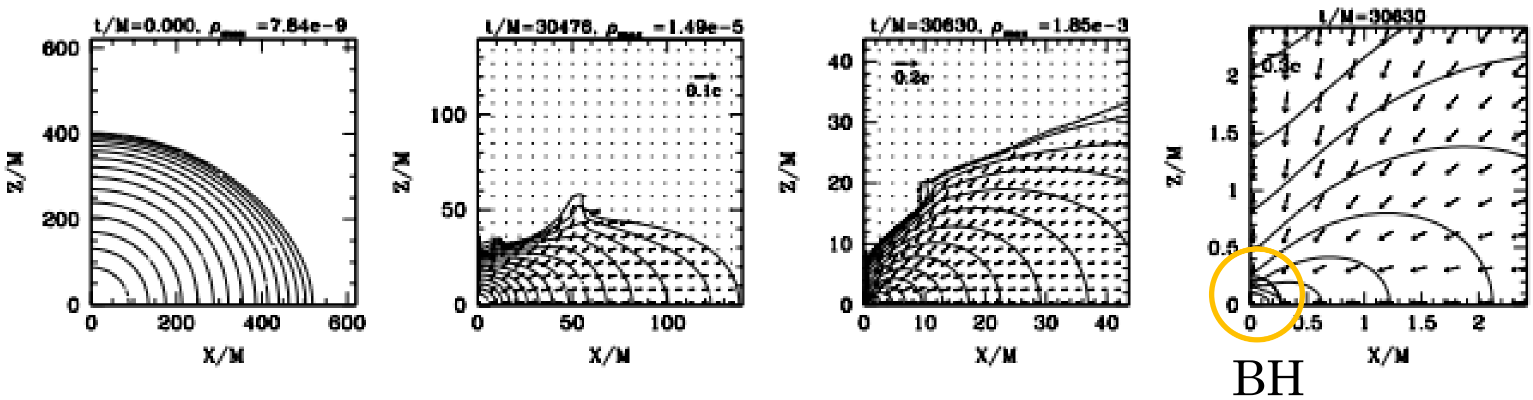
M_{NS} / R_{NS}

1. Formation of black hole-torus systems

Supermassive star collapse (Shibata & Shapiro (02))

- Super massive star is modeled with Γ=4/3
- Uniform rotation

Density on meridional plane



$M_{torus} / M_{BH} \sim 0.1$

In any case, there is possibility to produce a massive torus.

2. Instabilities in black hole-torus systems

- BH-torus systems as a central engine of GRB

Proposed mechanism for lunching relativistic jets

- Neutrino-antineutrino annihilation (Popham+ 99)
- Blandford-Znajeck mechanism (Blandford-Znajeck 77)

Basic assumption on both scenarios : BH-torus systems survive for a sufficiently long time

Objection : Dynamical instabilities associated with BH-torus systems

- BH-torus systems as a consequence of SMS collapse
  - Less observational constraint

Once the instabilities emerge, gravitational waves are emitted

⇒ Verification of SMBH formation process

2. Instabilities in black hole-torus systems

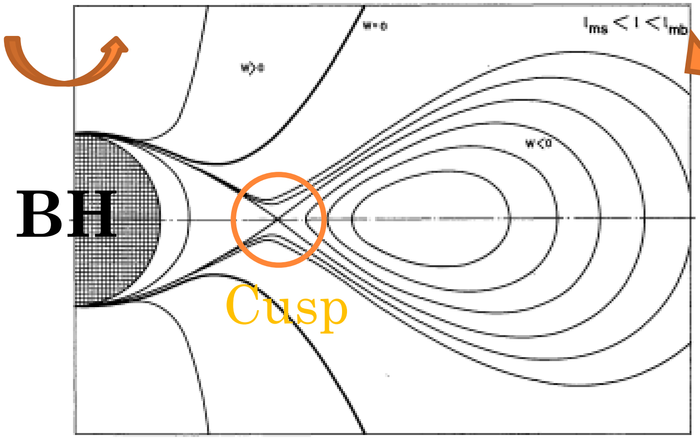
The dynamical instabilities

- Runaway instability (Abramowicz+83)
- Paparouizou-Pringle instability (Paparouizou-Pringle 84)

<u>Runaway instability</u>

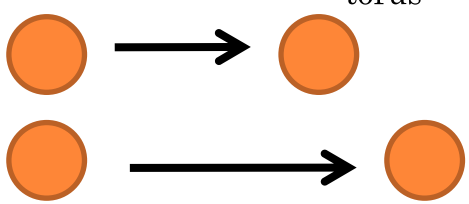
Effective potential contour line

Rotation axis



Drop fluid elements through the cusp（Axismmetric process)

