ブラックホール・中性子星連星からの重力波と状態方程式の影響

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Black hole-neutron star binaries

- Ones of **the most promising GW sources**

  - emit 1-a few kHz GWs just before the merger

    fairly promising for ground-based detectors

  - a robust test of GR / a new prove for the NS

- Possible candidates of the short GRB engine

  - merger scenario <-> accretion disk formation

- A candidate of the r-process environment

(do not go into detail today)

Gravitational-wave detectors


LIGO at Hanford


LCGT at Kamioka

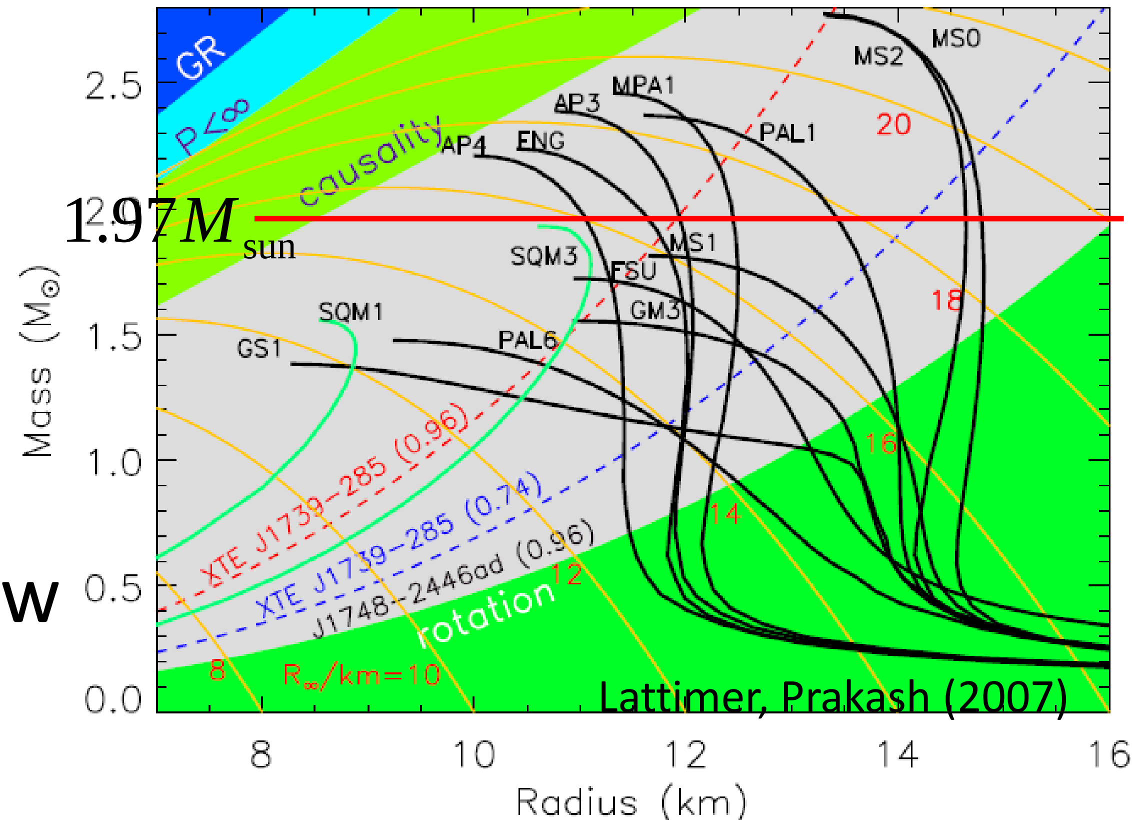

VIRGO at Cascina

Sensitive in 10-1000Hz

… astrophysical sources

Neutron star equations of state

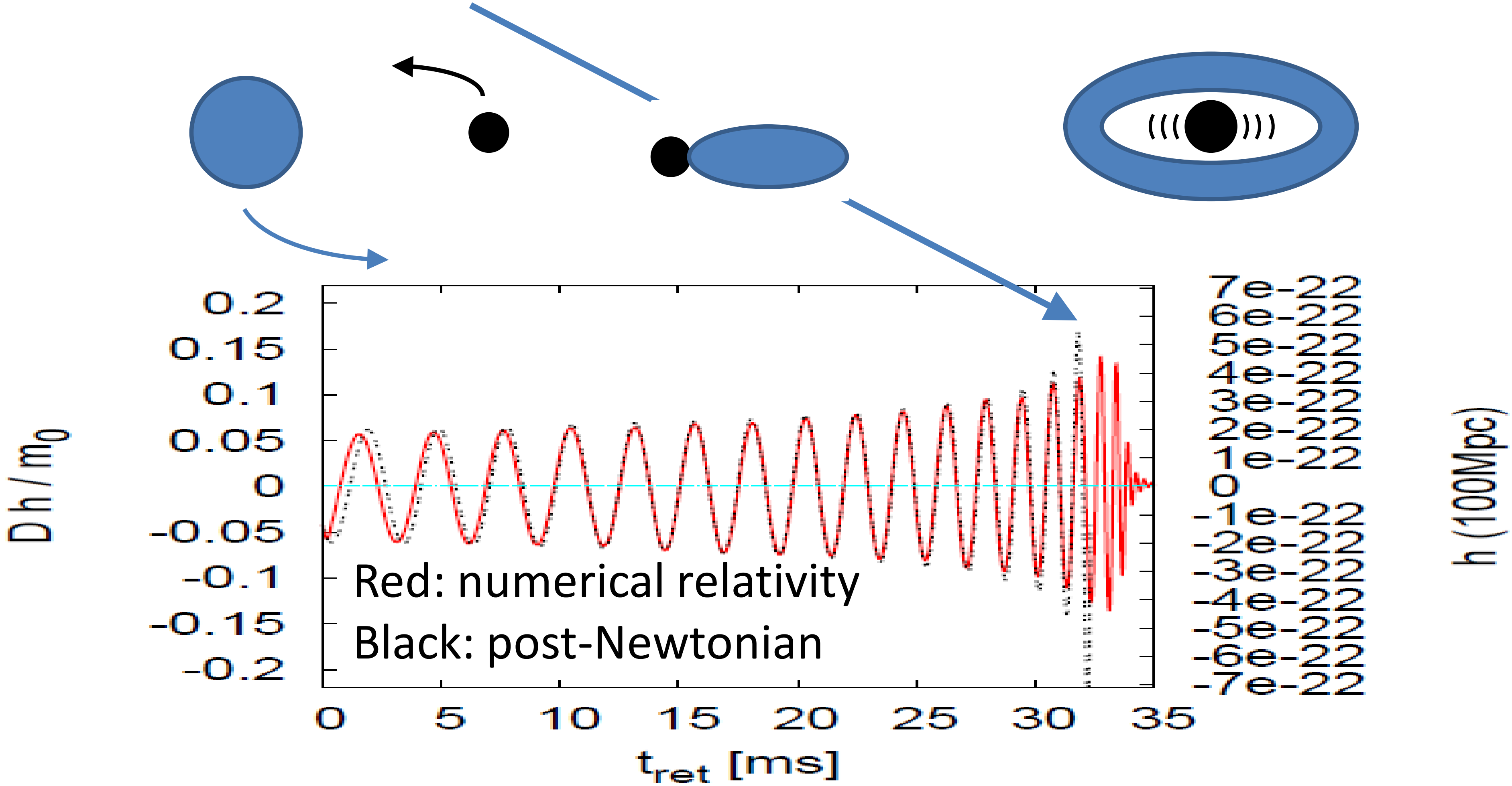
- The EOS at high density is not confirmed yet
- NS radii are determined by the cold (T=0) EOS, but not constrained accurately by (X-ray) observ.
- Can we determine the NS radius by GW observation?
- We can obtain the EOS if we know the M-R relation



Lattimer, Prakash (2007)

Typical GWs from BH-NS binaries

- Classified as inspiral-merger-ringdown (if any)


Red: numerical relativity

Black: post-Newtonian

Importance of numerical relativity

- Appropriate methods differ among the three phases

  1. inspiral phase … post-Newtonian approx.
  2. merger phase … numerical relativity
     strong (=nonlinear) gravity, hydrodynamics
  3. ringdown phase … BH perturbation technique

- Numerical relativity is the unique approach for the merger phase of compact binary coalescences

- **Tidal disruption of the NS** determines the GWs and properties of the remnant disk, such as the mass

Advantages of binary GW observation

- Less systematic errors than EM observation
  - the largest model is the EOS and GR itself
- The dynamics **before** the merger is nearly free of the finite-temperature effects, magnetic fields…
  - in BH-NS, all GWs are determined by T=0 EOSs

  (- in NS-NS, hypermassive NSs also emits GWs)
- The early inspiral gives us different information
  - masses of each component, the BH spin

When the tidal disruption occurs?

