Gravitational waves from binary neutron star mergers ~measuring the equation of state~

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Ref) K.Hotokezaka, et al. PRD 83. 124008 (2011)

Outline

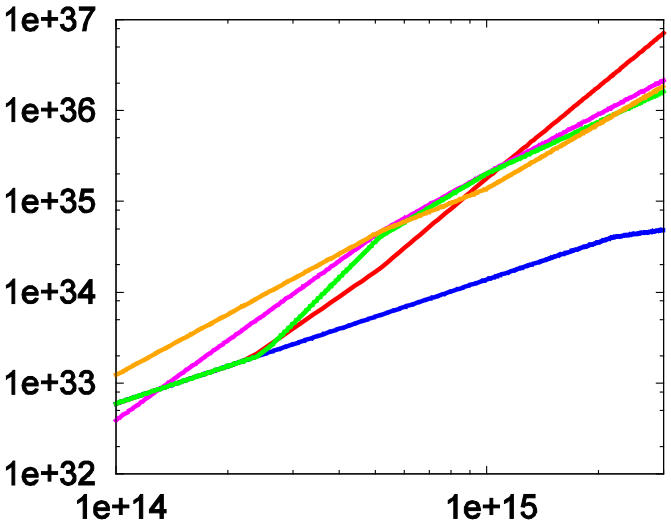
- Introduction
- BNS merger simulations ~dependence on EOS~
- Gravitational waves ~measuring the EOS~
- Summary

Introduction ~Equation of State~

Several candidates of the real EOS
from nuclear theory
(e.g. including hyperon, quark ……)

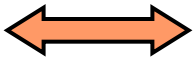
Mass-Radius relation of
neutron star for each EOS

log P $[\mathrm{dyne/cm^2}]$

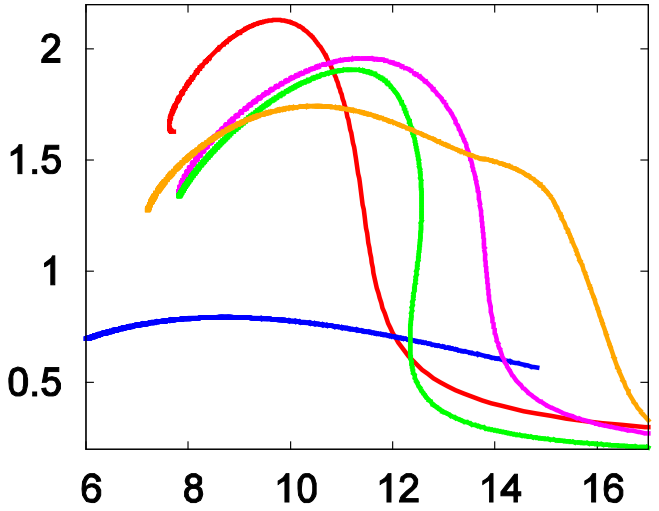


log ρ $[\mathrm{g/cm^3}]$

TOV equation
One to one



M $[M/M_\odot]$



R $[\mathrm{km}]$

Measuring M-R of neutron star simultaneously
⇒ we can construct the EOS !!

Astronomical observation

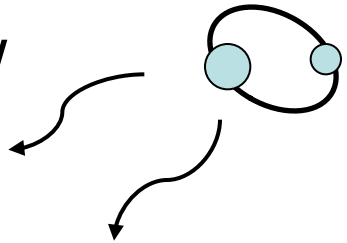
	Mass	Radius	Integrated EOS e.g. Moment of inertia	messenger
Isolated Pulsar	×	×	△	radio~γ
Isolated NS (non Pulsar)	△	△	×	opt～X
Pulsar-NS/WD	◎	×	○	radio
LMXB	△ ~ ○	△ ~ ○	×	X
NS-NS/BH merger	◎	○	○	**GW**

——— : Future expected

Introduction ~Gravitational Wave Astronomy~

Advanced detectors
(2015~)

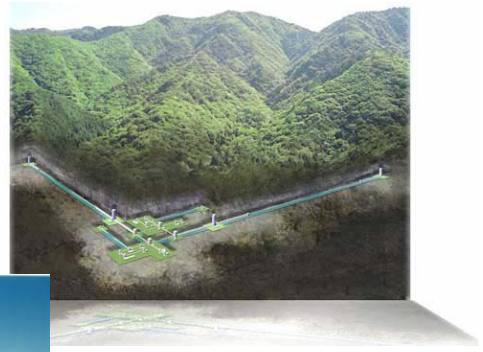
GW



Binary Neutron Star merger
(BNS)

Expected event rate
~10 times / yr

Advanced LIGO



LCGT

Advanced Virgo

- High energy astrophysics
- Supernuclear-density matter

:

Need!
precise prediction of
the gravitational waveform

Numerical Relativity Simulation

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Set up ~Numerical simulations~