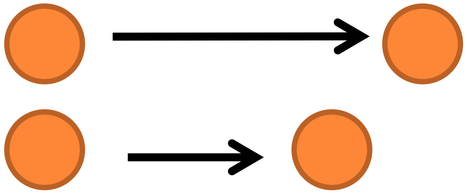
Disk inner edge M_{torus}↘



Cusp M_{BH}↗

Unstable

Disk inner edge



Cusp

Stable

2. Instabilities in black hole-torus systems

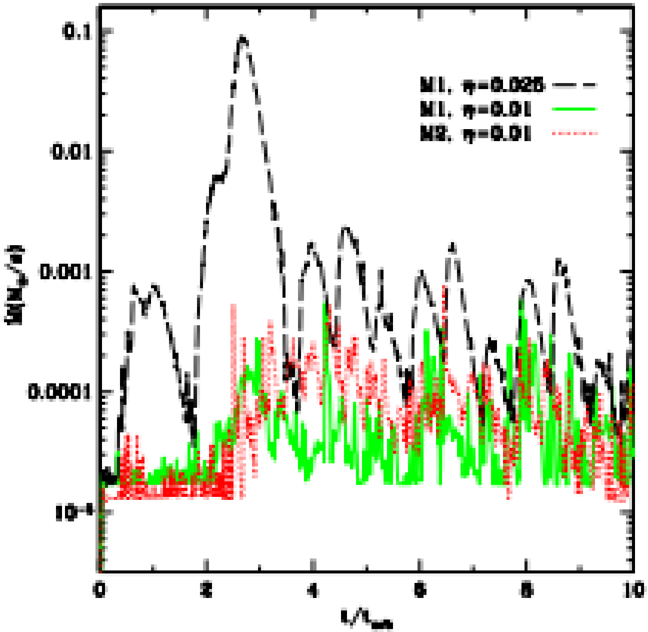
Elements for favoring/disfavoring Runaway instability

- favor : Self gravity of tori (Nishida+ 96)
- disfavor : GR effect, specific angular momentum profile, BH rotation
  (Abramowicz+ 98, Wilson 84)

Comprehensive study by Montero (Montero+10)

- Axisymmetric Numerical Relativity simulation

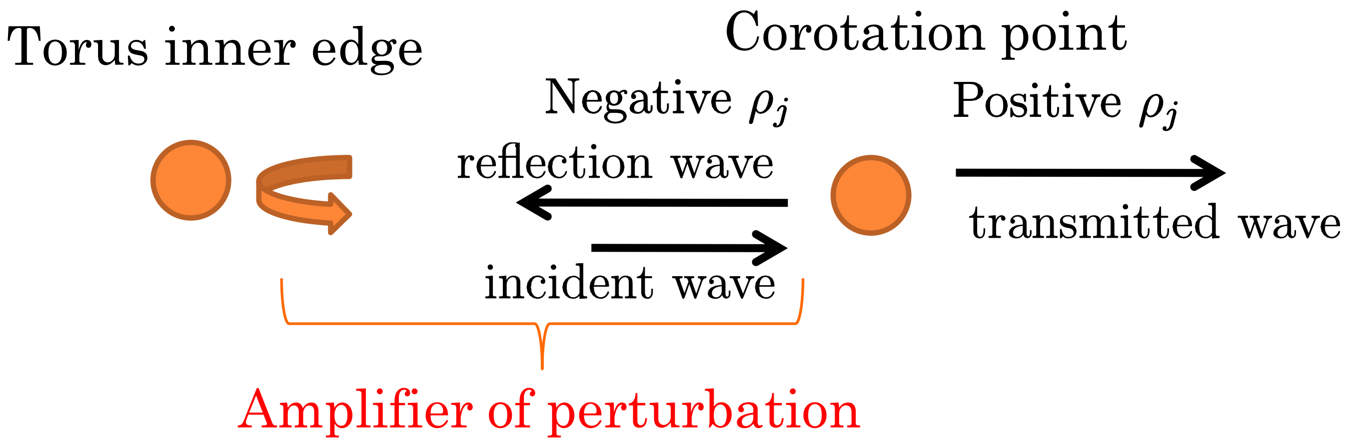
Mass accretion rate



- Stable mass accretion for several dynamical timescales
- No runway instability for the wide-class of BH-torus systems

