BH-NS Merger Simulation in Numerical Relativity

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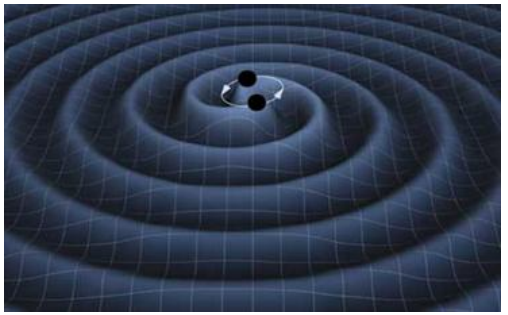
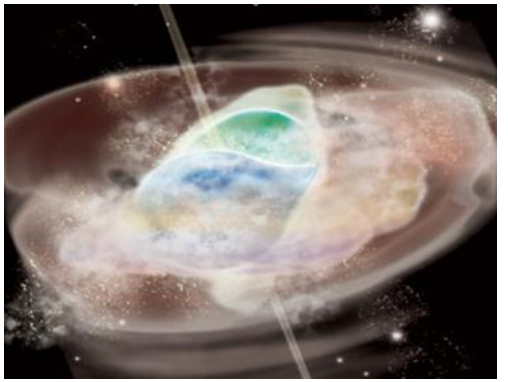
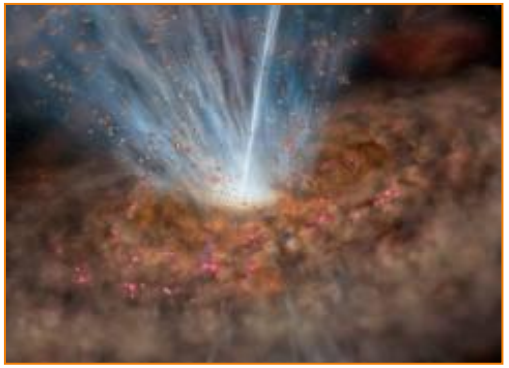
Why BH-NS mergers are interesting ?

- 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
    - BH-NS merger as a cosmological collider
- Theoretical candidate of gamma-ray bursts (GRB)
  - Central engine : BH + accretion disk
    - Energy source : neutrino pair annihilation ?





