General relativistic simulation of black hole – neutron star binary mergers

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INTRODUCTION

- Direct observation of G.W. within 5 – 10 years
  - Coalescence of compact binaries composed of NS or BH : Primarily target of KAGRA, adv. LIGO, adv. VIRGO

- What BH-NS, NS-NS mergers tell us ?
  - Verification of GR in strong gravitational field
  - The equation of state of high density matter (G.W. ⇒ Mass and radius of NS ⇒ Reconstruction of M-R relation)
  - Central engine of short-hard gamma-ray burst (Narayan+92)

- Importance of electromagnetic counter part

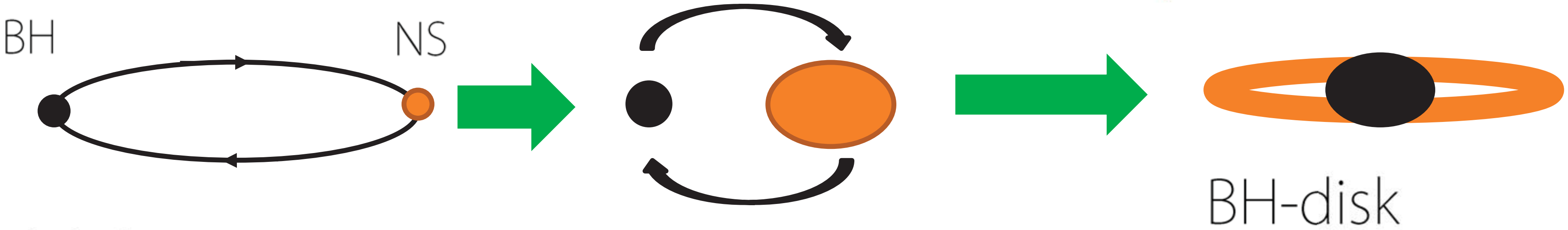
Scenario 1：Mass ejection in merger process ⇒ synchrotron radiation (radio) (Nakar & Piran 11)

Scenario 2：Radioactive decay of r-process element (infrared-optical) (Li-Paczynski 98, Metzger+10, 12)

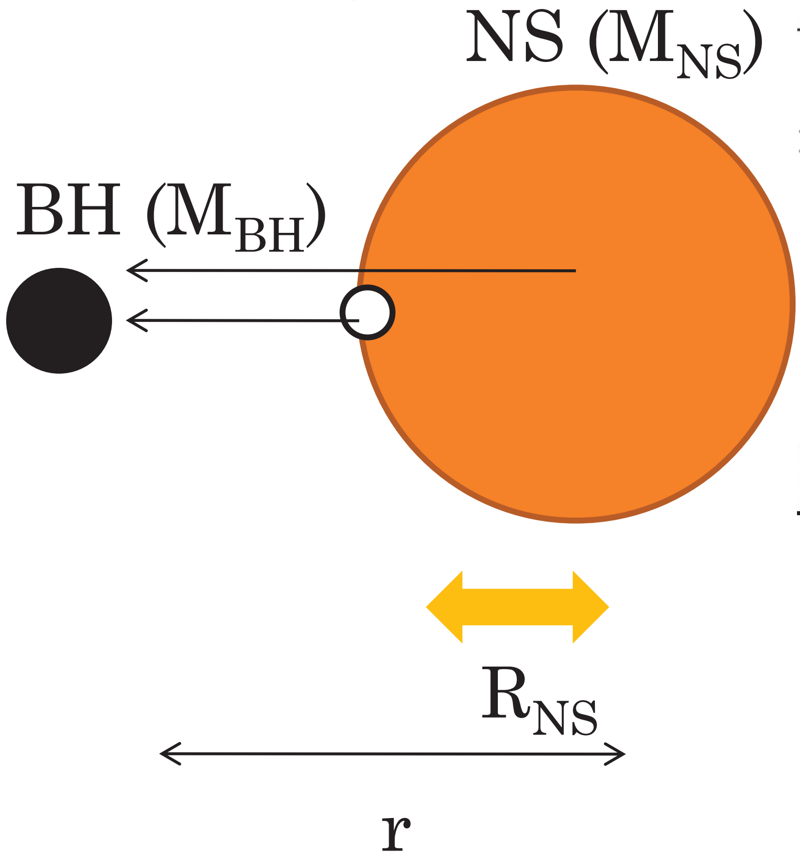
We should verify the properties of ejected element ; mass and velocity

Overview of BH-NS binary merger

Tidal disruption or not ?



Tidal disruption



Tidal force > Self-gravity of NS

$\Rightarrow r \lesssim (M_{BH}/M_{NS})^{-2/3} (M_{NS}/R_{NS})^{-1} M_{BH} \equiv r_{tidal}$

If $r_{tidal} > r_{isco} \Rightarrow$ Tidal disruption

$r_{tidal} < r_{isco} \Rightarrow$ No tidal disruption

Key ingredients

- Mass ratio $q \equiv M_{BH}/M_{NS}$
- Compactness $C \equiv M_{NS}/R_{NS}$
- BH spin a ($a \nearrow \Rightarrow r_{ISCO} \searrow$)

Current status of BH-NS merger GR simulations

- YITP (Japan)
  - Γ -law EOS without BH spin (Shibata-Uryu 06,07, Shibata-Taniguchi 08)
  - Nuclear theory based T=0 EOS with/without (aligned) BH spin (Shibata +09, Kyutoku+10, Kyutoku+ 11)
- Illinois University (USA)
  - Γ -law EOS with/without BH spin (Etienne+ 08,09)
  - Γ -law EOS with B-field (Etienne+ 11,12)
- Louisiana University+ (USA)
  - Γ -law with B-field (Chawla+ 10)
- Caltech-Cornell University (USA)
  - Γ -law with/without (tilted) BH spin (Duez+ 08, Foucart+11)
  - $T \neq 0$ EOS without neutrino cooling (Duez+ 10)

BH-NS merger simulations implementing $T \neq 0$ EOS and neutrino cooling are mandatory.