2. Instabilities in black hole-torus systems

Papaloizou-Pringle instability



- Low m mode is most unstable ($\delta Q \propto e^{im\varphi}$)
- Angular momentum transport through the corotation point

Numerical simulations

- Zurek & Bentz 86 : Newtonian
- Blaes & Hawley 88, Hawley 91 : Schwartzschild spacetime
- Villiers & Hawley 02 : Kerr spacetime
- Korobkin+ 10 : Numerical Relativity

3. Result

Model : BH＋torus systems in equilibrium (Shibata 07)

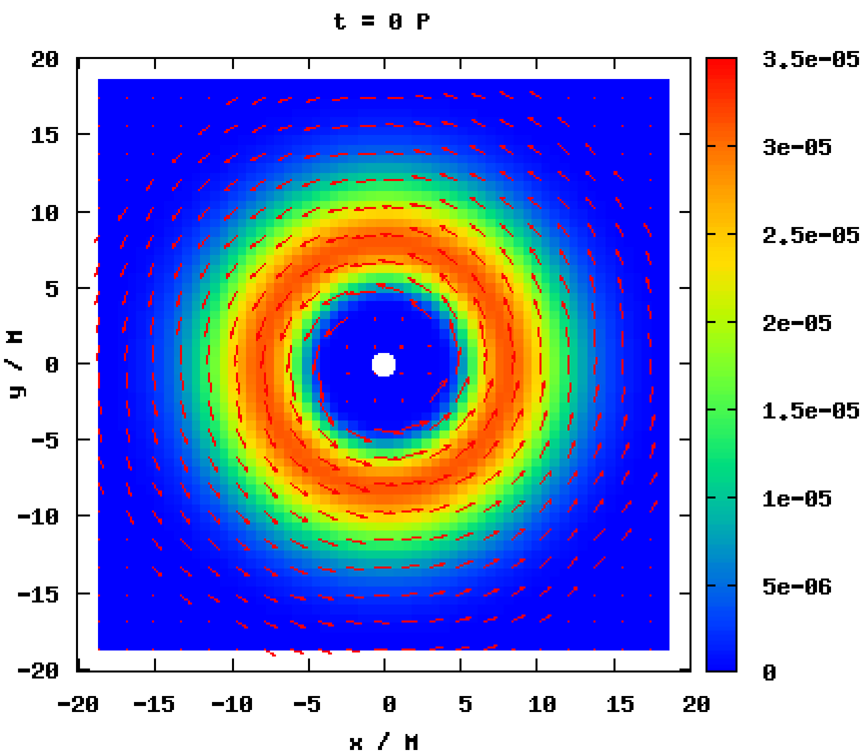
Model	Ang. Mom.	Mass ratio (torus/BH)	Simulation time / P_{orb}
C1	Constant	0.1	34
C06	Constant	0.06	40
NC1	Non-constant	0.1	41
NC06	Non-constant	0.06	34

- Tori are modeled with Γ–law with Γ=4/3
- Non-constant angular momentum profile $\propto r^{\alpha}$ $(0 \leq \alpha \leq 0.5)$
- Long-term simulation to explore a saturation of the instability
- Numerical Relativity simulation in 3D