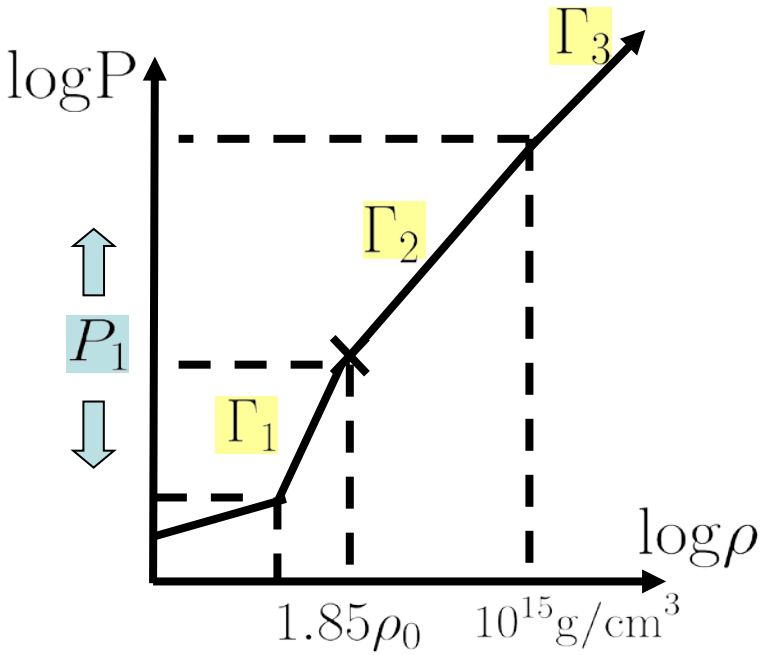
- Solving Einstein equation & Hydrodynamics (SACRA code)
- Equal mass binary neutron star $M_1 = M_2 = (1.35, 1.4, 1.45 M_\odot)$
- Adapted EOS : $P = P_{\rm cold}(\rho) + P_{\rm th}(\rho, e_{\rm th})$

$P_{\rm cold} = K_i \rho^{\Gamma_i}$ (Piecewise-polytropic EOS. Read et al. 2009)

for systematical study

⇨ Fitting 6 nuclear theory based EOSs

- APR4 npe + 3body
  (Akmal, et al. l 1998)
- Sly npe
  (Douchin and Haensel 2001)
- H3, H4 npeΛΣ…
  (Glendenning and Moszkowski 1991)
- PS nπ
  (Pandharipande and Smith 1975)
- ALF2 npe+quark
  (Alford et al. 2005)

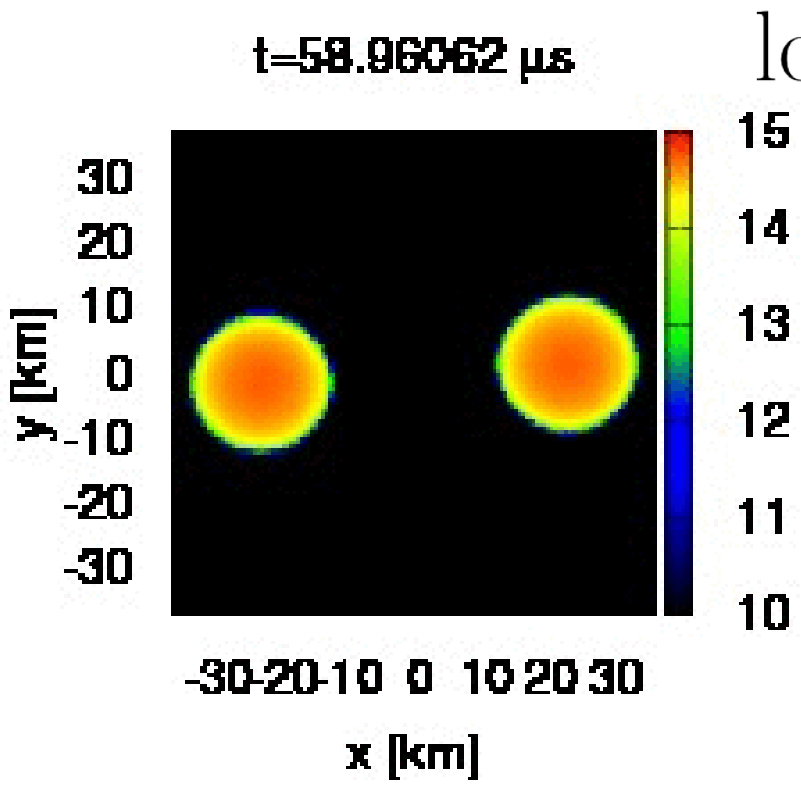


$P_{\rm th} = (\Gamma - 1) e_{\rm th} \rho$ (ideal gas)

Numerical Simulation

EOS = Relativistic Mean Field with Hyperon

Total mass = $2.7M_\odot$ ($M_1 = M_2 = 1.35M_\odot$)



