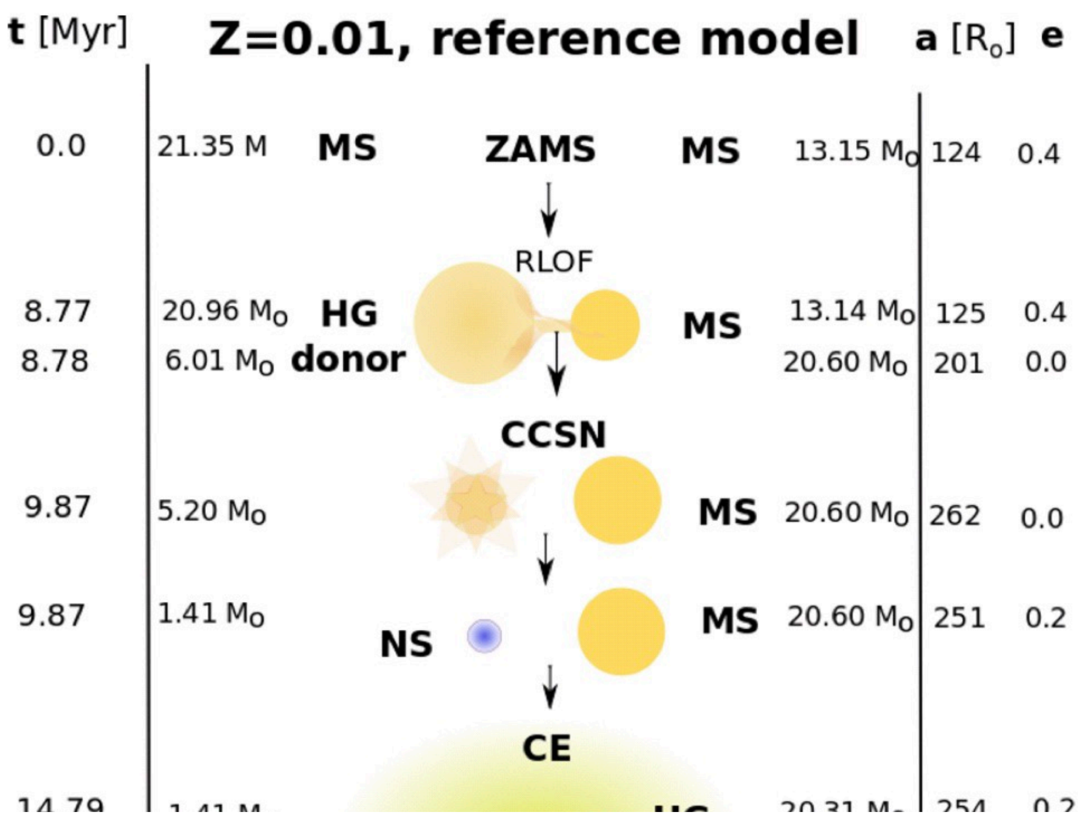
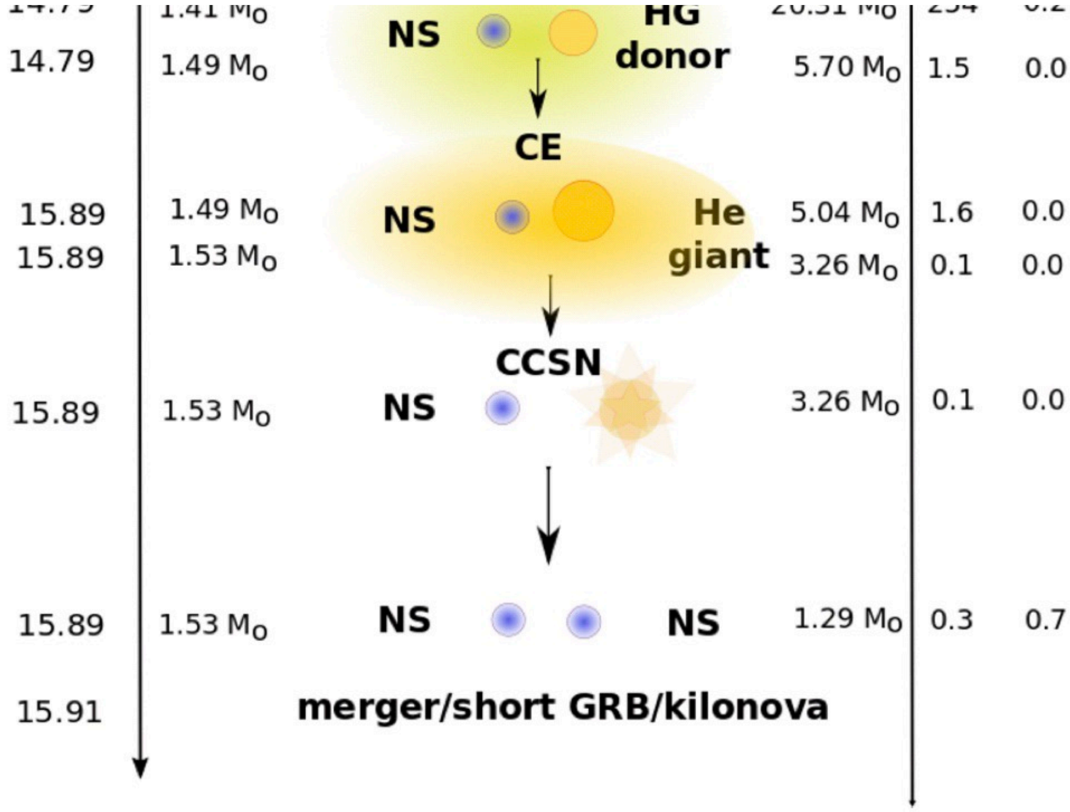
Lecture24