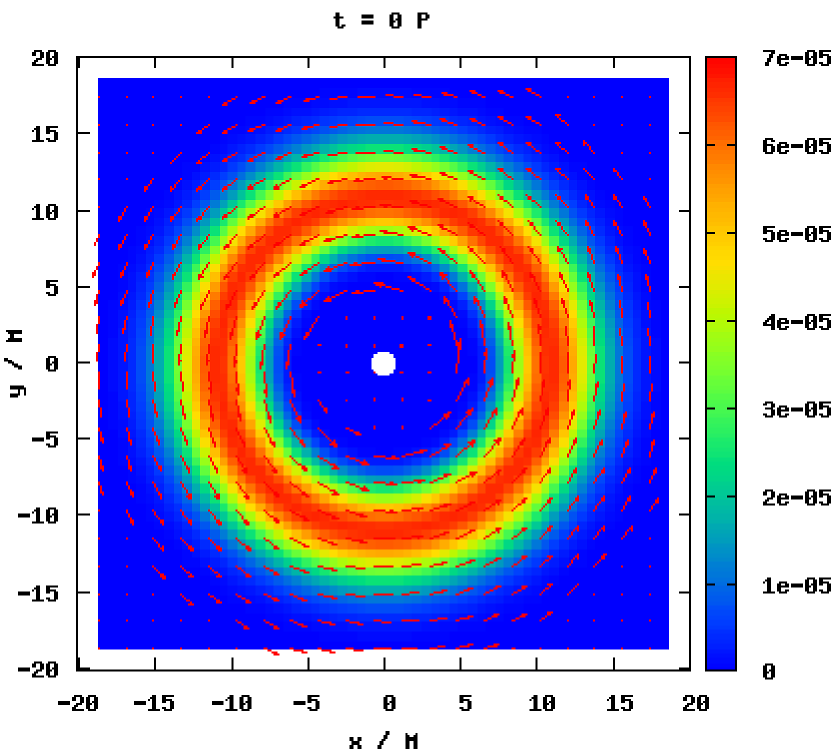
3. Emergence of the instability

Density contour on the equatorial plane

C06



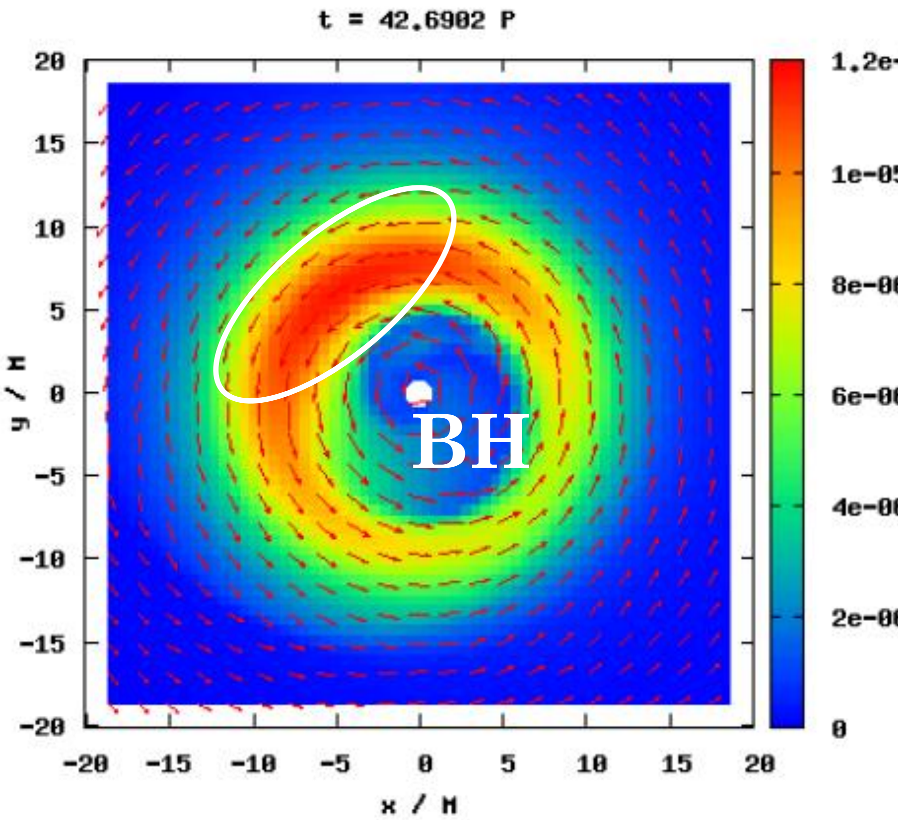
NC1

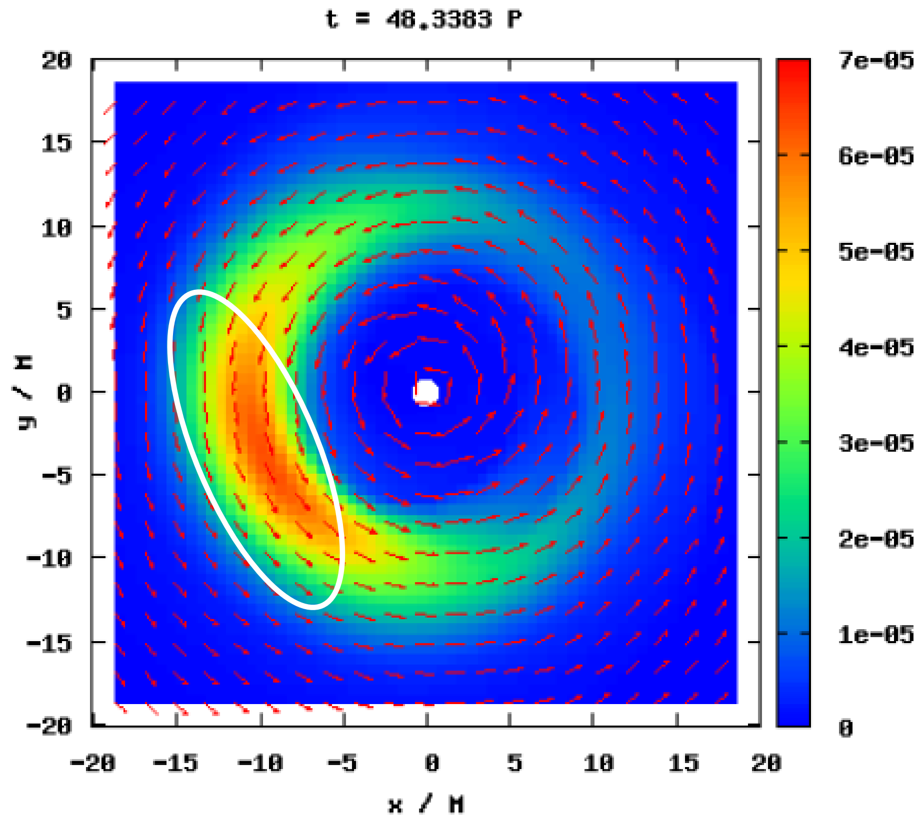