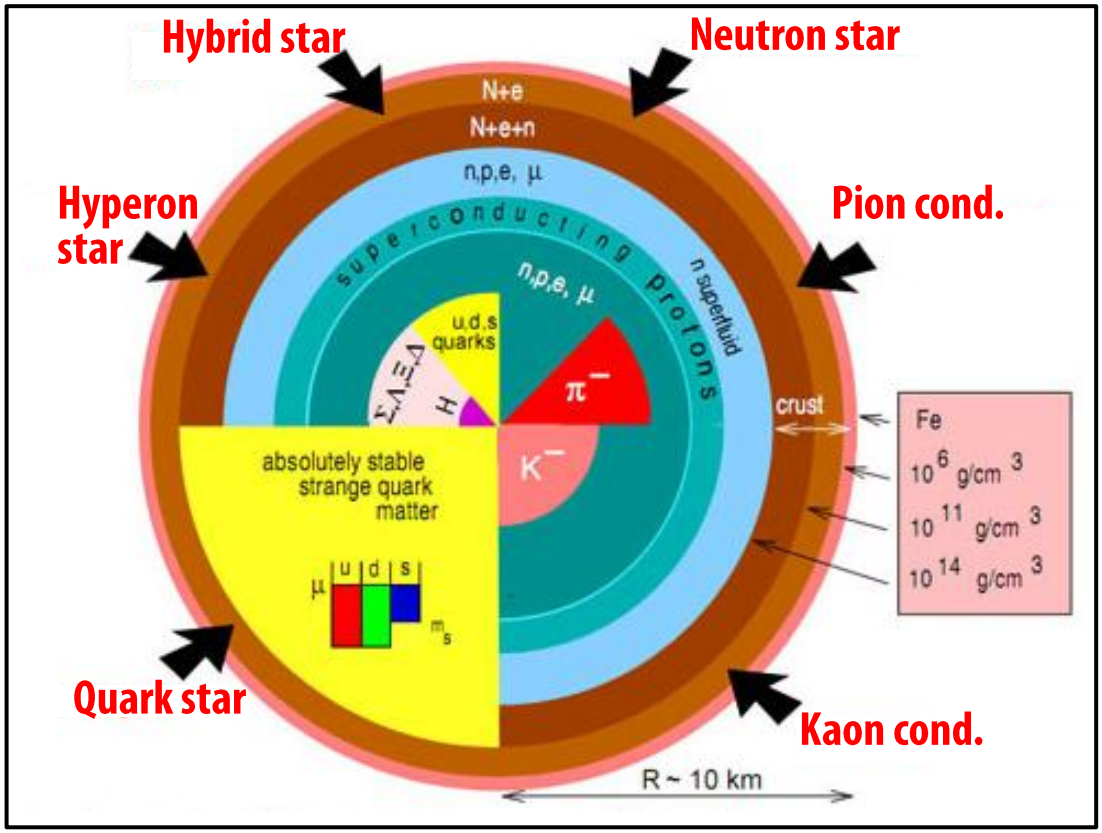


General relativistic gravity is important
Highly nonlinear and dynamical

→ **Numerical Relativity**

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