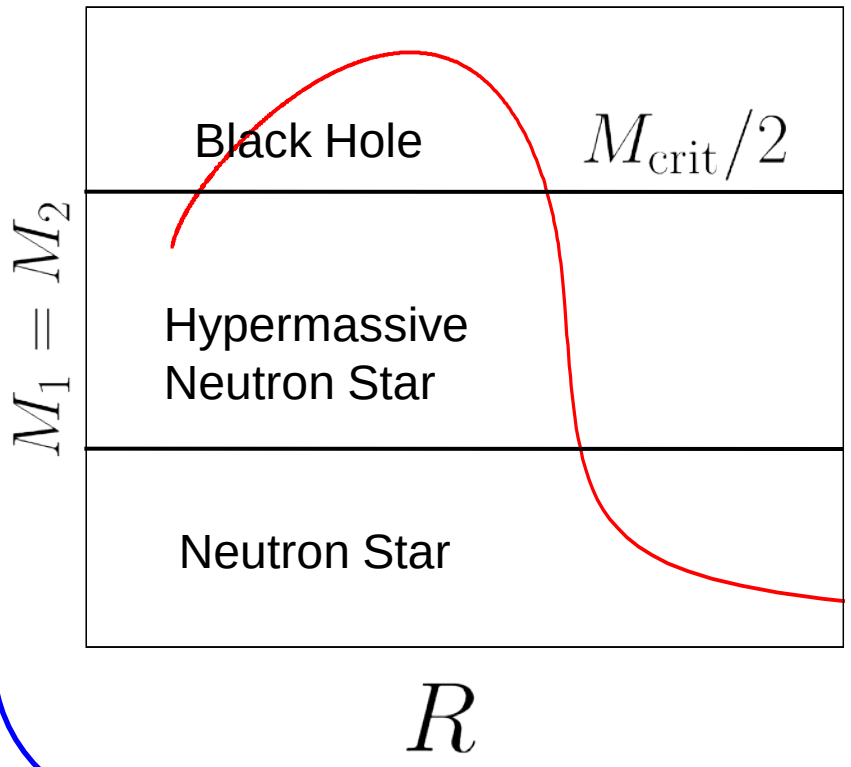
In cgs

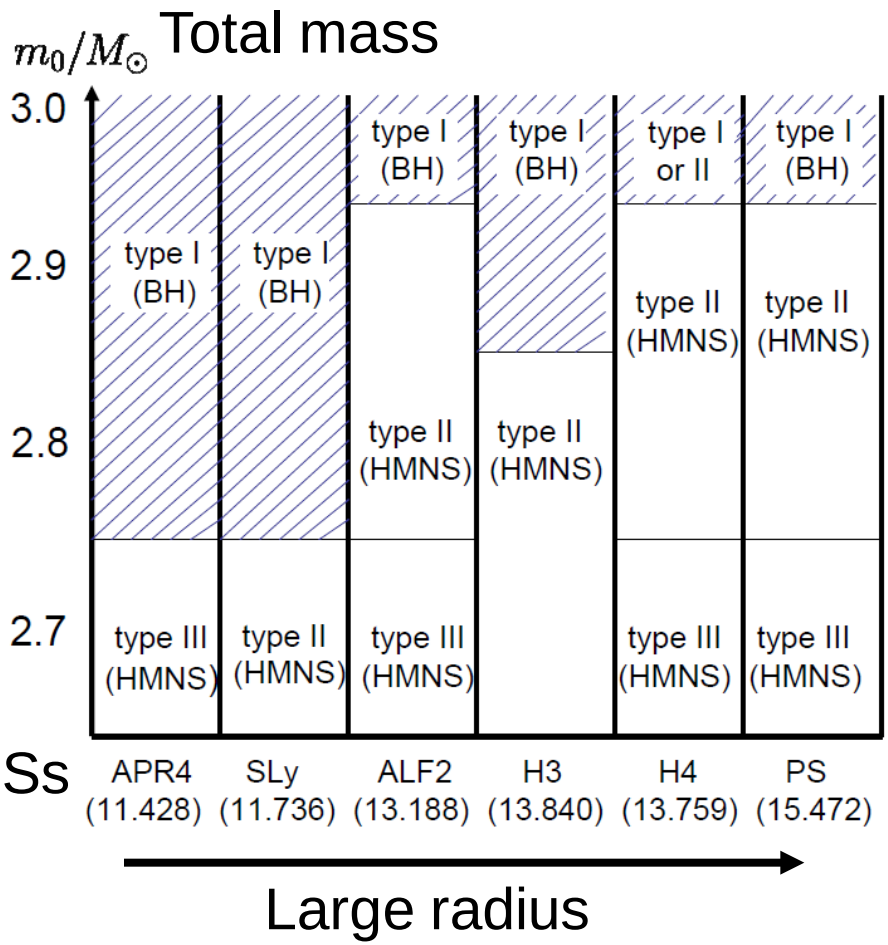
Result: Type of First Remnants

The evolution after the merger strongly depend on the EOS.

