Strangeness, Gravitational Waves and Neutron Stars, 10 June 2016 INFN - Laboratori Nazionali di Frascati

The Physics of Binary Neutron Star merger from general relativistic numerical simulations.

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Abstract

In the eve of Gravitational Wave physics the characterisation of the gravitational wave signal emitted by compact binary sources will play a prominent role.

We present three-dimensional simulations of the dynamics of binary neutron star (BNS) mergers from the late inspiral stage up to ~20 ms after the system has merged, either to form a hyper-massive neutron star (HMNS) or a rotating black hole (BH).

We report results for equal and un-equal-mass models and on the strength of the Gravitational Signal and its dependence on the EOS, the mass ratio of the two stars, the radiated energy and angular momentum.

We use a semi-realistic description of the equation of state (EOS) where the EOS is described by a seven-segment piece-wise polytropic with a thermal component given by Gamma_th=1.8

One of the important characteristics of the present investigation is that it is entirely performed using only **publicly available open source software**, the Einstein Toolkit for the dynamical evolution and the LORENE code for the generation of the initial models.

Based on:

- Modeling Equal and Unequal Mass Binary Neutron Star Mergers Using Public Codes,
R. De Pietri, A. Feo, F. Maione and F. Loeffler, arXiv:1509.08804 [gr-qc], doi:10.1103/PhysRevD.93.064047

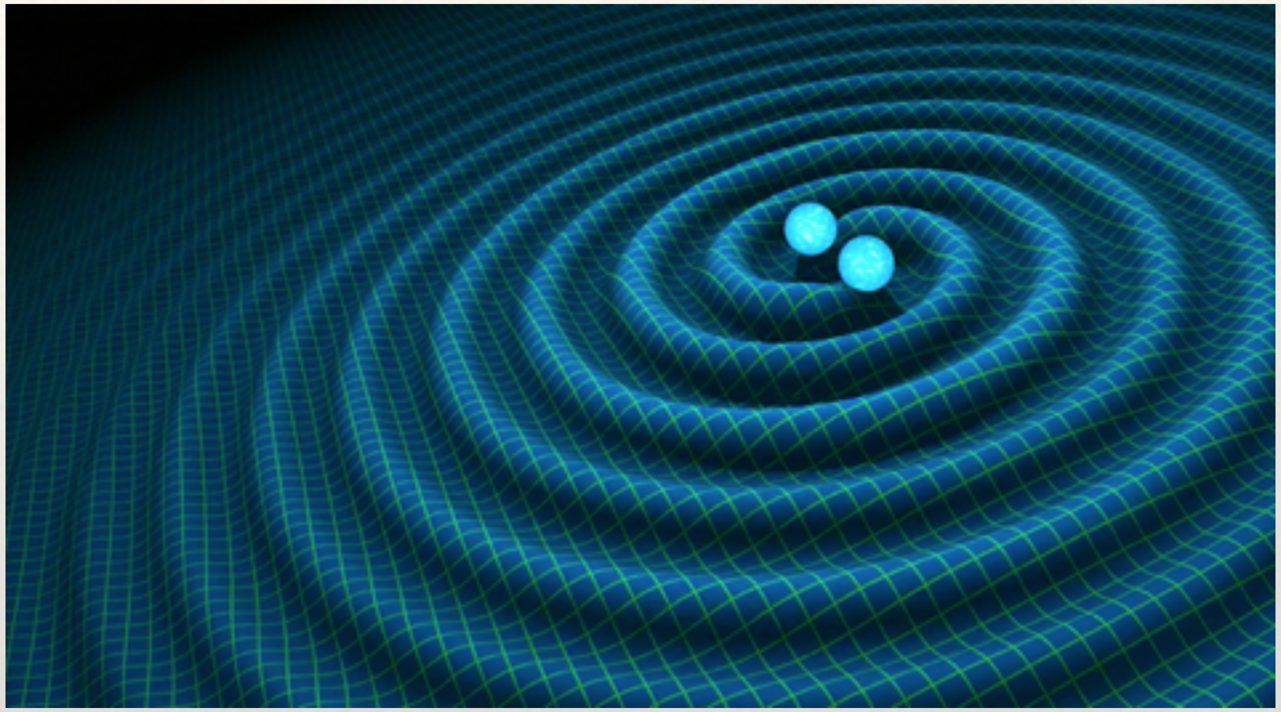
- Binary neutron star merger simulations with different initial orbital frequency and equation of state, F. Maione, R. De Pietri, A. Feo and F. Loeffler, arXiv:1605.03424 [gr-qc]

work in collaboration with :
R.De Pietri, F. Maione, F. Loeffler

A network of advanced detectors

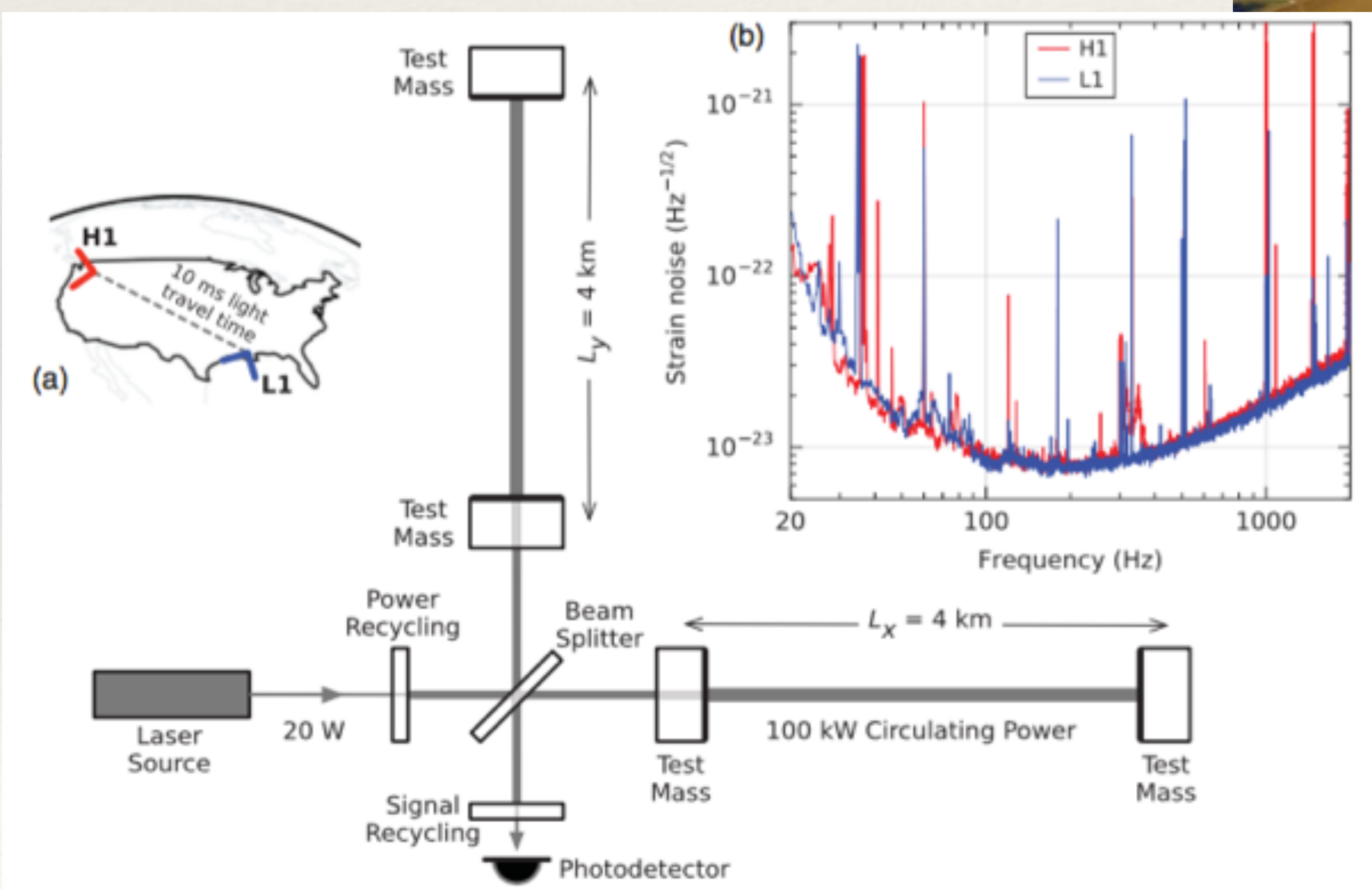
Gravitational Waves: The Sound of the Universe

- Predicted by the General Relativity
- Are ripples in the metric of space-time that propagate like a wave
- Caused by some of the most violent and energetic processes in the Universe (most powerful sources are binaries of compact objects)
- Carry information about the source (BH, NS, …)
- GW will provide a new way to listen the Universe and open a new frontier
- They are the only way to detect BH directly!



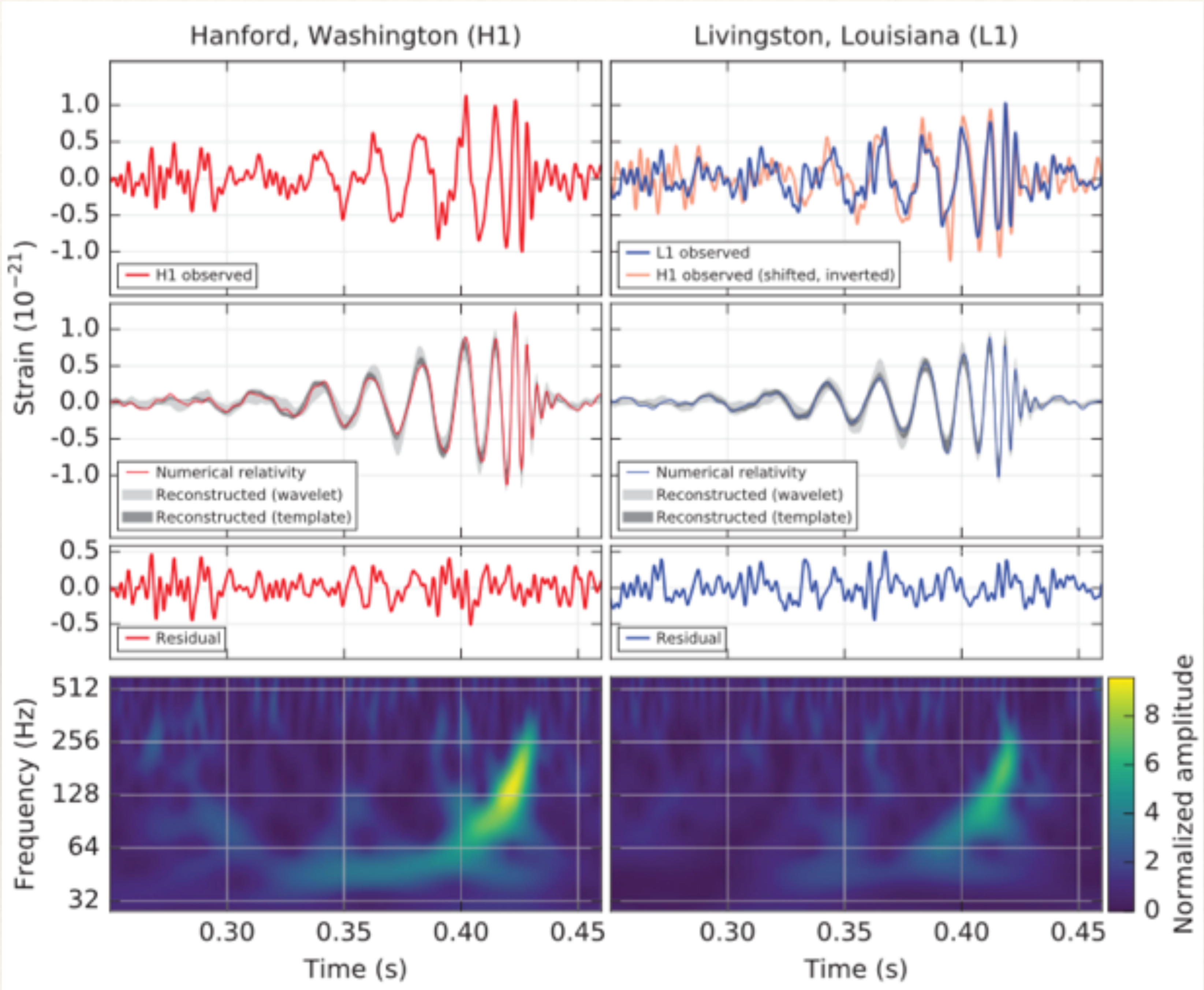
these waves travel at the speed of light through the Universe

Advanced LIGO/Virgo Interferometers



Gravitational Wave detected!

- **The gravitational waves were detected on September 14, 2015 at 5:51 a.m. Eastern Daylight Time (09:51 UTC)** by both of the twin Laser Interferometer Gravitational-wave Observatory (LIGO) detectors, located in Livingston, Louisiana, and Hanford, Washington, USA.
- The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than **5.1σ**. The source lies at a luminosity distance of **410**(18) **Mpc** corresponding to a redshift z=0.09(4). In the source frame, the initial black hole masses are **36**(5)$\mathbf{M_\odot}$ and **29**(4)$\mathbf{M_\odot}$, and the final black hole mass is **62**(4)$\mathbf{M_\odot}$, with 3.0(5) $\mathbf{M_\odot c^2}$ radiated in gravitational waves. ***All uncertainties define 90% credible intervals***.

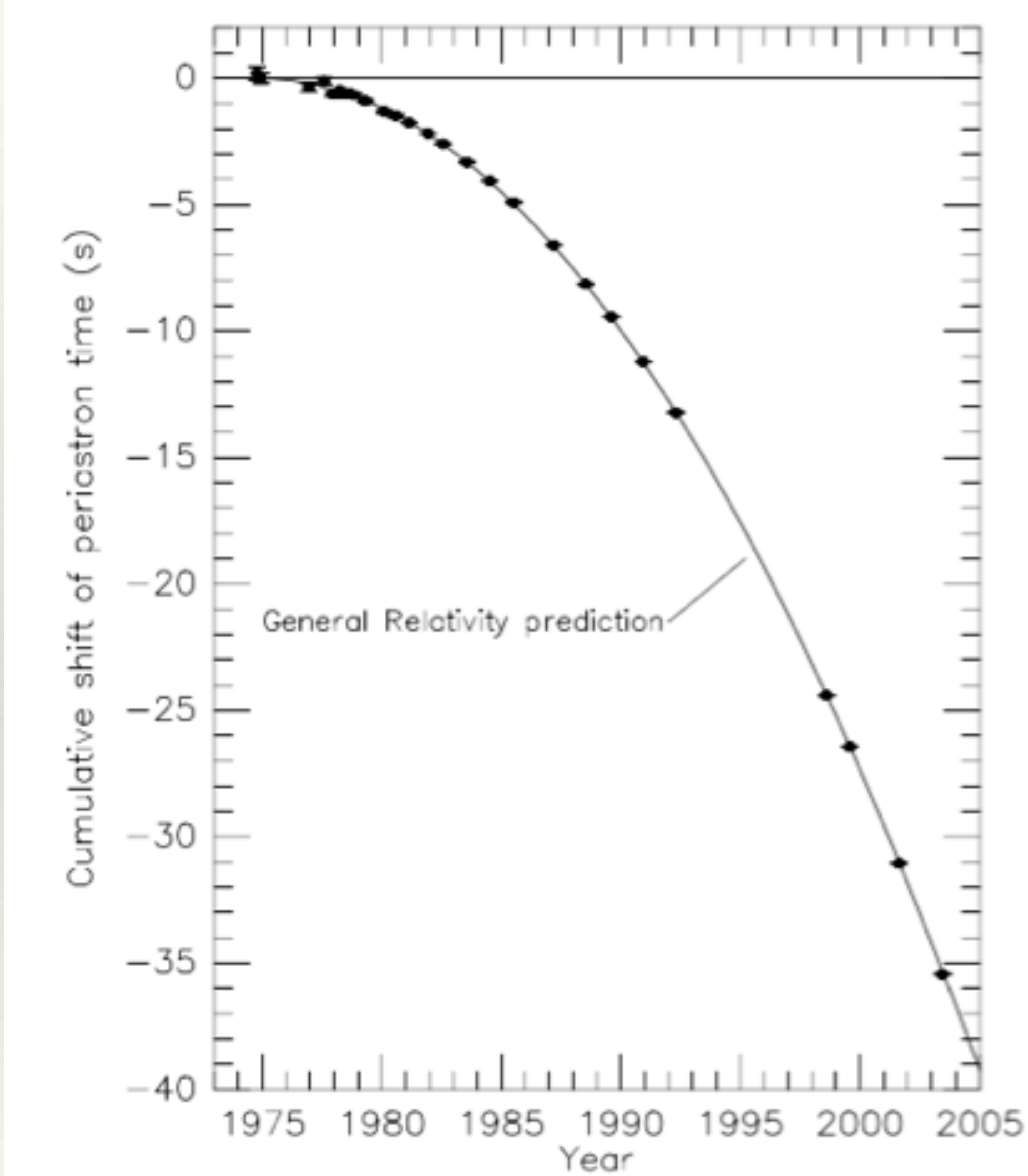


GW150914

Observation of Gravitational Waves from a Binary Black Hole Merger B. P. Abbott et al. (LIGO Scientific Collaboration and **Virgo Collaboration**)
Phys. Rev. Lett. 116, 061102 – Published 11 February 2016

We already knew they (GW) exists!

- PSR B1913+16 (also known as J1915+1606) is a pulsar in a binary star system, in orbit with another star around a common center of mass. In 1974 it was discovered by Russell **Alan Hulse and Joseph Hooton Taylor, Jr., of Princeton University, a discovery for which they were awarded the 1993 Nobel Prize in Physics**
- Nature 277, 437 - 440 (08 February **1979**), J. H. TAYLOR, L. A. FOWLER & P. M. McCULLOCH: Measurements of second- and third-order relativistic effects in the orbit of binary pulsar PSR1913 + 16 have yielded self-consistent estimates of the masses of the pulsar and its companion, **quantitative confirmation of the existence of gravitational radiation at the level predicted by general relativity**, and detection of geodetic precession of the pulsar spin axis.