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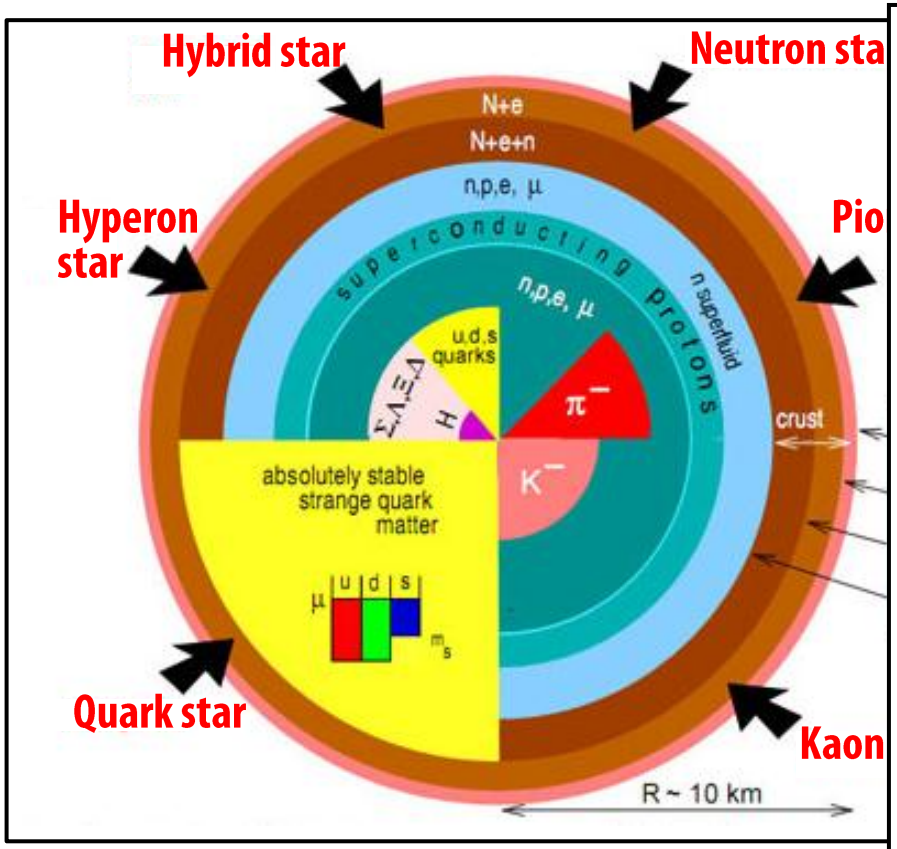

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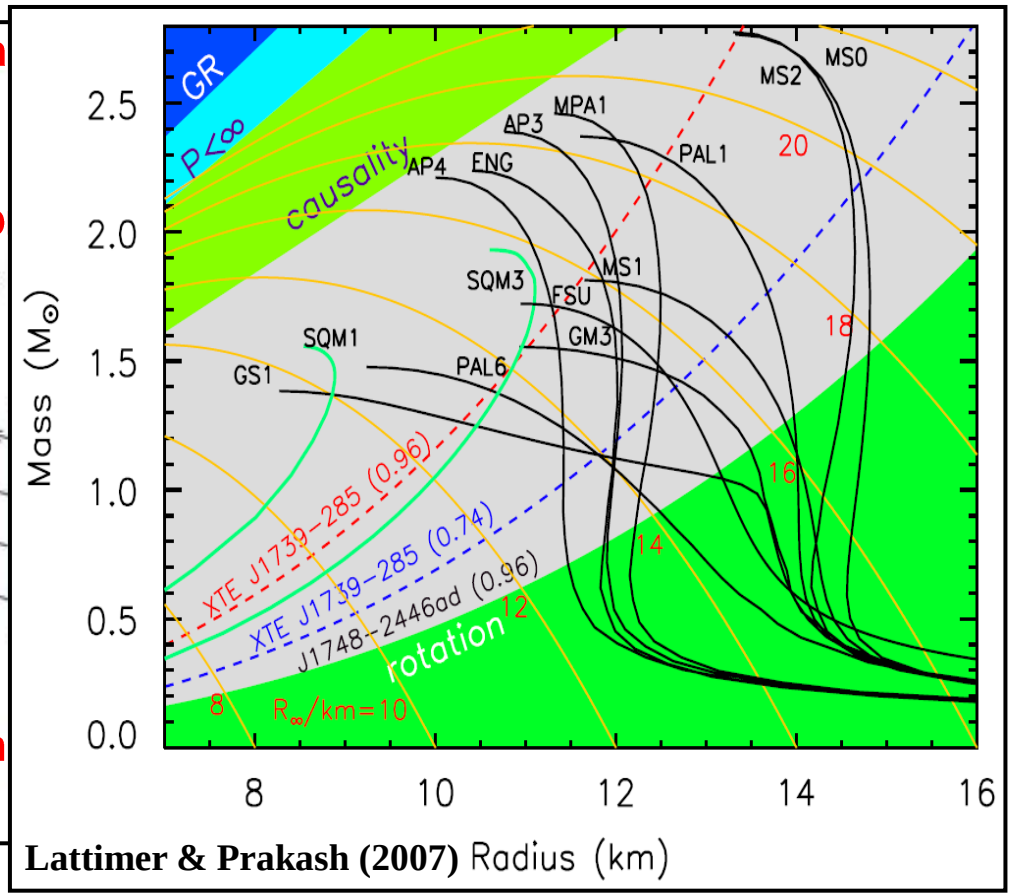