Set up

Code description (Talk by Sekiguchi)

- Einstein solver (BSSN-puncture) (Shibata-Nakamura 95, Baumgarte-Shapiro 99, Campanelli + 06, Baker + 06)
- GR hydro. + neutrino cooling (GR-leakage) (Sekiguchi 10)
- Fixed-mesh refinement (Yamamoto+ 08)

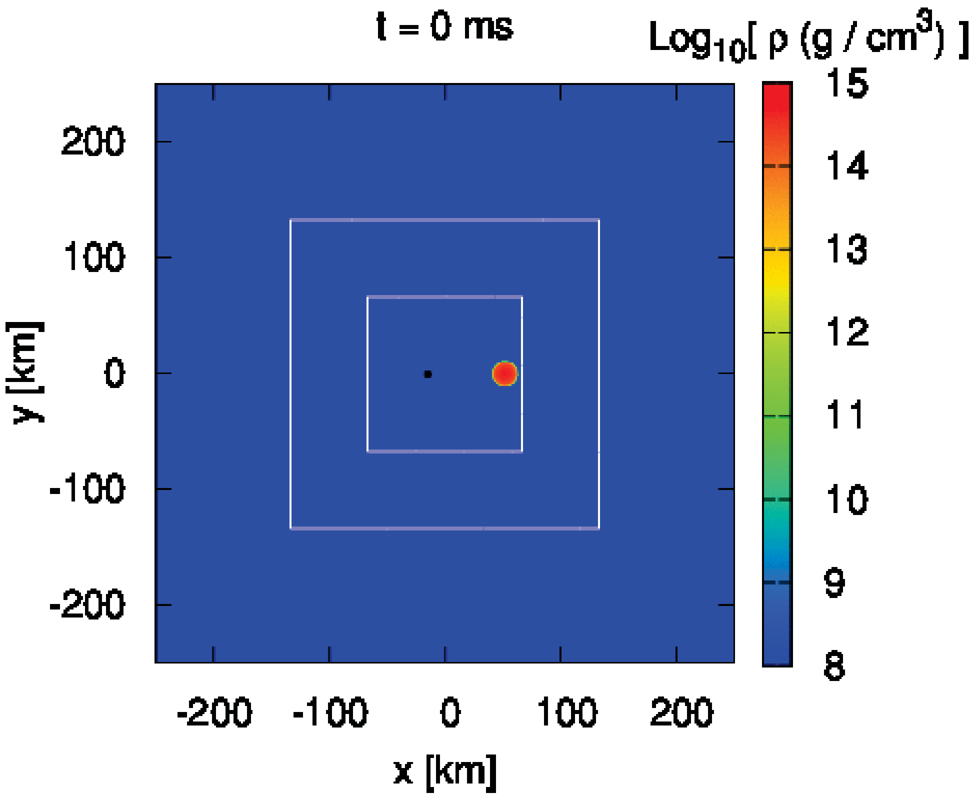
Model

- Shen EOS (Shen+ 98)
- $M_{NS} = 1.35\ M_{\odot}$ ($C \approx 0.133$)
- $M_{BH}/M_{NS} = 3$
- BH spin : a = 0, 0.5

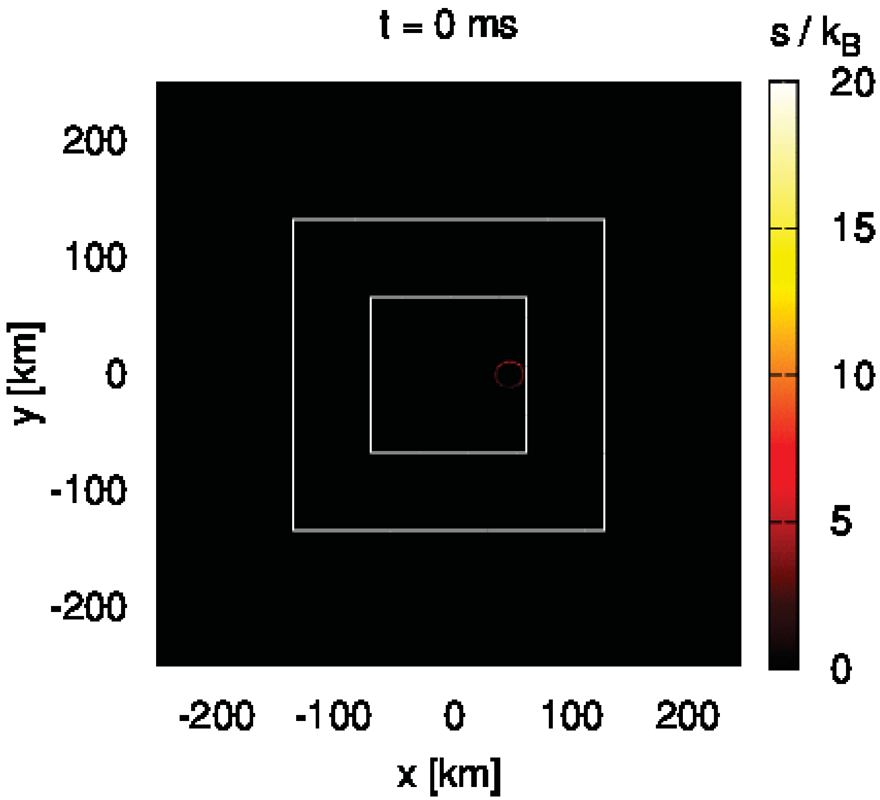
Result

a = 0.5 (Orbital plane)