Gravitational Waves sources: compact objects

- MAIN TARGET LIGO/Virgo coll.:
  NS-NS merger
  sensitive frequency band approx. (40-2000) Hz
  Expected to rate ≈ 0.2 – 200 events per year events between 2016 – 19
  [J. Abadie et al. (VIRGO, LIGO Scientific), Class. Quant. Grav. 27, 173001 (2010)]

- **Core collapse in supernova**
- **BH-BH merger** —— **(FOUND!)**
- **BH-NS merger**
- **"*Mountains*" (deformation) on the crust of Neutron Stars**
- **Secular instability of Neutron stars**
- **Dynamical instability of Neutron star**

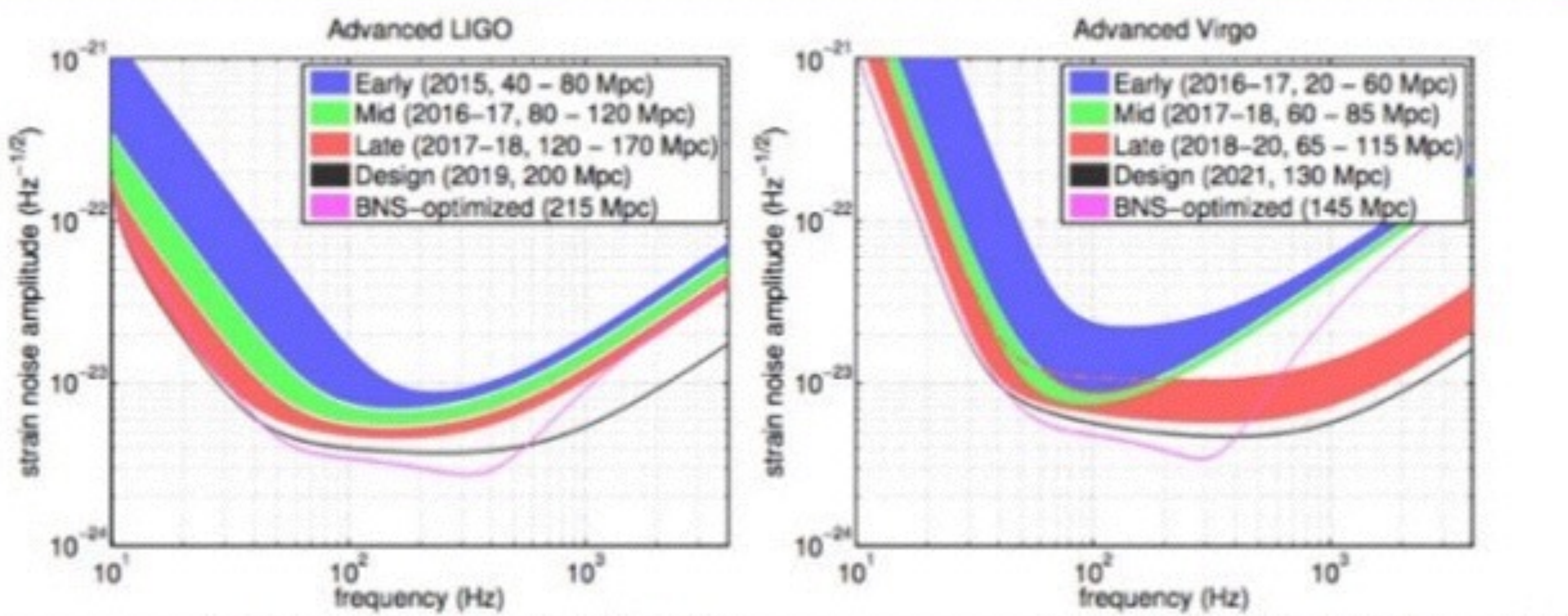
Table 1: Double neutron star systems known in the Galaxy

Pulsar	Period (ms)	P_b (days)	x (lt-sec)	e	M ($M_\odot$)	M_p ($M_\odot$)	M_c ($M_\odot$)	References
J0737−3039A	22.699	0.102	1.415	0.0877775(9)	2.58708(16)	1.3381(7)	1.2489(7)	1
J0737−3039B	2773.461		1.516					
J1518+4904	40.935	8.634	20.044	0.24948451(3)	2.7183(7)	-	-	2
B1534+12	37.904	0.421	3.729	0.27367740(4)	2.678463(4)	1.3330(2)	1.3454(2)	3
J1753−2240	95.138	13.638	18.115	0.303582(10)	-	-	-	4
J1756−2251	28.462	0.320	2.756	0.1805694(2)	2.56999(6)	1.341(7)	1.230(7)	5
J1811−1736	104.1	18.779	34.783	0.82802(2)	2.57(10)	-	-	6
J1829+2456	41.009	1.760	7.236	0.13914(4)	2.59(2)	-	-	7
J1906+0746*	144.073	0.166	1.420	0.0852996(6)	2.6134(3)	1.291(11)	1.322(11)	8
B1913+16	59.031	0.323	2.342	0.6171334(5)	2.8284(1)	1.4398(2)	1.3886(2)	9
J1930−1852	185.520	45.060	86.890	0.39886340(17)	2.59(4)	-	-	10
J0453+1559	45.782	4.072	14.467	0.11251832(4)	2.734(3)	1.559(5)	1.174(4)	This Letter
Globular cluster systems								
J1807−2500B*	4.186	9.957	28.920	0.747033198(40)	2.57190(73)	1.3655(21)	1.2064(20)	12
B2127+11C	30.529	0.335	2.518	0.681395(2)	2.71279(13)	1.358(10)	1.354(10)	13

Table from: Martinez et al.: "Pulsar J0453+1559: A Double Neutron Star System with a Large Mass Asymmetry" arXiv:1509.08805v1

Why we do want to study BNS mergers?

- First: the LIGO/Virgo collaboration will see the signal from BNS system. They are among the most powerful sources of GWs



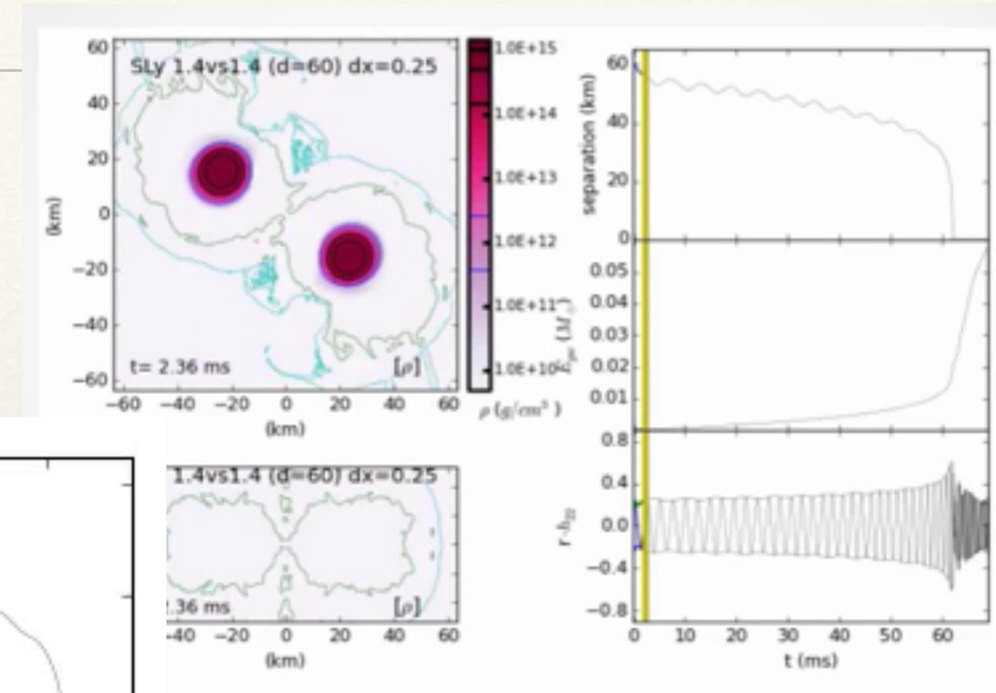
O1 → 2015
O2 → 2016–17

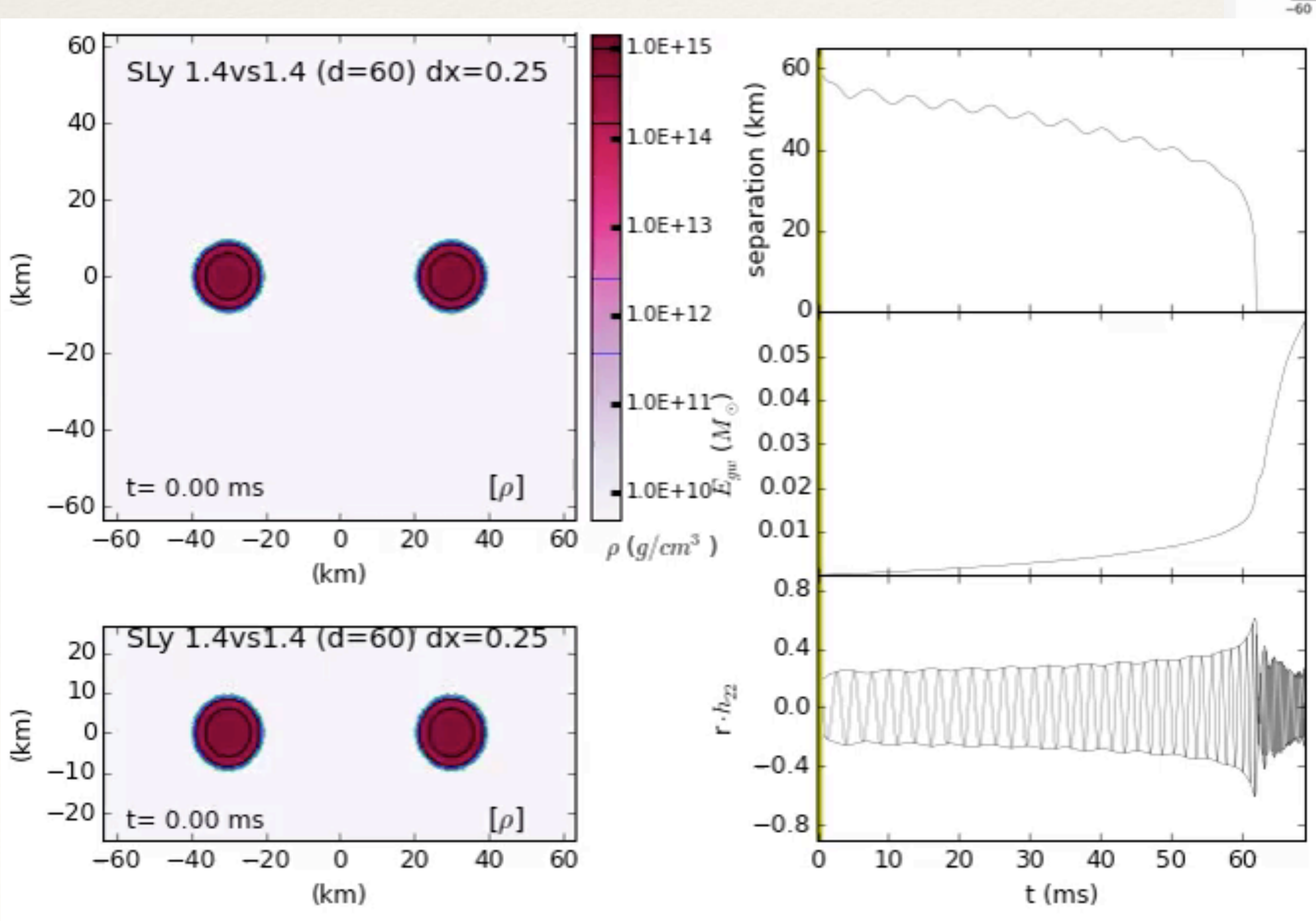
Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

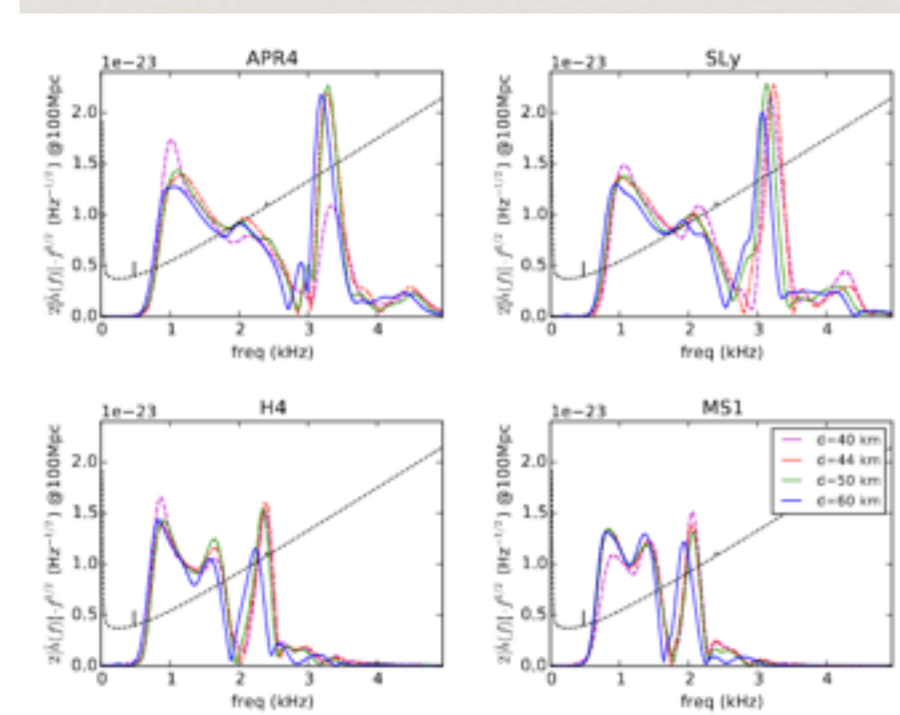
UKZN: Jan 20, 2014 [Aasi+ (LSC+Virgo), arXiv:1304.0670] 25

Gravitational Waves from our BNS merger simulations (or…what we do)

- GW signal from BNS merger simulations using different EOS.
- We look at the EOS signature in the GW signal. Different EOS give different signal.







16 orbits before merger

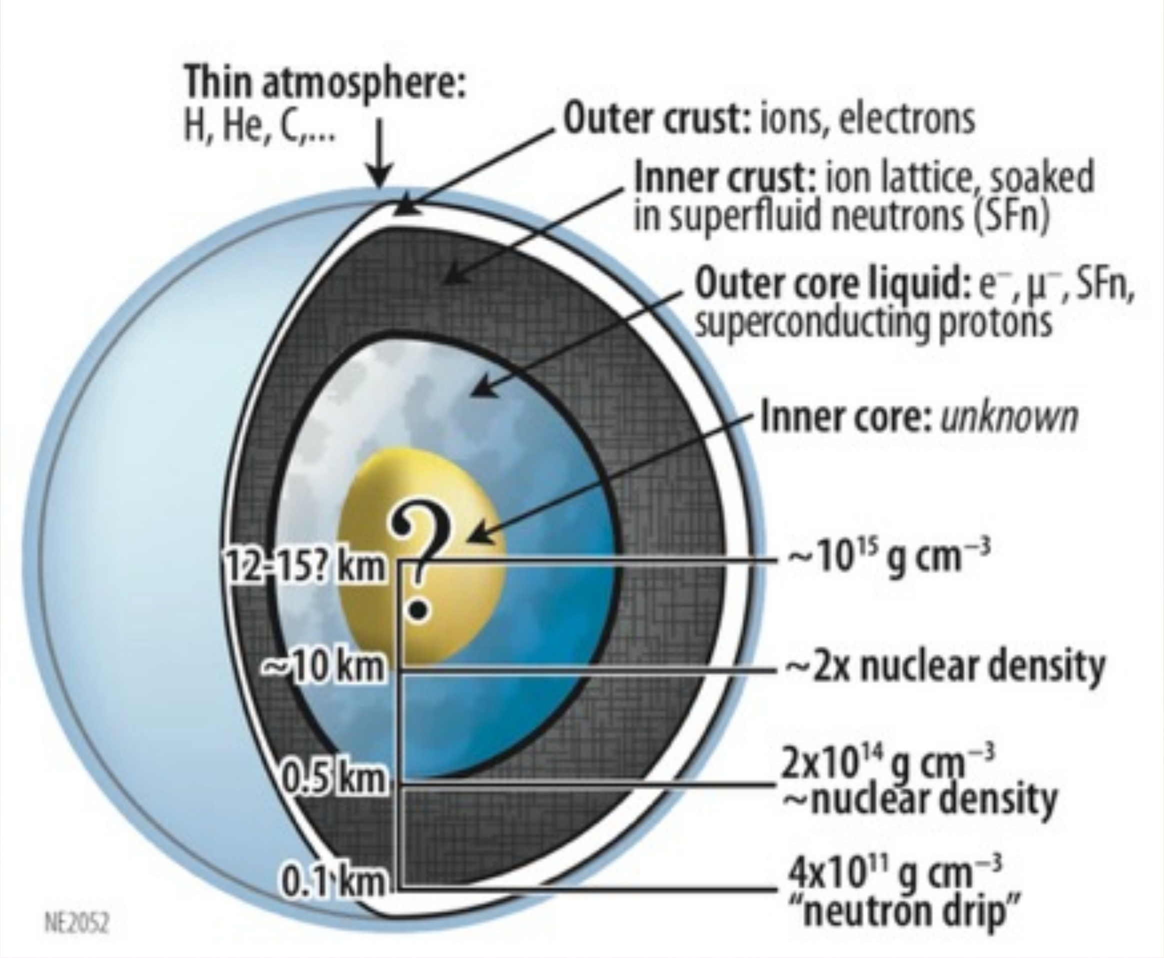
Neutron Stars

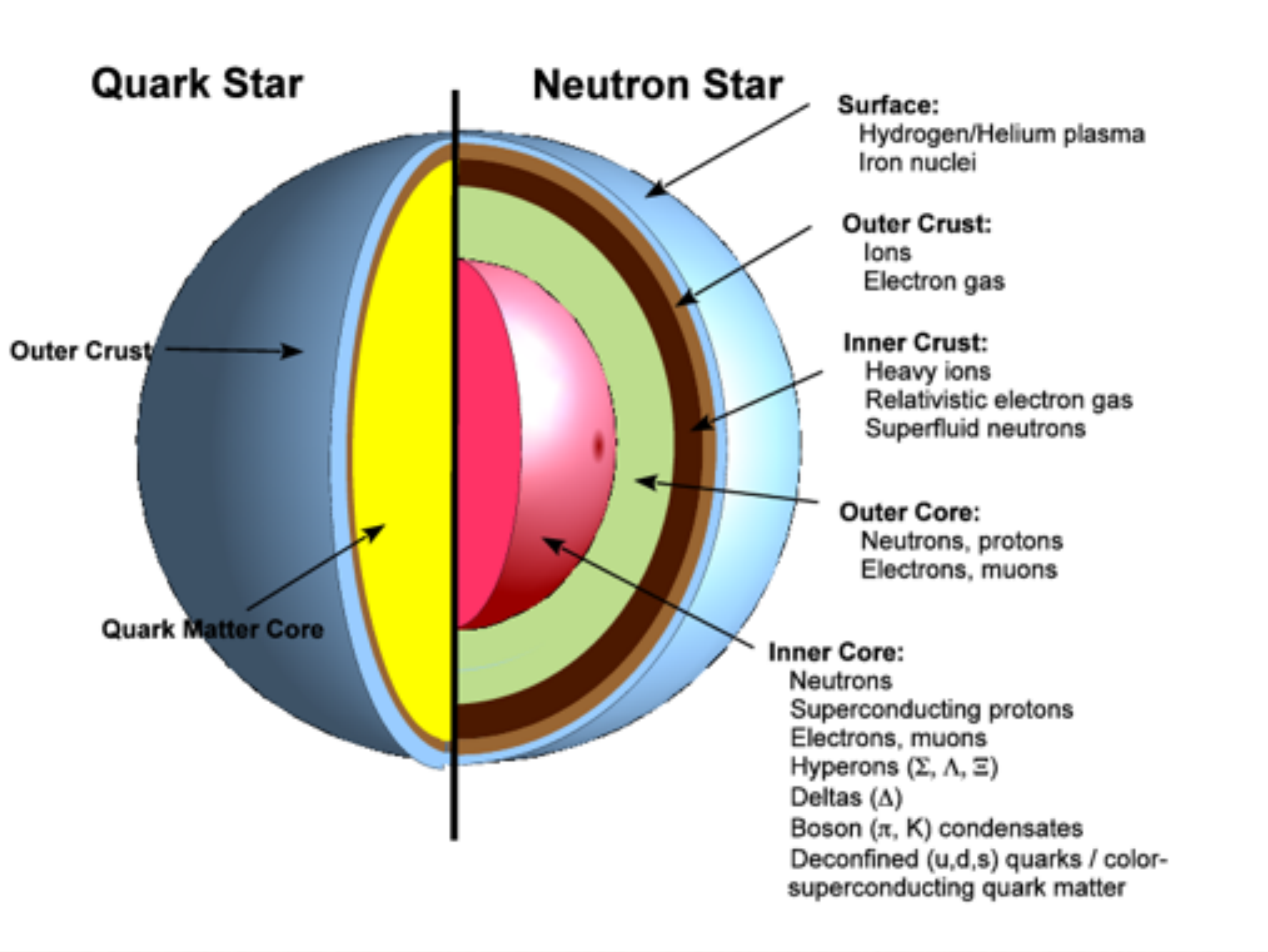
- Neutron Stars are a degenerate state of matter that is formed after the core collapse in a supernova event (where the electrons fall into nuclear matter and get captured by protons forming neutrons).
- Excellent laboratory to study high-density nuclear physics and EOS.
- Neutron star composition still unknown (neutron, resonance, hyperons,…)
- The extreme condition inside a NS cannot be reproduced in a laboratory.
- Typical properties of NS:

$$R \simeq 10Km$$
$$M \simeq 1.4M_\odot$$
$$T \in [1.4ms, 8.5s]$$
$$B \in [10^8, 10^{14}]Gauss$$

