Symposium on
Quarks to Universe in Computational Science (QUCS 2012)

Numerical Relativity Simulations of NS-NS binary merger

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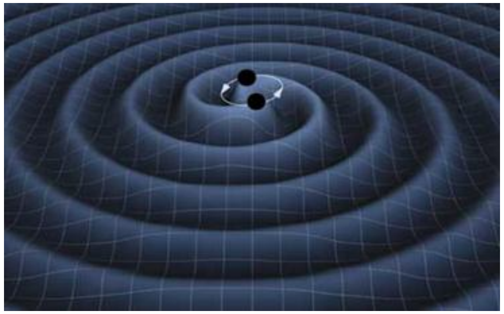
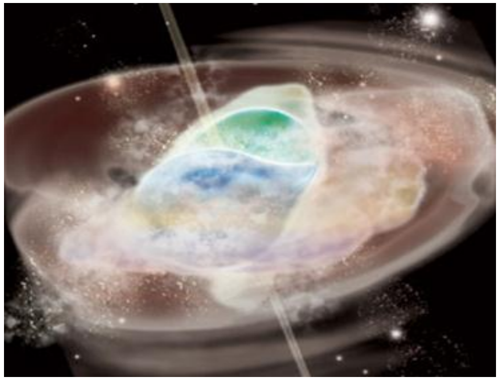
K. Kiuchi, K. Kyutoku, M. Shibata, & Hotokezaka

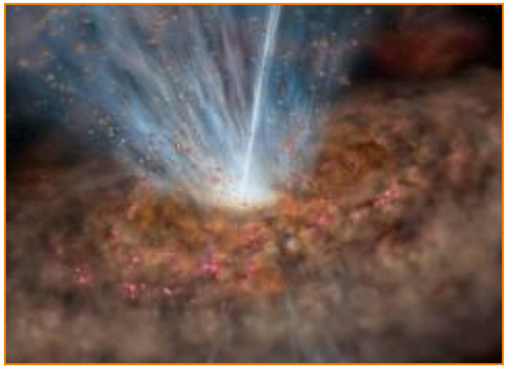
K computer

Why NS-NS mergers are interesting ?

- Promising source of gravitational wave (GW)
  - Direct detection of GW within 5-10 years by adv. LIGO(USA), adv. VIRGO (ITA/FRA), KAGRA (JPN)
- Laboratory for fundamental physics
  - Verification of GR in strong field regime
  - Physics of dense nuclear matter
    - NS-NS merger as a cosmological collider
- Theoretical candidate of gamma-ray bursts (GRB)
  - Central engine : BH + accretion disk
    - Energy source : neutrino pair annihilation ?



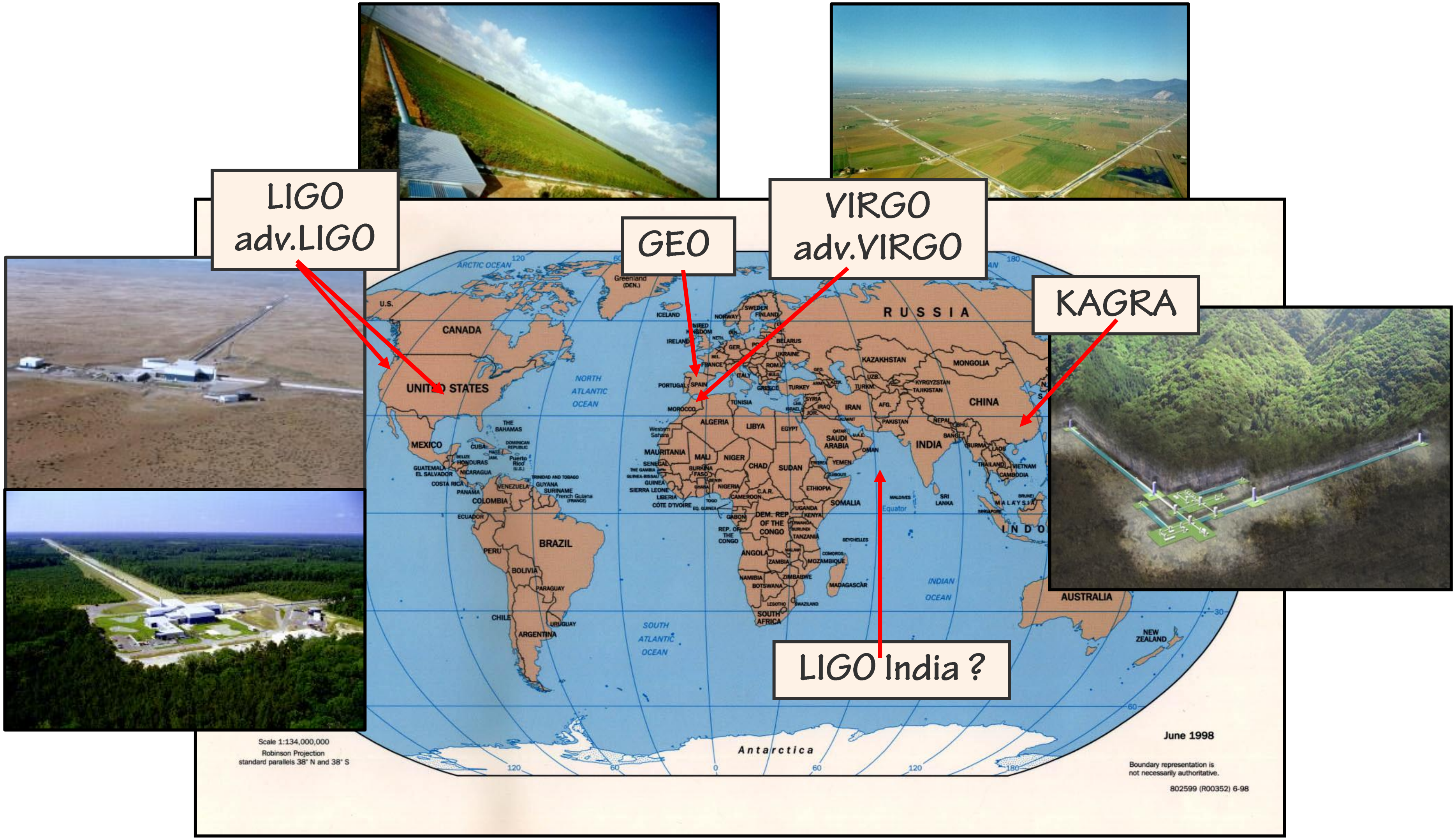




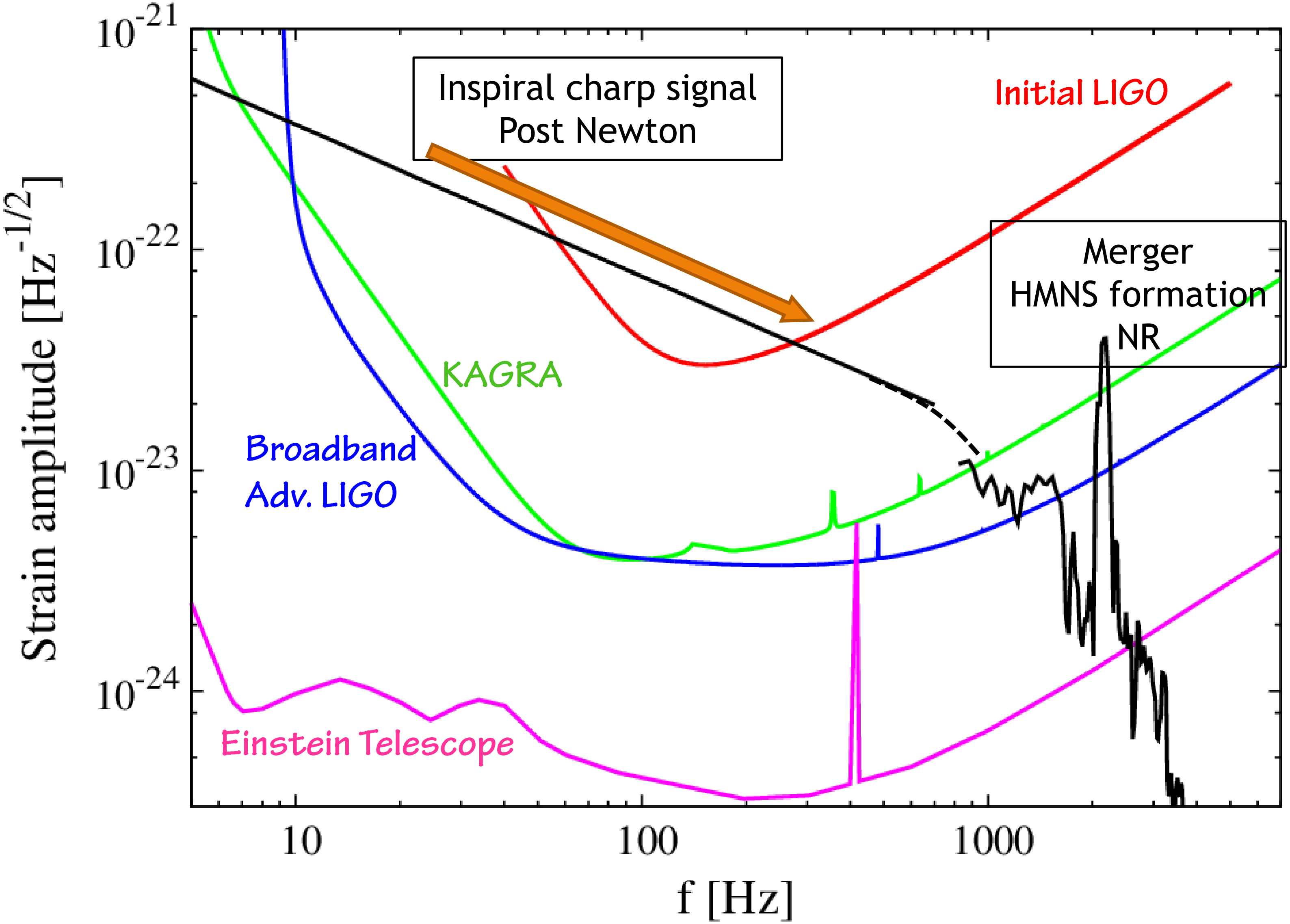
General relativistic gravity is important
Highly nonlinear and dynamical

→ **Numerical Relativity**

Current & up-coming GW detectors



BNS 1.35-1.35Msolar optimal @ 100Mpc



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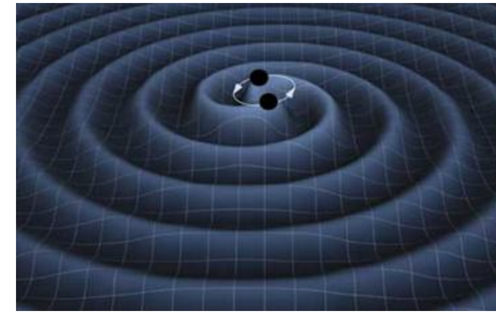
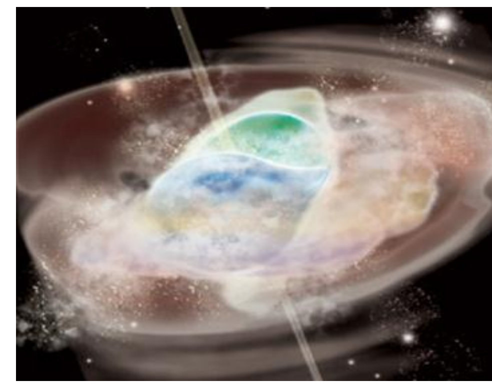
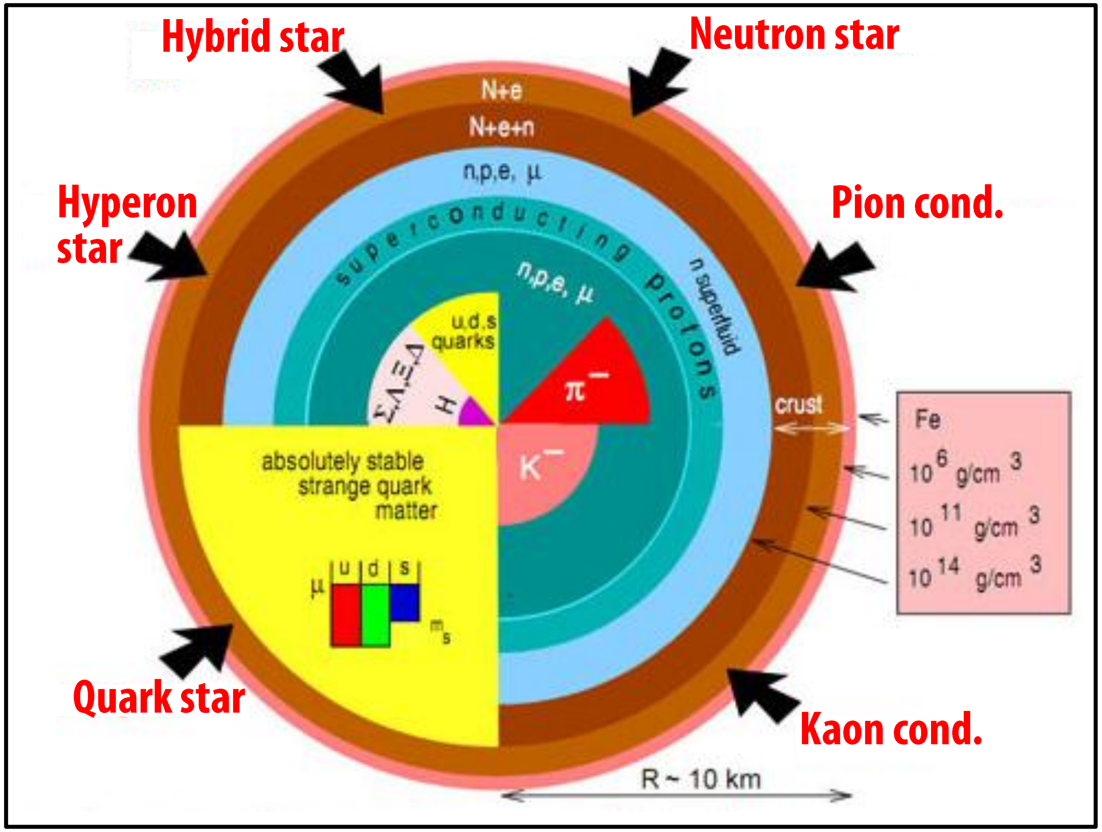




NS structure ⇔ Theoretical model

- For given equation of state, structure of NS is uniquely determined
- Information of NS structure ⇒ constraining EOS model



F. Weber (2005)

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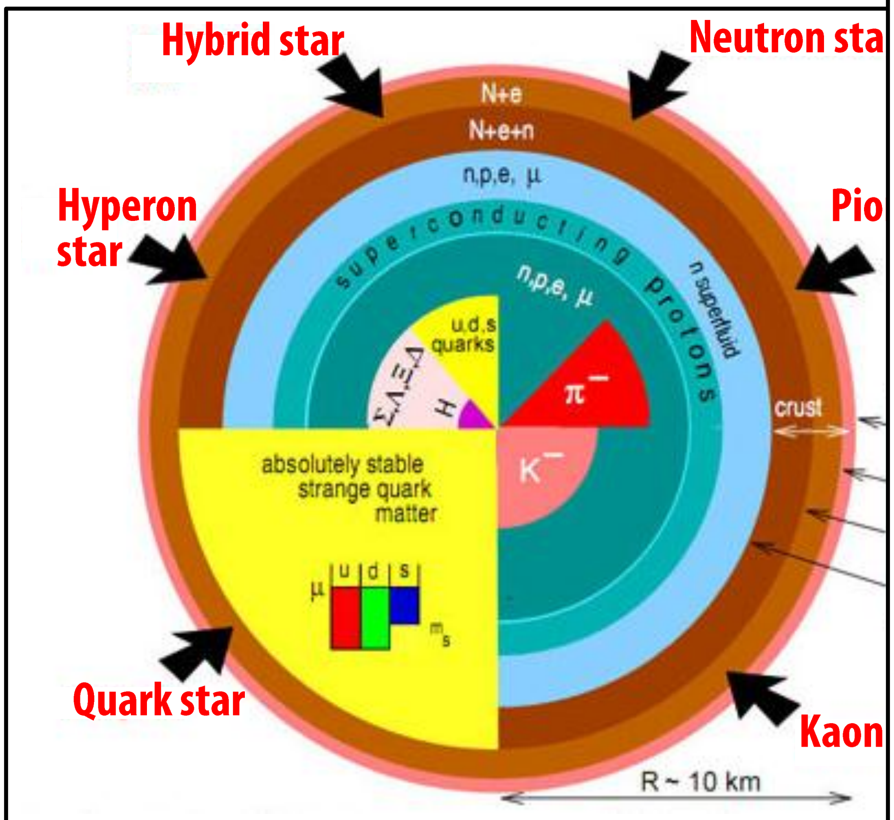

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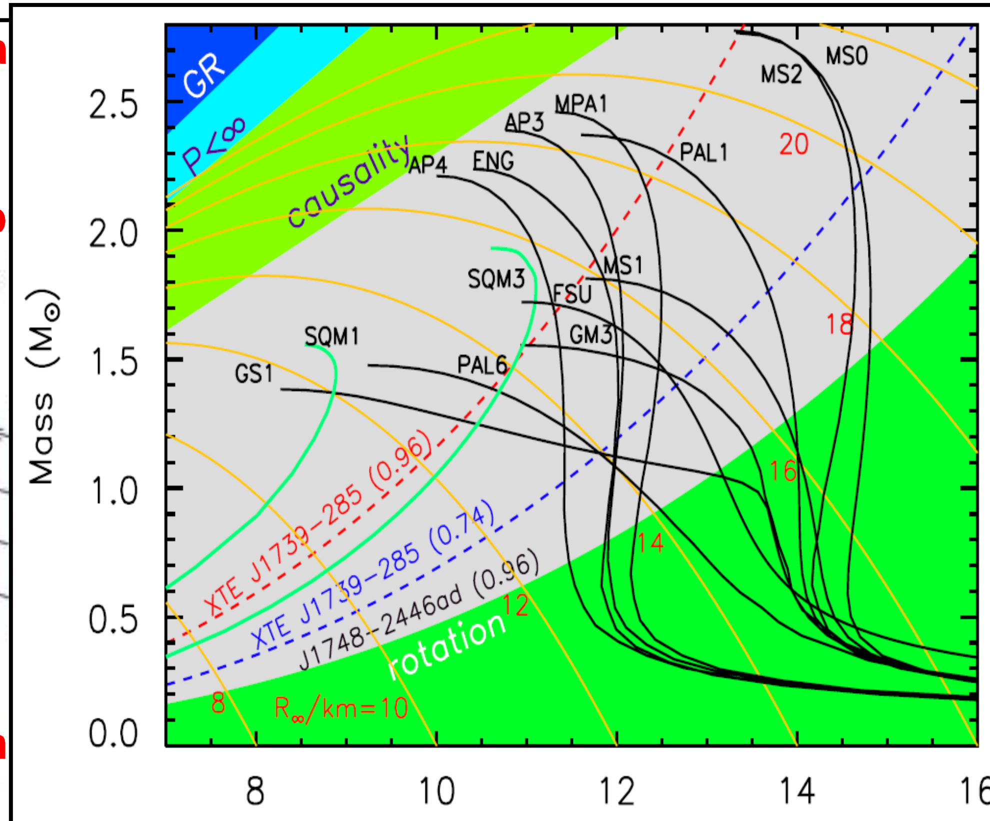