Lattimer & Prakash (2007)

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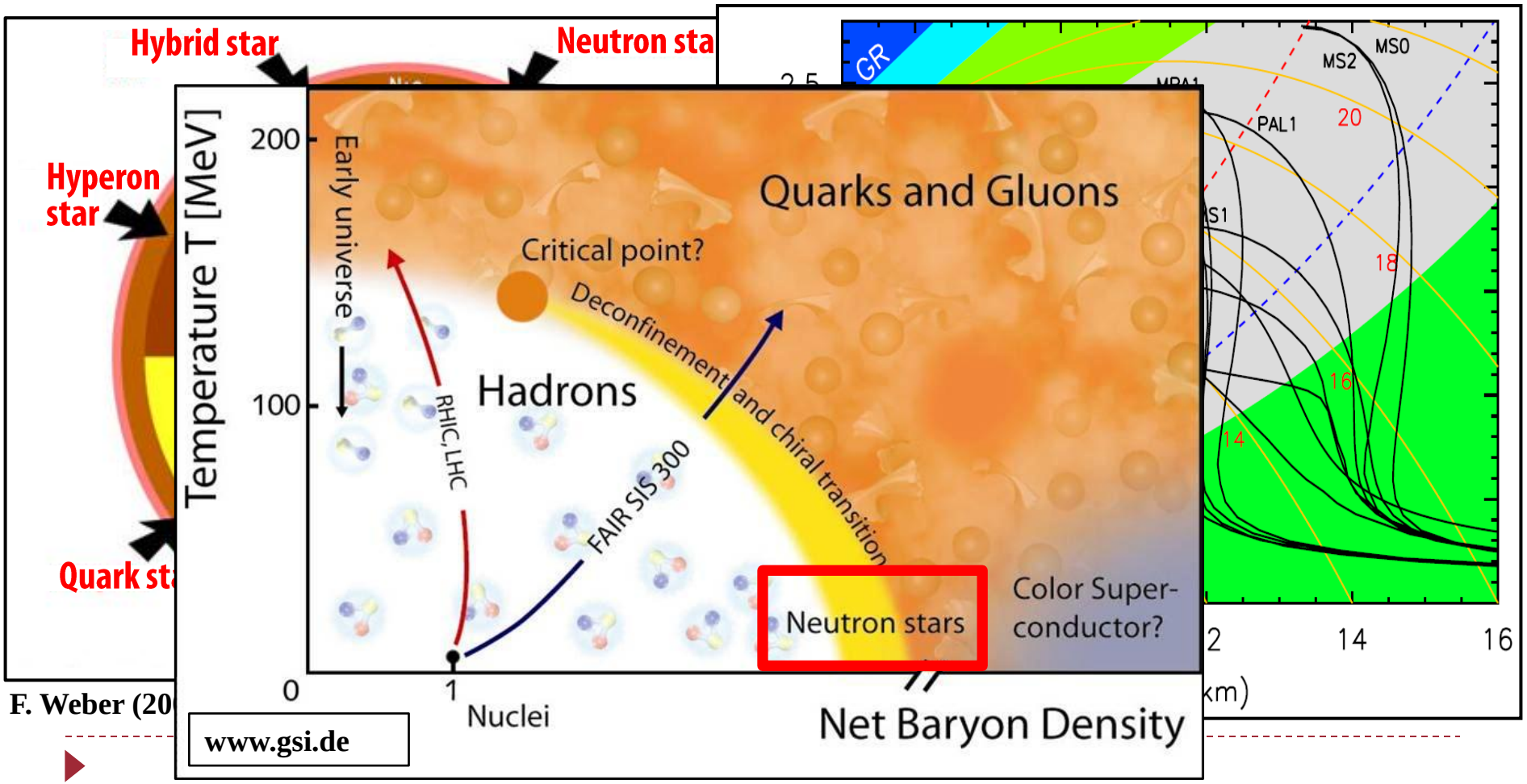


What is Numerical Relativity ?

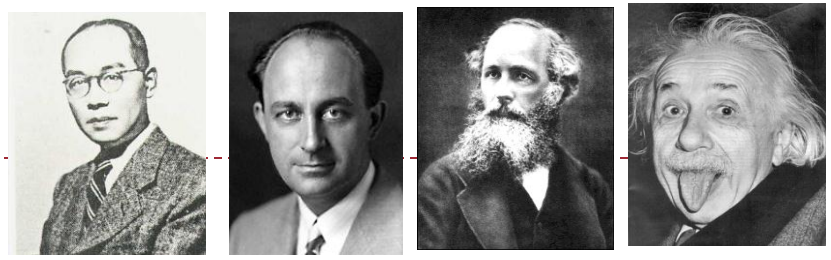
- Solving Einstein eq. and source field eqs. to clarify dynamical phenomena in the universe where strong gravity plays a role