Tuesday, April 23, 2019 10:19 AM

Binary Neutron Star Mergers

- see review by Baiotti & Rezzolla (2017, Reports on Progress in Physics, 80, 096901)
- 2 possible channels for producing BNS:
  - binary stellar evolution
  - dynamical capture in dense stellar environments





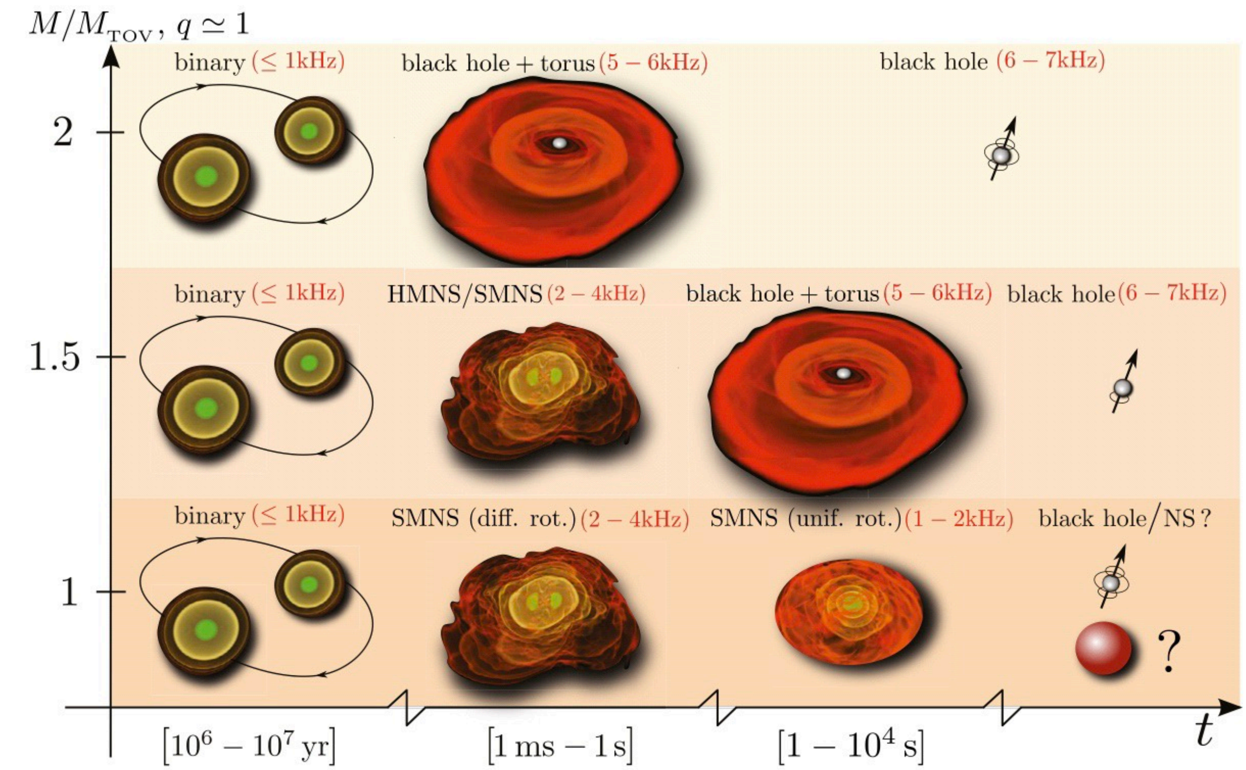
→ from Chruslinska et al. (2018, MNRAS)