Lattimer & Prakash (2007)

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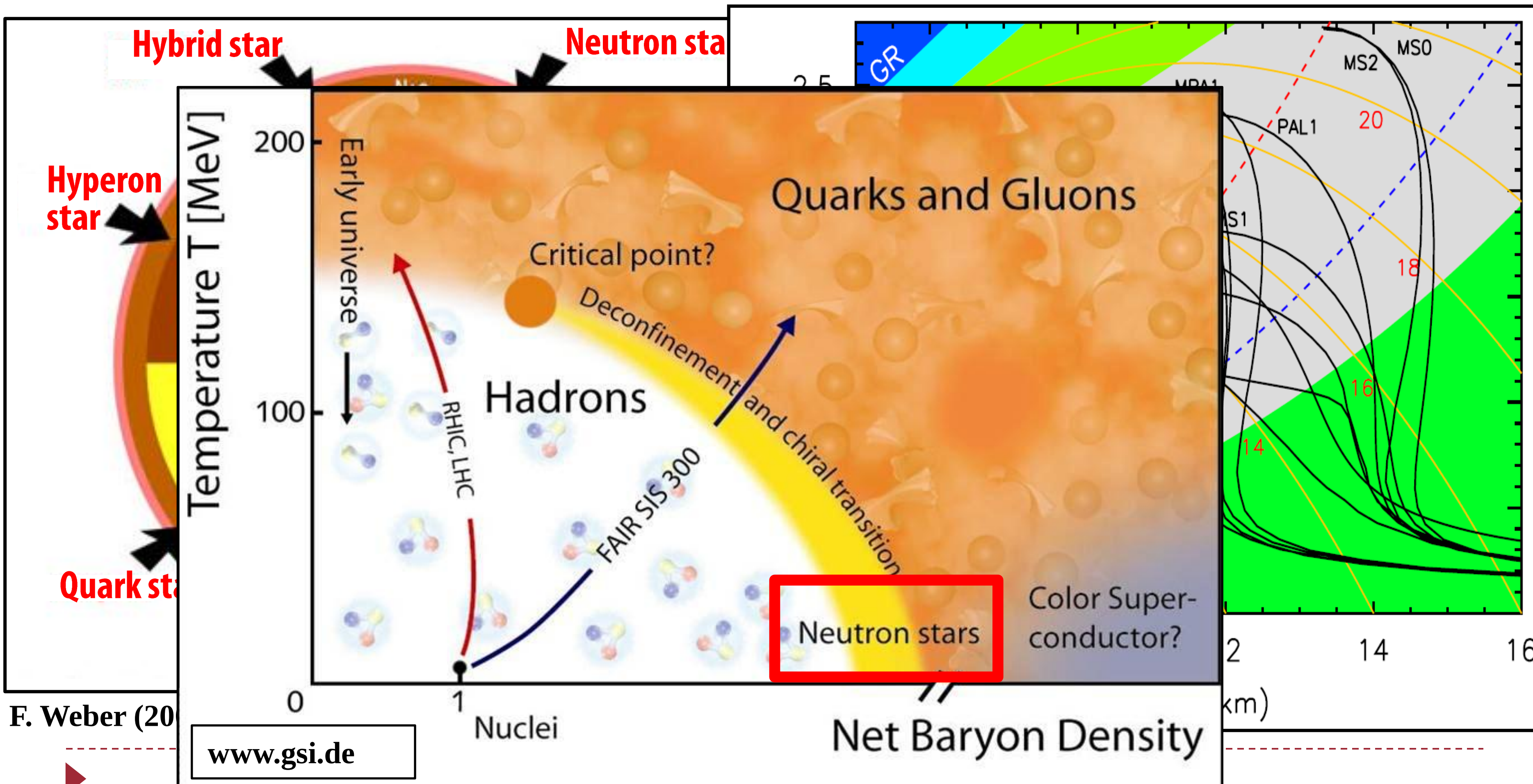
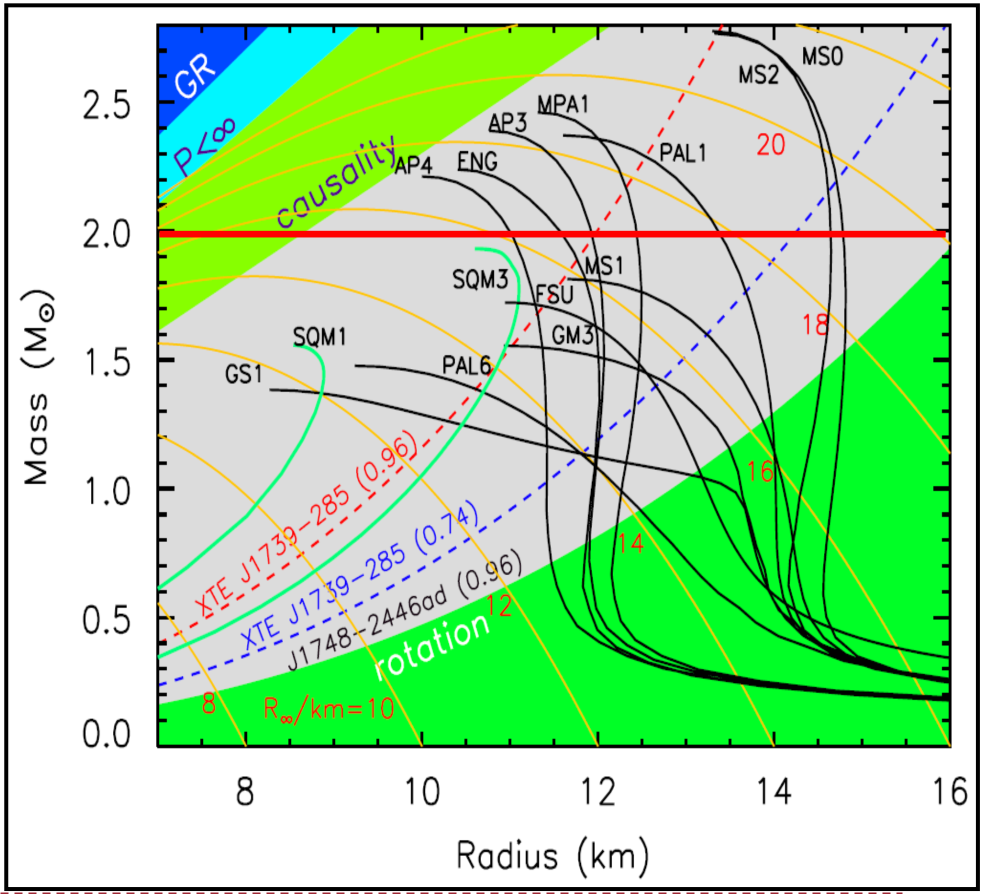


Open Question

- Given the theoretical uncertainty, which one is the right one ?
- Traditional method to constrain the models
  - **Mass-Radius relation** :
    - Estimation of mass and radius observation of X-ray binary
    - Large systematic error
  - **Maximum mass** :
    - Just find a massive NS
  - **PSR J1614-2230 (NS-WD)**
    - NS of 1.97Msolar
    - Mass measurement by Shapiro time delay
    - Too soft EOSs are excluded
  - Still we have a number of theoretical models



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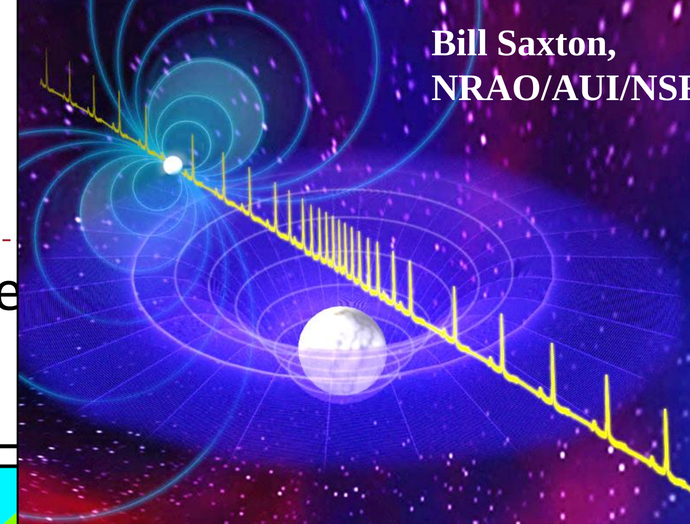

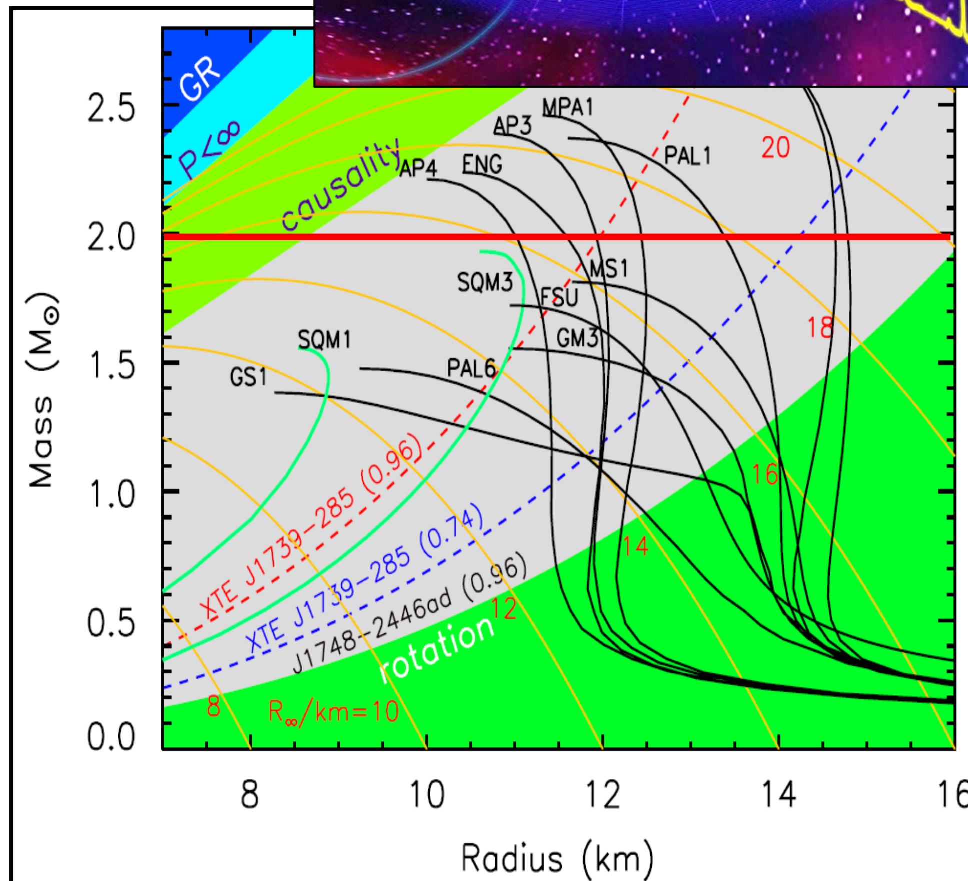

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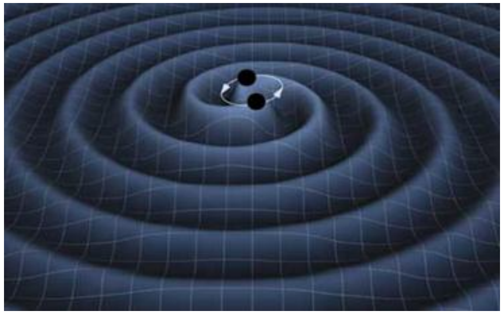
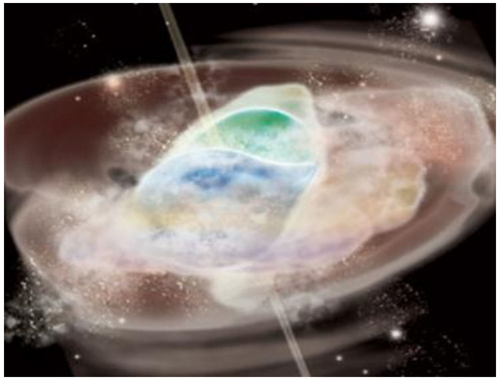
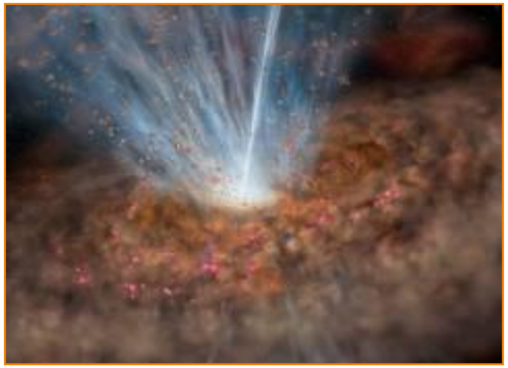






General relativistic gravity is important
Highly nonlinear and dynamical

→ **Numerical Relativity**

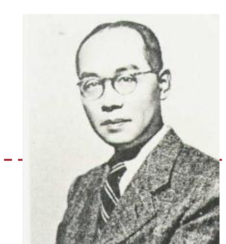
What is Numerical Relativity ?

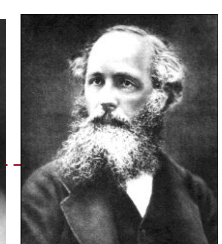
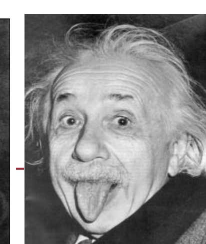
- Solving Einstein eq. and source field eqs. to clarify dynamical phenomena in the universe where strong gravity plays a role

$$G_{ab} = \frac{8\pi G}{c^4} T_{ab}$$

$$\nabla_a T^{ab} = 0 \quad (T^{ab} = (T_{\rm Fluid} + T_{\rm EM} + T_\nu + ...)^{ab})$$
$$\nabla_a J^a = 0 \quad (J^a \sim (n_{\rm baryon},\ n_{\rm lepton}(n_e, n_\nu, ...),\ ...)u^a)$$

- All four known interactions play important roles
  - **Gravity** : GR, BH formation, ISCO, etc
  - **Strong** : EOS (equation of state) of dense nuclear/hadronic matter
  - **EM** : MHD phenomena, EOS of dense matter
  - **Weak** : Electron capture, Neutrino production, neutrino pair annihilation
    - 99% gravitational binding energy released is carried away by neutrinos in SNe



NR simulations with a physical modeling is now possible !

- Einstein's equations: Shibata-Nakamura (BSSN) formalism
  - 4^{th} order finite difference in space, 4^{th} order Runge-Kutta time evolution
  - Gauge conditions : 1+log slicing, dynamical shift
- GR Hydrodynamics ***with neutrinos*** (Sekiguchi 2010)
  - **Nuclear-theory-based finite temperature EOS table**
  - **EOM of Neutrinos (leakage scheme, moment scheme)**
  - **Lepton Conservations**
  - **Weak Interactions**
    - $e^{\pm}$ captures, pair annihilation, plasmon decay, Bremsstrahlung
  - A detailed neutrino opacities
  - High-resolution-shock-capturing scheme
- **BH excision technique**
- **(Fixed) Mesh refinement technique**

$$\nabla_a T_b^{\ a} = -Q_b^{(\mathrm{leak})}$$

$$\nabla_a T_b^{\ a\ (\nu,\mathrm{stream})} = Q_b^{(\mathrm{leak})}$$

$$\nabla_a(\rho Y_e u^a) = -\gamma_{\mathrm{e-\,cap}} + \gamma_{\mathrm{e+\,cap}}$$

$$\nabla_a(\rho Y_{\nu e} u^a) = \gamma_{\mathrm{e-\,cap}} + \gamma_{\mathrm{pair}} + \gamma_{\mathrm{plasmon}} + \gamma_{\mathrm{Brems}} - \gamma_{\nu_e\mathrm{leak}}$$

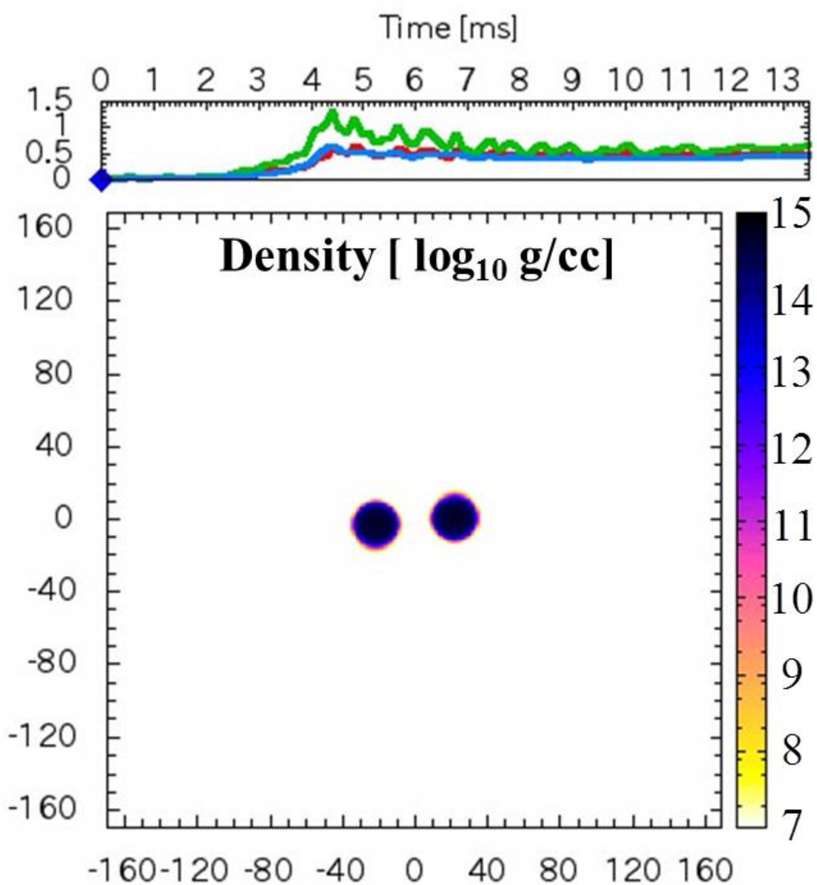
$$\nabla_a(\rho Y_{\bar{\nu} e} u^a) = \gamma_{\mathrm{e+\,cap}} + \gamma_{\mathrm{pair}} + \gamma_{\mathrm{plasmon}} + \gamma_{\mathrm{Brems}} - \gamma_{\bar{\nu}_e\mathrm{leak}}$$