Density



Entropy / baryon

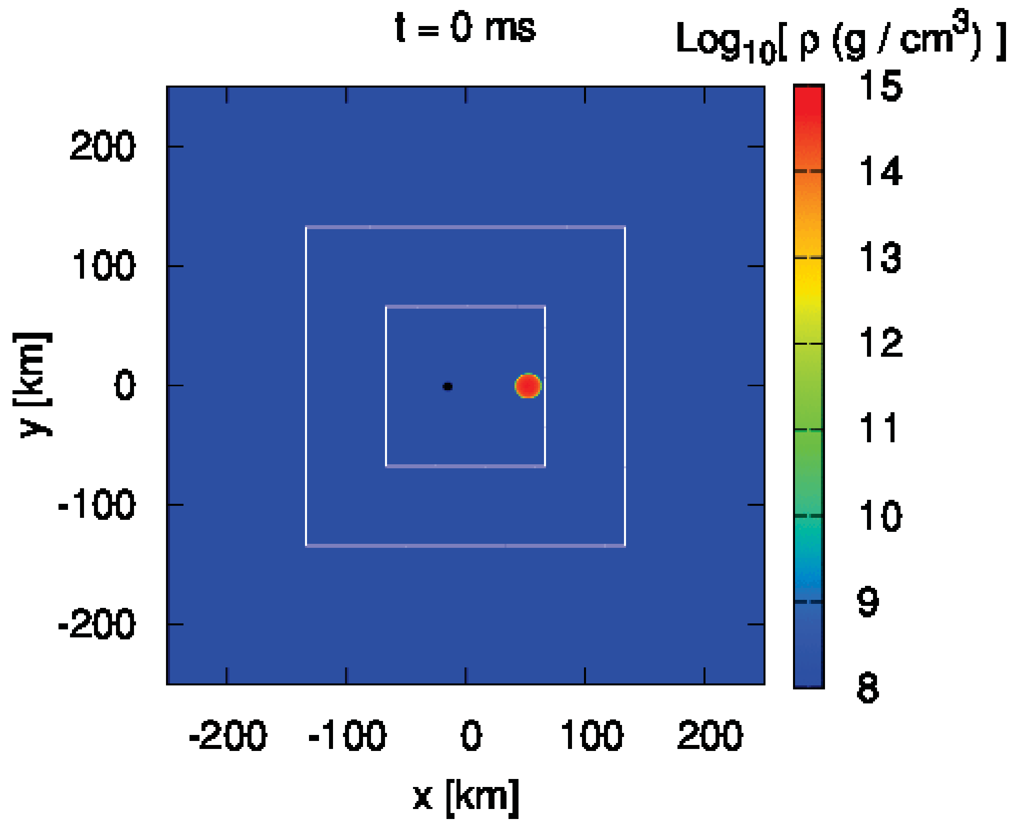


- Tidal disruption
- Formation of massive and hot disk (ρ_{max}~$10^{11\text{-}12}$g/cc, T_{max} ~10 MeV)

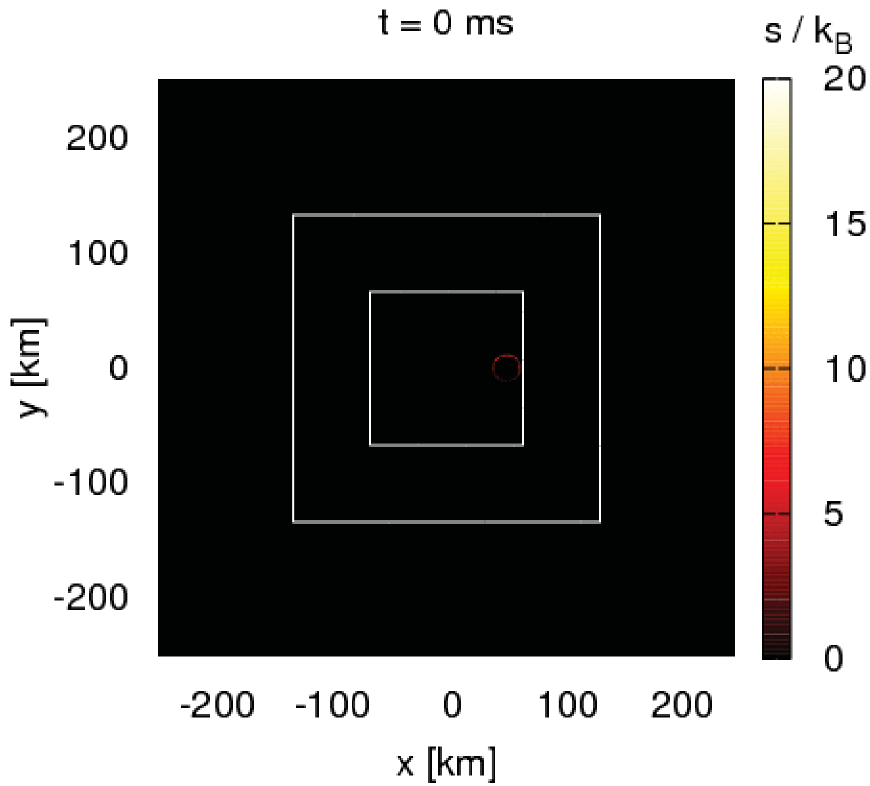
Result

$a = 0.0$ (Orbital plane)

Density



Entropy / baryon



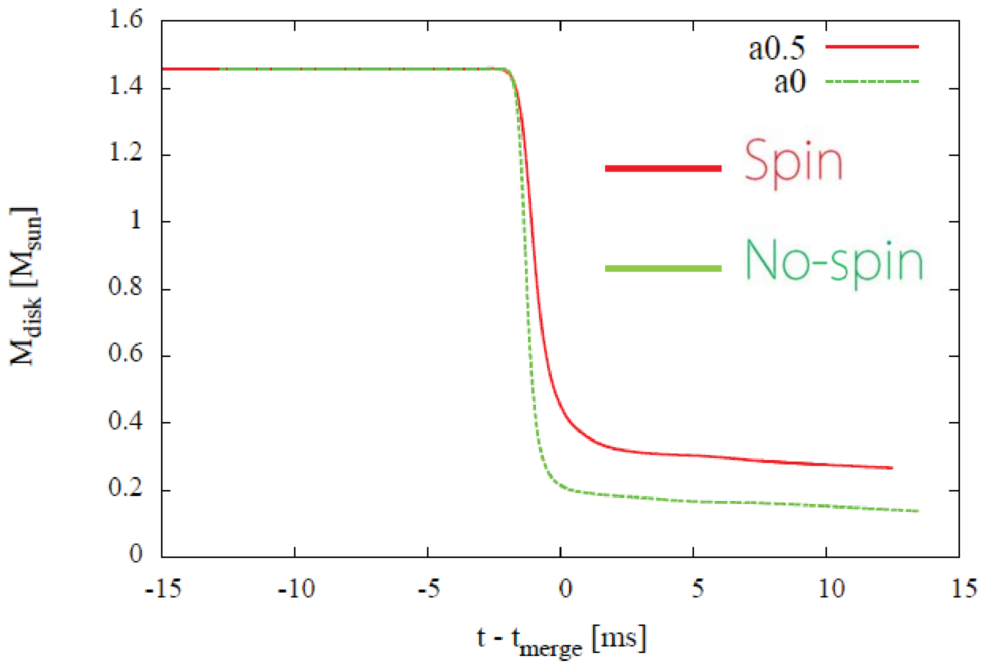
- Spin-orbital coupling (repulsive force if positive spin)