Time is given in the units of the orbital Period

3. Emergence of the instability

Density contour @ the saturation





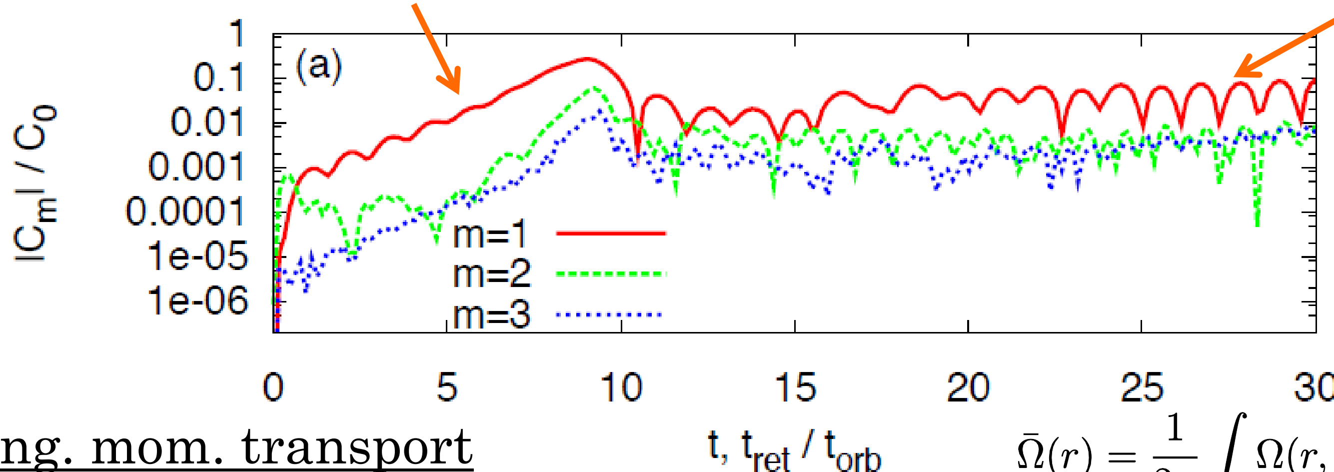
Both models are unstable : the "planet" is left