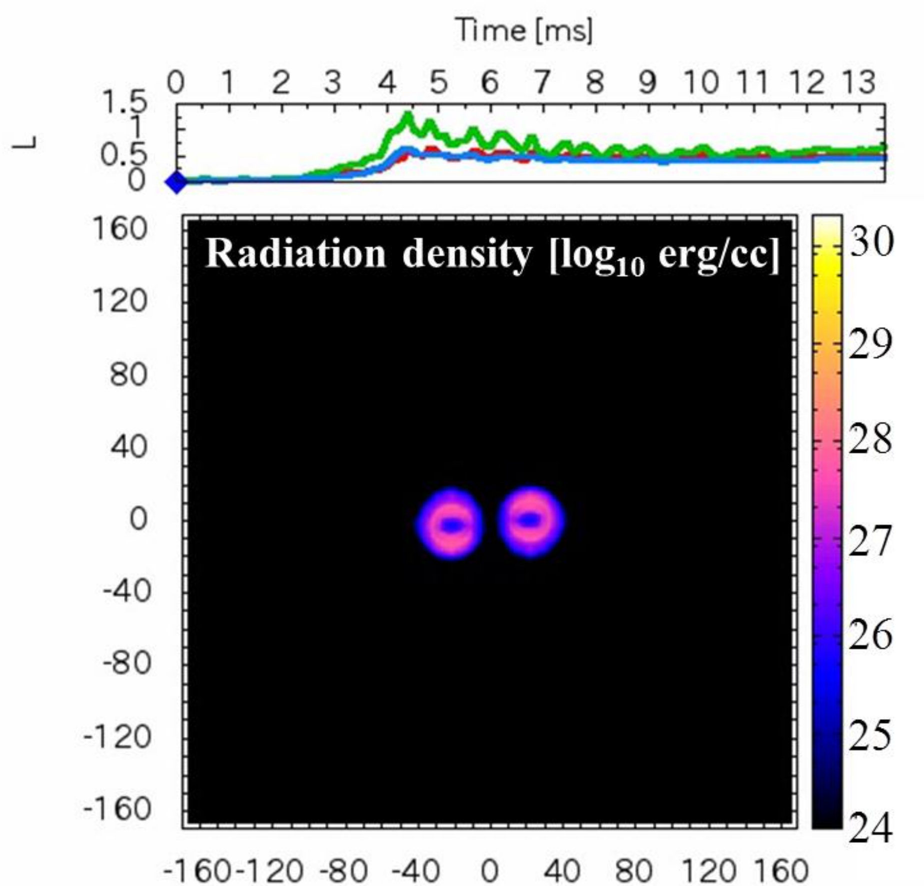
$$\nabla_a(\rho Y_{\nu_{\mu,\tau}} u^a) = \gamma_{\mathrm{pair}} + \gamma_{\mathrm{plasmon}} + \gamma_{\mathrm{Brems}} - \gamma_{\nu_{\mu,\tau}\,\mathrm{leak}}$$

Sekiguchi (2010) Progress of Theoretical Physics **124**, 331

Neutrino transfer : a preliminary result

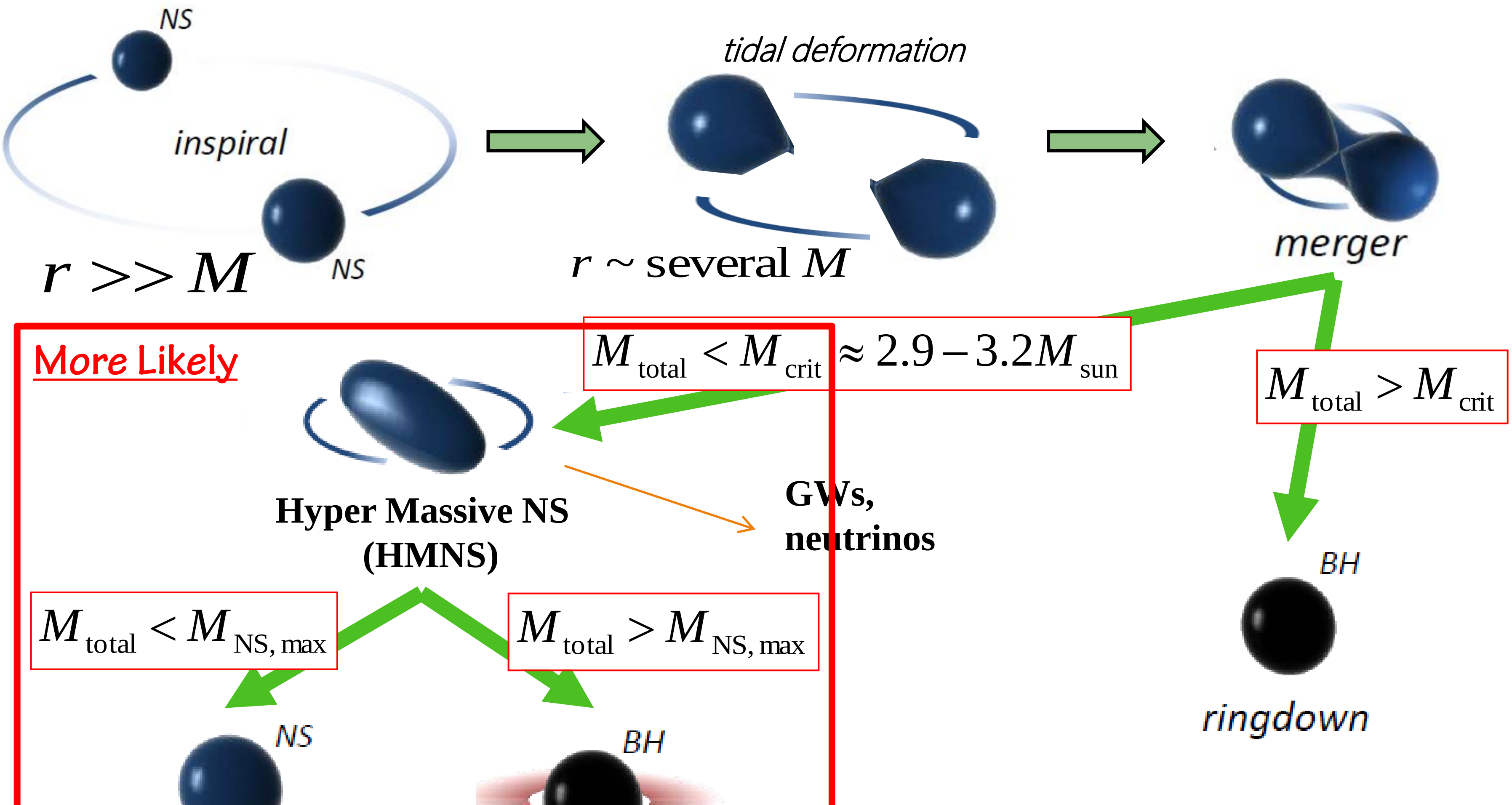
- Solving Boltzmann equation (6+1 dims. !) is not feasible at current status
- Approximate solution by Thorne's Moment scheme with a closure relation
  - Neutrino heating (absorption on proton/neutron) can be treated
  - But some (approximate) treatment is required for ν annihilation





Evolution of NS-NS Binary

Shibata et al. 2005,2006



Imre Bartos, GECo, Columbia University
(Bartos et al. 2013, in prep.) with permission

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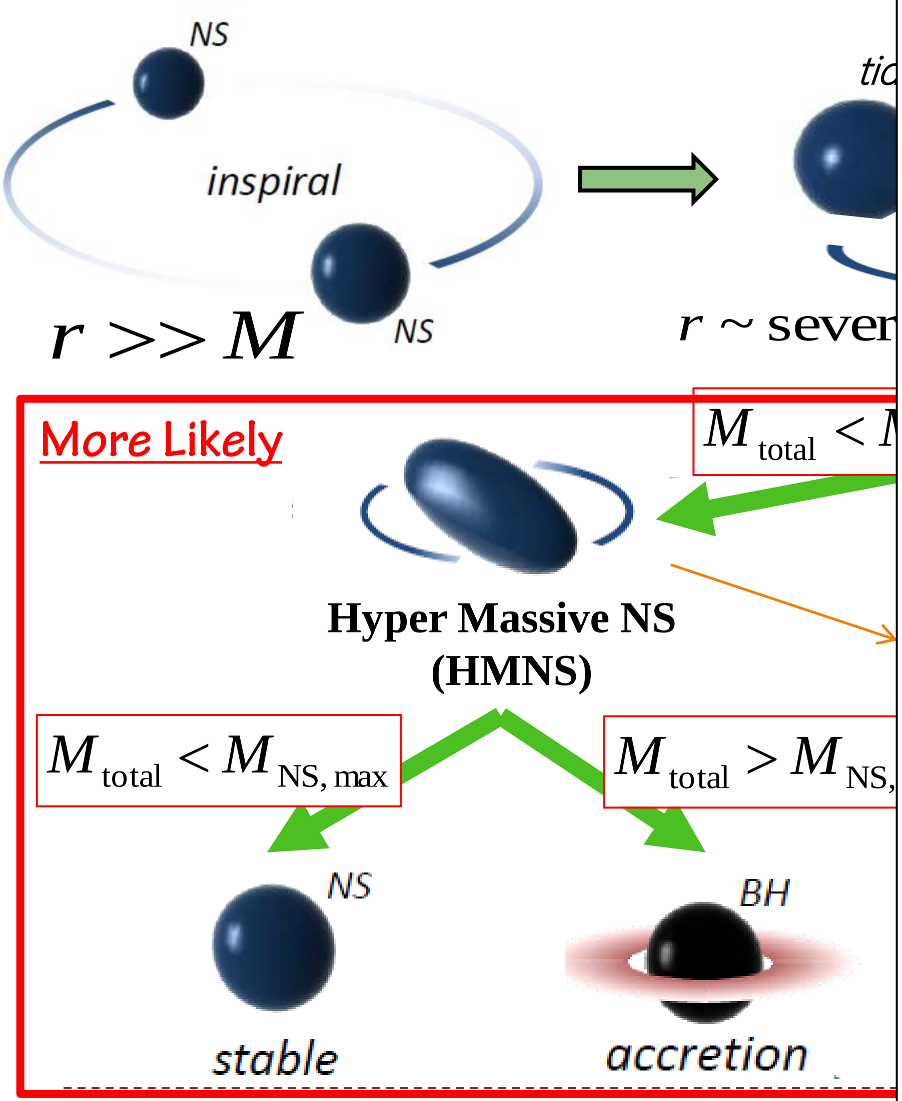
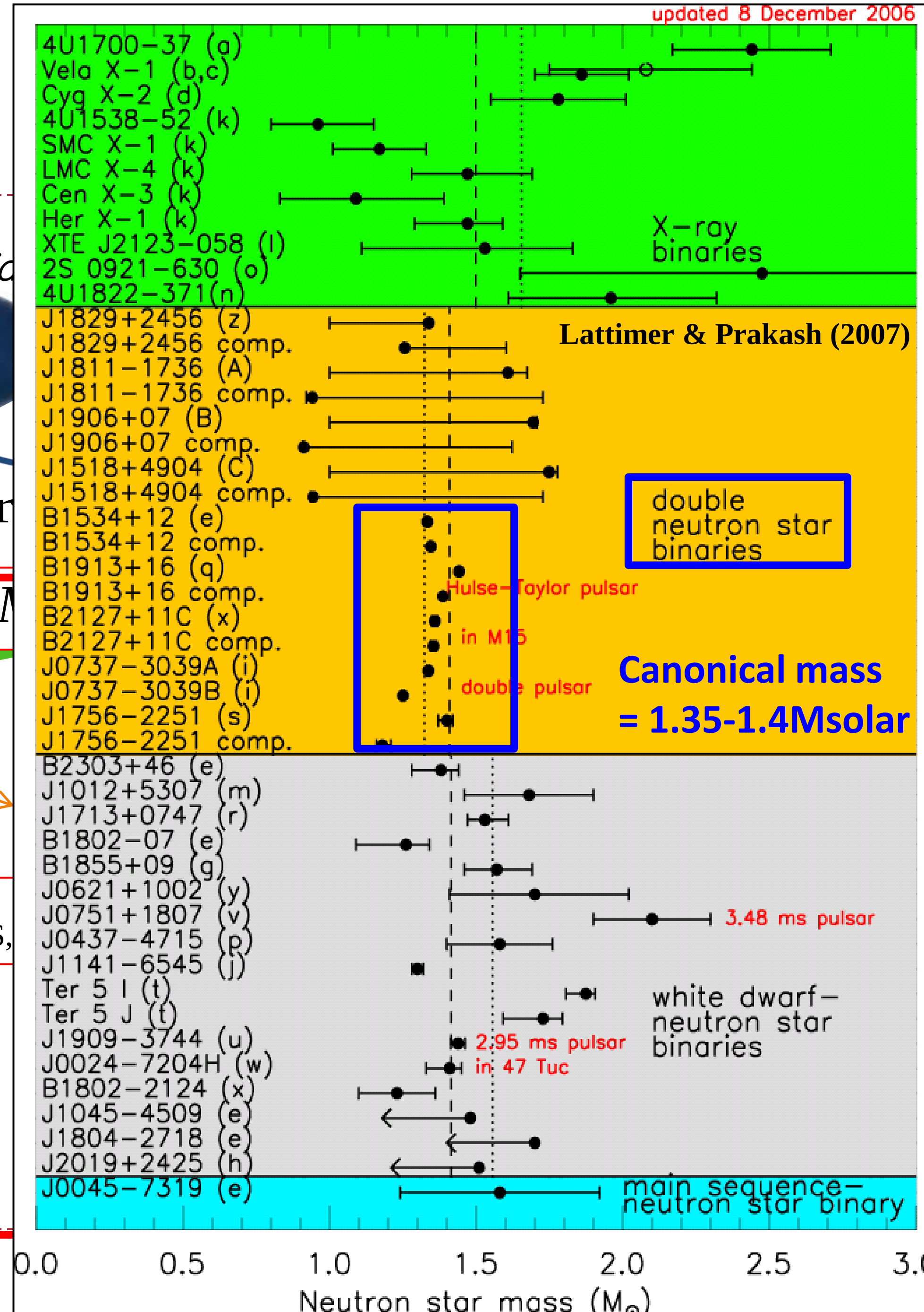
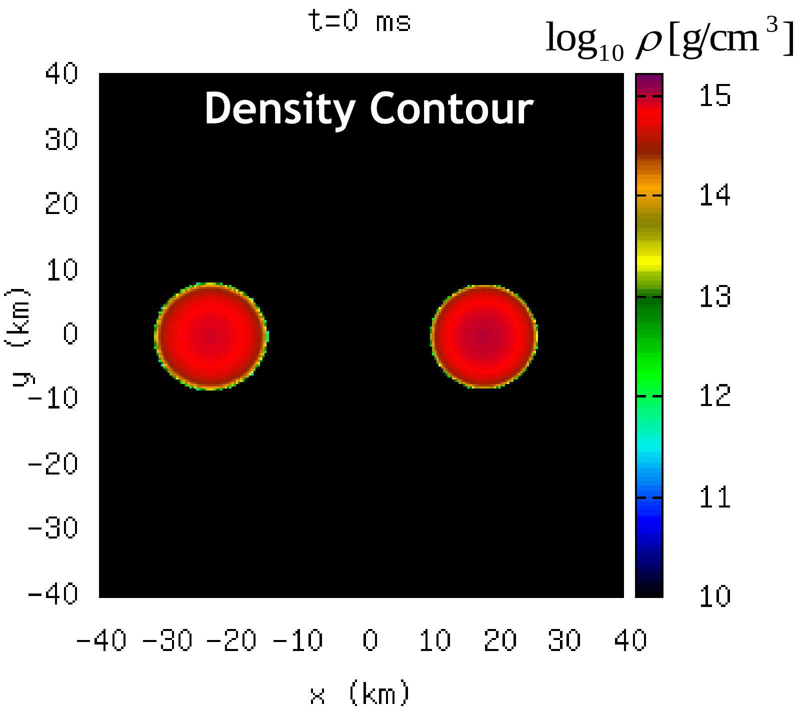


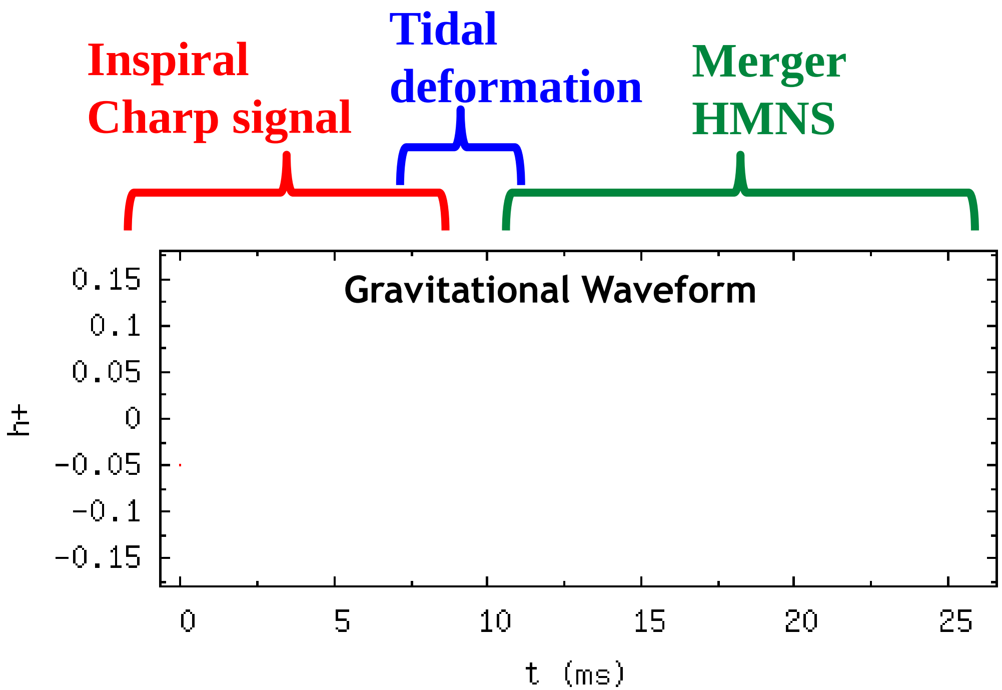


Sekiguchi et al. PRL (2011a, 2011b)
Kiuchi et al. PRL (2010); Hotokezaka et al. (2011); (2012)