$M_{\rm tot} > M_{\rm crit}$

BH is formed promptly





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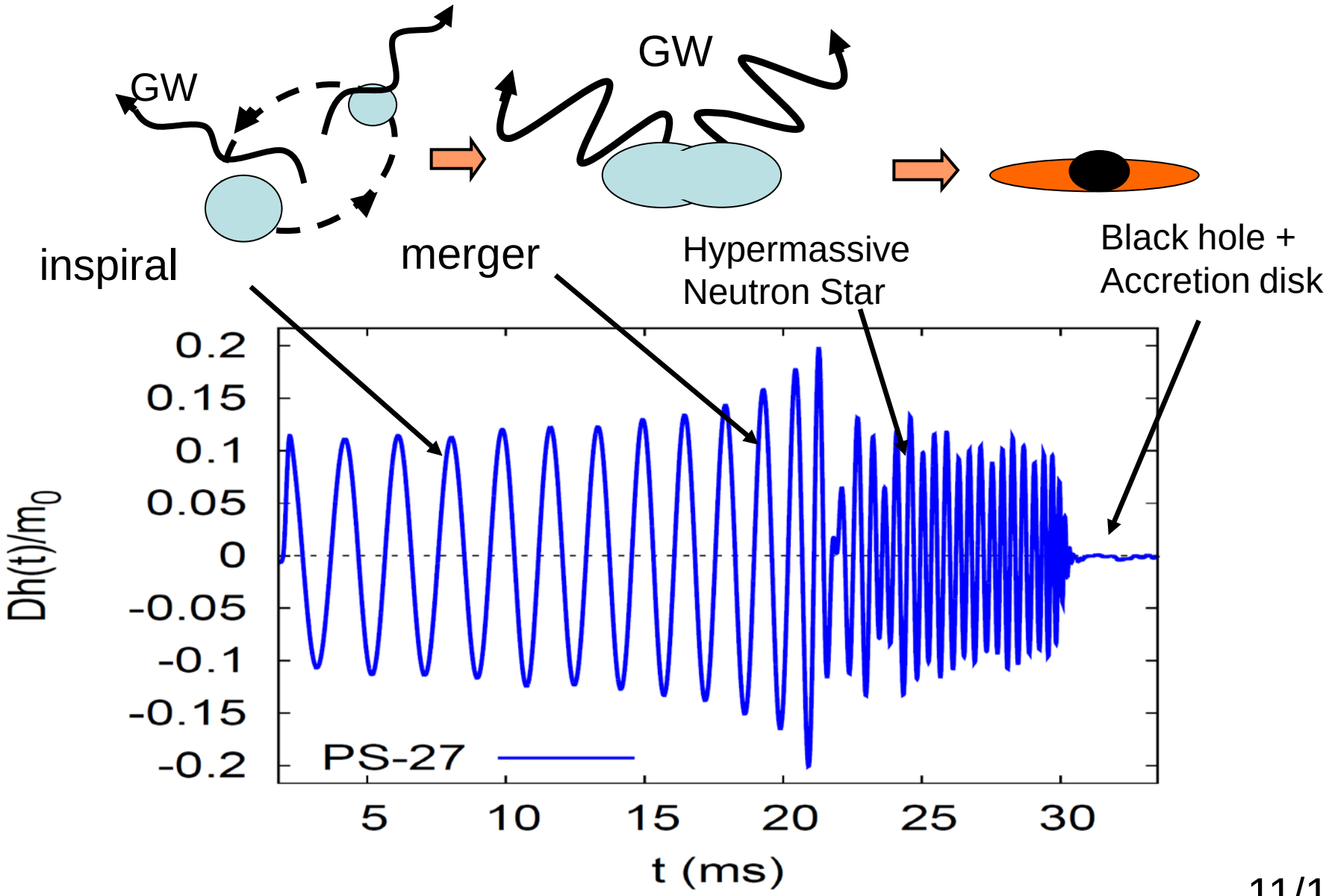
Gravitational waveform of BNS merger