3. Mode and angular momentum transport

Mode analysis $C_m = \int \rho e^{-im\phi} d^3x$

Prominent growth of m=1

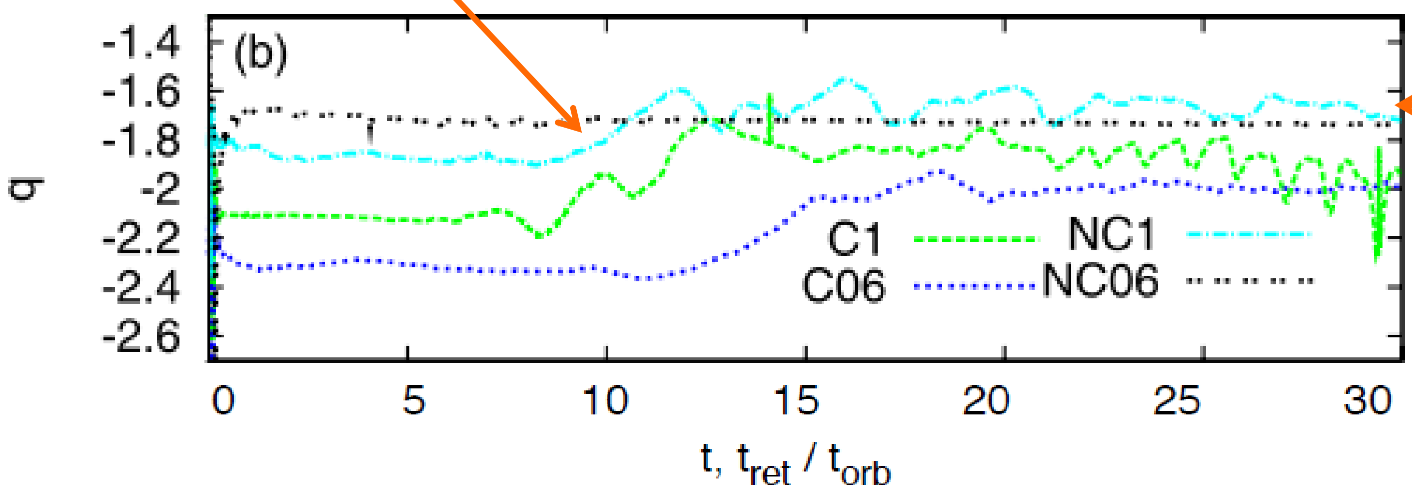
Saturation



Ang. mom. transport

$$\bar{\Omega}(r) = \frac{1}{2\pi} \int \Omega(r, \pi/2, \phi) d\phi \propto r^q$$