GW from NS-NS (**long lived HMNS**)

NS(1.2Msolar)-NS(1.5Msolar) binary (APR EOS)





Animation by Hotokezaka

Exploring Dense matter physics by GW

Inspiral phase

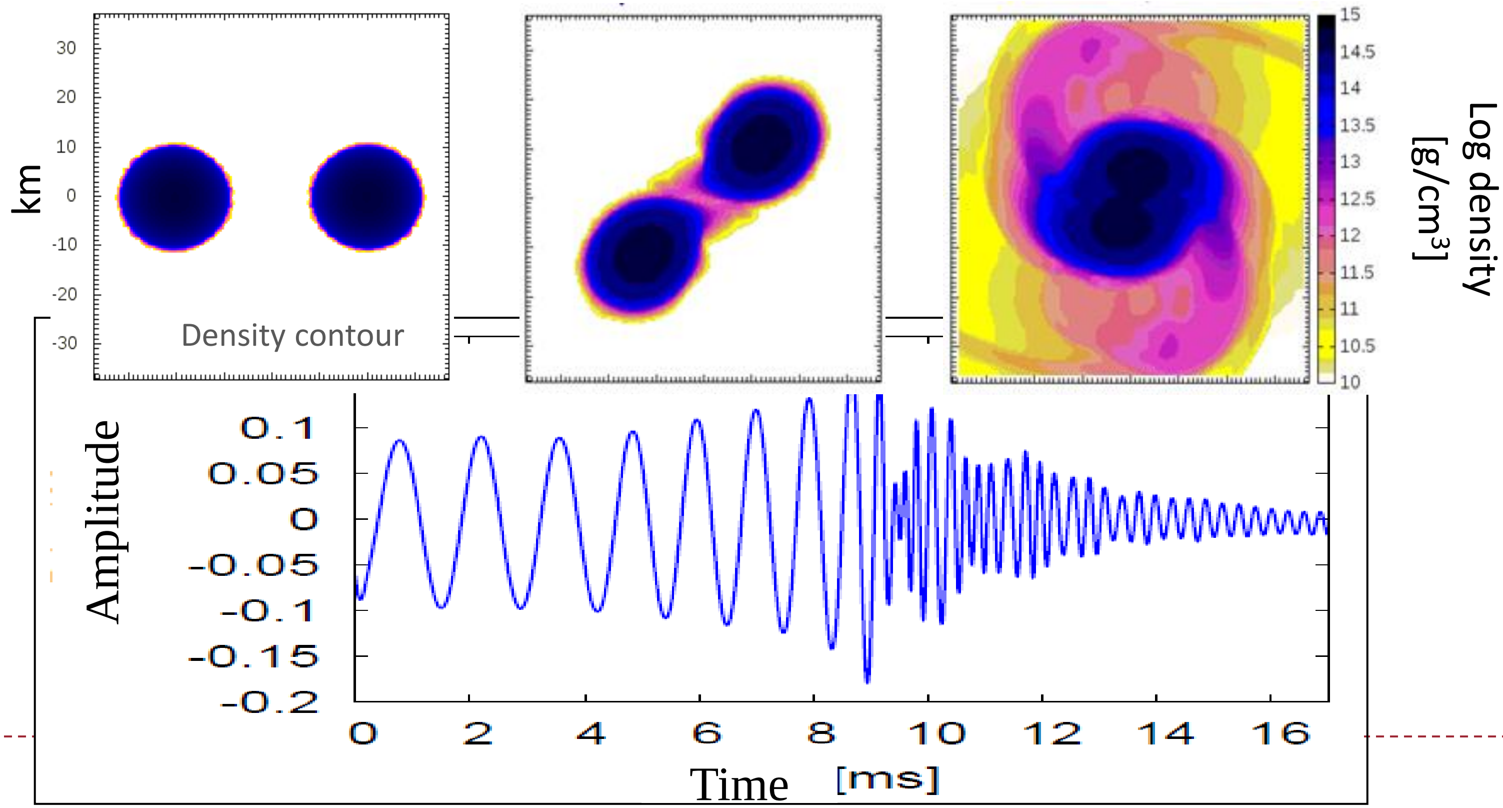
- Point particle approximation
- Information of orbits, **neutron star mass** etc.

Tidal deformation

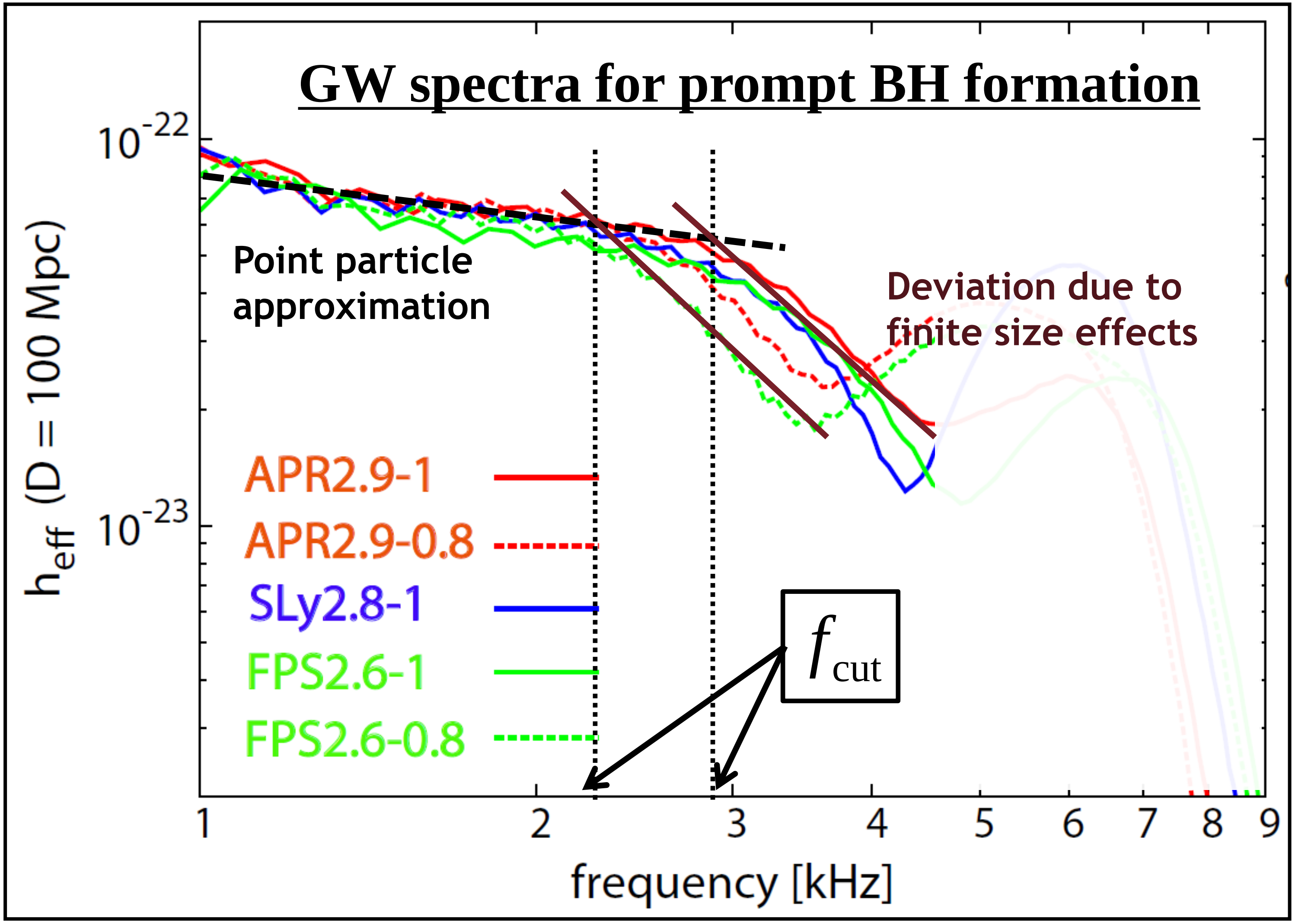
- Finite size effect
- Deviation from charp ⇒ **NS radius**