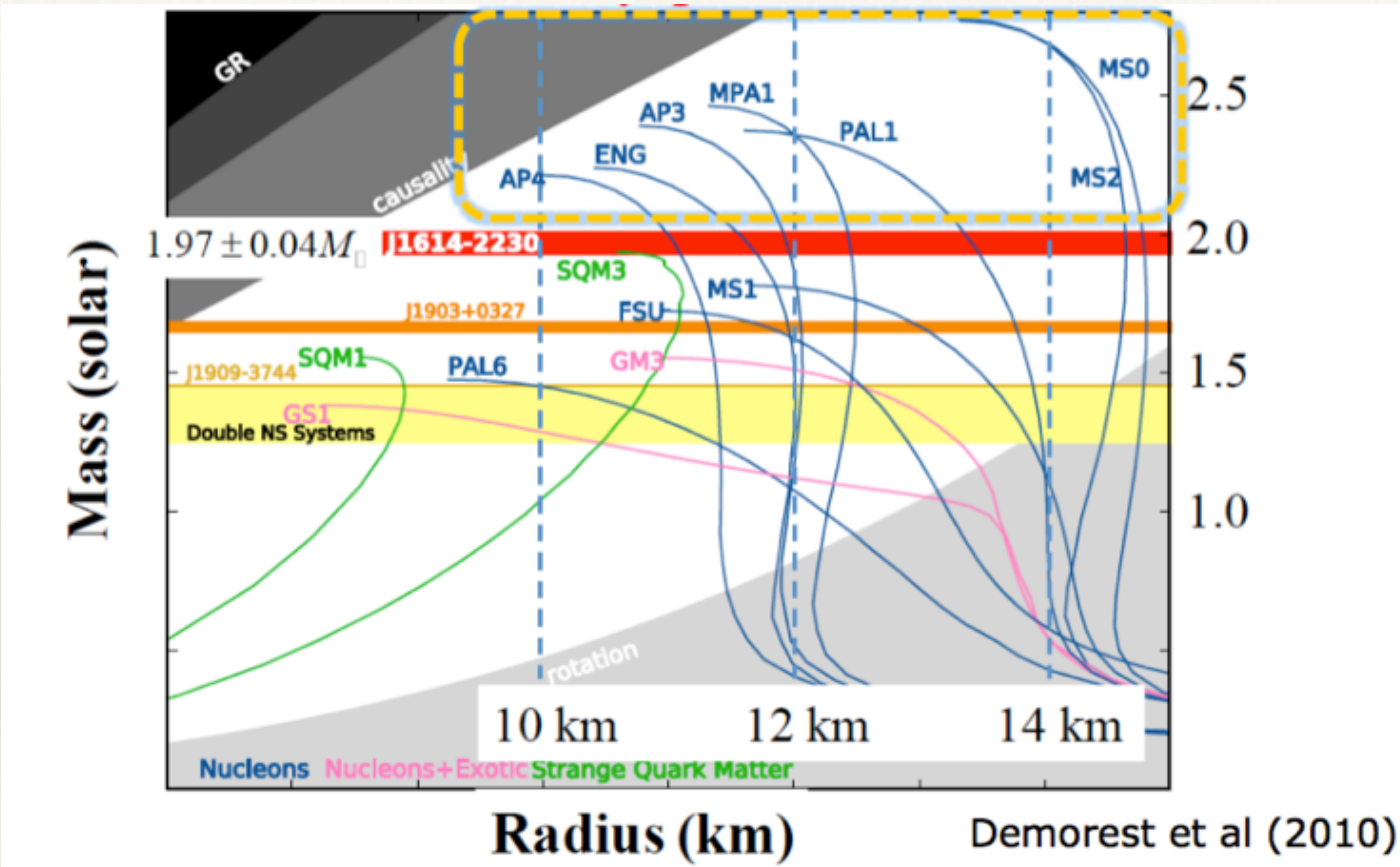
BNS as a probe for Nuclear Matter EOS

- Gravitational wave detection by BNS system will give us information on the EOS that cover matter at extreme conditions.
- Different possibilities:





Many different possibilities depending on the EOS

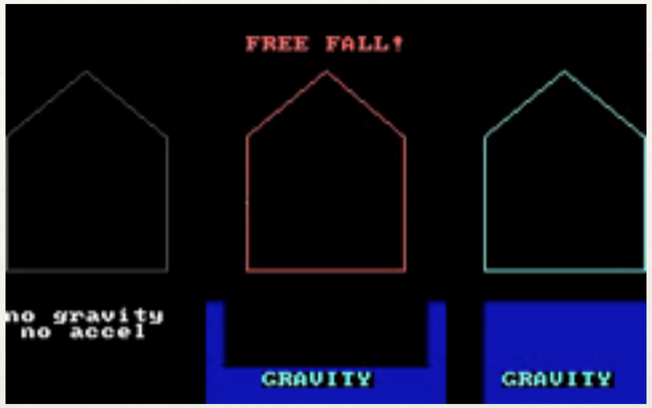


Many different possibilities depending on the EOS. **GWs** in the late inspiral and merger phases could constrain NS EOS. **Many GW templates from Numerical Relativity are necessary**

The Einstein elevator:

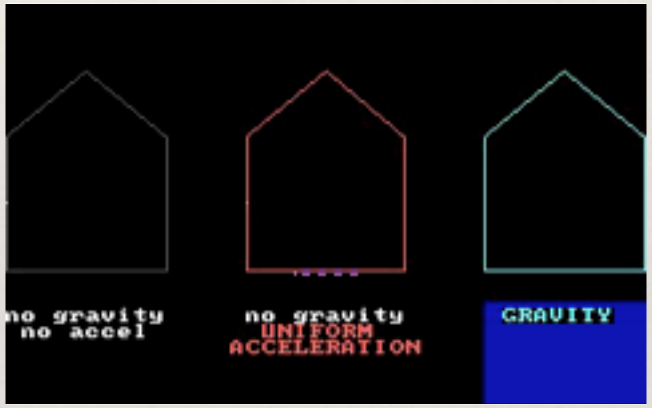
The real differences in the Einstein's Gravity Theory (General Relativity): GRAVITY can not be distinguished by INERTIA

- Assumption 1: the space-time is locally described by the Minkowski's geometry. Clocks measure the proper time with respect to a geometry that is locally the same of Special Relativity.



- Assumption 2: it is not possible (locally) to distinguish the presence of gravitational force with respect to the presence of **non-inertial** force generated by being in an accelerated reference system.

(This is a consequence of the equivalence between inertial and gravitational mass)



$$m^I \frac{d^2x^i}{dt^2} = -m\delta^{ij}\partial_j\varphi(x) + F^i \qquad \varphi(x) = -\sum_i \frac{Gm_{(i)}}{|x^k - x^k_{(i)}|}$$

- **Inertial systems are the freely-falling system !**

$$\frac{d^2x^i}{dt^2} + \delta^{ij}\partial_j\varphi(x)\frac{dt}{dt}\frac{dt}{dt} = \frac{1}{m}F^i$$

Freely falling system are the one for which the right hand side is zero!

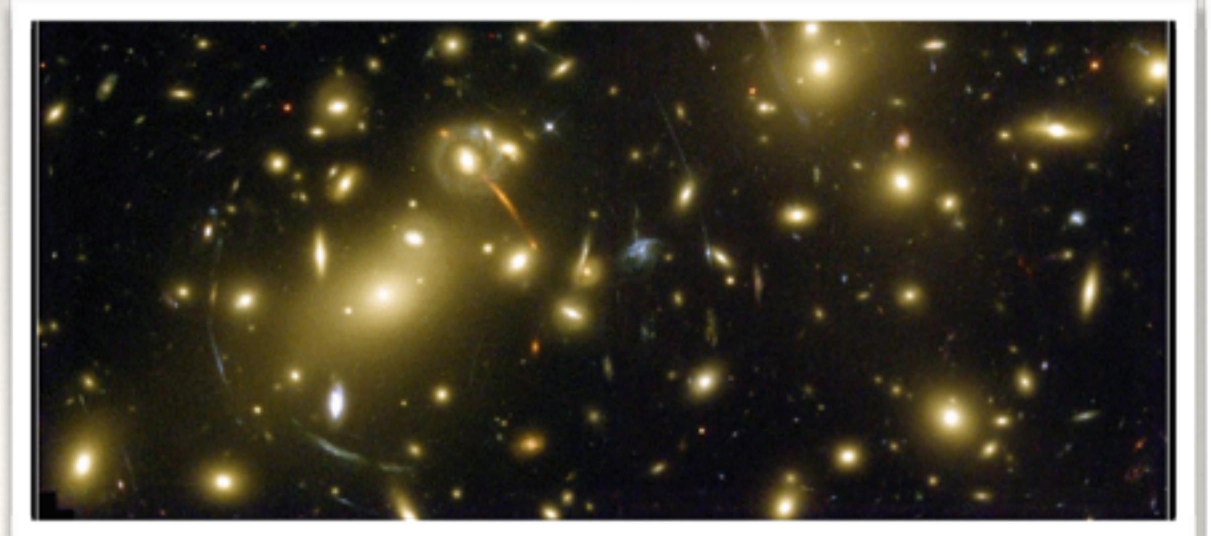
- **The straight line (meaning the freely-falling trajectory) are the geodetic of a curved space-time.**
- **Question: how do we implement these ideas ?**

General Relativity (in short)

- The gravity is shown as a result of the fact that the space-time is curved!
  - Each mass-energy curved the space-time
  - Freely falling objects follow the geodetic (straight line) of a curved space-time.
  - Einstein's fields equation are:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- There is a real space-time but we are free to choose any reference systems (atlas) to describe physical laws.



John Archibald Wheeler:
spacetime tells
matter how to move;
matter tells
spacetime how to curve

A challenging numerical problem

- The accurate simulation of a BNS merger is among the most challenging tasks in numerical relativity.
- Involve strong gravitational fields, matter motion with relativistic speeds, relativistic shock waves, (and strong magnetic fields).
- Increasing difficulty due to the multidimensional character of the PDE and by the complexity of the Einstein's equations such as coordinates degrees of freedom and formation of black holes (curvature singularity).
- Despite the problems, major progress achieved during the last decade in numerical simulations of BNS mergers (since the seminal work by Shibata and Uryu, 2000) due to: improved numerical methods (high resolutions methods and adaptive mesh refinements), improved physics (nuclear physics EOS, thermal effects) and increased computational resources!!

A challenging numerical problem (2)

- In the description of BNS mergers are involved three stages, the inspiral, the merger and the evolution to its final state (post-merger stage) that would quite likely be a BH surrounded by an accretion disk.

- The inspiral stage can be modeled with good accuracy by analytical techniques (PN calculations and EOB). Produce accurate waveforms up to a time very close to the merger. Useful to quickly computing waveform templates to matched filtering searches in GW detector data analysis. The role of NR in this regime is mainly to test and help improve these techniques.

- For the merger and post-merger stage, NR is the only available investigation tool to compare the experimental results that would be obtained by LIGO/Virgo detection with the underlying physics of the NS.

- An accurate description of GW emission of different model sources (different choice of the underlying NS physics through different choices of EOS) are useful for developing empirical relations to be able to infer NS parameter from future GW detections, as well as, to get information on the correct EOS that describe matter at this extreme conditions.

GR NS-NS simulations: State of the Art

- One of the main and hottest research topic in Numerical Astrophysics.
- A comprensive discussion of the subject can be found in (www.livingreviews.org): J.A. Faber & F.A. Rasio, "Binary neutron star mergers", Living Reviews in Relativity (2012). This review contains 338 references.
- Impossible to give a comprensive list of all the individual contributor and their roles.
- Among them is worth citing:
  - The people that start it back in '99: Shibata&Uryu: **Phys. Rev. D 61 064001** (gr-qc/9911058)
  - and (in alphabetic order): Alic, Anderson, Baiotti , Bauswein, Bernuzzi , Bruegmann , Ciolfi, Dietrich , Duez , Etienne , Foucart, Giacomazzo , Gold, Haas , Hotokezaka, Janka, Kastaun , Kawaguchi, Kidder , Kiuchi, Kyutoku, Lehner , Liebling , Liu, Nielsen , Ott , O'Connor , Pachalidis, Palenzuela , Pfeiffer, Rezzolla , Scheel , Sekiguchi , Shapiro , Shibata, Stergioulas, Taniguchi, Uryu, …

Numerical Relativity in a nutshell

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}$$ **Einstein Equations**

$$\nabla_\mu T^{\mu\nu} = 0$$ **Conservation of energy momentum**

$$\nabla_\mu (\rho\, u^\mu) = 0$$ **Conservation of baryon density**

$$p = p(\rho, \epsilon)$$ **Equation of state**

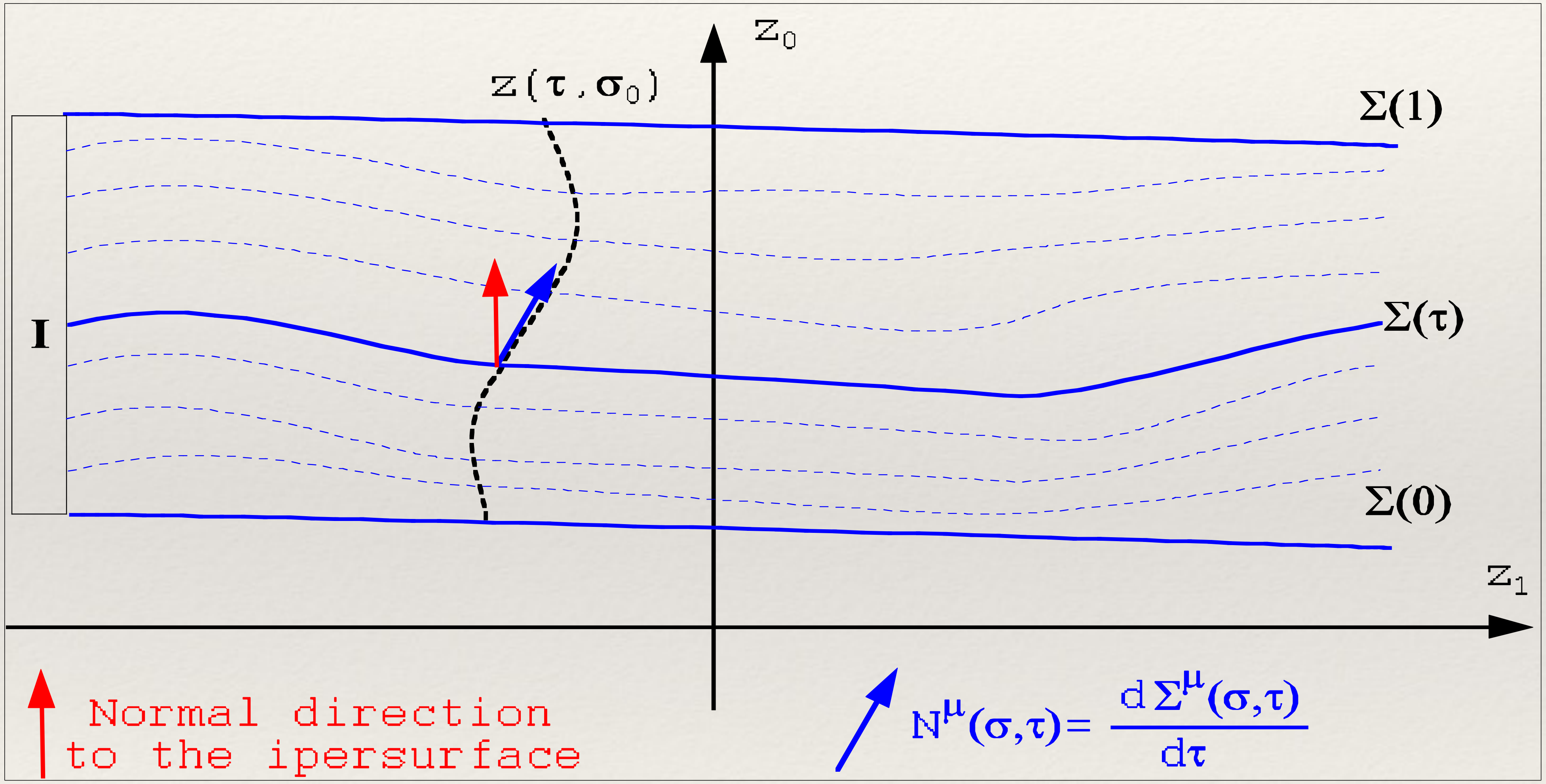
Ideal Fluid Matter

$$T^{\mu\nu} = (\rho(1+\epsilon) + p) u^\mu u^\nu + p g^{\mu\nu}$$

- But these are 4D equations! Need to write as 3+1 evolution equations.
- Spacetime get foliated into 3D spacelike surfaces, in which we define our variables. We evolve them along a time direction normal to those surfaces.
- (Magneto)Hydrodynamics is written in terms of conservative form and special numerical techniques are used for the fluxes calculations.
- All physical variables and equations are discretized on a 3D Cartesian mesh and solved by a computer. Uses finite differences for derivative computations and standard Runge-Kutta method for time integrations.
- Different formulation of the Einstein Eqs have been developed in the last 20 years. BSSN-NOK version of the Einstein's Eqs.