⇒Longer inspiral phase

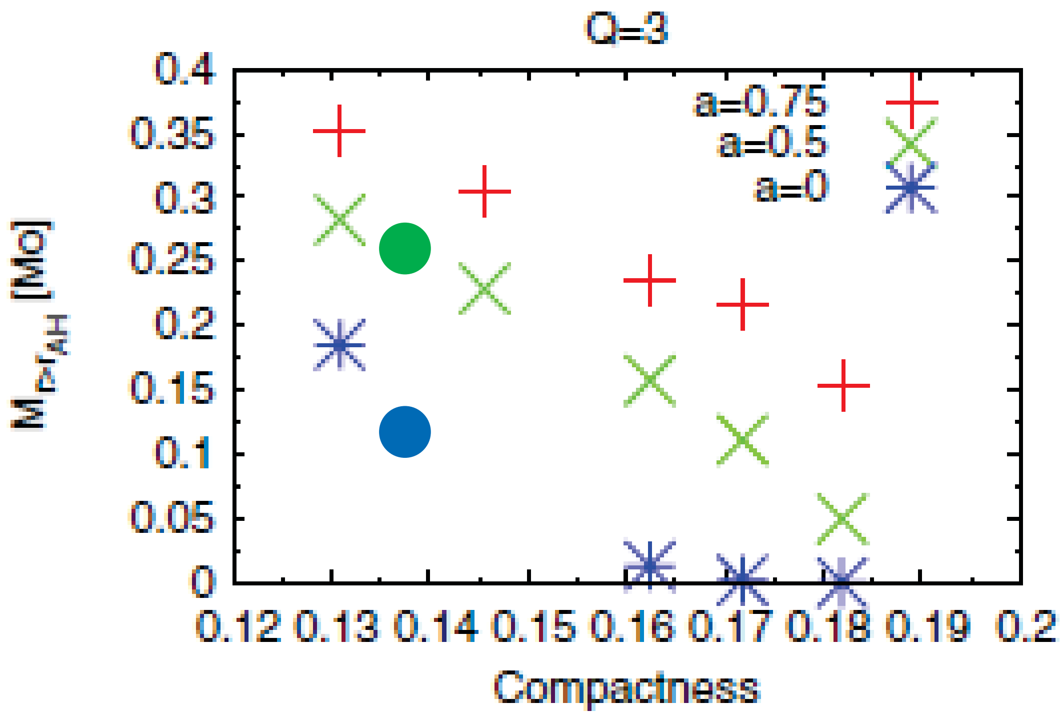
- Spin model ⇒ Massive disk (r_{isco} ↘)

Result

Evolution of disk mass



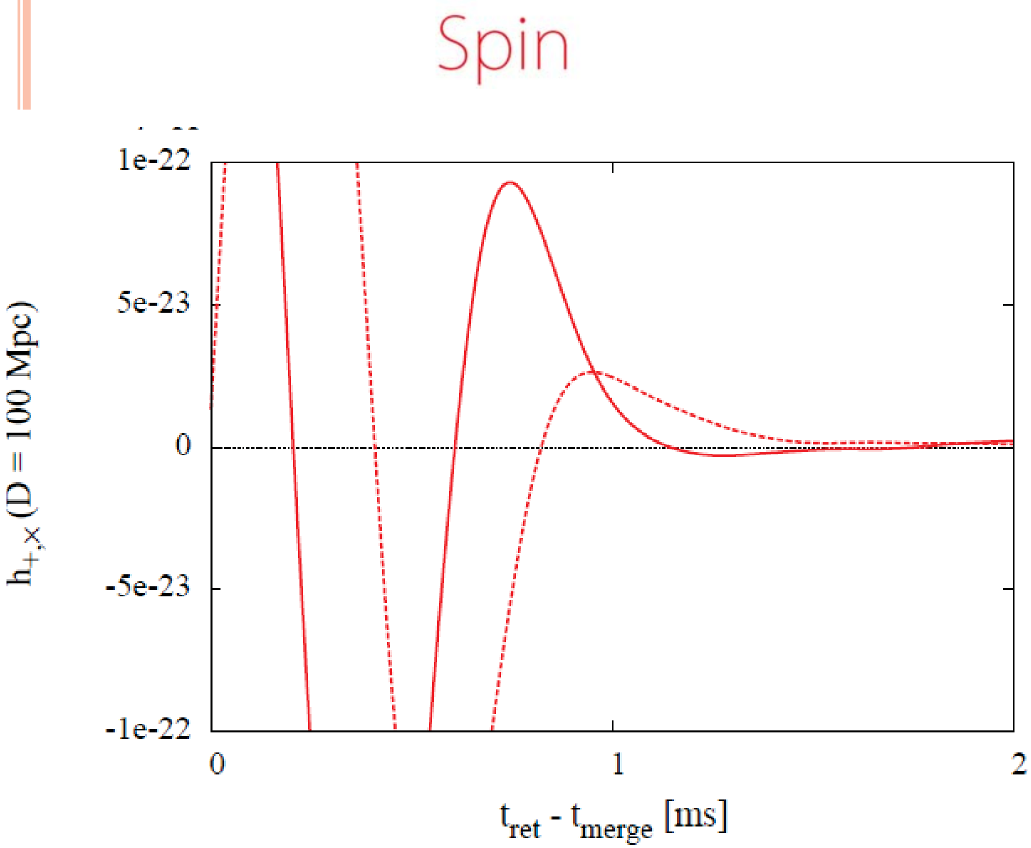
Comparison with the previous work (Kyutoku+11)