Merger and oscillation of HMNS

- BH or NS ⇒ **maximum mass**
- GW from rotating HMNS ⇒ **NS radius (and EOS)**

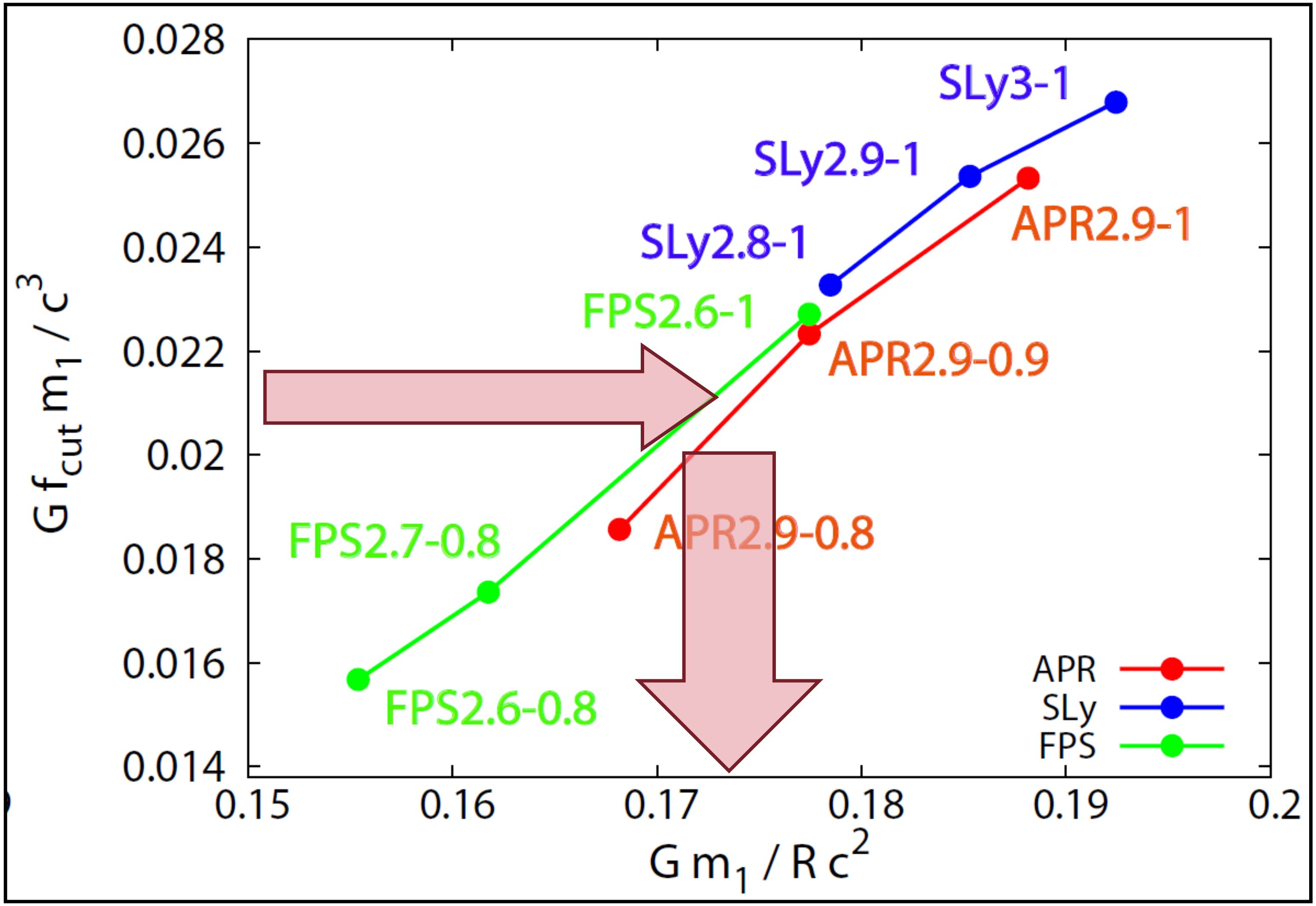


Prompt BH formation
GW spectra : deviation from point particle



Kiuchi, YS et al. (2010) PRL 104 141101

$f_{\rm cut}$ may be used to estimate $R_{\rm NS}$



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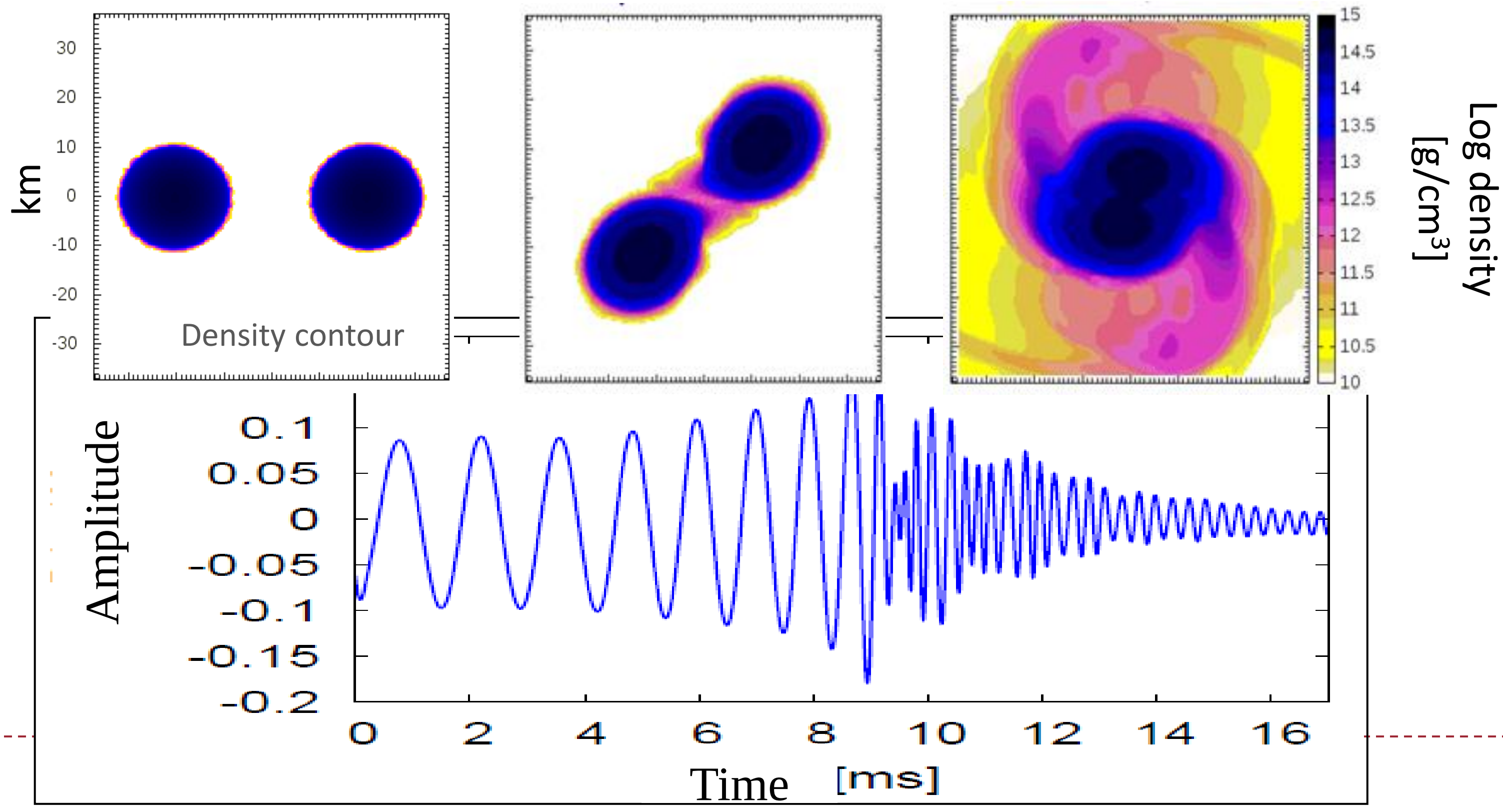
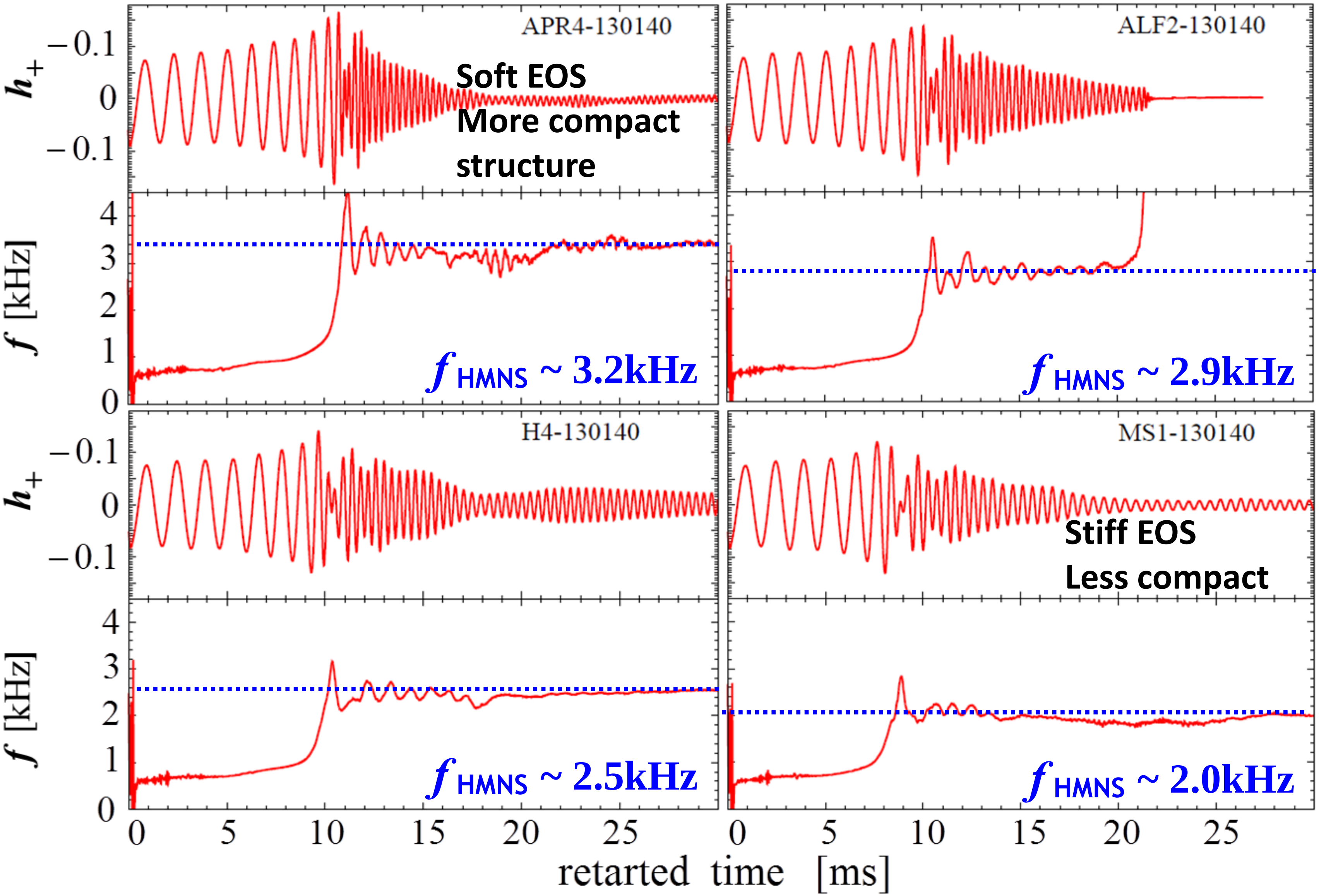
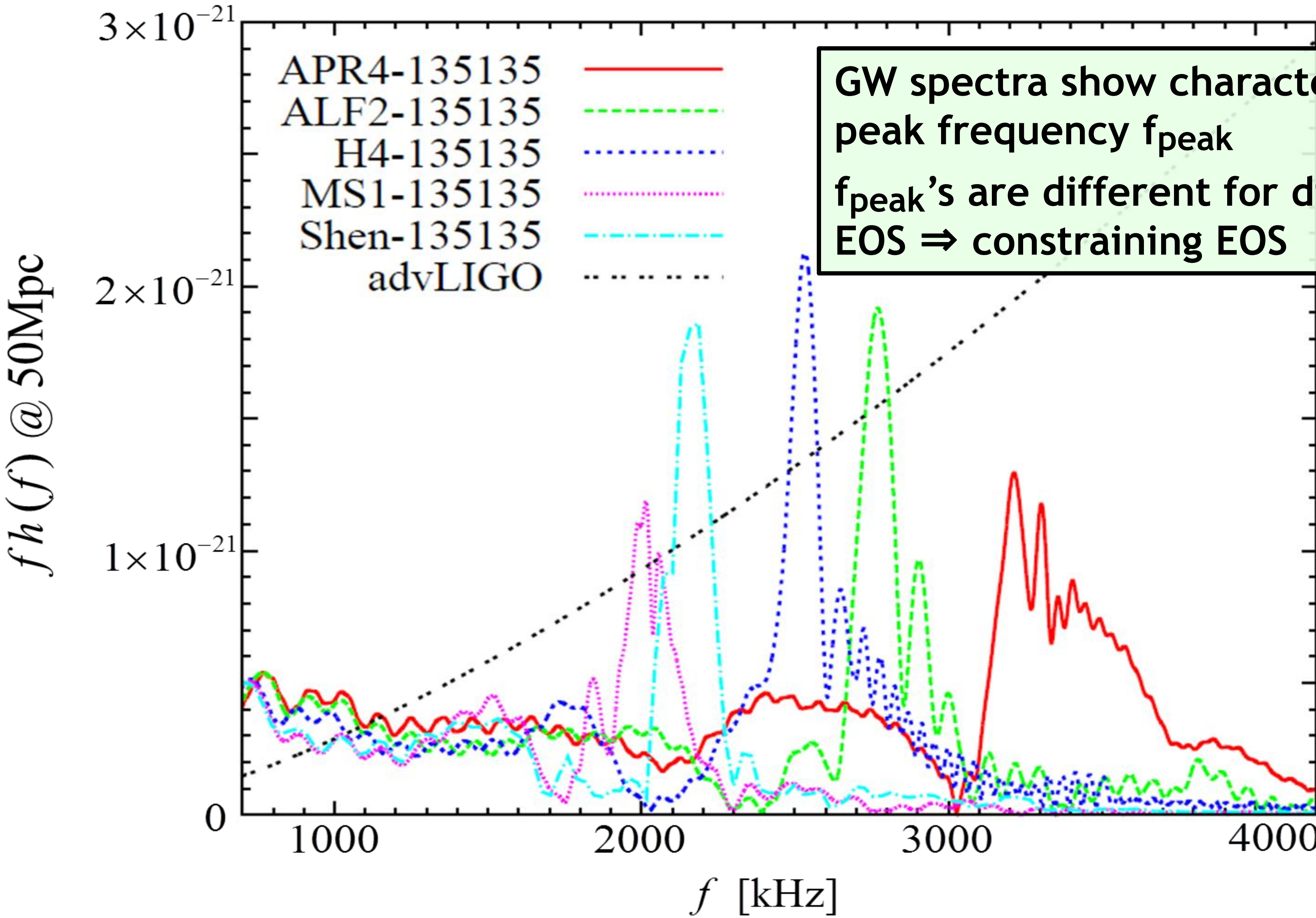


Hotokezaka et al. (2011); (2012)

GWs from HMNS (1.3-1.4 Msolar Merger)



GW spectra (1.35-1.35 Msolar)

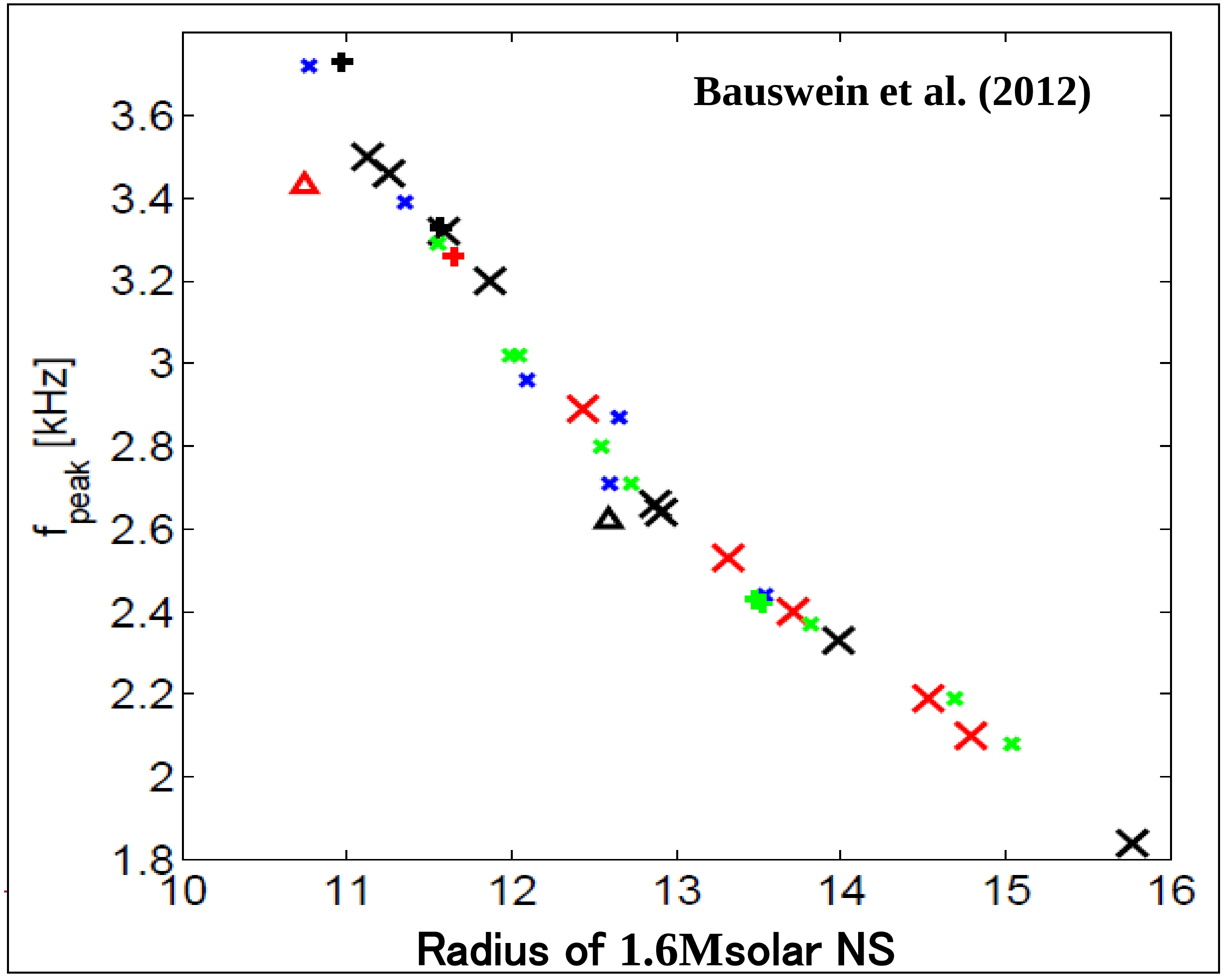


GW spectra show characteristic peak frequency f_{peak}

f_{peak}'s are different for different EOS ⇒ constraining EOS

Relation between f_{peak} and NS structure

- The peak GW frequency depends strongly on EOS
- The frequency has correlation with NS radius and stiffness of EOS
  - Bauswein & Janka. 2011
  - Bauswein et al. 2012
  - Hotokezaka et al. 2012



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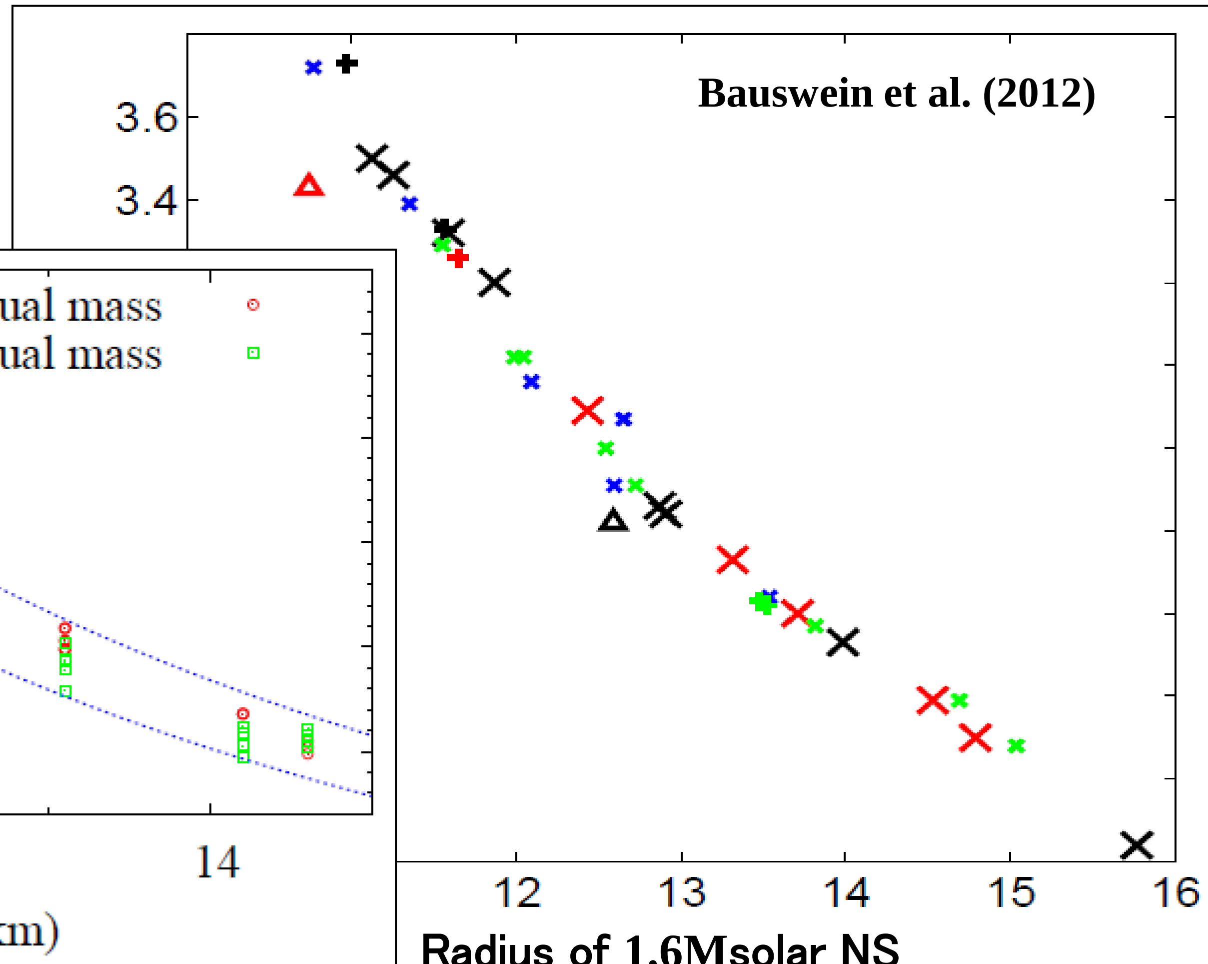