- strong connection to short gamma-ray bursts (sGRBs)
- associated optical emission generally referred to as kilonova : 1000x brighter than a typical nova (NOT <u>super</u>-nova)

- likely site for production of heavy r-process elements

- overview of evolution of BNS to

merger (Baiotti & Rezzolla):



- HMNS: hypermassive NS: $M >$ maximum for uniformly rotating NS
  → collapse to BH delayed by differential rotation support

- SMNS: supramassive NS: rotating NS w/ $M > M_{TOV}$ + the mass limit for non-rotating NS

Numerical simulation of BNS

- complicated.
  - must be 3D
  - needs dynamical spacetime
  - microphysical nuclear EOS
  - magnetohydrodynamics
  - neutrino transport
  - Oh my!

- BSSN a common approach (see previous lecture 23)

gauge choice for BNS sims

- hyperbolic singularity avoiding "1 + log" slicing conditions:

$$(\partial_t - \beta^i \partial_i)\alpha = -f(\alpha)\alpha^2 (K - K_0)$$

where $f(\alpha) > 0$ & $K_0 \equiv K(t=0)$

- "Gamma-driver" shift conditions:

$$\partial_t^2 \beta^i = F \partial_t \tilde{\Gamma}^i - \eta \partial_t \beta^i$$

F & η : positive functions of space & time

→ drives $\tilde{\Gamma}^i$ to be constant

- first-order implementation of these gauge conditions:

$$\partial_t \beta^i - \beta^j \partial_j \beta^i = \frac{3}{4} \alpha B^i$$

$$\partial_t B^i - \beta^j \partial_j B^i = \partial_t \tilde{\Gamma}^i - \beta^j \partial_j \tilde{\Gamma}^i - \eta B^i$$

B^i : auxilliary variable (NOT mag. field)

η : acts as a damping coefficient to avoid oscillations in β^i

- '1+ log' + 'Gamma-driver" gauge conditions ensure:
  - singularities are avoided
  - coordinate distortions due to large spatial curvature are minimized

Spacetime evolution w/ CCZ4 & Z4c

- alternatives to BSSN

→ combine some advantages of both BSSN and generalized harmonic coordinates

- CCZ4: conformal & covariant "Z4"
  - in Z4, elliptic constraints converted into algebraic conditions for a new 4-vector Z_μ that measures the deviation from Einstein field eqns.
  - derived from covariant Lagrangian:

$$\mathcal{L} = g^{\mu\nu}\left[R_{\mu\nu} + 2\nabla_\mu Z_\nu \right]$$

- $Z_\mu = 0$ amounts to satisfying both Hamiltonian & momentum constraints

- damped formulation of Z4:

$$R_{\mu\nu} + \nabla_\mu Z_\nu + \nabla_\nu Z_\mu + \kappa_1\left[n_\mu Z_\nu + n_\nu Z_\mu - (1+\kappa_2) g_{\mu\nu} n_\sigma Z^\sigma \right] = 8\pi\left(T_{\mu\nu} - \tfrac{1}{2} g_{\mu\nu} T\right)$$

... Z4 field eqns.

- in CCZ4, energy-momentum constraints

become evolution eqns. for Z_μ

$\to$ "3+1" goes from weakly to strongly hyperbolic

- CCZ4 eqns.:

$$(\partial_t - \mathcal{L}_{\vec\beta})\gamma_{ij} = -2\alpha K_{ij}$$

$$(\partial_t - \mathcal{L}_{\vec\beta})K_{ij} = -\nabla_i \alpha_j + \alpha\big[R_{ij} + 2\nabla_{(i}Z_{j)}$$
$$-2K_i{}^l K_{lj} + (K - 2\Theta)K_{ij} - \kappa_1(1+\kappa_2)\Theta\gamma_{ij}\big]$$
$$-8\pi\alpha\left[S_{ij} - \tfrac{1}{2}(S-E)\gamma_{ij}\right]$$

$$(\partial_t - \mathcal{L}_{\vec\beta})\Theta = \frac{\alpha}{2}\Big[R + 2\nabla_j Z^j + (K-2\Theta)K - K^{ij}K_{ij}$$
$$-2\frac{Z^j \partial_j \alpha}{\alpha} - 2\kappa_1(2+\kappa_2)\Theta - 16\pi E\Big]$$

$$(\partial_t - \mathcal{L}_{\vec\beta})Z_i = \alpha\Big[\nabla_j(K_i{}^j - \delta_i{}^j K) + \partial_i\Theta - 2K_i{}^j Z_j$$
$$-\Theta\frac{\partial_i \alpha}{\alpha} - \kappa_1 Z_i - 8\pi S_i\Big]$$

where,

$$E \equiv n_\alpha n_\beta T^{\alpha\beta}$$

$$S_i \equiv -\gamma_{i\alpha} n_\beta T^{\alpha\beta}$$

$$S_{ij} \equiv \gamma_{i\alpha}\gamma_{j\beta} T^{\alpha\beta}$$

$D_{ij} \equiv \gamma_{i\alpha}\gamma_{j\beta}$ ' '