- Two nondimensional parameters are important

  - Mass ratio of BH/NS

  - NS compactness

  $$\boxed{\begin{array}{l} Q = M_{\mathrm{BH}} / M_{\mathrm{NS}} \geq 1 \\ C = M_{\mathrm{NS}} / R_{\mathrm{NS}} \sim 0.15 - 0.2 \end{array}}$$

  tidal disruption occurs outside the ISCO if the mass ratio Q and/or compactness Q are small

  = the small BH mass and/or the large NS radius

  ∵ tidal effect is a finite size effect of the NS

- **The large BH spin** $a \equiv S_{\mathrm{BH}} / M_{\mathrm{BH}}^2$ **is also favored**

  ∵ The ISCO radius is small for a large BH spin

The formulation and methods

- Solve $\boxed{G_{ab} = 8\pi T_{ab}, \nabla_b T^b{}_a = 0, \nabla_a(\rho u^a) = 0}$
- Compute initial conditions

  - the spectral method library LORENE

  http://www.lorene.obspm.fr/

  - developed new code for the BH spin / NS EOS
- Perform simulations of time evolution

  - AMR code SACRA developed in our group

  Yamamoto, Shibata, Taniguchi PRD (2008) 78 064054
- EOSs closes the system of equations

The piecewise polytrope (PWP)

- T=0, nuclear-theory based EOSs are approximated by analytic broken-polytropes

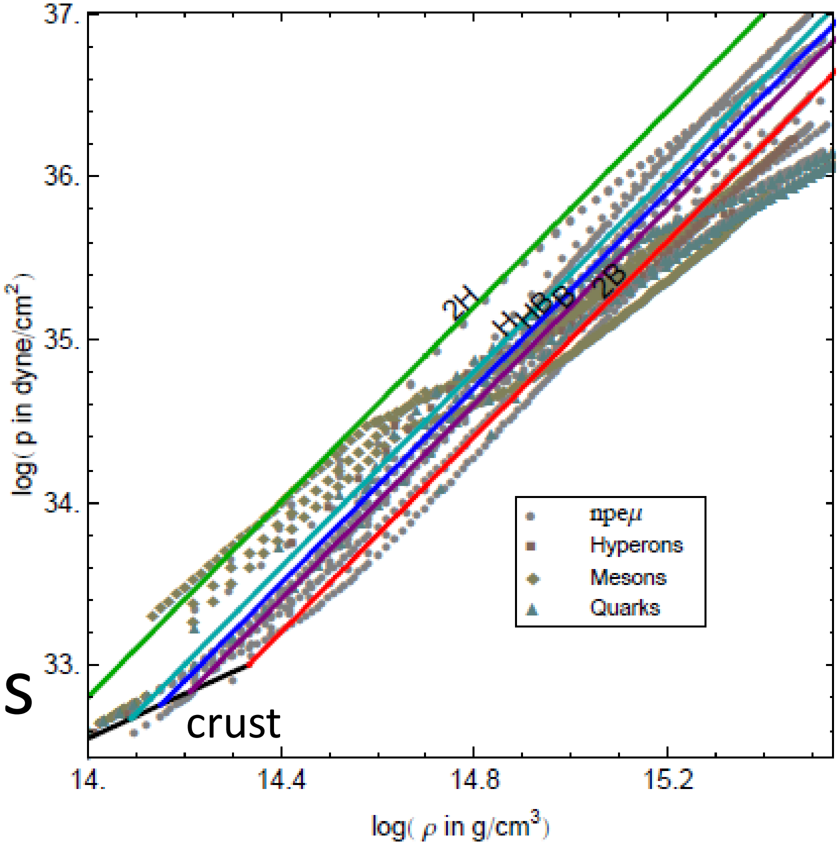
$$P=\begin{cases}\kappa_1\,\rho^{\Gamma_1}\;(\rho<\rho_1) & \text{~crust}\\ \kappa_2\,\rho^{\Gamma_2}\;(\rho>\rho_1) & \text{~core}\end{cases}$$

- less computational costs

- only a few parameters

- Thermal effects are incorporated by ideal gases

$$P_{\rm th}=(\Gamma_{\rm th}-1)\rho\varepsilon_{\rm th}$$

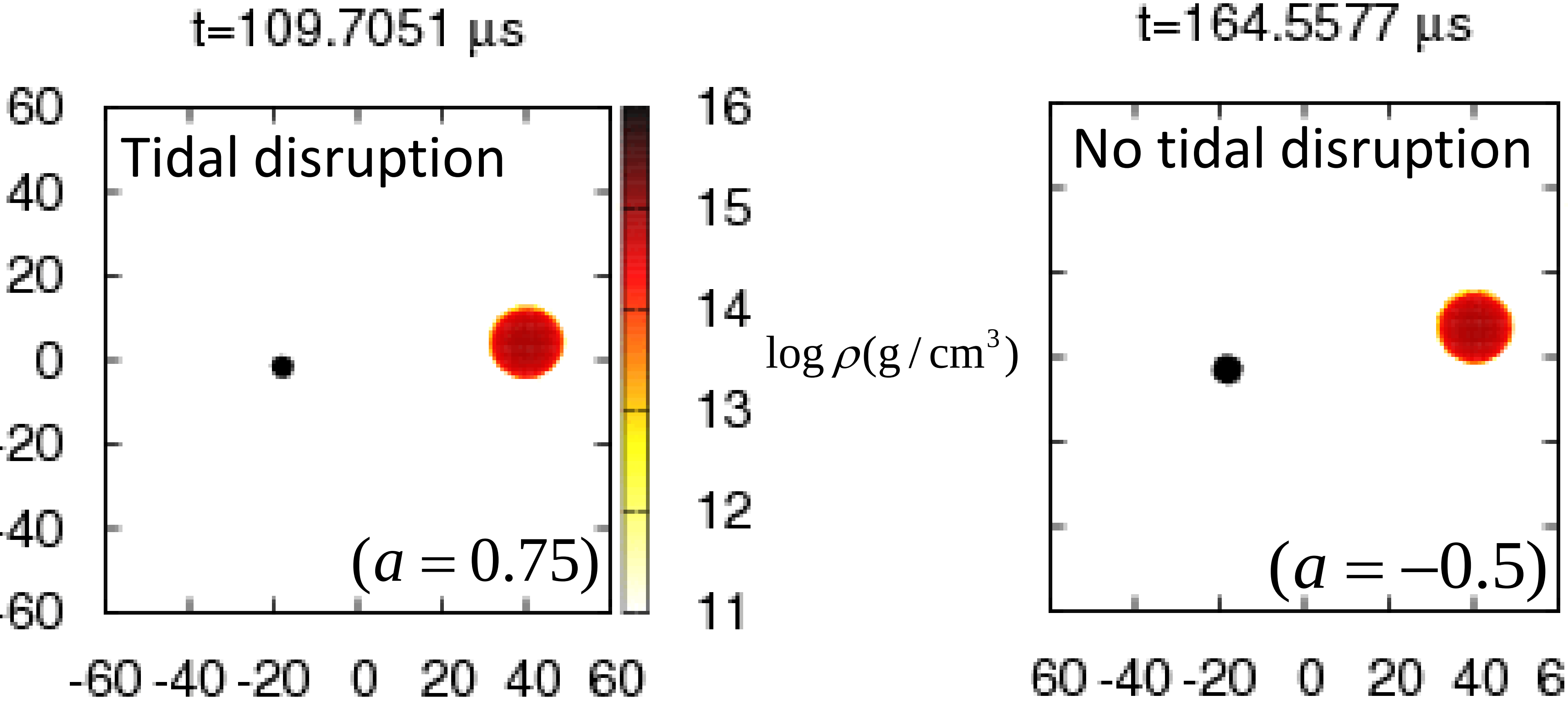


Read+ (2009)