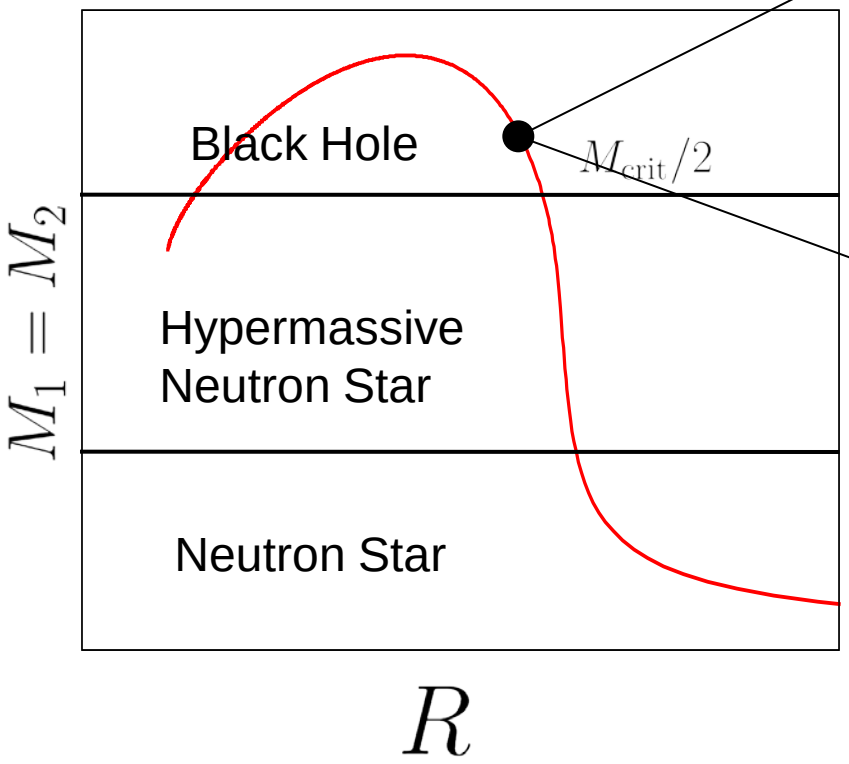
Measuring the EOS with BNS merger

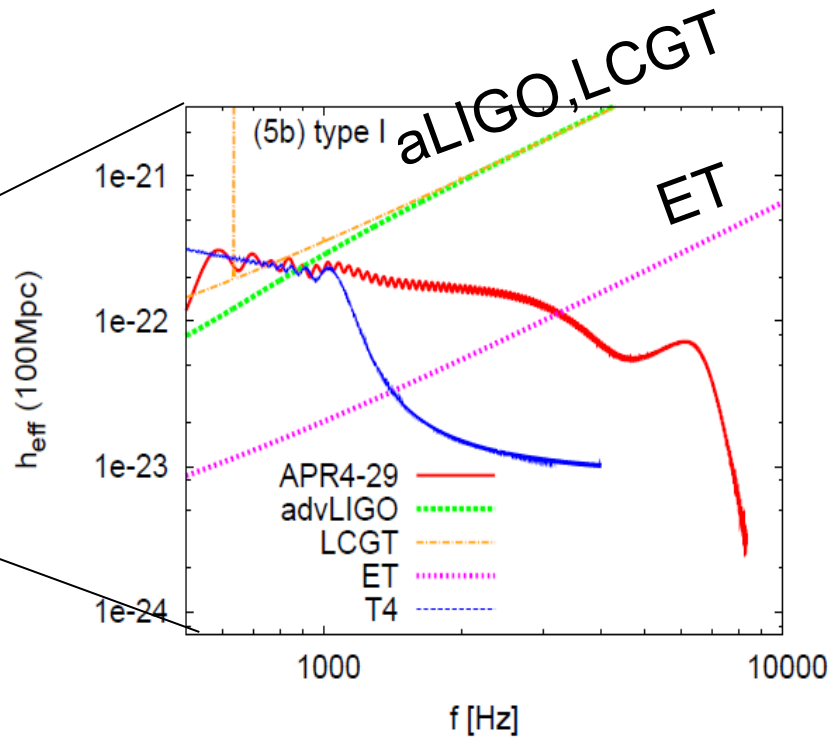
- Inspiral GW ⇒ Mass
  (less than 1% for $1.4M_\odot$ when S/N~10)
  Cutler & Flanagan (1994)
- late inspiral GW ⇒ tidal deformation
- HMNS GW ⇒ rotation and oscillation
- No HMNS GW ⇒ Cut off frequency
  Kiuchi + 2010