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

$$\nabla_a T^{ab} = 0 \quad (T^{ab} = (T_{\rm Fluid} + T_{\rm EM} + T_\nu + ...)^{ab})$$

$$\nabla_a J^a = 0 \quad (J^a \sim (n_{\rm baryon},\ n_{\rm lepton}(n_e, n_\nu, ...),\ ...)u^a)$$

- 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



Current status of NR (1)

- **Solving Einstein equation (1995)○**
  - Constrained system (like Maxwell eq.) ⇒ problem of constraint violation
    - BSSN formulation (Shibata & Nakamura 1995, Baumgarte & Shapiro 1999)
  - General covariance ⇒ find good coordinate conditions
- **Numerical scheme for GR hydrodynamics (late 1990's)○**
  - Shocks appear in general ⇒ High resolution shock capturing scheme
- **Treatment of BH (2005) ○**
  - First successful binary BH simulation by Pretorius in 2005
  - BSSN-puncture : adopt nice coordinates and variables (Campanelli+ 2006)
- **Other issues ○**
  - Locating Apparent Horizon
  - Techniques of GW extraction from the metric
  - Mesh refinement techniques (E.g. Yamamoto+ 2008)
  - Powerful Supercomputers

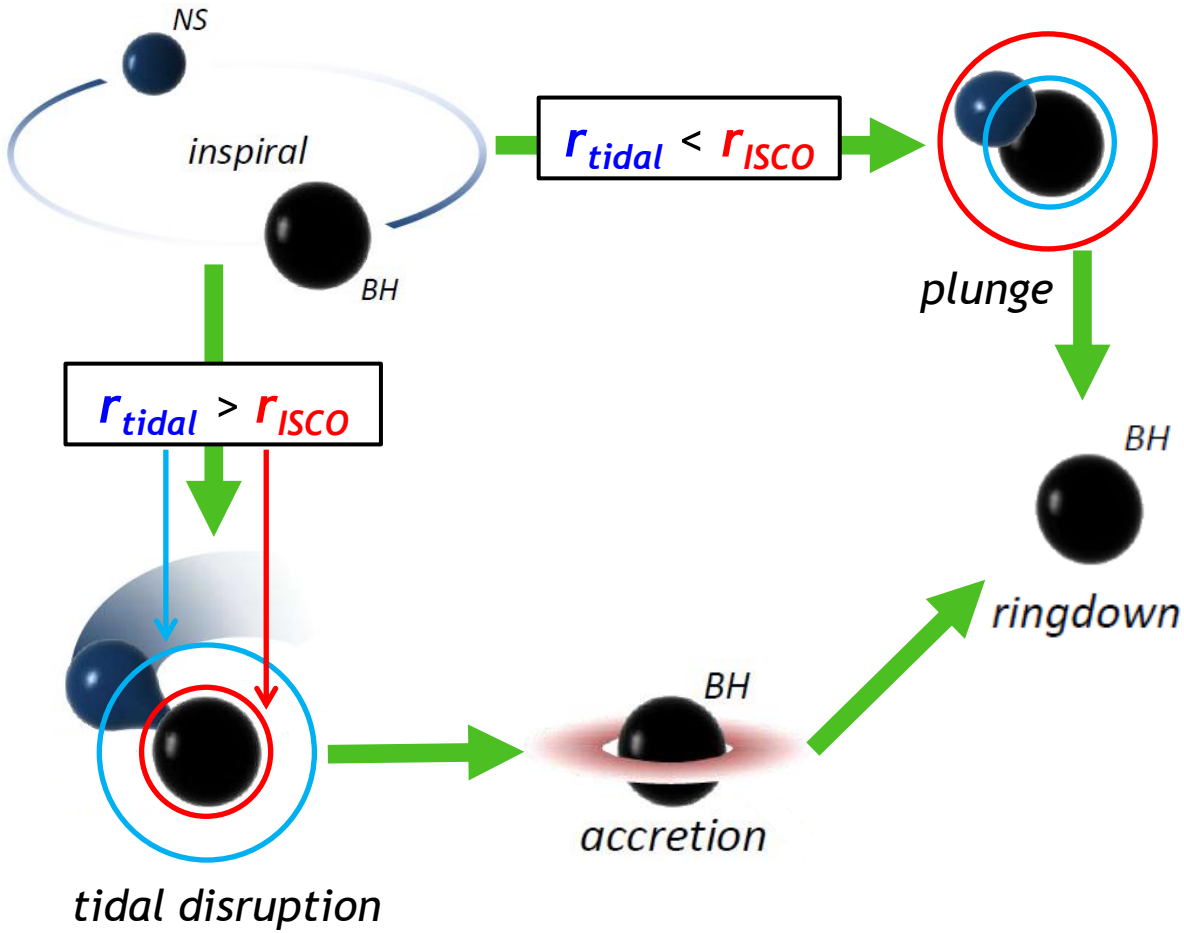
Current status of NR (2)

- **Towards more 'realistic' or physical modeling …….**
  - **Trend in 2010~**
- **Equation of state (EOS) ○**
  - Nuclear-theory-based finite temperature EOS tables
    - Sekiguchi 2007,2010; Ott et al. 2009
- **Neutrino treatment ○～△**
  - Weak interactions (Sekiguchi 2010)
  - Neutrino cooling (Sekiguchi 2010)
  - Neutrino heating (Kuroda+ 2012, Sekiguchi+ in prep)
  - Neutrino transfer based on Thorne's Moment scheme (Shibata+ 2011)

NR simulations with a physical modeling become possible now !