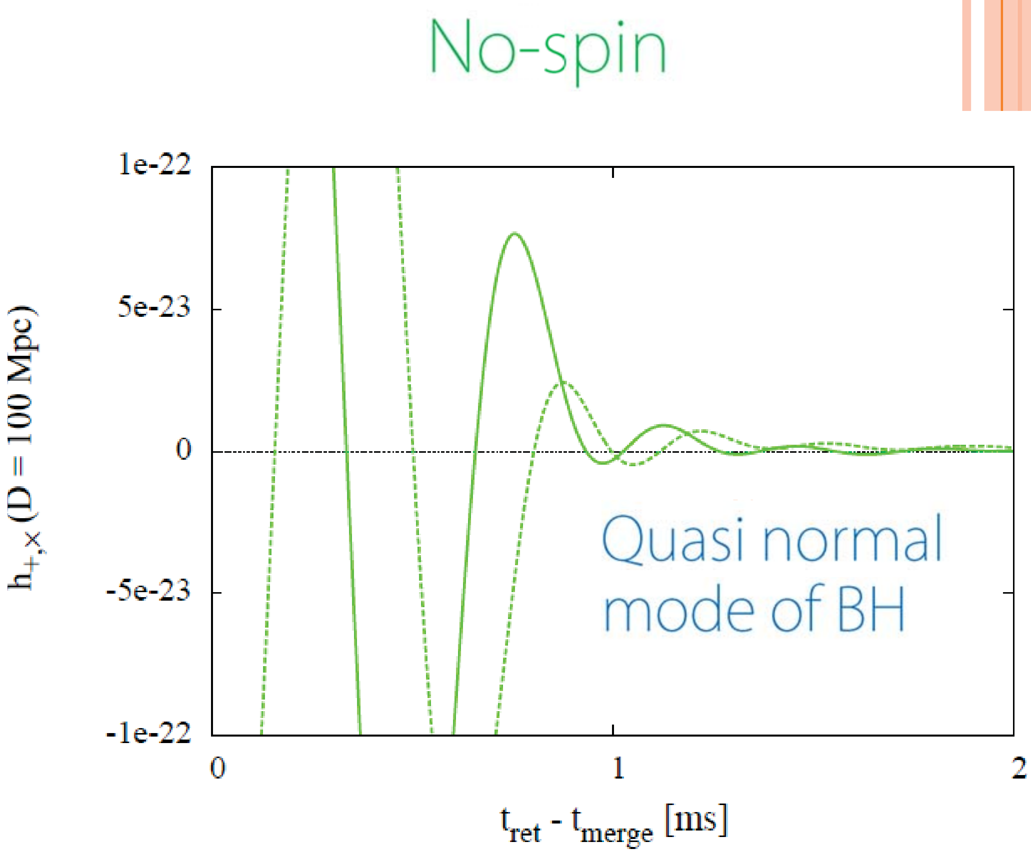


- Spin model ⇒ Smaller r_{ISCO} ⇒ More massive disk
- Kyutoku+11⇒Systematic survey with Piece-wise Polytrope EOS
- Good agreement with the mass – compactness relation

Result

Gravitational waves



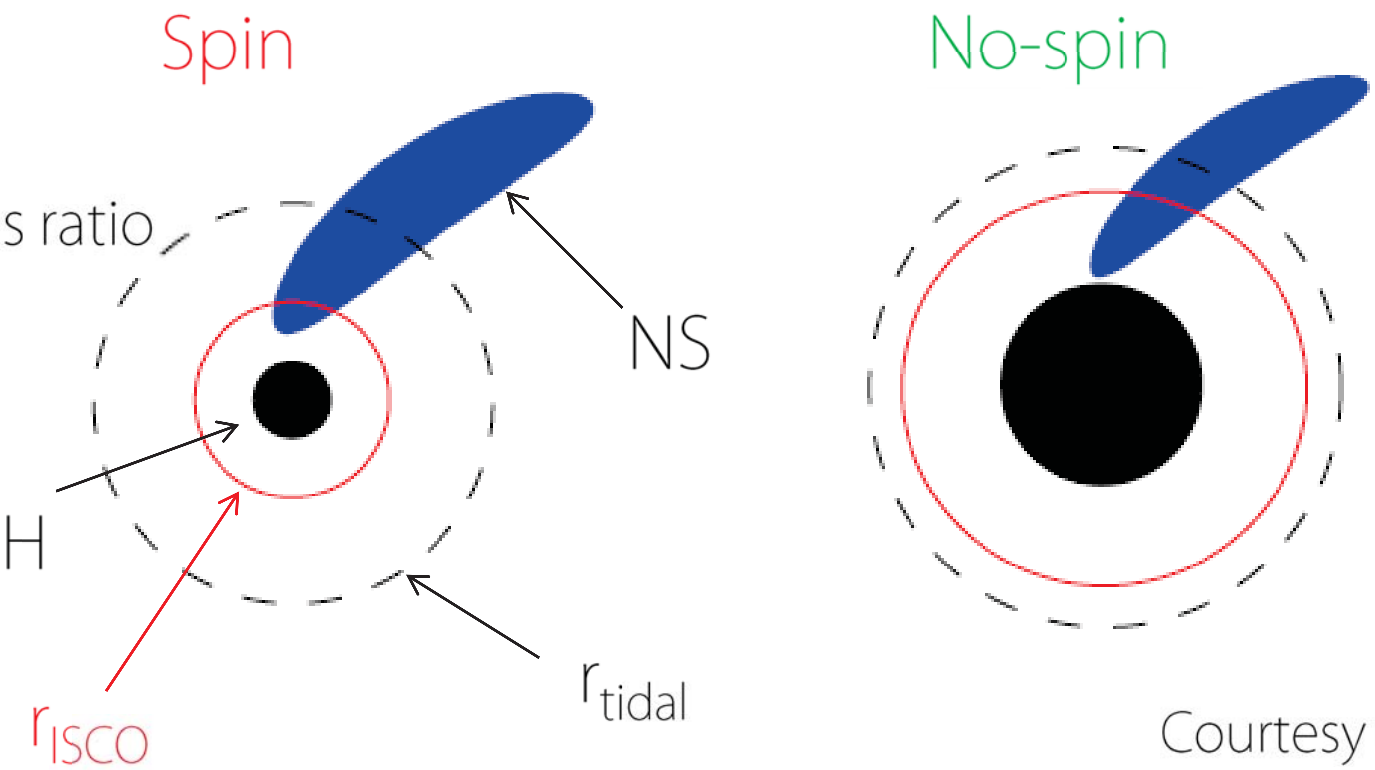


Sudden shut down of GW
⇒ Tidal disruption

Result

Why is the BH-QNM excited in the no-spin case ?