Comparison of tidal disruption

- (only the BH is different in this example)

$$M_{\rm NS}=1.35M_{\rm sol}, M_{\rm BH}=2.7M_{\rm sol}\ (Q=2)$$



t=109.7051 μs

Tidal disruption

$(a=0.75)$

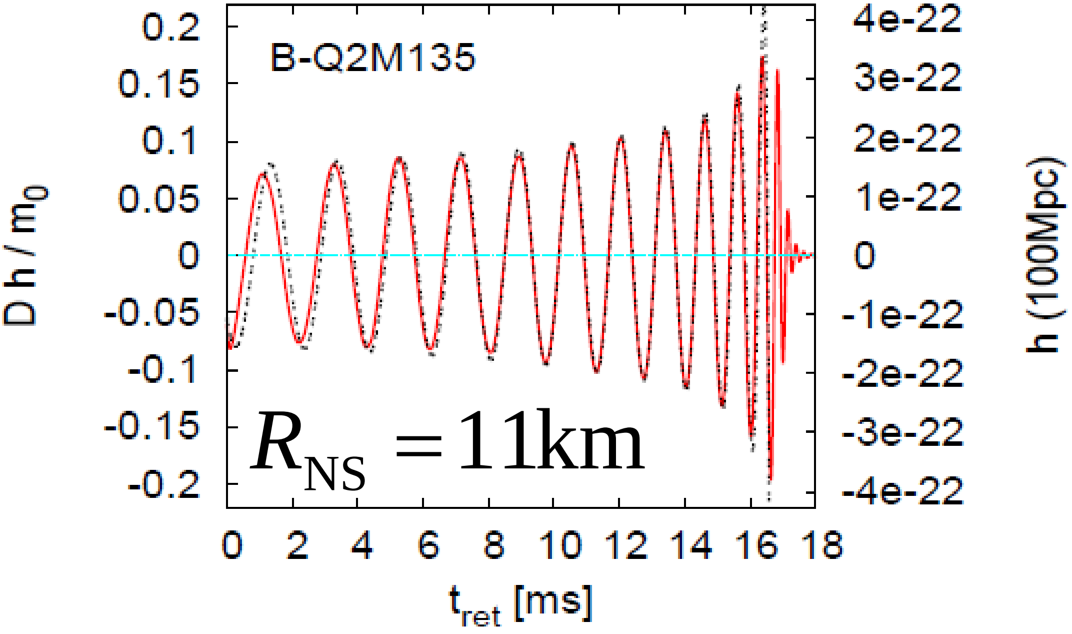
$\log\rho(\mathrm{g/cm^3})$

t=164.5577 μs

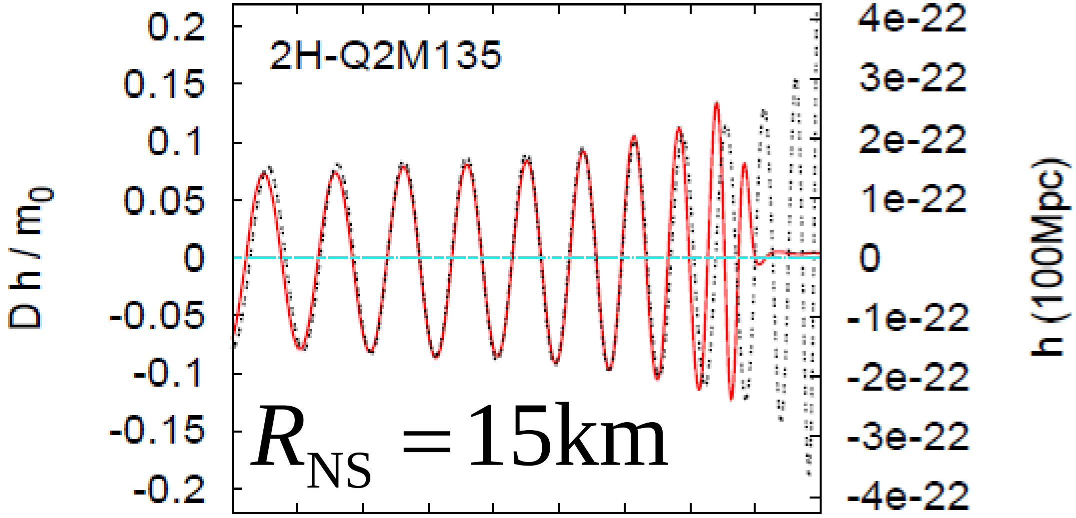
No tidal disruption

$(a=-0.5)$

GWs: differences due to the EOS



$R_{\mathrm{NS}} = 11\mathrm{km}$



$R_{\mathrm{NS}} = 15\mathrm{km}$

$$M_{\mathrm{BH}} = 2.7 M_{\mathrm{sol}}$$

$$M_{\mathrm{NS}} = 1.35 M_{\mathrm{sol}}$$

$$a = 0$$

Top: soft EOS

the small NS radius

weak disruption

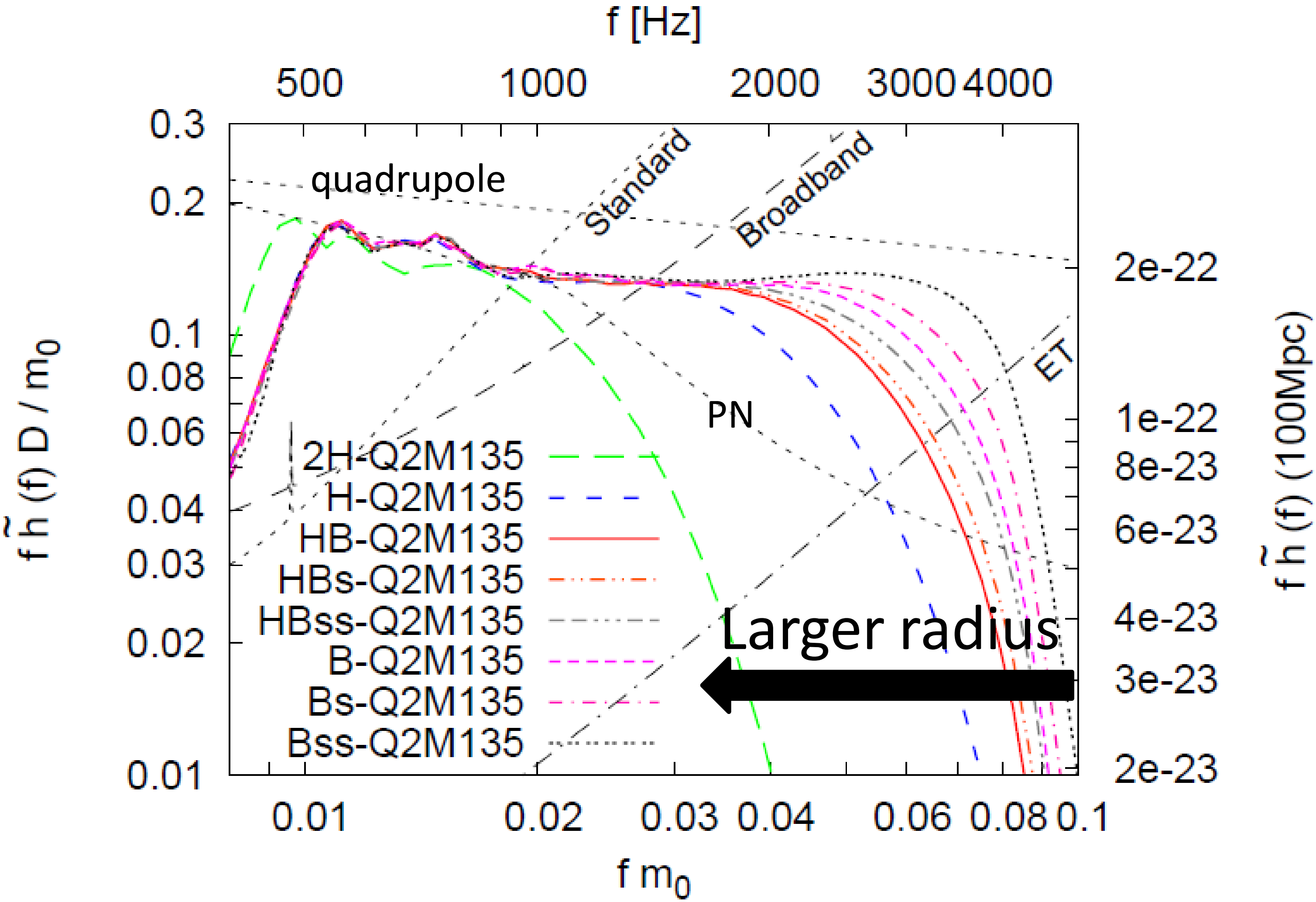
Bottom: stiff EOS