3+1 formulations of the metric

$$ds^2 = -(\alpha^2 - \beta_i\beta^i)dt^2 + 2\beta_i dx^i dt + \gamma_{ij}dx^i dx^j$$



α :: lapse

β^i :: shift vector

γ_{ij} :: 3-metric

$$N^\mu \frac{\partial}{\partial x^\mu} = \frac{1}{\alpha}\left(\frac{\partial}{\partial t} - \beta^j \frac{\partial}{\partial x^j}\right)$$

ADM evolutions

$$\partial_t \gamma_{ij} = -2\alpha K_{ij} + \nabla_i \beta_j + \nabla_j \beta_i, \tag{2.1}$$

6 equations for the metric

$$\begin{aligned}\partial_t K_{ij} = & -\nabla_i \nabla_j \alpha + \alpha \Big[R_{ij} + K\, K_{ij} - 2 K_{im} K^m_j \\ & -8\pi \left(S_{ij} - \frac{1}{2}\gamma_{ij} S \right) - 4\pi \rho_{\text{ADM}} \gamma_{ij} \Big] \\ & + \beta^m \nabla_m K_{ij} + K_{im} \nabla_j \beta^m + K_{mj} \nabla_i \beta^m .\end{aligned} \tag{2.2}$$

+6 equations for the time-coordinate derivative of the metric (extrinsic curvature)

Hamiltonian + Momentum constraints

$$^{(3)}R + K^2 - K_{ij}K^{ij} - 16\pi \rho_{\text{ADM}} = 0$$

+1 constrain equation

$$\nabla_j K^{ij} - \gamma^{ij} \nabla_j K - 8\pi j^i = 0$$

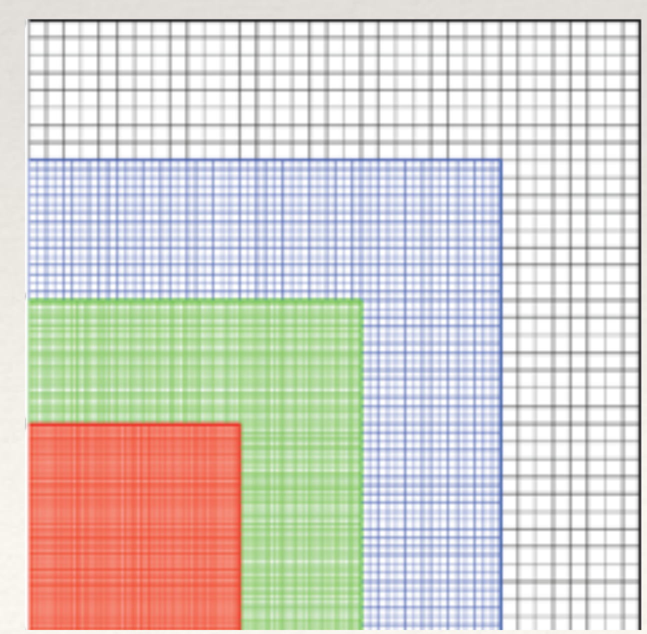
+3 constrain equation

The code: Einstein TOOLKIT + LORENE

- **Einstein Toolkit** open set of over 100 Cactus thorns for computational relativity along with associated tools for simulation management and visualization
- **Cactus** framework for parallel high performance computing (Grid computing, parallel I/O)
- Data are evolved on a Cartesian Mesh with 6 levels of refinement with **Carpet**
- Matter Evolution with the module **GRHydro:**
  (Magnetic+**CT evolution** of Magnetic Field)
  HLLE Riemann Solver
  WENO Reconstruction method (*)
  PPM Reconstruction methods
- Spacetime Metric evolution is performed with the module MacLachlan implementing a 3+1 dimensional split of the Einstein Eqs.
  BSSN-NOK Gravitational Evolution scheme (*)
  CCZ4 gravitational evolutions
- Initial data computed using the **LORENE CODE**

einsteintoolkit.org

cactus code

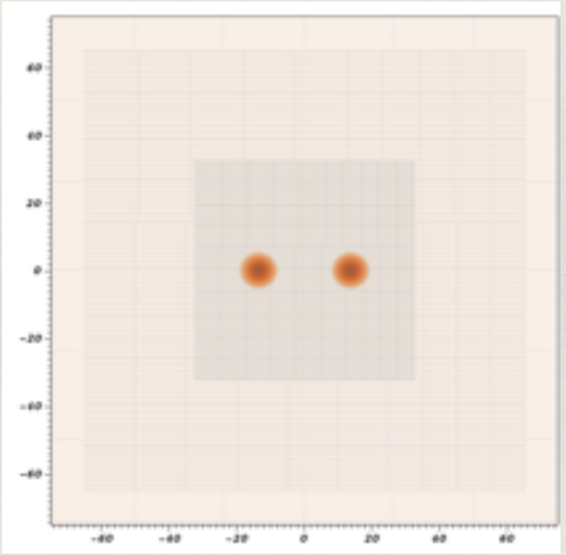


The computational challenge

- Cartesian grid with 6 refinement levels (7 when we get a BH).
- Standard Resolution in the finest grid 0.25 CU and up to 0.125 CU. => from 5,337,100 points up to 42,696,800 per grid.

Level	min(x/y) (CU)	max(x/y) (CU)	min(z) (CU)	max(z) (CU)	(N_x, N_y, N_z) $dx = 0.25$
1	−720	720	0	720	(185,185,96)
2	−360	360	0	360	(205,205,106)
3	−180	180	0	180	(205,205,106)
4	−90	90	0	90	(205,205,106)
5	−60	60	0	30	(265,265,76)
6	−30	30	0	15	(265,265,76)
(7	−15	15	0	7.5)	(265,265,76)

1 CU = 1.4 km



- Outer grid extends to (1063Km) to extract gravitational waves far from the source.
- One extra refinement level added just before collapse to black hole.
- 12 spacetime variables + 4 gauge variables + 5 hydrodynamical variables evolved in each point.
- MPI+OpenMP code parallelization.

Δx (CU)	0.75	0.50	0.375	0.25	0.185	0.125
# threads	16	64	128	256	512	2048
# MPI	2	8	16	32	64	256
Memory (GBytes)	3.8	19	40	108	237	768
speed (CU/h)	252	160	124	53	36	16
speed (ms/h)	1.24	0.78	0.61	0.26	0.18	0.08
cost (SU/ms)	13	81	209	974	2915	26053
total cost (kSU, 50 ms)	0.65	4	10.5	49	146	1300

Initial models studied

- The initial data of our simulations is calculated using the **LORENE** code ["LORENE: Langage Objet pour la RElativité NumériquE," **http://www.lorene.obspm.fr/**] that provides the possibility to generate arbitrary initial data for irrotational BNS.
- The code is GPL free and can be freely and easily used to generate the initial data for the simulations.
- The initial data generated by LORENE show a residual eccentricity and we will show how this can be seen in numerical simulation **(SLy14vs14)**

name	$M_0^{(1)}$ $[M_\odot]$	$M_0^{(2)}$ $[M_\odot]$	$M^{(1)}$ $[M_\odot]$	$M^{(2)}$ $[M_\odot]$	Ω $\left[\frac{\text{krad}}{s}\right]$	M_{ADM} $[M_\odot]$	J $\left[\frac{GM_\odot^2}{c}\right]$
SLy12vs12	1.20	1.20	1.11	1.11	1.932	2.207	5.076
SLy13vs13	1.30	1.30	1.20	1.20	1.989	2.373	5.730
SLy14vs14	1.40	1.40	1.28	1.28	2.040	2.536	6.405
SLy15vs15	1.50	1.50	1.36	1.36	2.089	2.697	7.108
SLy16vs16	1.60	1.60	1.44	1.44	2.134	2.854	7.832
SLy135vs145	1.35	1.45	1.24	1.32	2.040	2.536	6.397
SLy13vs15	1.30	1.50	1.20	1.36	2.040	2.535	6.376
SLy125vs15	1.25	1.55	1.16	1.40	2.040	2.533	6.337
SLy12vs16	1.20	1.60	1.11	1.44	2.039	2.531	6.281
G275th14vs14	1.40	1.40	1.29	1.29	2.053	2.554	6.513
G300th14vs14	1.40	1.40	1.26	1.26	2.028	2.498	6.243

Pulsar	M_p $[M_\odot]$	M_c $[M_\odot]$	q	$M^{(1)}$ $[M_\odot]$	$M^{(1)}$ $[M_\odot]$
J0737-3039A	1.3381(7)	1.2489(7)	0.93	1.36	1.47
B1534+12	1.3330(2)	1.3454(2)	0.99	1.46	1.47
J1756-2251	1.341(7)	1.230(7)	0.92	1.33	1.47
J1906+0746*	1.291(11)	1.322(11)	0.98	1.41	1.45
B1913+16	1.4398(2)	1.3886(2)	0.96	1.53	1.59
J0453+1559	1.559(5)	1.174(4)	0.75	1.27	1.74

Table from: Martinez et al.: "Pulsar J0453+1559: A Double Neutron Star System with a Large Mass Asymmetry" arXiv:1509.08805v1

EOS used in our simulations

- Piecewise polytropic representation of SLy EOS + thermal component:
- 7 pieces EOS => realistic treatment of the NS crust and the BH accretion disk eventually produced
- High density region similar to Gamma = 3.00 polytropic.
- Still only approximate treatment of thermal component.

$$P(\rho, \epsilon) = P_{\rm cold}(\rho) + P_{\rm th}(\rho, \epsilon),$$

$$P_{\rm cold} = K_i \rho^{\Gamma_i}$$

$$\epsilon_{\rm cold} = \epsilon_i + \frac{K_i}{\Gamma_i - 1}\rho^{\Gamma_i - 1}$$

$$P_{\rm th} = \Gamma_{\rm th}\rho(\epsilon - \epsilon_{\rm cold}),$$

Read et al. 2009

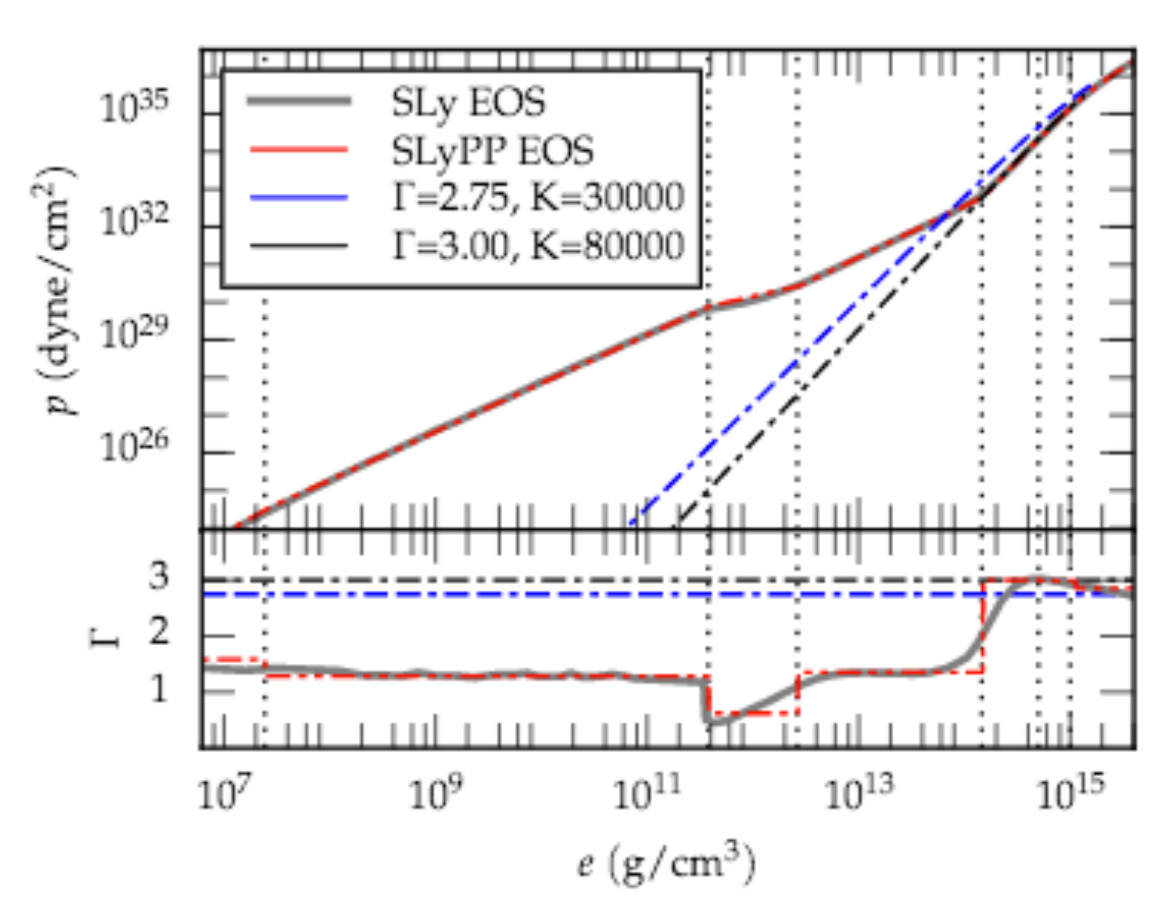


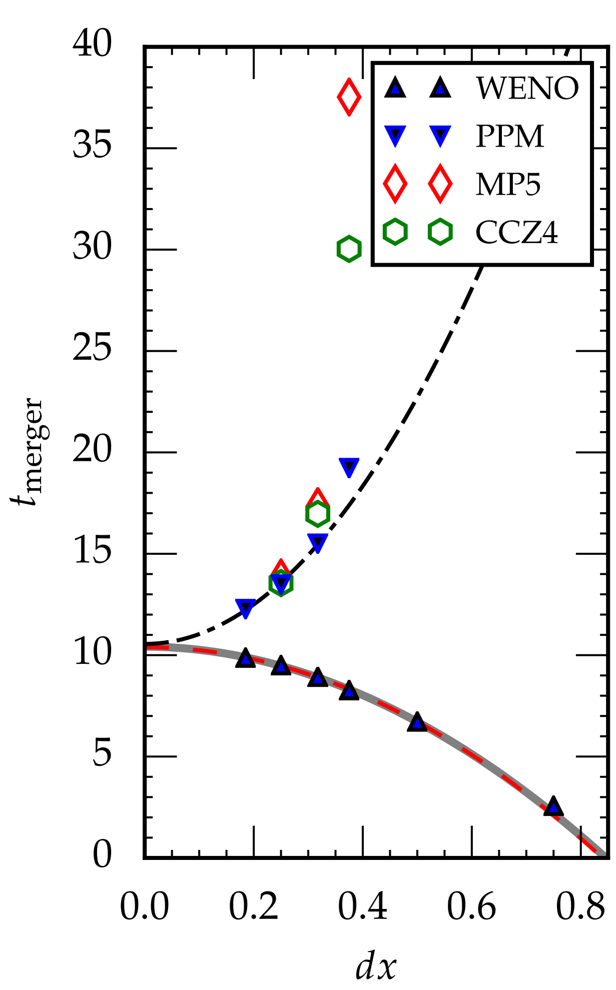
FIG. 1. Plot of the pressure (P) and of the adiabatic index ($\Gamma = d\log(P)/d\log(\rho)$) as a function of the energy density ($e = \rho(1+\epsilon)$) for the SLy EOS, its piece-wise polytropic approximation (the one used in the present work) and two isentropic polytropic EOS $P = K\rho^{\Gamma}$.

Douchin and Haensel 2000,2001

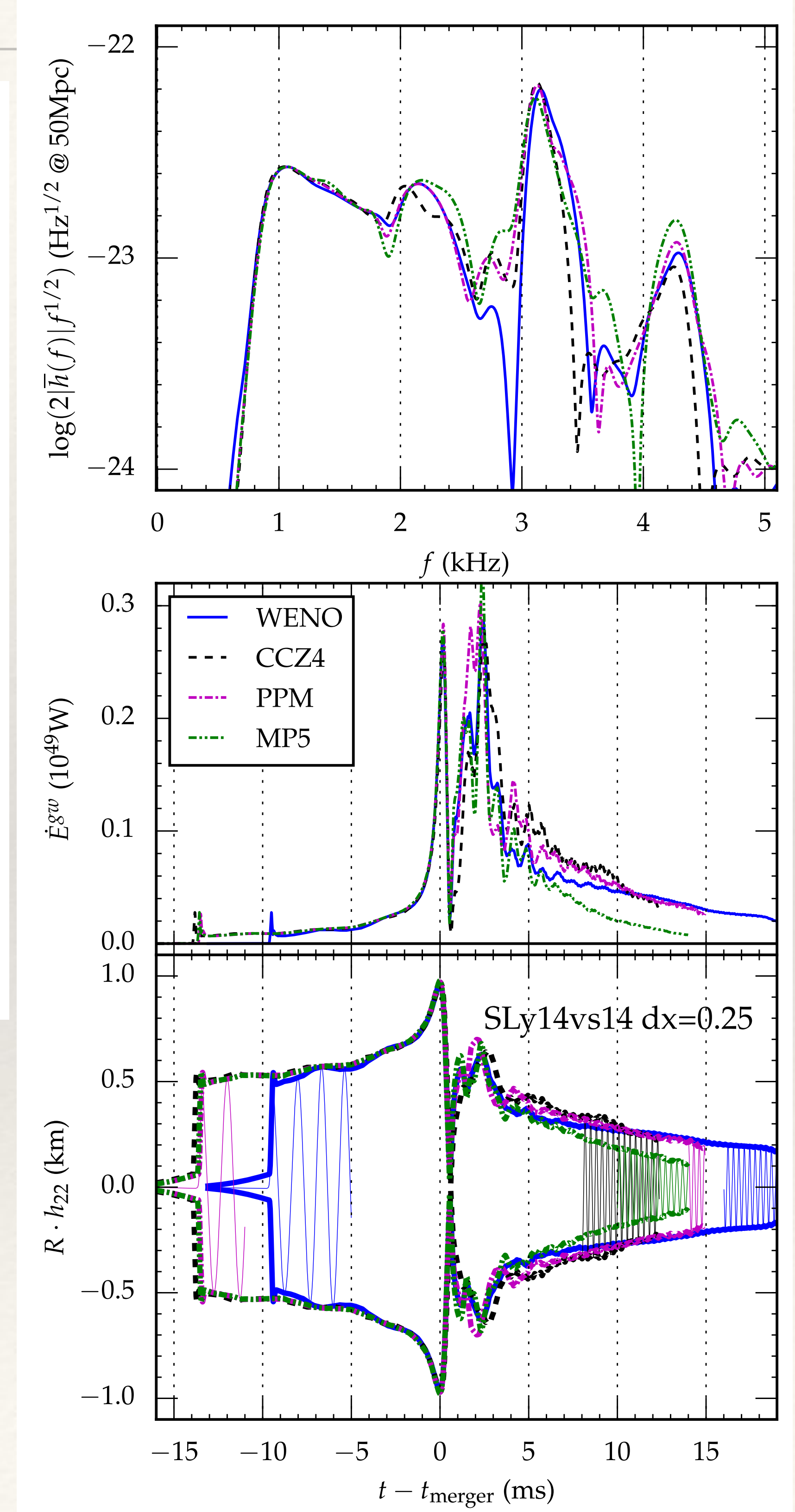
Results on Numerical Methods comparisons

Comparison between three different reconstruction methods for hydrodynamics (**WENO**,**PPM**,**MP5**)

and two gravity (metric) evolution schemes (**BSSN**,**CCZ4**).



	dx (CU)	t_{merger} (ms)
WENO	0.75	2.56
WENO	0.50	6.72
WENO	0.375	8.27
WENO	0.3125	8.93
WENO	0.25	9.50
WENO	0.185	9.87
PPM	0.375	19.23
PPM	0.3125	15.50
PPM	0.25	13.49
PPM	0.185	12.28
MP5	0.375	37.53
MP5	0.3125	17.34
MP5	0.25	13.81
CCZ4	0.375	30.03
CCZ4	0.3125	16.97
CCZ4	0.25	13.56



- The combination BSSN + WENO is the best for running sensible simulations at low resolution.
- With those methods you can run a qualitatively correct BNS simulation on your laptop!