Evolution of BH-NS

Shibata & Taniguchi (2008)
Kyutoku et al. (2010), (2011)



ISCO: innermost stable circular orbit

$$r_{\rm ISCO} = r_{\rm ISCO}(M_{\rm BH}, a_{\rm BH})$$

BH spin dependence
larger a_{BH} ⇒ smaller r_{ISCO}

Tidal radius :

tidal force = self gravity of NS

$$\frac{r_{\rm tidal}}{M_{\rm BH}} = \left(\frac{M_{\rm NS}}{M_{\rm BH}}\right)^{2/3} \left(\frac{M_{\rm NS}}{R_{\rm NS}}\right)^{-1}$$

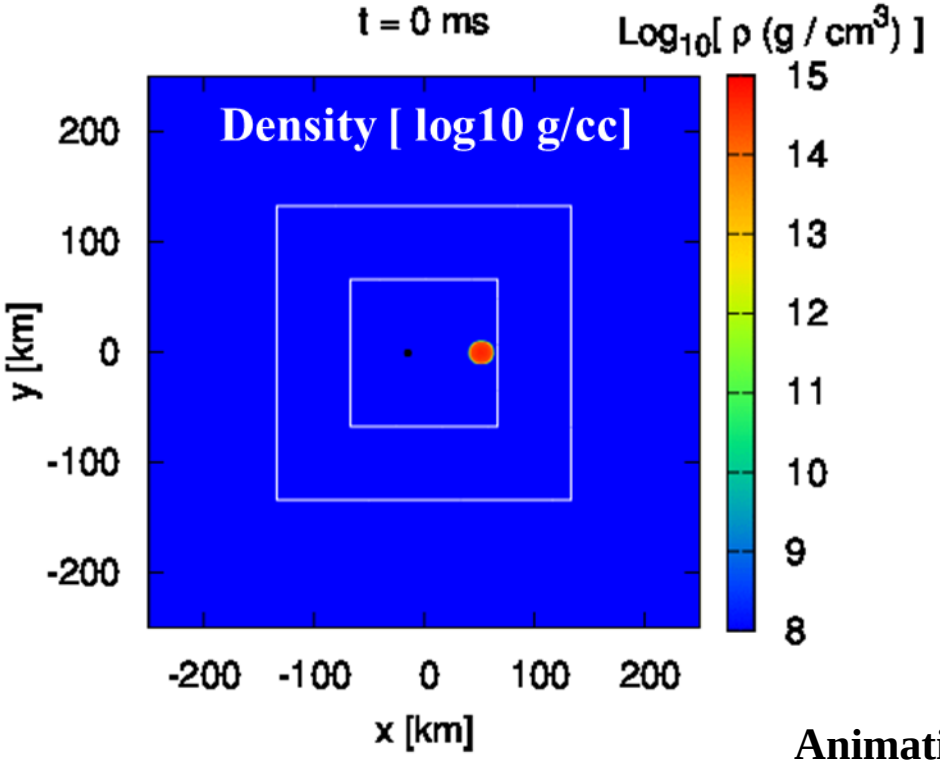
Compactness of NS
⇒ NS structure (EOS)

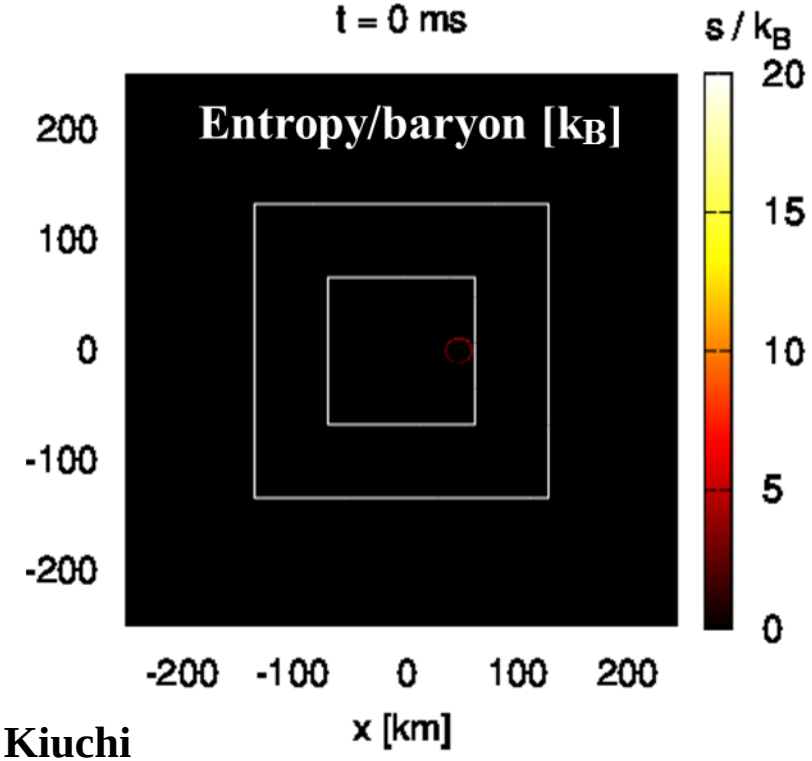
Imre Bartos, GECo, Columbia University
(Bartos et al. 2013, in prep.)