the large NS radius

strong disruption

The GW spectrum

- $M_{\rm NS} = 1.35 M_{\rm sol}, M_{\rm BH} = 2.7 M_{\rm sol}\ (Q = 2), a = 0$



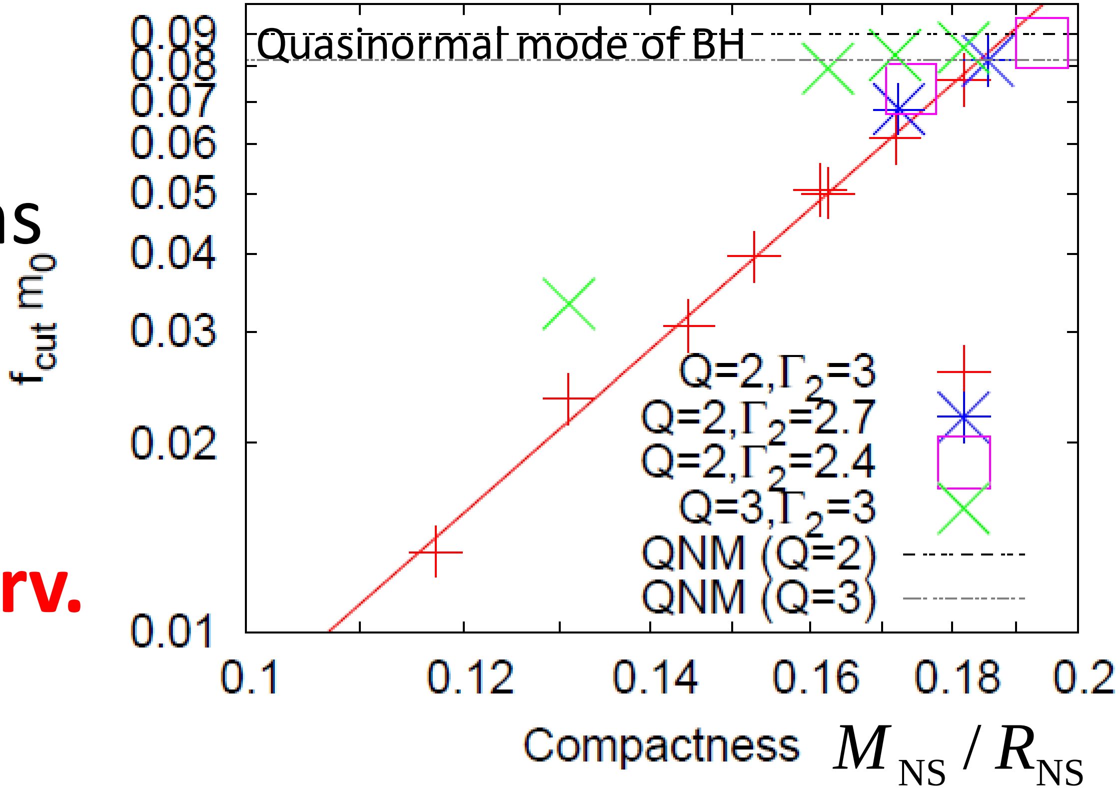
Compactness vs cutoff frequency

- $a = 0$ cases
- Strong correlations

  = **The NS radius**

  can be read off

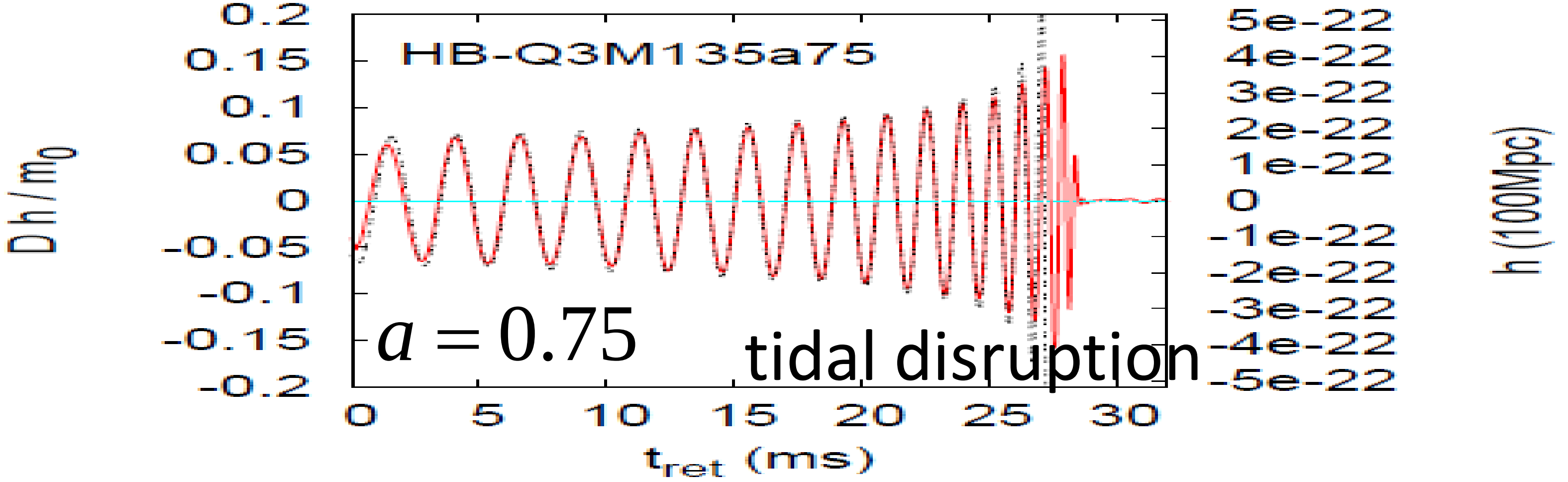
  from GW observ.



- $f_{cut} m_0 \propto C^4$ when tidal disruption occurs
- $Q \geq 3 \, (M_{\mathrm{BH}} \geq 4.05 M_{\mathrm{sol}})$ seems to bring no tidal disruption -> an unrealistically story?

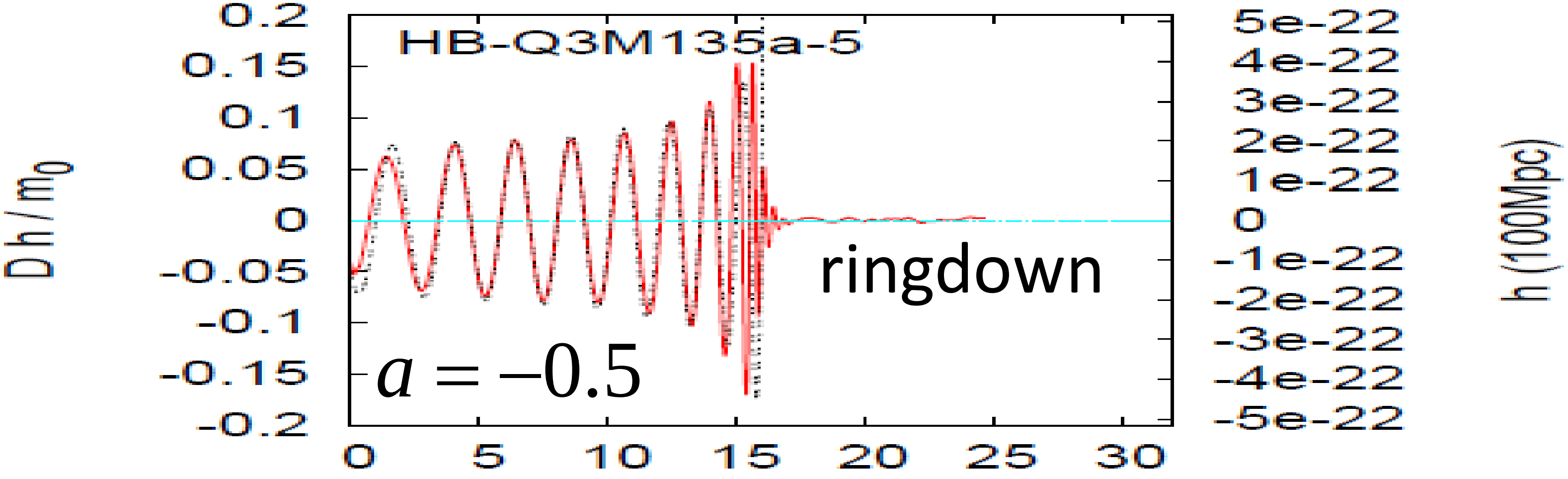
GWs: difference due to the BH spin

- Strong if the BH spin is parallel to orbit.ang.mom.