GW spectrum & MR relation

$M_{\rm tot} > M_{\rm crit}$

BH is formed promptly



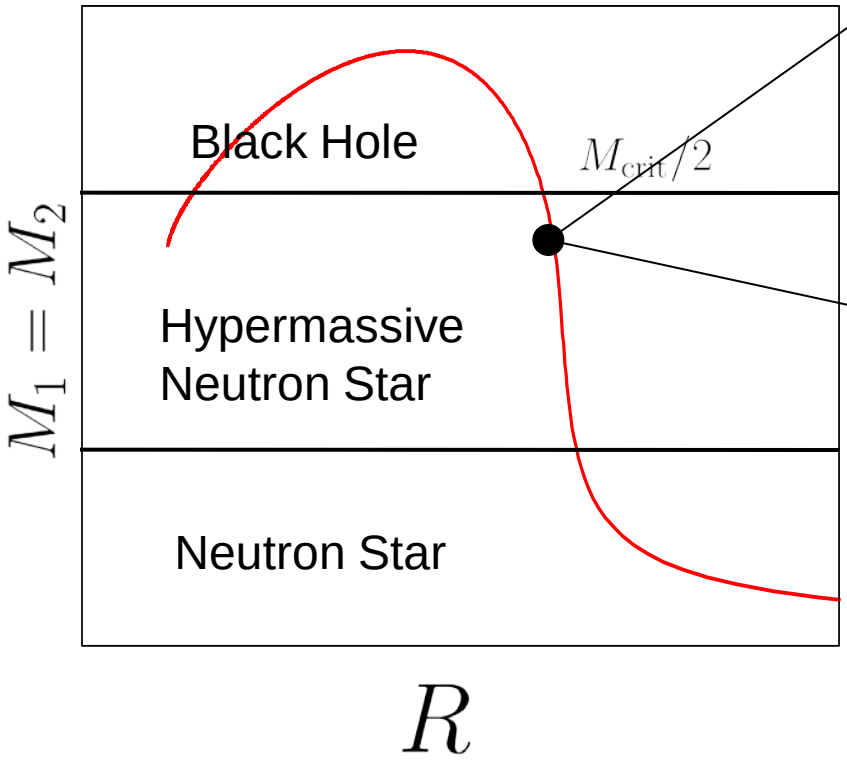


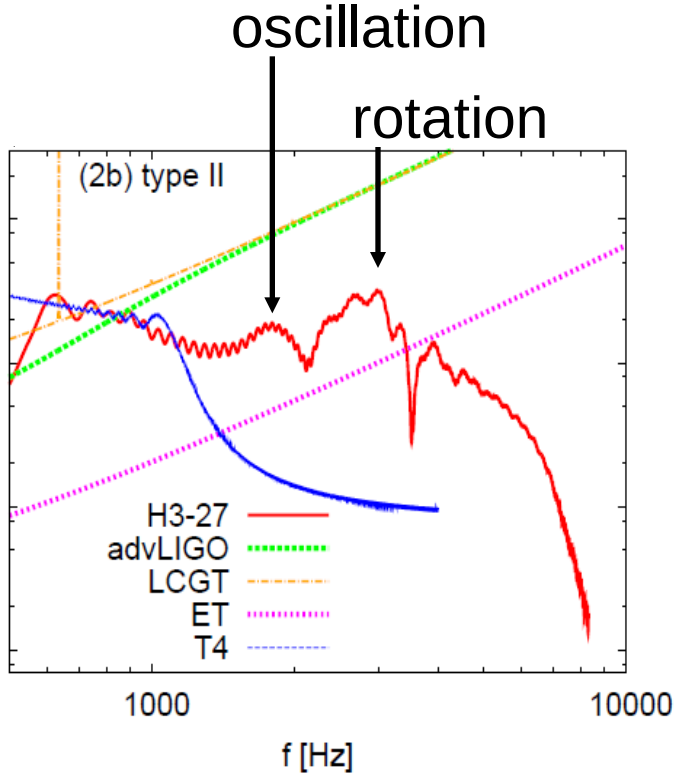
The spectral shape is simple

GW spectrum & MR relation

$M_{\rm tot} < M_{\rm crit}$

HMNS is formed





Short-lived HMNS

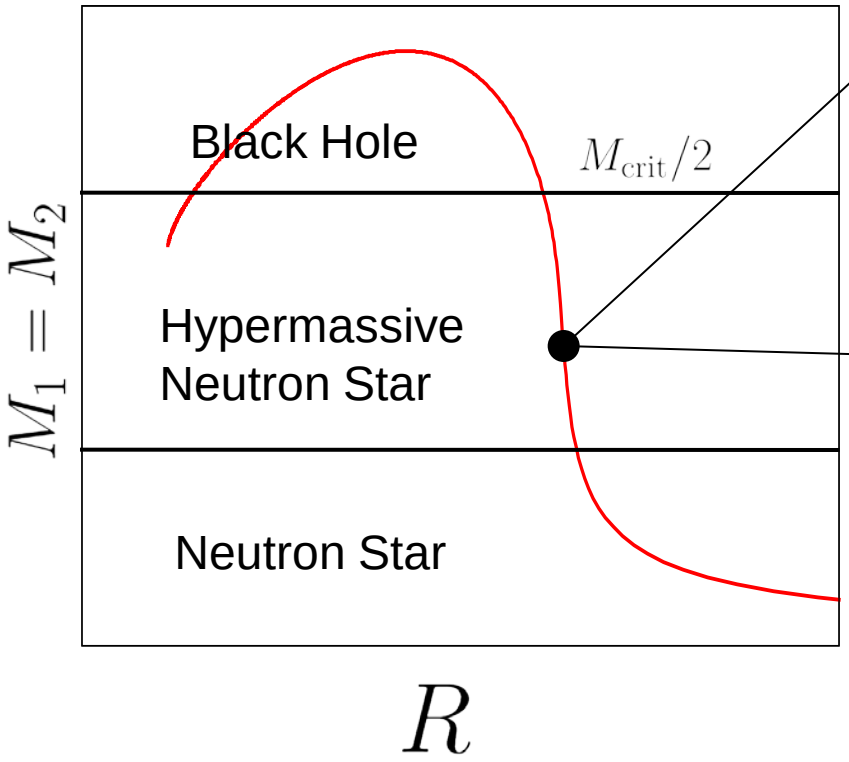
⇒ Spectral shape is complicated

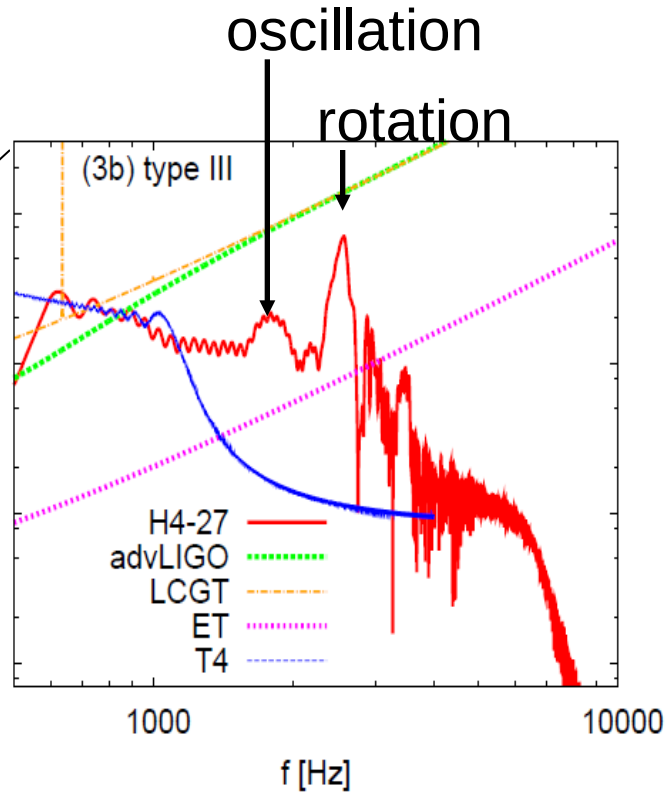
- rotation of the HMNS
- oscillation of the HMNS