Sekiguchi et al. in prep.

BH-NS merger (4 -1.35 Msolar, a_{BH} = 0.5)

- NS is tidally disrupted and single spiral arm is formed
- The spiral arm interacts with itself and shock wave occur there
- A massive (O(0.1Msolar)) and hot accretion disk eventually forms around the BH



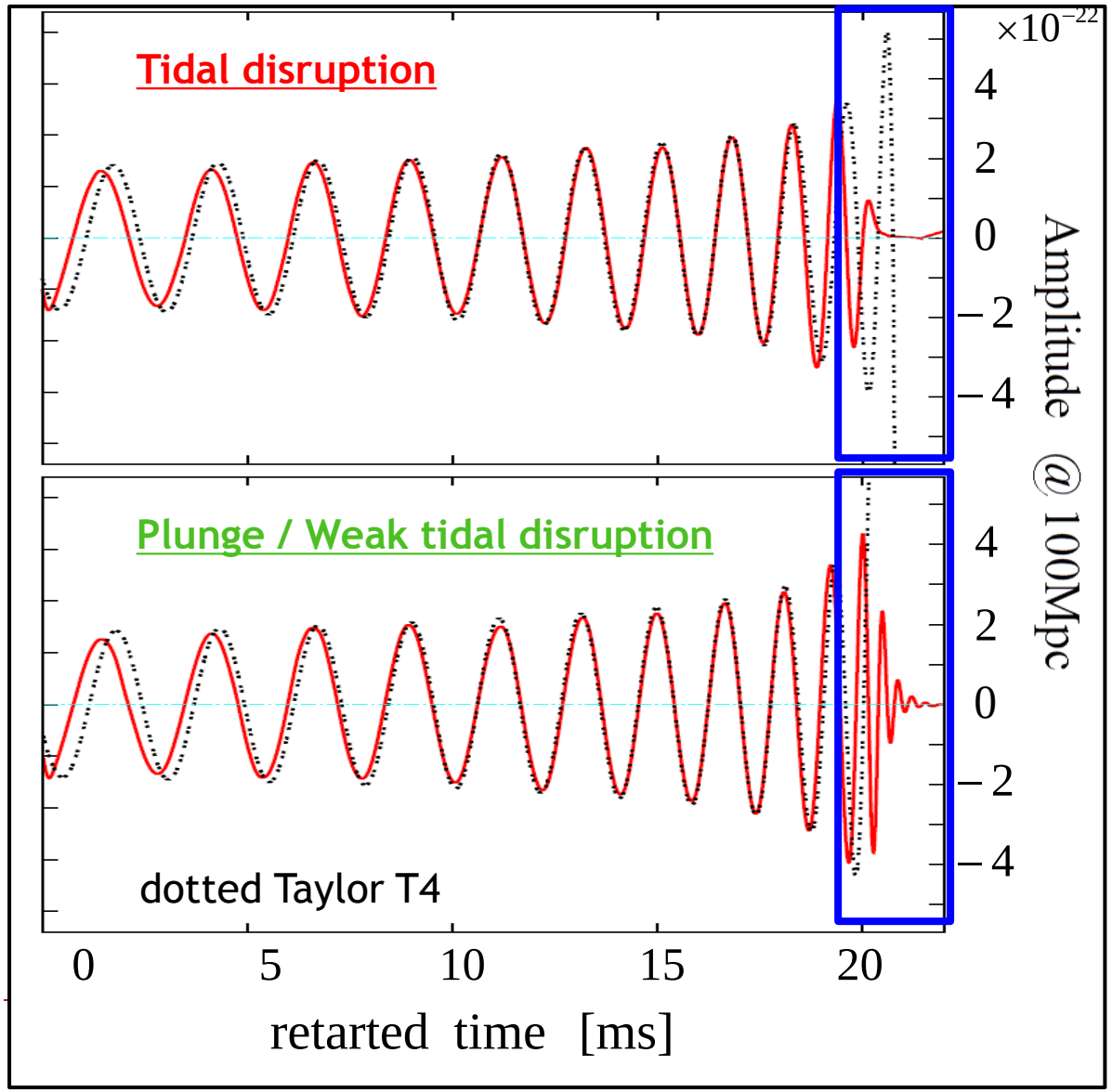


Animation by Kiuchi

GW from BH-NS merger

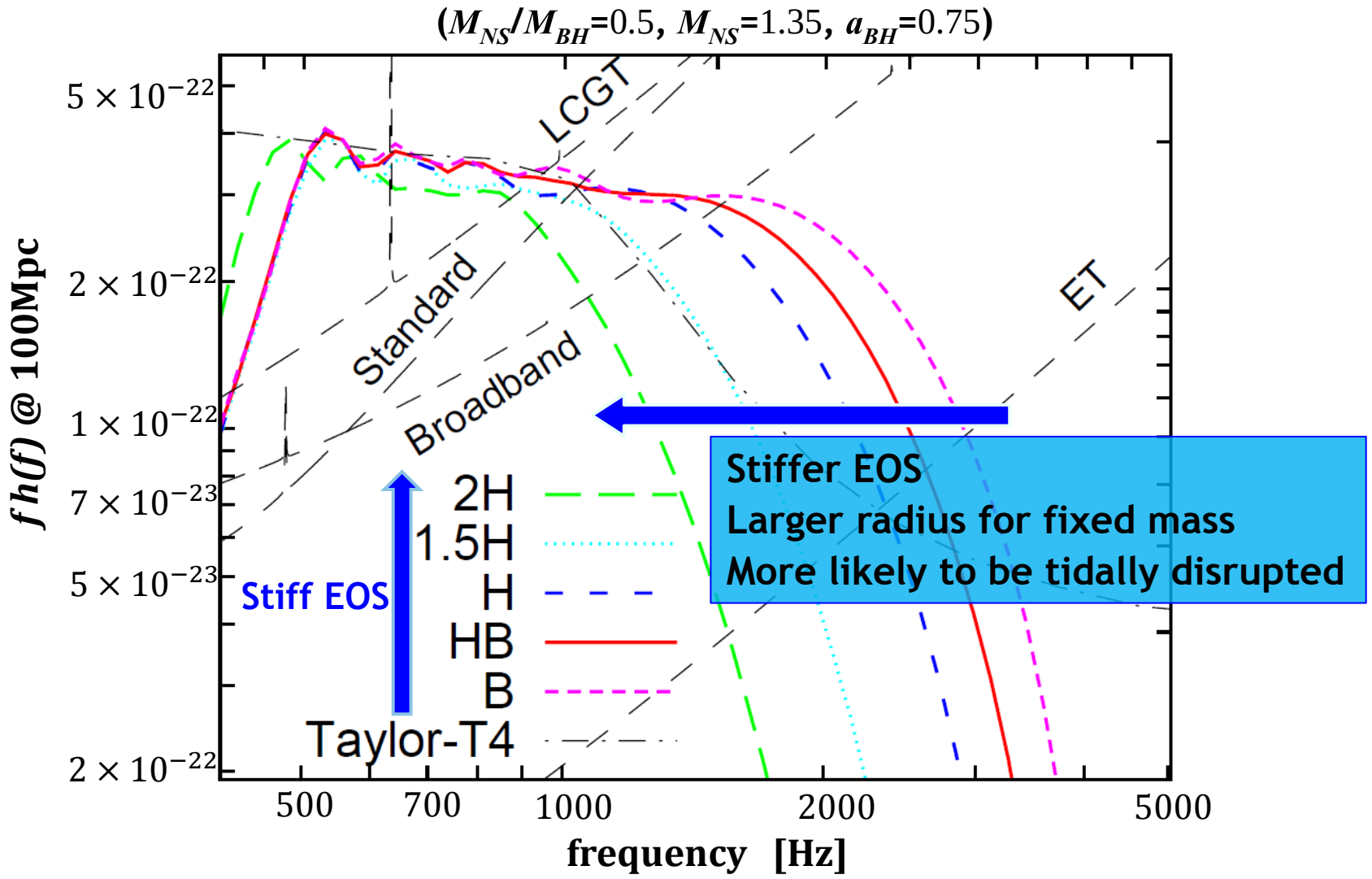
Kyutoku et al. (2010), (2011)

- **Tidal disruption**
  - GW amplitude shutdown suddenly
  - Widespread tidal arm and accretion disk form
- **Plunge/Weak disruption**
  - inspiral orbit sustains in more inner regions
  - NS hits BH and quasi-normal mode is excited



What GW spectra tell us

Kyutoku et al. (2010), (2011)