$a = 0.75$

tidal disruption

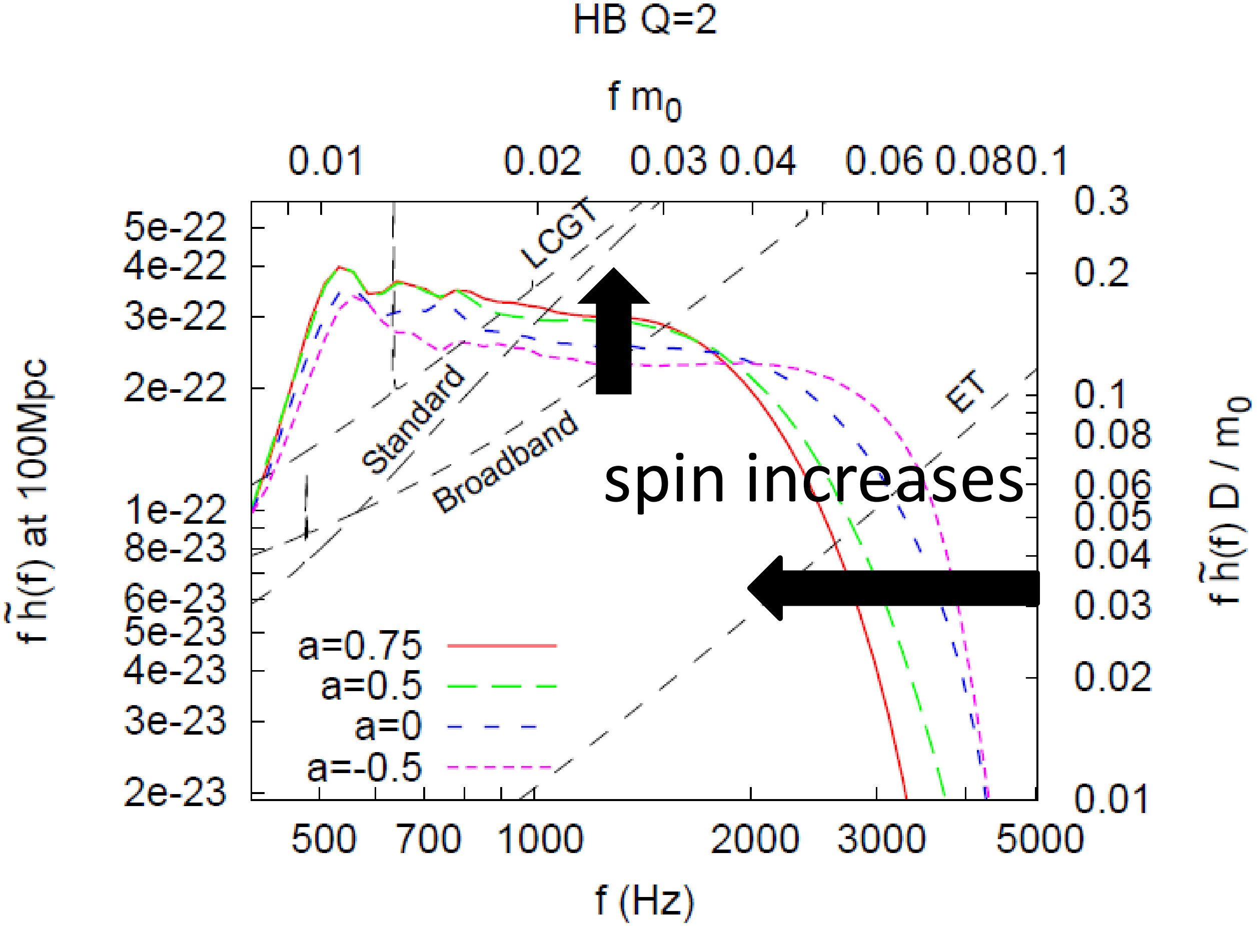


$a = -0.5$

ringdown

Changes of spectra due to the spin

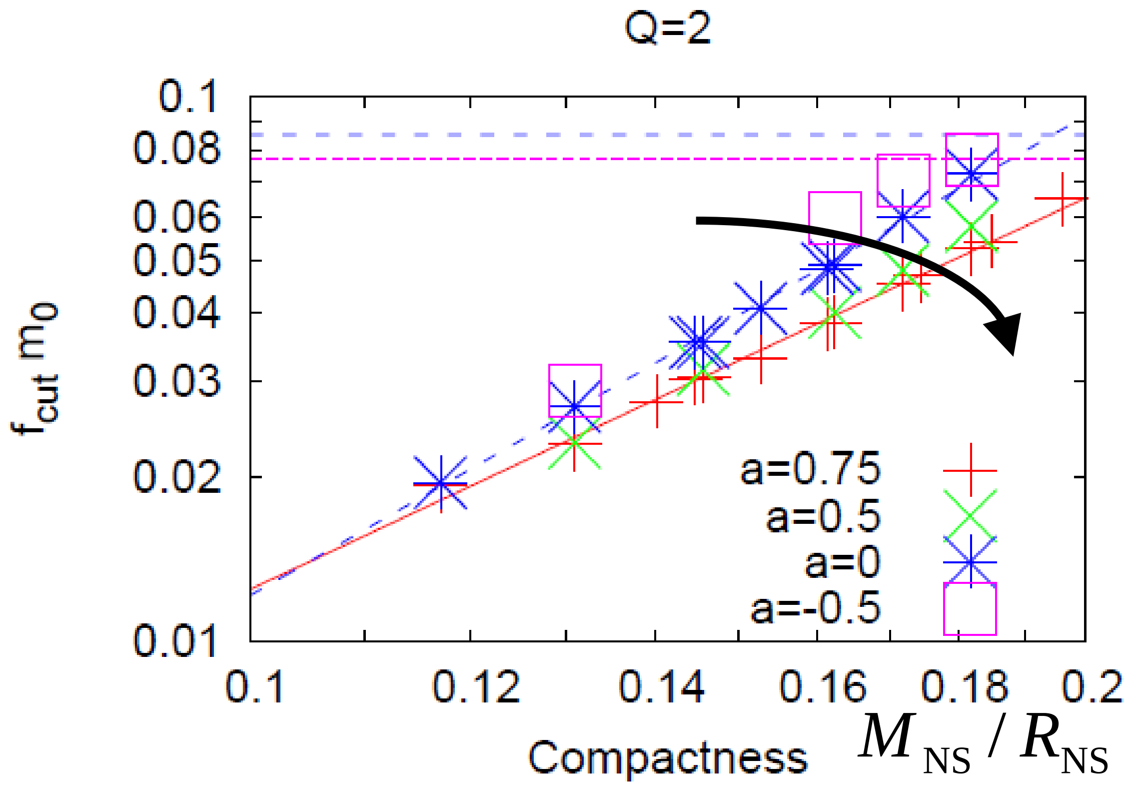
- The large amplitude at low frequency
- Cutoff occurs at lower frequency



Compactness – cutoff frequency

- BH spins lower the cutoff frequency

  - the low frequency is preferred from observ.