Saturation



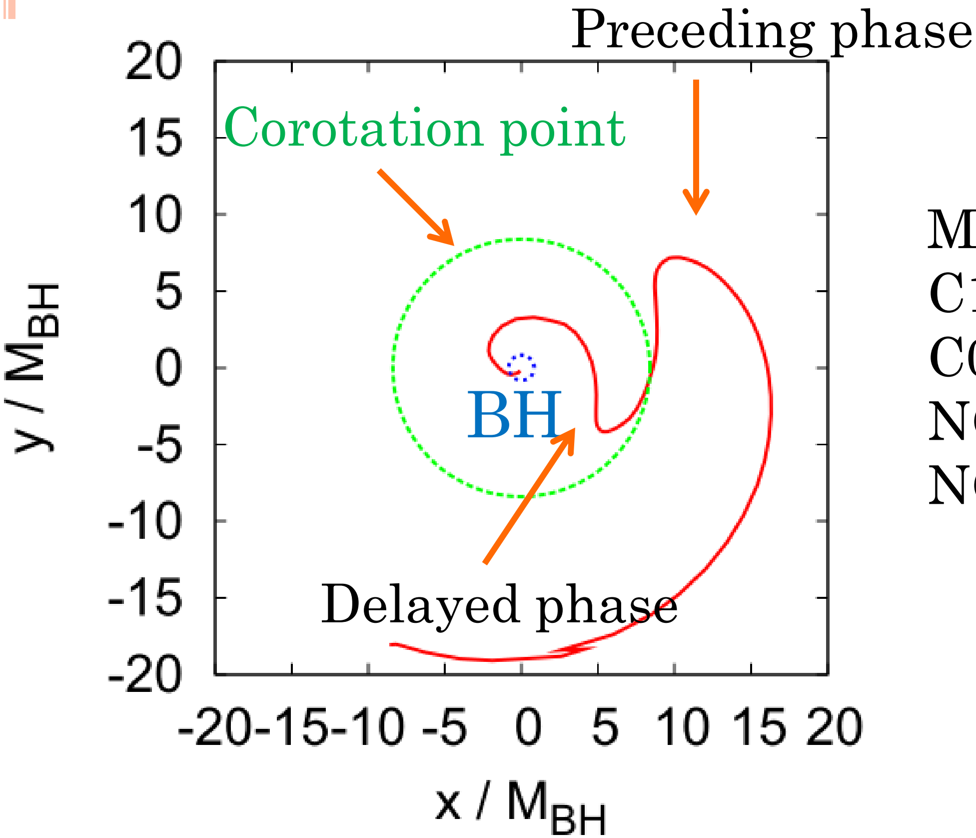
3. Phase velocity

$\delta Q \propto \mathrm{e}^{-i\omega t + im\phi}$

Phase velocity : $Re(\omega)/m = d\phi_m/dt$

Corotation point : $Re(\omega)/m = \Omega(r_{\rm corot})$

phase ϕ_m



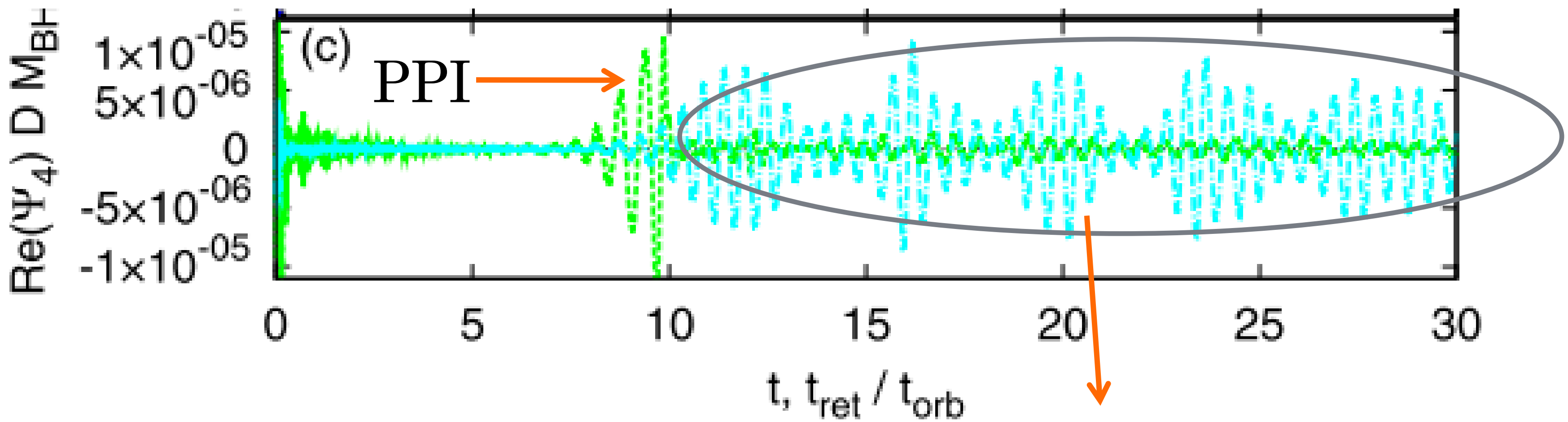
Model	Growth rate (/Ω) (m=1)
C1	0.142
C06	0.089
NC1	0.056
NC06	--------