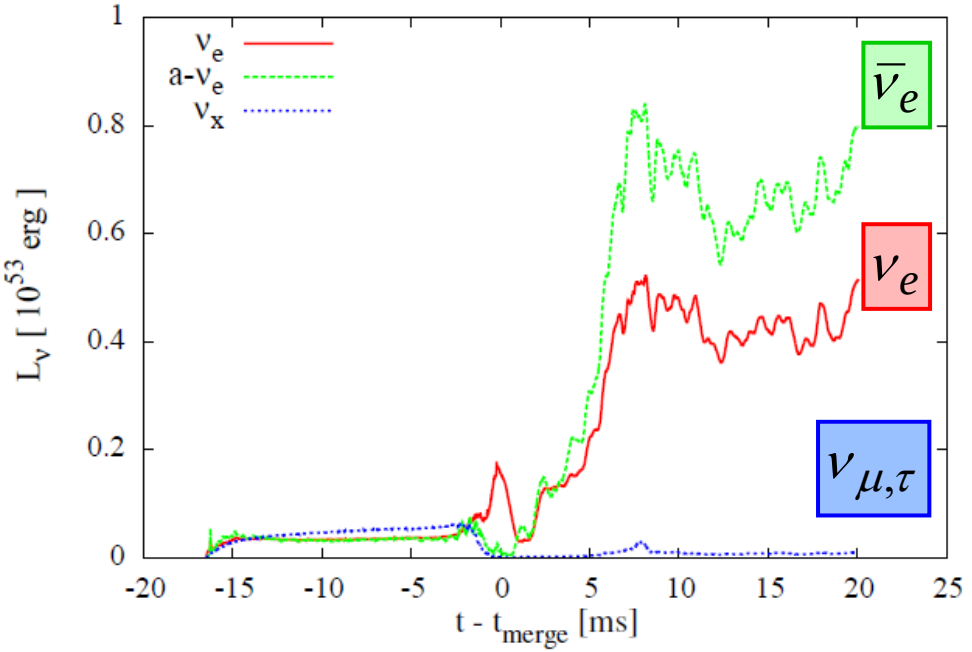


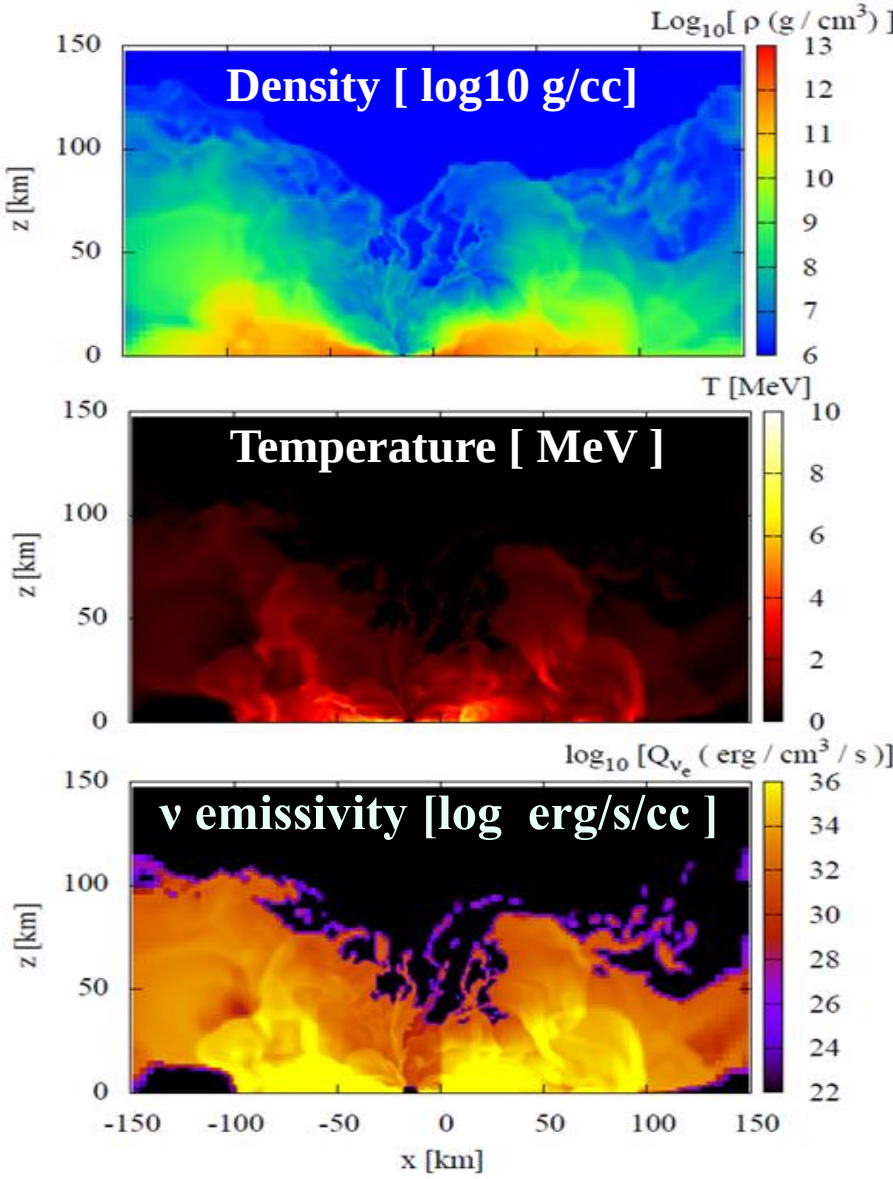
Kyutoku et al. (2011)

Sekiguchi et al. in prep.

Neutrino emission (BH-NS)

- Copious neutrinos (5-8 × 10^{52} erg/s) are emitted from the hot disk
- Low density region above BH
  - A potential site for ν-pair annihilation





Possible EM counterpart

- Expected electromagnetic (EM) wave emission from the merger
  - Detection of EM counterpart enhances reliability and detectability of GW
- Sweeping inter stellar matter ⇒ shock ⇒ **Synchrotron radiation**
  - 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 ⇒ **radioactive decay**
  - Li & Paczynski (1998)
  - $L_{peak} \sim \mathbf{2.6 \times 10^{42}\ erg/s}\ (f/3\times10^{-6})\ (v/0.3c)^{1/2}\,(M_{eje}/10^{-2}\ M_{\odot})^{1/2}$
- These transient event could be detected with upcoming radio or optical detectors

Summary

- Numerical Relativity is the unique tool to study dynamical phenomena such as BH-NS merger where strong gravity plays a role
  - Recent developments enable us to perform simulations in physical modeling
- BH-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 is a future work