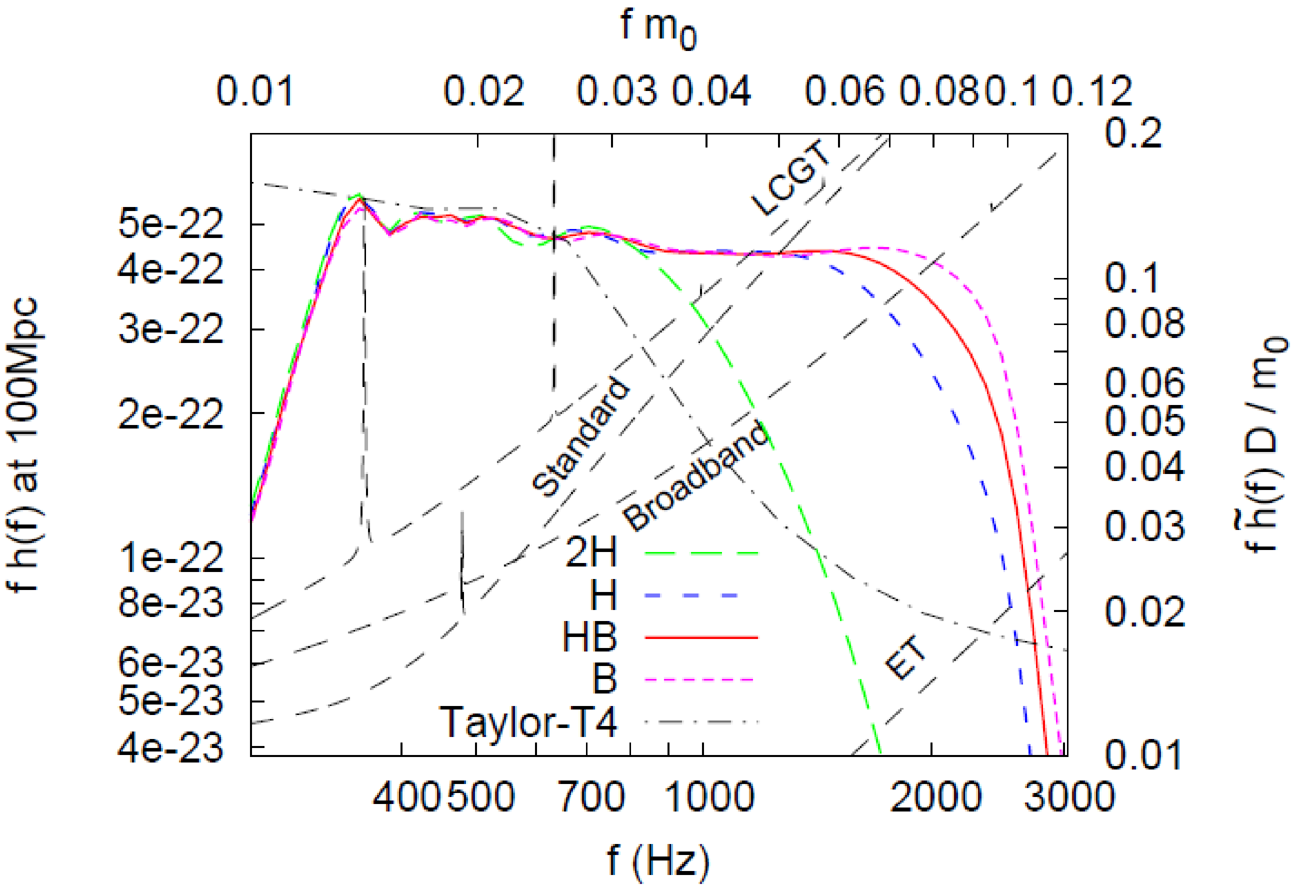


quasinormal modes for different BH spins

we have to know the BH spin using inspiral GWs

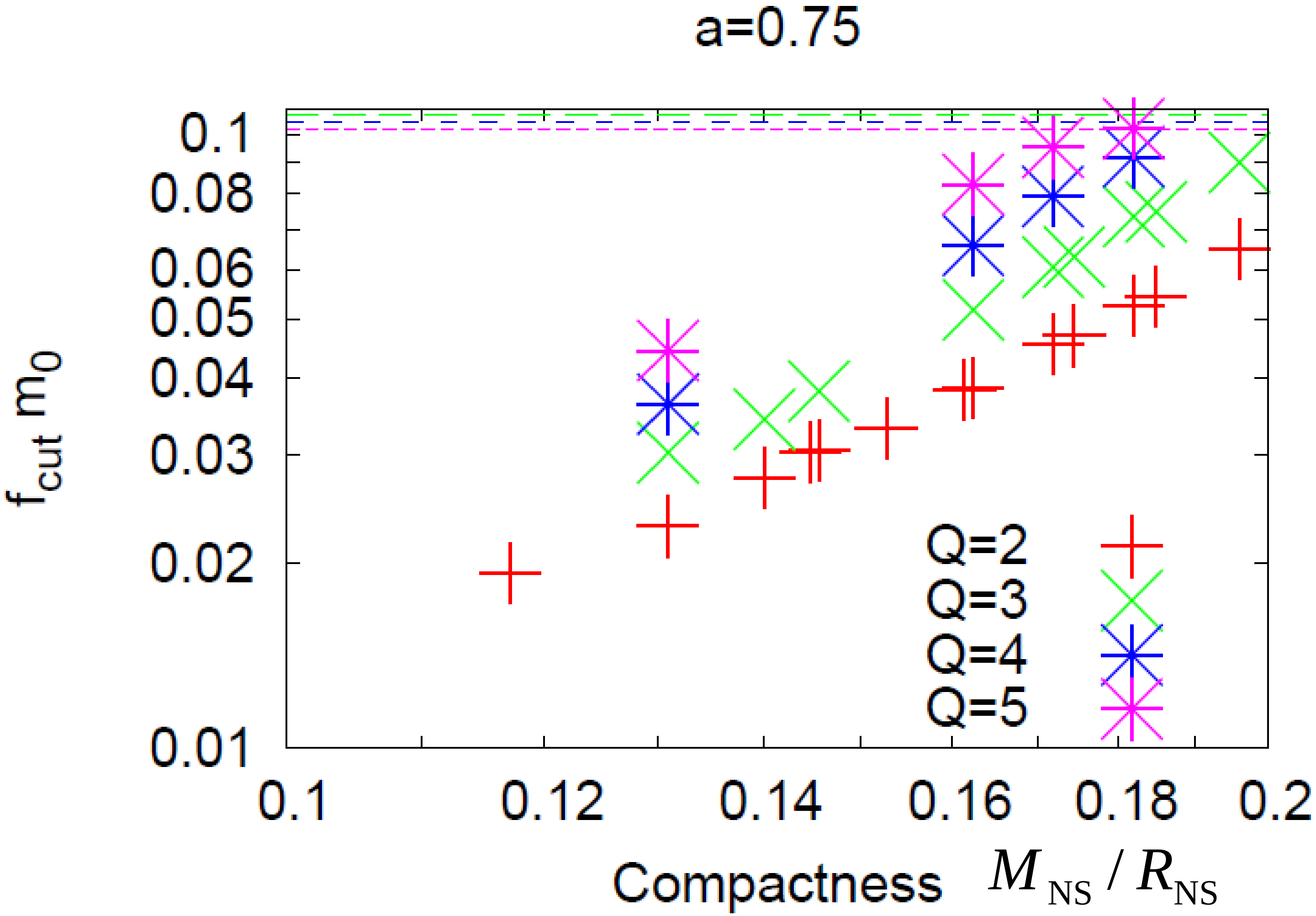
The GW spectrum for Q=5

- In this case, $M_{\mathrm{BH}} = 6.75 M_{\mathrm{sol}}$ -> maybe realistic
- Adv. LIGO/LCGT will observe the spectrum cutoff