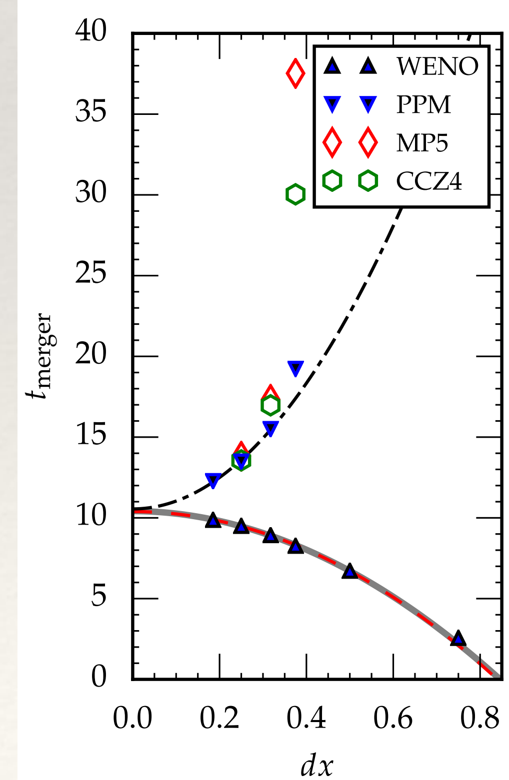
Data Analysis: Convergence

- Merger time measured from at least three different resolution simulations for each model.
- Convergence order and extrapolated “infinite” resolution merger time obtained with a fit to:

$$t_{\text{merger}}(dx) = t_{\text{merger}}^{dx=0} + A \cdot dx^{\gamma}$$

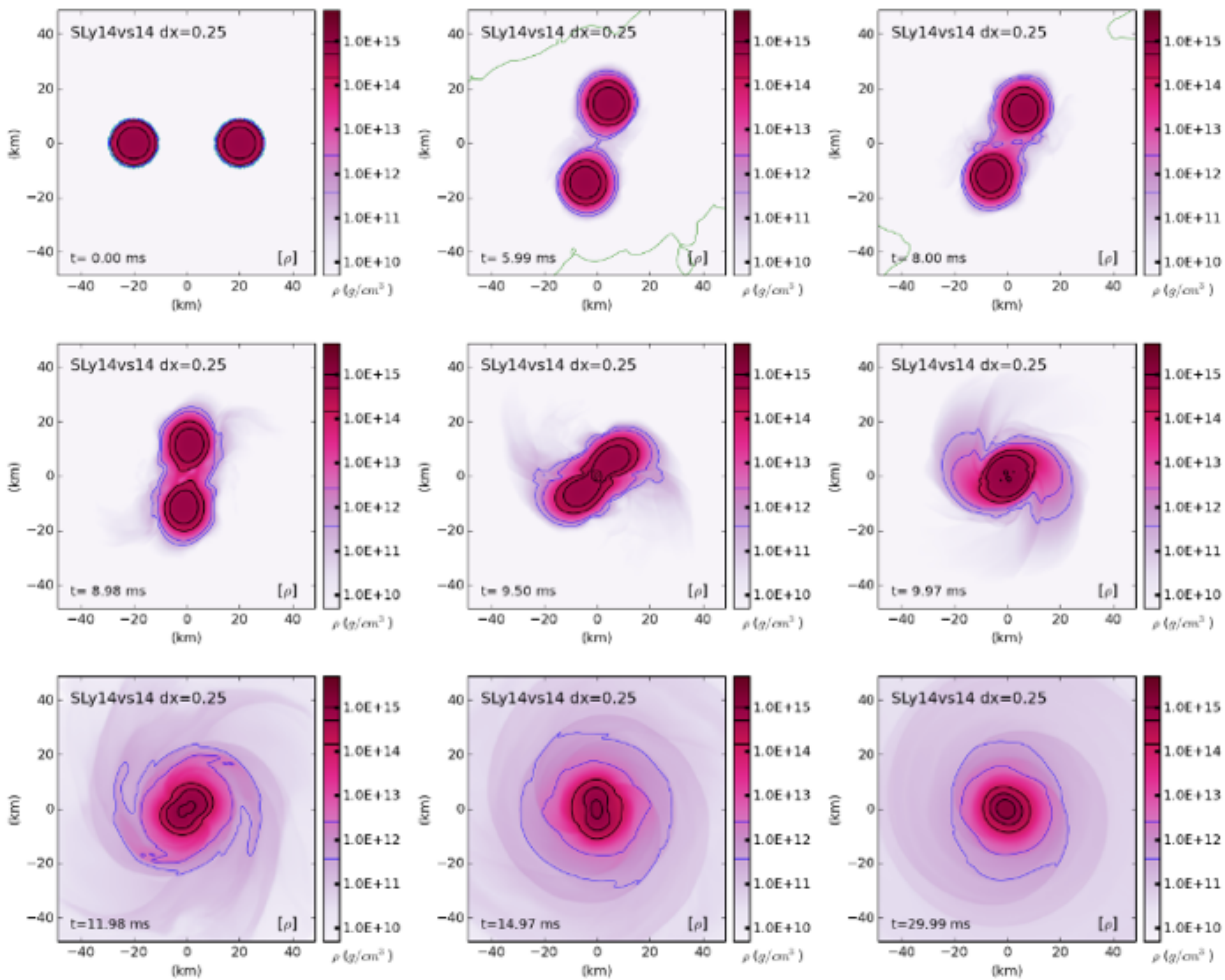
- Despite all observed differences it is important to make sure that all tested method lead to the same determination of the “true” merger time t_merger(dx=0).

name	$t_{\text{merger}}^{dx=0.50}$ [ms]	$t_{\text{merger}}^{dx=0.375}$ [ms]	$t_{\text{merger}}^{dx=0.25}$ [ms]	$t_{\text{merger}}^{dx=0\ (ext)}$ [ms]	$t_{\text{merger}}^{\text{EOB}}$ [ms]
SLy12vs12	9.22	11.76	13.61	15.07±0.03	21.55
SLy13vs13	8.21	10.02	11.25	12.28±0.04	17.25
SLy14vs14	6.72	8.27	9.50	10.39±0.08	14.08
SLy15vs15	5.93	6.99	7.71	8.31±0.02	11.64
SLy16vs16	5.00	6.13	6.81	7.44±0.08	9.78
SLy135vs145	6.66	8.19	9.45	10.34±0.10	14.09
SLy13vs15	6.52	7.91	9.31	10.14±0.25	14.12
SLy125vs155	6.19	7.60	9.09	9.93±0.29	14.21
SLy12vs16	5.52	7.26	8.73	9.75±0.13	14.33
G275th14vs14	4.22	4.81	5.52	5.88±0.17	13.63
G300th14vs14	7.63	9.69	10.55	11.67±0.37	14.78



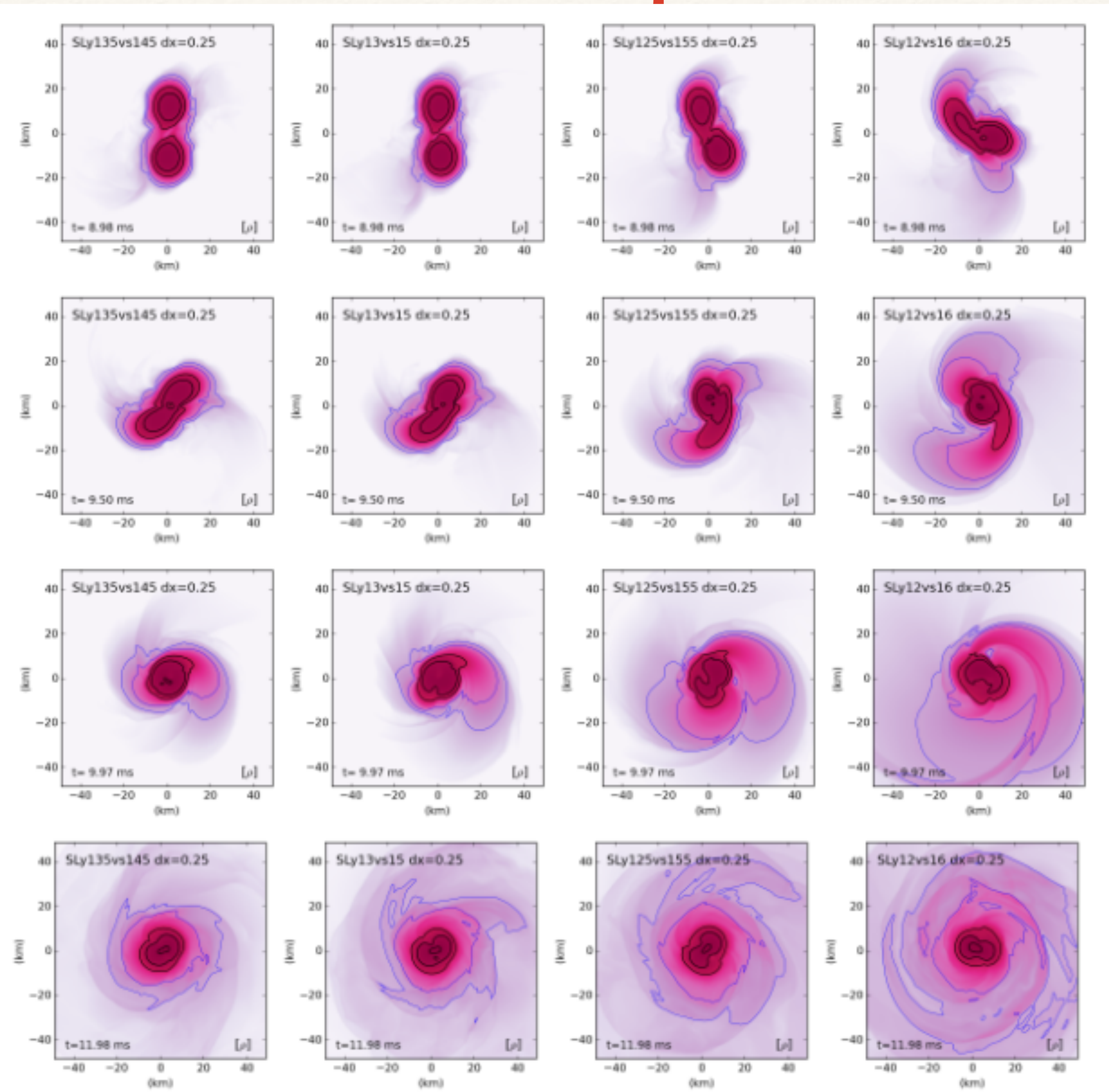
	dx (CU)	t_{merger} (ms)
WENO	0.75	2.56
WENO	0.50	6.72
WENO	0.375	8.27
WENO	0.3125	8.93
WENO	0.25	9.50
WENO	0.185	9.87
PPM	0.375	19.23
PPM	0.3125	15.50
PPM	0.25	13.49
PPM	0.185	12.28
MP5	0.375	37.53
MP5	0.3125	17.34
MP5	0.25	13.81
CCZ4	0.375	30.03
CCZ4	0.3125	16.97
CCZ4	0.25	13.56

SLy14vs14 (general picture)



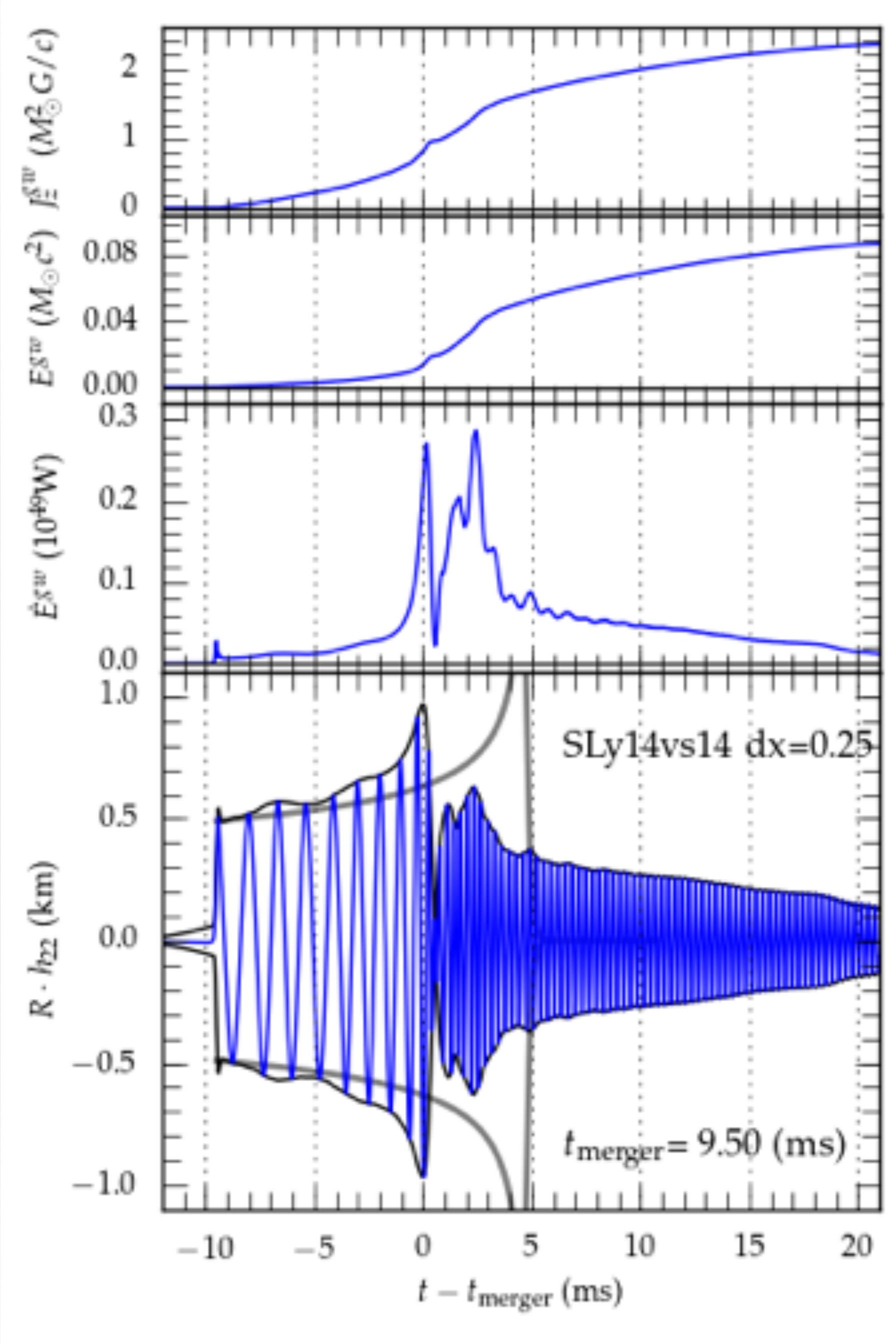
Dynamics of the evolution of the model with equal mass where it is plotted the matter density (rho) at various time. In the evolution of the equal mass models, SLy16vs16 promptly forms a BH after the merger while SLy15vs15 shows a delayed BH formation.

Four Unequal mass models

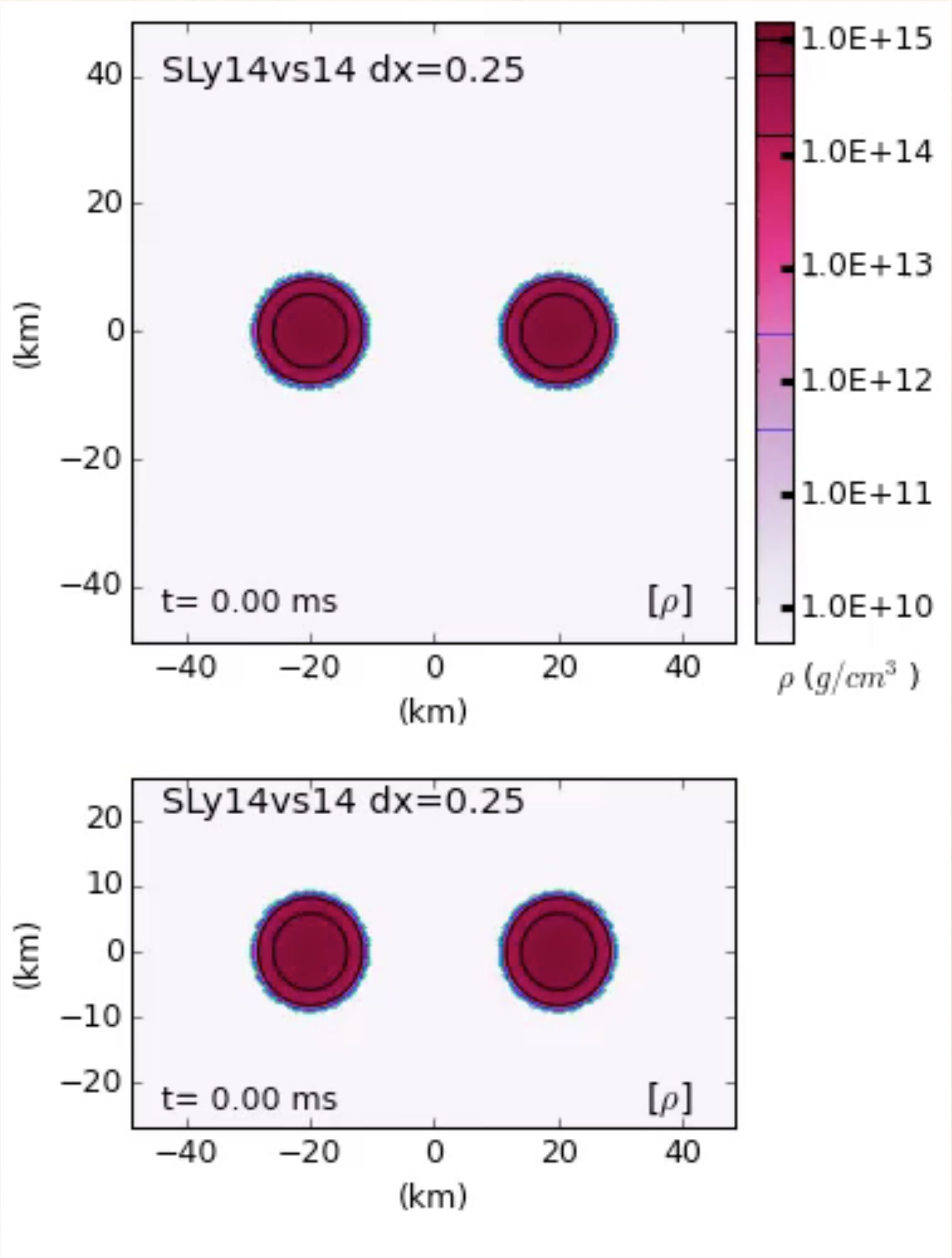


In the case of unequal mass models the remaining star shows a single bar deformation. In the merger phase the two arms structure present in the case of equal mass systems is transformed into a single arm structure as the mass ratio increases.