Caution：
Fixed mass ratio

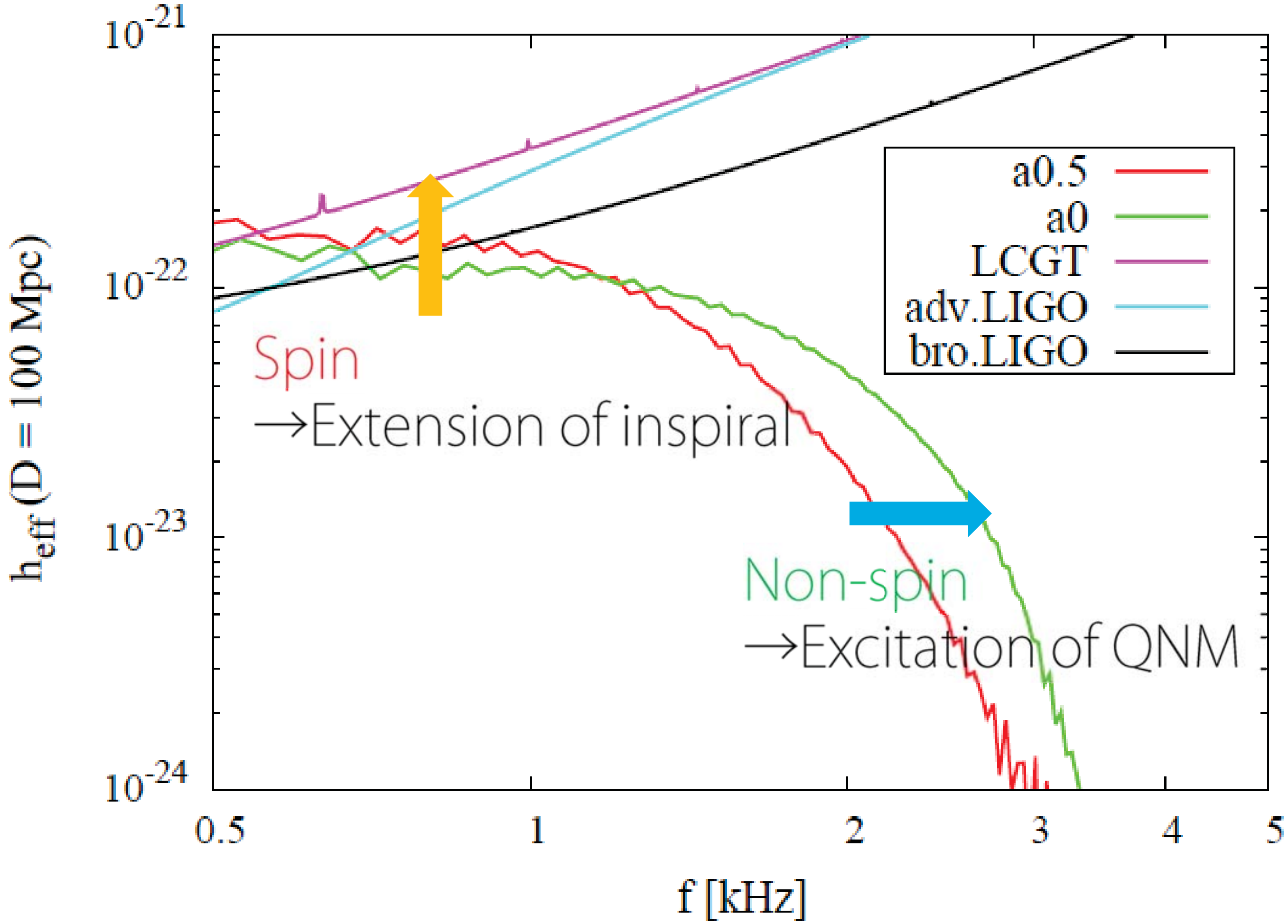


Courtesy to Kyutoku

- Spin→ Formation of axisymmetric disk→Surppression of QNM
- No-spin→ Coherent accretion →Excitation of QNM