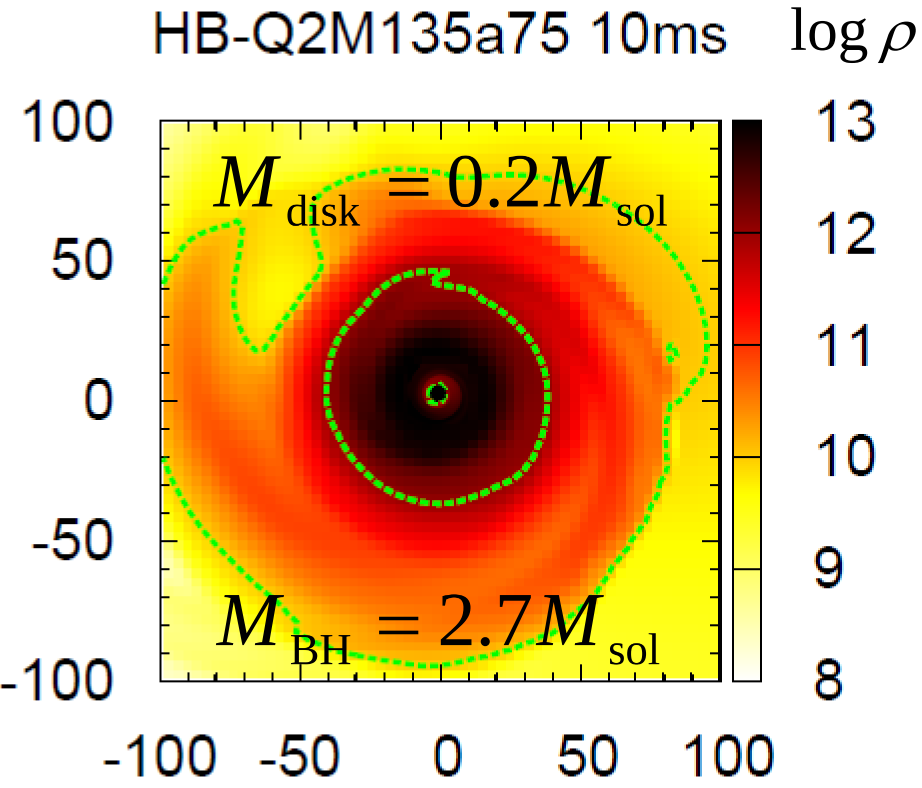
Cutoff frequencies for a=0.75

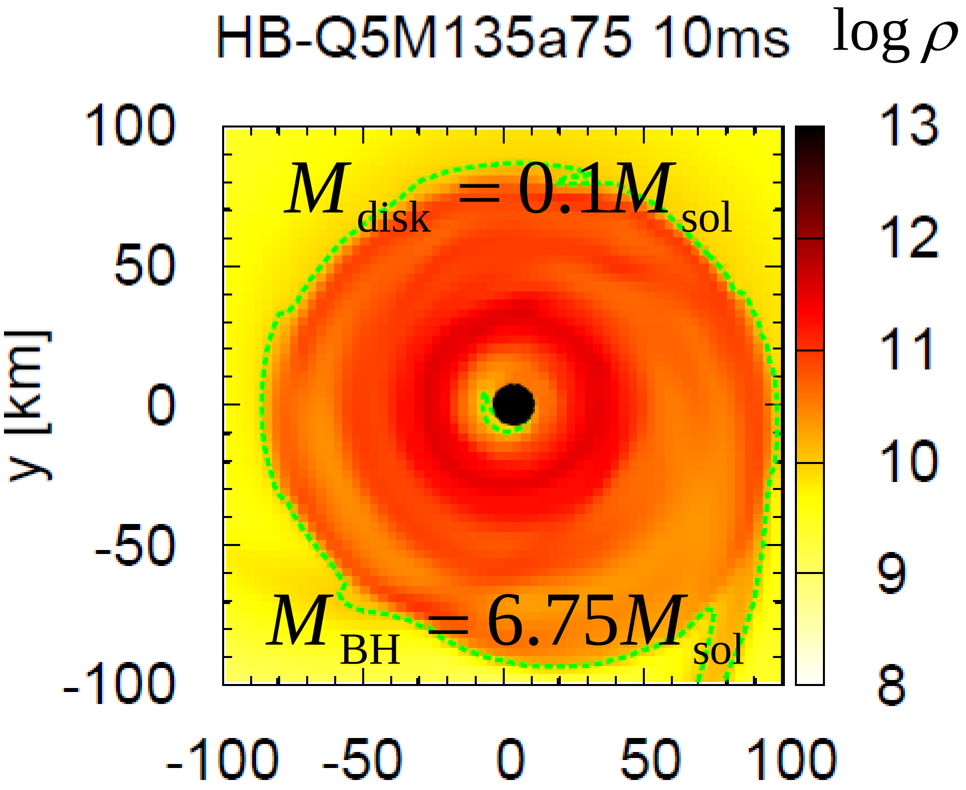
- Massive (realistic) BH-NS will tell us the NS EOS



Formed accretion disks

- The mass of the disk can exceed $0.1M_{\mathrm{sol}}$ when the tidal disruption is strong





Summary

- We computed gravitational waves from black hole-neutron star binaries by numerical relativity.
- Gravitational waves from black hole-neutron star binaries will tell us the equation of state of neutron star matter, especially when tidal disruption occurs.
- Astrophysically realistic black hole-neutron star binaries will also tell us the equation of state if the BH spin is moderately strong.
- The mass of the accretion disk can be sufficiently high to bring the short-hard gamma-ray burst.

Future work

- More waveforms for generic configurations

  - an urgent task for the GW astronomy

- Incorporate neutrinos and magnetic fields

  - essential for GRBs, multi-messenger astron.

- Analyze how accurately we can know the EOS

  - the Fisher analysis using numerical relativity

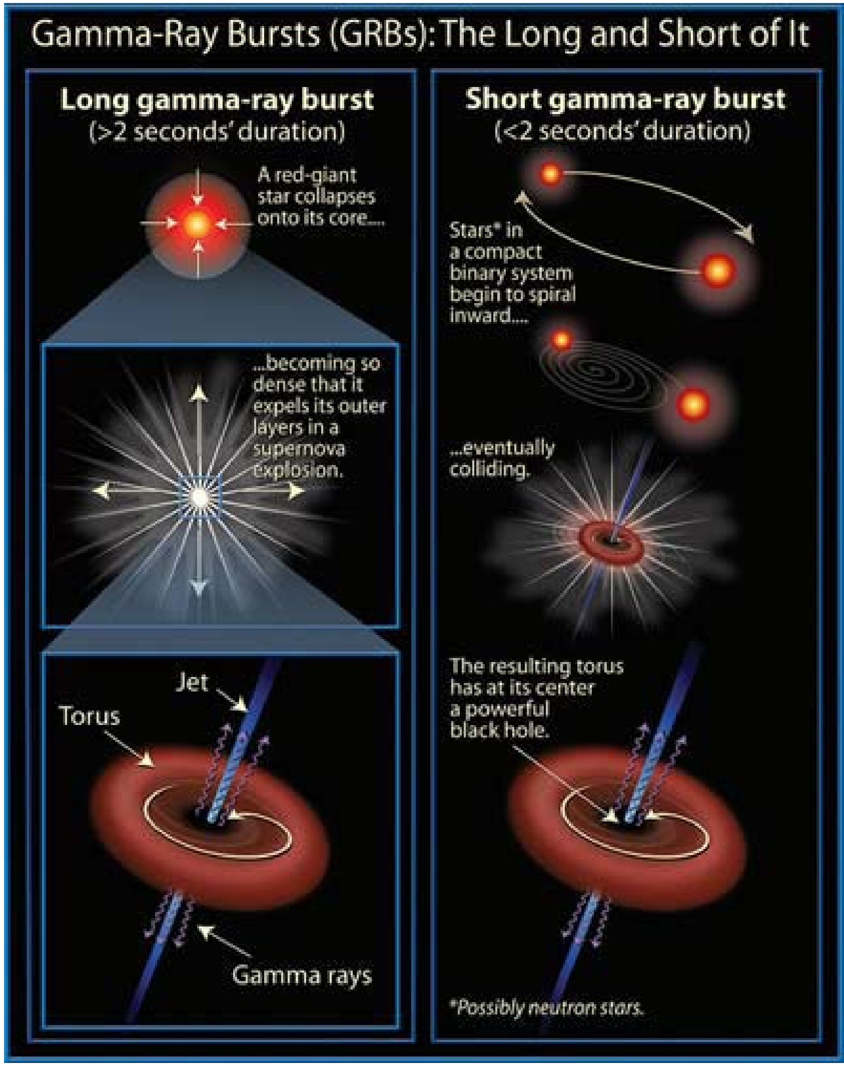
Lackey, KK, Shibata, Brady, Friedman PRD submitted

appendix

Short-hard gamma-ray burst

- Release $10^{49-51}\,\mathrm{erg}$
  within $\sim 2\,\mathrm{s}$
  - jet opening angle -> ?
- BH-accretion disks?
  - LGRB: “collapsar” model
  - SGRB: merger scenario?
    BH-NS or NS-NS

  Is a massive disk formed?