SLy14vs14



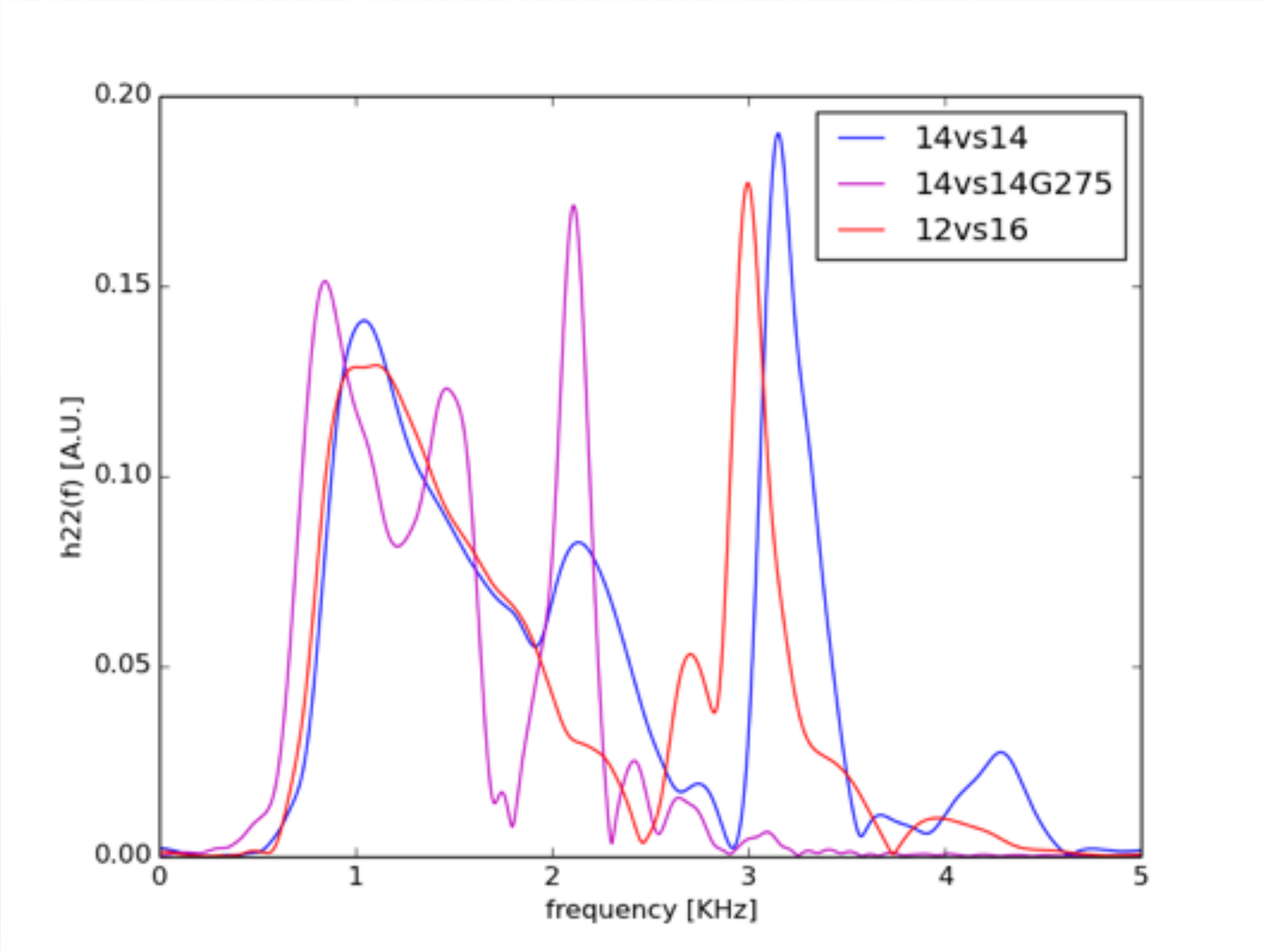
SLy14vs14 dx=0.25
t_{merger}= 9.50 (ms)
$t - t_{merger}$ (ms)
$R \cdot h_{22}$ (km)



SLy14vs14 dx=0.25
t= 0.00 ms
[ρ]
(km)
ρ (g/cm^3)
1.0E+15
1.0E+14
1.0E+13
1.0E+12
1.0E+11
1.0E+10
SLy14vs14 dx=0.25
t= 0.00 ms
[ρ]

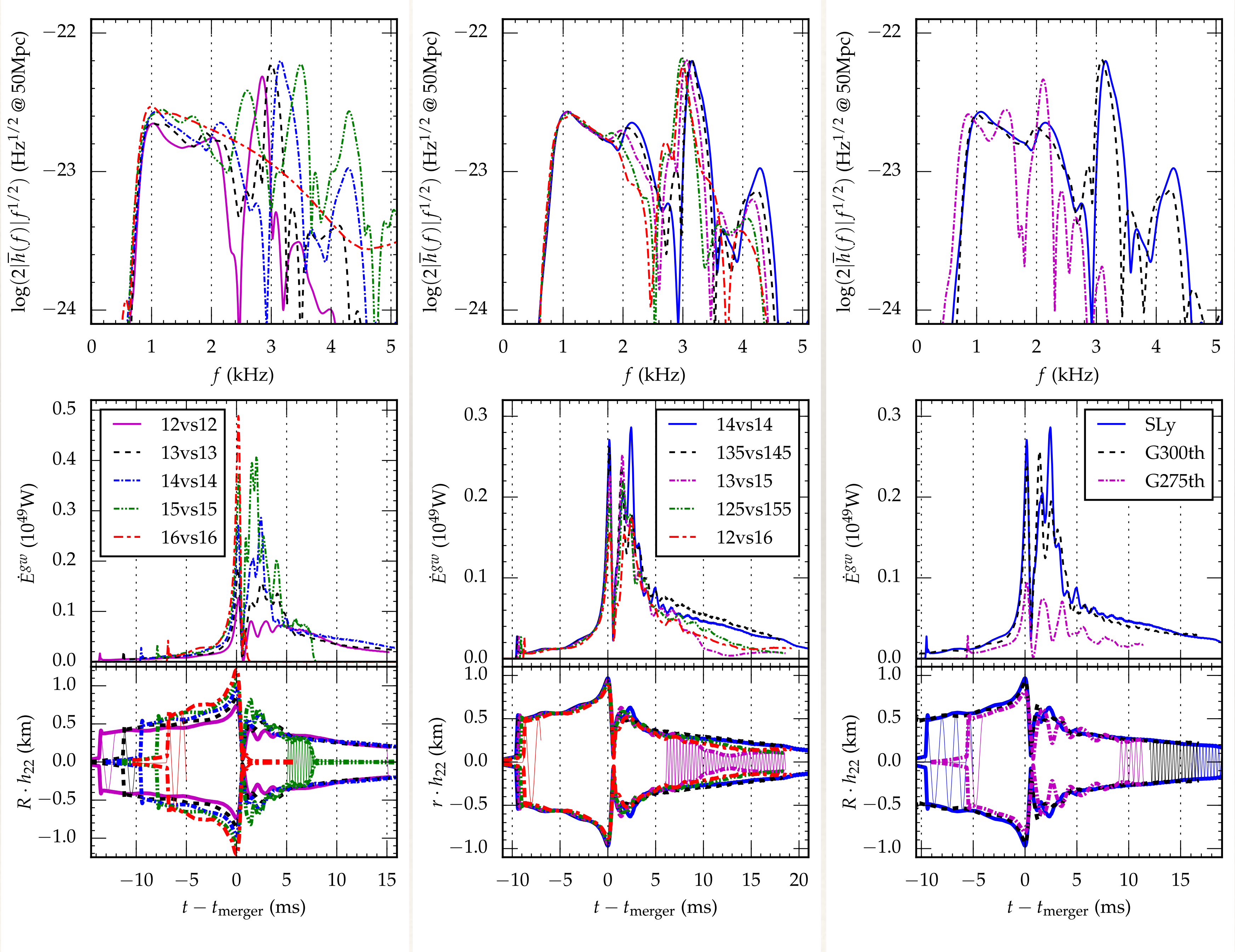
Results: gravitational waves signal properties

- Example of the FFT of the gravitational wave signals and the oscillation of the maximum density for three simulations: an equal mass and an unequal-mass one and the one with a significant softer EOS.
- Only the equal mass one show the two side peaks
- The softer one show a clear effect of its greater deformability.



Result for the post merger spectrum

- Position of the peaks depends on the EOS and on the fact that the two masses are equal or unequal.
- Spectroscopic data are a direct route to the investigation of the true-EOS governing matter at extreme conditions.

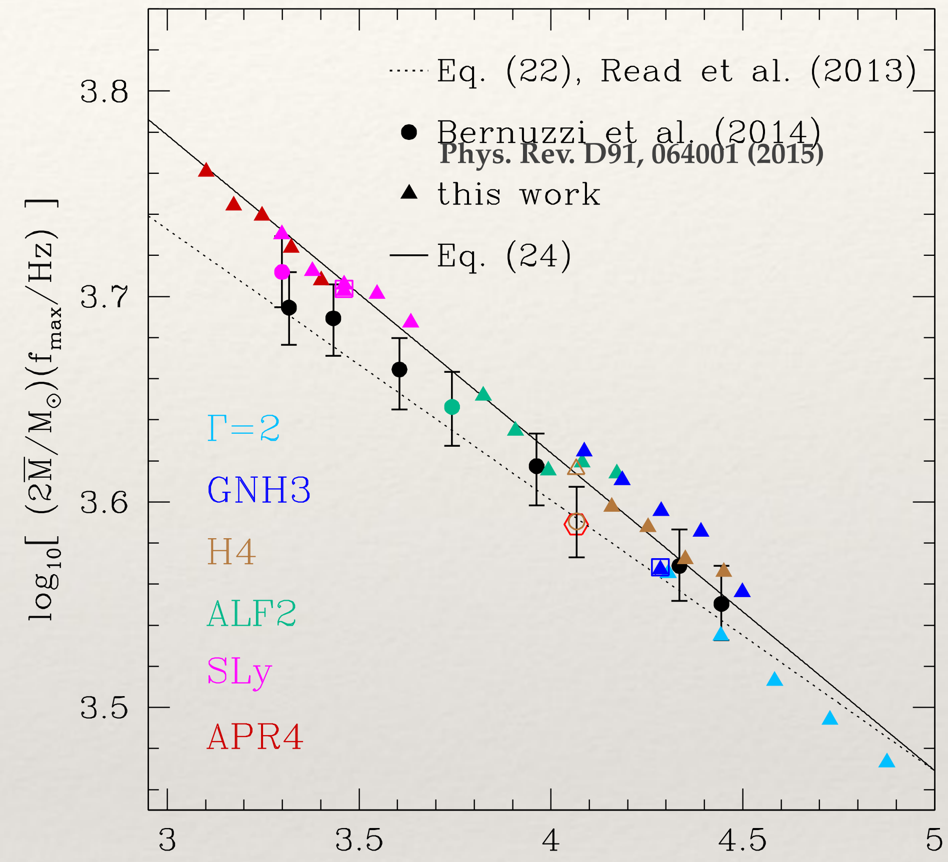


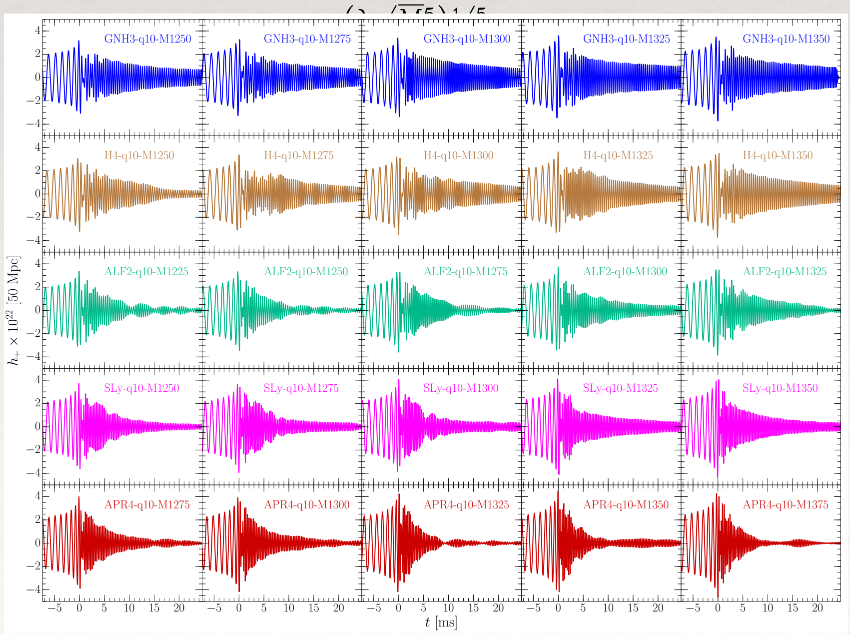
See for example: K. Takami, L. Rezzolla, and L. Baiotti, Phys. Rev. D91, 064001 (2015), arXiv:1412.3240 [gr-qc] and reference there in..

An example of comparison with literature.

K. Takami, L. Rezzolla, and L. Baiotti, Phys. Rev. D91, 064001 (2015), arXiv:1412.3240 [gr-qc]

- Tidal deformability λ/M^{-5} as a root to understand the position of the peaks?
- There is a loot of debated in literature about universal relation between frequency of the packs of the properties of the NS like its Mass, Compactness and or the deformability of the star.
- Problem: are this properties really described by this phenomenological relations ?
- All depends on the properties of the TRUE EOS and indeed all the observable are correlated to the each others.
- The question is: which one is the correct EOS describe the NS and indeed its Mass, Angular Momentum and rotational profile, characteristic frequency, ...