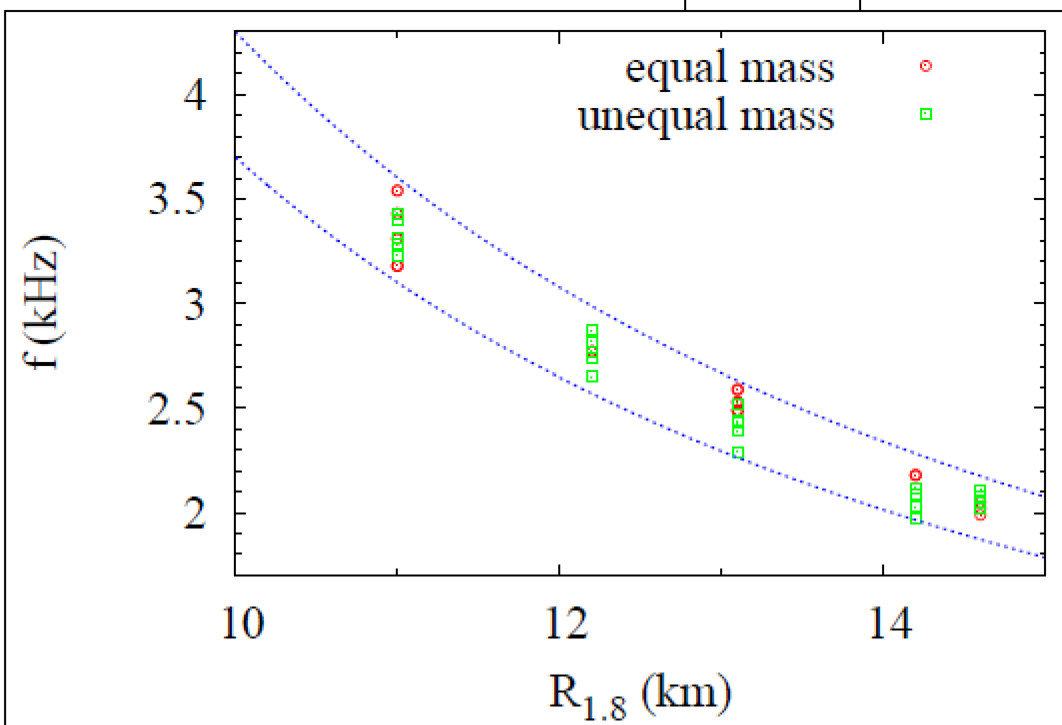

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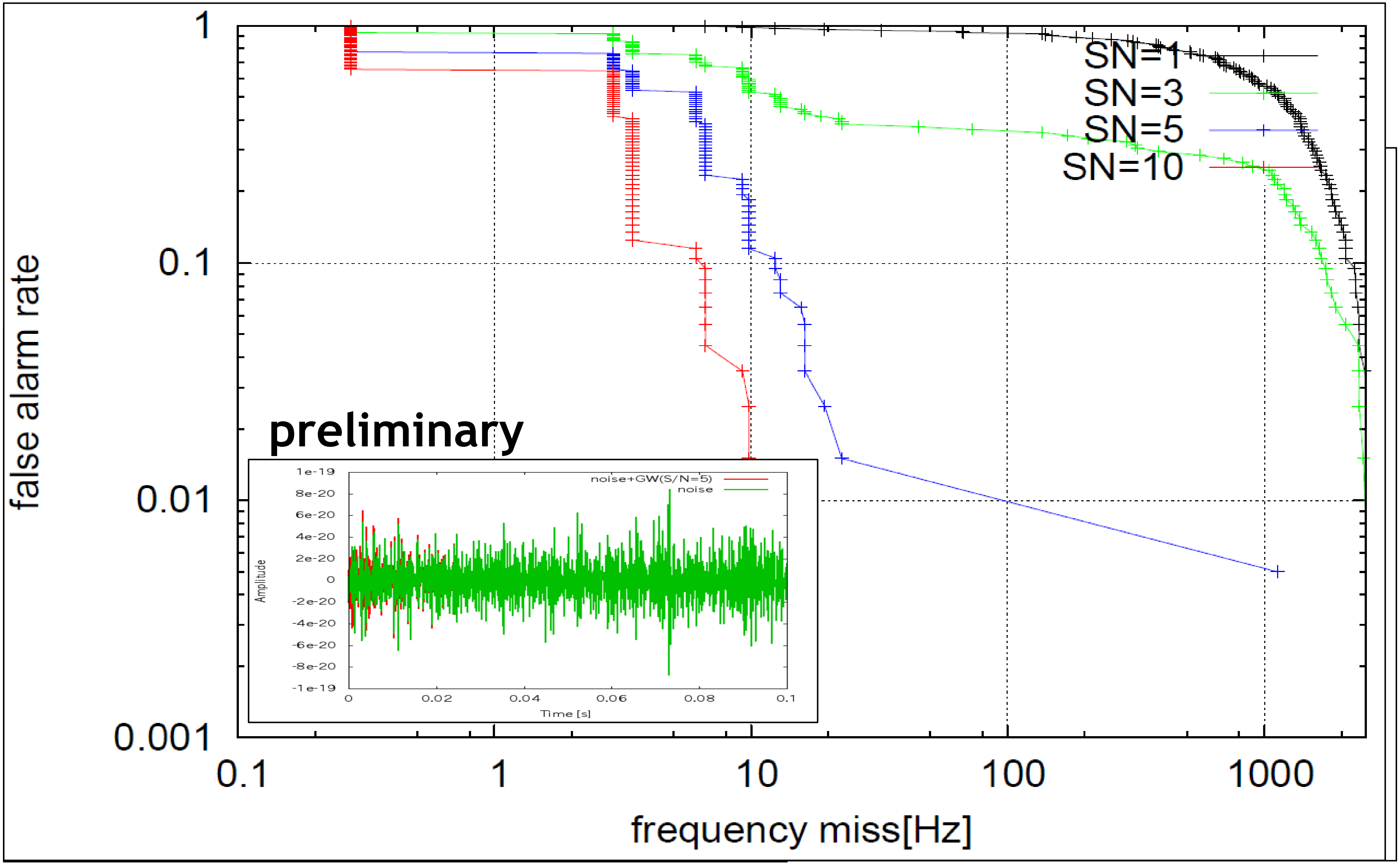
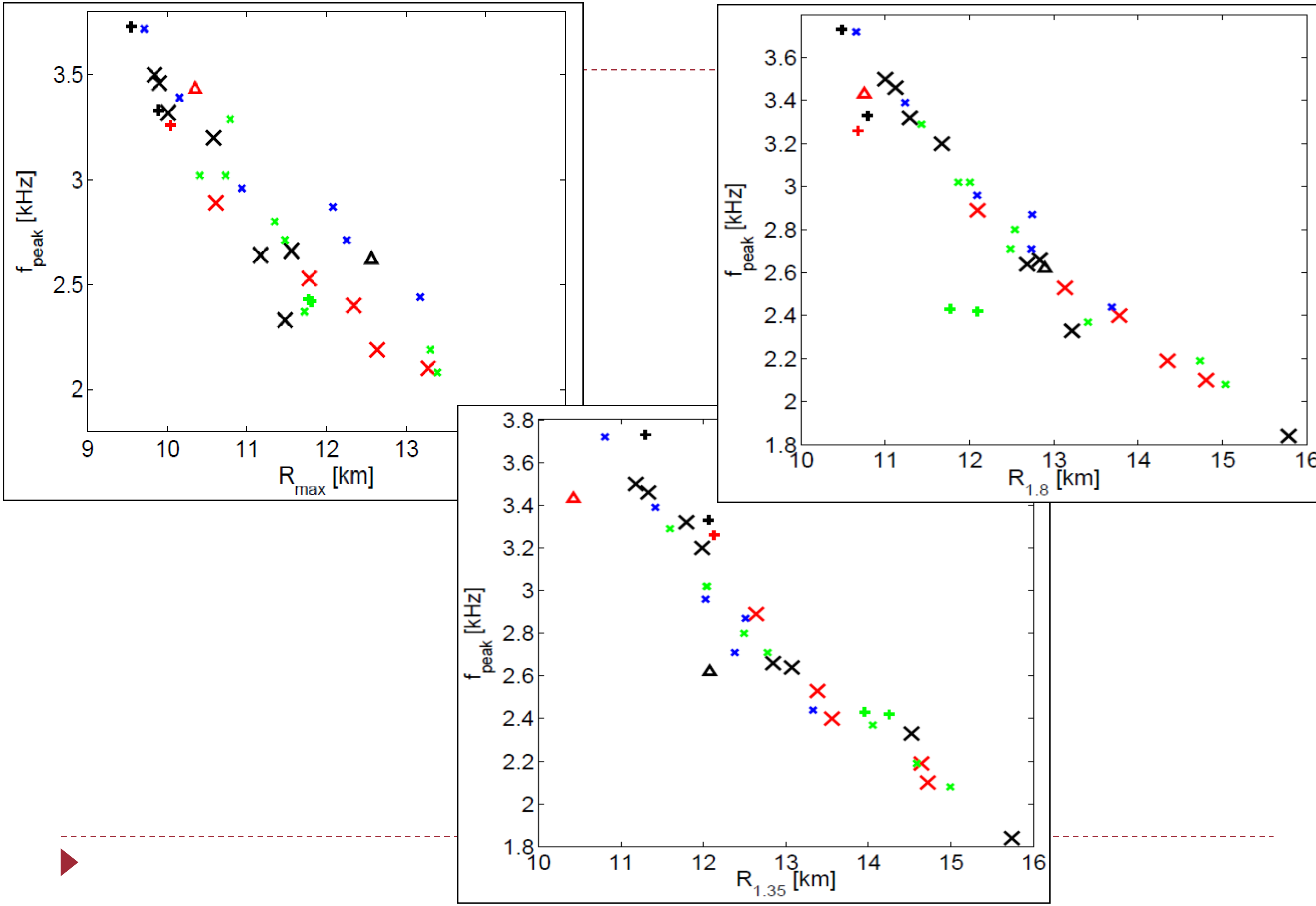


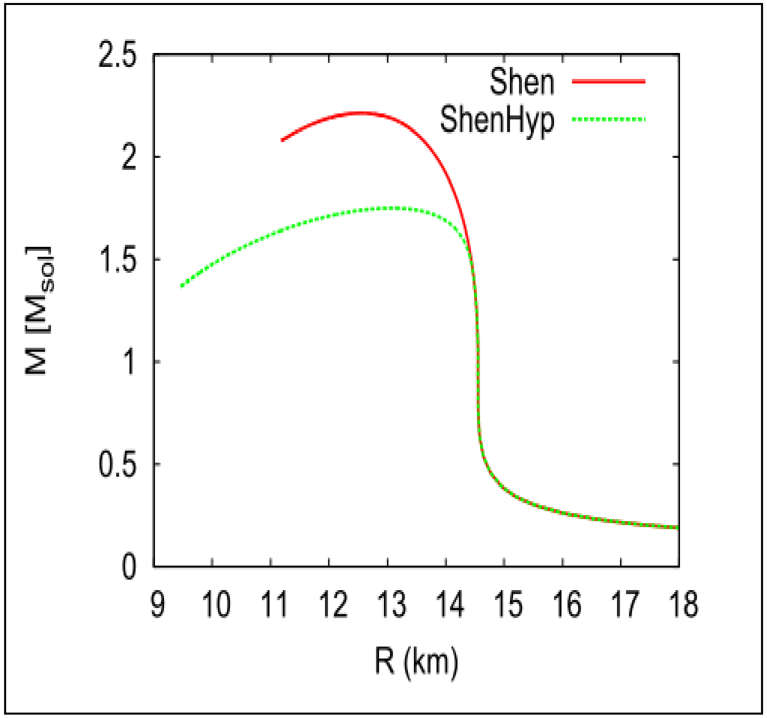
fpeak vs. NS radius

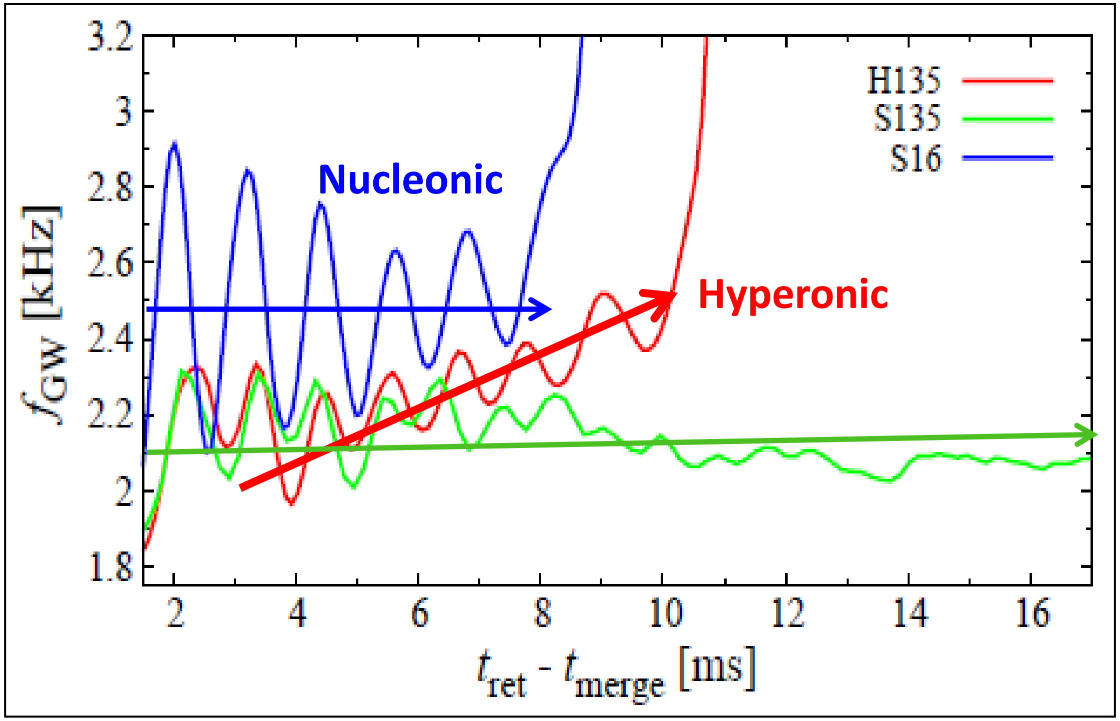


Sekiguchi et al. PRL (2011)

Emergence of Hyperon is putted in GW ?

- Dynamics of HMNS formed after the merger
  - **Nucleonic** : HMNS shrinks by angular momentum loss in a long GW timescale
  - **Hyperonic** : GW emission ⇒ HMNS shrinks ⇒ More Hyperons appear ⇒ EOS becomes softer ⇒ HMNS shrinks more ⇒ ....
  - **As a result, the characteristic frequency of GW increases with time**
    - ***Might*** providing potential way to tell existence of hyperons (exotic particles)

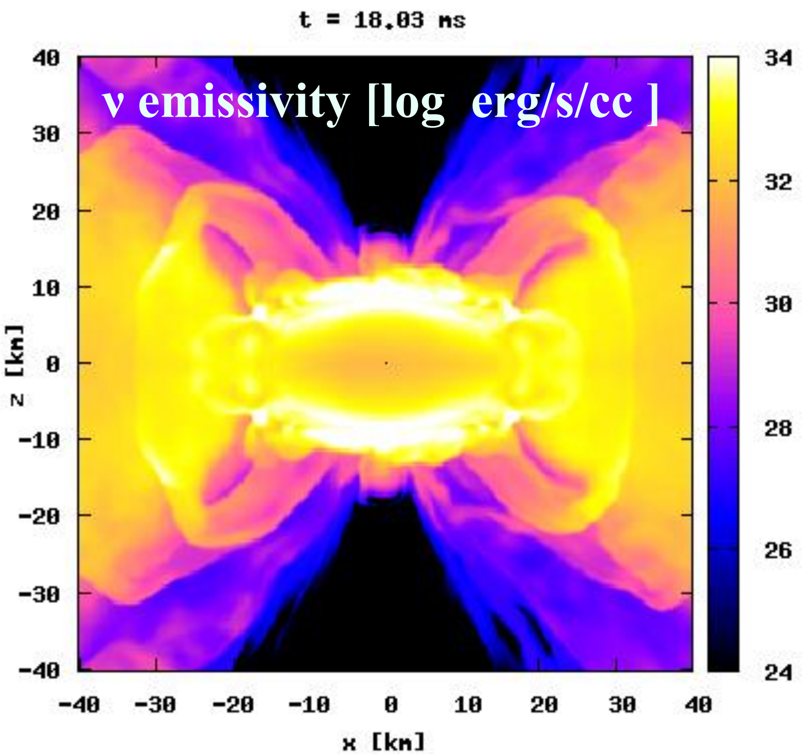


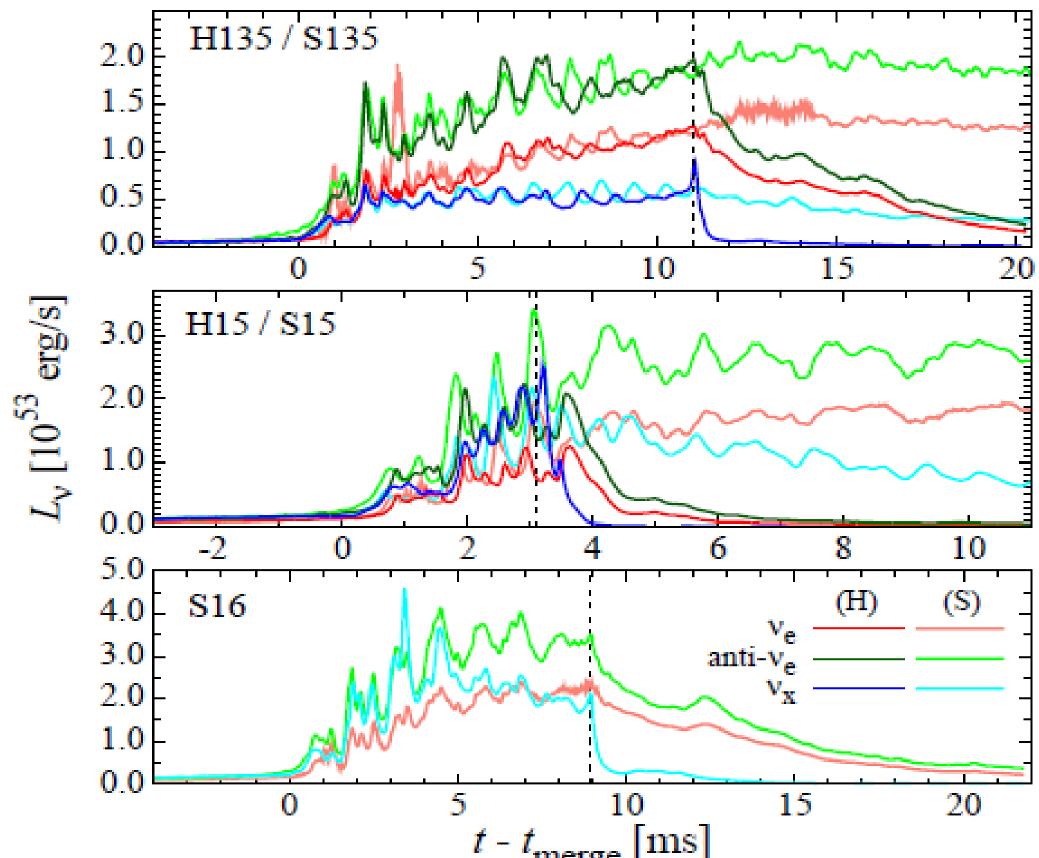


Sekiguchi et al. PRL (2011)

Neutrino signal (w. and w.o. hyperons)

- There is no difference except for the duration until the BH formation
  - **Difficult to tell the existence of hyperons using the neutrino signals alone**
- Copious neutrinos are emitted from disk around BH
  - NS-NS merger as a progenitor of short GRBs ?