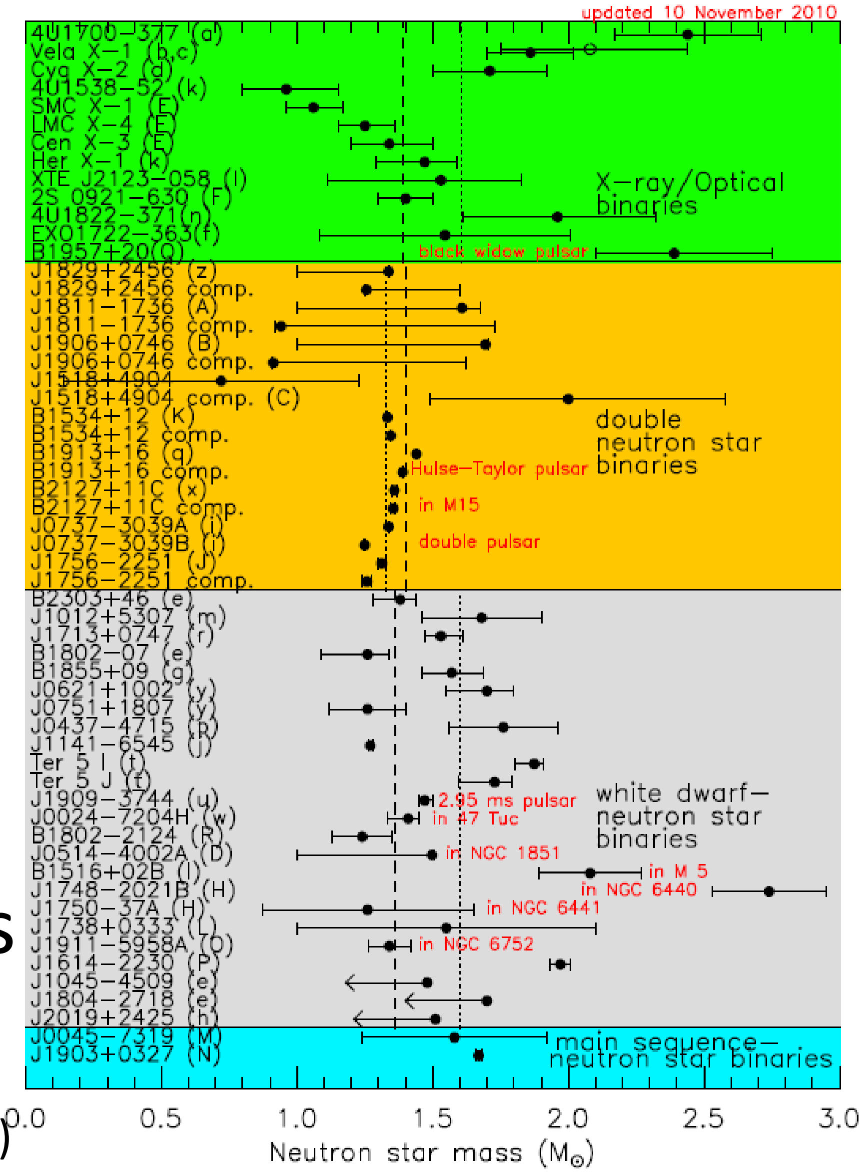
From encyclopedia of science

The mass of the neutron star

- EOSs are constrained by the NS maximum mass, recently 1.97Mo found
- Radius measurement is fairly difficult

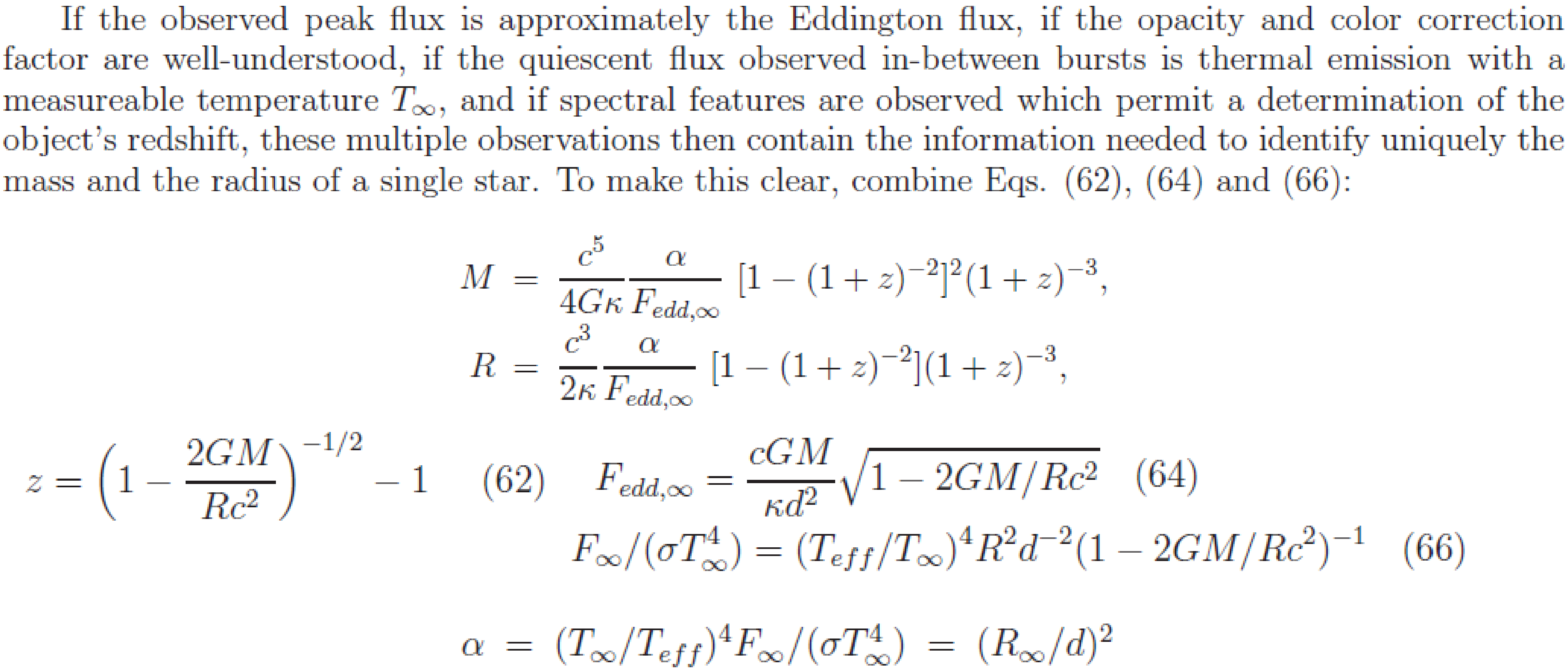
  \- degeneracy w/ distance

  \- rad./atmosphere models



Lattimer, Prakash (2010)

Lattimer & Prakash (2007)



If the observed peak flux is approximately the Eddington flux, if the opacity and color correction factor are well-understood, if the quiescent flux observed in-between bursts is thermal emission with a measureable temperature T_∞, and if spectral features are observed which permit a determination of the object's redshift, these multiple observations then contain the information needed to identify uniquely the mass and the radius of a single star. To make this clear, combine Eqs. (62), (64) and (66):

$$\begin{aligned} M &= \frac{c^5}{4G\kappa}\frac{\alpha}{F_{edd,\infty}}\,[1-(1+z)^{-2}]^2(1+z)^{-3}, \\ R &= \frac{c^3}{2\kappa}\frac{\alpha}{F_{edd,\infty}}\,[1-(1+z)^{-2}](1+z)^{-3}, \end{aligned}$$

$$z = \left(1-\frac{2GM}{Rc^2}\right)^{-1/2} - 1 \quad (62) \qquad F_{edd,\infty} = \frac{cGM}{\kappa d^2}\sqrt{1-2GM/Rc^2} \quad (64)$$

$$F_\infty/(\sigma T_\infty^4) = (T_{eff}/T_\infty)^4 R^2 d^{-2}(1-2GM/Rc^2)^{-1} \quad (66)$$

$$\alpha = (T_\infty/T_{eff})^4 F_\infty/(\sigma T_\infty^4) = (R_\infty/d)^2$$