GW spectrum & MR relation

$M_{\rm tot} < M_{\rm crit}$

HMNS is formed



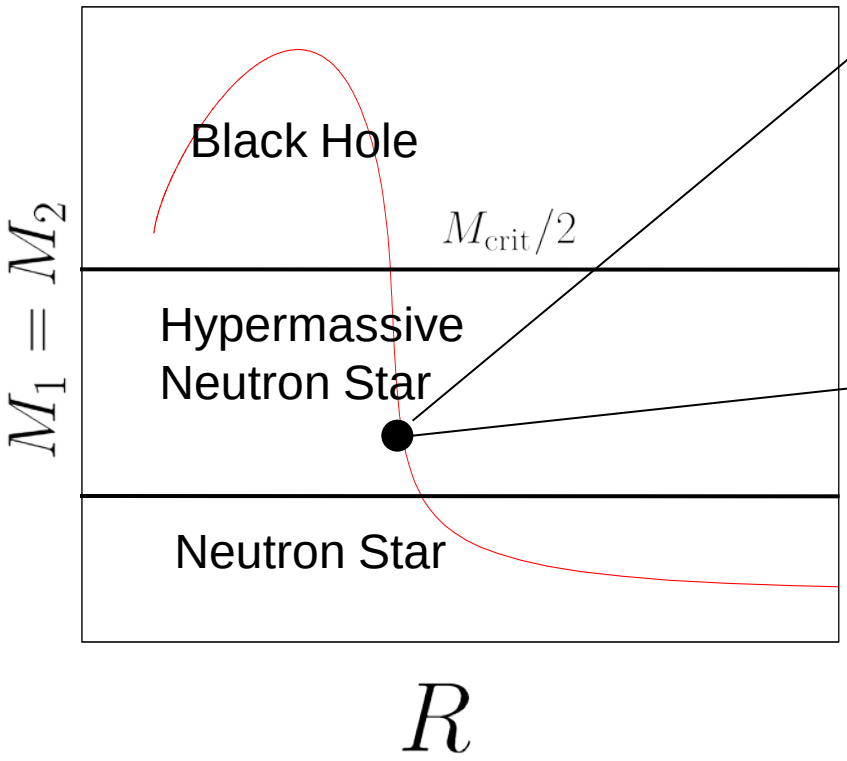


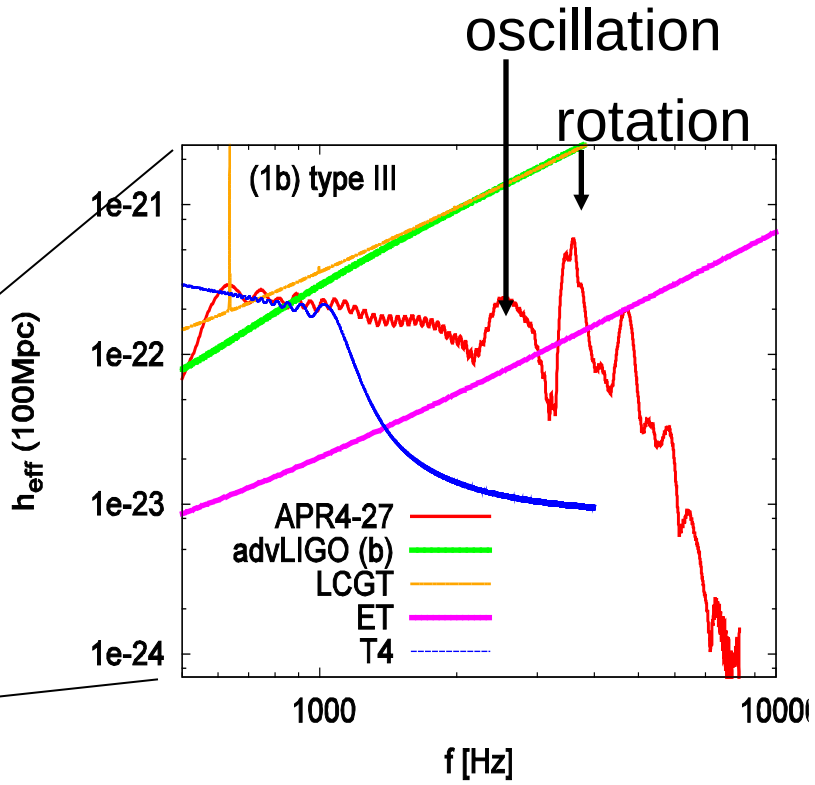
Long-lived HMNS is form

⇒ Peak width is more narrow

GW spectrum & MR relation

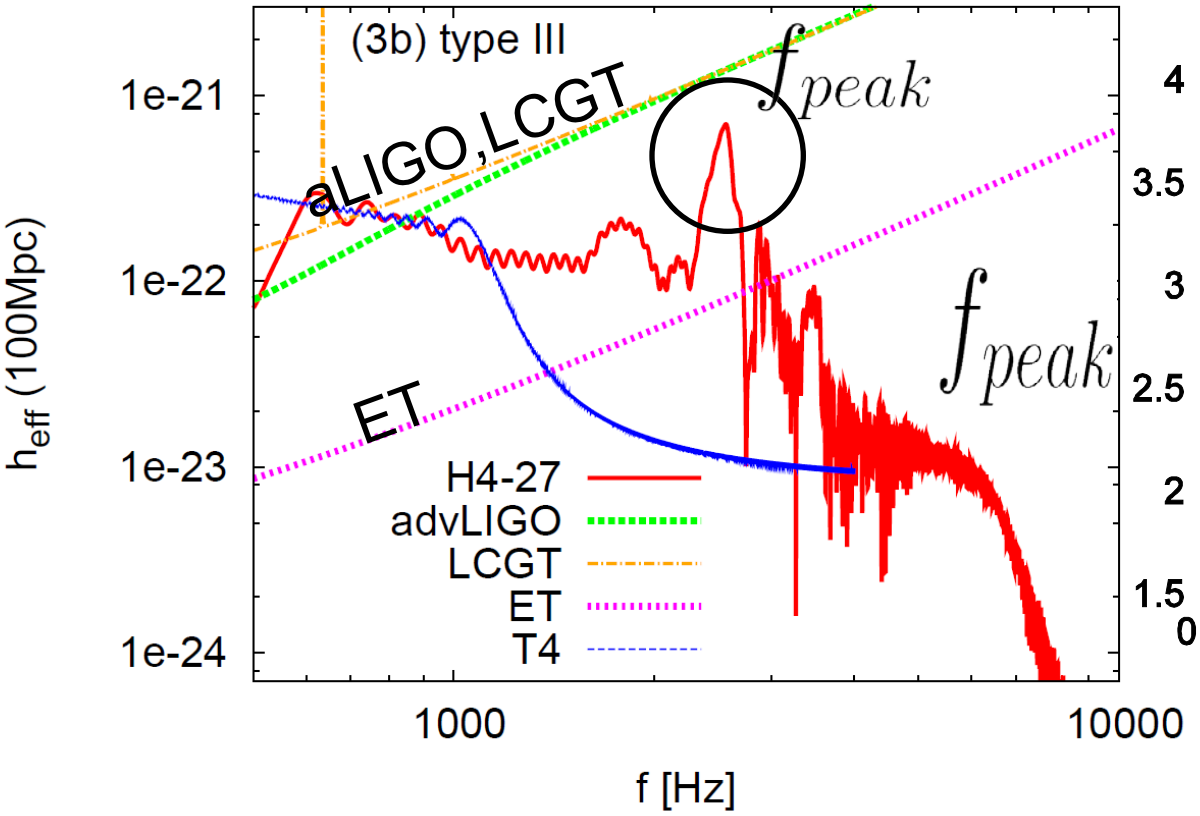
More compact EOS

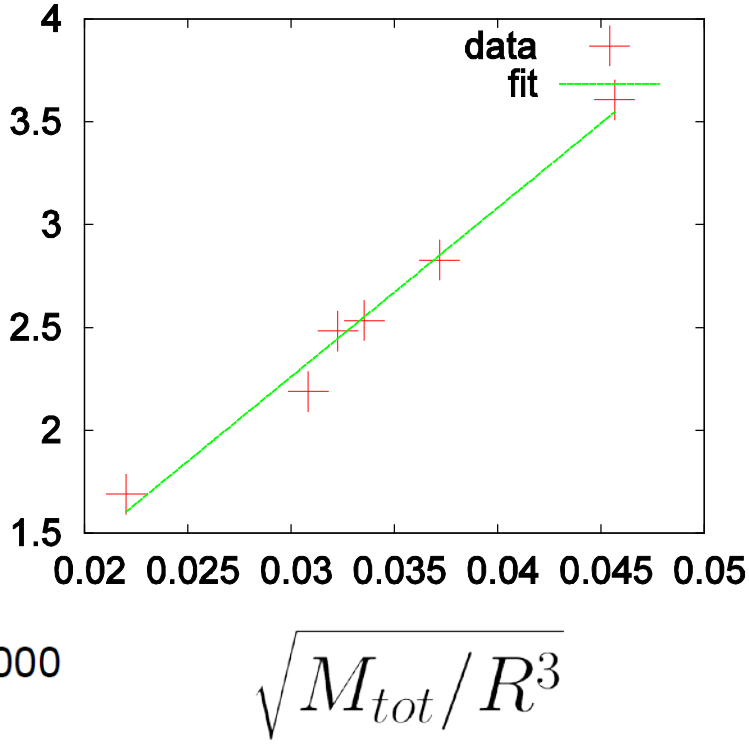




Soft EOS
⇒peak frequency ↑

Result GW spectrum from HMNS





This peak frequency relates to R of the NS

⇨ GWs from a HMNS is useful for constraining on the EOS

See also Bauswein and Janka (2011)

Summary

- the dependence of BNS merger on EOS
  - ⇨ The first remnants of BNS are classified into 3 types
    (1) A black hole is promptly formed
    (2)A short-lived HMNS is formed (lifetime ＜5ms)
    (3)A long-lived HMNS is formed (lifetime ＞5ms)
  - ⇨ A HMNS should be formed in the BNS merger

- Gravitational waves
  - ⇨ The shape of the GW spectrum ⇒ shape depends on 3 types
  - ⇨ The GW spectrum from a HMNS ⇒ f_{peak} and the radius of NS

皆様、研究会お疲れ様でした。