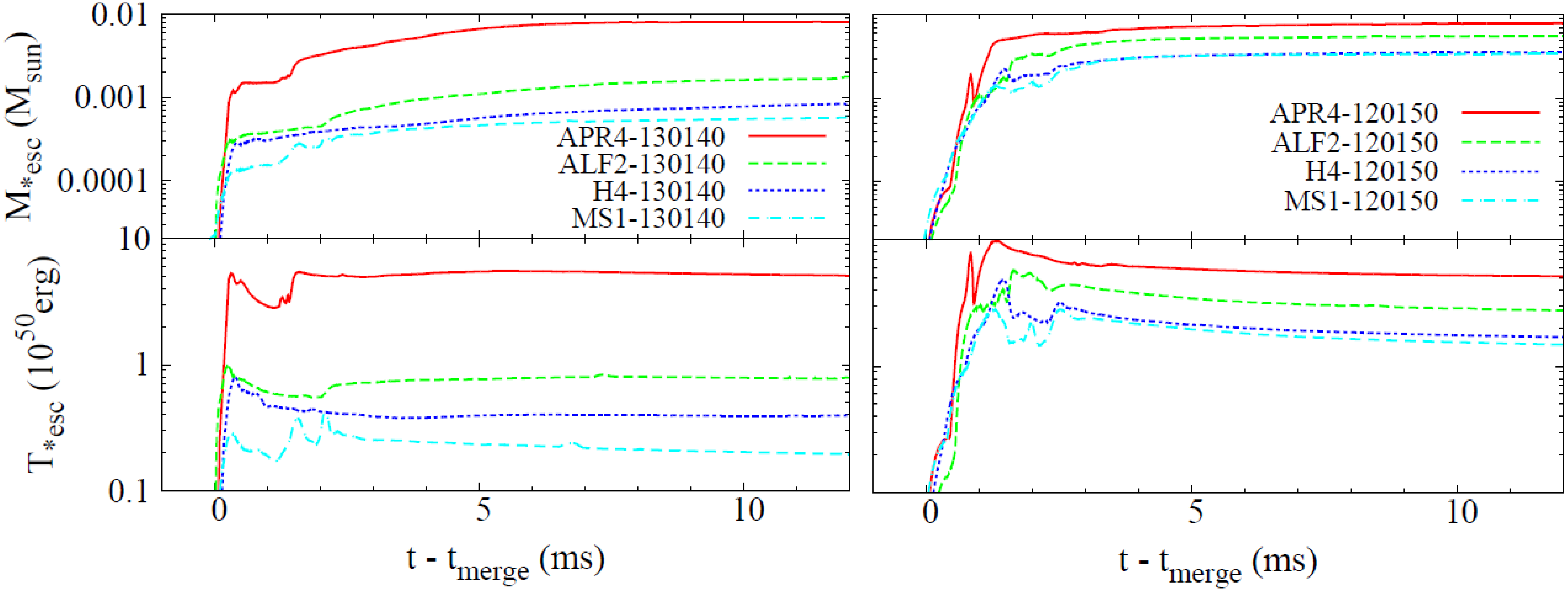
Possible EM counterpart

- Expected electromagnetic (EM) wave emission from the merger
  - Detection of EM counterpart enhances reliability and detectability of GW
- **Ejecta** Sweeping inter stellar matter ⇒ shock ⇒ **Synchrotron rad.**
  - Nakar & Piran (2011) Nature
  - $\sim \mathbf{90\mu Jy}\ (E_0/10^{50}\mathrm{erg})(n_0/1\mathrm{cm}^{-3})^{0.9}(v/0.3c)^{-2.8}\ (D/200\mathrm{Mpc})^{-2}\ (\nu_{obs}/1.4\ \mathrm{GHz})^{-0.75}$
- Neutron rich **ejecta** ⇒ R-process ⇒ **radioactive decay** (talk by Wanajo san)
  - Li & Paczynski (1998)
  - $L_{peak} \sim \mathbf{2.6 \times 10^{42}\ erg/s}\ (f/3\times 10^{-6})\ (v/0.3c)^{1/2}\ (M_{eje}/10^{-2}\ M_{\odot})^{1/2}$
- **These transient event could be detected with upcoming radio or optical detectors**

Hotokezaka et al. (2012)

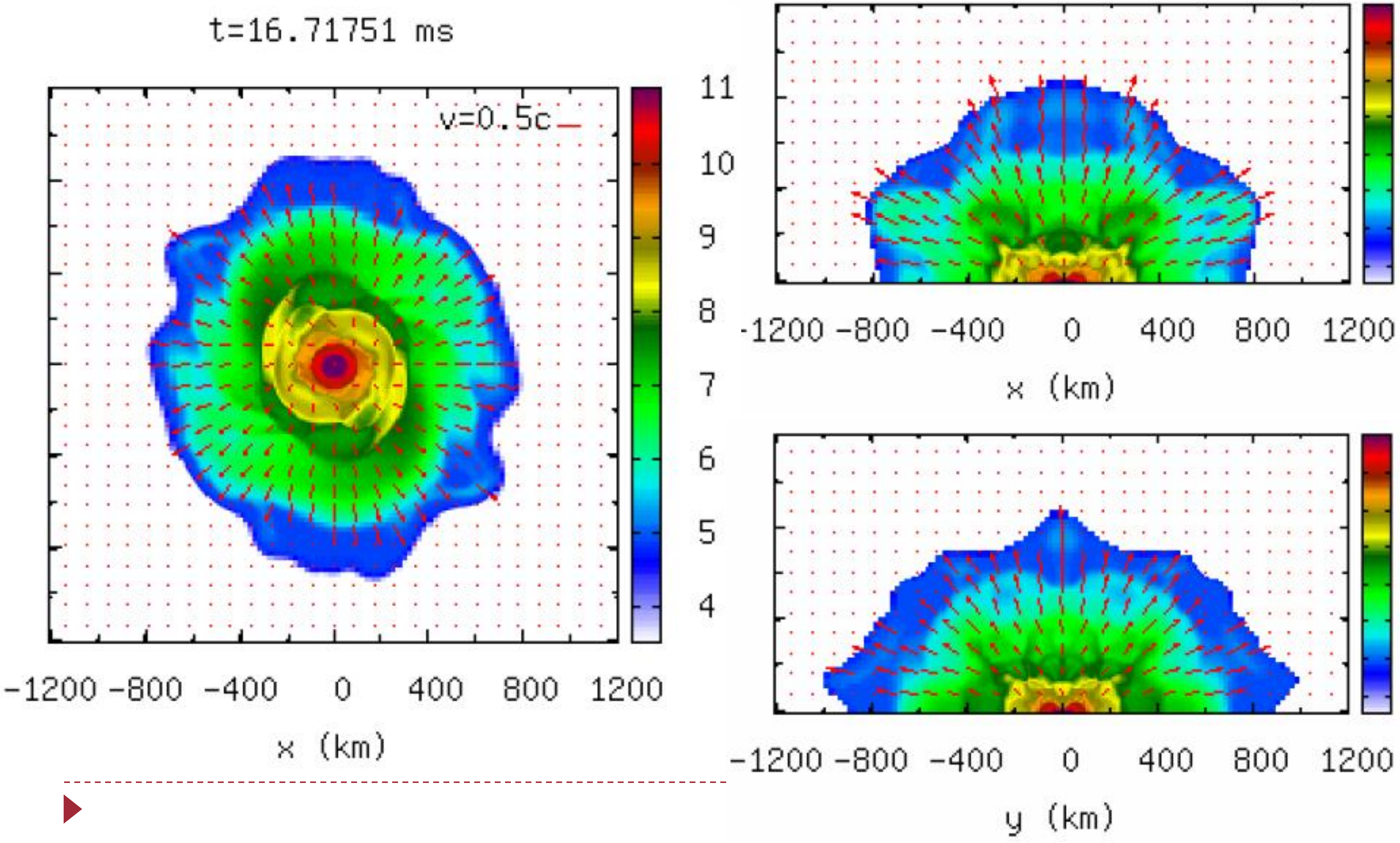
Mass ejection depends strongly on EOS

- More compact NS results in more massive ejecta
  - For mass ratio close to unity (q~1) and more compact NS, mass ejection is driven by shocks. Tidal effects are relatively less important
  - For larger mass ratio and less compact NS, tidal effect is also important
- Coupled observations of GW and EM will be important !



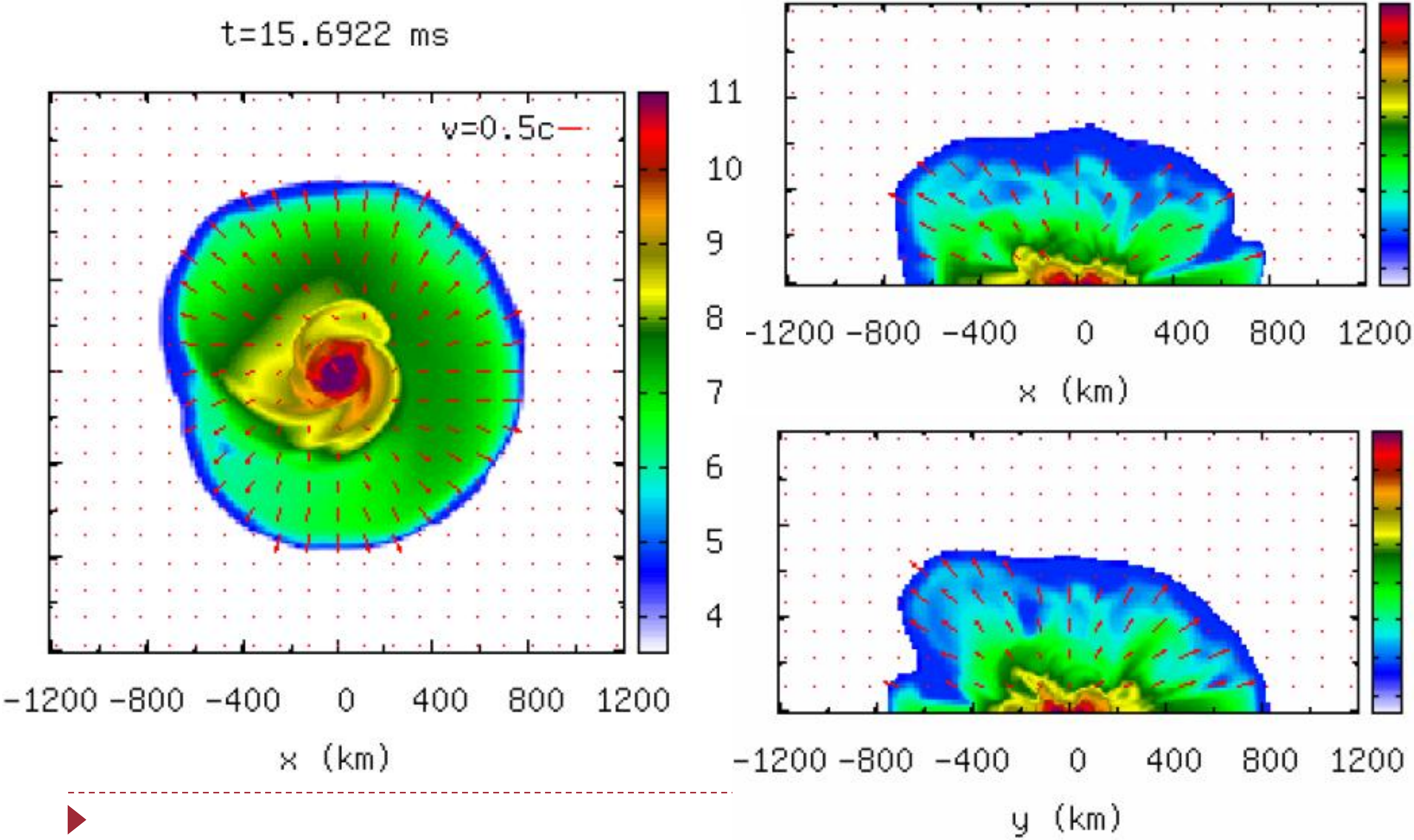
Hotokezaka et al. (2012)

Homologous mass ejection for q~1



Hotokezaka et al. (2012)

Tidal effects play role for q<1 and stiff EOS



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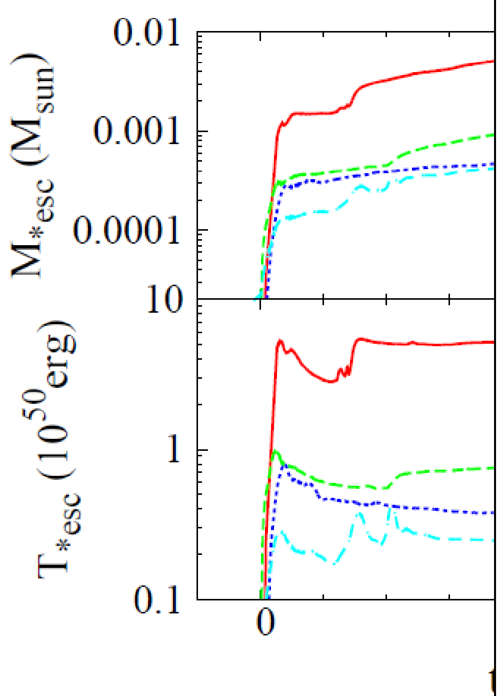
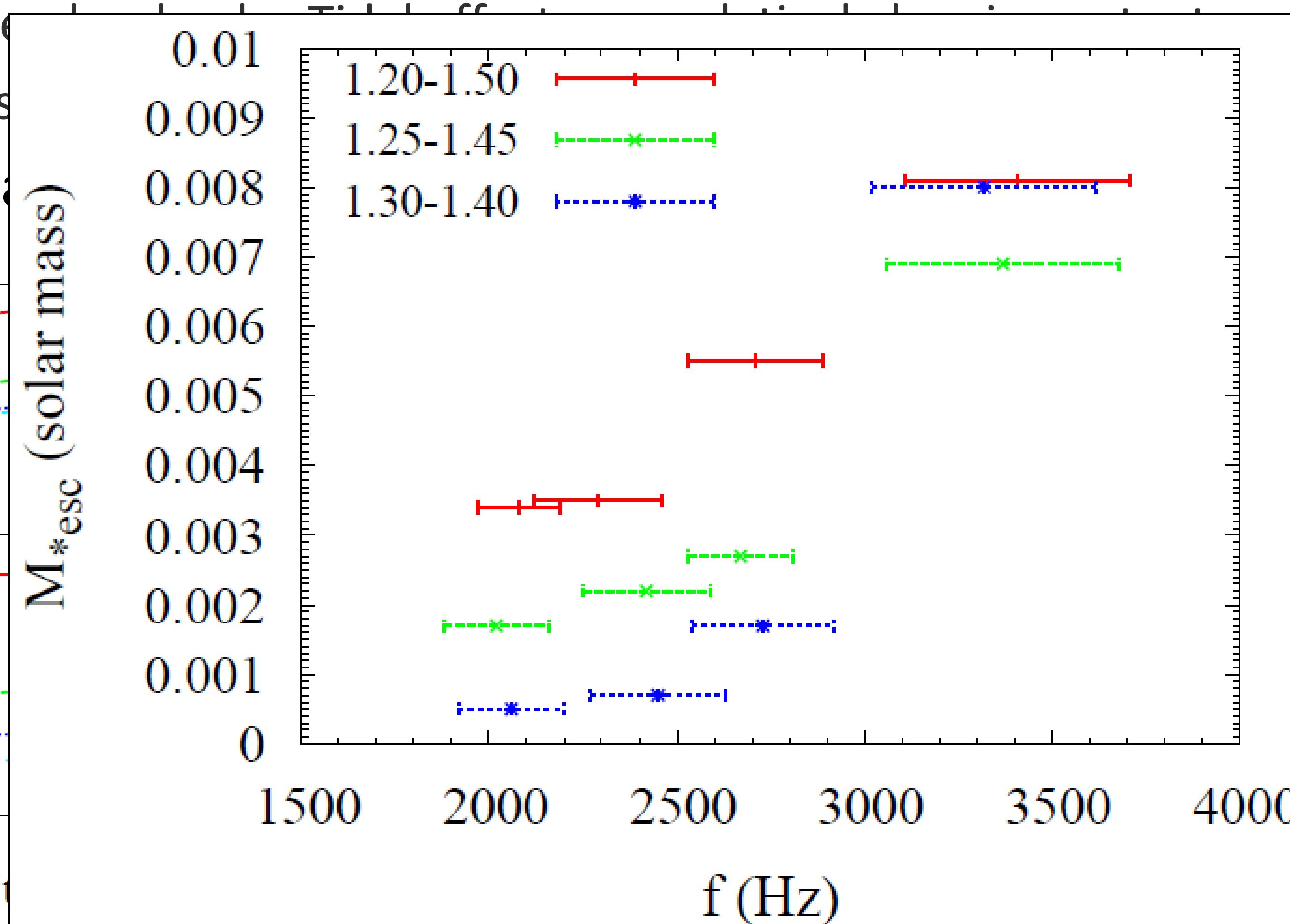
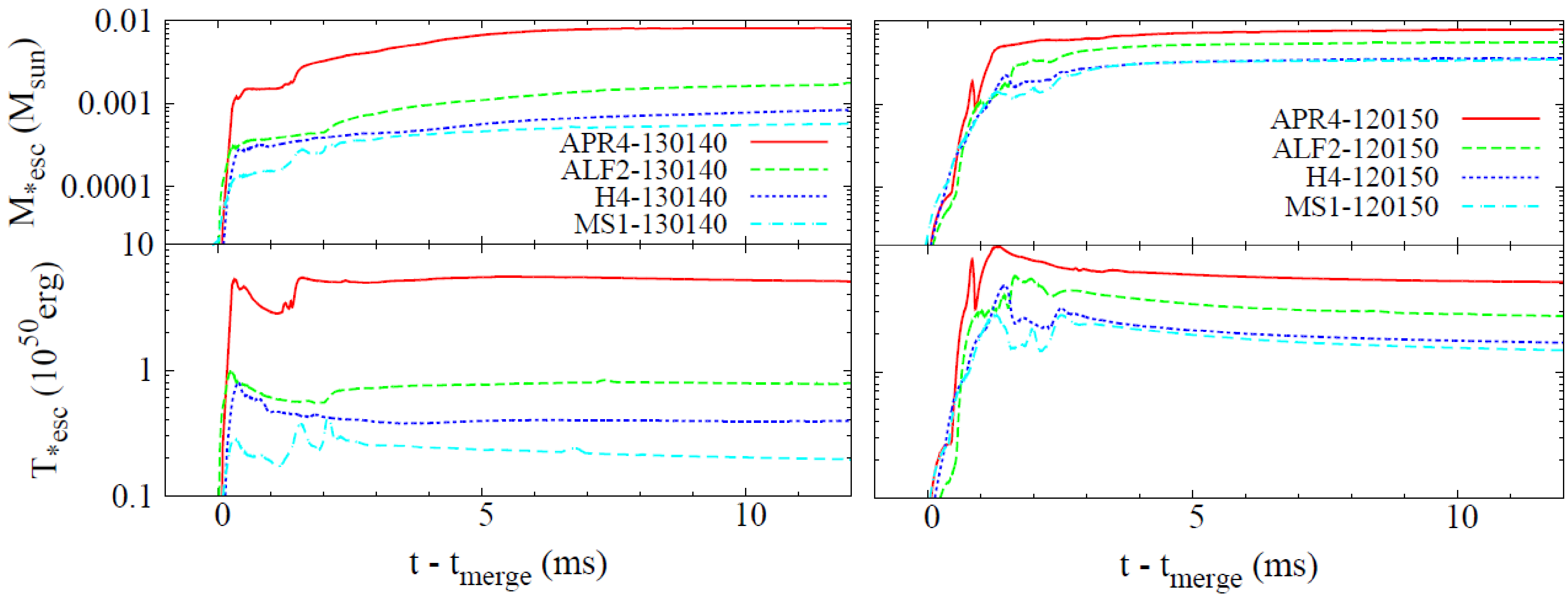
  - For larger mass
- Coupled observa





Mass ejection depends strongly on EOS

- More compact NS results in more massive ejecta
  - For mass ratio close to unity (q~1) and more compact NS, mass ejection is driven by shocks. Tidal effects are relatively less important
  - For larger mass ratio and less compact NS, tidal effect is also important
- Coupled observations of GW and EM will be important !