← Stable

- All the features is consistent with PP instability

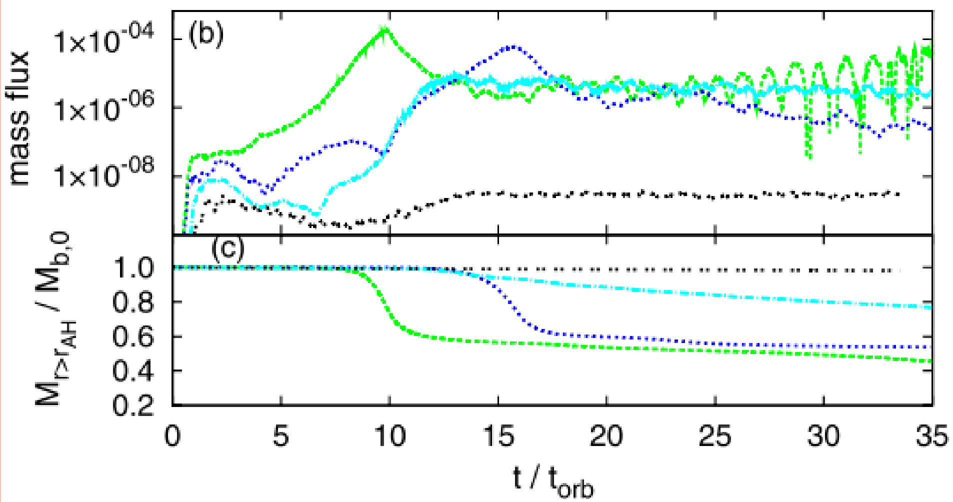
3. Gravitational waves

Wave forms



After the saturation, the "planet" orbits around the BH

Mass accretion rate



Torus mass / initial value

$$t_{\rm duration} \sim 10^4 M_{\rm BH} \ (t_{\rm orb} \sim 200 M_{\rm BH})$$

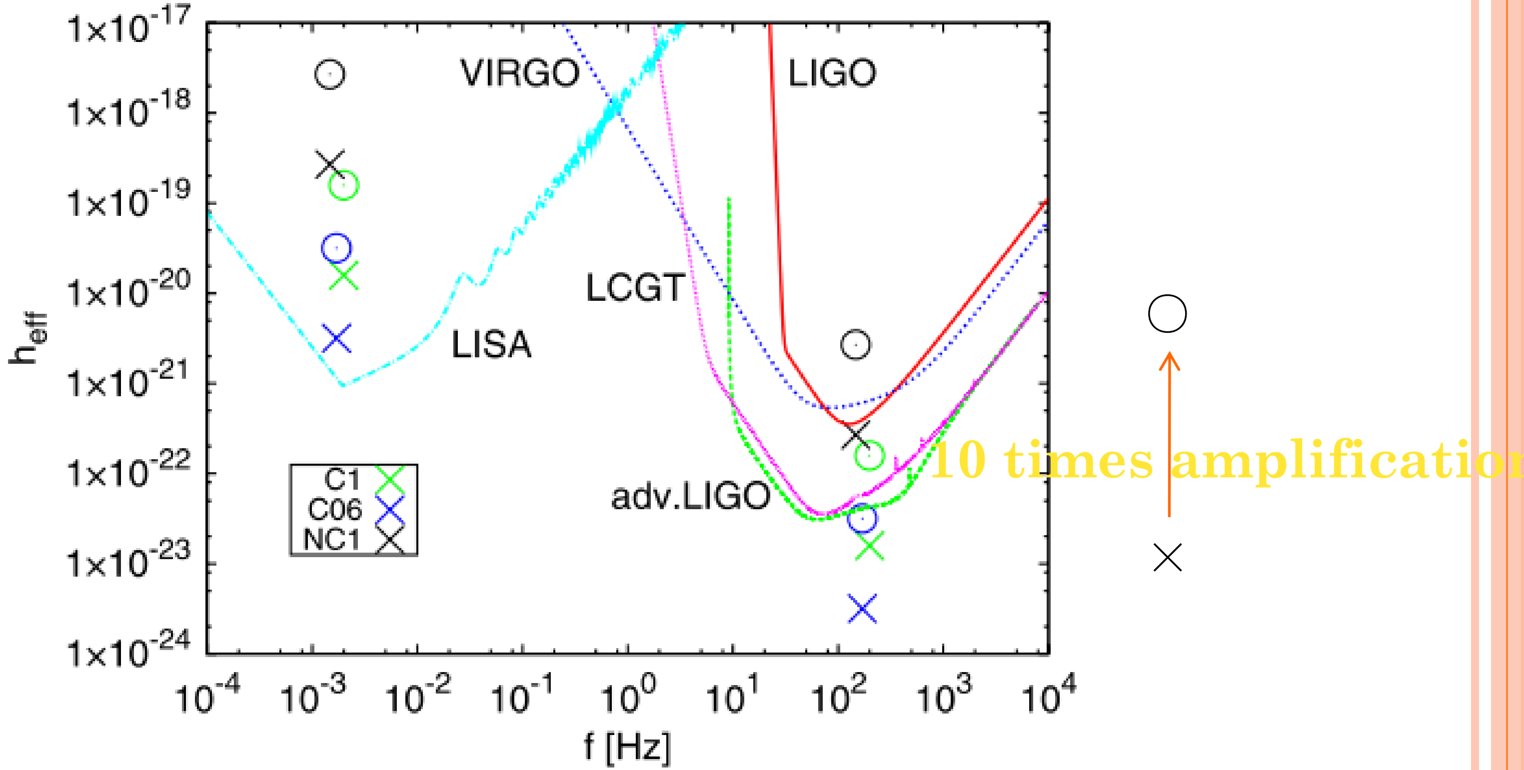
$$\sqrt{N_{\rm cycle}} = \sqrt{t_{\rm duration}/t_{\rm orb}} \sim 10$$

- Amplify the GW amplitude

3. Gravitational waves

GW spectrum

$(M_{BH}, D) = (10^6\ M_\odot,\ 10\ \mathrm{Gpc})$ $(M_{BH}, D) = (10\ M_\odot,\ 100\ \mathrm{Mpc})$



- Verification of a central engine of GRB
  - Largest amplitudes along the rotation axis (Jet direction ?)

c.f. zero amplitude along the rotation axis if axisymmetry

- Verification of SMBH formation

4. Summary

- BH-torus systems：Subject to Papaloizou-Pringle instability
  - Growth of non-axisymmetric structure
  - Strong emitters of GWs
- Exploring the hypothesis of GRB central engine
- Verification of SMBH formation process

Future work

- More sophisticated models of BH-torus systems
  - 3D NR collapse simulation implementing the finite temperature EOS and neutrino cooling / heating (with Y. Sekiugchi and M. Shibata)