$\Theta \equiv n_\mu Z^\mu = \alpha Z^0$ ... projection

→ use same gauge conditions as for BSSN

Conformally-flat spacetime

- "Isenberg-Wilson-Matthews" approach

$$\gamma_{ij} = \phi^4 \hat{\gamma}_{ij} \quad ; \quad \hat{\gamma}_{ij} = \eta_{ij}$$

- simplifies things a lot
- results in system in which constraints are solved at every step (elliptic)
  → does not admit gravitational radiation! Evolution of BNS orbit put in by hand via a post-Newtonian approx.

Initial Data

- must satisfy field eqns. including

Hamiltonian & momentum constraints:

$$\mathcal{H} \equiv {}^{(3)}R + K^2 - K_{ij}K^{ij} - 16\pi E = 0$$

$$\mathcal{M}^i \equiv D_j\left(K^{ij} - \gamma^{ij}K\right) - 8\pi S^i = 0$$

- conformal flatness usually used to solve this
- also assume initially helical symmetry: ie, a corotating frame in which the BNS is stationary
  - mathematically equivalent to the existence of helical Killing vector:

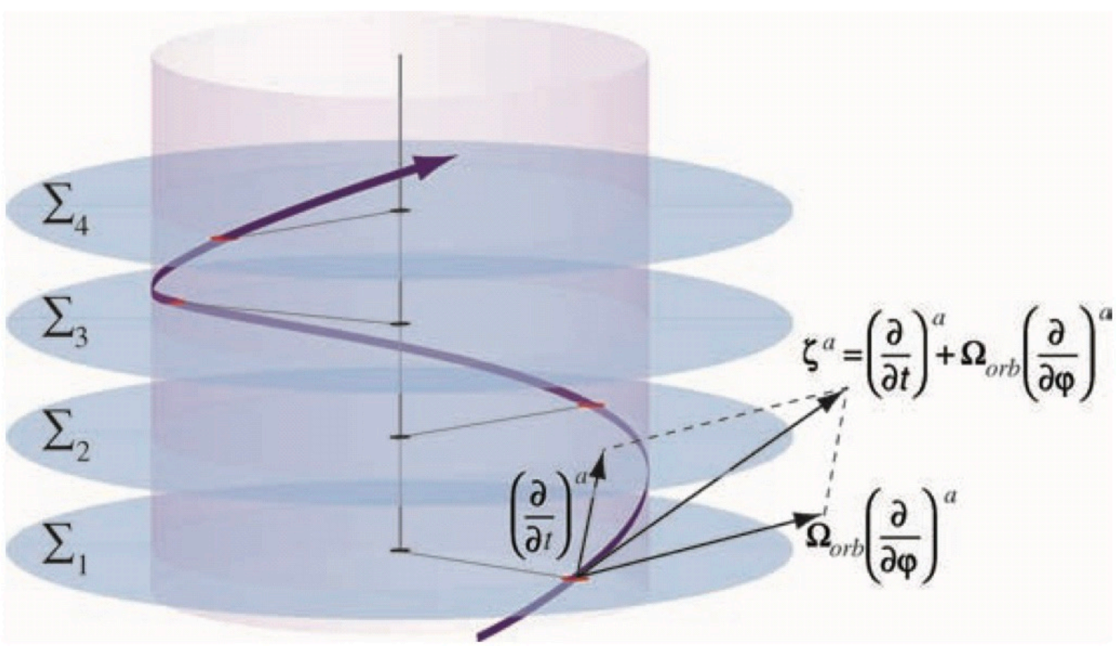


Figure 12.4 Illustration of a helical Killing vector generating a circular binary orbit.

- the LORENE code incorporates the above requirements & is publicly-available: Www.lorene.obspm.fr
- must choose to construct either irrotational or corotational BNS systems
  - the latter likely don't exist: too fast rotation!
- a problem in initial data is spurious eccentricity. Arises from assumptions of conformal flatness and circular binary orbit initially