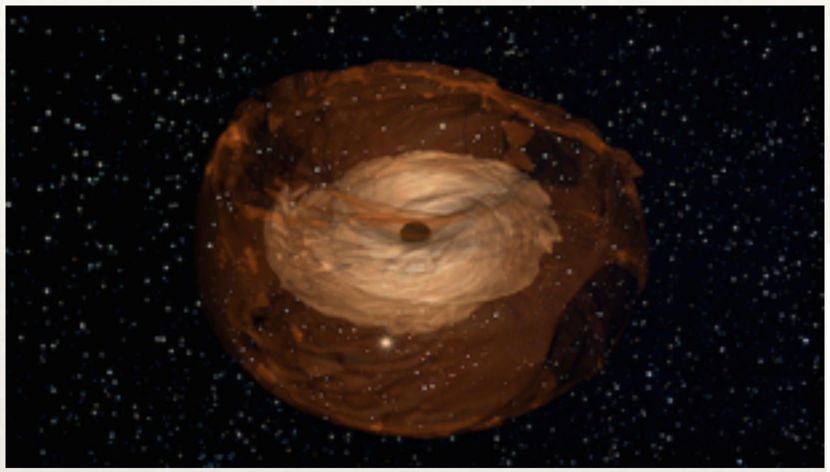


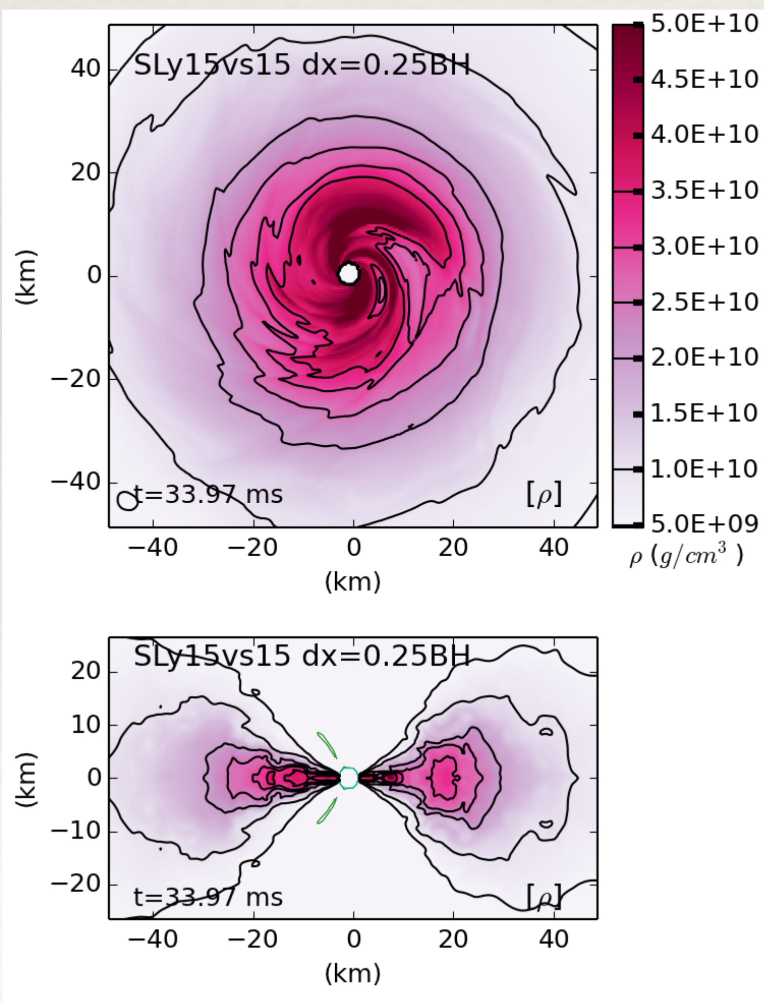
Difficult to reproduce results…

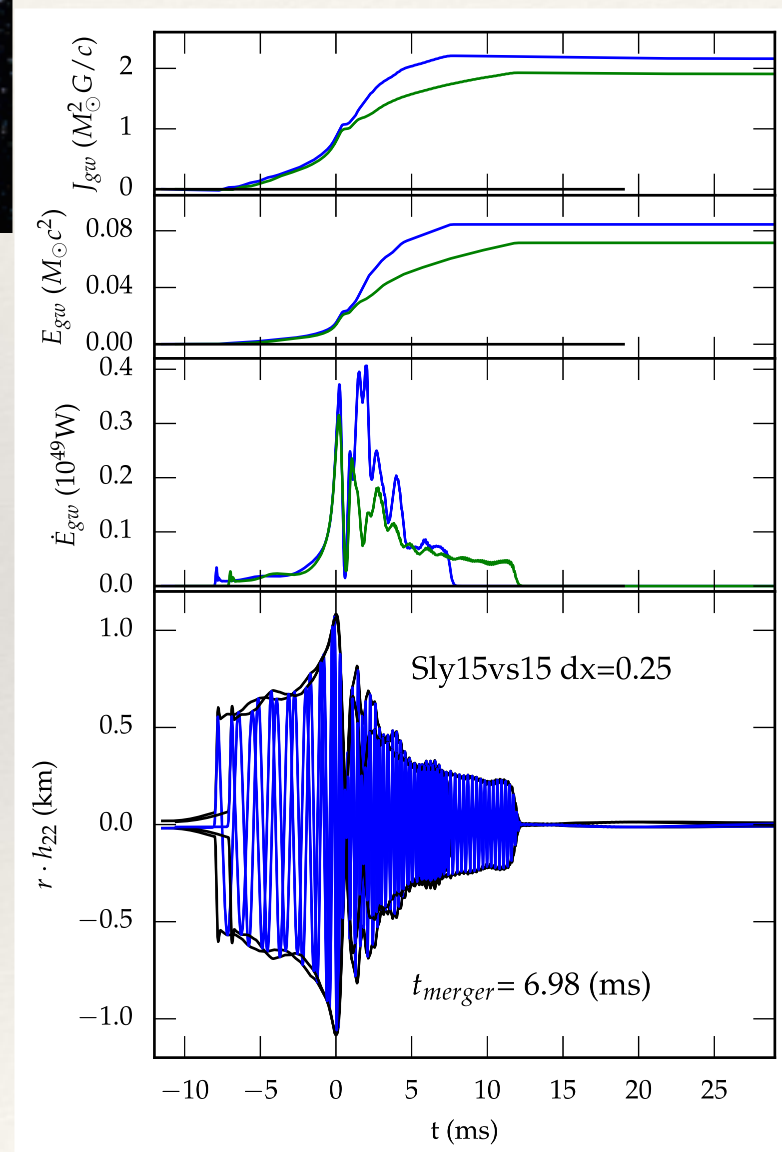
- “Initial data for neutron star binaries with arbitrary spins”, Tsatsin and Maronetti in PHYSICAL REVIEW D 88, 064060 (2013)
- Reduced eccentricity: “Binary Neutron Stars with Generic Spin, Eccentricity, Mass ratio, and Compactness - Quasi-equilibrium Sequences and First Evolutions”, Dietrich et all 2015 (1507.07100)
- “New code for quasiequilibrium initial data of binary neutron stars: Corotating, irrotational, and slowly spinning systems“ by Antonios Tsokaros et all. PHYSICAL REVIEW D 91, 104030 (2015)
  Realistic Spins: “Mergers of binary neutron stars with realistic spin”, Bernuzzi et all (2014) PHYSICAL REVIEW D 89, 104021 (2014).
- Properties of the port-merger HMNS: “Properties of hypermassive neutron stars formed in mergers of spinning binaries” Kastaum et.all. PHYSICAL REVIEW D 91, 064027 (2015)

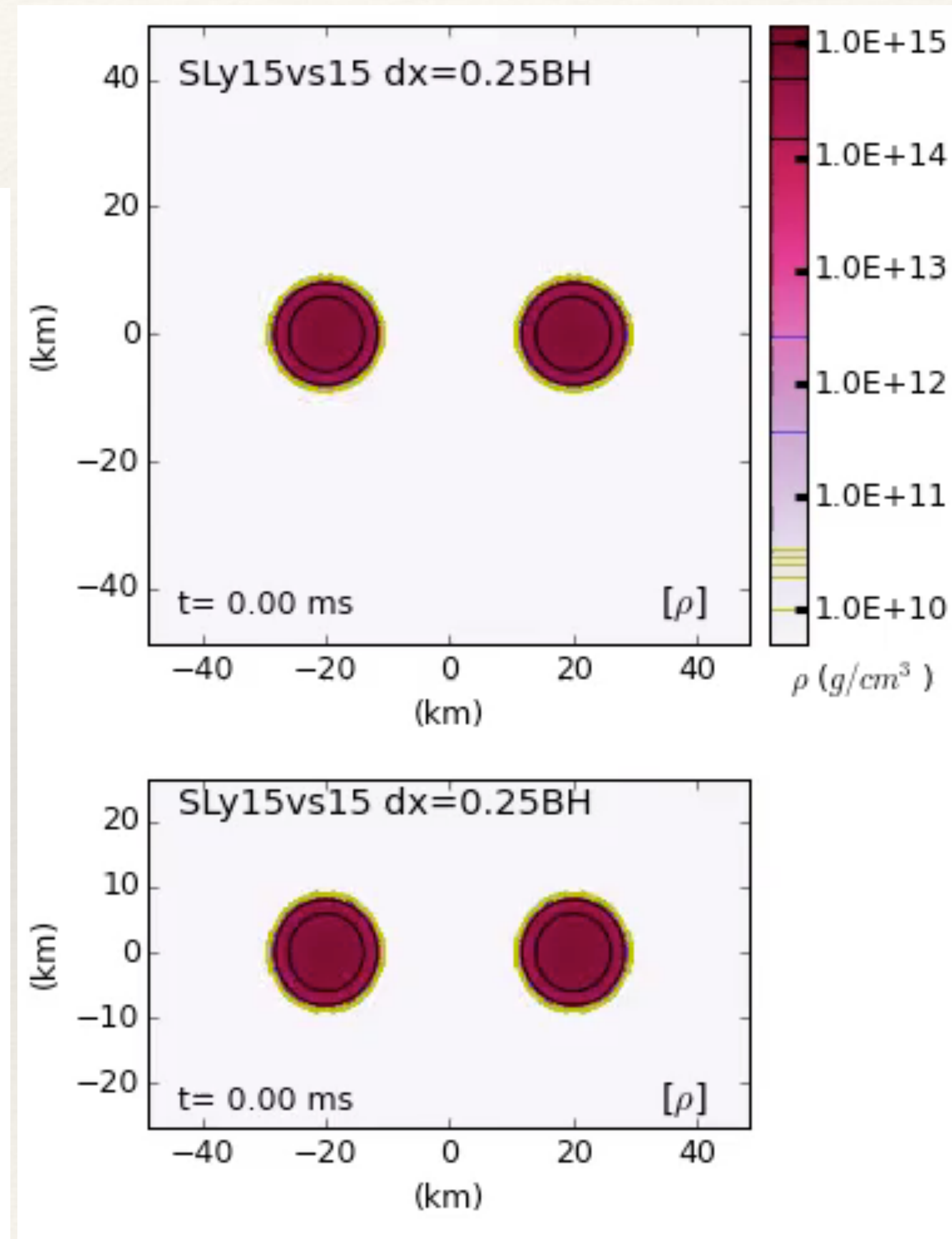
SLy15vs15

Model	dx=0.50	dx=0.375	dx=0.25
Sly15vs15	6.11 ms	11.81 ms	7.36 ms

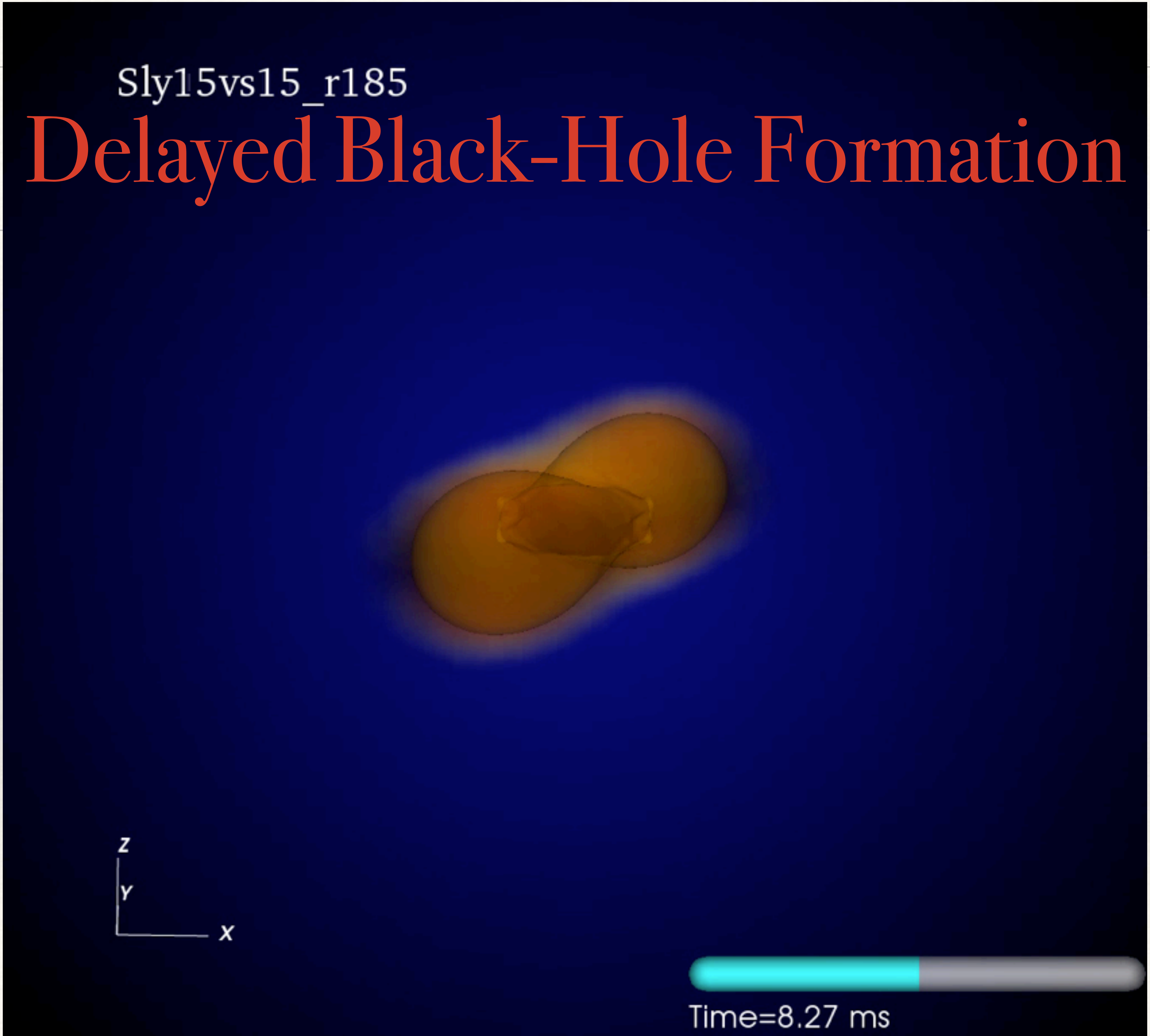






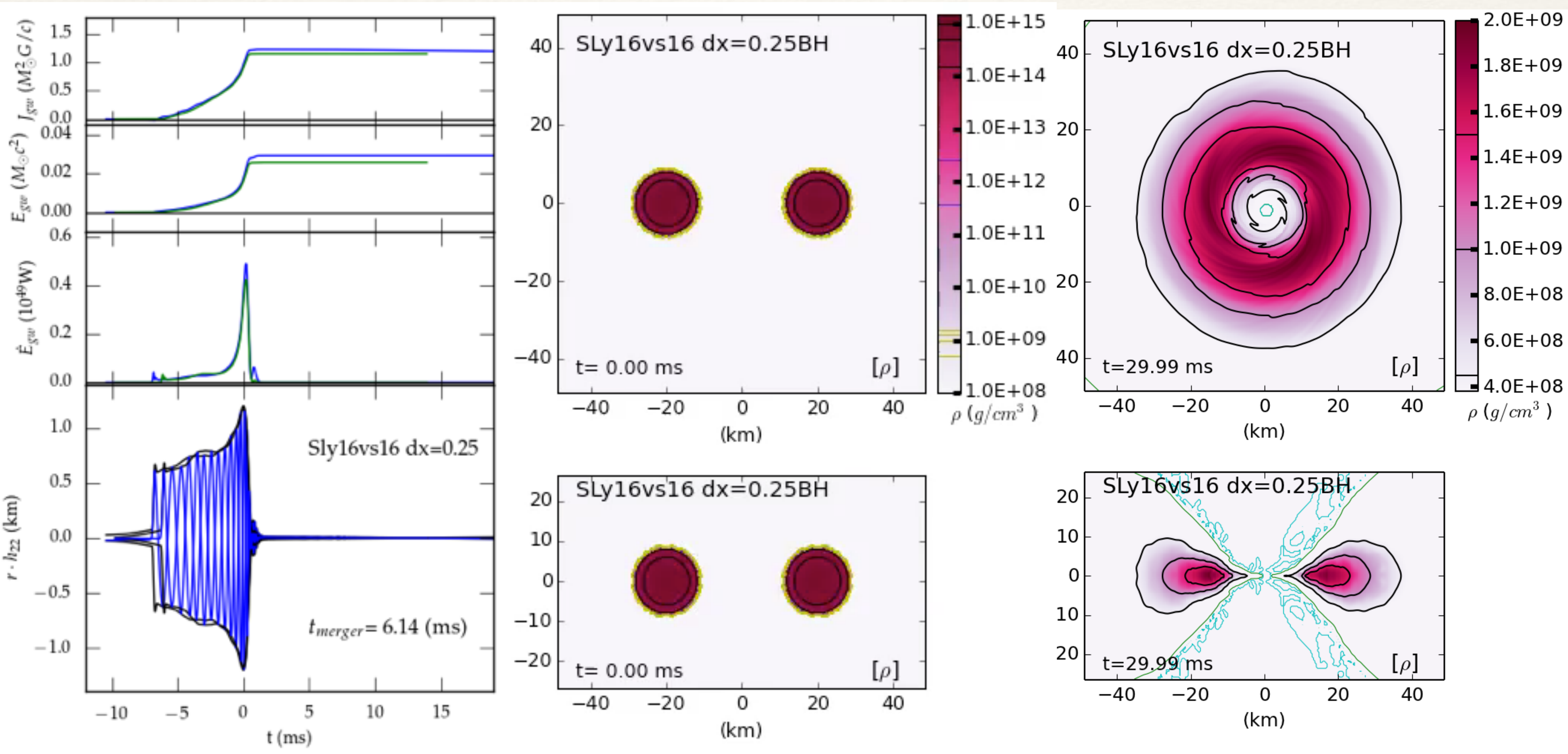


Delayed Black-Hole Formation



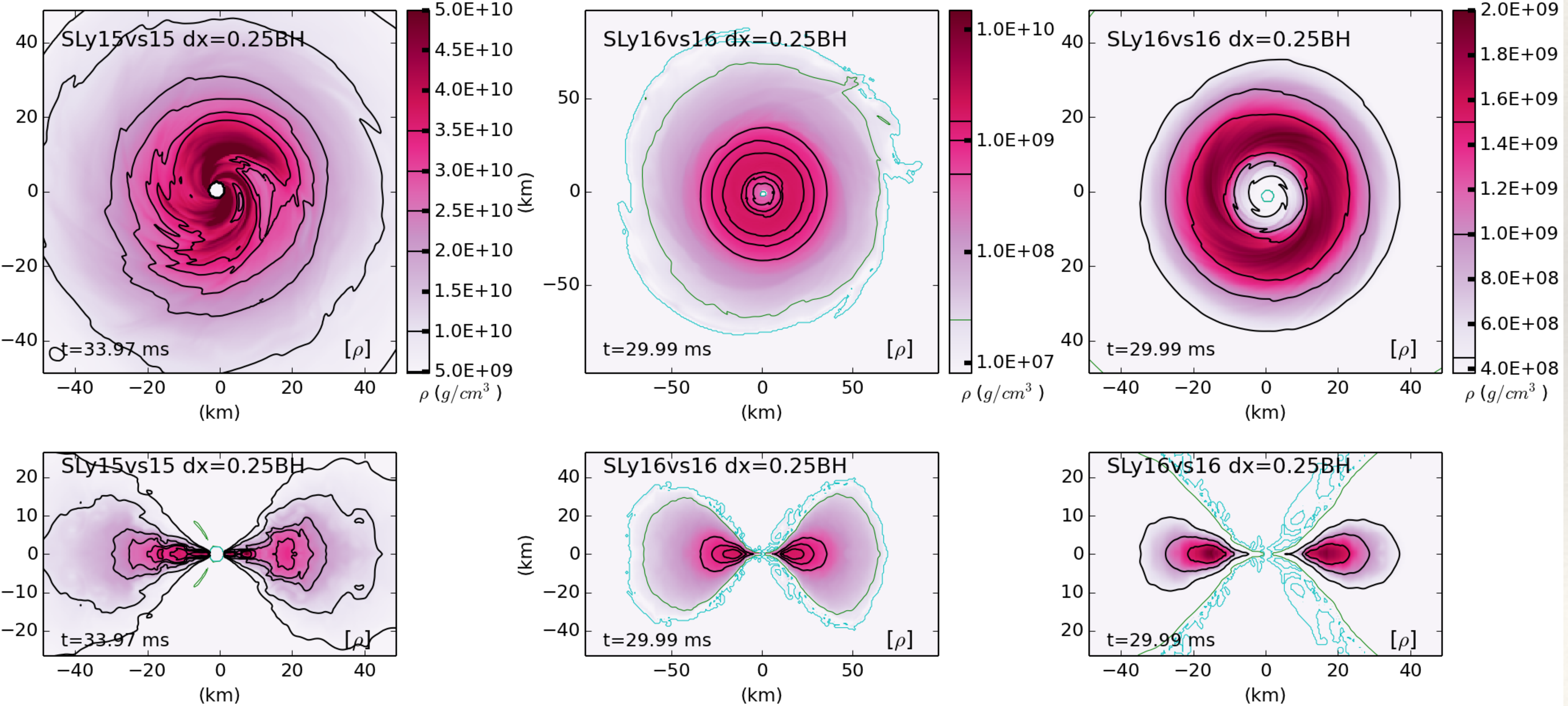
SLy16vs16

Model	dx=0.50	dx=0.375	dx=0.25
Sly16vs16	0.83 ms	0.81 ms	0.79 ms



Collapse time to Black Hole (after Merger)

Model	dx=0.50	dx=0.375	dx=0.25
Sly15vs15	6.11 ms	11.81 ms	7.36 ms
Sly16vs16	0.83 ms	0.81 ms	0.79 ms