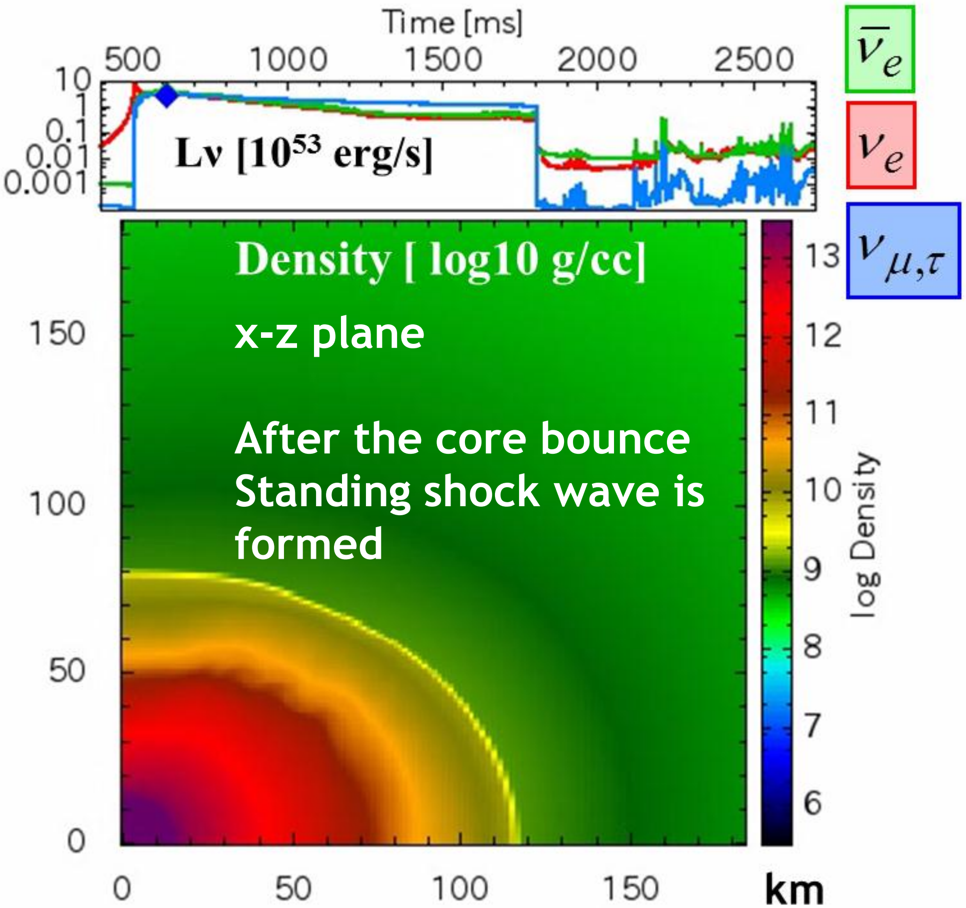


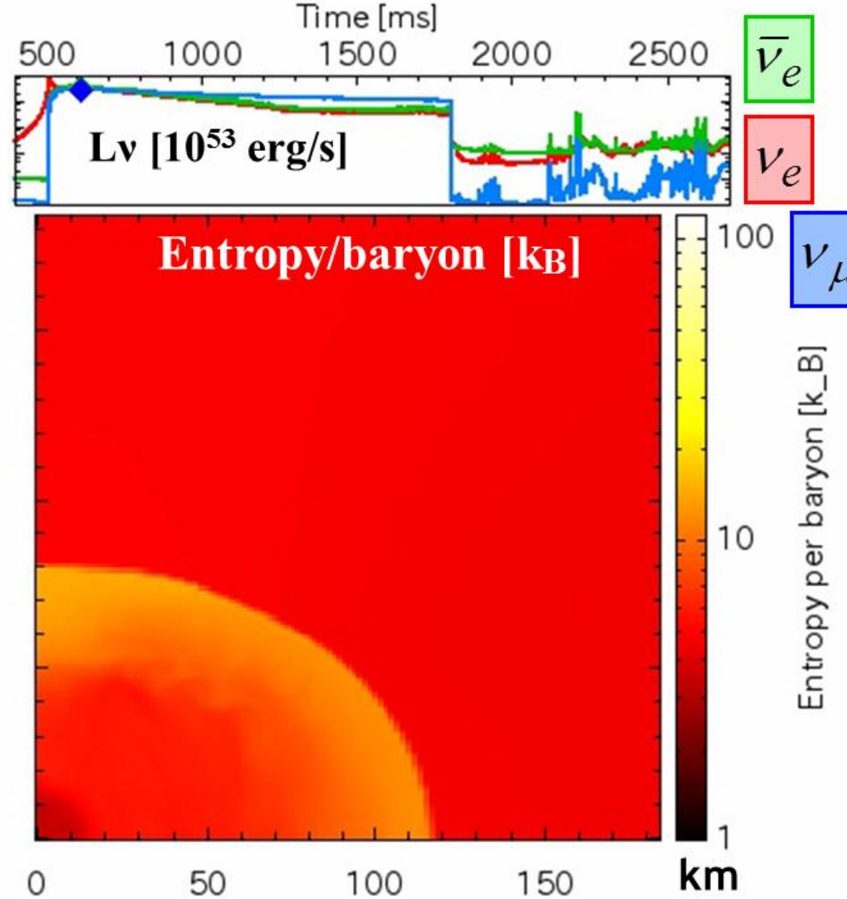
Summary

- Numerical Relativity is the unique tool to study dynamical phenomena such as NS-NS merger where strong gravity plays a role
  - Recent developments enable us to perform simulations in physical modeling
- NS-NS merger is interesting both in physics and astrophysics
  - Promising sources of ground-based GW detectors
  - As laboratory for exploring physics of dense matter
    - It may be possible to constrain EOS by GW from the merger
  - Central engine of SGRB
    - A large number of neutrinos are emitted from the hot disk
  - Exploring EM counterpart will be also important

BH+Disk formation in stellar core collapse (2D)

- 100Msolar model by Umeda & Nomoto (2008) + rotation
- Torus-structured shock : accumulation of matter to the proto-NS
- **Time varying, large (~10^{52} erg/s) neutrino luminosity after BH formation**





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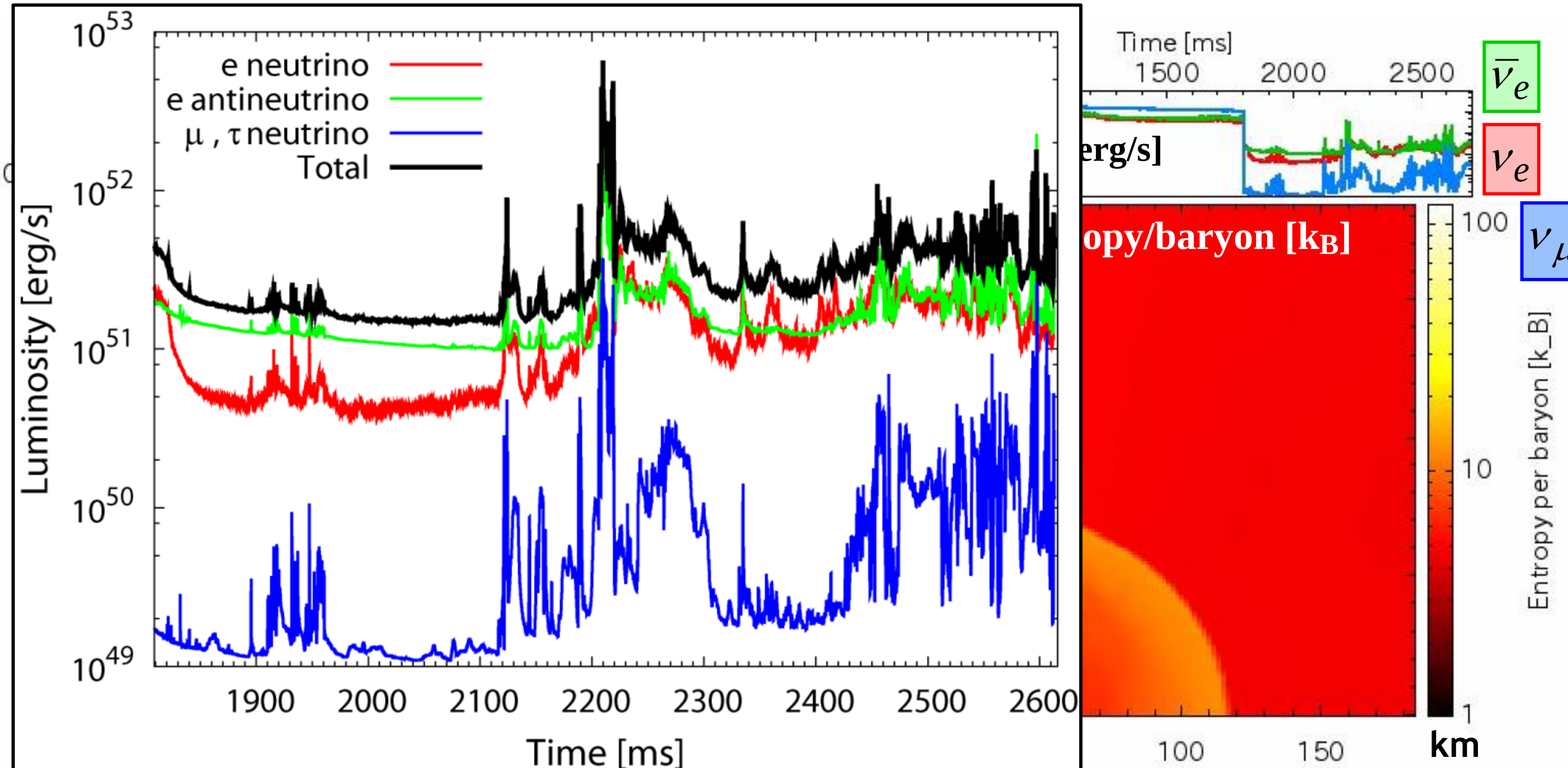
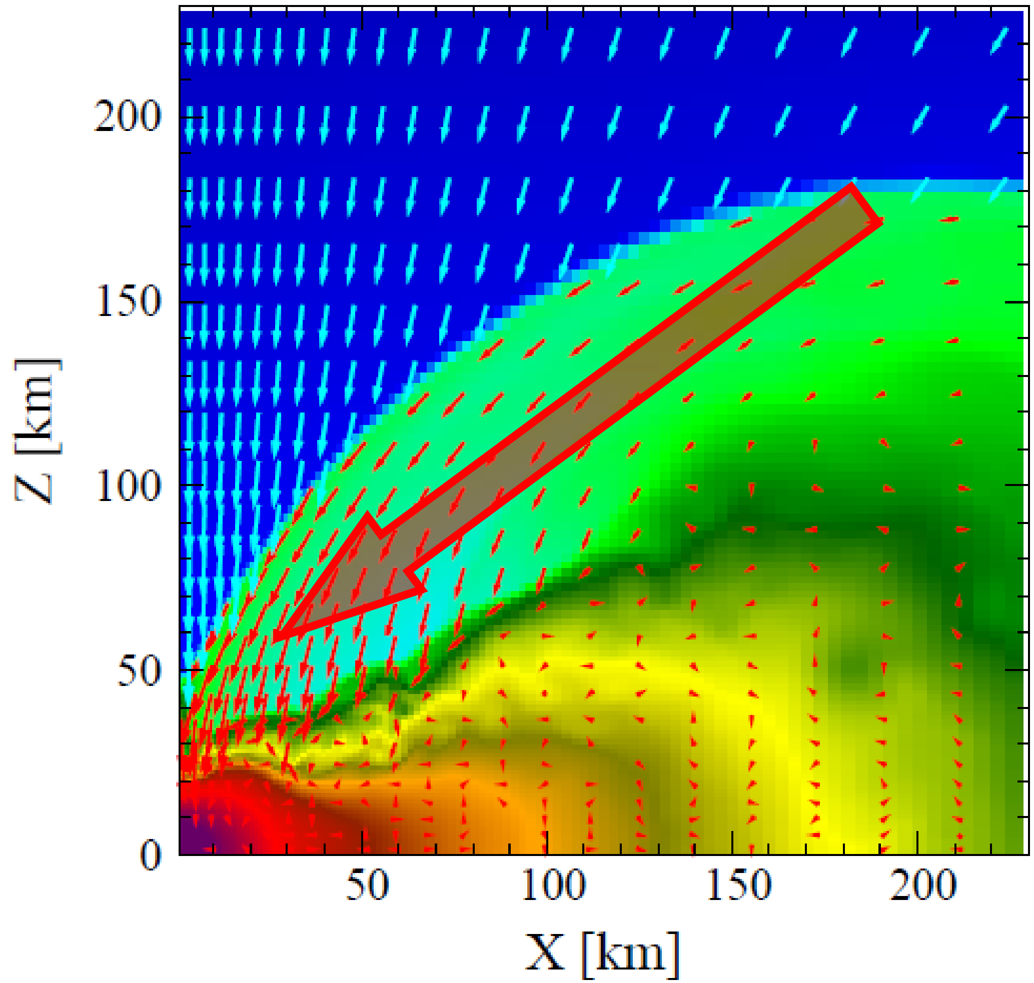


Importance of Rotation: **Oblique Shock**

- Torus-structured shock
- Infalling materials are accumulated into the PNS due to the **oblique shock**
- **Thermal energy is efficiently stored in the pole of PNS**
  - Ram pressure ↓
  - **⇒Outflow**
- **Flows hit central PNS**
  - NS oscillation
  - ⇒ **PdV work** , Lν ↑



Importance of High Entropy/Rotation : **Energy balance**

- **Compact core / Oblique shock ⇒ high mass accretion rate**
- Energy balance may not be satisfied ……
  - **Rotation decreases |Qadv| & |Qν| (dense disk)**
  - **Additional 'cooling' sources required**

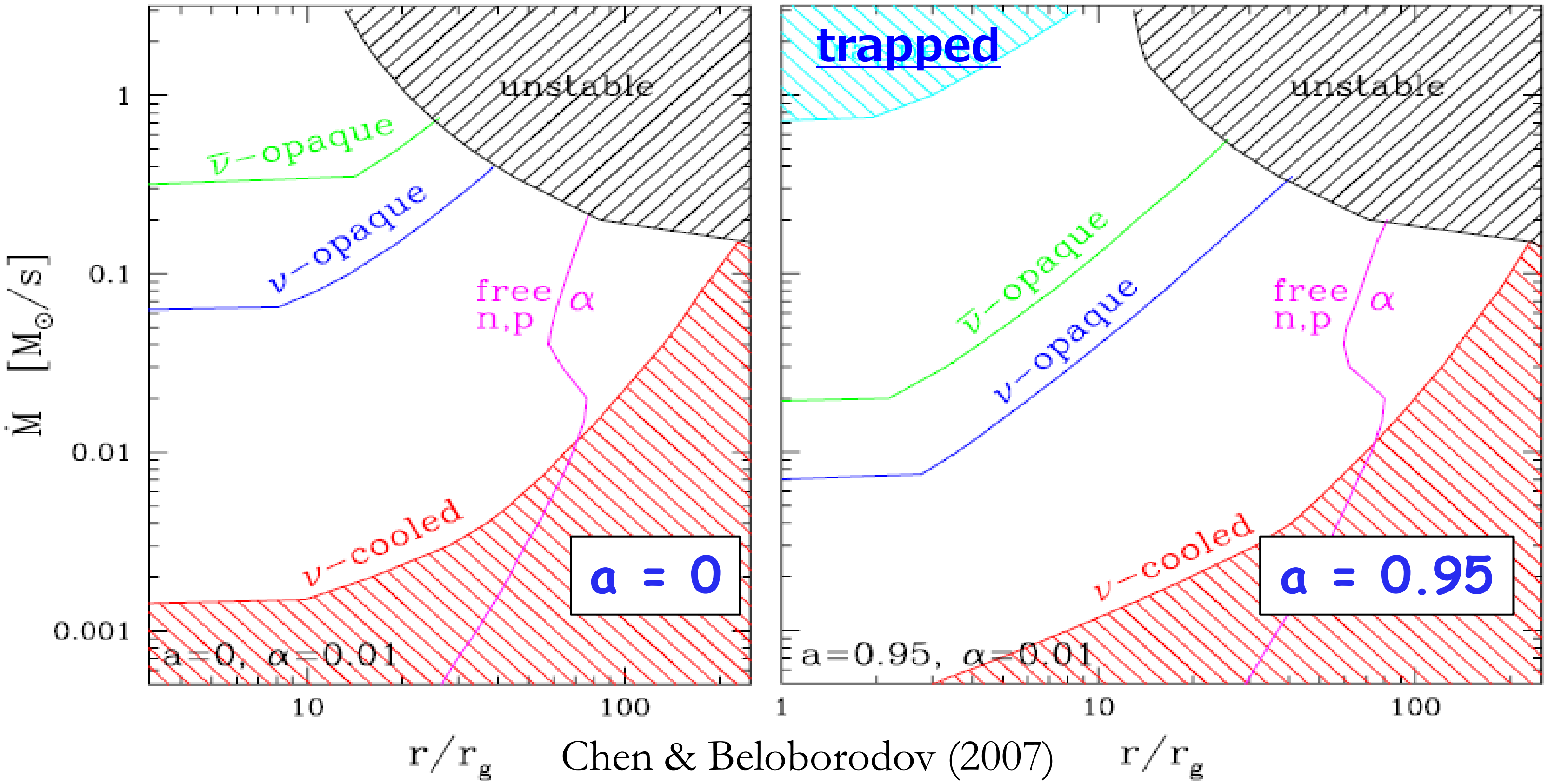
$$\dot{Q}^{+}_{\rm acc} = \dot{Q}^{-}_{\rm adv} + \dot{Q}^{-}_{\nu}$$

$$\Rightarrow \dot{Q}^{+}_{\rm acc} = \dot{Q}^{-}_{\rm adv} + \dot{Q}^{-}_{\nu} + \dot{Q}^{-}_{\rm outflow/expansion} + \dot{Q}^{-}_{\rm convection}$$

  - Strong dependence of Qν (ν-cooling) on T (and ρ)
    ⇒ slight change of configuration leads to dynamically large change
    - Torus is partially supported by the (thermal) pressure gradient
- **Smaller amount of heavy nuclei ⇒ more energetic SNe ?**
  - **Dissociation of 0.1 Msolar Fe costs ~ 10^{51} erg**
- Higher temperature : Less Pauli blocking in neutrino pair annihilation

Importance of Rotation: **BH spin**

- **Energy conversion efficiency can change two orders of magnitude**
- **Disk properties to neutrinos strongly depend on BH spin**
  - **Slow rot. BH ⇒ ISCO (disk edge) located far ⇒ low density / opacity ⇒ Efficient cooling ⇒ the local valance satisfied ⇒ weak/no time variability**



Chen & Beloborodov (2007)

Similarities to ordinary SN

- Same components: 'stalled' shock + neutrino sphere/torus
  - SASI-like activities are likely to occur ?
  - The gain (neutrino-heated) regions do exist (Sumiyoshi+ 2012)
- **Only topology is different**
  - How will this system evolve in the presence of ν-heating
  - The next study using GR-νRad-Hydro Code (recently developed)

Sumiyoshi+ 2012