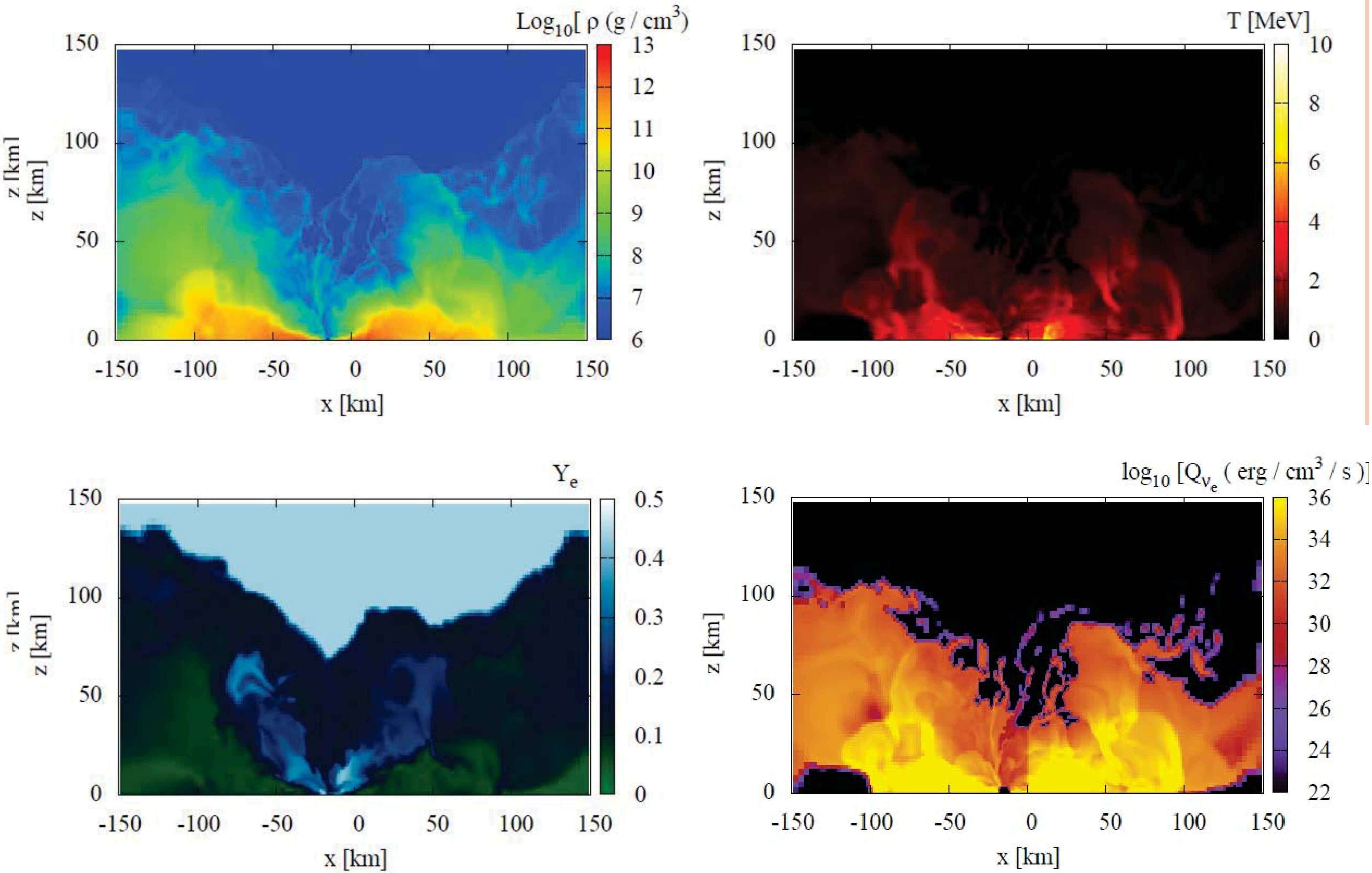
Result

GW Spectra



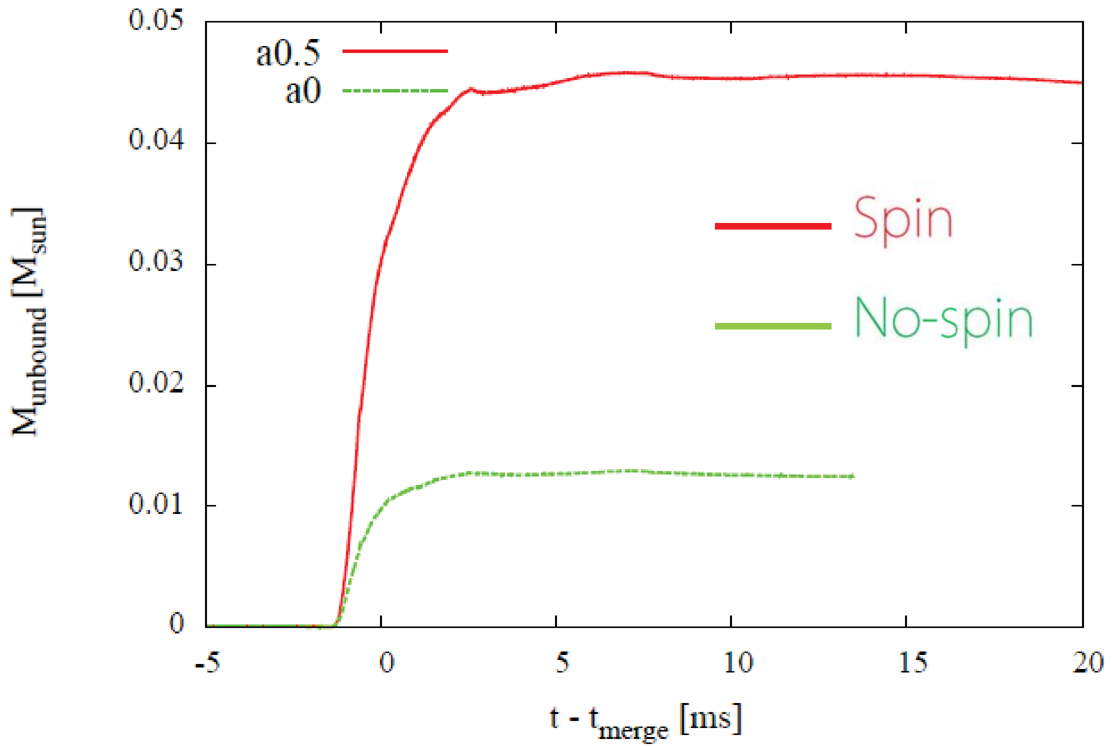
Result

Neutrino luminosity curve



Result

Ejected mass ($\int_{ut<-1} \rho_* dV$)



- Synchrotron radiation (Nakar & Piran 11)

$\sim 90\,\mu$Jy $(E_0/10^{50}\mathrm{erg})(n_0/1\mathrm{cm}^{-3})^{0.9}(v/0.3c)^{-2.8}(D/200\mathrm{Mpc})^{-2}(\nu_{obs}/1.4\,\mathrm{GHz})^{-0.75}$

- r-process element (Li-Paczynski 98, Metzger+10, 12)

$t_{peak} \sim 0.24$ day $(v/0.3c)^{-1/2}(M_{eje}/10^{-2}M_\odot)^{1/2}$

$L_{peak} \sim 2.6\times10^{42}$ erg/s $(f/3\times10^{-6})(v/0.3c)^{1/2}(M_{eje}/10^{-2}M_\odot)^{1/2}$

Could be detected with future-planed radio or infrared-optical detectors

Summary

▸ Numerical relativity BH-NS simulation implementing $T \neq 0$ EOS and neutrino cooling

▸ NS:$1.35M_\odot$ −BH: spin ／zero spin

▸ spin／zero spin→Tidal disruption

Inspiral phase ：positive spin model → Extension due to the spin-orbit coupling

GW：zero spin model→ Excitation of QNM

neutrino：luminosity 10^{52-53} erg/s from the accretion disk after the merger

(anti-electron neutrino＞electron neutrino＞ μ , τ -neutrino)