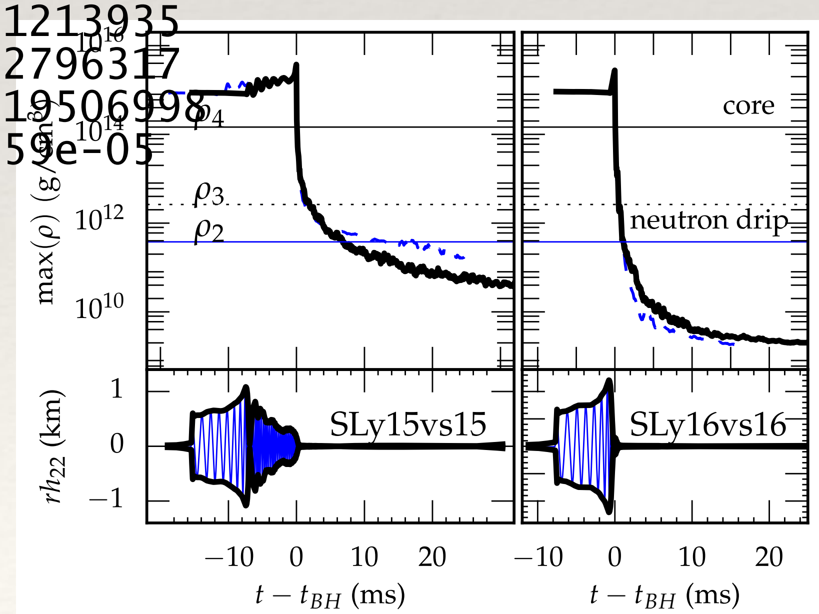


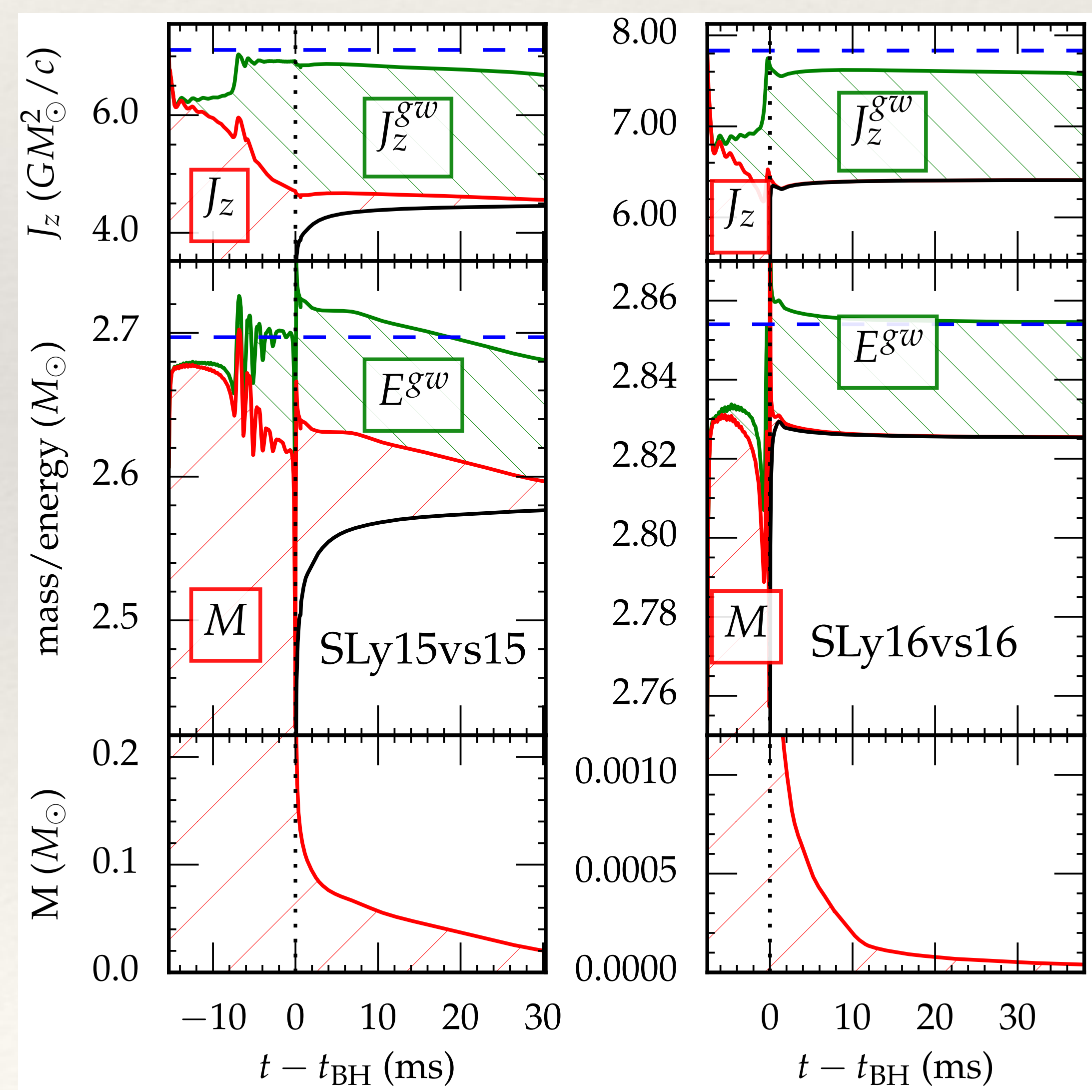
Collapse time to Black Hole (after Merger)

```
BUDGET for model 15vs15
   Final mass BH np.max(Mbh[0]) is: 2.57733745845
   Final J    BH np.max(Lbh[0]) is: 4.46170131712
   Mass in disk  np.min(MATTER) is: 0.0162523005579
   Total simulated time after BH  : 33.9091725788
   Values 25 ms after BH formation
        BH M      =  2.57531472352
        BH J      =  4.44682924429
        BH J/M^2 =  0.670486181372
        Mass =  0.0278916700256
```

Model	dx=0.50	dx=0.375	dx=0.25
Sly15vs15	6.11 ms	11.81 ms	7.36 ms
Sly16vs16	0.83 ms	0.81 ms	0.79 ms

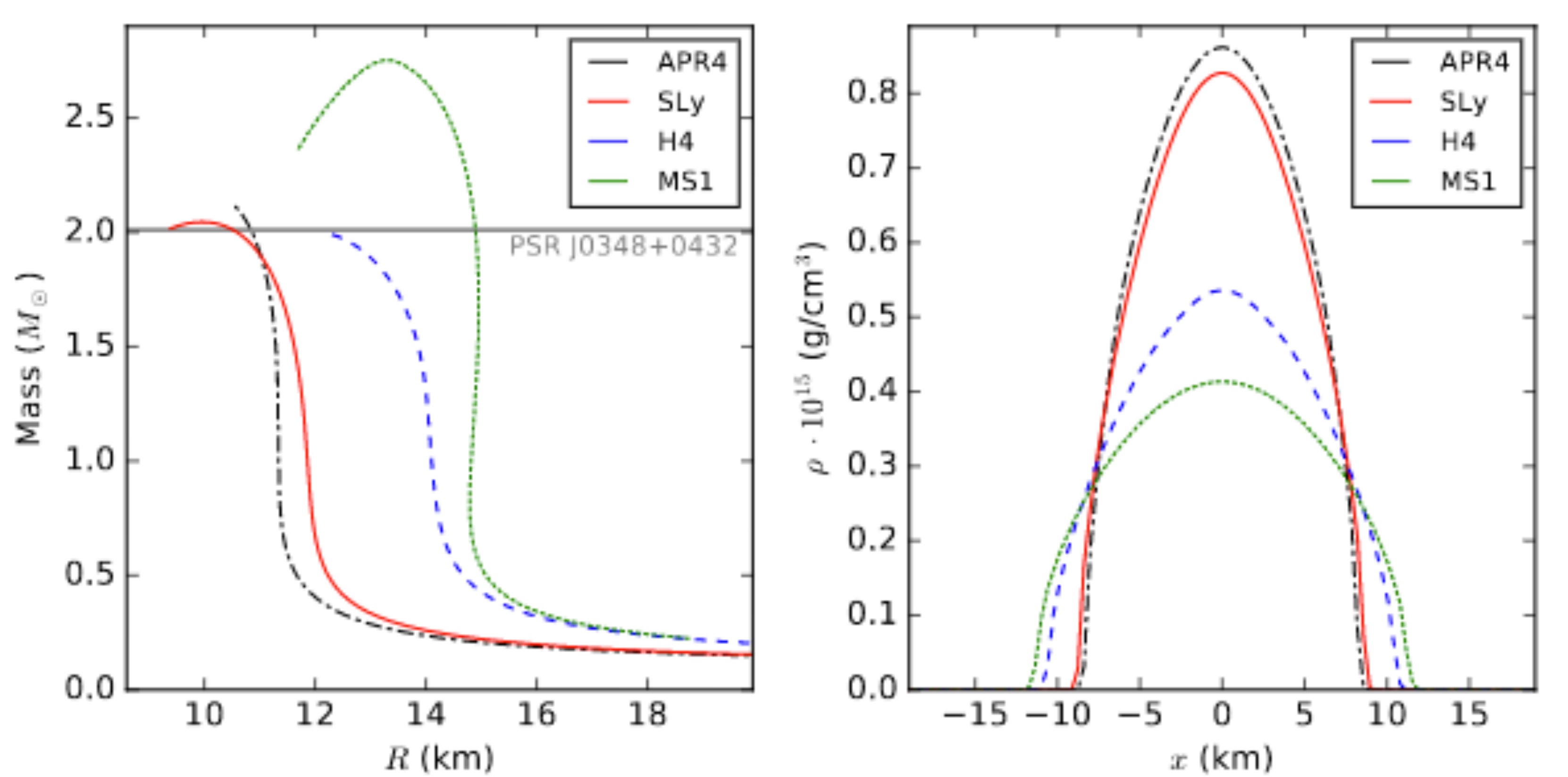
```
BUDGET for model 16vs16
   Final mass BH np.max(Mbh[1]) is: 2.82937414009
   Final J    BH np.max(Lbh[1]) is: 6.40877814116
   Mass in disk  np.min(MATTER) is: 3.60524241442e-05
   Total simulated time after BH  : 41.6623738628
   Values 25 ms after BH formation
        BH M      =  2.82551213935
        BH J      =  6.40772796317
        BH J/M^2 =  0.802619506998
        Mass =  6.18757282599e-05
```





Multi orbits simulations (four different EOS)

- APR4 EOS obtained using variational chain summation methods with the Argonne two-nucleon interaction and including also boost corrections and three-nucleon interactions
- The SLy EOS based on the Skyrme Lyon effective nuclear interaction
- The H4 EOS constructed in a relativistic mean field framework including also Hyperons contributions and tuning the parameters to have the stiffest possible EOS compatible with astrophysical data
- The MS1 EOS constructed with relativistic mean field theory considering only standard nuclear matter.



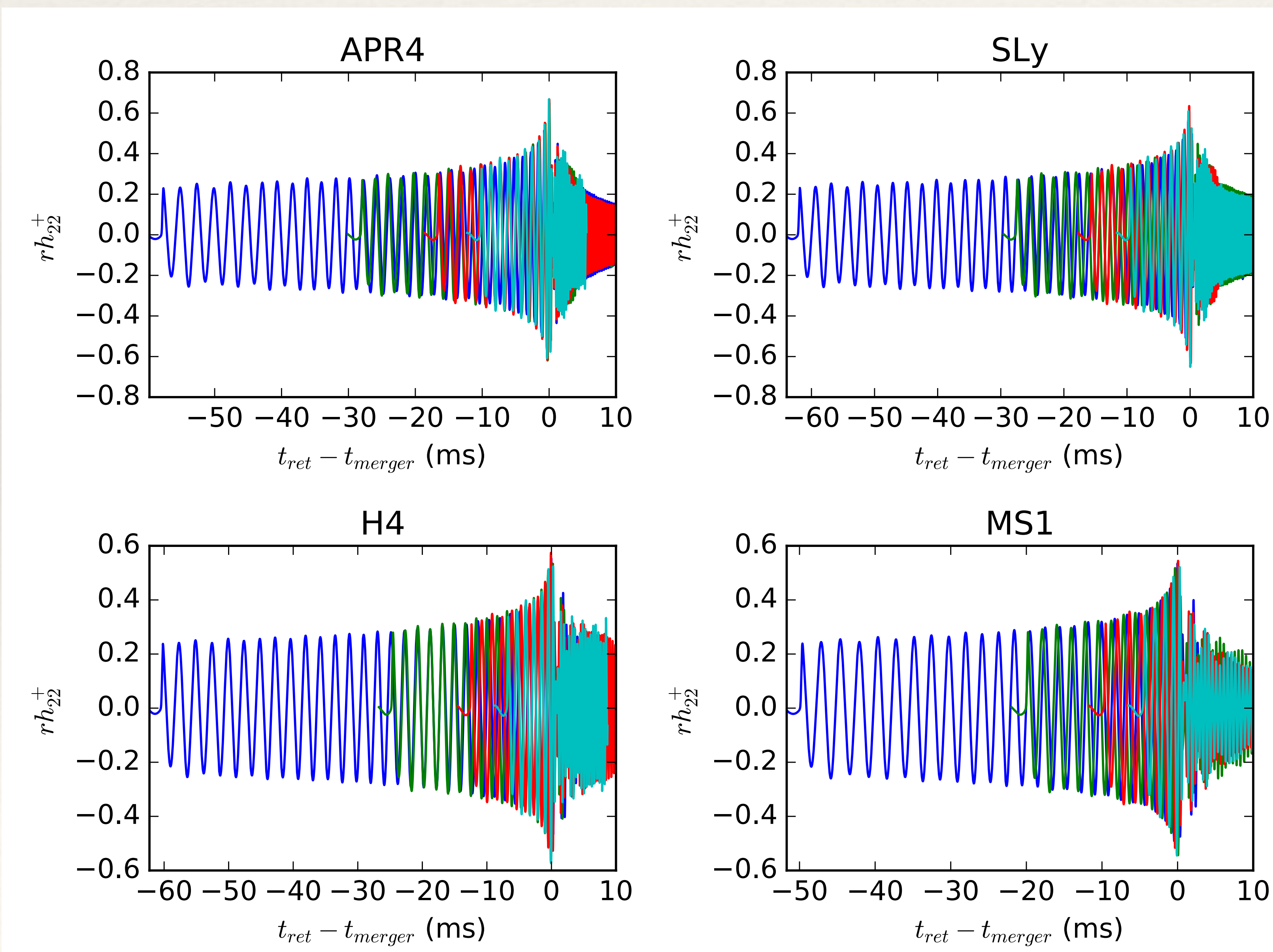
(a) Mass-Radius relations (b) Initial density profiles

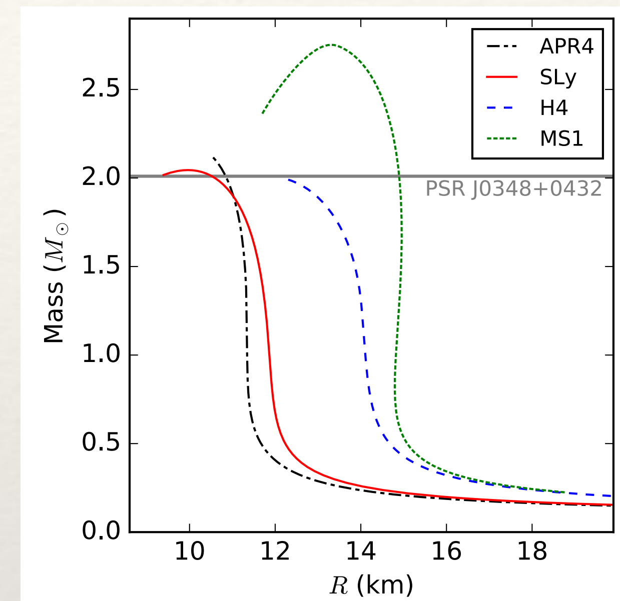
We present new long term (up to 16 orbits) equal mass BNS simulations with four different EOS, starting with four different values of the star center d=(40,44.3,50,60)Km.

The true EOS for nuclear matter in a system similar to a NS is still unknown, not even assuming a small effect on the temperature, i.e., cold neutron star, as expected here for initial data.

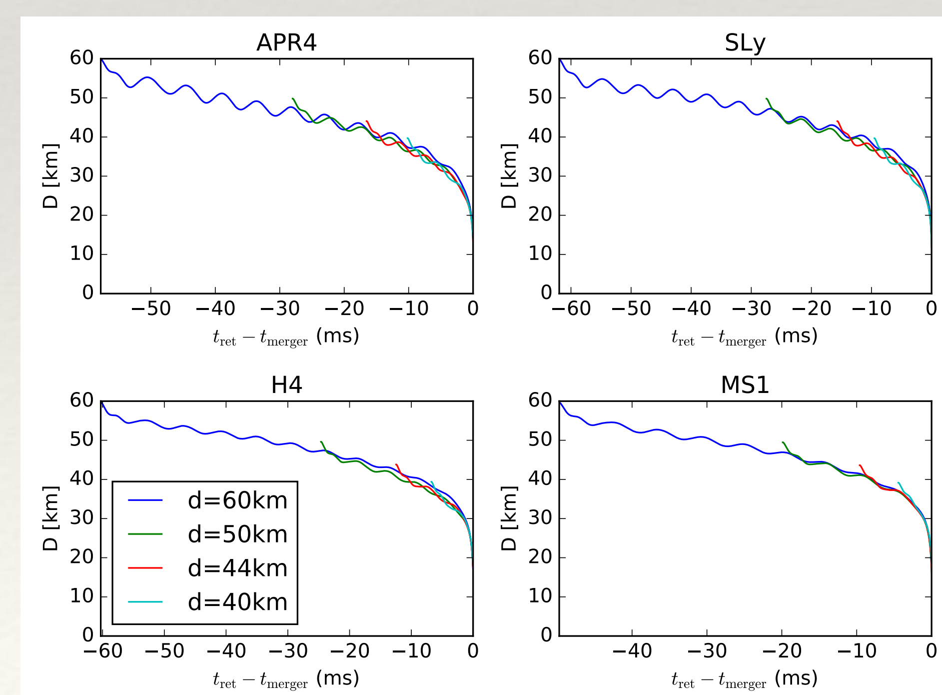
Multi Orbits simulations

- Simulation starting from different initial distance of the two stars (d=40,44.3,50,60 km) and different EOS





Separation as function of time (eccentricity)



Conclusions

- With the first detection of GWs the era of Gravitational waves astronomy just started.
- Long term simulation of BNS mergers using only public codes: **You can re-run all the models on your own**.
- It is possible to check the code on a laptop … (Using our setting).
- All the simulation presented here were performed on Tier-1 system.
- More insight improving the resolution of the simulation.
- Confirmation of previous results published in literature.
- Just a starting point for new research ….

What's next ?

- Investigate dependence of collapse time on resolution and EoS.
- Matter expelled not-axisymmetrically during merger => study accretion disk formation, mass, composition and development to an equilibrium configuration.
- Can (magneto)hydrodynamical instabilities develop in the disk?
- (Black hole like) kicks from linear momentum emitted in gravitational waves and unbound matter expelled not-axisymmetrically.
- Realistic treatment of EOS thermal component (ex. Using finite temperature EOS from relativistic mean field theory like Shen EOS).
- Simulations with magnetic fields to study the development of magnetic instabilities during the merger (Kelvin-Helmotz), in the hypermassive NS and the accretion disk (MRI).
- Studying possible electromagnetic and jet emissions after collapse.
- Use of OpenMP4 to test at least part of the code on GPUs and Intel MICs.