Future issues

▸ r-process calculation as post-process

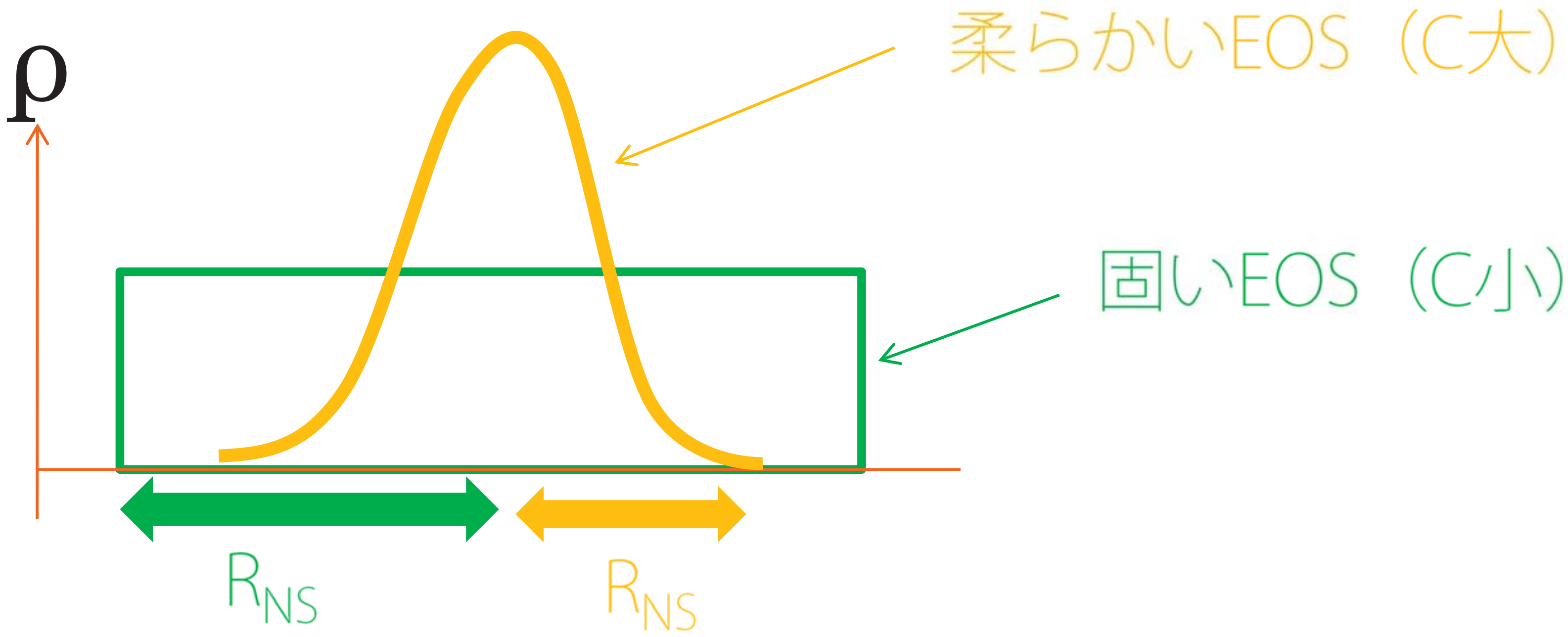
▸ Systematic study

q, C, と aの依存性

$r_{tidal} / M_{BH} \sim q^{-2/3} C^{-1}$

▸質量比：q ↗ ⇒ 潮汐破壊は起こりにくい
良テスト粒子近似⇔有限サイズの効果小
▸ コンパクトネス：C ↗ ⇒ 潮汐破壊は起こりにくい

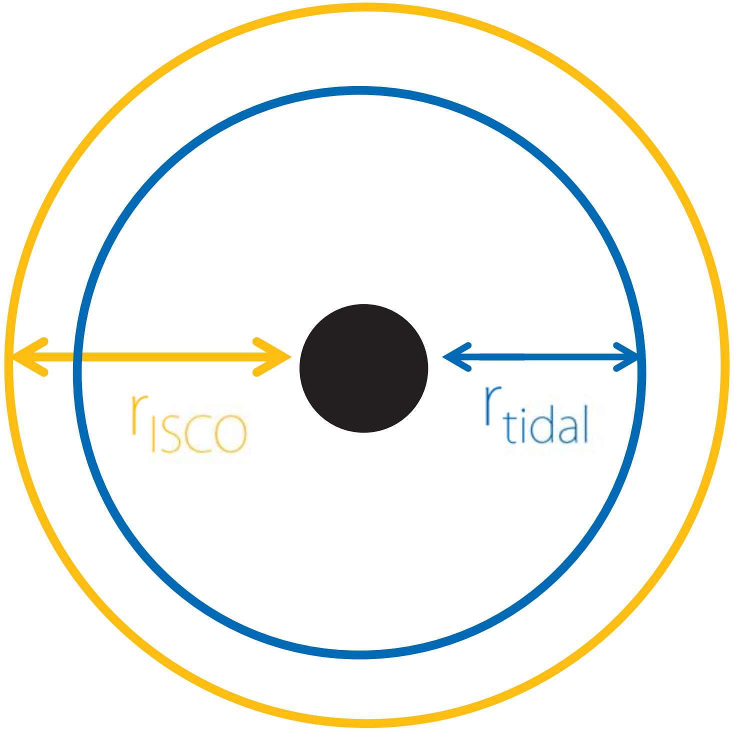
中性子星密度場の略図



q, C, と aの依存性（続き）

- BH spin：a ↗ ⇒潮汐破壊を起こしやすい

BH (M_{BH}, a=0)



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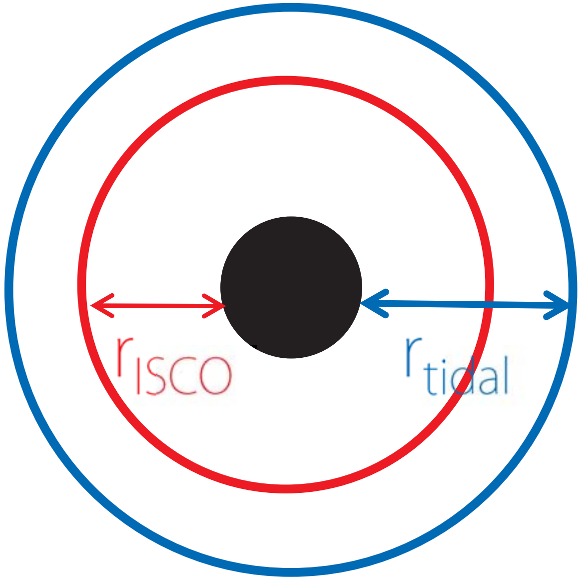
BH (M_{BH}, a>0)



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